The outskirts of spiral galaxies: phases and mass budget of the interstellar medium in outer disks

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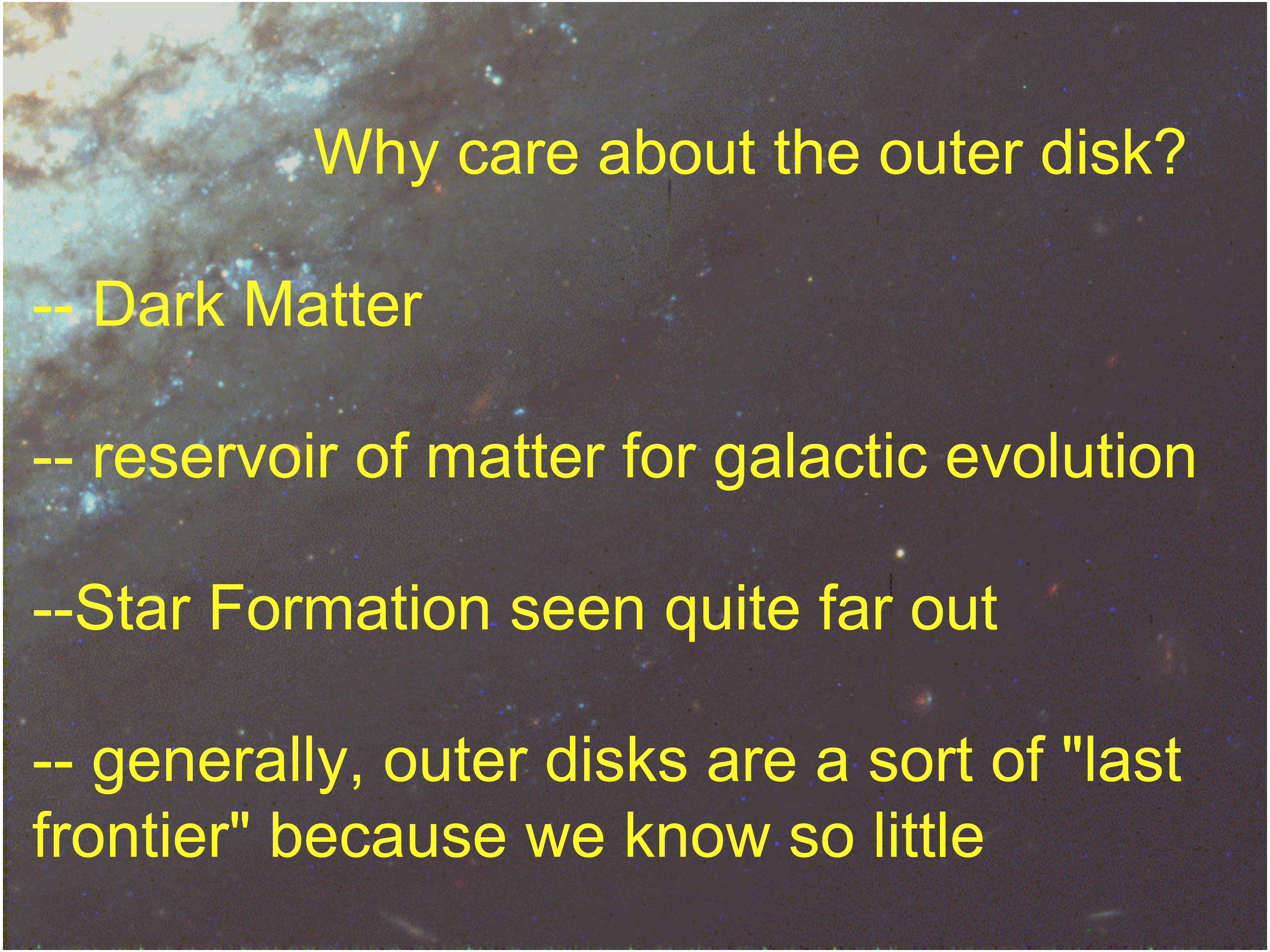
with ... N. Brouillet, **E. Gardan**, F. Herpin, A. Ferguson....


Why care about the outer disk?
-- Dark Matter
-- reservoir of matter for galactic evolution
--Star Formation seen quite far out
-- generally, outer disks are a sort of "last frontier" because we know so little

What is outer ?

We know galaxies extend beyond the "R25" radius, both the disks (gas, SF) and the (stellar) spheroid. For M/L = 1, R25 corresponds to 6.6 Msun pc^{-2}, which is very close to the typical HI surface density at R25 in normal spirals (6 x 10^{20} H/cm^2 = 6.6 Msun pc^{-2} incl. He)

"outer" ==> Σgas ≥ Σstars ?

This definition may be more physical than a brightness criteria but also brings the "outer" disk further in for later types of galaxies (more gas, younger stellar population).

What was outer ?

For a wide range of scenarios, the gas mass was a few times higher at redshift 1 than today. This naturally brings the "outer" disk further in by at least one scale length using the Σgas ≥ Σstars definition.

The inner disk was then about half the size of what it is today for evolution without major mergers.

If the HI --> H2 --> stars process varies with the gas/star mass ratio, then the study of outer disks may in fact be relevant to mid-z work, where it looks like the Star Formation Efficiency is higher.

Outer disk conditions

-- some stars, low interstellar radiation field (ISRF)

-- Σgas ≥ Σstars.

-- subsolar metallicity

In recent years better measurements of lines from HII regions have shown that electron temps rise with distance, resulting in weaker gradients.

