The scaling relations of star formation and cold gas on galactic scales

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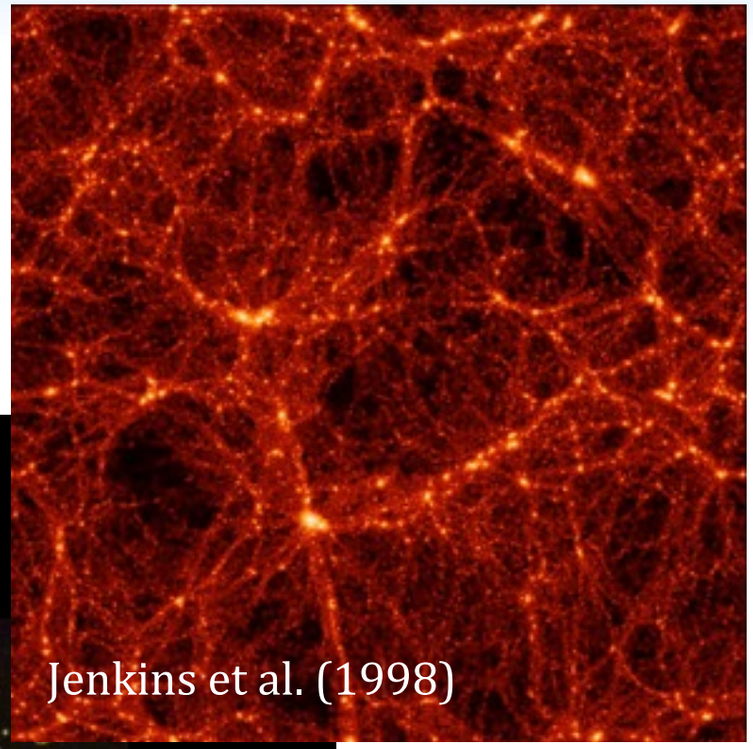
w/ G. Accurso, T. Bisbas, S. Viti, and the xCOLD GASS team

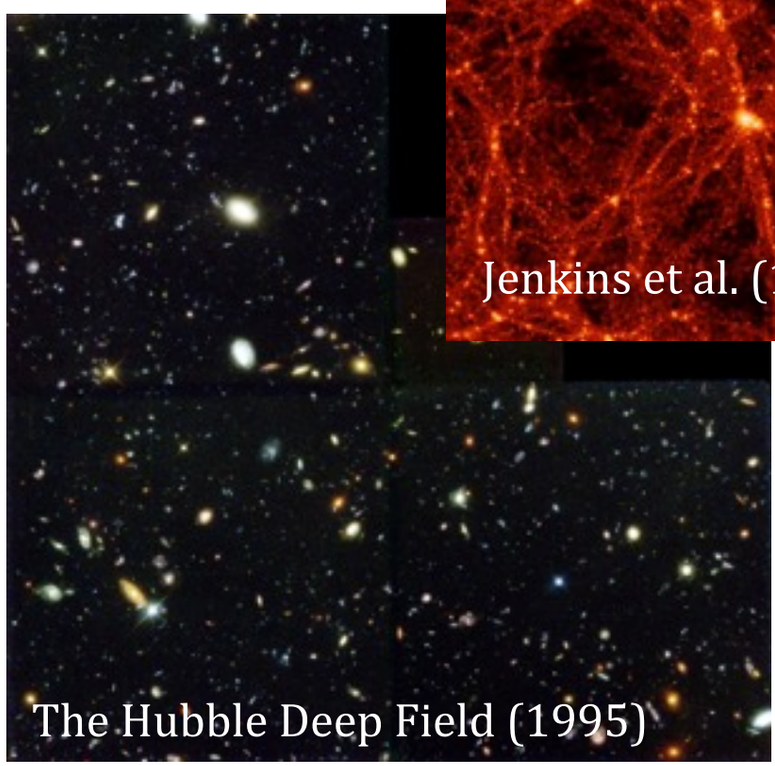
UCL

THE ROYAL SOCIETY

mid 1990s: Observations and theory suggest galaxy evolution is merger-driven

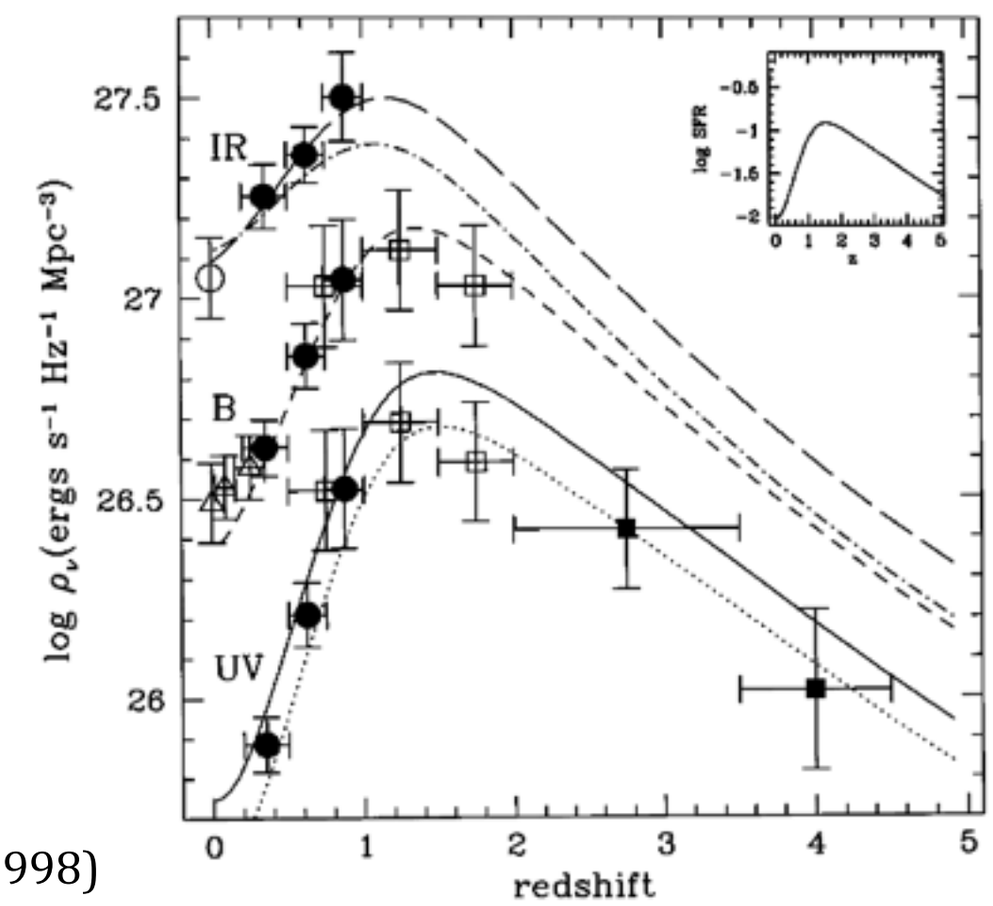


Jenkins et al. (1998)



The Hubble Deep Field (1995)

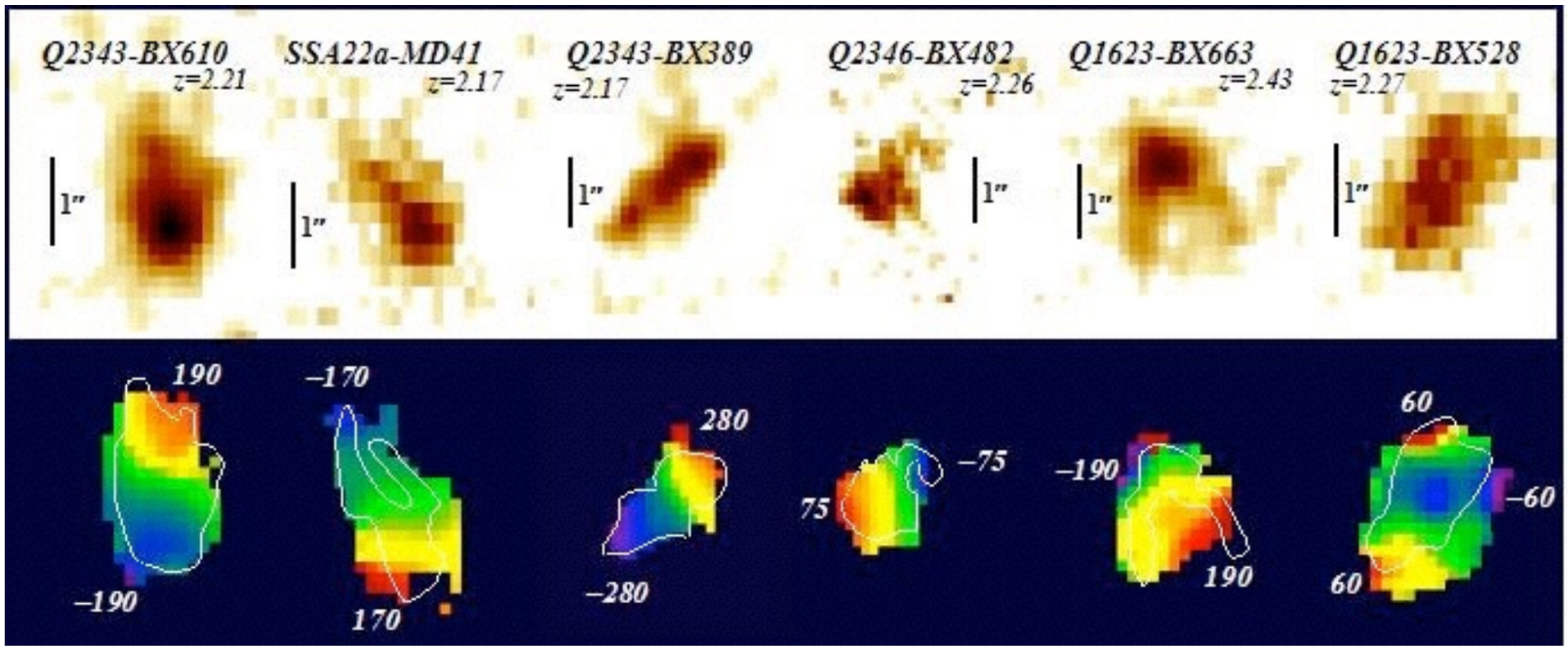
Deep HST field observations reveal:
- a population of high-redshift compact blue galaxies
- a significant number of distant galaxies with irregular morphologies.
- the redshift evolution of the SFR density in the Universe



Madau et al (1998)

In the local Universe, galaxies with such high SFRs are major mergers, so…

early 2000s: near-IR integral field spectroscopy revels that the clumpy, highly star-forming distant galaxies are in fact kinematically normal rotating discs.

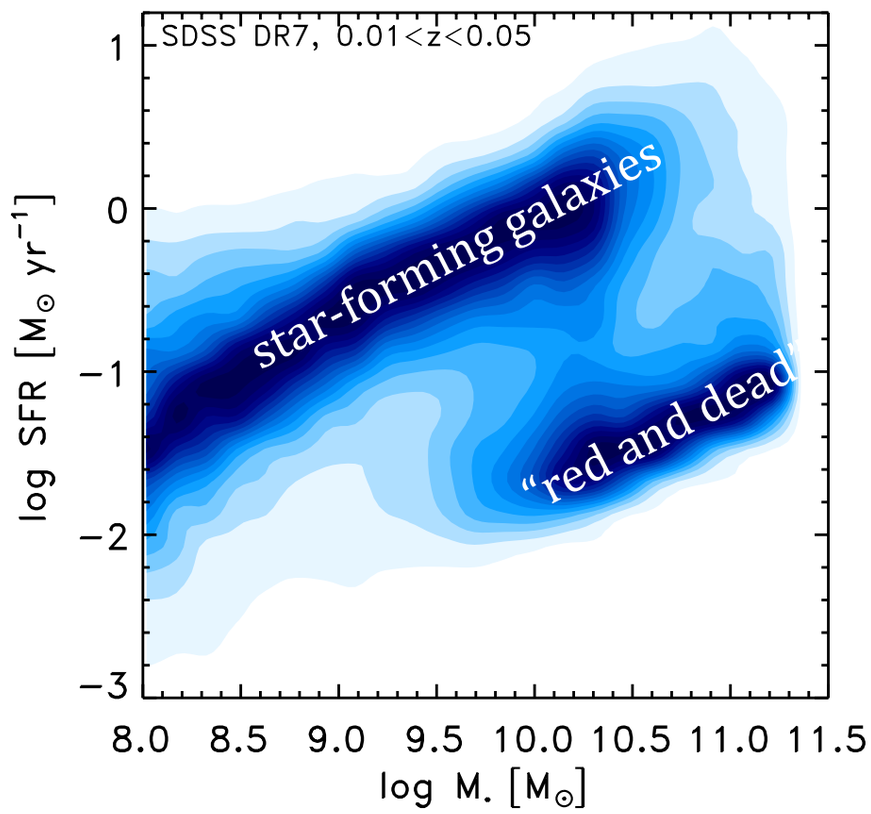


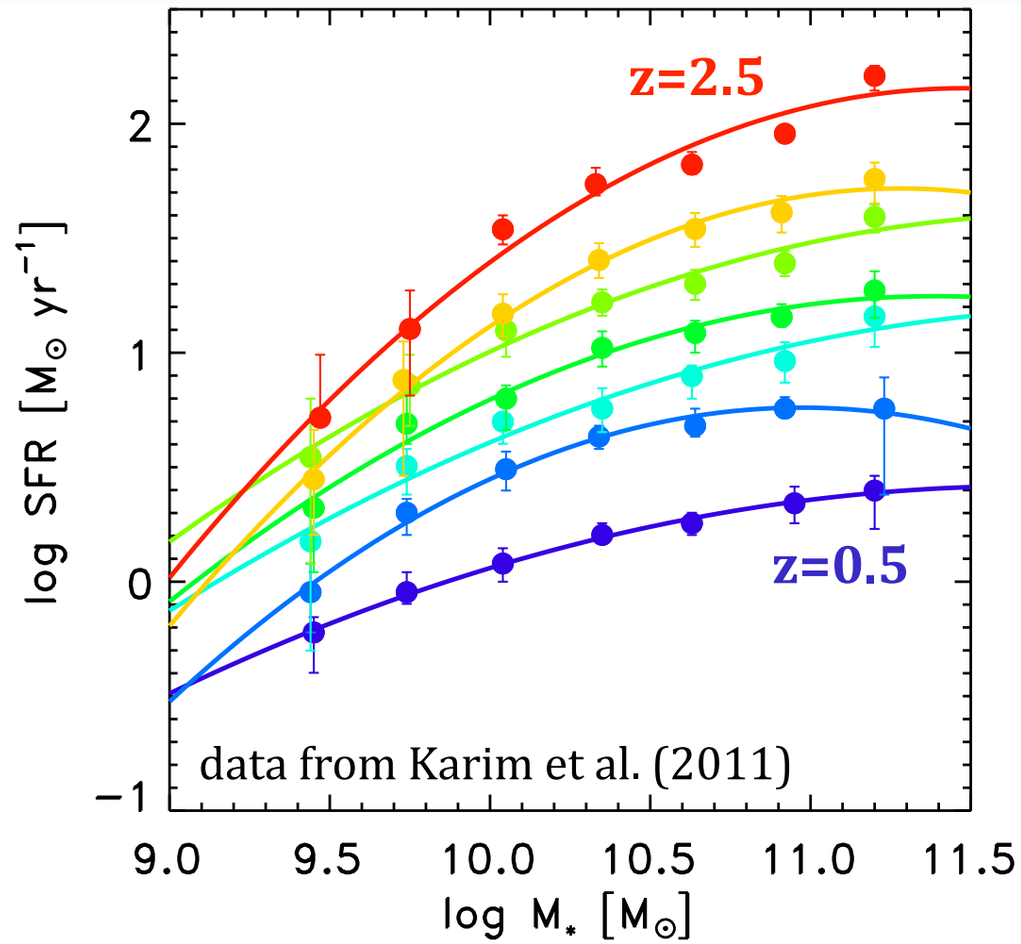
Forster Schreiber et al. (2006)

late 2000s: far-IR and other long wavelength studies allow for robust SFRs at high redshift and a simple global observational picture emerges

the star formation "main sequence"

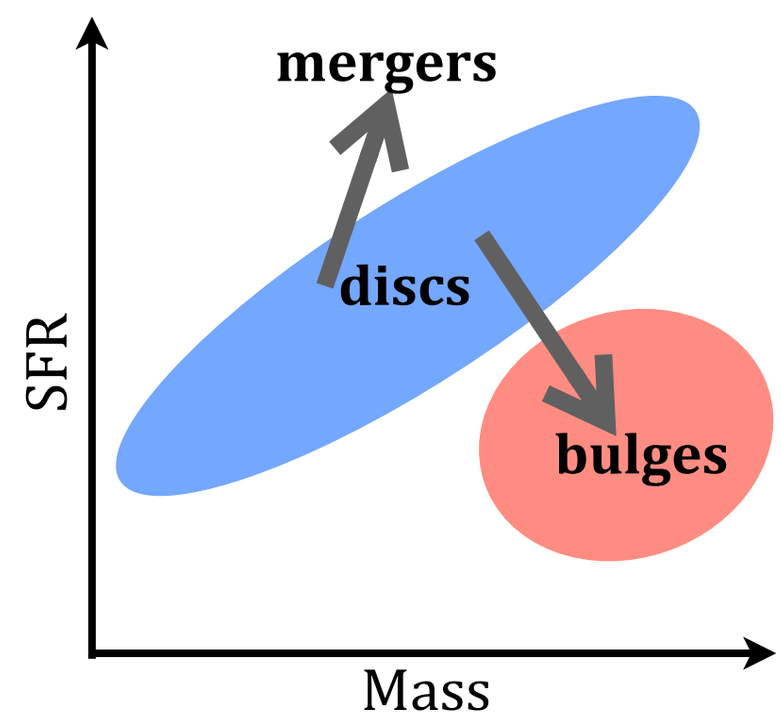
see e.g.: Schiminovich et al. (2007), Elbaz et al. (2007), Noeske et al. (2007), Daddi et al. (2007), Perez-Gonzalez et al. (2008), Peng et al. (2010)





$SFR \sim M_*^a(1+z)^b$, where a~0.8, b~2.5

- Galaxies on the main sequence (MS) contribute ~90% of the star formation.
- Duty cycles on the MS are high at 40-70% implying that "catastrophic" events like **major mergers cannot be the main agent responsible for regulating star formation.**



2010: mm-wave observatories now able to detect molecular gas in high redshift normal star-forming galaxies

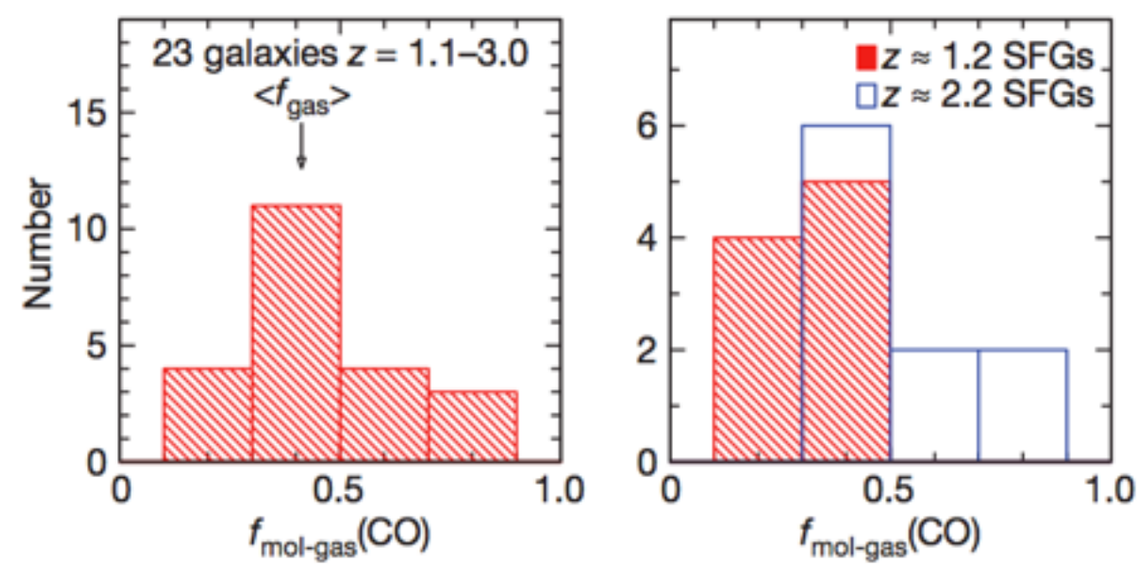
Vol 463|11 February 2010|doi:10.1038/nature08773 nature

LETTERS

High molecular gas fractions in normal massive star-forming galaxies in the young Universe

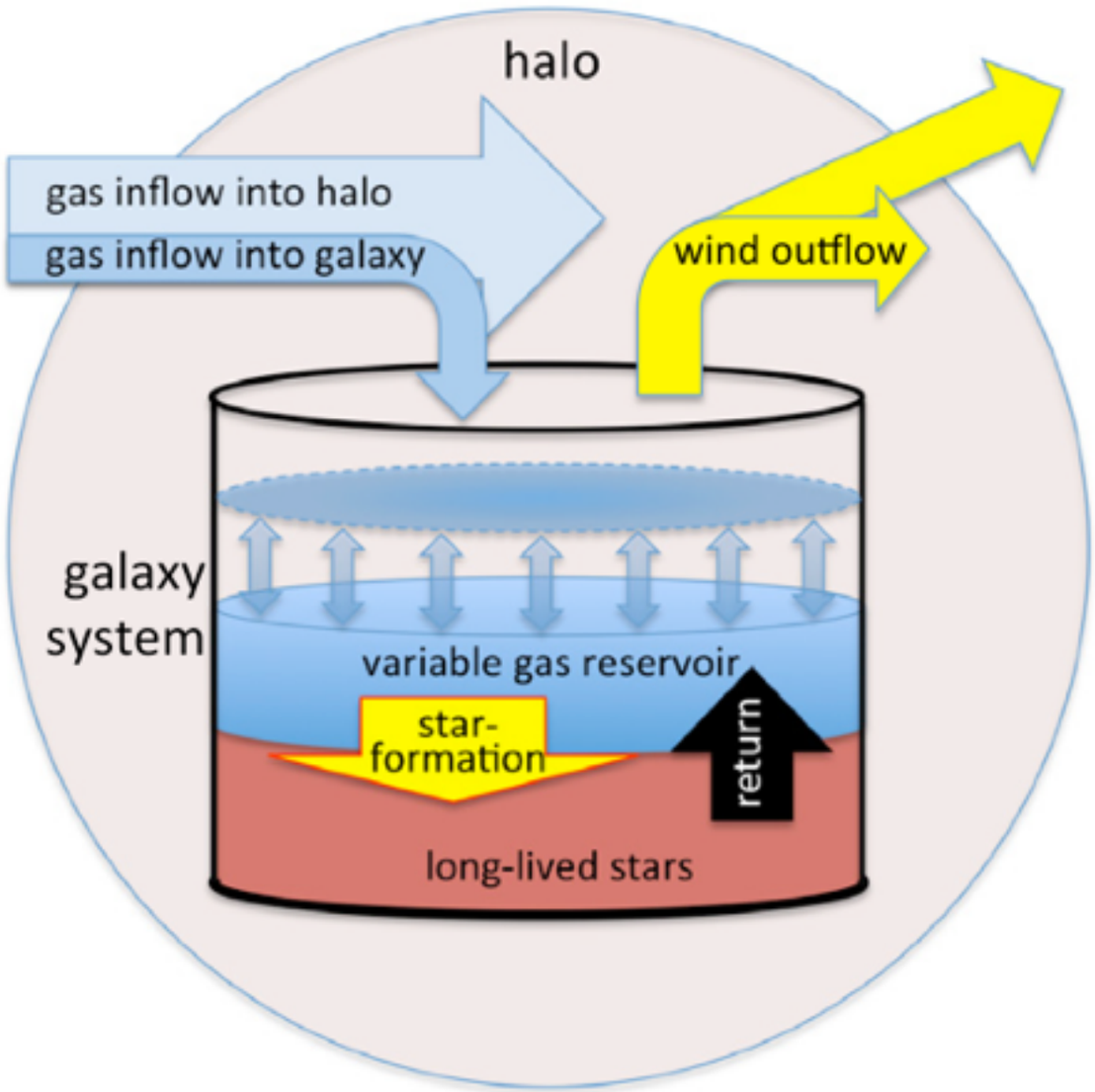
L. J. Tacconi[1], R. Genzel[1,2], R. Neri[3], P. Cox[3], M. C. Cooper[4], K. Shapiro[5], A. Bolatto[6], N. Bouché[1], F. Bournaud[7], A. Burkert[8], F. Combes[9], J. Comerford[5], M. Davis[5], N. M. Förster Schreiber[1], S. Garcia-Burillo[10], J. Gracia-Carpio[1], D. Lutz[1], T. Naab[8], A. Omont[11], A. Shapley[12], A. Sternberg[13] & B. Weiner[4]

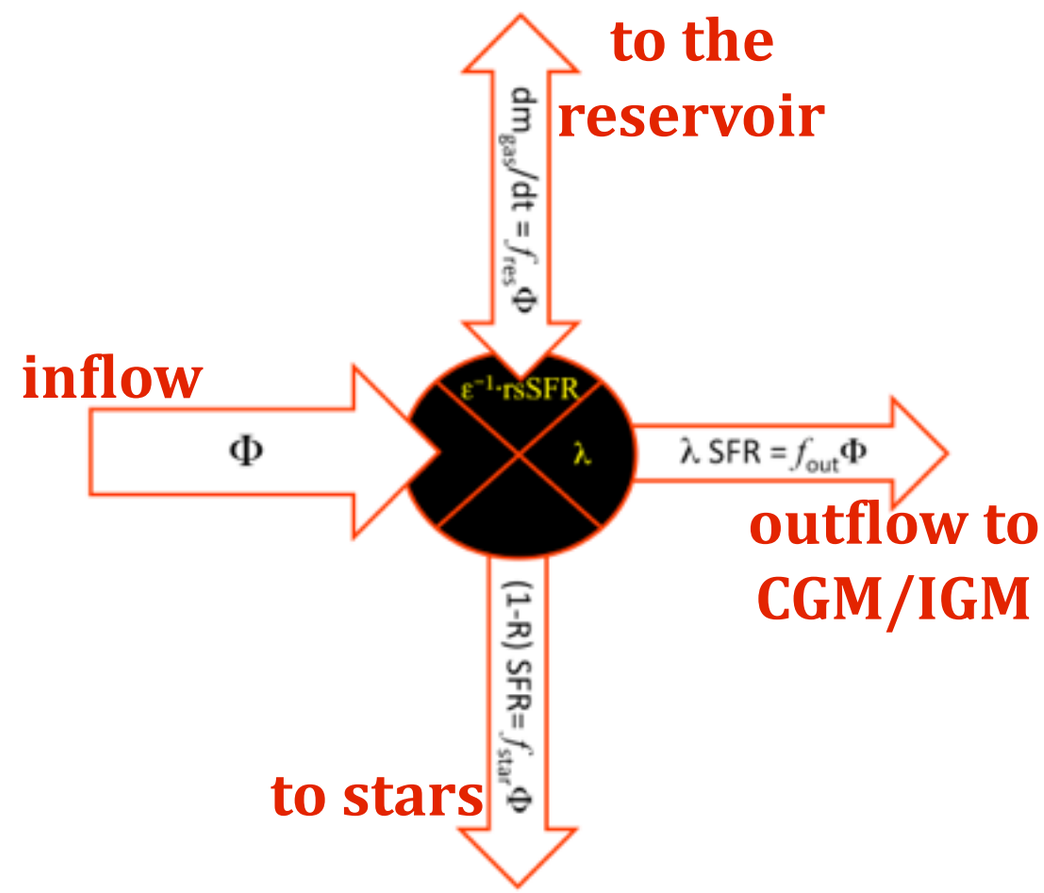
Sensitive instrumentation finally allows for the detection of CO in high-redshift *normal* galaxies.
Galaxies at high-z have large gas mass fraction, naturally explaining their very large SFRs.



