Interstellar Medium in galaxies

1. The atomic and molecular components

2. Small scale structure, the Milky Way

3. ISM in external galaxies, SFR, ULIRGs

4. Accretion and evolution in a cosmological context

Françoise Combes,
Paris Observatory

HI line 21cm

Ewen & Purcell 1951: Discovery of HI 21cm line from the Galaxy

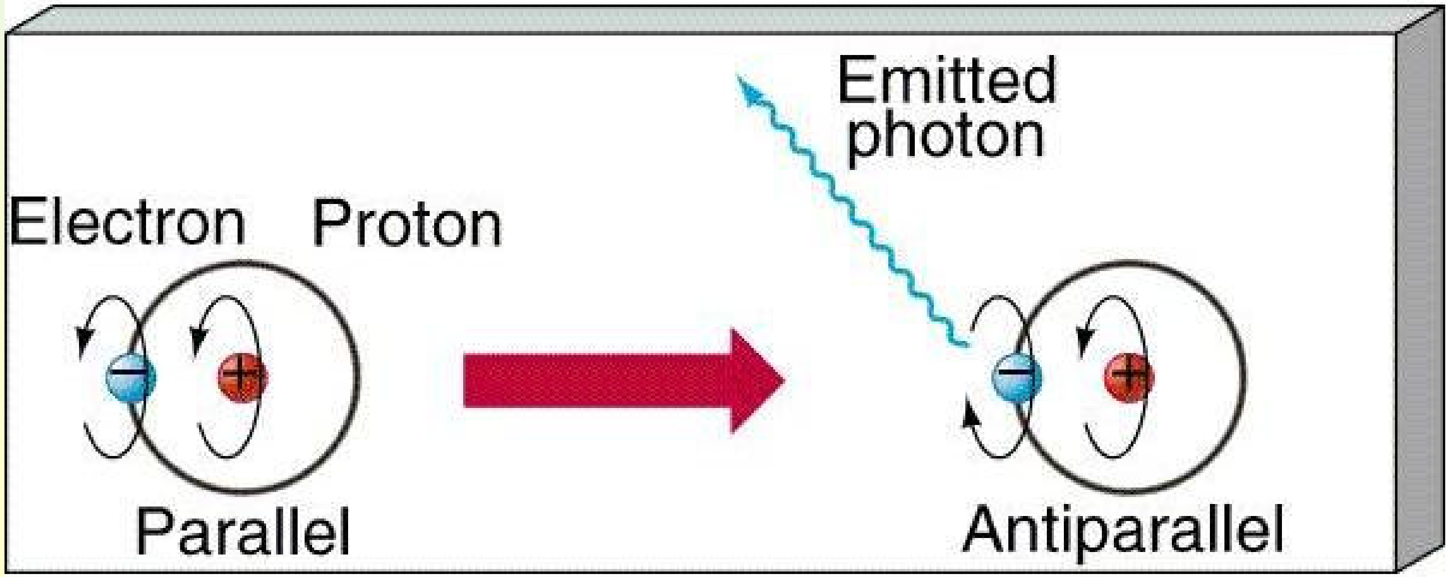
Spin-flip transition, in the ground state $1\ ^2S_{1/2}$

Predicted by van de Hulst in 1945

F=1 ➔ F=0, distant from $h\nu = kT$, with T= 0.07 K << 3K

ν = 1420 MHz

$A = 2.9\ 10^{-15}\ s^{-1}$

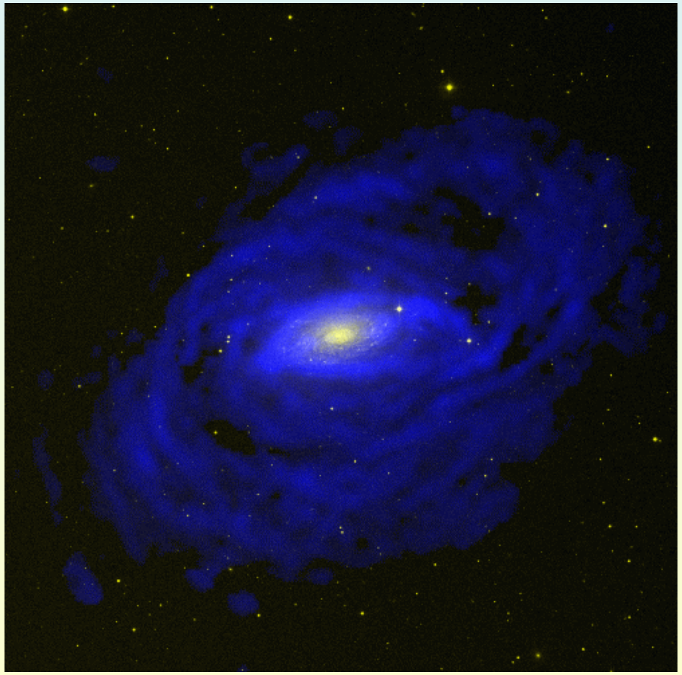


Extension of galaxies in HI

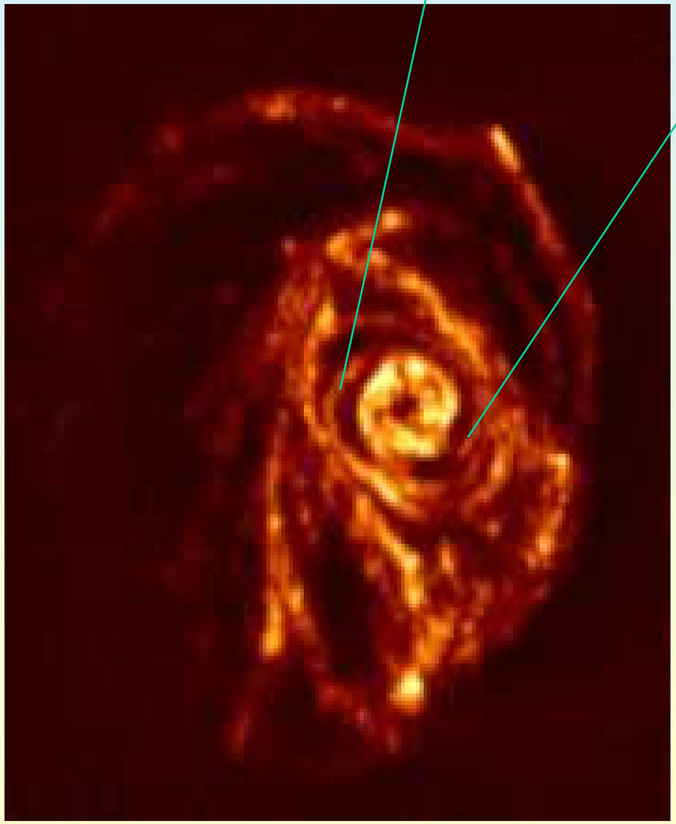
M83: optical

Dark halo exploration

HI

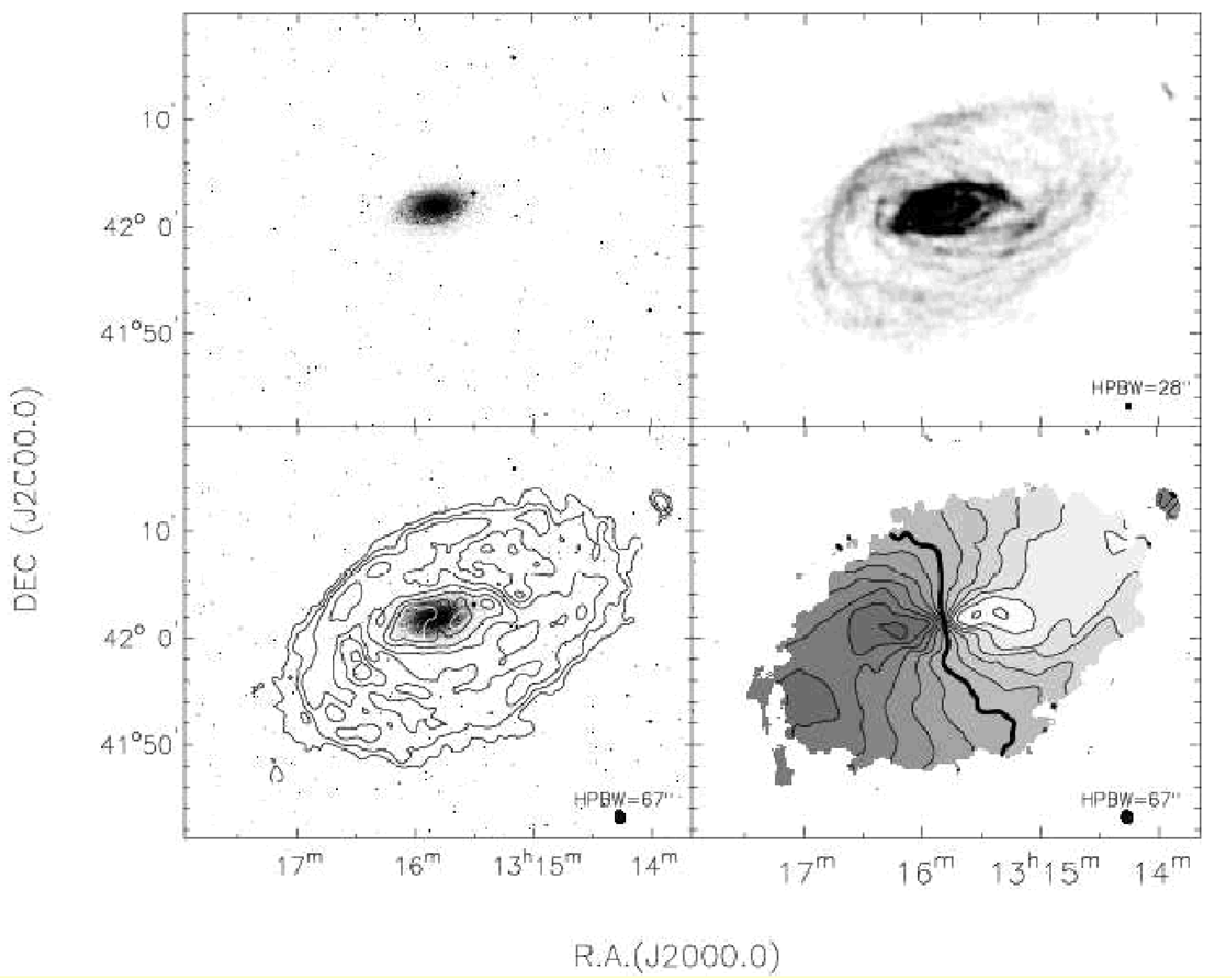


NGC 5055 Sbc



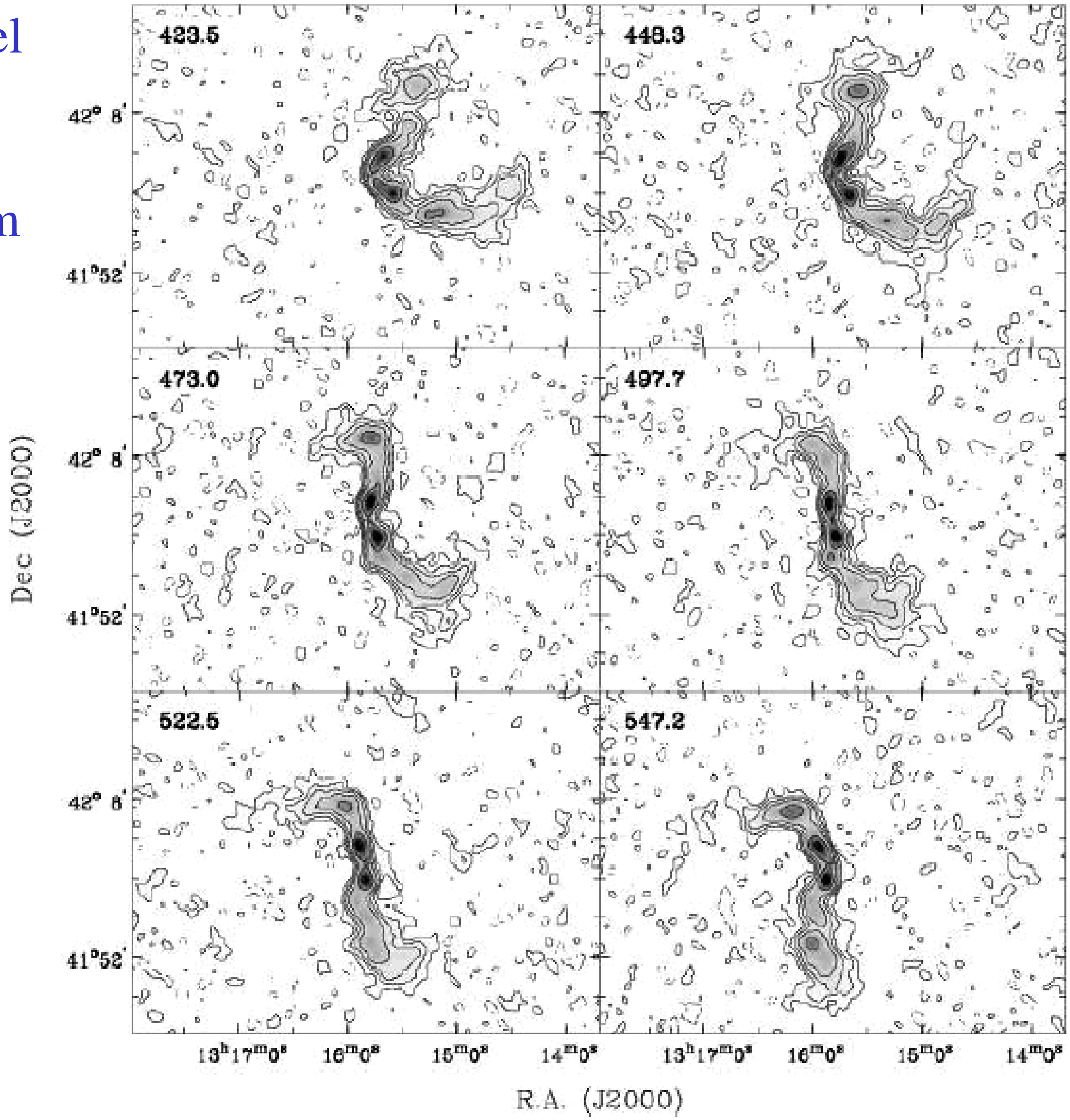
Milky Way-like spiral (10^9 $M_\odot$ of HI): M83

NGC 5055, rotation curve (Battaglia et al 2006)

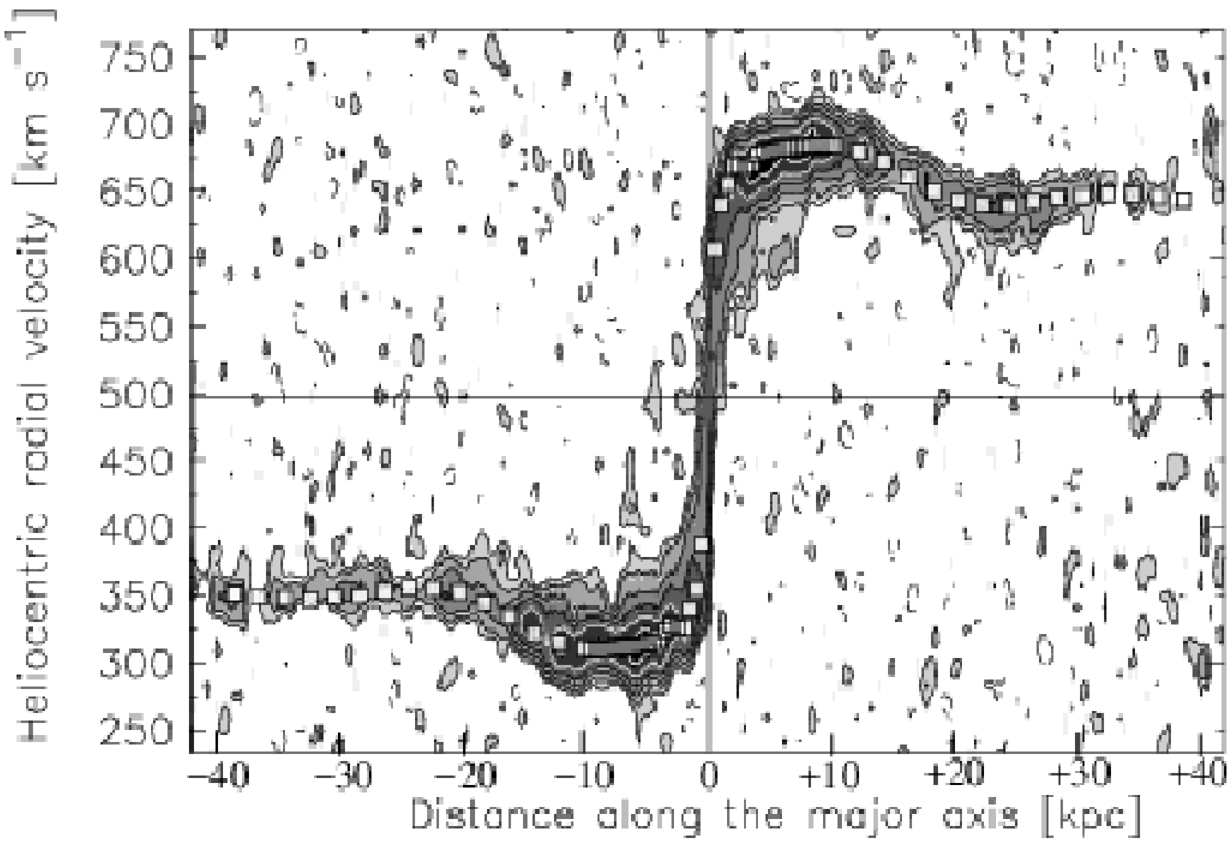


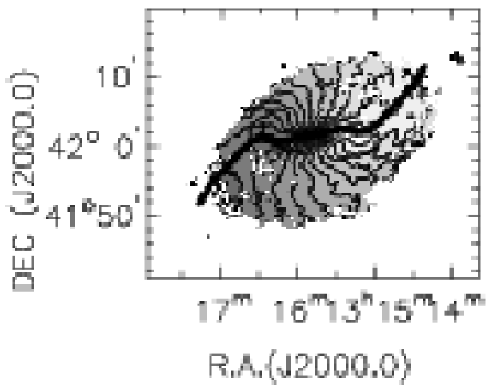
Channel maps Spider diagram

N5055



Rotation curve of NGC 5055 (Battaglia et al 2006)

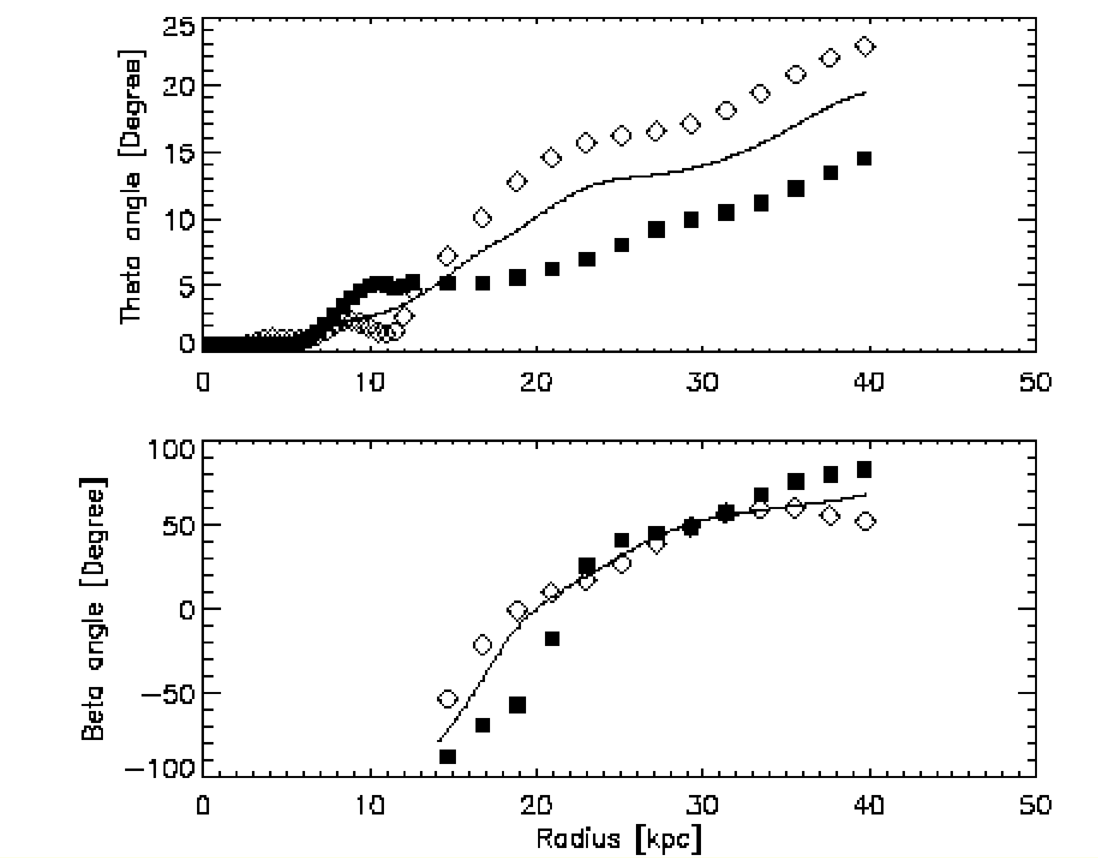




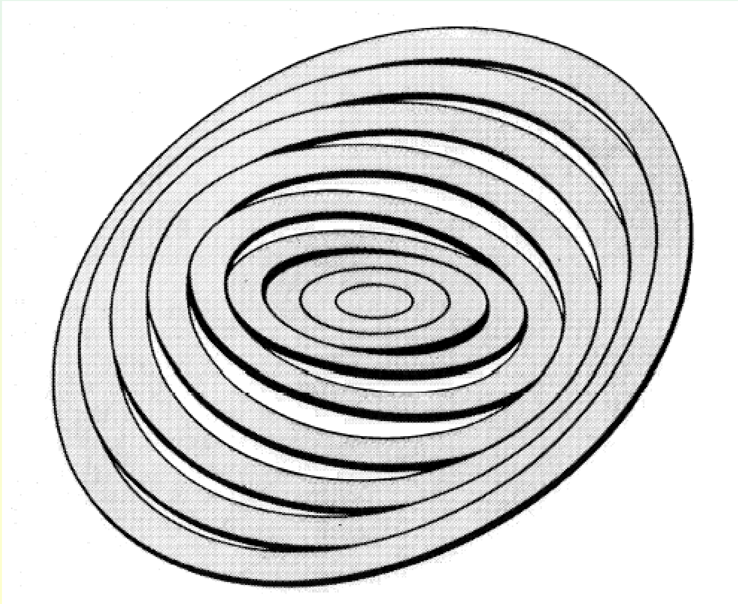
Bump in the center, and decrease by 25km/s

