Moving past the Kennicutt-Schmidt law?

Using galaxy spectra for gas determinations: Gas-star formation scaling laws for 200,000 galaxies in the SDSS

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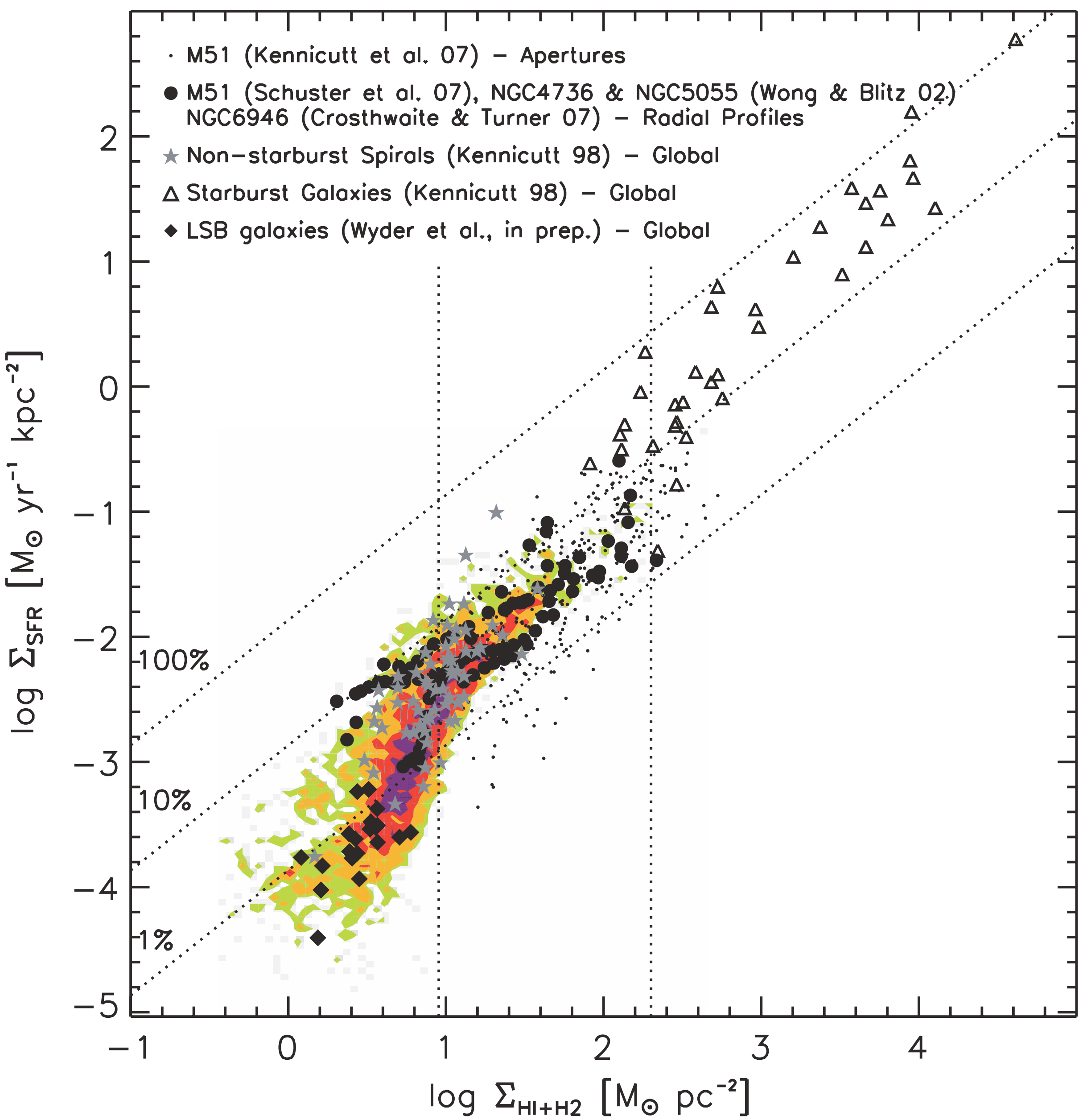
Background

- We have estimated star formation rates for galaxies using Balmer lines for many decades and inferred star formation activity using colours at least since the days of Tinsley.
- We routinely obtain stellar mass estimates for galaxies. Thus we have a fairly good idea of the stellar content for large samples of galaxies.
- However, the gas content of galaxies is much harder to measure for large (or distant) samples. So we haven’t got mass estimates for samples of comparable size to those we have SFRs & masses for.
- Hence people often make recourse to the Kennicutt-Schmidt scaling law to estimate gas masses, because it is usually the only way to do so.

The Kennicutt-Schmidt relation

Kennicutt 1998
Bigiel et al 2008



An empirically determined scaling-law between the star-formation rate per unit area and the gas surface density.

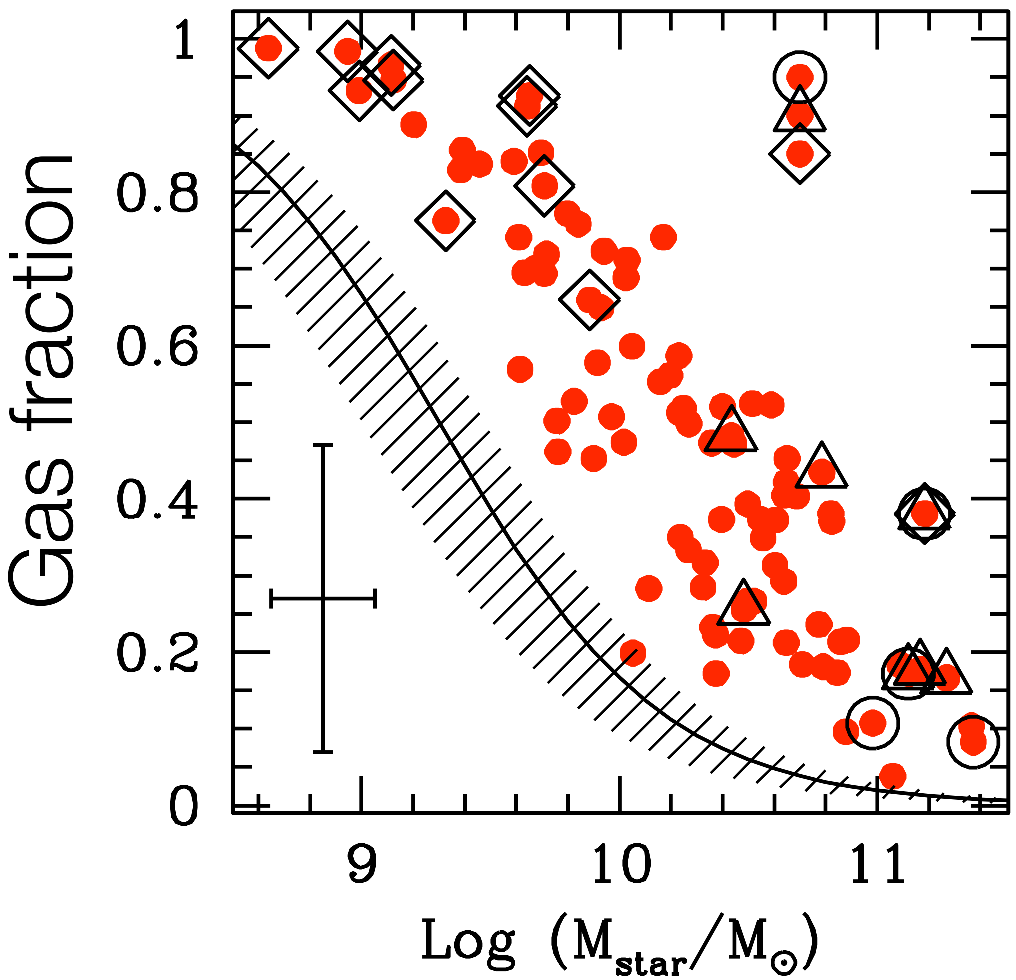
$$\mu_{SFR} \propto \mu_{gas}^{\alpha}$$
$$\alpha \sim 1.4$$

We can then use:

$\mu_{SFR} \propto L_{H\alpha}$/"size"

to constrain μ_{gas}.

Applications to high redshift



Gas-masses at z~2 from the K-S relation (Erb et al 2006)

$$\mu_{SFR} = 2.5\times10^{-4}\,\mu_{gas}^{1.4}$$

The K-S relation is interesting in that it can provide gas mass estimates without time-consuming (sub-)mm observations

