Molecular gas in galaxies, now and in the past

Amélie Saintonge
University College London

UCL

THE ROYAL SOCIETY

Large spectroscopic surveys - stars, atomic gas and molecular gas

SDSS

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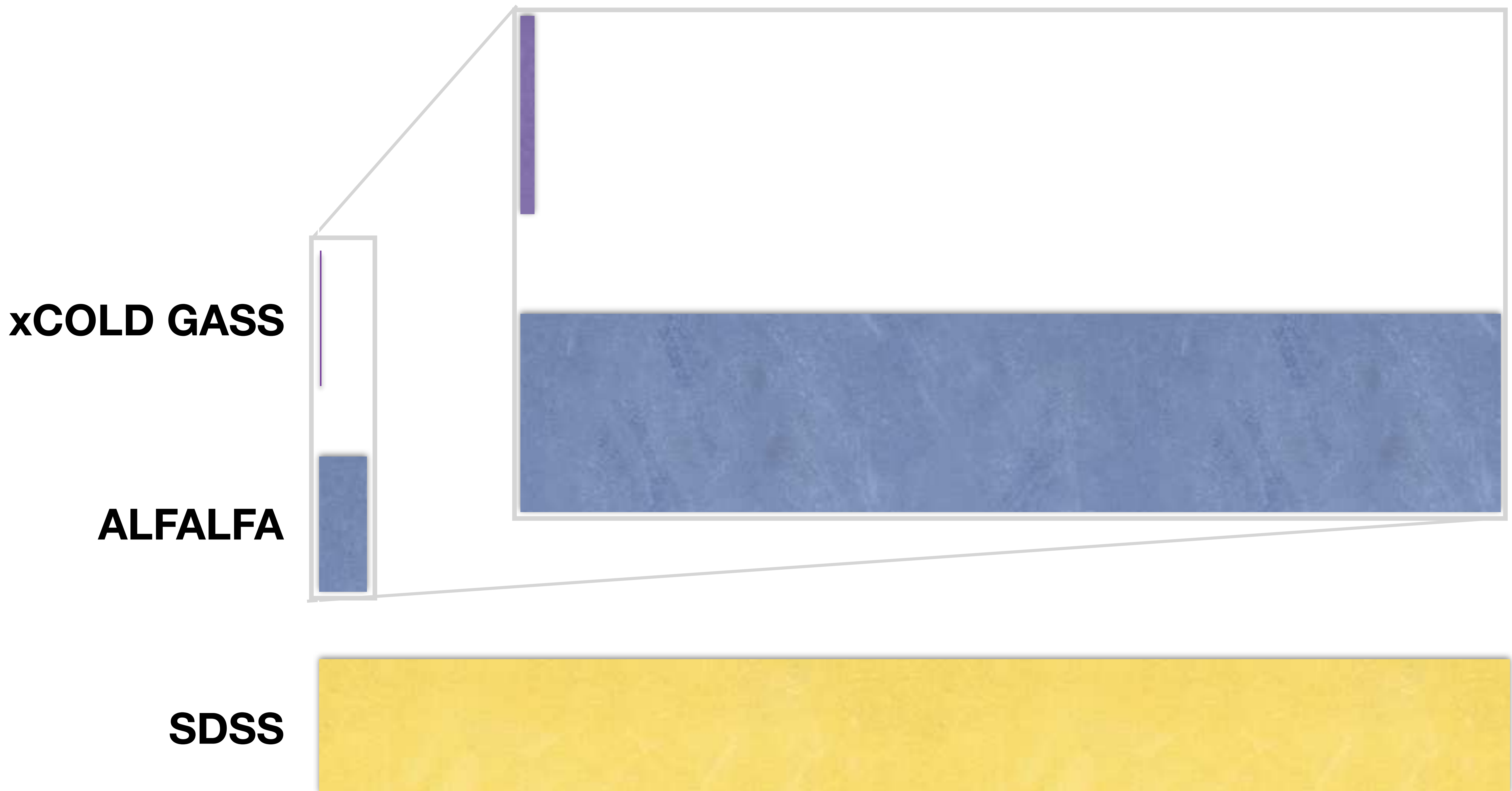
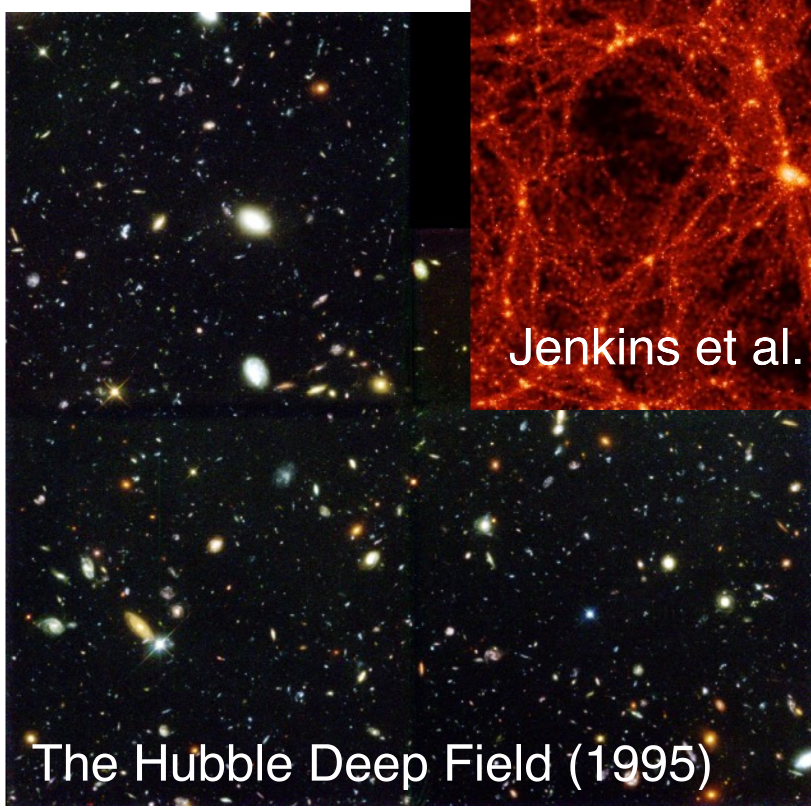
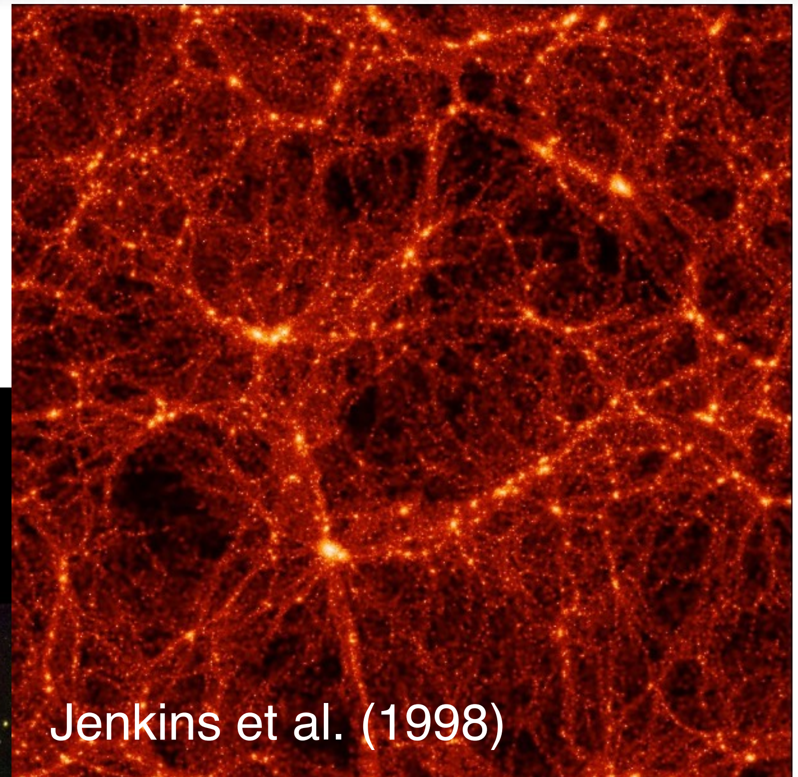
Large spectroscopic surveys - stars, atomic gas and molecular gas



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

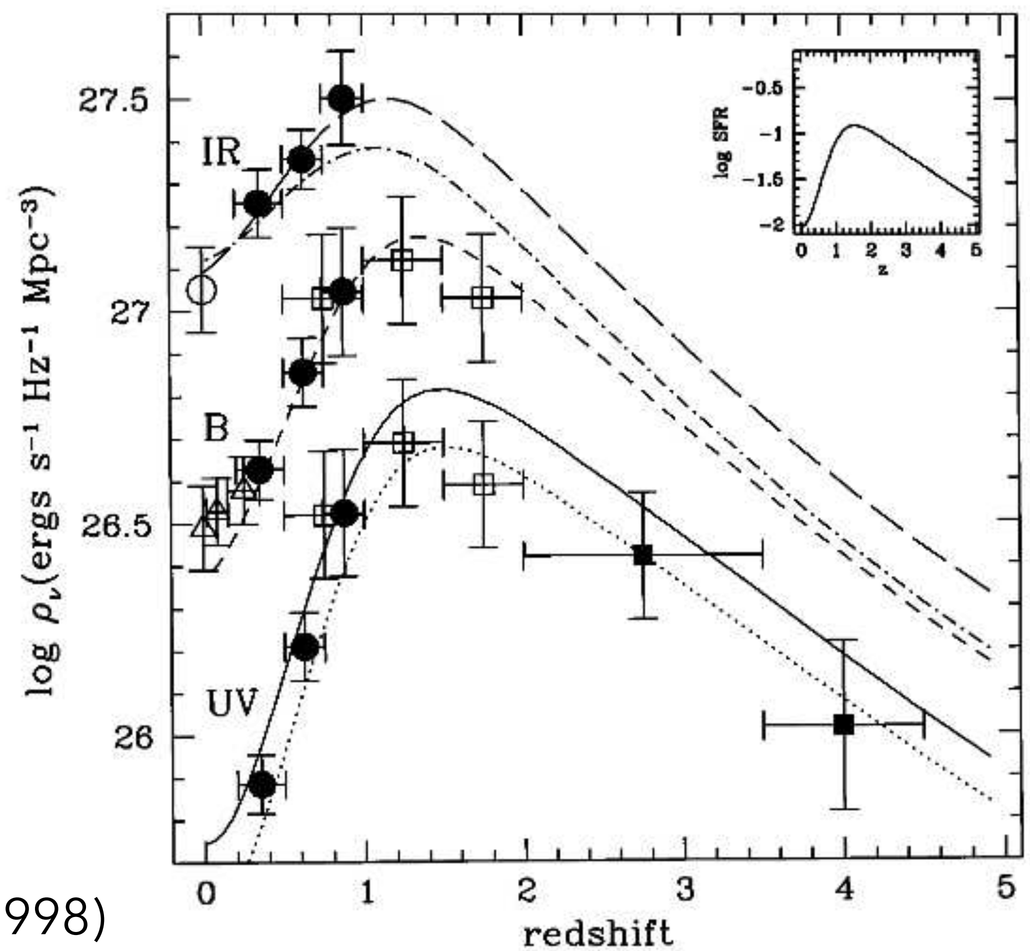


The Hubble Deep Field (1995)



Jenkins et al. (1998)

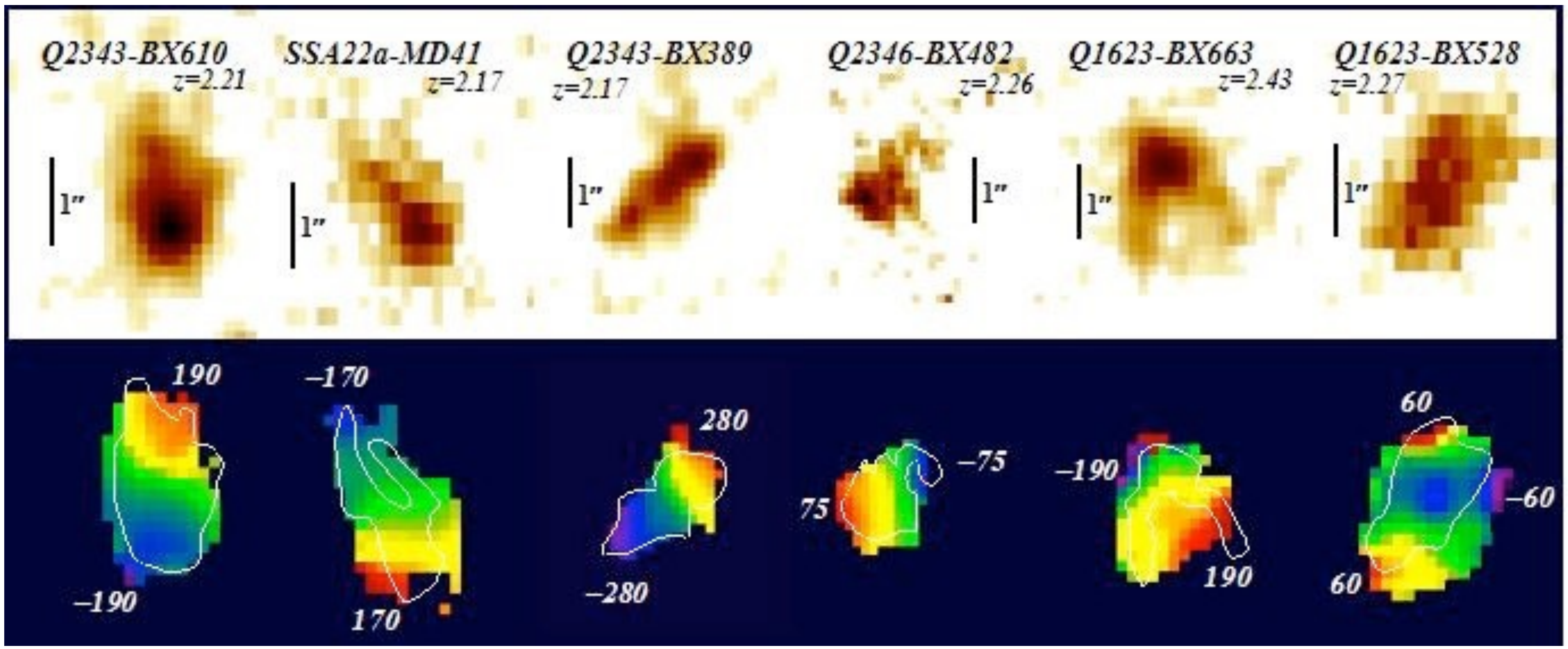
Deep HST field observations reveal:
- a population of high-redshift compact blue galaxies
- a significant number of distant galaxies with irregular morphologies.
- the redshift evolution of the SFR density in the Universe



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)

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

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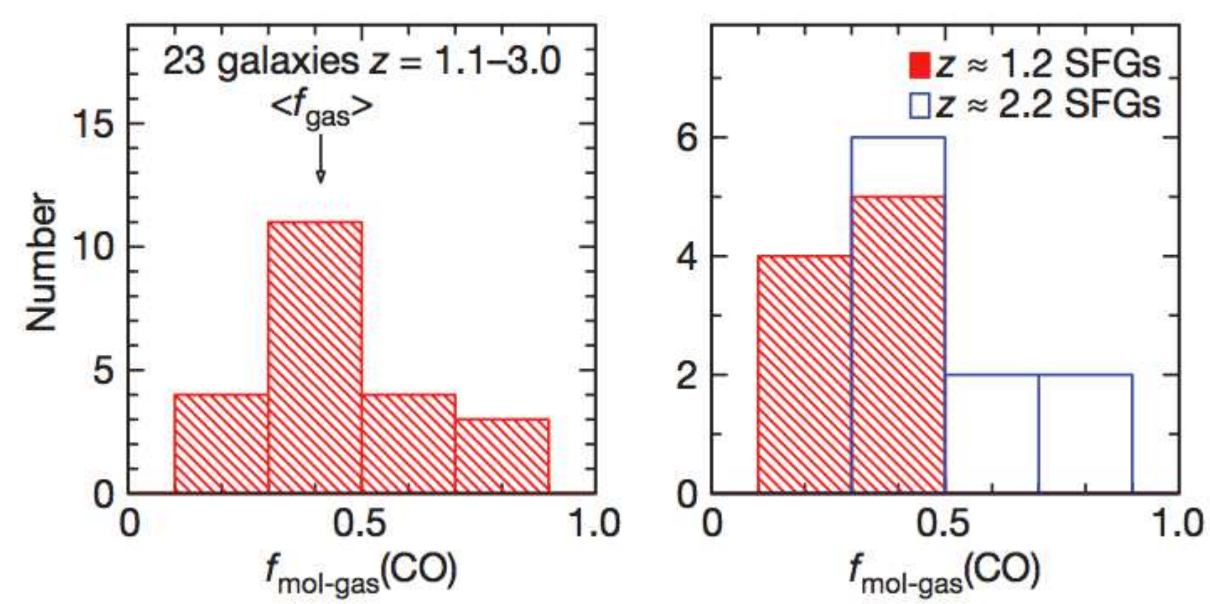
LETTERS

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.

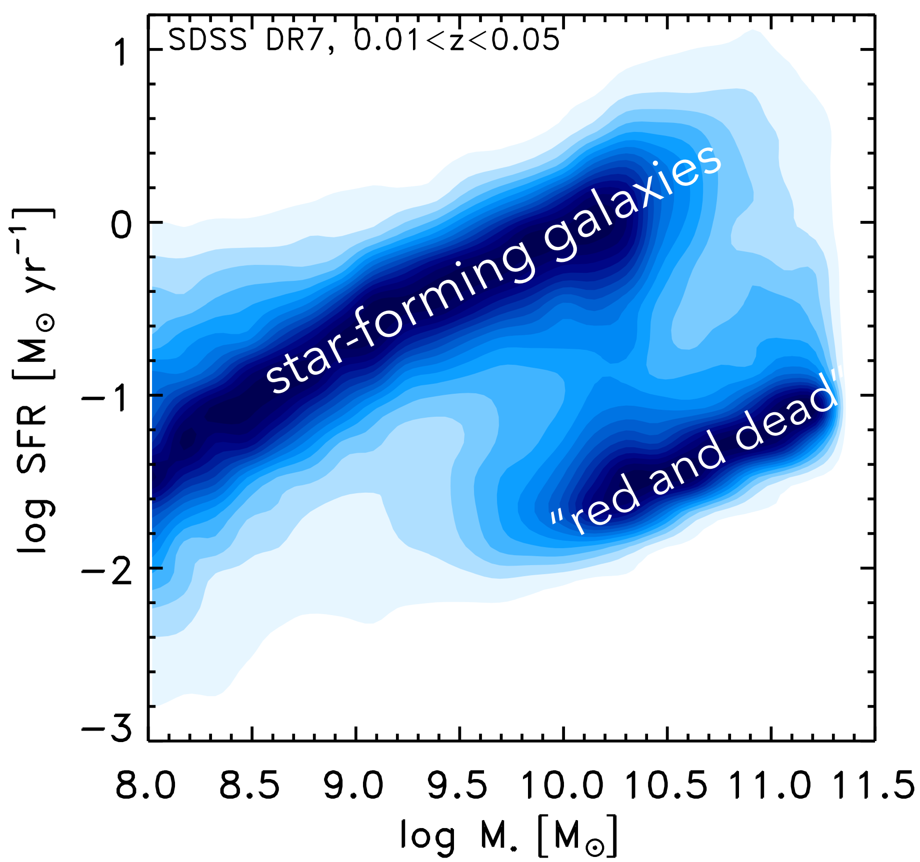


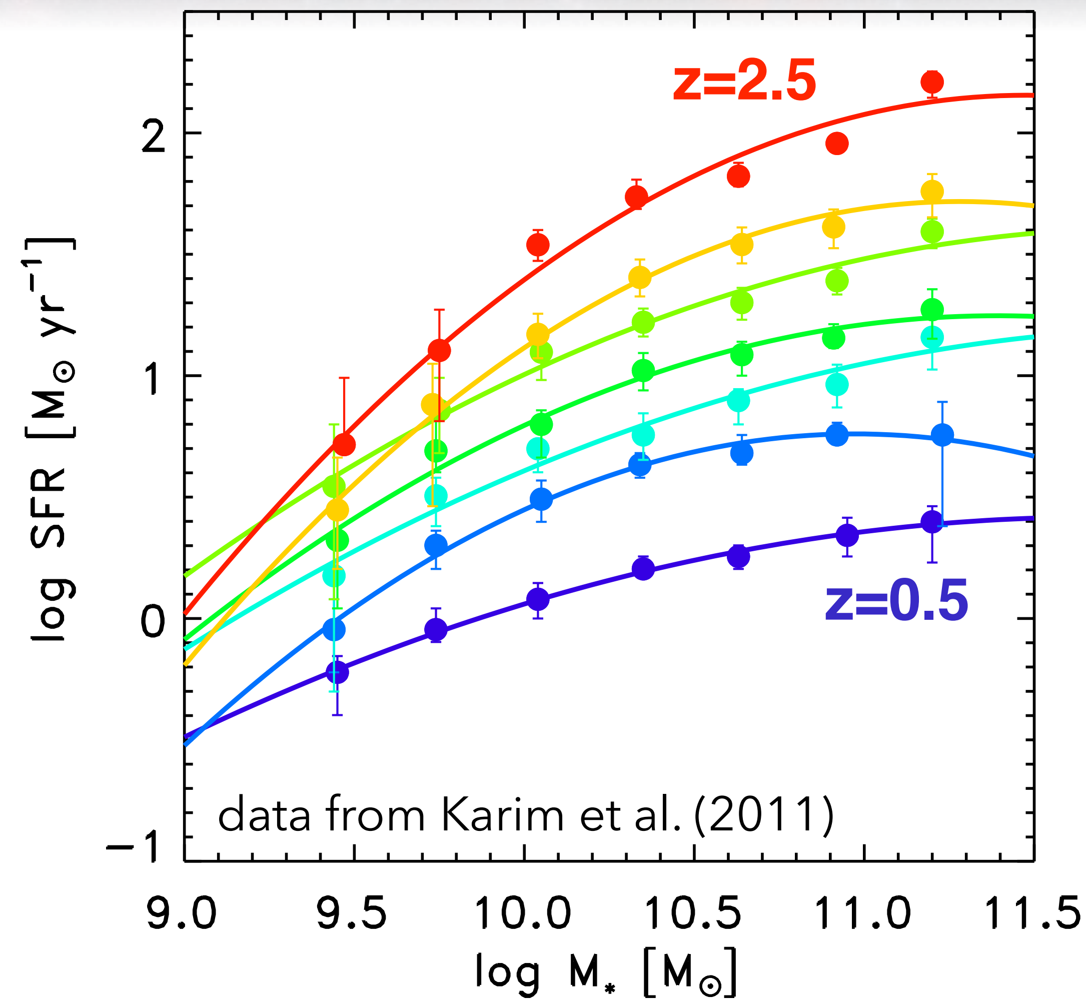
See also Daddi et al. (2010)

The current observational picture

the star formation "main sequence"

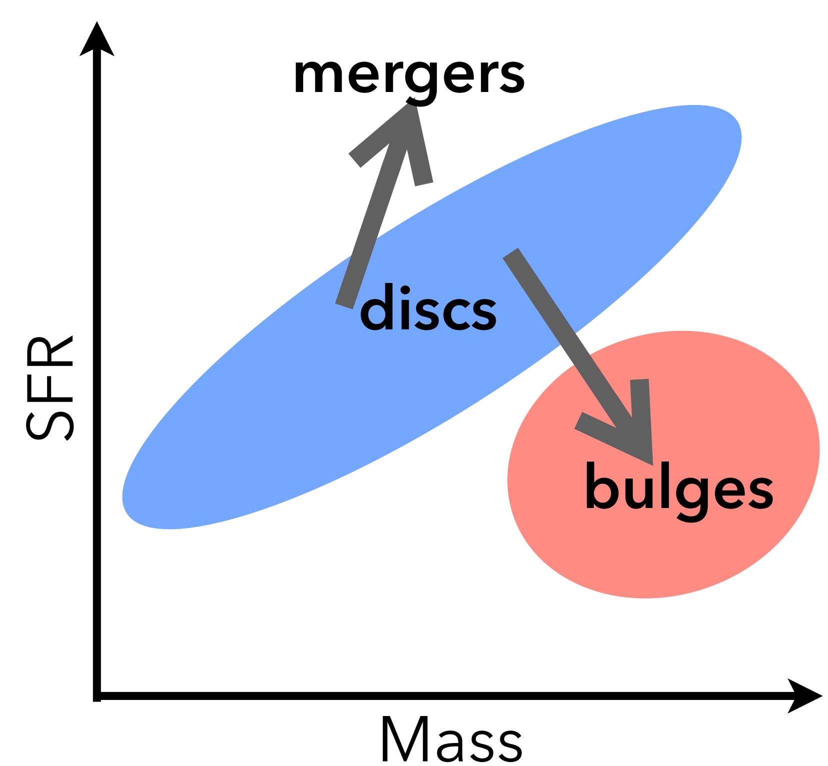
see e.g.: Schiminovich et al. (2007), Elbaz et al. (2007), Noeske et al. (2007), Daddi et al. (2007), Perez-Gonzalez et al. (2008), Peng et al. (2010)



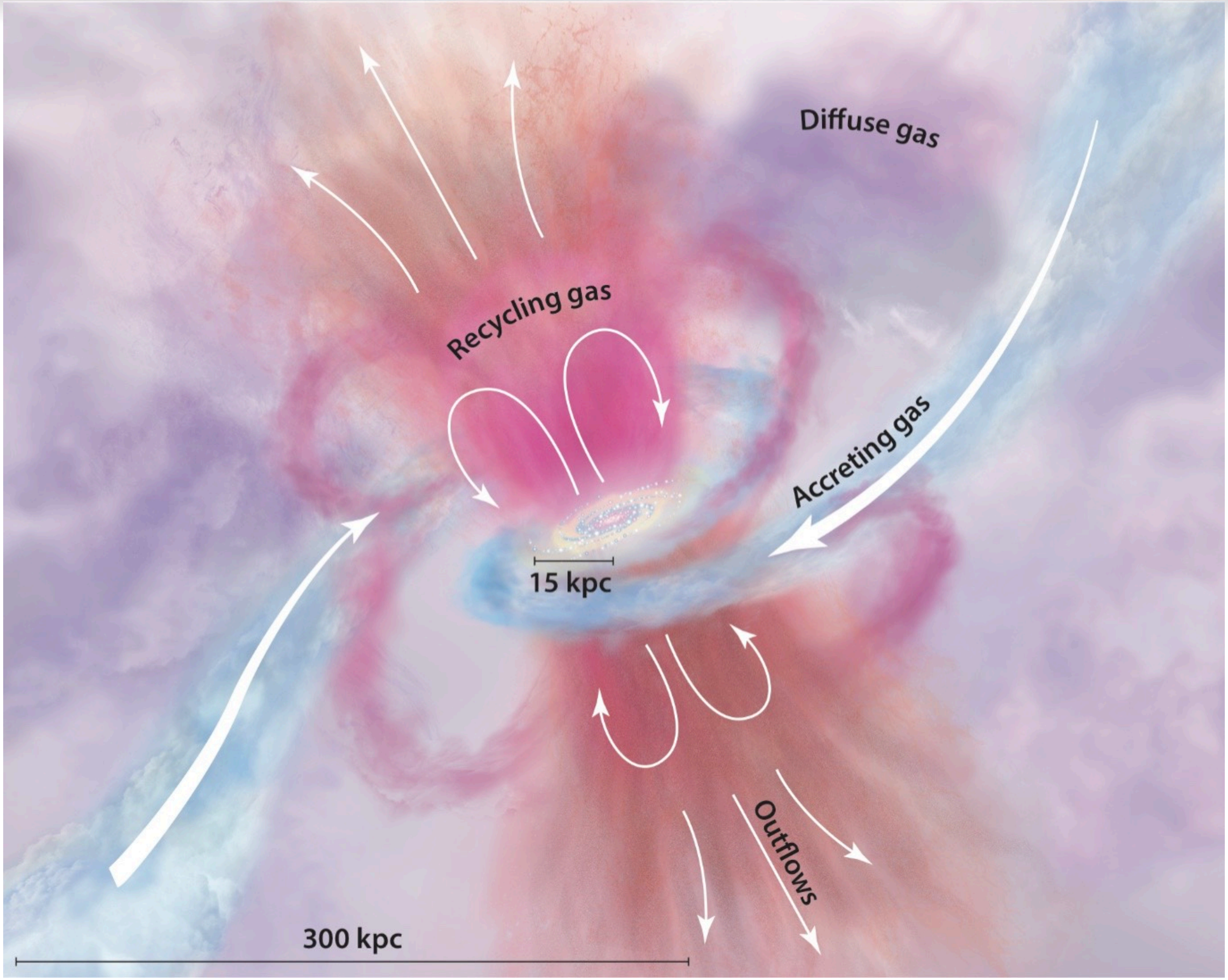


SFR ~ $M_*^a(1+z)^b$, where a~0.8, b~2.5

- 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.**



Star formation and the baryon cycle



Tumlinson, Peeples and Werk (2017)

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

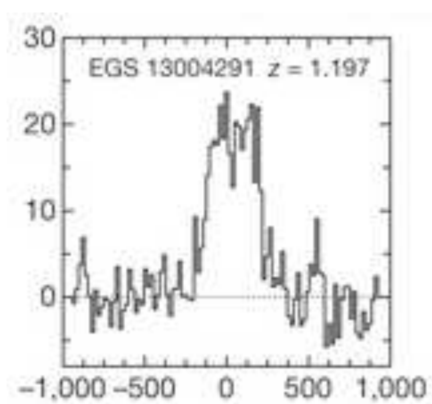
PIs A. Saintonge (UCL) , B. Catinella (UWA), G. Kauffmann (MPA), C. Kramer (IRAM)
950h IRAM 30-m Large Programmes
+1500h Arecibo Programme for HI

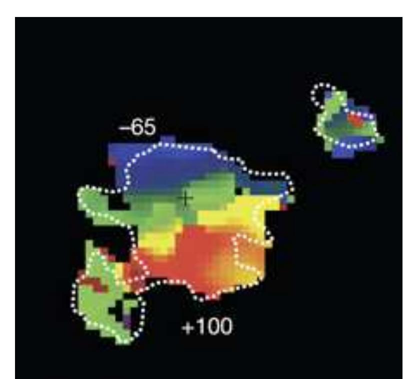
532 SDSS-selected galaxies with
0.01<z<0.05, M*>109
see e.g. Saintonge et al. 2011a, 2017

PHIBSS

PIs L. Tacconi, R. Genzel (MPE), F. Combes (Paris)
500h IRAM PdBI Large Programmes

150 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. 2010,2018, Genzel et al. 2010,2012,2013,2015 Freundlich et al. 2013.