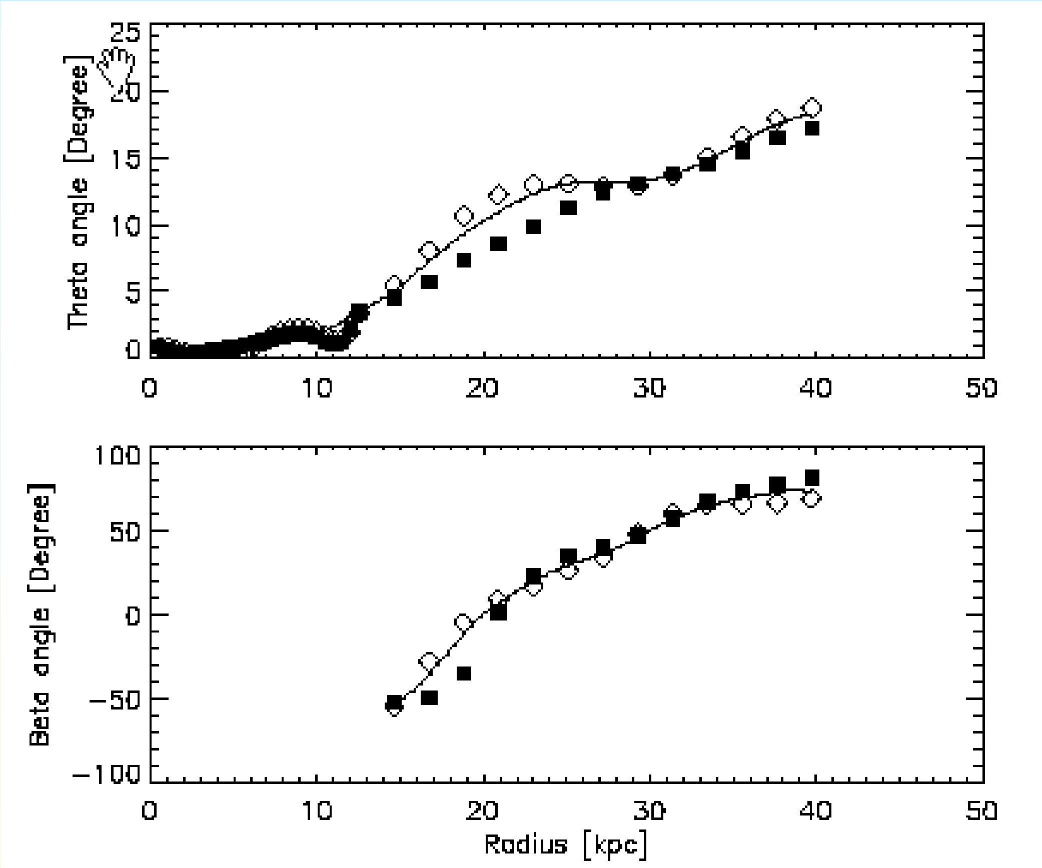
➔ Disk maximum M/L > 1.4

Warping of the plane, lopsidedness



N5055: warp fit
By tilted ring model
R(HI) = 40kpc





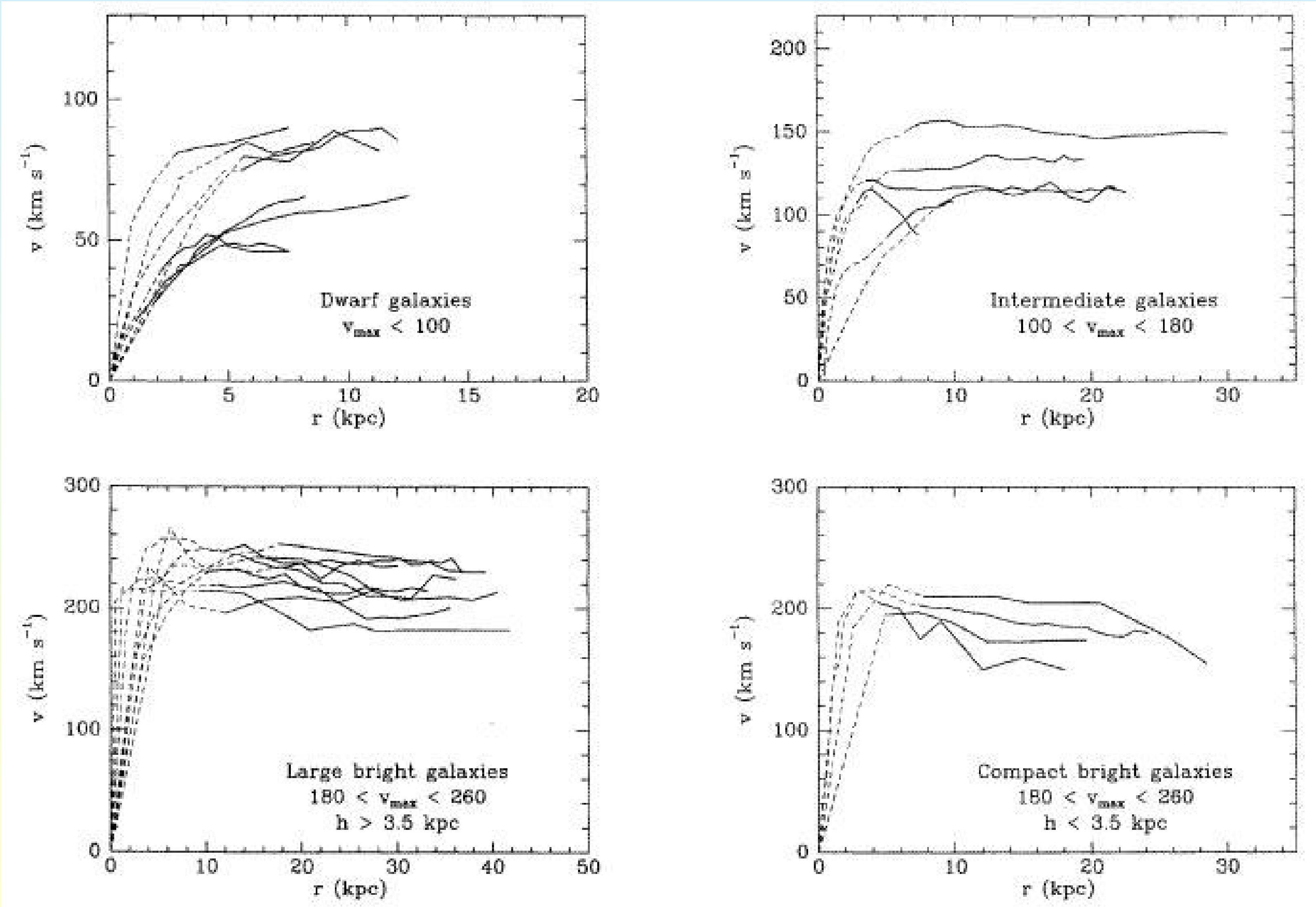
The warp is better fit when the center is shifted in the outer parts

Symmetrical➔ long-lived?
1.5 Gy period
Towards the companion UGC 8313

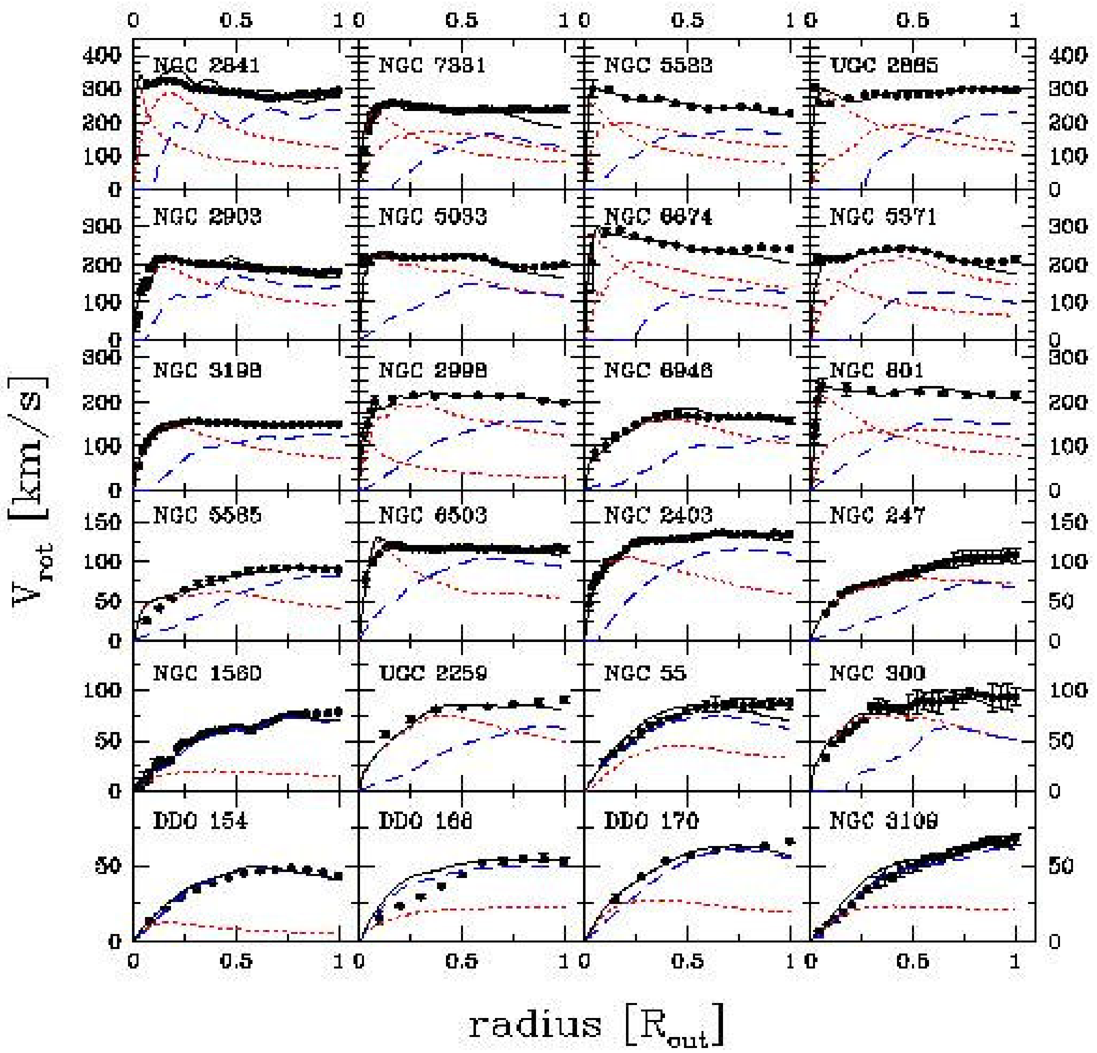
➔As if the galaxy was in two regimes:

--Dominated by the visible matter inside 10kpc
--Then domination of the dark halo, with varying center and Vsys

HI rotation curves: conspiration?

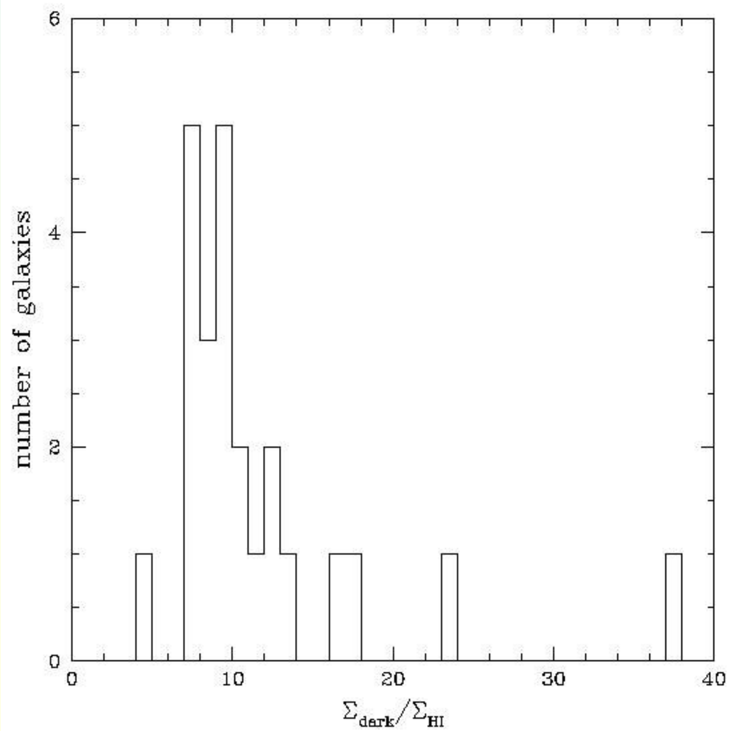


Casertano & van Gorkom 1991



σ_{DM}/σ_{HI} = cste

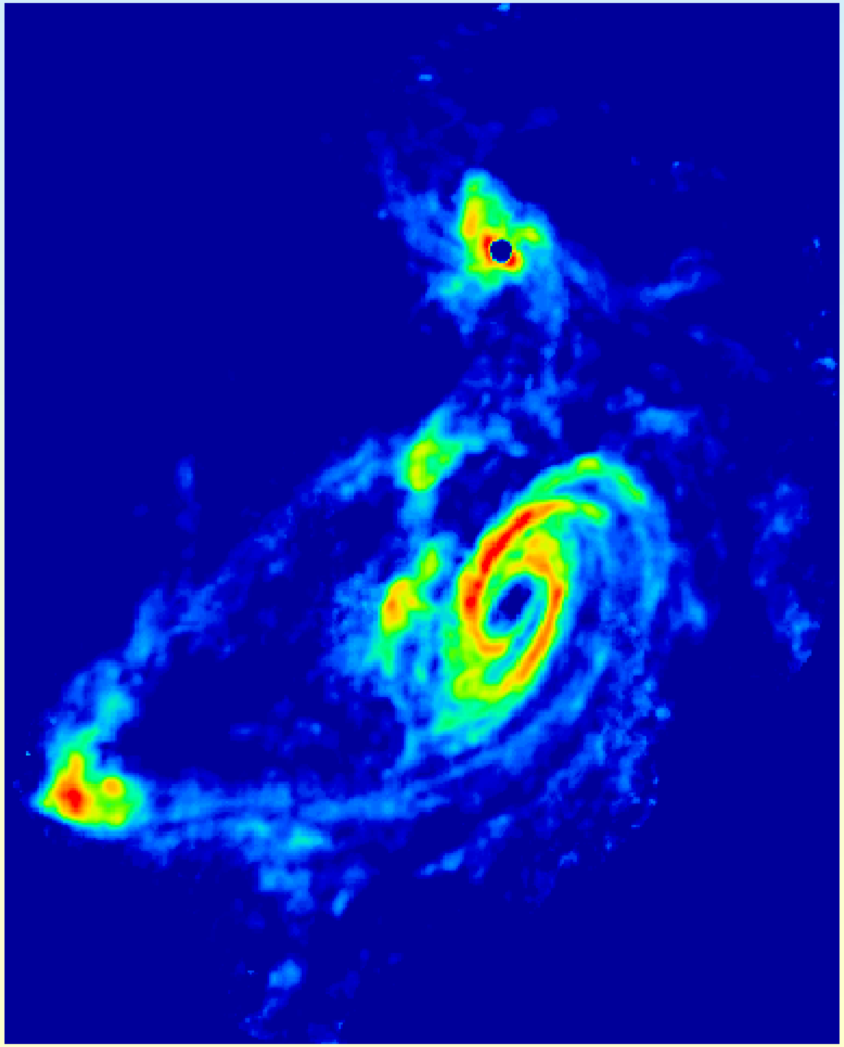
In average ~10



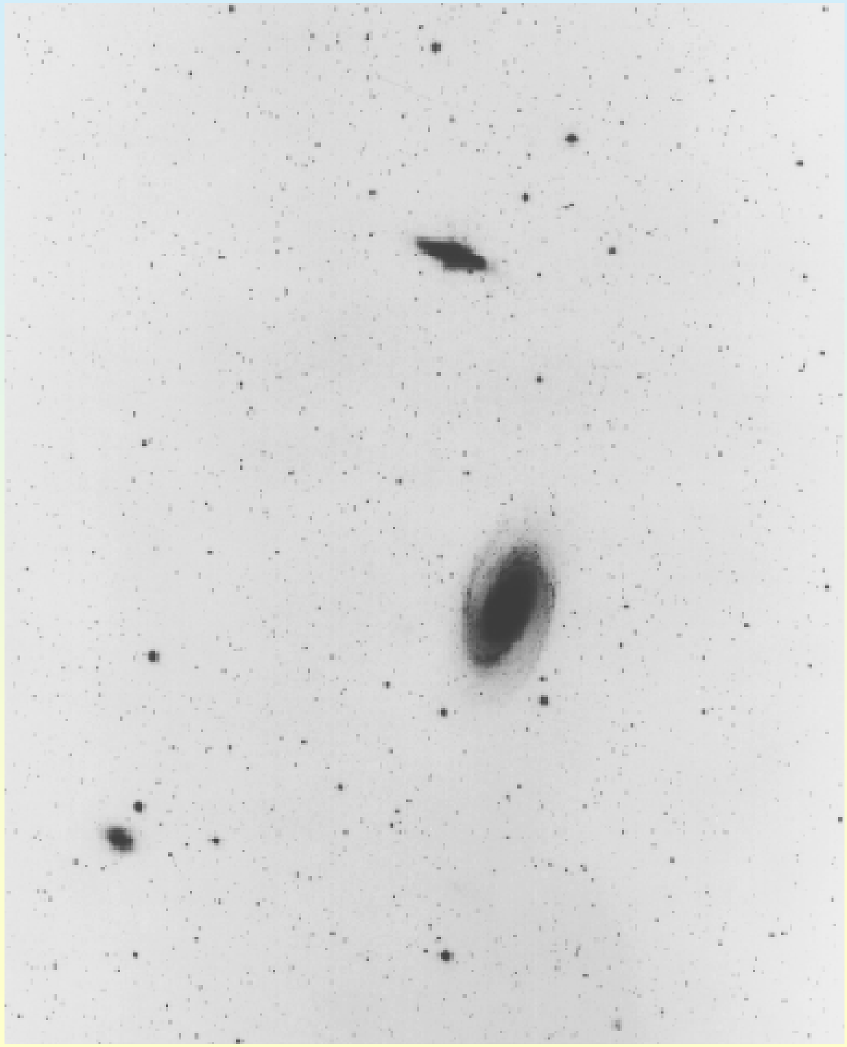
Hoekstra et al (2001)

Splash of interstellar gas

HI



Messier 81, Messier 82, NGC 3077



High Velocity Clouds infalling onto the Galaxy

Origin still unknown

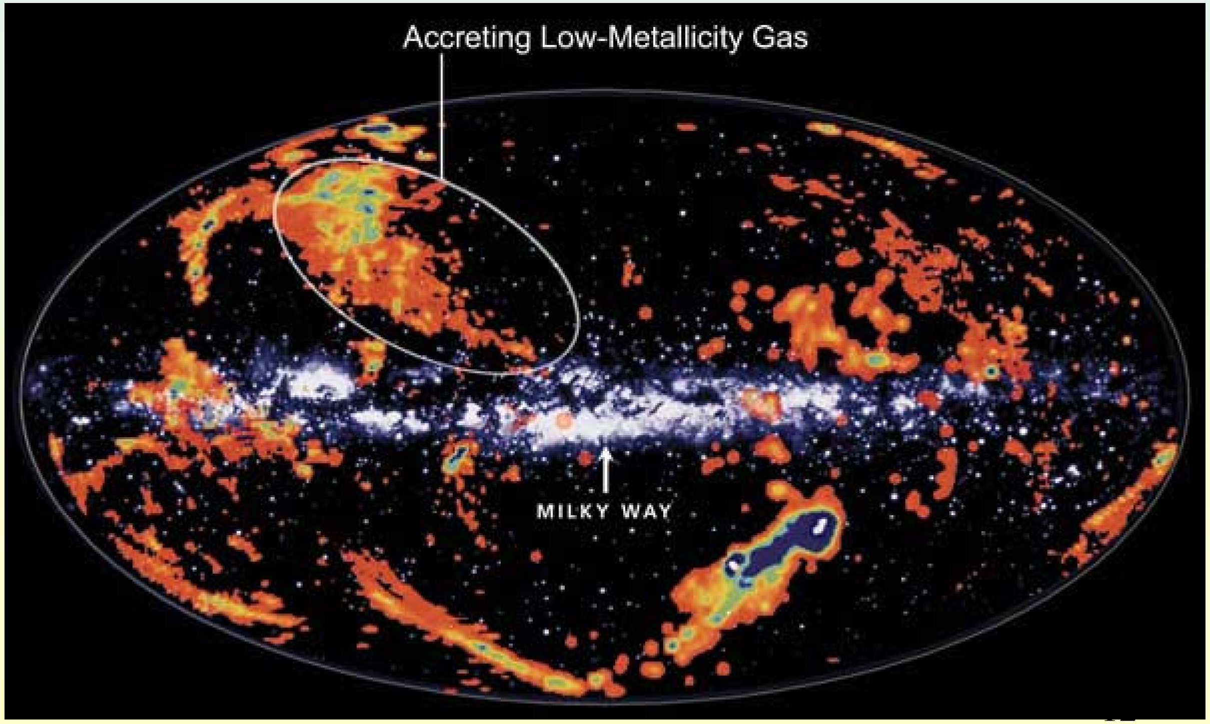
Their mass depends on their distance (D^2)

Residuals from the formation of Local Group? ➔ very massive

Or just infalling from Magellanic Clouds?

Multiple origins

Also, fountain effect after formation of supernovae..