See also Daddi et al. (2010)

2010+: simple analytical models for galaxy evolution centred on gas + new suite of hydro simulations

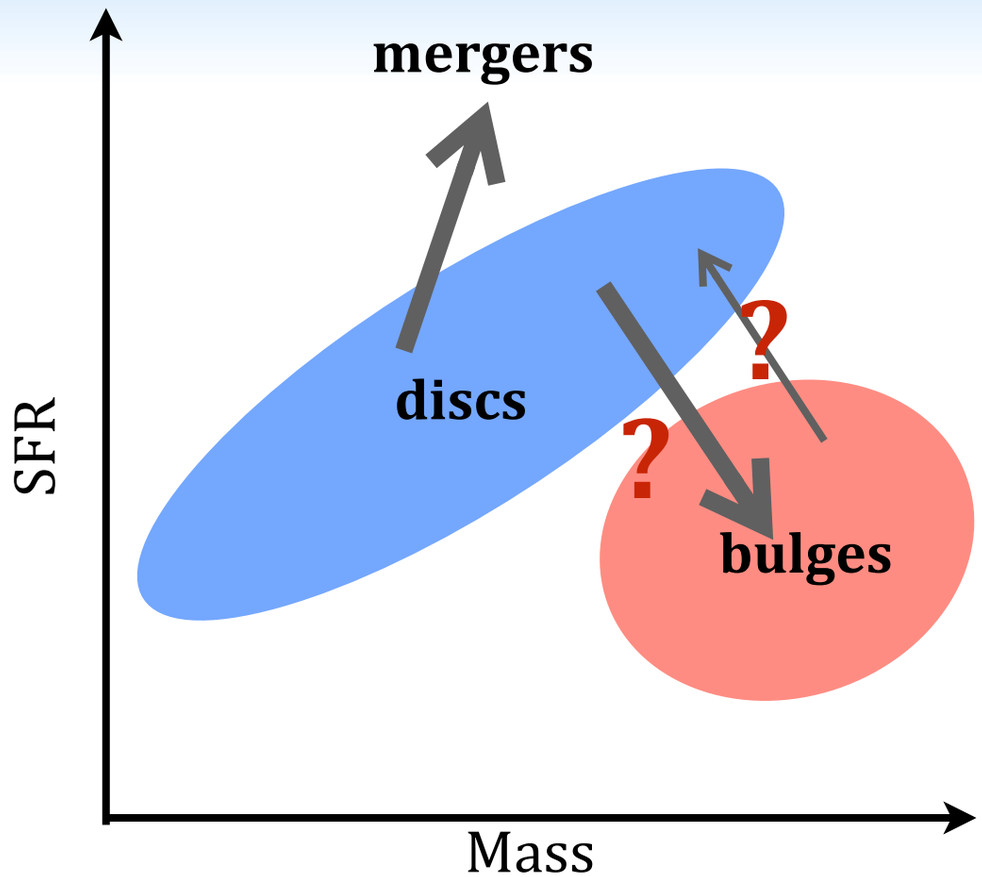




$$\Phi = (1 - R + \lambda) \cdot \mathrm{SFR} + \frac{dm_{\mathrm{gas}}}{dt}$$

Lilly et al. (2013), see also, e.g. Genel et al. (2008), Bouché et al. (2010), Davé et al. (2011,2012), Krumholz & Dekel (2012)

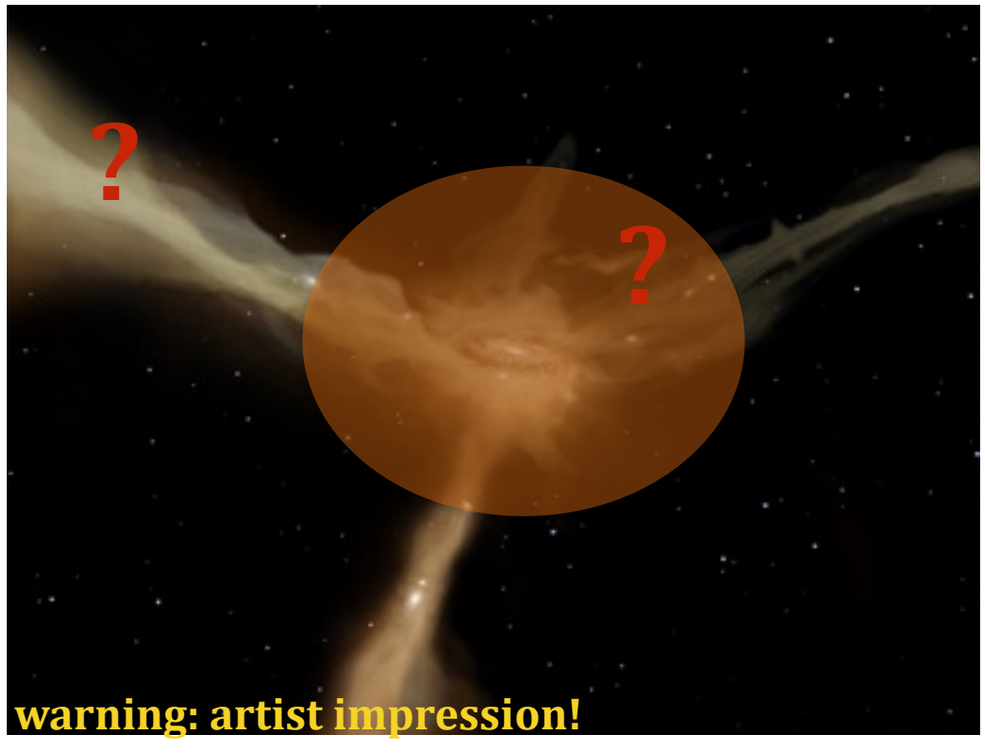
Many open questions in galaxy evolution / star formation



(1) Scaling relations between gas, star formation and global galaxy properties

(2) Star formation efficiency: extending studies to low mass/metallicity galaxies with a new alpha_CO conversion function

(3) Can we improve the accuracy of gas measurements on galactic scales? Exploring dust as a probe of the cold ISM



xCOLD GASS + PHIBSS: IRAM legacy surveys for galaxy evolution studies

direct molecular gas measurements for large, representative samples of ***normal star forming galaxies*** from both IRAM facilities

xCOLD GASS

PIs A. Saintonge (UCL) ,G. Kauffmann (MPA), C. Kramer (IRAM)

950h IRAM 30-m Large Programmes

+1500h Arecibo Programme for HI

500 SDSS-selected galaxies with 0.01<z<0.05, M*>109

see e.g. Saintonge et al. 2011a, 2016

PHIBSS

PIs L. Tacconi, R. Genzel (MPE), F. Combes (Paris)

500h IRAM PdBI Large Programmes

64 star forming galaxies with $1.0<z<2.5$, $3\times10^{10}<M^*<3\times10^{11}$

+ high-resolution follow-up

see e.g. Tacconi et al. 2010,2013, Genzel et al. 2010,2012,2013,2015 Freundlich et al. 2013.

Lensed galaxies

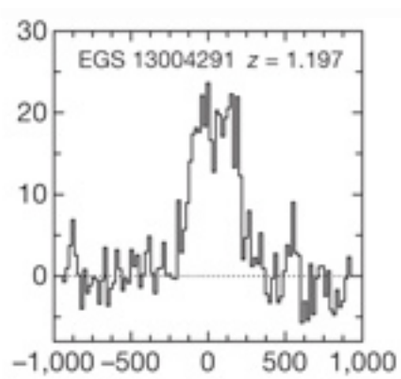
PI D. Lutz (MPE), A. Baker (Rutgers)

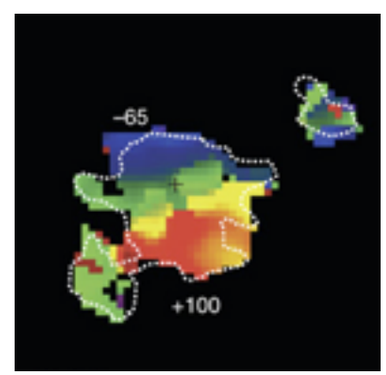
IRAM PdBI

17 lensed star forming galaxies with $1.5<z<3.1$, $M^*>10^9$

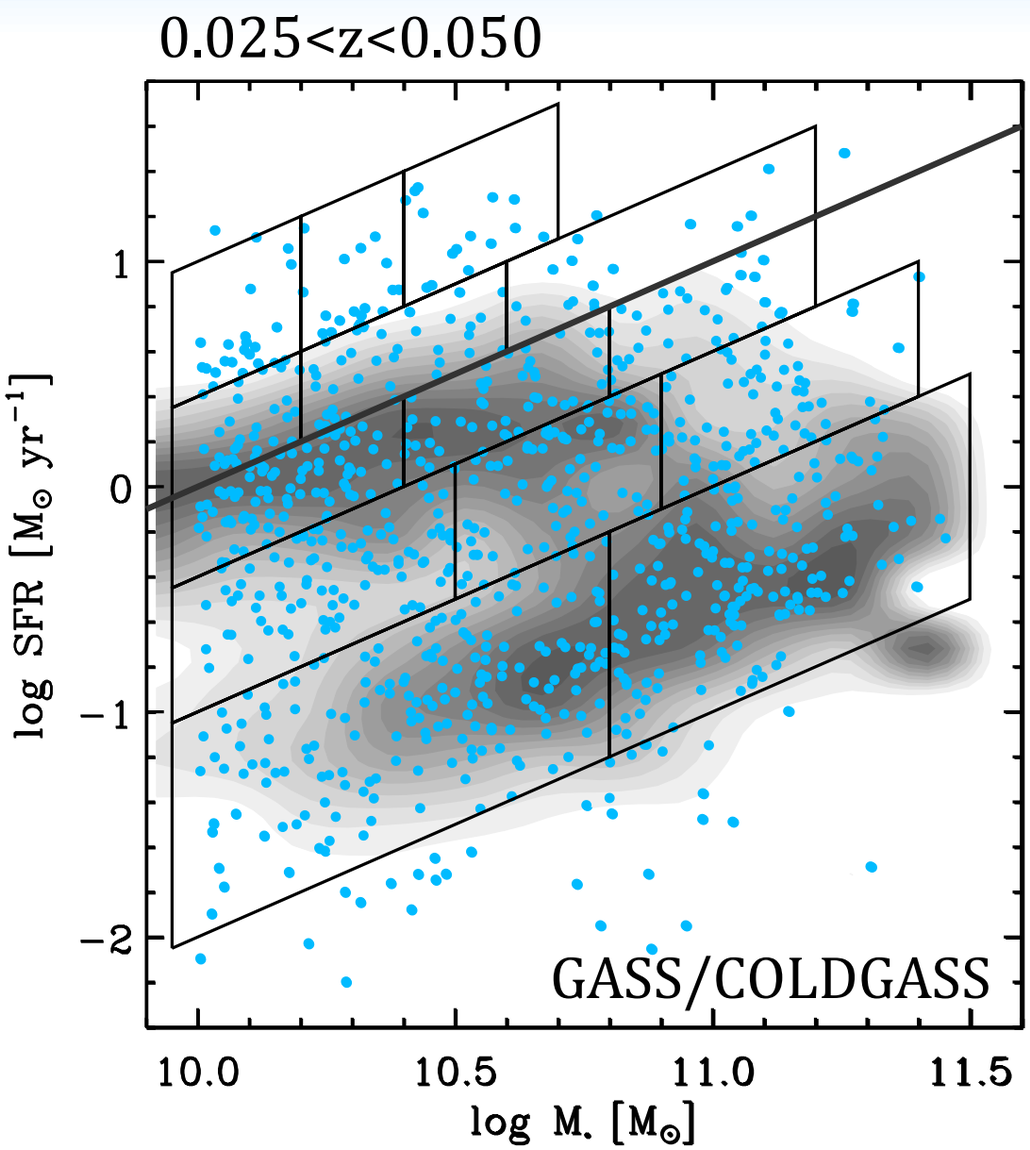
includes full Herschel PACS+SPIRE photometry

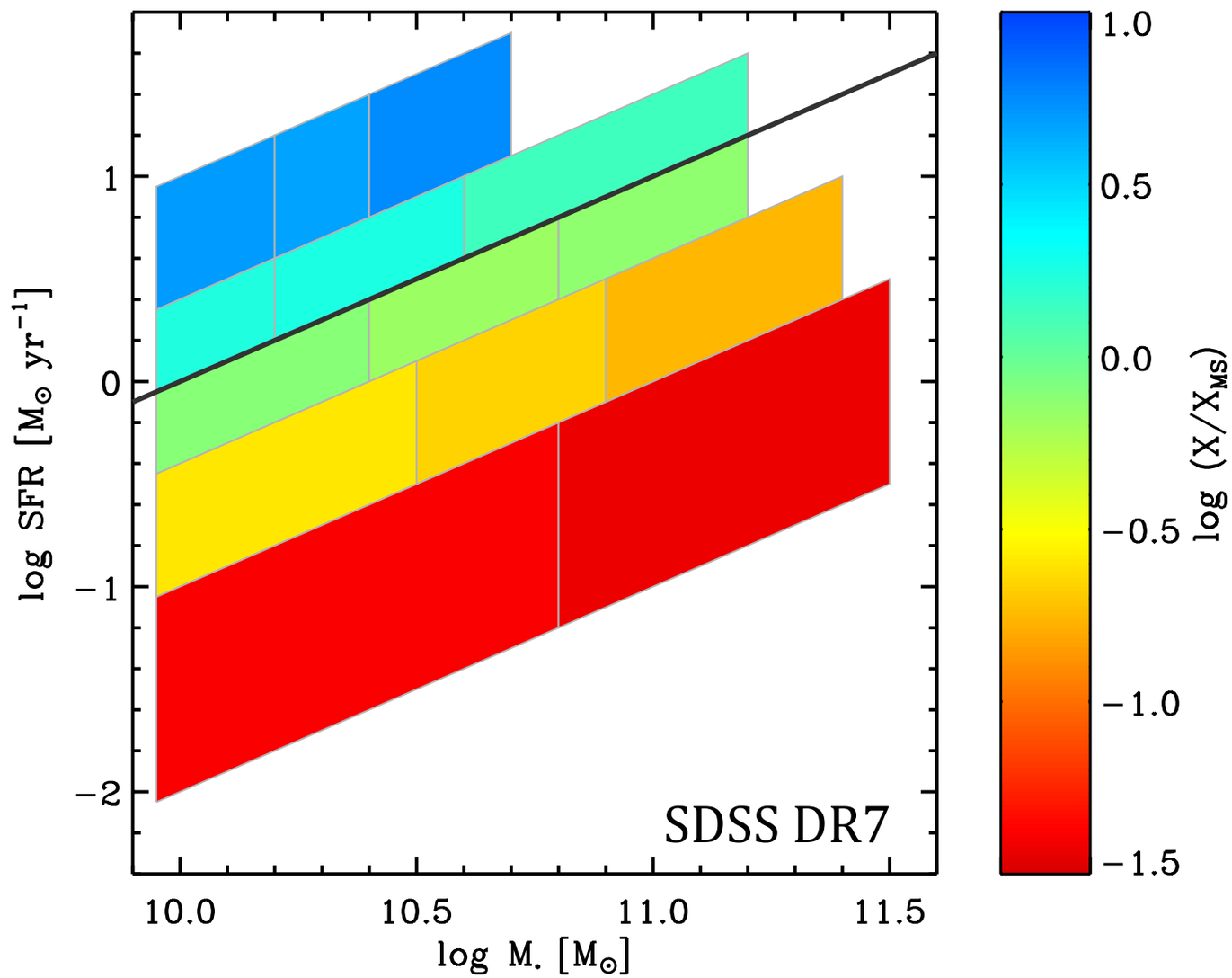
see Saintonge et al. 2013





Cold gas in the SFR-M* plane



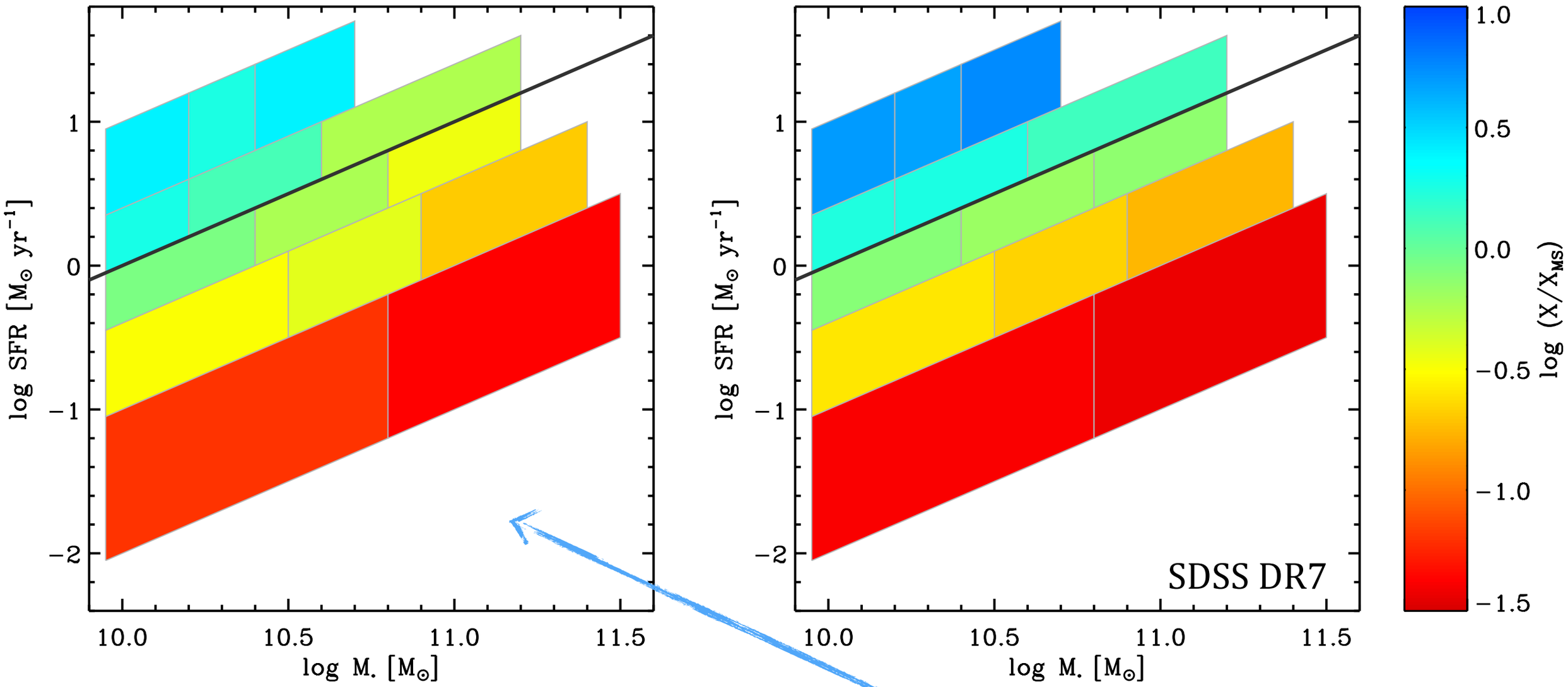


$$\mathrm{sSFR} = \frac{\mathrm{SFR}}{M_*} = \frac{M_{HI}}{M_*}\,\frac{M_{H2}}{M_{HI}}\,\frac{\mathrm{SFR}}{M_{H2}}$$

$$= f_{HI}\ R_{mol}\ \mathrm{SFE}$$

Saintonge et al. (2016)

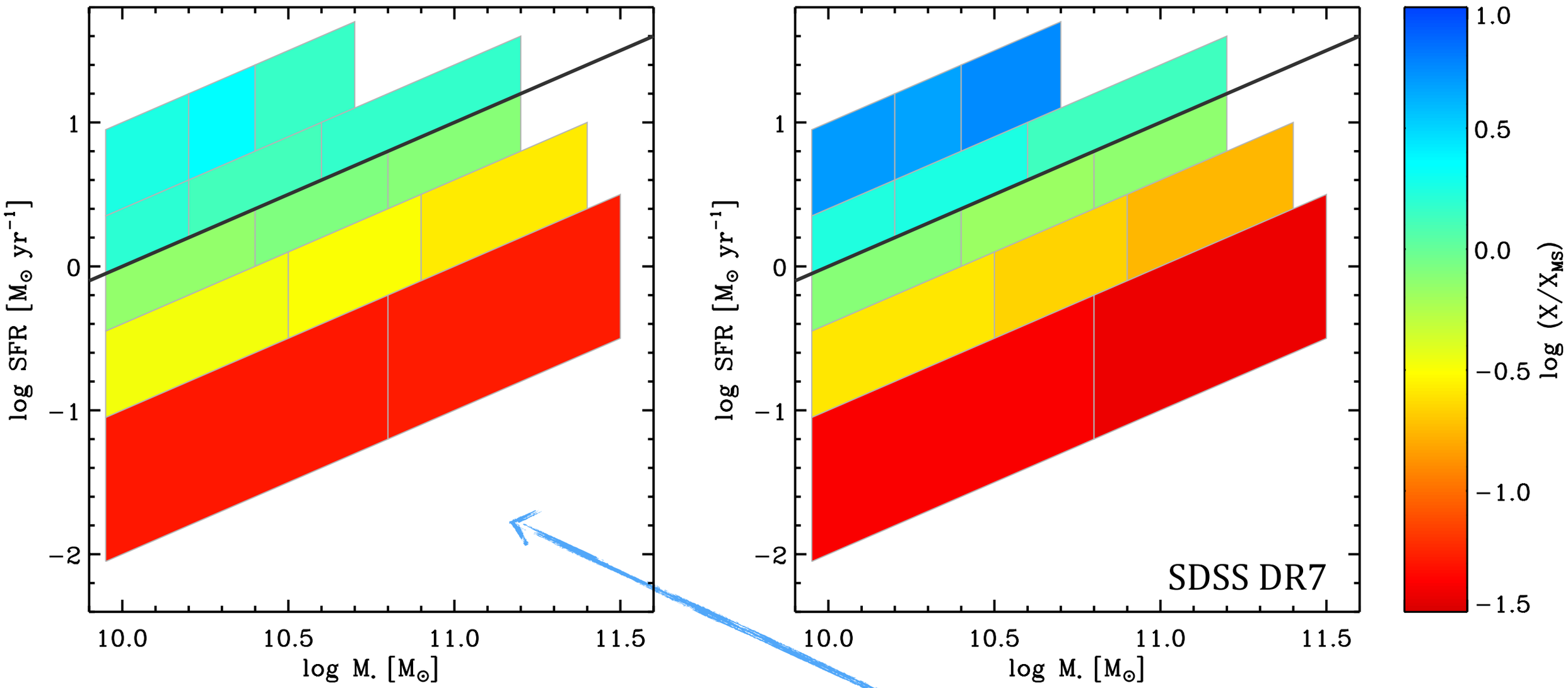
Cold gas in the SFR-M* plane



$$sSFR = f_{HI}\, R_{mol}\, SFE$$

HI contents varies mostly ***across*** the MS, but also ***along*** (high SFR+low M* = more HI)

Cold gas in the SFR-M* plane

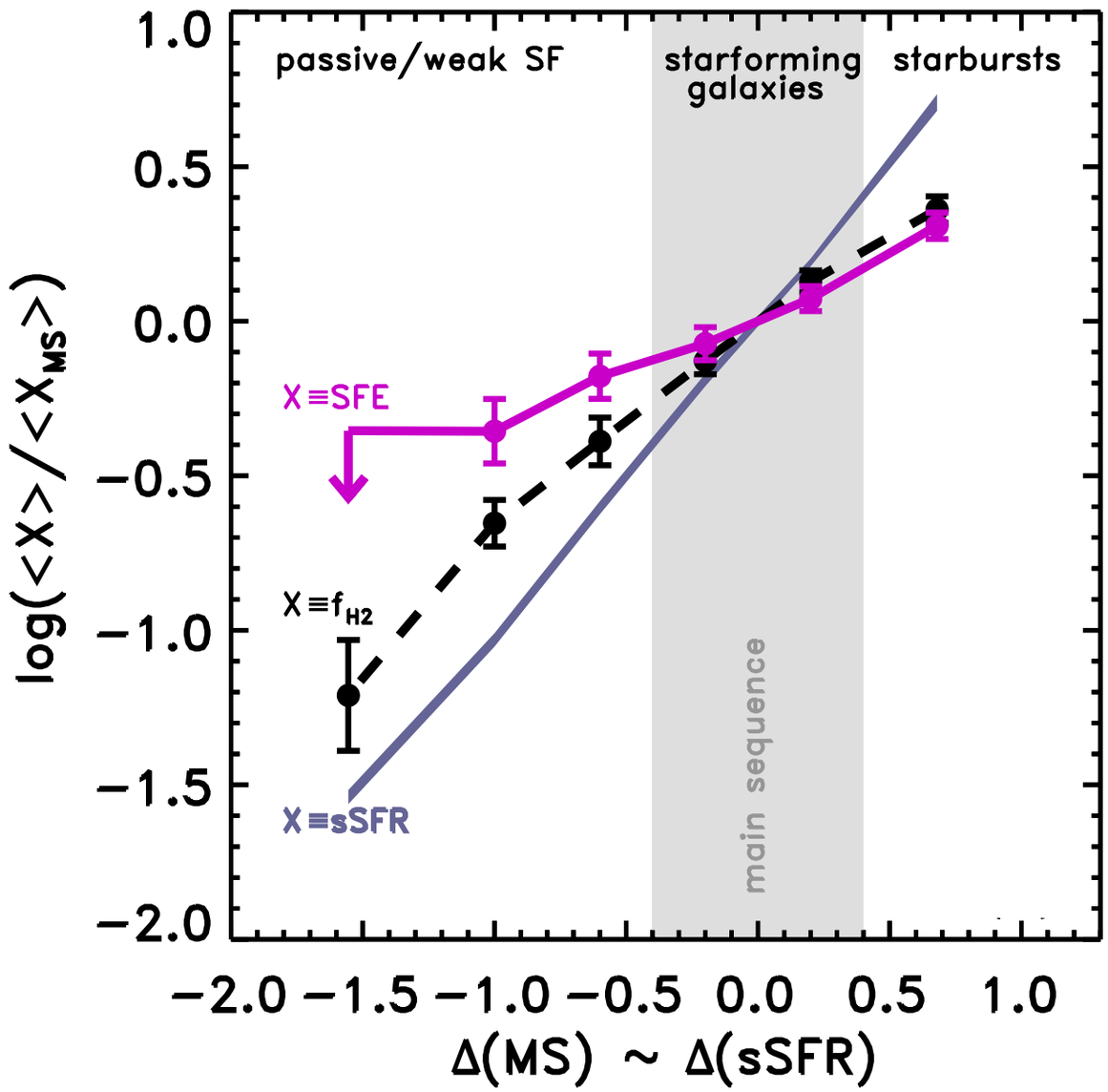


$$sSFR = f_{HI}\ R_{mol}\ SFE$$

$R_{mol} = f_{H2}$

H2 contents varies almost exclusively ***across*** the MS (high SFR = more H_2)

