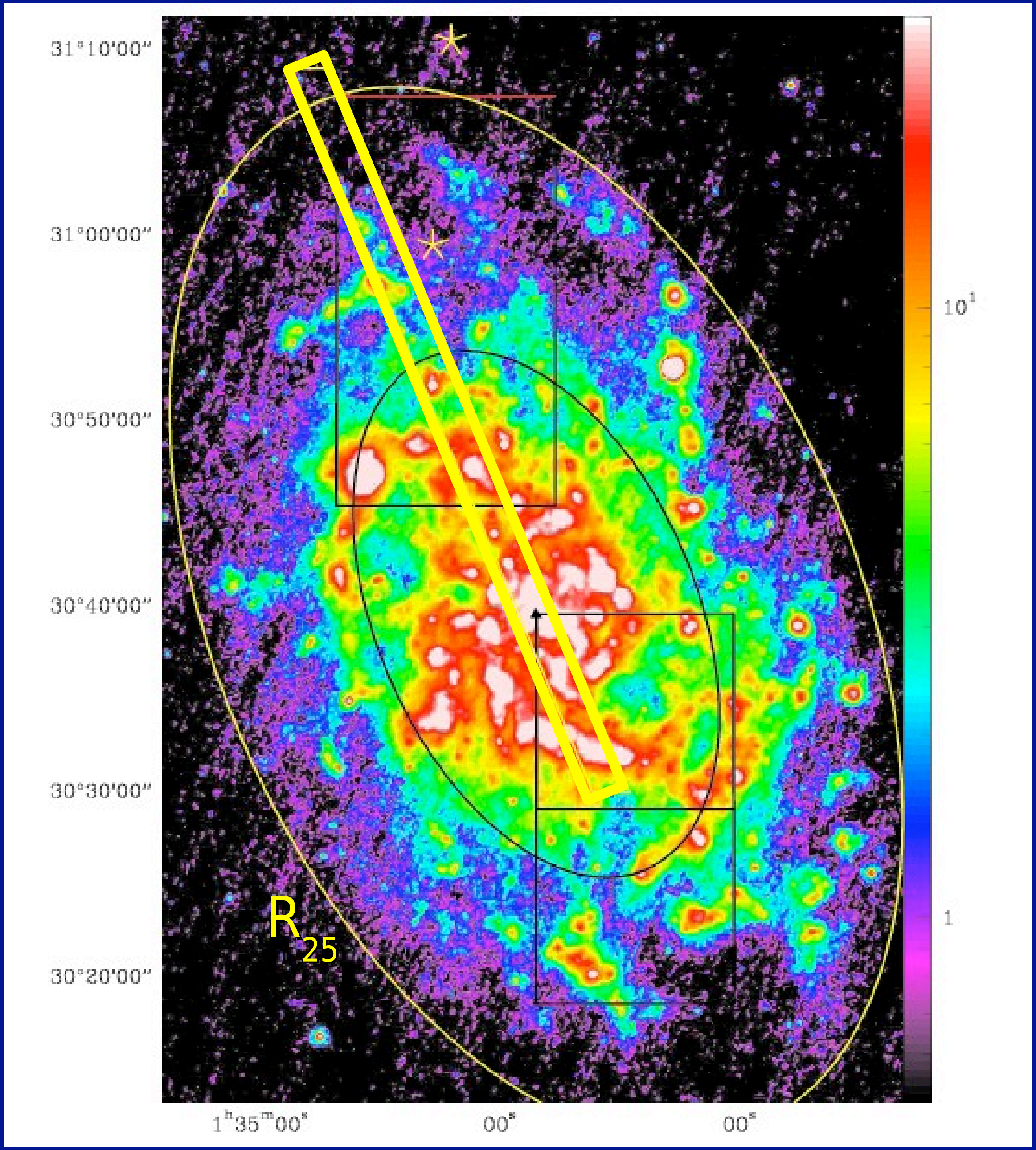
Dense gas in M33

Carsten Kramer (IRAM/Granada)

Christof Buchbender,
Guillermo Quintana-Lacaci,
Albrecht Sievers,
Pierre Gratier,
Jonathan Braine,
Erik Rosolowsky



Spitzer 70µm image (Tabatabaei et al. 2007)
Radial 2'x40' stripe to be observed with HIFI/PACS (HERM33ES project)

Dense gas in M33

I. Overview

Ia. Why studying the dense gas ?

Ib. And why in M33 ?

II. Tracing the dense gas

IIa. 1.1mm dust continuum in M33

IIb. Dense molecular gas in M33 (prel. results)

III. HERM33ES project

I. Why studying dense gas?

+ Dense gas is much more sensitively linked to the star formation process than CO

E.Lada et al. 1991-1997:
CS 2-1 & 2.2μm survey of the L1630/GMC

Only ~20% of total gas traced by CO in dense cores traced by CS

Star formation in Orion B requires dense + massive cores
which constitute only ~6% of the total gas

The overall SFE is ~3%-4%, while the three dense + massive cores exhibit ~30%-40%

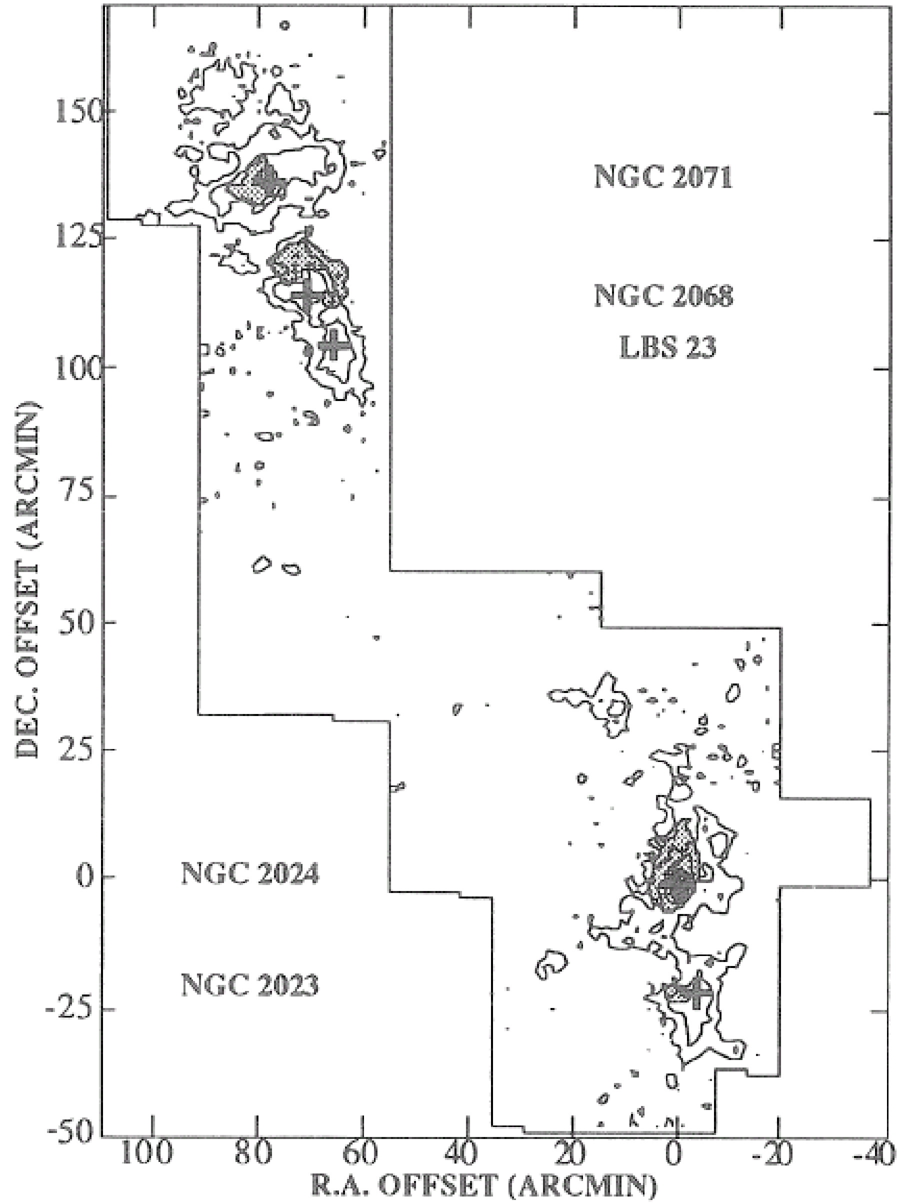


FIG. 2.—Locations of the embedded stellar clusters and dense gas in the L1630 molecular cloud. The shaded regions represent the location and extent of the embedded clusters. The distribution, of dense gas is presented as intensity contours of the CS($2 \rightarrow 1$) emission. In addition, the peak intensity positions of the five most massive CS cores ($M > 200\ M_{\odot}$) are represented by crosses.

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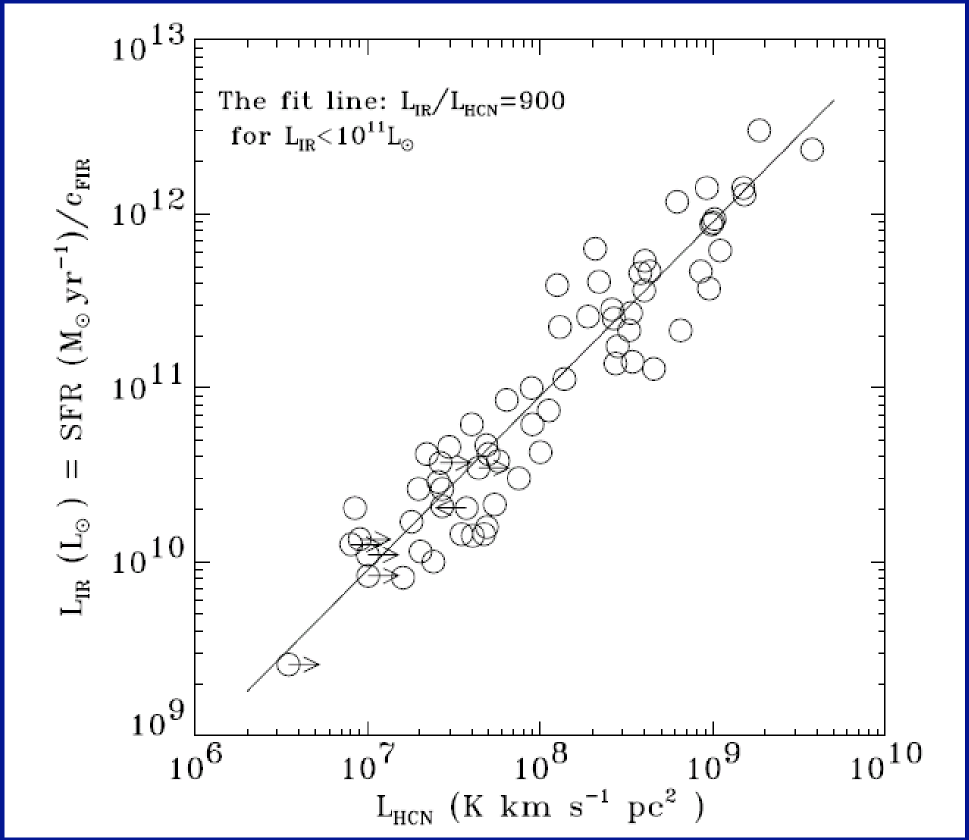
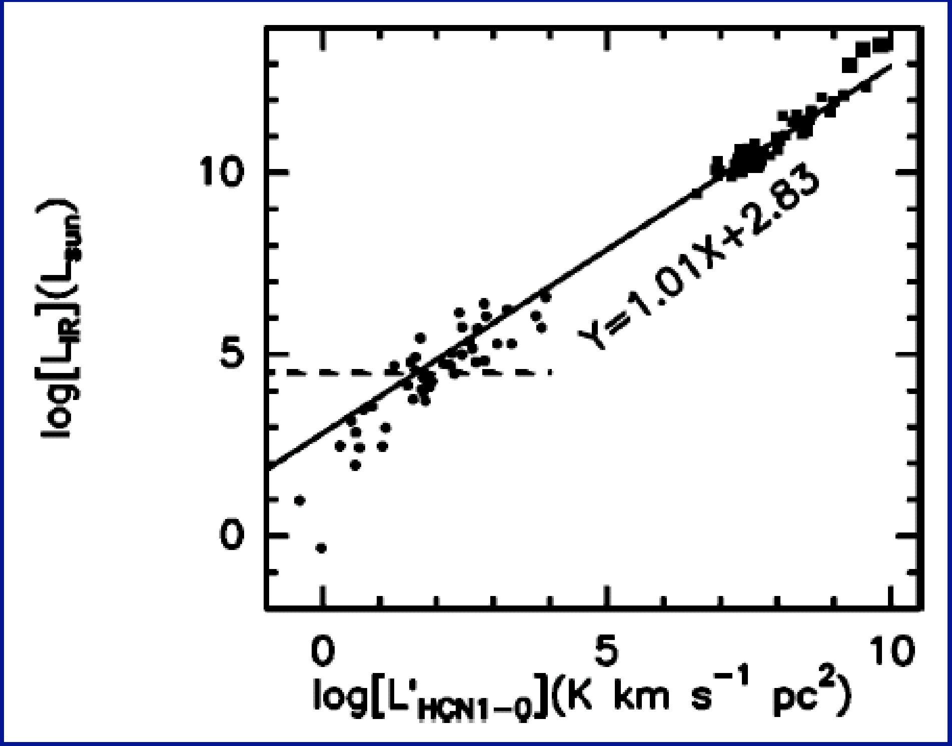


Gao & Solomon 2004:
Tight HCN 1-0 vs. IR/SFR relation from 65 IR galaxies



Wu et al. 2005:
tight HCN 1-0 vs. FIR/SFR relation over more than 7 order of magnitude combining Galactic cores with galaxies

Galactic SF regions are good templates!

HCN/CO ~ dense molecular gas fraction
Does it vary with local environment?

Ib. Why studying the dense gas in M33 ?

+ Dense gas is much more sensitively linked to the star formation process than CO (e.g. E.Lada 1992)

+ Improve our understanding of star formation and feedback/quenching mechanisms (SFE is in general low)

+ M33 perfect target:
    + nearby (12” - 49pc) to resolve GMAs
    + almost face-on (little los contamination)

+ M33: Environment changes with radius:
    + arm/interarm, outer/inner galaxy
    + HI/H_2 rises with radius (Heyer et al. 2004, Gardan et al. 2007)
    + Star formation rate drops with radius, High SFE ! (Gardan et al. 2007)
    + Metallicity drops with radius
    + Heating mechanisms may change (UV/CRs/shocks ?) (Meijerink, Spaans et al.)

