Gas accretion and star formation: drivers of galaxy evolution

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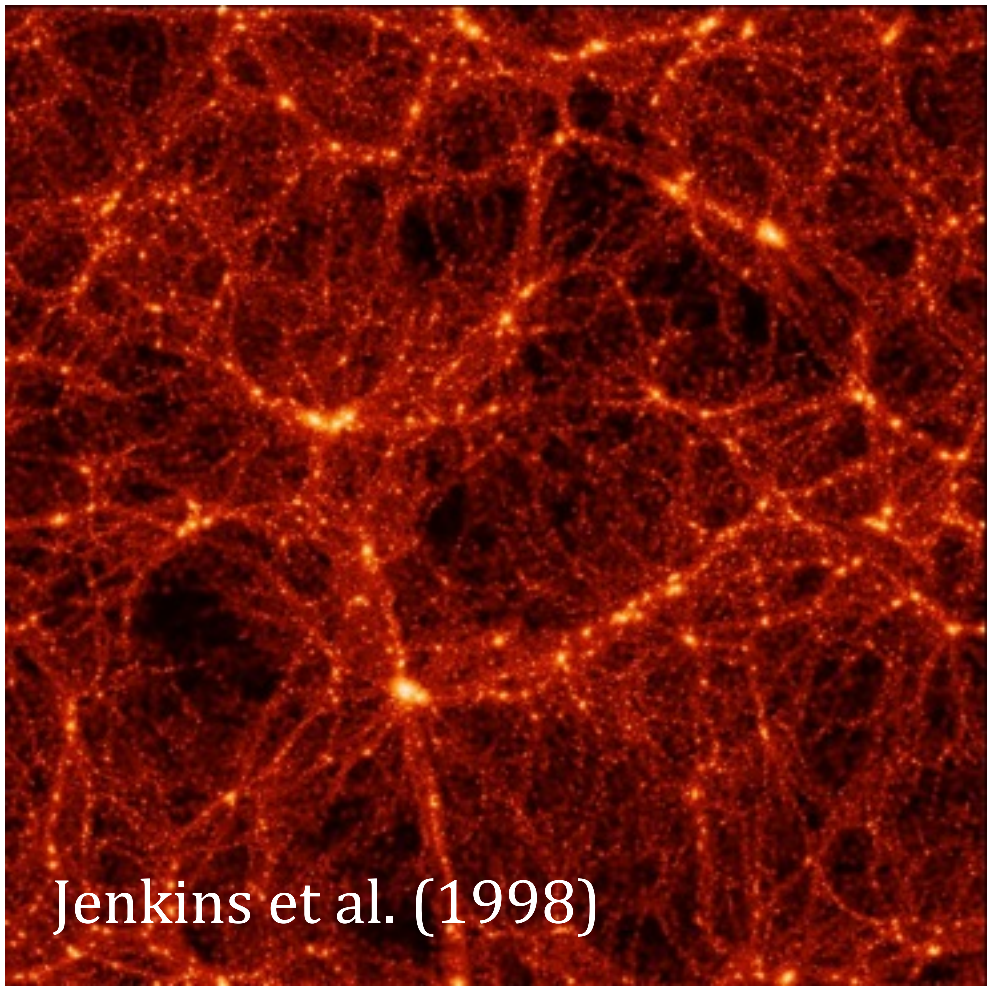
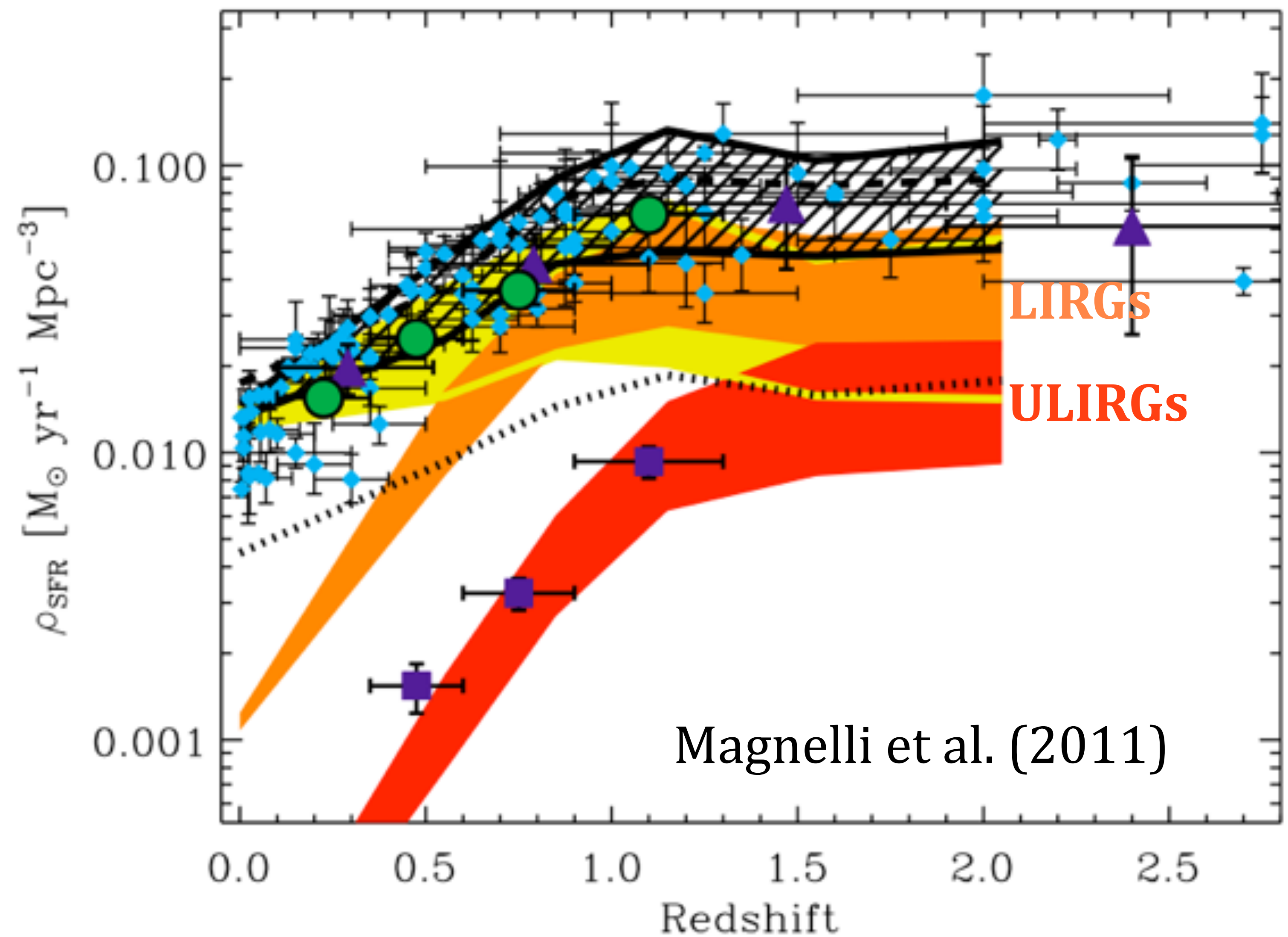
Royal Society Research Fellow

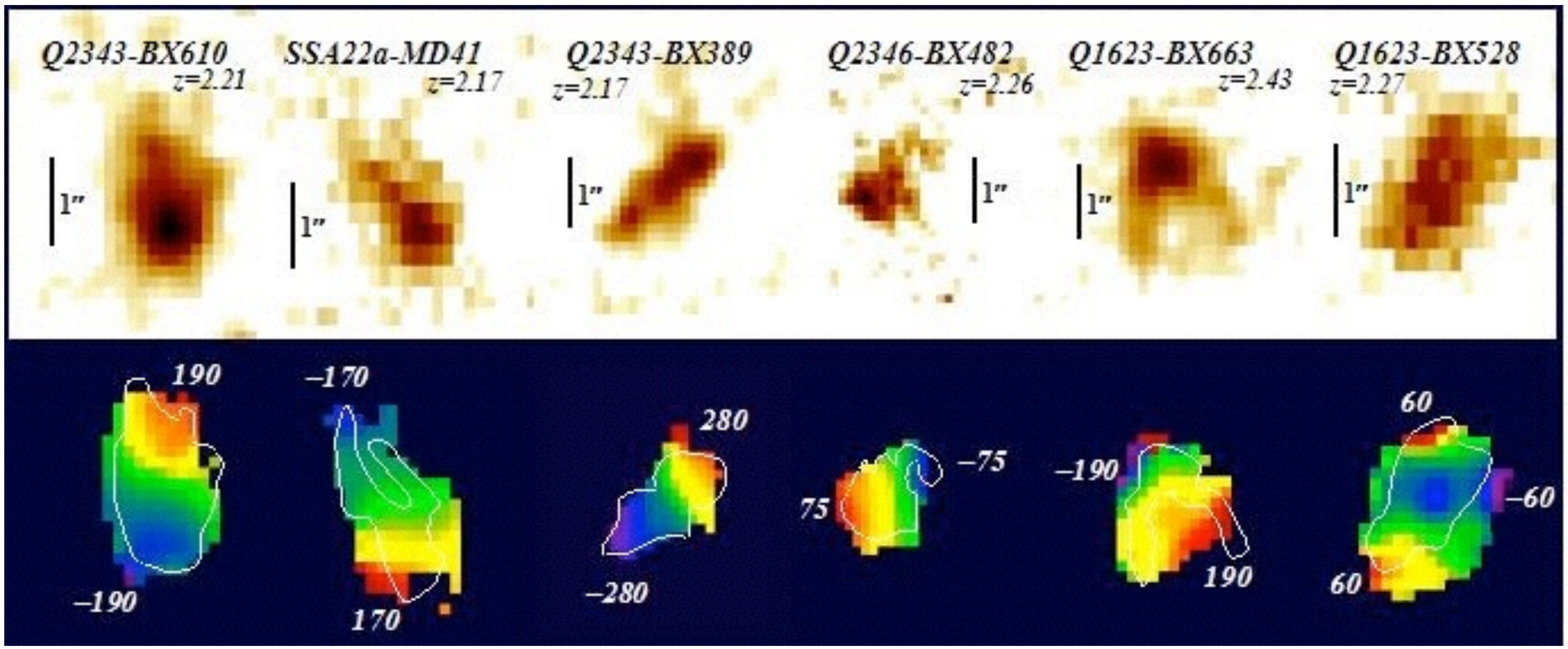
The old picture: merger-driven galaxy evolution





from mid-80s to 5-10 years ago: merging of galaxies seen as the main driver of galaxy evolution

The global picture: accretion-driven galaxy evolution



Forster Schreiber et al. (2006)

near-IR IFU work: z~2 galaxies with high SFRs are in large part well ordered discs, and not major mergers.

The global picture: accretion-driven galaxy evolution

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LETTERS

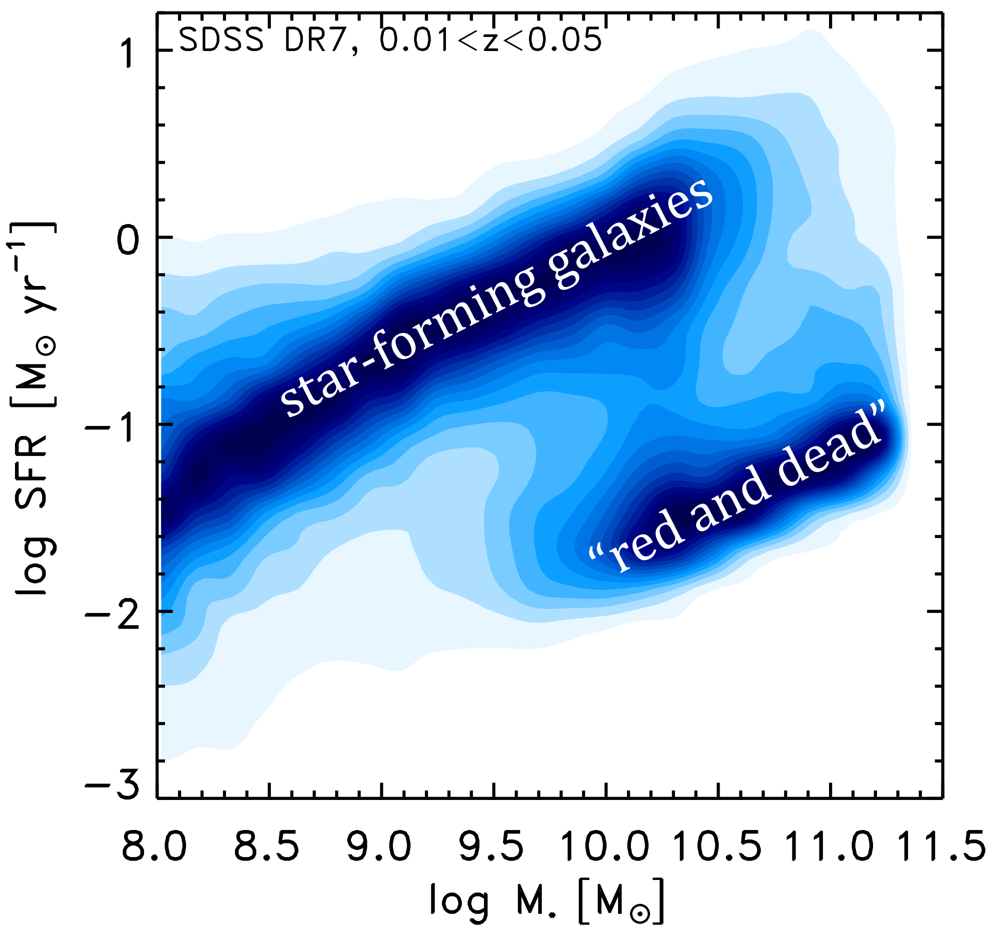
High molecular gas fractions in normal massive star-forming galaxies in the young Universe

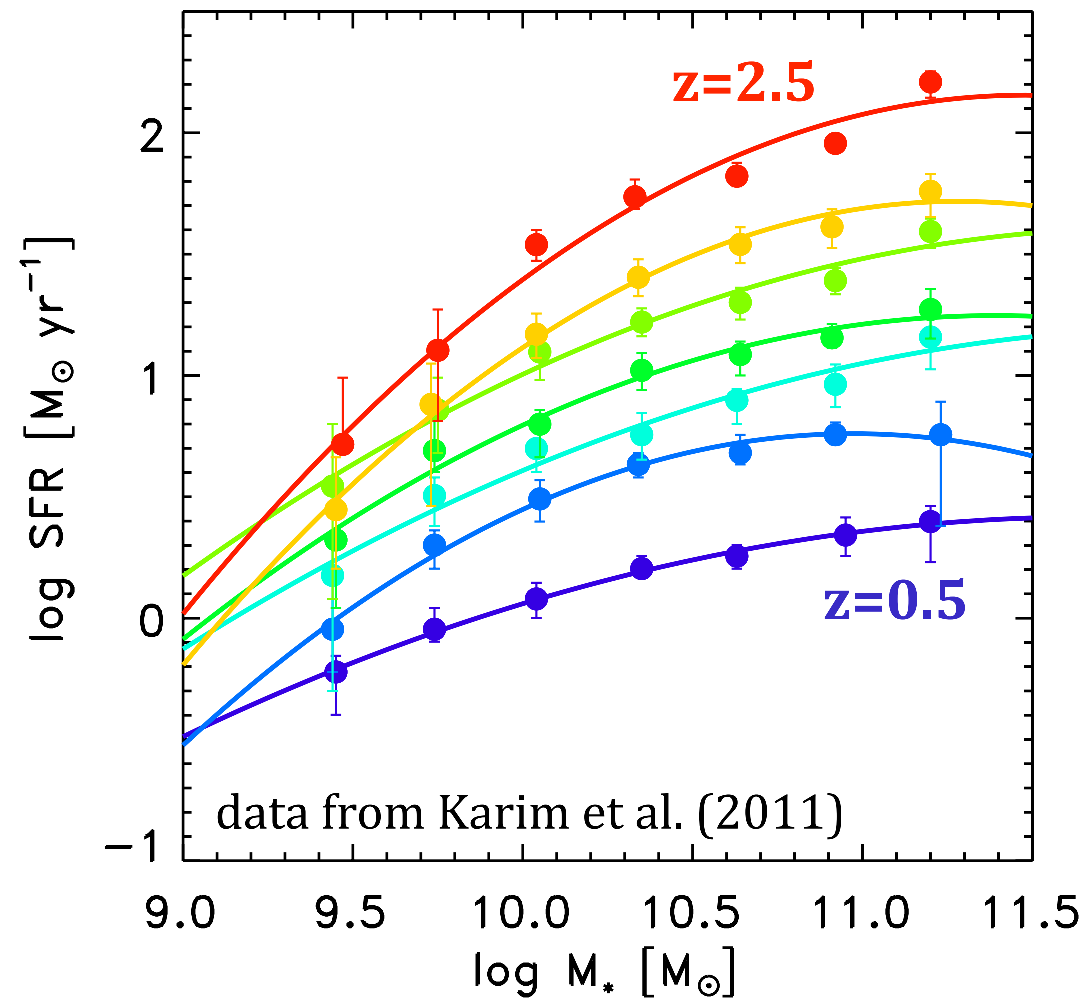
L. J. Tacconi[1], R. Genzel[1,2], R. Neri[3], P. Cox[3], M. C. Cooper[4], K. Shapiro[5], A. Bolatto[6], N. Bouché[1], F. Bournaud[7], A. Burkert[8], F. Combes[9], J. Comerford[5], M. Davis[5], N. M. Förster Schreiber[1], S. Garcia-Burillo[10], J. Gracia-Carpio[1], D. Lutz[1], T. Naab[8], A. Omont[11],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

mm work: z~2 galaxies with high SFRs have significantly more gas than counterparts in the local Universe!