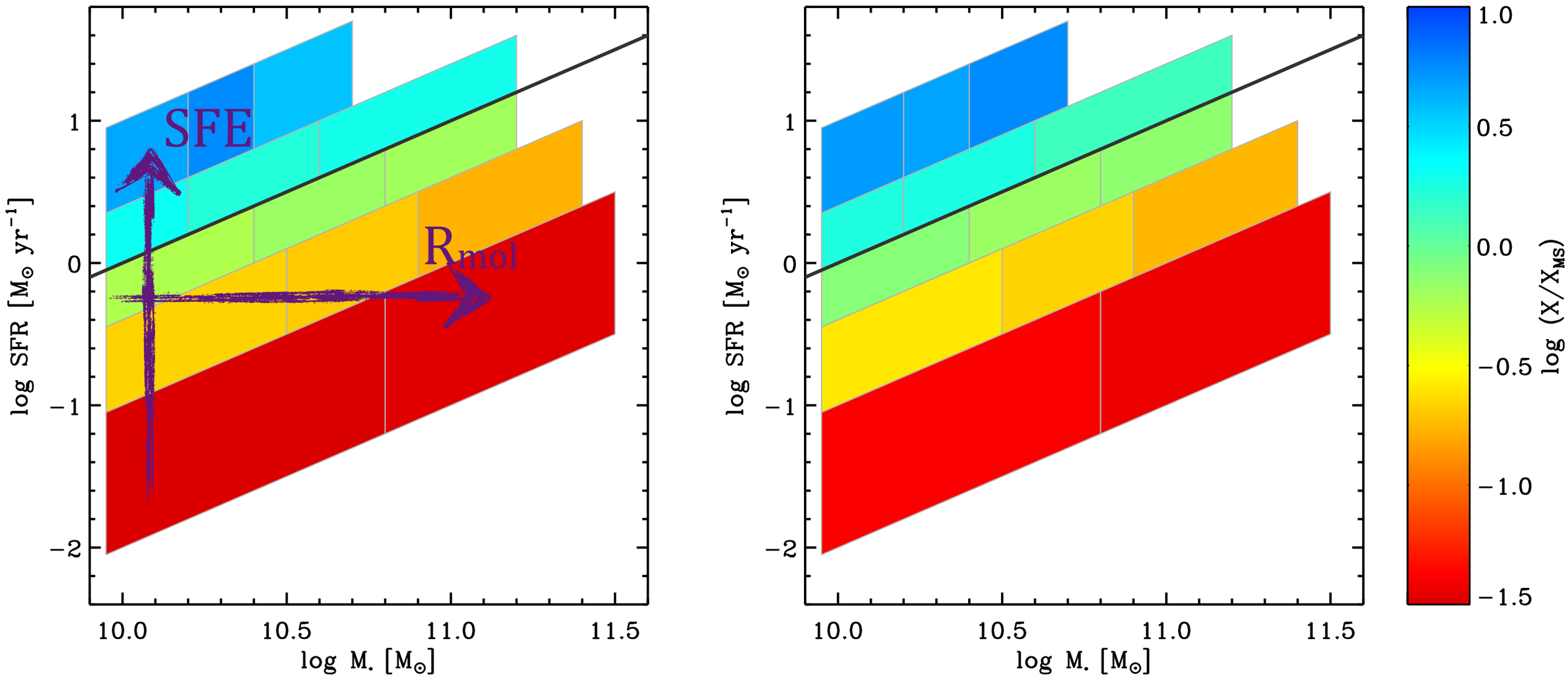
Cold gas in the SFR-M* plane



Saintonge et al. (2012)

BOTH H_2 contents and star formation efficiency vary ***across*** the MS

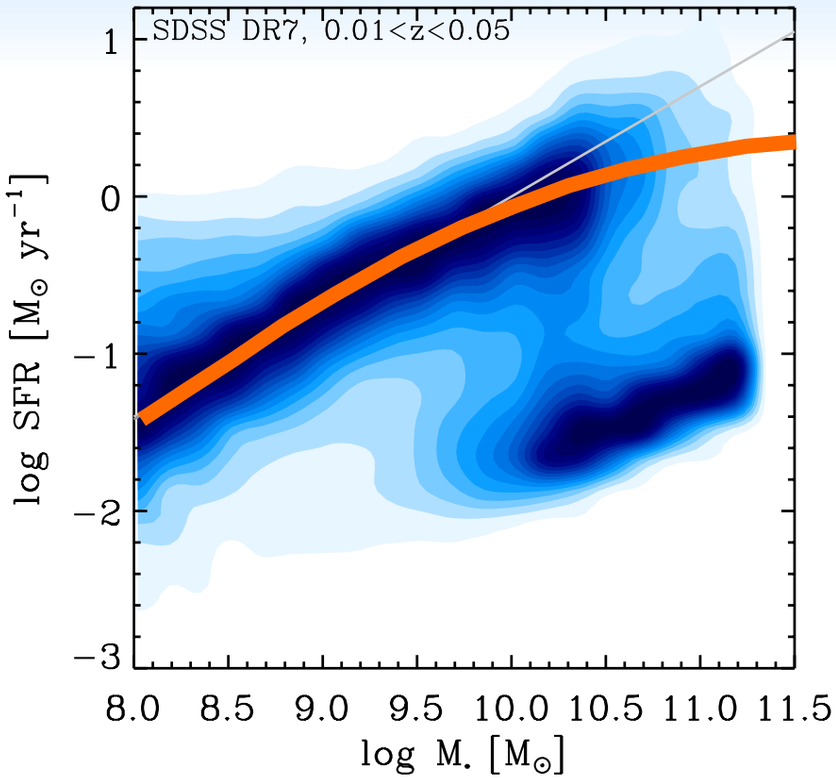
Cold gas in the SFR-M* plane

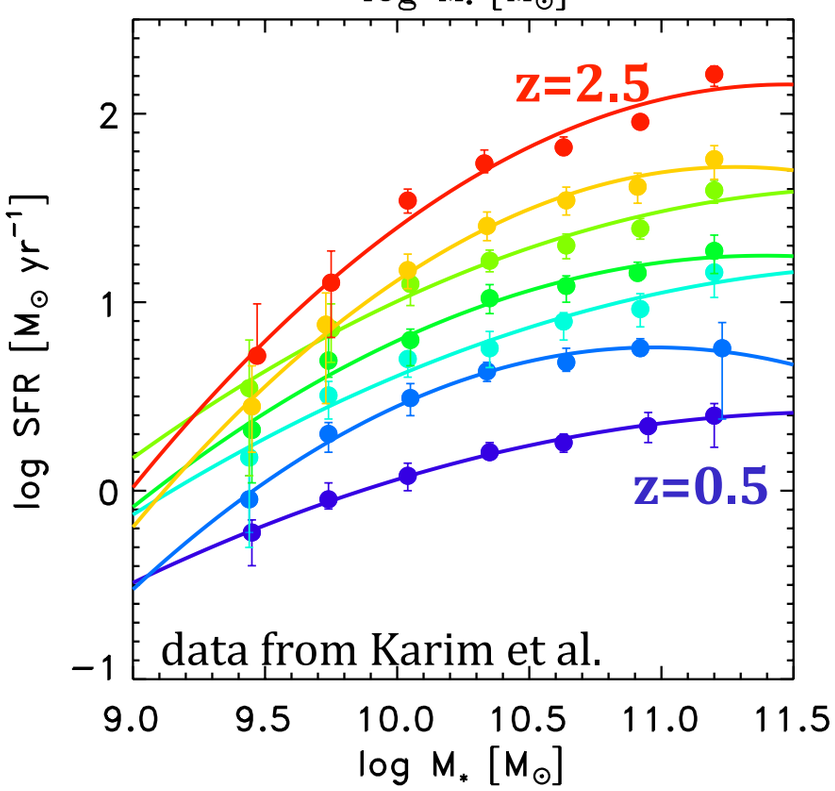


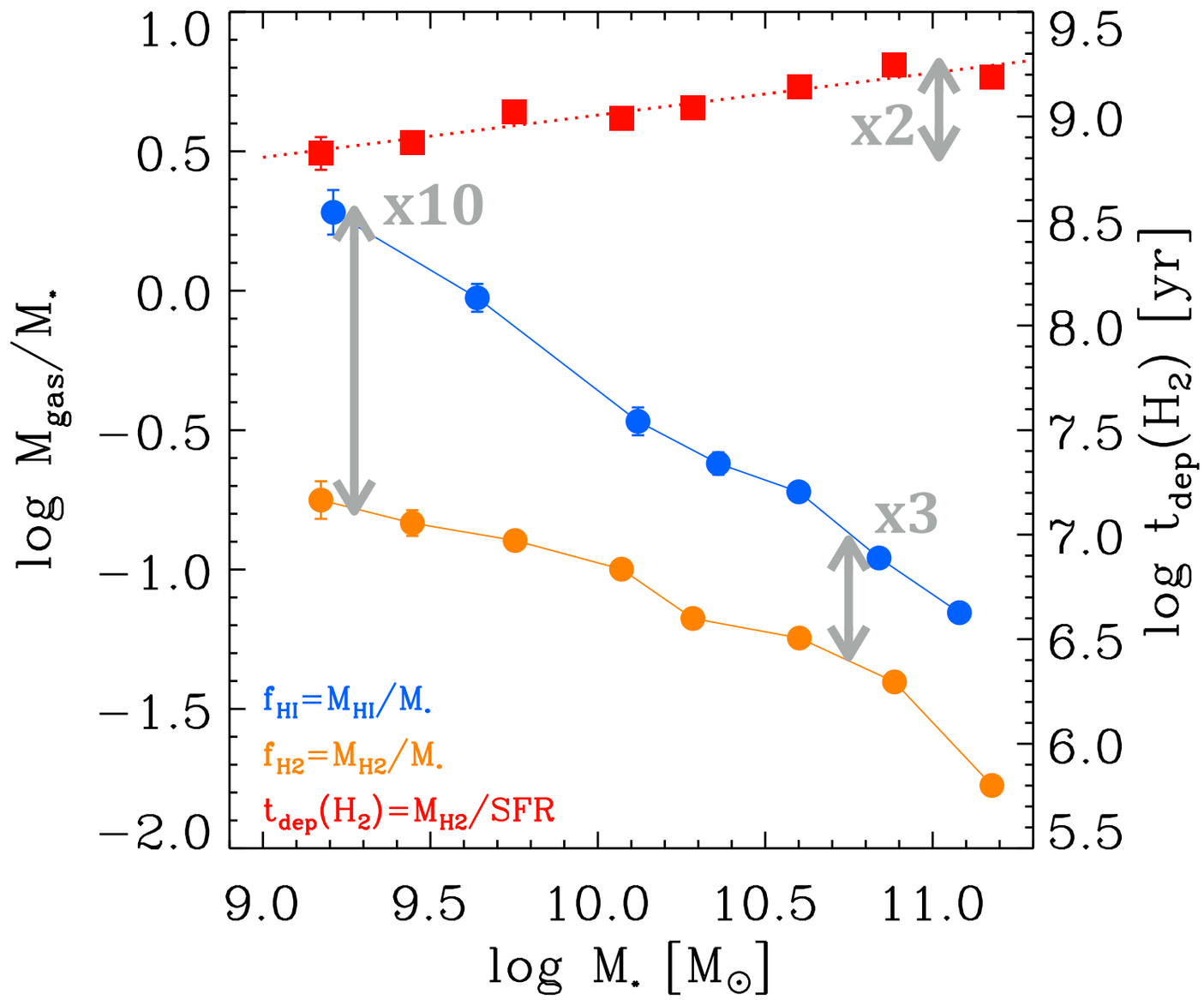
The position of a galaxy in the SFR-M* plane depends on:
(1) how much fuel it has
(2) how much of it is available for star formation
(3) the efficiency of the conversion of this gas into stars

Saintonge et al. (2016)

Gas on the main sequence and quenching

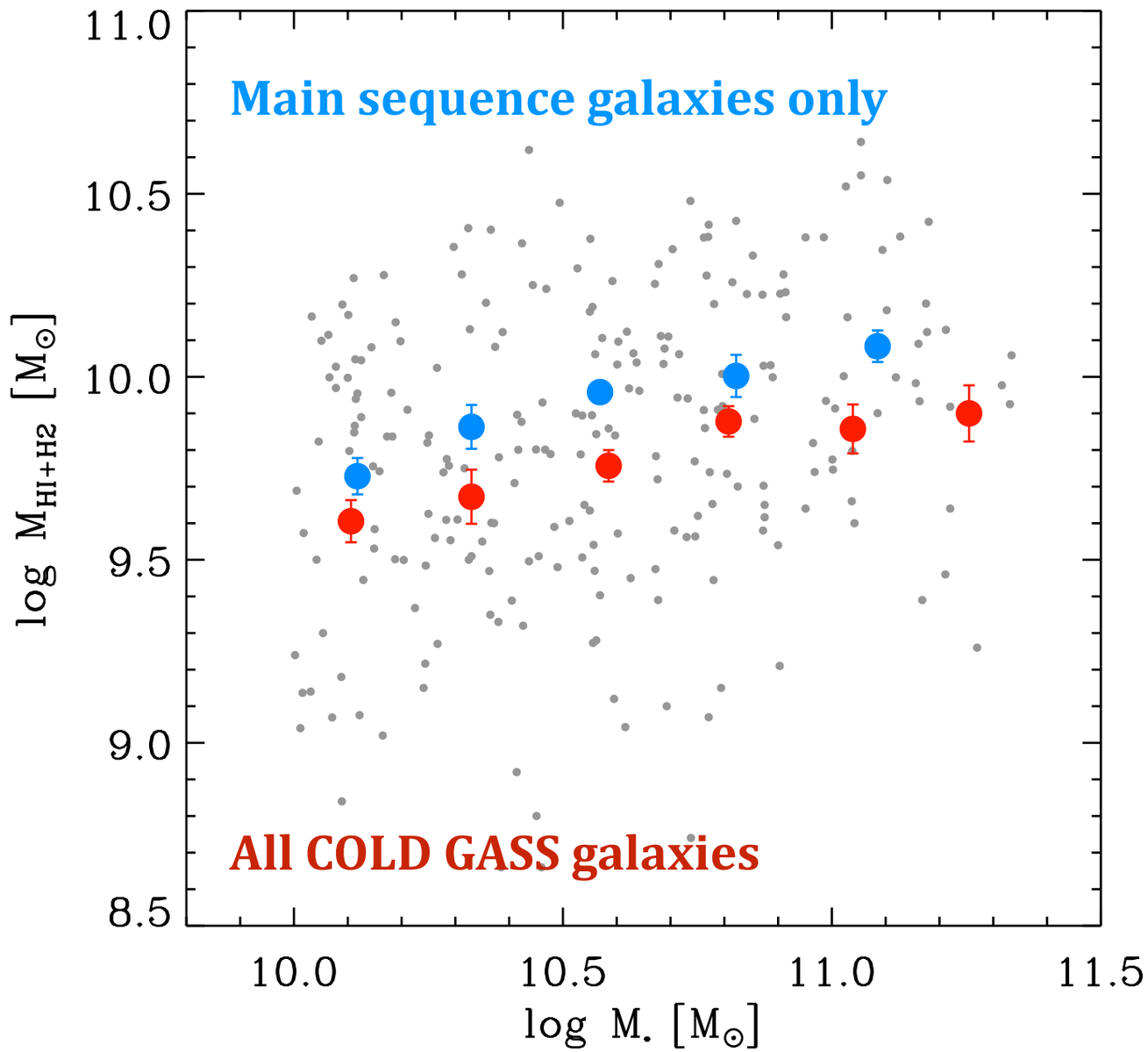






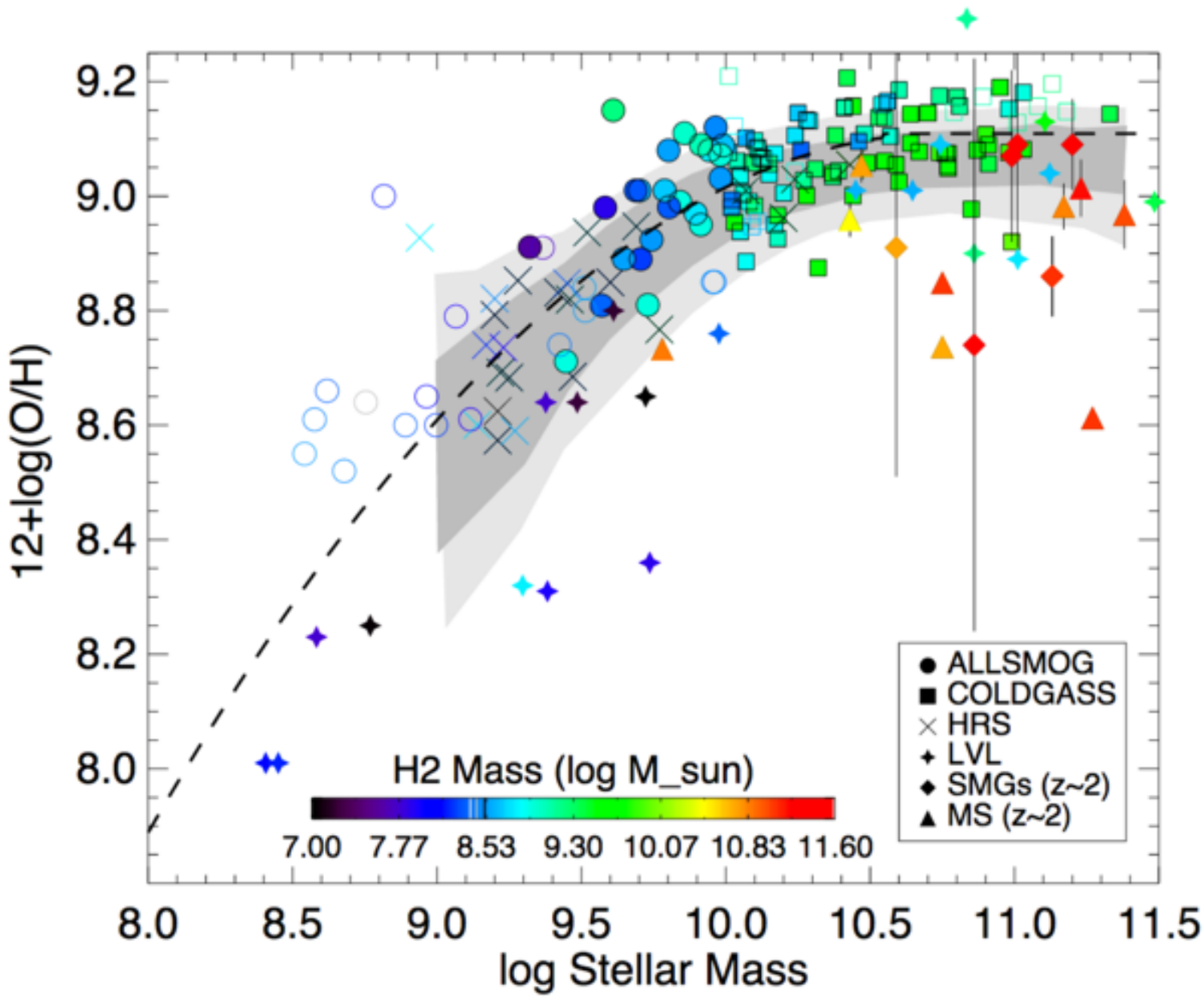
as galaxies evolve along the main sequence, they steadily consume their gas supply

Gas on the main sequence and quenching



while gas fractions decrease, the **total mass** of the cold gas reservoir is increasing, suggesting accretion is ongoing at z=0 even in the most massive galaxies

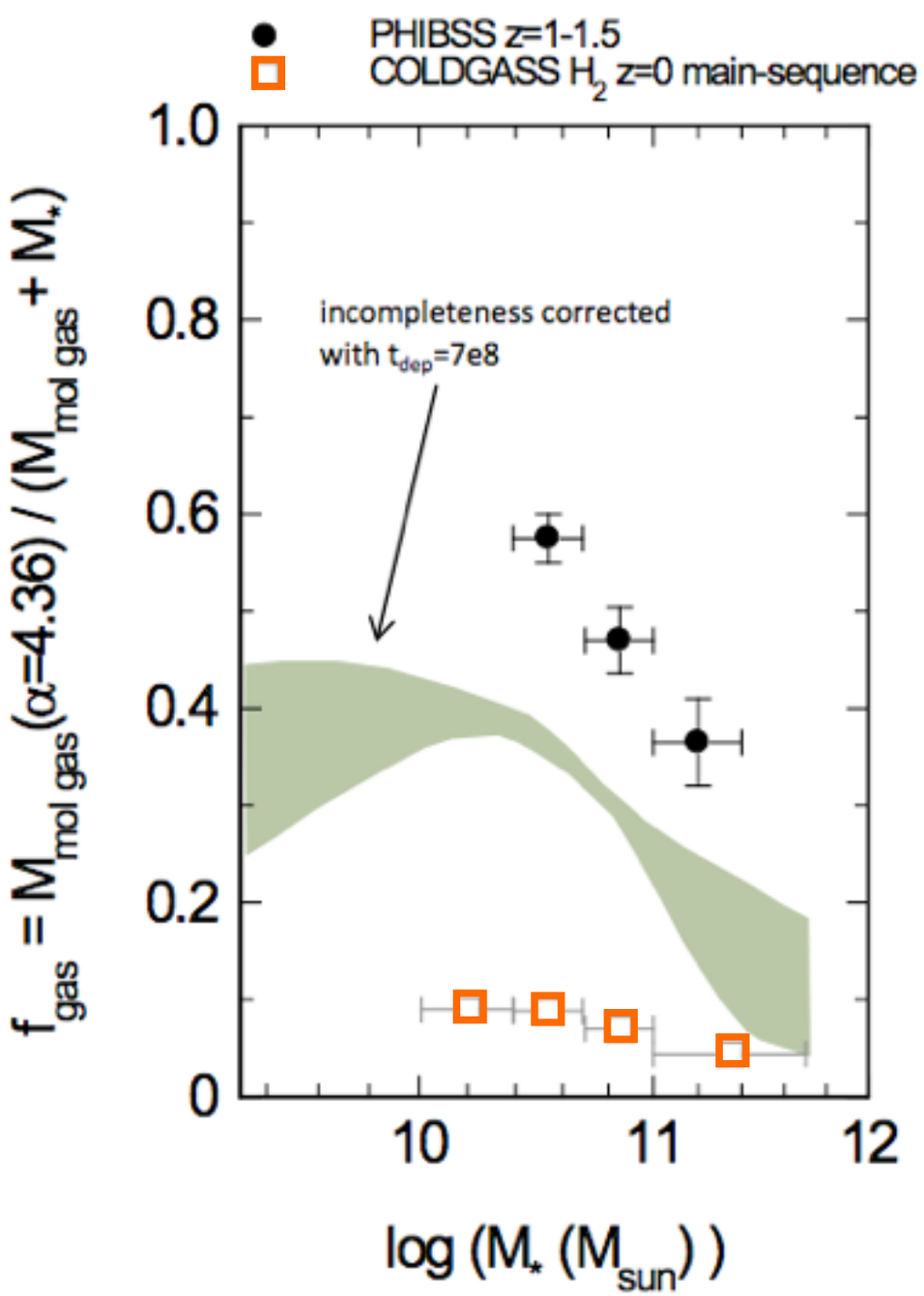
Gas as the third parameter in the mass-metallicity relation?