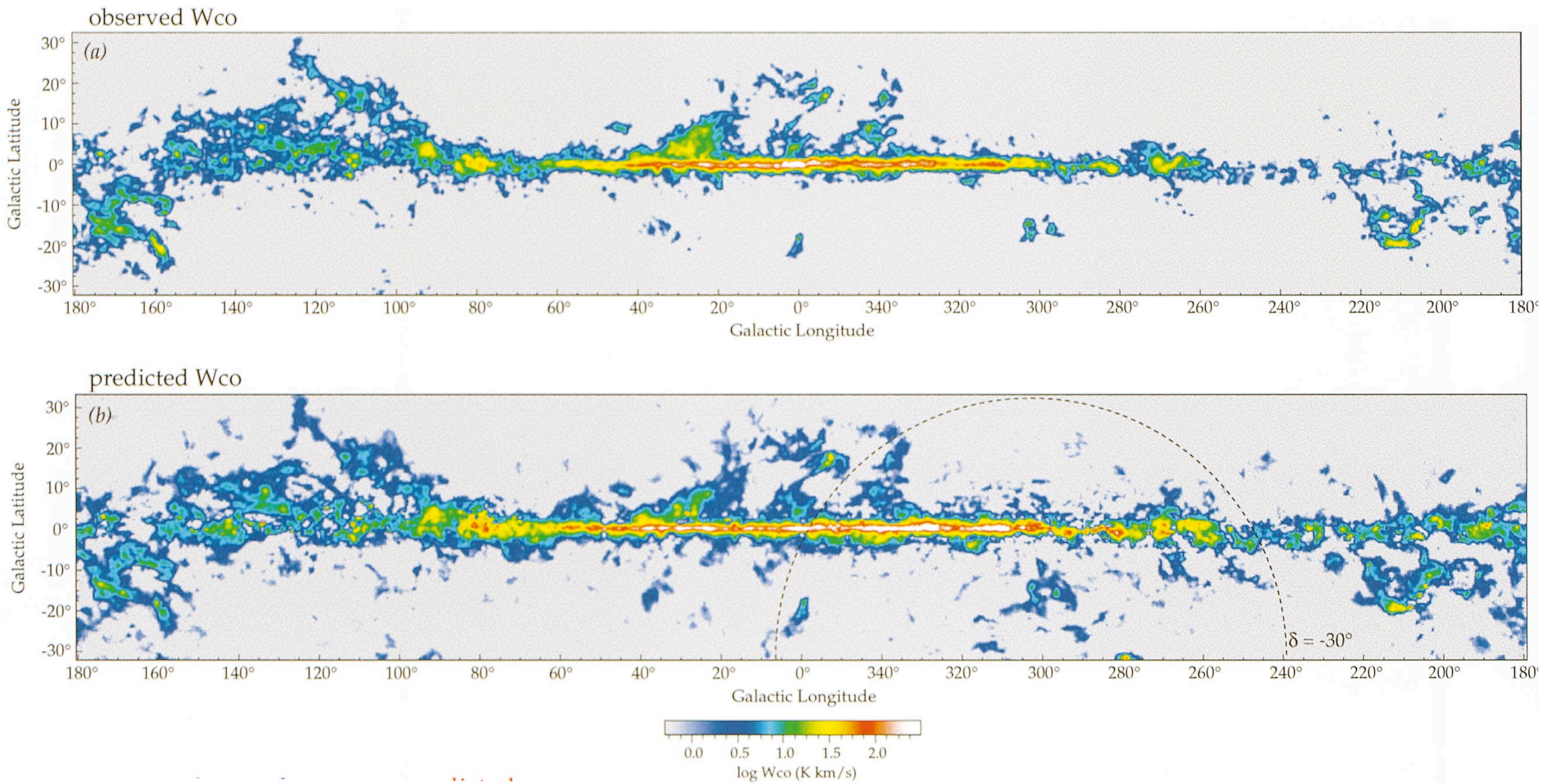
Does it really hold?
What is the physical quantity estimated?
μ_{gas} vs μ_{SFR} is not a useful plot...

The target for now - the SDSS DR7

- Spectral measurements, star formation rates, stellar masses for ~10^6 galaxies. Spectra cover 3800Å-9000Å in observed frame, redshift spans from z=0 to z~0.2-0.3 for the main galaxy sample.
- Around 200,000 of these have emission line spectra whose dominant ionising source is stellar. For these we also can get metallicities, and, hopefully, estimate gas content.
- We also have imaging, and many of the objects have been observed by other surveys and on-going surveys will provide us with many more gas content measurements (see T. Heckman’s talk later today).
- The large sample allows us to sample much wider ranges in parameter space.

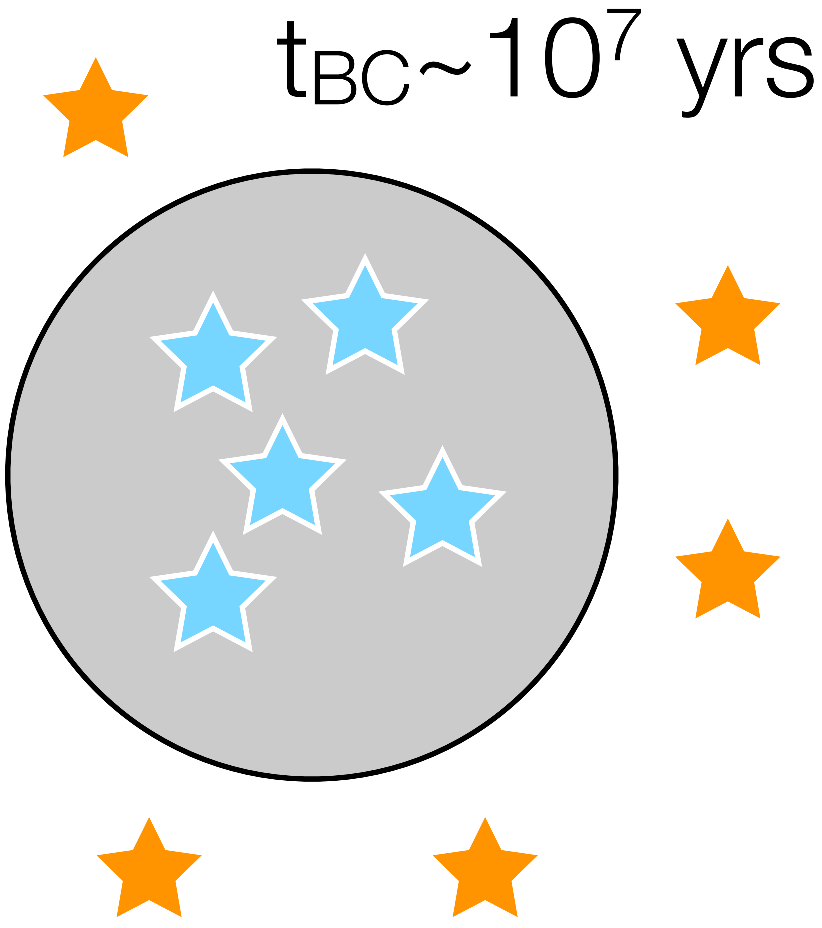
Dust is a good tracer of gas - in the MW at least!

From Dame et al (2001): Based on IRAS 100µm maps it is possible to reproduce the observed CO distribution in the MW way:



See also: Boulanger, Baud & Van Albada 1985; Désert, Bazell & Boulanger 1988, Reach, Wall & Odegard (1998)

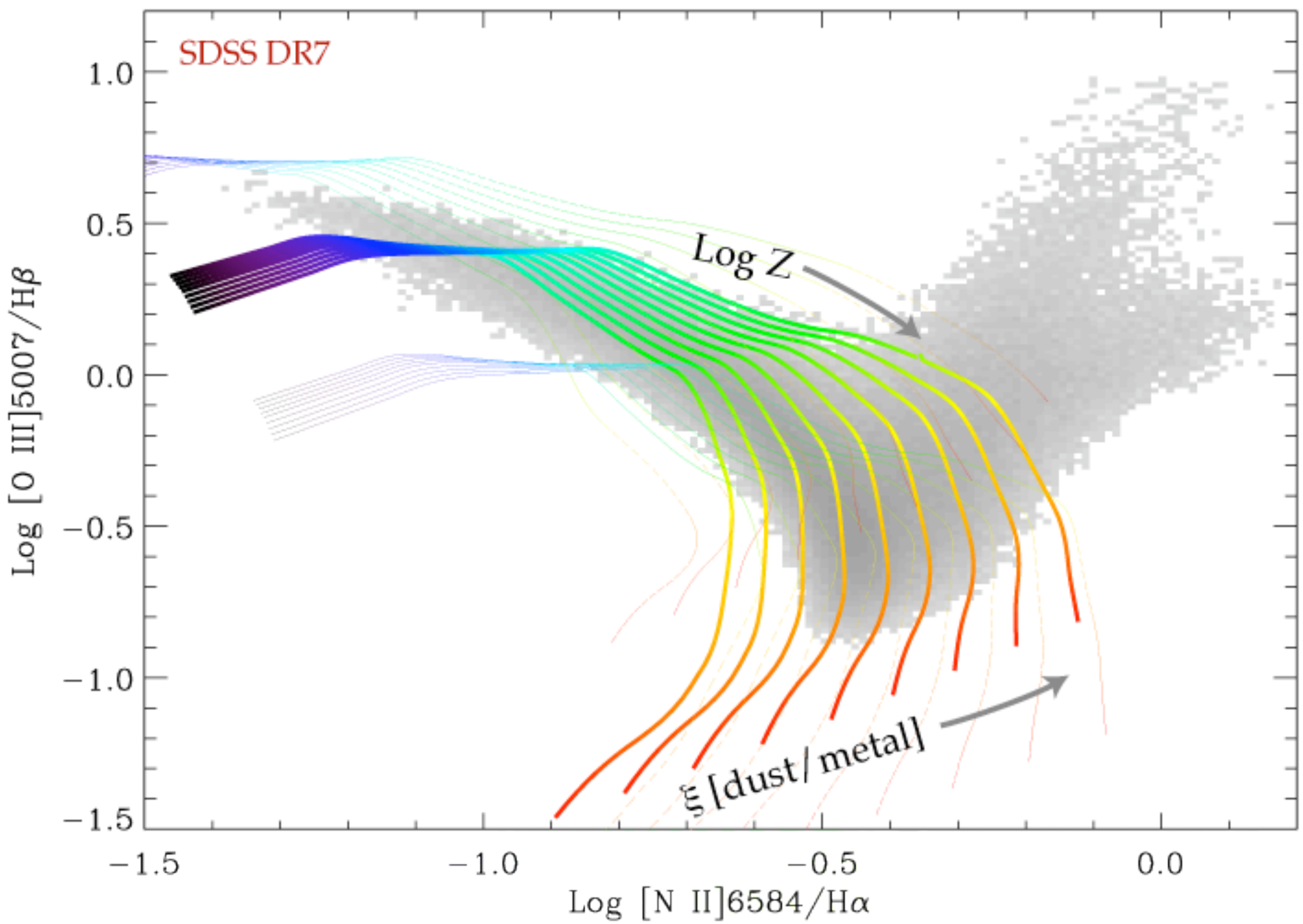
A simple model for line emission



Dust model: Star formation takes place in birth clouds with finite life-time (Charlot & Fall 2000).

