Questions about Star Formation Efficiency

+ interest in molecular cloud formation. The latter is the first step towards star formation and may/should influence it.

+ OQ on CO as tracer of H_2

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Star Formation Efficiency

Two definitions: $SFE=SFR/M_{gas}$ or $SFE=SFR/M_{H2}$
When interested in the transformation into stars rather than the whole cycle, use $SFE=SFR/M_{H2}$

Uncertainties: variability of IMF (measure of SFR) ?
measure of M_{gas} and particularly M_{H2}

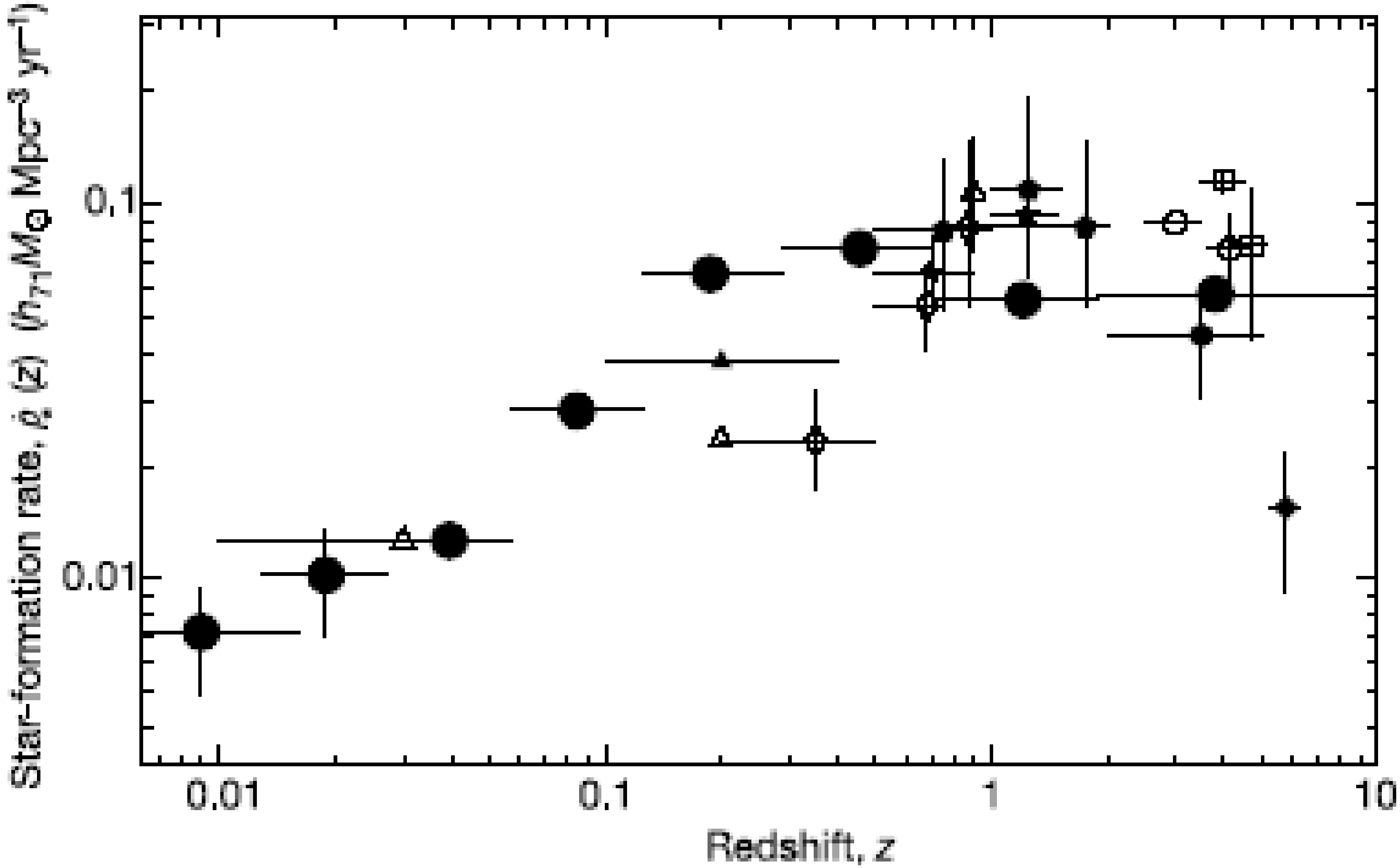
In the large spirals that dominate today's universe, the SFE, the inverse of the molecular gas consumption time, is about
$SFE = dM/dt / M(H2) \sim 1/(2 \times 10^9)\ yr^{-1}$ (Kennicutt 1989, 1998; Murgia et al 2002).

However, in the Kennicutt but also Blitz, Leroy, Rosolowsky articles, the SFE of small, subsolar metallicity galaxies appeared high but the measure of the H_2 mass was quite uncertain. The SFE in ULIRGS is also quite high: attributed to high dense gas fraction, like in gal nuclei.

Here we present observations of M33 to try and answer this question.

The Cosmic Star Formation Rate increases by a factor 10-30 to redshift 0.5 - 1

(Heavens et al 2004 below but also Madau et al 1996, Wilkinson et al 2008 .....)



Galaxies smaller and bluer with less stellar enrichment at earlier epochs.

Local galaxies with these characteristics (e.g. M33) have low H2/HI ratios.

H2 in Milky-Way like galaxies not yet detectable at redshift ~1 but clearly SFE quite high (i.e. higher than local large spirals). What factors control the SFE ?

OQ: Can we measure the H2 mass ?

Via CO ==> what is CO to H_2 conversion factor ?

In the Milky Way, most of the molecular gas is in GMCs.

==> If we can measure their properties, then estimate GMC masses and total H2

==> Need to be able to resolve molecular clouds. **M33 !**

"Virial" masses provide an overestimate to cloud masses (real mass is lower if cloud not in "virial" equilibrium) but good first step.

Other check -- isotopic lines such as ^{13}CO, other transitions of CO, HCN

If ratios very different from Milky Way disk, then cloud sizes or CO optical depths may be very different (DANGER).

If not, virial masses probably OK (not underestimate) or even a scaling of a "Galactic" conversion factor.

Via dust measurements ==> uncertainty in dust temperature and cross-section *Totally independent of CO*. Can also "calibrate" on likely H2-free zones.

Estimate total gas mass from dust emission then subtract HI to estimate H_2 mass (e.g. Israel 1997, Gratier et al 2009). Can also try using PAH emission, implicitly assuming a constant cloud structure.

Sodroski 2005 (and others) found H2/CO ratio increases with distance from center.

Yes we can ! (at least in nearby galaxies)

The star Formation Rate in M33

The estimates for the SFR of M33 from Halpha, dust continuum, or UV emission fall in the range SFR = 0.5 ± 0.2 solar masses per year.
(Hoopes & Walterbos, Greenawalt, Kennicutt, Blitz & Rosolowky, Hippelein...)
This makes assumptions about the IMF (typically assumed to be Salpeter) but a variation in the IMF would be as interesting as a variation in the SFE.

H2 mass from CO:

Rosolowsky et al 2007: 1.2 10^8 solar masses

Heyer et al (2004): 2.6 10^8 solar masses

Gardan et al (2007): 1.2 10^8 solar masses extrapolated from NE quadrant

Allowing for a metallicity gradient of .05dex/kpc starting from solar at the center and H2/CO ~ Z, the NE quadrant H2 mass increases by 50%.