accretion-driven galaxy evolution

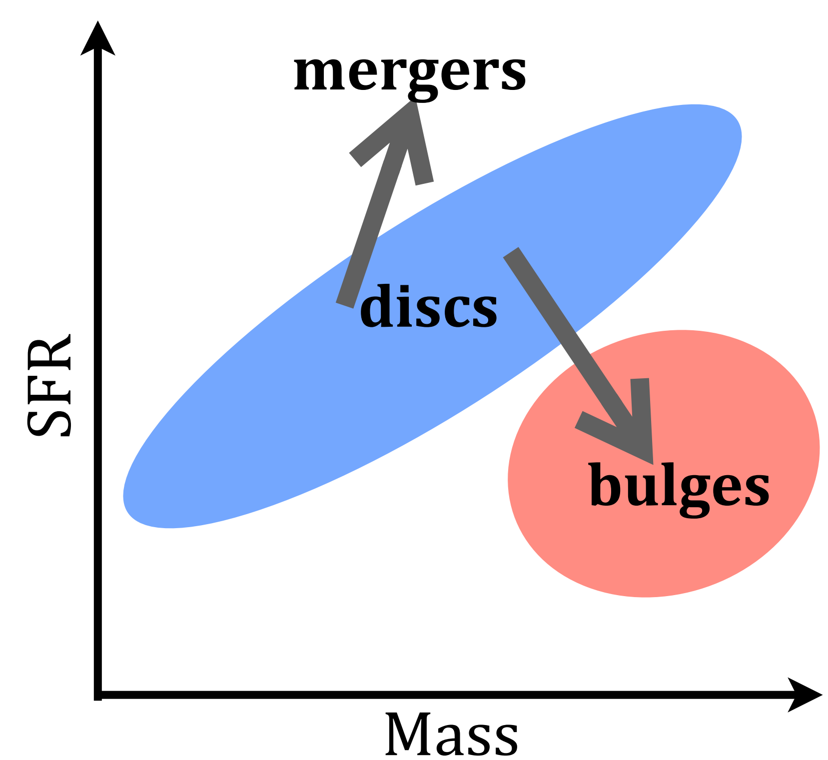
the star formation "main sequence"
see e.g.: Schiminovich et al. (2007), Elbaz et al. (2007), Noeske et al. (2007), Daddi et al. (2007), Perez-Gonzalez et al. (2008), Peng et al. (2010)





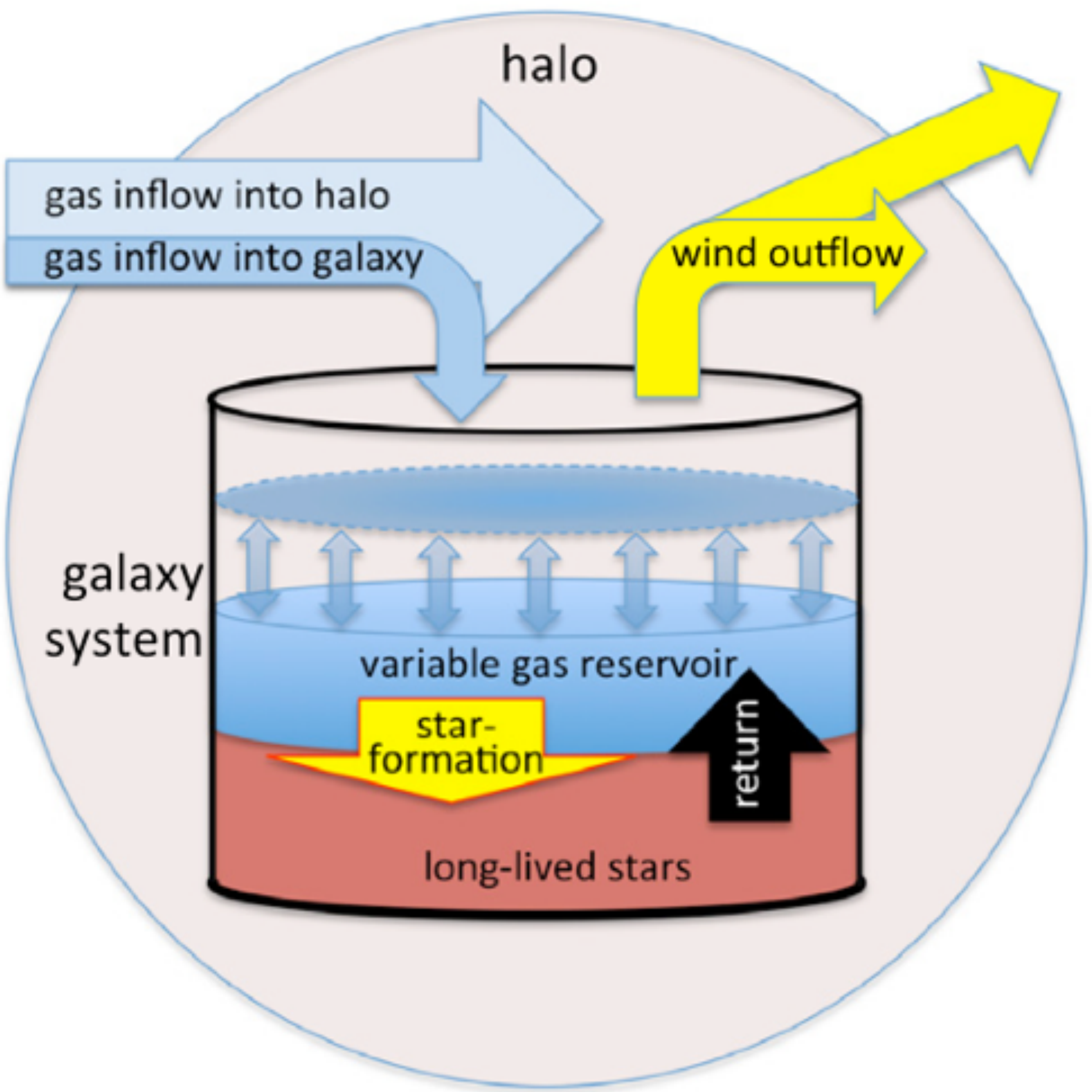
SFR ~ $M_*^a(1+z)^b$, where a~0.8, b~2.5

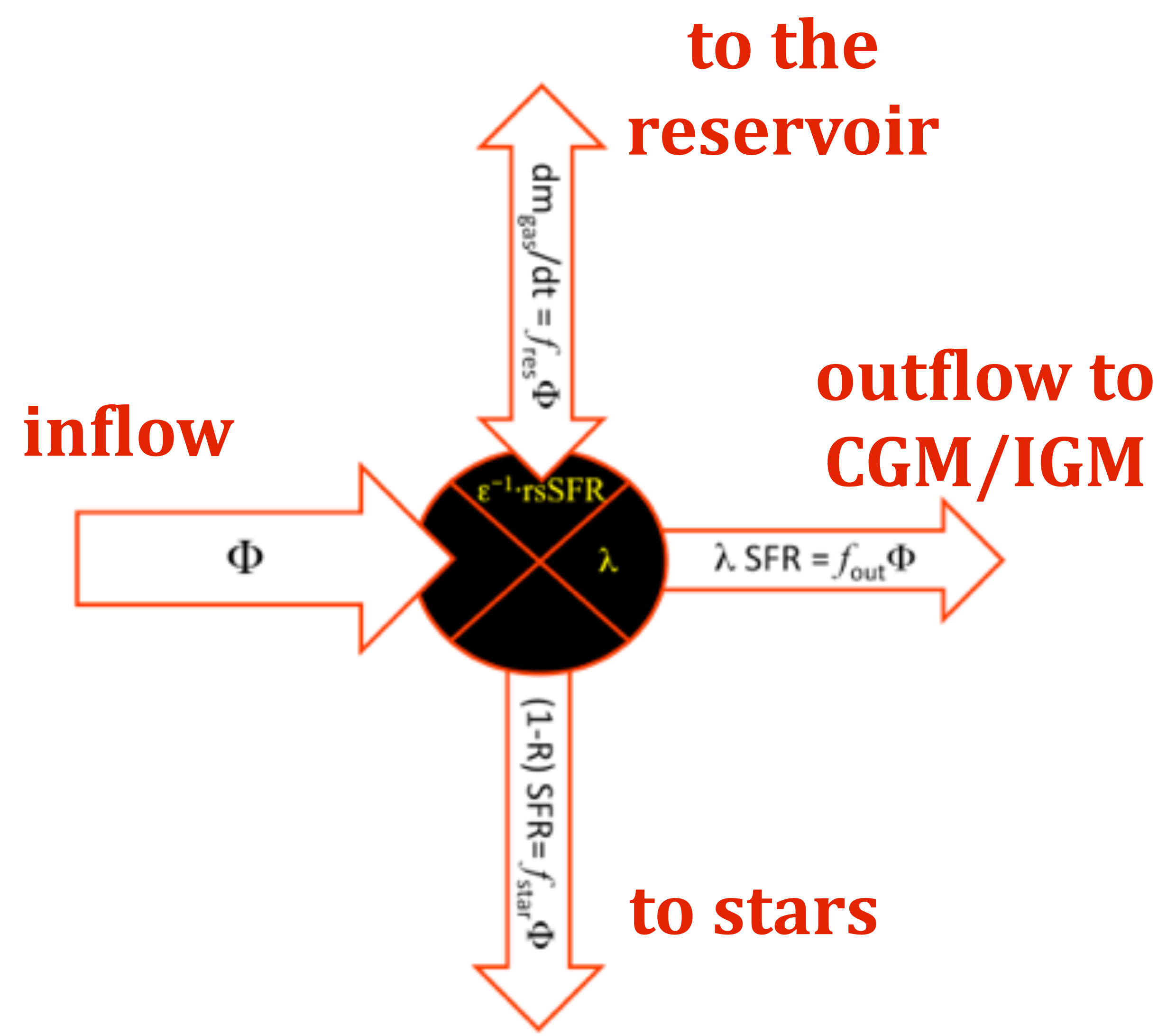
- Galaxies on the main sequence (MS) contribute ~90% of the star formation.
- Duty cycles on the MS are high at 40-70% (e.g. Noeske et al. 2007)



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)

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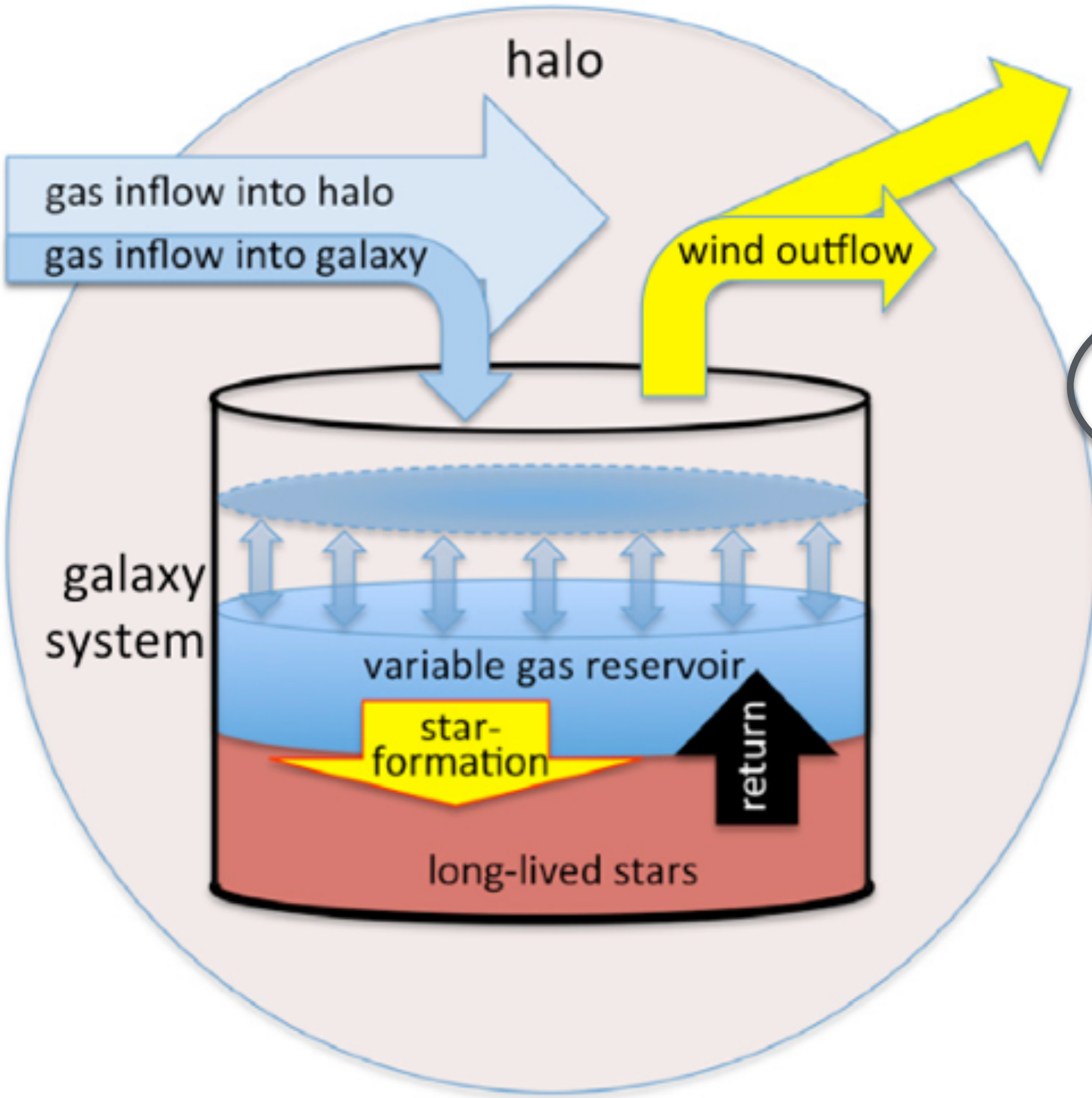

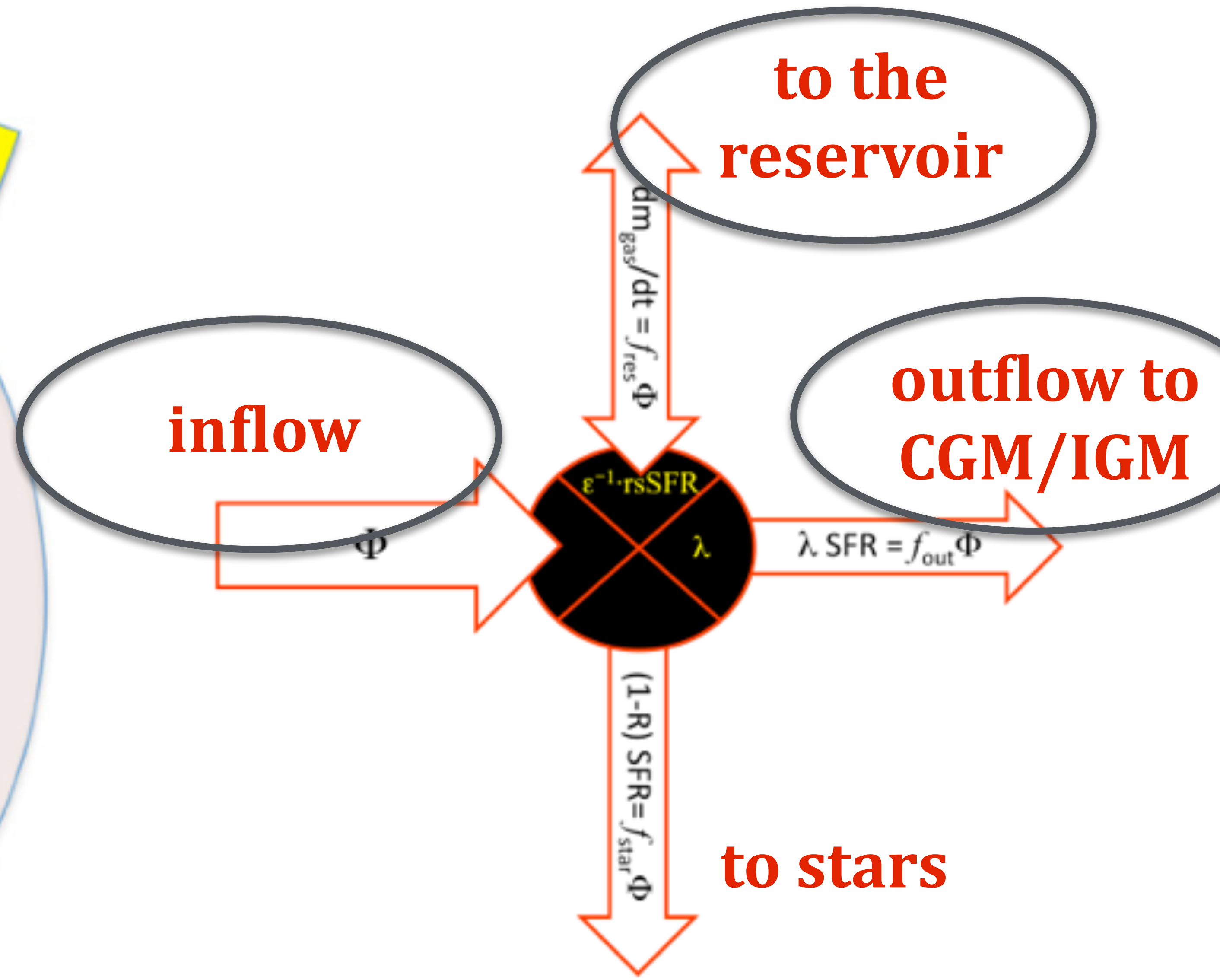

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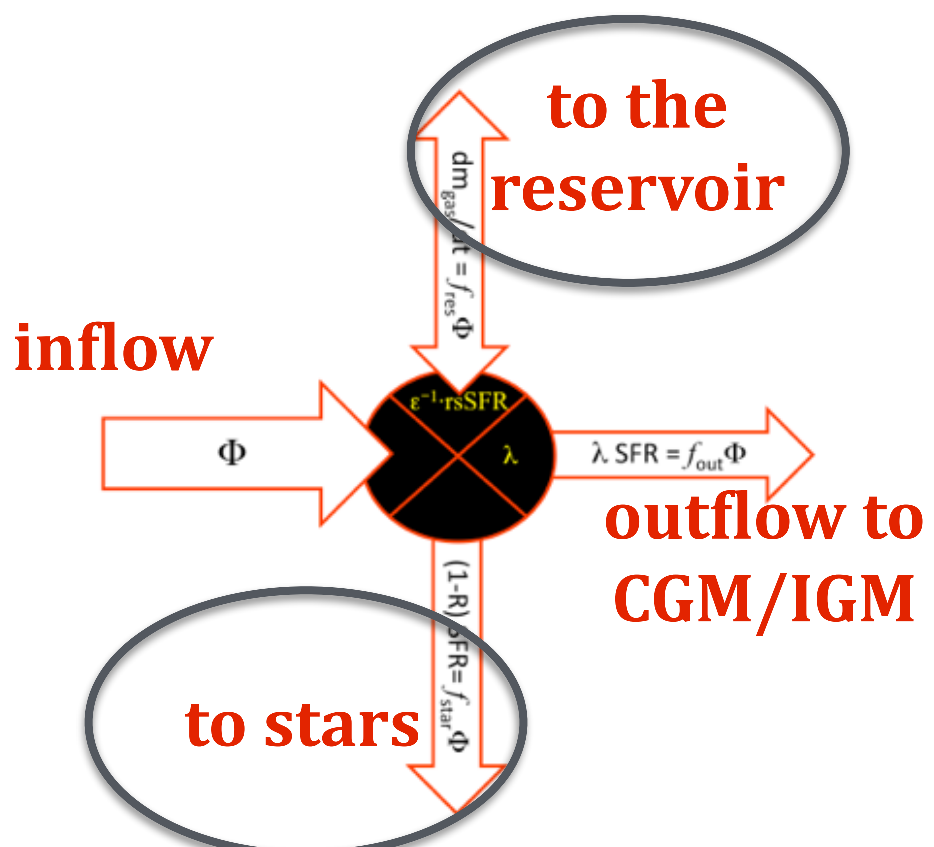
(1) Star formation efficiency, the gas reservoir and its redshift evolution



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)
600h IRAM 30-m Large Programme
+1000h Arecibo Programme for HI

365 SDSS-selected galaxies with
$0.025<z<0.050$, $M^*>10^{10}$
see Saintonge et al. 2011a,b, Kauffmann et al. 2012, Saintonge et al. 2012.