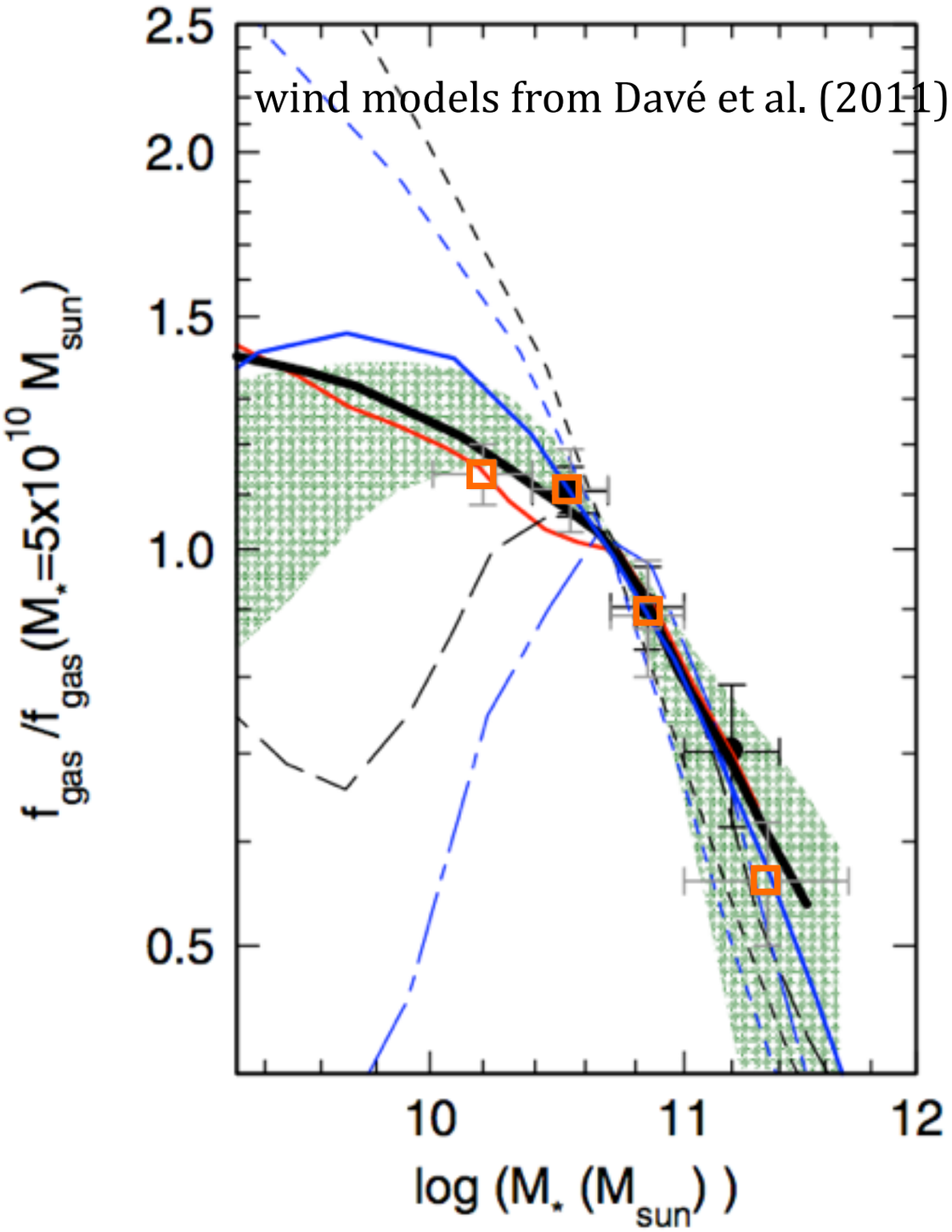


Bothwell et al. (2016)

tentative evidence that Mgas is more fundamental than SFR in driving the scatter in the mass-metallicity relation

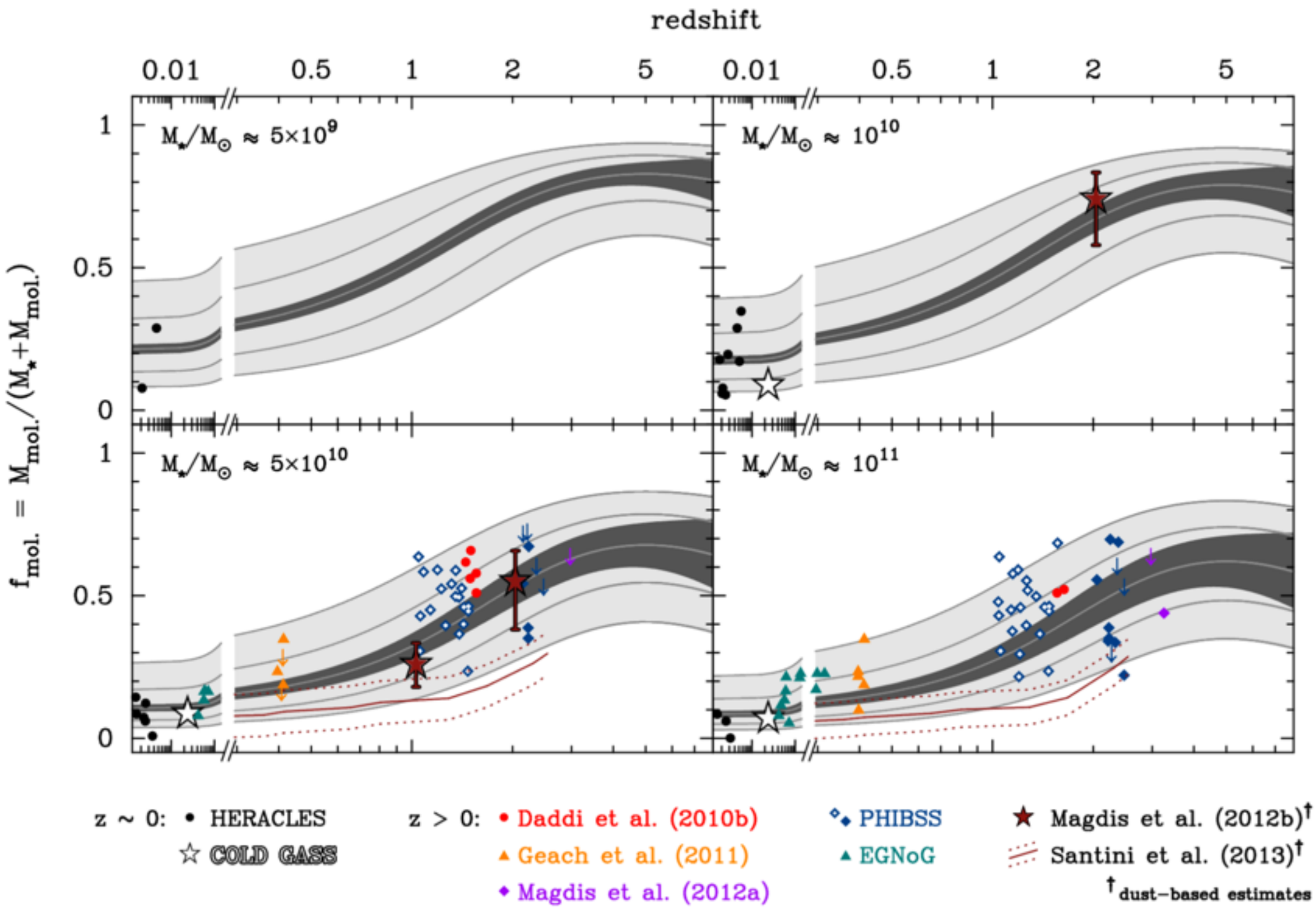
Redshift independence of gas scaling relations + constraints for models





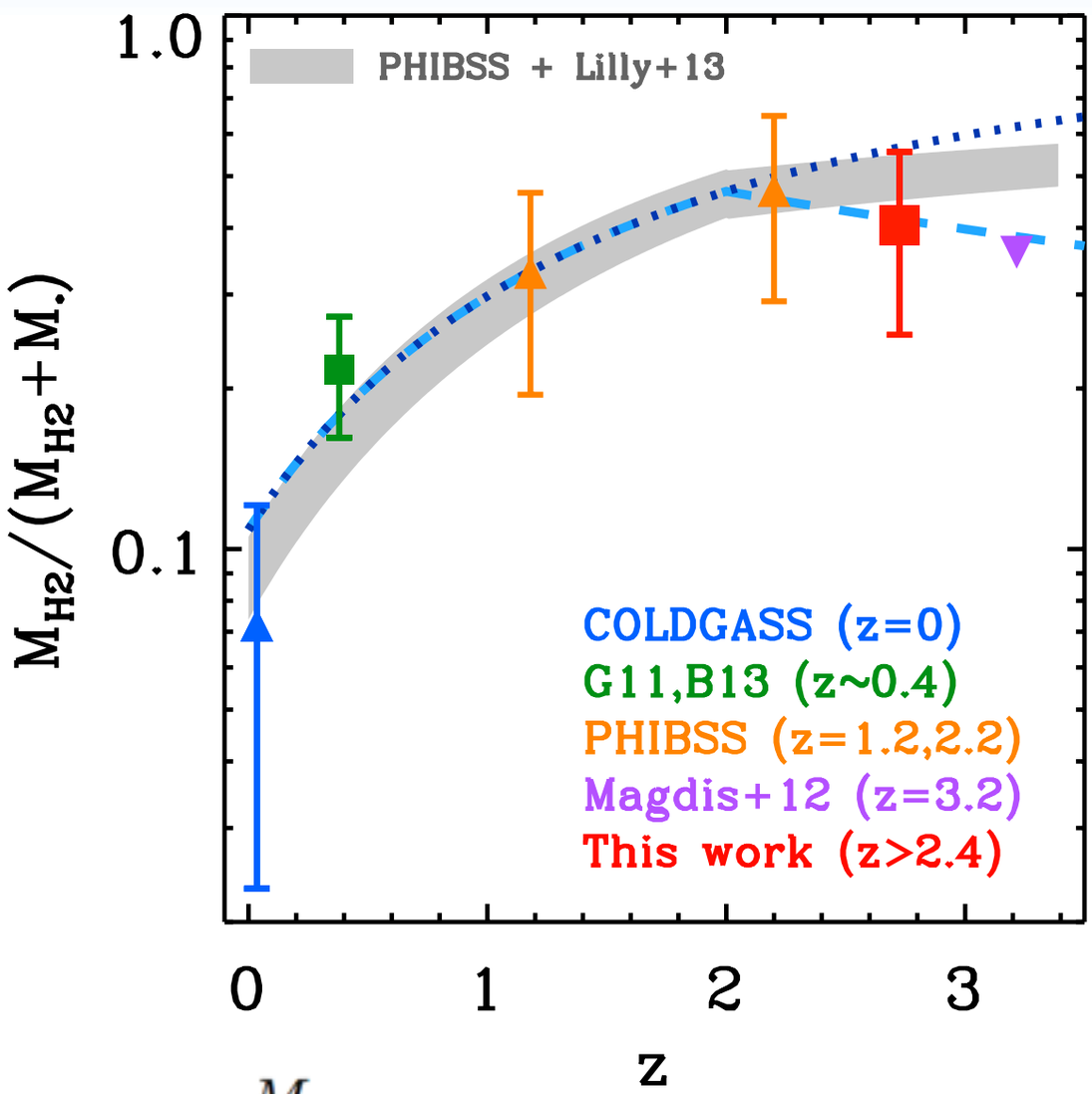
Tacconi et al. (2013), Magdis et al. (2012), Genzel et al. (2015)

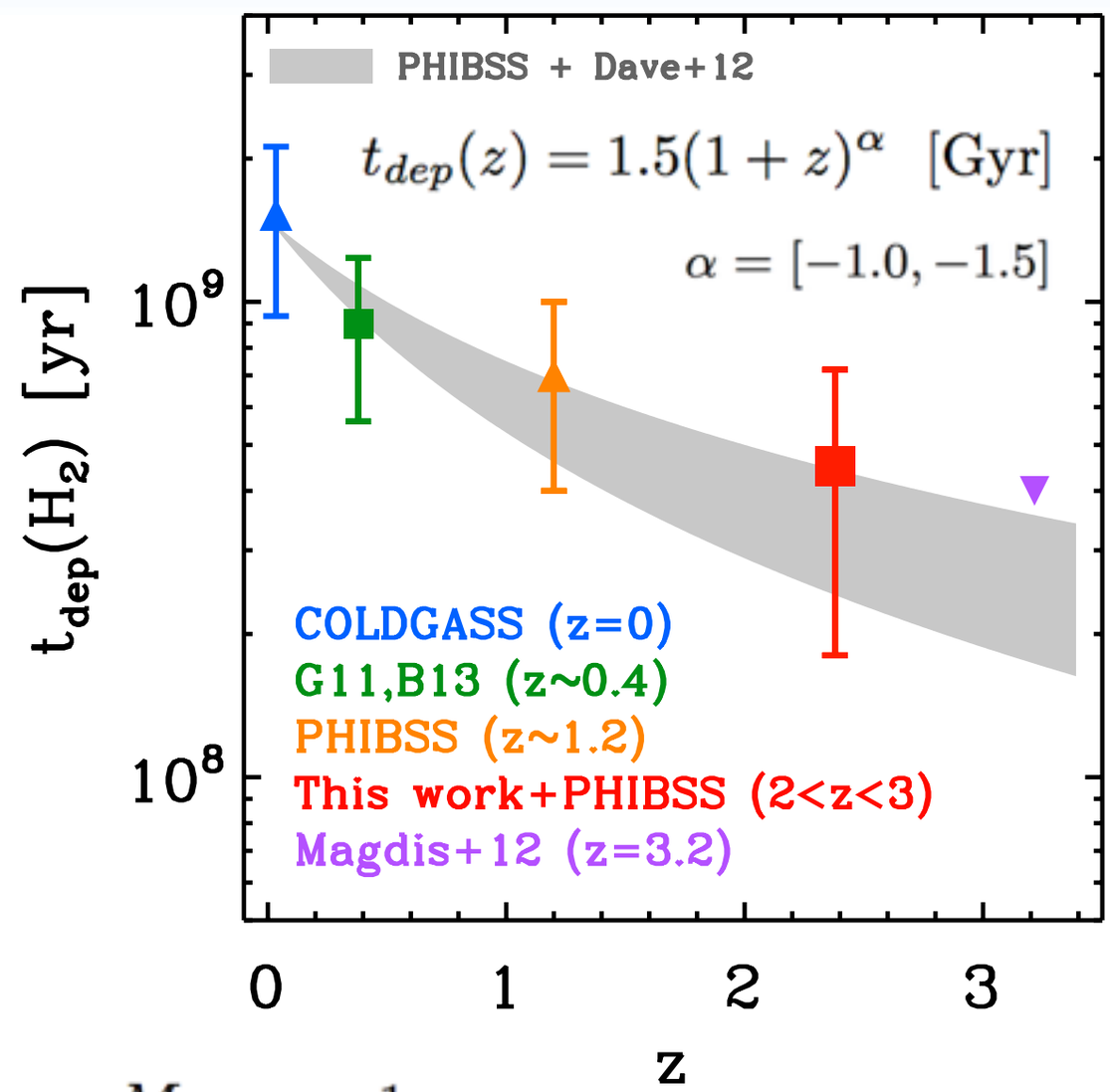
Redshift evolution of gas fractions



Sargent et al. (2014)

Redshift evolution of gas fractions





$$f_{gas} = \frac{M_{H2}}{M_{H2} + M_*}$$

$$= \frac{1}{1 + (t_{dep}\ \mathrm{sSFR})^{-1}}$$

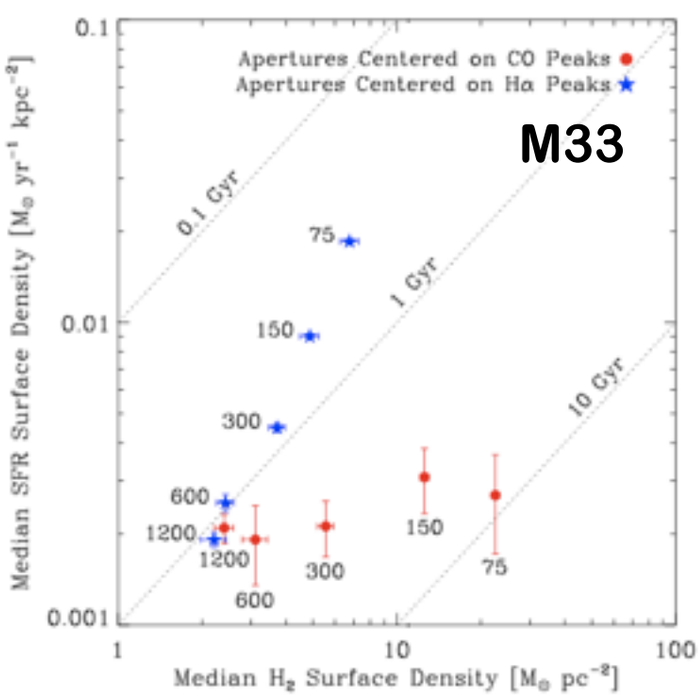
$$t_{dep}(H_2) = \frac{M_{H_2}}{\mathrm{SFR}} = \frac{1}{\mathrm{SFE}}$$

The redshift evolution of the mean SSFR is mainly driven by gas fractions and a slowly evolving depletion timescale. This observation is in strong support of the equilibrium model for galaxy evolution.

Saintonge et al. (2013), Tacconi et al. (2013), Genzel et al. (2015)

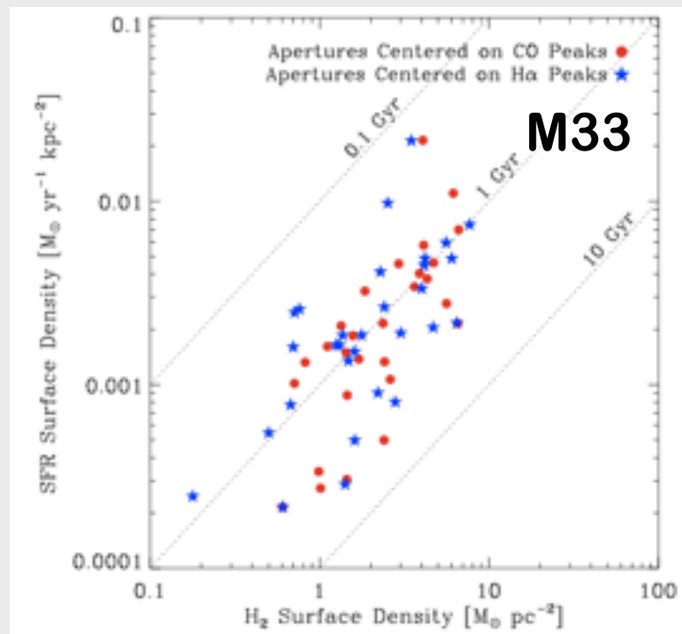
The star formation relation on multiple scales

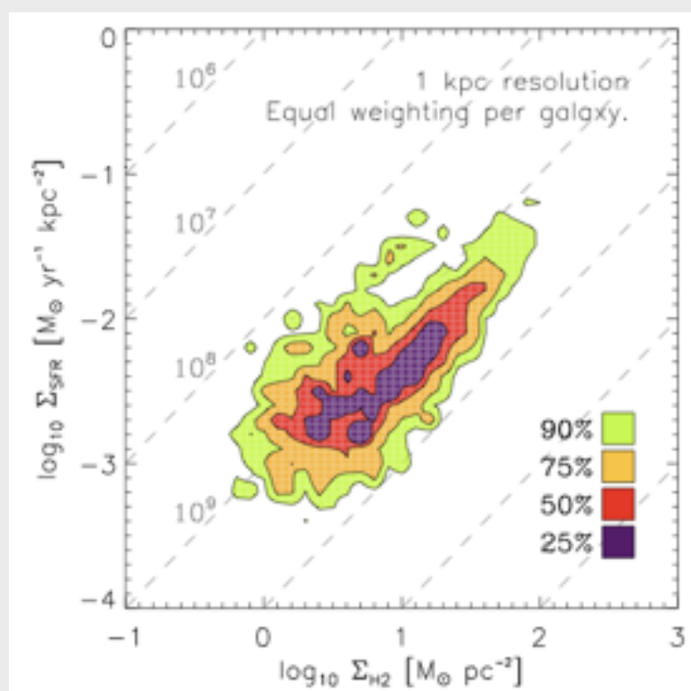
<500pc scales



Schruba et al. (2010)

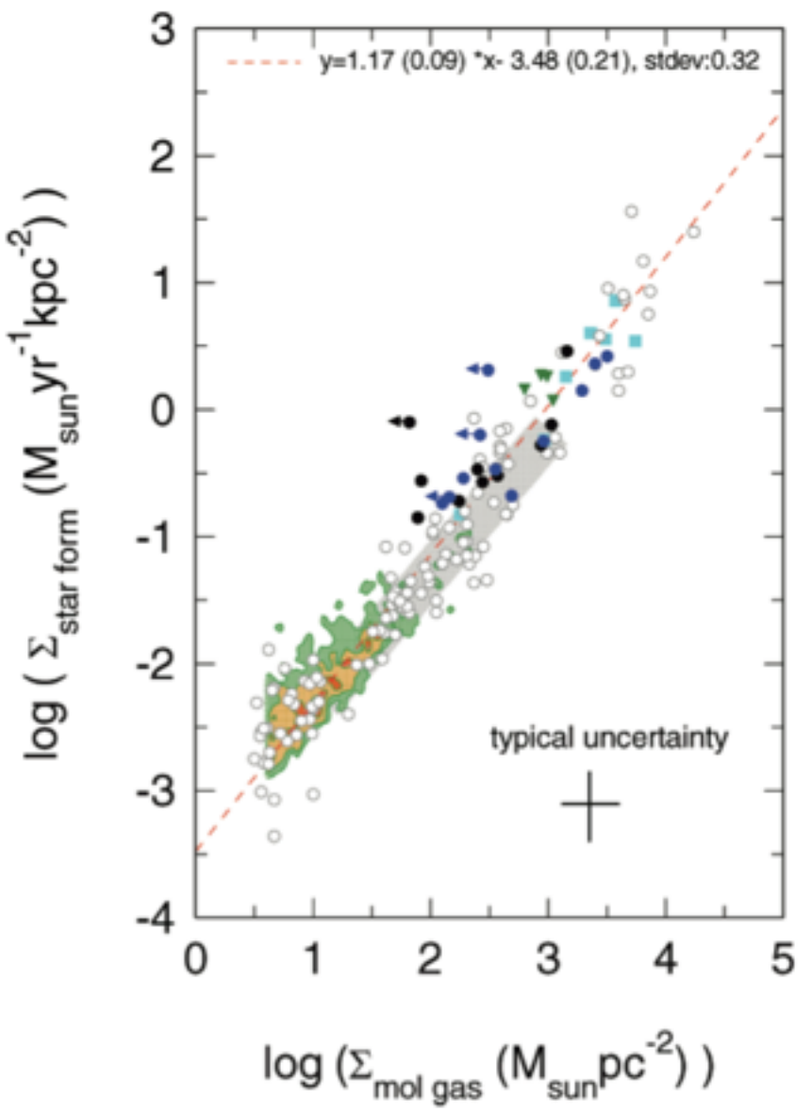
~kpc scales





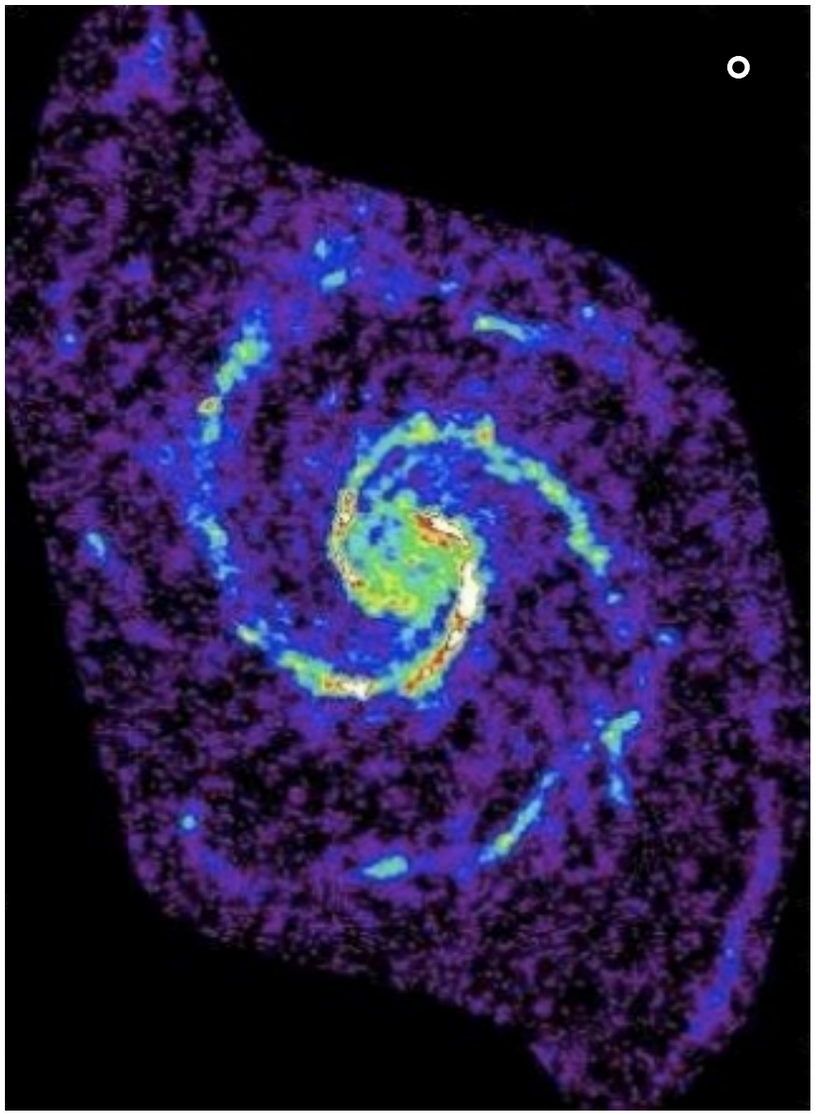
Bigiel et al. (2011)

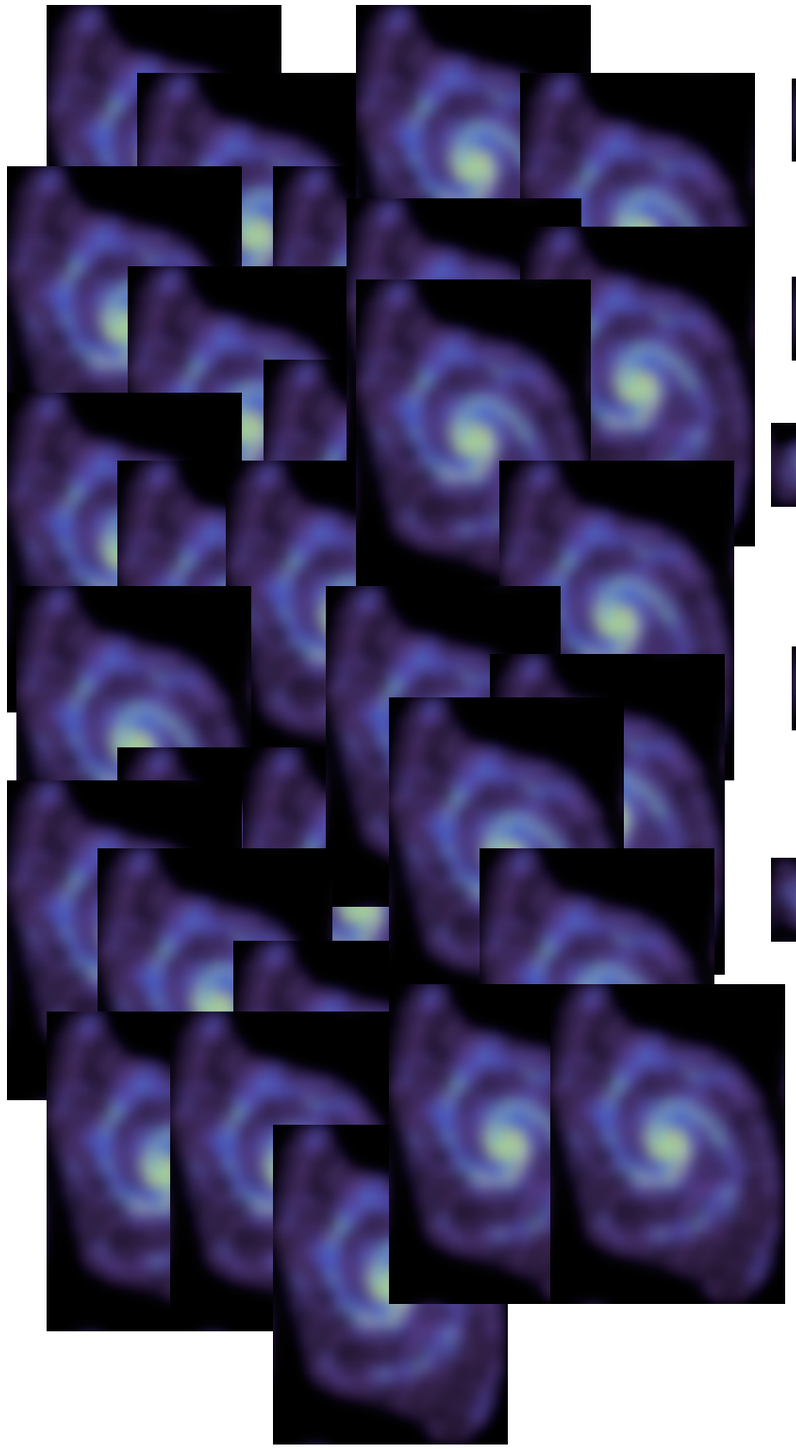
global scales

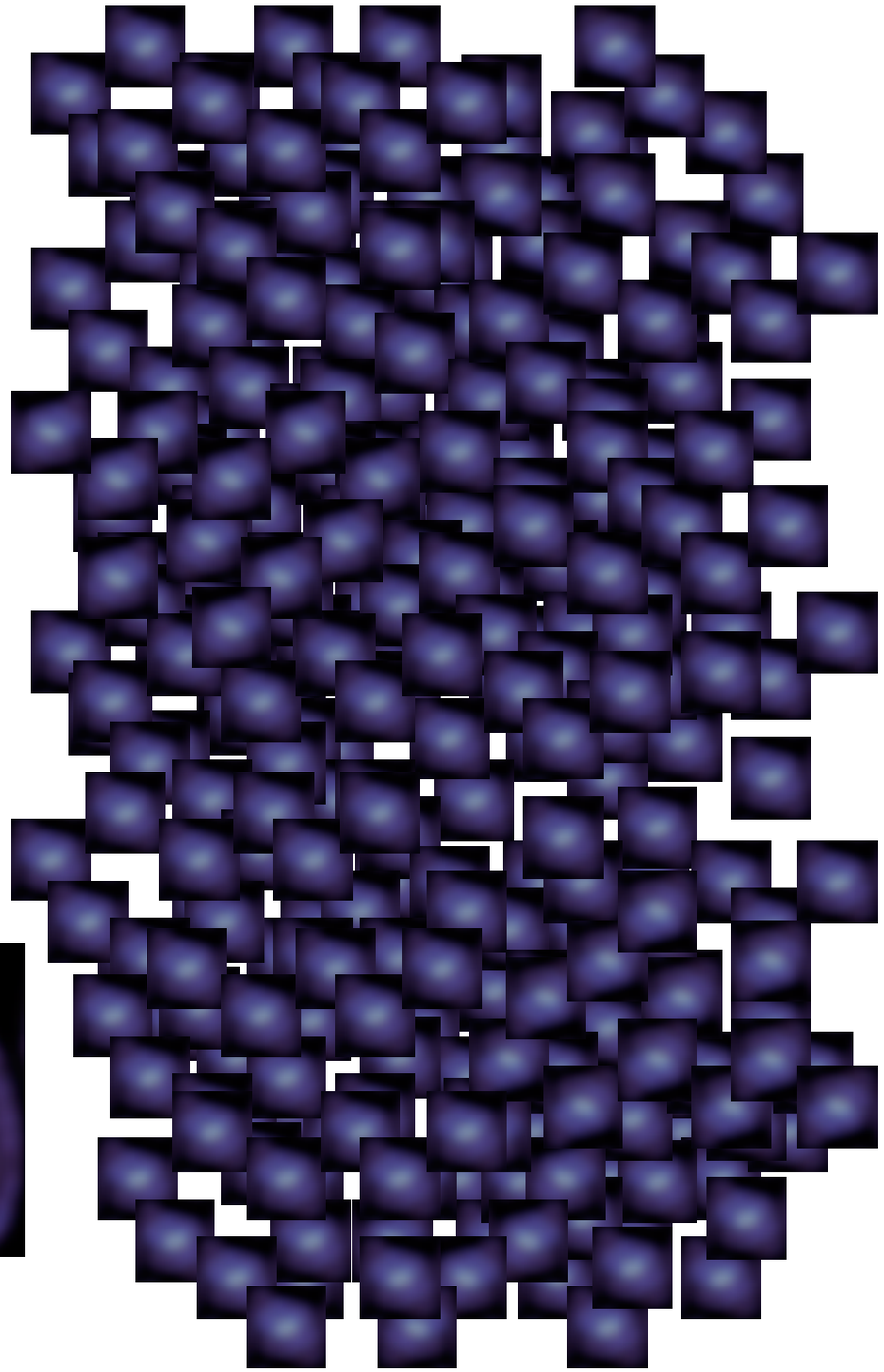


Genzel et al. (2010)