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Ib. Molecular & atomic gas

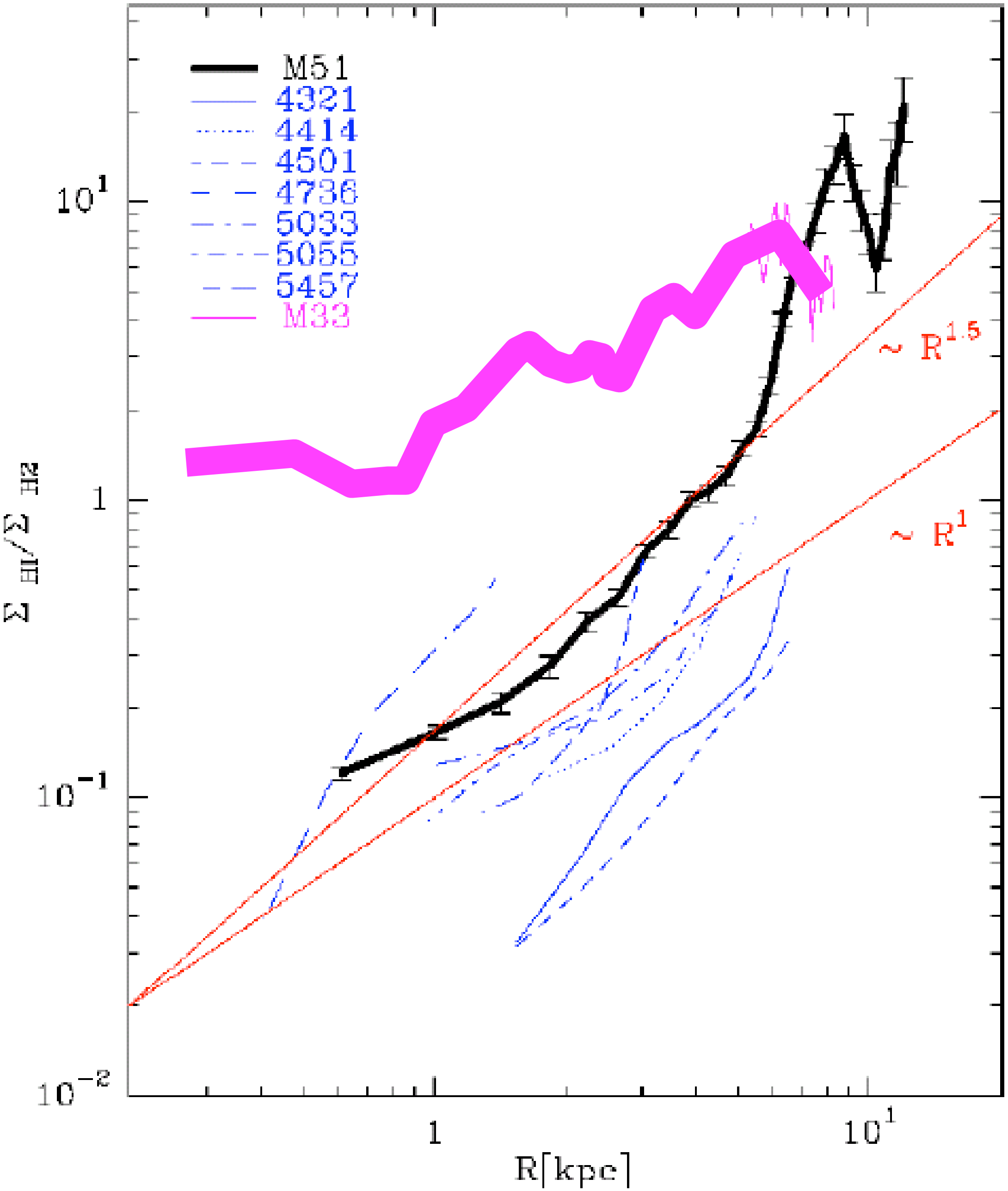
HI/H_2:

- M51 (Schuster et al. 2007)

  0.1 at ~1 kpc
  1 at ~4 kpc
  20 at ~12 kpc

- NGC4321, ... NGC 5457
  (Wong & Blitz 2002)

- M33 (Heyer et al. 2004)



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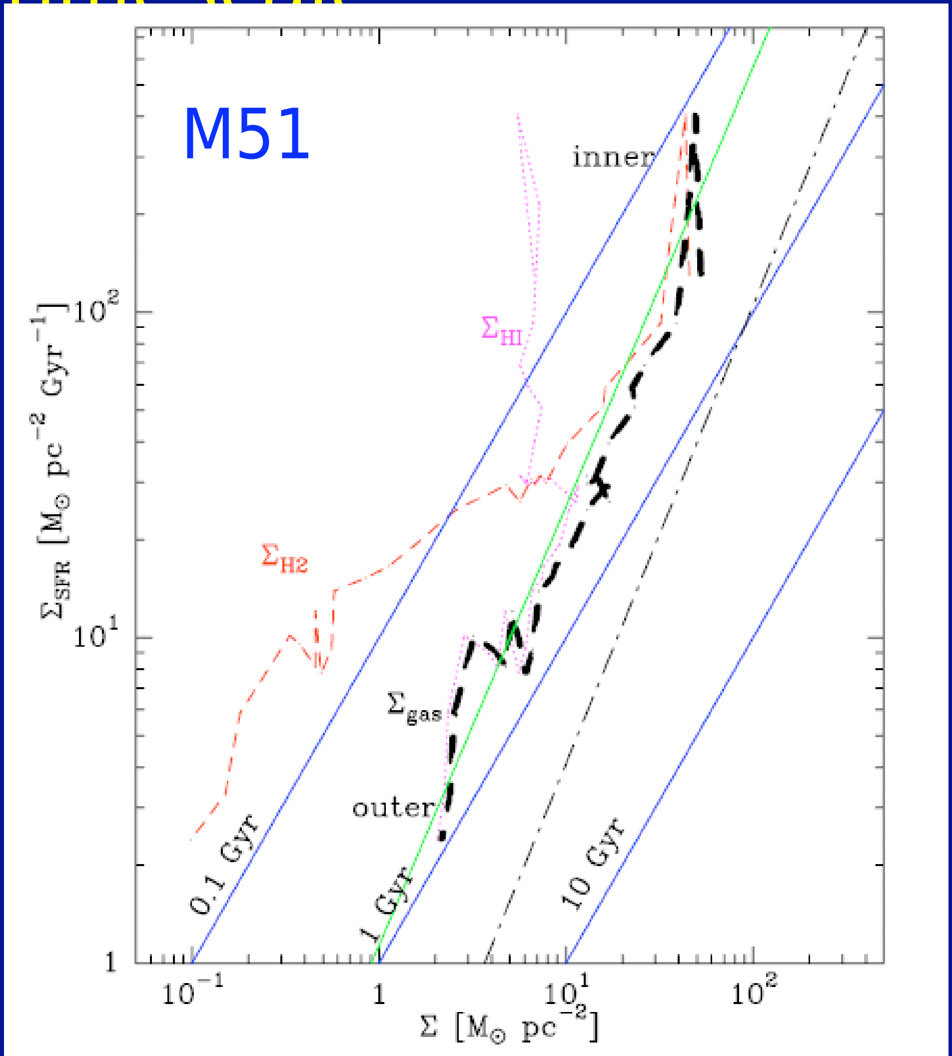
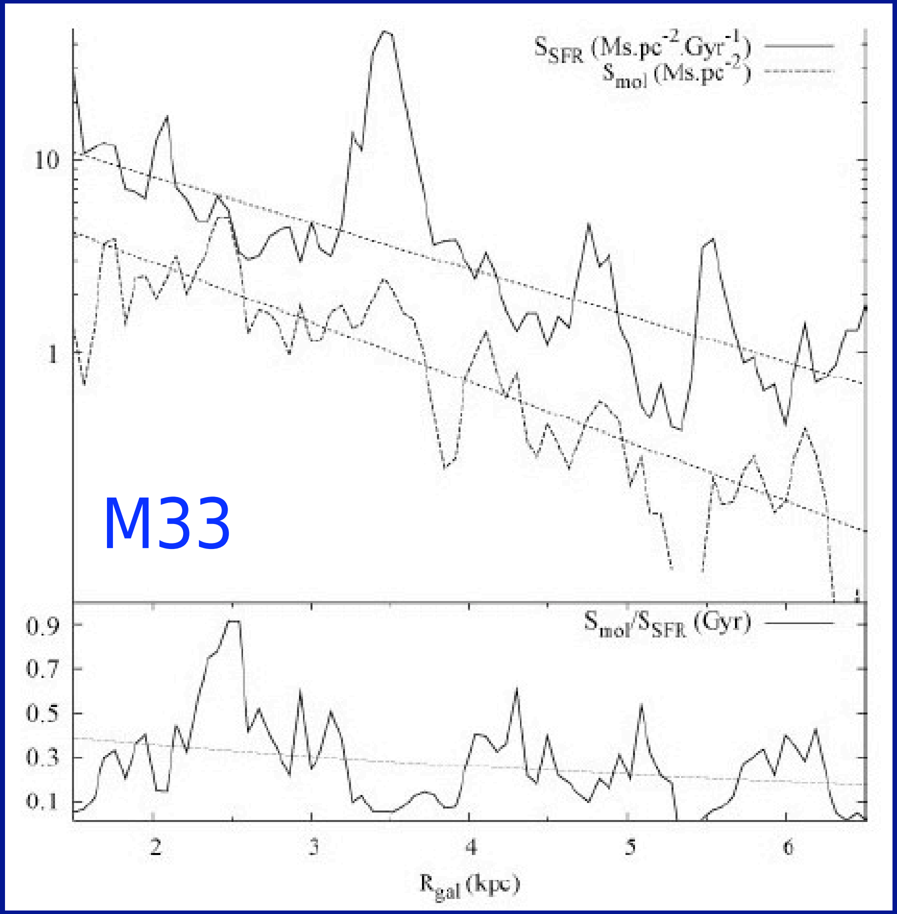
Ib. M33: High SFE – short molecular depletion timescale



Schuster, Kramer et al. 2007
Hitschfeld, Kramer et al. 2009



Gardan et al. 2007

Typical molecular depletion timescales in normal spiral galaxies (Kennicutt 1998b): 0.9 - 2.5Gyr

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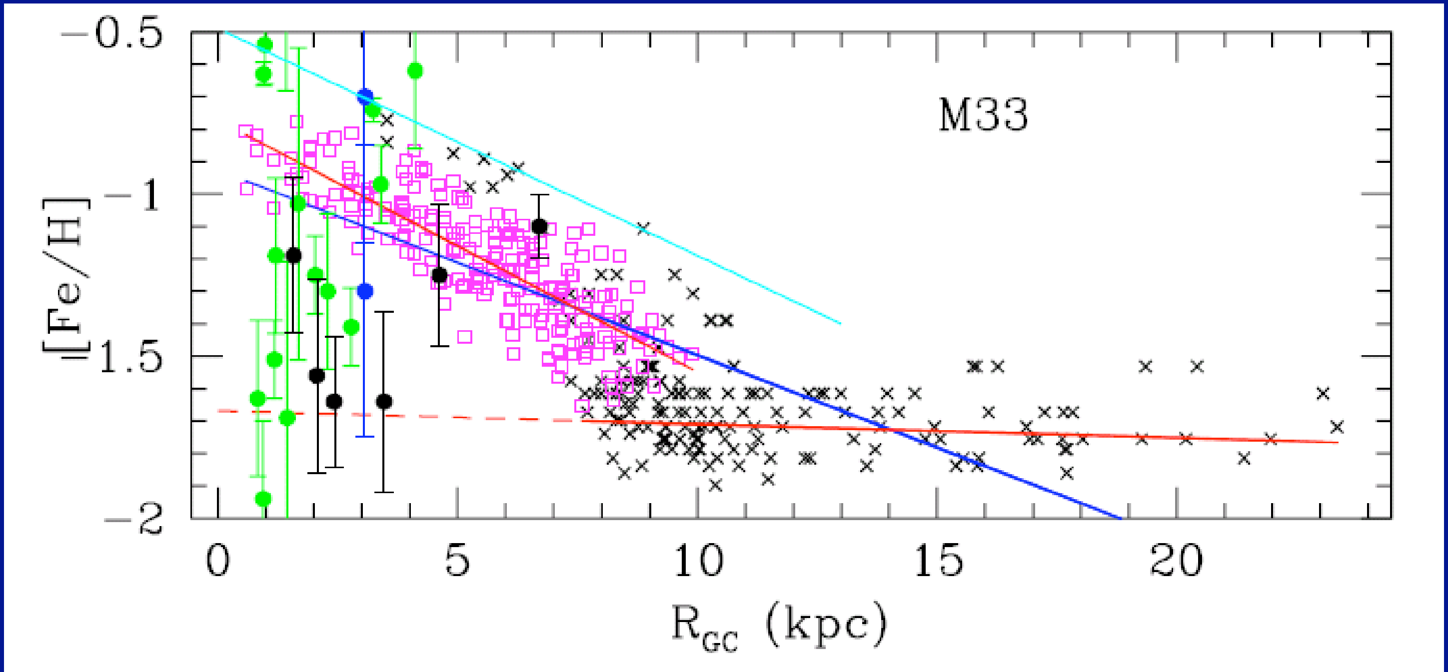
Ib. The Metallicity of M33



+ slightly subsolar (2-3)
  (Garnett et al. 1997)

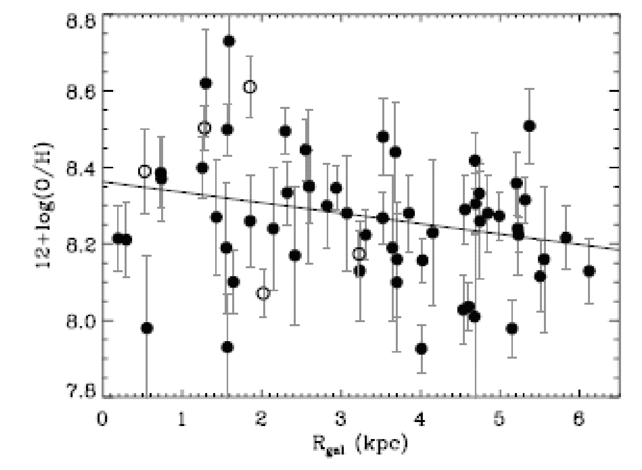
+ metallicity gradient?

see talk of L.Magrini

Metallicity gradient of M33 derived from **AGB stars** (see above, Cioni 2009). Bimodal metallicity distribution with a flattening of the slope at ~9kpc. The gradient is -0.078 dex kpc^{-1} for R<9kpc.

Note that the metallicity gradient derived from **HII regions** is only -0.03 dex kpc^{-1} for [O/H] and correspondingly for [Fe/H] (see right, Rosolowsky & Simon 2008).

This indicates a flattening of the gradient with time (Cioni 2009).