-- slowly varying gravitational potential

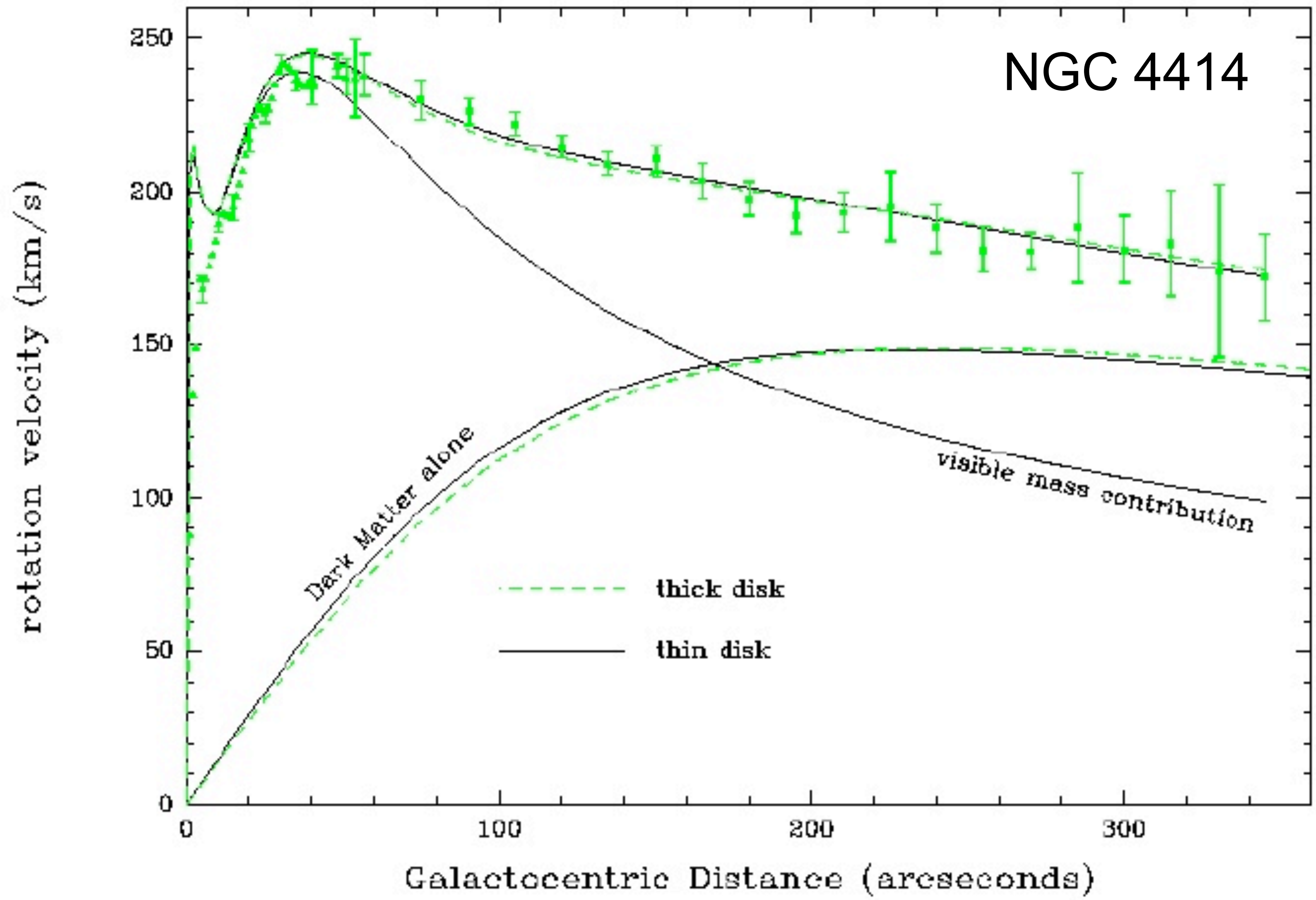
==> low tidal forces on clouds

-- low large-scale magnetic field

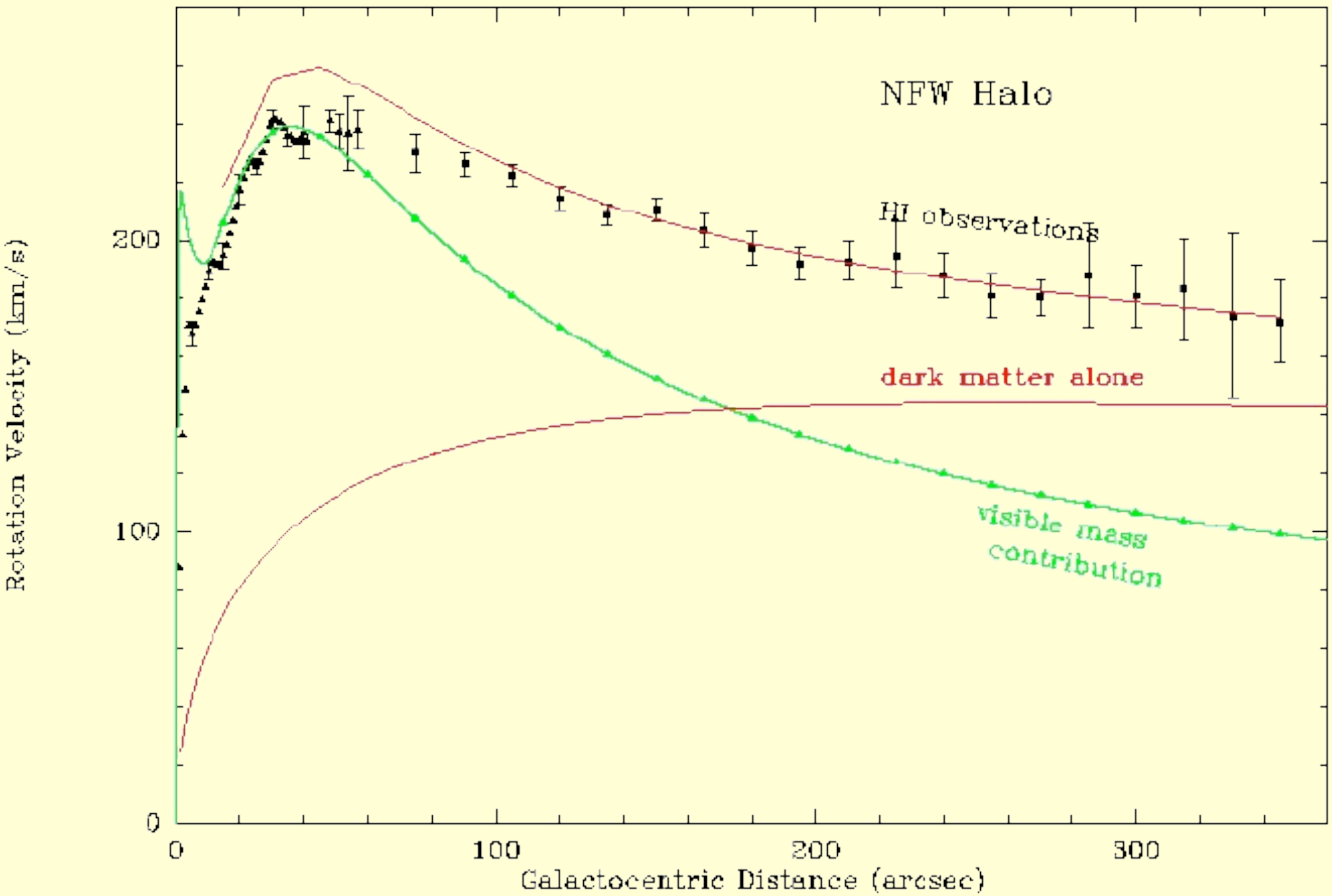
-- dominant source of heating not known

-- HI present far far out, CO (proxy for H2) only recently

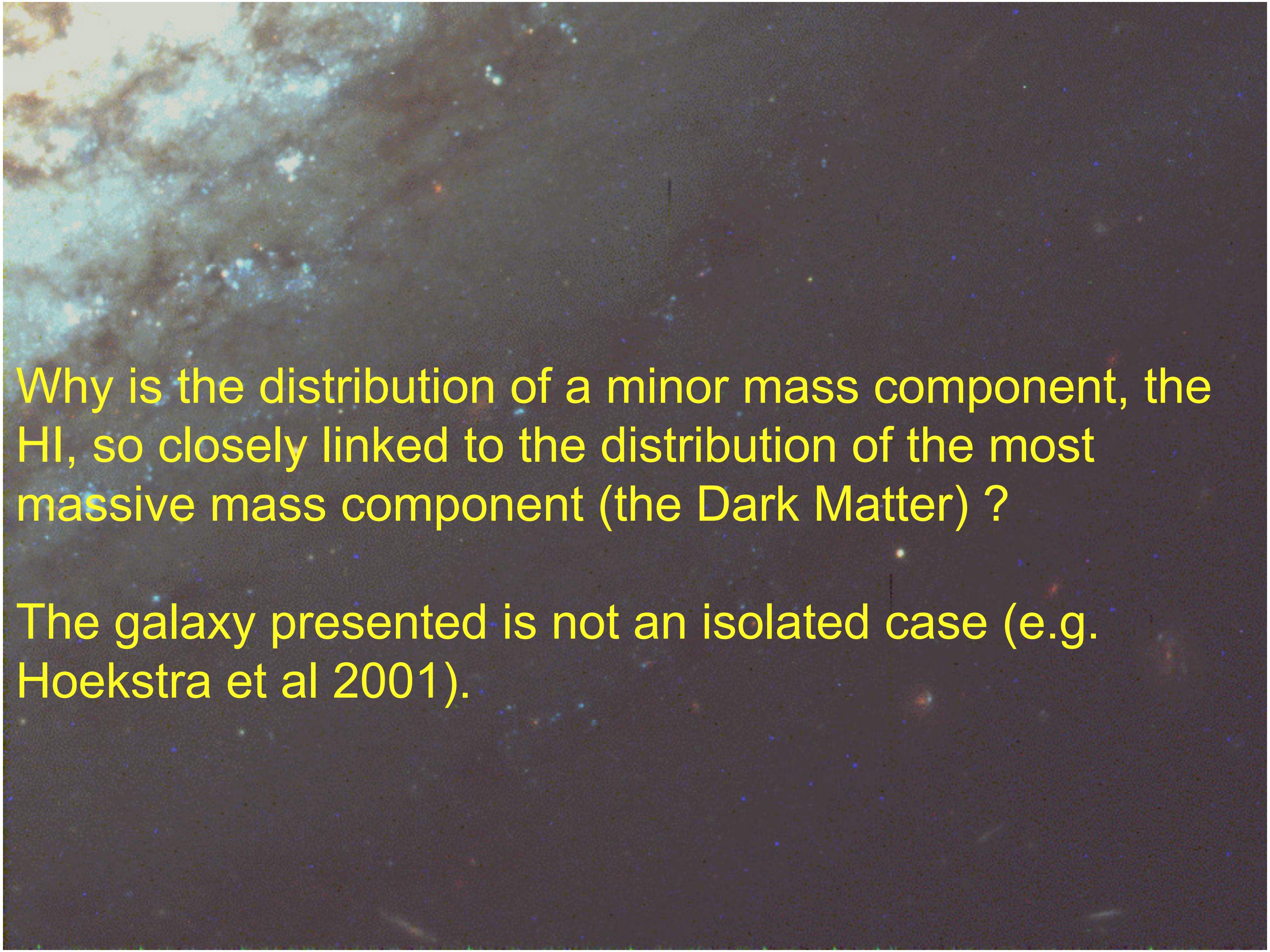
For many spirals, disk DM fits very well (here HI scaled up by 17 (thin disk) or 18 (thick disk) -- 1 free parameter.



Navarro, Frenk, & White   CDM halo



Two free parameters in the NFW, Burkert, Moore models



Why is the distribution of a minor mass component, the HI, so closely linked to the distribution of the most massive mass component (the Dark Matter) ?

The galaxy presented is not an isolated case (e.g. Hoekstra et al 2001).