What is new ?

Virial mass estimates

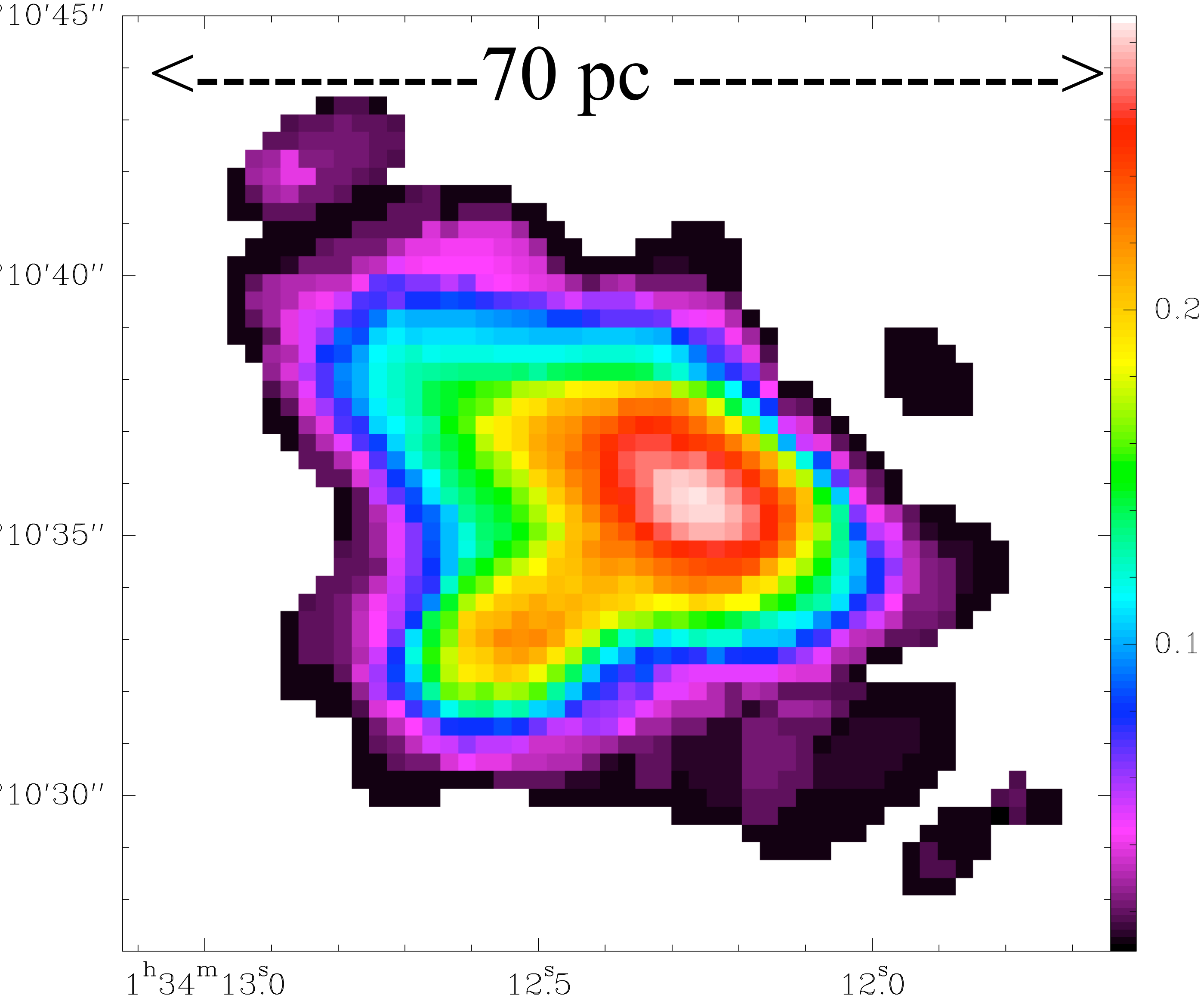
^{13}CO observations

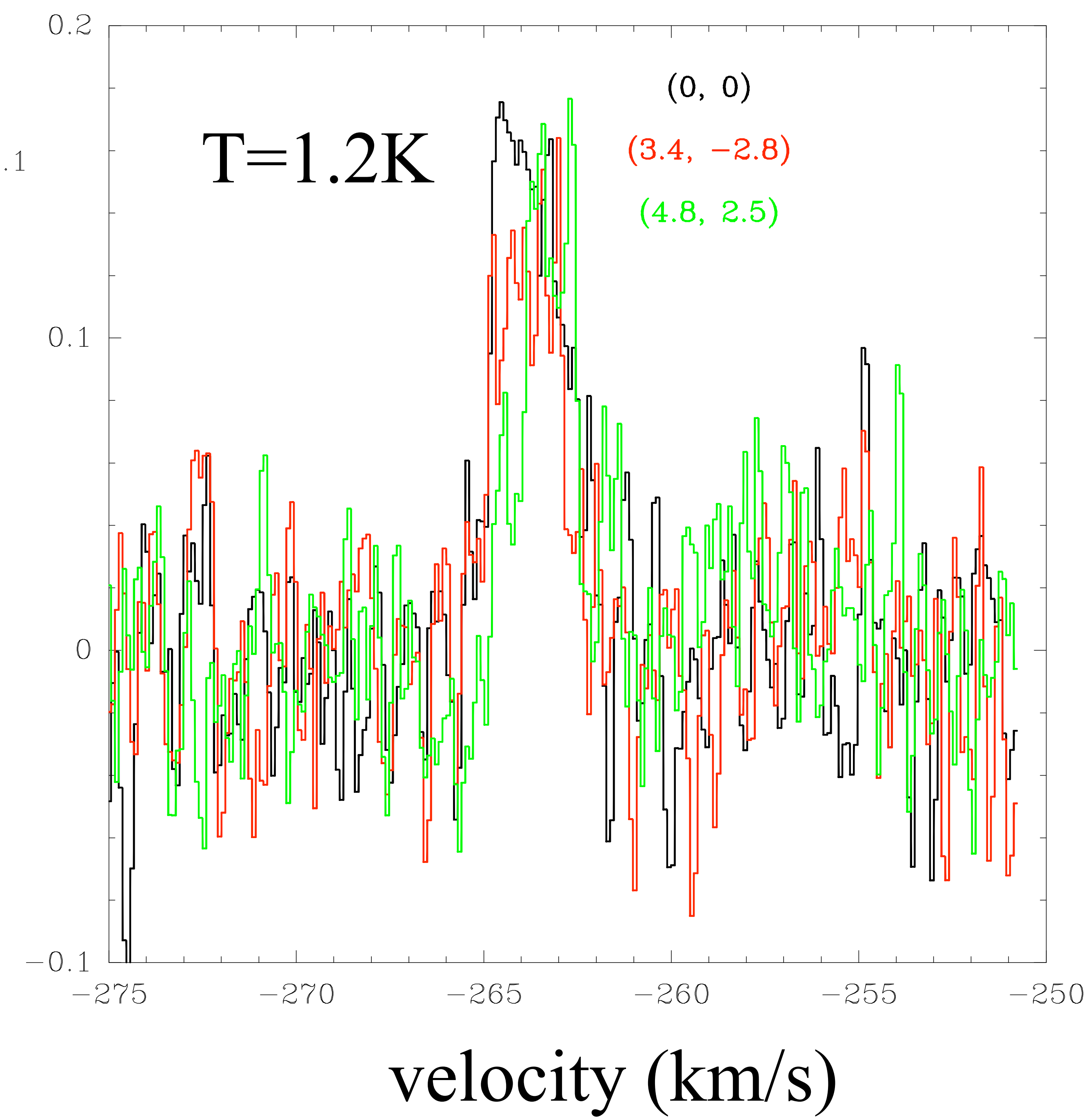
High-res observations of GMCs

Other tests with dust observations

M33

CO(1-0) observations with the Plateau de Bure resolve the outer disk cloud. Narrow line.