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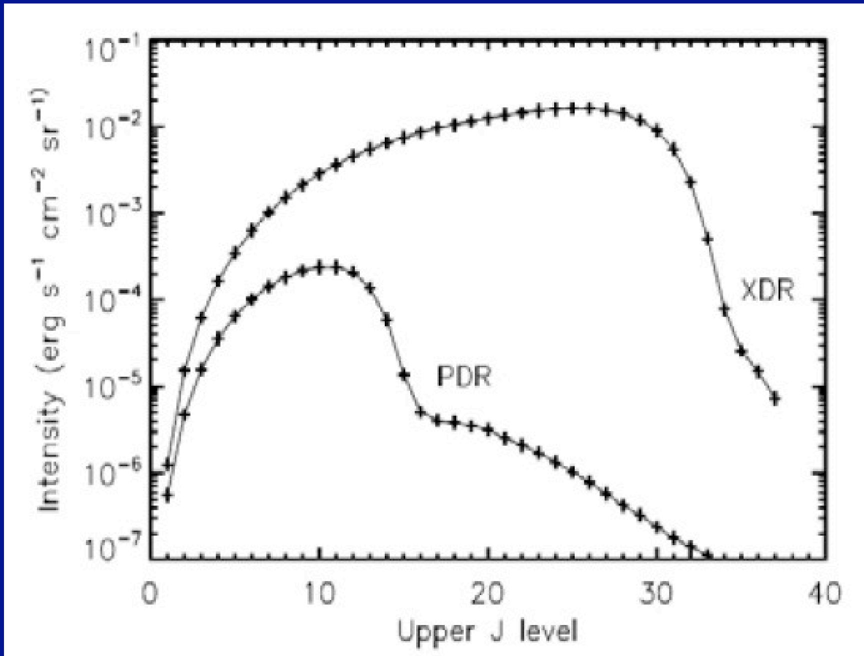
Ib. Discerning heating mechanisms



Rotation transitions of CO:
Models of PDR and XDR
(Meijerink, Spaans et al.)

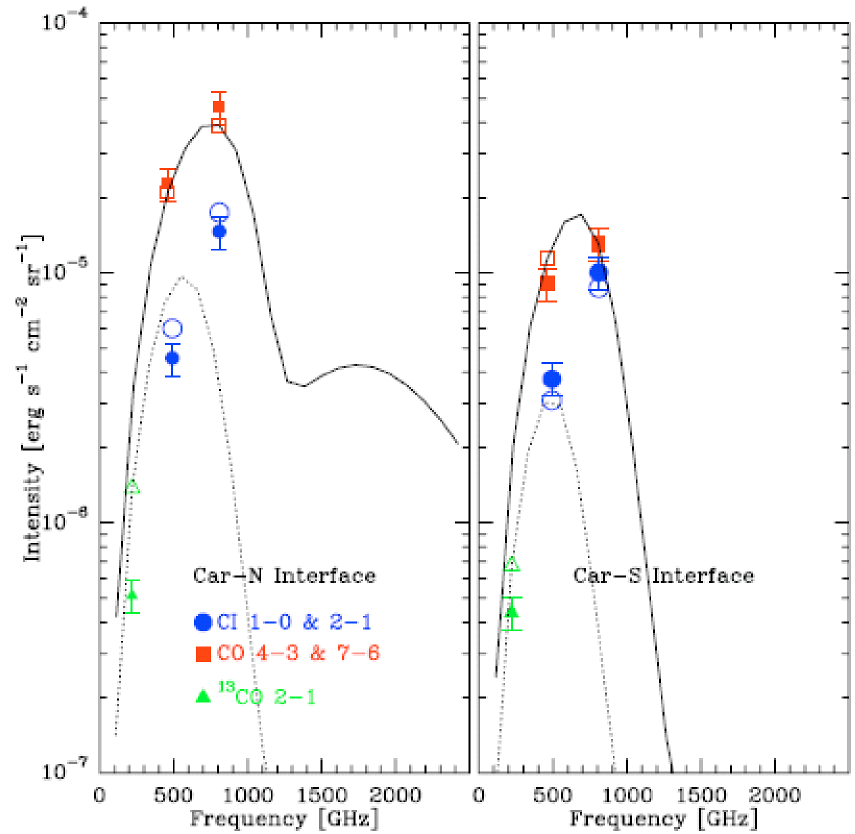
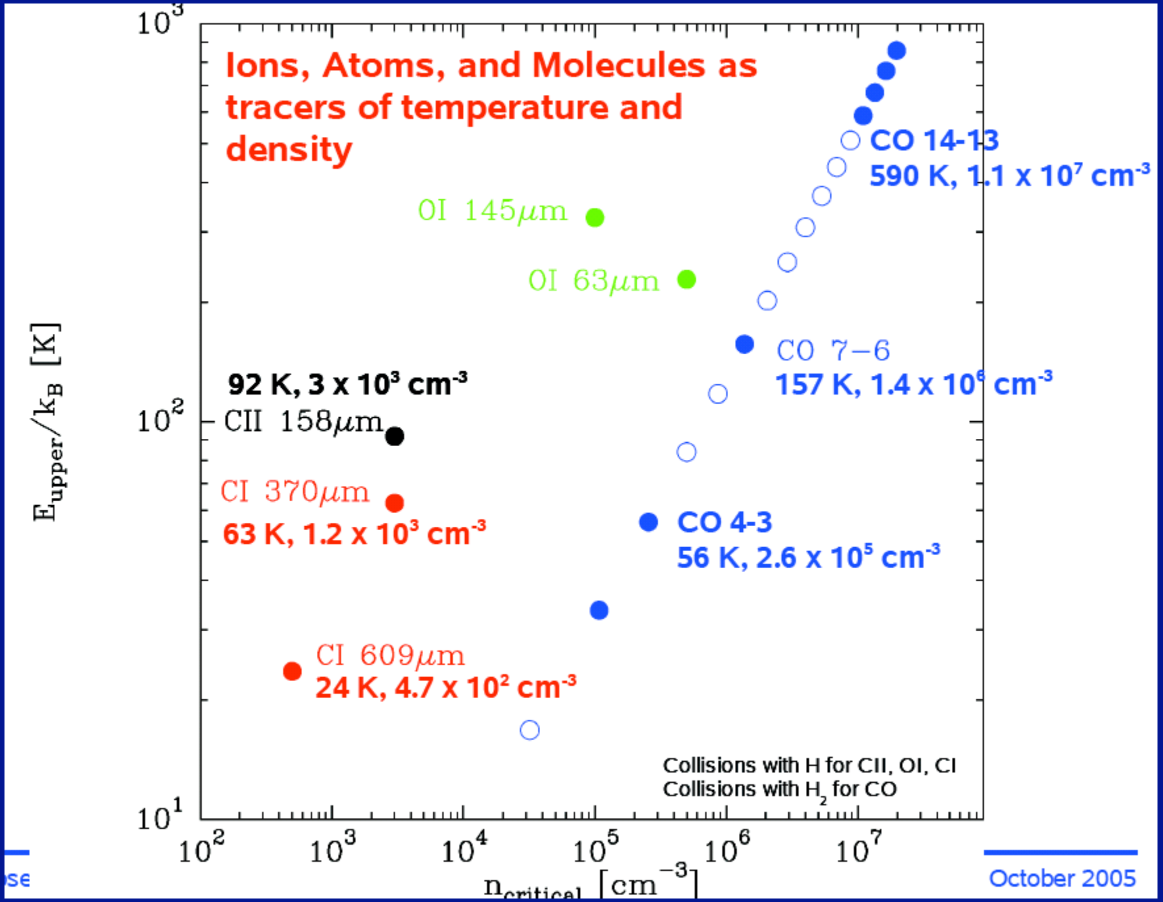


Fig. 9. Integrated intensities at the two interface positions in Carina-North and South (Table 1). Filled symbols show the observed ^{13}CO 2–1, [C I] 1–0, 2–1, ^{12}CO 4–3, and 7–6 intensities. Error bars denote the 15% calibration error. Model results of the best fitting clumpy PDR model (Table 2) are shown by solid (^{12}CO) and dotted lines (^{13}CO), and open symbols.

Carina region: Observations and PDR modeling
(Kramer et al. 2008)

II. Tracing the dense gas

+ Low-J transitions of HCN, HCO^+, CS — Cold gas (T, n, N)
+ Mid-J transitions of CO, HCN, HCO^+, CS — Warm gas (T, n, N)
+ Millimeter Dust emission — Cold dust (N, T)
+ Fine structure lines [CI], [OI], [CII], [NII], [NIII], ... — Gas phases (CNM, WNM, WIM)



Tracing local densities and temperatures – a simple minded view

IIa. Tracing the dense gas

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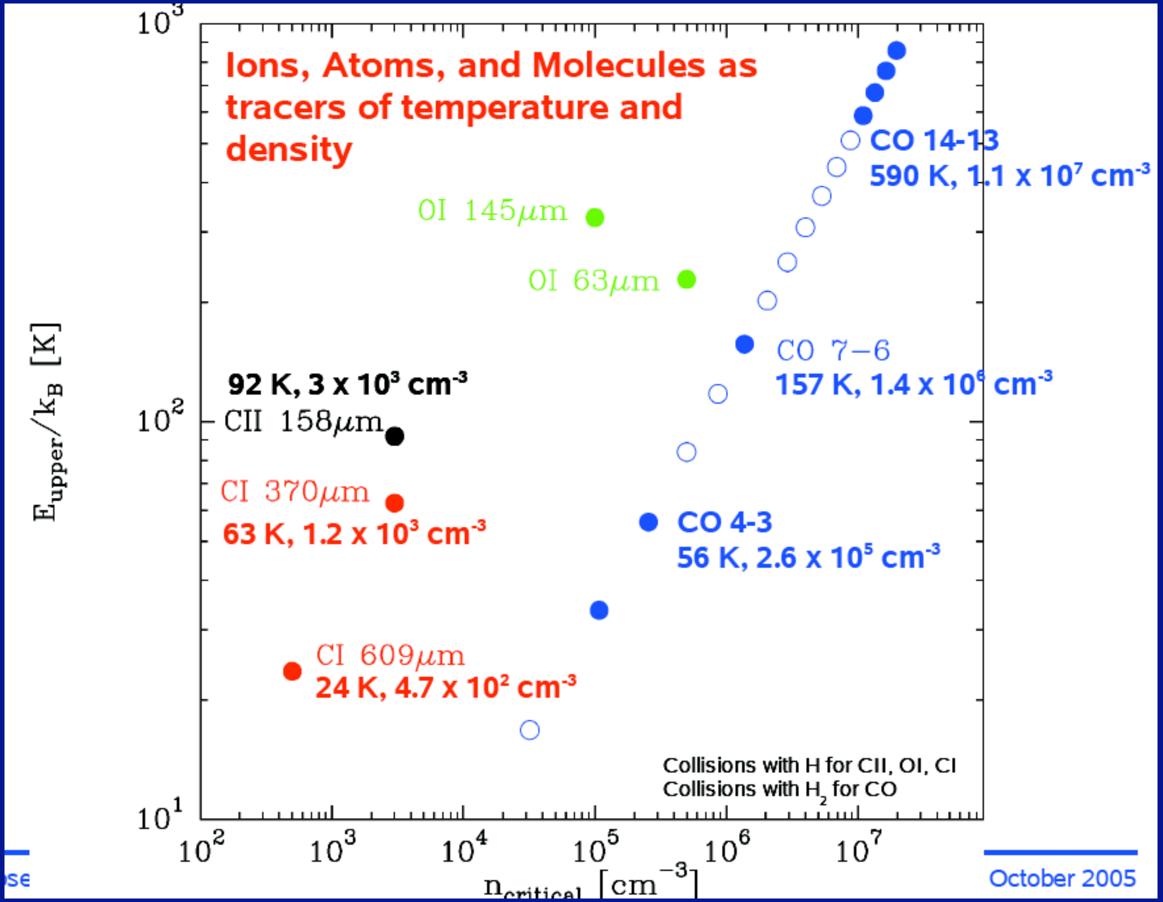
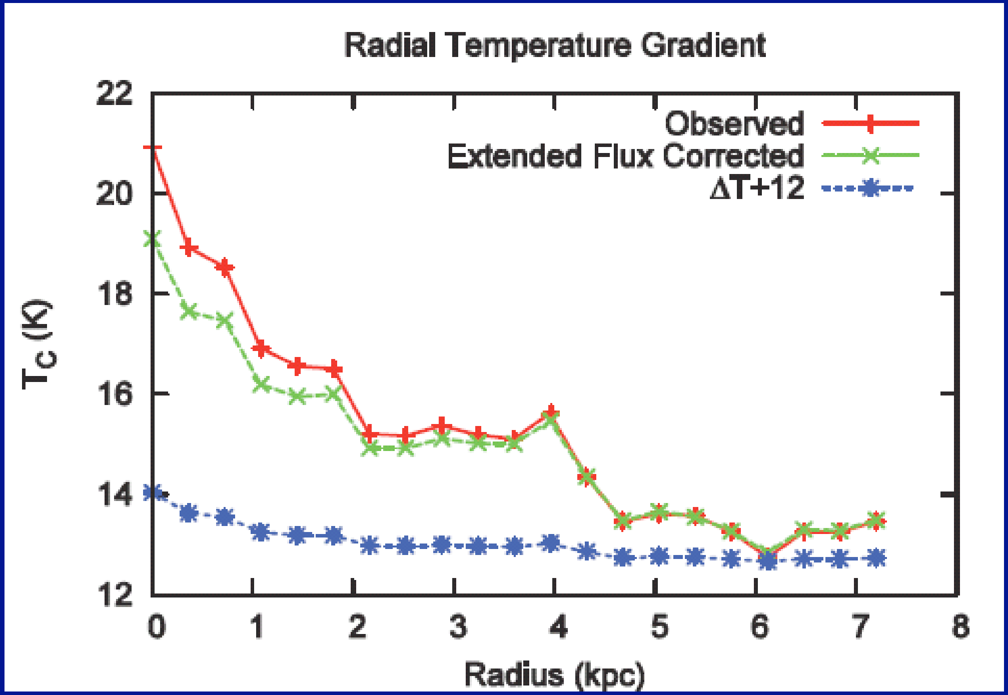
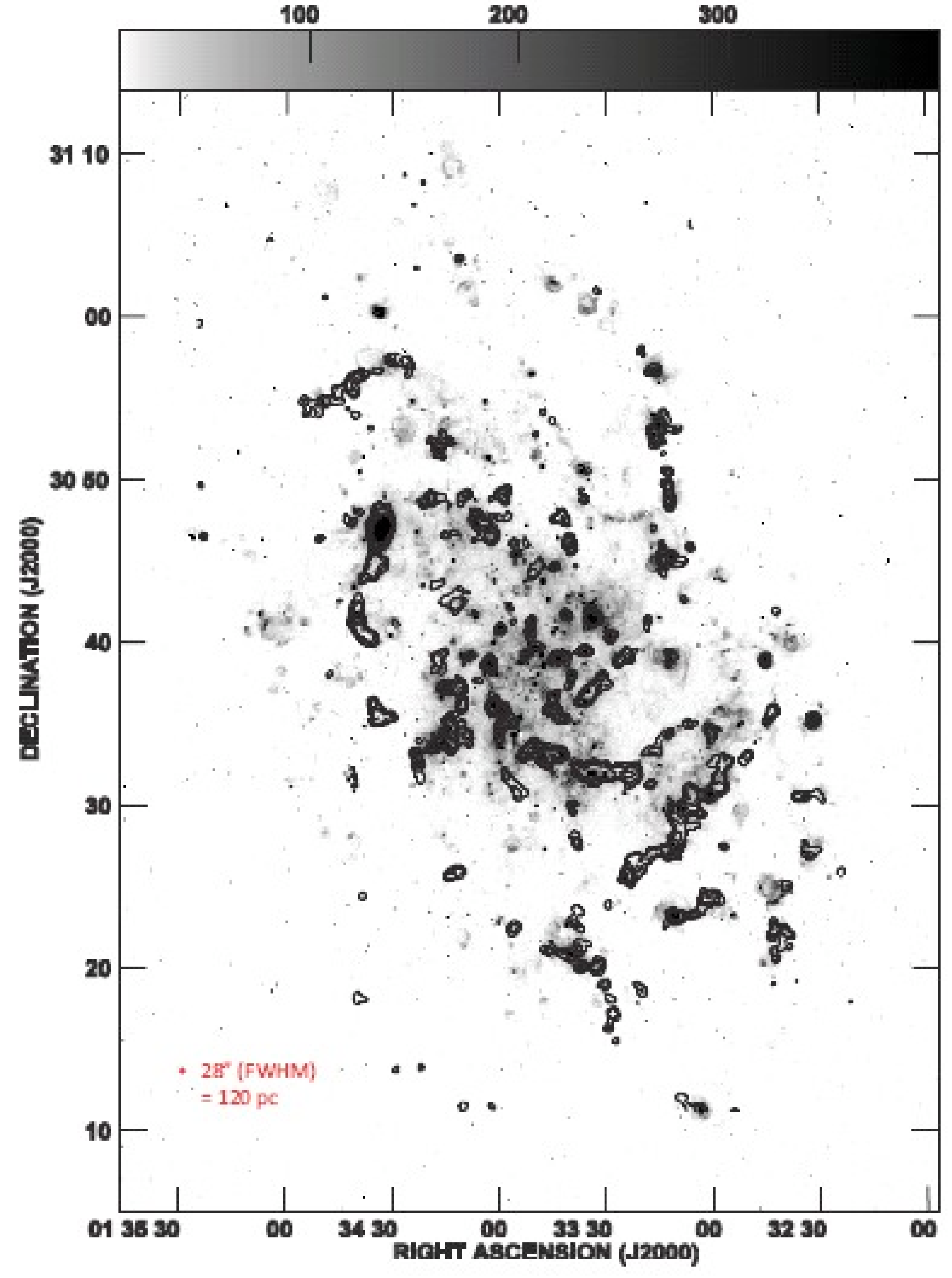