Gas in the outer disk

H+ -- probably a minor component within $2R_{25}$
(~10^{18} H/cm^2 or 10^6 Msun per 10 x 10 kpc area)

HI -- probably dominant and found in 2 phases
warm: n ~ 0.1 H/cm^3 and T ~ 8000K   and
cool: n ~ 1-100 H/cm^3 and T ~ 50 - 200K
mass measurable via 21cm line

H2 -- first CO detections beyond R25 in 2004
Is CO the only tracer of molecular gas?
Currently only 4 galaxies with CO detected beyond R25
Milky Way, NGC 4414, NGC 6946, and M33
Focus of this talk: CO, Star Formation, and HI --> H2

CO Observations of NGC 4414

IRAM-30m telescope in 2003 and 2004

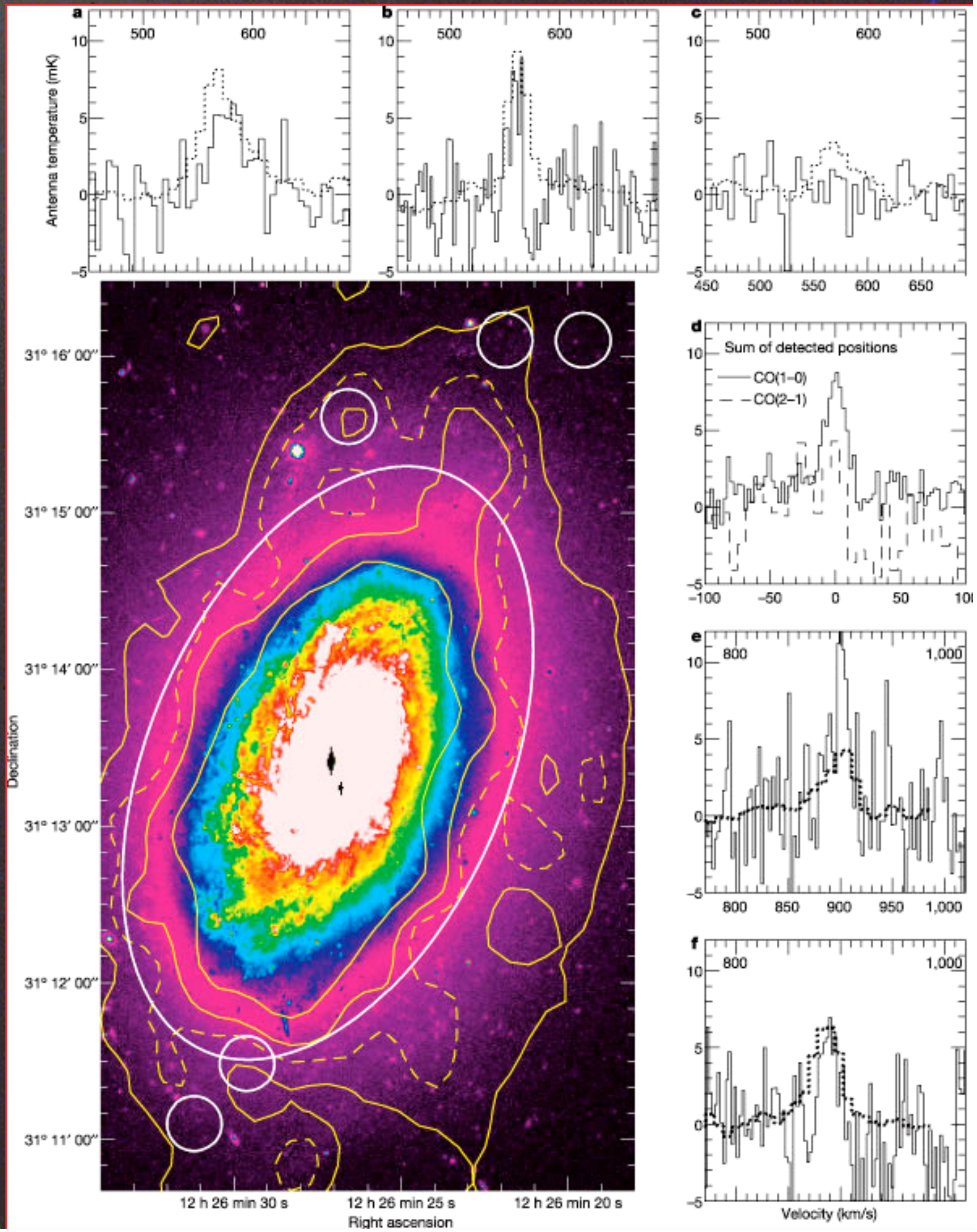
= First detection of molecular gas in an isolated spiral far beyond the optical edge.

An R band image of NGC4414 taken with the CFHT is shown with HI contours at column densities of 4, 6, 8, 12 x10^{20} atoms cm^{-2}, the 6 x10^{20} atoms cm^{-2} contour being dashed.

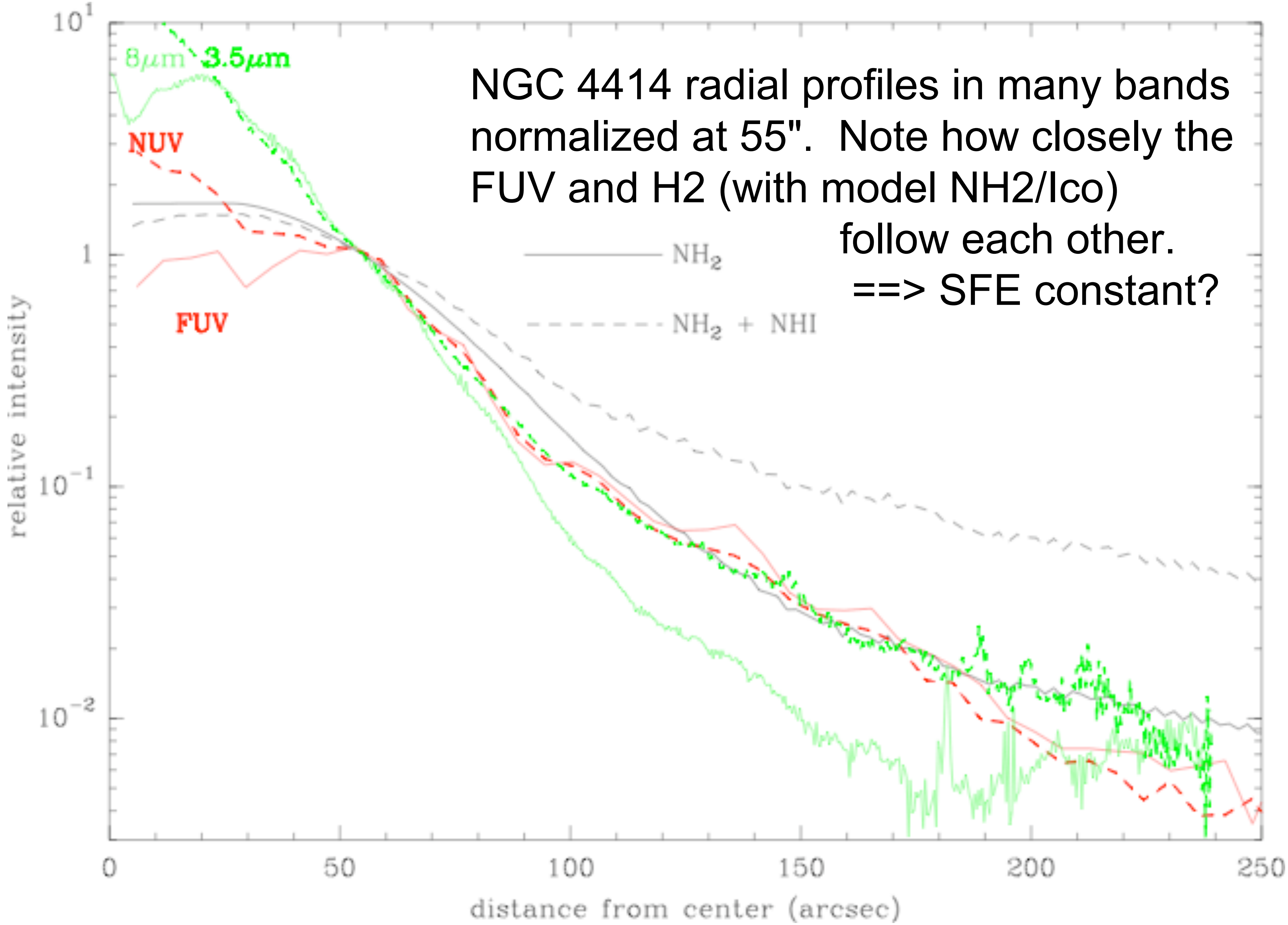
The surrounding boxes show the CO (1-0) (full line) and HI (dotted line) spectra ndicated by circles.

The CO(2-1) line was not clearly detected but the conditions were very good.