PHIBSS

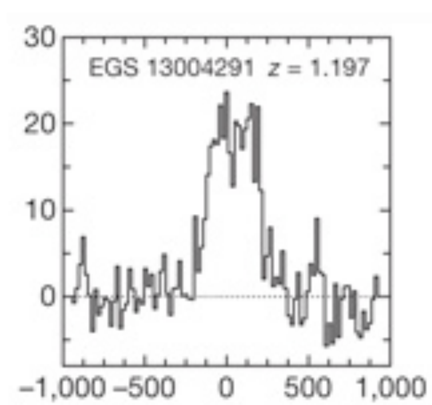
PIs L. Tacconi, R. Genzel (MPE), F. Combes (Paris)
500h IRAM PdBI Large Programmes

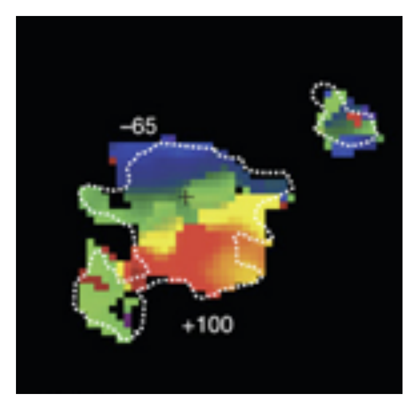
64 star forming galaxies with
$1.0<z<2.5$, $3\times10^{10}<M^*<3\times10^{11}$
+ high-resolution follow-up
see Tacconi et al. 2010,2013, Genzel et al. 2010,2012,2013, Freundlich et al. 2013.

Lensed galaxies

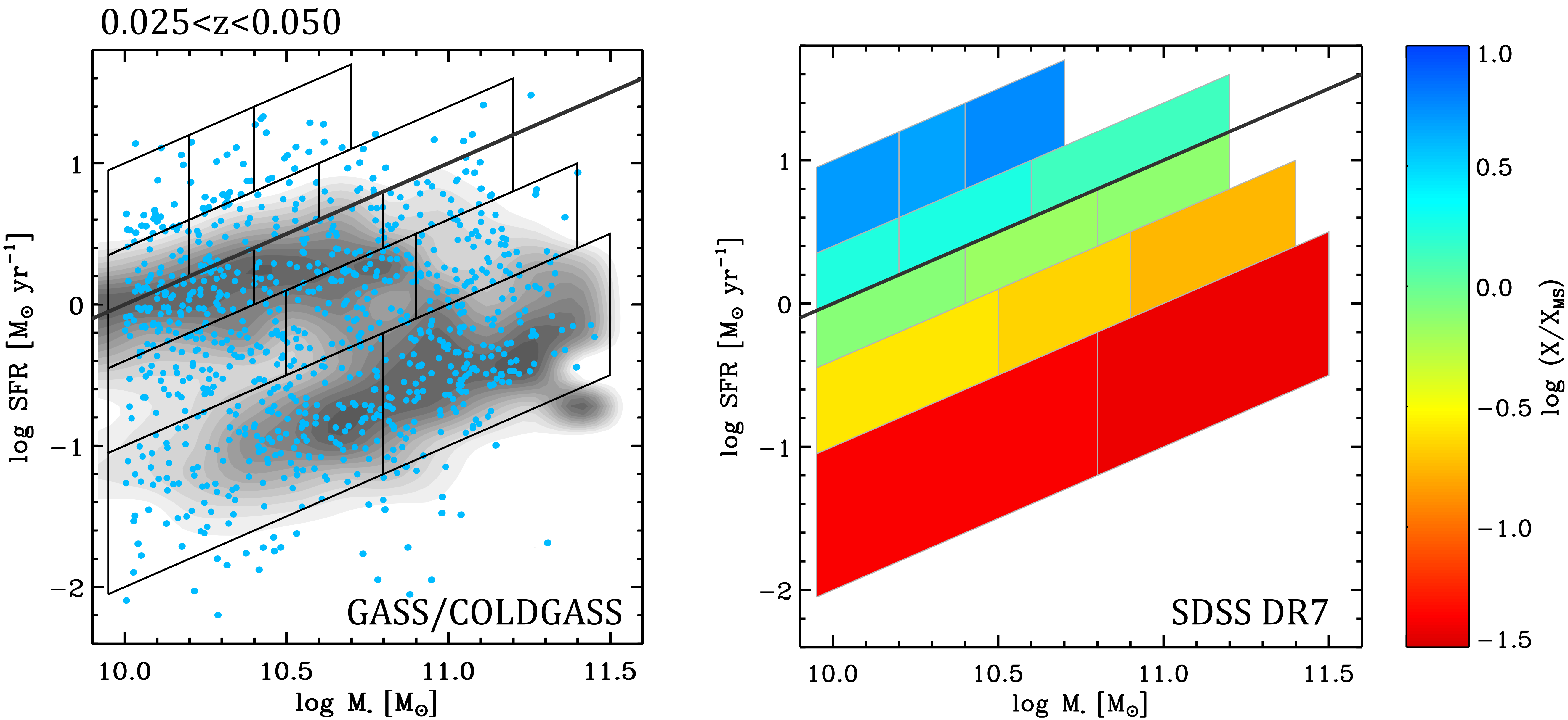
PI D. Lutz (MPE), A. Baker (Rutgers)
IRAM PdBI

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





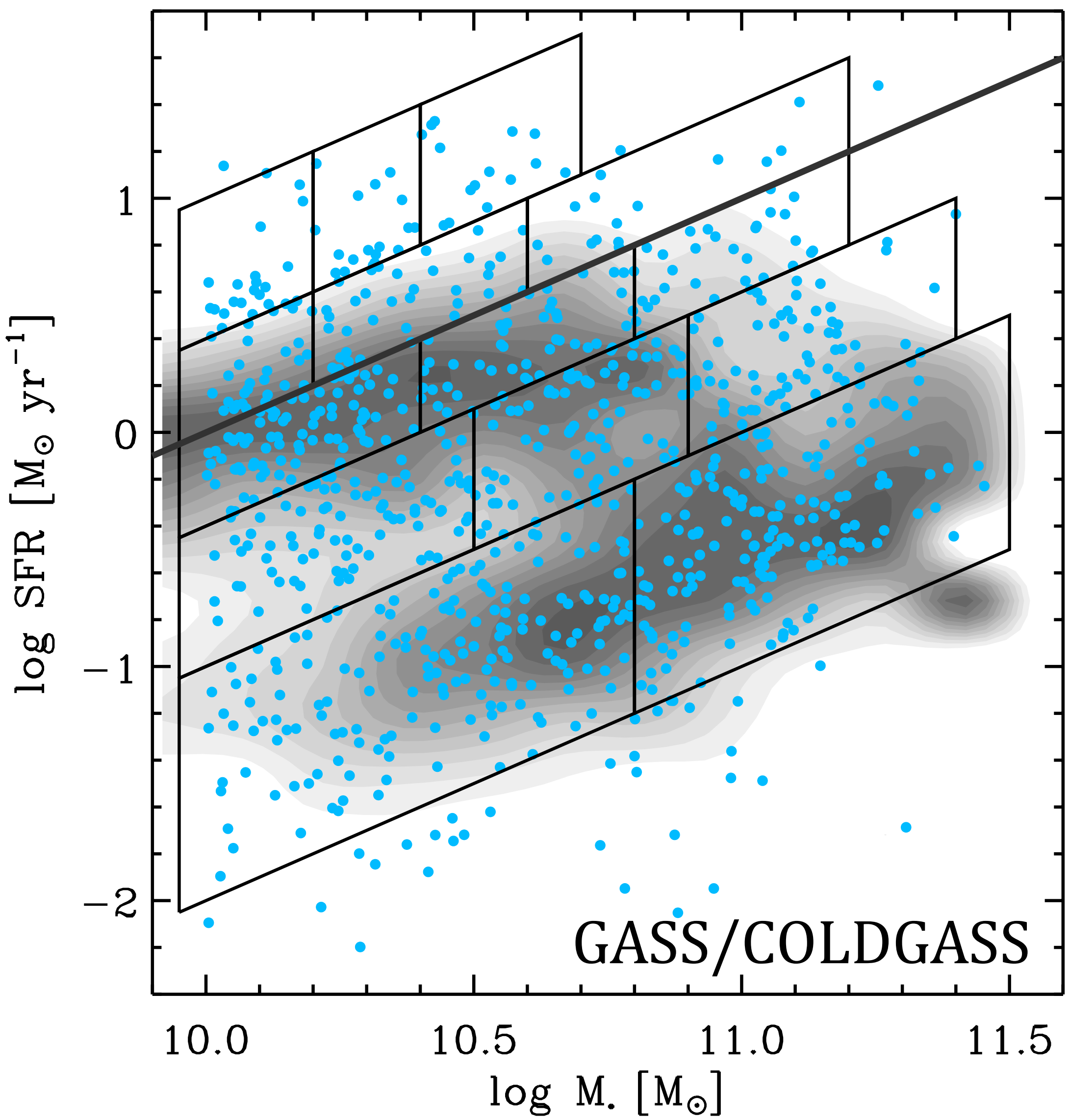
Cold gas in the SFR-M* plane

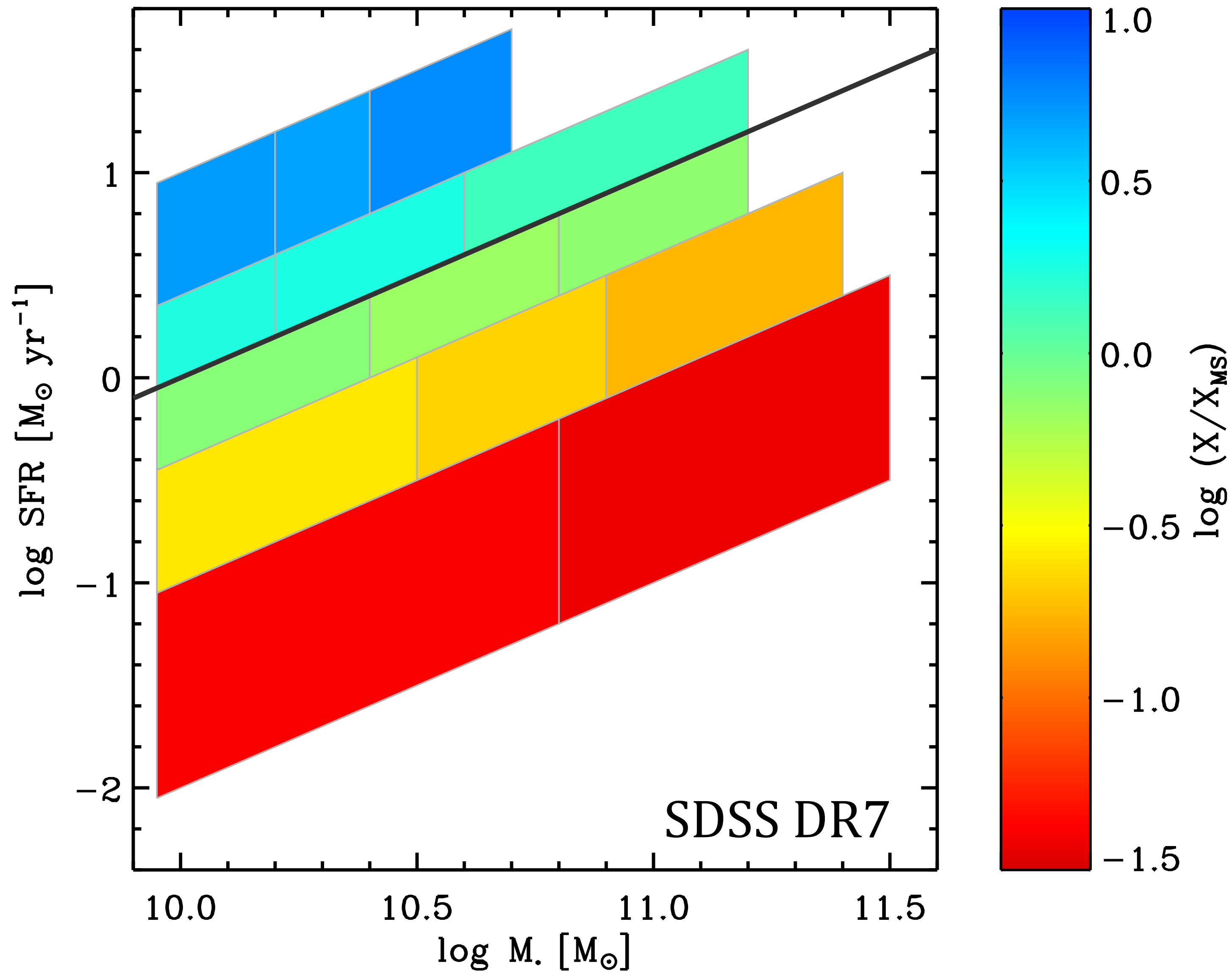


$$\mathrm{sSFR} = \frac{\mathrm{SFR}}{M_*} = \frac{M_{HI}}{M_*}\frac{M_{H2}}{M_{HI}}\frac{\mathrm{SFR}}{M_{H2}}$$

