Life Cycle of Gas in Galaxies: A Local Perspective
ASTRON - 3.9.2015

The link between HI, H_2 and star formation in the local Universe (and beyond)

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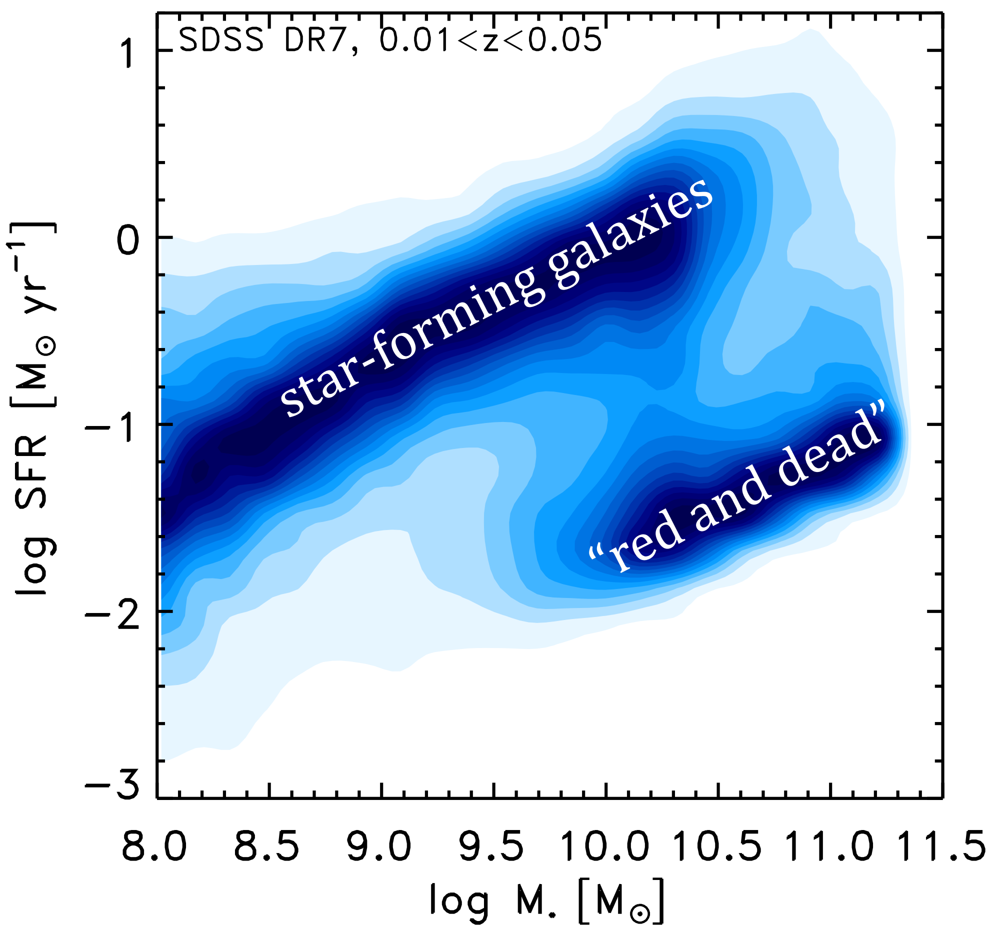
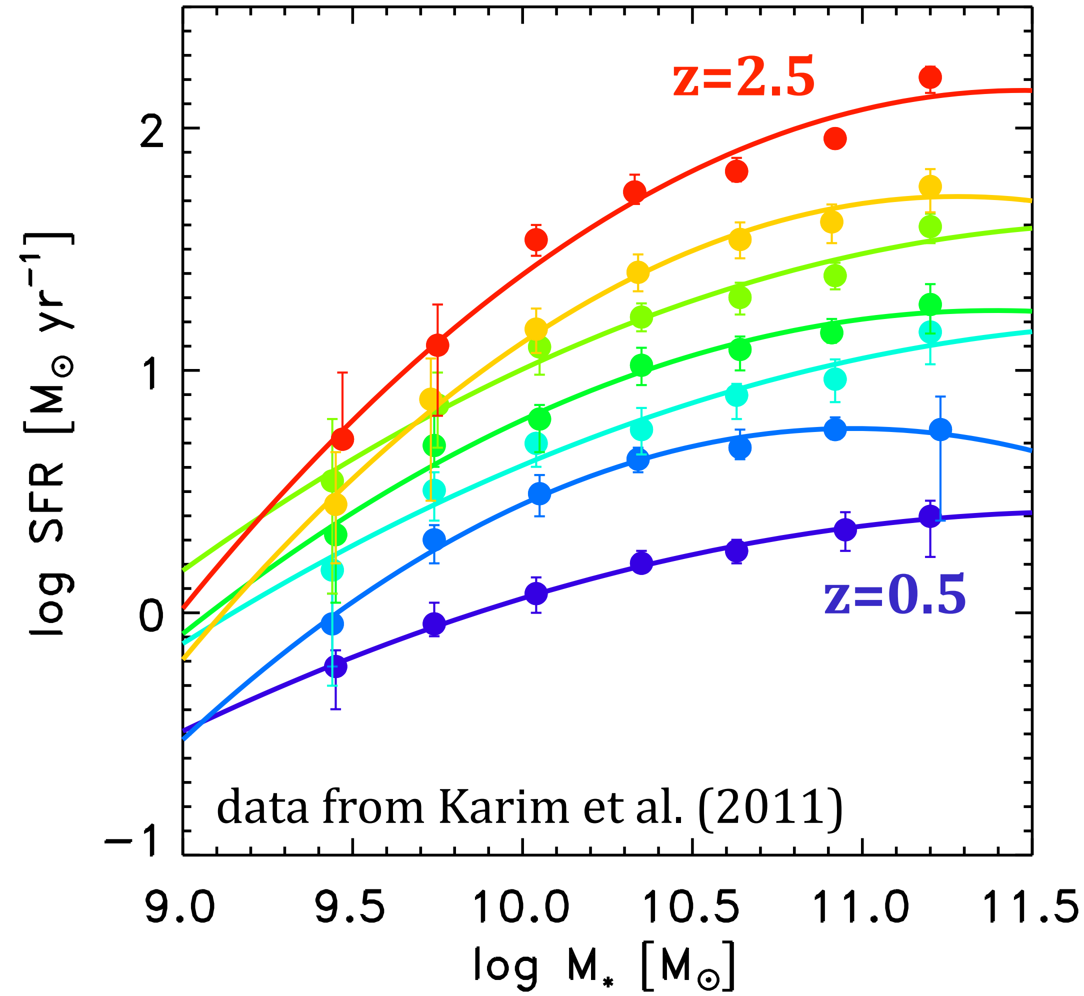
current observational view of galaxy evolution

the star formation "main sequence"

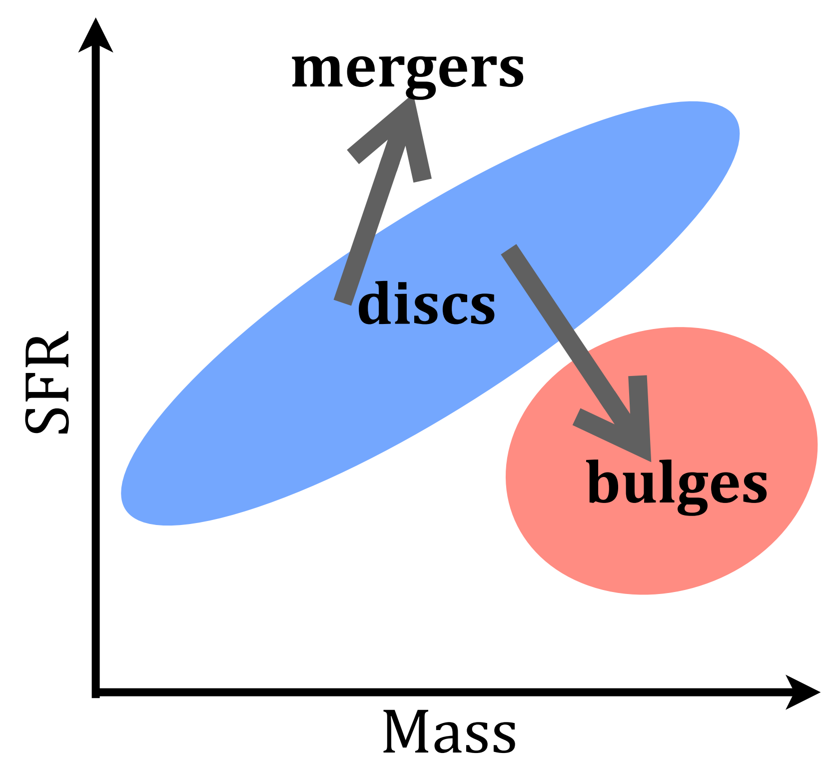
see e.g.: Schiminovich et al. (2007), Elbaz et al. (2007), Noeske et al. (2007), Daddi et al. (2007), Perez-Gonzalez et al. (2008), Peng et al. (2010)





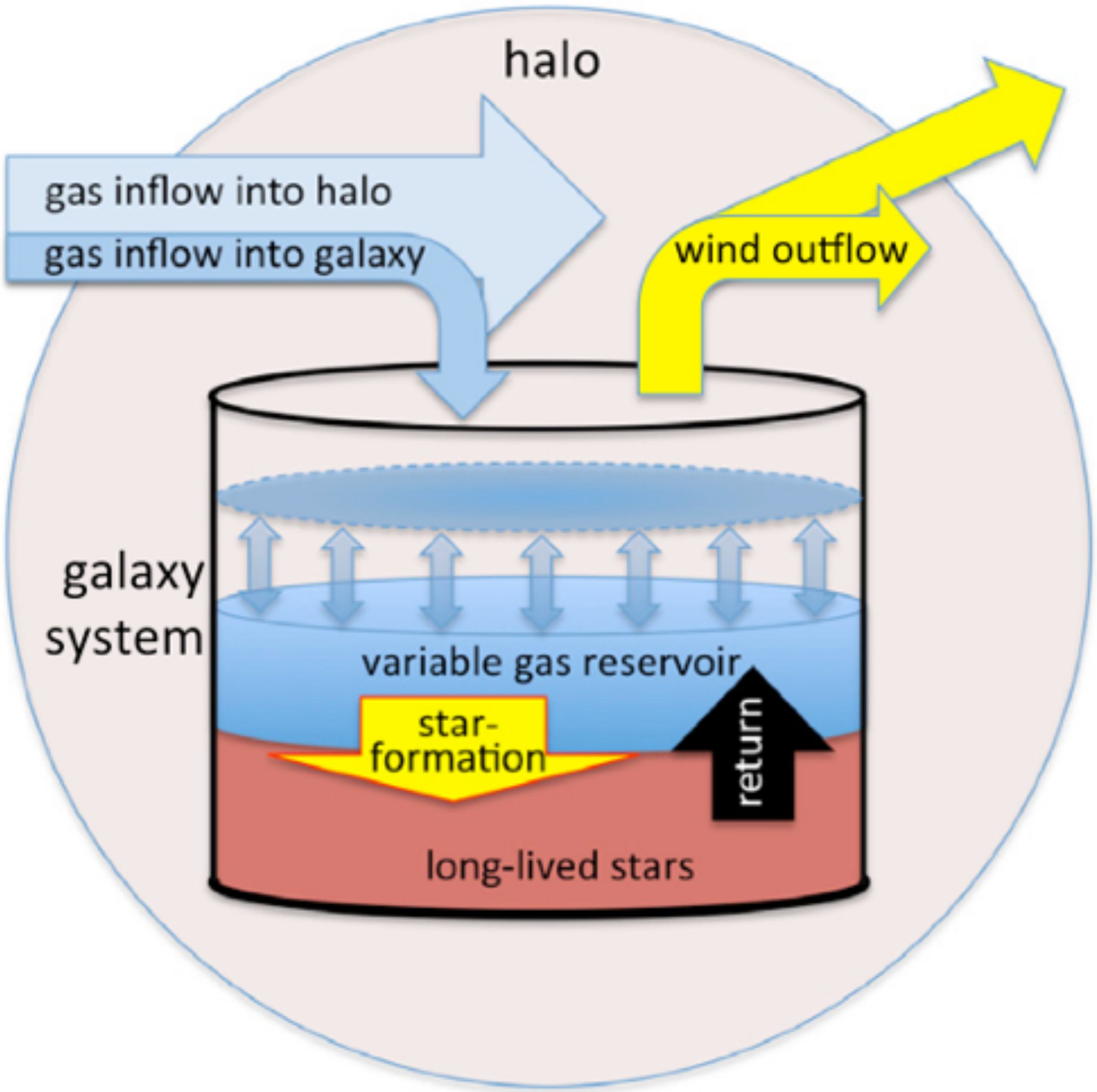
$SFR \sim M_*^a(1+z)^b$, where a~0.8, b~2.5