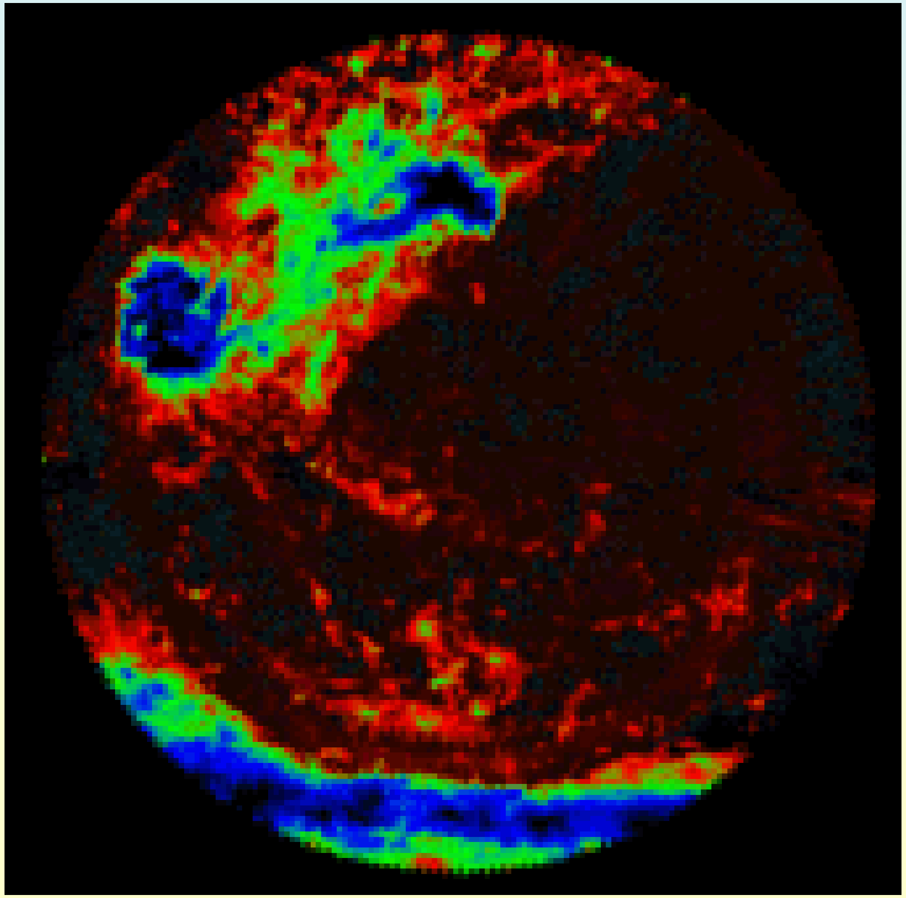


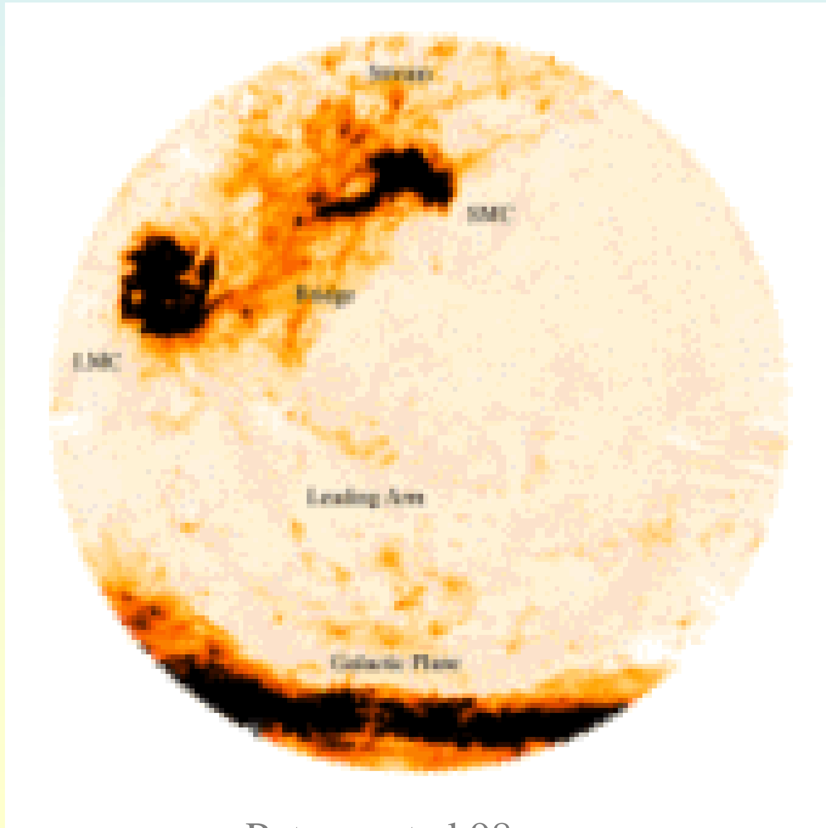
Wakker et al 99

The Magellanic Stream

Detected in neutral hydrogen HI at 21cm in wavelength
As much HI gas in Small as in Large Magellanic Clouds

The gas must have been dragged out of the SMC, according to simulations





Putman et al 98

Reconstitution of the interaction

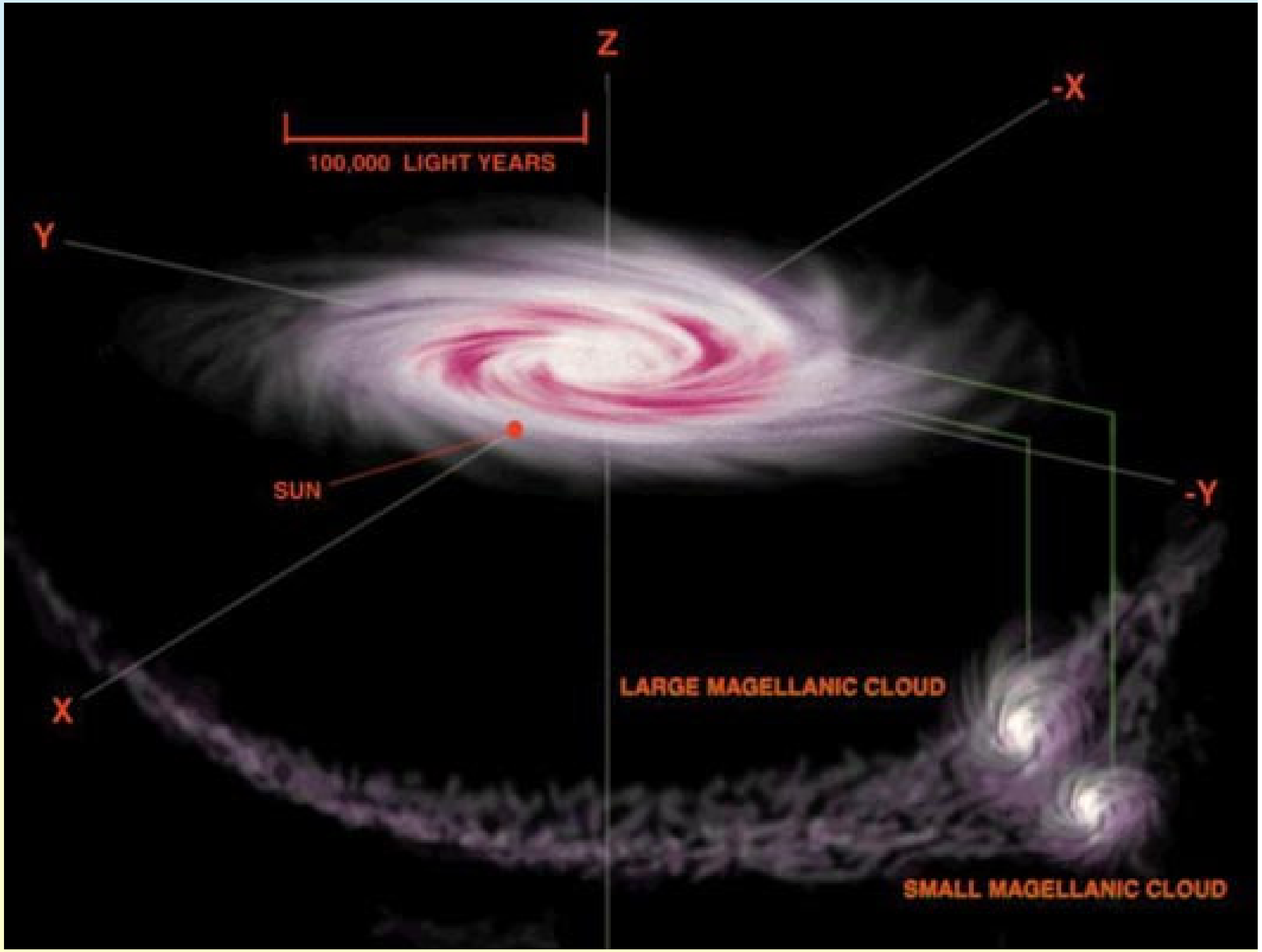
Low mass ratio, of the order of a few %

Several passages since the formation of Local Group

Clouds are passing in front

Constraints on the Milky Way mass

V ~200 km/s



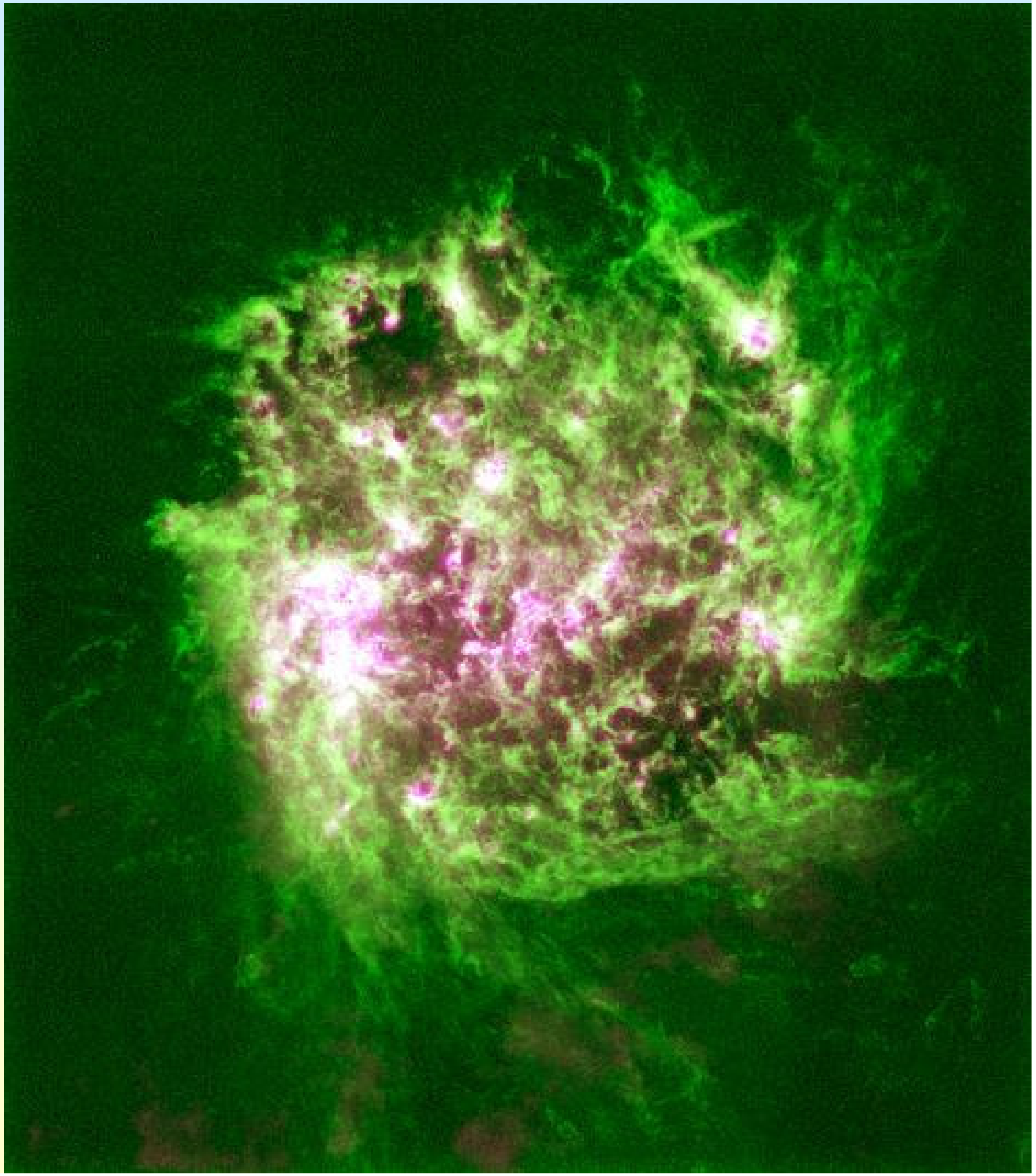
HI map of Large Magellanic Cloud LMC

Kim et al (1998, 2003)

Large range of 2.8
in scales, from 15pc

Determination of the
cloud mass spectrum

Bubbles due to SF
Size distribution

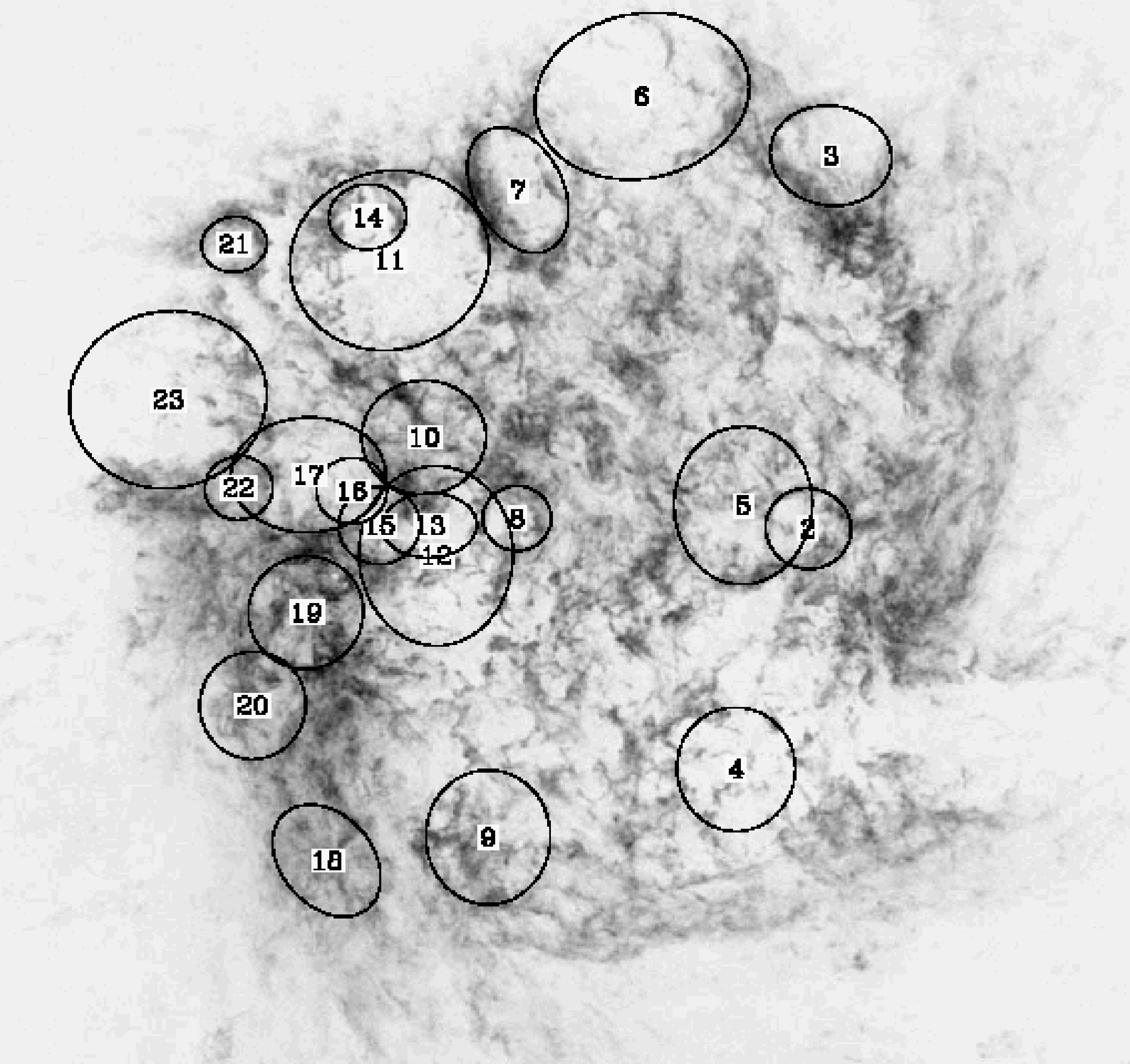


Feedback due to star formation

Holes and shells

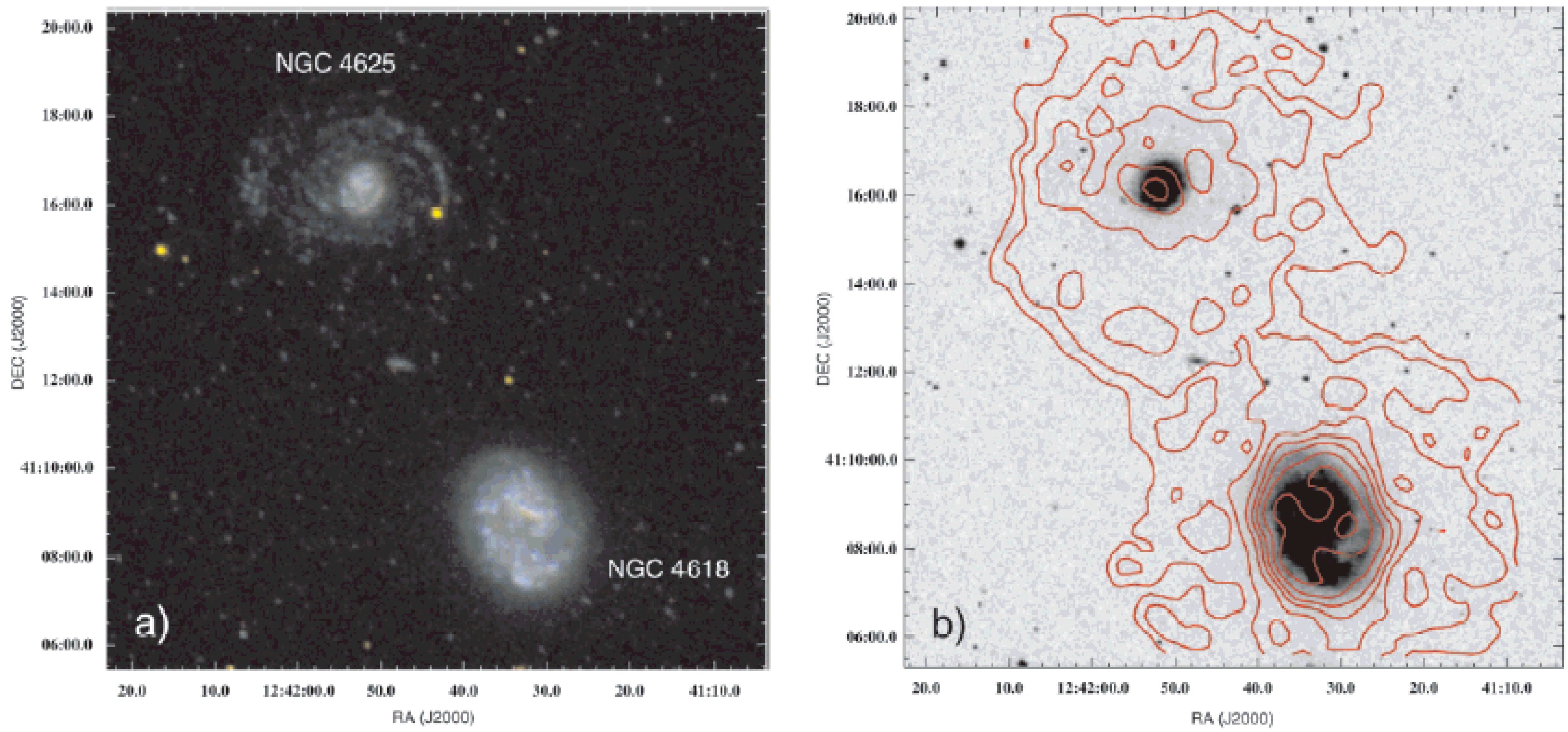
Same power-law distribution as that of clumps

Fractal with D=1.4

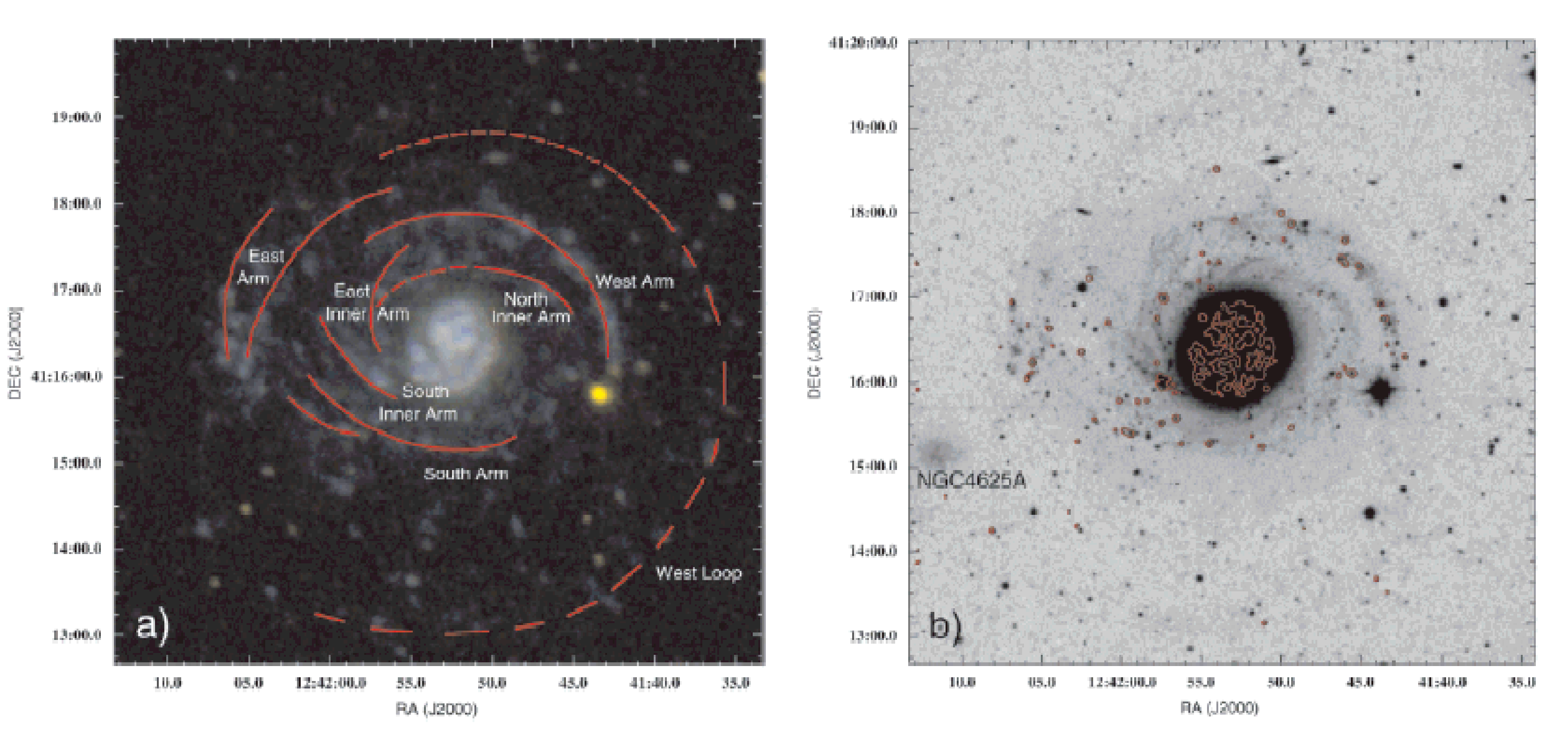


Kim et al (2003)

Extension in UV (GALEX)



NGC 4625 interacting with NGC 4618 (Gil de Paz et al 2005)