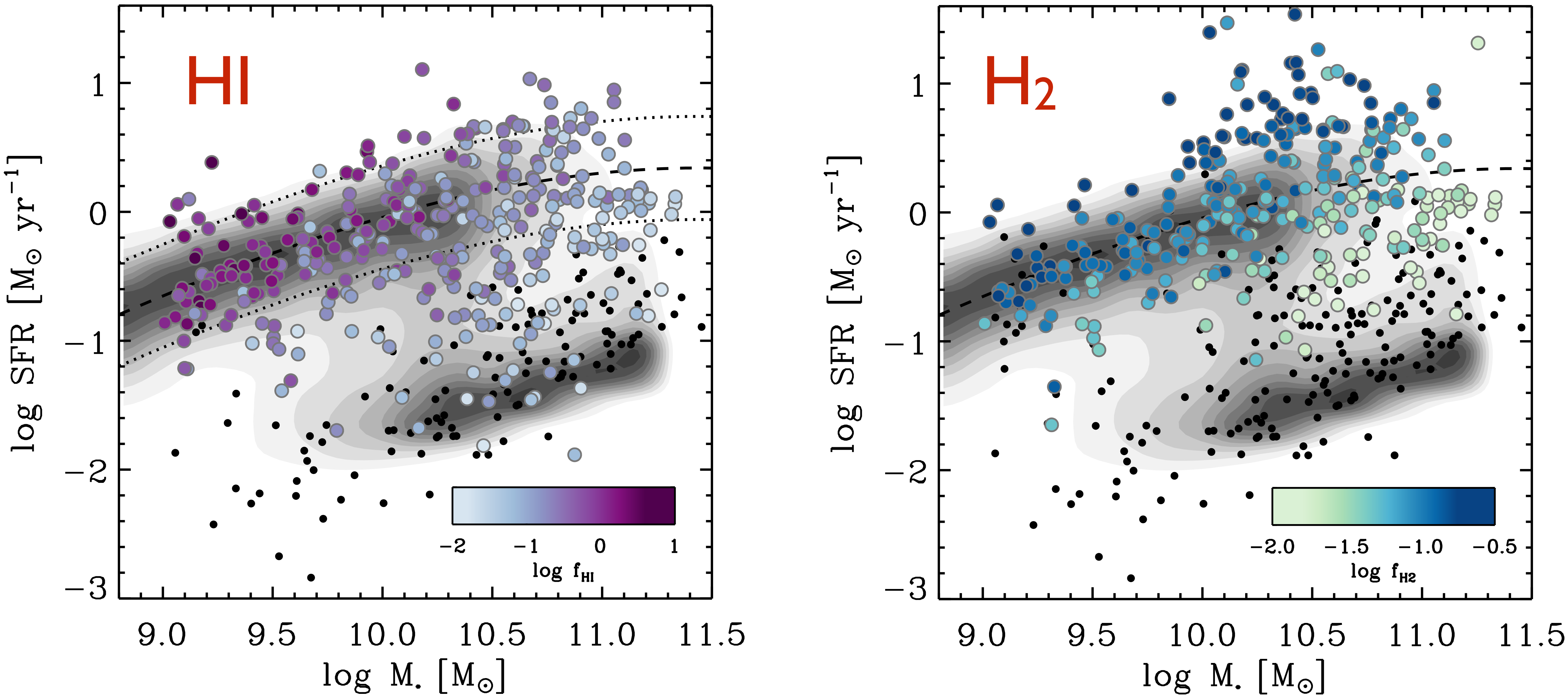


Lensed galaxies

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



The position of a galaxy in the SFR-M* plane depends on:

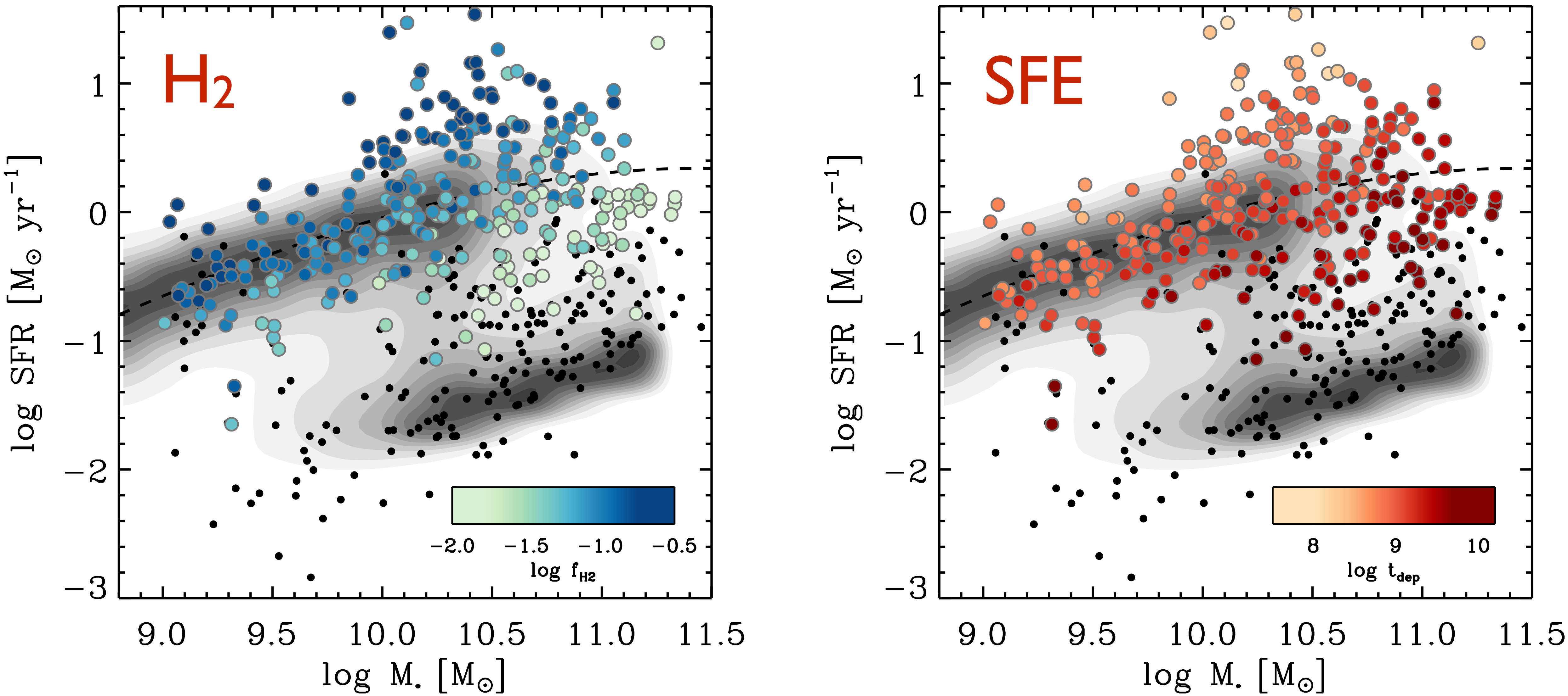
(1) how much fuel it has

(2) how much of it is available for star formation

(3) the efficiency of the conversion of this gas into stars

Saintonge et al. (2017)

Cold gas in the SFR-M* plane



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Saintonge et al. (2017)

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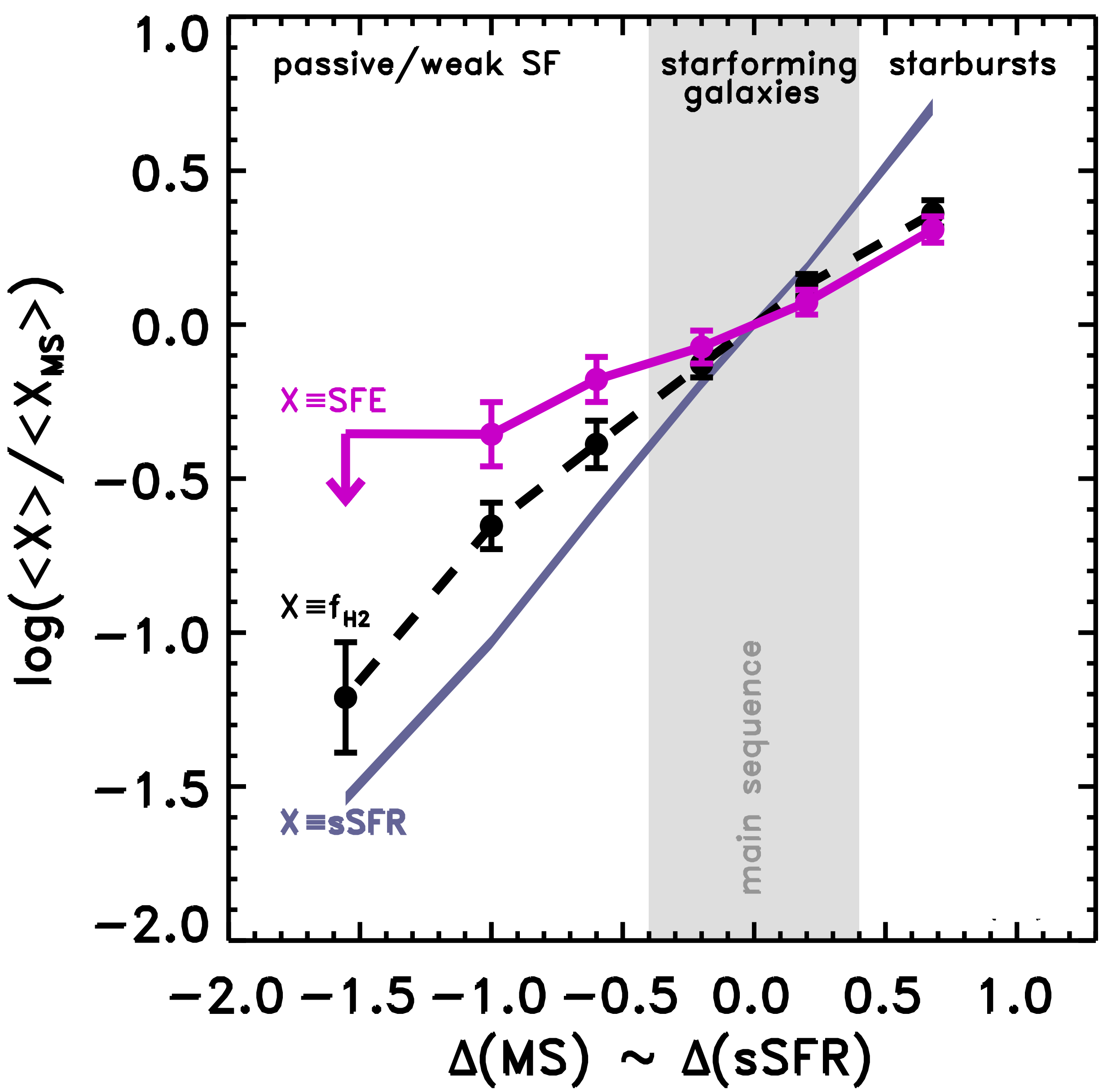
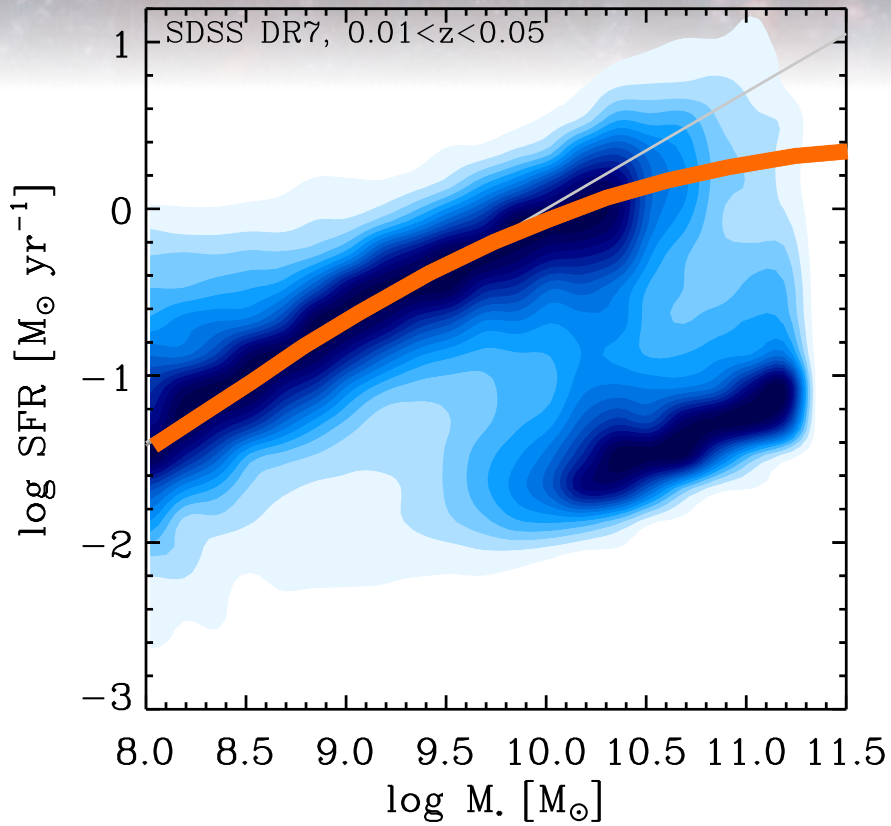
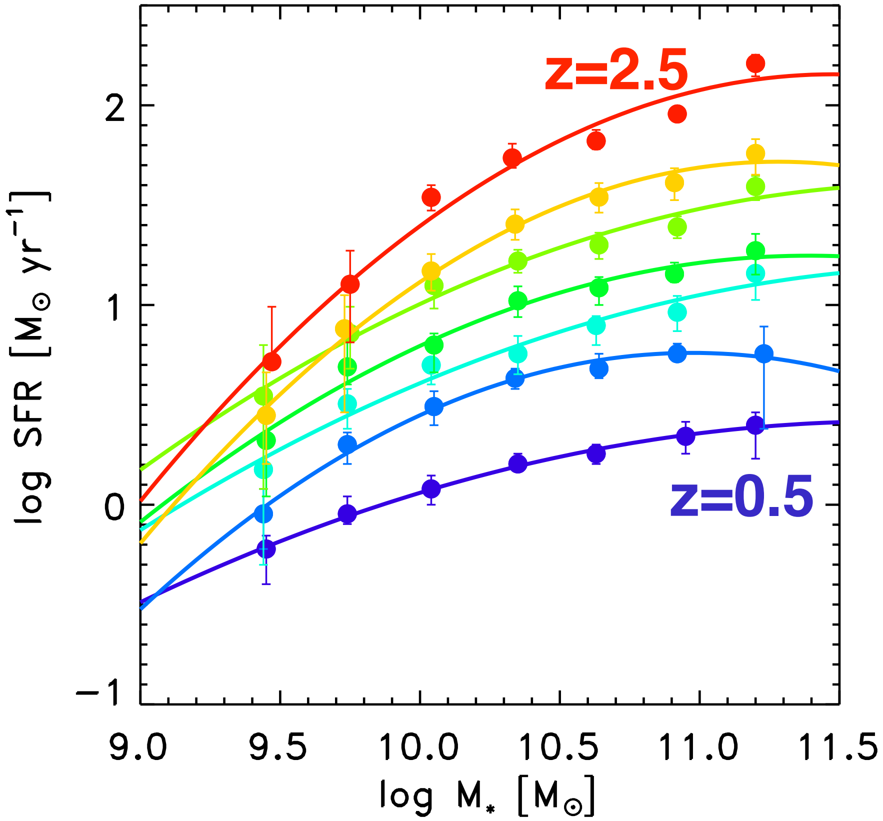


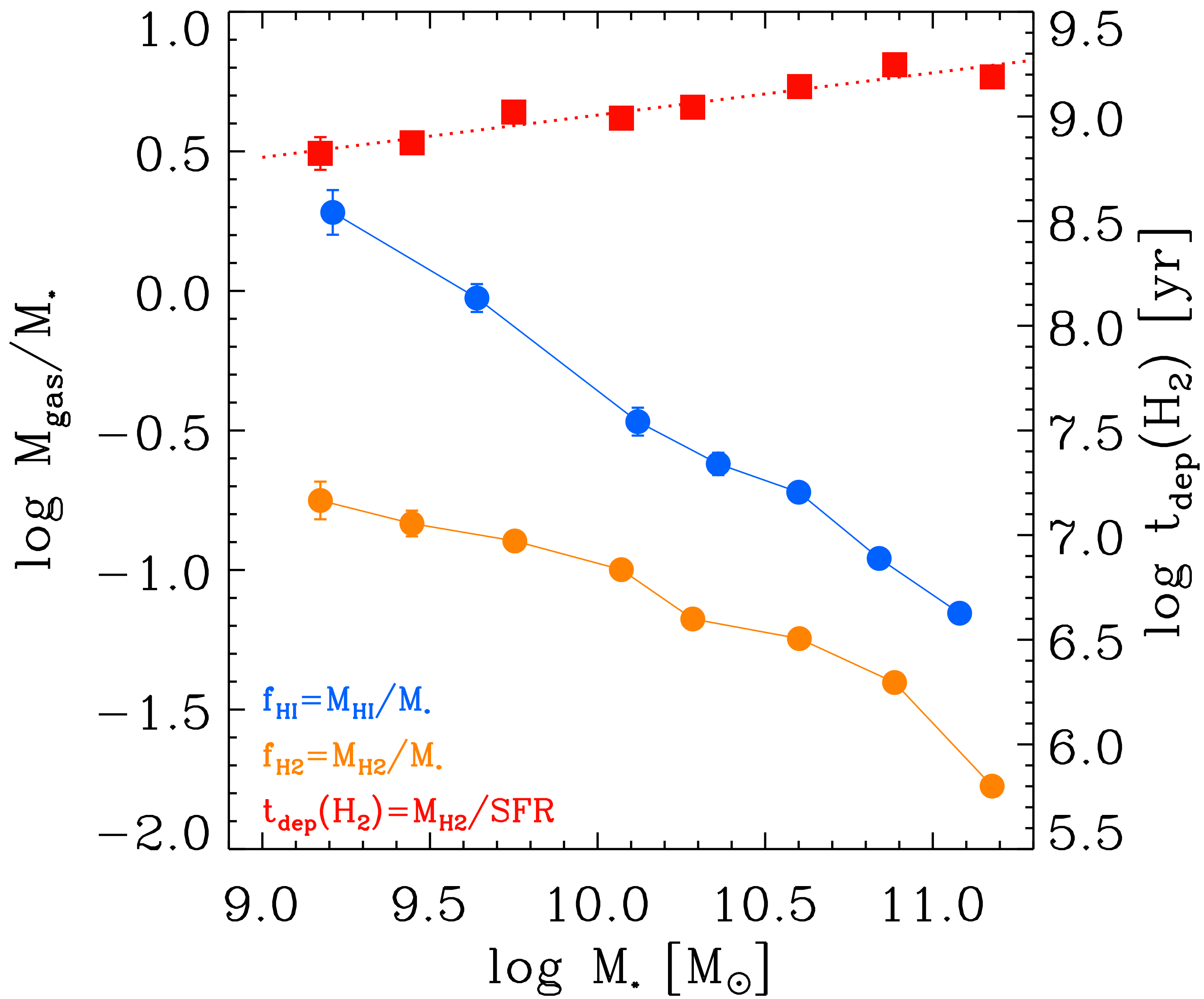
Saintonge et al. (2012)

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

Gas on the main sequence and quenching

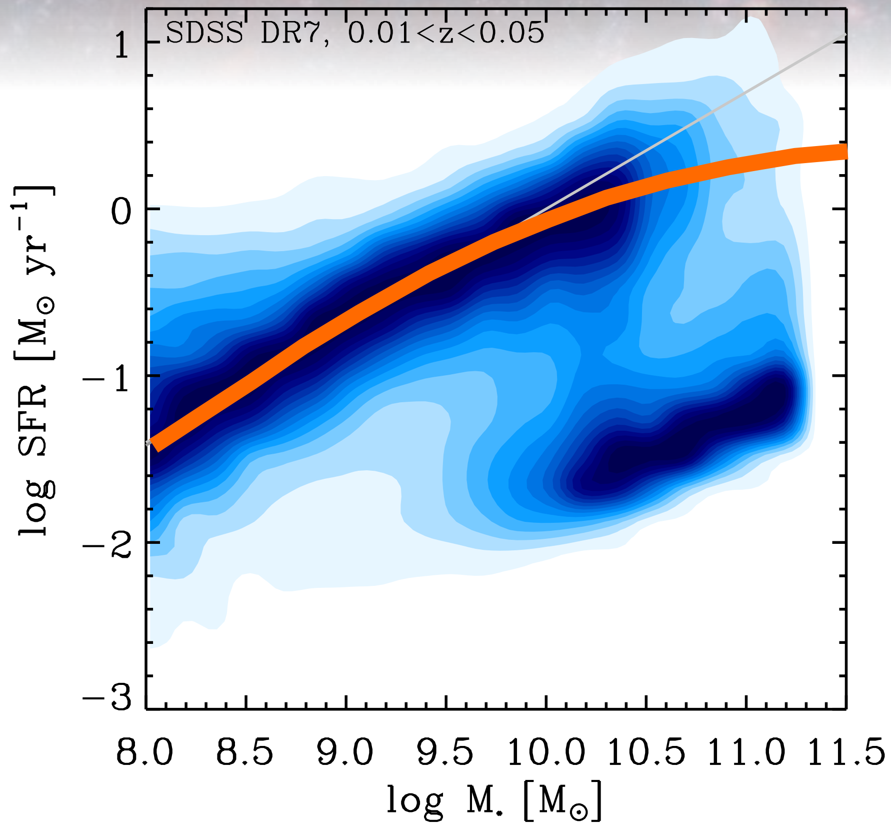


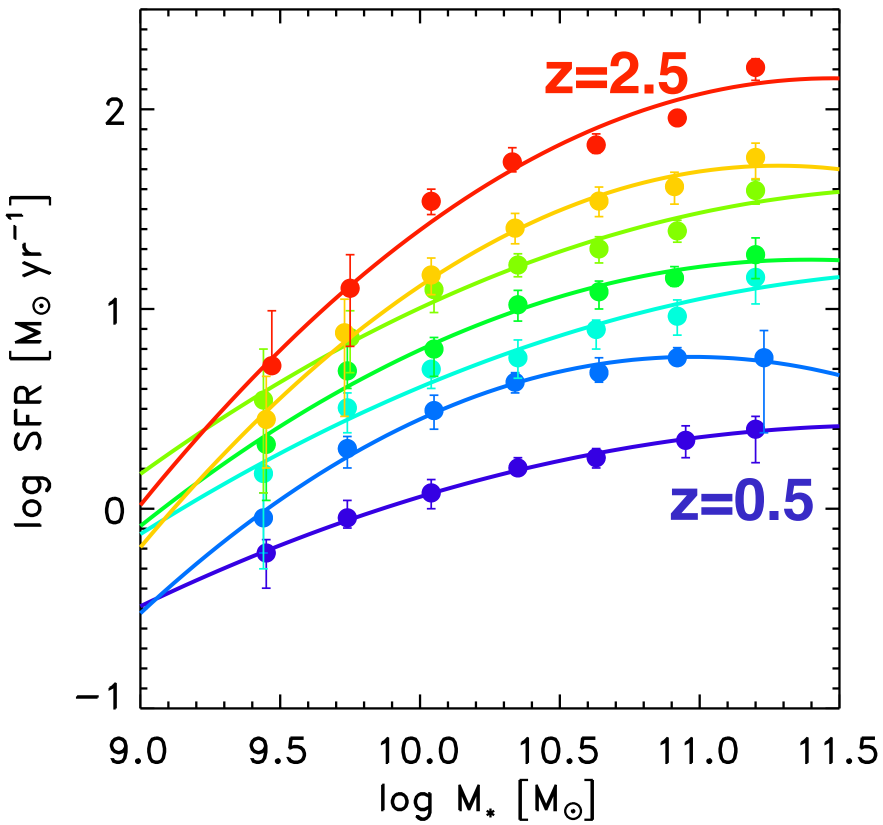


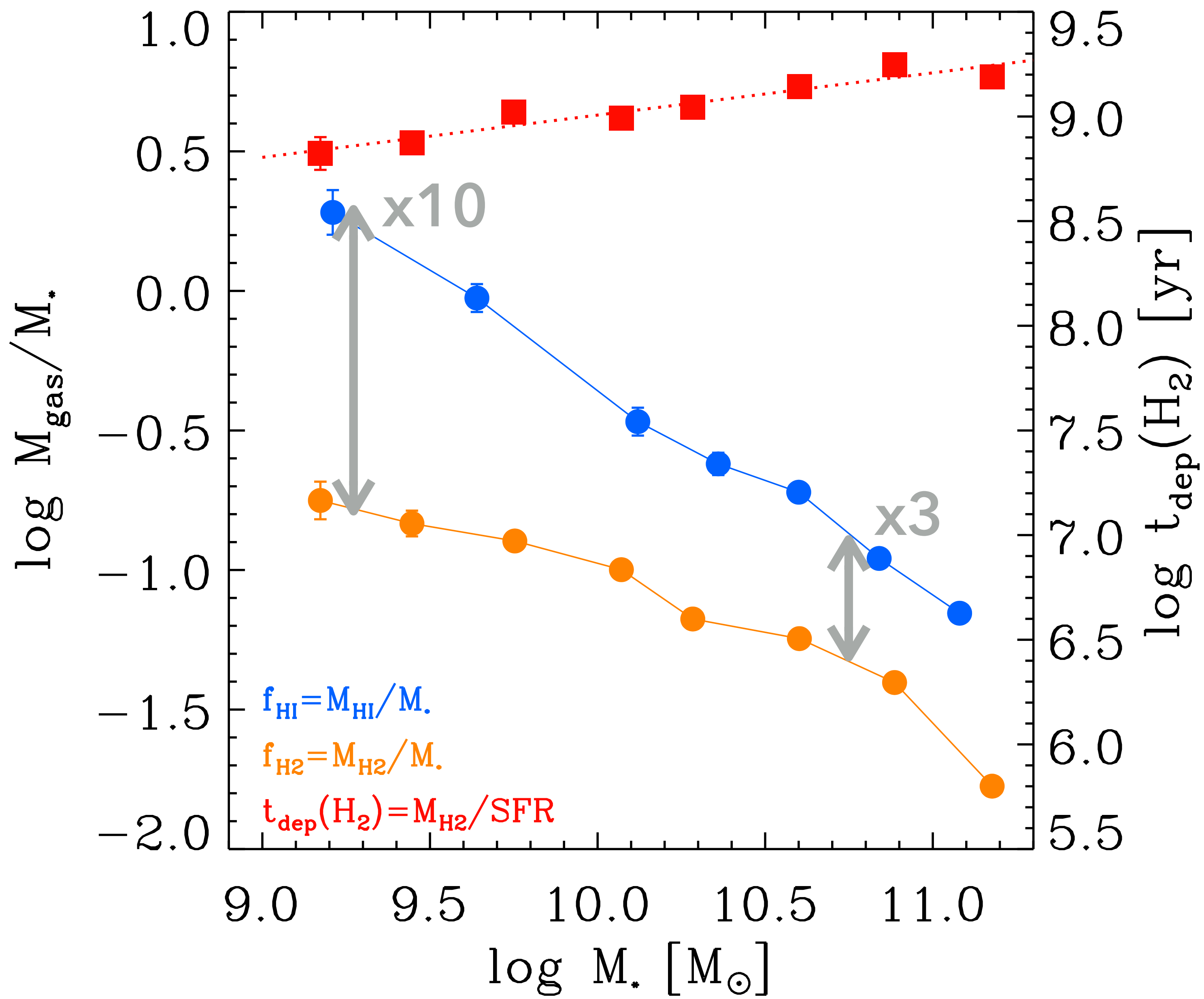


as galaxies evolve along the main sequence, they steadily consume their gas supply