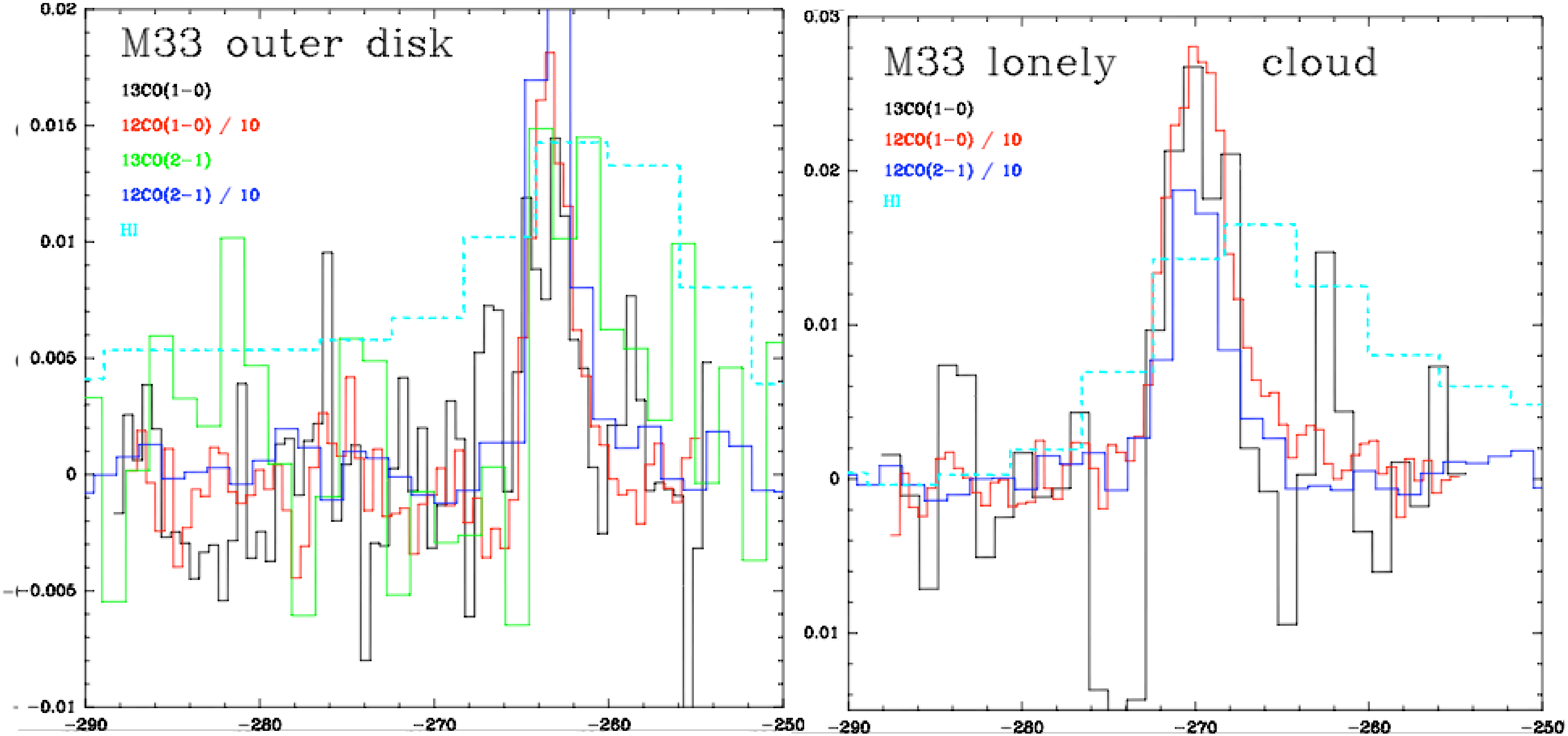


Integrated intensity and spectra at 3 positions in the outer disk GMC of, M33, beyond R_{25}.

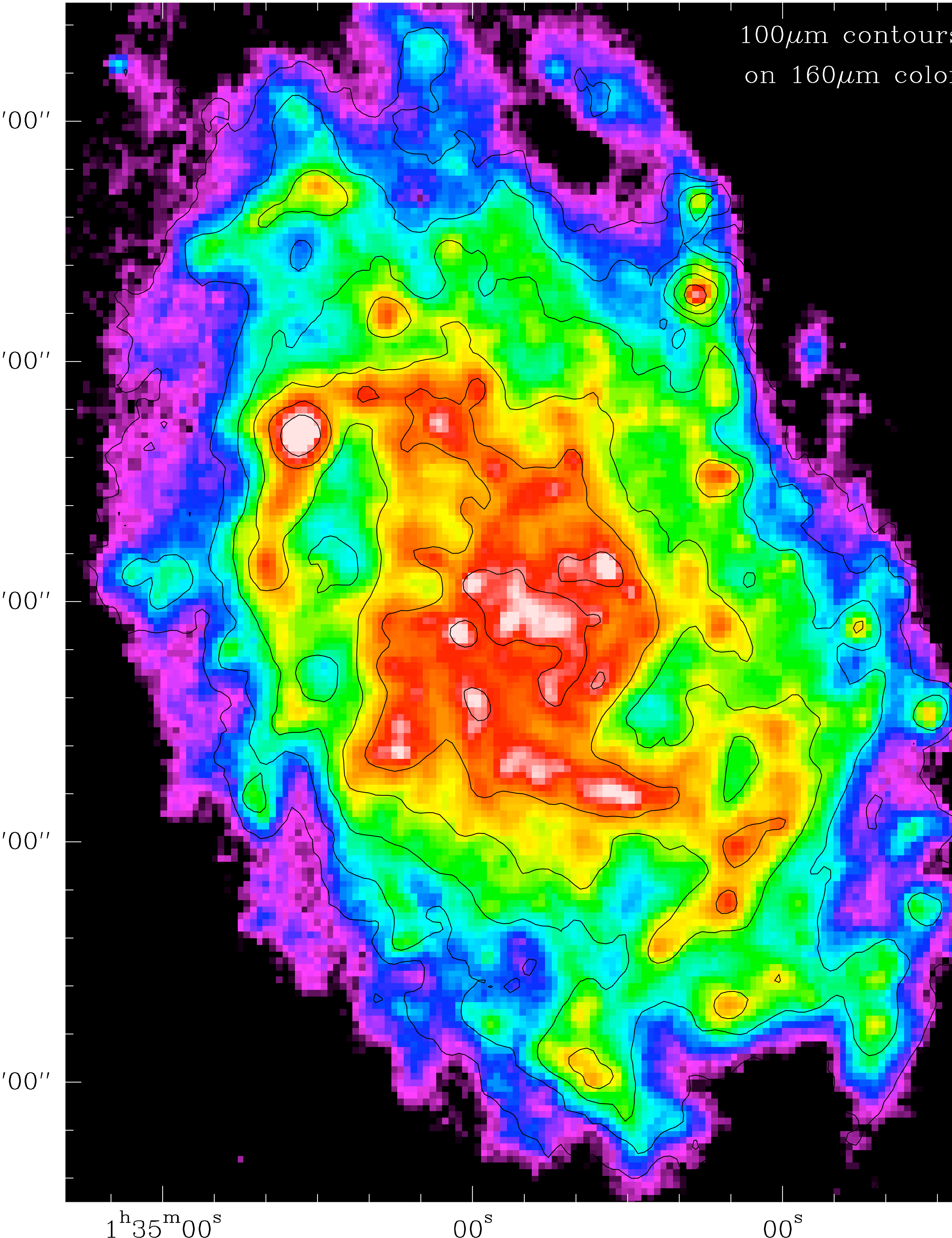
Note how strong the CO line is despite the subsolar metallicity and low radiation field: over 1K at 12pc resolution!