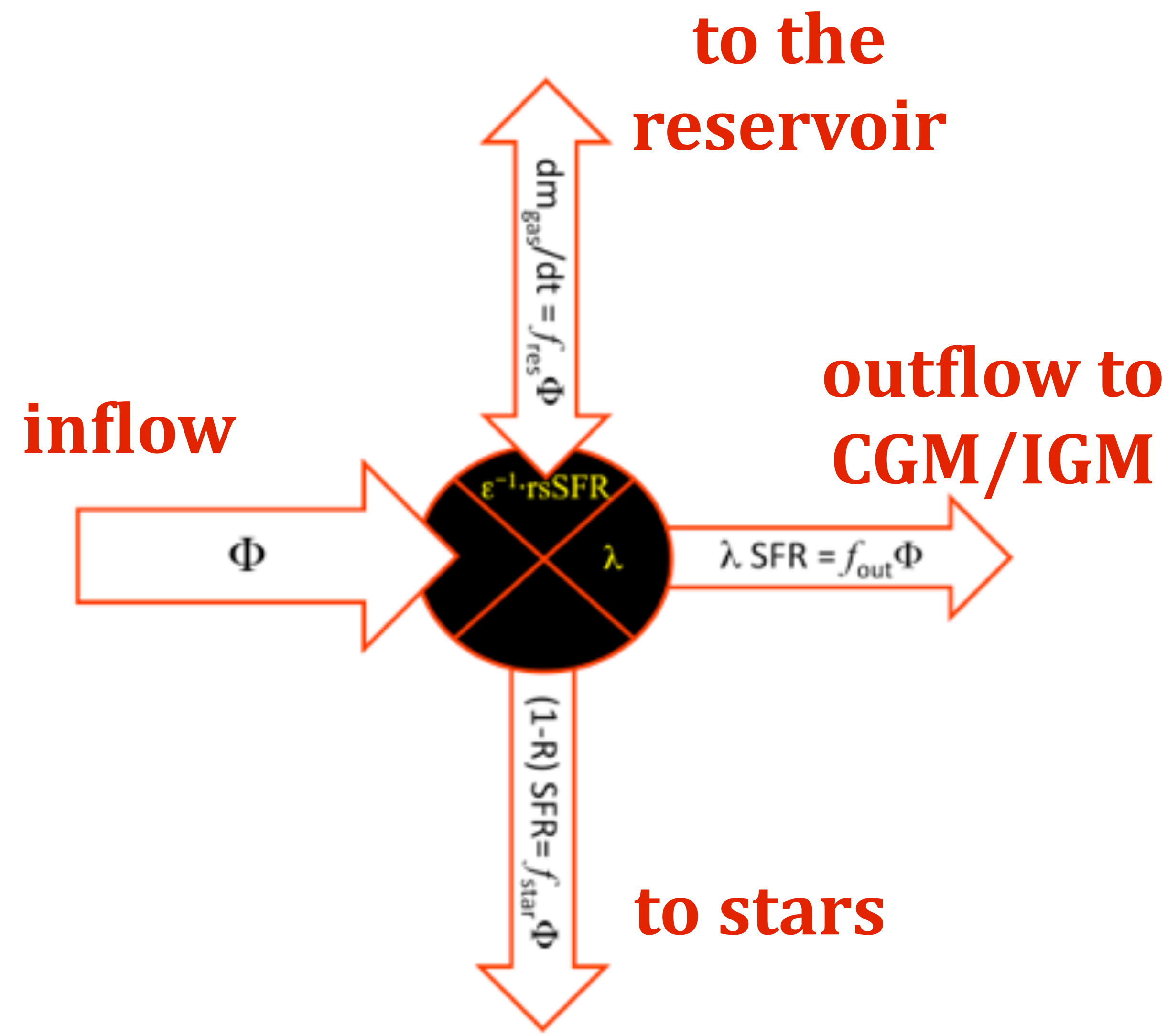
- Galaxies on the main sequence (MS) contribute ~90% of the star formation.
- Duty cycles on the MS are high at 40-70% (e.g. Noeske et al. 2007)



the "equilibrium" (or regulator) model

Star formation is regulated by the mass of gas in a reservoir, which itself is affected by the inflow rate, the star formation efficiency, and the mass loading factor of outflows.





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

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

IRAM surveys for molecular gas in normal galaxies

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

COLD GASS

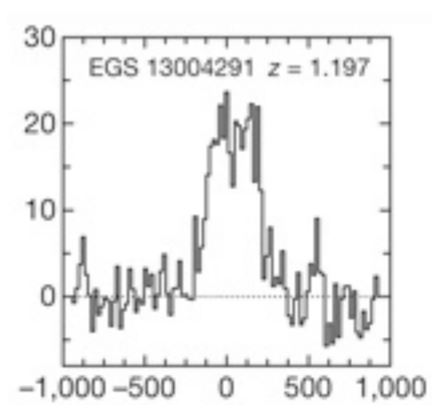
PIs G. Kauffmann (MPA), C. Kramer (IRAM)
1000h IRAM 30-m Large Programmes
+1300h Arecibo Programme for HI

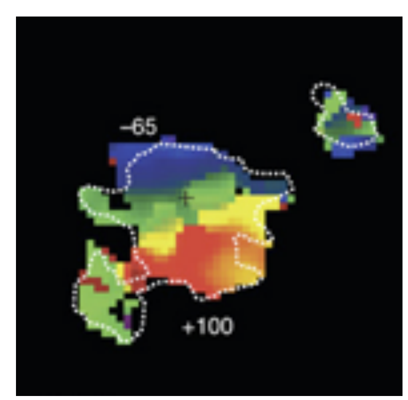
500 SDSS-selected galaxies with
$0.01<z<0.05$, $M^*>10^9$
see Saintonge et al. 2011a,b, Kauffmann et al. 2012, Saintonge et al. 2012.

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 Tacconi et al. 2010,2013, Genzel et al. 2010,2012,2013, 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 GASS: a multi-wavelength legacy survey

the first statistical sample of massive galaxies with homogeneously measured stellar and ***atomic+molecular gas masses***

COLD GASS: molecular gas

PIs G. Kauffmann (MPA),
C. Kramer (IRAM), A. Saintonge(UCL)
1000h **IRAM 30-m** Large Programmes

500 SDSS-selected galaxies with $0.01<z<0.05$, $M^*>10^9$

see Saintonge et al. 2011a,b, Kauffmann et al. 2012, Saintonge et al. 2012.

+**APEX** CO(2-1) and **JCMT** CO(3-2) fluxes for a subsample of ~30 galaxies.

GASS: atomic gas

PIs D. Schiminovich (Columbia),
B. Catinella (Melbourne)
1500h **Arecibo** Large Programme

~1500 SDSS-selected galaxies with $0.01<z<0.05$, $M^*>10^9$

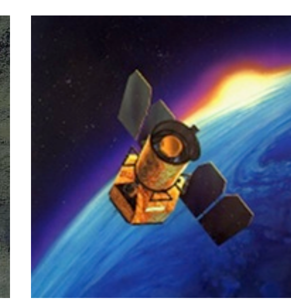
see Catinella et al. 2010, 2012, 2013, Schiminovich et al. 2010,

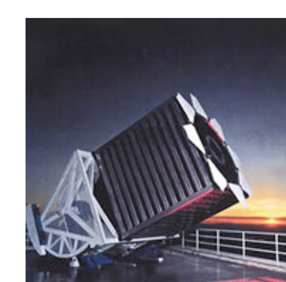
Ancillary multi-wavelength data

SDSS/GALEX/WISE photometry
Herschel (PACS) IR spectroscopy
HST (COS) UV spectroscopy
MMT/NTT long-slit optical spectroscopy

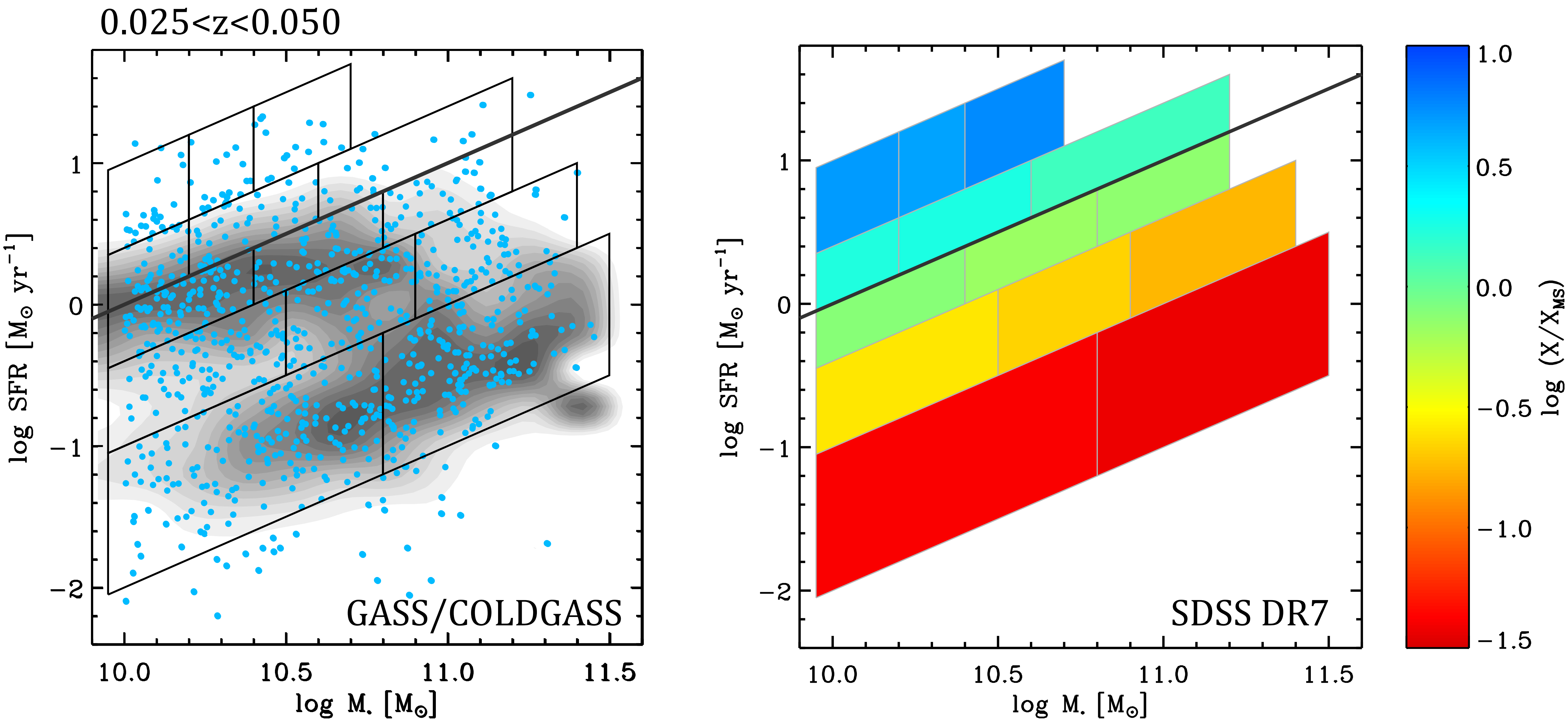
M*, SFR, morphological parameters, chemical properties, stellar populations, presence of AGN…