Photoionization: Cloudy, as implemented in Charlot & Longhetti (2001). Parametrised by τ_V, ξ, U, Z, time, μ.

Predicting emission lines



Increasing the metallicity increases the cooling.

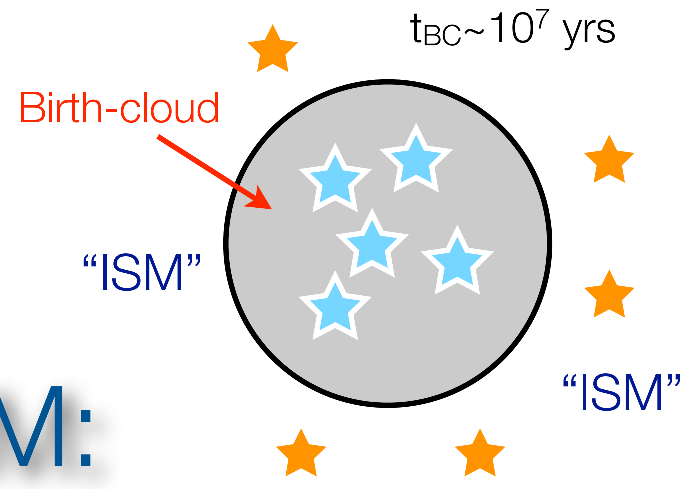
At high temperature this is insensitive to abundance variations, but at low T (high Z), small variations in abundance (for instance due to depletion) has strong effects on the emission lines.

$\xi = \mu_{dust}/\mu_{metals}$

$Z = \mu_{metals}/\mu_{gas}$

So we have dust, dust-to-gas & metallicty

$$\xi = \mu_{dust}/\mu_{metals}$$
$$Z = \mu_{metals}/\mu_{gas}$$



In the ISM:

$$\mu_{gas}^{ISM} \approx \frac{\tau_{ISM}\, m_{dust}}{\sigma_{dust}\, \xi\, Z}$$

In the birth-clouds:

$$\mu_{gas}^{BC} = \frac{\tau_{BC}\, m_{dust}}{\sigma_{dust}\, \xi\, Z}$$

This assumes:

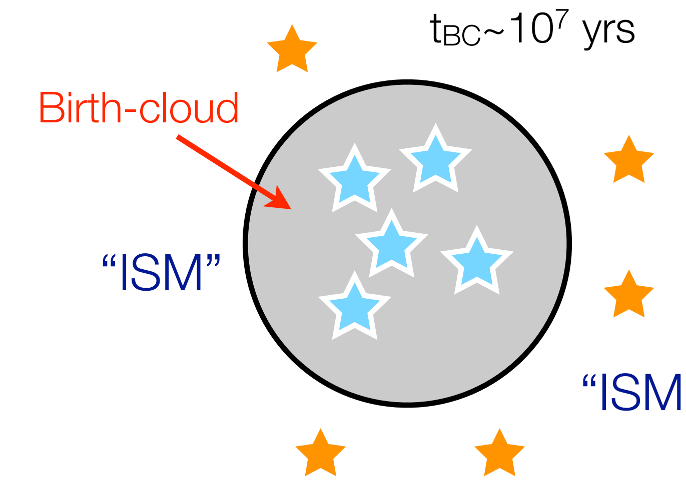
✓That the ISM is not dominated by optically thick clouds, and a Poissonian distribution of clouds.

✓That scattering is typically forward.

✓That Z & ξ are the same in the ISM and the birth-clouds.

So we have dust, dust-to-gas & metallicty

$$\xi = \mu_{dust}/\mu_{metals}$$
$$Z = \mu_{metals}/\mu_{gas}$$



Put together:

$$\mu_{gas} = 0.2 \frac{\tau_V}{\xi Z} \ M_\odot/pc^2$$

$$\mu_{gas}^{ISM} \approx \frac{\tau_{ISM} \, m_{dust}}{\sigma_{dust} \, \xi \, Z}$$

$$\mu_{gas}^{BC} = \frac{\tau_{BC} \, m_{dust}}{\sigma_{dust} \, \xi \, Z}$$

This is sensitive to the total gas column and the absolute scaling is probably uncertain to a factor of 2-3, but **relative measures** should be more reliable.

We estimate this by fitting to a grid of photoionization models and calculate $P(\mu_{gas}|\text{data})$.

Plenty of assumptions - can we test it?

Comparisons to H I data

Match to SDSS
(2165 matches)

H I compilation → Aperture corrections → Compare gas content from H I to that from the spectrum

Springob et al (2005)

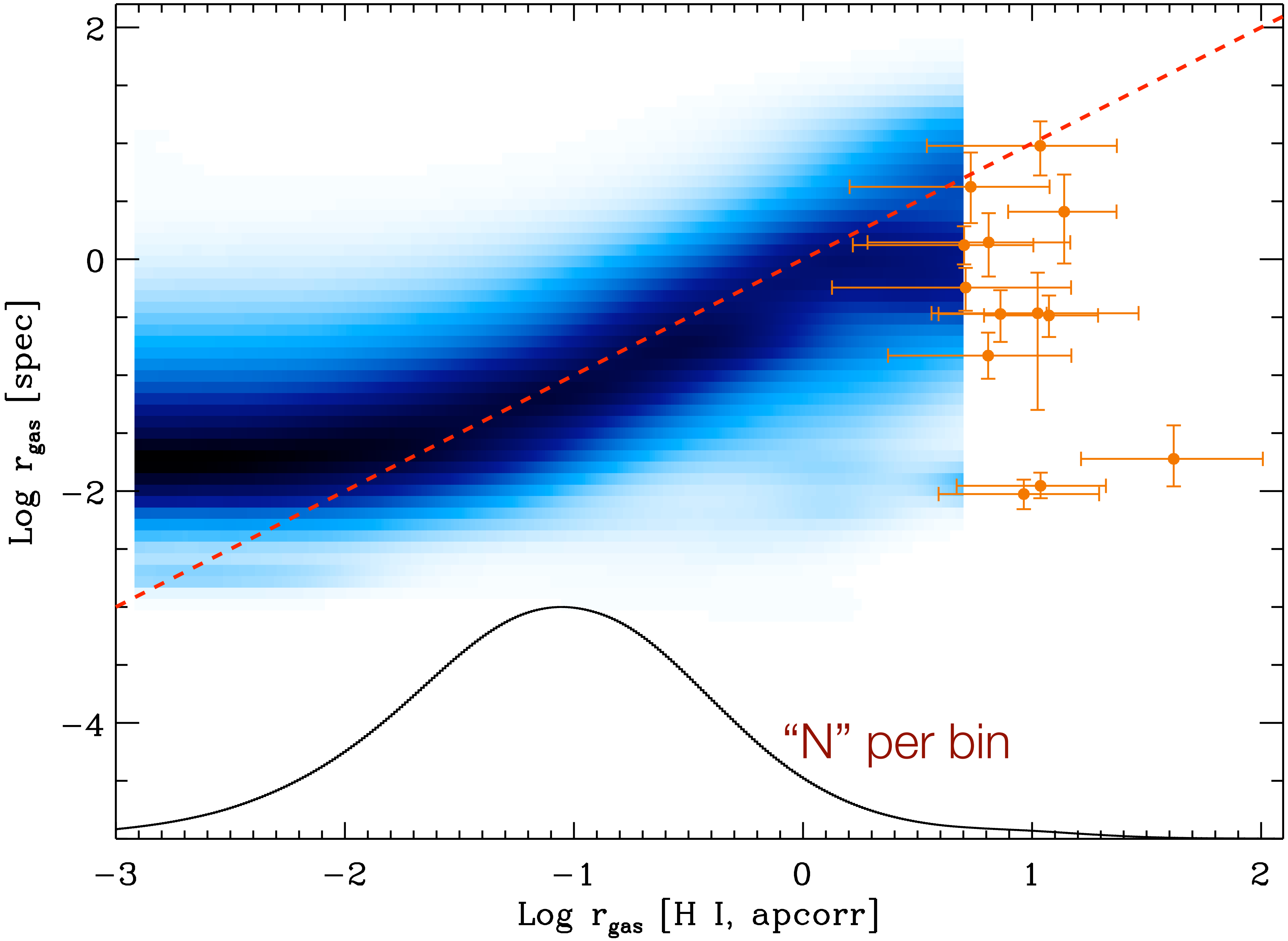
UMa cluster survey (Verheijen et al)
WHISP survey (Noordermeer et al;)

Surface gas density: μ_{gas}
Gas fraction: $f_{gas} = \mu_{gas}/(\mu_{gas}+\mu_{*})$
Gas mass ratio: $r_{gas} = \mu_{gas}/\mu_{*}$

$\mathbf{r_{gas}}$ and $\mathbf{f_{gas}}$ much easier to aperture-correct than $\boldsymbol{\mu_{gas}}$.