Studying the star formation relation on multiple scales



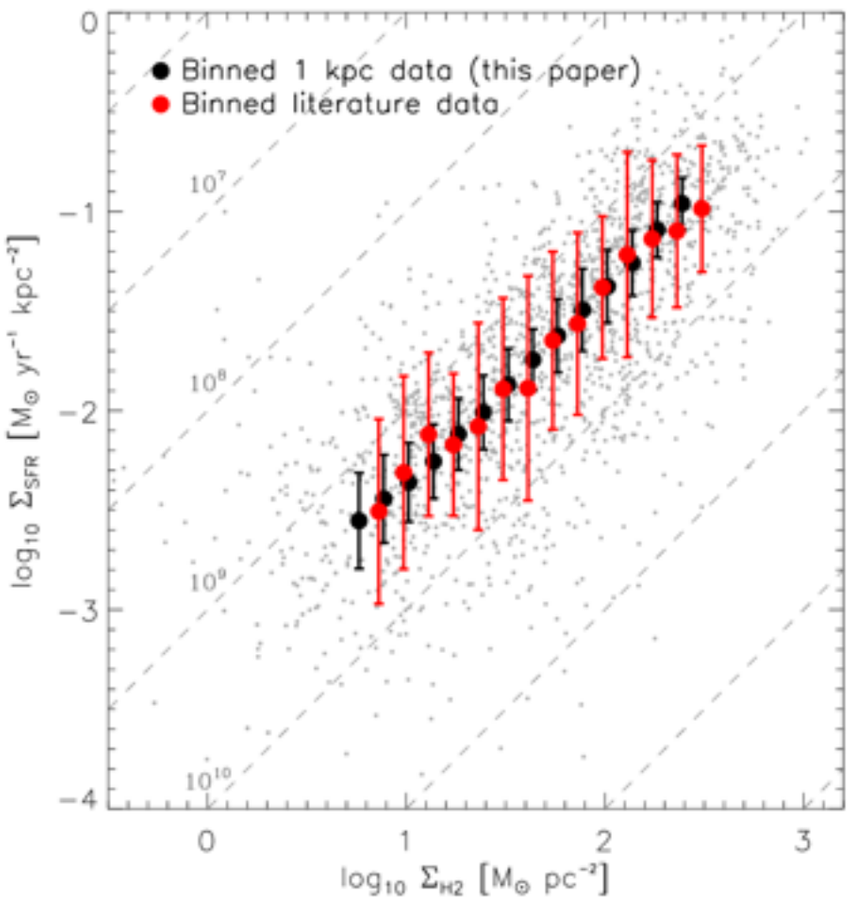




What is the link between the physics of star formation on small scales and the properties of entire galaxies?

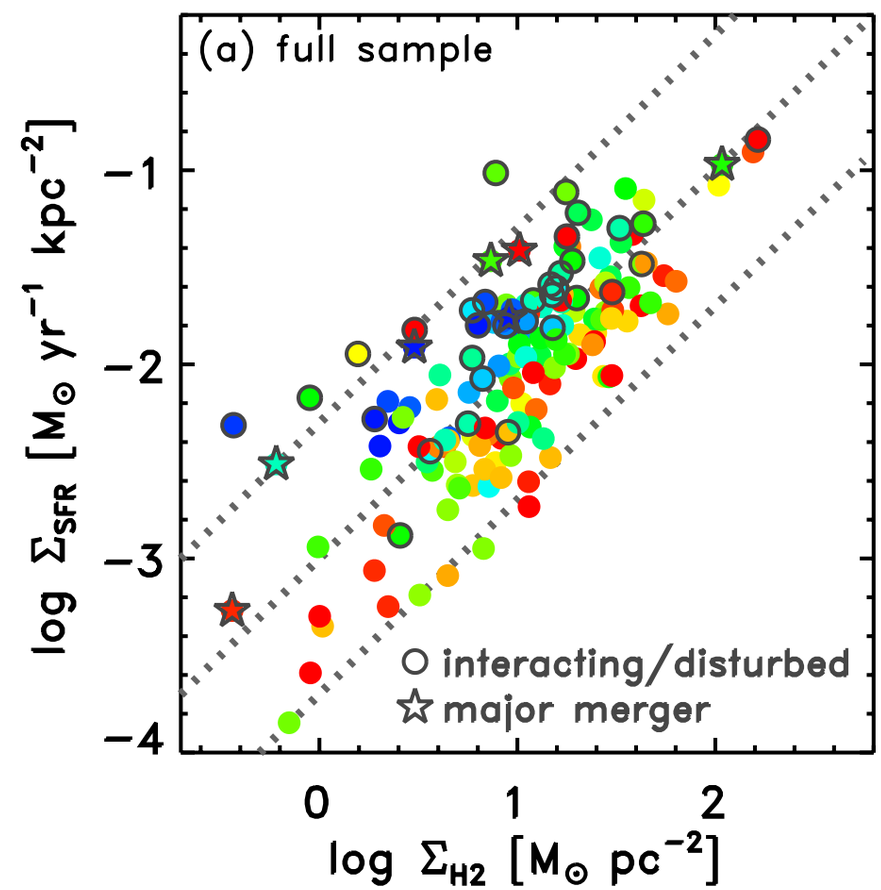
Some important questions:

- Do the properties of the GMC population of a galaxy depend on its global properties?
- How does the environment influence the formation of GMCs?
- Once GMCs are formed, does star formation occur with the same efficiency in all environments?



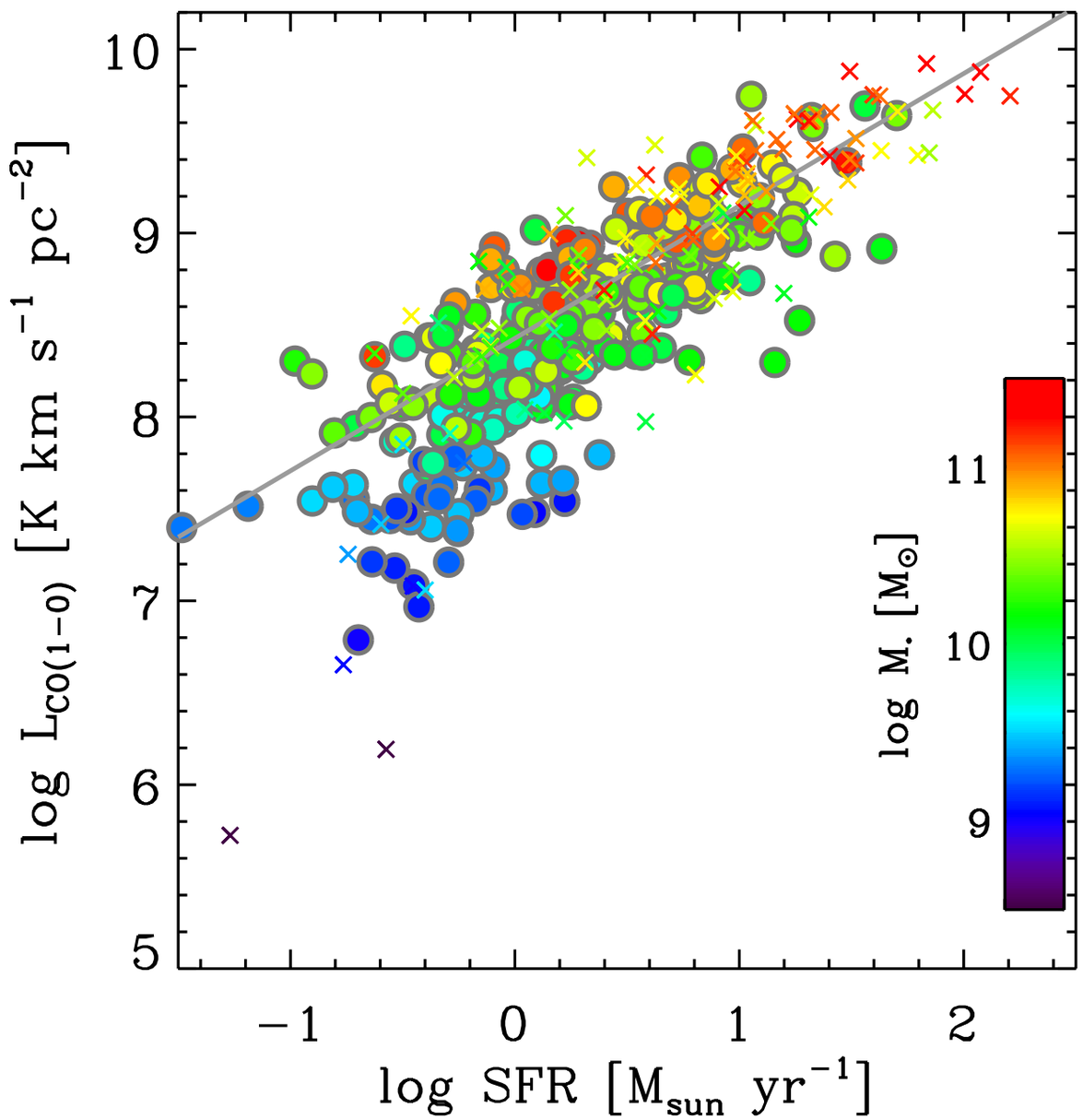
Bigiel et al. (2011)

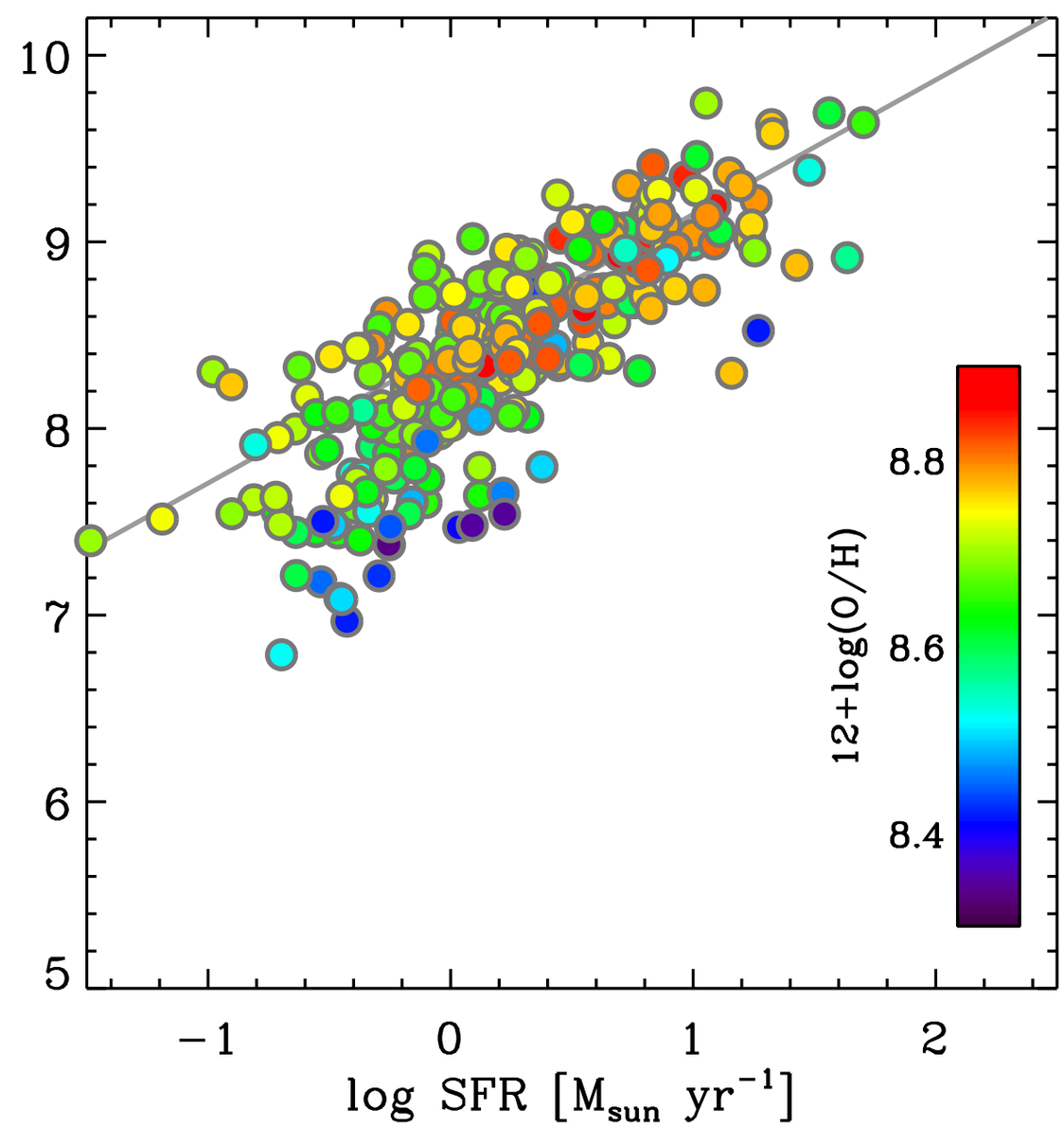
Universal SF law, or systematic variations with global environment ???



Saintonge et al. (2012)

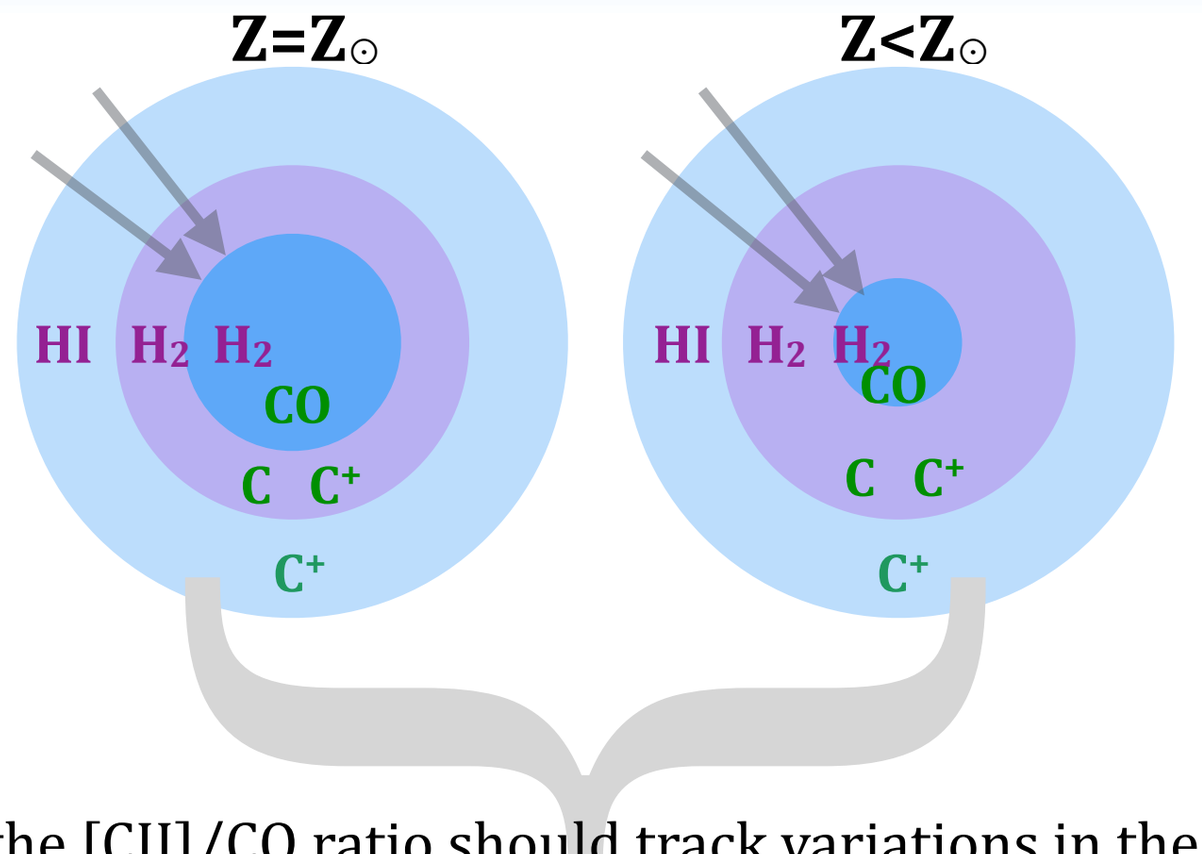
How efficient is star formation in low mass galaxies and/or at high redshifts?



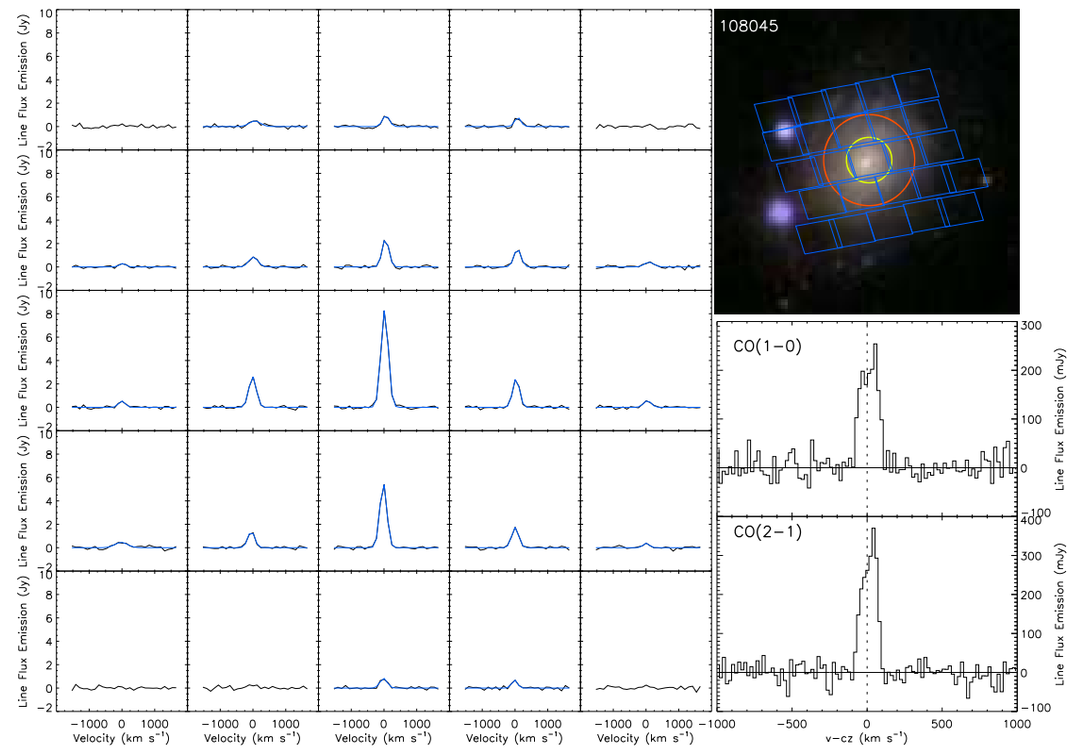


Are low mass galaxies under-luminous in CO at fixed SFR because they have high SF efficiency, or because CO is a poor tracer of total molecular gas?

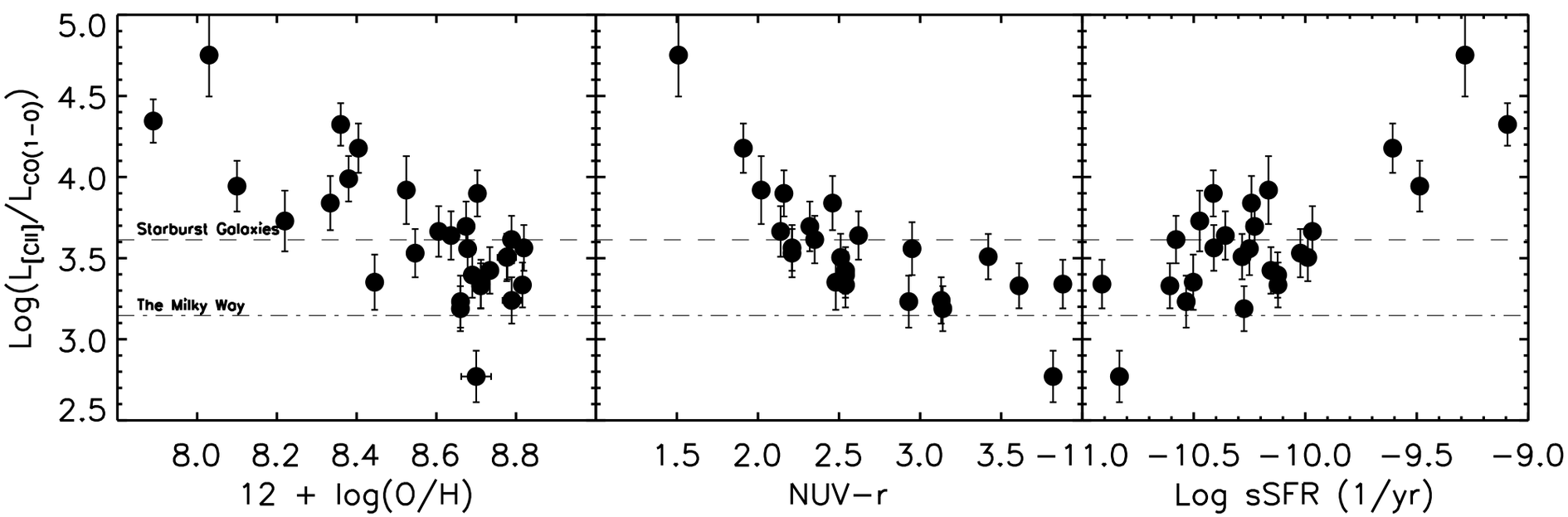
Technical challenge How do we increase the accuracy of molecular gas measurements?



the [CII]/CO ratio should track variations in the level of photodissociation of CO, and therefore give us a handle on X_{CO}



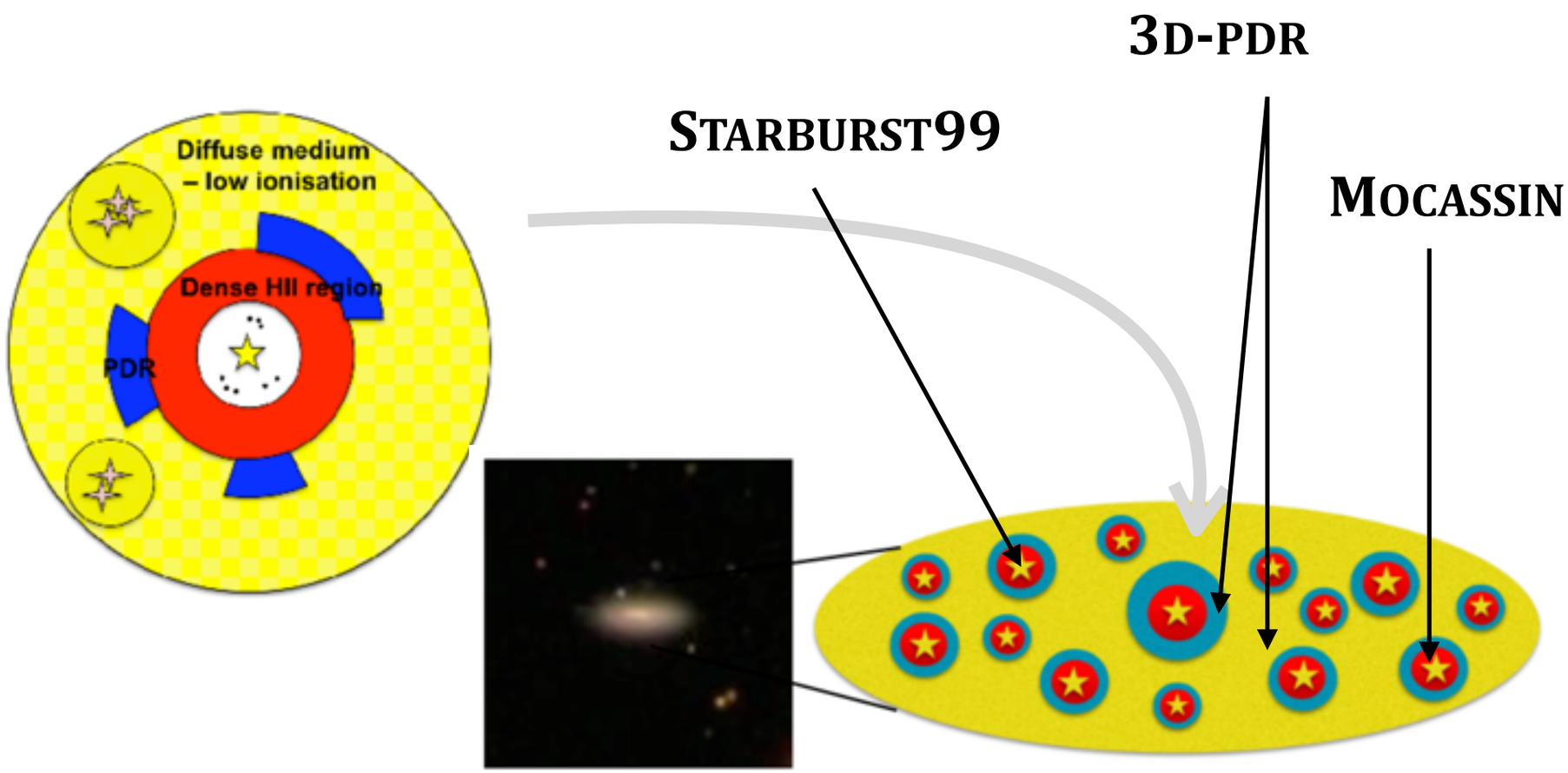
example galaxy: Herschel/PACS and IRAM-30m



work by UCL PhD student **Gio Accurso**

Where does [CII] emission come from?