COLD GASS
CO LEGACY DATABASE FOR GASS
AN IRAM LARGE PROGRAM





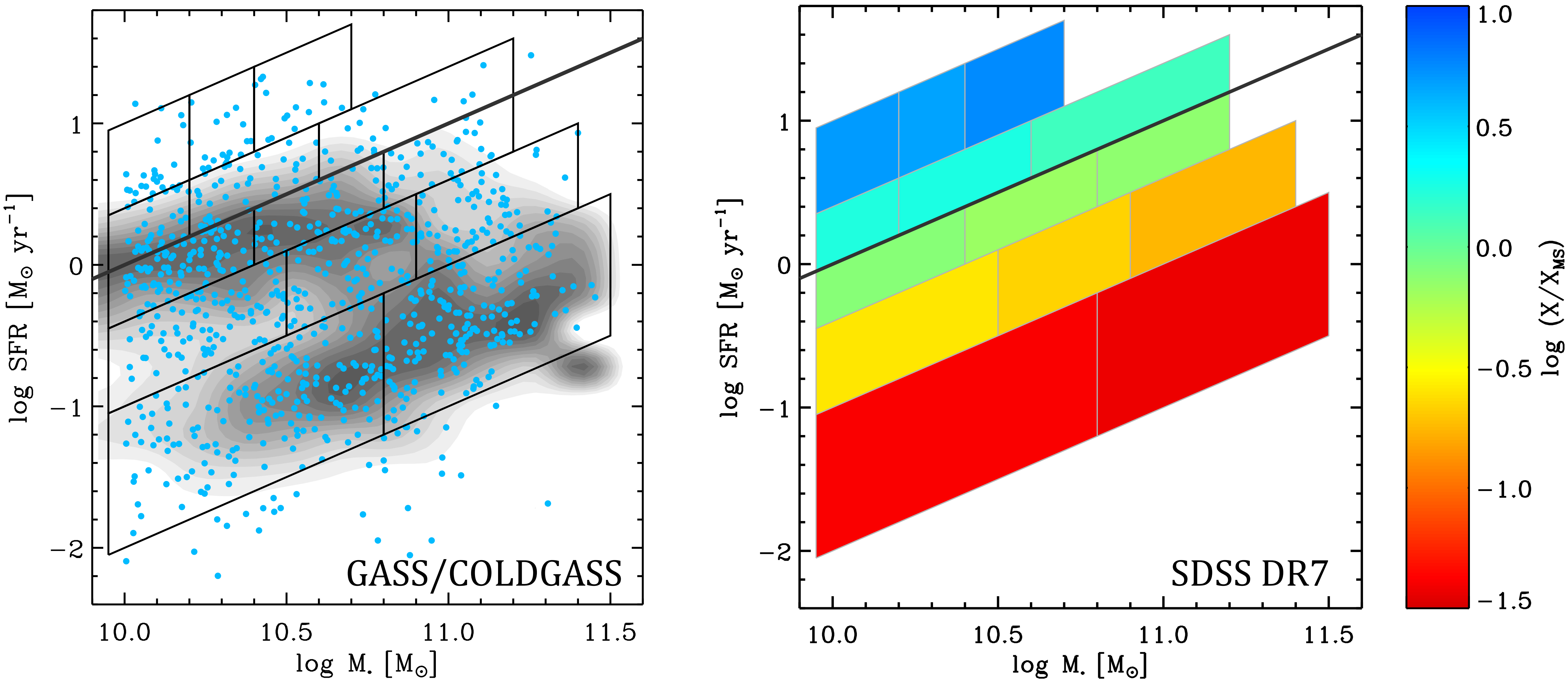
Cold gas in the SFR-M* plane



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

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

Cold gas in the SFR-M* plane



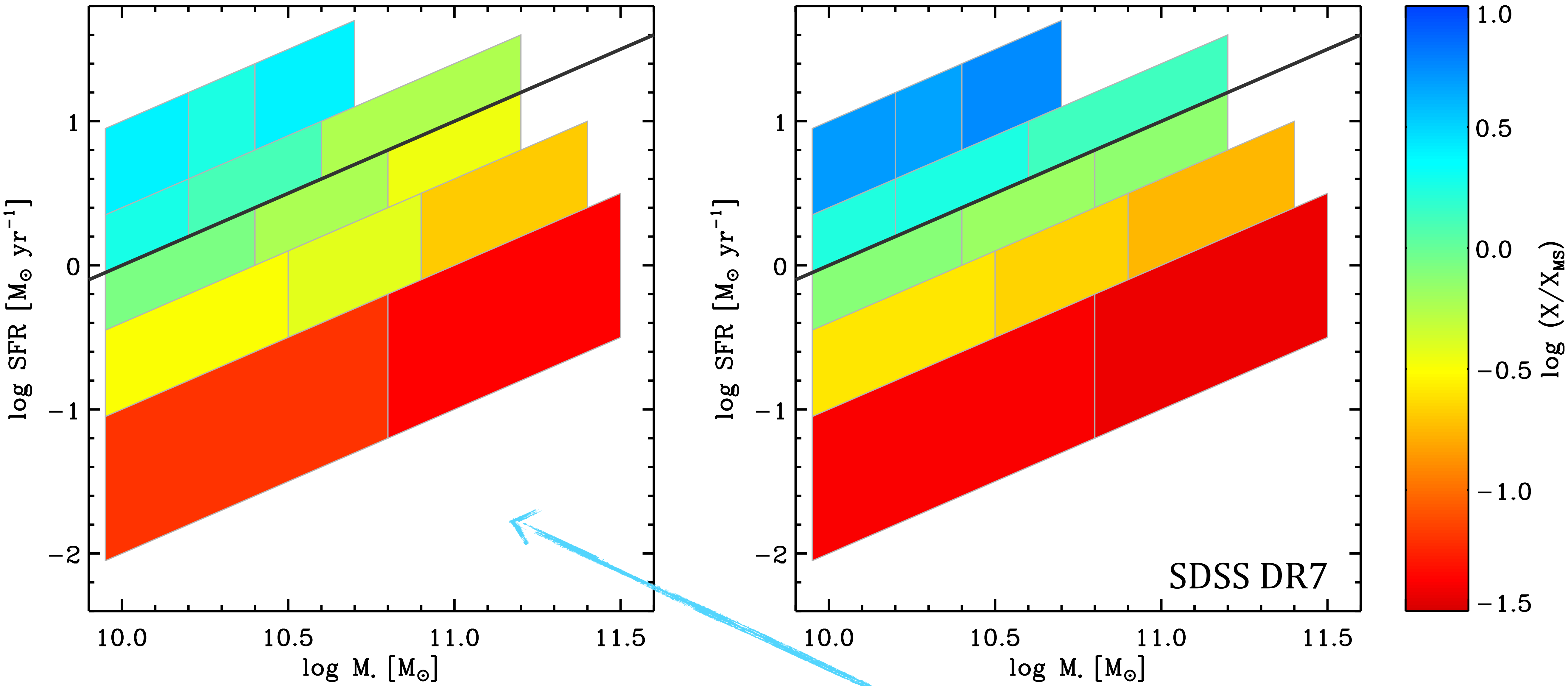
$$\mathrm{sSFR} = f_{HI}\ R_{mol}\ \mathrm{SFE}$$

"feeding"

"fueling"

"consuming"