We only use H I.
Typical aperture corrections ~ x10 - and non-Gaussian.
We therefore construct full PDFs

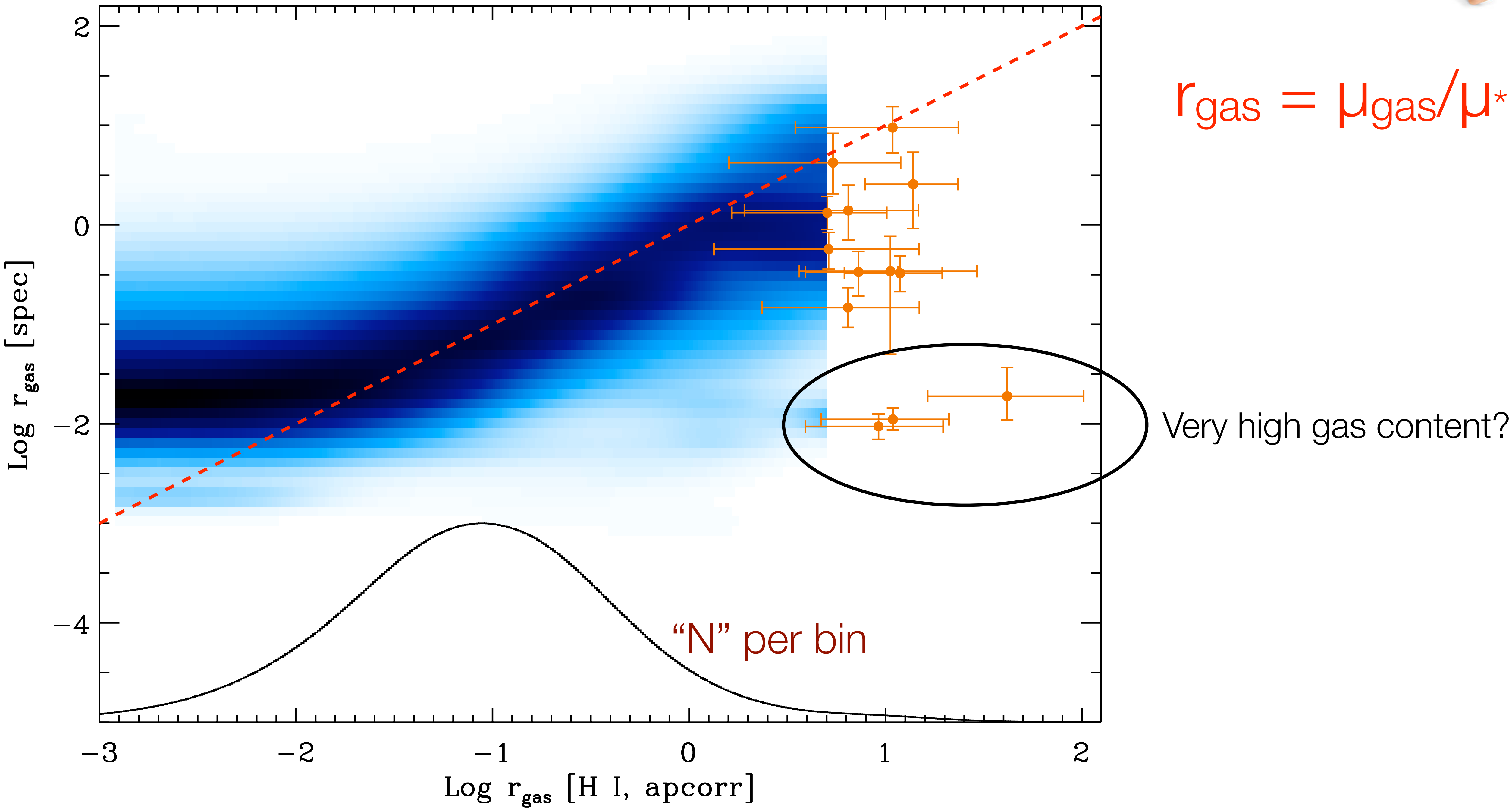
The pudding



$r_{gas} = \mu_{gas}/\mu_*$

Best fit slope is 0.96. The scatter is ~0.5-0.7 dex

The pudding



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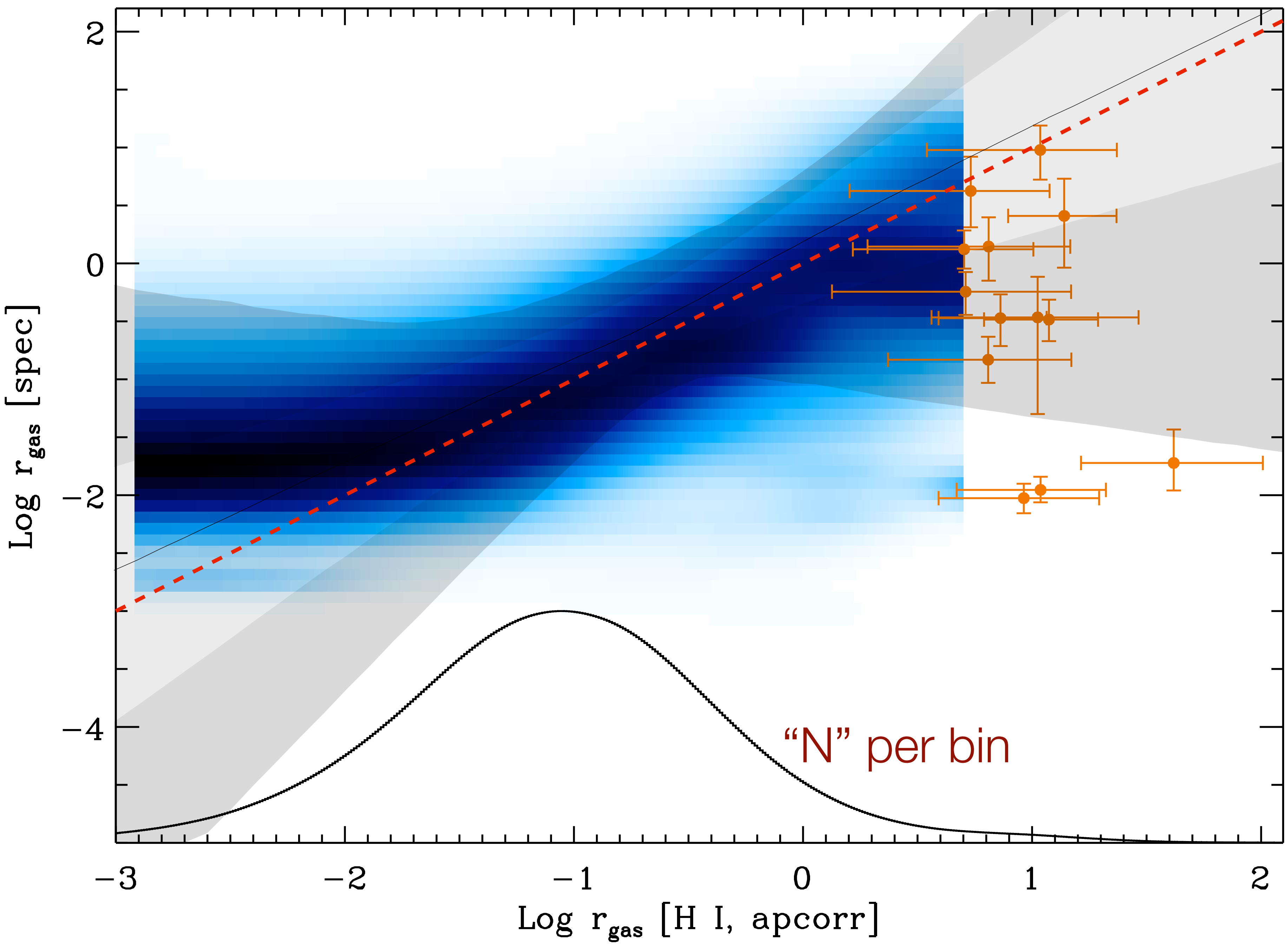
The pudding



$r_{gas} = \mu_{gas}/\mu_{*}$

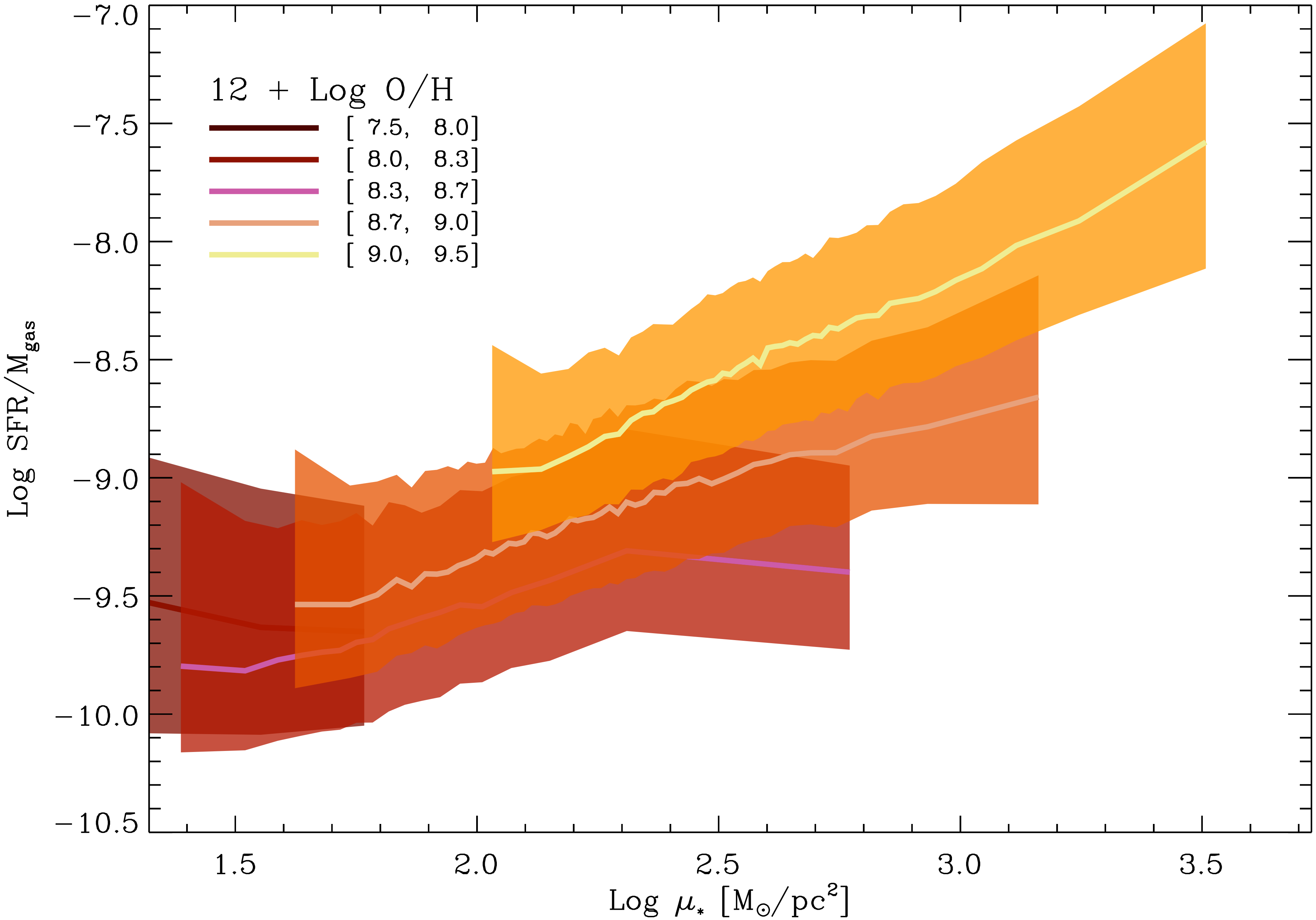
Best fit slope is 0.96. The scatter is ~0.5-0.7 dex