Tracing local densities and temperatures – a simple minded view

IIa. The cold dust in M33

1.1mm AzTEC/ASTE map (HPBW=28"). In combination with the 160μm Spitzer map, assuming β=2, they derive a steep radial gradient of dust temperatures from 19K to 13K. (Komugi et al. 2009, FIR2009/IAU)





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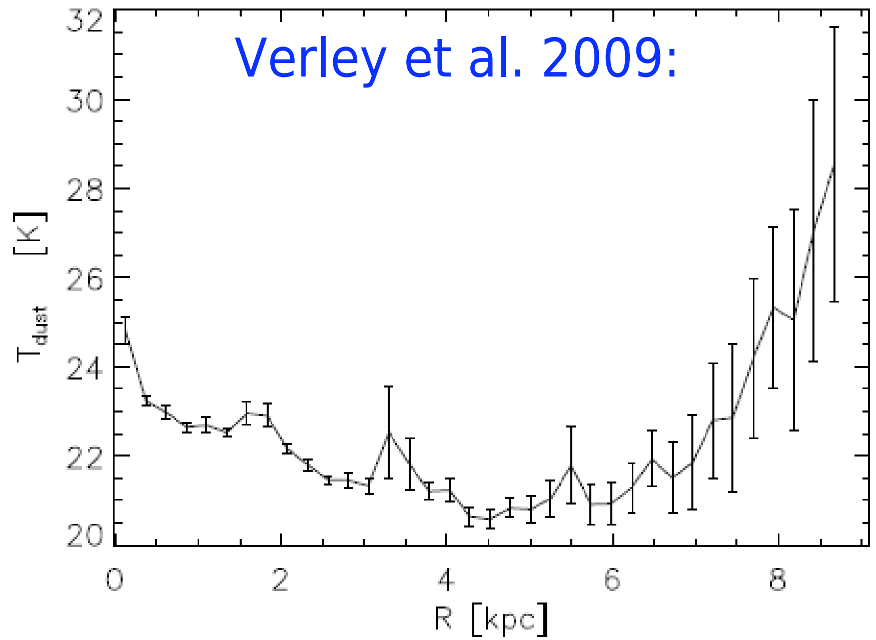
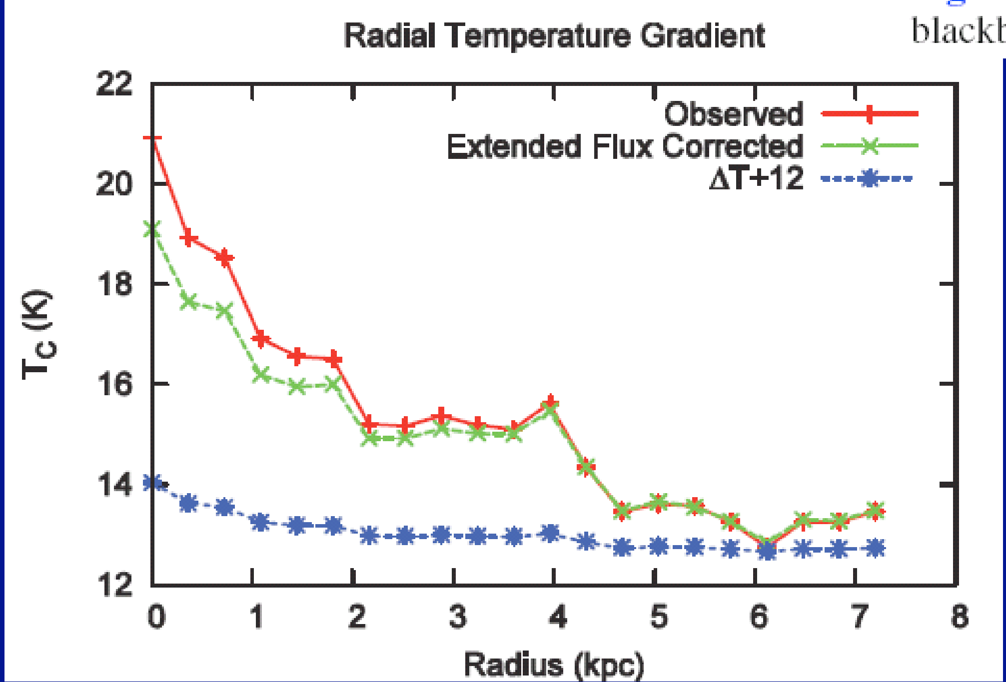
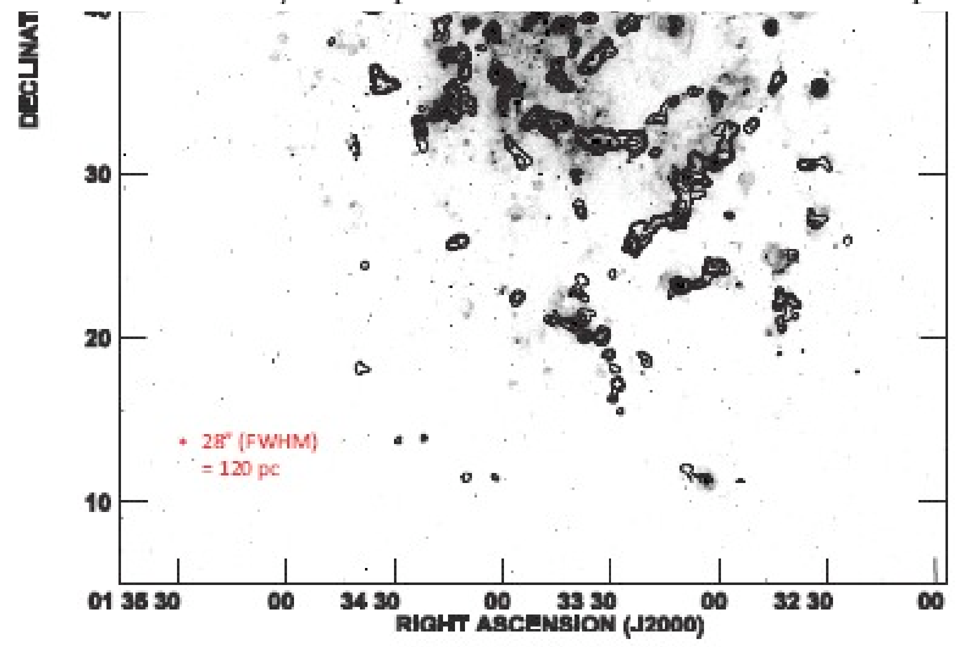


Fig. 9. Dust temperature as a function of radius, estimated by fitting a blackbody to the 70 and 160 μm elliptical emissions, in bins of 0.24 kpc.





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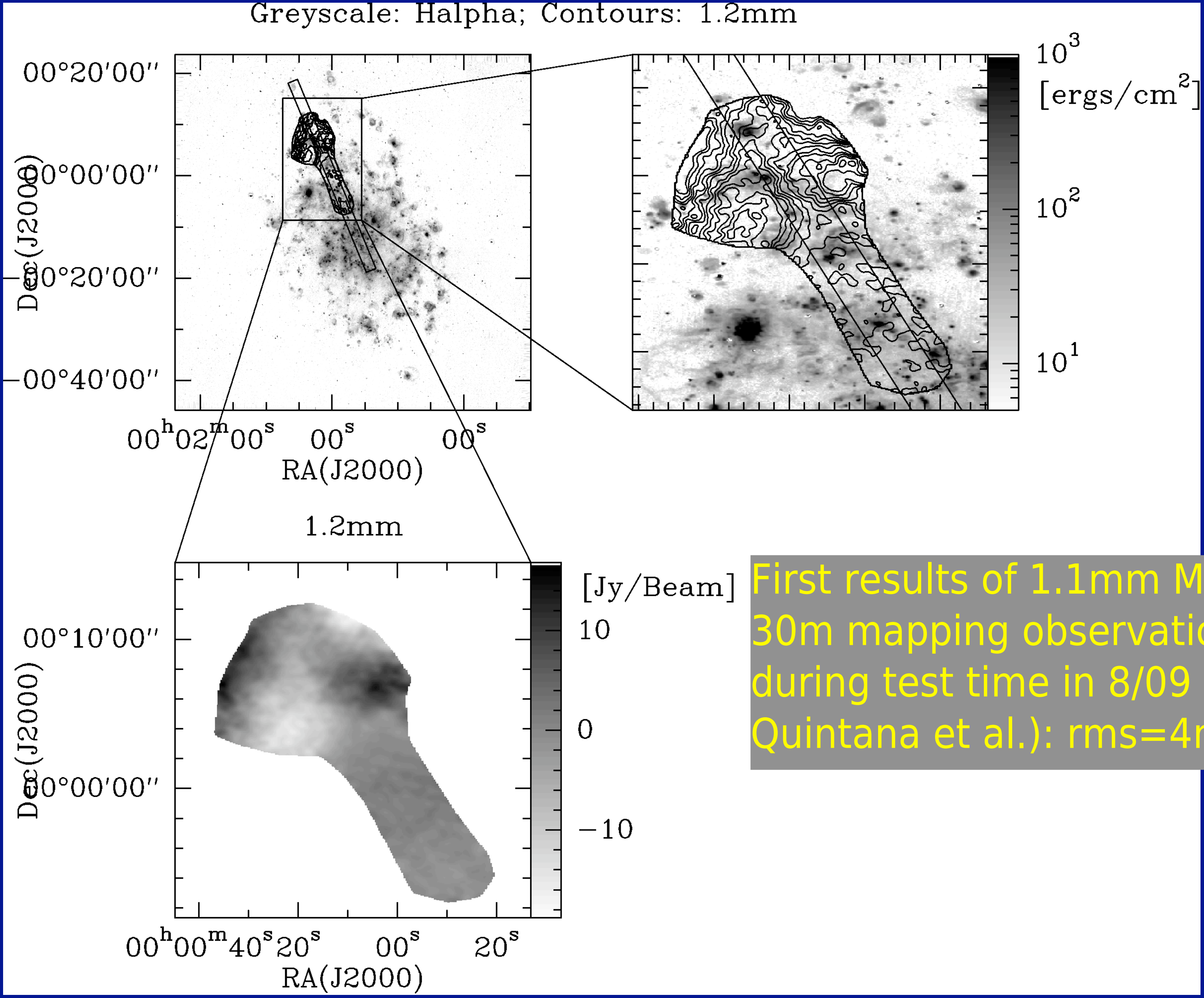
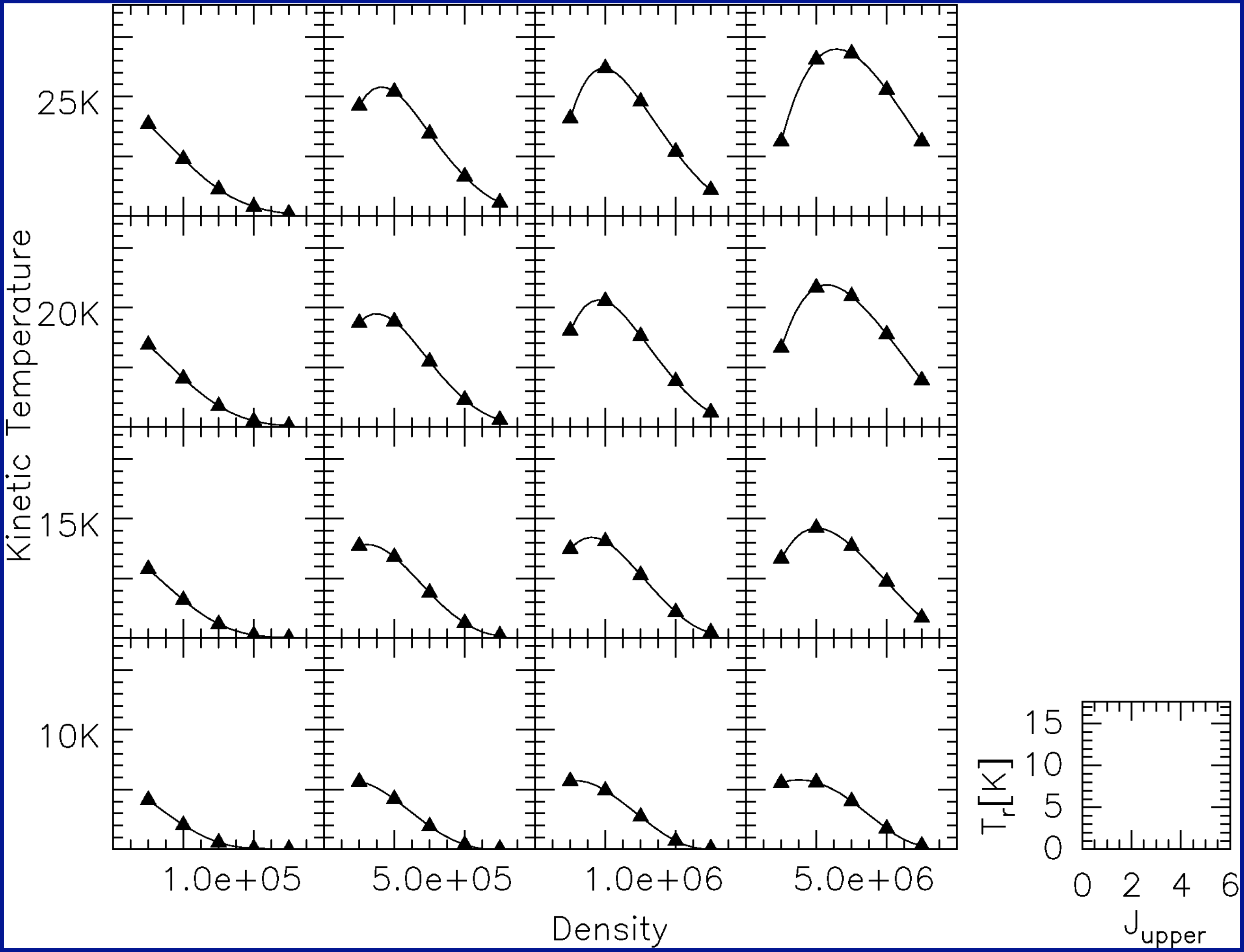


First results of 1.1mm MAMBO3/IRAM-30m mapping observations at 11" taken during test time in 8/09 (Guillermo-Quintana et al.): rms=4mJy/beam.