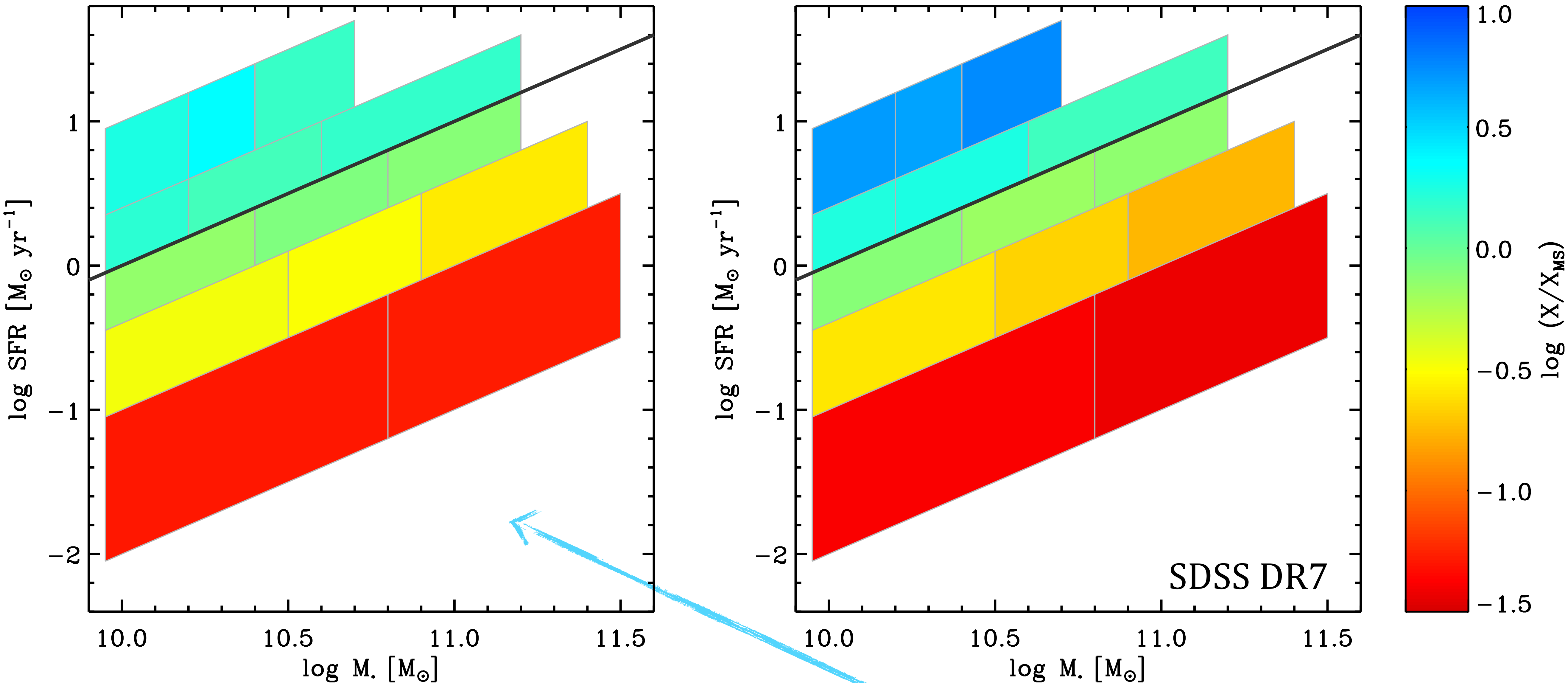
Cold gas in the SFR-M* plane



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

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

Cold gas in the SFR-M* plane

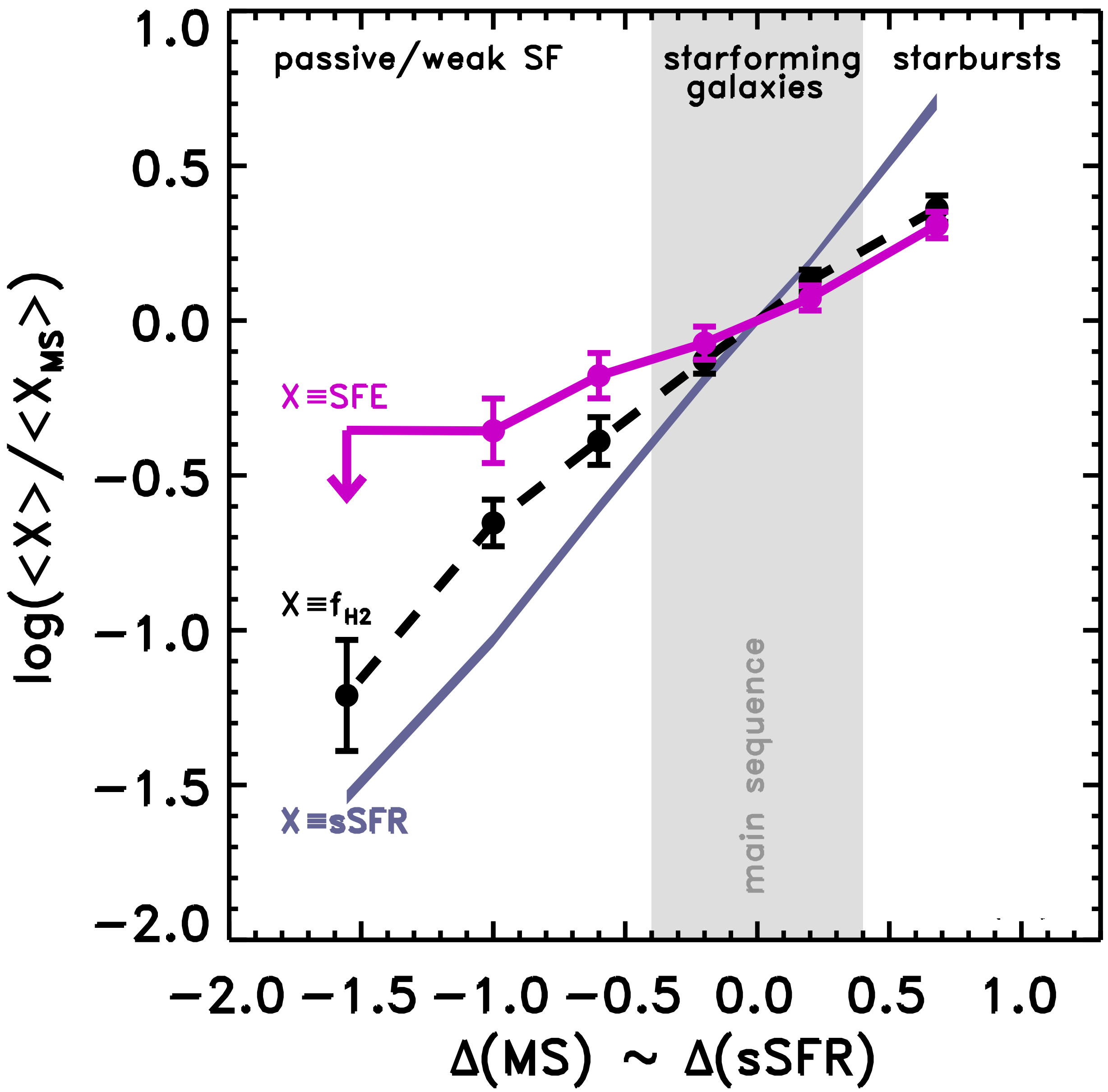


$$\mathrm{sSFR} = f_{HI}\ R_{mol}\ \mathrm{SFE}$$

$= f_{H2}$

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

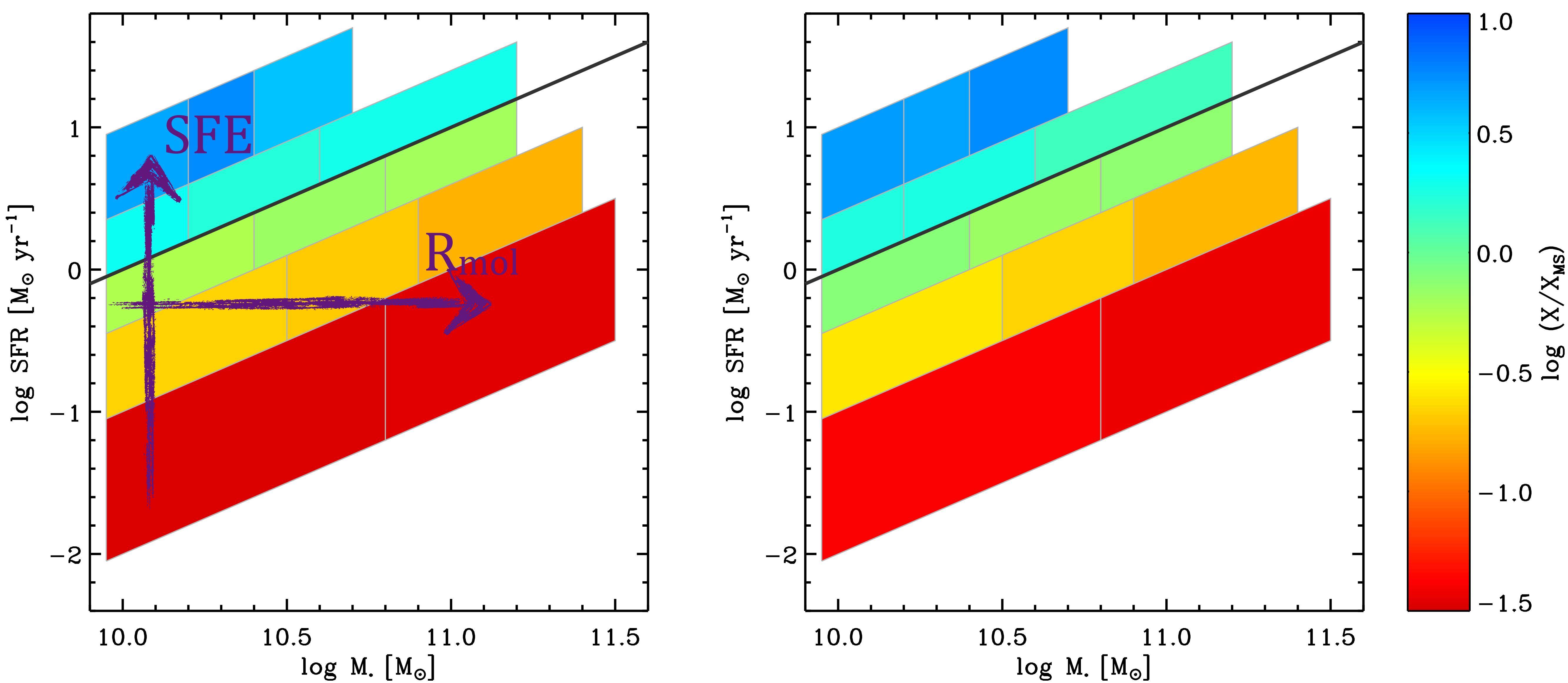
Star formation efficiency variations in the SFR-M* plane



Saintonge et al. (2012)

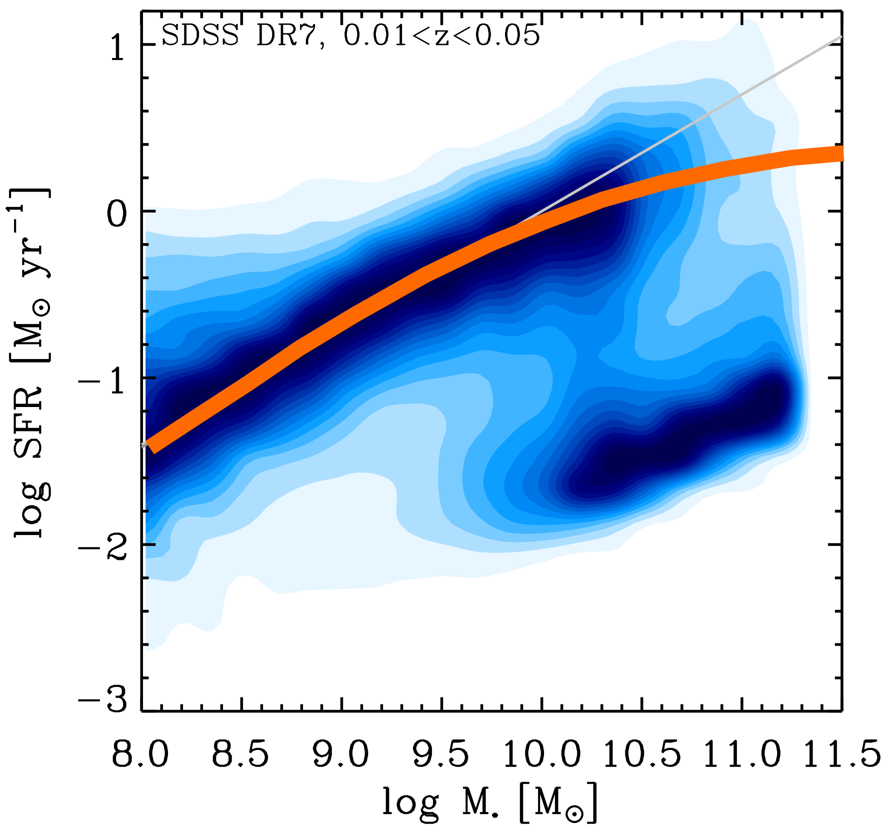
BOTH H_2 contents and star formation efficiency vary ***across*** the MS

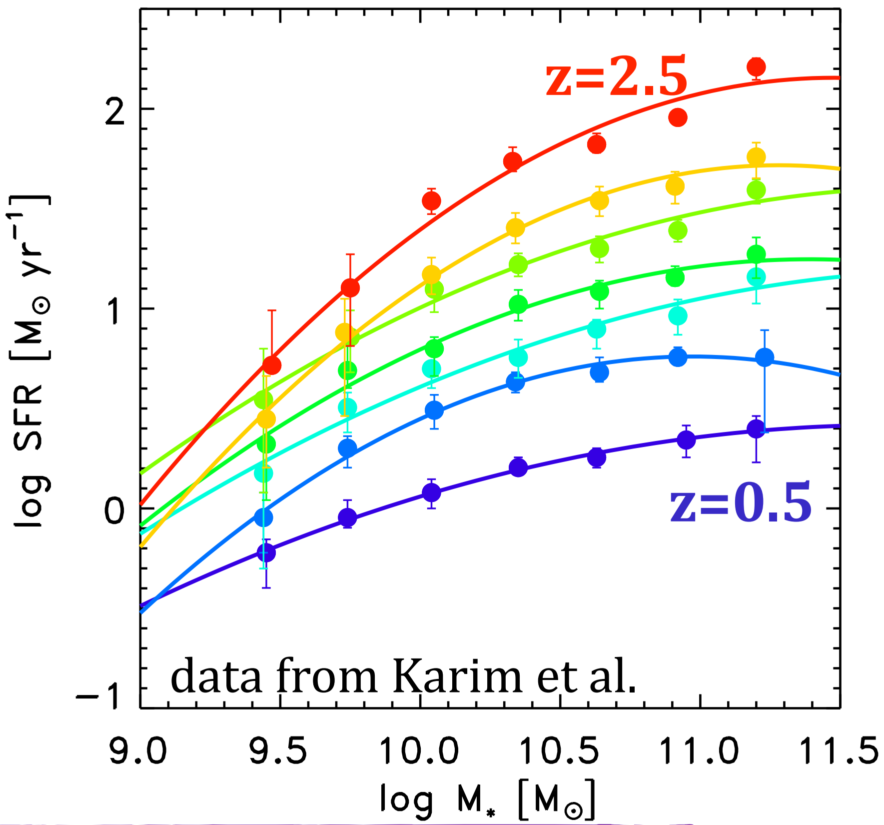
Gas and star formation efficiency explain the SFR-M* plane

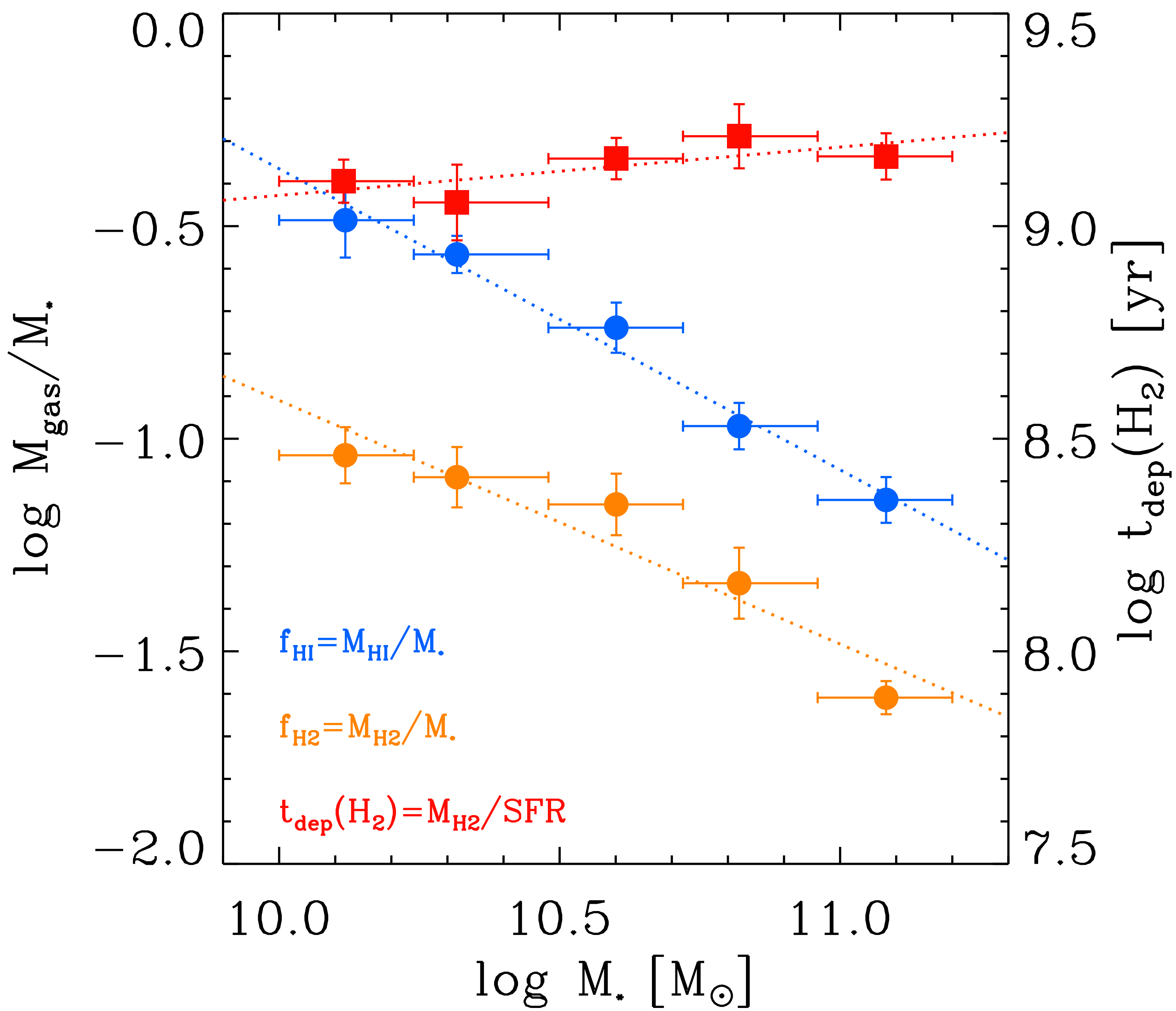


The position of a galaxy in the SFR-M* plane depends on:
(1) how much fuel it has
(2) how much of it is available for star formation
(3) the efficiency of the conversion of this gas into stars