13CO observations of M33

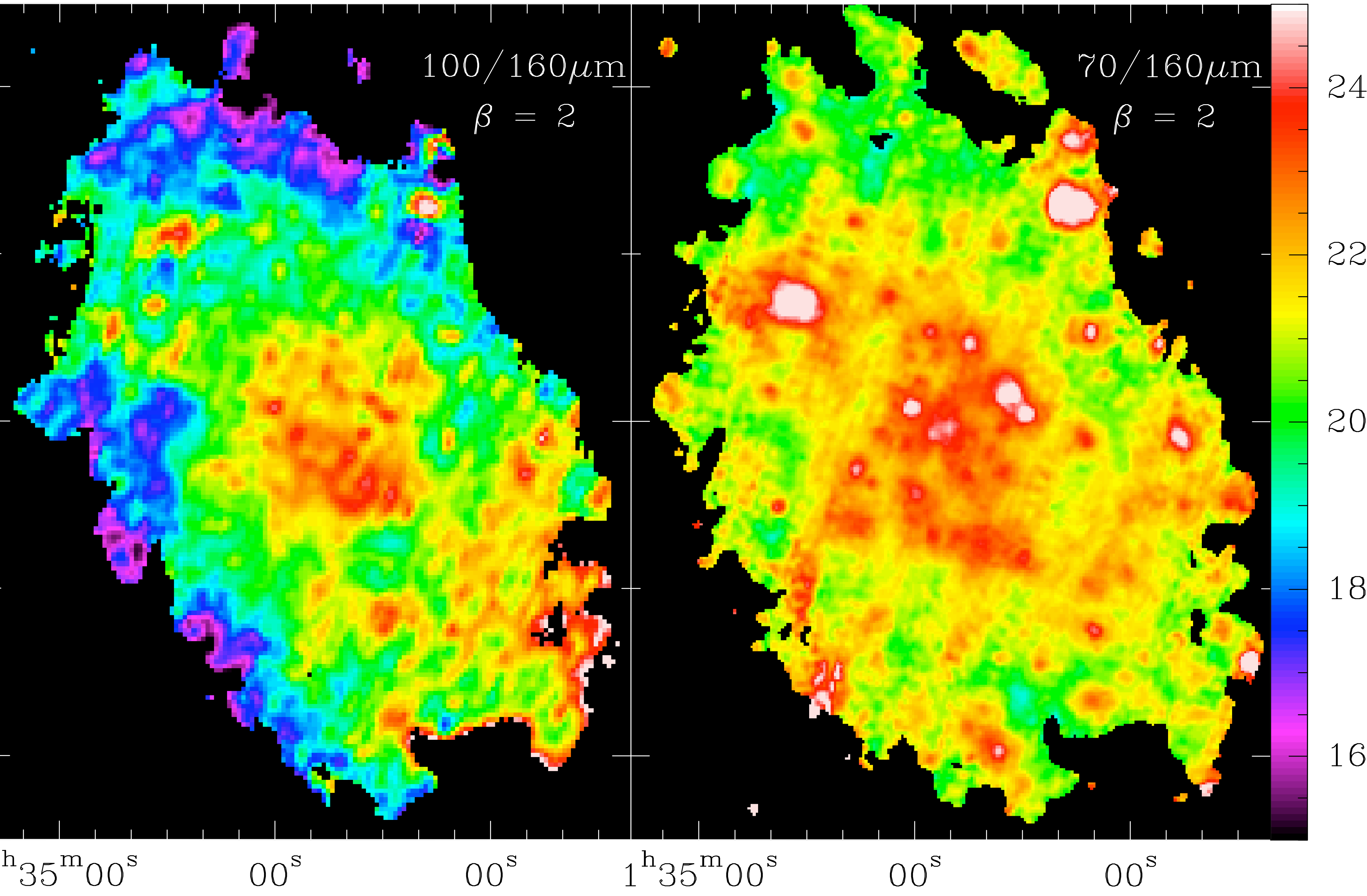
Even beyond R25 ("outer disk" cloud), the 13CO is detected with a fairy normal line ratio of $^{12/13}$CO ~ 10, showing that the gas is quite optically thick in 12CO.



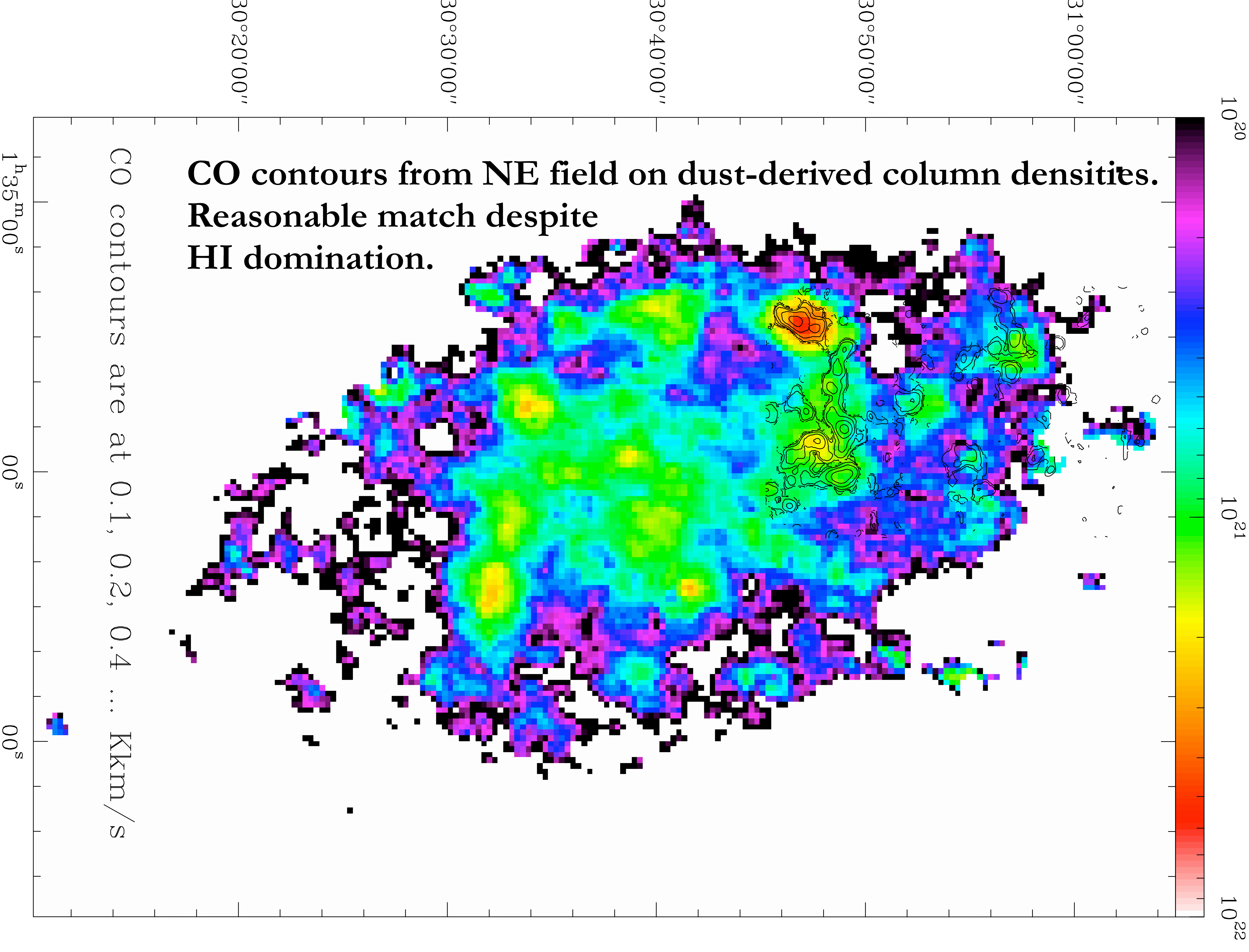
"Virial" theorem suggests NH2/Ico ~ 4 -6 x 10^{20} cm^{-2}/(Kkm/s)