IIb. Tracing the dense molecular gas

+ Low-J transitions of HCN, HCO^+, CS

Cold gas (T, n, N)



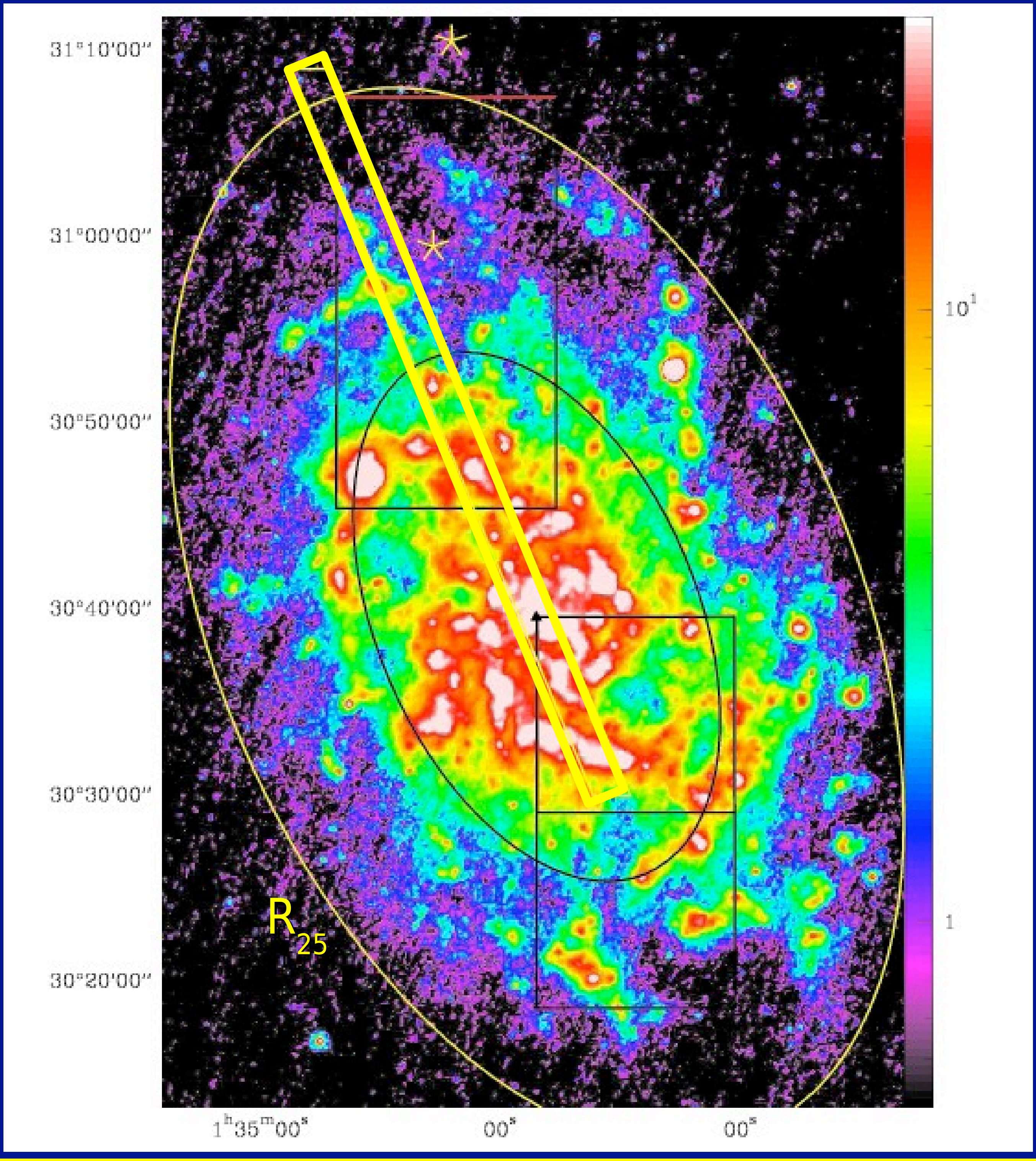
Dipole moments:
+ 0.112 Debye (CO)
+ 0.8 Debye (C_2H)
+ 2.98 Debye (HCN),
+ 3.30 Debye (HCO^+)

RADEX radiative transfer calculation of HCO^+ intensities:

T_{kin} vs. density

PhD work of Christof Buchbender

IIb. M33

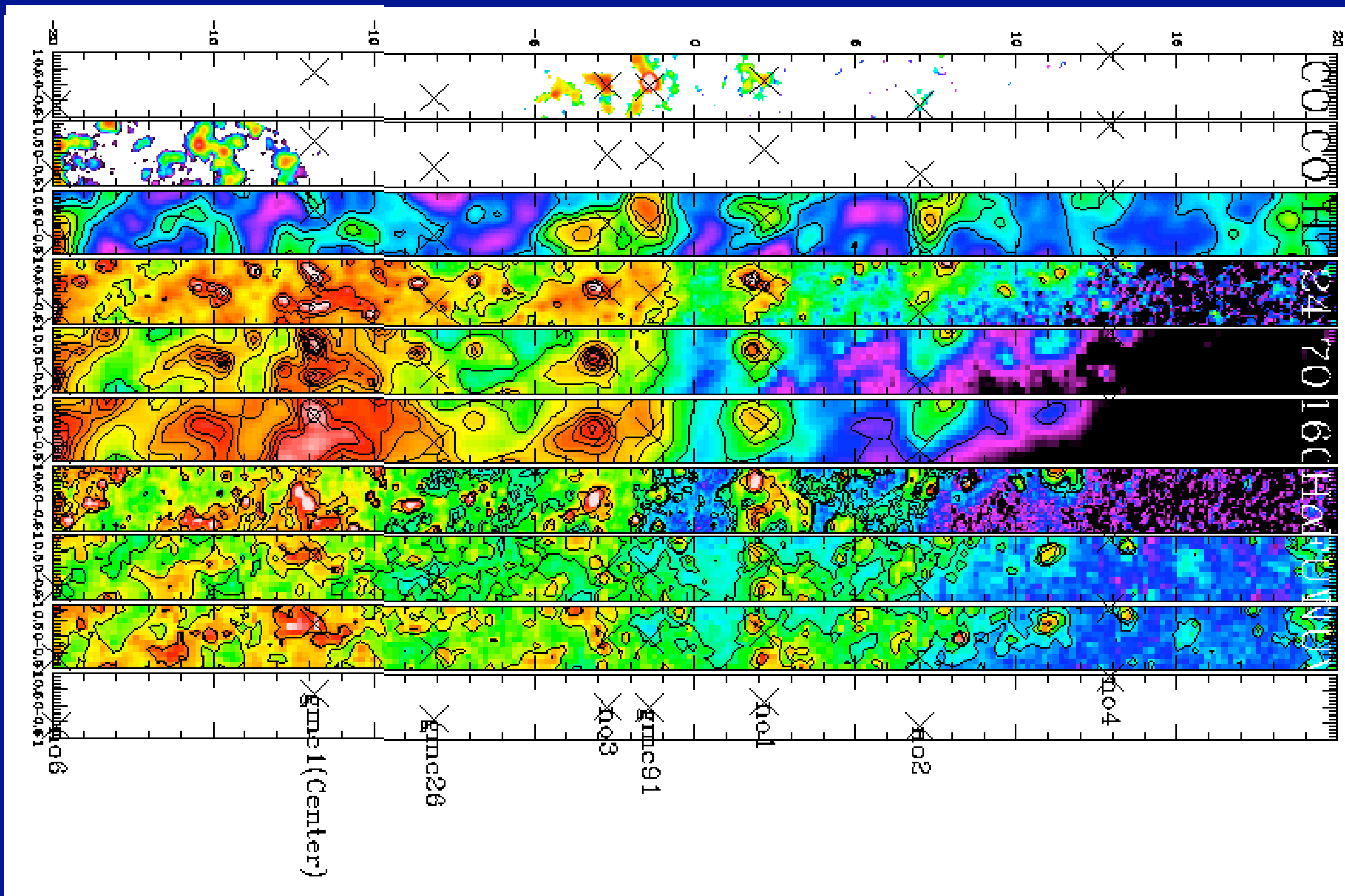


Spitzer 70µm image (Tabatabaei et al. 2007)

and radial stripe

Yellow ellipse shows R_{25} radius (7.5kpc = 30.8')

IIb. Radial stripes and dense gas

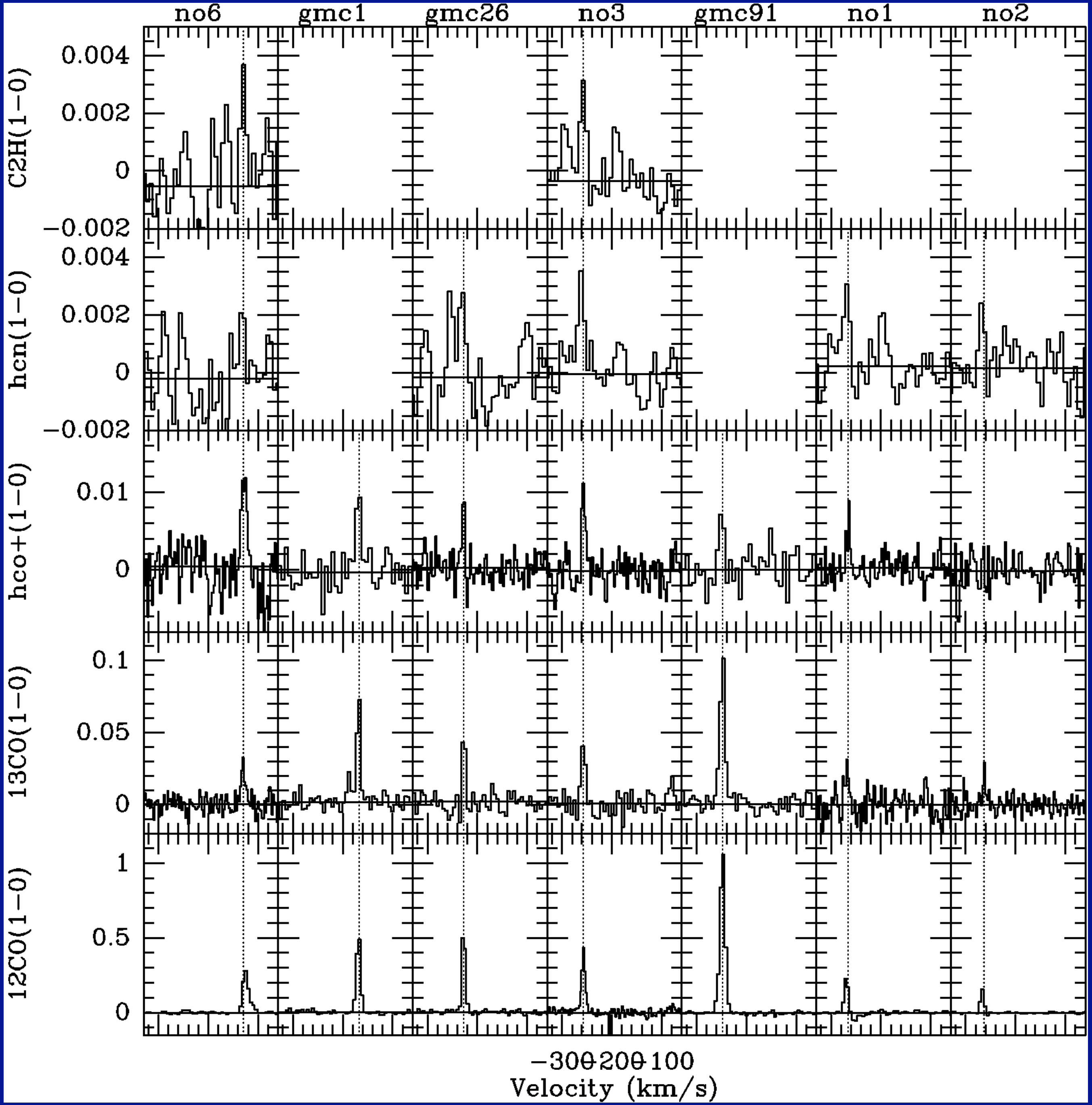


CO 2-1
CO 2-1
HI
24µm
70µm
160µm
Hα
NUV
FUV

Center

Here, all molecular clouds embedded in HI clouds and associated with recent star formation with the exception of position no.4