Star-formation efficiency trends

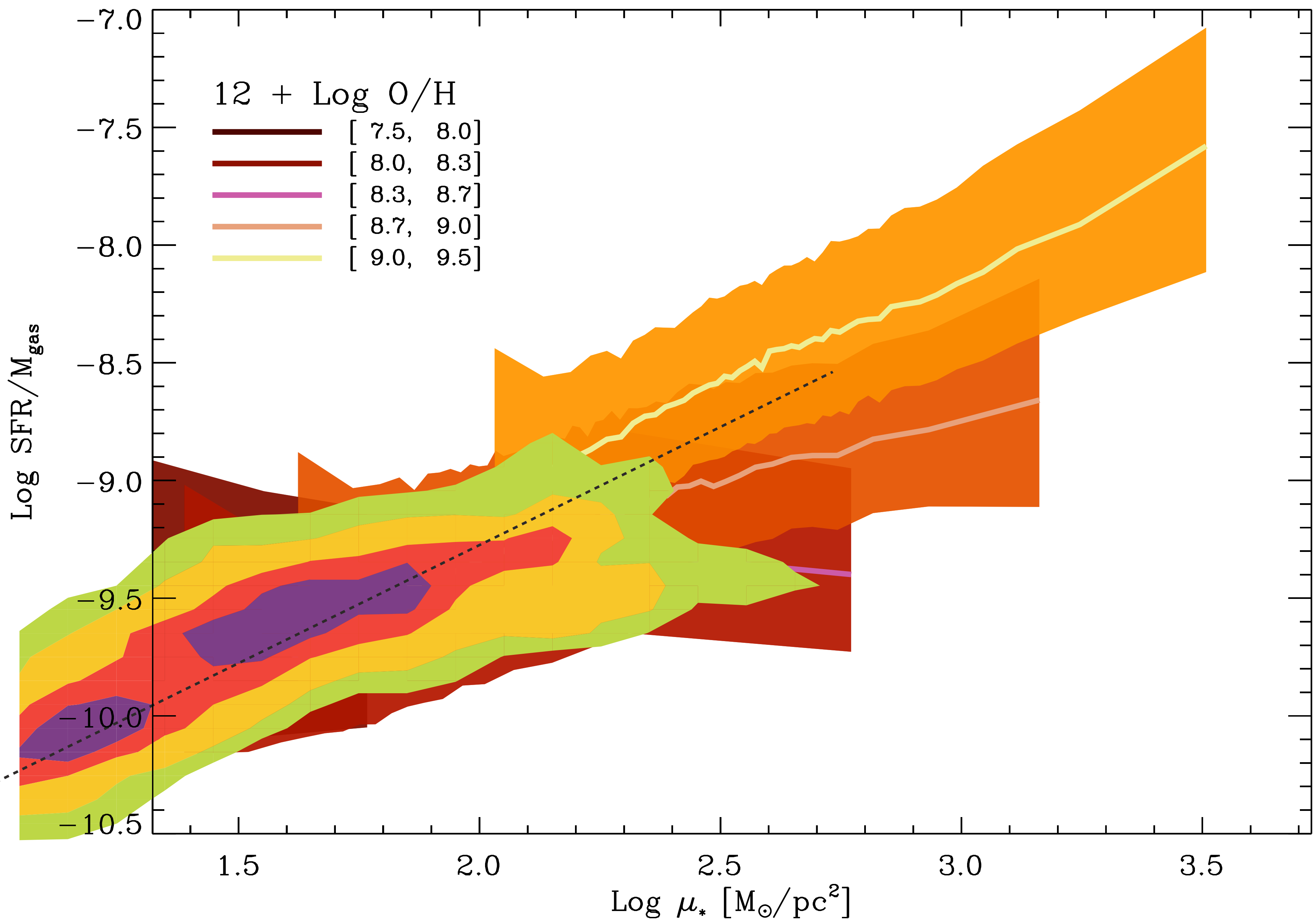
That comparison used only H I data, but we need to test more extensively. A logical next step is to study trends and see whether we recover other known trends.

We will next make use of the relationship between SFR/M_{gas} and μ_*, the stellar mass surface density, found by Leroy et al (2008).