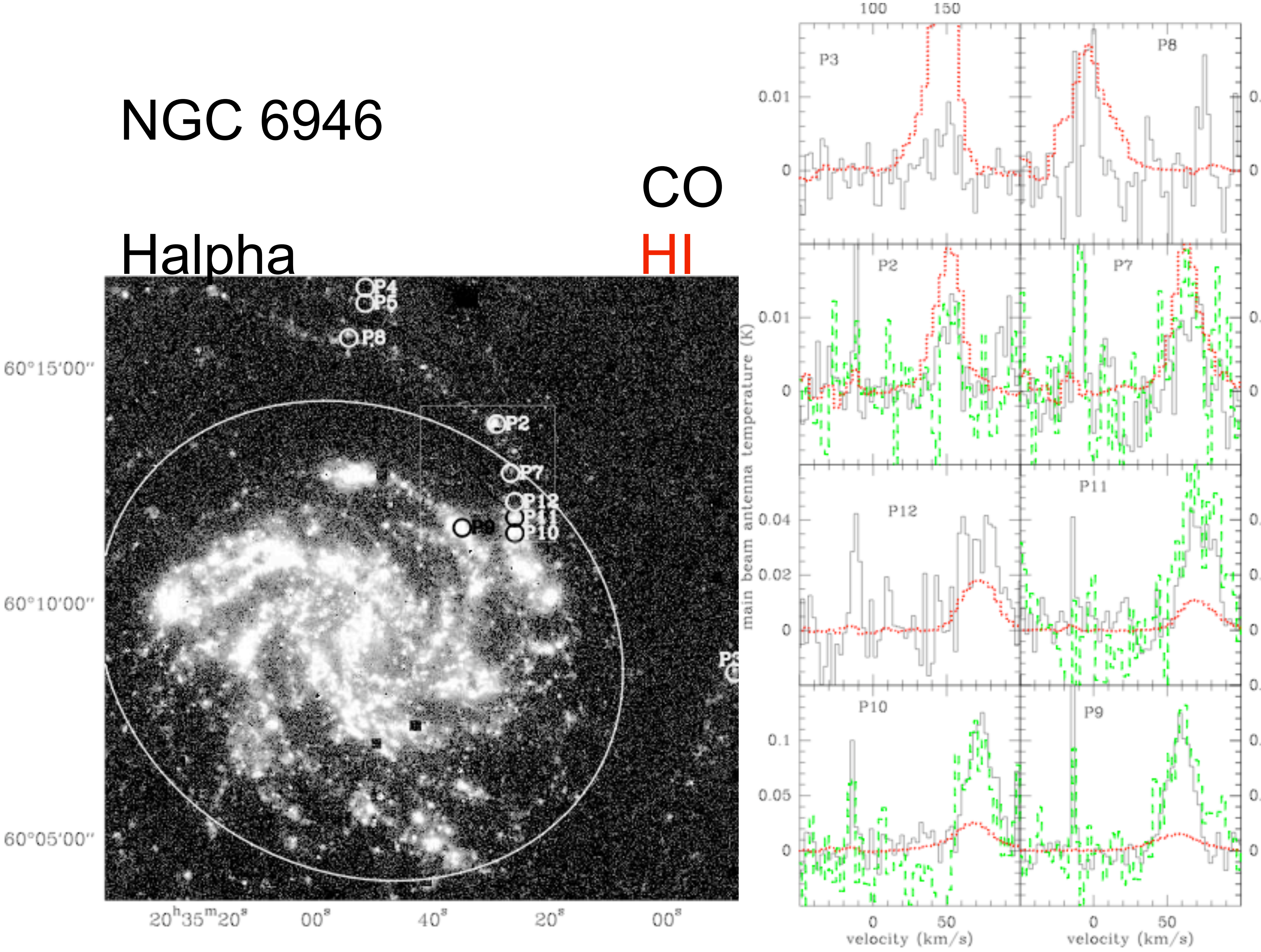
HI and CO line widths seem related



NGC 4414 radial profiles in many bands normalized at 55". Note how closely the FUV and H2 (with model NH2/Ico) follow each other.
==> SFE constant?



NGC 6946



CO
HI
Halpha
P2
P3
P4
P5
P7
P8
P9
P10
P11
P12
60°15′00″
60°10′00″
60°05′00″
20h35m20s
00s
40s
20s
00s
main beam antenna temperature (K)
velocity (km/s)
100
150
0
50
0.01
0.02
0.04
0.05
0.1

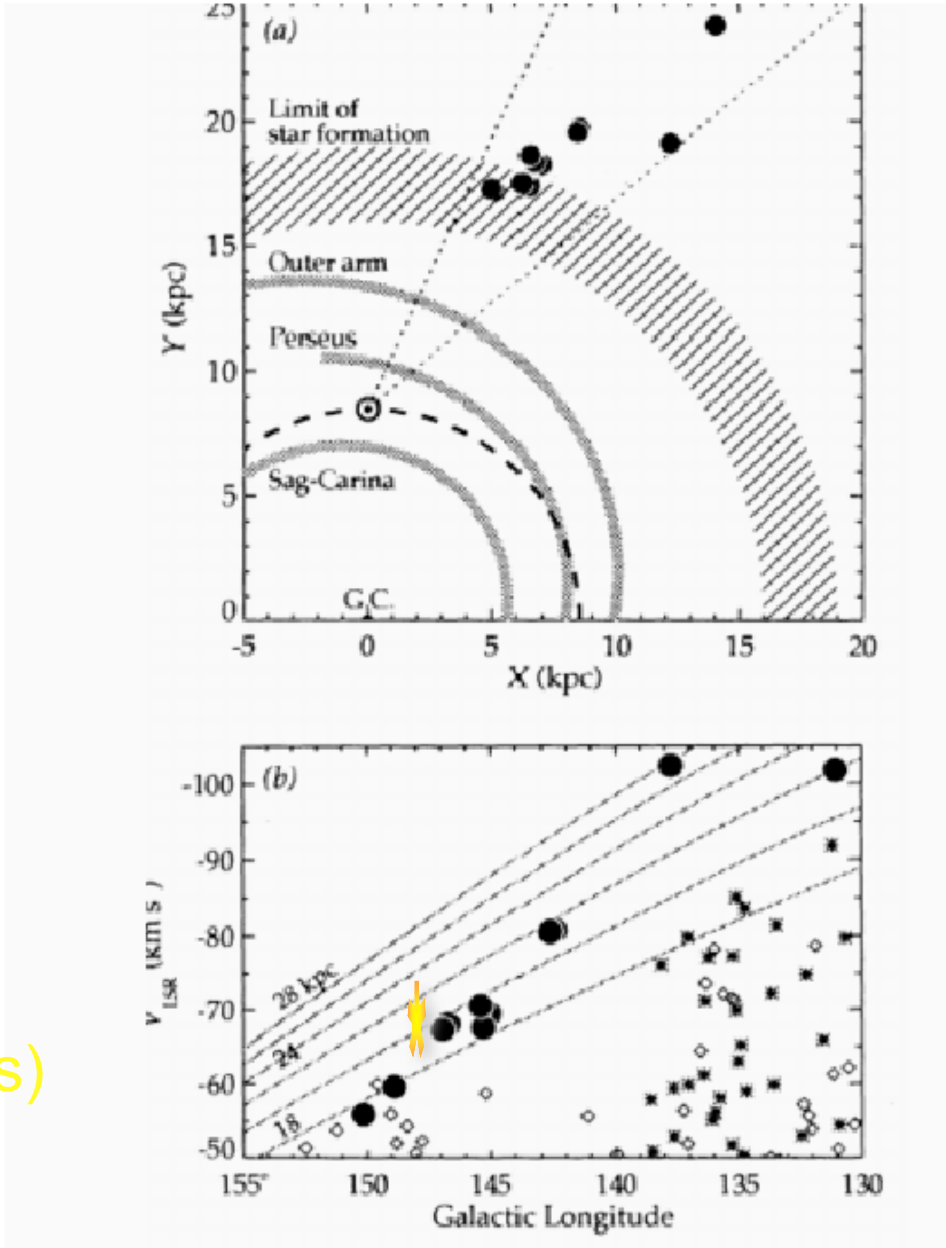
Outer disk clouds from Digel et al 1994

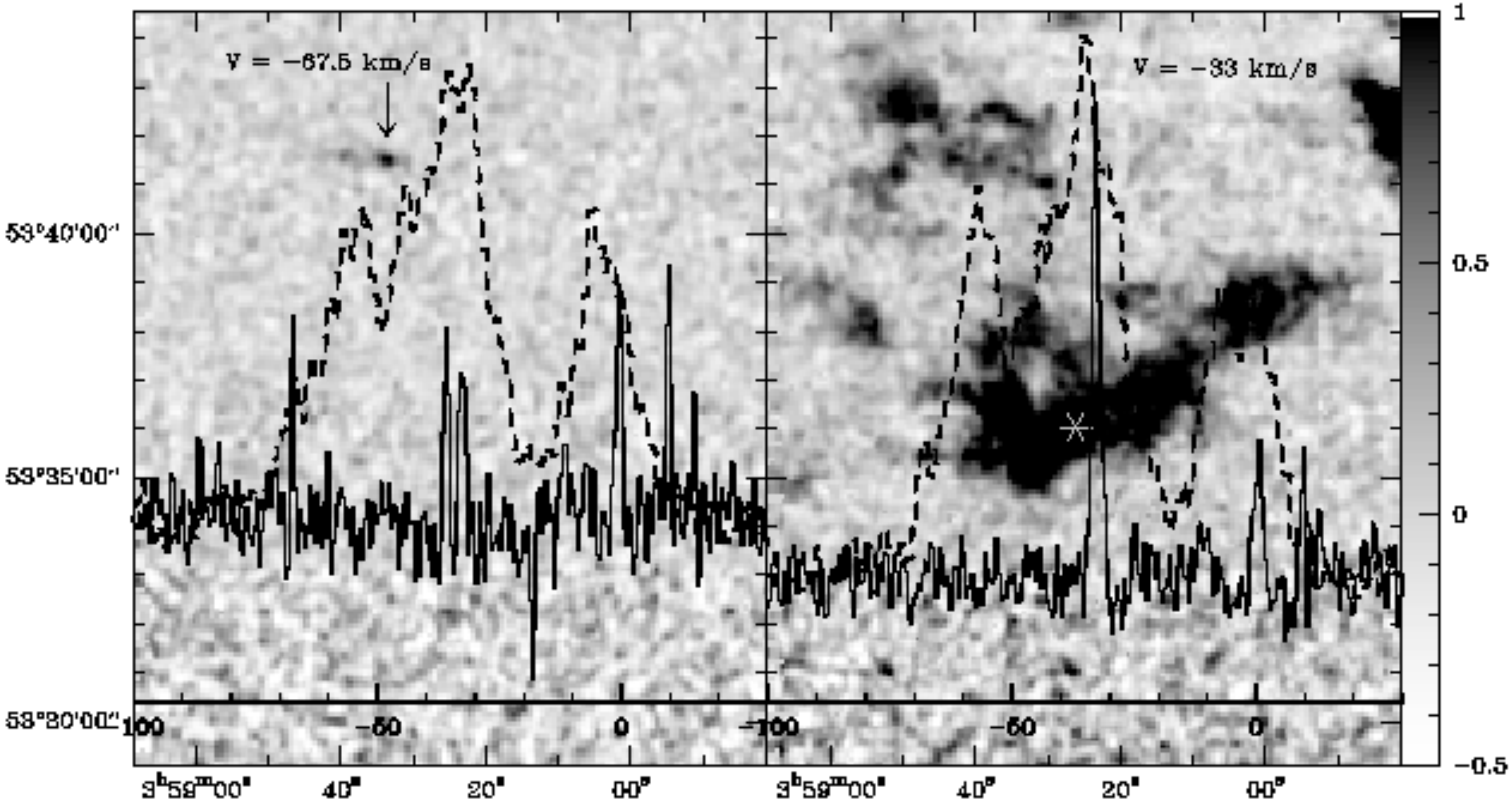
CO associated with HI clouds but not always with HI maxima.