Gas on the main sequence and quenching







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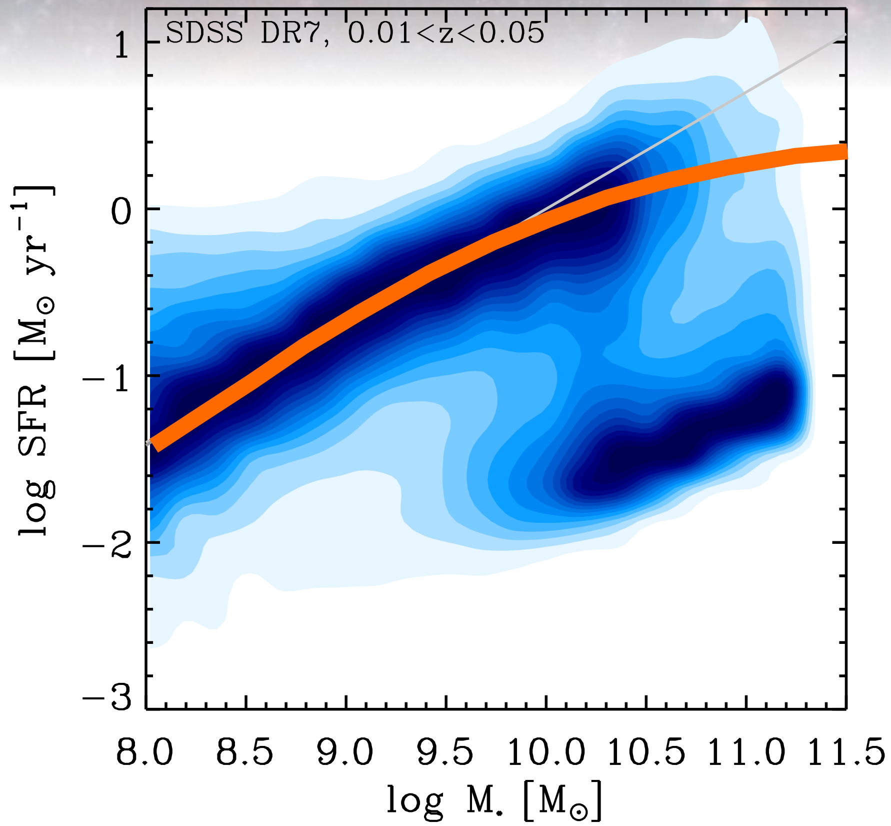
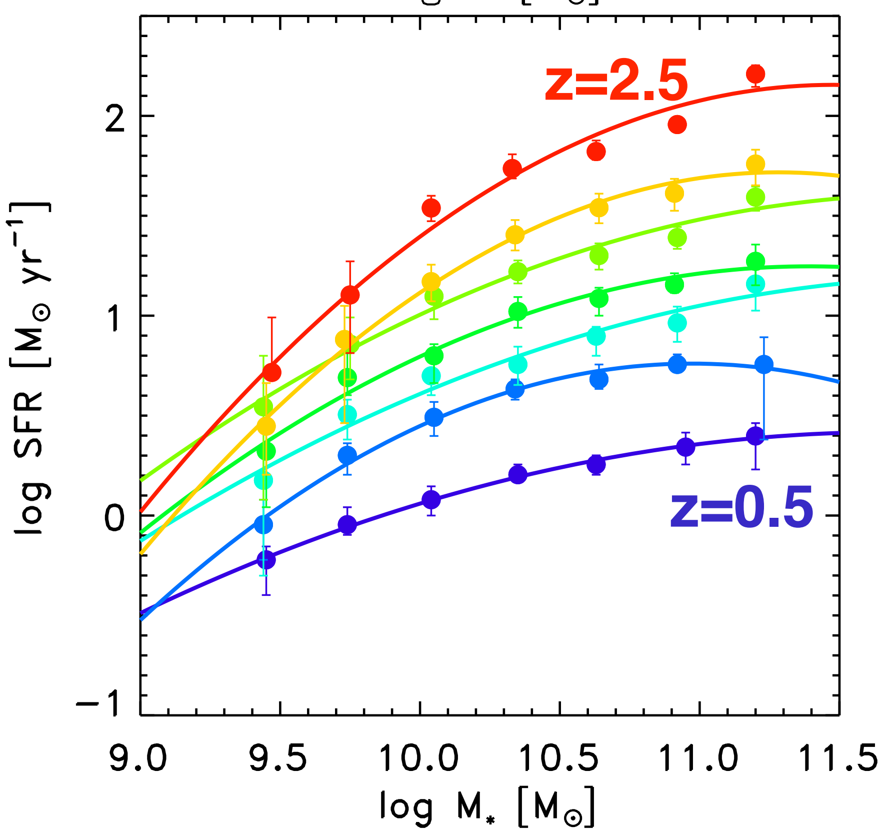
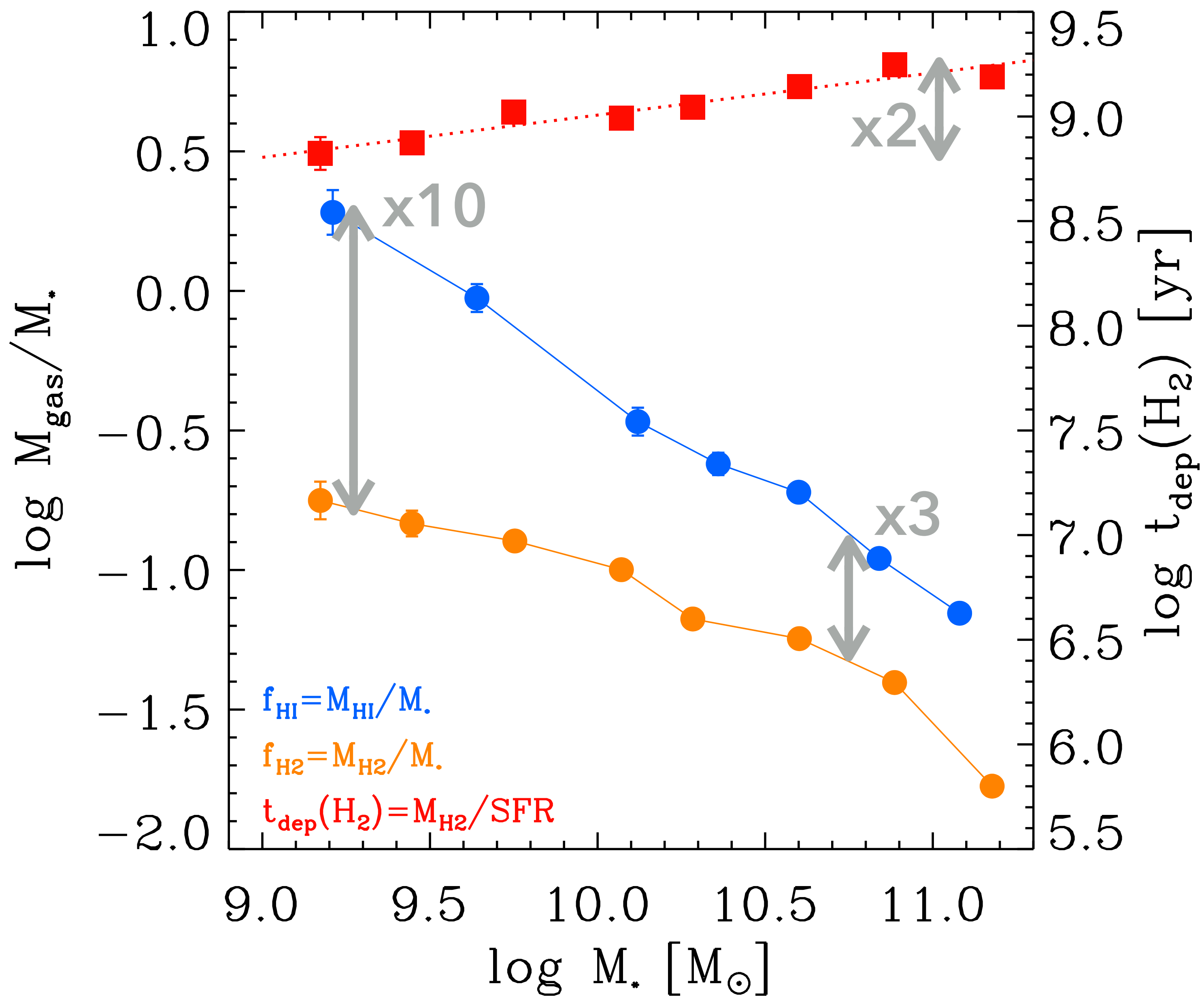
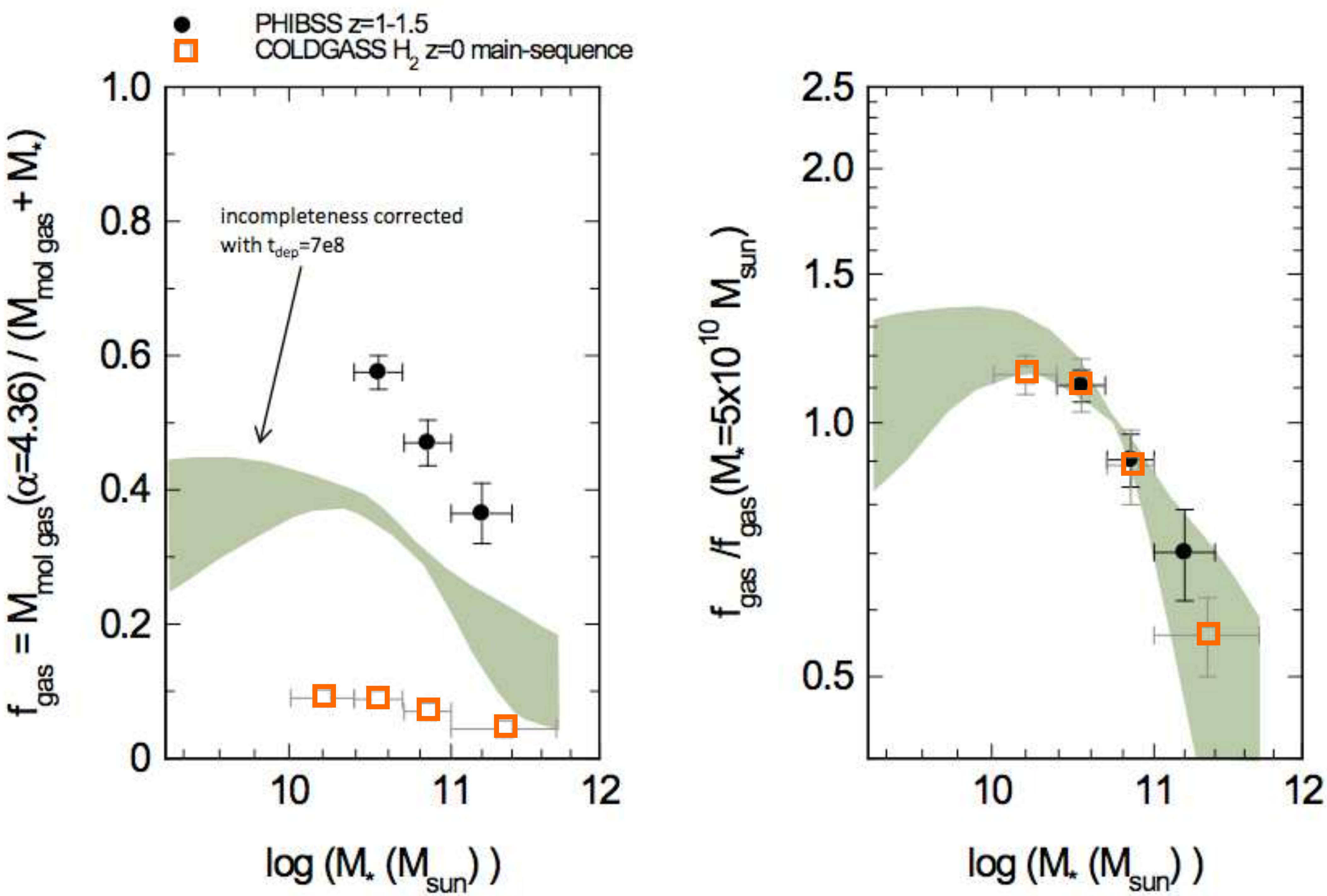






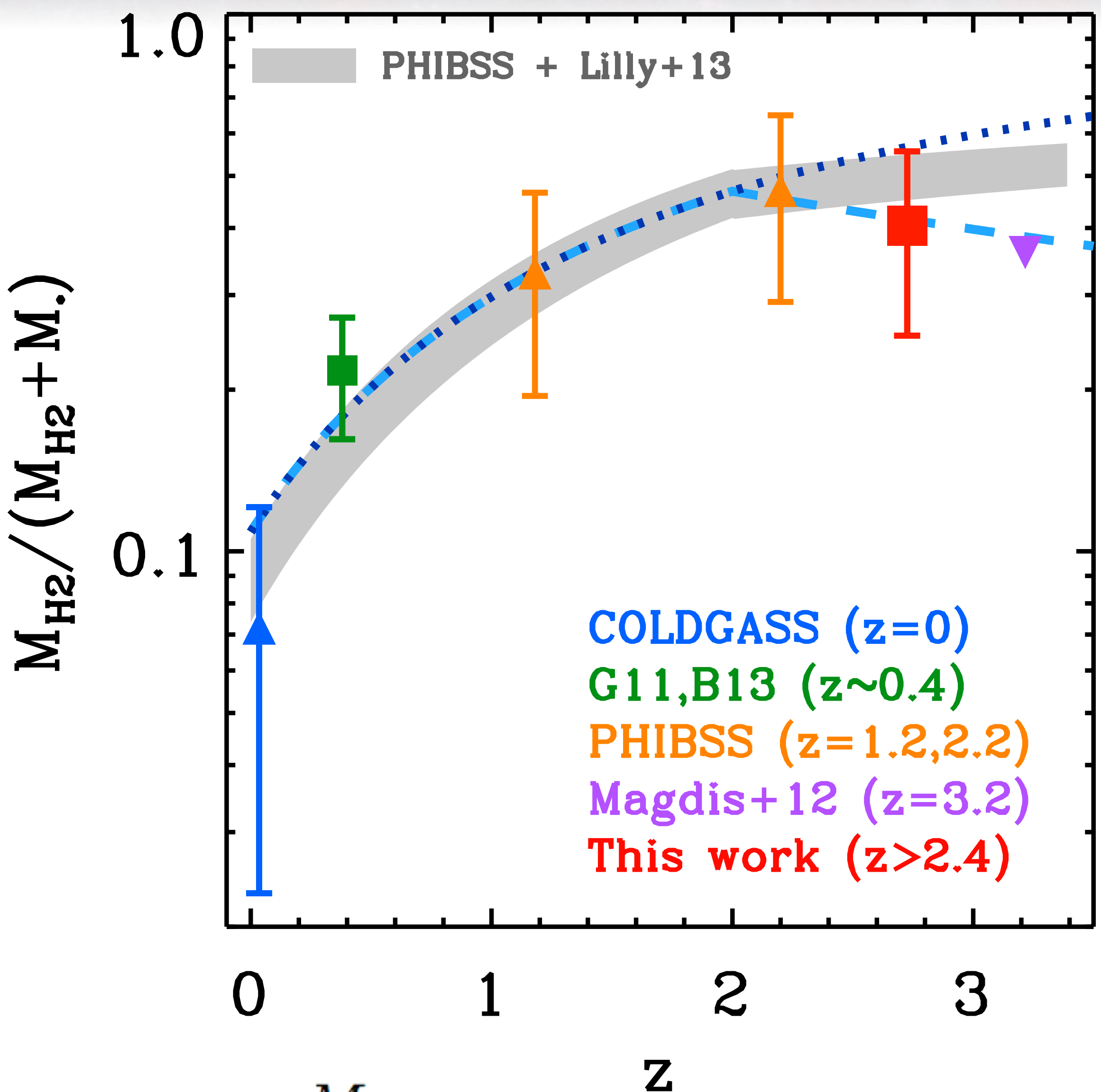
as galaxies evolve along the main sequence, they steadily consume their gas supply

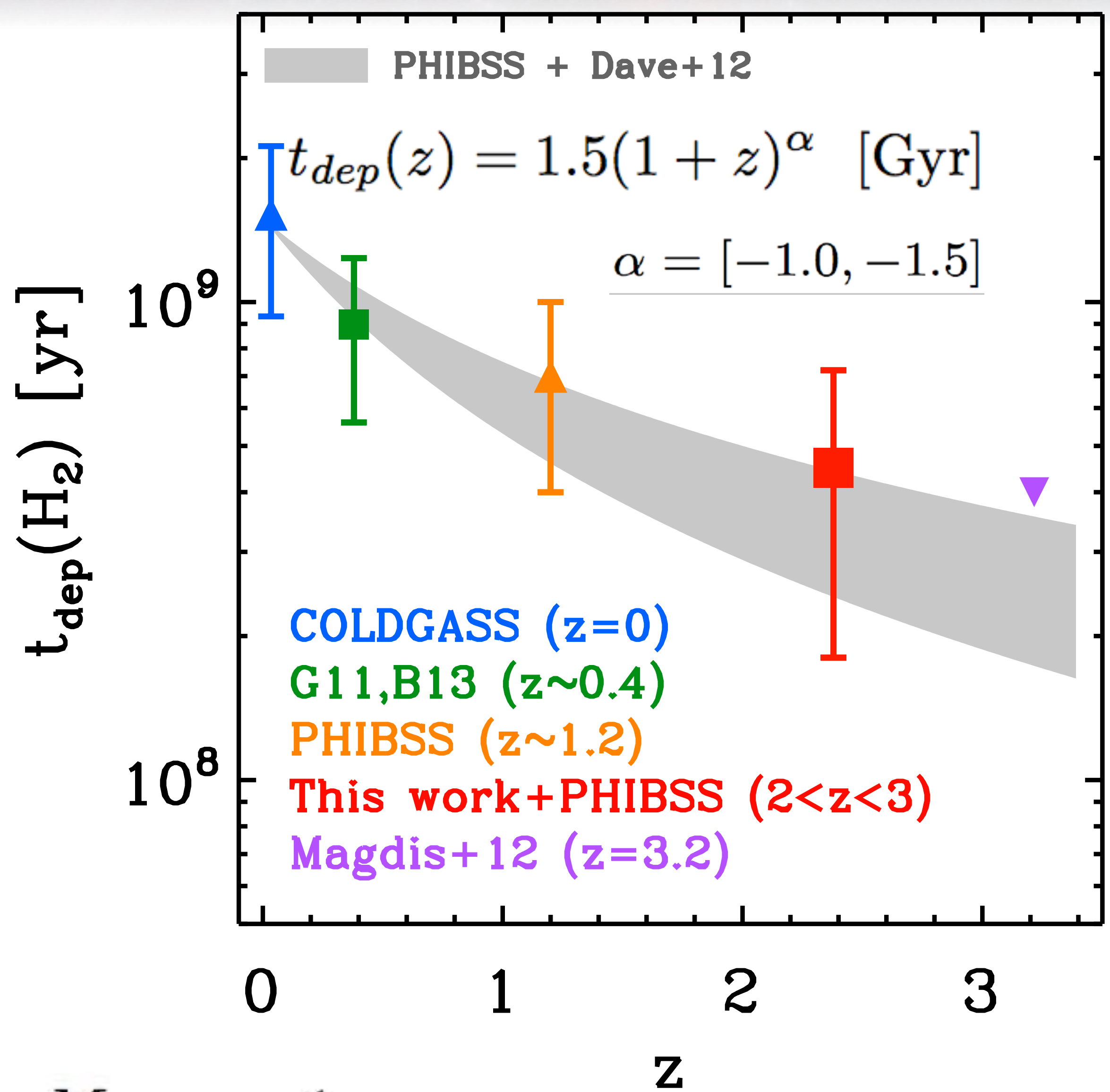
Redshift independence of gas scaling relations



Tacconi et al. (2013)

Redshift evolution of gas fractions





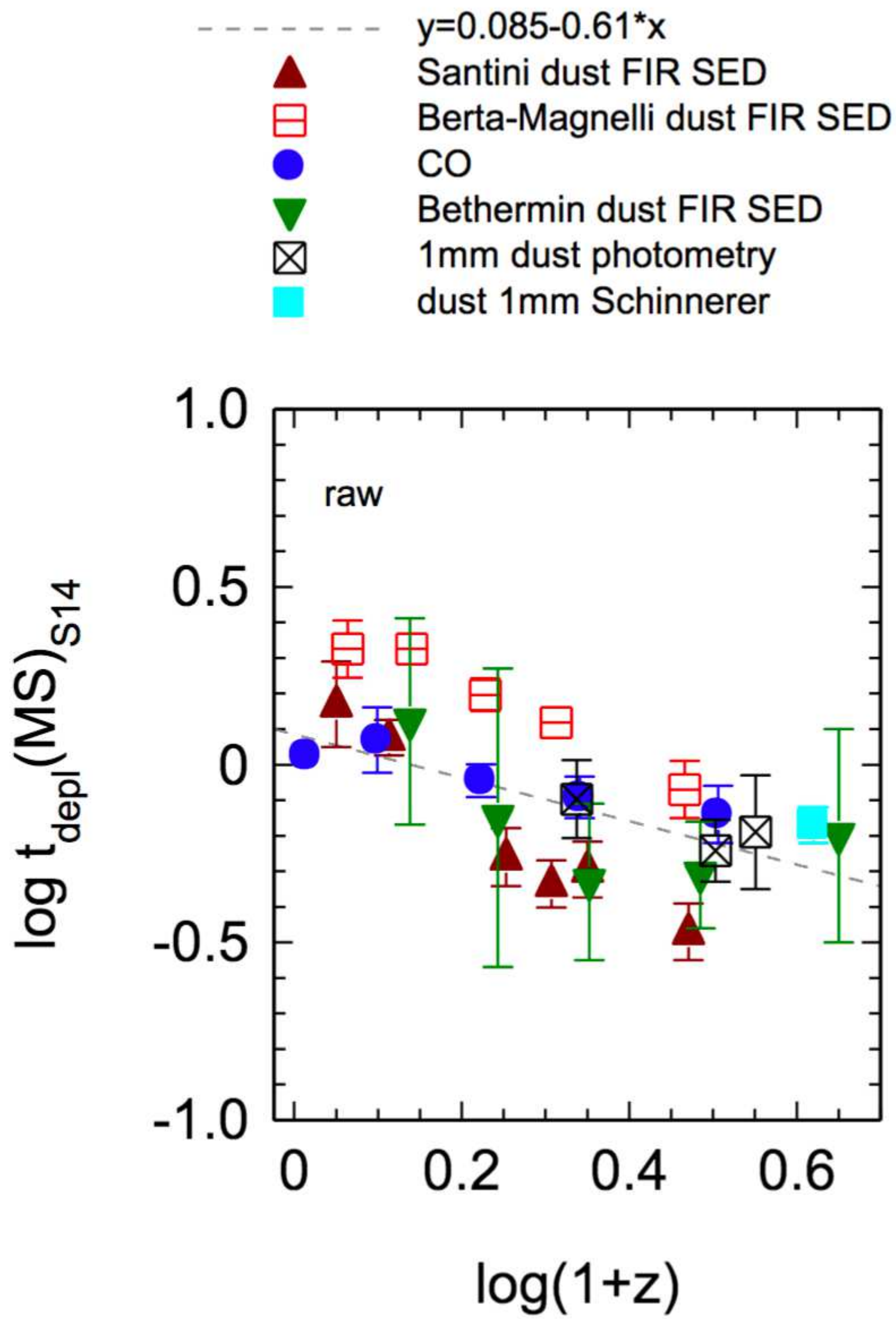
$$f_{gas} = \frac{M_{H2}}{M_{H2} + M_*} = \frac{1}{1 + (t_{dep}\,\mathrm{sSFR})^{-1}}$$

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

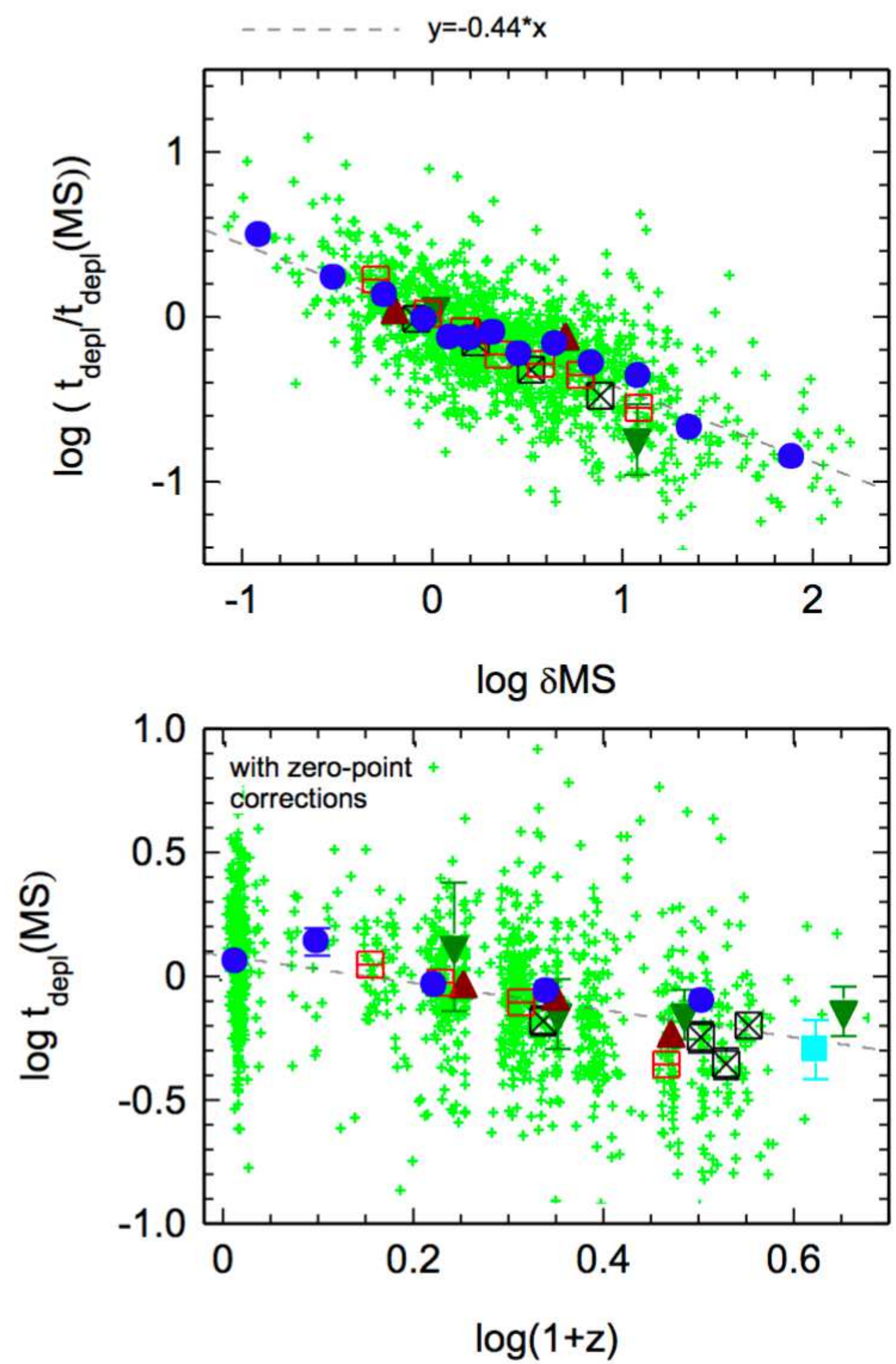
The redshift evolution of the mean SSFR is mainly driven by gas fractions and a slowly evolving depletion timescale. This observation is in strong support of the equilibrium model for galaxy evolution.