100μm contour
on 160μm colo
'00''
'00''
'00''
'00''
'00''
1h35m00s
00s
00s

Note the temperature difference between using the 70/160 ratio and the 100/160 ratio. The 70 micron traces a mixture but the 100 almost only cool dust.



CO contours from NE field on dust-derived column densities. Reasonable match despite HI domination.



H_2 mass measurement from dust

We use the Draine & Lee (1984 but very similar to 2001 and 2007) dust cross-section. Originally estimated for diffuse gas in the Milky Way near the sun, we scale by the ratio of the metallicity in M33 to solar. The DL cross-section is lower than that used by Mezger or Chini/Kruegel or Guelin. A low cross-setion (in cm^2 per H) yields a higher gas mass.

Dust cross-section appears reasonable because in regions expected to be empty of H2 the H column density was close to that of the HI.

Our best estimate yields M(H2) ~ 2.4 10^8 Msun, equivalent to the Gardan or Rosolowsky estimates scaling by Z or close to Heyer et al..

For an SFR of 0.5 Msun/yr, this results in an SFE of 1/5e8 yr^{-1}, a transformation rate 4 times greater than in large spirals.

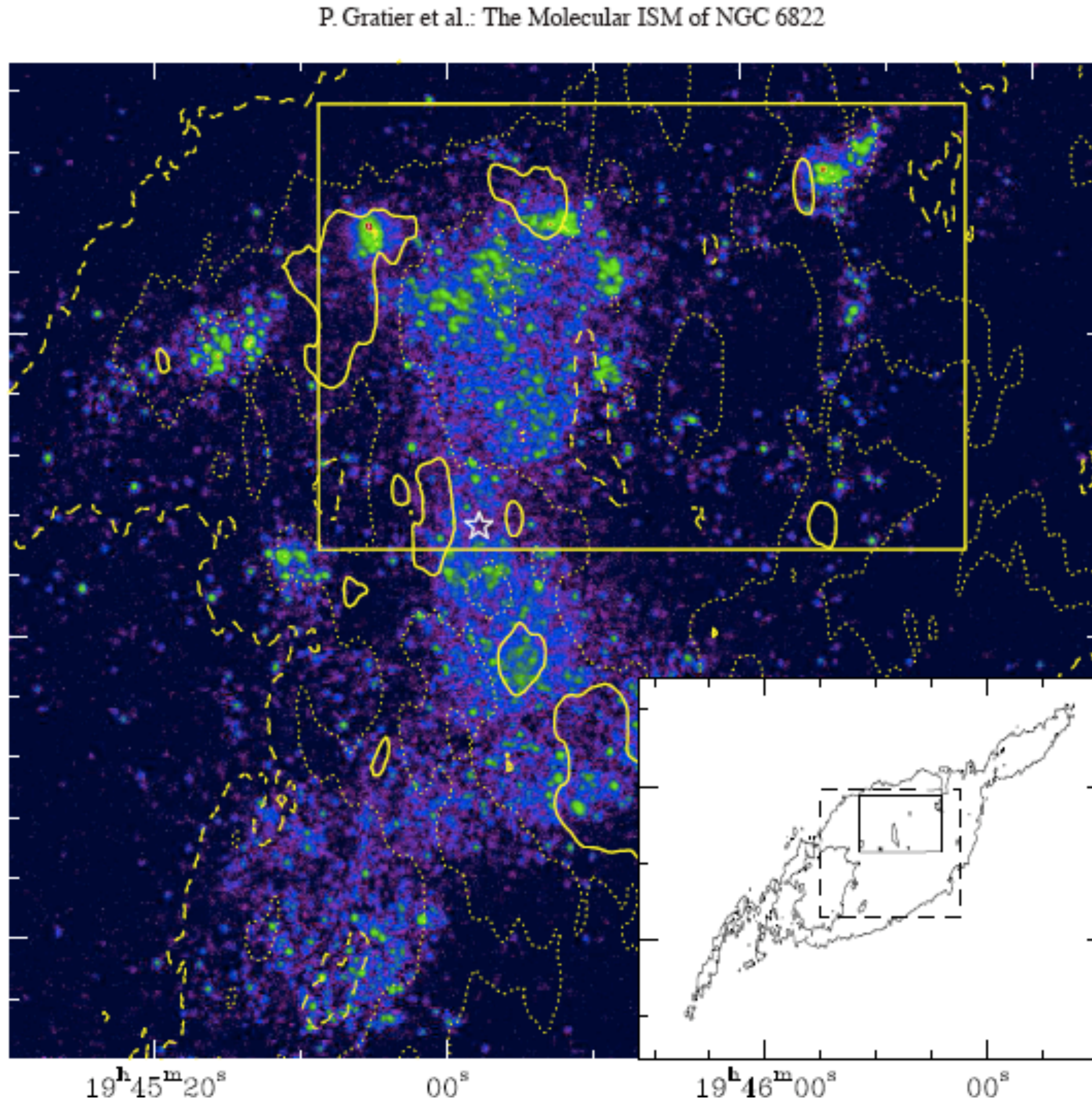
H_2 mass measurement in the Dwarf NGC 6822