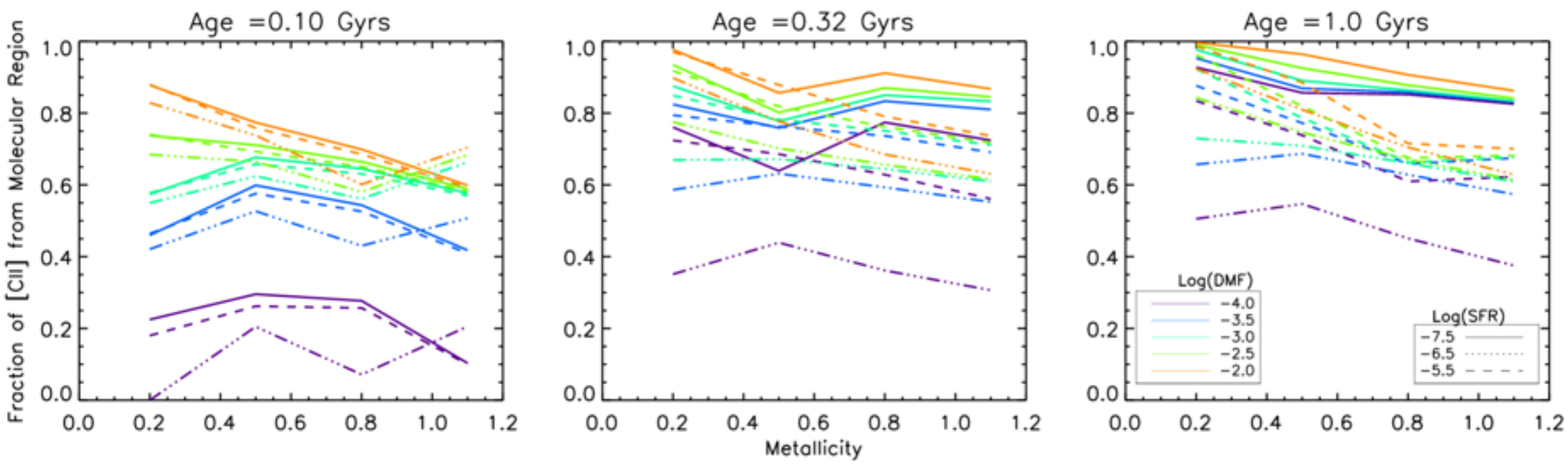
Not all [CII] emission comes from the PDR region
→new radiative transfer multi-phase ISM model combining STARBURST99 (stellar radiation field), MOCCASIN (ionised region) and 3D-PDR (PDR and diffuse neutral medium)



Where does [CII] emission come from?

A large 7-dimensional parameter space….

Input parameter	Minimum value	Maximum value	Number of Variations	Model
Gas-phase metallicity	$0.20Z_\odot$	$1.1Z_\odot$	4	MOCASSIN, 3D-PDR, SB99
Stellar mass of the cloud	10^2 $M_\odot$	10^4 $M_\odot$	3	SB99
Stellar population age	10^2Myr	$10^{3.0}$Myr	3	SB99
HII region electron number density	$10^{1.5}$ cm^{-3}	$10^{3.0}$ cm^{-3}	4	MOCASSIN
Cosmic ray ionisation rate	10^{-17} s^{-1}	10^{-14} s^{-1}	4	3D-PDR
Dust mass fraction	10^{-4}	10^{-2}	5	3D-PDR
Specific star formation rate	$10^{-11.5}$ yr^{-1}	$10^{-9.5}$ yr^{-1}	3	SB99



…. produces a very large number of scaling relations

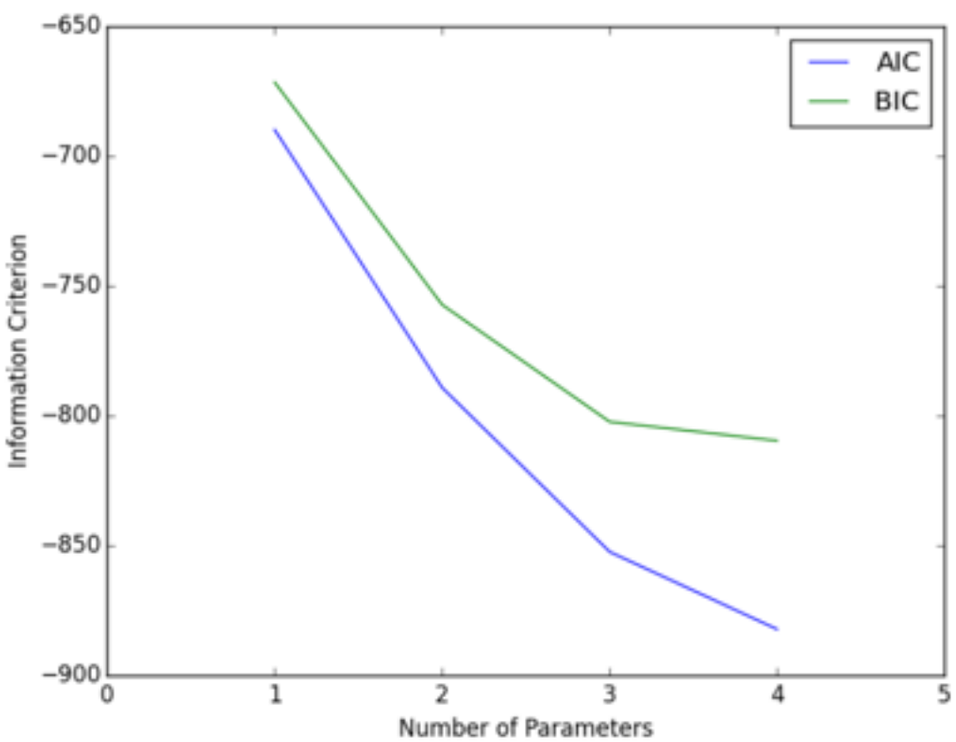
Accurso et al. (2016a)

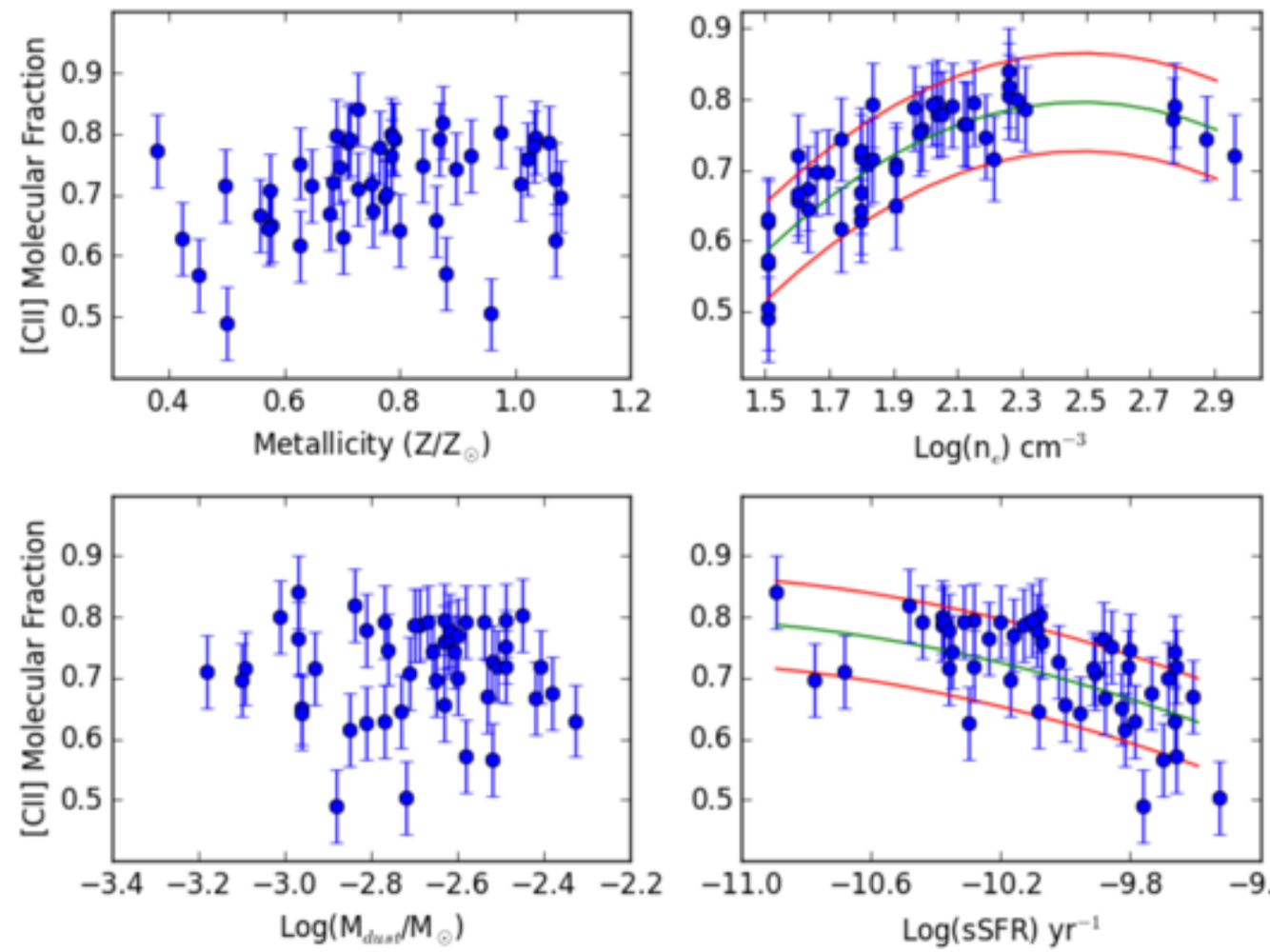
Where does [CII] emission come from?

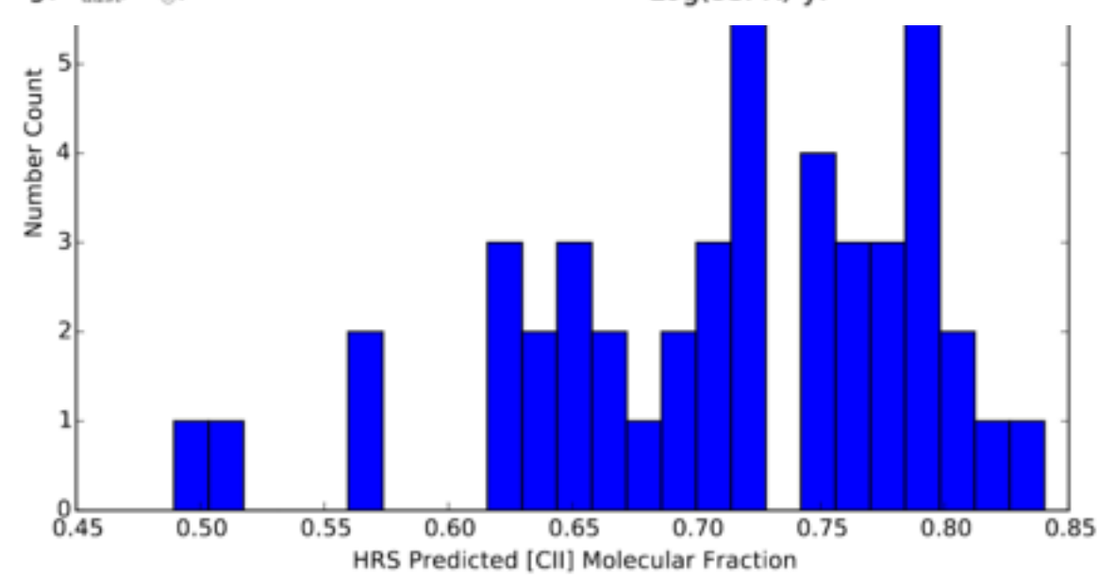
Bayesian information criterion used to determine the parameters required to predict the [CII] "molecular fraction"

Four key parameters

- metallicity
- density
- dust mass fraction
- SSFR

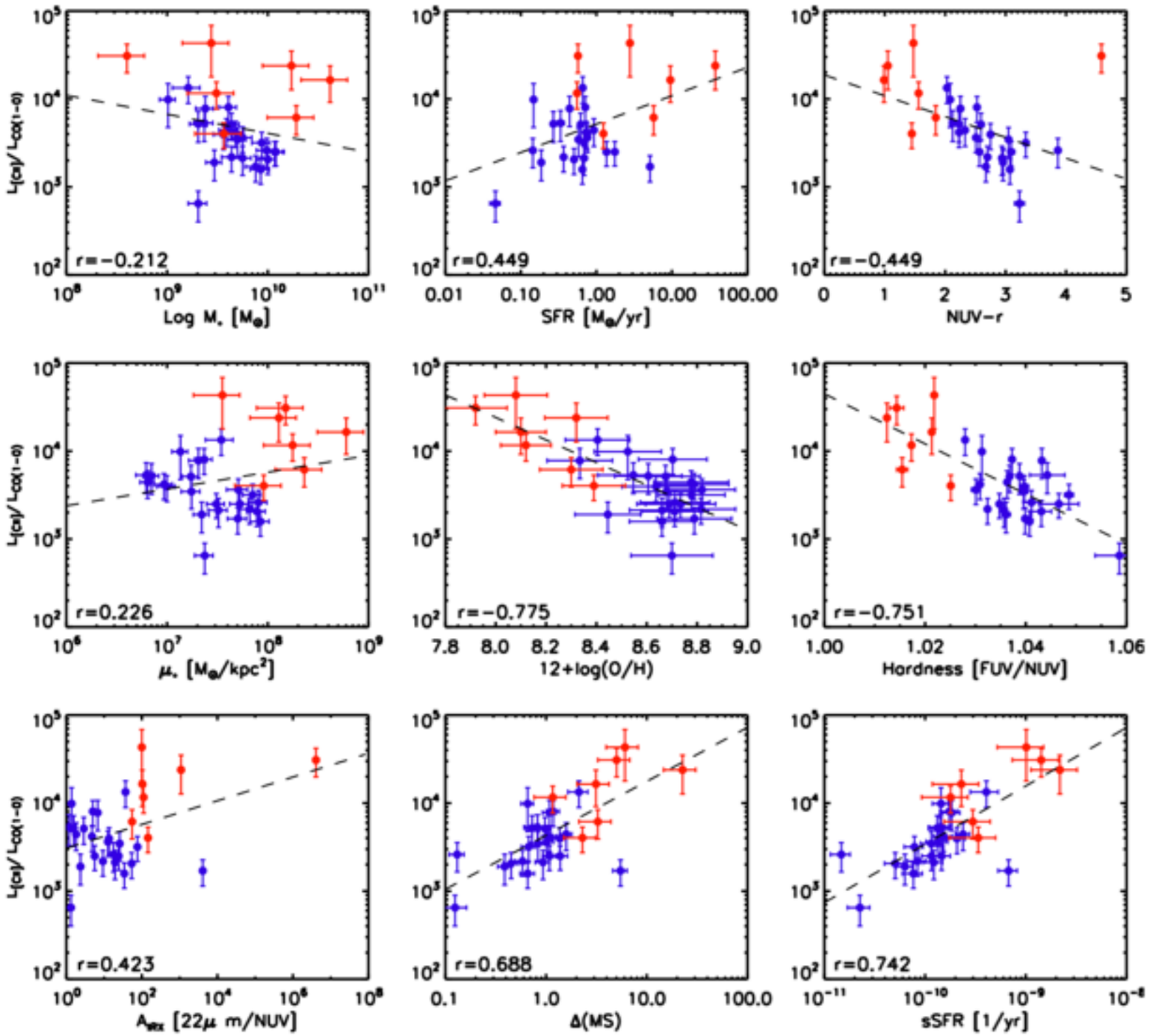






Accurso et al. (2016a)

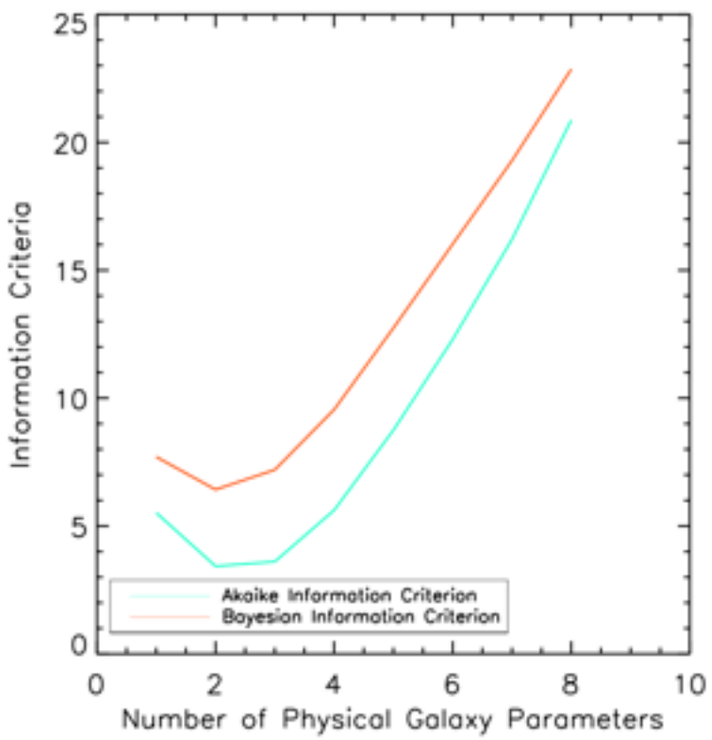
Using the [CII]/CO ratio to derive a new conversion function

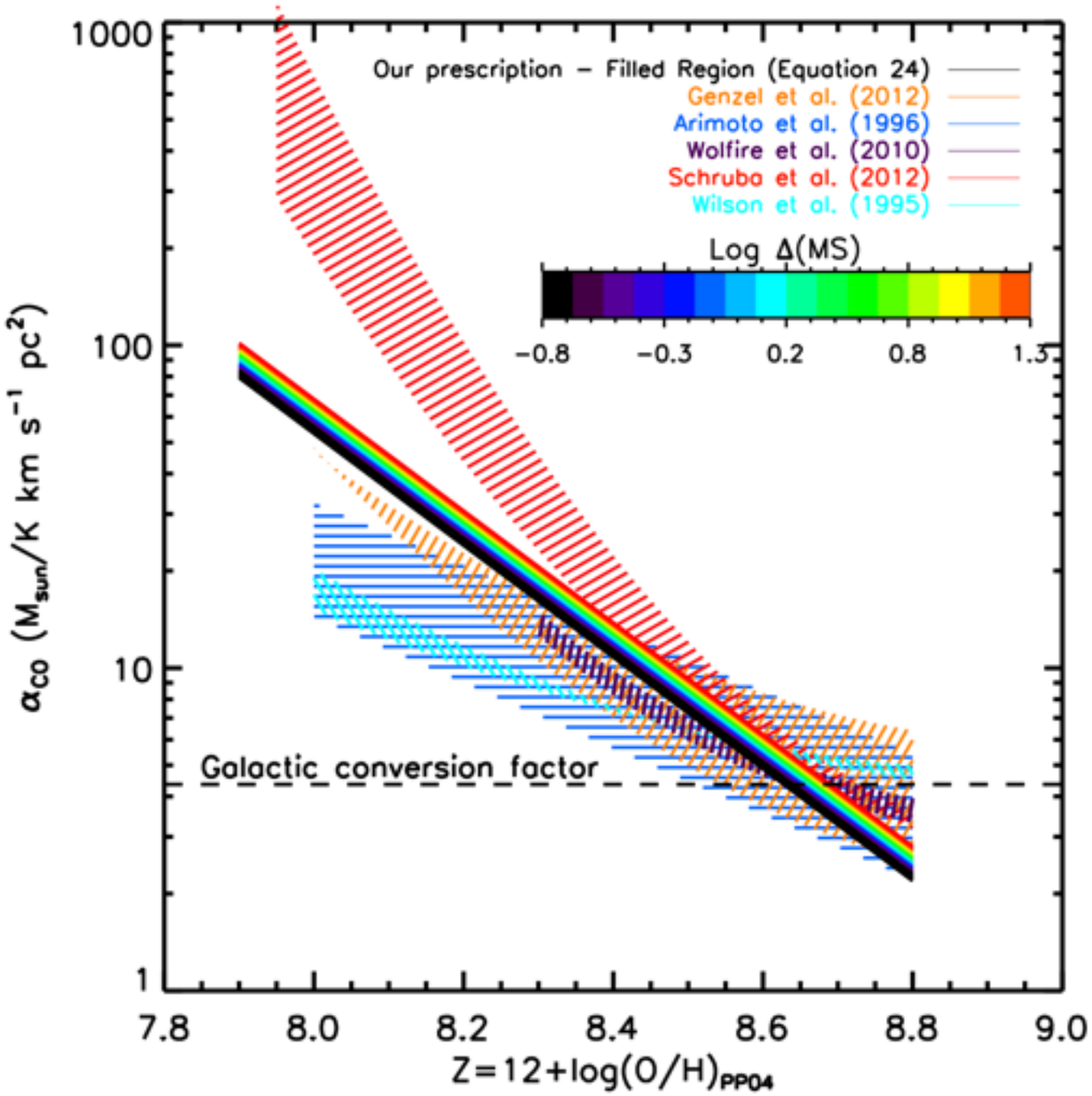


Accurso et al. (2016b)

[CII]/CO correlates particularly strongly with quantities that describe either the dust content or the strength of the radiation field.

Using the [CII]/CO ratio to derive a new conversion function

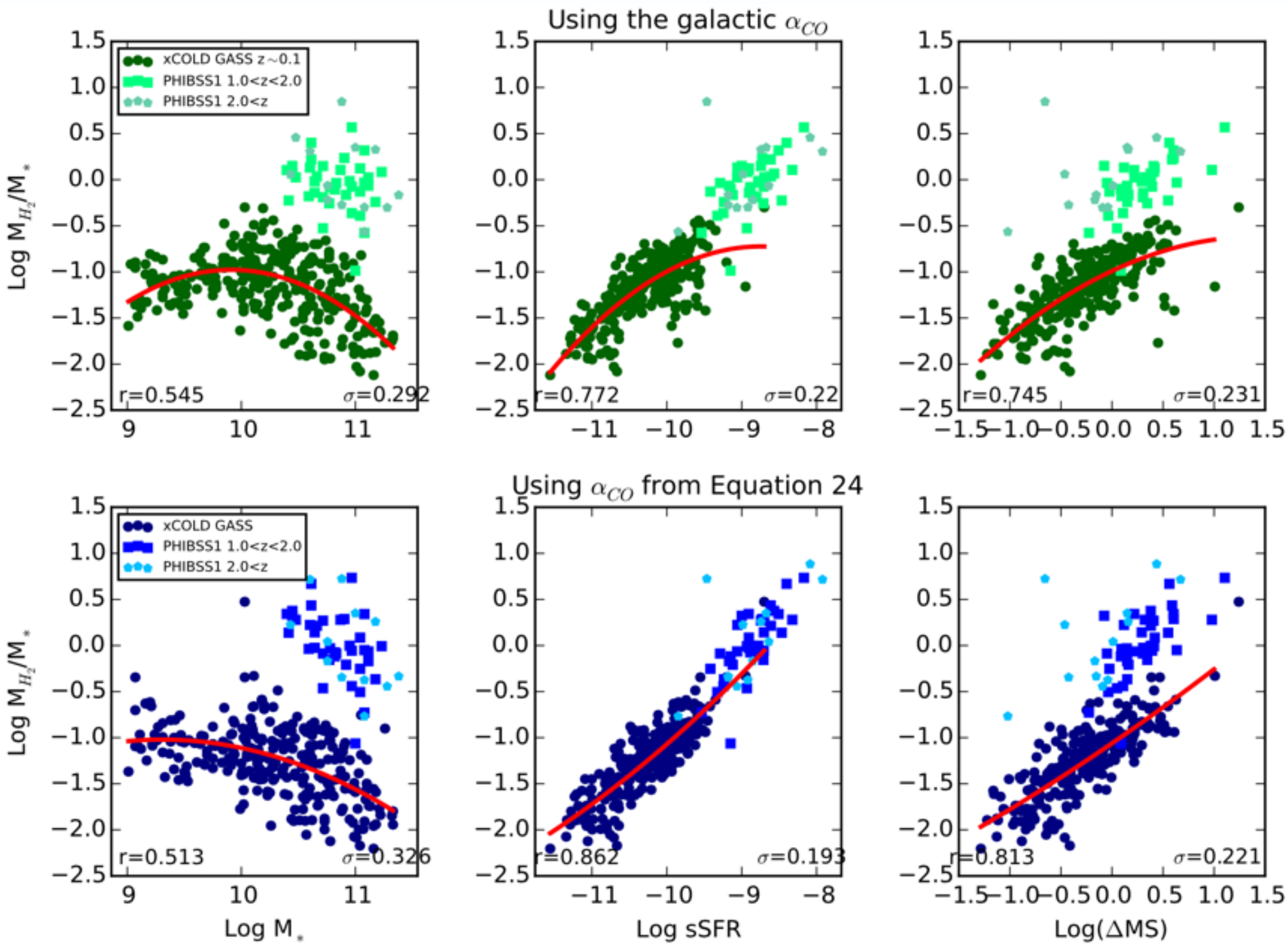




Accurso et al. (2016b)

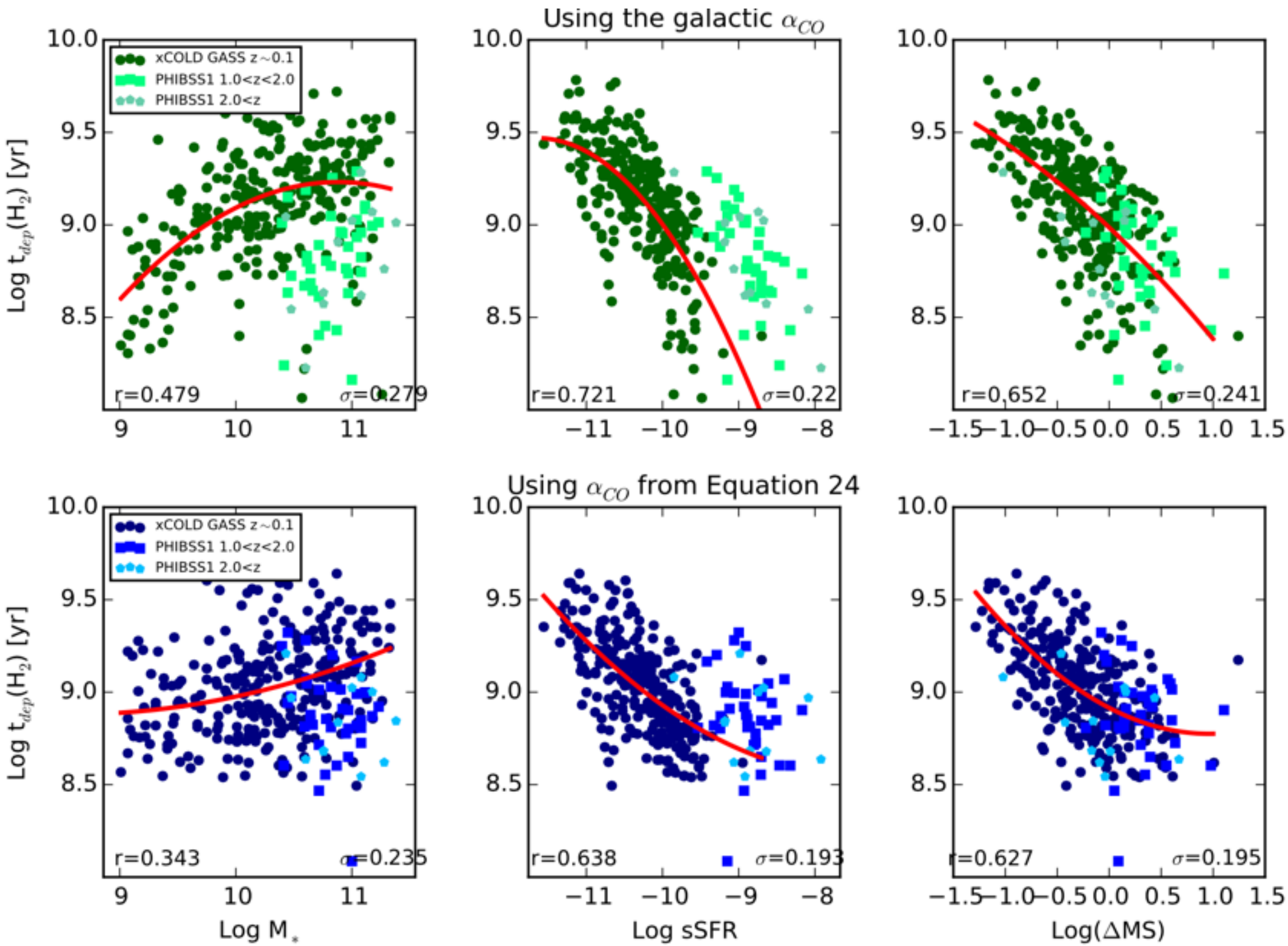
The conversion function derived from [CII]/CO depends mostly on metallicity, but also on offset from the star-forming sequence (or sSFR)