Star-formation efficiency trends

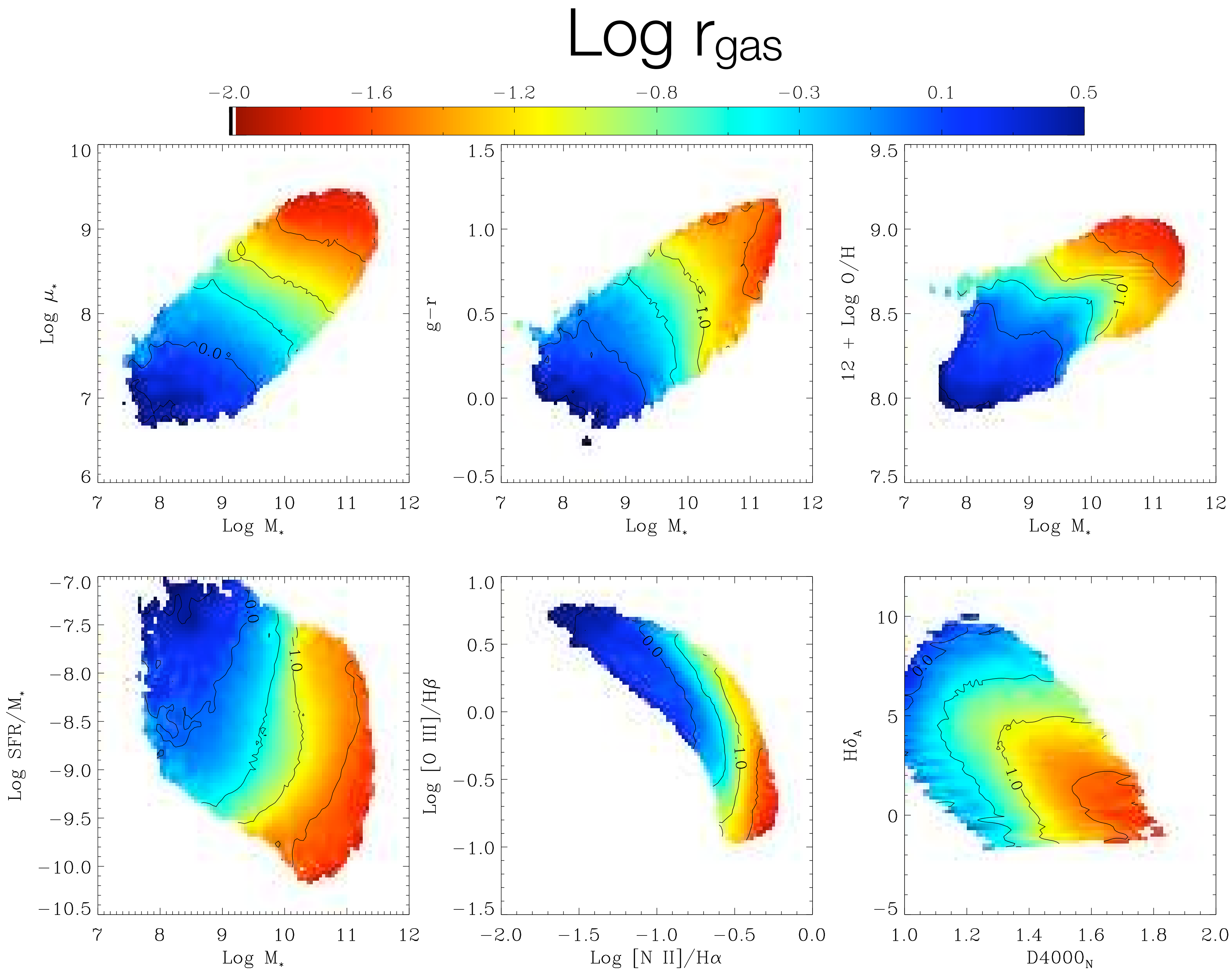


Star-formation efficiency trends

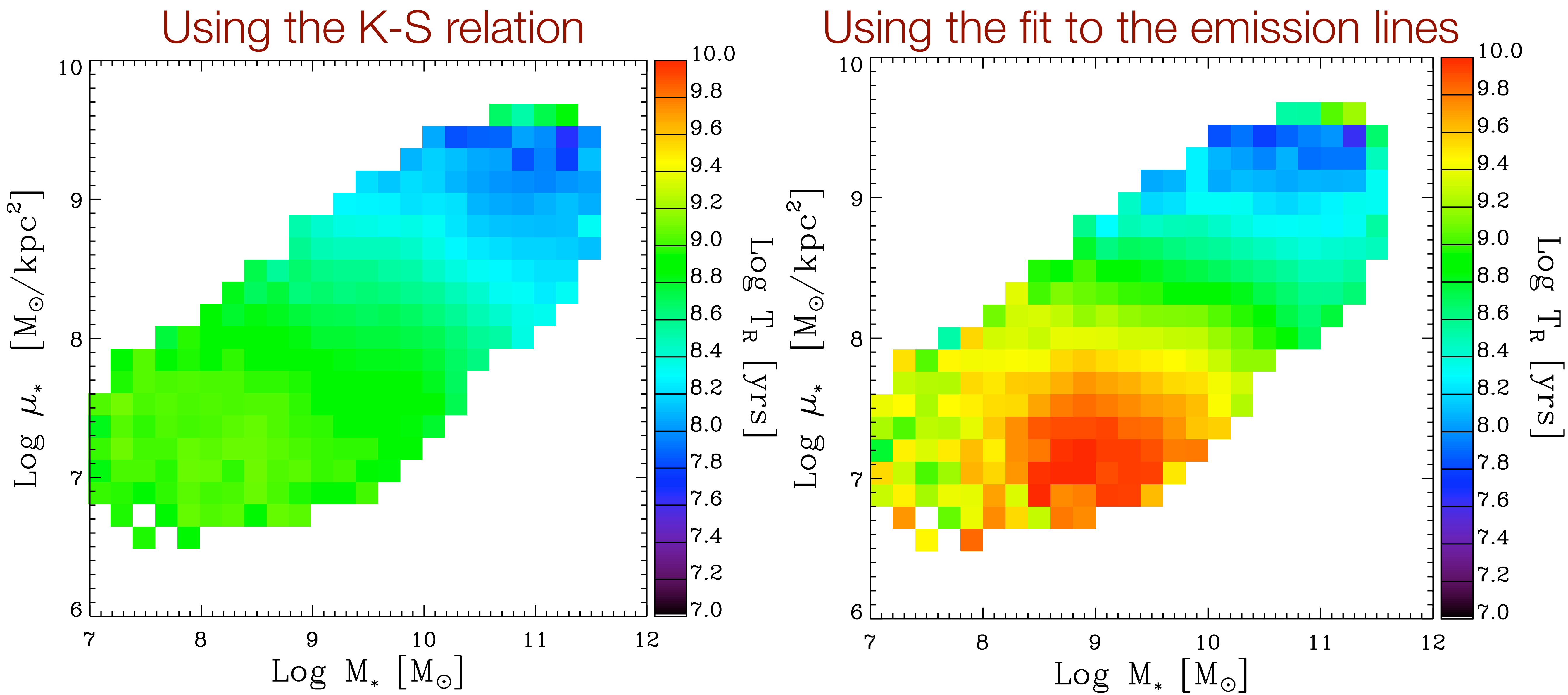


So within the uncertainties we recover well the trend found with stellar surface density in Leroy et al (2008).

Gas-content variation in the SDSS

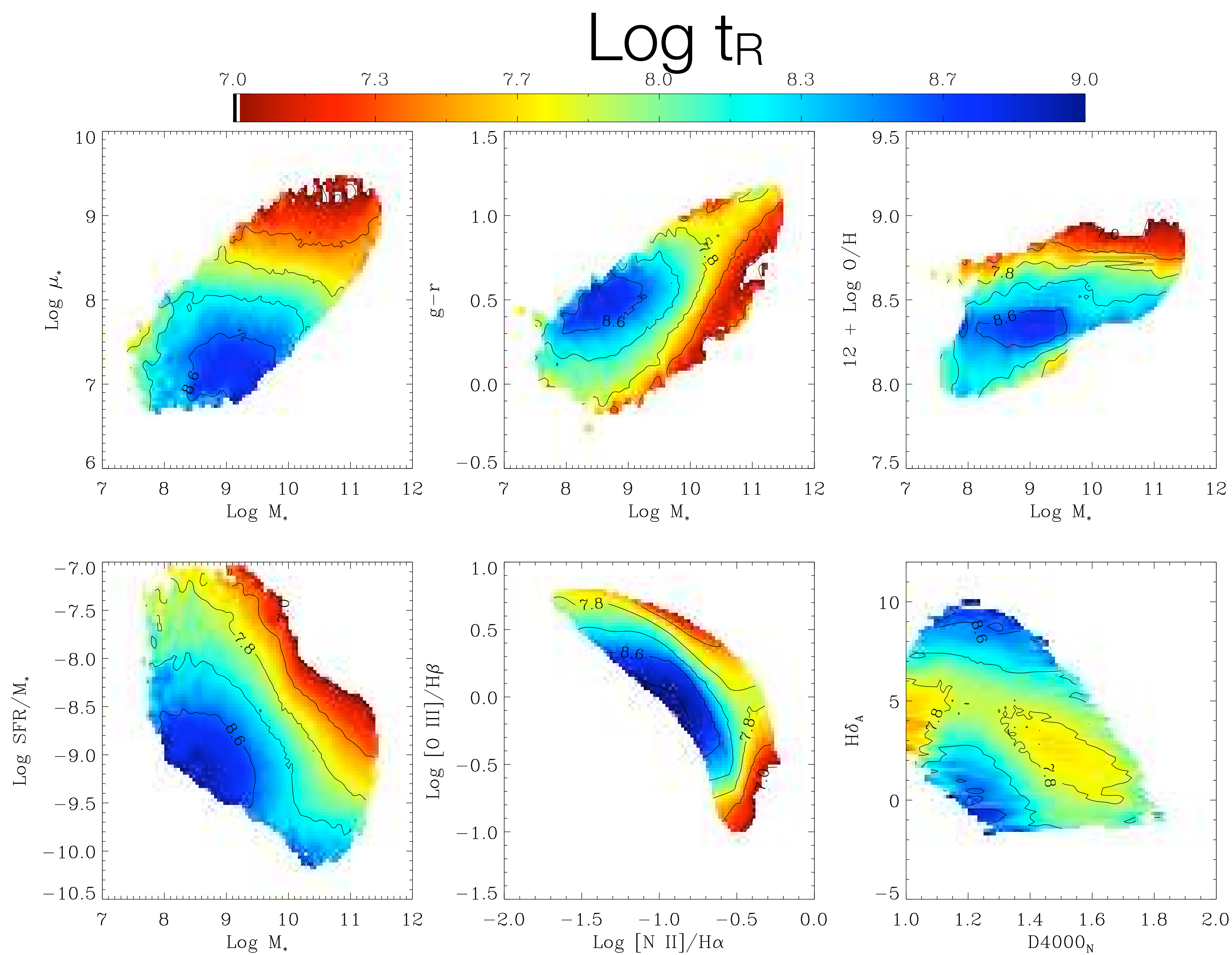


Gas-depletion time-scales ($T_R = M_{gas}/SFR$)

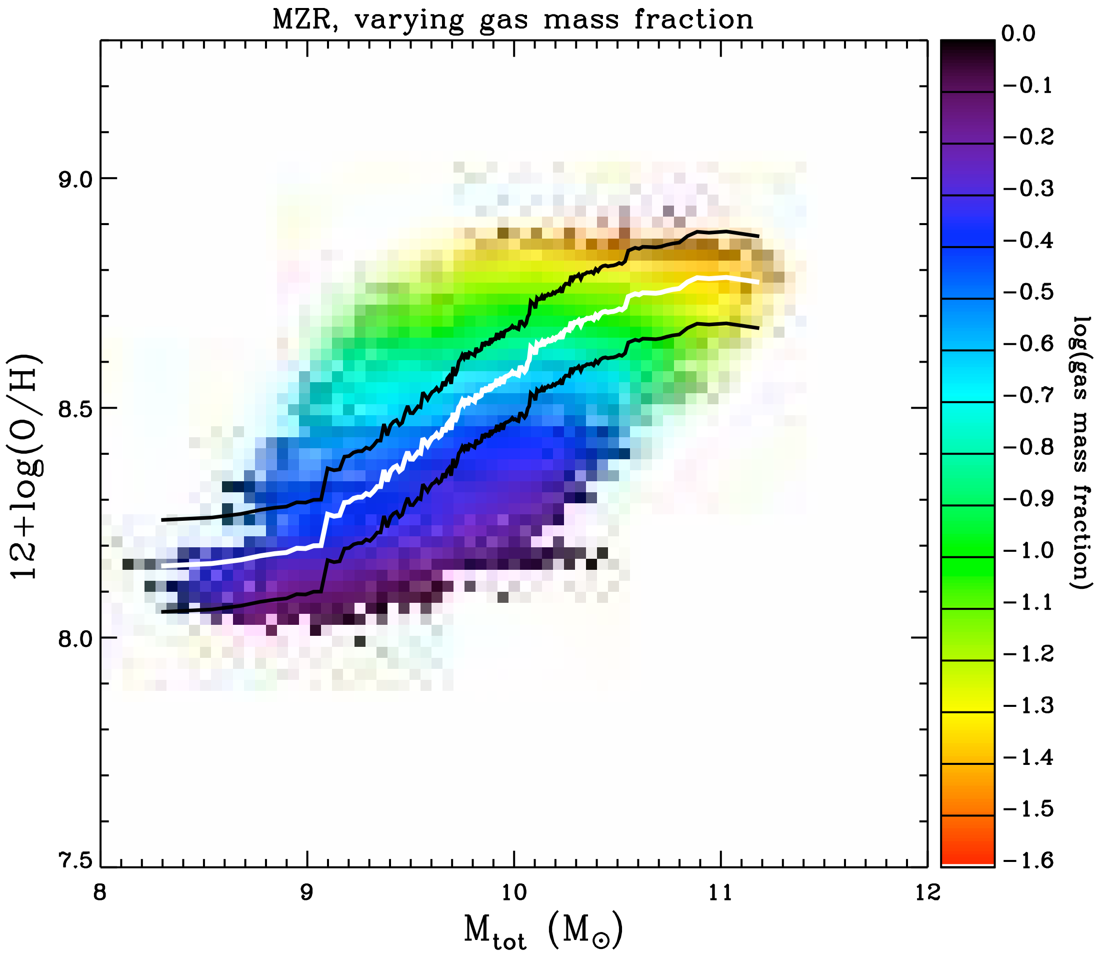


Using the technique described here we identify a set of low surface-brightness galaxies with long depletion time-scales.