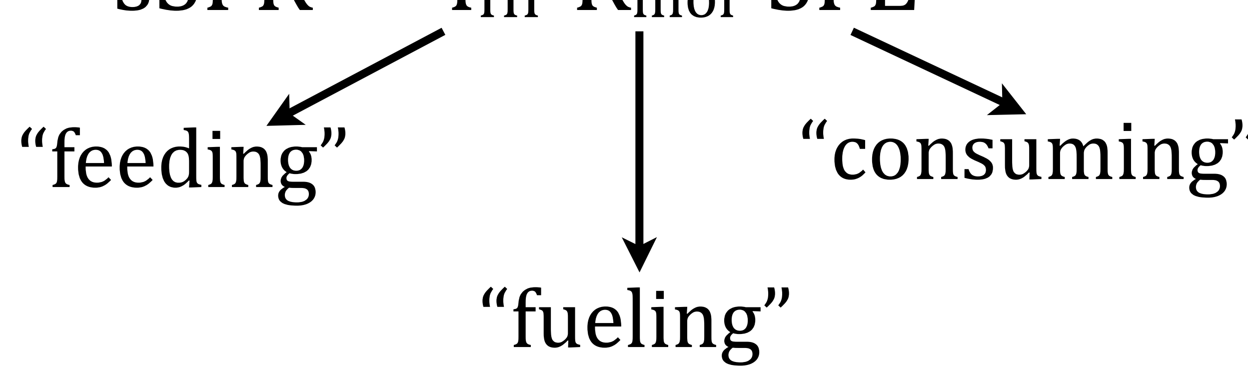
$$= f_{HI}\ R_{mol}\ \mathrm{SFE}$$

Cold gas in the SFR-M* plane





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



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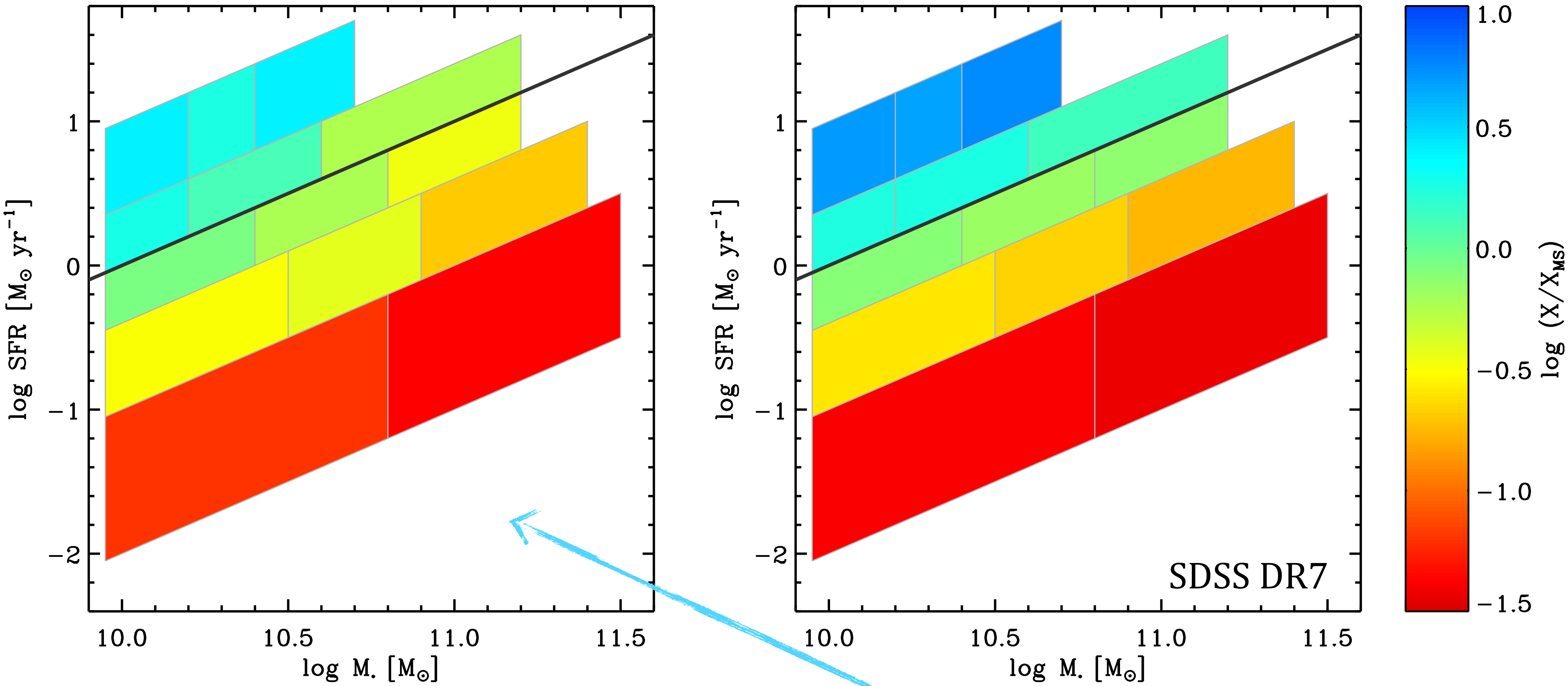
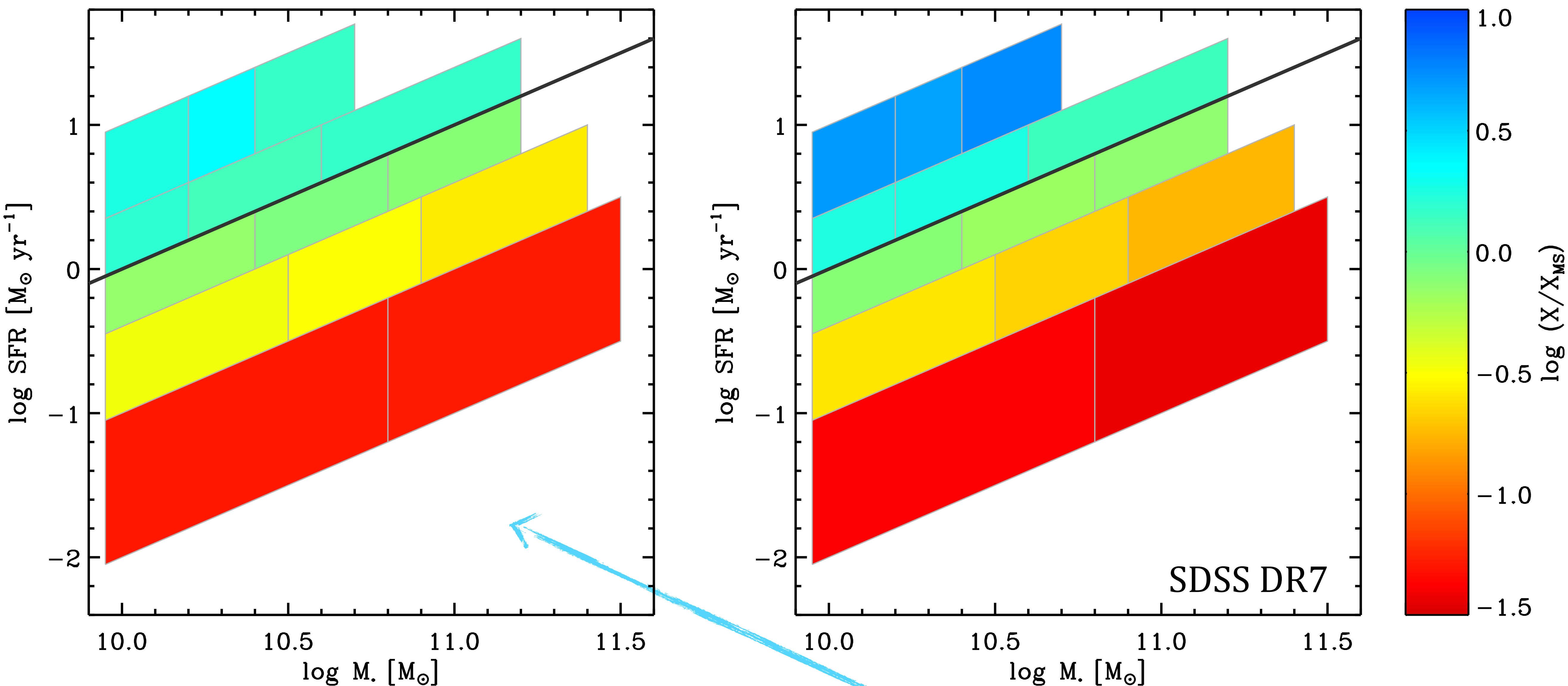


$$sSFR = f_{HI}\, R_{mol}\, SFE$$

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

Cold gas in the SFR-M* plane

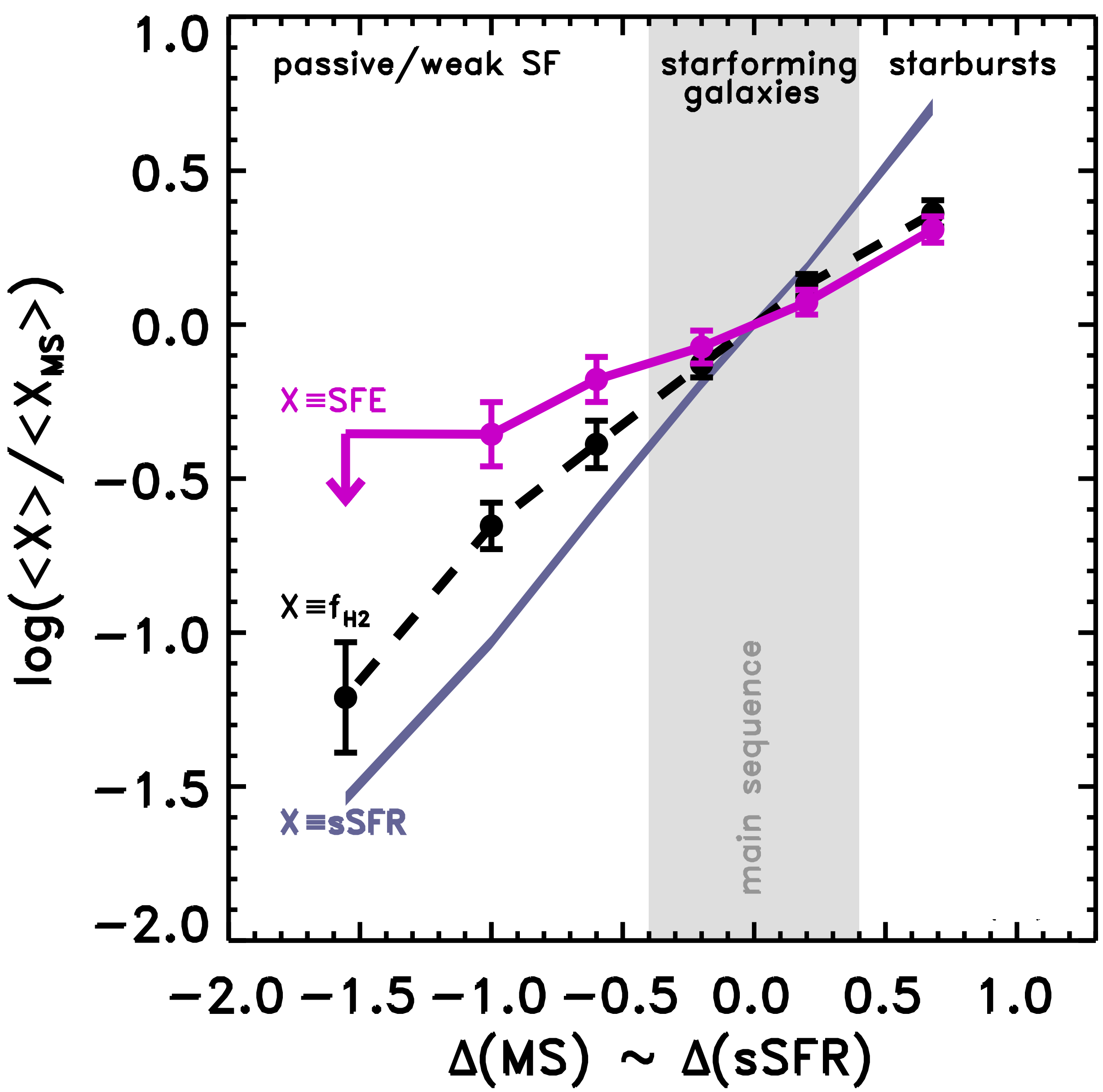


$$sSFR = f_{HI}\ R_{mol}\ SFE$$

($f_{HI}\ R_{mol} = f_{H2}$)

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

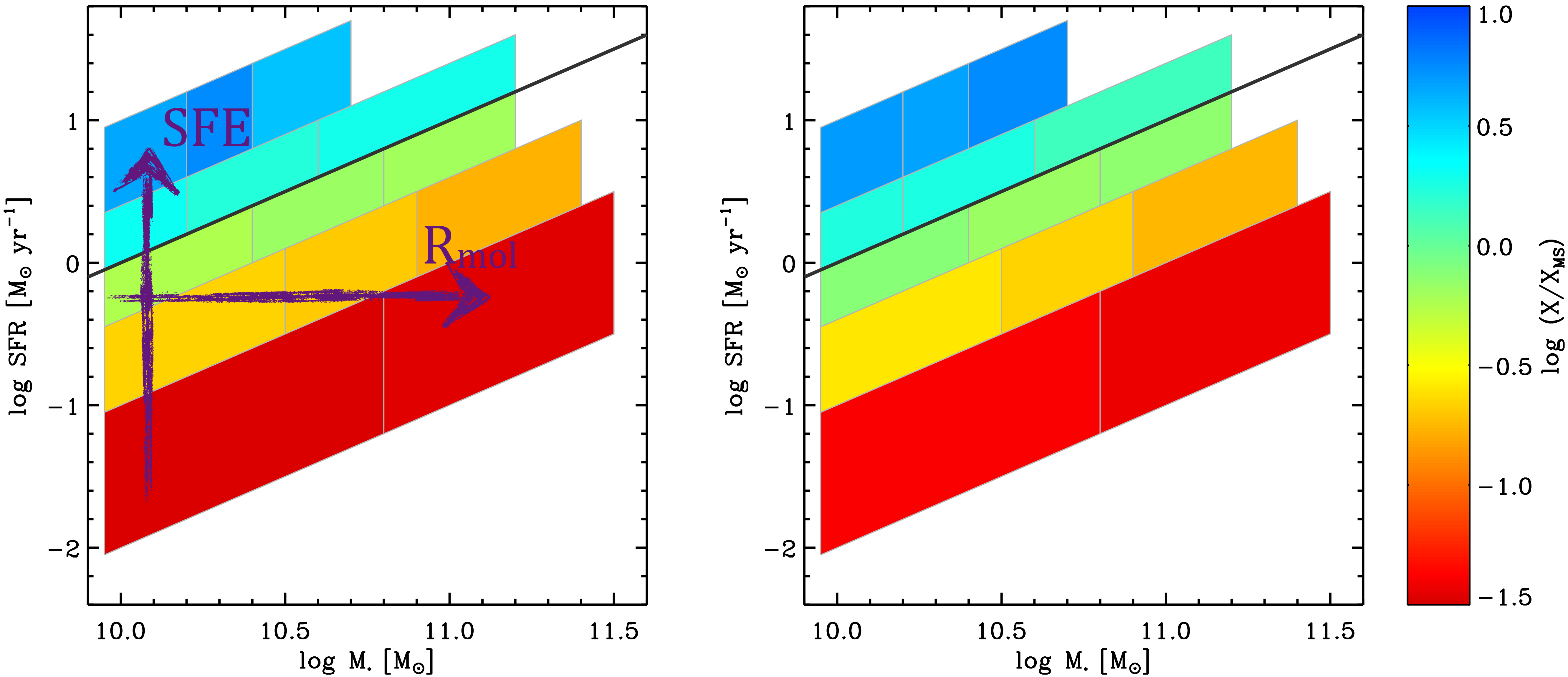
Star formation efficiency variations in the SFR-M* plane



Saintonge et al. (2012)

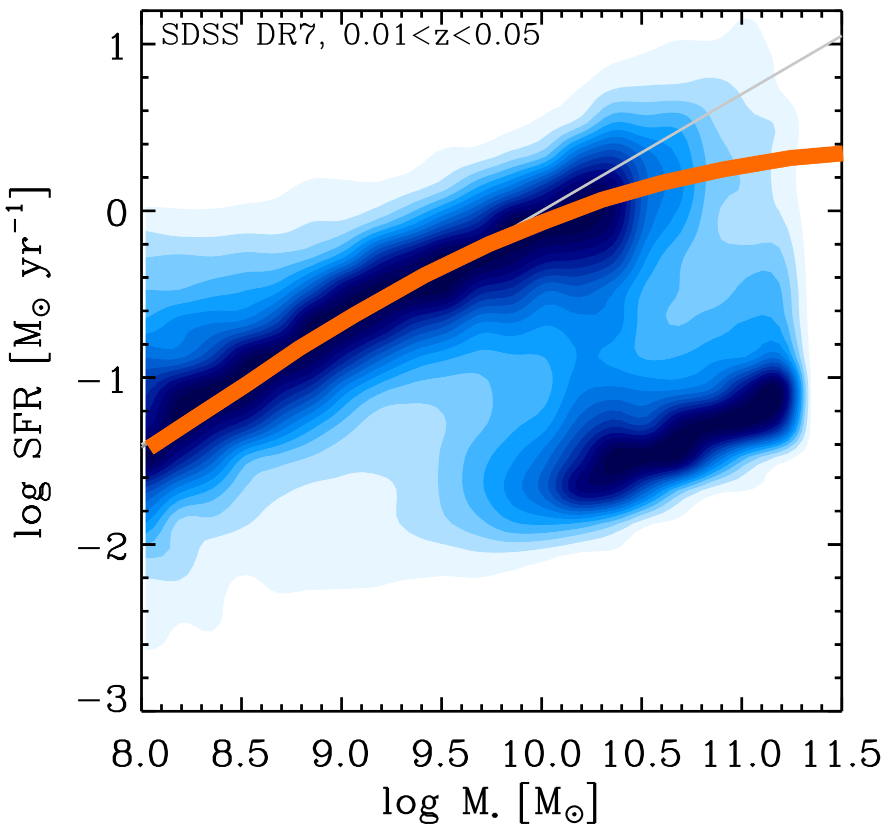
BOTH H_2 contents and star formation efficiency vary ***across*** the MS

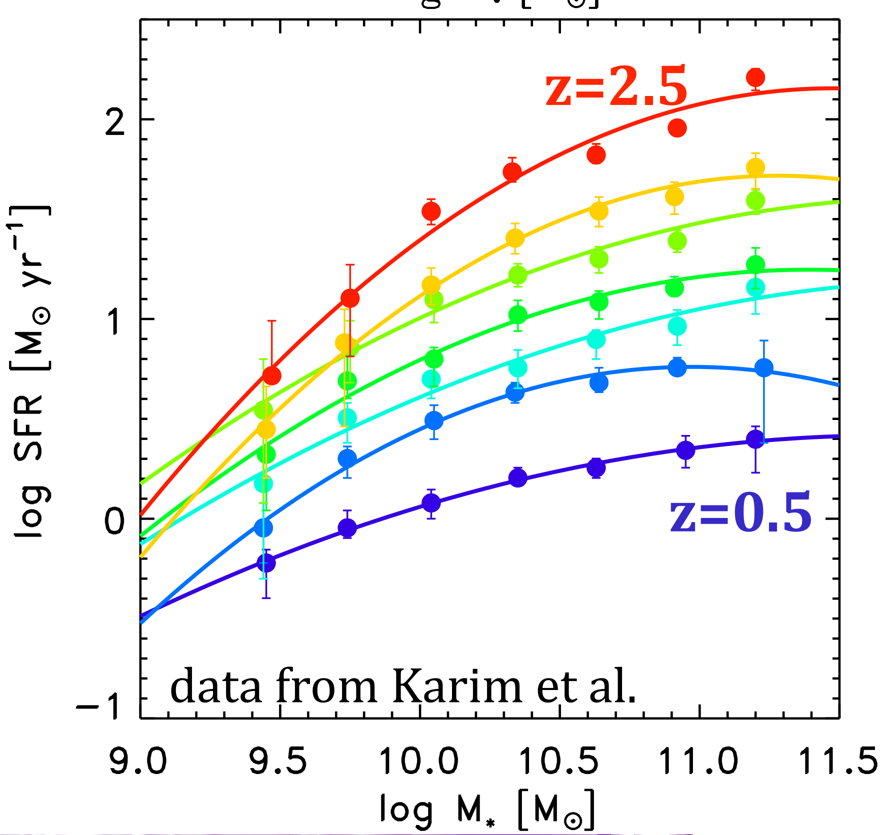
Gas and star formation efficiency explain the SFR-M* plane