Disentangling star formation efficiency from CO photodissociation effects



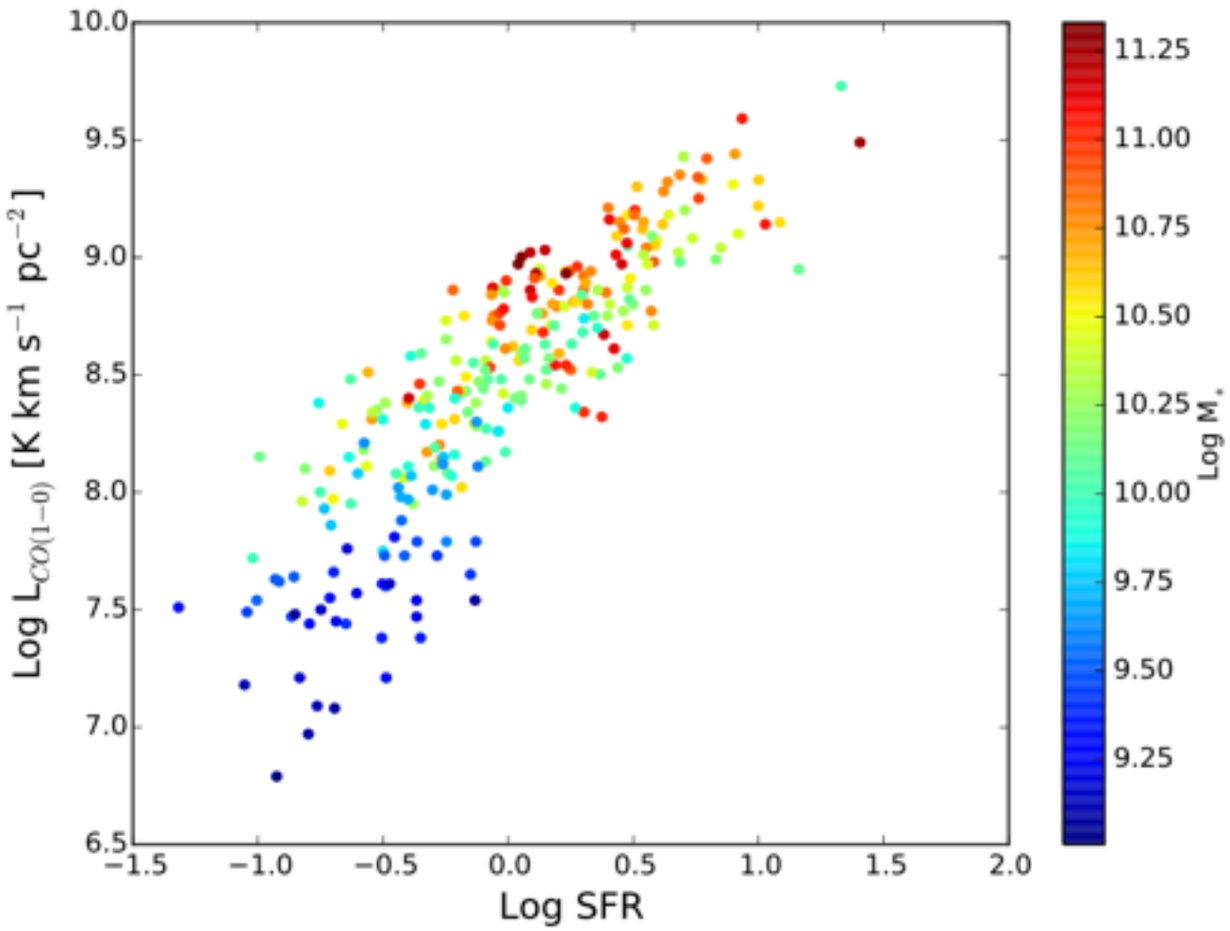
Accurso et al. (2016b)

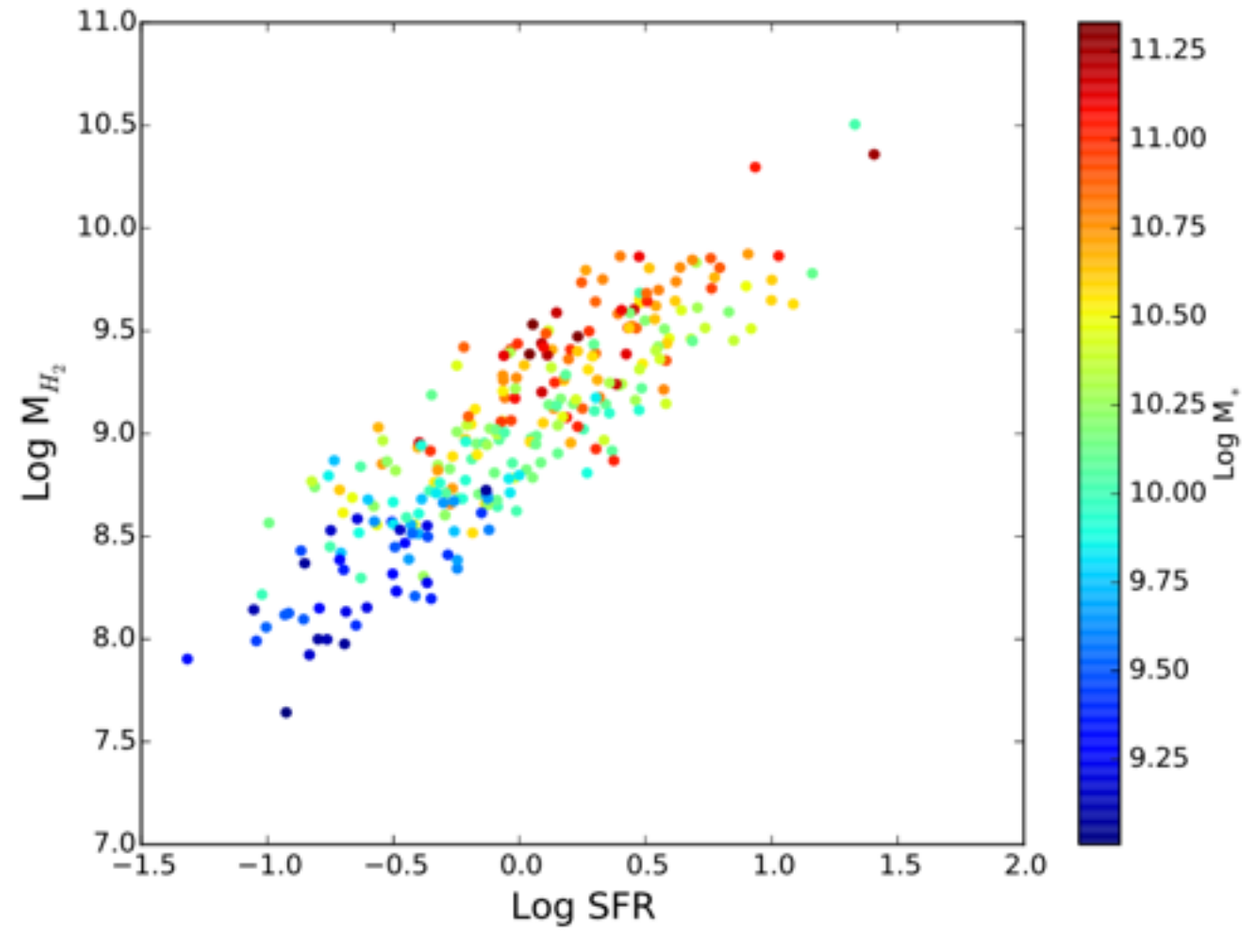
Disentangling star formation efficiency from CO photodissociation effects



Accurso et al. (2016b)

Disentangling star formation efficiency from CO photodissociation effects

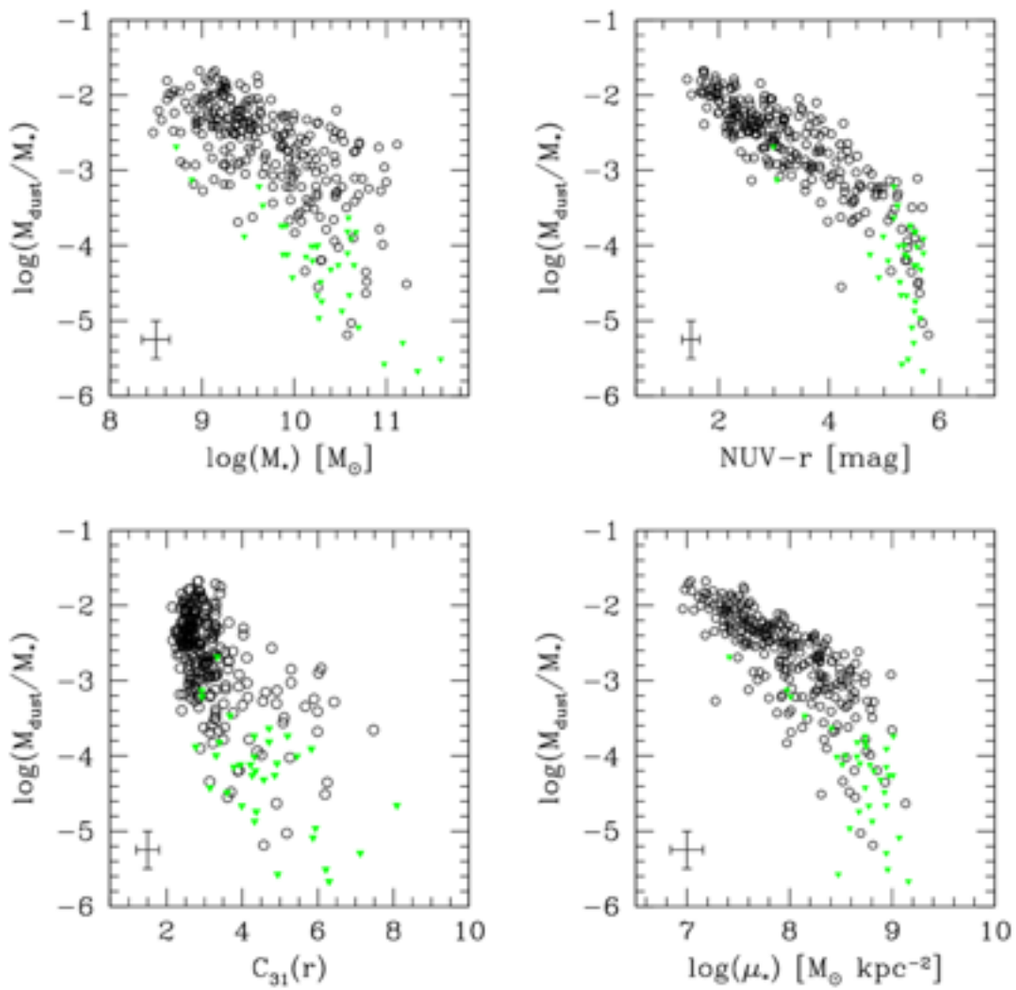




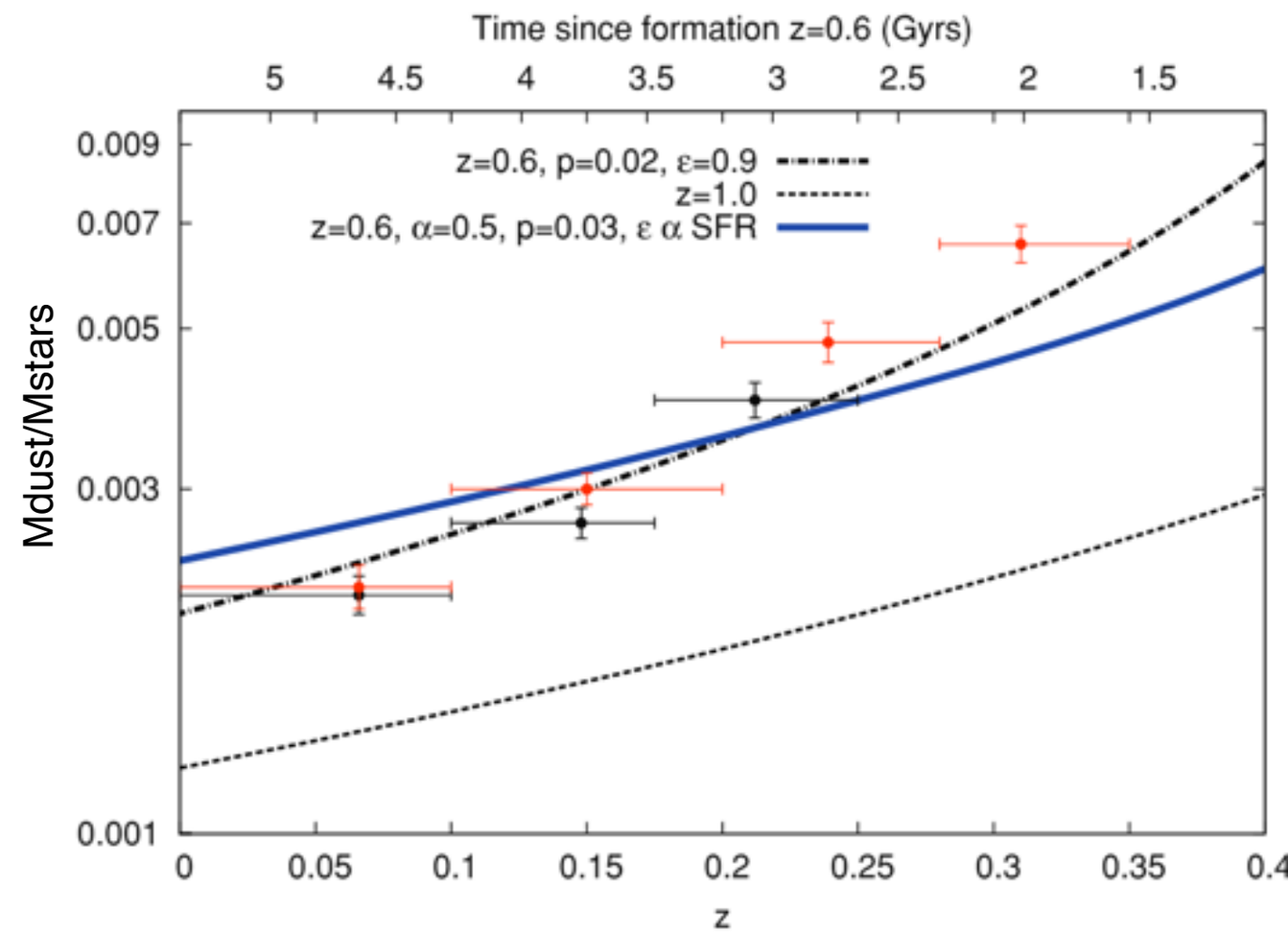
Low mass/metallicity galaxies are CO-faint due to the impact of photodissociation; their star formation efficiency is not systematically higher.

Accurso et al. (2016b)

Beyond CO: using dust as a probe of the cold ISM



Cortese et al. (2011)



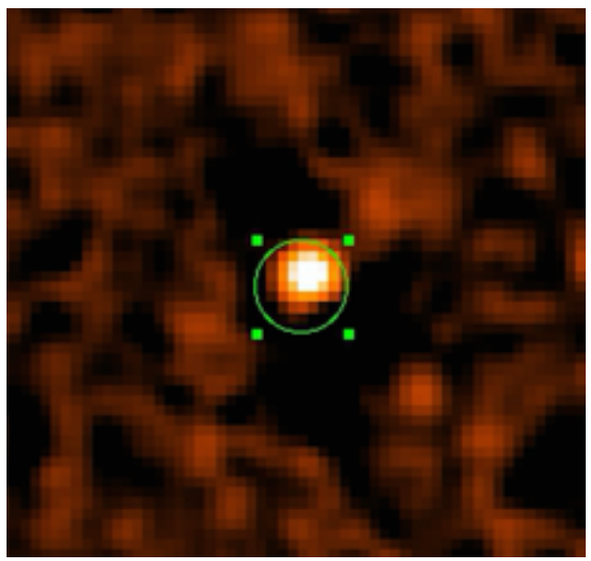
Dunne et al. (2011)

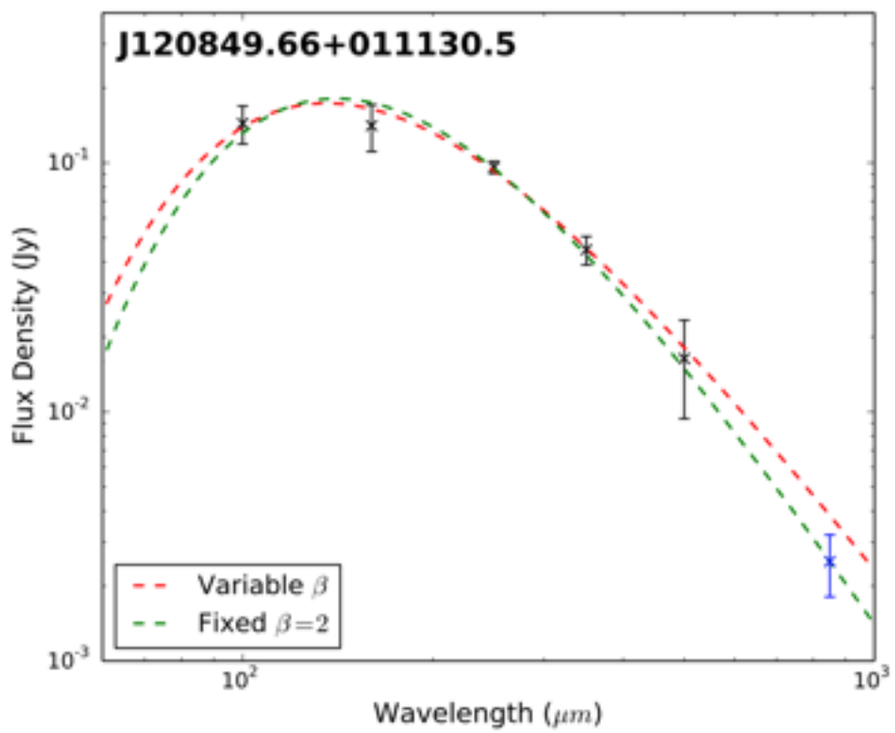
On galactic scales, dust scaling relations behave similarly than those involving cold gas.

Dust as a probe of the cold ISM

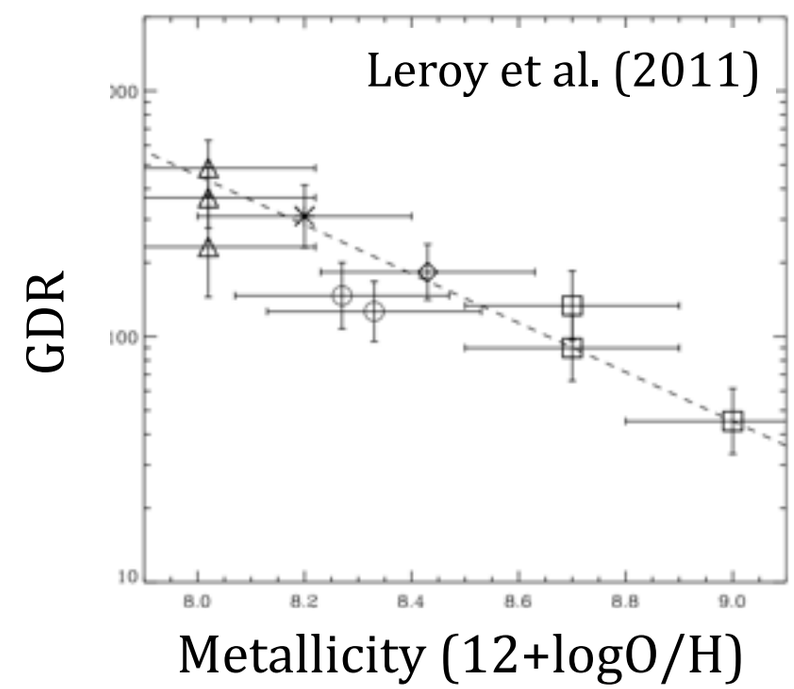
An alternative approach to CO line observations:

FIR/submm continuum observations → **dust mass measurements** → **gas mass estimations**





$$M_{gas} = M_{dust} \times GDR$$



Dust as a probe of the cold ISM

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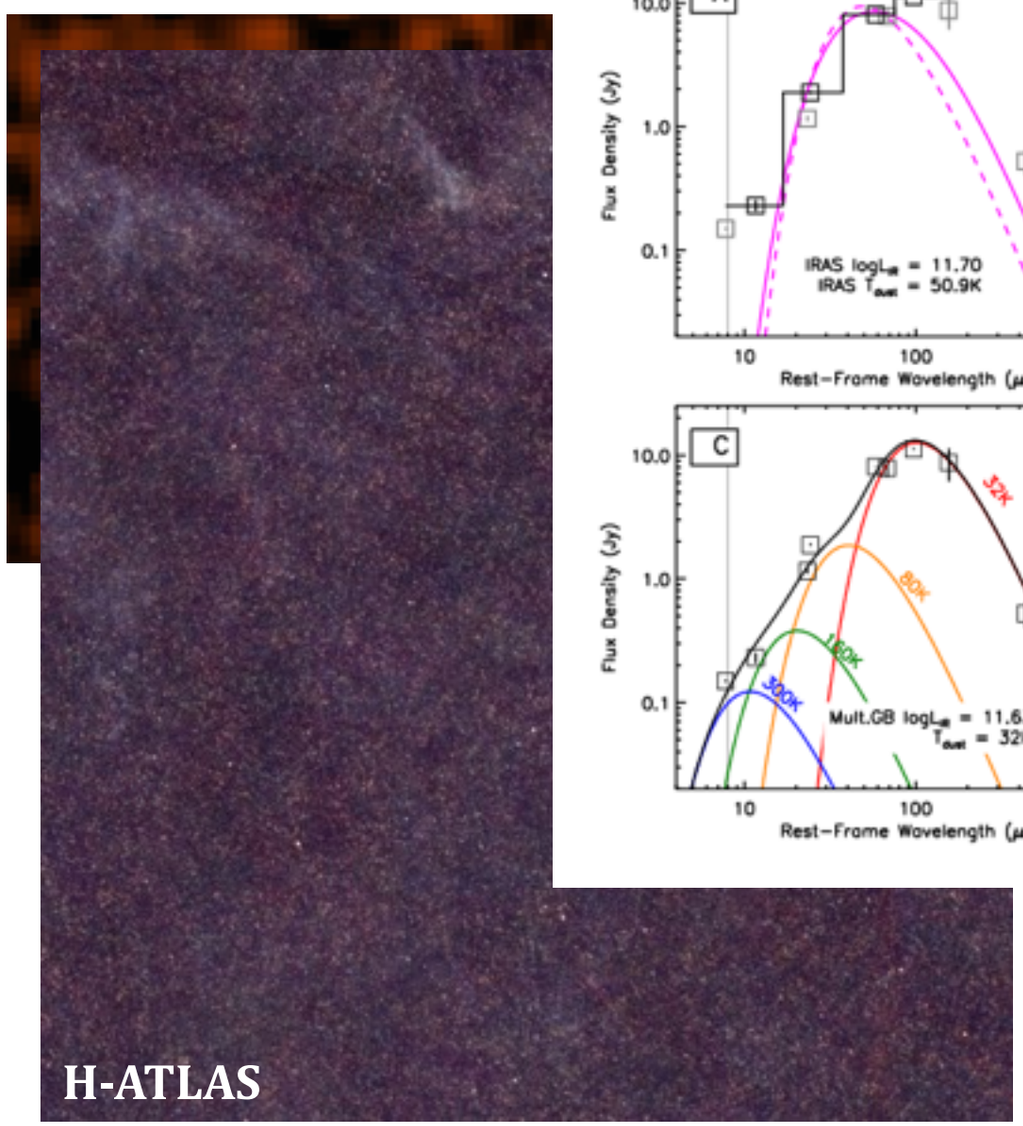
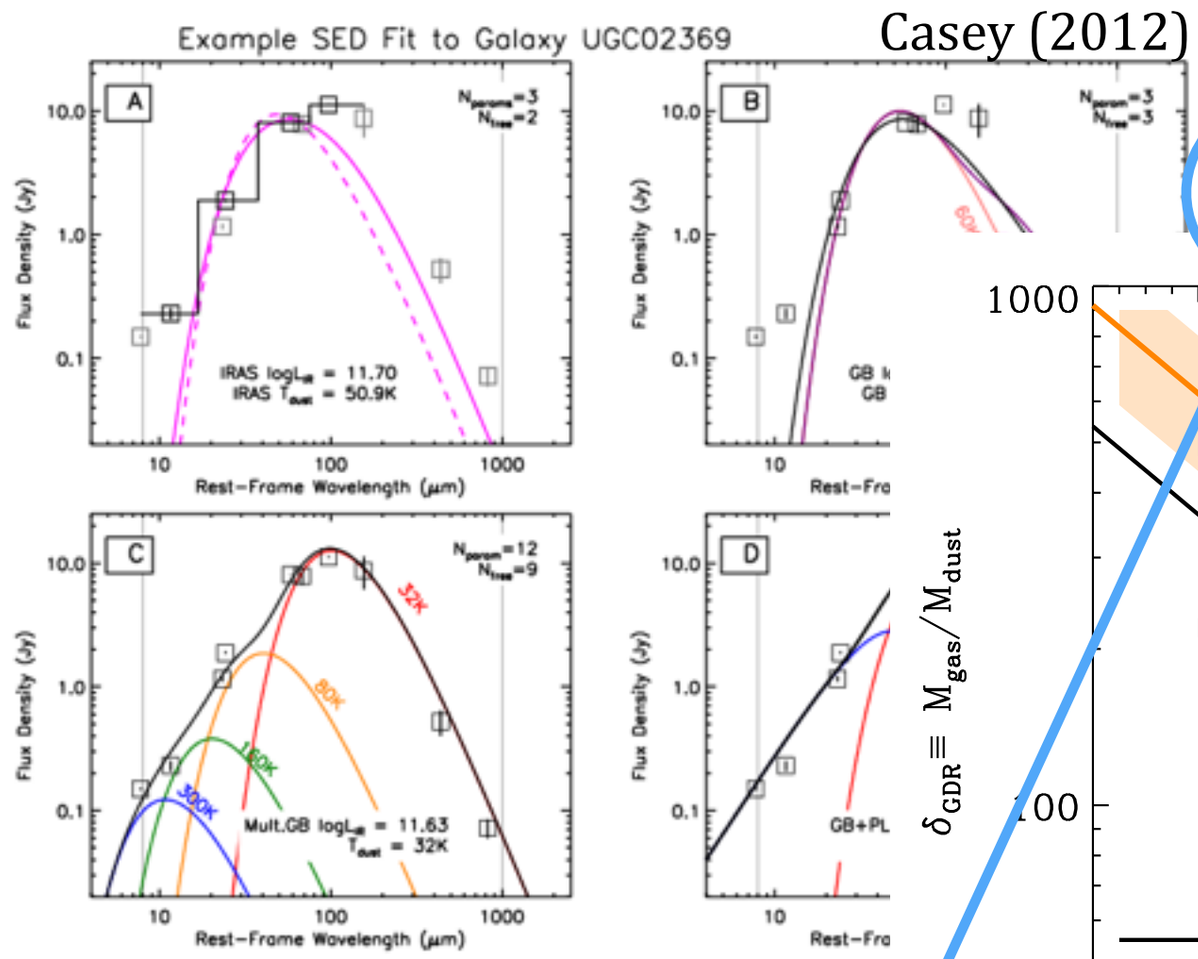
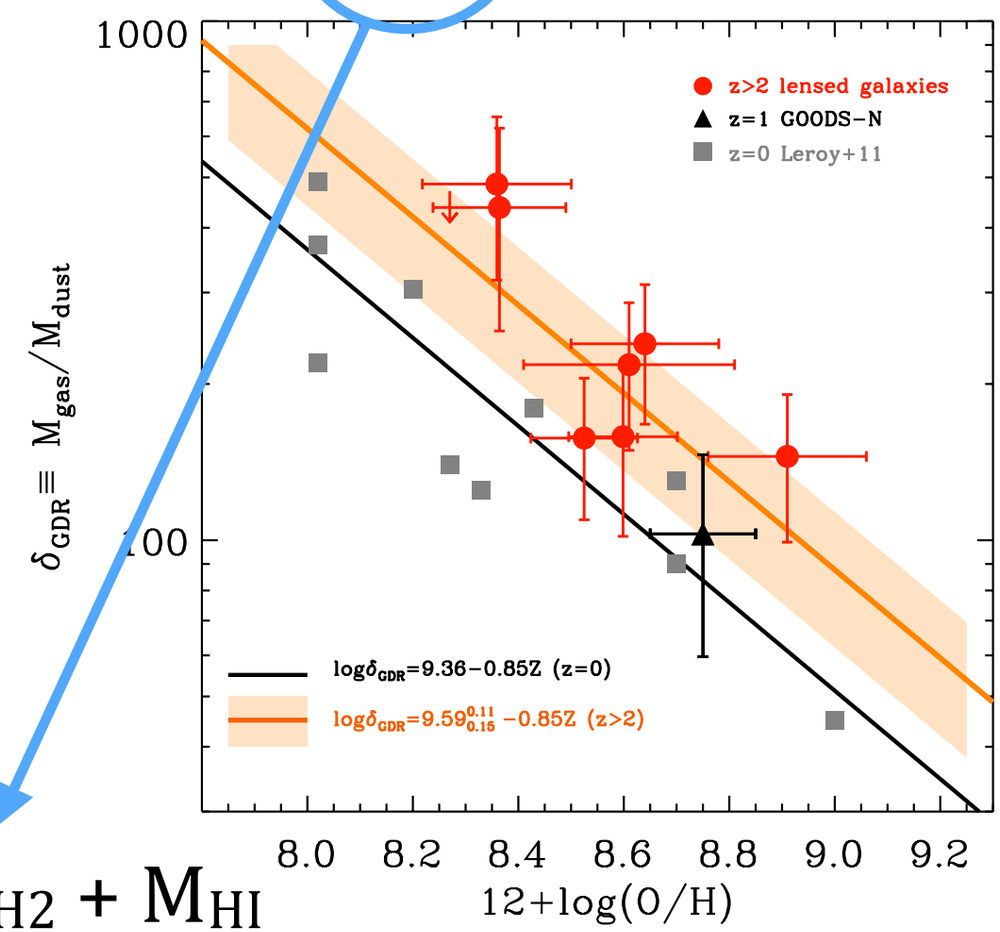