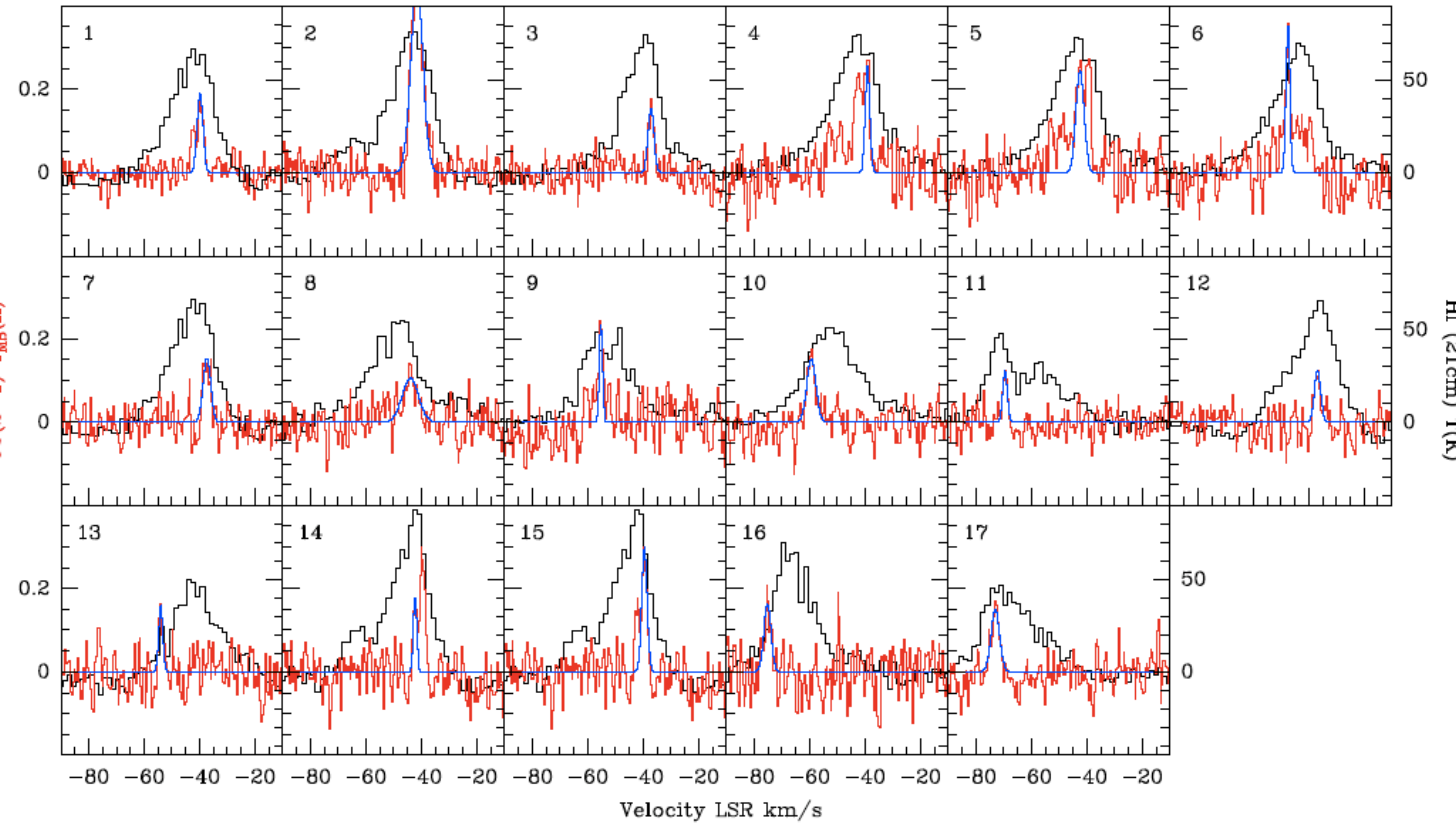
Gratier et al (2009) present similar work for the Local Group dwarf NGC 6822.

The NH2/Ico estimates for this lower-metallicity galaxy are very high, in the range 2 -- 5 10^{21} cm^2 per Kkm/s, rougly an order of magnitude greater than in the Galaxy and several times the M33 value. Dust cross-sec checked on H2 blank regions.

SFE ~ 1/2 10^8 yr^{-1}.

Estimate of H2 mass from 8micron as well.




1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
0.2
0
50
−80 −60 −40 −20
Velocity LSR km/s

NGC 6822

Method		$N(H_2)/I_{CO(2-1)}$ $cm^{-2}/K\ km\ s^{-1}$	Range $cm^{-2}/K\ km\ s^{-1}$
8μm	by eye	$1.9 \pm 0.8 \times 10^{21}$	$0.8 - 3.0 \times 10^{21}$
	CPROPS	$1.9 \pm 1.0 \times 10^{21}$	$0.7 - 3.8 \times 10^{21}$
160μm with	by eye	$1.7 \pm 0.9 \times 10^{21}$	$0.4 - 3.2 \times 10^{21}$
T_{dust} map	CPROPS	$1.4 \pm 1.0 \times 10^{21}$	$0.3 - 3.0 \times 10^{21}$
M_{vir}	by eye	$2.2 \pm 3.2 \times 10^{21}$	$0.2 - 12 \times 10^{21}$
	CPROPS	$1.4 \pm 1.0 \times 10^{21}$	$0.3 - 3.1 \times 10^{21}$

Table 4. Molecular gas masses, $N(H_2)/I_{CO}$ conversion factor and characteristic time to transform molecular gas into stars derived from IR emission. The second column refers to the area mapped in CO. The last column is the inverse of the SFE.

	total M_{H_2} $M_\odot$	map M_{H_2} $M_\odot$	$N(H_2)/I_{CO}$ $\frac{cm^{-2}}{K\ km\ s^{-1}}$	τ yr
8μm	9.2×10^6	5.7×10^6	5.3×10^{21}	2.2×10^8
160μm (Tdmap)	4.6×10^6	3.4×10^6	2.3×10^{21}	1.3×10^8

The SFE in M33 and NGC 6822 appears greater than in the Milky Way size spirals that dominate the local universe.

'Why' remains an open question.

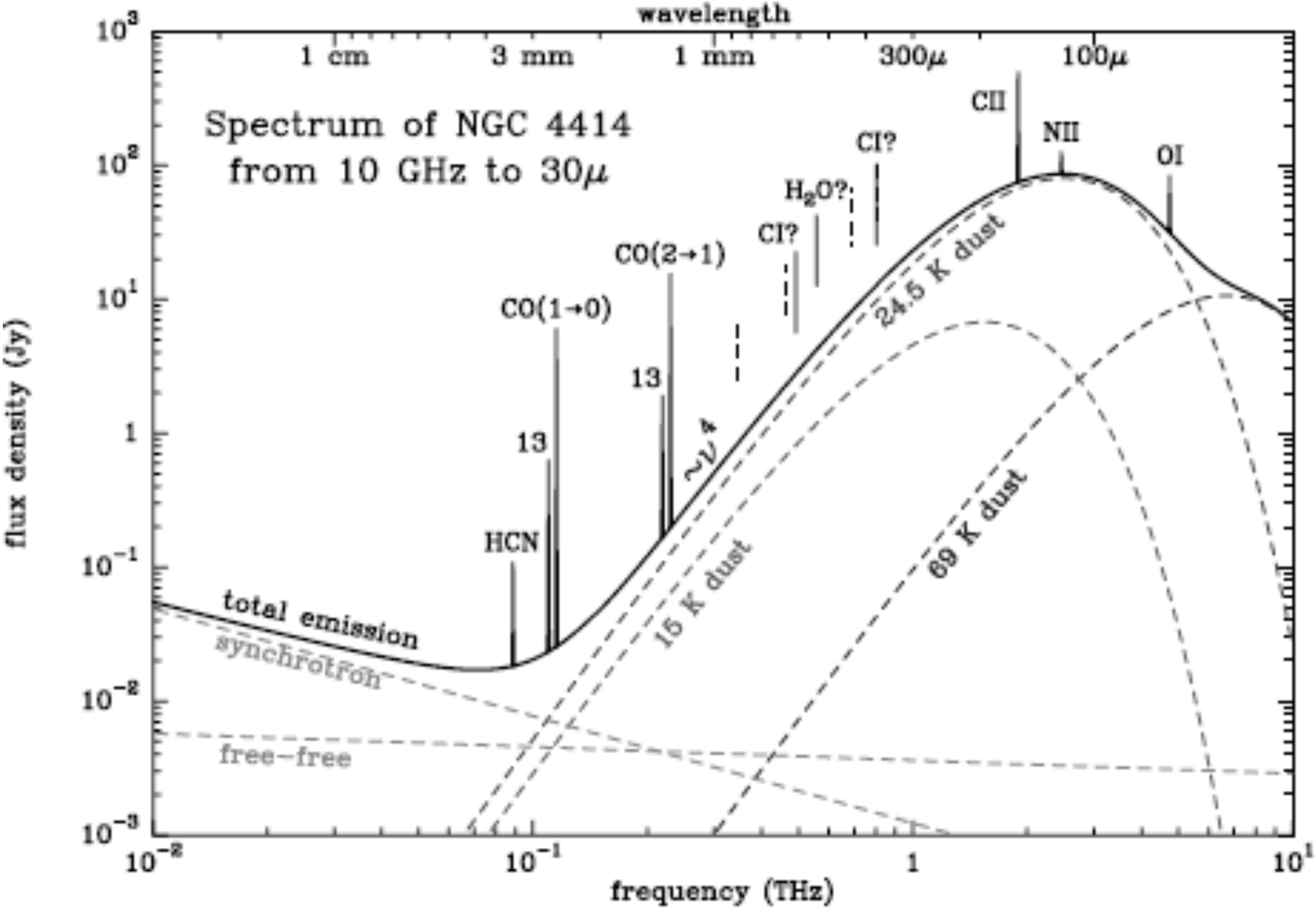
IMF ?
Something linked to chemical enrichment ?
Something linked to magnetic fields ?