Gas on the main sequence and star formation quenching

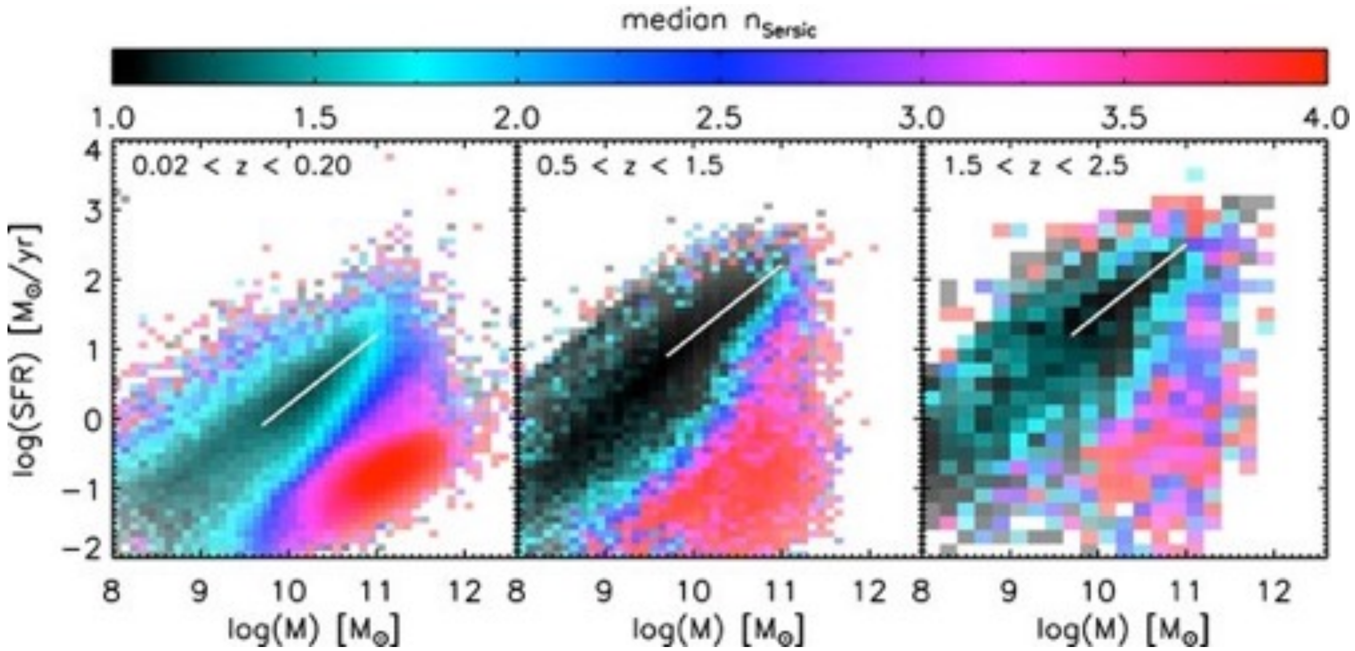




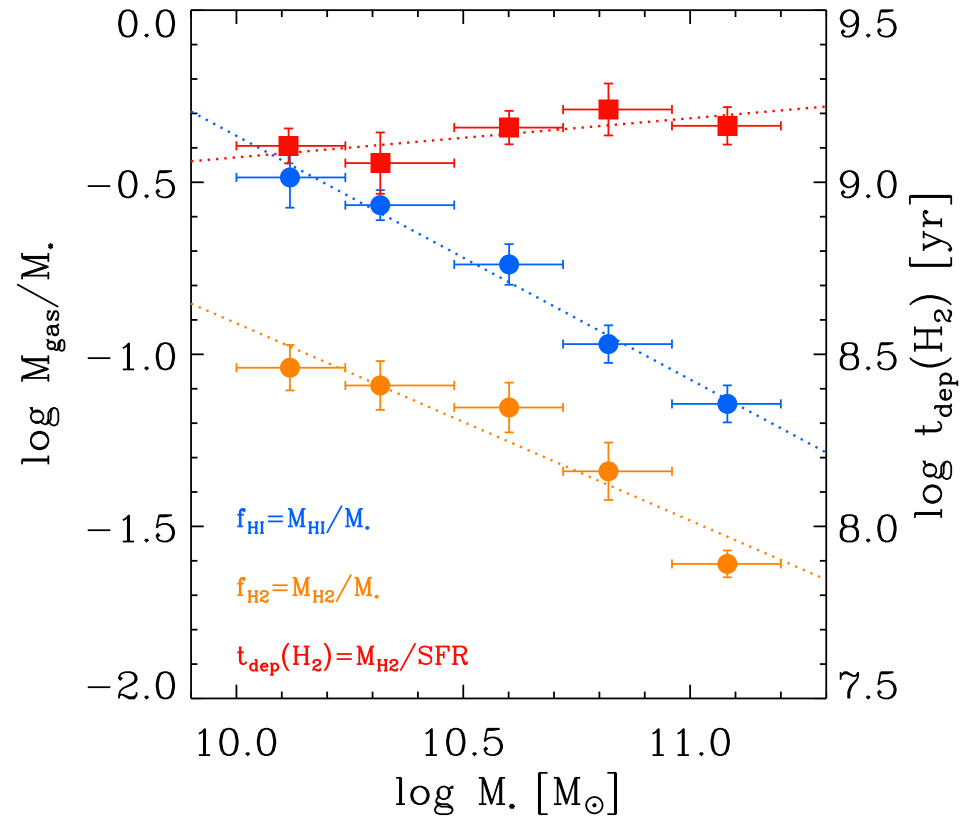


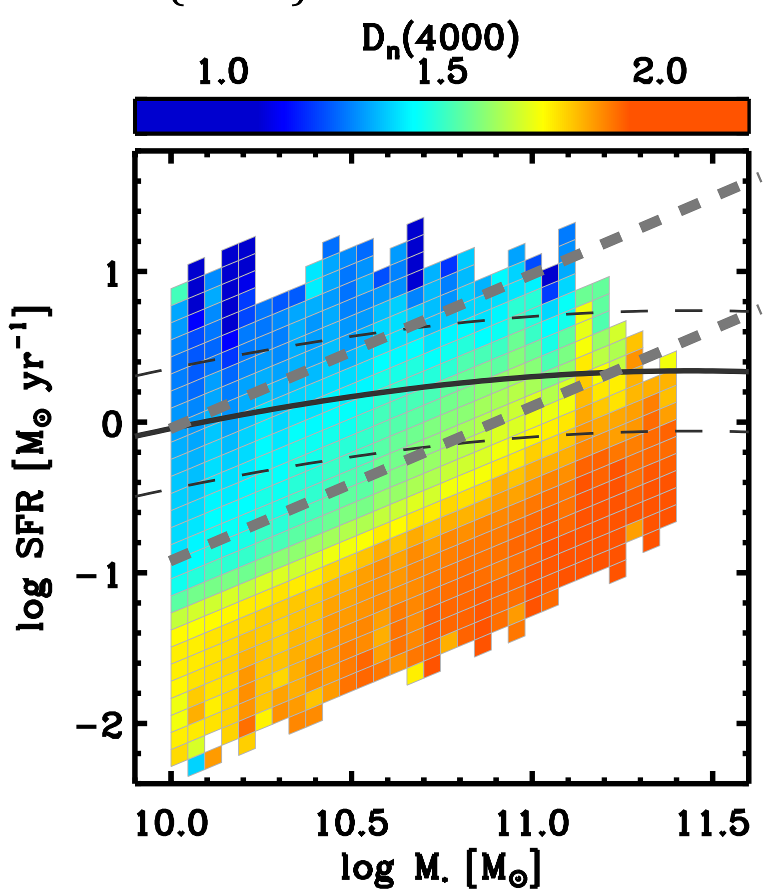
as galaxies evolve along the main sequence, they steadily consume their gas supplies

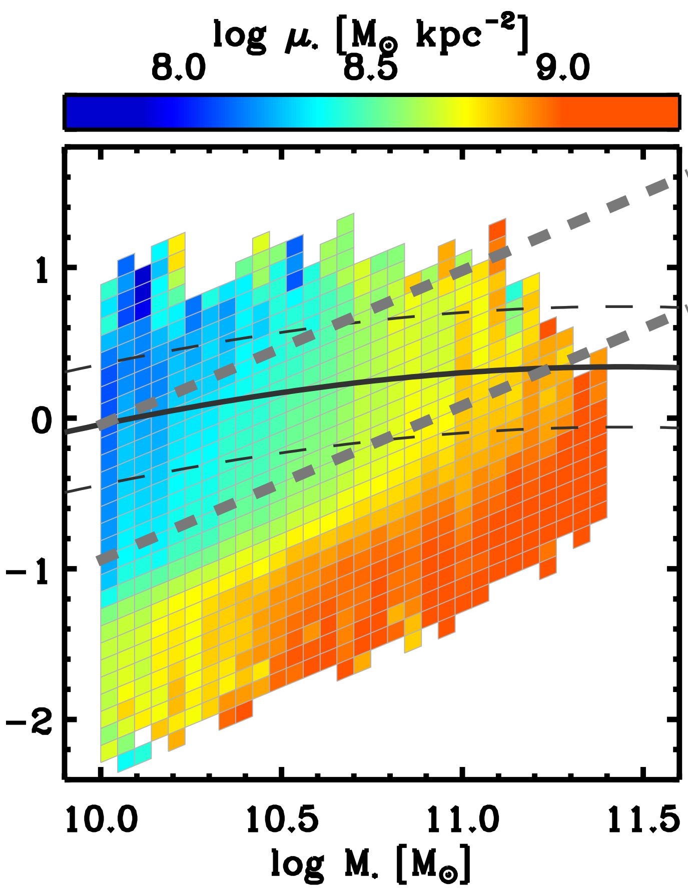
Morphology in the SFR-M* plane

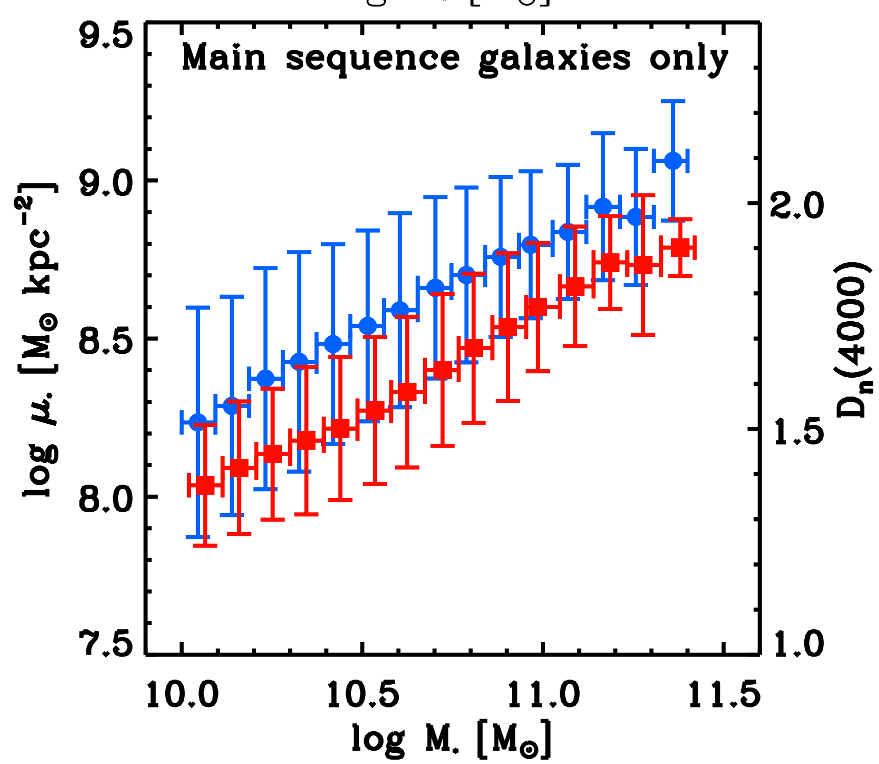


Wuyts et al. (2011)