Saintonge et al. (2013), Genzel et al. (2015), Tacconi et al. (2013,2017)

Combined dust and gas scaling relations

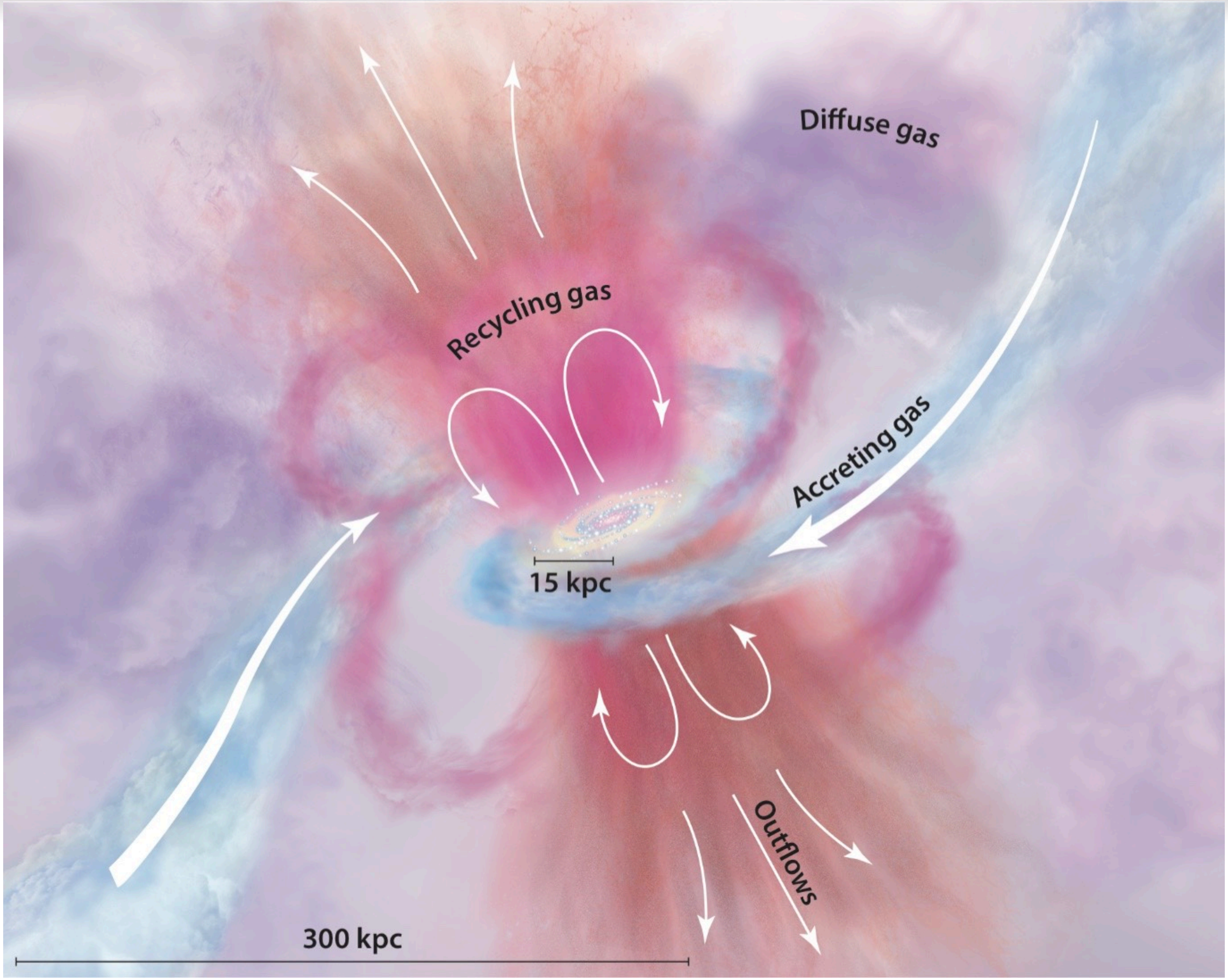


taking out zero-point offset



Tacconi, Genzel, Saintonge et al. (2018)

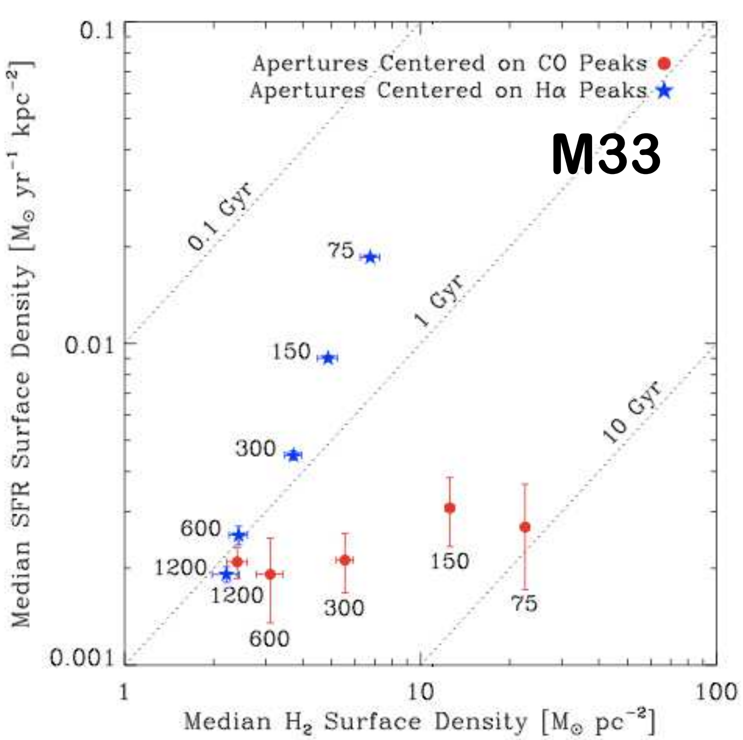
Star formation and the baryon cycle



Tumlinson, Peeples and Werk (2017)

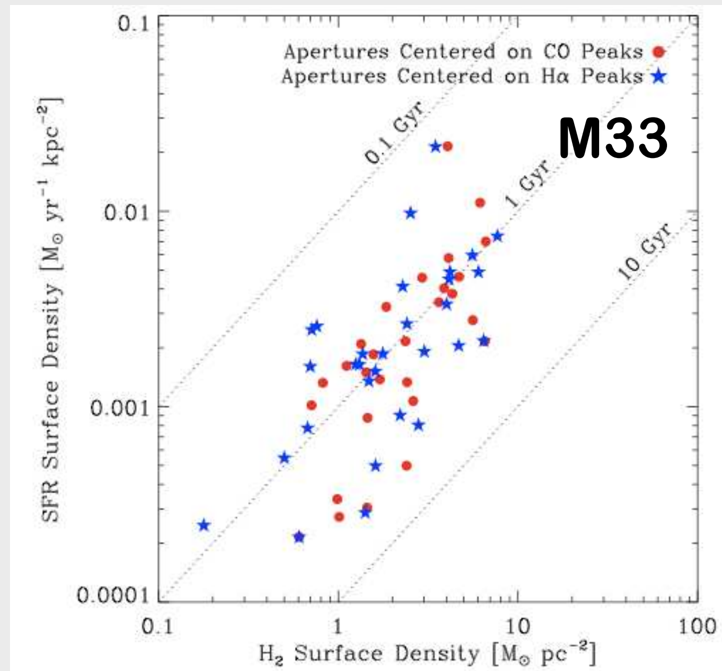
Studying the star formation relation on multiple scales

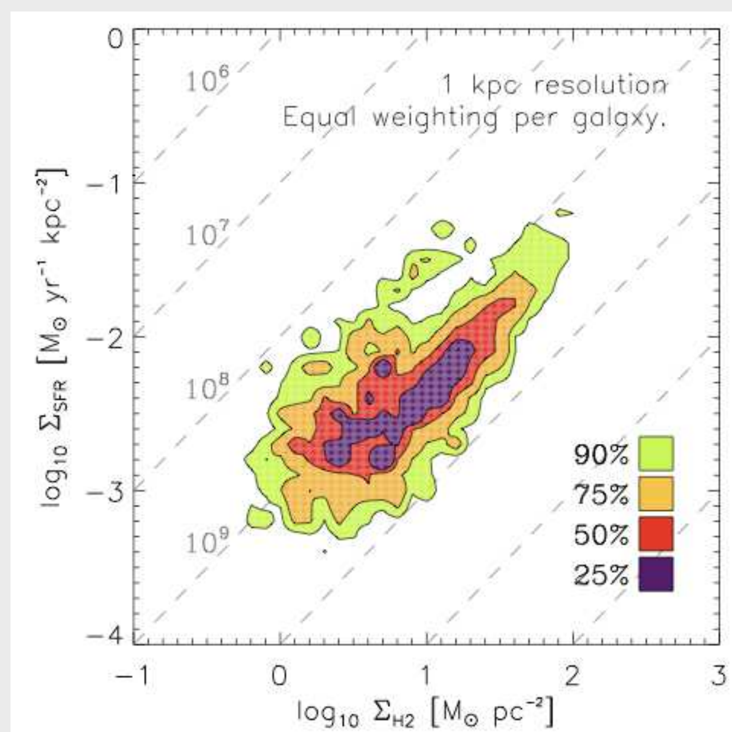
<500pc scales



Schruba et al. (2010)

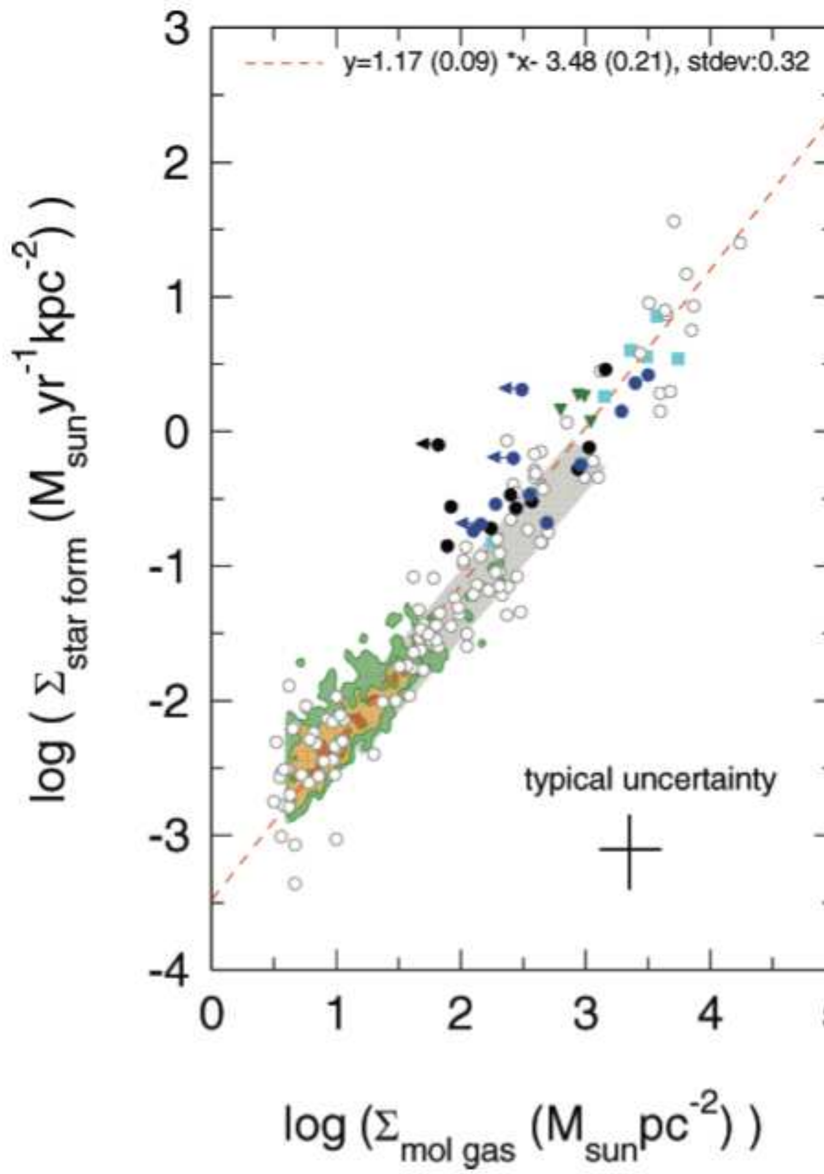
~kpc scales





Bigiel et al. (2011)

global scales



Genzel et al. (2010)

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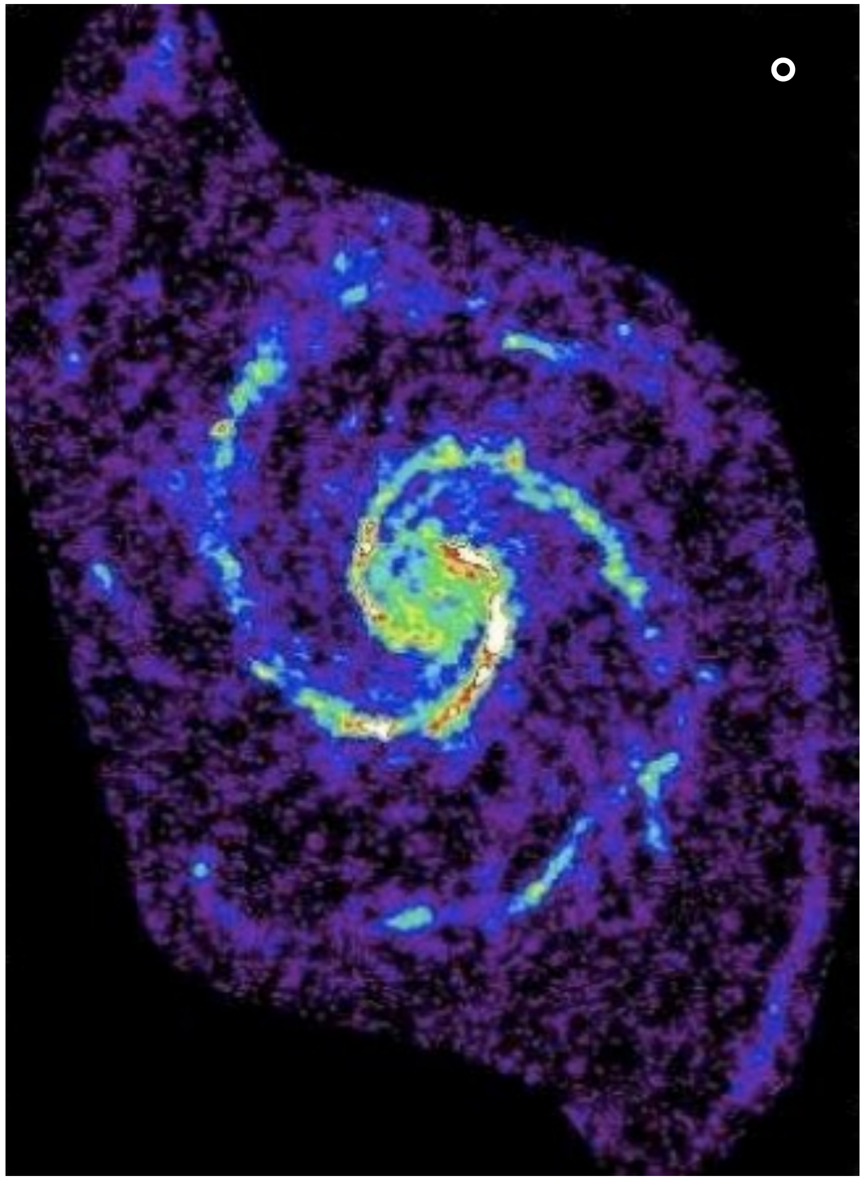
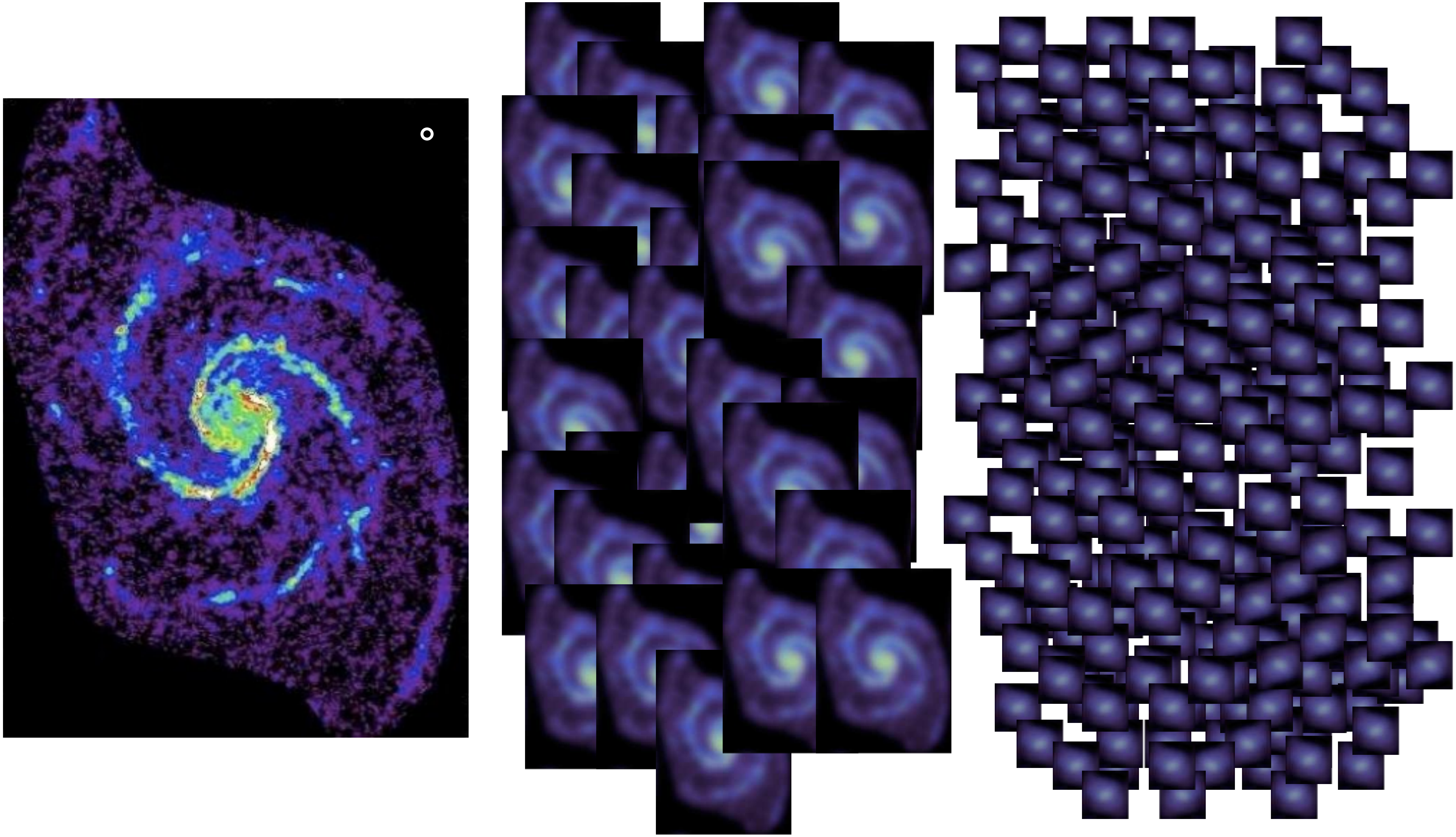


Koda et al. (2009)

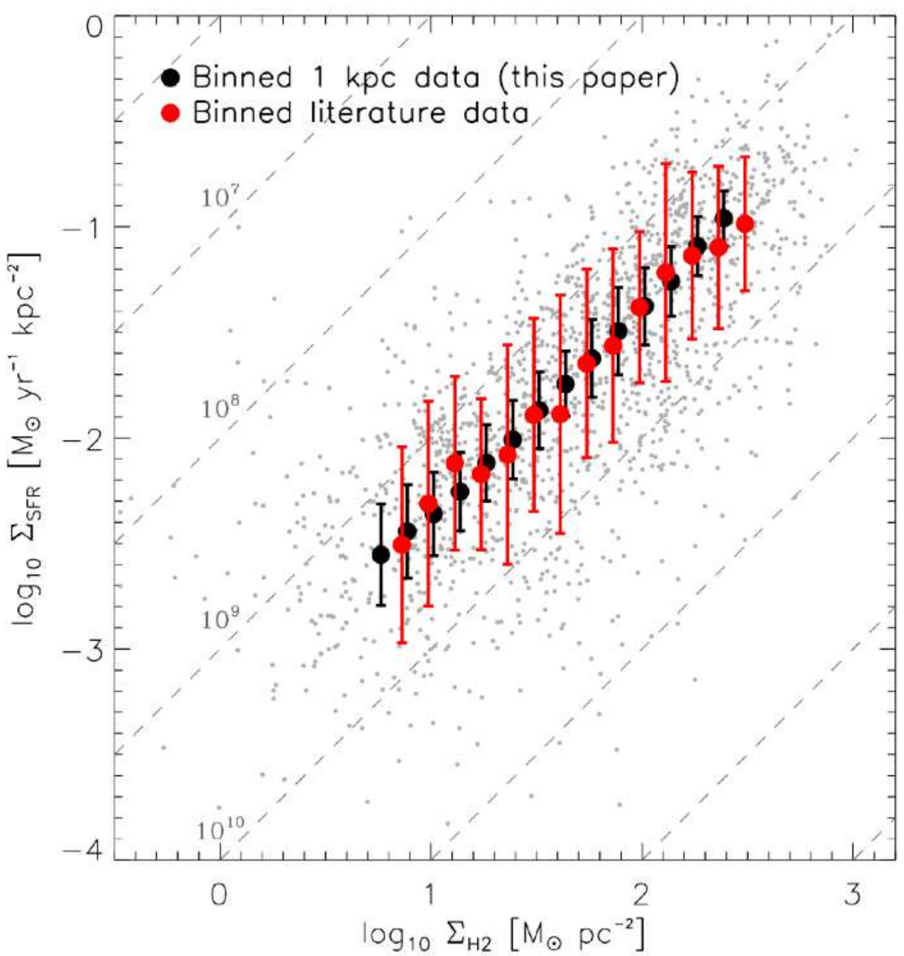
Studying the star formation relation on multiple scales