Is there a link to the apparent high SFEs of $z \sim 1$ galaxies ?

Some open questions,

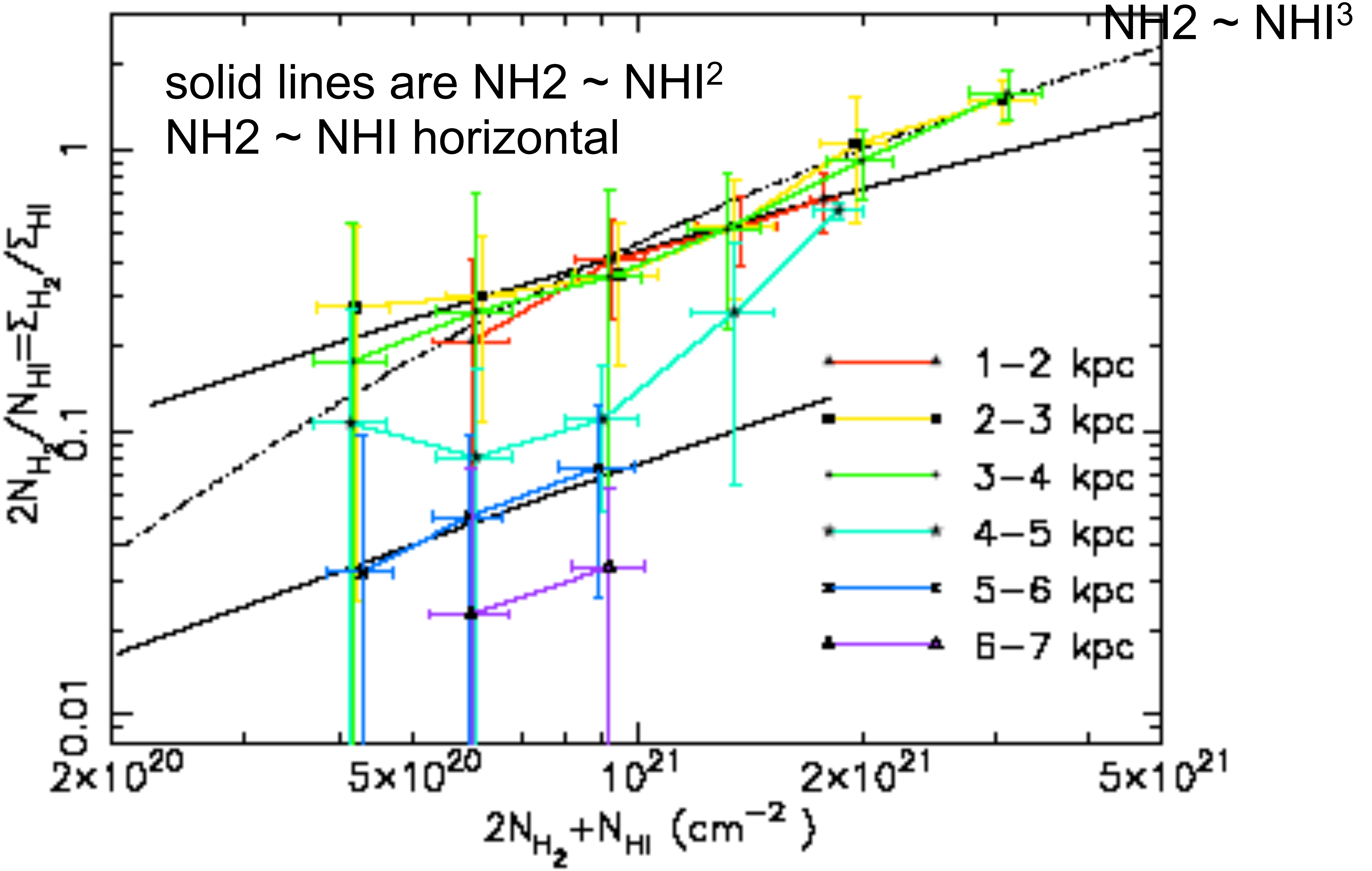
Like the extent of dust in galactic disks