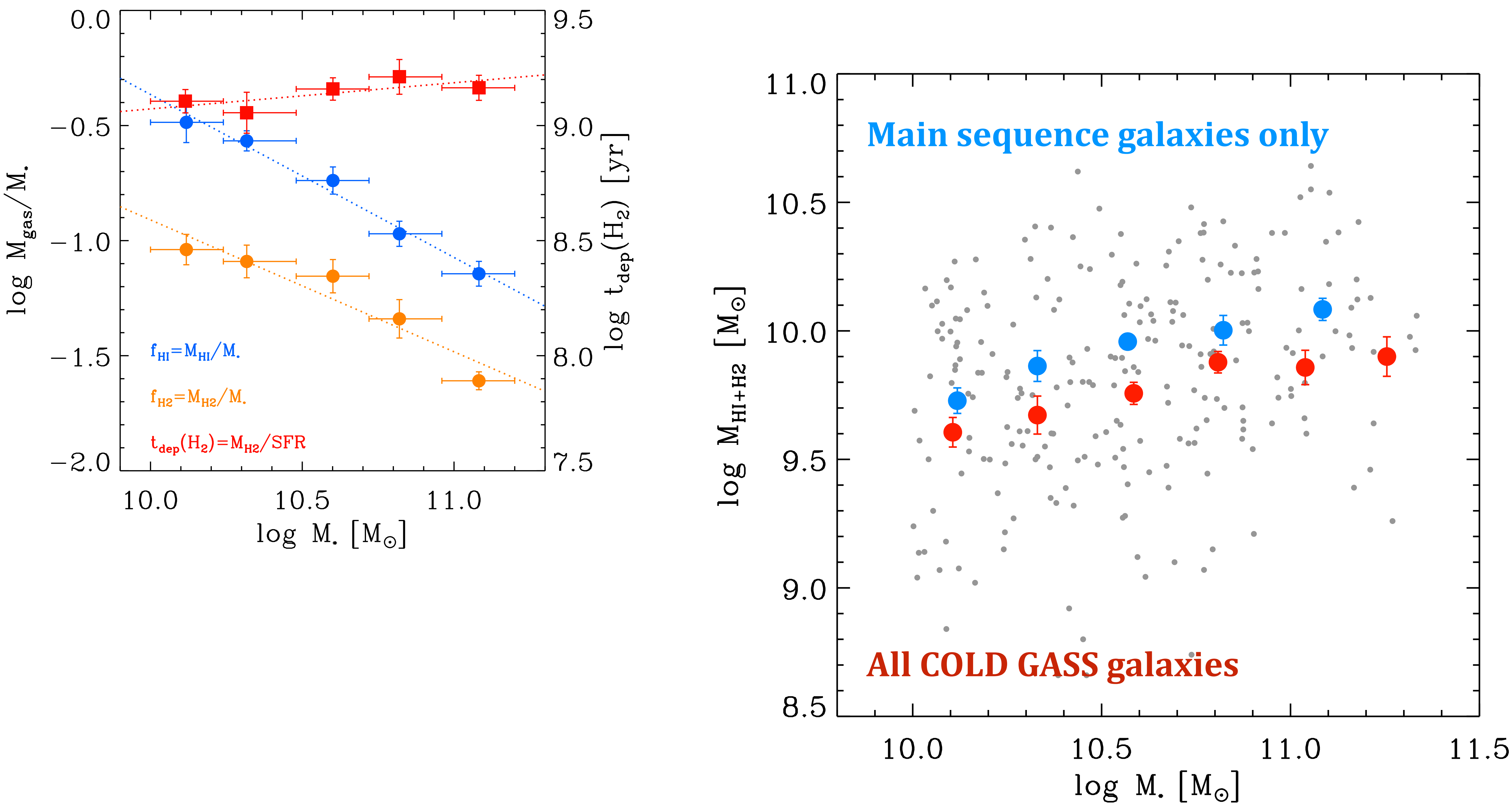






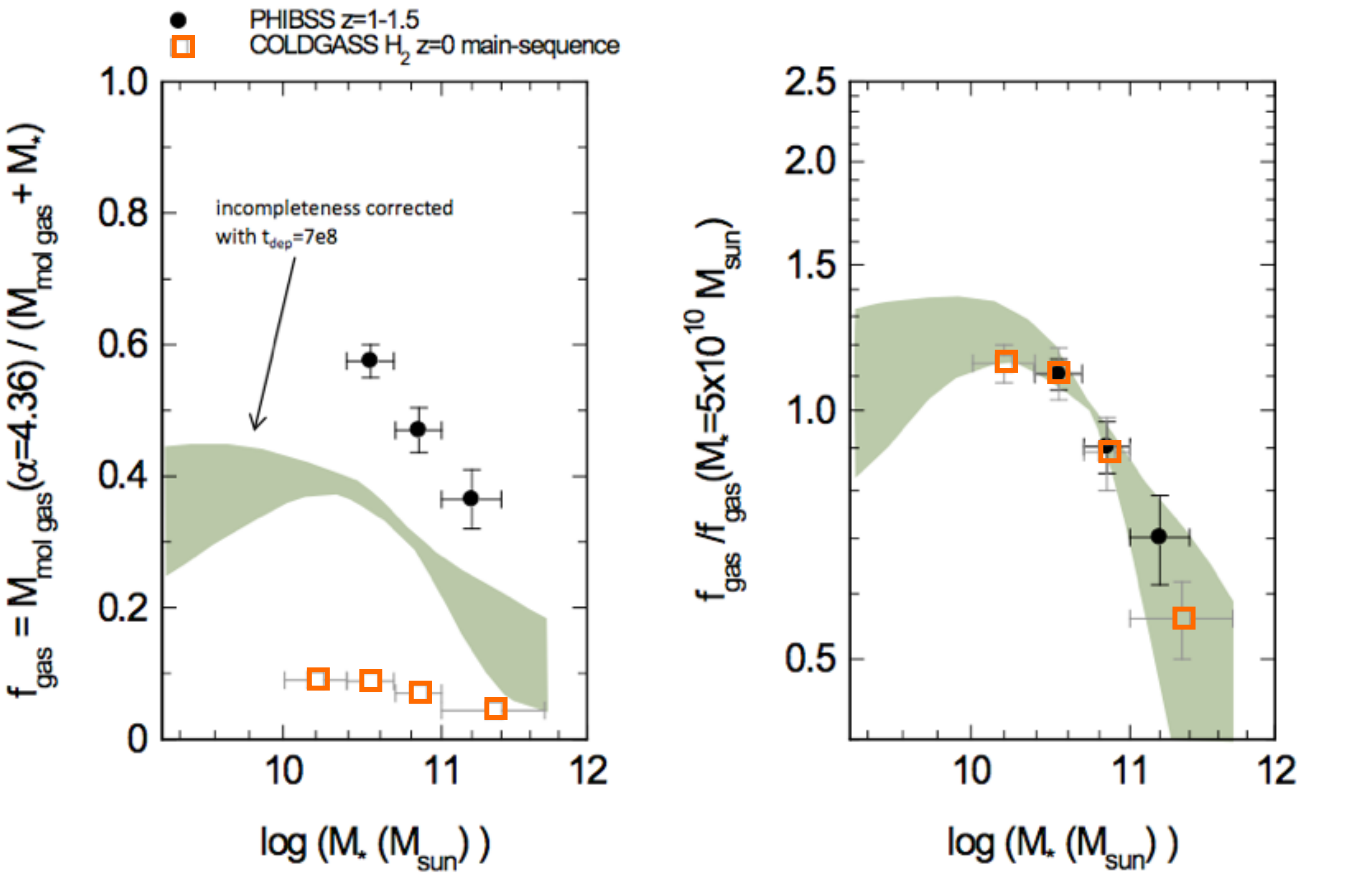
as galaxies evolve along the main sequence, they steadily consume their gas supplies
and grow more prominent bulges

Gas on the main sequence and star formation quenching



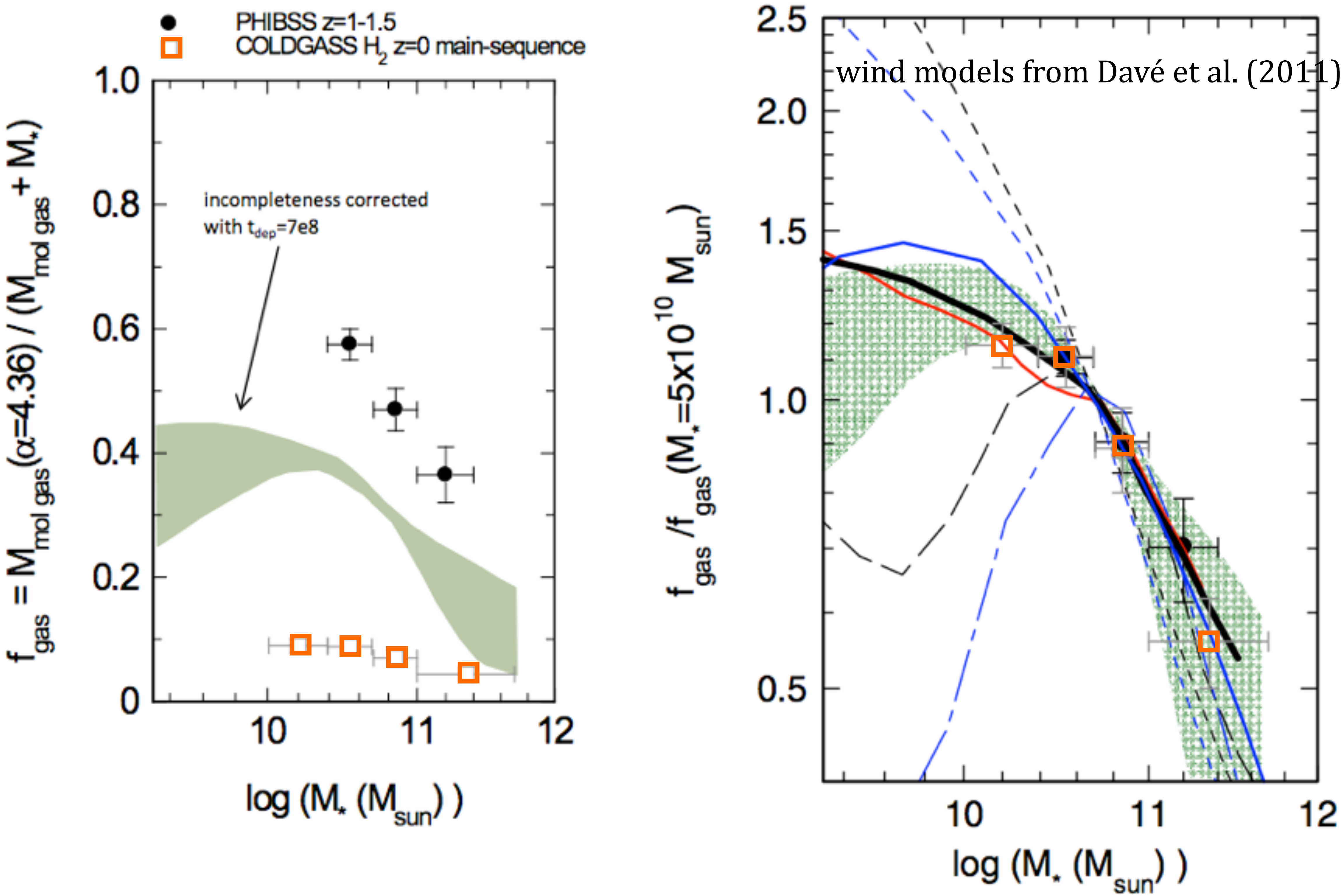
while gas fractions decrease, the **total mass** of the cold gas reservoir is increasing, suggesting accretion is ongoing at z=0 even in the most massive galaxies

Gas fractions decrease with stellar mass, irrespective of *z*



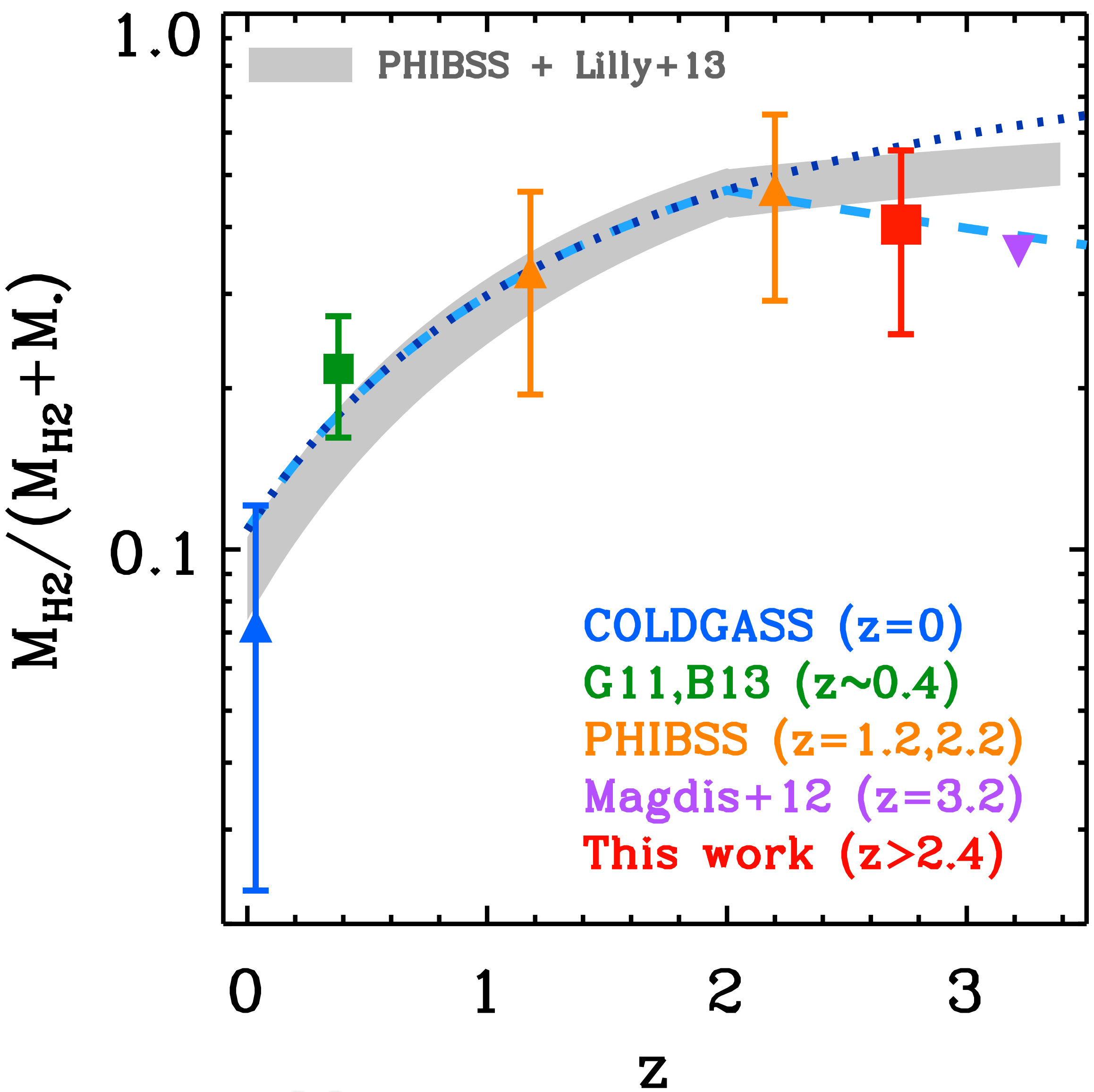
Tacconi et al. (2013), Saintonge et al. (2011a)