Casey (2012)

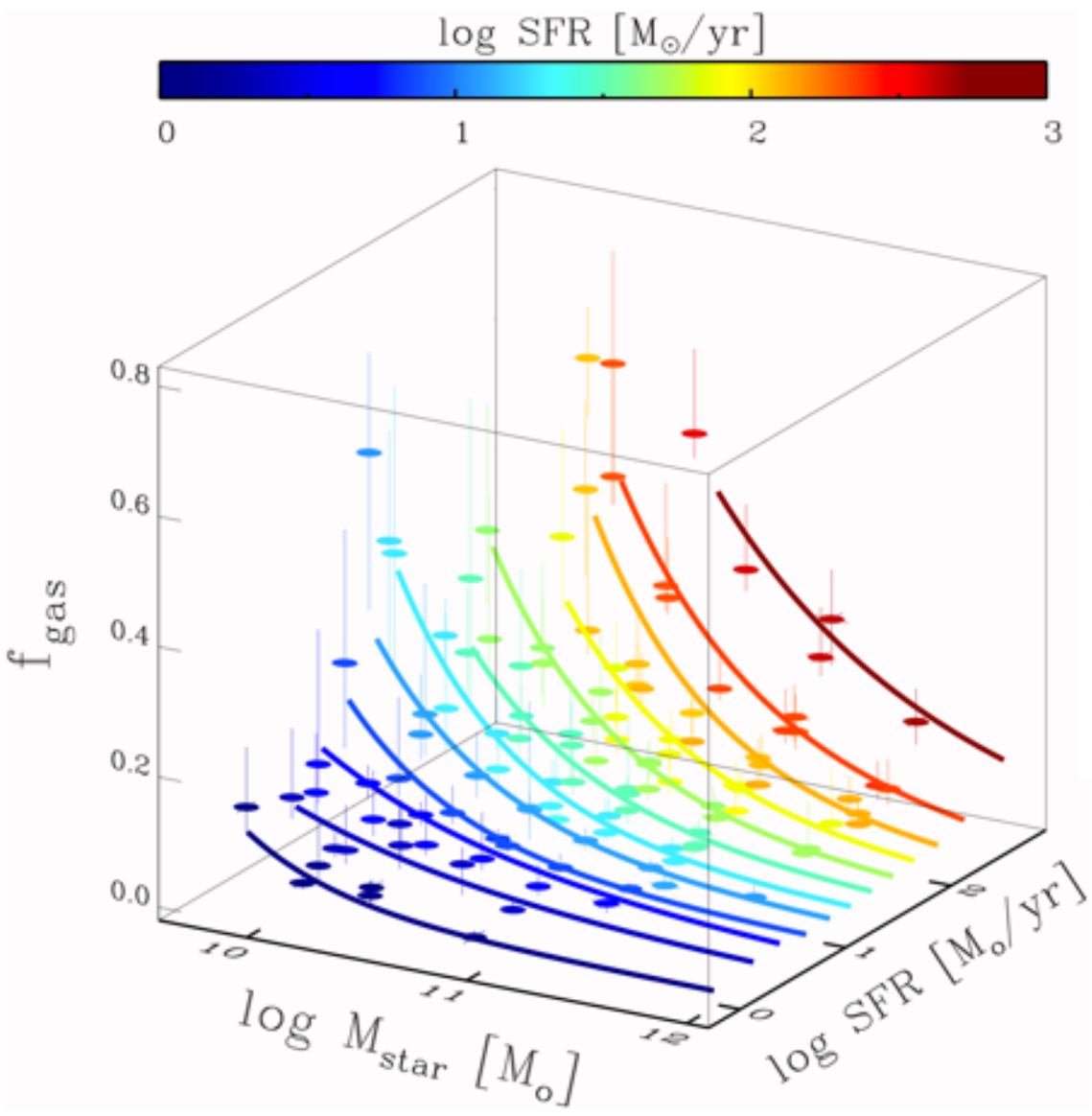
$M_{gas} = M_{dust} \times GDR$



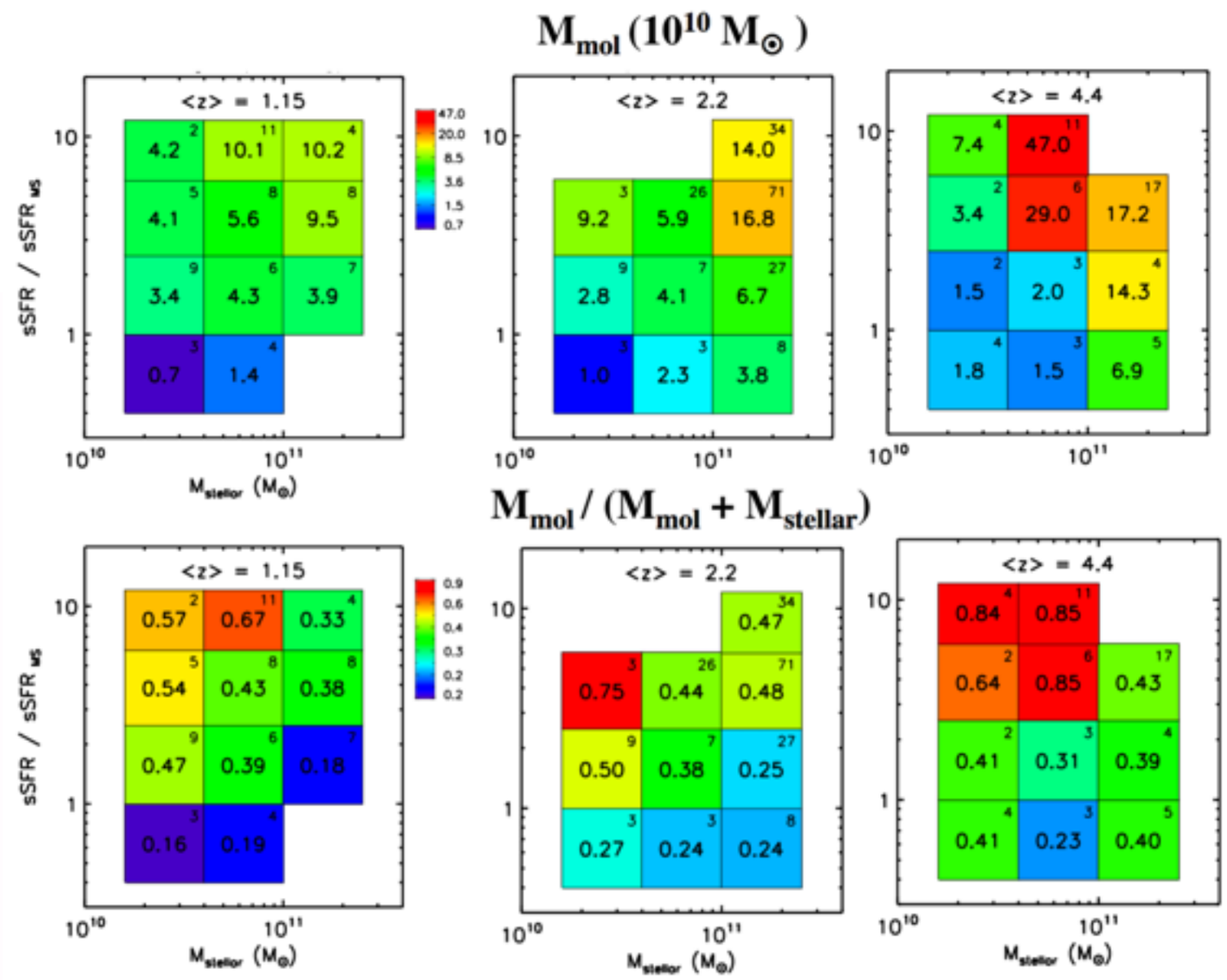
$M_{gas} = M_{H2} + M_{HI}$

Saintonge et al. (2013)

Dust as a probe of the cold ISM



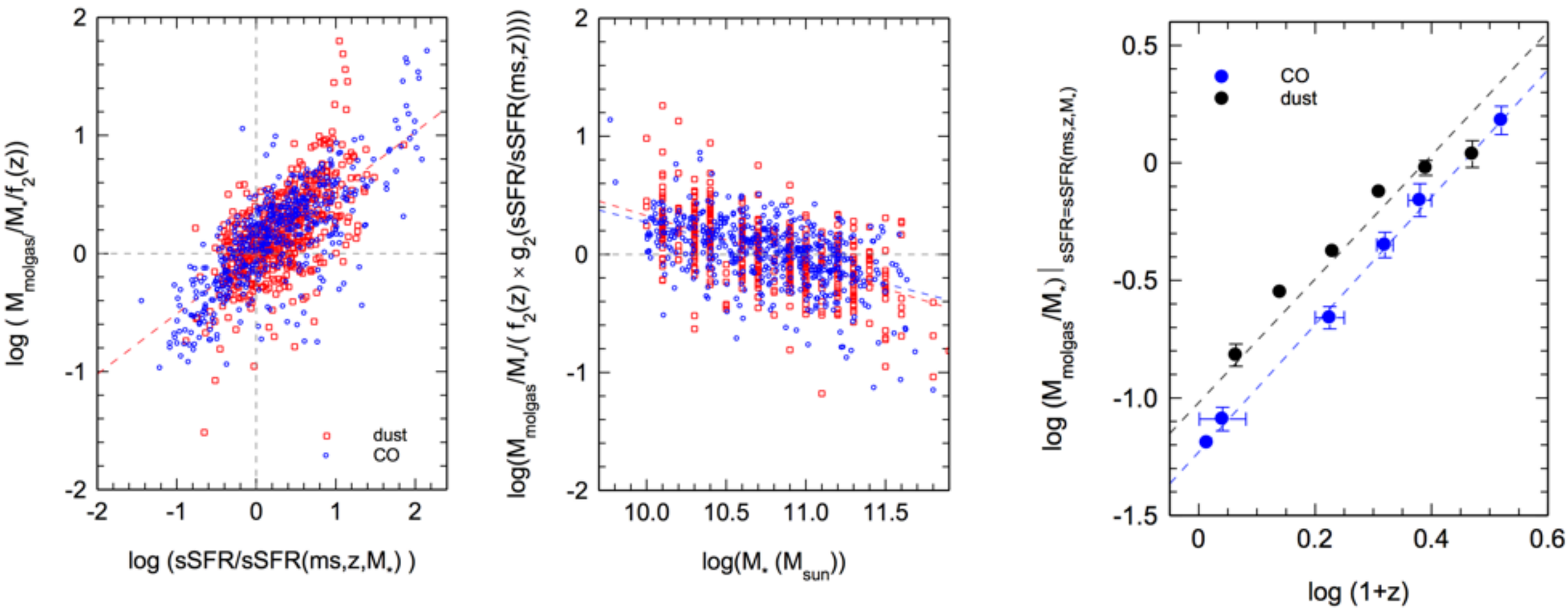
Santini et al. (2014)



Scoville et al. (2016)

Dust as a probe of the cold ISM

In the regime of high mass/metallicity galaxies, the CO and dust methods produce very comparable results -> **we need to extend calibrations to a wider range of galaxies**.

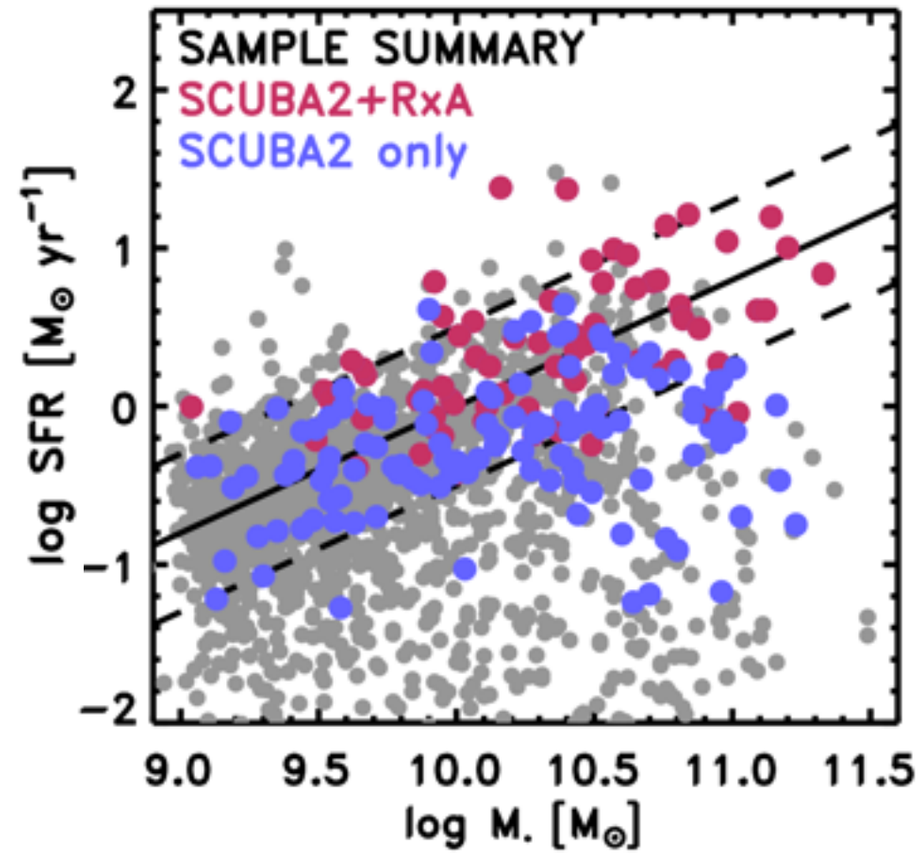


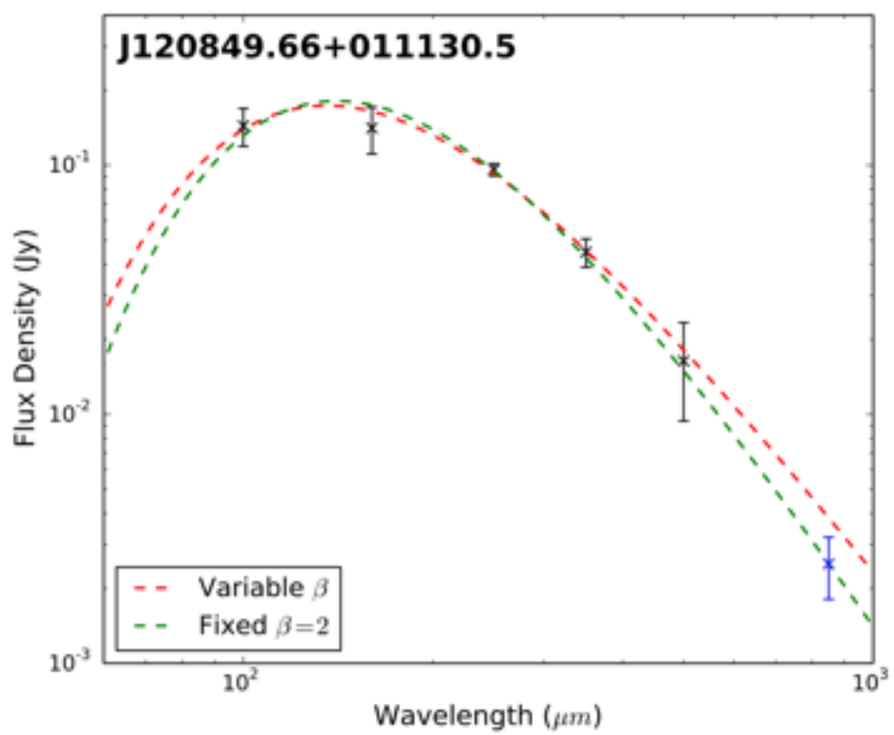
Genzel et al. (2015)

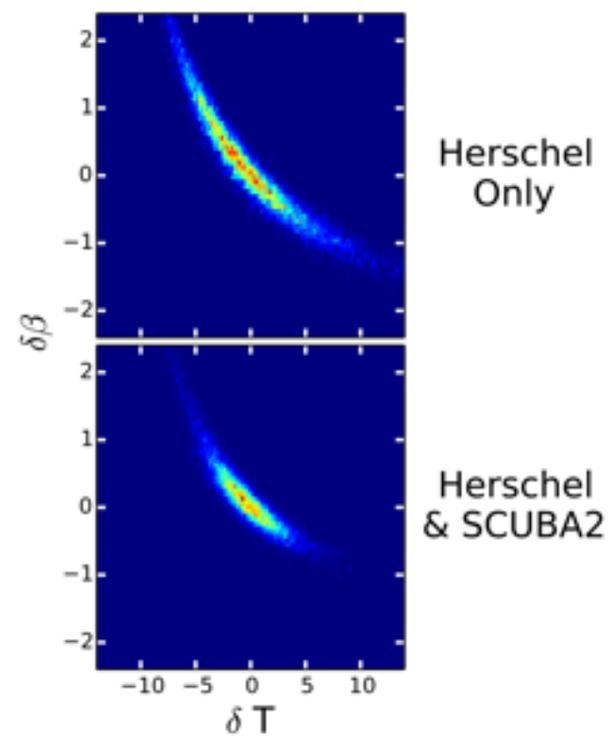
JINGLE: a systematic exploration of the properties of dust in the local Universe

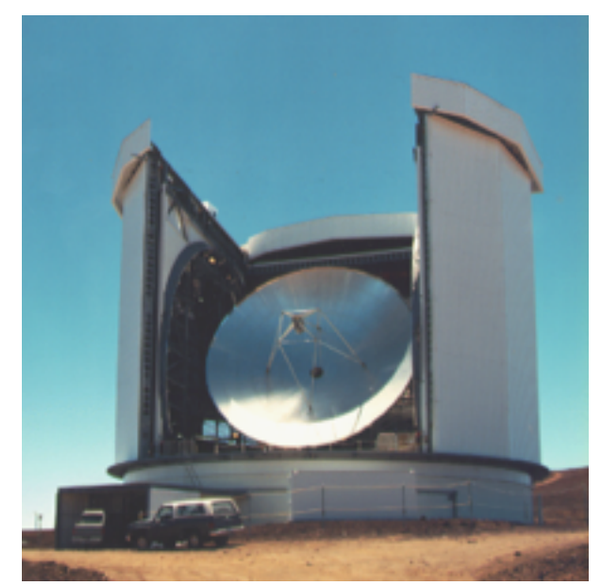
New 780h JCMT legacy survey:
- 850um SCUBA-2 flux measurements for 200 galaxies
- CO(2-1) RxA line measurements for a subset of 75 galaxies

Sample builds on SDSS, H-ATLAS, MaNGA, HI surveys,…





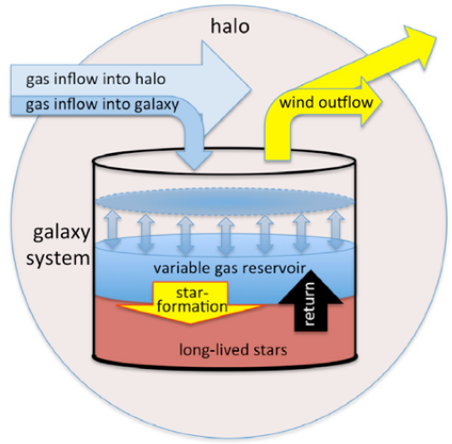


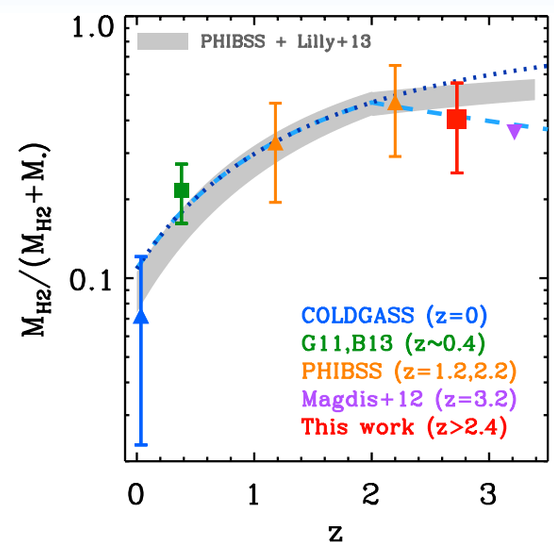


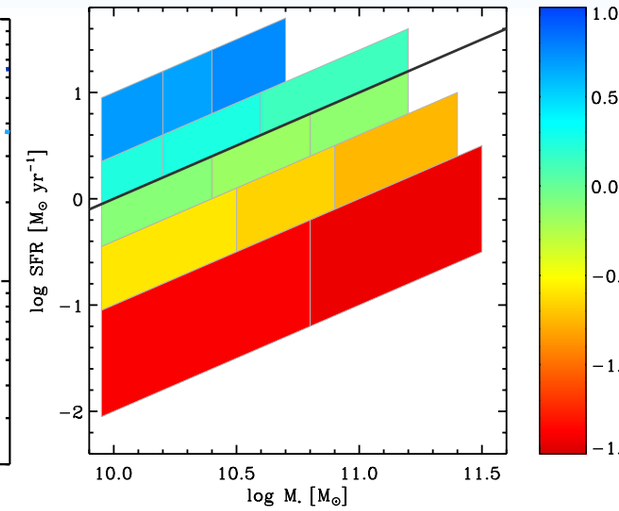
Status update: SCUBA-2 observations well underway w/ 85% detection rate and analysis under way.

Conclusions and outlook

Large unbiased galaxy samples with molecular and atomic gas measurements are key to refine star formation models and canvas parameter space for detailed studies.







COLD GASS2

Extension of COLD GASS to lower stellar masses

PI A. Saintonge (UCL) + MPE group

JINGLE

New JCMT legacy survey for dust +gas in nearby galaxy

PIs A. Saintonge (UCL), C. Wilson (McMaster), T. Xiao (SHAO)

PHIBSS2

Quadrupling the PHIBSS sample and extending to lower/higher masses, lower/higher redshift...

PIs L. Tacconi (MPE), F. Combes (Paris), R. Neri (IRAM), S. Garcia-Burillo (Madrid)

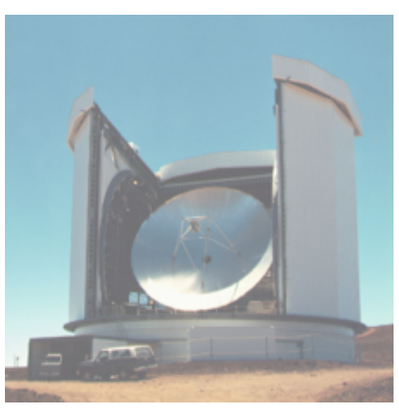
1700h IRAM PdBI Legacy Programme

~200 star forming galaxies with $0.5<z<2.5$, $10^{10}<M^*<5\times10^{11}$

ALMA ?

Yes, for high-res follow-up and z>2.5, but must first understand the systematics in low metallicity environments.

+ connect global properties to physics of star formation on sub-kpc to cloud scales!



ALMA