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

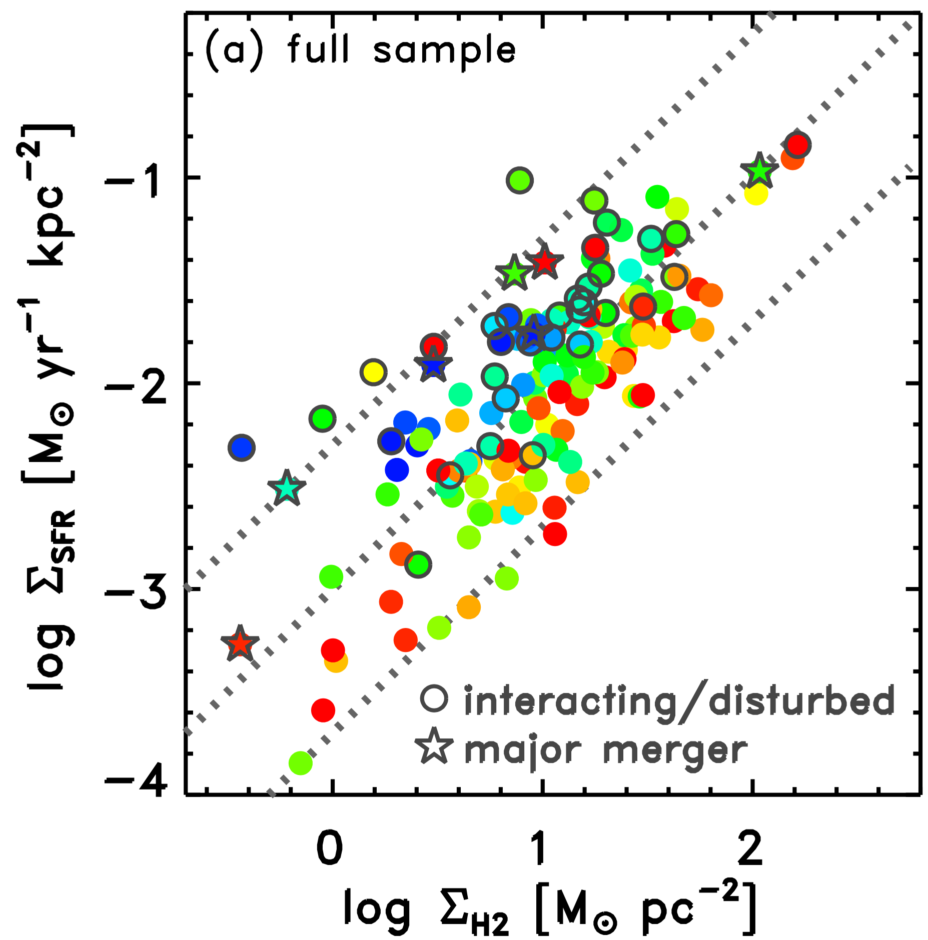
Some important questions:

- 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)

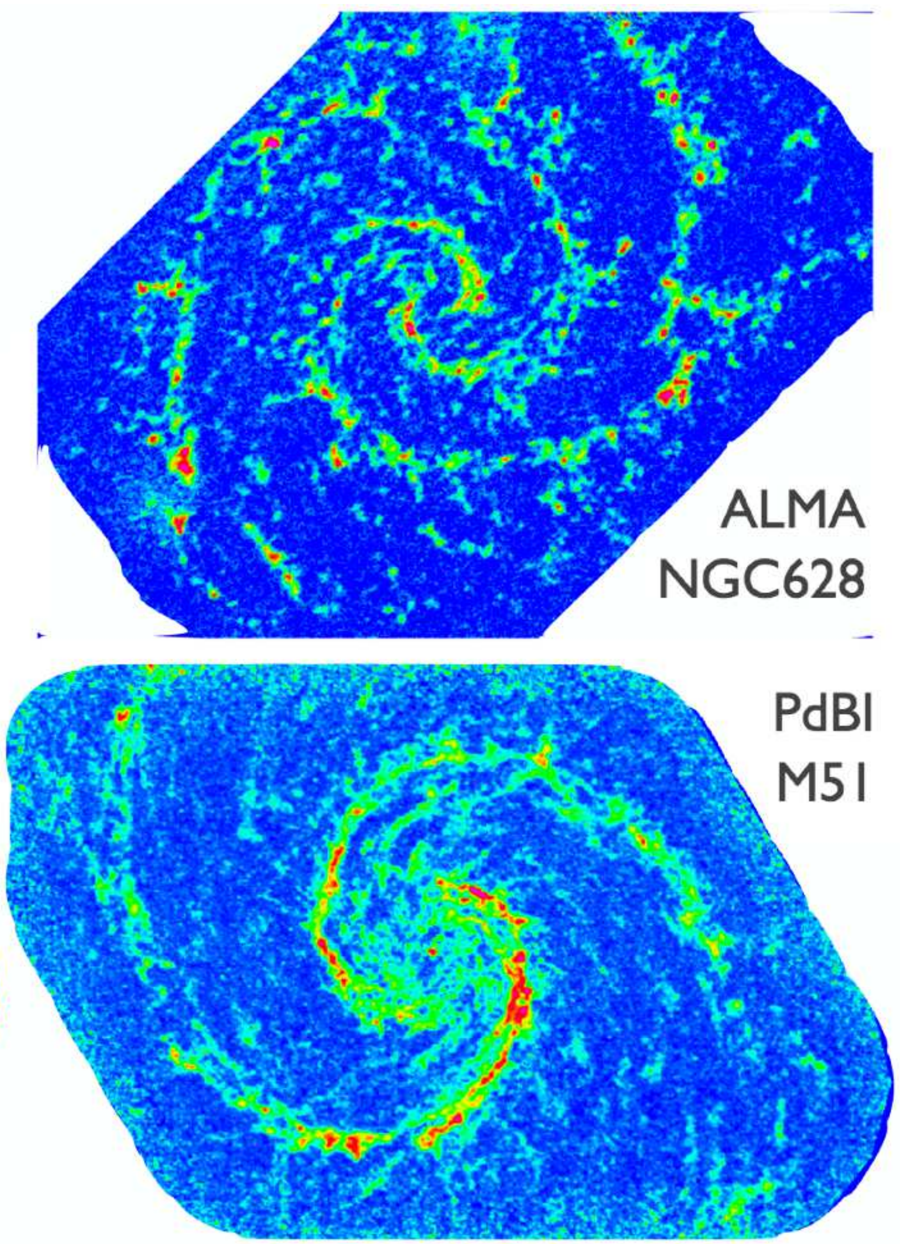
Universal SF law, or systematic variations with global environment ???

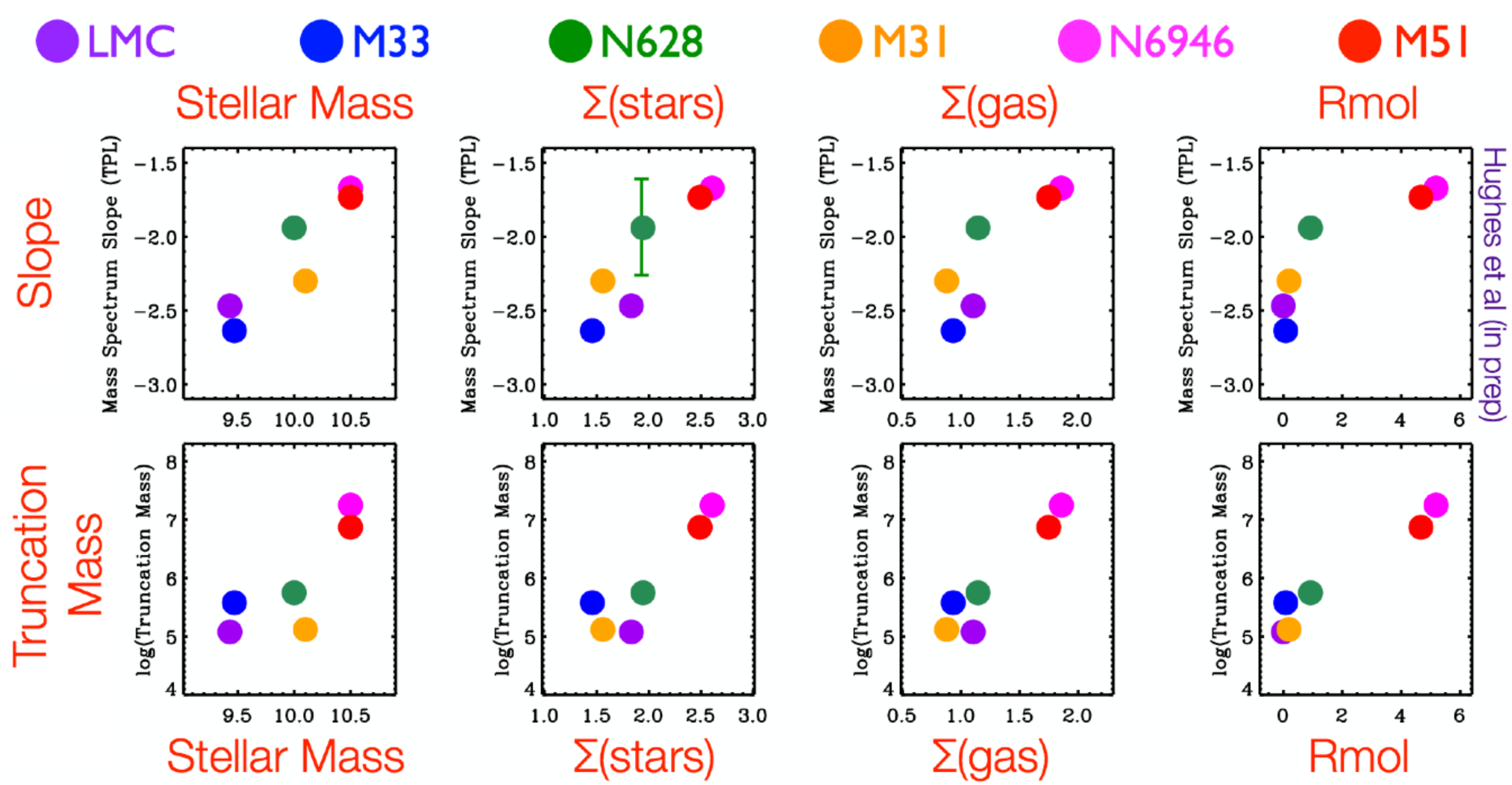


Saintonge et al. (2012)

GMC properties depend on global galaxy properties!

ALMA/NOEMA studies of the GMCs in a range of nearby galaxies:

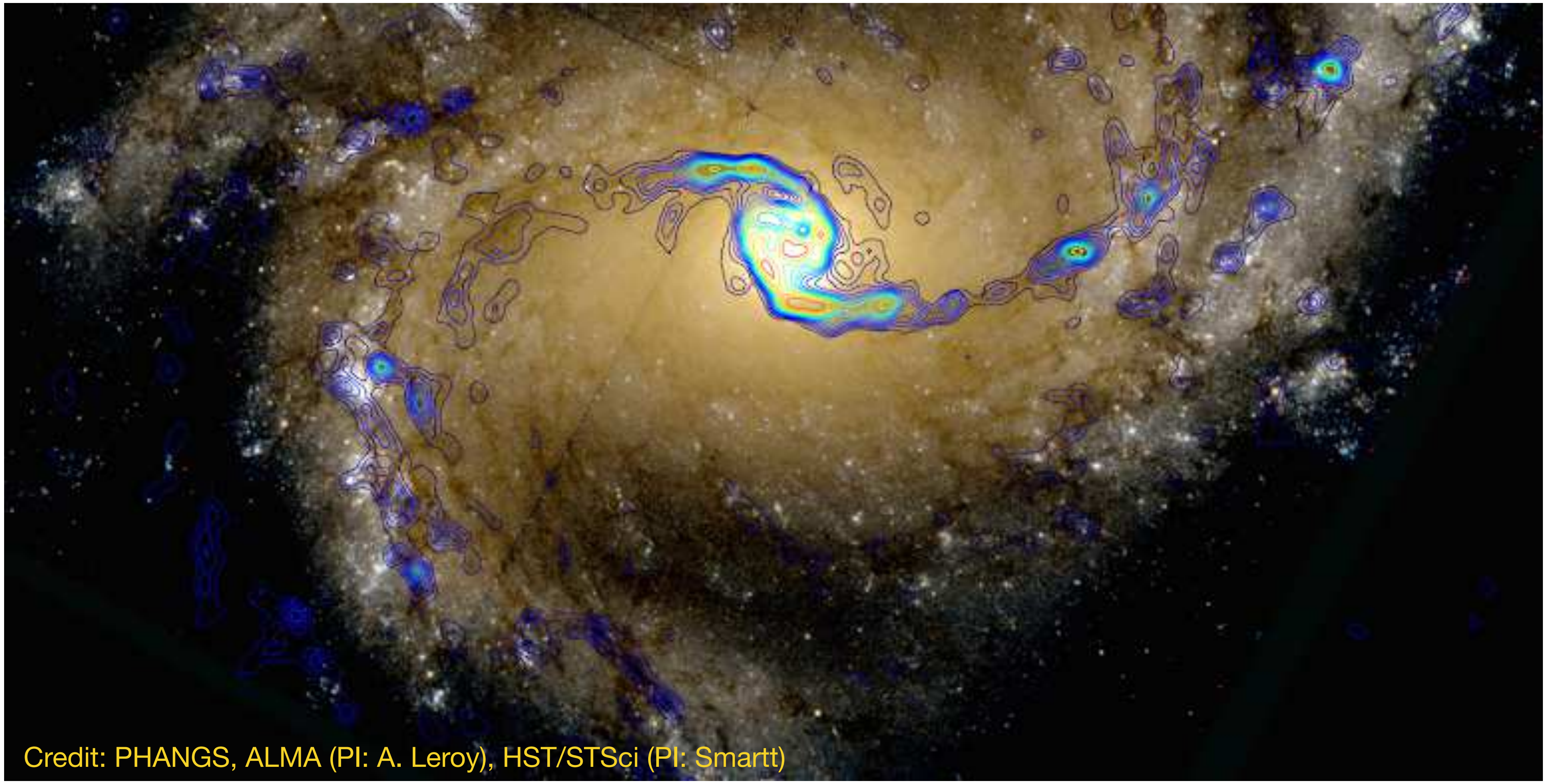




shape of GMC mass distribution is not universal: slope and turnover mass increase in more massive systems

Images from A. Hughes

PHANGS: ALMA+VLT/MUSE survey for star formation in an extragalactic context



ALMA Large Programme: 1″ imaging in CO(2-1) of ~60 nearby disc galaxies (PI: E. Schinnerer)

\+ associated programmes with VLA, VLT/MUSE, IRAM/NOEMA

PHANGS: ALMA+VLT/MUSE survey for star formation in an extragalactic context

(slide from A. Schruba at "The Laws of Star Formation", Cambridge, July 2018)

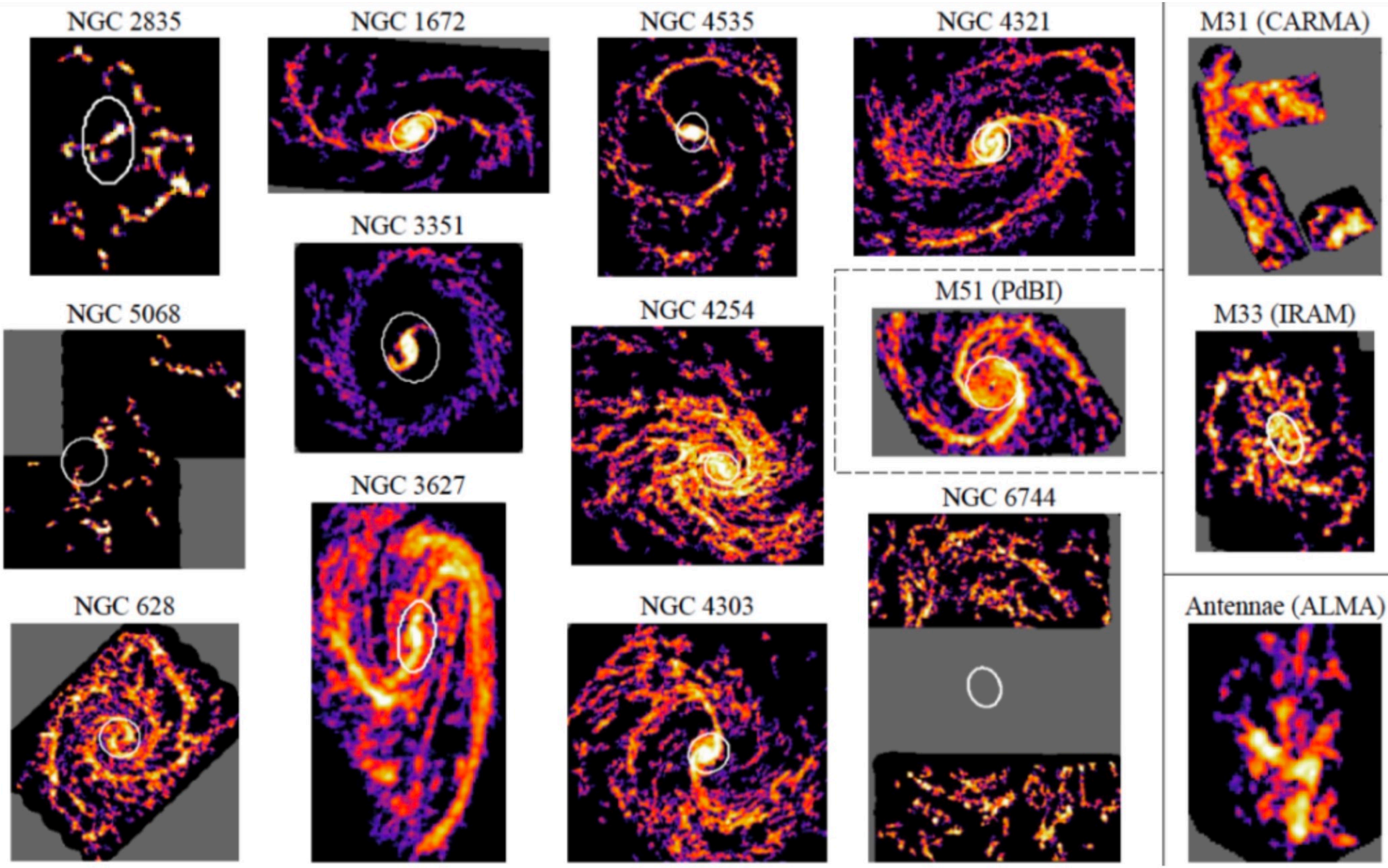


Figure: Sun, Schruba & Phangs 18

http://phangs.org

PHANGS: ALMA+VLT/MUSE survey for star formation in an extragalactic context

(slide from A. Schruba at "The Laws of Star Formation", Cambridge, July 2018)

Comparing the mass-weighted average state of the gas at high physical resolution and correlate it with the balance between star formation and gas observed on larger scales (capturing time-averaged cycling).

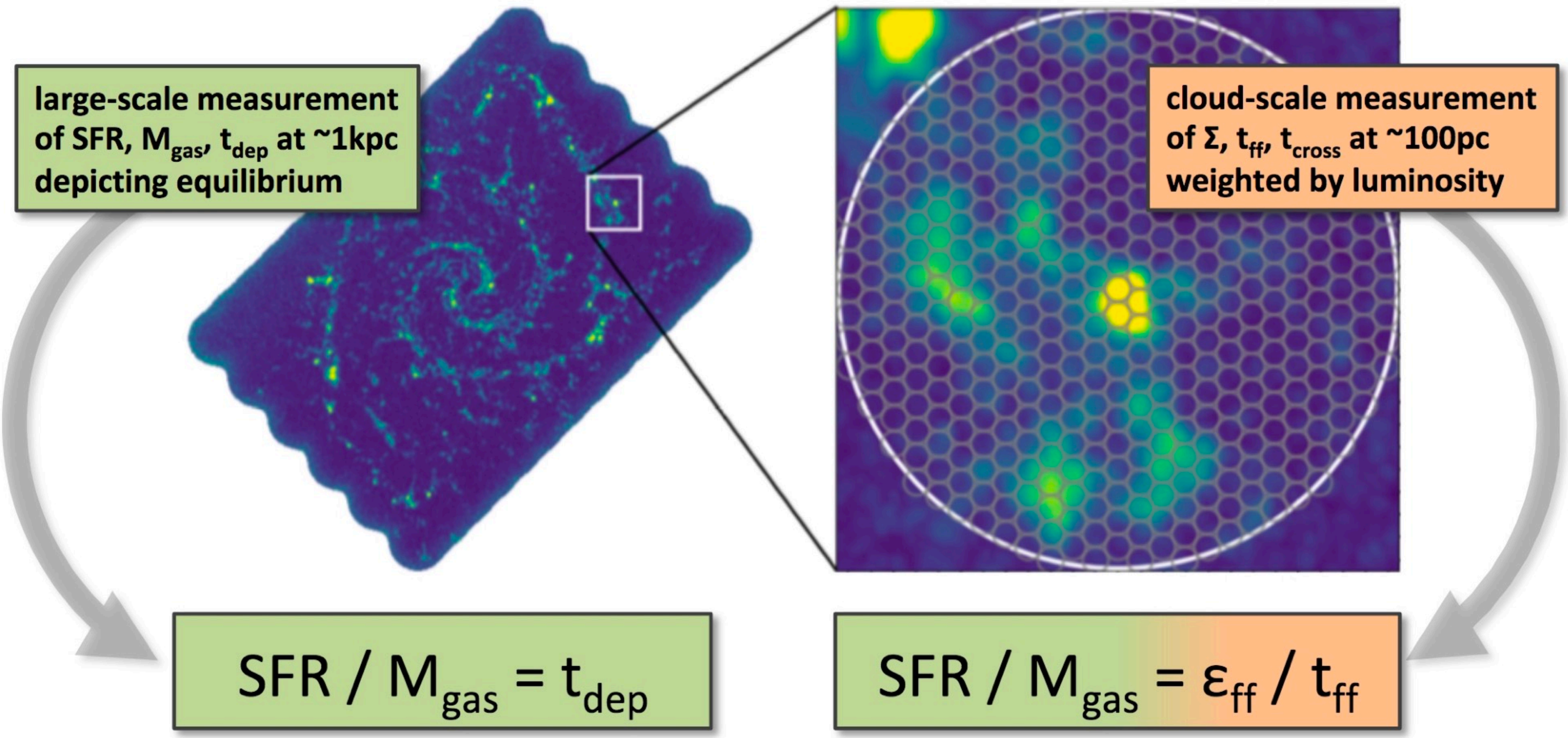


Figure: Utomo, Schruba & Phangs 18 (on arXiv today)

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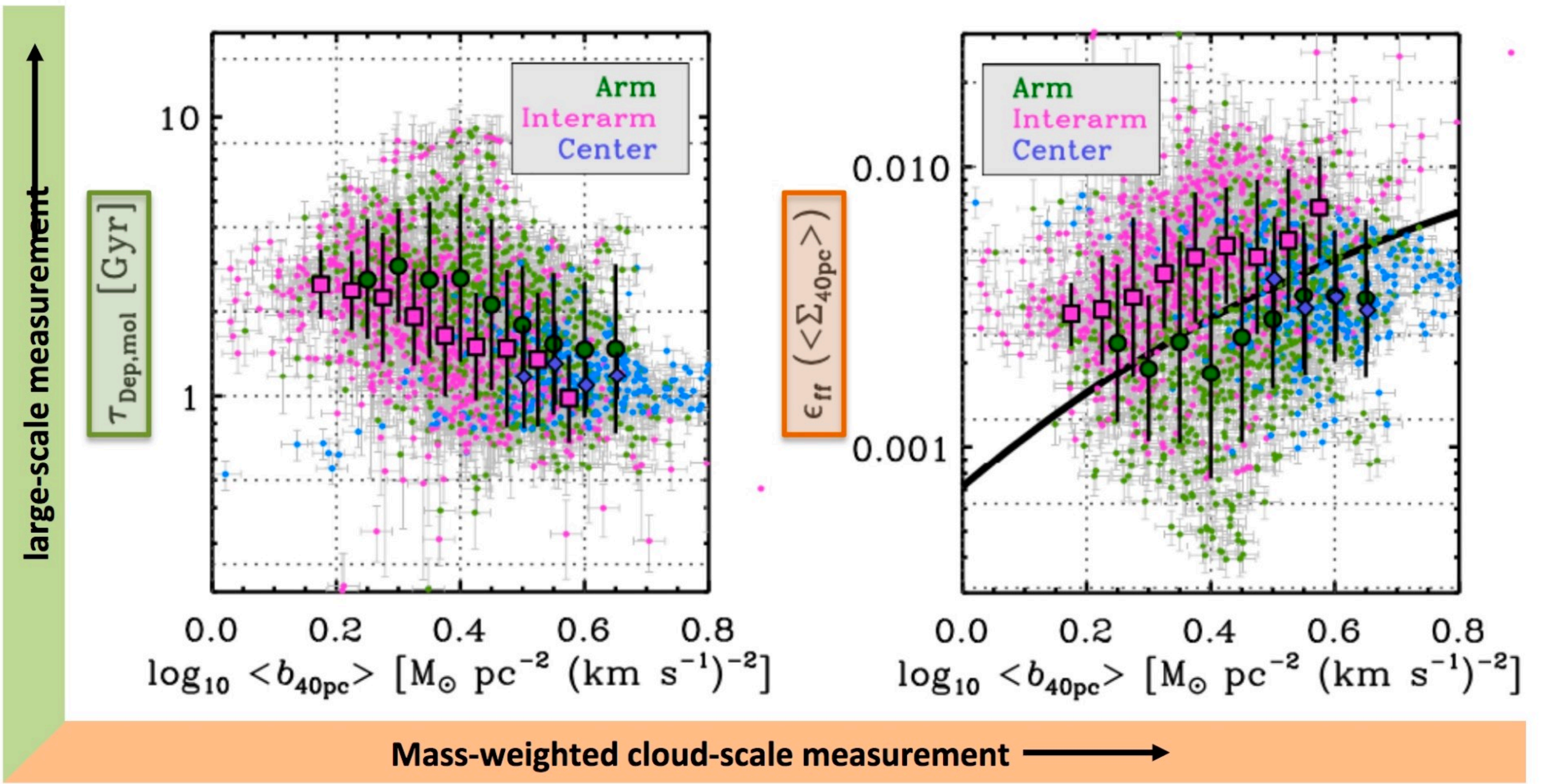


Leroy, Schruba & Phangs 18

$$SFR = \varepsilon_{ff}\, M_{gas} / t_{ff} \quad \text{with} \quad t_{ff} \sim (\Sigma/h)^{-0.5}$$

EMPIRE: IRAM/30m survey for dense molecular gas

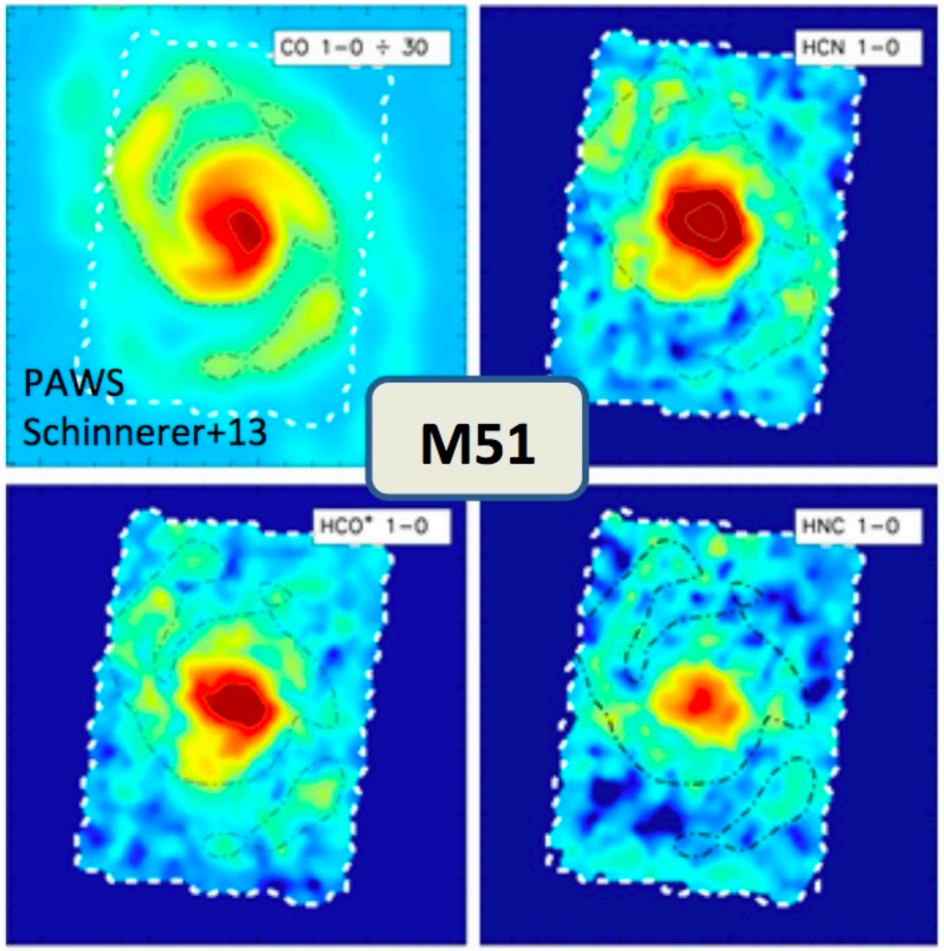
(slide from M. Jimenez-Donaire at "The Laws of Star Formation", Cambridge, July 2018)