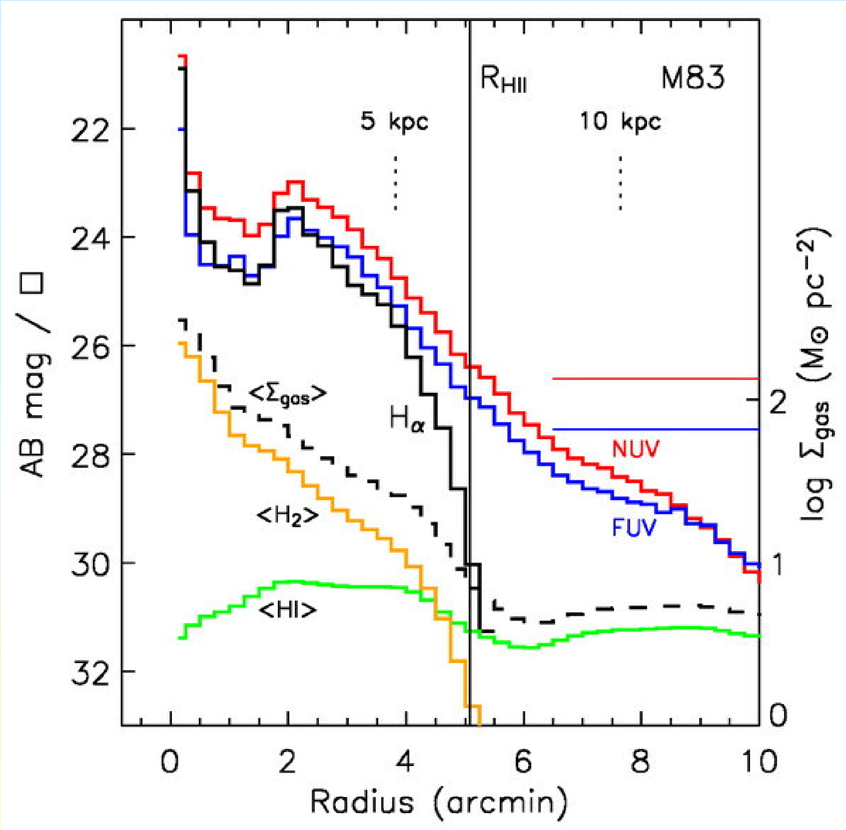


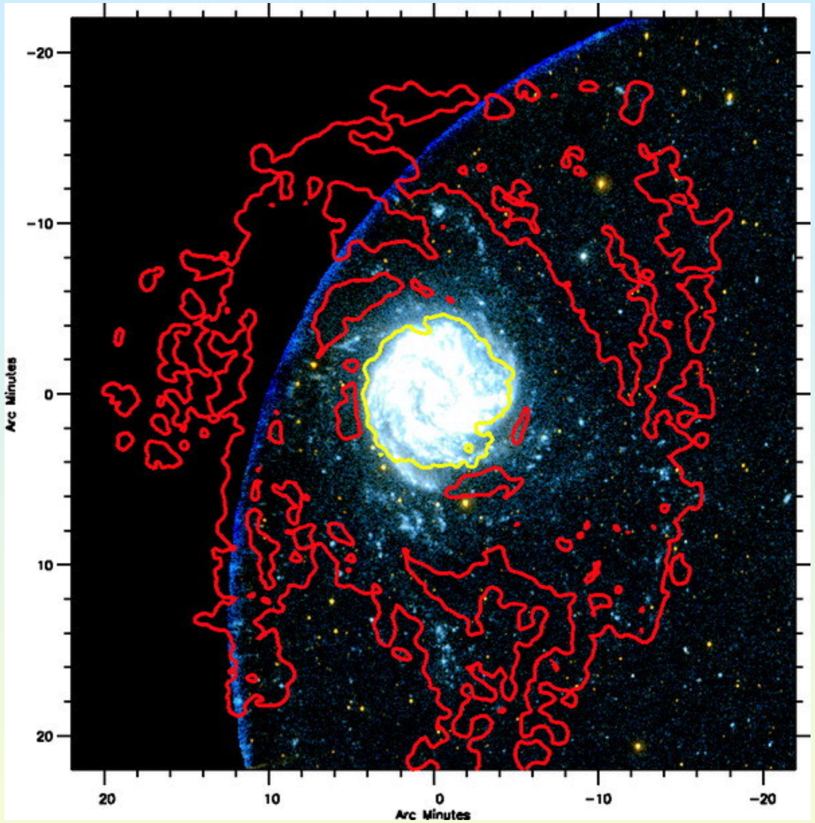
Halpha contours, superposed to the B-image, compared to the UV image (Gil de Paz et al 2005)

➔UV extends to 4 times the optical radius and coincides with HI peaks

Small companion NGC 4625A, close to the main galaxy

XUV disks, M83 and others





Bluer regions outside

Younger SF + scattered light

M83, Galex, +HI contours (red)

Thilker et al 2005

Yellow line RH_{II}, $10M_o/pc^2$ in HI

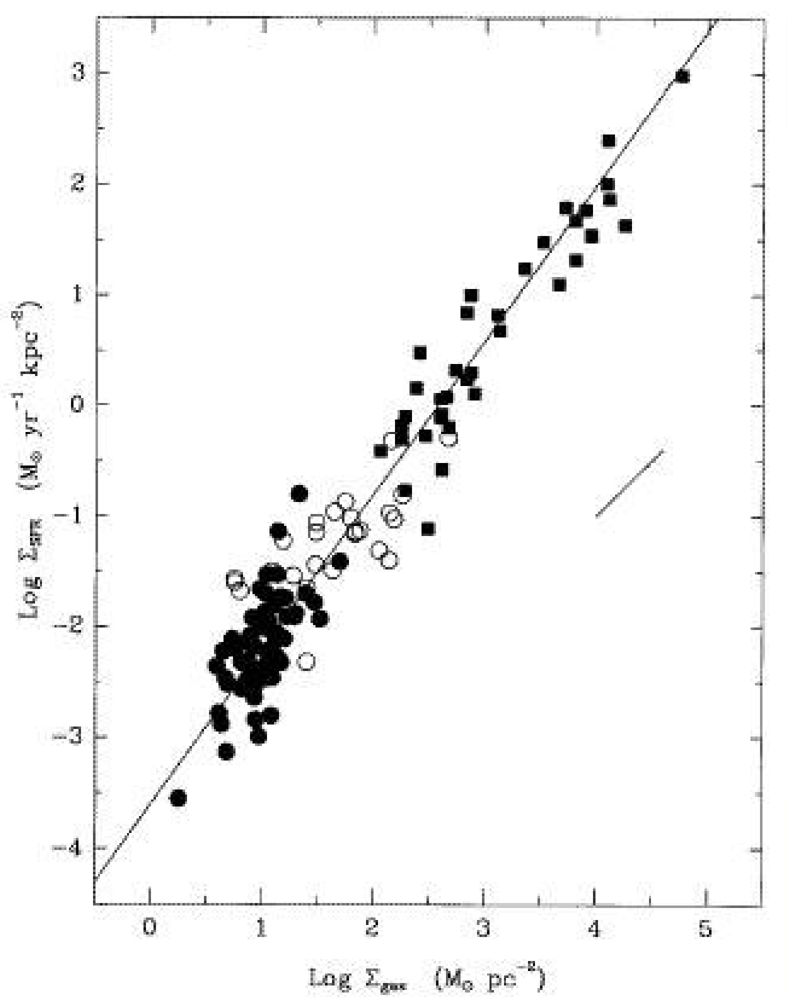
Star formation rate: Schmidt law

SFR empirically proportional to gas density, exponent n=1.5
(global Schmidt law, not local, *Kennicutt 1998*)
Same for interacting and non-interacting

$\Sigma_{SFR} \sim \Sigma_g^{1.5}$

Processes: Jeans instability,
dynamical time $\rho^{3/2}$
or Cloud-cloud collisions
(Elmegreen 1998)

+density threshold

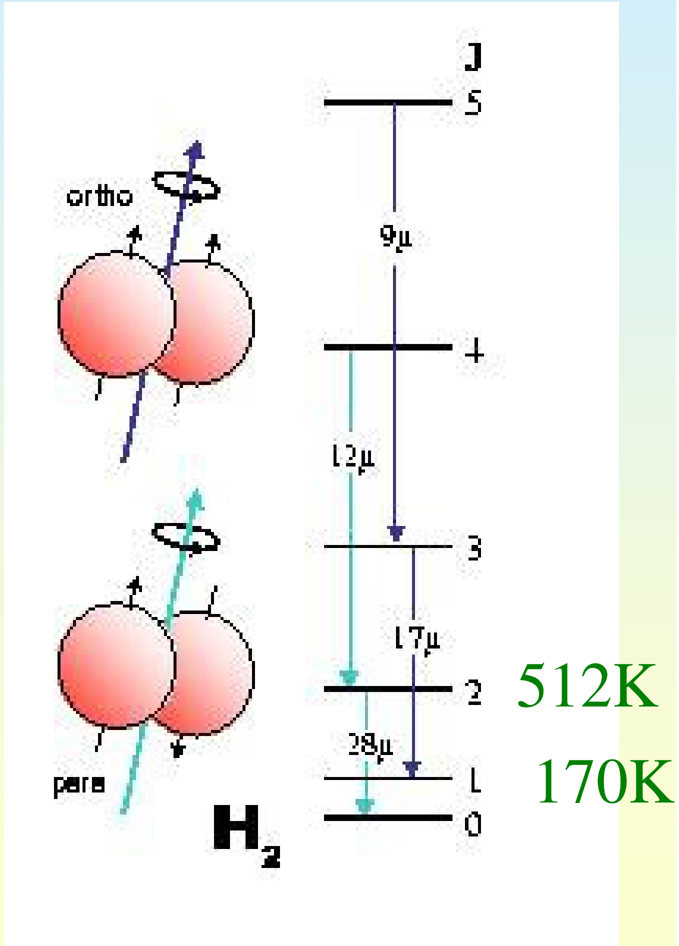


The H_2 molecule

- **Symmetrical, no dipole**
- **Quadrupolar transitions $\Delta J = \underline{+}2$**

- **Light molecule ➔ low inertial moment and high energy levels**

- **Para (even J) and ortho (odd J) molecules (behave as two different species)**



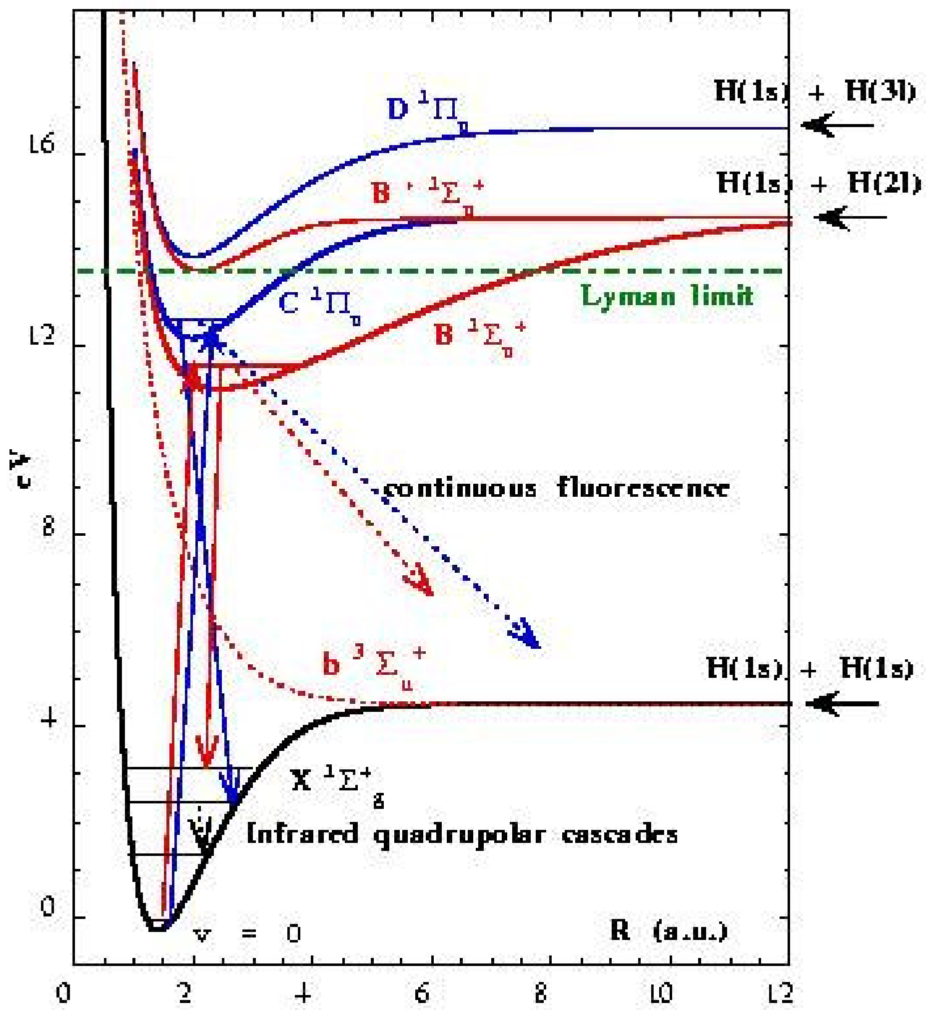
H_2 is the most stable form of hydrogen at low T dominant in planetary atmospheres?

Formation: on dust grains at 10K
However formation still possible in primordial gas
($H + H^-$ Palla et al 1983)

Destruction: through UV photons (Ly band)
Shielded by HI, since the photodissociation continuum starts at 14.7eV, and photo-ionization at 15.6 eV
(HI ionization at 13.6 eV)

Self-shielding from low column densities
10^{20} cm^{-2} in standard UV field

H_2 will be present, while other molecules such as CO would be already photo-dissociated



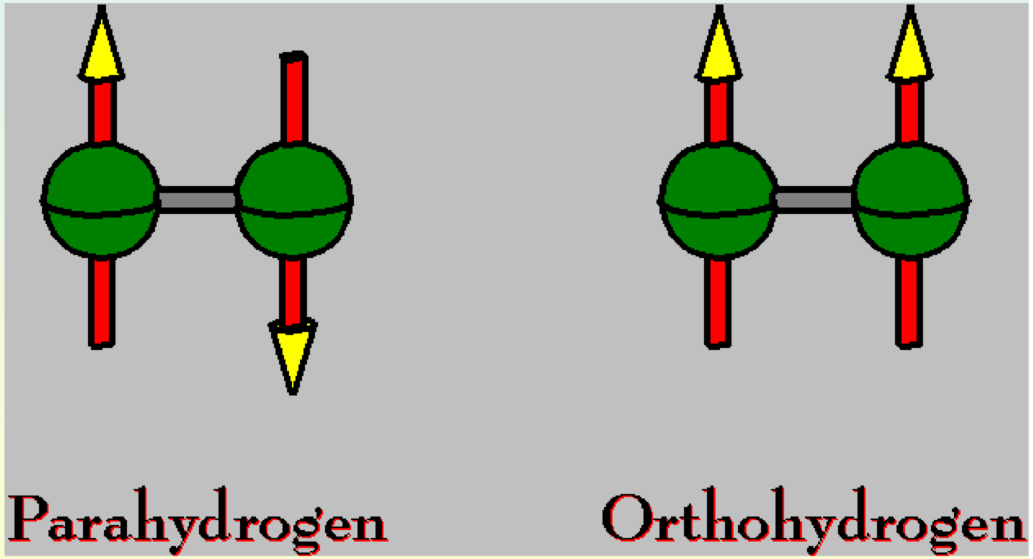
Potential curves involved in the Lyman and Werner bands (Roueff 2000)

Ortho-Para transitions?

- Formation in the para state not obvious
- Large energy of formation 2.25 eV/atom
- ortho-para conversion in collisions $H^+ + H_2$

- n(O)/n(P) ~ exp(-170/T)
- Anormal ratios

observed (ISO)

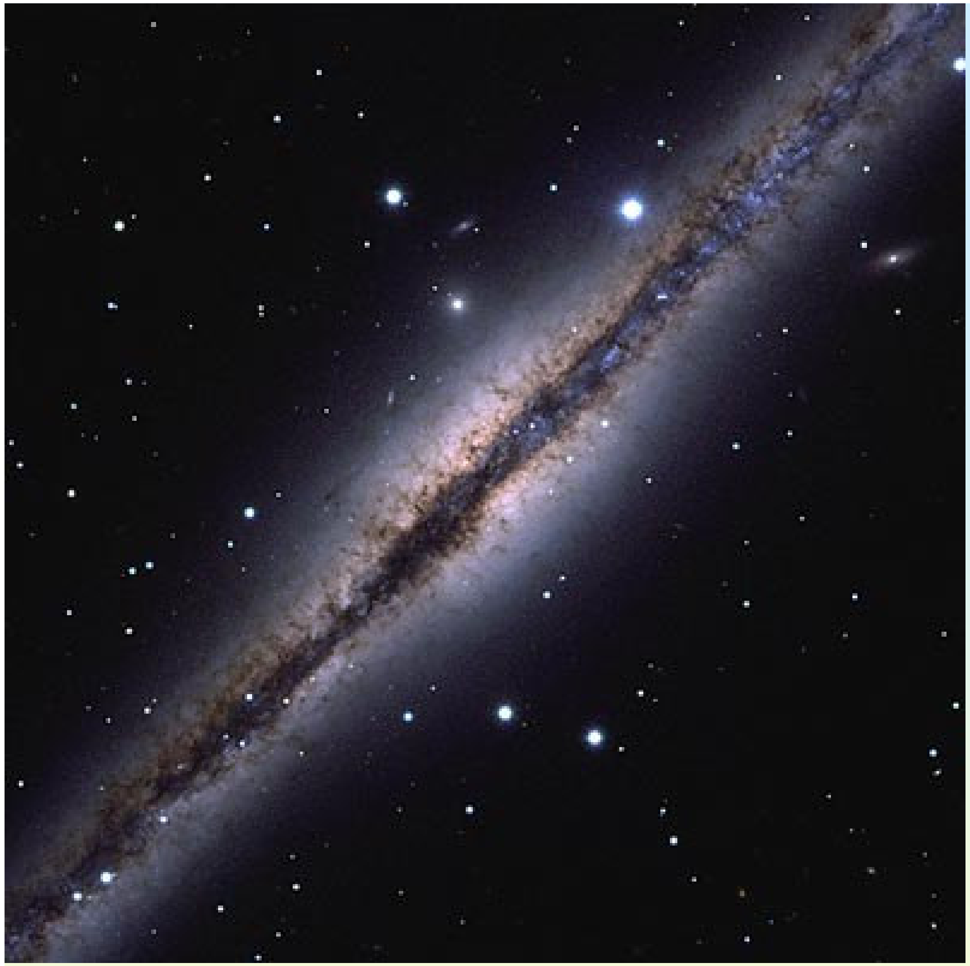


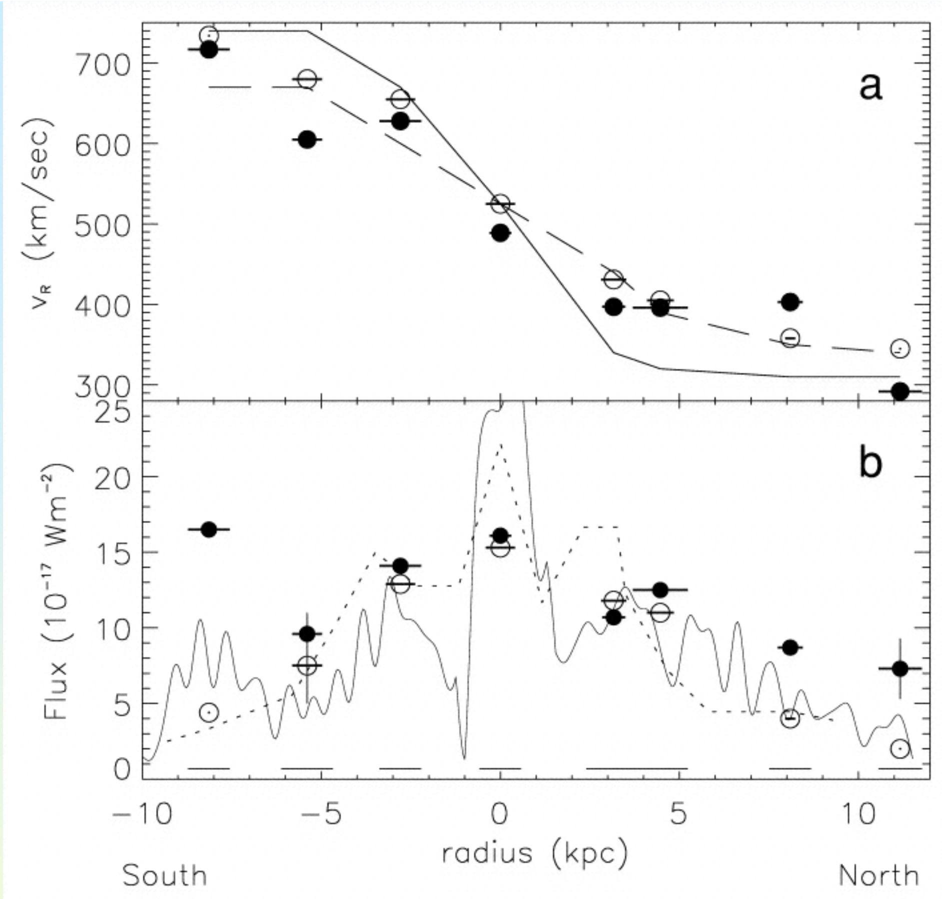
- IR lines J=2-1 at 42 μ, 1-0 at 84 μ ?
- A = 10^{-10} cm^3/s (Black & Dalgarno 1976)
- A=2 10^{-10} cm^3/s (Gerlich 1990) reaction favors o-H_2

Infrared Lines of H_2

- Ground state, with ISO (28, 17, 12, 9μ)
- S(0), S(1), S(2), S(3)

- From the ground, 2.2 μ, v=1-0 S(1)
- excitation by shocks, SN, outflows
- or UV-pumping in starbursts, X-ray, AGN
- require $T > 2000K$, $nH_2 > 10^4 cm^{-3}$
- exceptional merger N6240: 0.01% of L in the 2.2 μ line (all vibration lines 0.1%?)