IIb. Dense gas in M33



C_2H

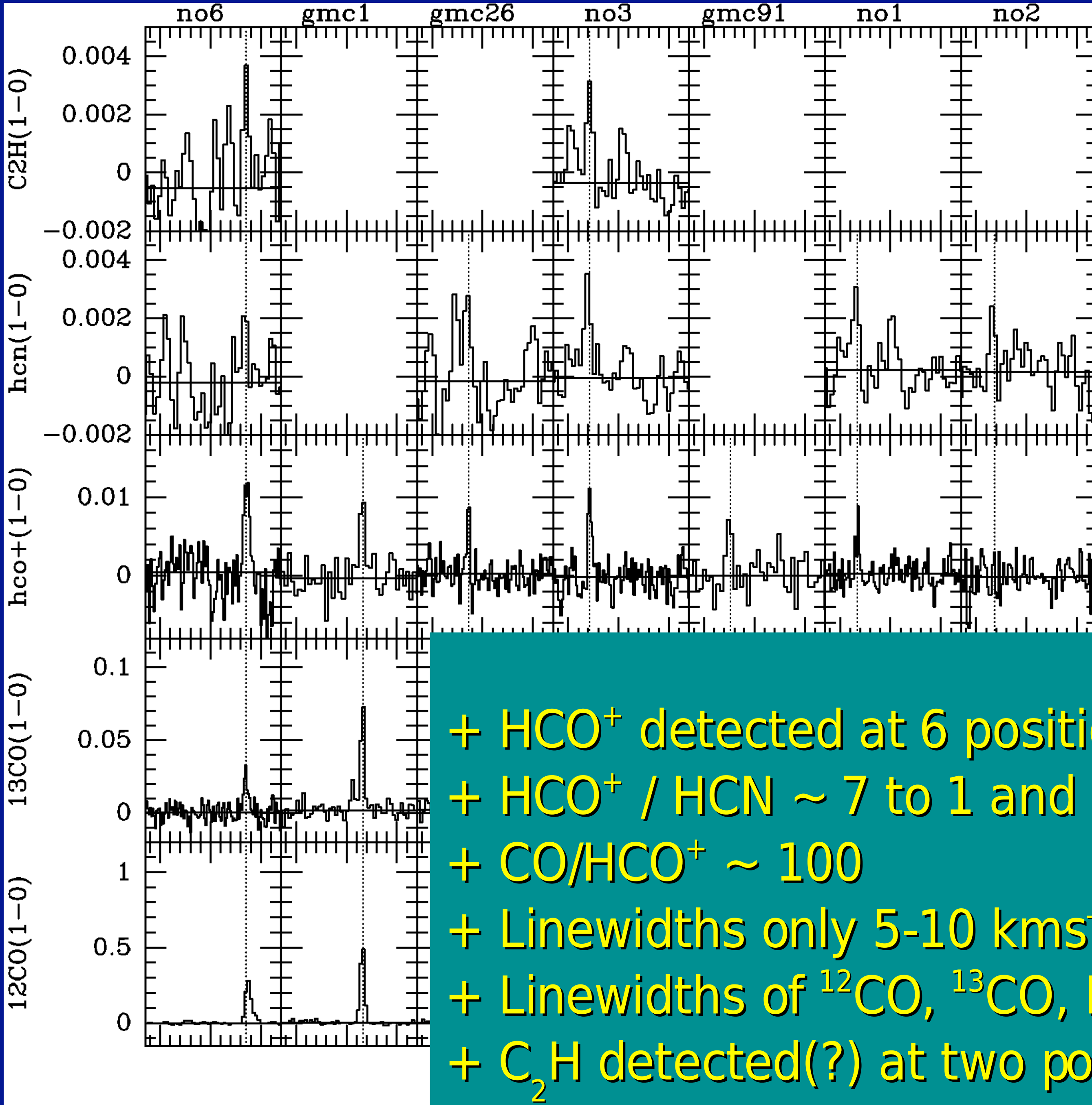
HCN 1-0

HCO^+ 1-0

^{13}CO 1-0

^{12}CO 1-0

IIb. Dense gas in M33



C_2H

HCN 1-0

HCO^+ 1-0

+ HCO^+ detected at 6 positions

+ HCO^+ / HCN ~ 7 to 1 and less

+ CO/HCO^+ ~ 100

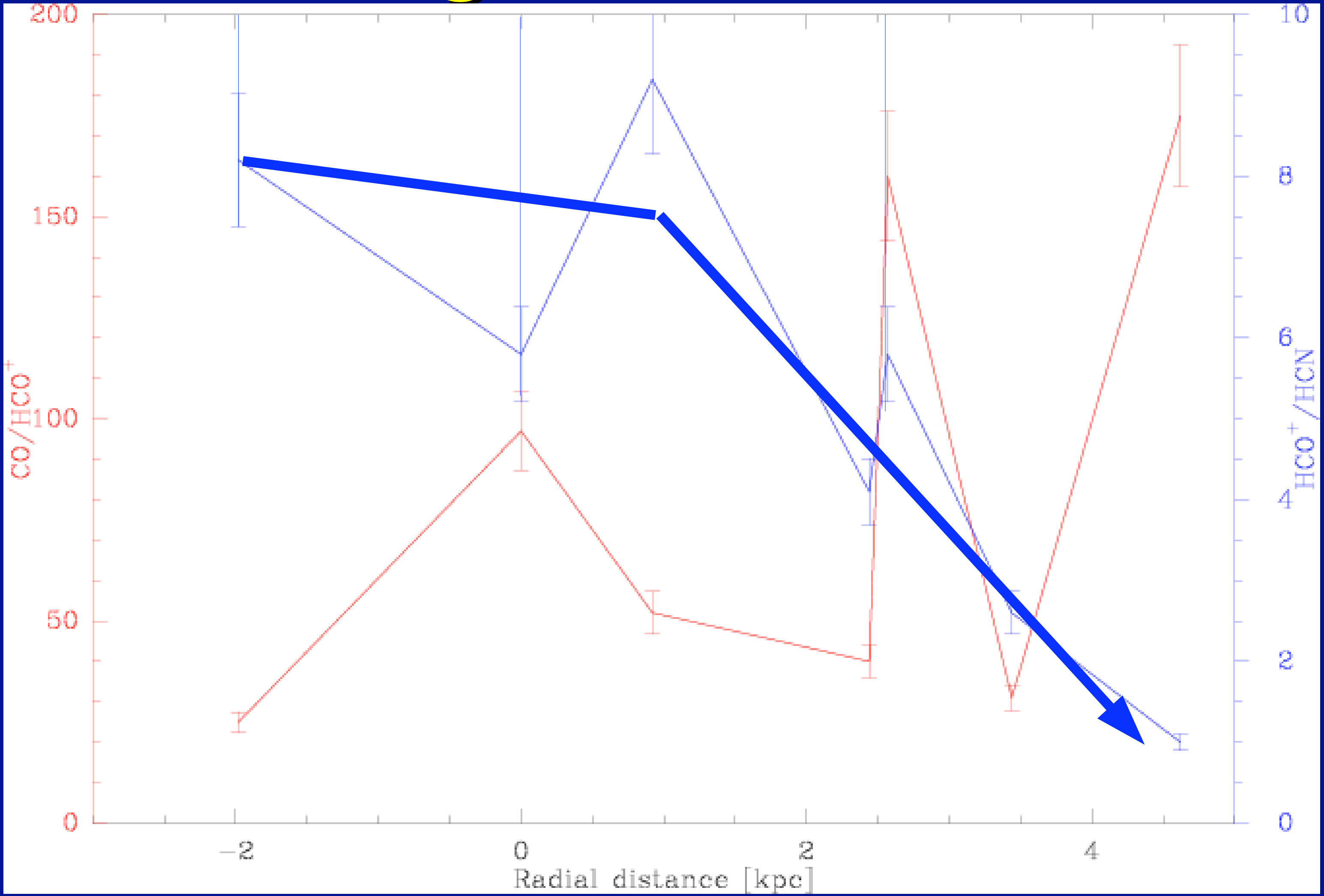
+ Linewidths only 5-10 kms^{-1}

+ Linewidths of ^{12}CO, ^{13}CO, HCN, HCO^+ similar

+ C_2H detected(?) at two positions

+ C_2H detected at

IIb. Dense gas



HCO^+ / HCN

+ M33: ratio drops from 9 to 1 between 1 and 4.5 kpc galacto-centric radius.
+ M31: ratio ~ 1.1 in M31 out to 15.5 kpc (Brouillet et al. 2005)
+ Active galactic nuclei: 0.5-1.6 (Krips et al. 2008):
   low in AGNs like NGC1068, high in SBs like M82

+ Link to SFR ?

III. Herschel M33 Extended Survey ***HERM33ES***
a Herschel open time key project

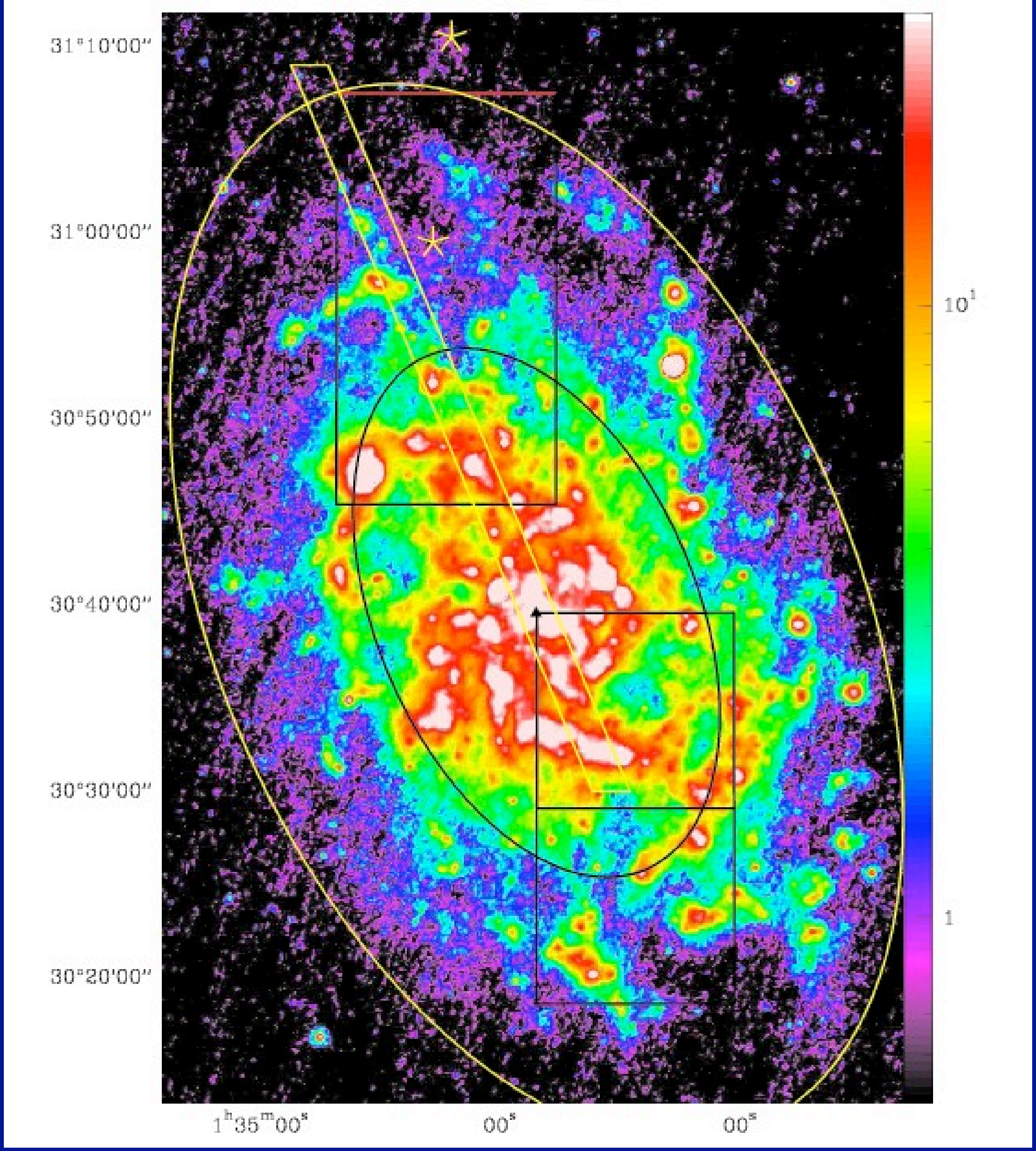
Planned Herschel Observations:

Extended Cut along the major axis:

- [CII] and H_2O with **HIFI** (150hrs)
- [CII], [NII], [OI], [NIII] with **PACS** (50hrs)

Entire galaxy:

- dust continuum between 85µm and 500µm with **PACS & SPIRE parallel mode** (6hrs)



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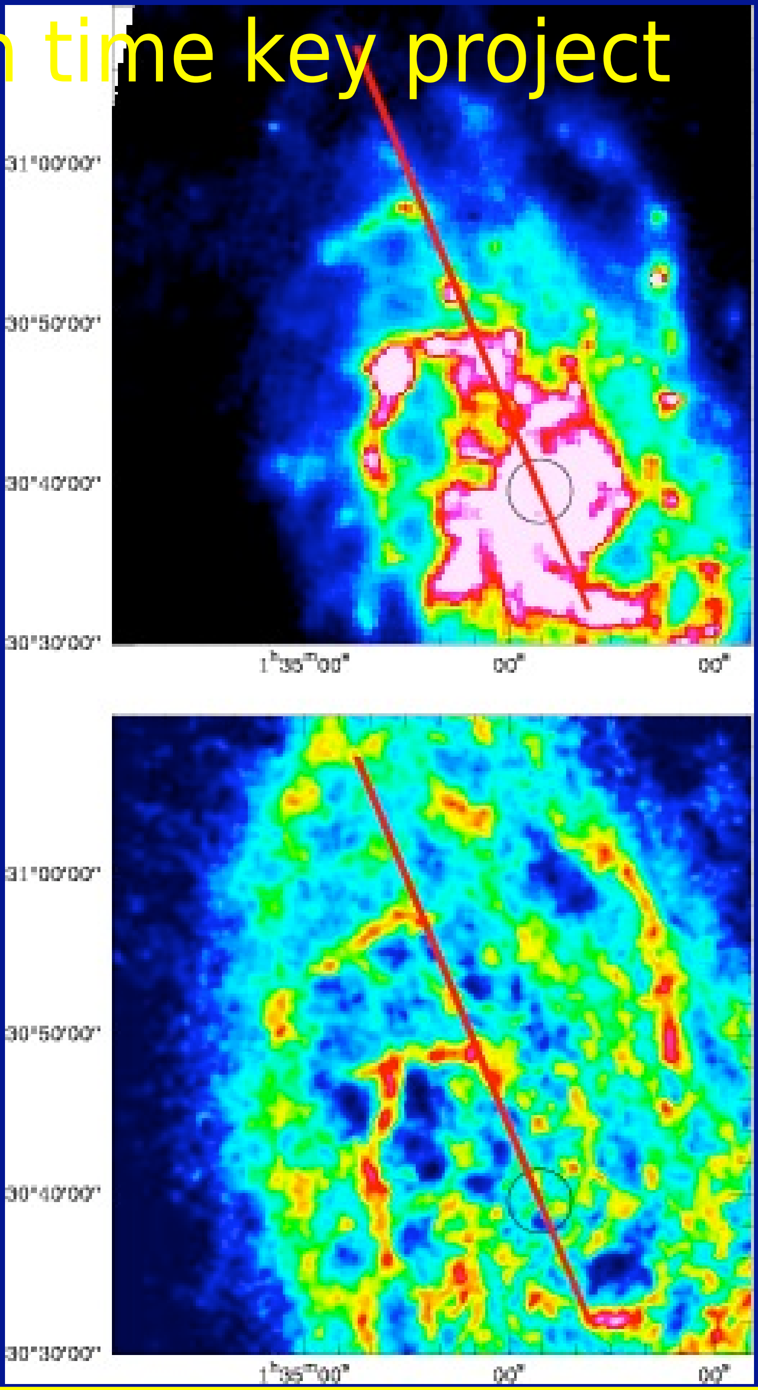