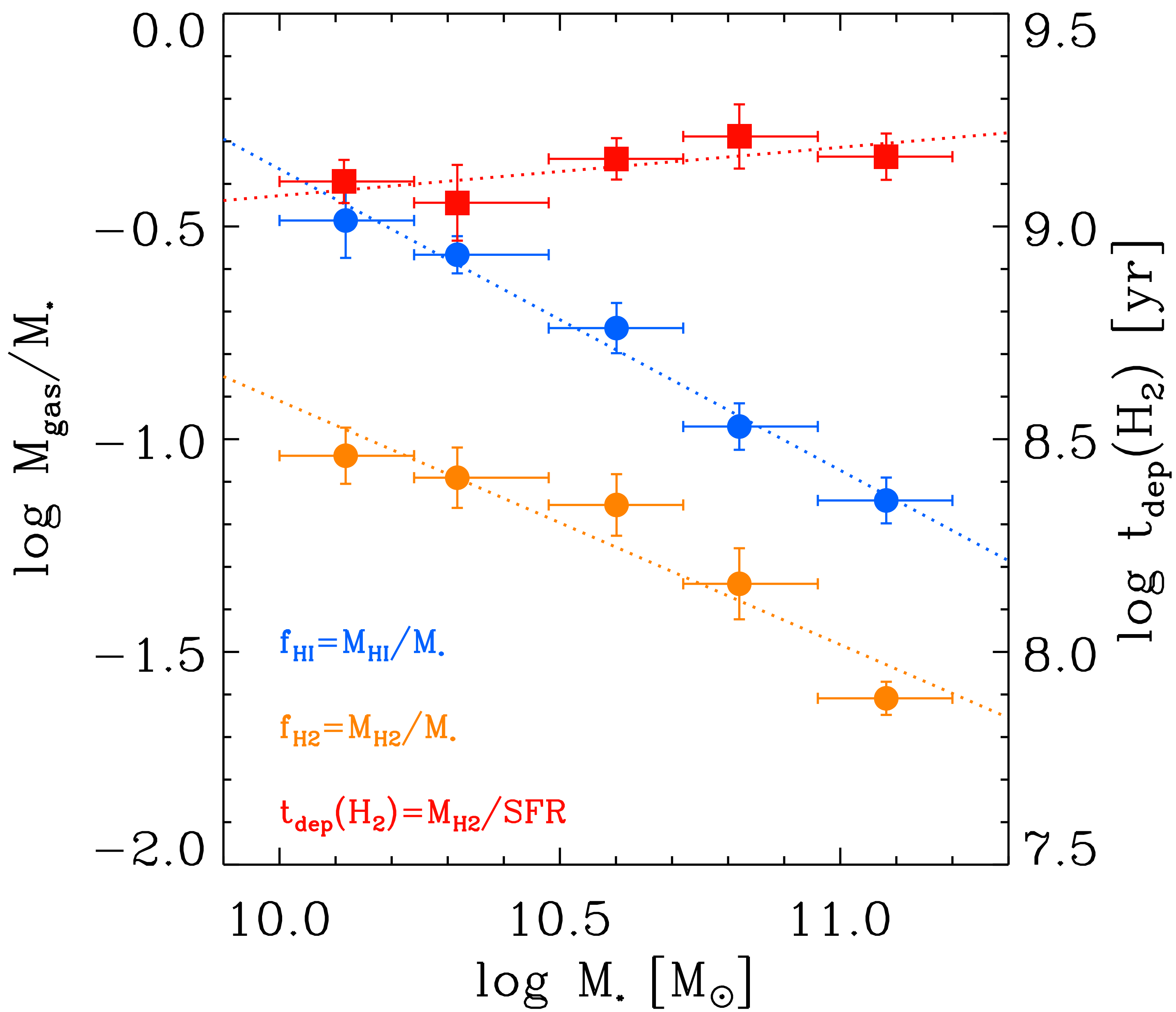


The position of a galaxy in the SFR-M* plane depends on:
(1) how much fuel it has
(2) how much of it is available for star formation
(3) the efficiency of the conversion of this gas into stars

Gas on the main sequence and star formation quenching

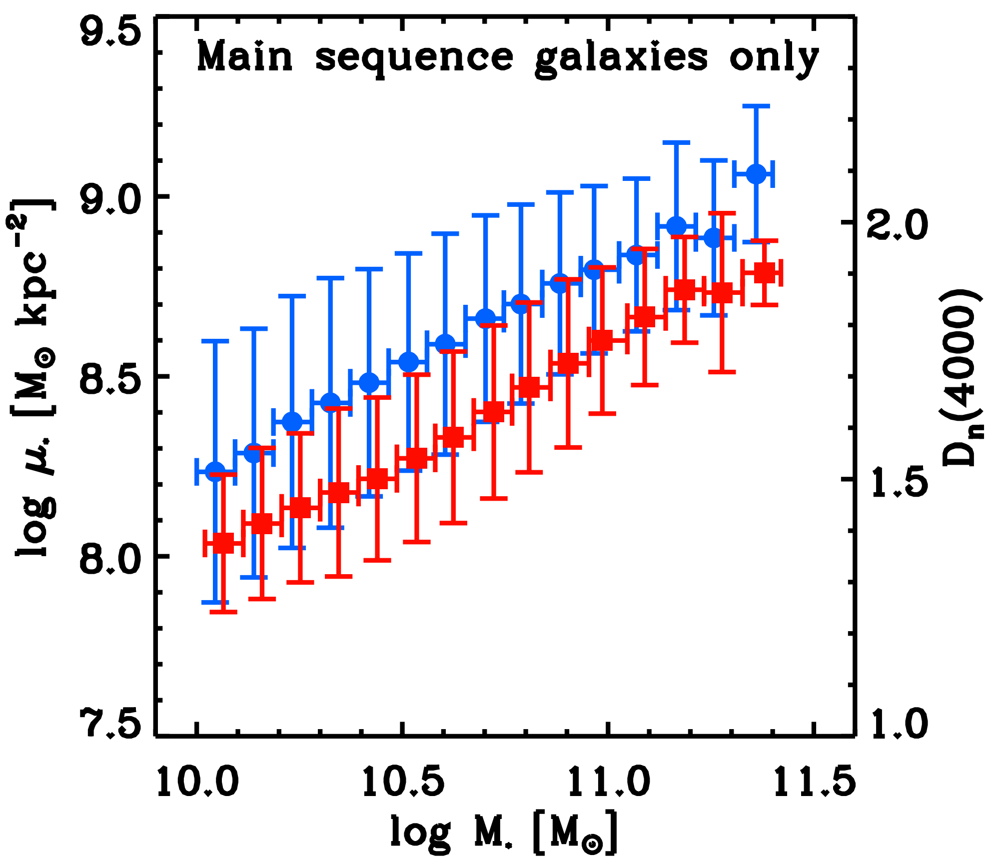


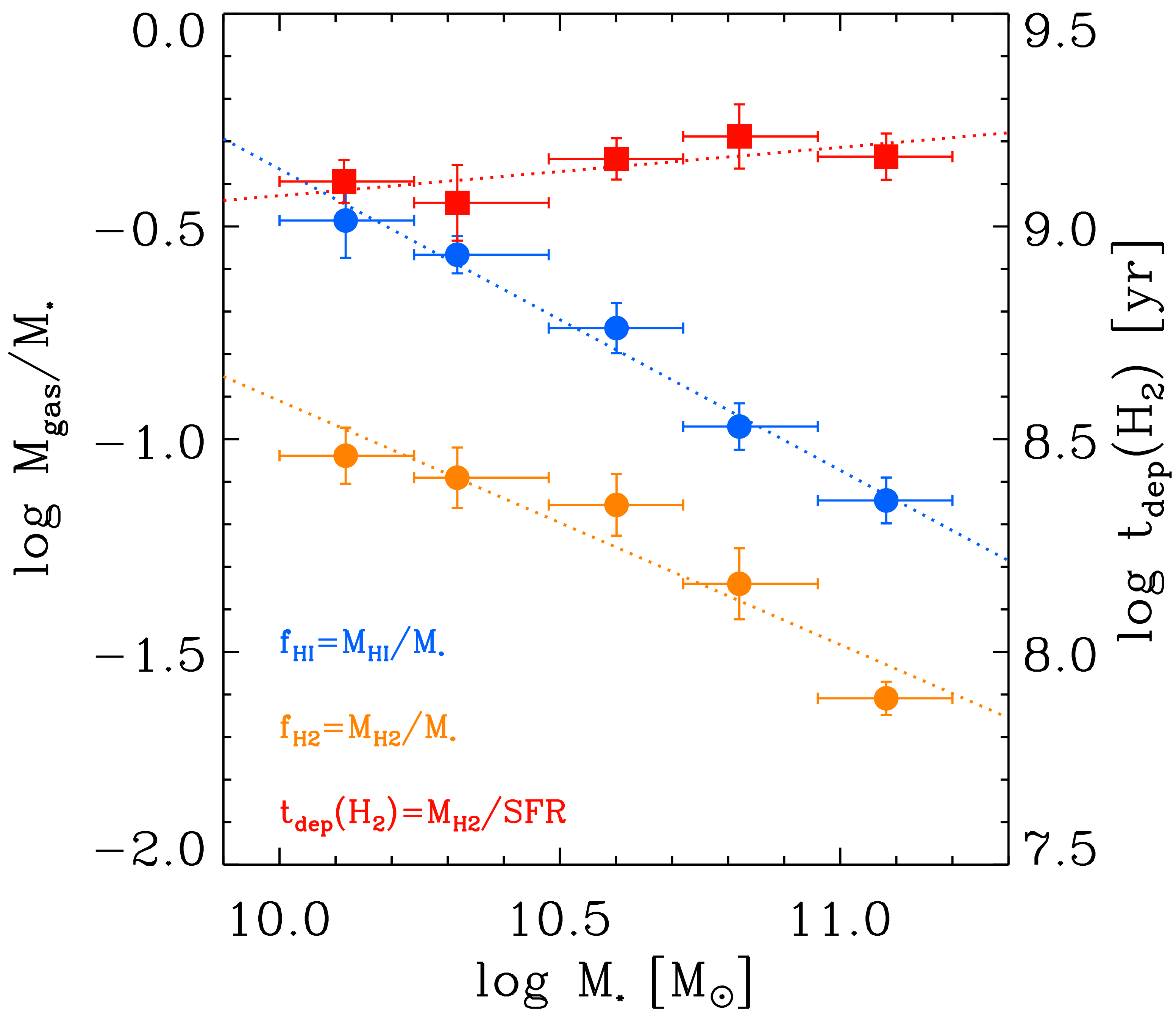




as galaxies evolve along the main sequence, they steadily consume their gas supplies

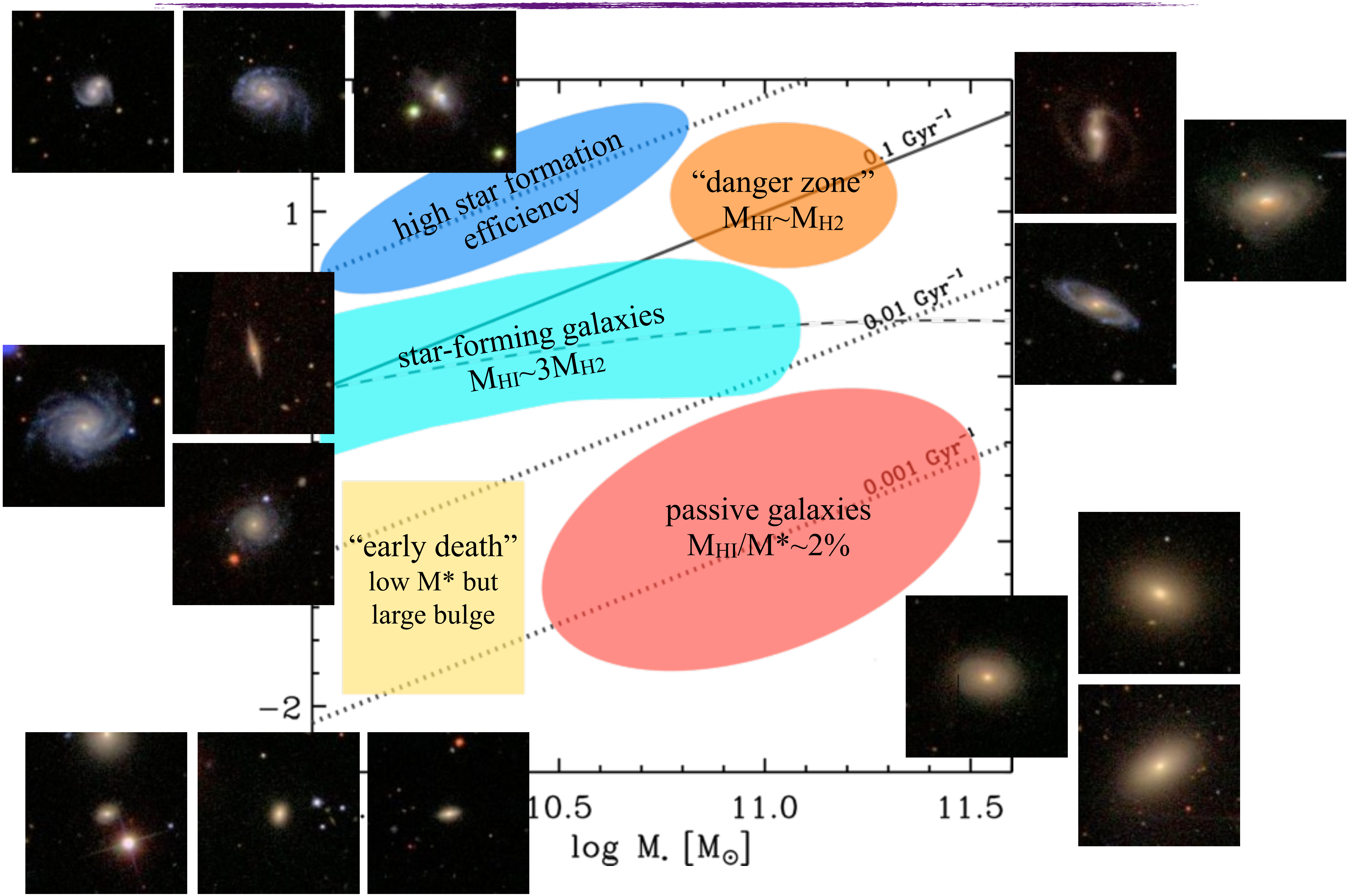
Gas on the main sequence and star formation quenching