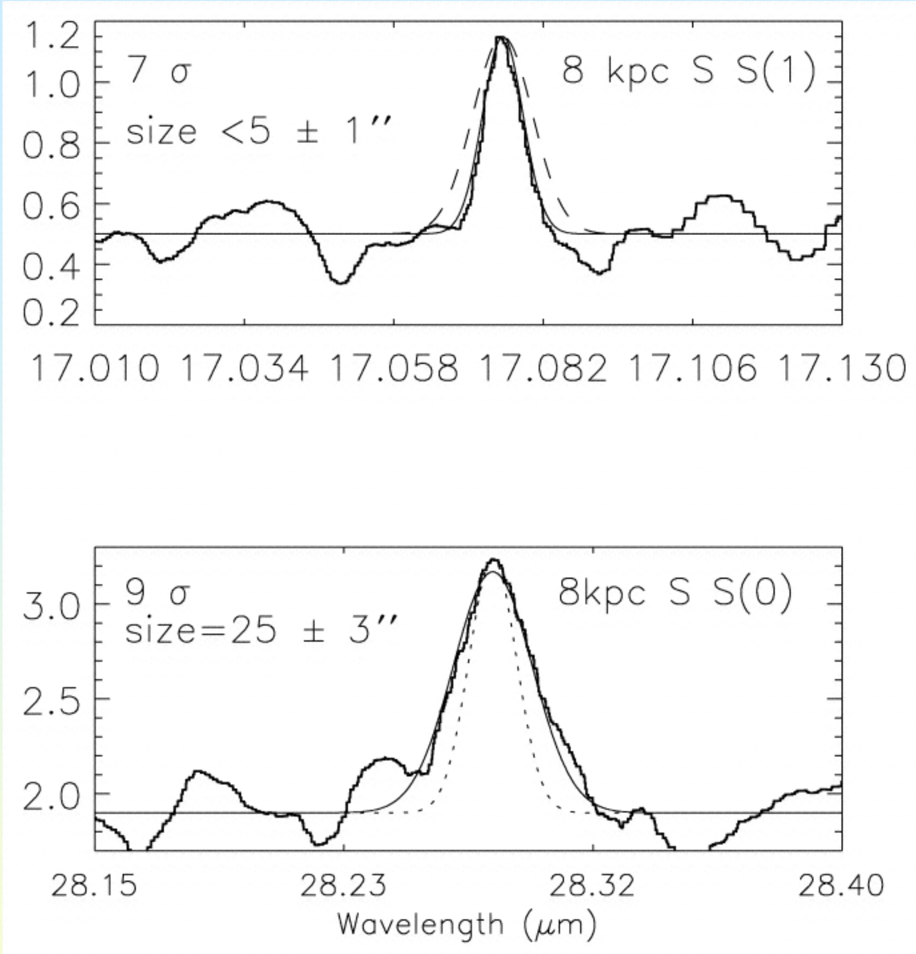




H_2 distribution in NGC891 (Valentijn, van der Werf 1999)

S(0) filled; S(1) open – CO profile (full line)

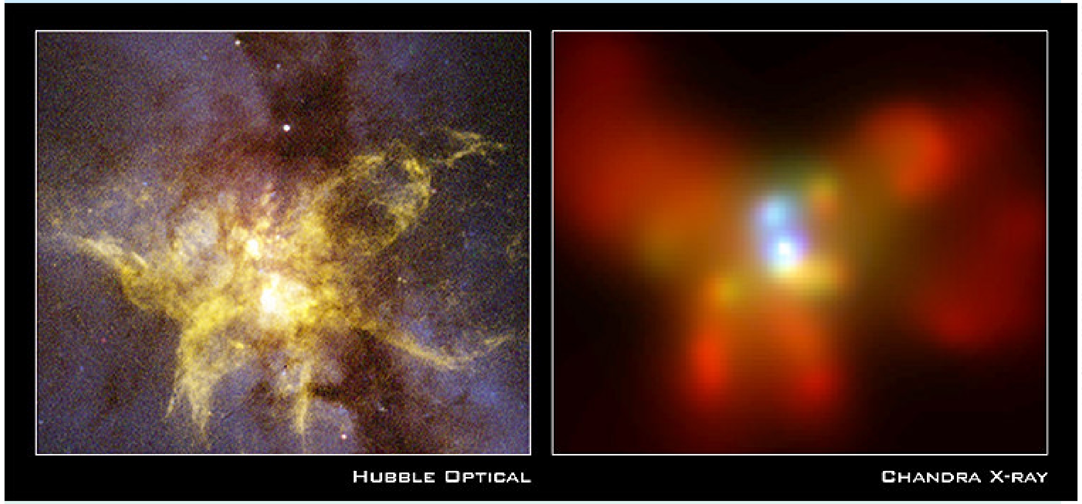
Large quantities of H_2 revealed by ISO

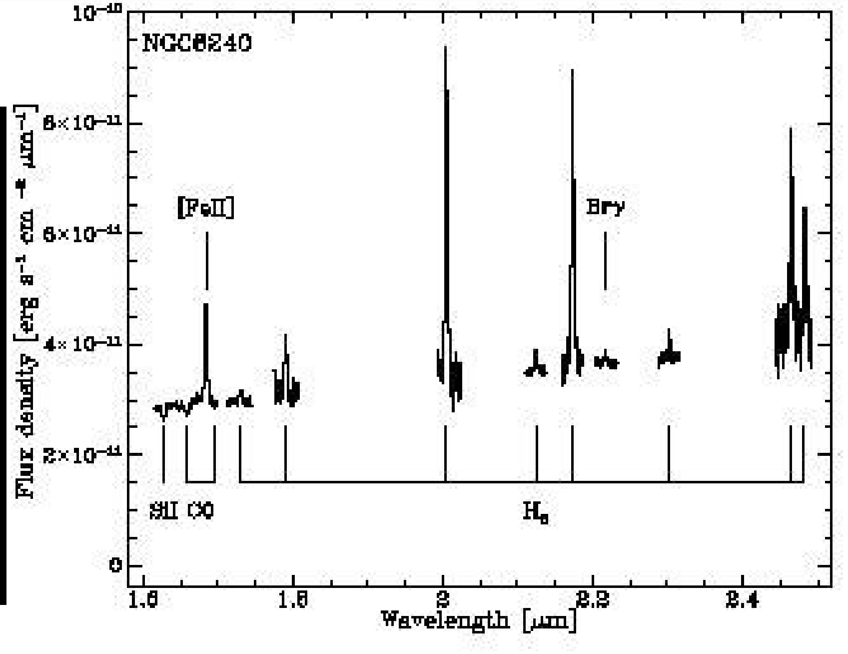


NGC 891, Pure rotational H_2 lines S(0) & S(1)

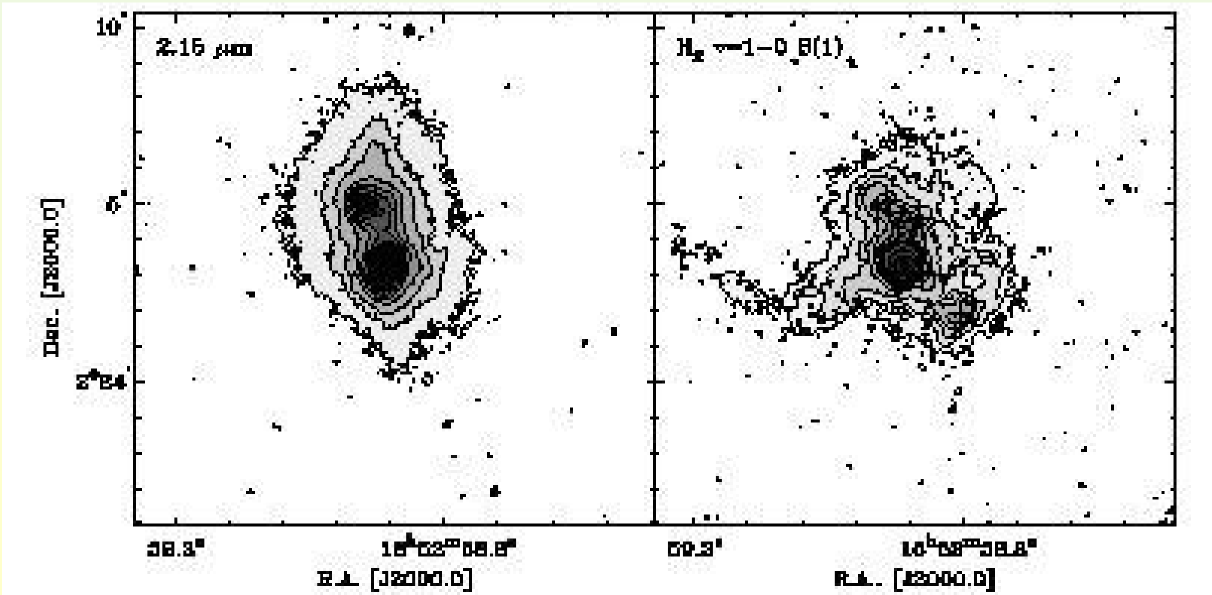
S(0) wider: more extended?

Derived $N(H_2)/N(HI) = 20$; **Dark Matter**?





H_2 v=1-0 S(1) 2.15μ in NGC 6240
van der Werf et al (2000) HST



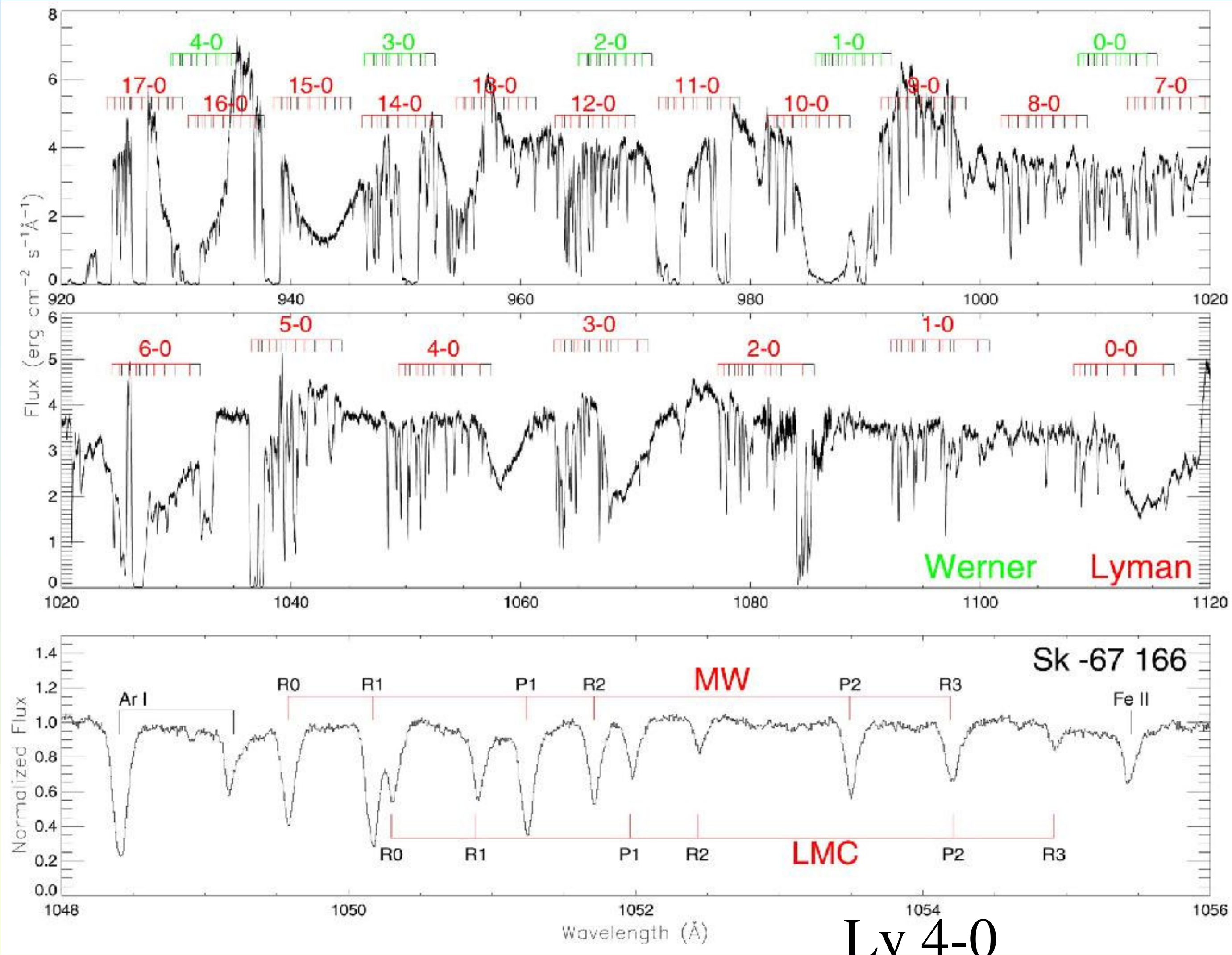
UV Lines of H_2

- **Absorption lines with FUSE (Av < 1.5)**
- **Very sensitive technique, down to column densities of NH_2 10^{14} cm-2**

- **Ubiquitous H_2 in our Galaxy (Shull et al 2000, Rachford et al 2001) translucent or diffuse clouds**

- **Absorption in LMC/SMC reduced H_2 abundances, high UV field (Tumlinson et al 2002)**

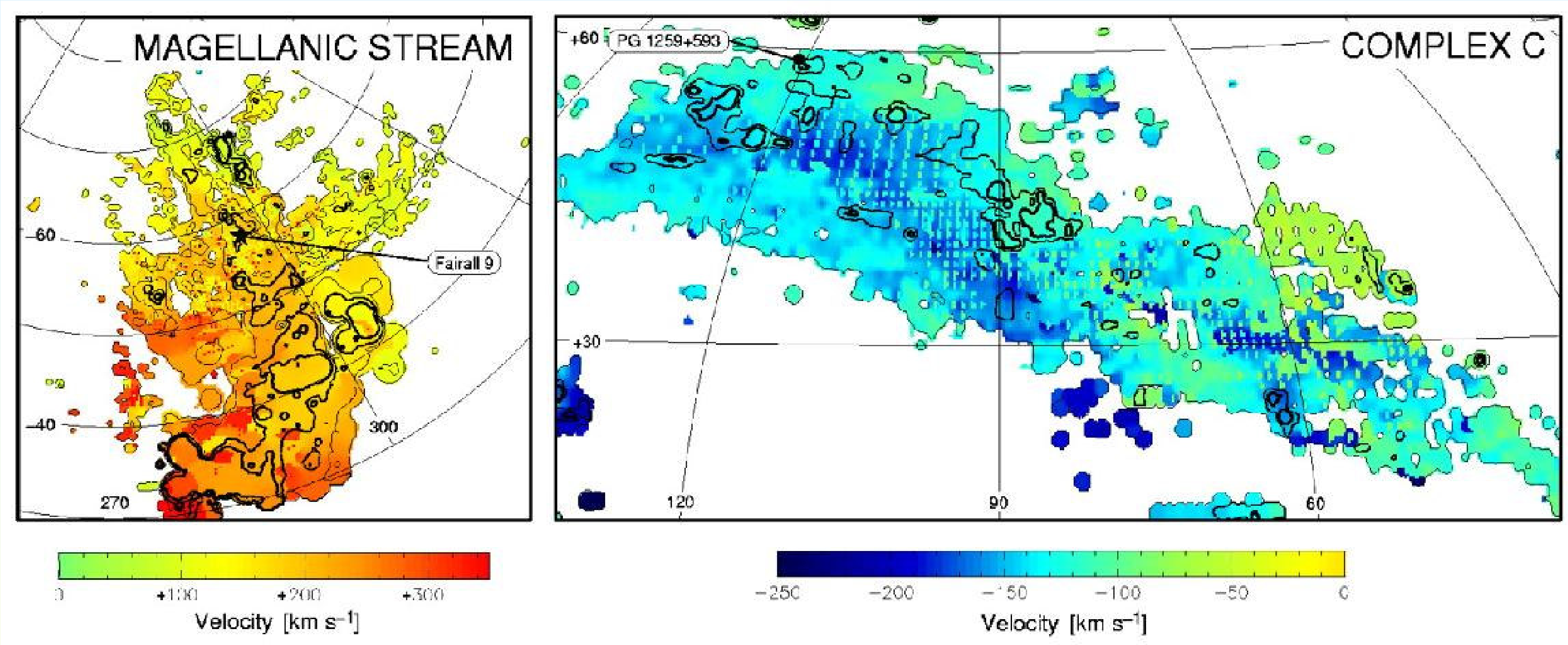
- **High Velocity Clouds detected (Richter et al 2001) in H_2**
- **(not in CO)**



Ly 4-0

FUSE Spectrum of the LMC star Sk-67-166 (Tumlinson et al 2002)

$NH_2 = 5.5\ 10^{15} cm^{-2}$

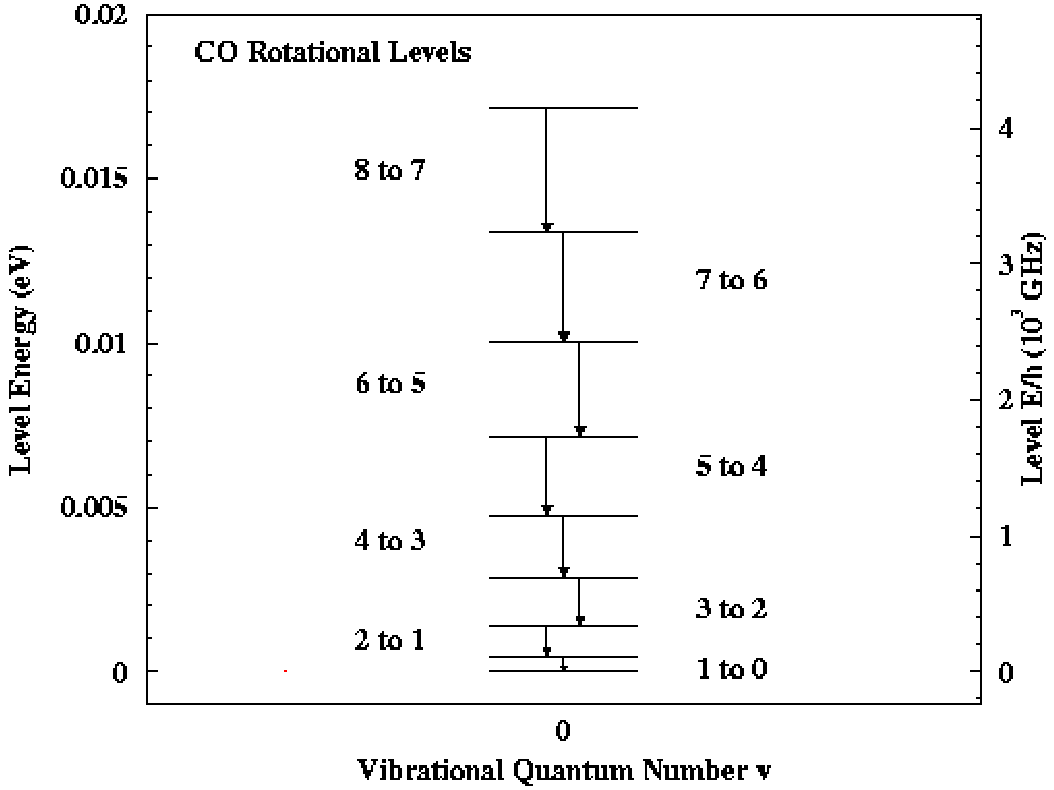


Detection of H_2 in absorption by FUSE in HVCs

Murphy et al (2000), Sembach et al 2001

The CO Tracer

- In galaxies, H_2 is traced by CO rotational lines
- CO/H_2 ~10^{-5}
- CO are excited by collision with H_2
- The dipole moment of CO is relatively weak
- μ ~0.1 Debye



- Spontaneous de-excitation rate A_{ul} α μ^2
- A_{ul} is low, molecules remain excited in low-density region about 300 cm^{-3}

- **Competition between collisional excitation and radiative transitions, to be excited above the 2.7K background**
- **J=1 level of CO is at 5.2K**

- **The competition is quantified by the ratio C_{ul}/A_{ul}**
- **varies as $n(H_2)T^{1/2} /(\nu^3 \mu^2)$**

- **Critical density n_{crit} for which $C_{ul}/A_{ul} = 1$**

Molecule	CO	NH_3	CS	HCN
μ (Debye)	0.1	1.5	2.0	3.0
n_{crit} (cm^{-3})	4E4	1.1E5	1.1E6	1.6E7

Various tracers can be used, CO for the wide scale more diffuse and extended medium, the dense cores by HCN, CS, etc..

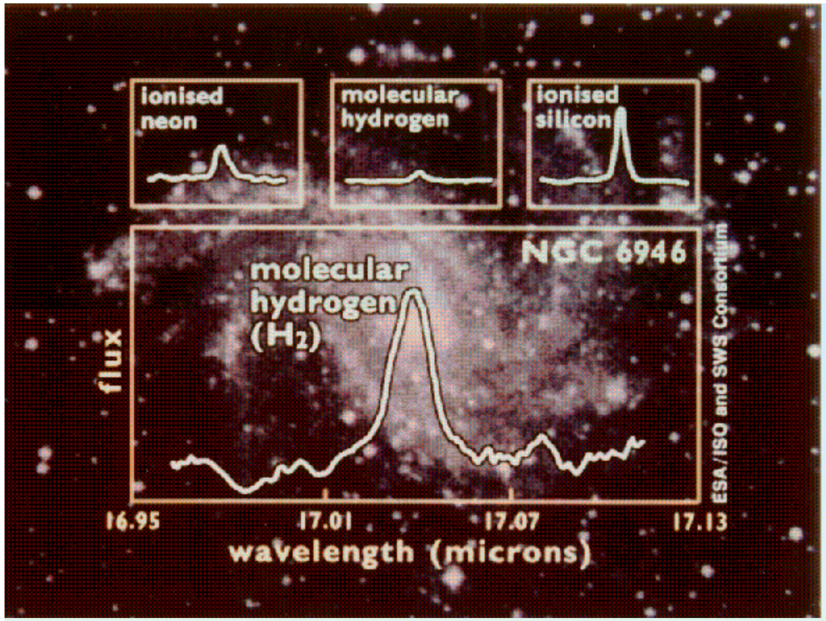
The CO lines (J=1-0 at 2.6mm, J=2-1 at 1.3mm) are most often optically thick

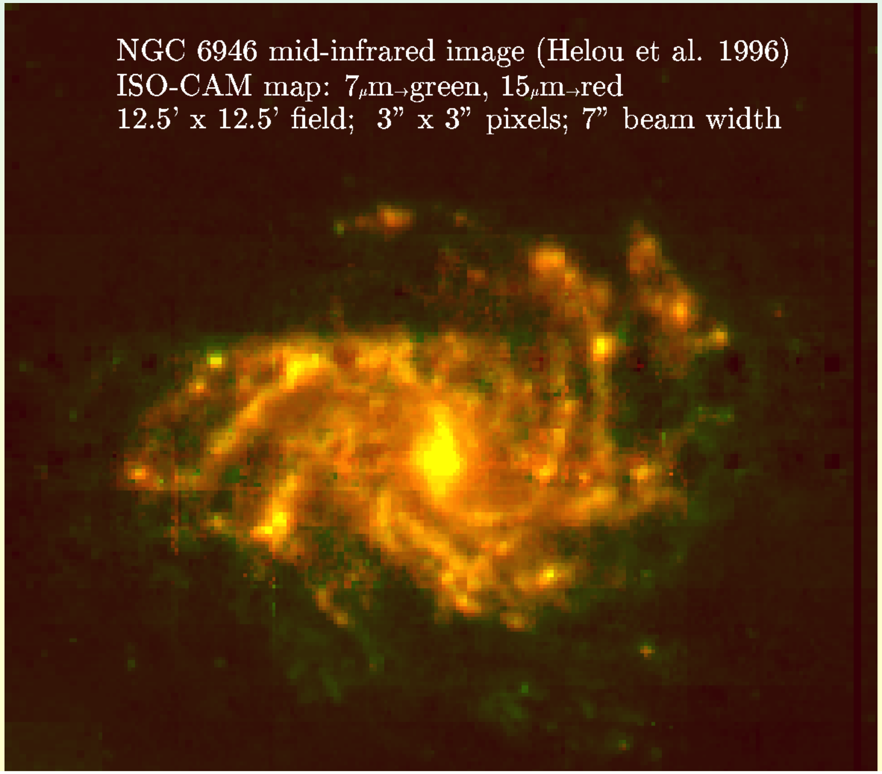
At least locally every molecular cloud is optically thick

Although the "macroscopic" depth is not realised in general, due to velocity gradients

Relation between CO integrated emission and H_2 column density?