EMIR Multi-line Probe of the ISM Regulating Galaxy Evolution

PI: F. Bigiel, IRAM-30m Large Program (~600 h), observations 2014-2017

- Full galaxy maps of:
  - ✓ Dense gas tracers: HCN, HCO+, HNC
  - ✓ CO isotop. ^{13}CO, $C^{18}O$ + **new ^{12}CO(1-0)**
  - ✓ Opportunity: N_2H^+, HNCO, C_2H, SiO
- 9 nearby (~10Mpc) disk galaxies
- Resolution ~ 1-2 kpc

Bigiel et al. 2016



The EMPIRE Team

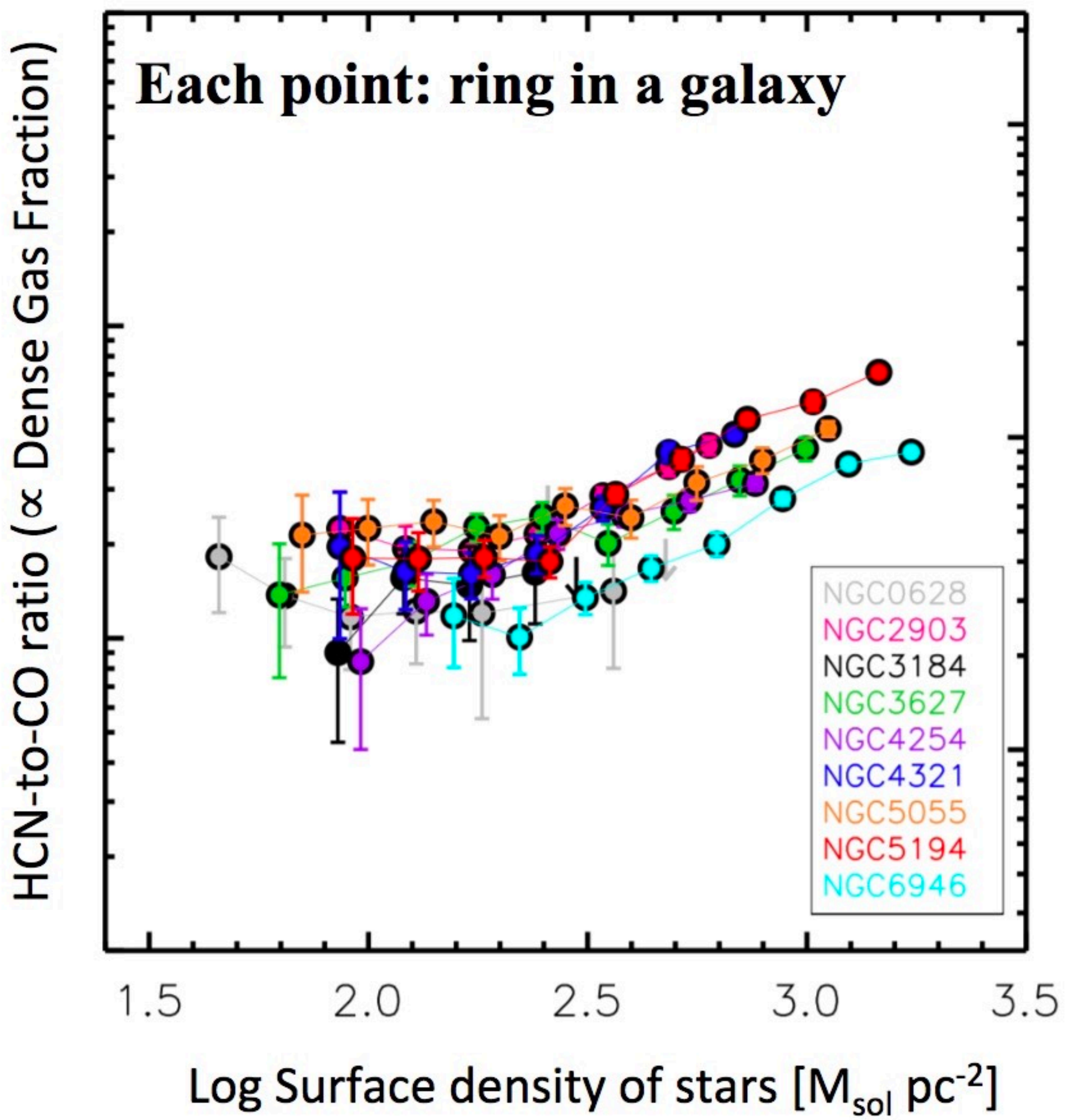
F. Bigiel, *M.J. Jimenez-Donaire*, *A. Leroy*, D. Cormier, A. Usero, M. Gallagher, *J. Puschnig*, D. Chatzigiannakis, *A. Bolatto*, S. Garcia-Burillo, A. Hughes , *A. Kepley*, C. Kramer, J. Pety, *K. Sandstrom*, *E. Schinnerer*, *A. Schruba*, K. Schuster, F. Walter, L. Zschaechner

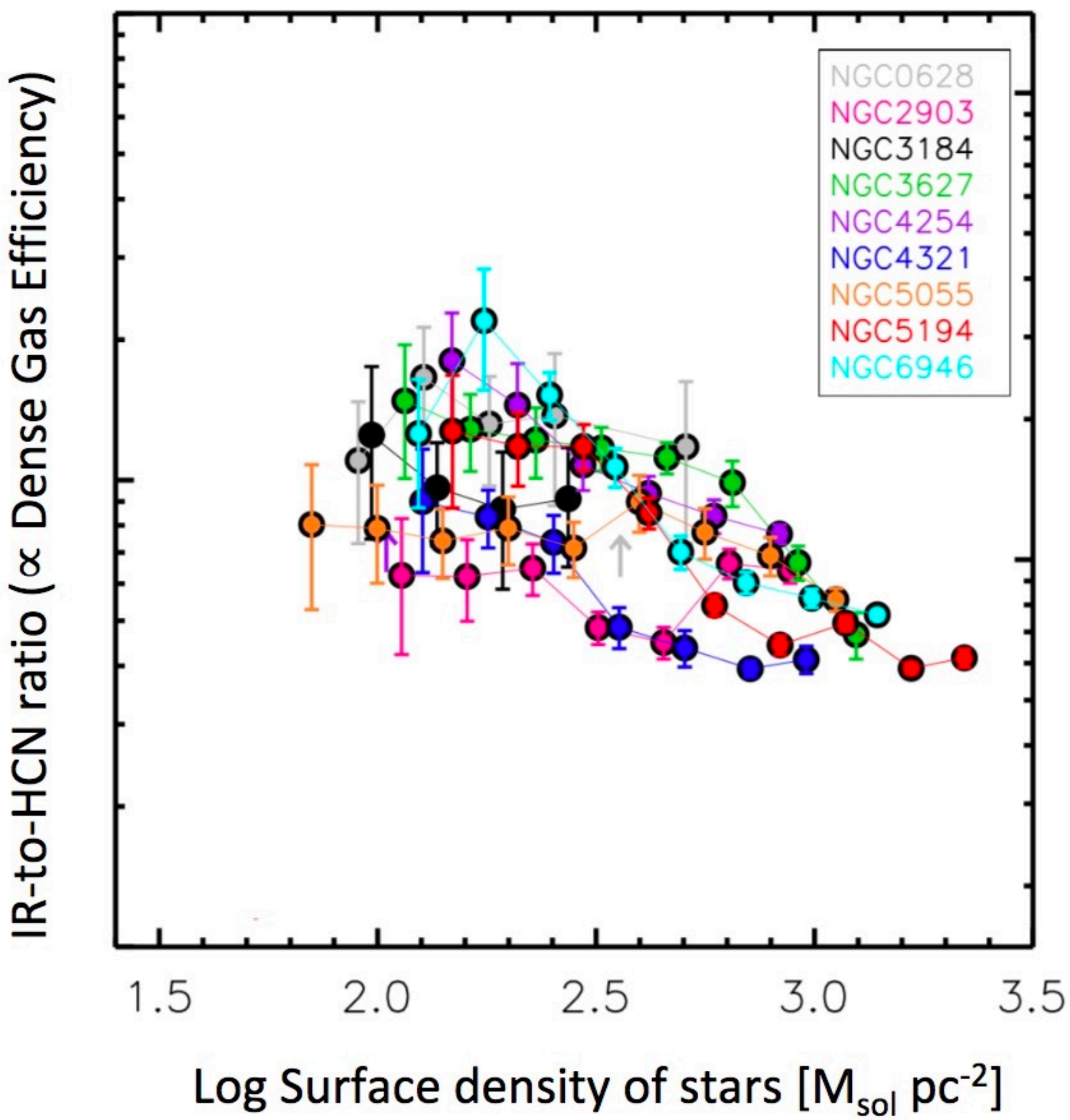
Papers: Usero+15, Bigiel+16, Jimenez-Donaire+17a,b, Leroy+17, Gallagher+18, Cormier+18, Jimenez-Donaire+(in prep.), Chatzigiannakis+(in prep.)

EMPIRE: IRAM/30m survey for dense molecular gas

(slide from M. Jimenez-Donaire at "The Laws of Star Formation", Cambridge, July 2018)

Efficiency of dense gas to form stars seems to drop towards galaxy center, high stellar surface densities, high pressure regions and high molecular gas fractions!



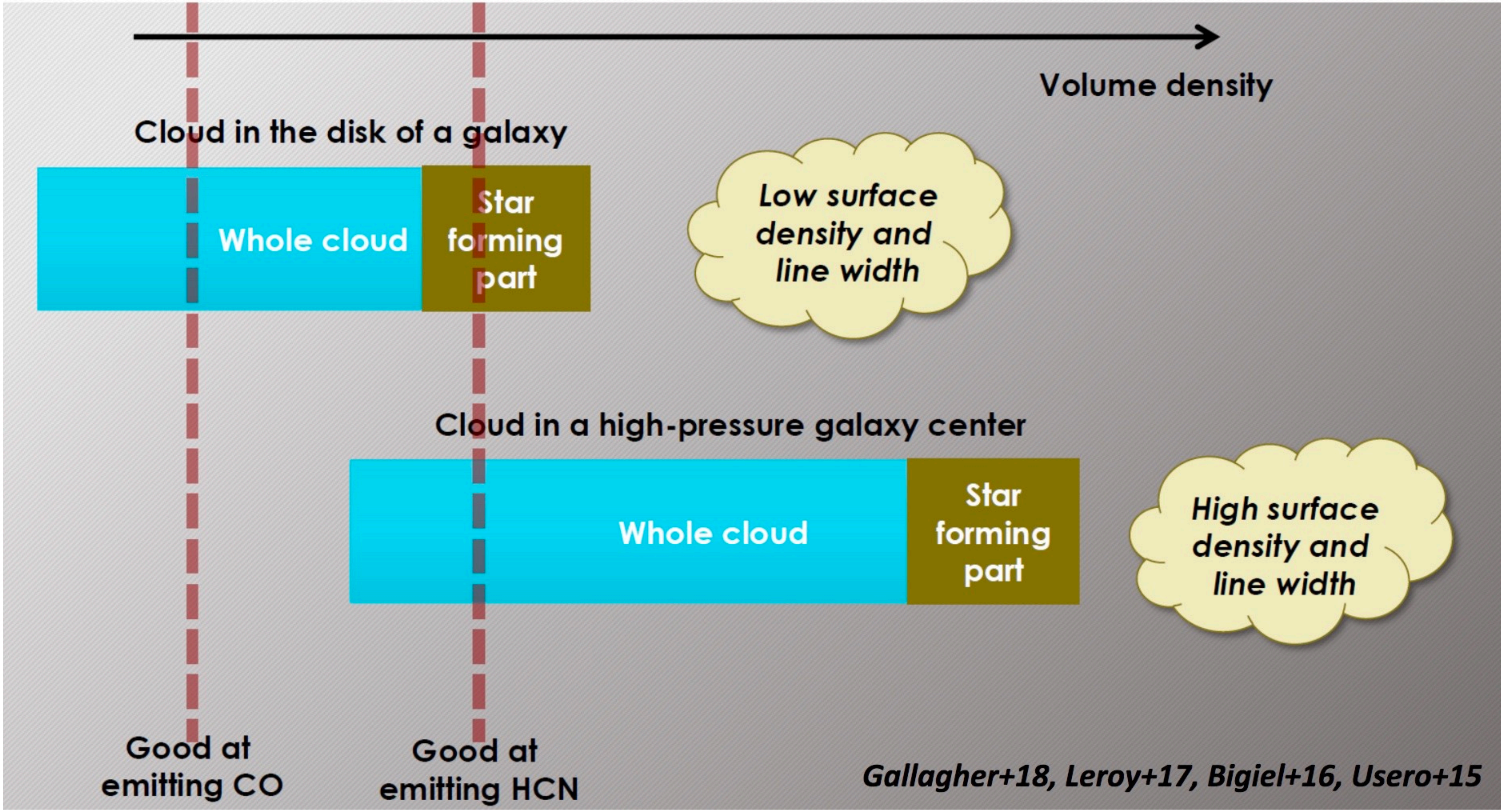


The EMPIRE Survey. Jiménez-Donaire *et al. (in prep.); Gallagher+18, Bigiel+16, Usero+15*

EMPIRE: IRAM/30m survey for dense molecular gas

(slide from M. Jimenez-Donaire at "The Laws of Star Formation", Cambridge, July 2018)

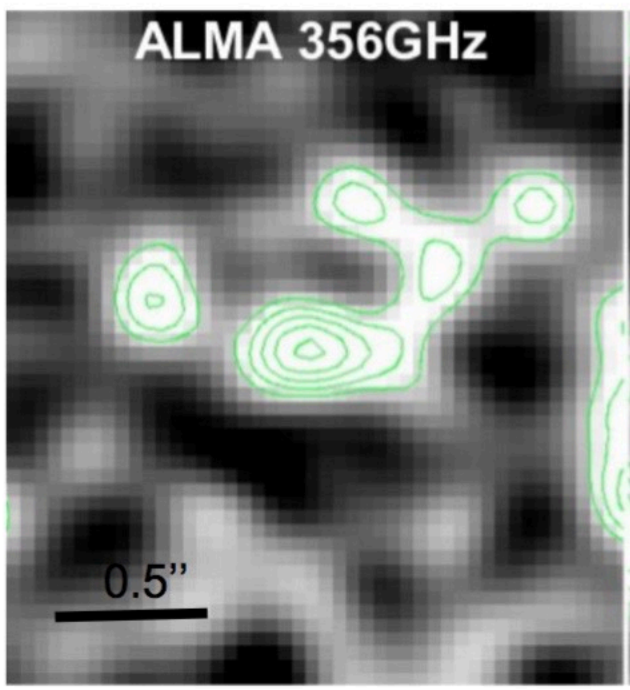
This appears to lead to a context-dependent role for the gas that emits in HCN and similar lines, evidenced by the changing IR-to-line ratios with environment.

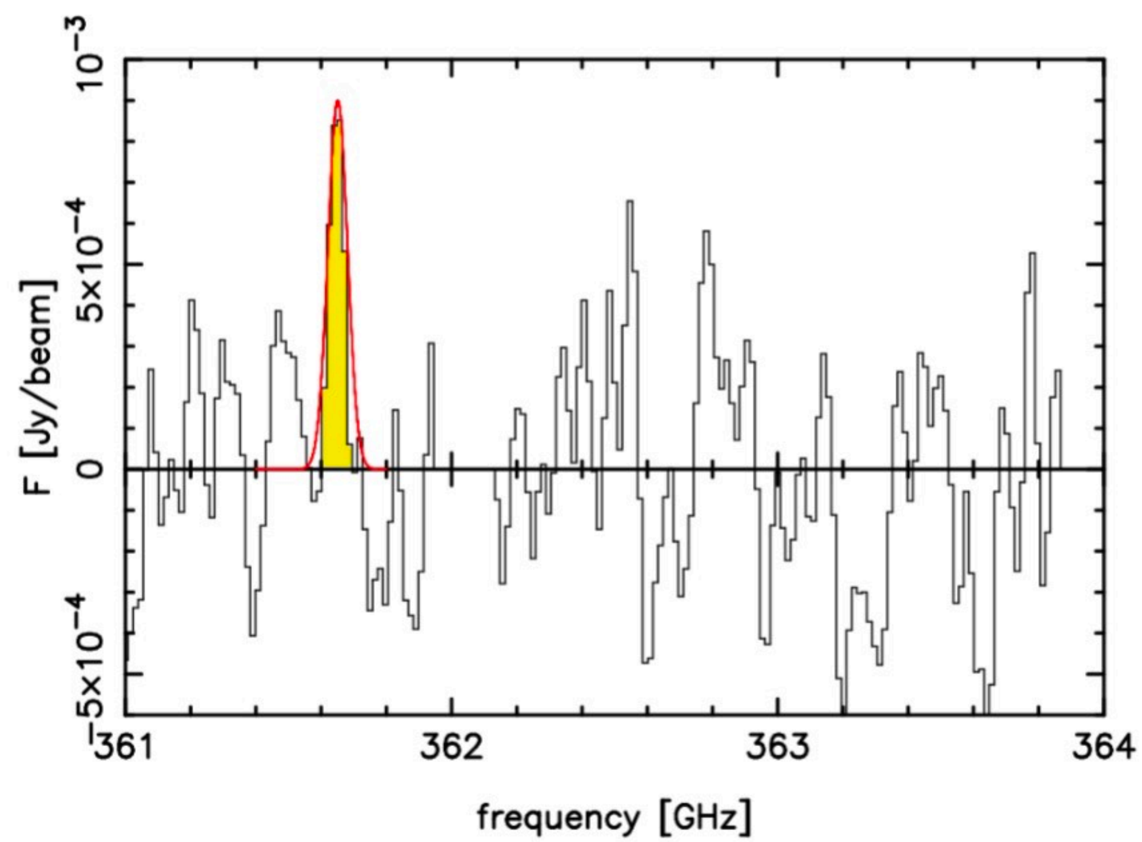


Technical challenge: How do we move forward and explore low mass and/or high redshift galaxies?

An example of very high redshift molecular gas work:

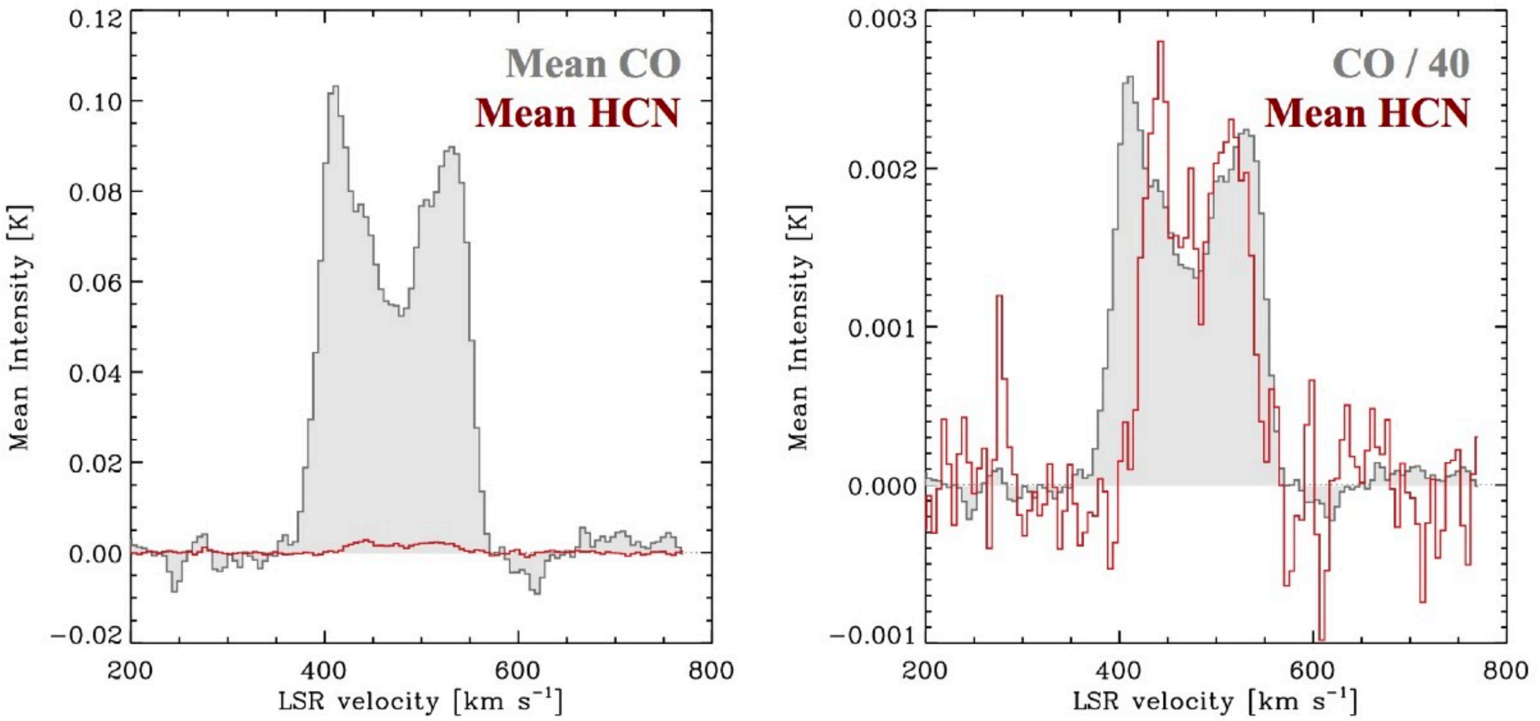
Lensed z=8.3 galaxy observed with ALMA (Laporte et al. 2017)



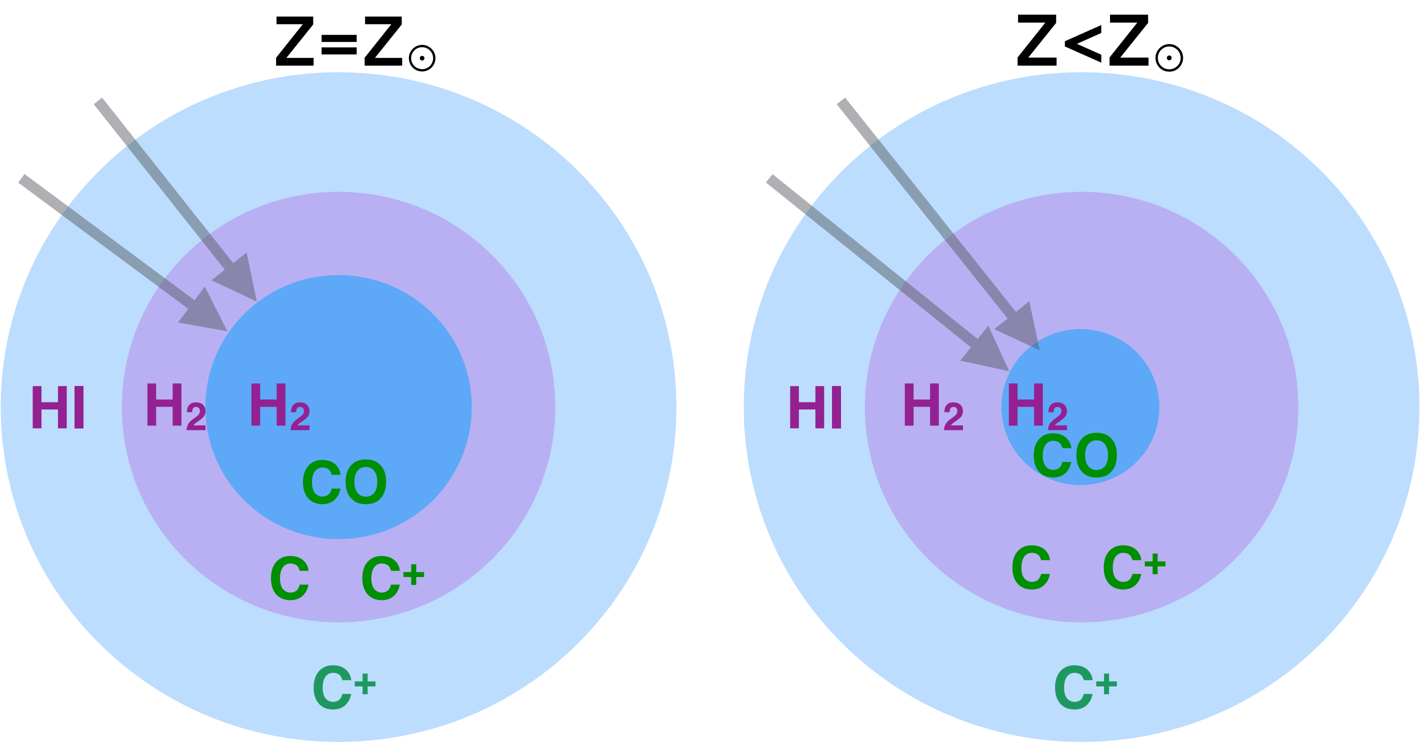


Analysis of the available photometric data and the modest gravitational magnification ($\mu \simeq 2$) indicates A2744_YD4 has a stellar mass of $\sim 2\times10^9$ $M_\odot$, a star formation rate of ~ 20 $M_\odot$/yr and a dust mass of $\sim6\times10^6$ $M_\odot$. We discuss the implications of the formation of such a dust mass only $\simeq$200 Myr after the onset of cosmic reionisation.