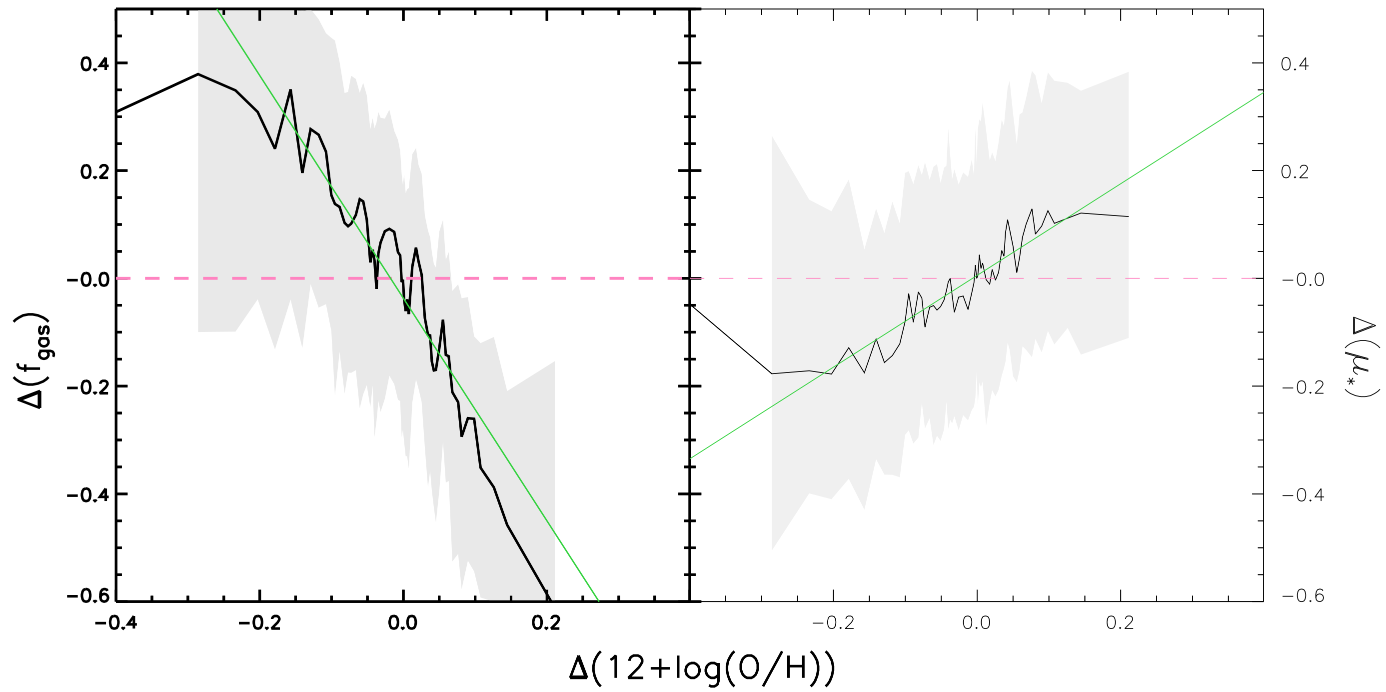
Continuing the depletion time-scale story



The mass-metallicity relation



There is considerable variation in gas content in the M-Z relation. This was also pointed out by Zhang et al (2009) using a different technique.



When quantified we find that the importance depends on what mass you consider, but for massive galaxies, the gas-fraction shows the strongest correlation with offsets in the M-Z relation (infall of low-Z gas?)

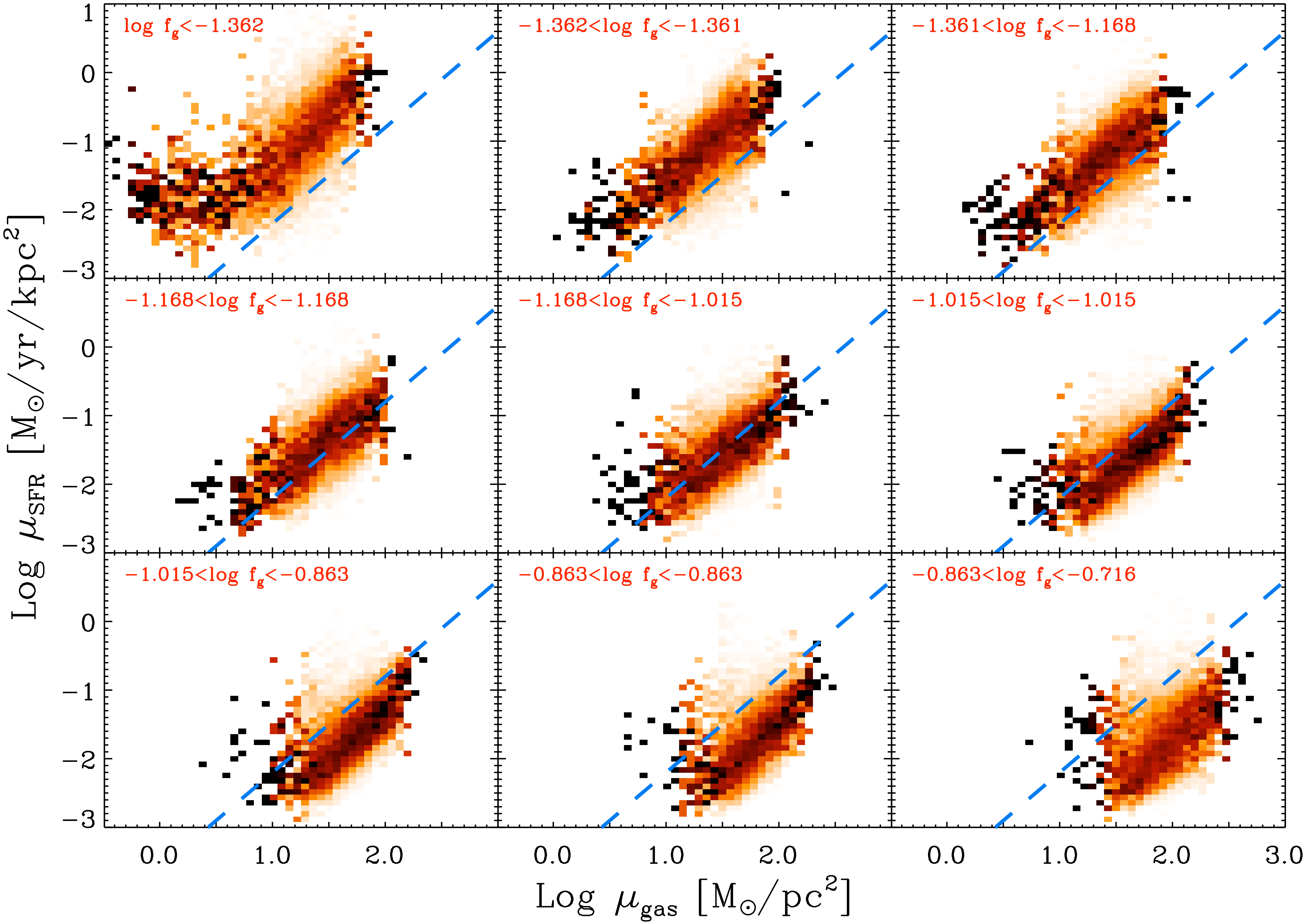
Returning to the K-S relation

It turns out that there is no clear K-S relation if all galaxies are lumped together.

This is not surprising since we span a much larger range in galaxy properties than is usual in these studies.

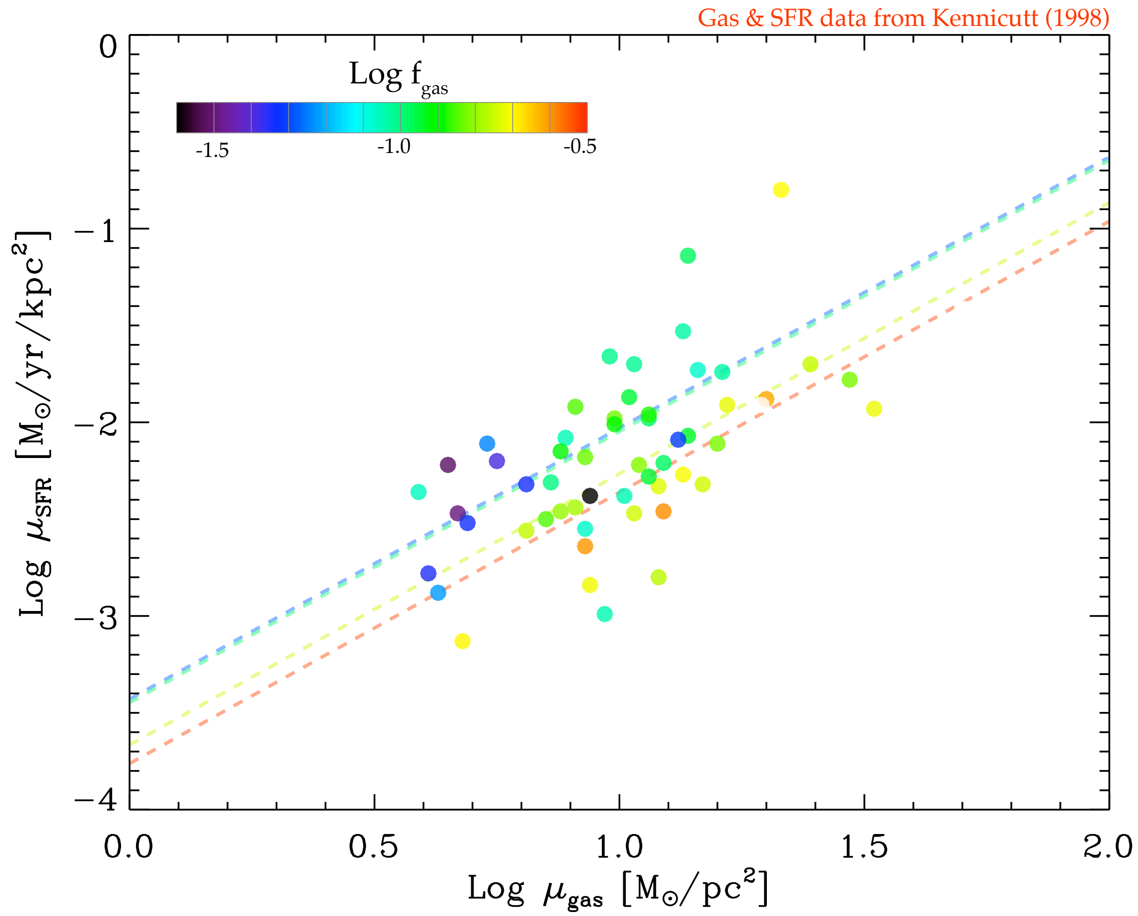
Many splits can be made, the best K-S relation is recovered if the sample is split by gas fraction.