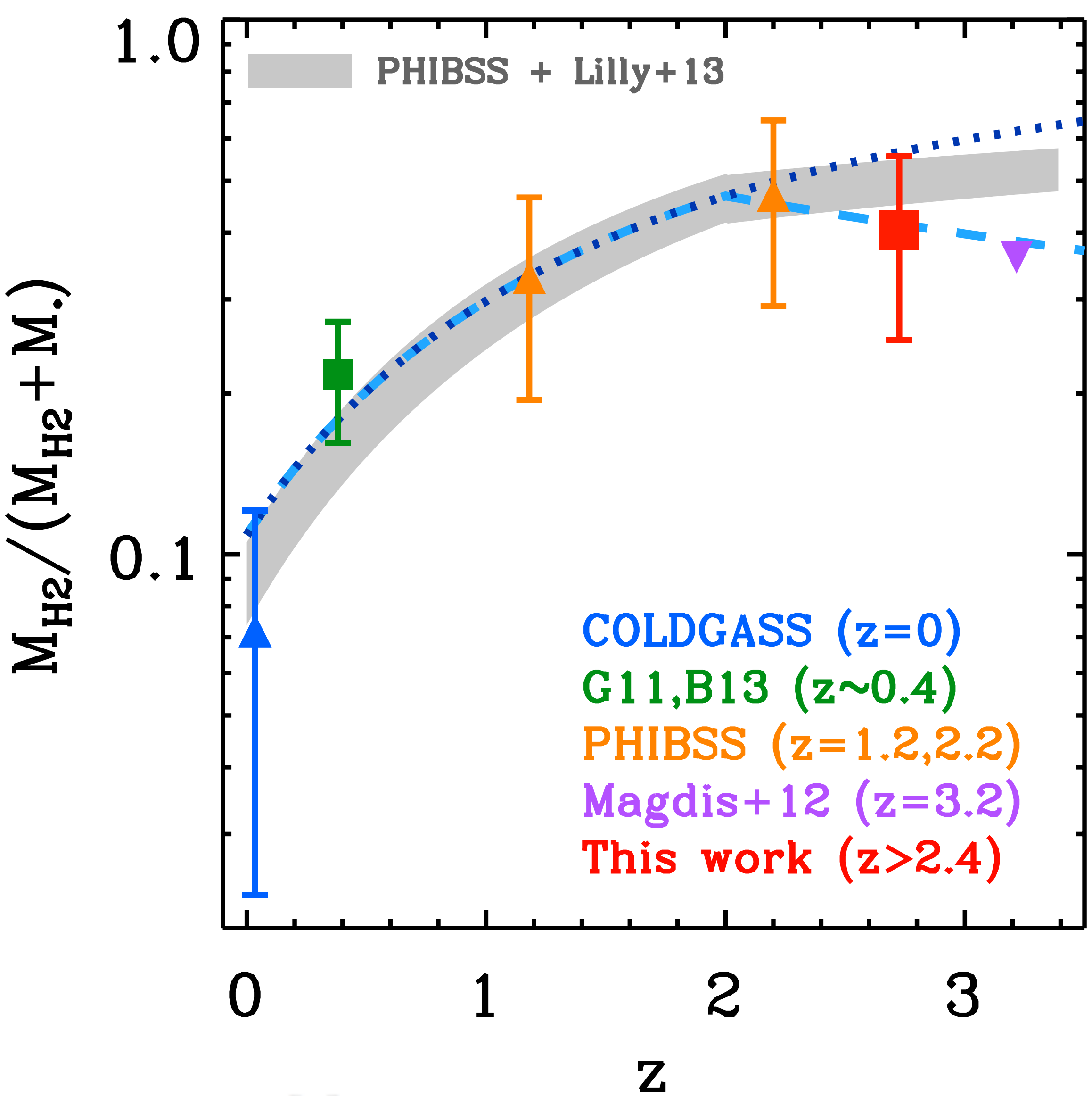


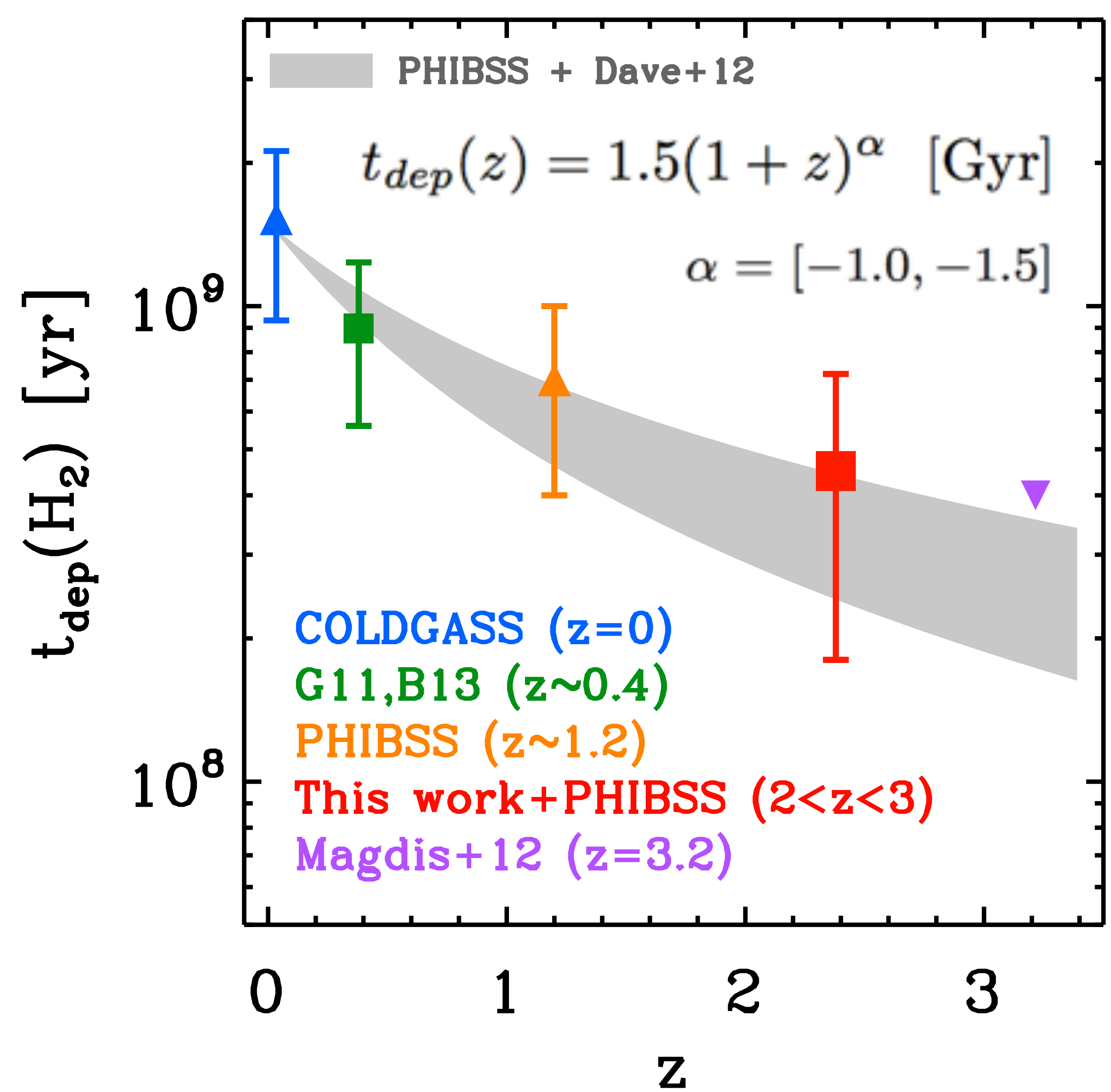
as galaxies evolve along the main sequence, they steadily consume their gas supplies
and grow more prominent bulges

Gas in the SFR-M* plan and what it teaches us



Gas fractions increase up to z=2





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

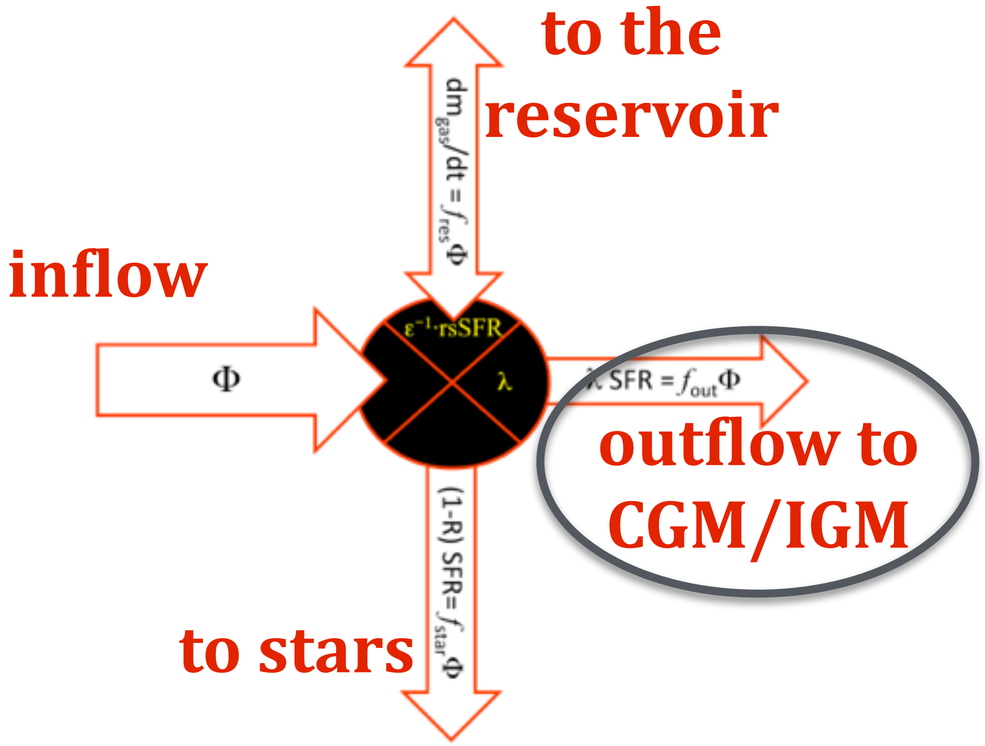
$$= \frac{1}{1 + (t_{dep}\ \mathrm{sSFR})^{-1}}$$

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

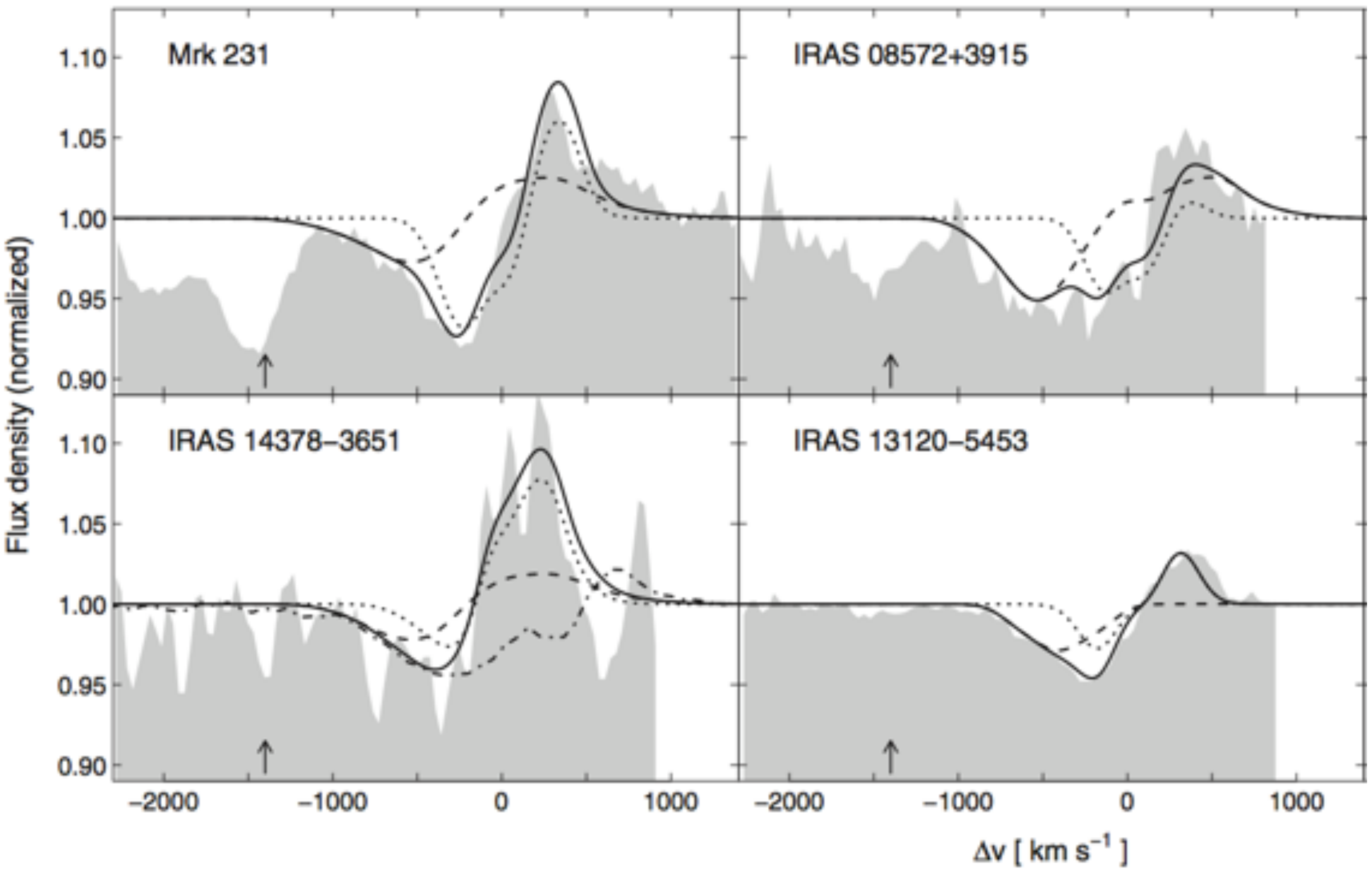
the redshift evolution of the mean SSFR is mainly driven by gas fractions and a slowly evolving depletion timescale

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

(2) Outflows and the return of gas and metals to the CGM/IGM



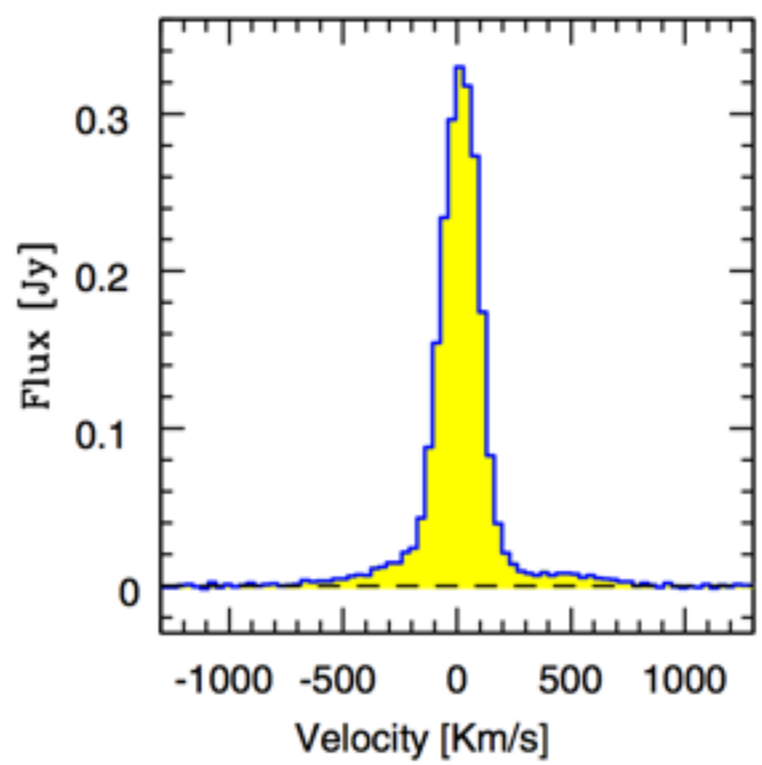
Direct observations of massive molecular outflows

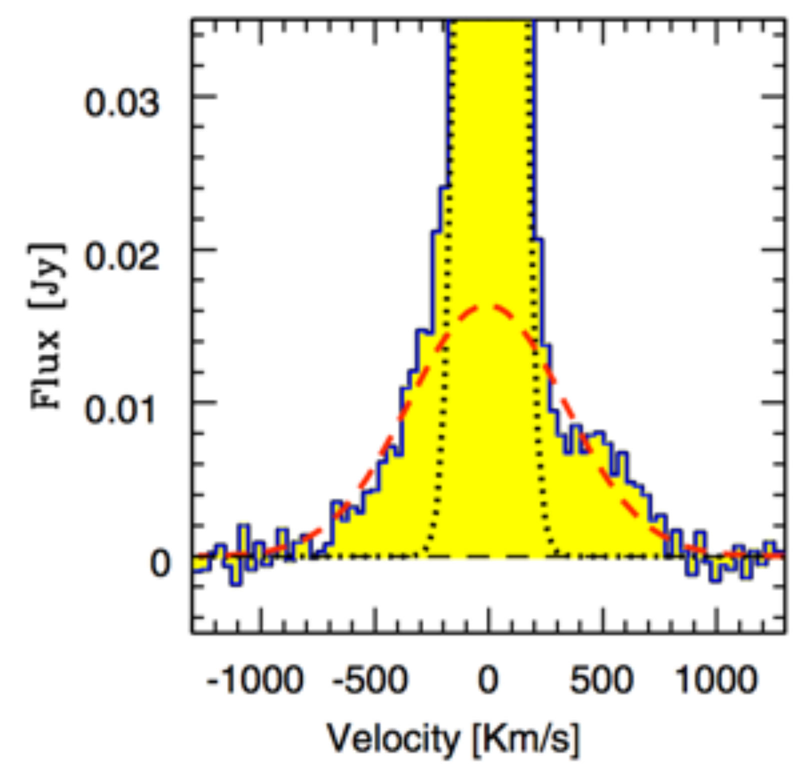


outflows of molecular gas observed in OH and CO in systems hosting powerful starbursts or AGN

Sturm et al. (2011)

Feruglio et al. (2010)





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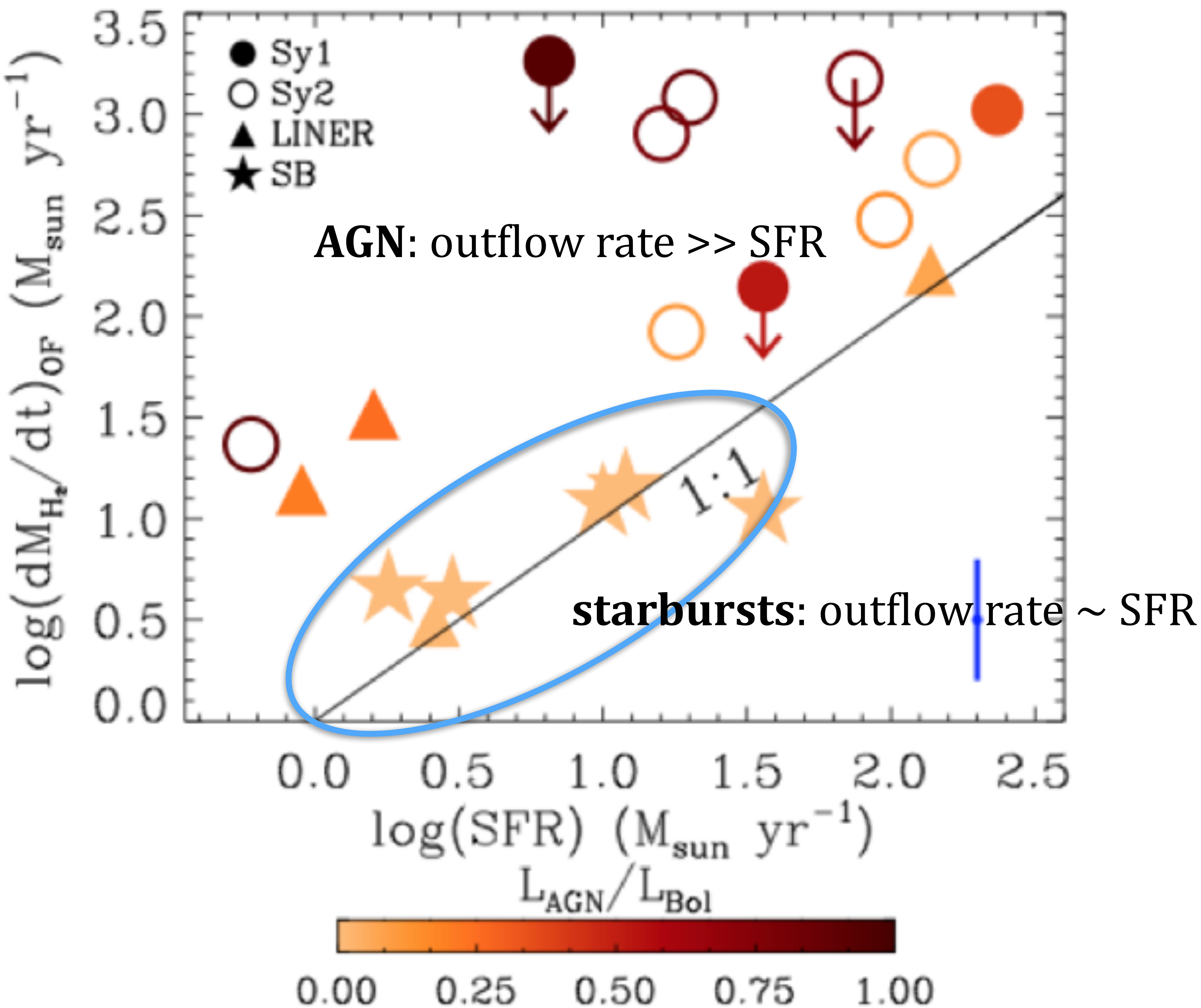
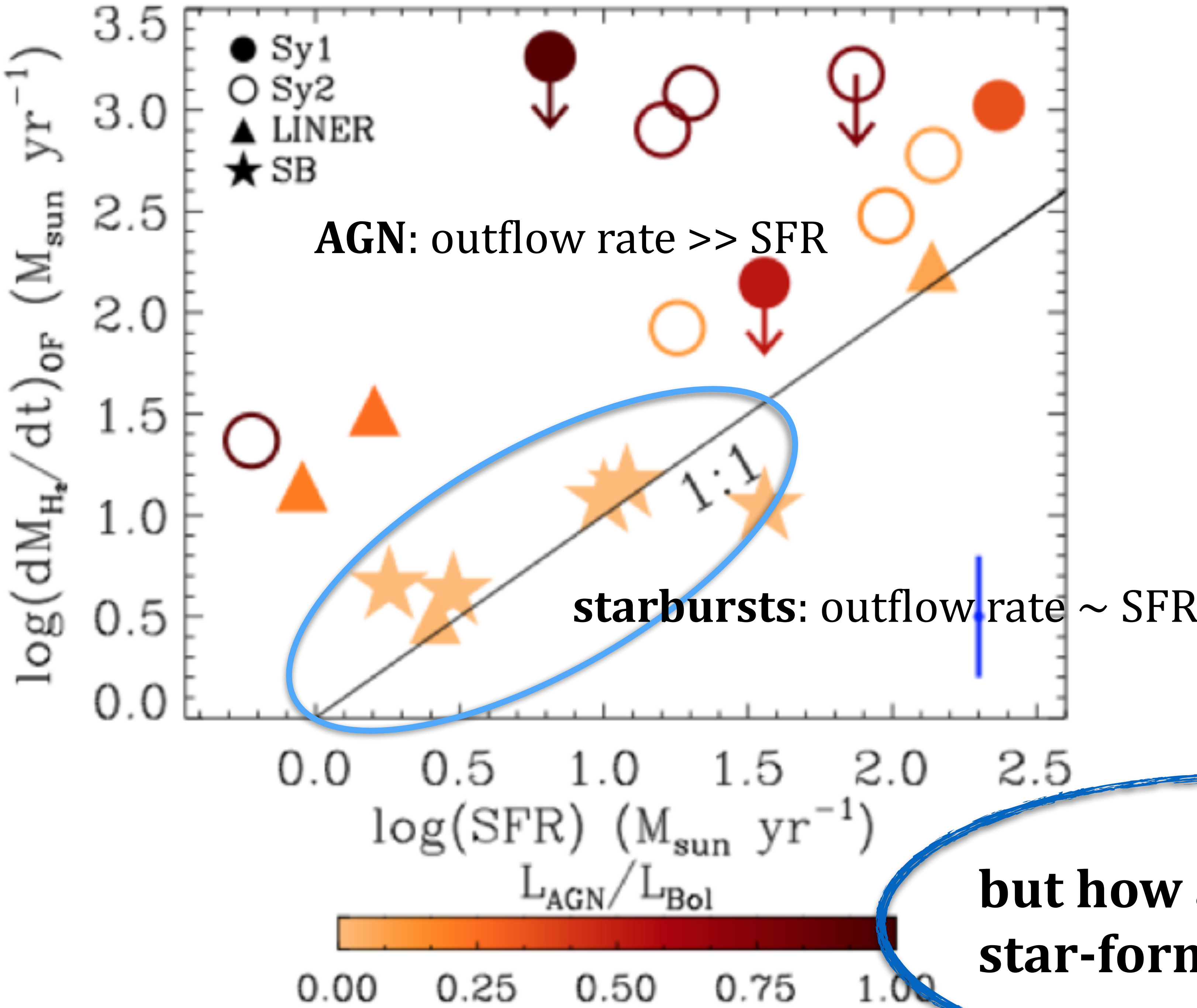