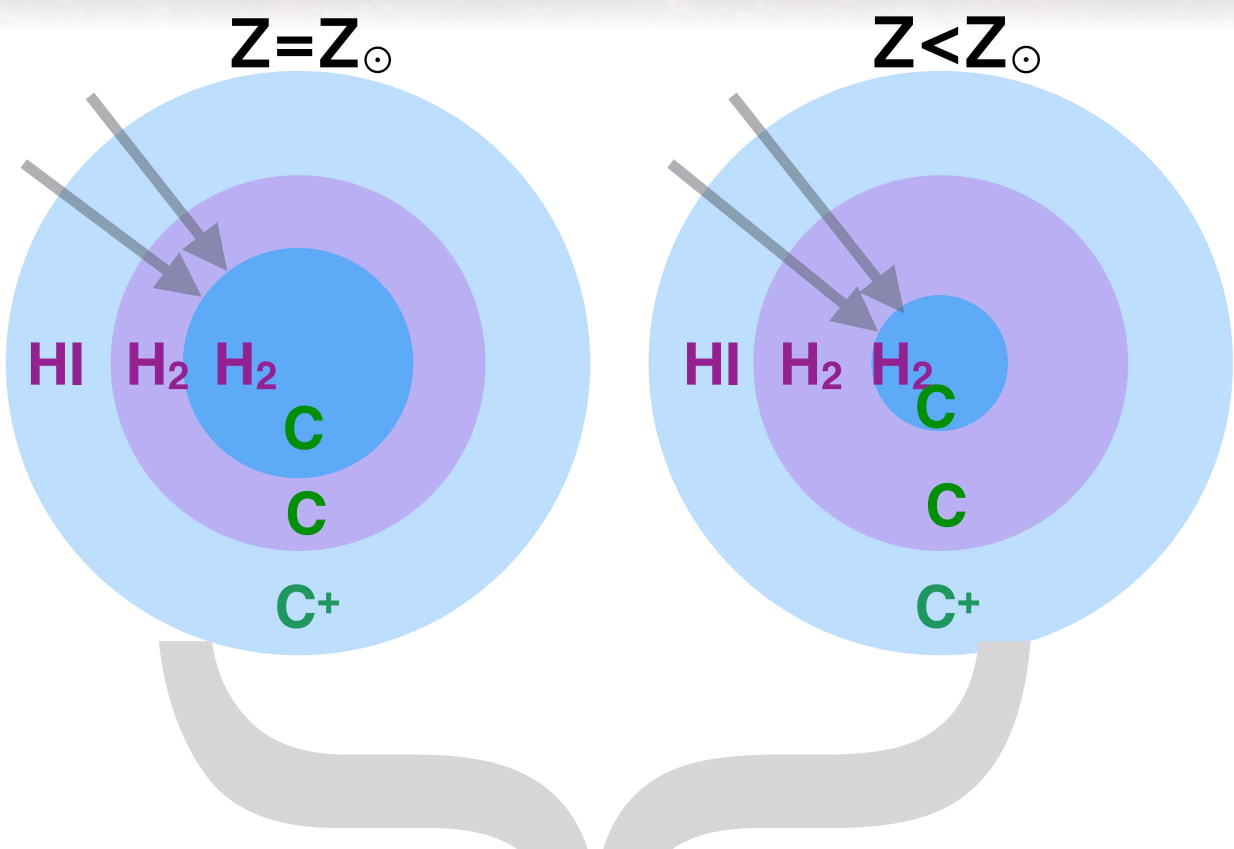
Technical challenge: How do we move forward and explore low mass and/or high redshift galaxies?



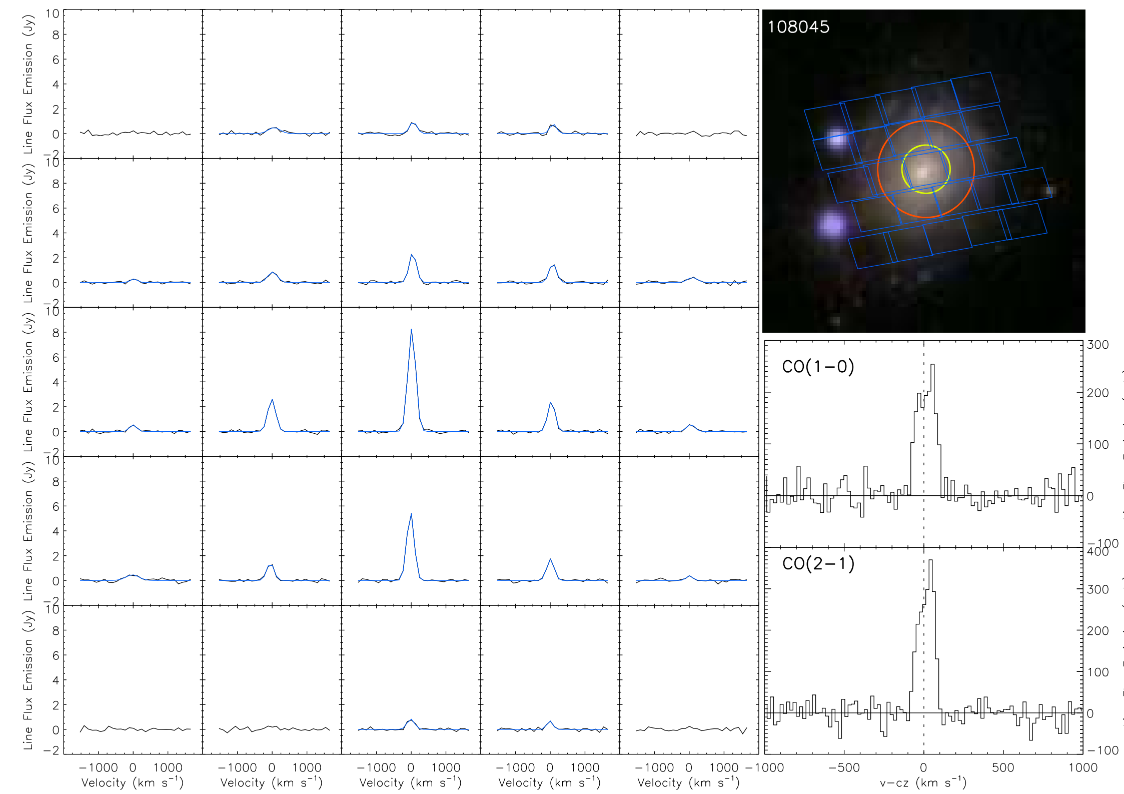
M51 EMPIRE *(Bigiel et al. 2016). Maps integrated from Pety et al. (2013).*



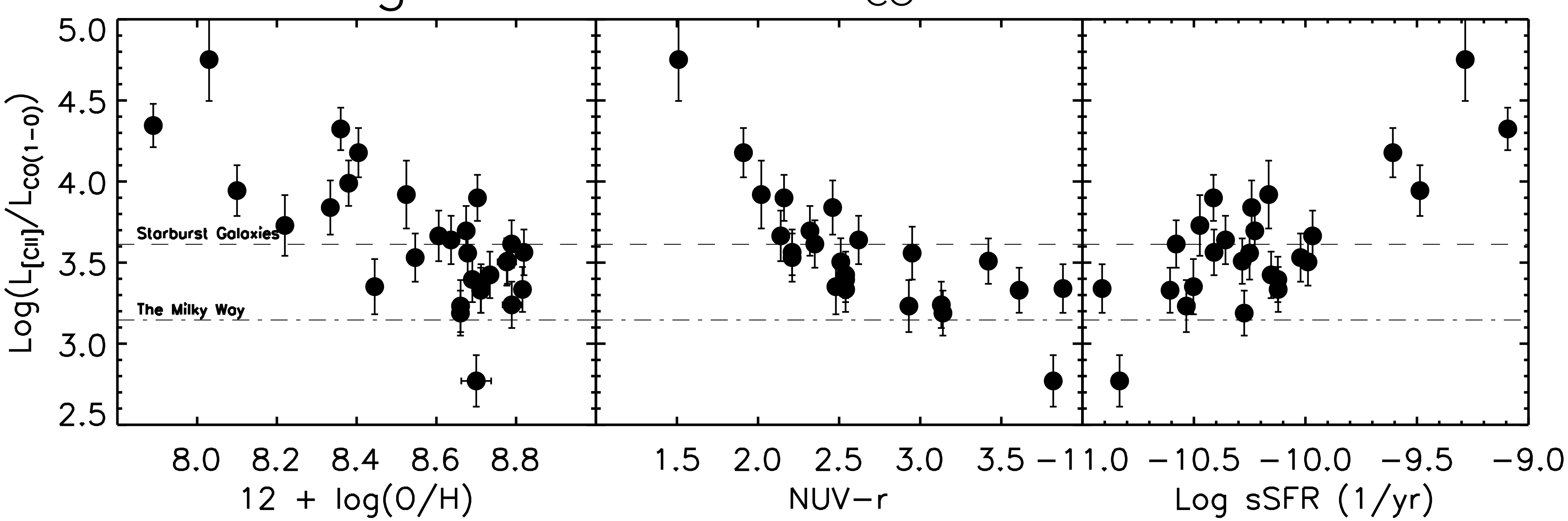
Technical challenge: How do we increase the accuracy of molecular gas measurements?



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

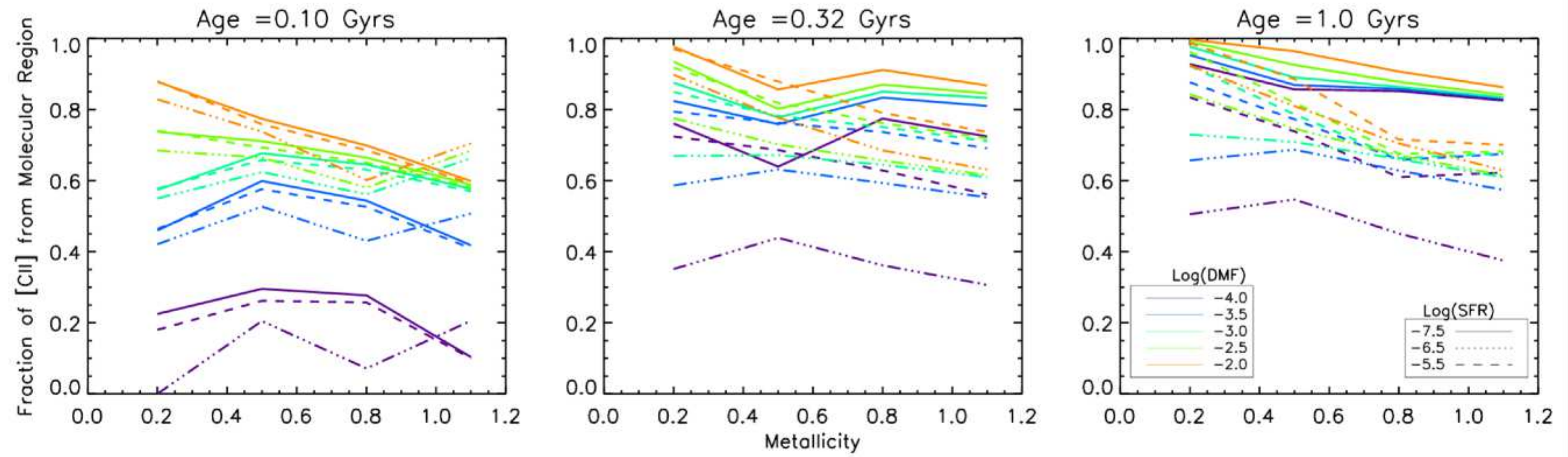


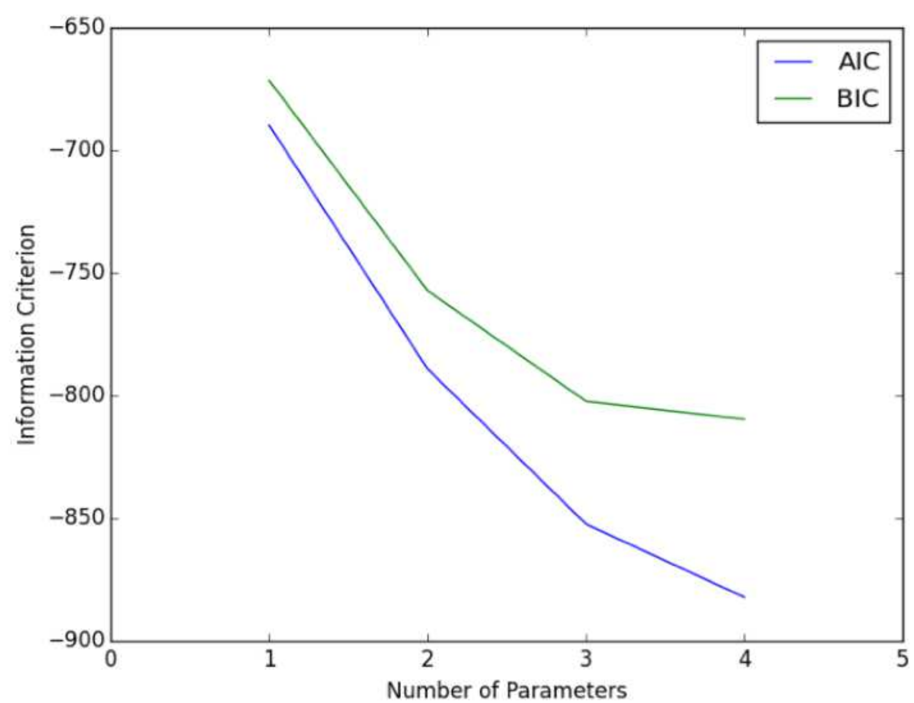
Where does [CII] emission come from?

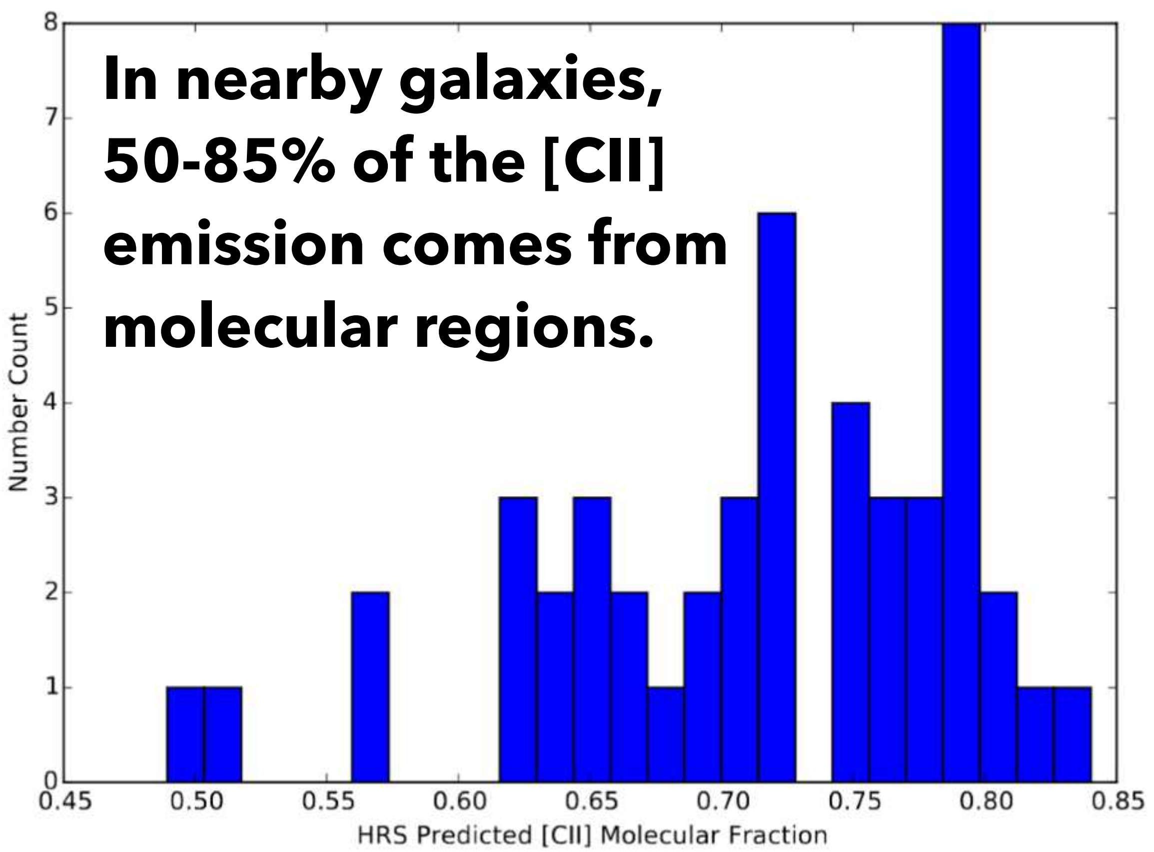
Bayesian information criterion used to determine the parameters required to predict the [CII] "molecular fraction"

Key parameters:

- metallicity
- density
- dust mass fraction
- SSFR





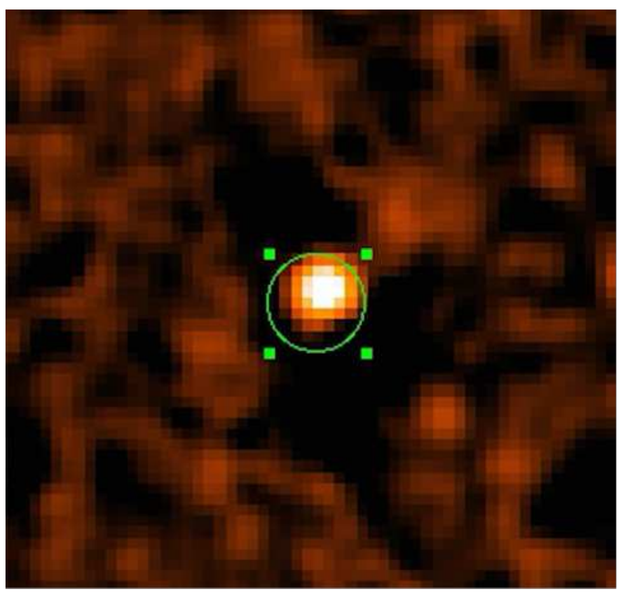


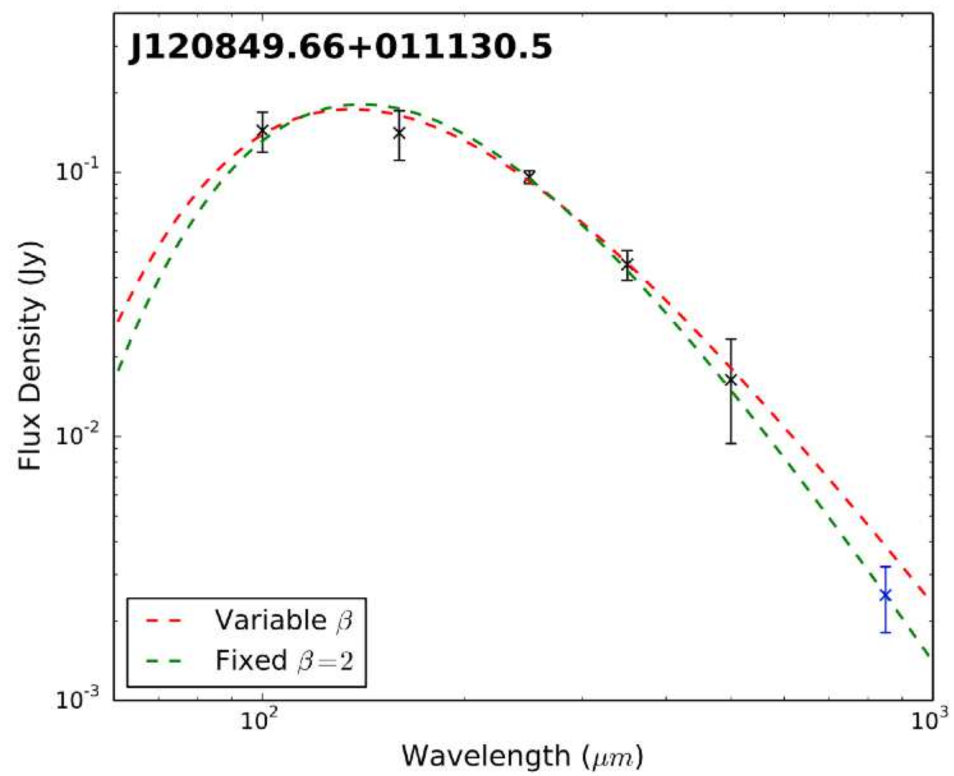
Accurso et al. (2016a)

Dust as a probe of the cold ISM

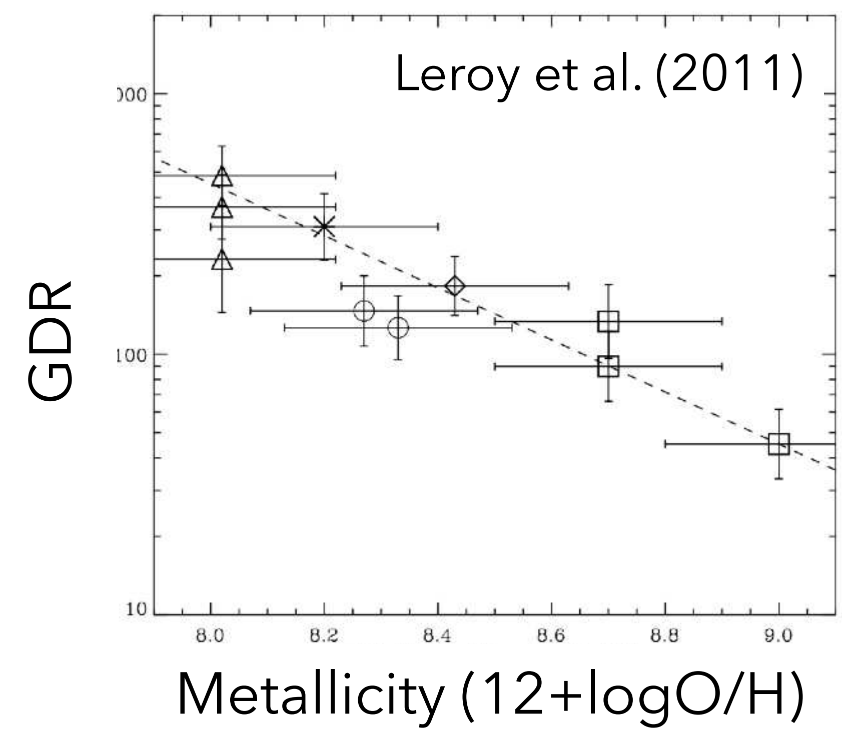
An alternative approach to CO line observations:

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





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



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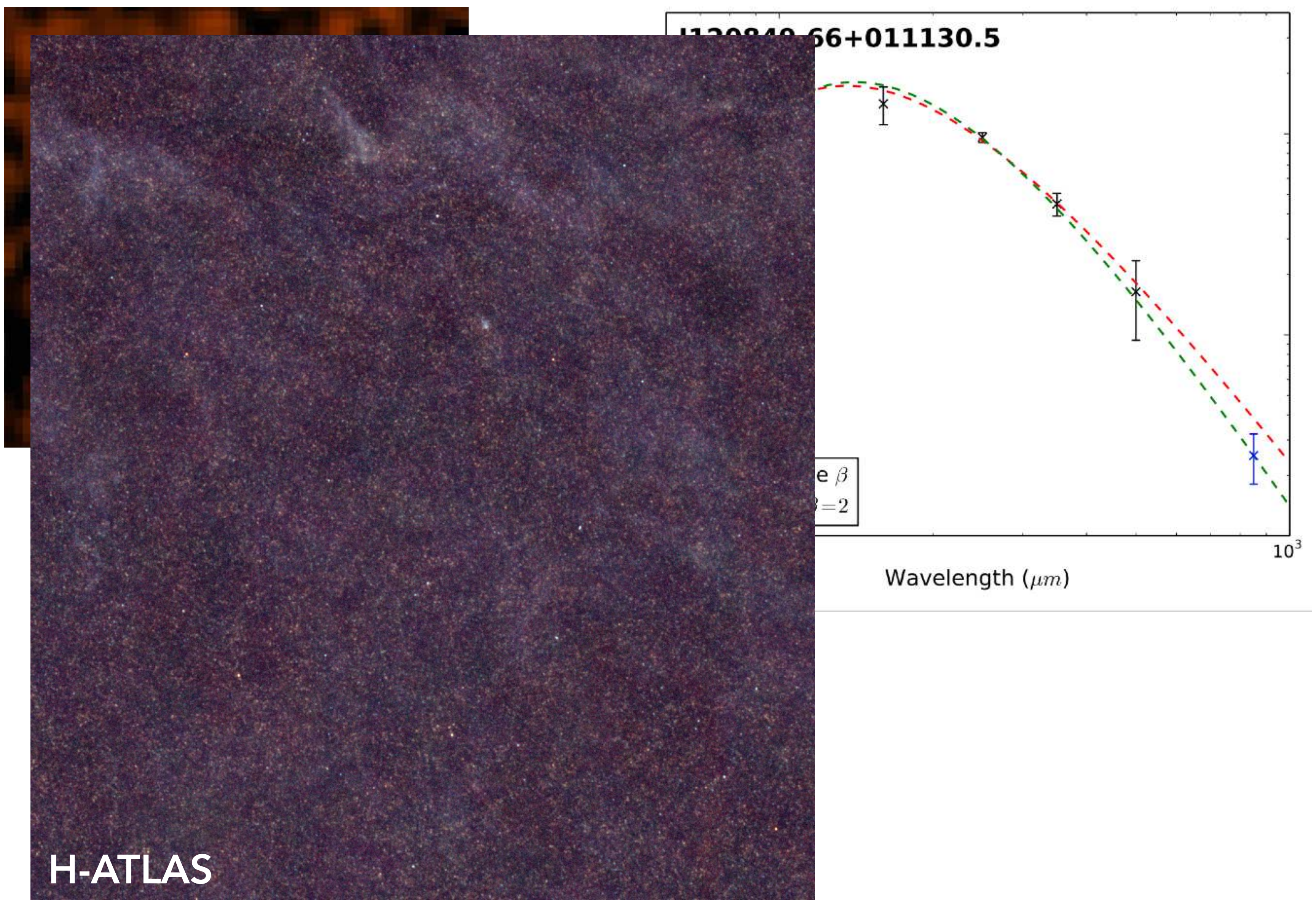

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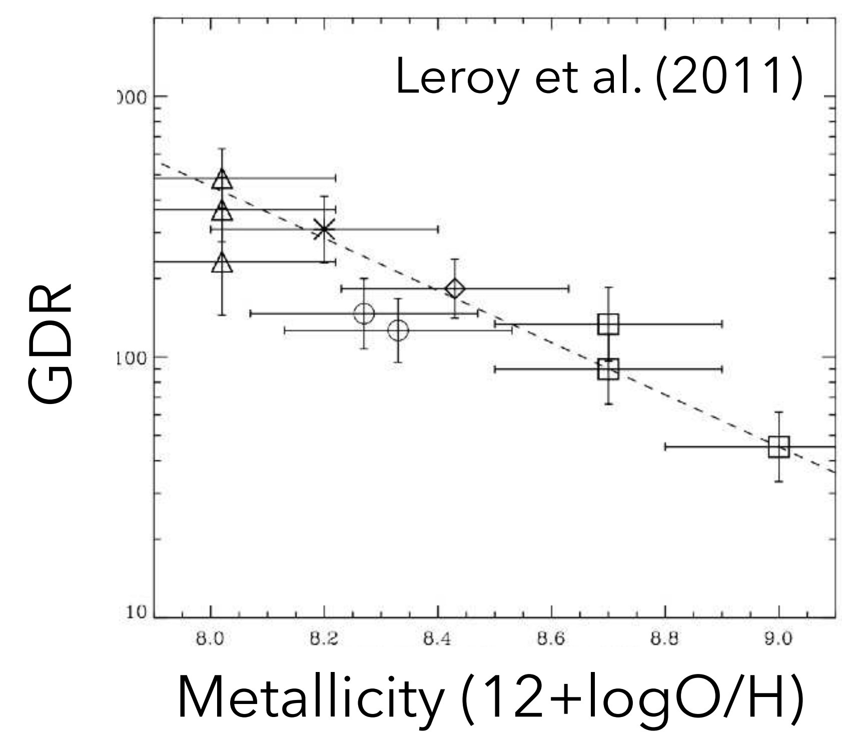