Tkin of 10-25 K but lower CO luminosities than inner disk clouds.

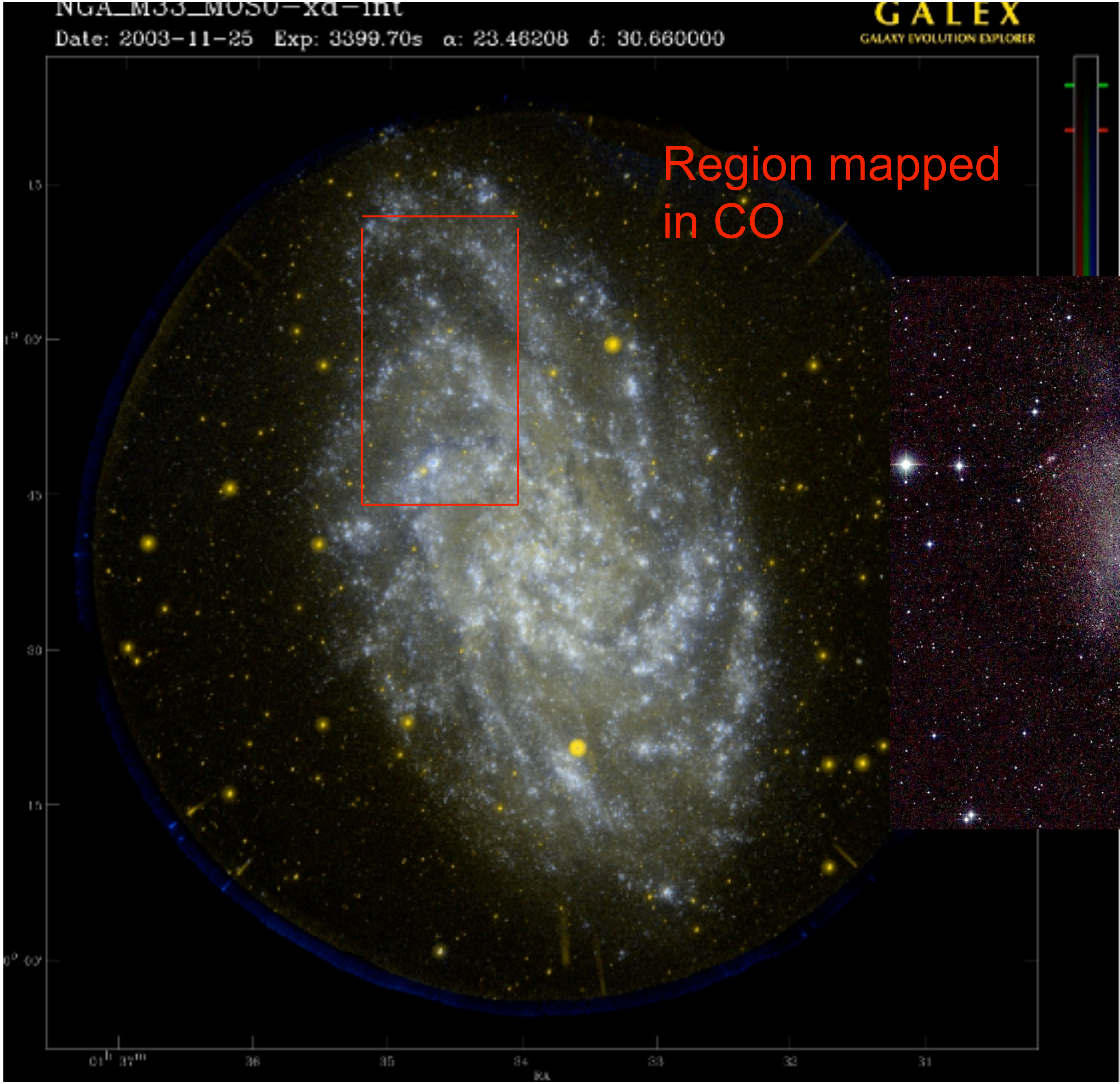
Difficult to identify sources of heating (lack of IR sources)

mass contribution small due to their rarity.