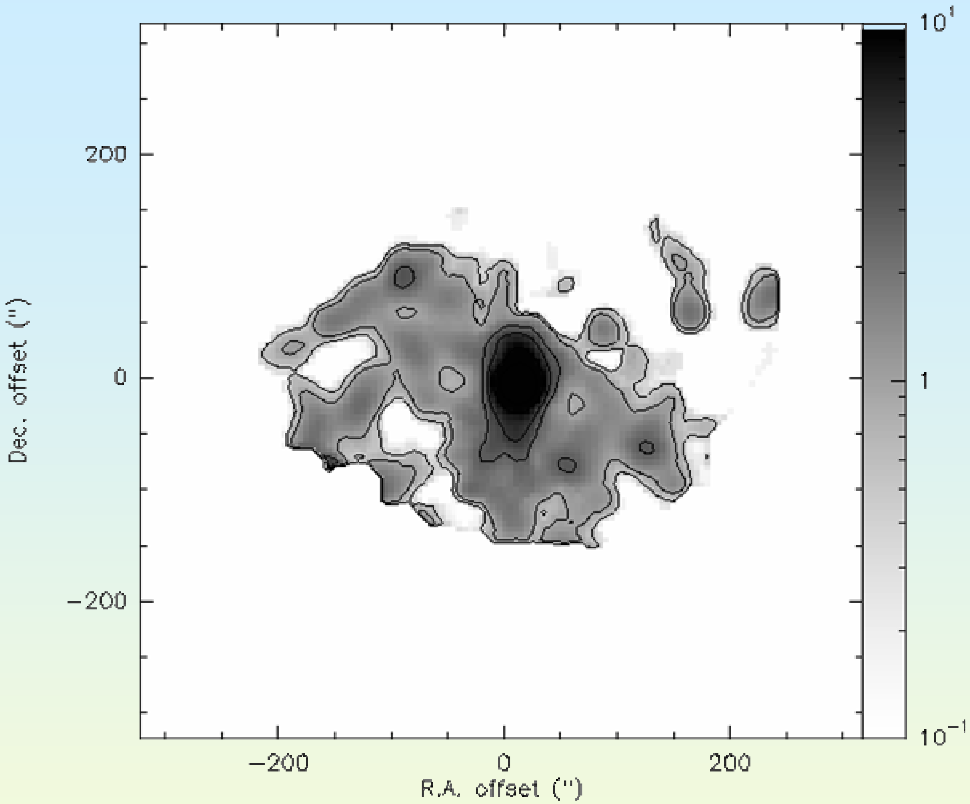
Is it proportional? How to calibrate?

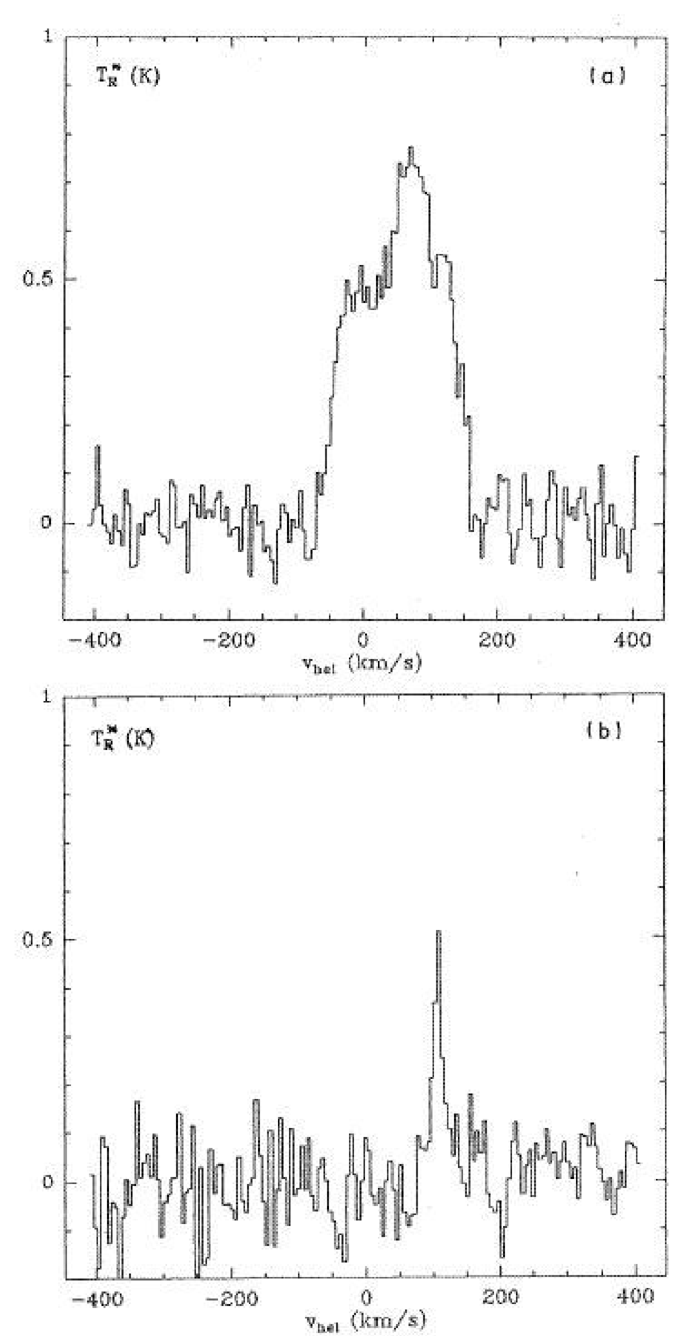




Gemini, Michaud 2005

NGC 6946





NGC 6946 CO(2-1) map 13" beam
IRAM 30m
Spectra, **Weliachew et al 1988**

- Isotopic molecule ^{13}CO, UV lines
- Statistics of "standard" clouds
- The Virial relation

1- Use the isotope ^{13}CO much less abundant at the solar radius: Ratio ~60

therefore ^{13}CO lines more optically thin

A standard cloud in the MW has τ_{CO} ~10

and τ_{13} ~ 0.1

The average ratio between integrated CO and ^{13}CO intensities is of the order of 10