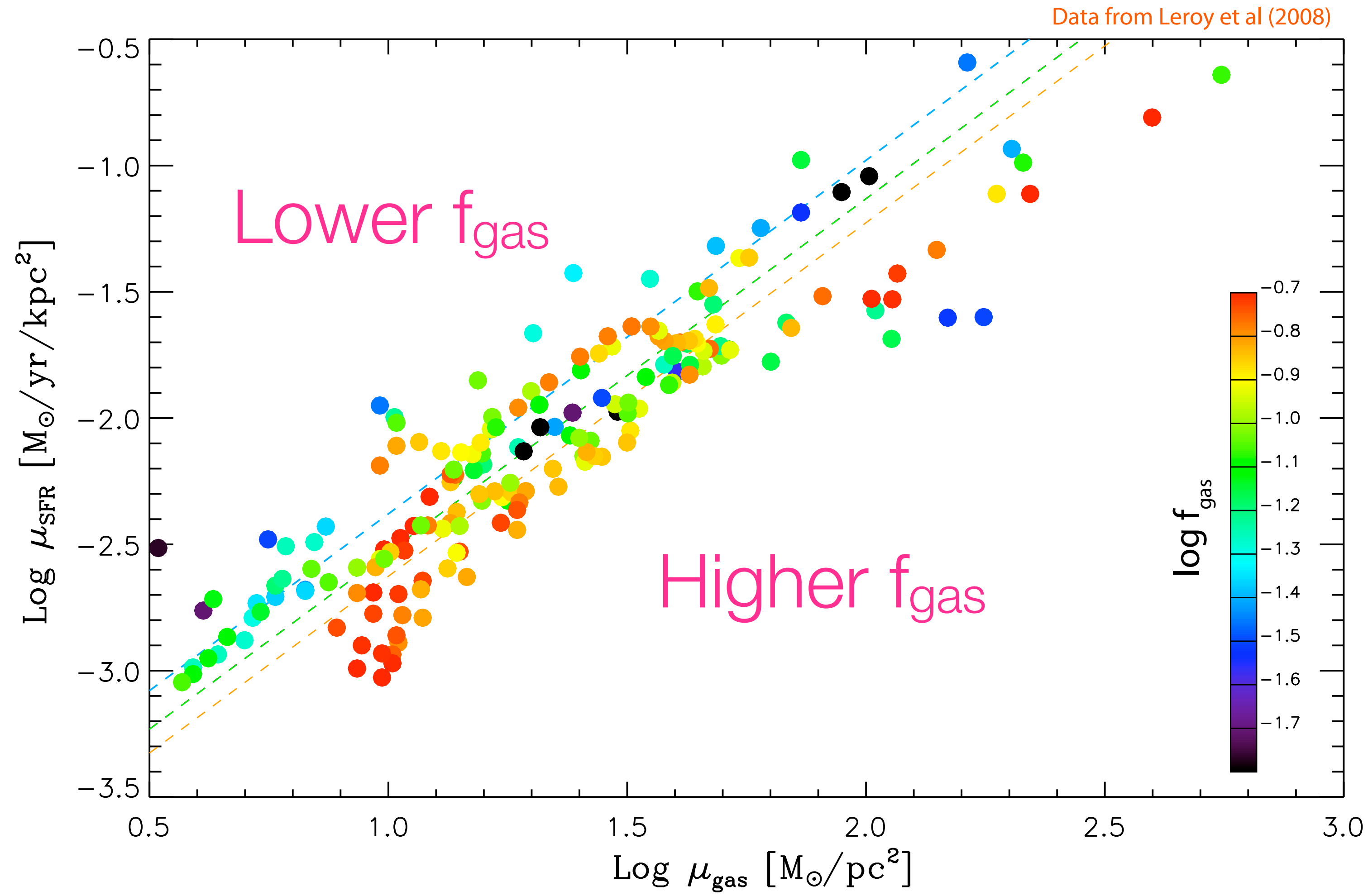
Returning to the K-S relation



Is this consistent with previous results?

Tentatively: Yes.



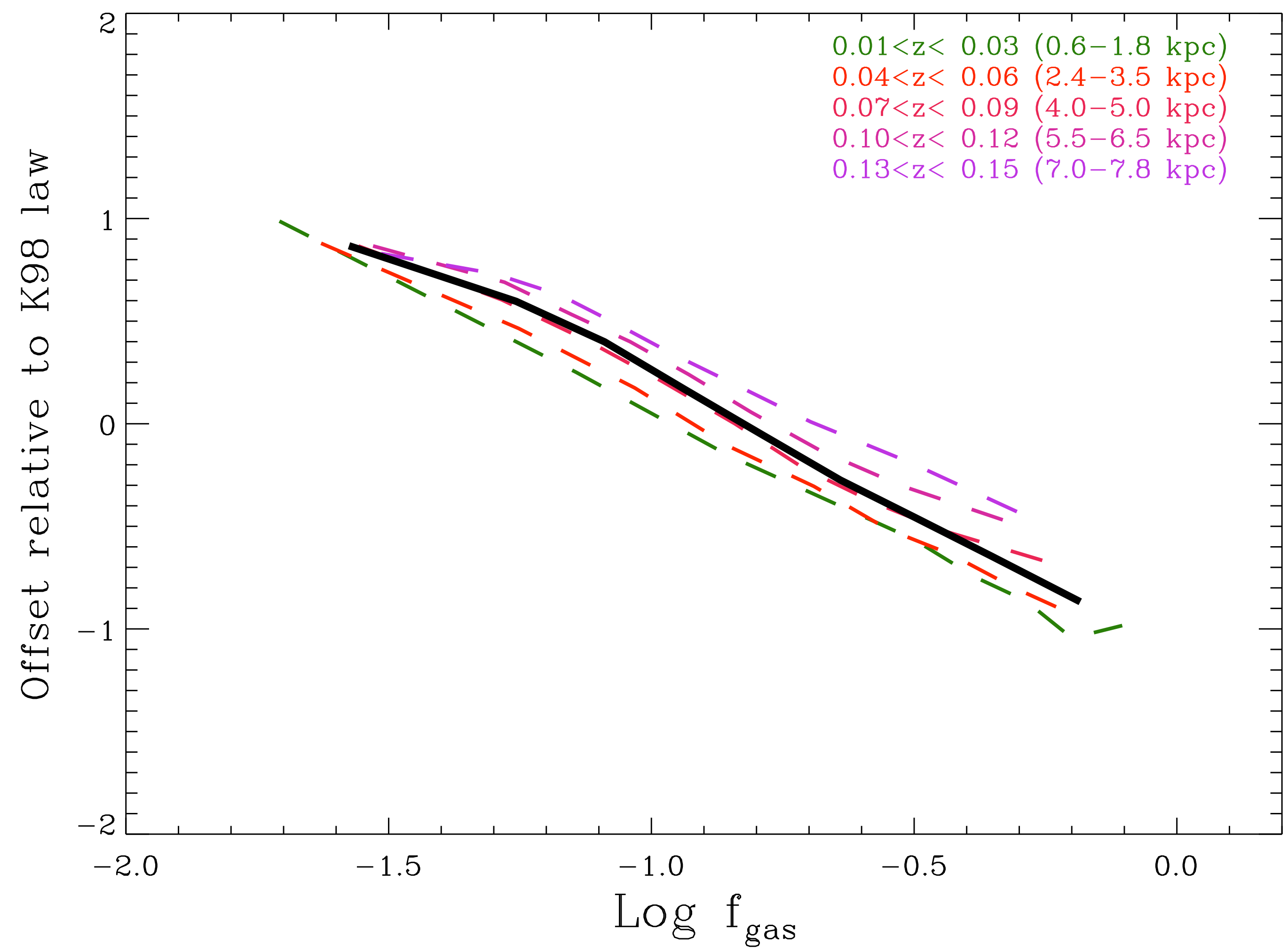


From Kennicutt's (1998) sample of normal spirals.

From the Leroy et al (2008) radial profiles for the THINGS++ data (also see Bigiel et al 2008)

Change in normalisation (SFE) with f_{gas}.

There is a clear shift in the relation with f_{gas}. If we fix the slope to be 1.4, we can estimate the offset relative to the Kennicutt-Schmidt law (splitting by r_{gas} gives the same result).



There is a similar, but weaker, shift with oxygen abundance.

Most other subdivisions of the data washes out any K-S relation.

The overall efficiency of converting gas into stars on 0.7-10 kpc scales depends on f_{gas}.

Conclusions

- It appears that estimating gas content from optical spectroscopy is possible, albeit with some limitations (e.g. does not trace optically very thick gas, total gas estimates depend on very uncertain aperture corrections etc.)
- Application to the SDSS shows a population of low surface density systems with very long depletion time-scales and a clear correlation between gas content and offset in the mass-metallicity relation - at least at high mass.
- We recover a Kennicutt-Schmidt-type law, but the overall normalisation appears to change systematically with gas fraction.
- A promising new technique in the toolbox for inferring the physical properties of distant galaxies, but also hopefully a useful complement to direct measures of gas content.