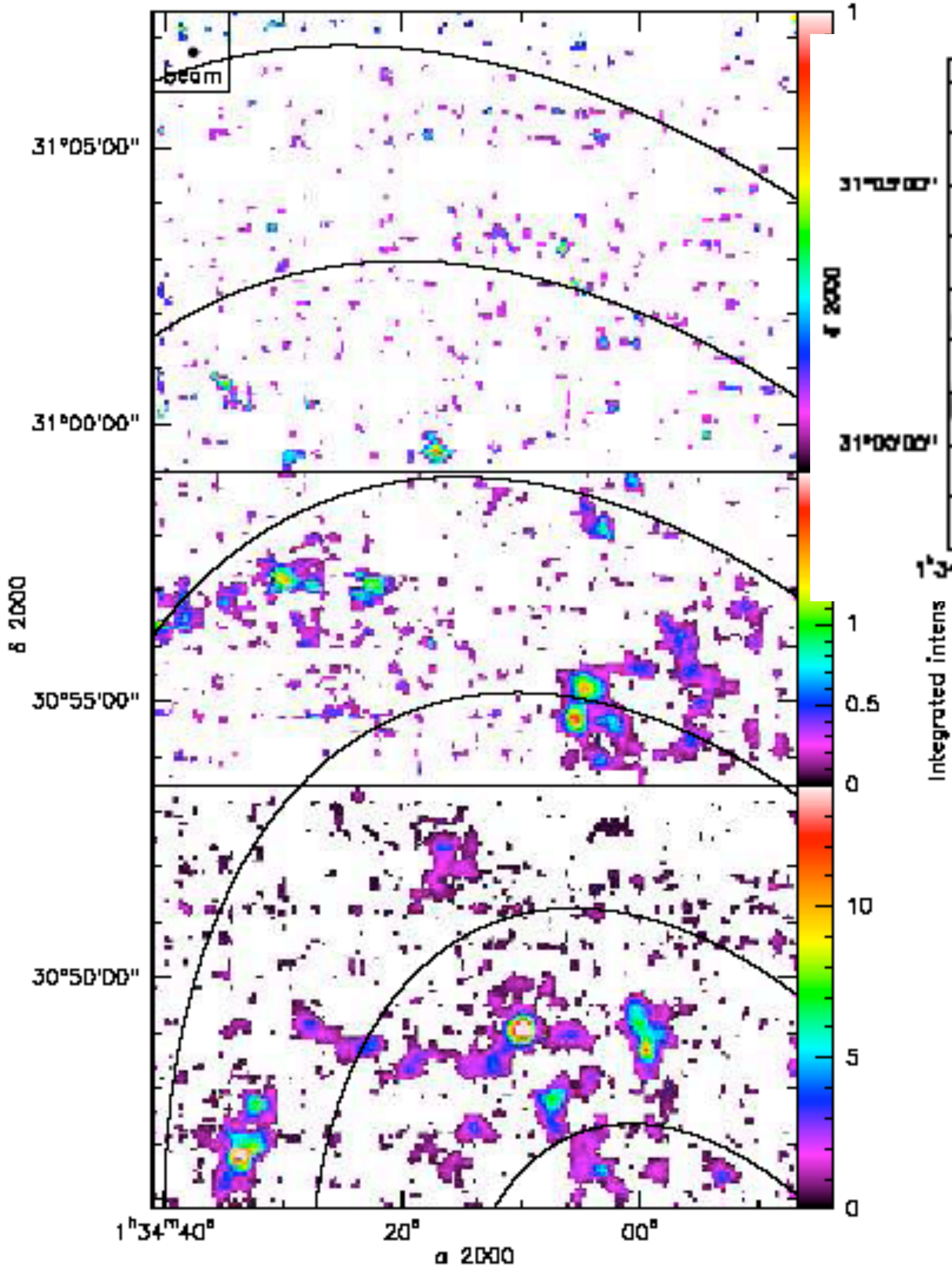


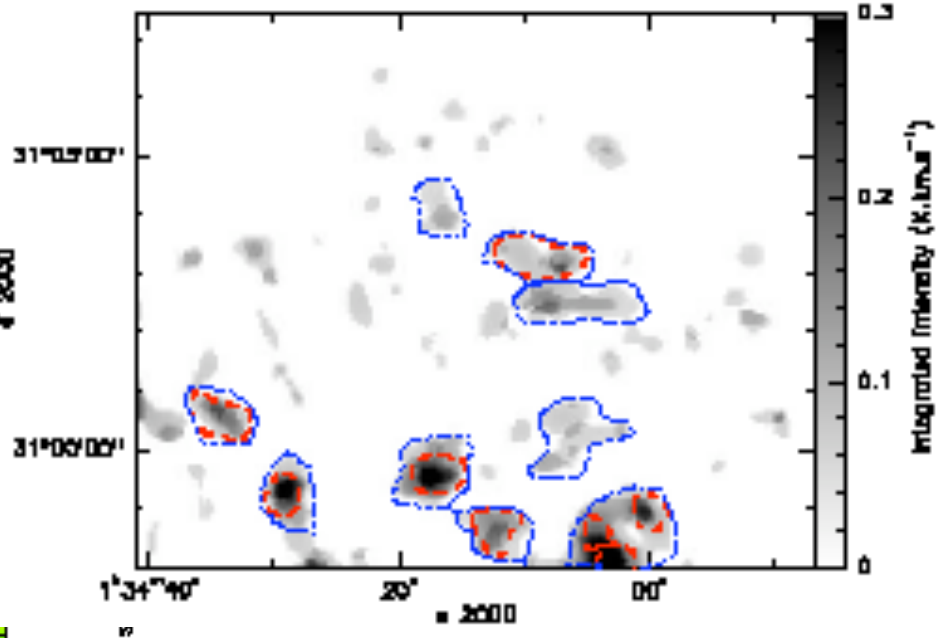


Two channel maps at -67.5 and -33 km/s with spectra at the positions indicated. Note the difference between the CO and HI line widths. The spiral arms are apparent in the two tracers. Sight lines typically meet two molecular clouds. (HI from CGPS, 1' res)



2MASS image at same scale

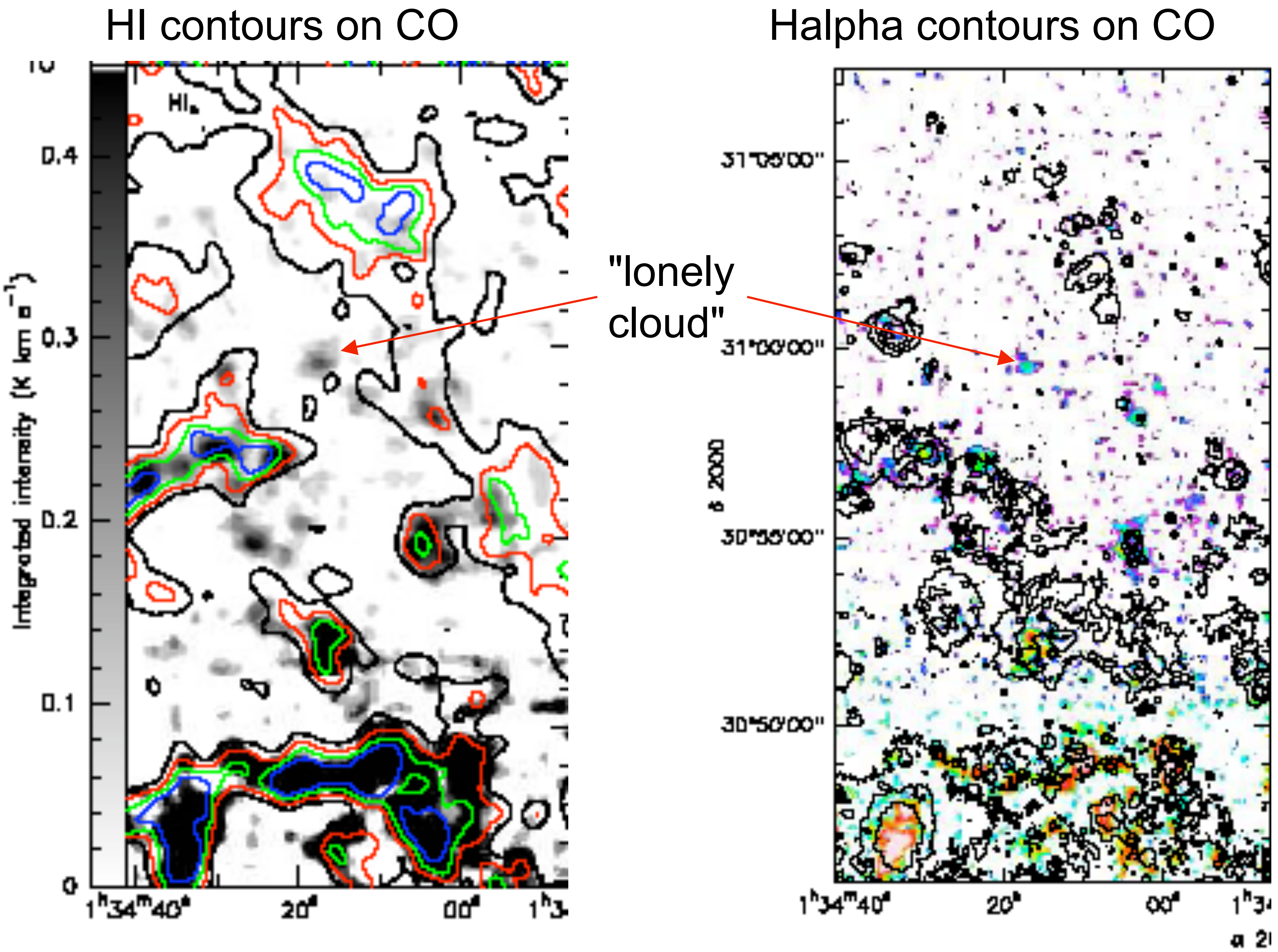




3sigma clipped map
of total CO emission.