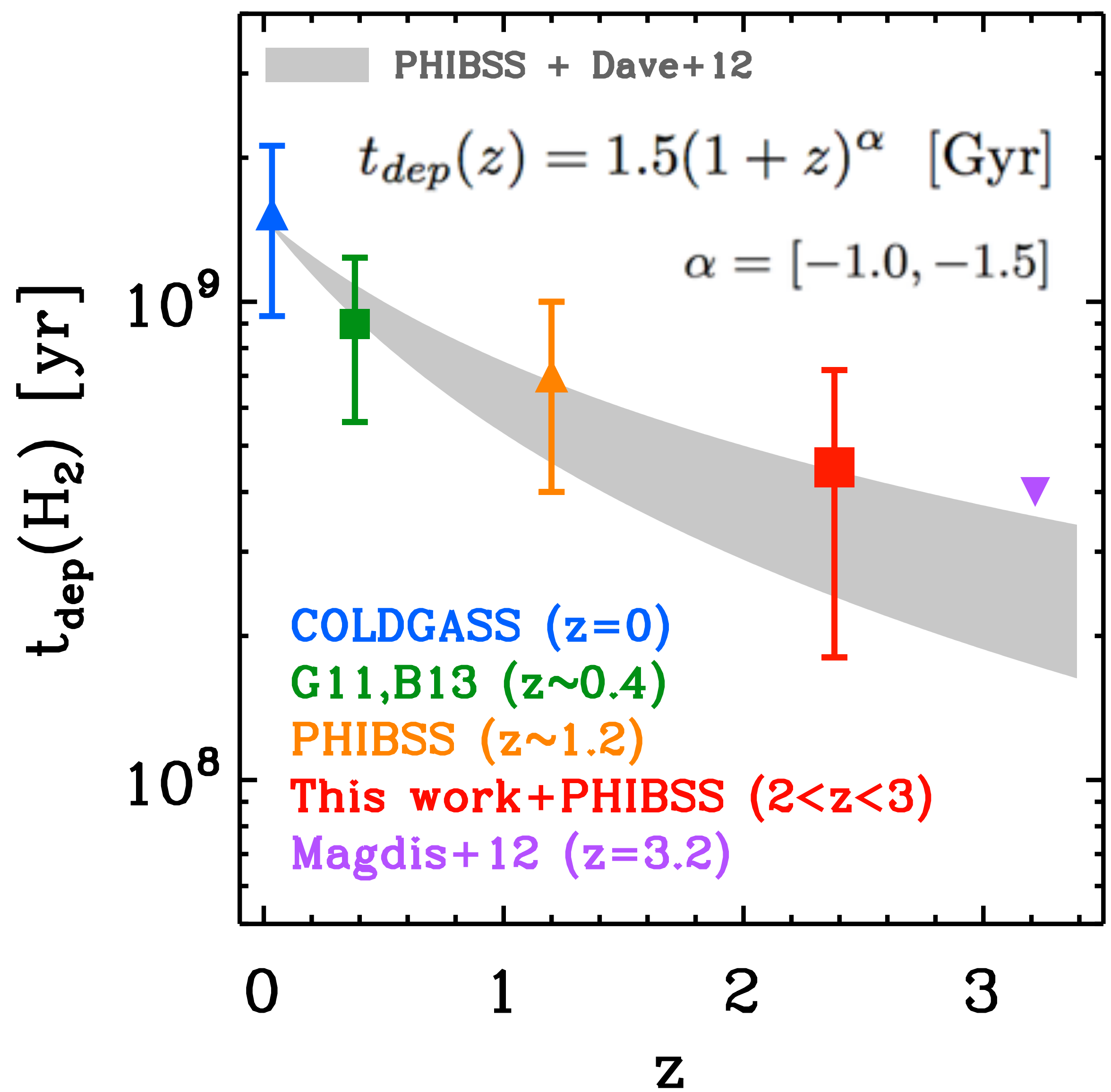
Gas fractions decrease with stellar mass, irrespective of z



Tacconi et al. (2013), Saintonge et al. (2011a), see also Magdis et al. (2012)

Gas fractions increase up to z=2





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

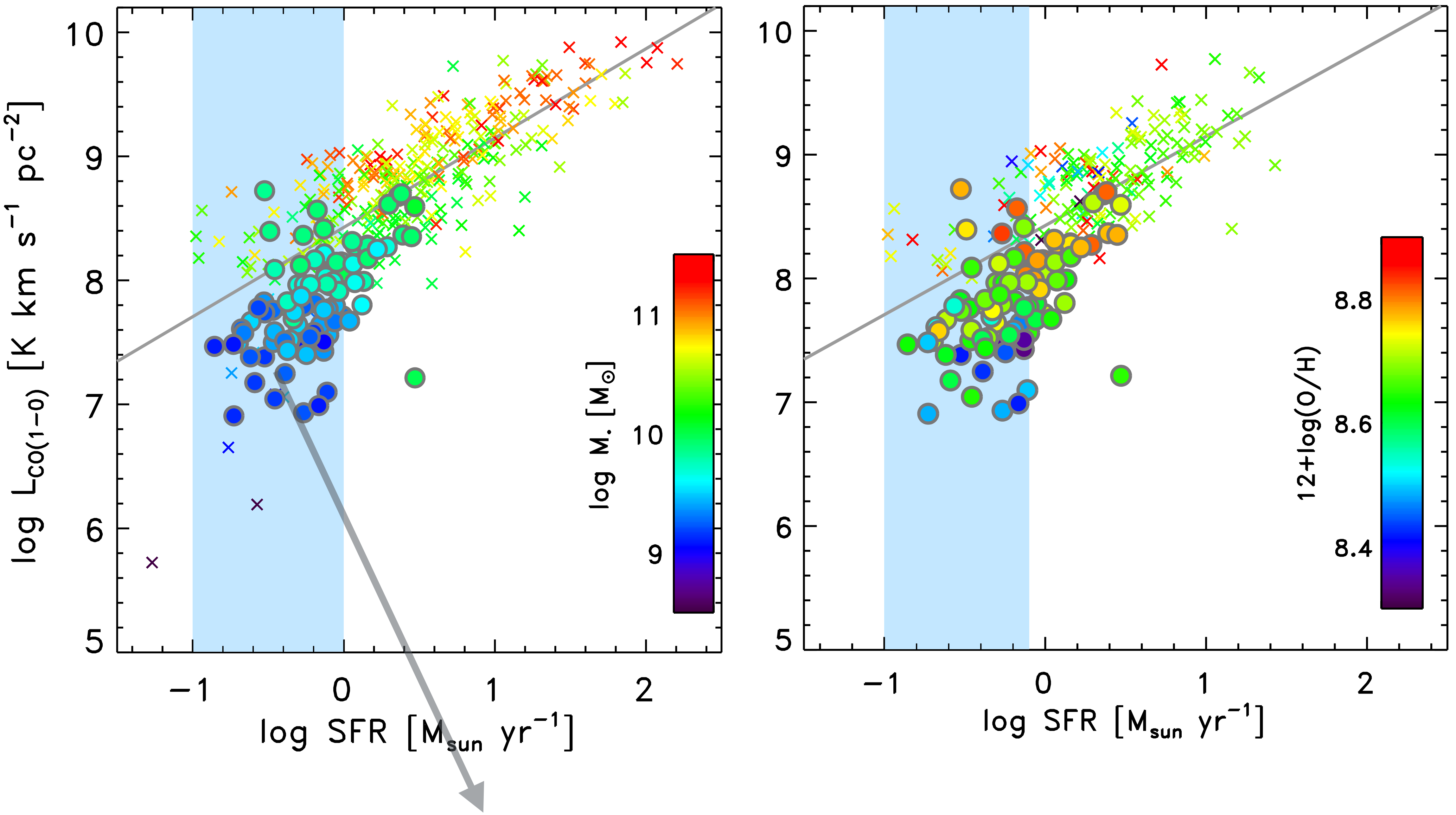
$$= \frac{1}{1 + (t_{dep}\ \mathrm{sSFR})^{-1}}$$

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

the redshift evolution of the mean SSFR is mainly driven by gas fractions and a slowly evolving depletion timescale

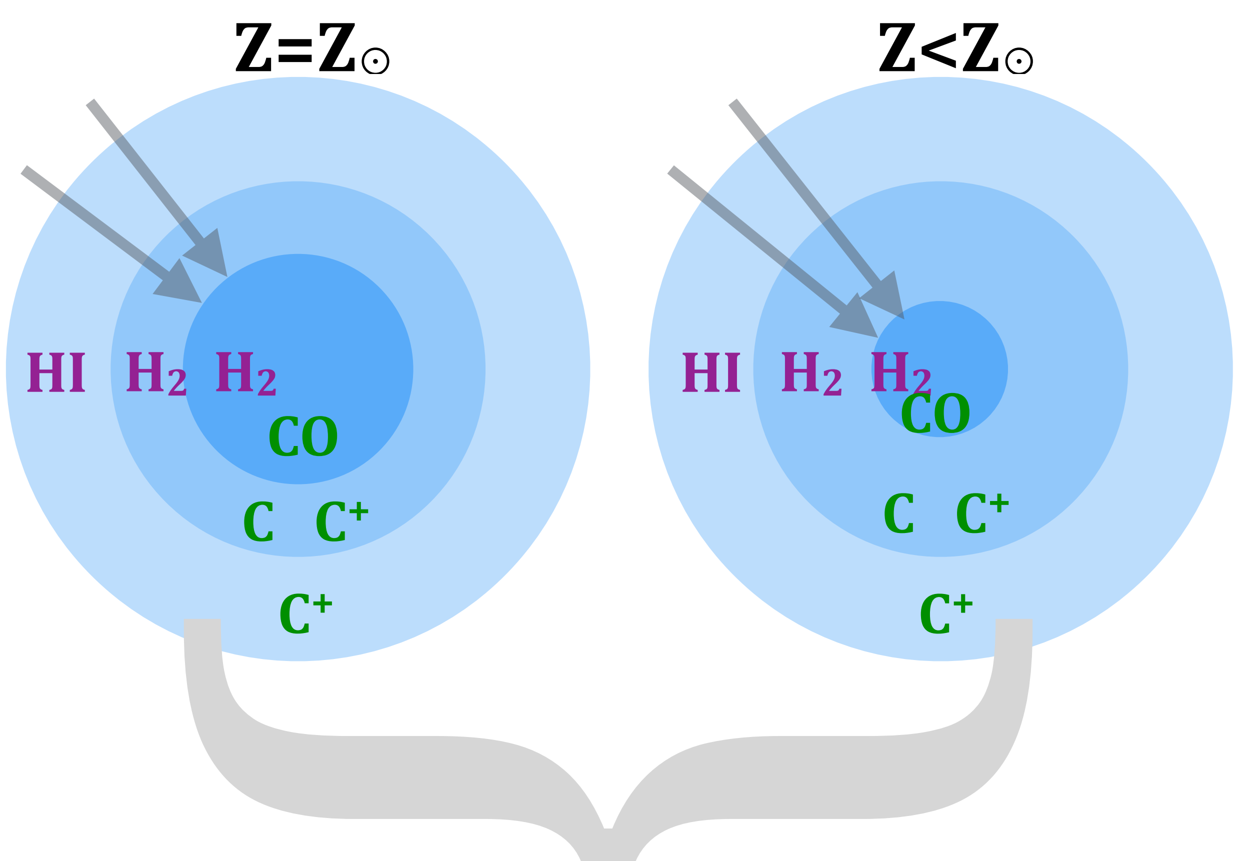
Saintonge et al. (2013), Tacconi et al. (2013)

X_{CO} and star formation efficiency in low mass galaxies

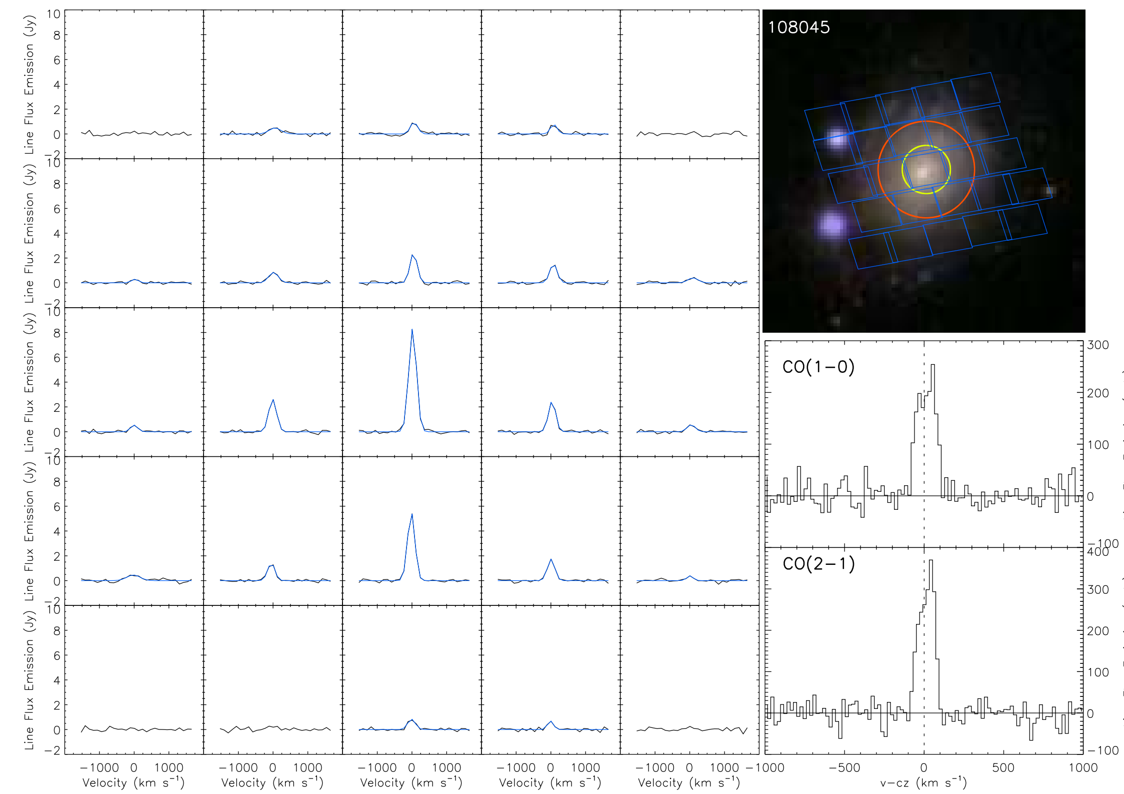


Are low mass galaxies under-luminous in CO at fixed SFR because they have high SF efficiency, or because CO is a poor tracer of total molecular gas?