Cicone et al. (2013)

Although starbursts are effective in driving massive molecular outflows, the presence of an AGN may strongly enhance such outflows.

Direct observations of massive molecular outflows

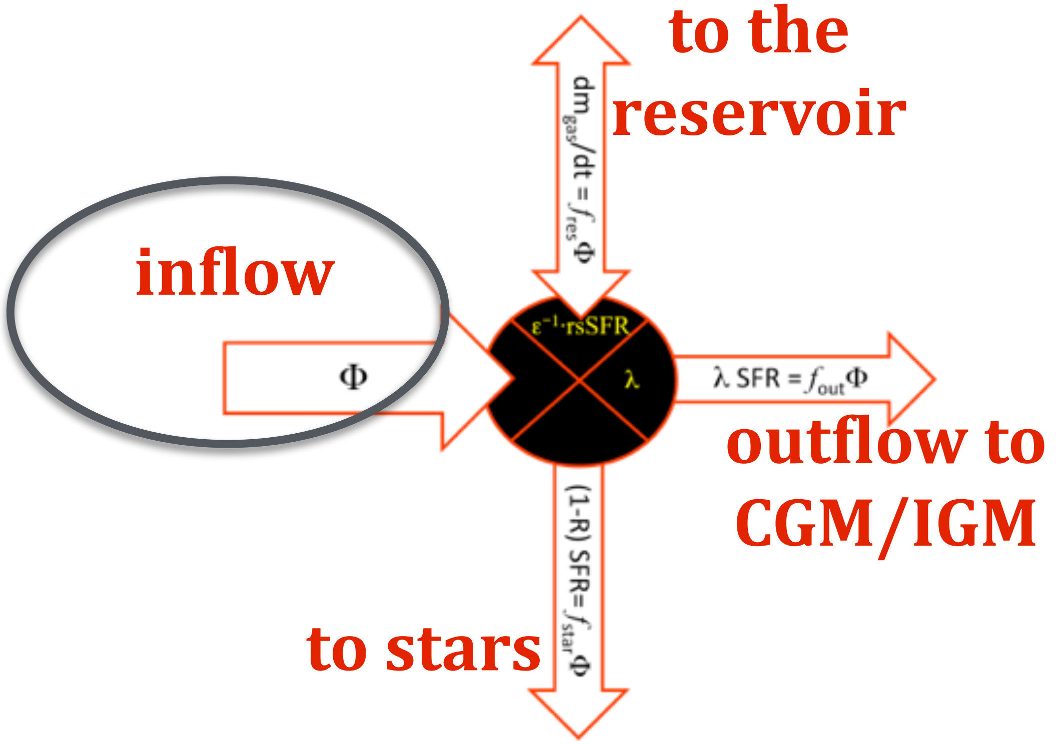


Cicone et al. (2013)

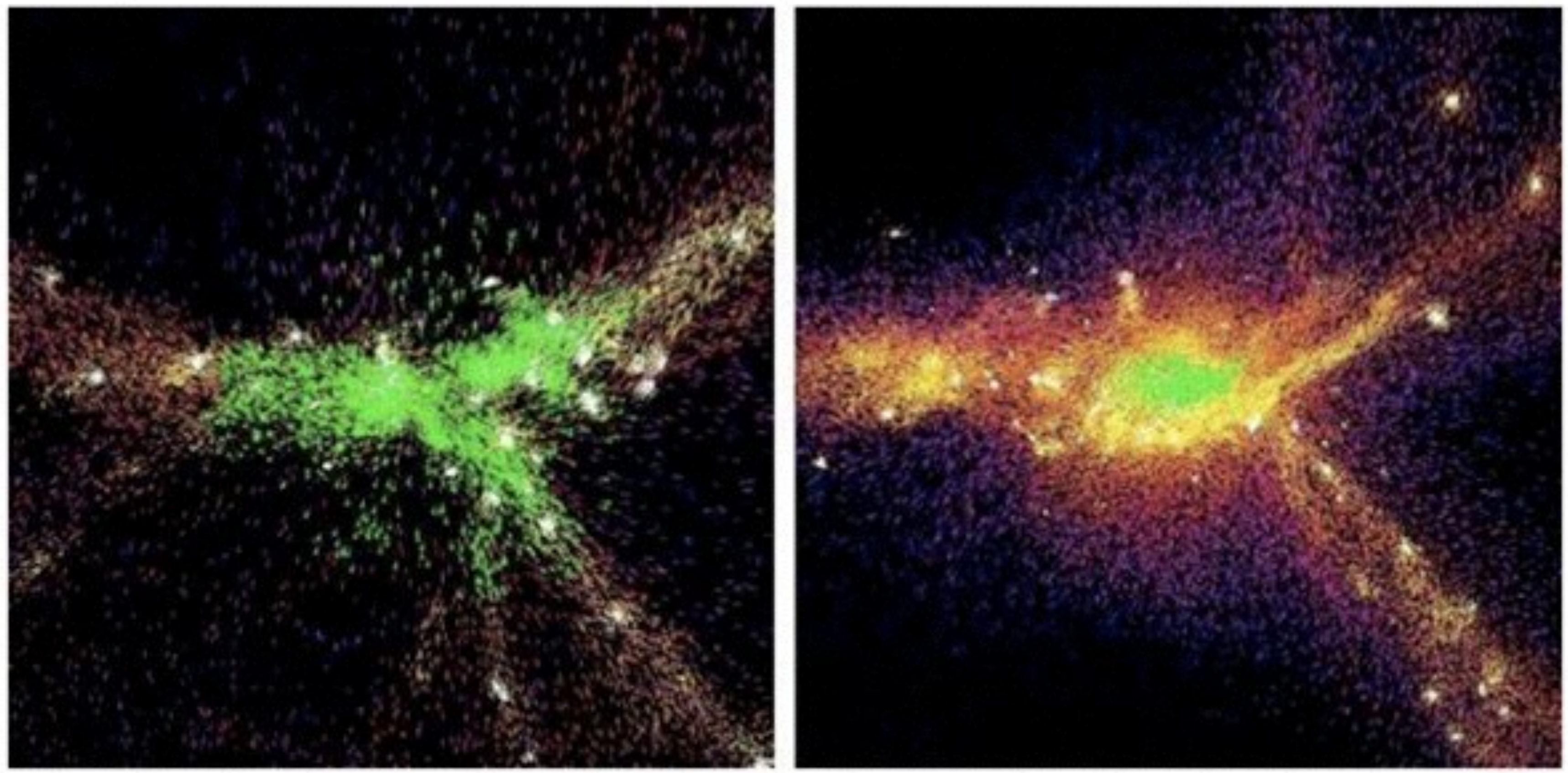
but how about normal star-forming galaxies?

Although starbursts are effective in driving massive molecular outflows, the presence of an AGN may strongly enhance such outflows.

(3) Inflows and the feeding of the galaxy system



Different modes of gas accretion

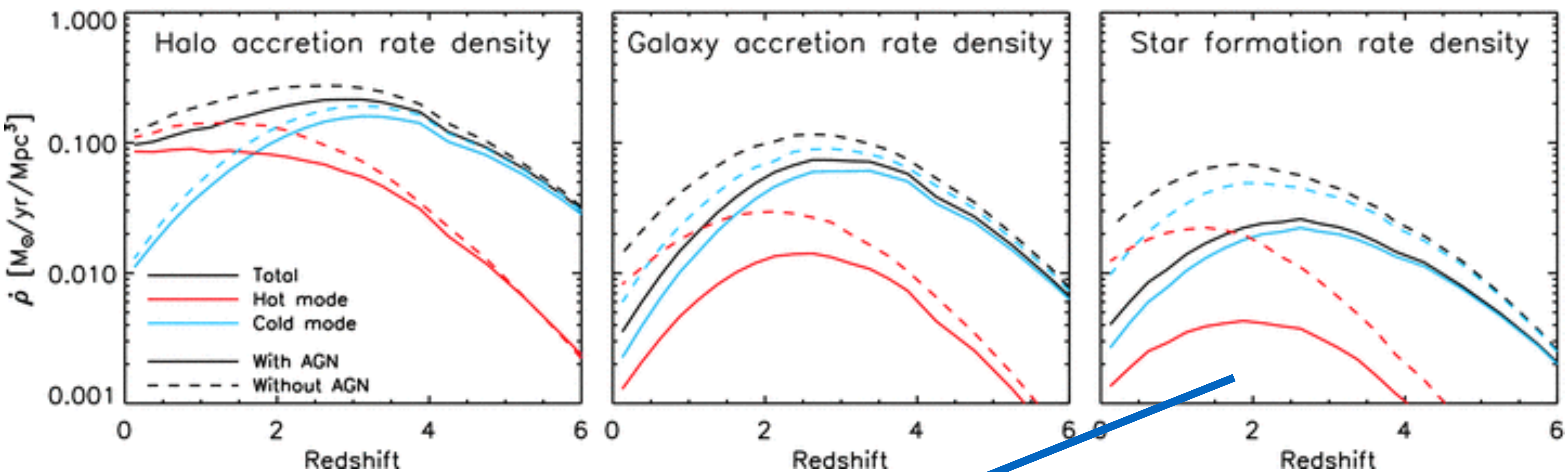


$z=5.5$, $M^*=1.6\times10^{10}M_\odot$ $z=3.0$, $M^*=7.0\times10^{10}M_\odot$

Keres et al. (2005)

see also: Rees & Ostriker (1977), Binney (1977), Katz et al. (1994), Kay et al. (2000), Birnboim & Dekel (2003), Dekel & Birnboim (2006), Dekel et al. (2009)

Different modes of gas accretion



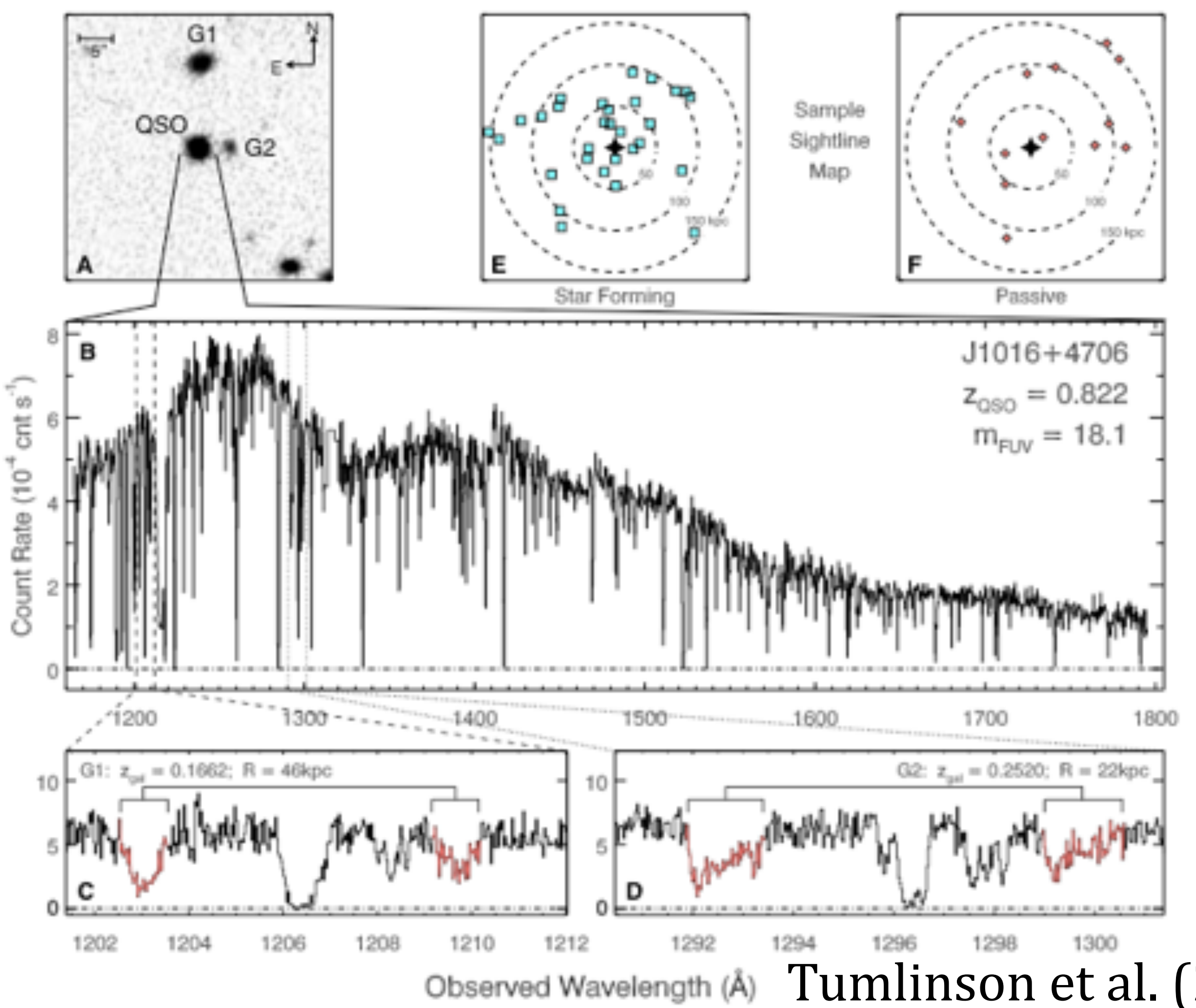
van de Voort et al. (2011)

In simulations, almost all of the star formation is due to gas accreted in the “cold mode”

Even at z=0 there is a need for the gas reservoirs to be replenished ($t_{dep} << t_{Hubble}$)

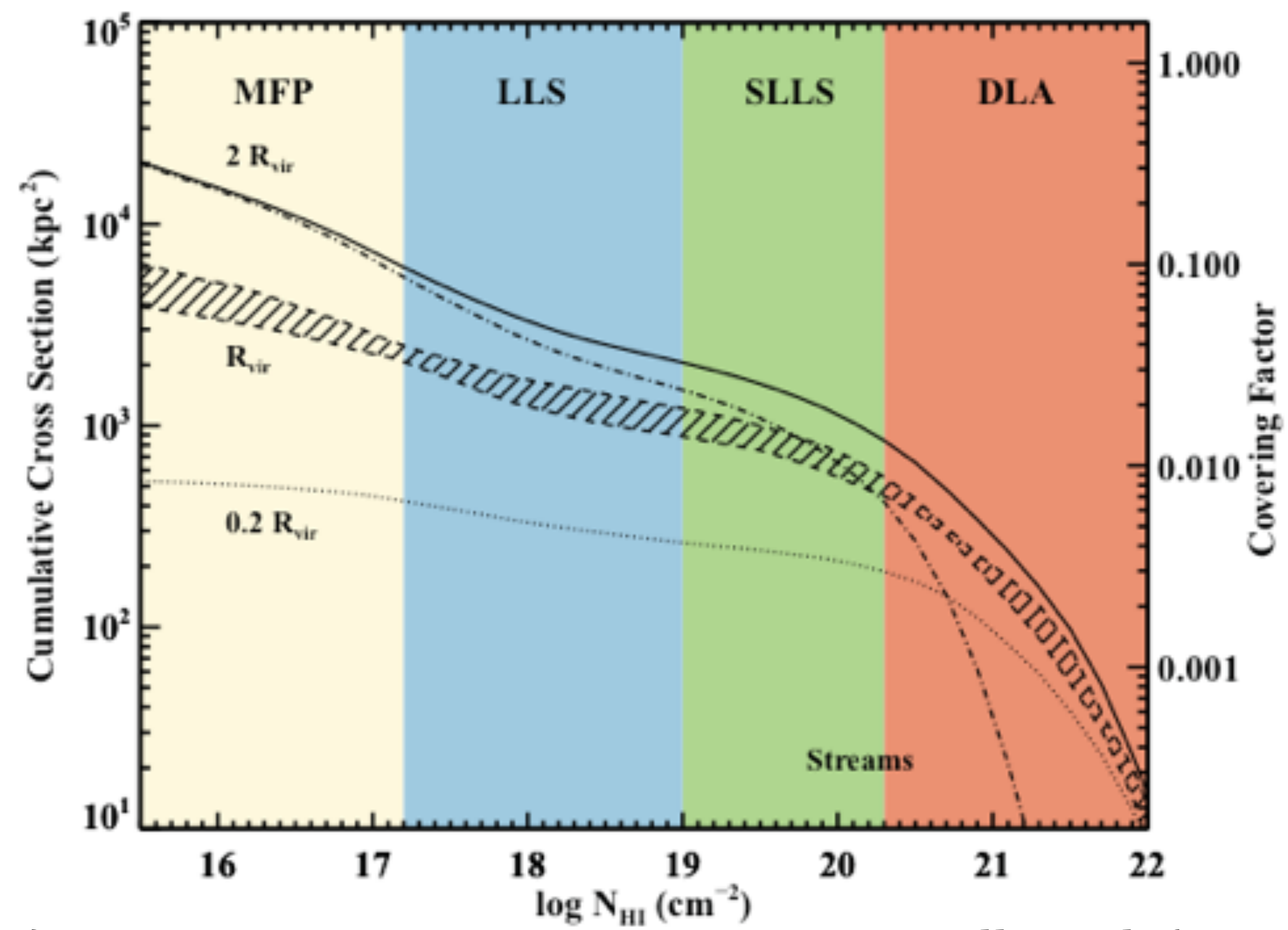
Observational evidence for cold flows?