Ellipses show radii of
2 3 4 5 6 7 kpc

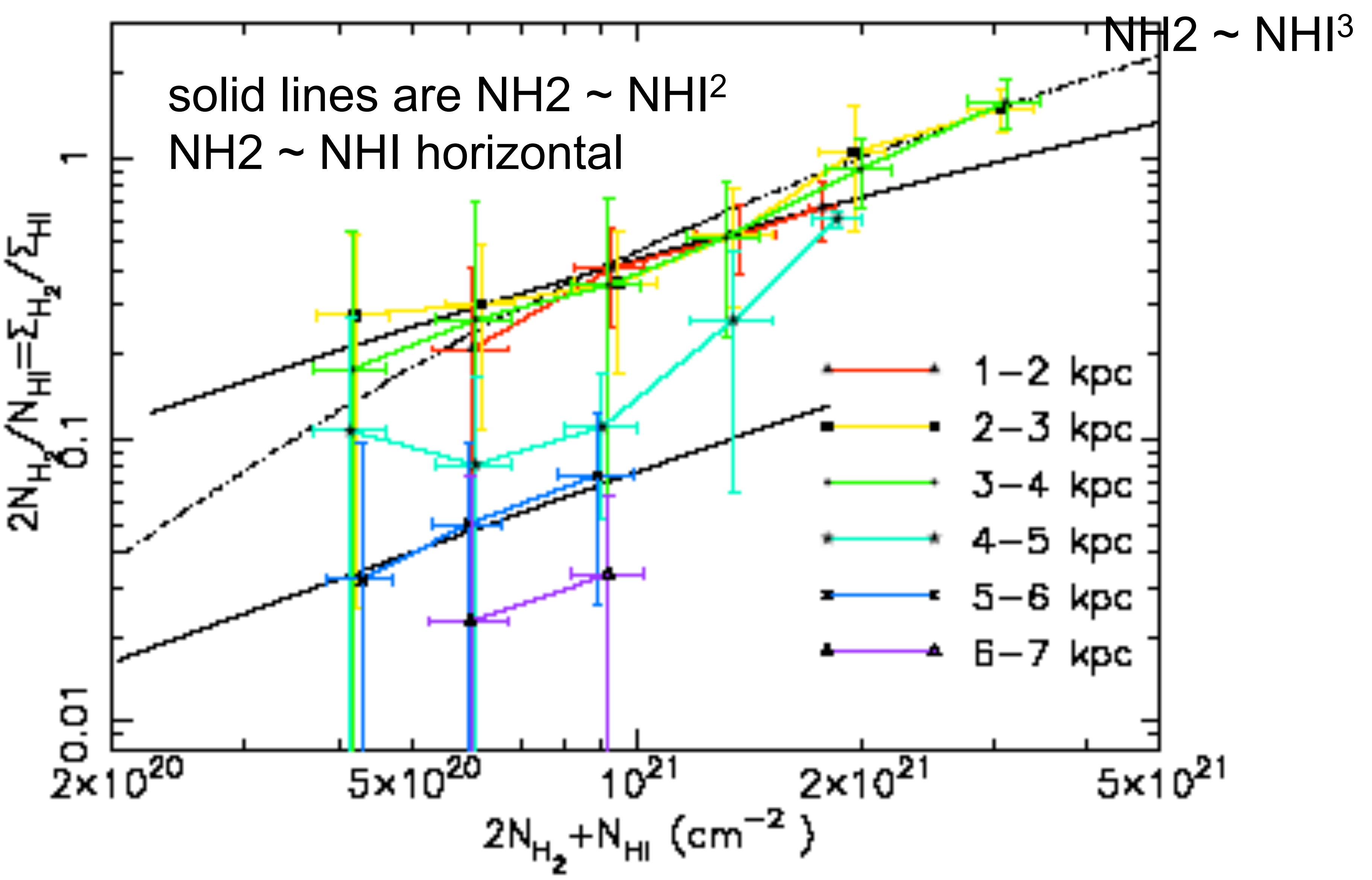
GARDAN et al 2007



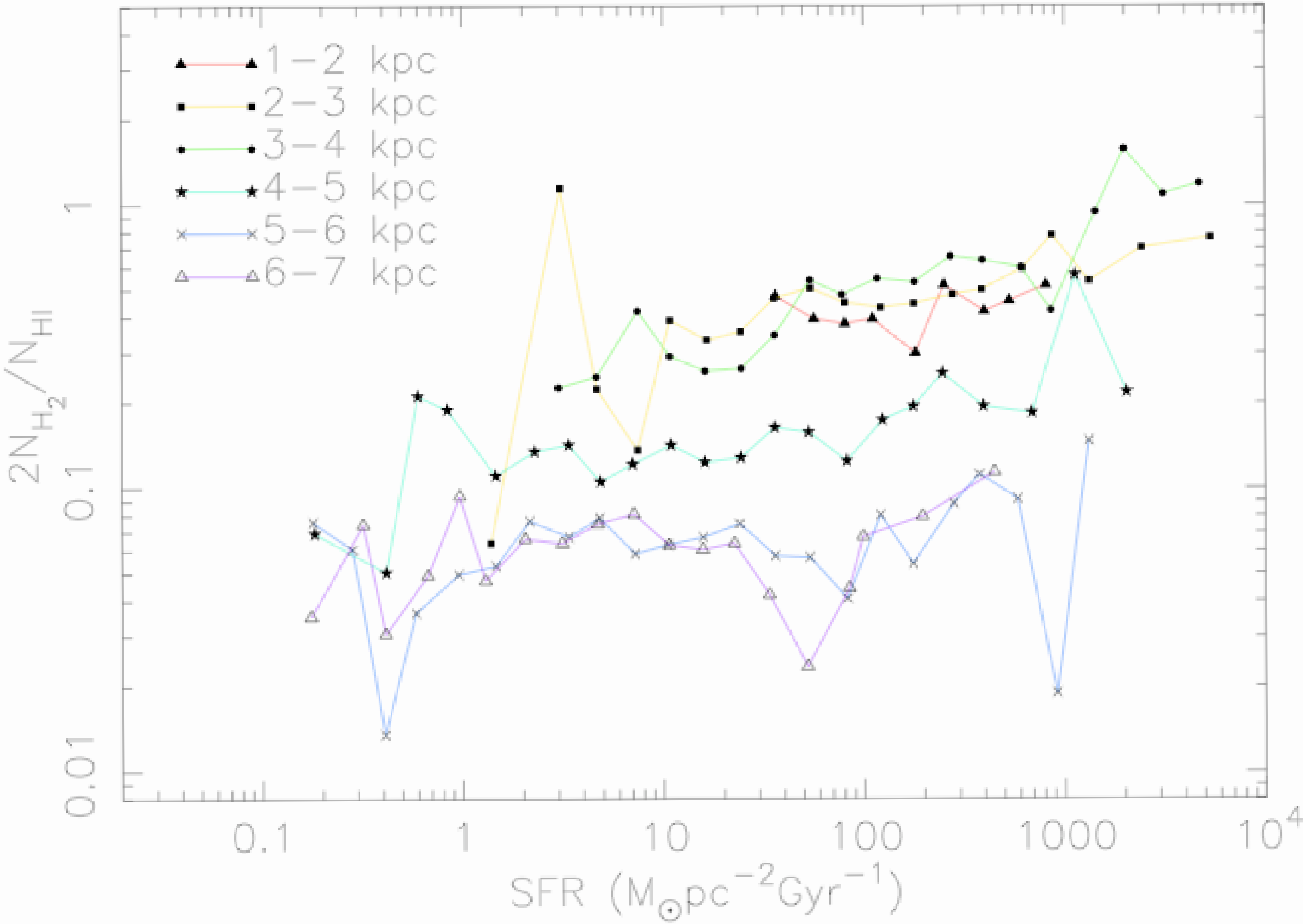
HI contours on CO
Halpha contours on CO
"lonely cloud"
HI
Integrated intensity (K km s⁻¹)
0.4
0.3
0.2
0.1
0
1h34m40s
20s
00s
31°05'00"
31°00'00"
30°55'00"
30°50'00"
δ 2000

H2 fraction increases with NH

But decreases with radius at same NH



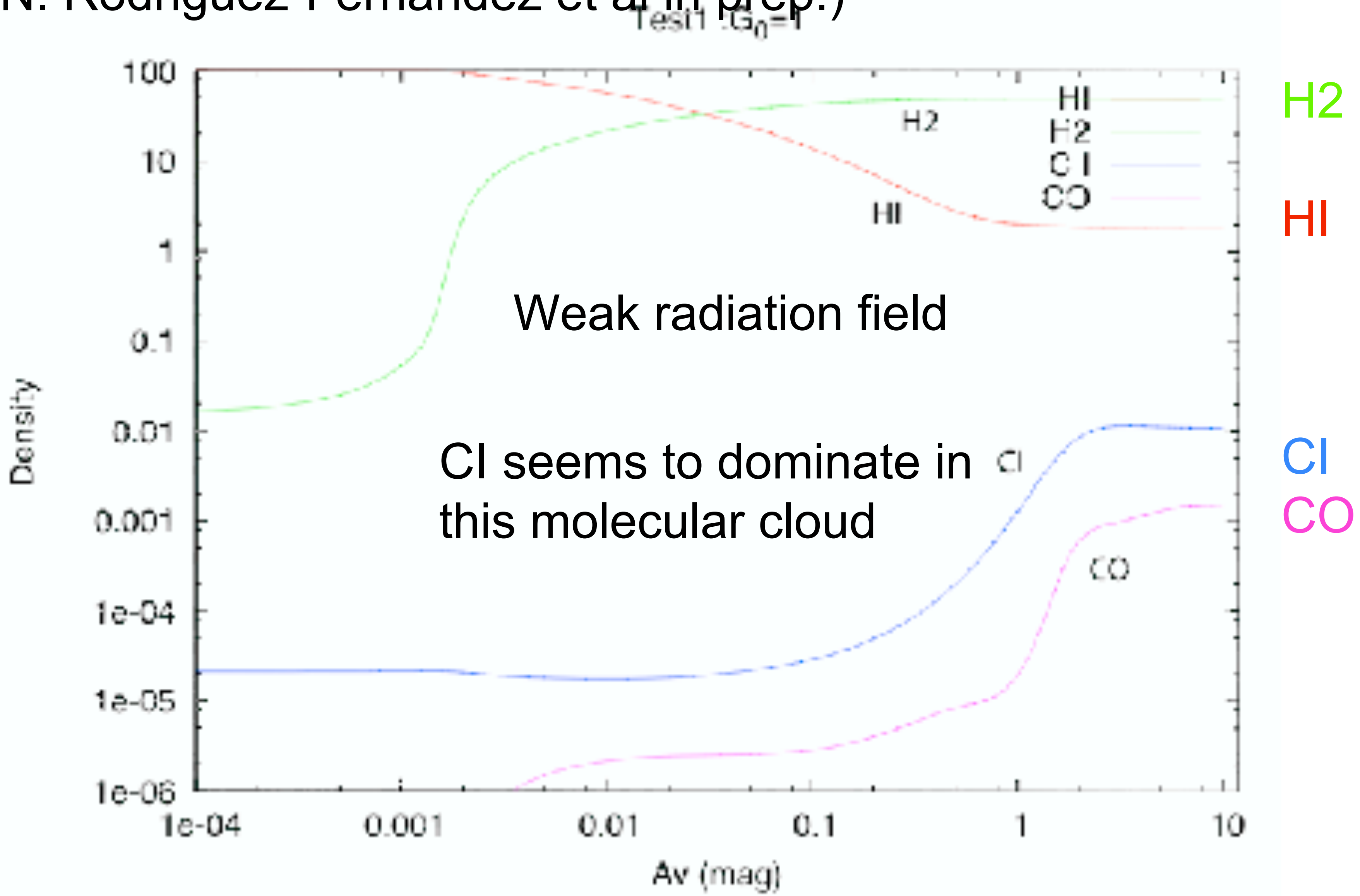
Even at a given star formation rate, the molecular fraction decreases with radius.