Top:
160μm
MIPS/Spitzer
(Tabatabaei et al. 2007)

Bottom:
HI 21cm
(Deul & van der Hulst 1987)

Key Topics:

A. Phases of the ISM:
The origin of [CII] emission

B. Energy Balance of the ISM

C. Star formation traced by
[CII] and [NII]

D. Formation of molecular clouds
from the diffuse atomic medium

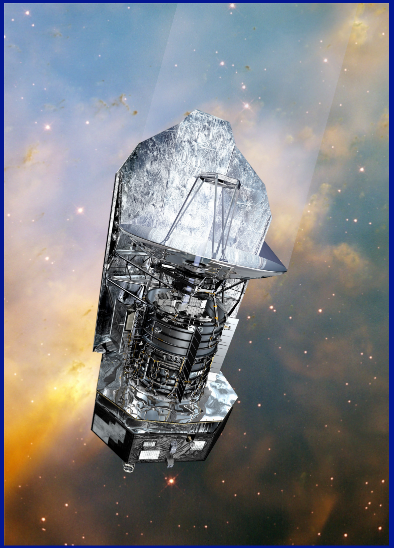
III. Herschel M33 Extended Survey ***HERM33ES***
a Herschel open time key project

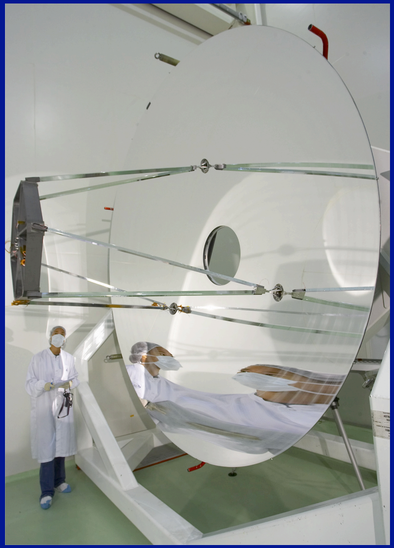
The Herschel open time key project: **HERMES-M33**

C.Kramer
D.Calzetti, G.Stacey, S.Lord, J.Braine

S.Aalto, R. Beck, F.Bertoldi, F.Combes, M. Dumke, S.Garcia-Burillo, R.Guesten, C.Henkel, F.Israel, B.Koribalski, A.Lundgren, J. Martin-Pintado, B.Mookerjea, M.Roellig, K.Schuster, K.Sheth, J.Stutzki, F.van der Tak, F.Tabatabaei, R.Tilanus, P.van der Werf, M.Wiedner, T.Wiklind, M.Xilouris

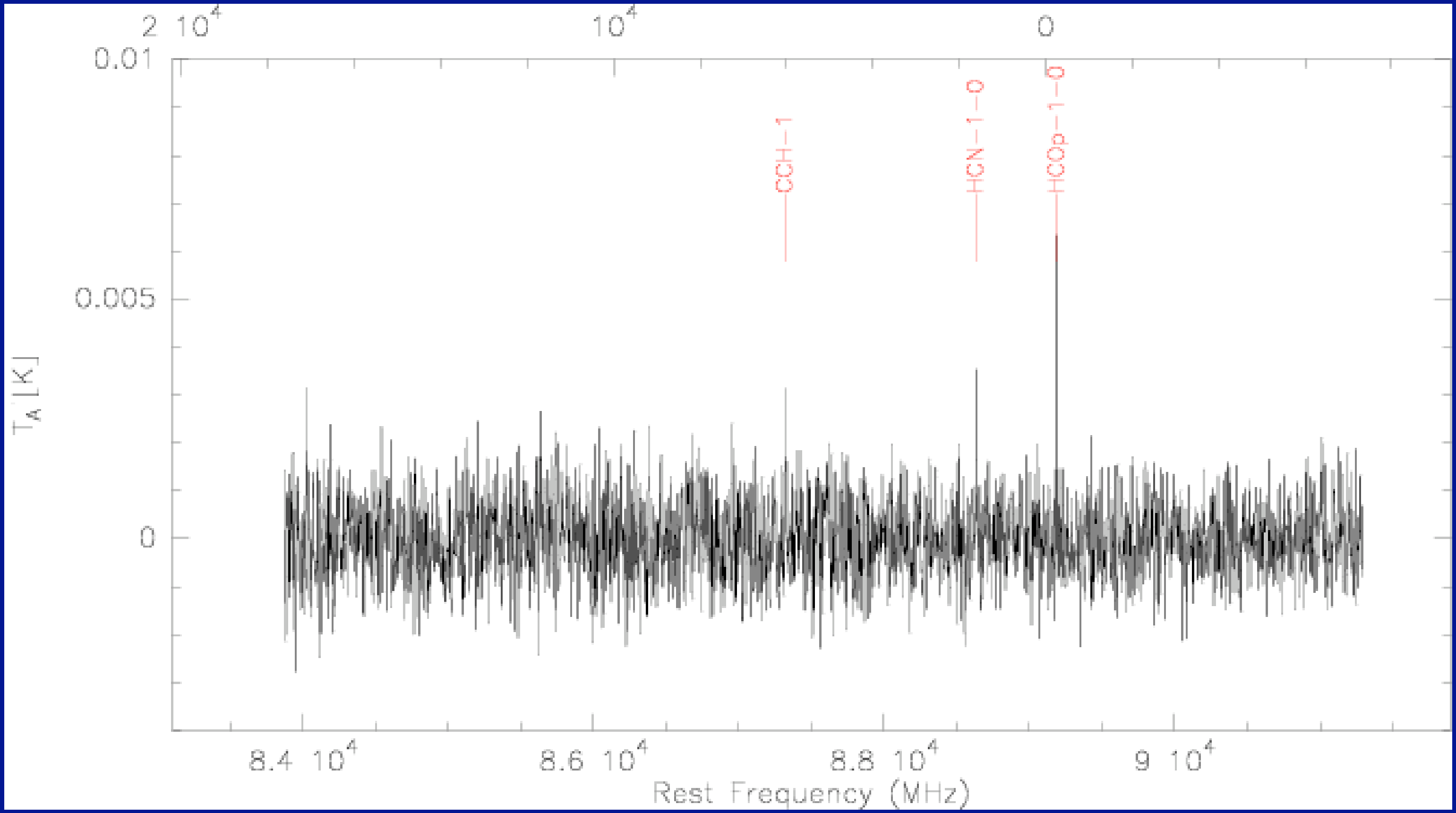
E.Rosolowsky, S.Verley, M.Boquiem, P.Gratier, G.Quintana-Lacaci, C.Buchbender, M.Gonzalez, A.Sievers, S.Anderl, A.Stavros





EMIR/IRAM 30m:

HCO^+, HCN, C_2H simultaneously (pos.no.3)



Band E090 with 8 GHz instantaneous bandwidth and 2MHz resolution

+ 500 MHz / 320 kHz high resolution backend centered on HCO^+

EMIR/IRAM 30m:

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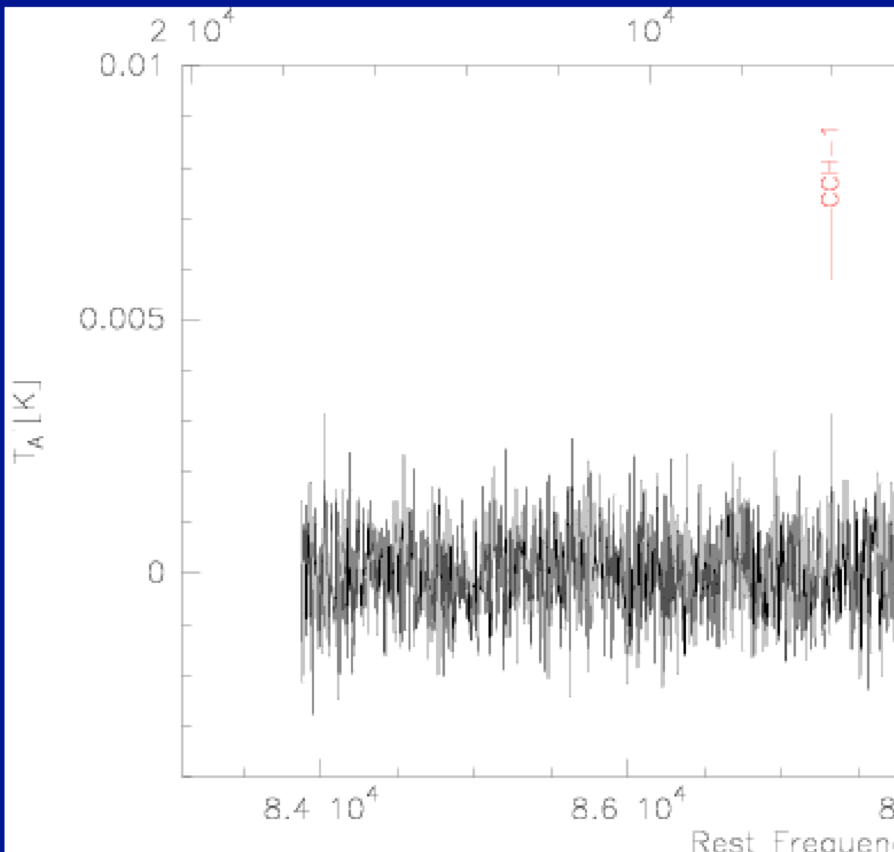


Why HCN & HCO^+ ?

Dipole moments:
+ 2.98 Debye (HCN),
+ 3.30 Debye (HCO^+)
+ 0.112 Debye (CO)

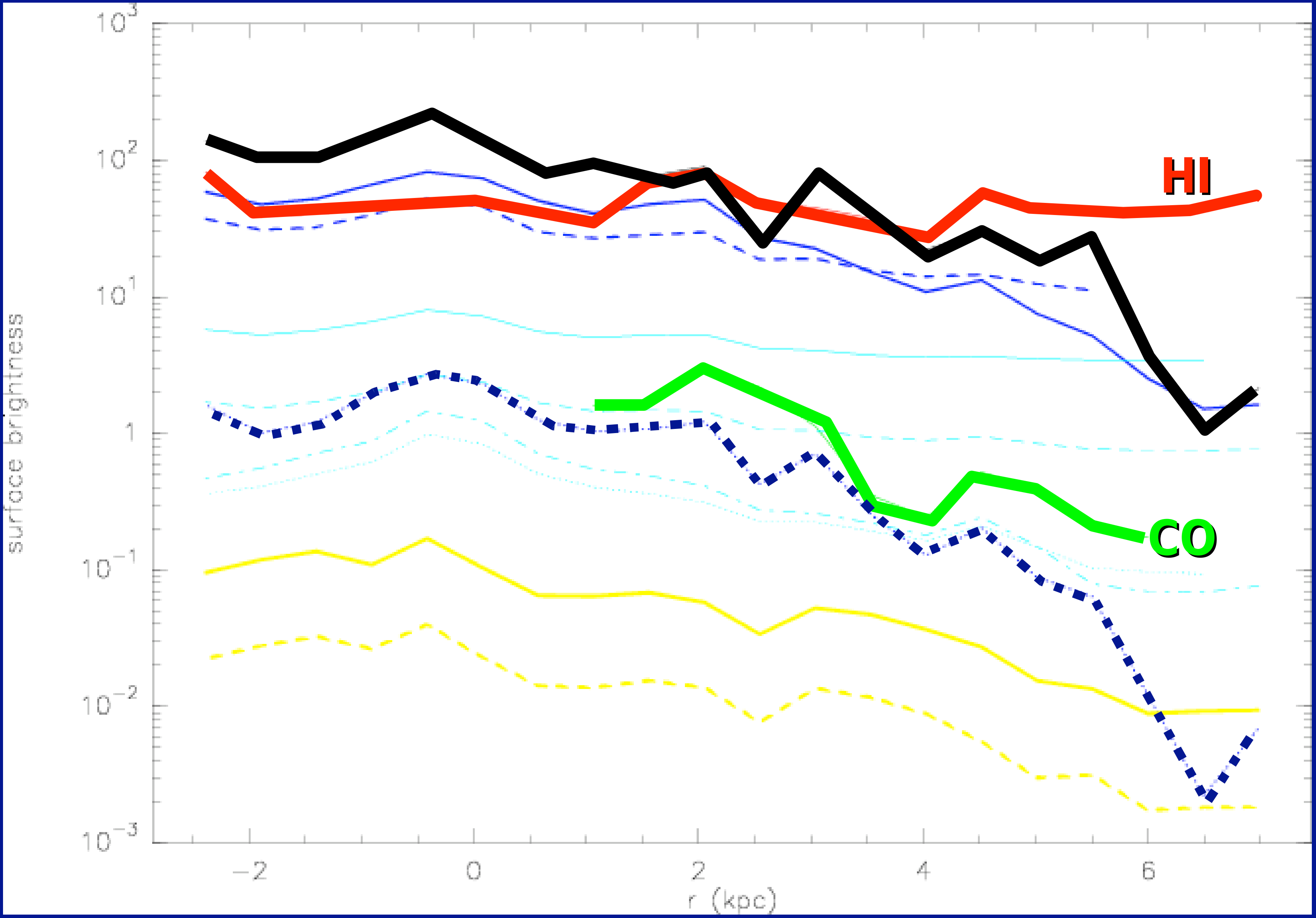
hence, HCN & HCO^+ have high critical densities of about 10^5 cm^{-3}, while their J=1 levels lie only few Kelvin about 0.

HCO+ abundance varies with CR flux.

So far, only few studies of HCN & HCO^+ in disk galaxies outside of the nucleus.