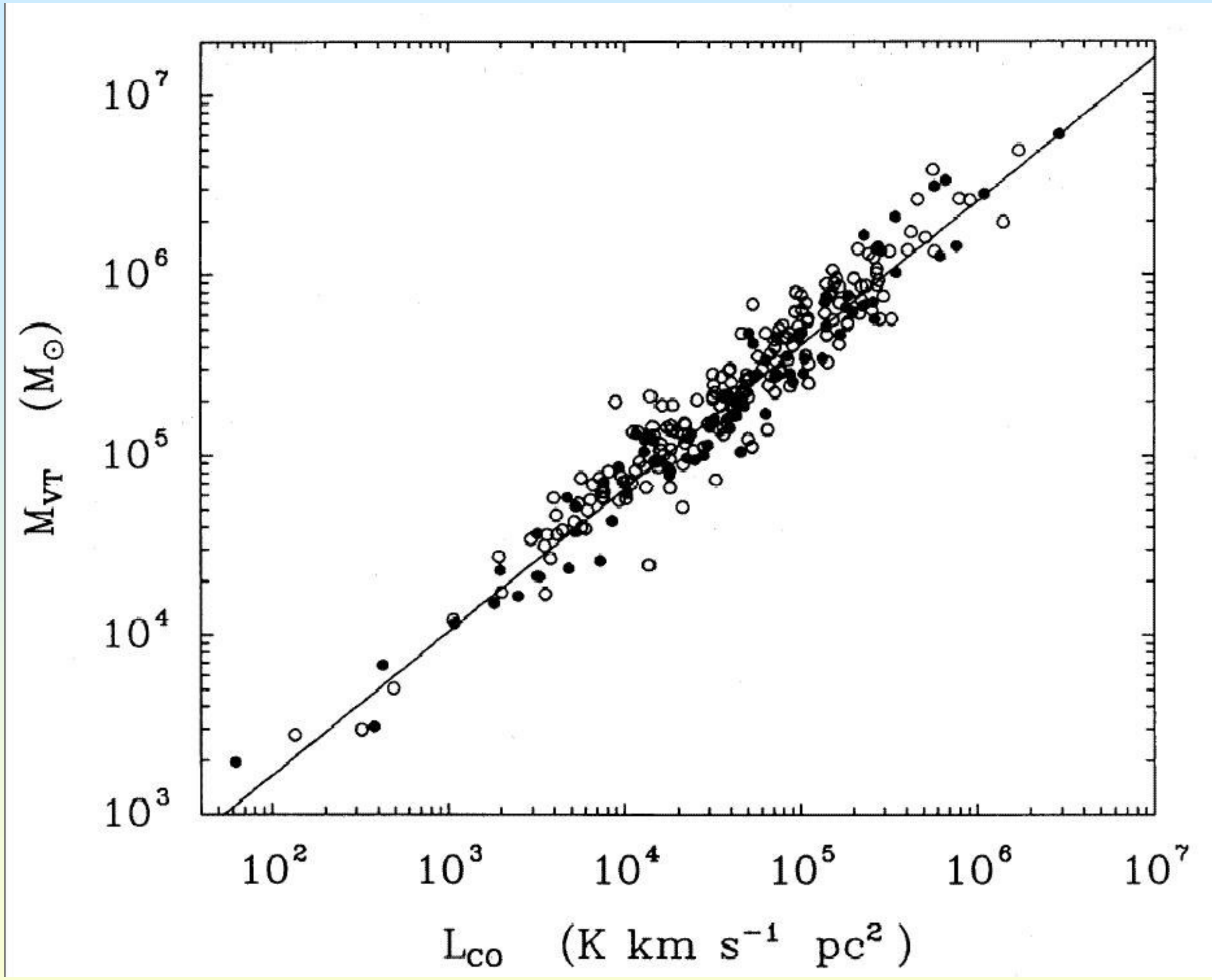
Milky Way

$V^2 r \sim GM$

Virial mass versus L_{CO}

$M_{vt}=39L_{CO}^{.81}$

Slope is not 1

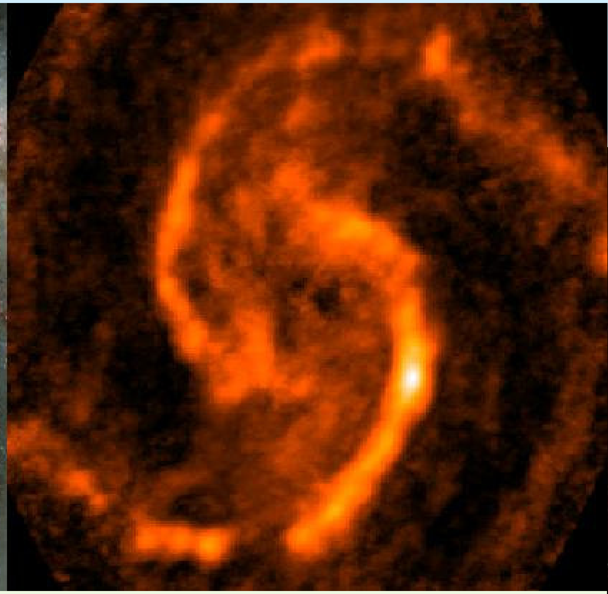


Solomon et al 1987

Messier 51, CO rich

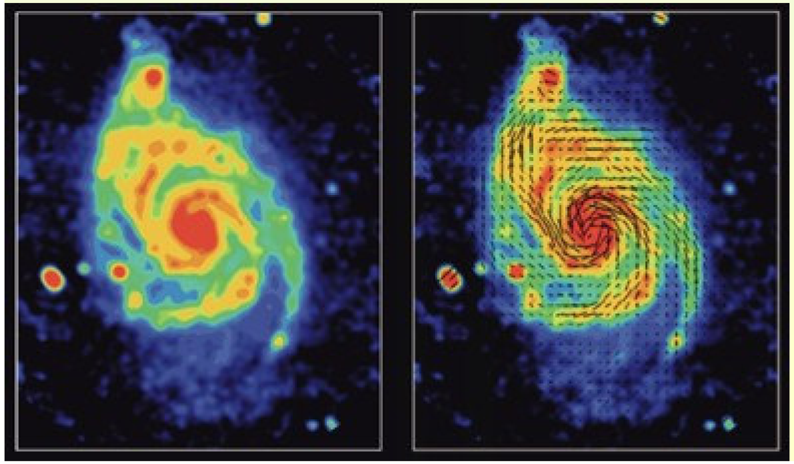
Optical HST

CO OVRO



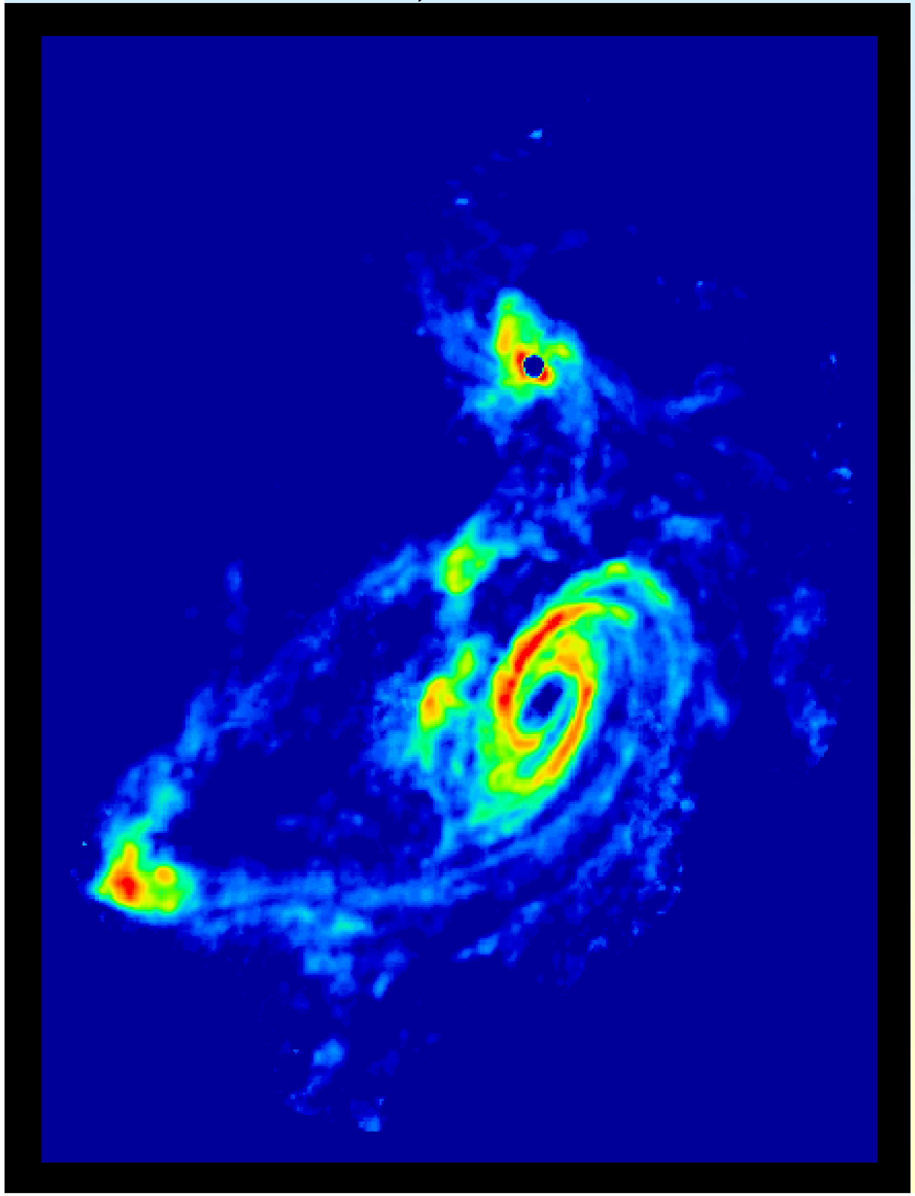
Spitzer IR

Radio, Magnetic field

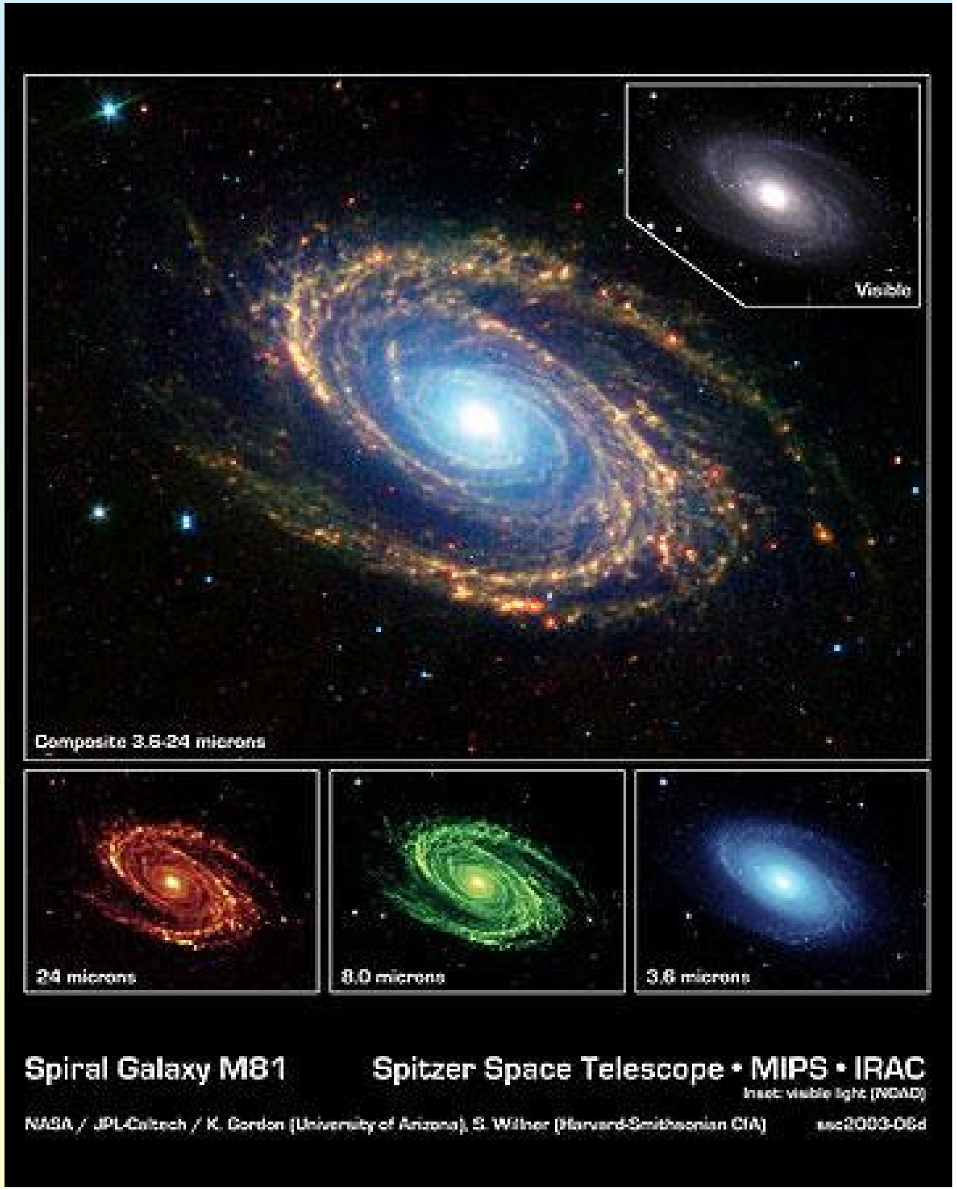


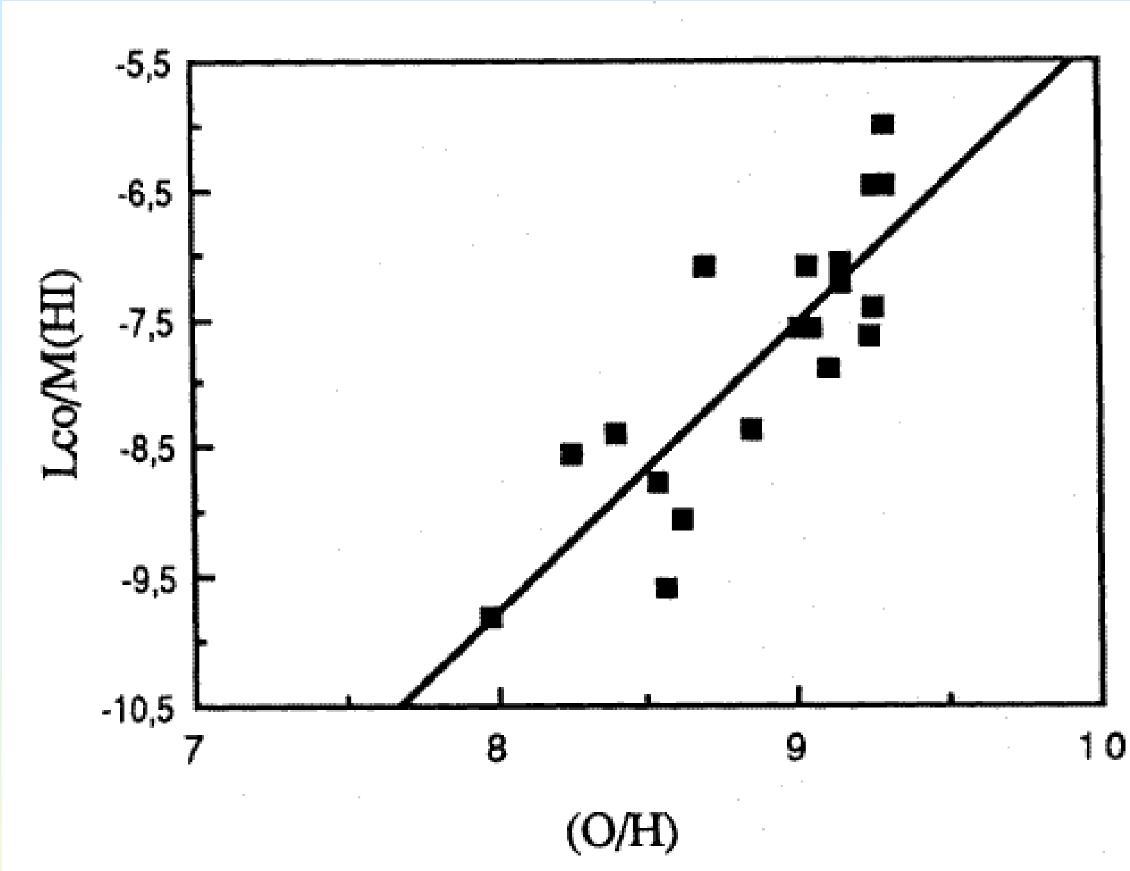
Messier 81, CO poor

M81, HI line VLA



Spitzer, 4, 8, 24 microns

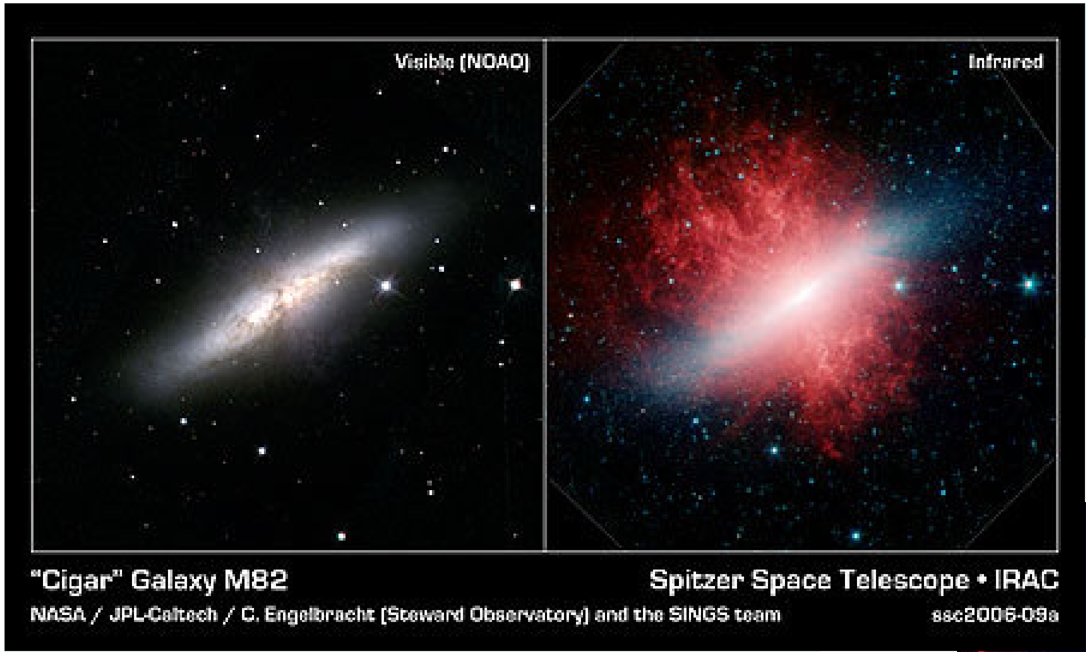




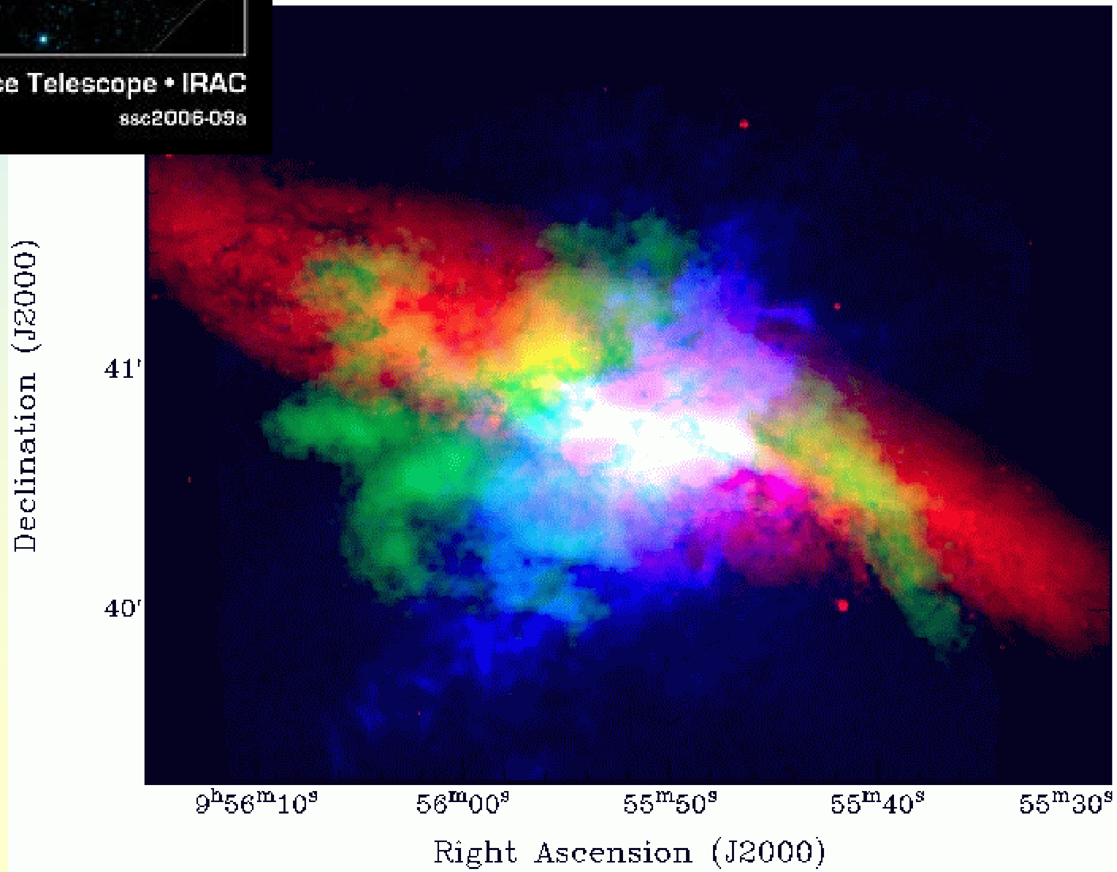
Arnault, Kunth, Casoli & Combes 1988

$L_{CO}/M(HI) \ \alpha \ (O/H)^{2.2}$

Confirmed by Taylor & Kobulnicky (98)
But see Walter et al (2003) Leroy et al (2005)



M82, Spitzer, dust FIR (PAH)



M82 in CO Streamers
Walter et al (2003)
Red: optical
Blue: Hα
Green CO (OVRO)

Another tracer: cold dust

At 1mm, the emission is Rayleigh-Jeans

$B(\nu, T) \sim 2\,k\,T / \lambda^2$

flux quasi-linear in T (between 20 and 40K)

In general optically thin emission

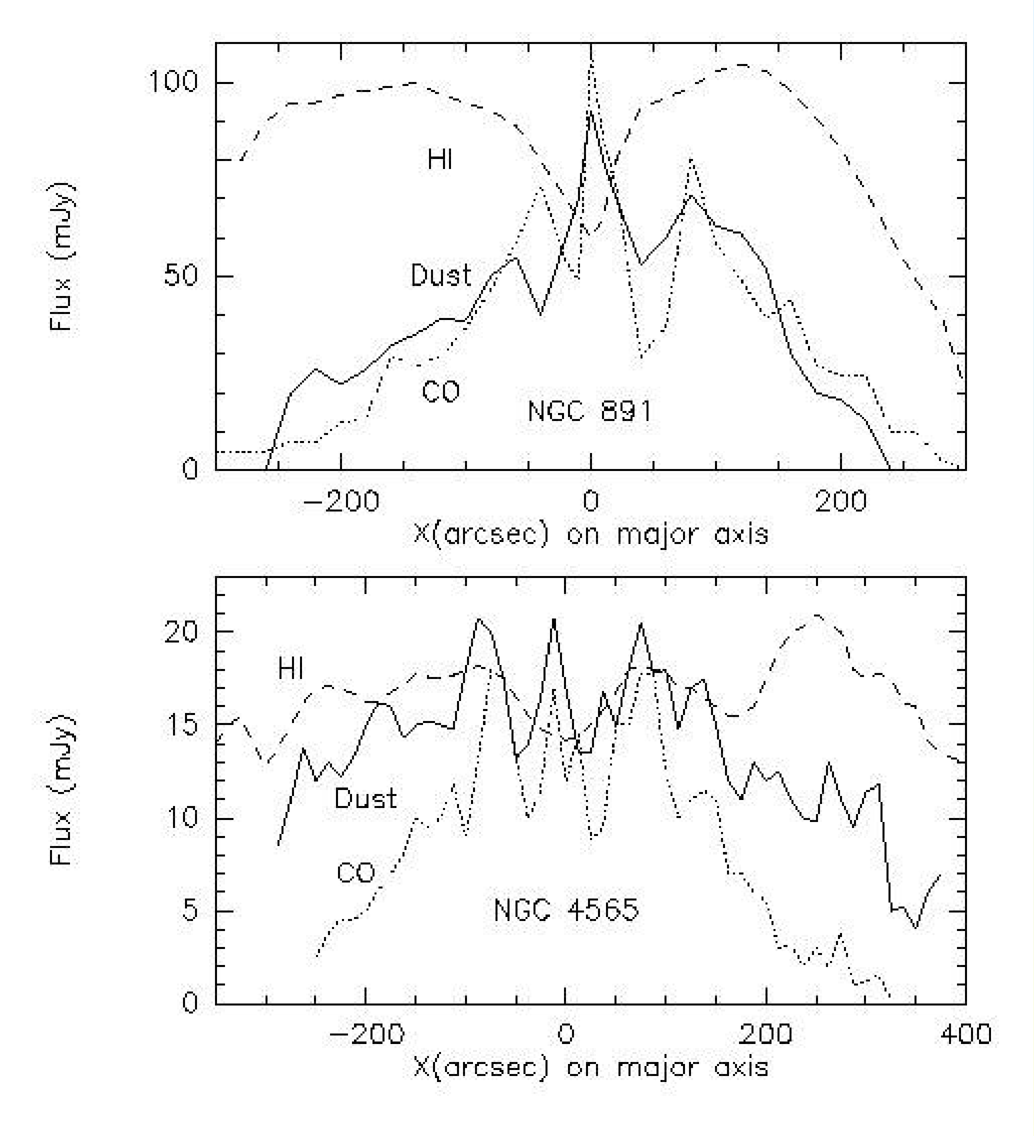
Proportional to metallicity Z

Z decreases exponentially with radius

When the molecular component dominates in galaxies, the CO emission profile follows the dust profile (example NGC 891)

When the HI dominates, on the contrary, the dust does not fall as rapidly as CO with radius, but follows more the HI (example NGC 4565)

→ **CO might be a poor tracer of H_2**



Radial profiles N891 (Guélin et al 93) & N4565 (Neininger et al 96)

The excitation effects combine to metallicity

Explains why it drops more rapidly than dust with radius

CO(2-1) line tells us about excitation

Boarder of galaxies, CO subthermally excited

When optically thick CO21/CO10 ratio ~1

If optically thin, and same T_{ex}, could reach 4

But in general < 1 in the disk of galaxies

T_{ex} (21) < T_{ex} (10) upper level not populated

even if T_{kin} would have allowed them

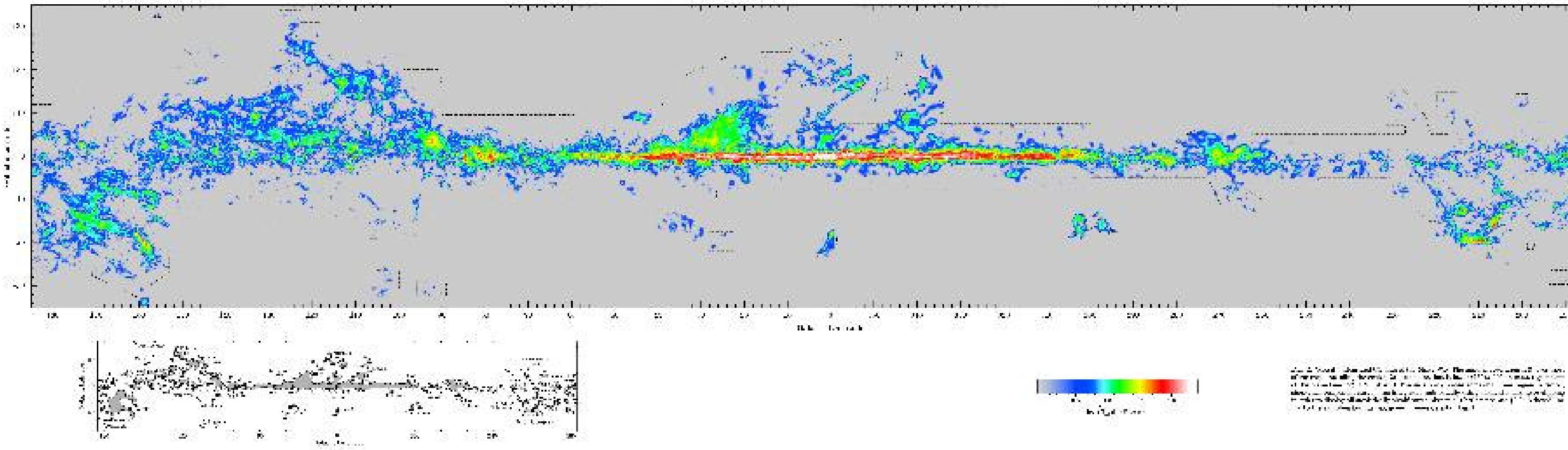
Summary on the H_2 component

The H_2 molecule is invisible, in cold molecular clouds (the bulk of the mass!)

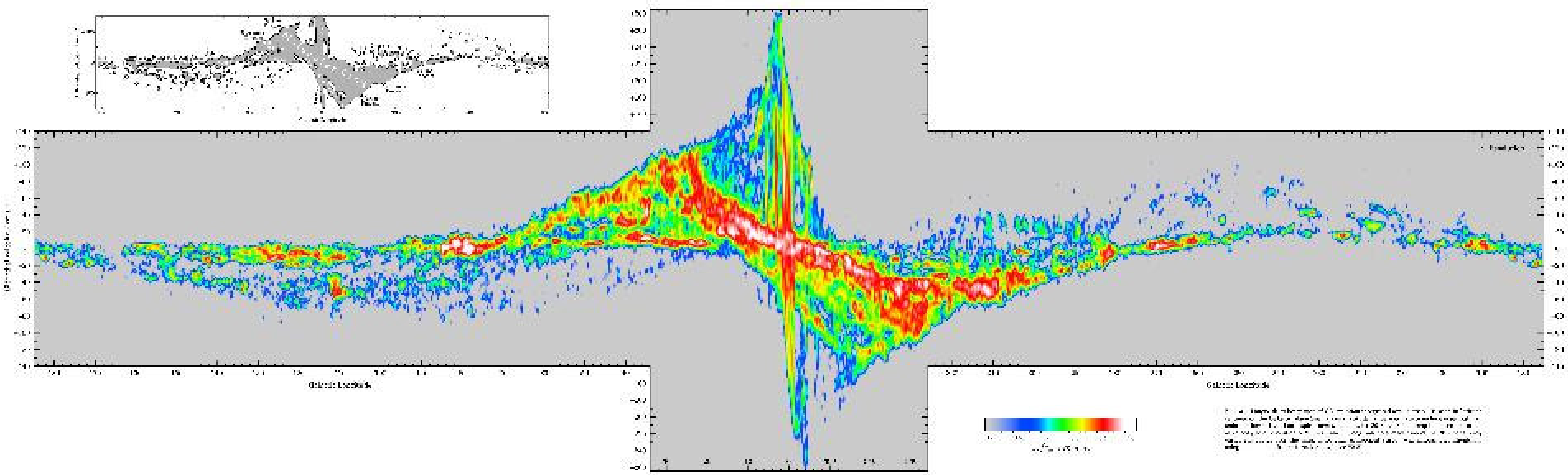
CO is not a good tracer, both because metallicity effect (non -linear, since depending on UV flux, self-shielding), and excitation

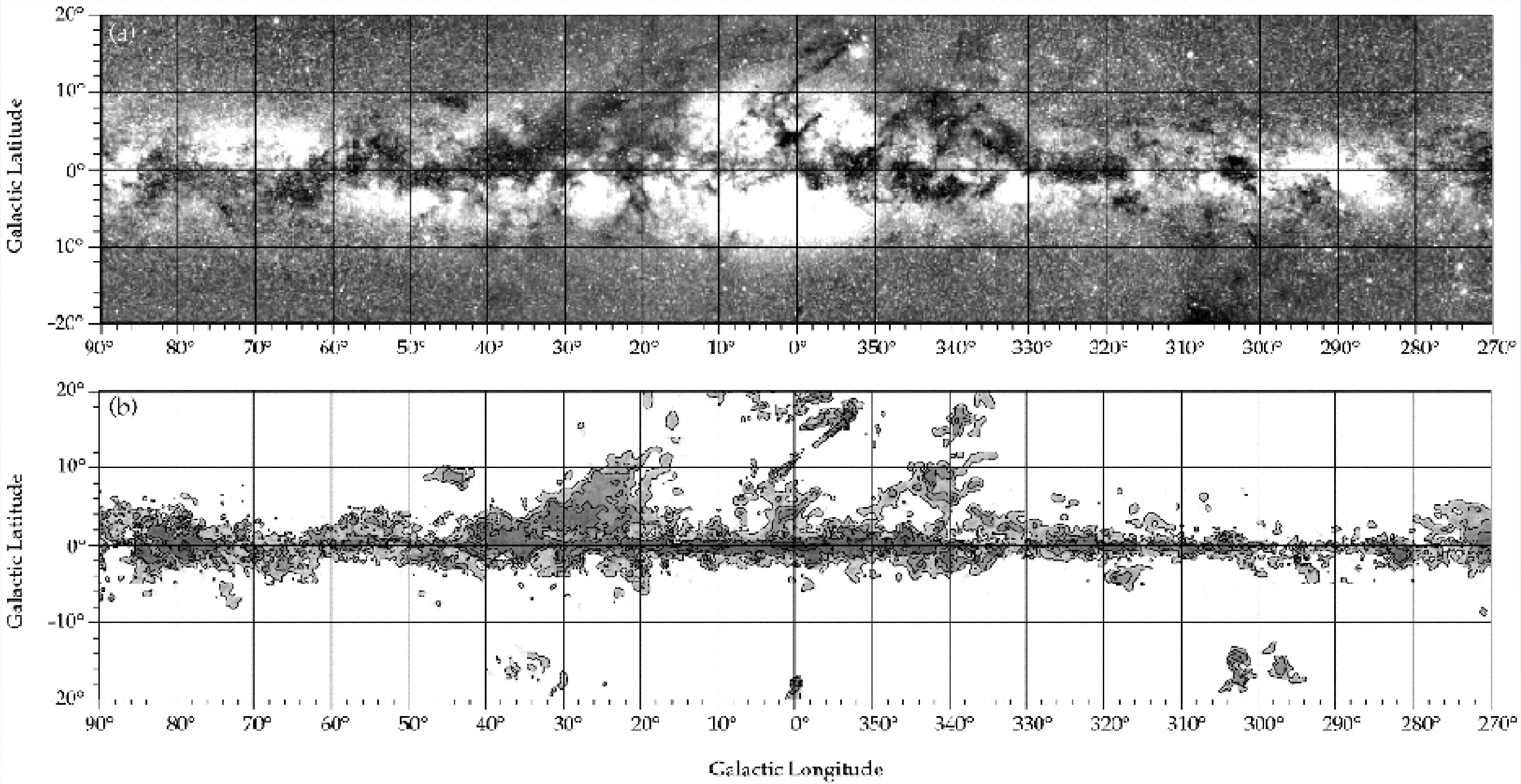
Very important to have other tracers
dense core tracers, HCN, HCO+, isotopes..

H_2 pure rotational lines, also a tracer of the "warm" H_2, always present when cold H_2 is there



CO in the Milky Way Dame et al. 2001





Comparison with an optical image, of the CO clouds within 2.5kpc distance (within 10 to 35km/s)
Dame et al (2001)

CO Distribution and Spiral structure of the Milky Way

How to obtain distances ?