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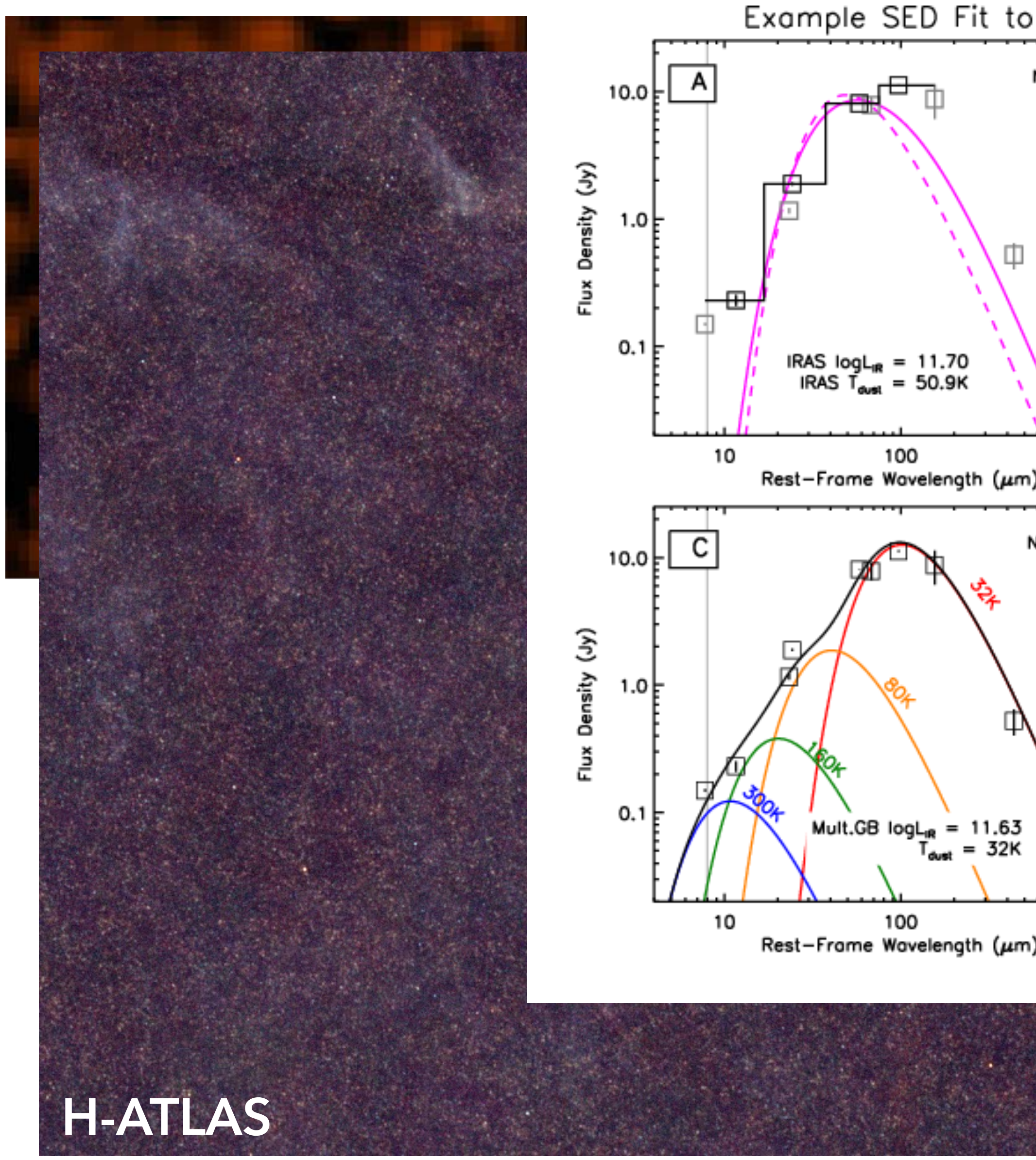
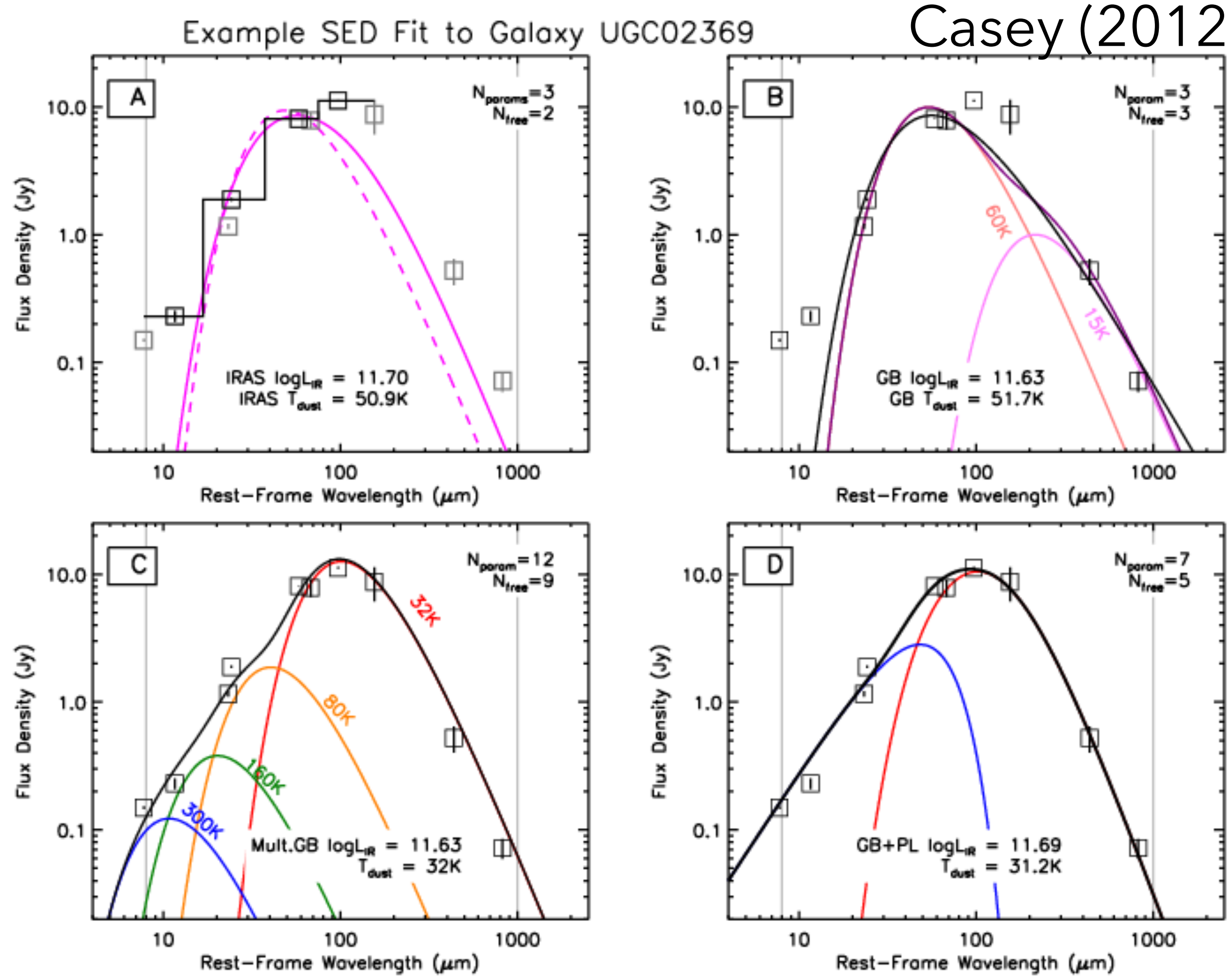
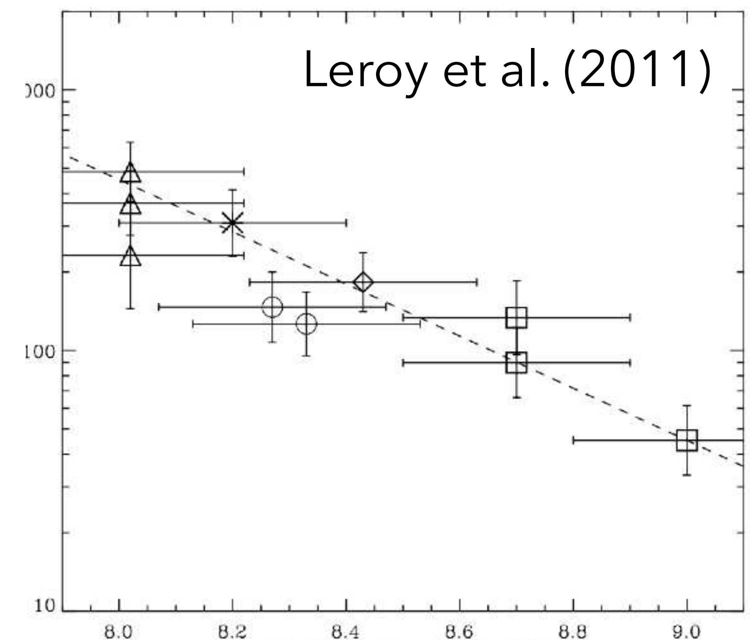




Casey (2012)

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

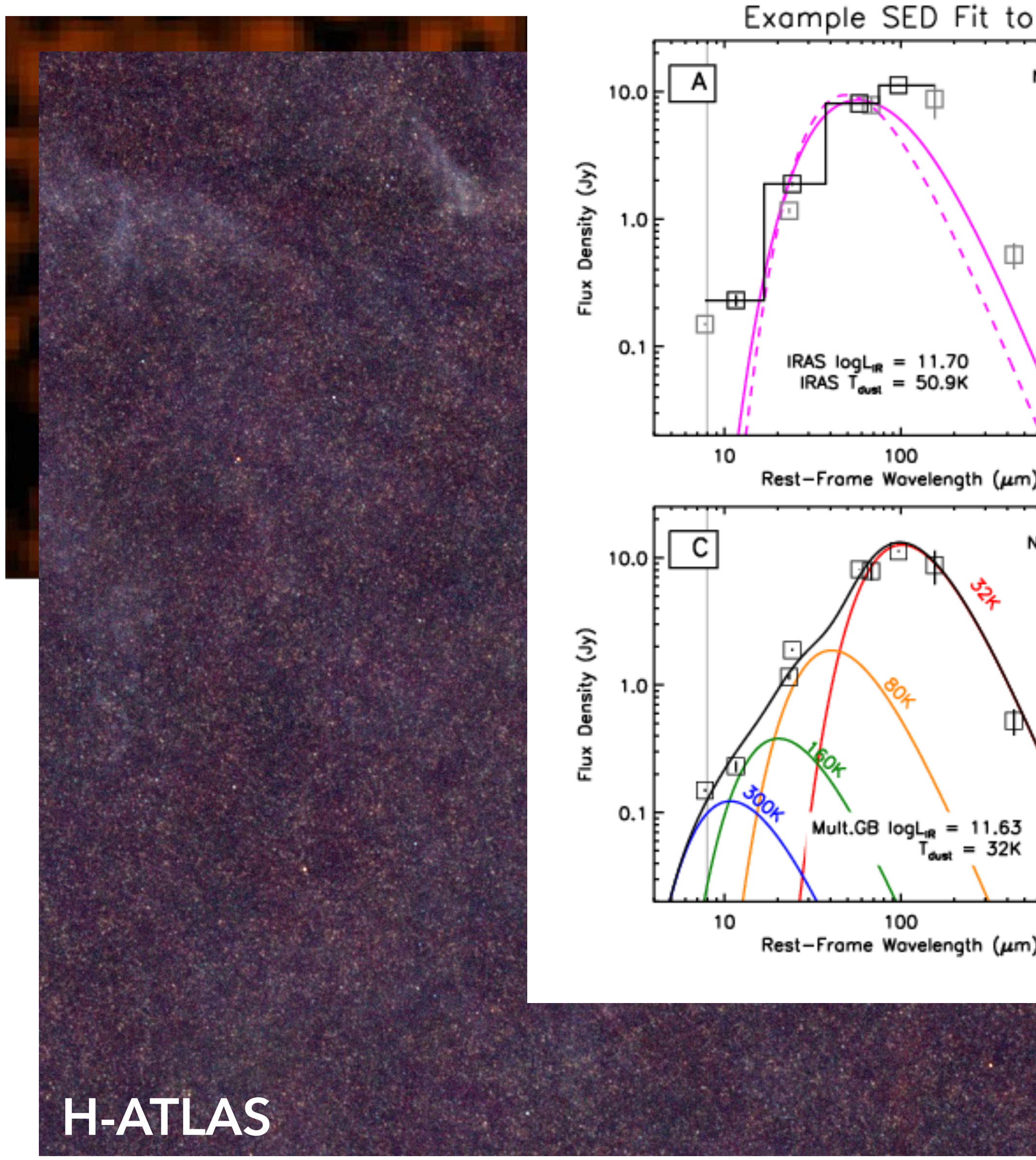


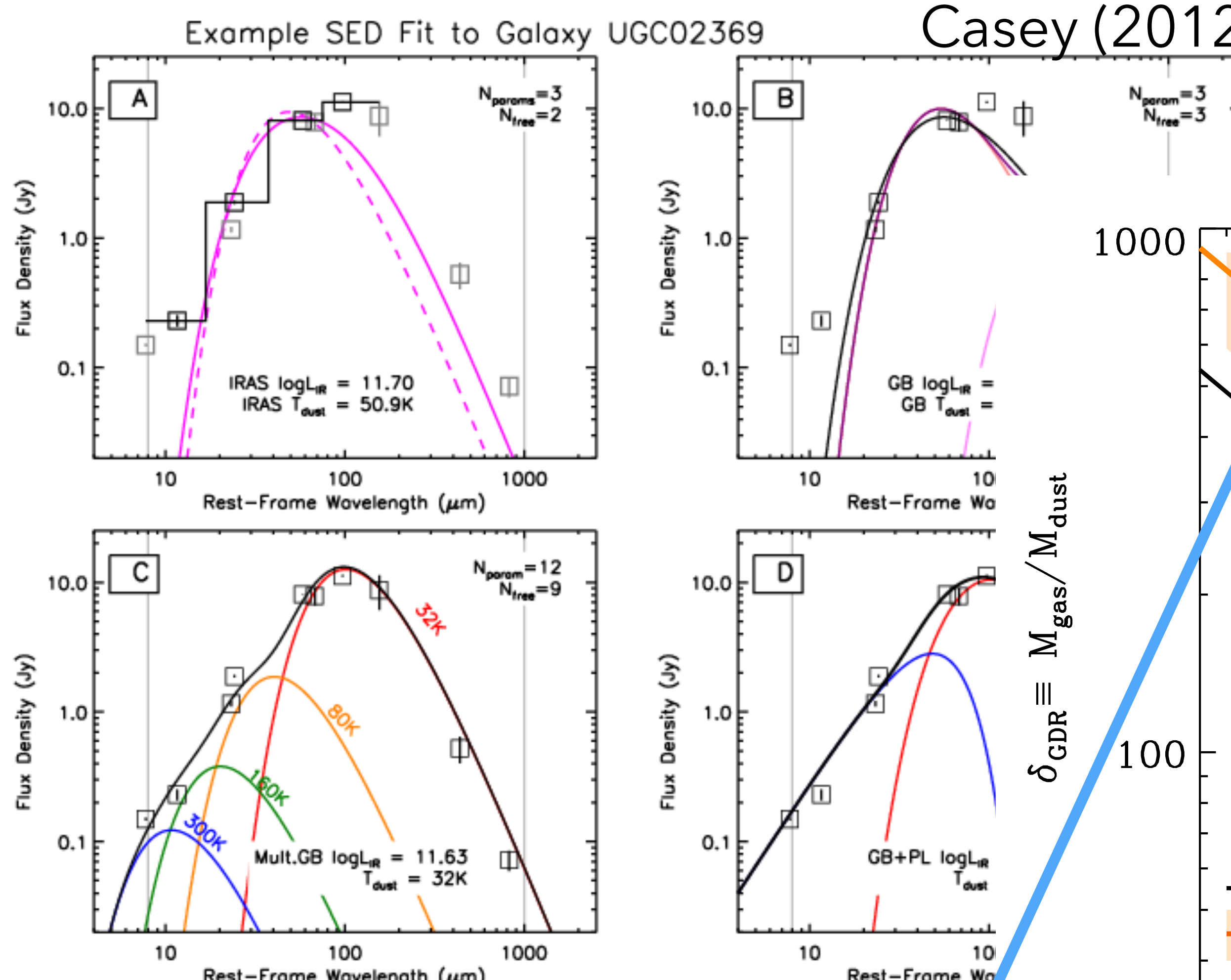
Metallicity (12+logO/H)

Dust as a probe of the cold ISM

An alternative approach to CO line observations:

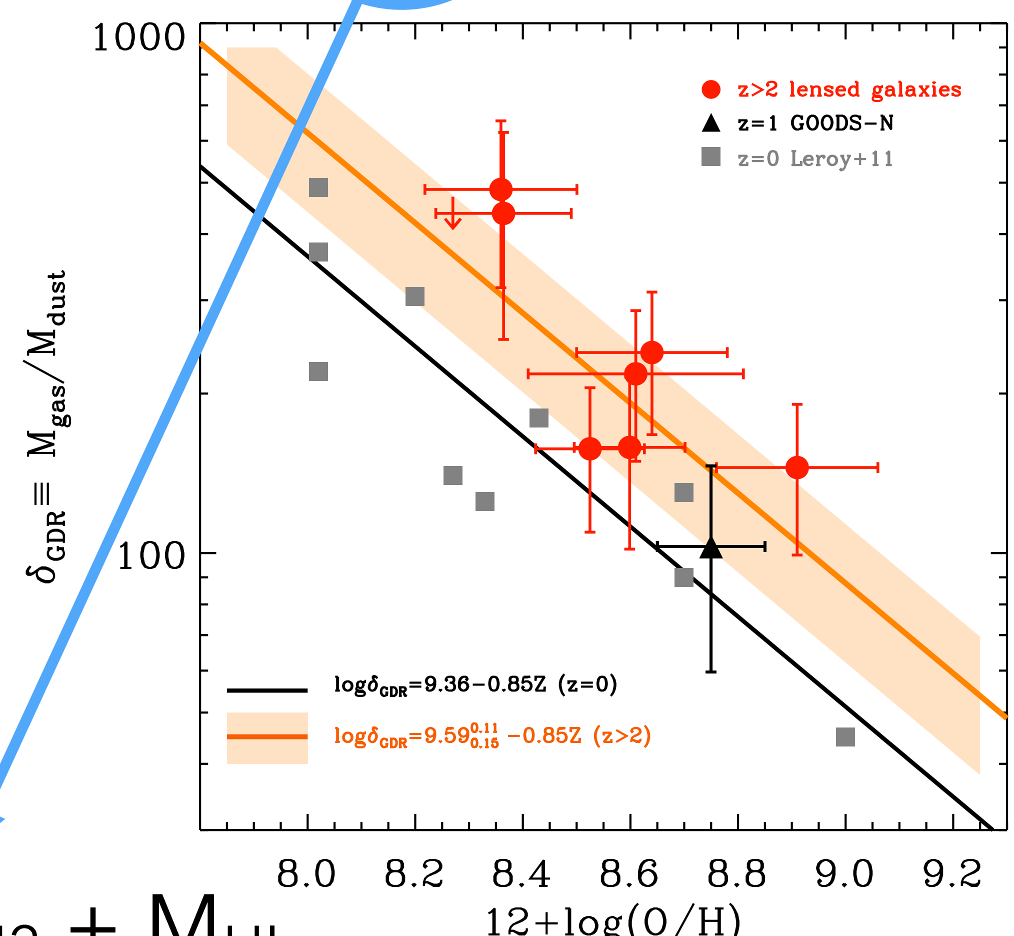
FIR/submm continuum observations → **dust mass measurements** → **gas mass estimations**





Casey (2012)

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



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

Saintonge et al. (2013)

Conclusions and outlook

Detailed studies of the cold ISM contain info about the entire galactic ecosystem, allow to sample large parameter space, and provide strong constraints for models.

z 0 1 2 3

PHANGS

High resolution ALMA imaging of a statistical sample

PI E. Schinnerer +A. Leroy

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 ?

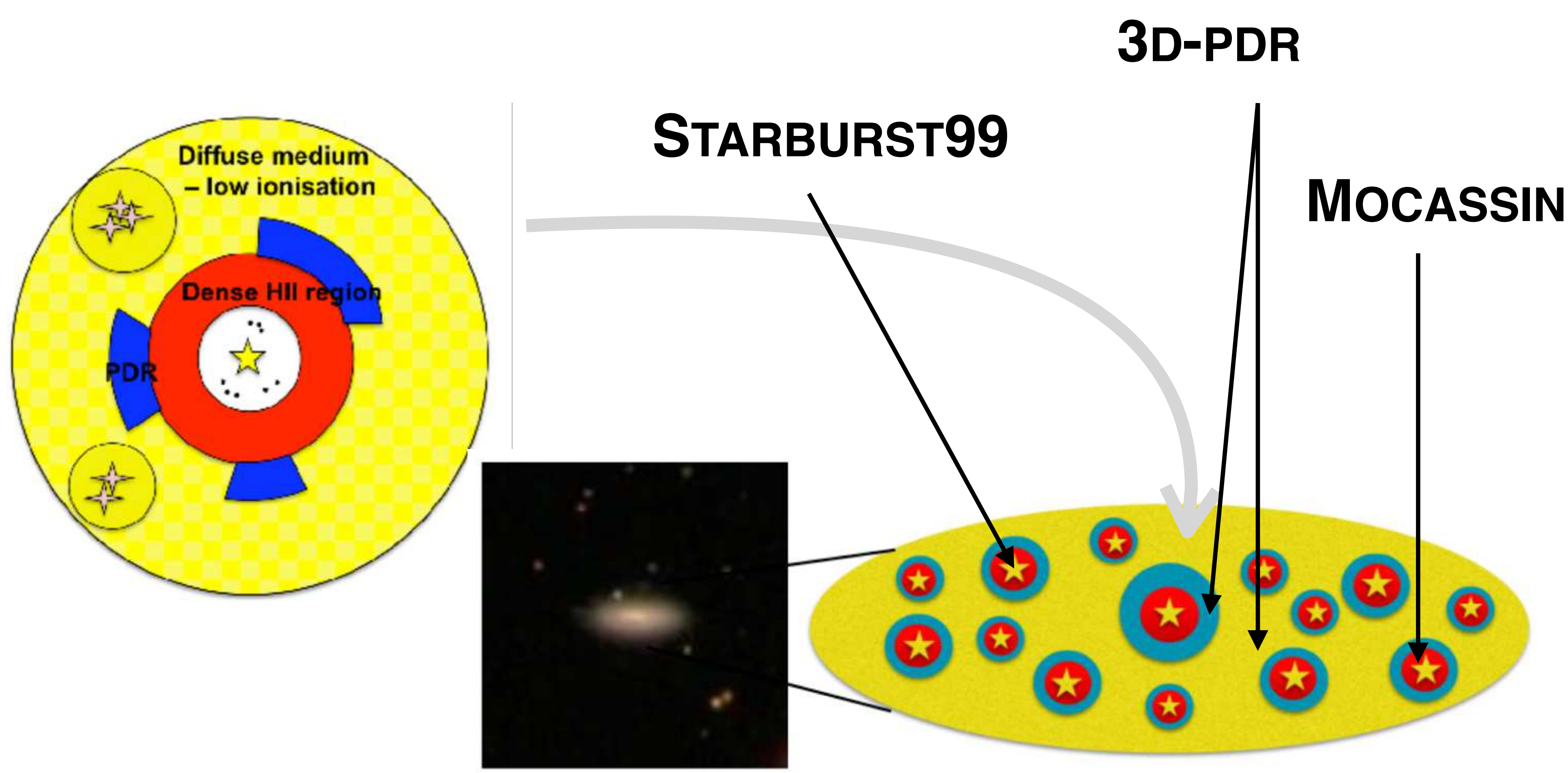
Yes, for high-res follow-up and z>2.5, but must first understand the systematics in low metallicity environments.

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

ALMA

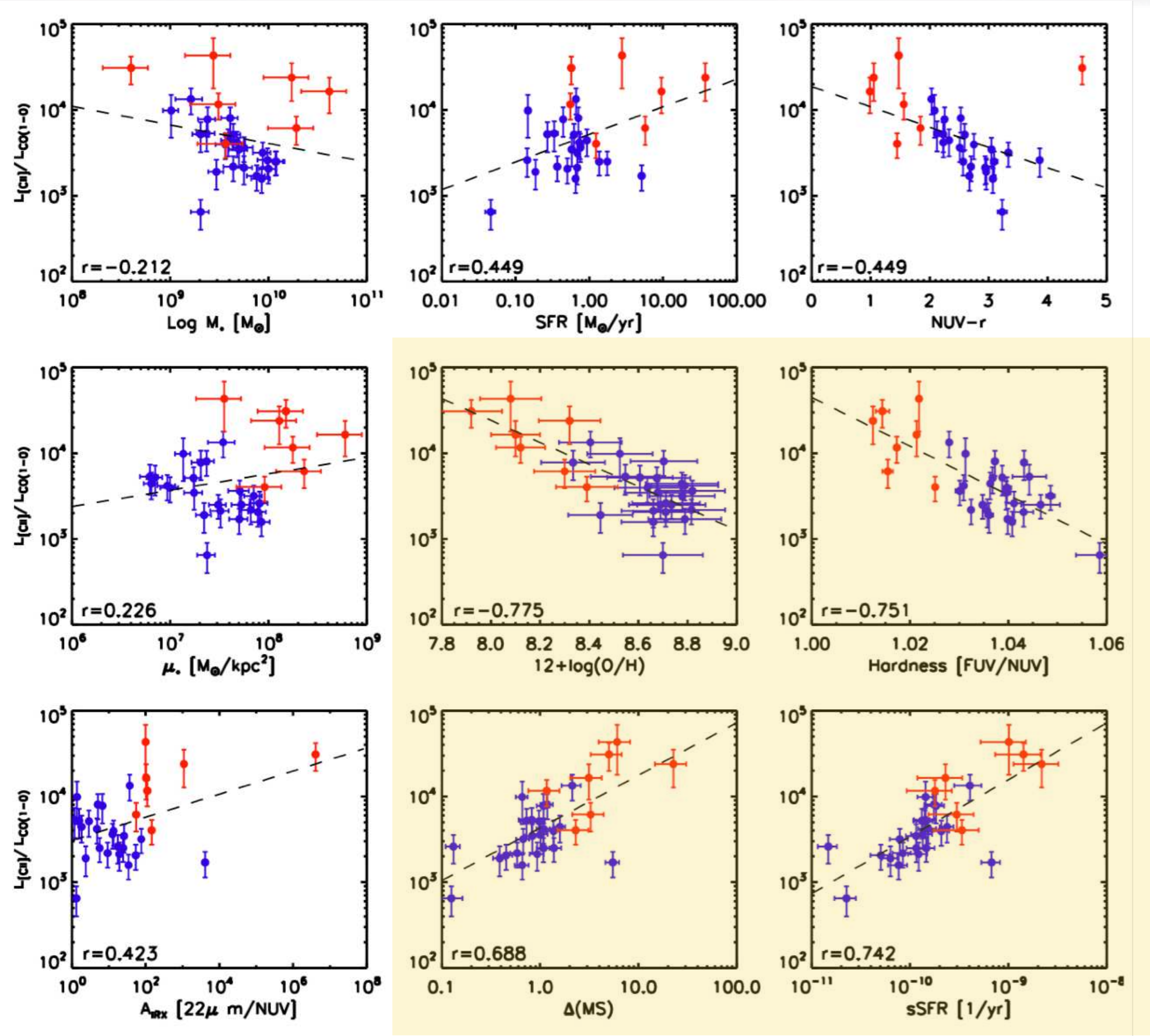
Where does [CII] emission come from?

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)



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.