Observations of the circumgalactic medium (CGM) with HST/COS



Tumlinson et al. (2011)

Other suggestions that Lyman-limit systems are actually cold flows…



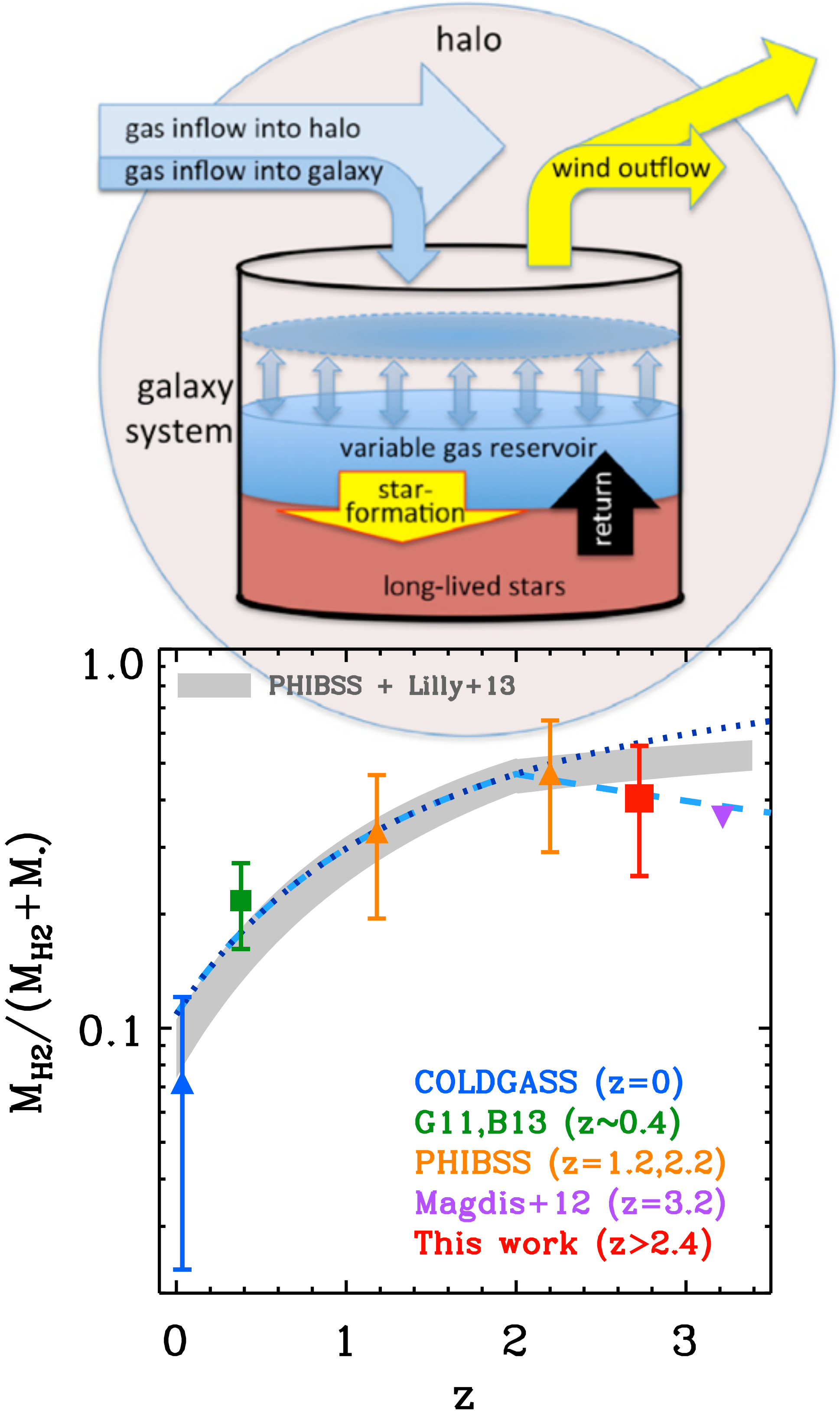
Fumagalli et al. (2011)

Unlikely that the gas detected is predominantly new material, either from 'cold' or 'hot' flows.

Observations of inward-moving gas, but may not match the specifications of cold flows. Can also use kinematic clues (e.g. Bouché et al. 2013)

Conclusion and outlook

Significant evidence for star formation and stellar mass growth of galaxies to be driven by the properties of the gas reservoir.



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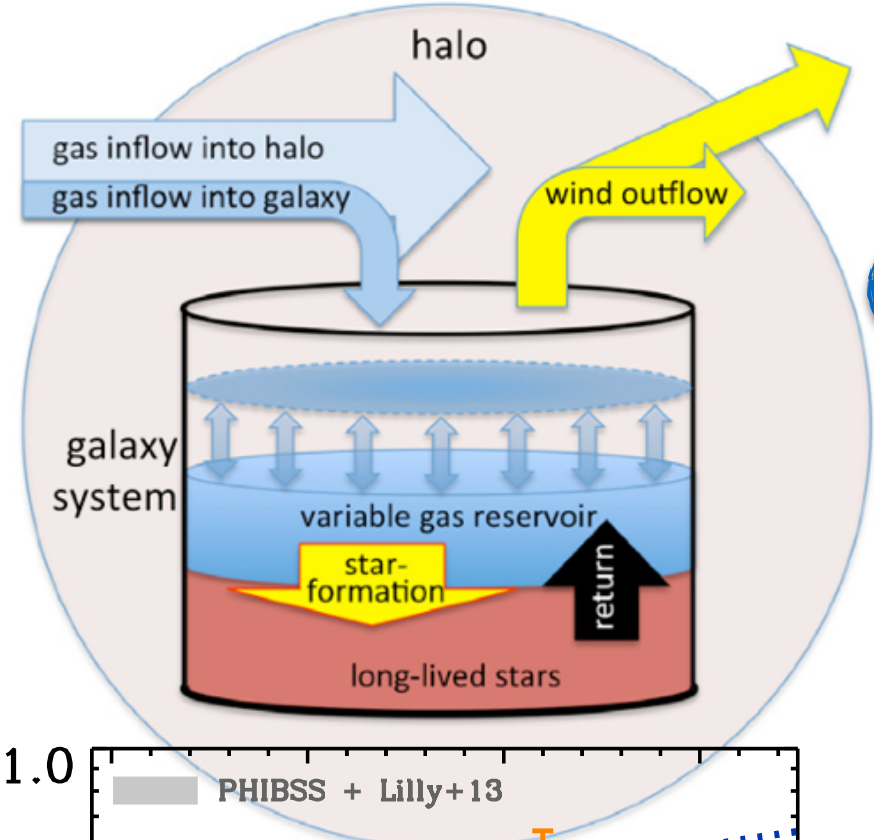
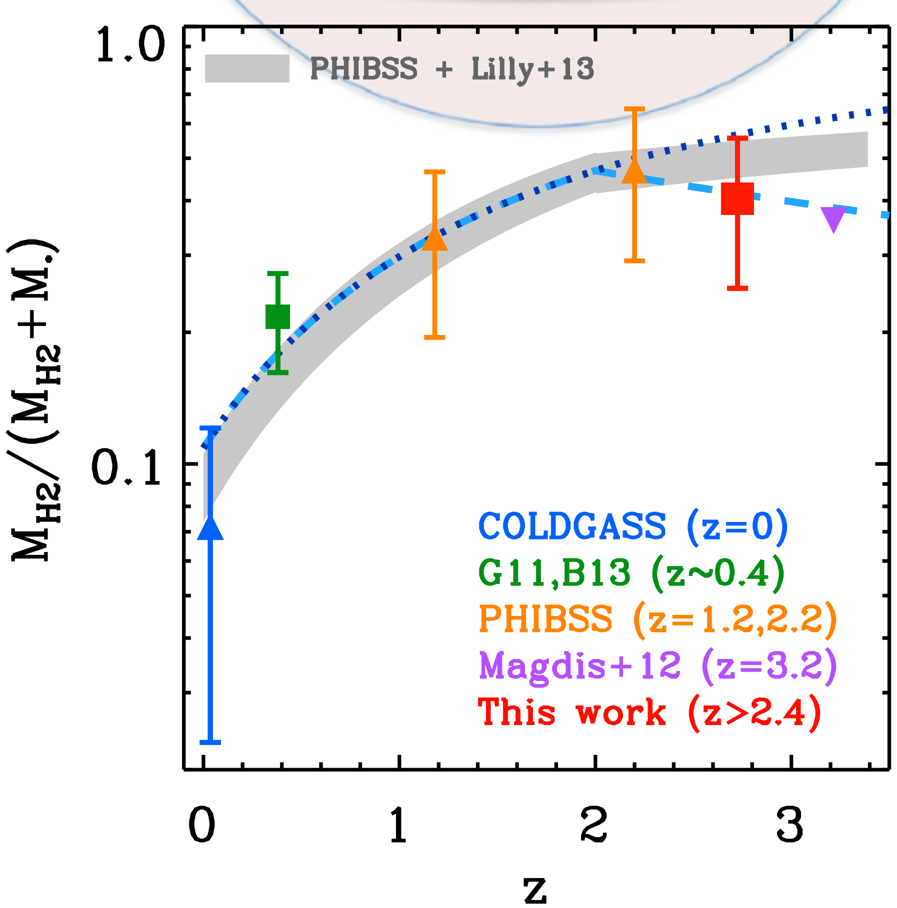


What is the role of environment in regulating the gas supply of galaxies at different epochs?



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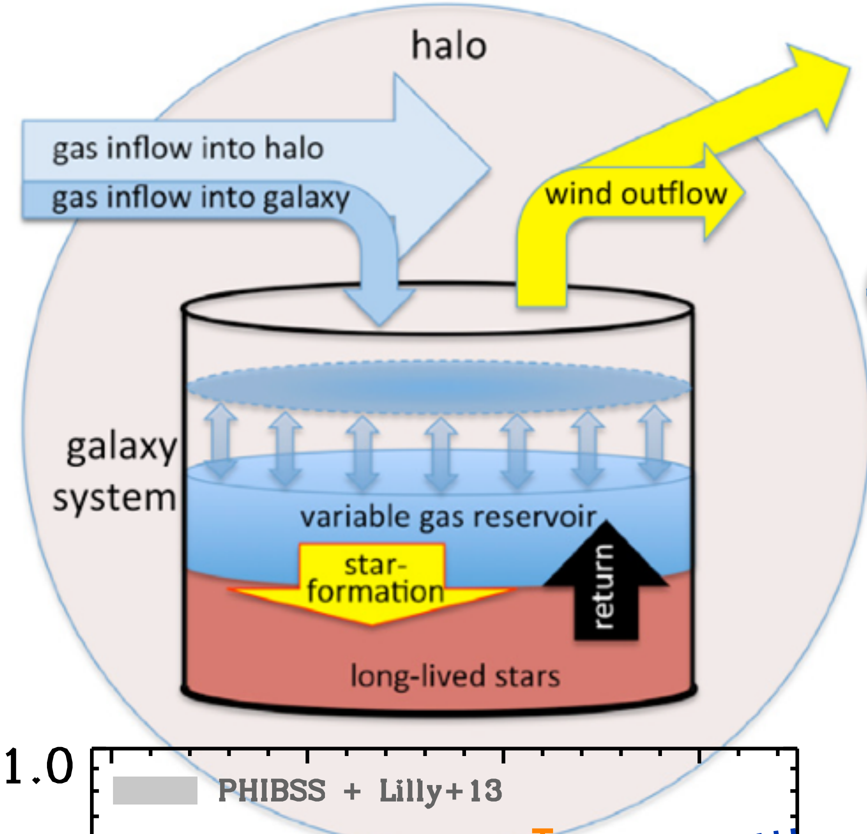

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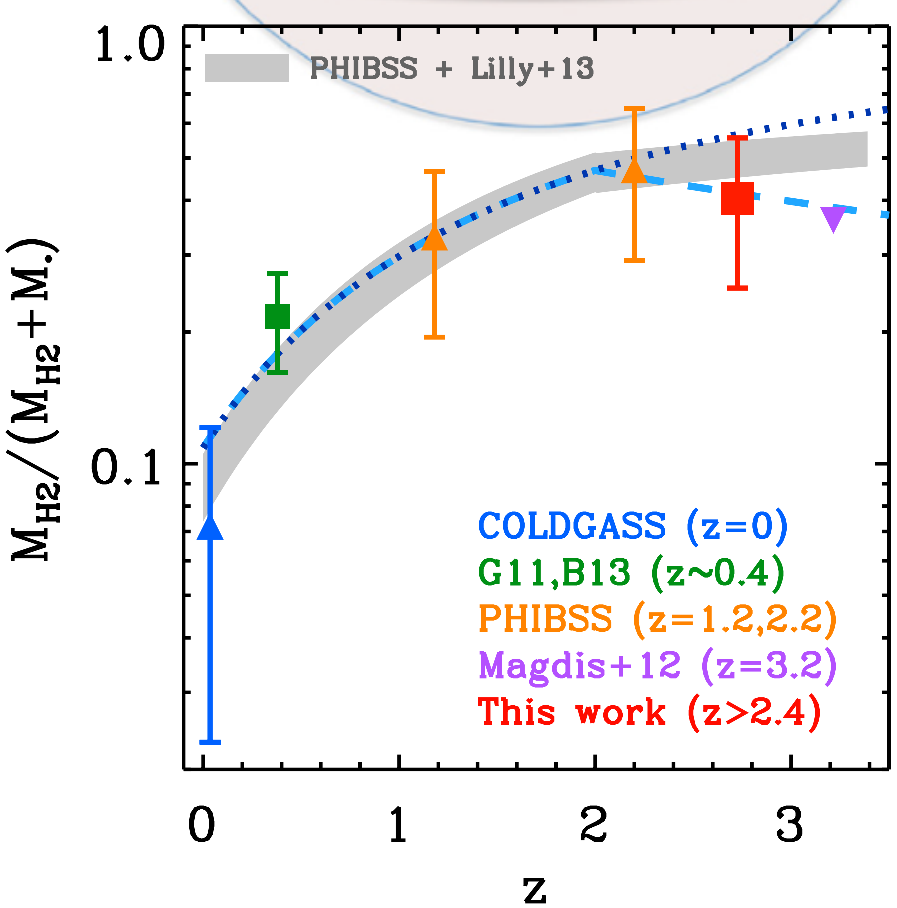

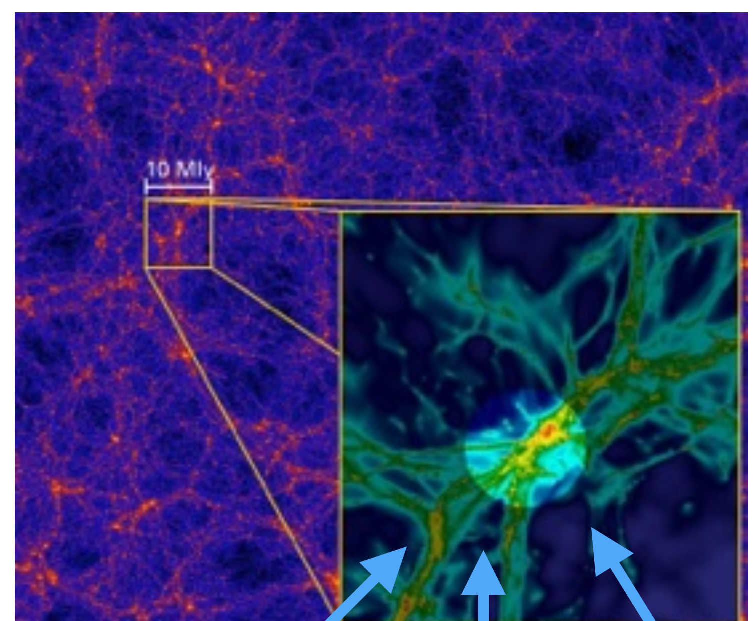

upcoming facilities will help getting the answers!