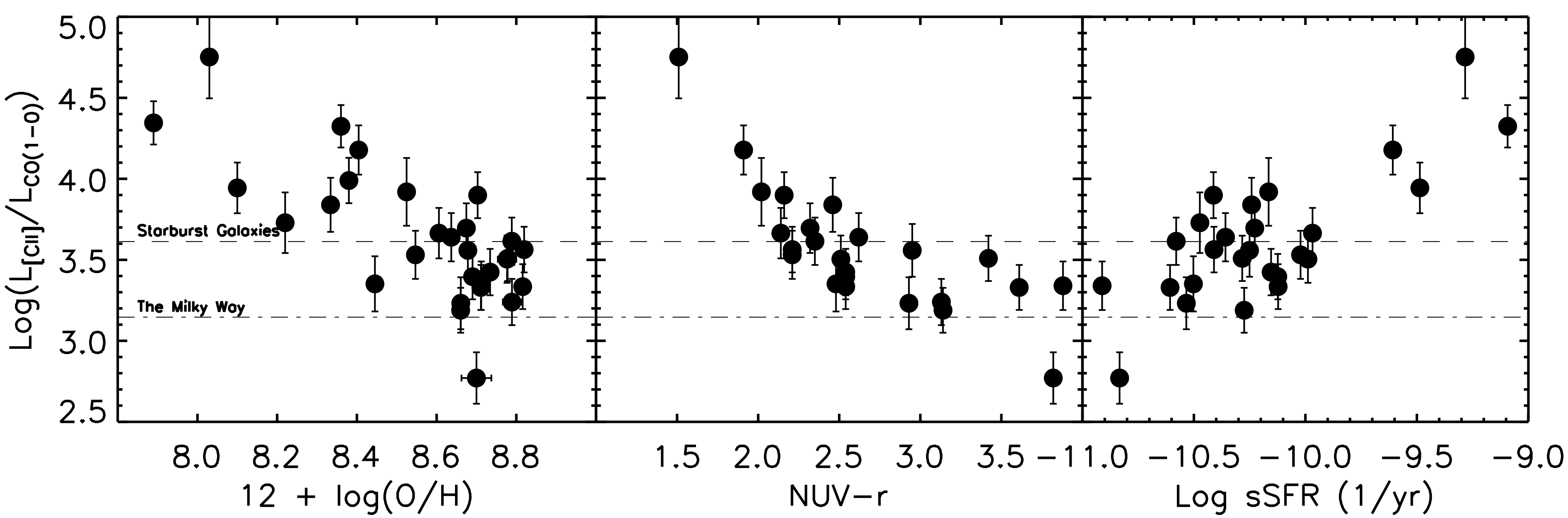
X_{CO} and star formation efficiency in low mass galaxies



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

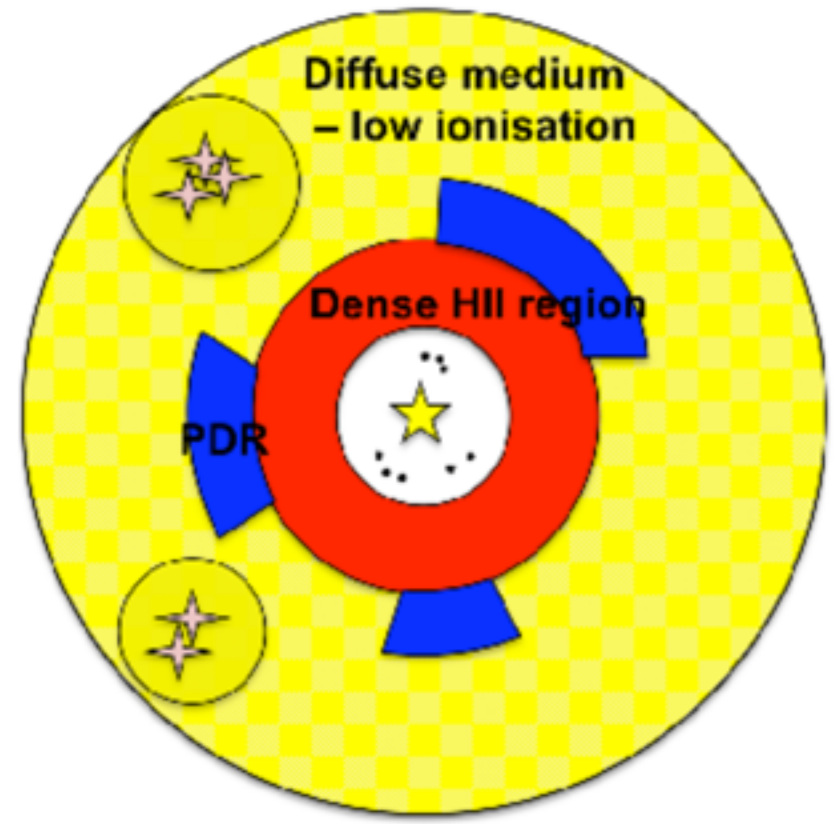


work by UCL PhD student **Gio Accurso**

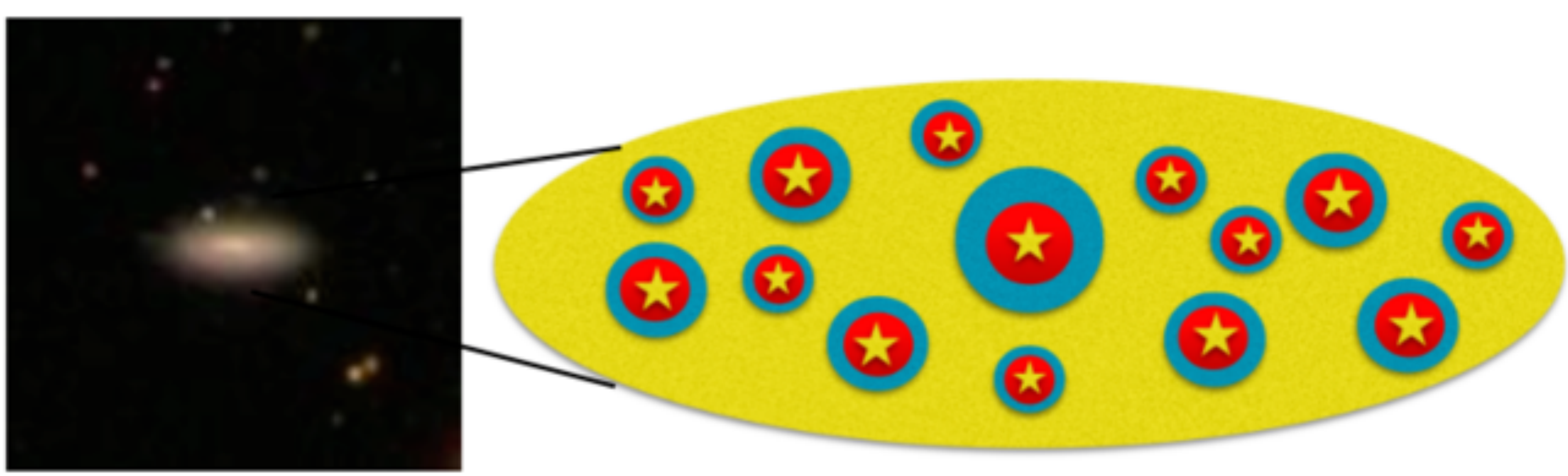
X_{CO} and star formation efficiency in low mass galaxies

Two hurdles requiring new computational tools:

(1) 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)



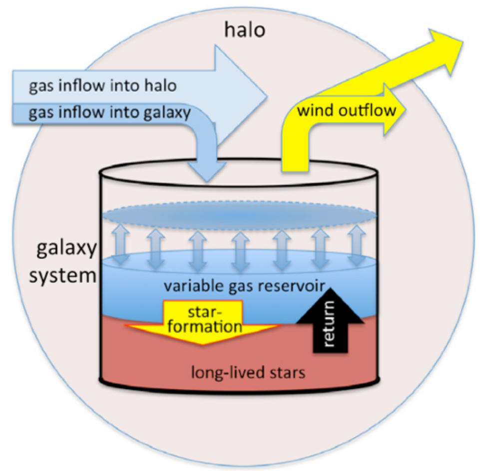
(2) Most galaxy observables are correlated
→new code using Bayesian information criteria to find the optimal number of variables

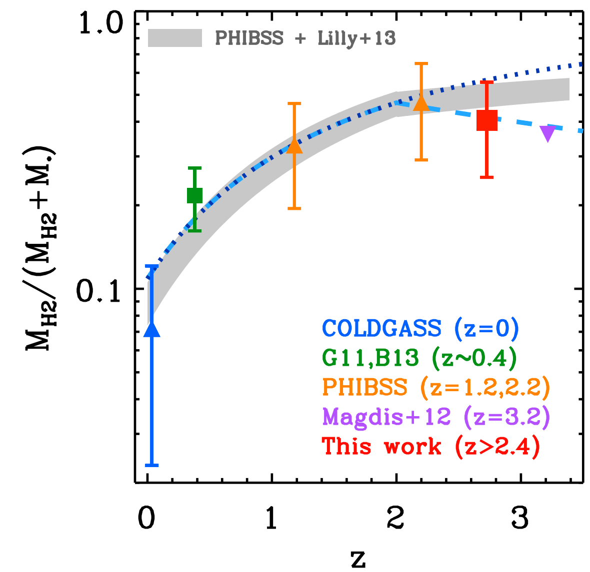


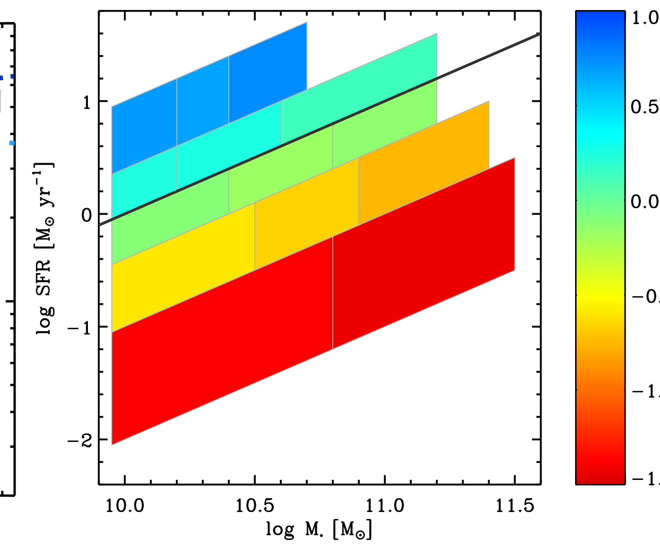
work by UCL PhD student **Gio Accurso**

Conclusions and outlook

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







z: 0 — 1 — 2 — 3

COLD GASS2

Extension of COLD GASS to lower stellar masses

PI A. Saintonge (MPE/UCL)

JINGLE

Proposed 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)

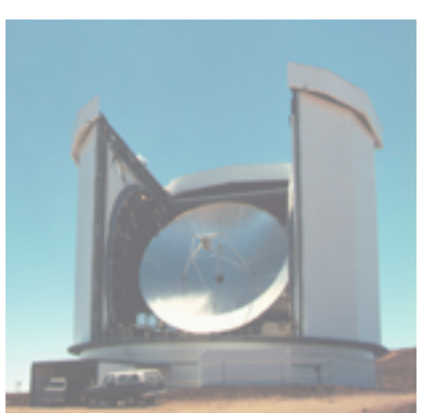
1700h IRAM PdBI Legacy Programme

~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