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

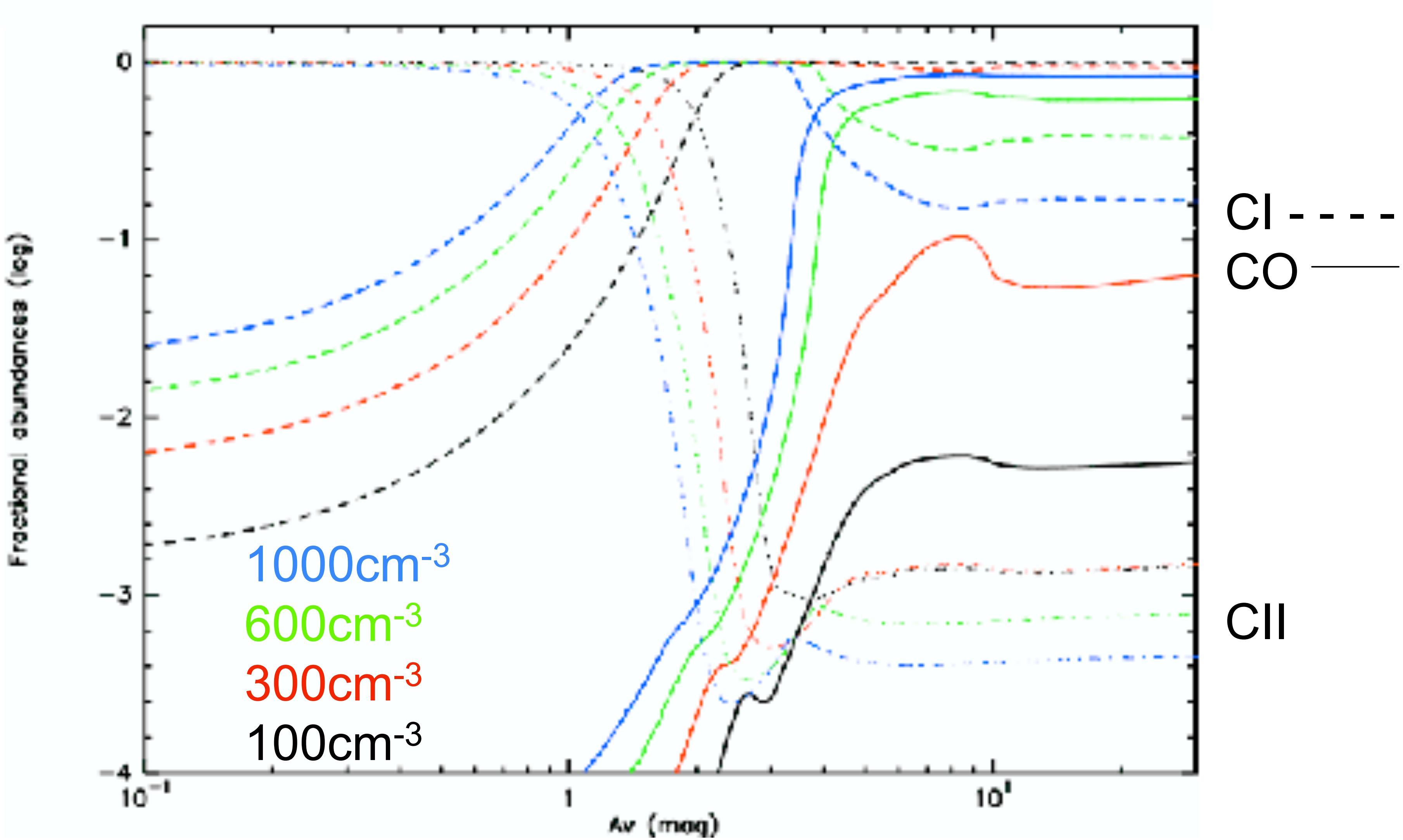
Is CO the best tracer of molecular gas?

Meudon PDR code (Le Bourlot), n = 100 cm^{-3}
(N. Rodriguez-Fernandez et al in prep.)



With CLOUDY (N. R-F)

In this close-up of the CII --> CI --> CO transition, the density varies but the cloud is molecular throughout the region shown. CI stronger than CO when $n < 600 cm^{-3}$

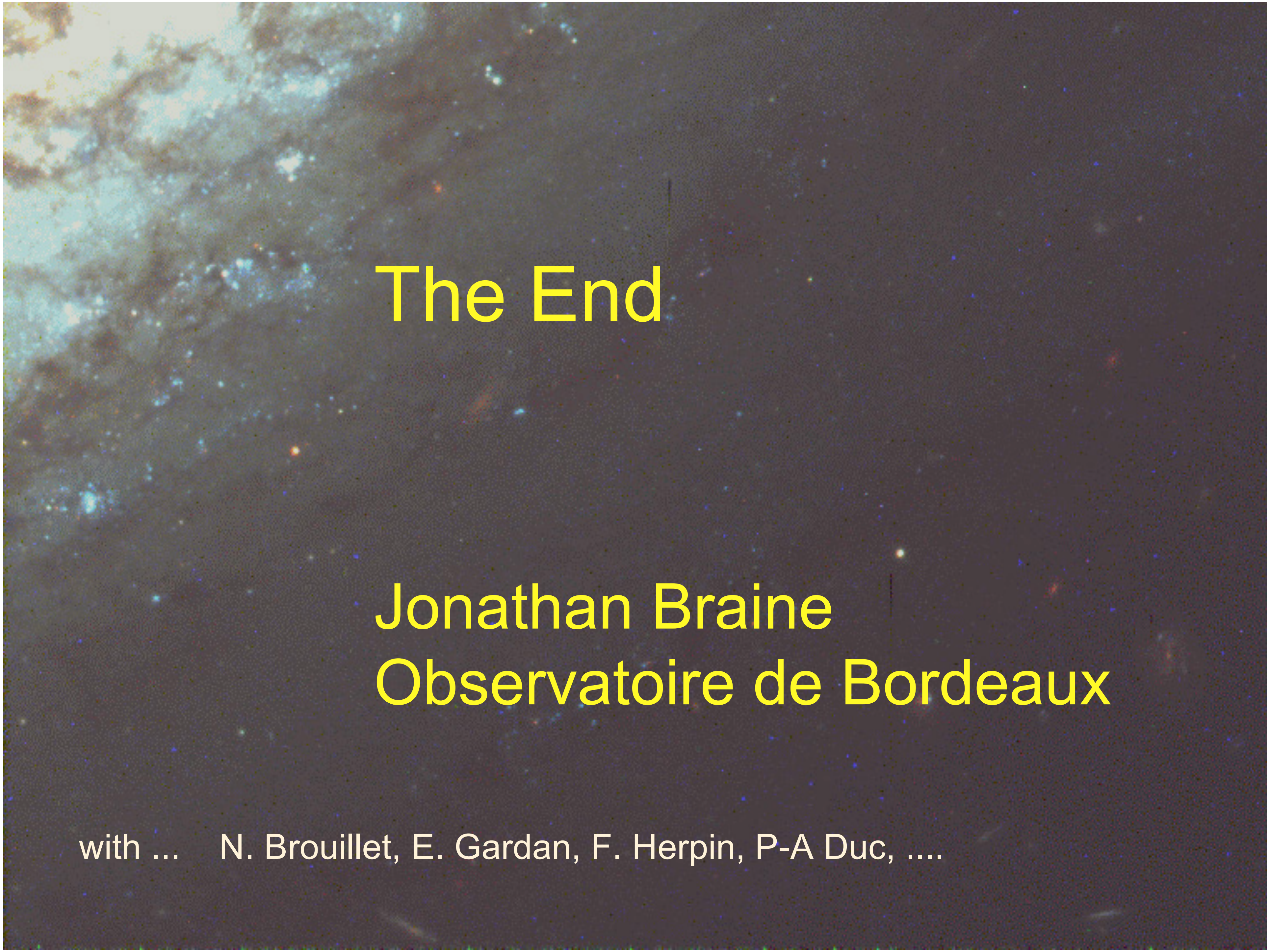


CO detectable far out in the Milky Way, M33, NGC 4414, and probably all spirals with extended HI. CO may require an HI column density above a threshold of order 3 x 10^{20} cm^{-2} (obs of NGC 4414). Star formation seems to behave similarly. In N4414, H2/HI mass ratio estimated to be ≤ 1/3 beyond R25.

Metallicity apparently not a problem for CO detection, despite MANY claims to the contrary (exception -- low Z and high ISRF). Heating of molecular gas sufficient for detection even far out. In the Galaxy, no sharp decrease in CO line intensity despite the lack of obvious heating sources for outer galaxy clouds.

Spitzer (IRAC, MIPS) did not detect outer disk of N4414 or M33.
==> not a lot of local heating, which would create bright spots

Assuming CO is a better tracer of H2 than CI, then H2 fraction well below unity in outer disks ==> dynamically unimportant, although very interesting for star formation.
Deep CI observations necessary.



The End

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