Holwerda et al 2009

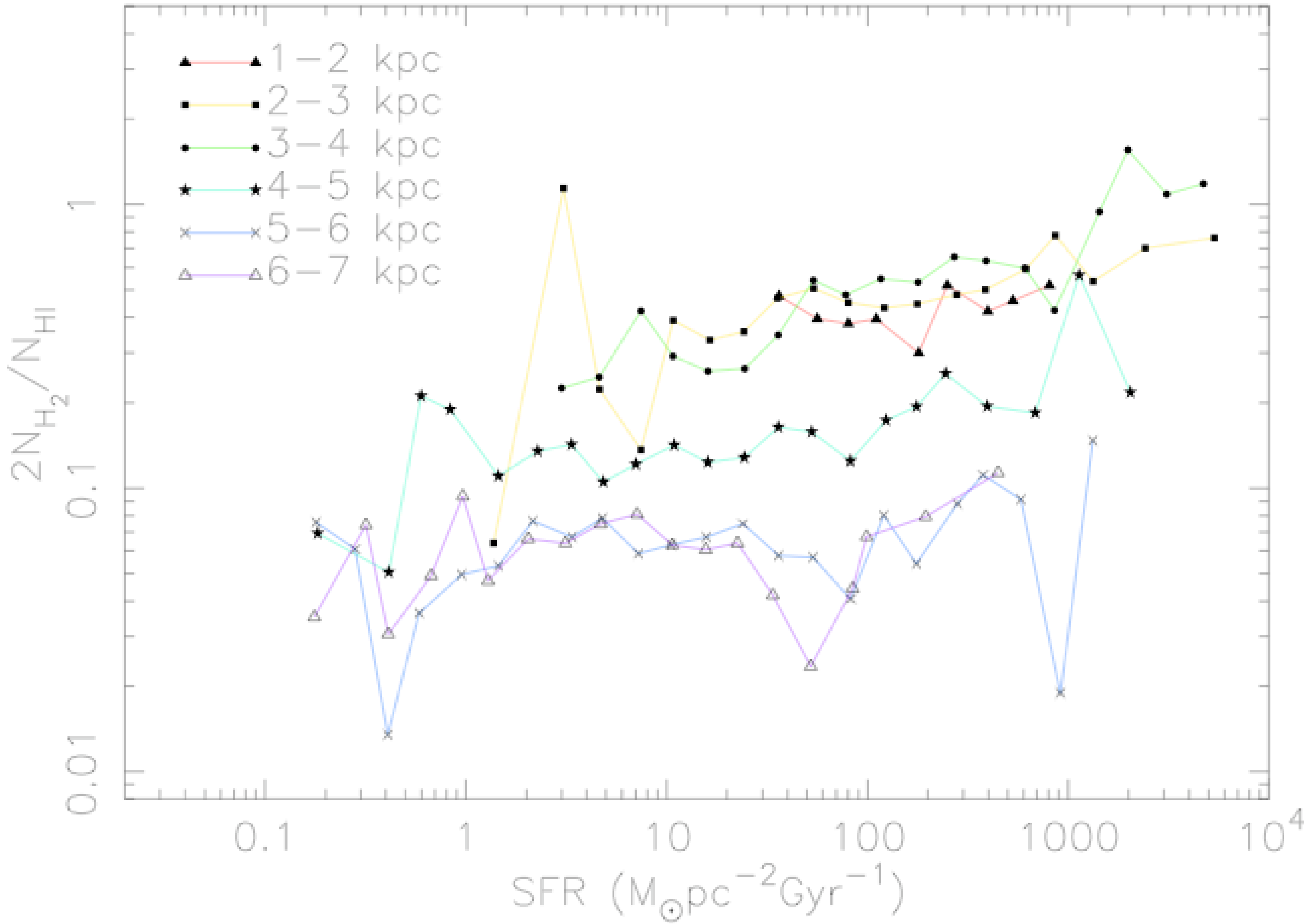

wavelength
1 cm
3 mm
1 mm
300μ
100μ
Spectrum of NGC 4414
from 10 GHz to 30μ
CII
NII
OI
CI?
H2O?
CI?
CO(2→1)
CO(1→0)
13
13
HCN
~ν^4
24.5 K dust
15 K dust
69 K dust
total emission
synchrotron
free–free
flux density (Jy)
frequency (THz)
10^3
10^2
10^1
1
10^-1
10^-2
10^-3
10^-2
10^-1
1
10^1

H2 fraction increases with NH

But decreases with radius at same NH



Even at a given star formation rate, the molecular fraction decreases with radius.

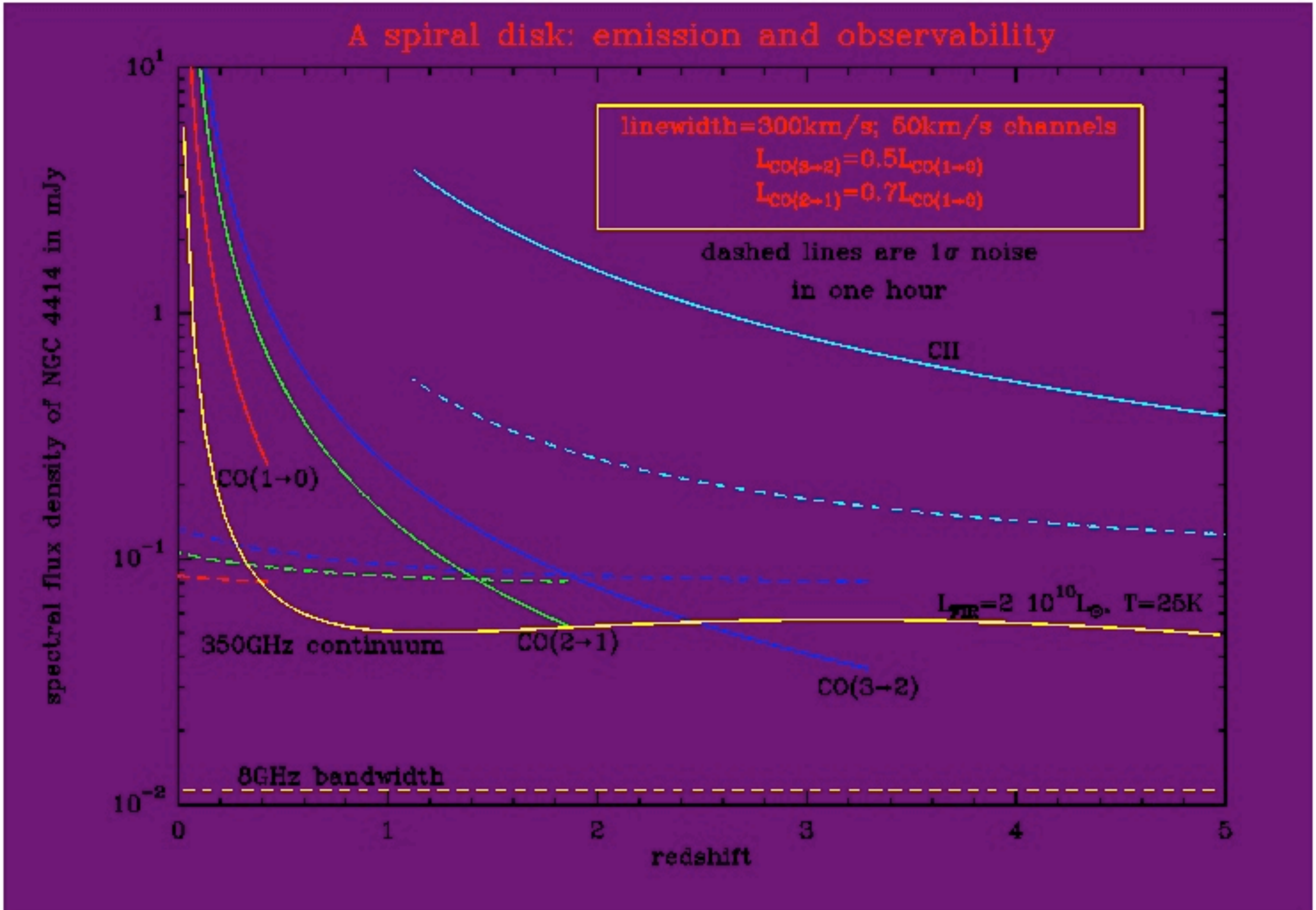


But this is not an increase in the SFE because NHI/SFR increases with radius.

In M33, in the zone we observed or extrapolated to the entire galaxy, the SFE is much higher, with
$dM/dt /M(H2) \sim 1/(3 \times 10^8)\ yr^{-1}$.

Rather close to what one expects for the intermediate redshift galaxies. Why?

Morphologie des galaxies et leur ISM à z ~ 1 -- 2



ALMA permet de suivre l'évolution de la morphologie de l'ISM à faible L_{FIR}