Band E090 with 8 GHz instantaneous bandwidth and 2MHz resolution
+ 500 MHz / 320 kHz high resolution backend centered on HCO^+

Radial stripes

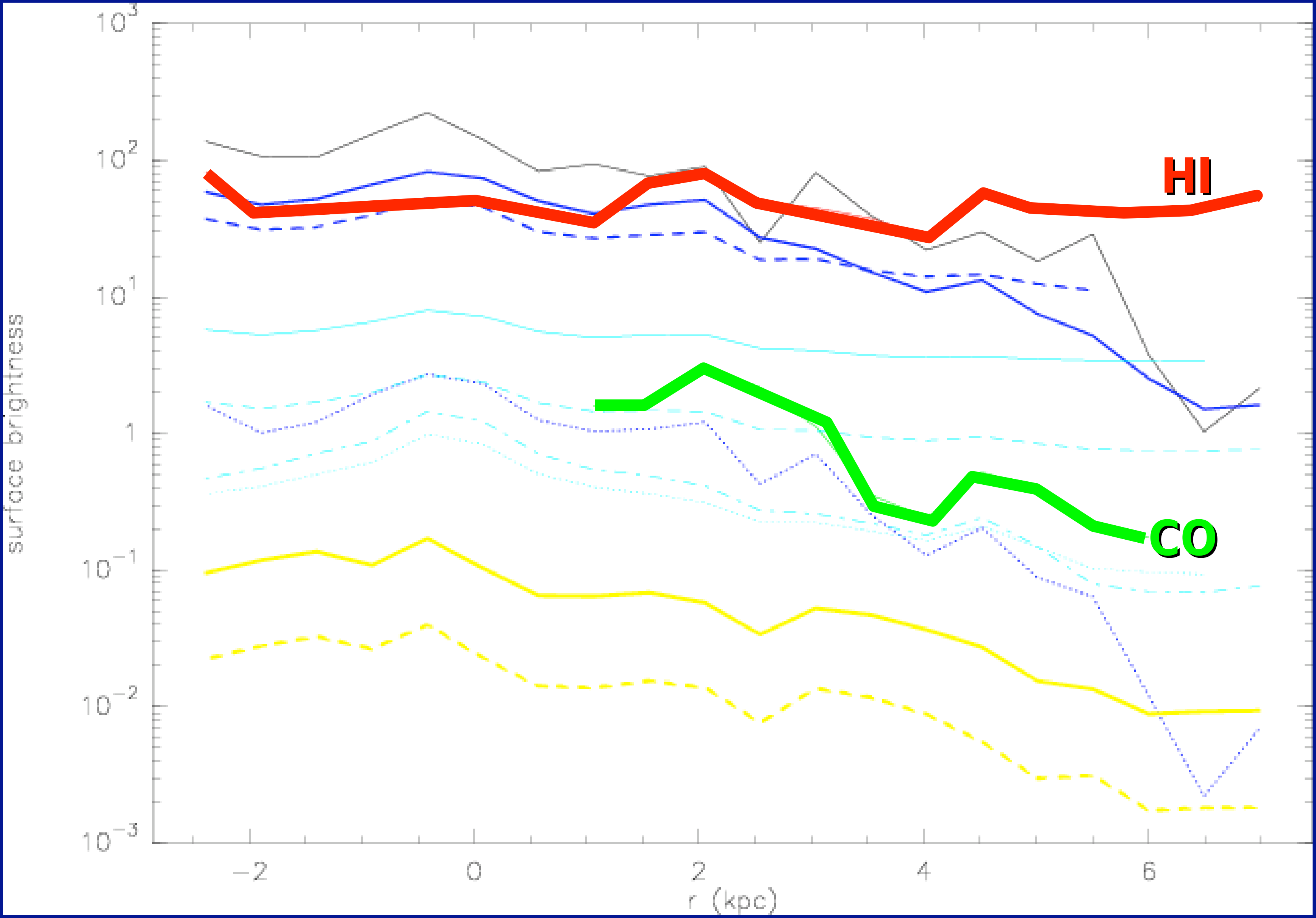


SFR-Tracers:

Hα

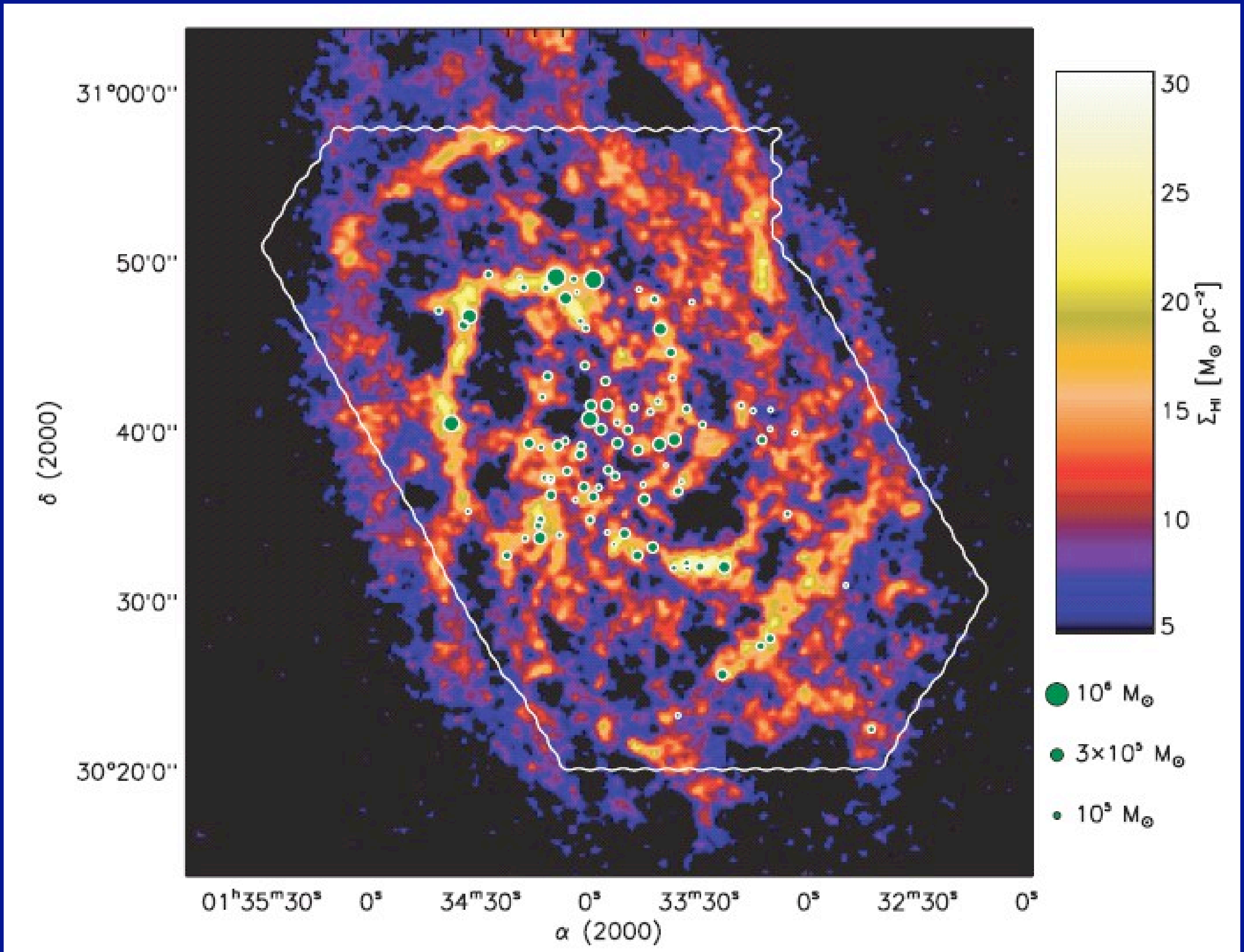
24μm

Radial stripes



Voyez (summer internship, IRAM)

Molecular & atomic gas



Location of Giant Molecular Clouds (GMCs) overlaid upon an integrated intensity map of the HI 21cm line (Engargiola et al. 2003, cf. Gardan et al. 2007). **GMCs are formed from large structures of atomic gas.**

The Local Group spiral galaxy M33

+ Morphological type: SA(s)cd

+ Major & minor diameters:
  70.8, 41.7 arcmin

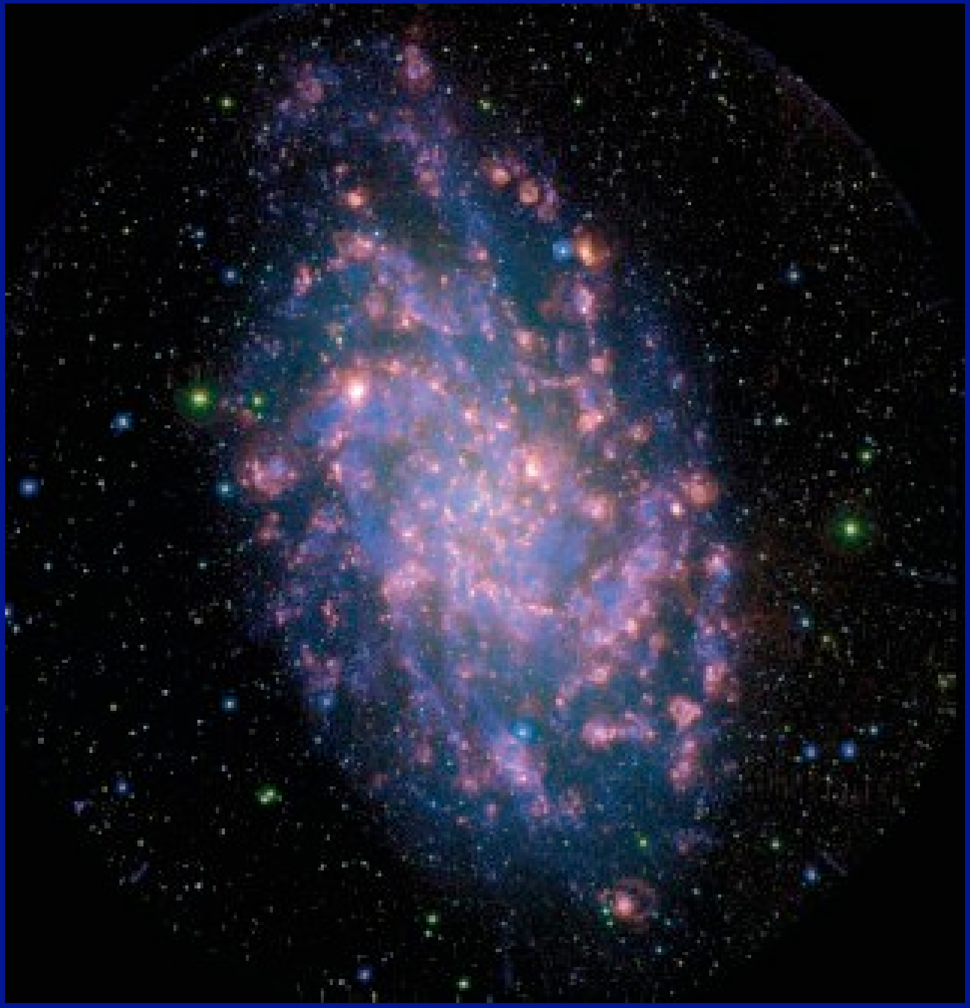
+ PA = 22.5 deg, Incl.: 55.0 deg

+ Distance = 840 kpc
  (180 kpc from M31)

+ 12 arcsec = 49 pc

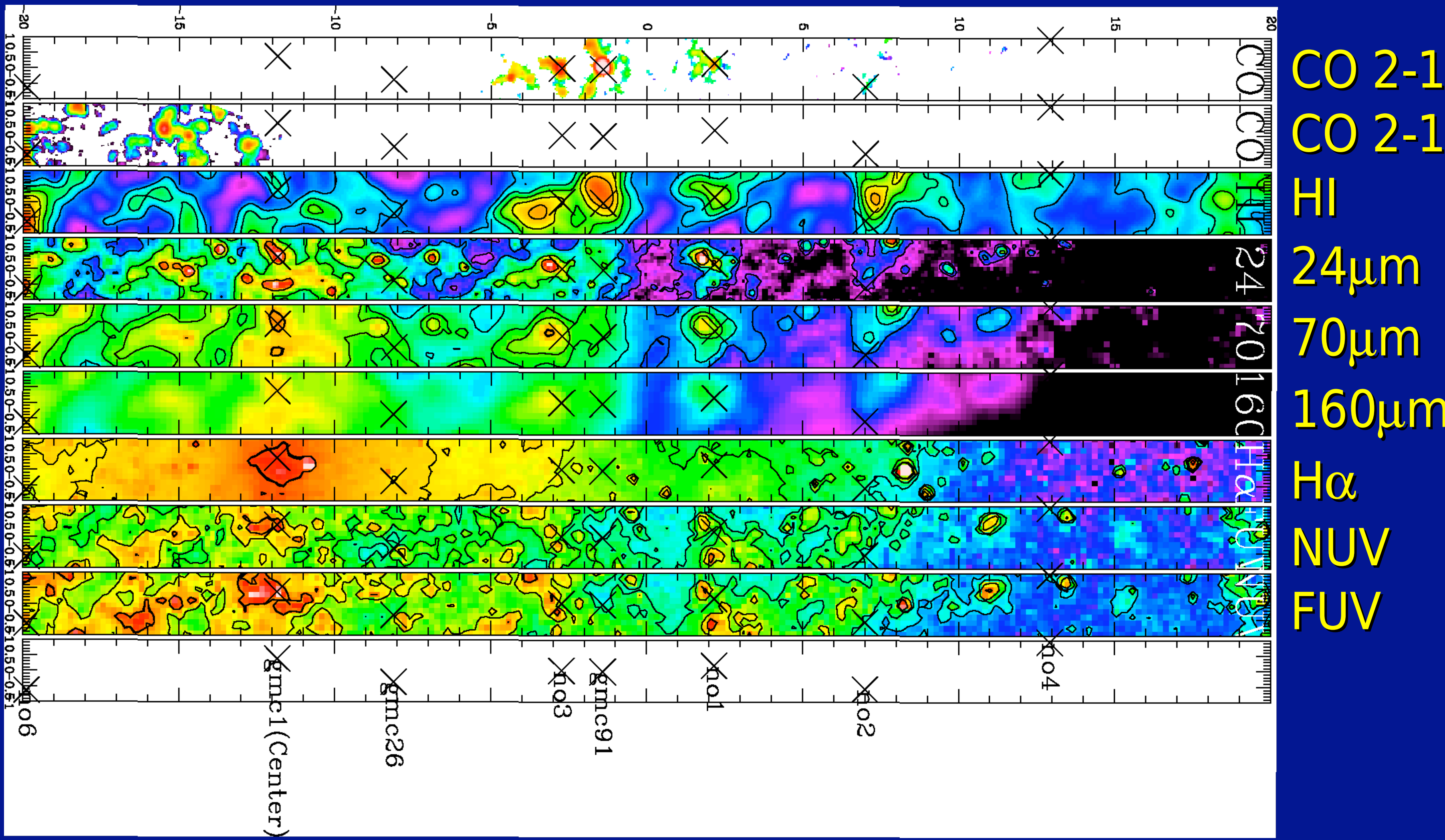
+ Brightest HII complex in
  Local Group (NGC604)

+ Metallicity: subsolar by a factor 2-3
  Shallow gradient!?



M33 in Hα (red) and NUV with GALEX (blue)

IIb. Radial stripes and dense gas



Center

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