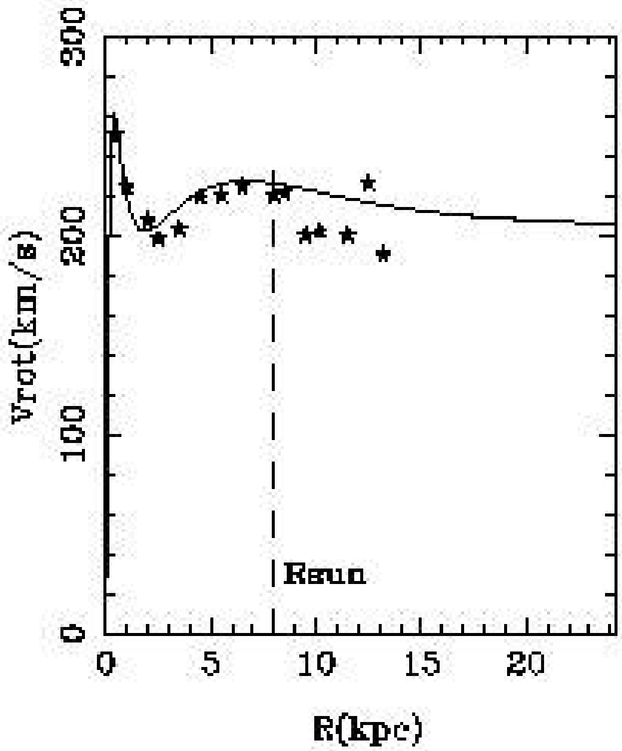
➔Kinematic models
Determination of the rotation curve, from terminal velocities

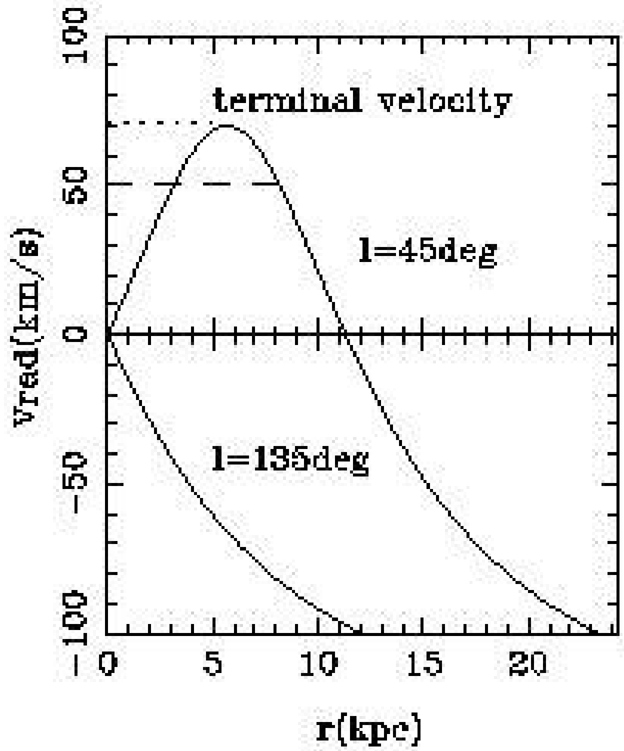
Assumption of circular velocity for the gas

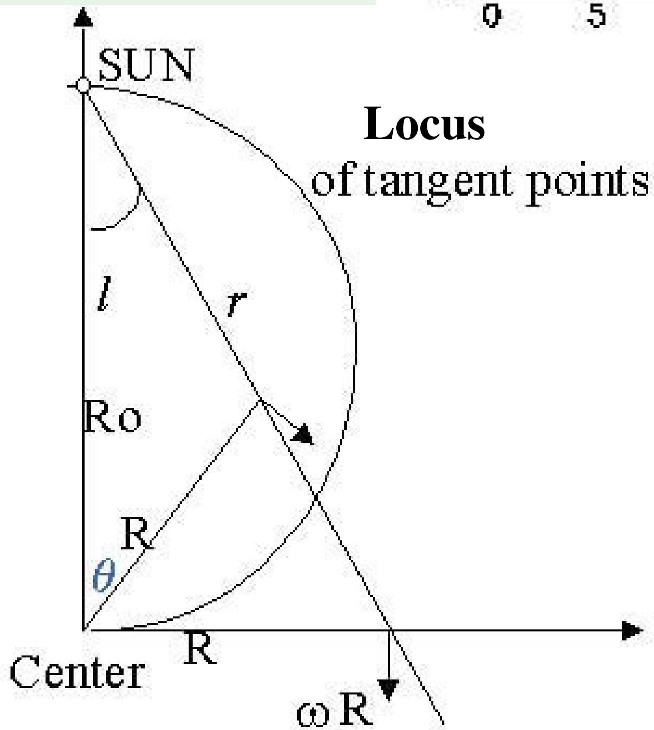
Ambiguities of distance, for material at longitudes below 90deg

To remove the degeneracy: the latitude or height above the plane Can play a role statistically

Also the distance of the near stars, determined by their spectrum or by absorption (in front or behind)





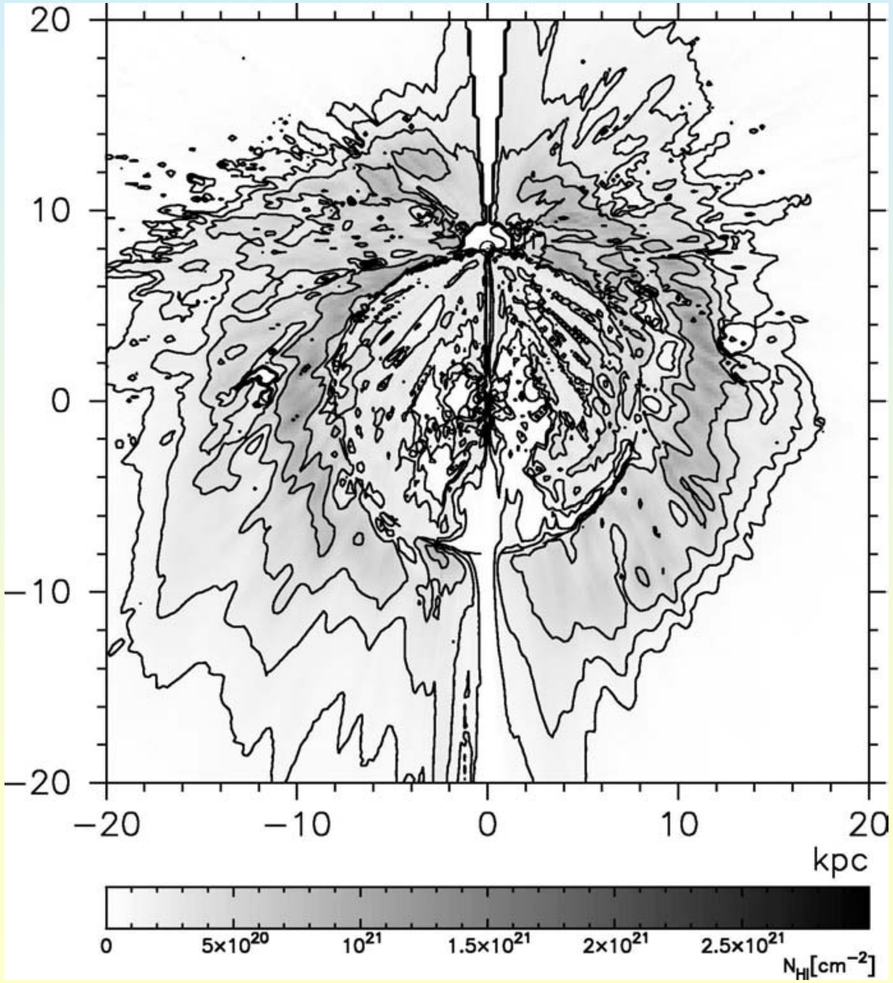


Ambiguity of distances

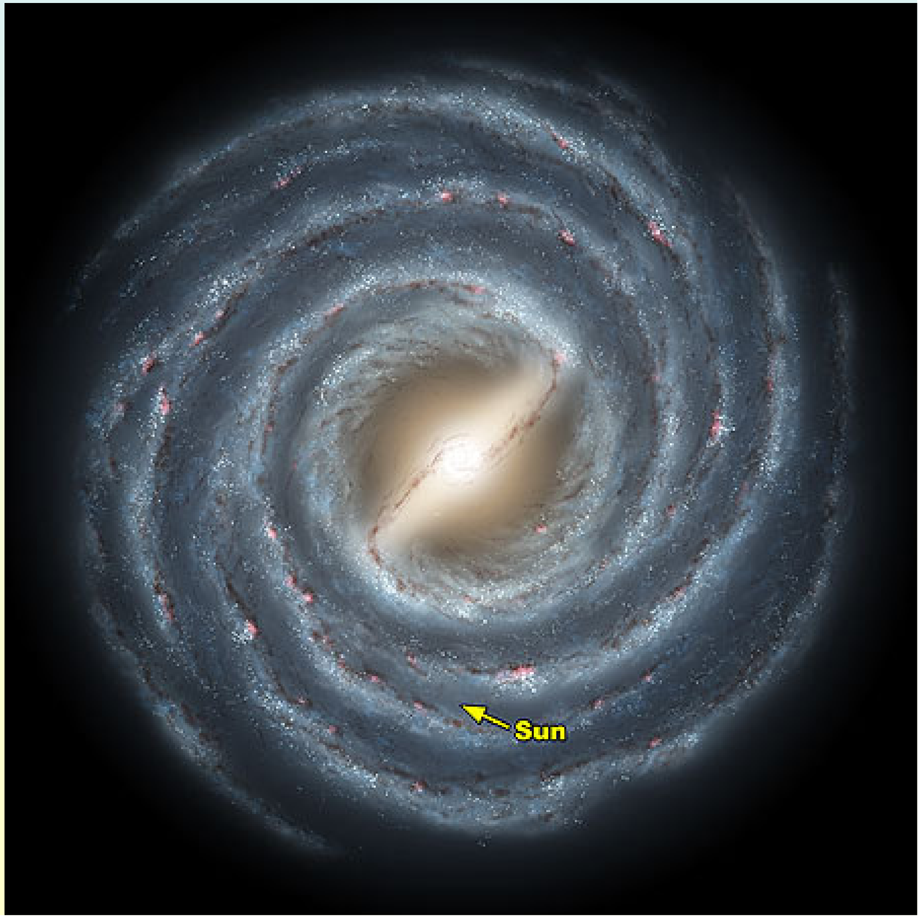
$$V\_rad\ (r,l) = Rsun\ \sin l\ (\Omega(R)-\Omega sun)$$

Milky Way

Nakanishi & Sofue (2003) HI disk reconstituted

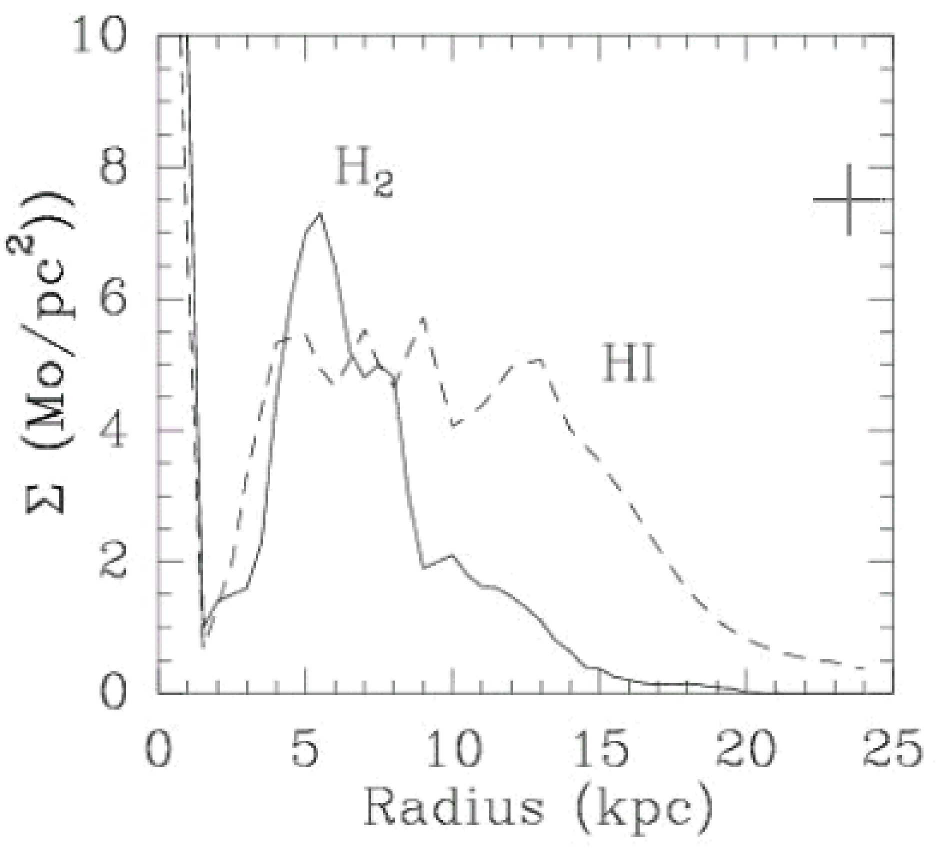


Artist view



CO Radial Distribution

- ➢Large concentration in the center
- ➢Hole around 2kpc
- ➢Galactic Molecular ring between 4 and 8 kpc
- ➢Exponential radial decrease in average



Spiral Structure

- **Evidence of a spiral structure, through the l-V diagram**

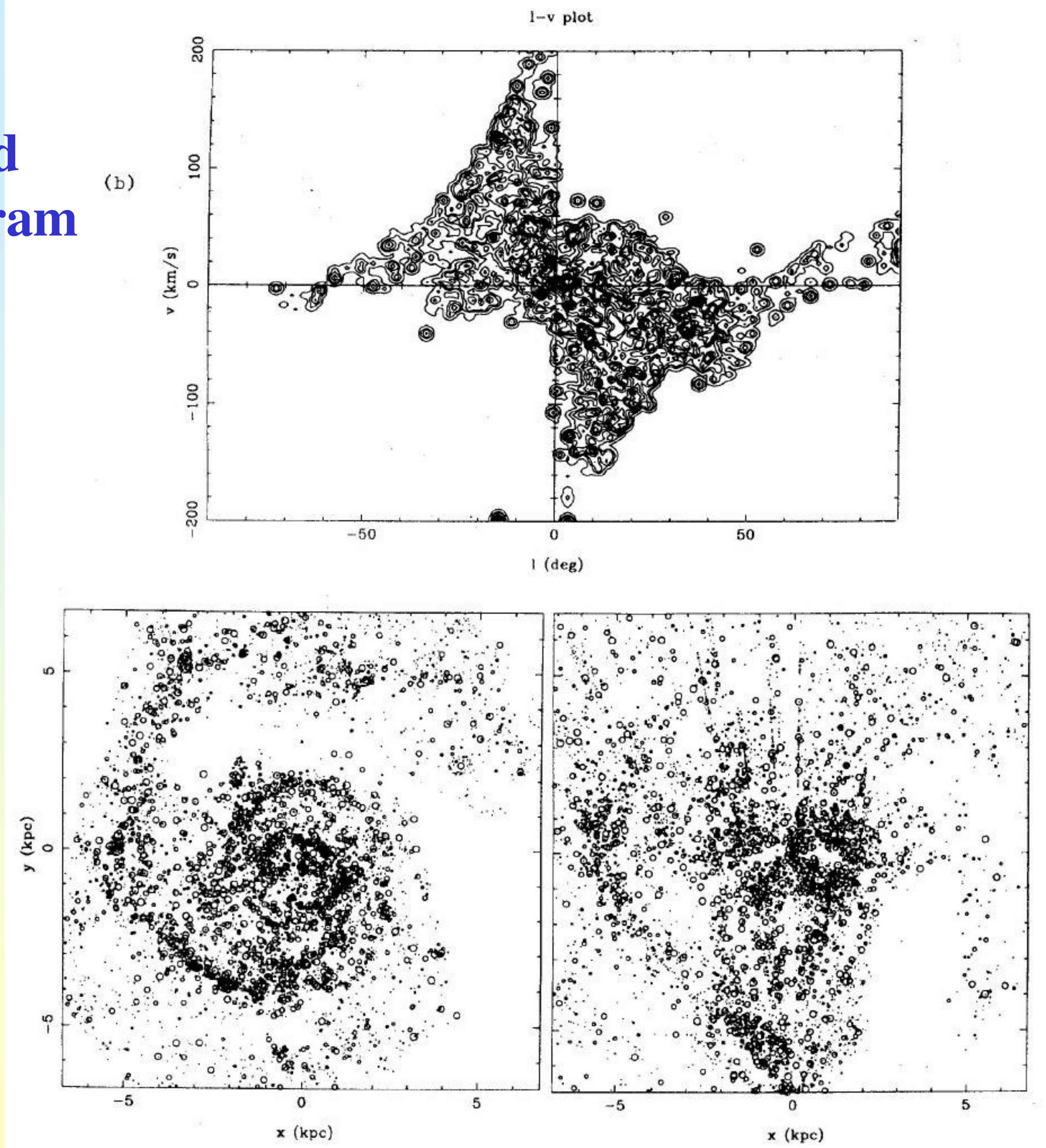
- **Very difficult to deproject**

- **Barred structure (through the orbits, parallelogram..)**

- **Best is to build N-body models (cf Mulder & Liem 86, Fux 99)**

- **Second (nuclear) bar? (visible with 2MASS, Alard 2001)**

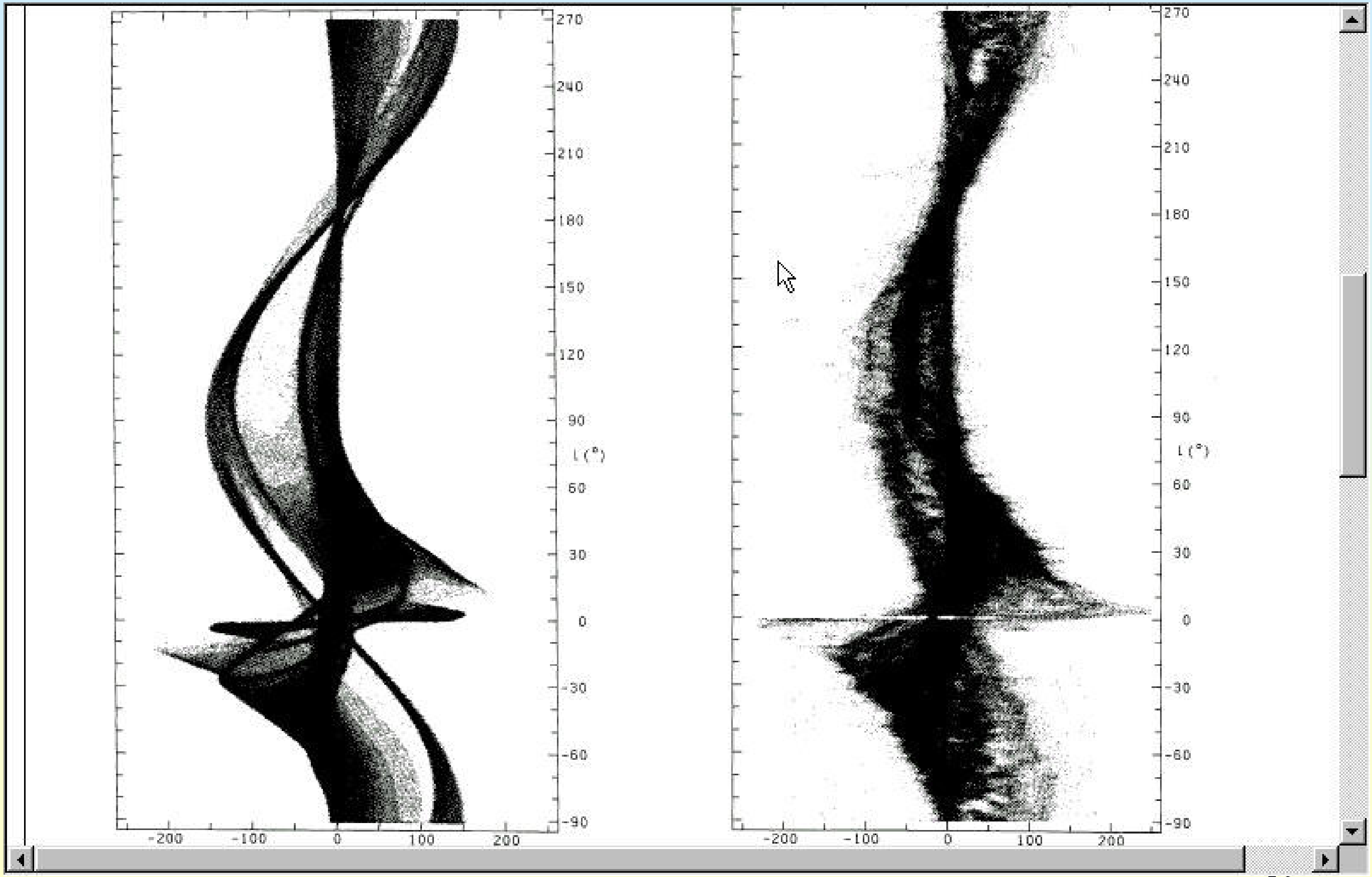
Observed l-V diagram



Original

Retrieved

Model Mulder & Liem 1986 HI PV diagram



The inner Galaxy

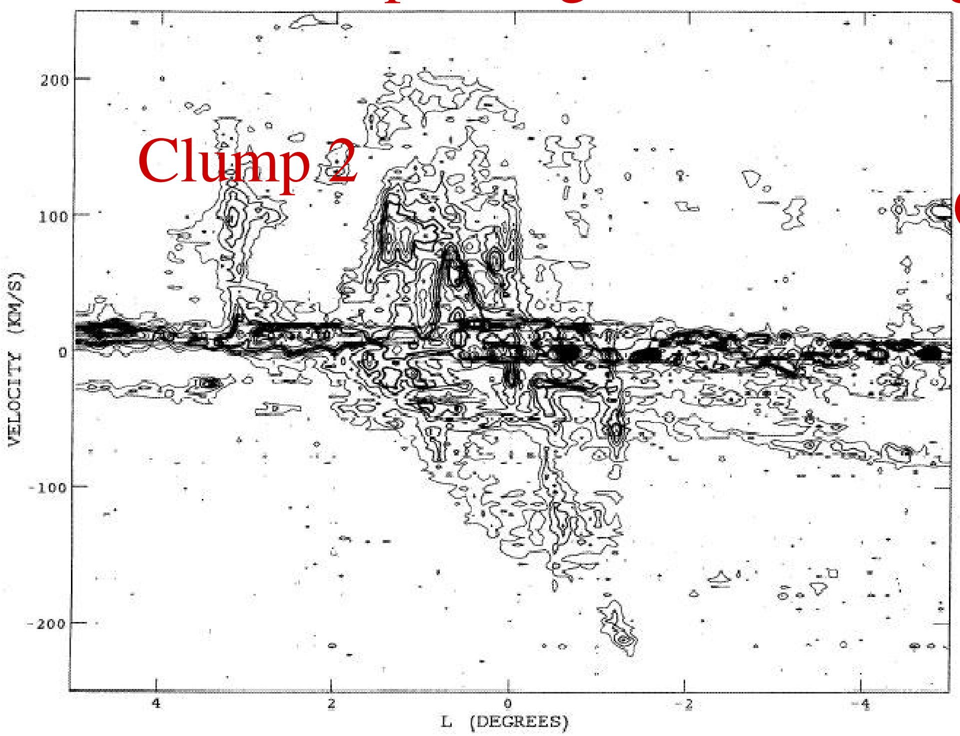
Always a big puzzle: forbidden velocities in the center

Expansion (Oort 77)? Explosion from the center? (Sanders 76)
Bar potential (Peters 1975)

Bar directly seen in COBE-DIRBE (Dwek et al 95)
Interpretation in terms of periodic orbits in a bar potential
parallel x1 orbits, perpendicular x2 orbits (Binney et al 97)

Characteristic parallelogram
Nuclear disk decoupled from the main disk

Expanding molecular ring EMR



Clump 2

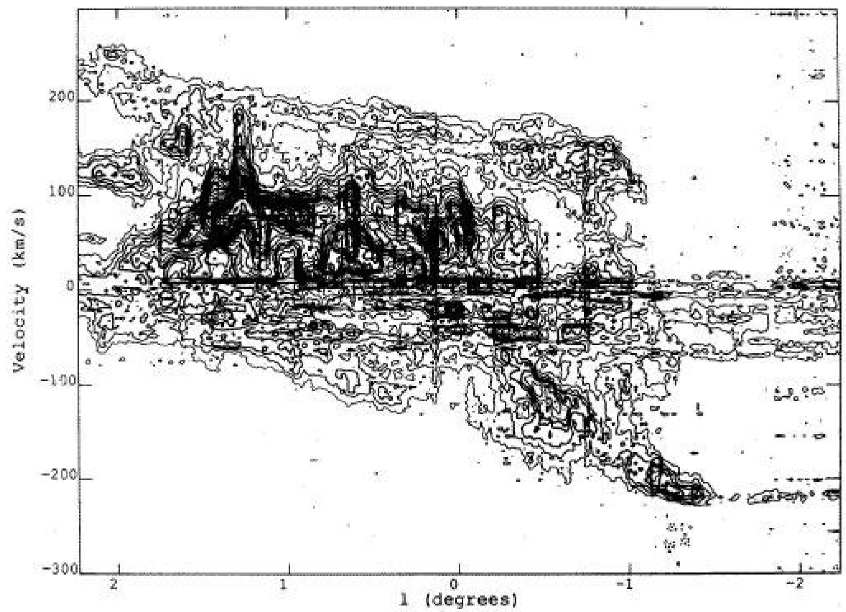
Clump 1

3kpc arm

-0.6° < b < 0.6°

^{13}CO Bally et al (1988)

parallelogram



-0.1° < b < 0.1°

^{12}CO Bally et al 87

From Fux (1999)

N-body simulations+SPH

Bar taken from DIRBE

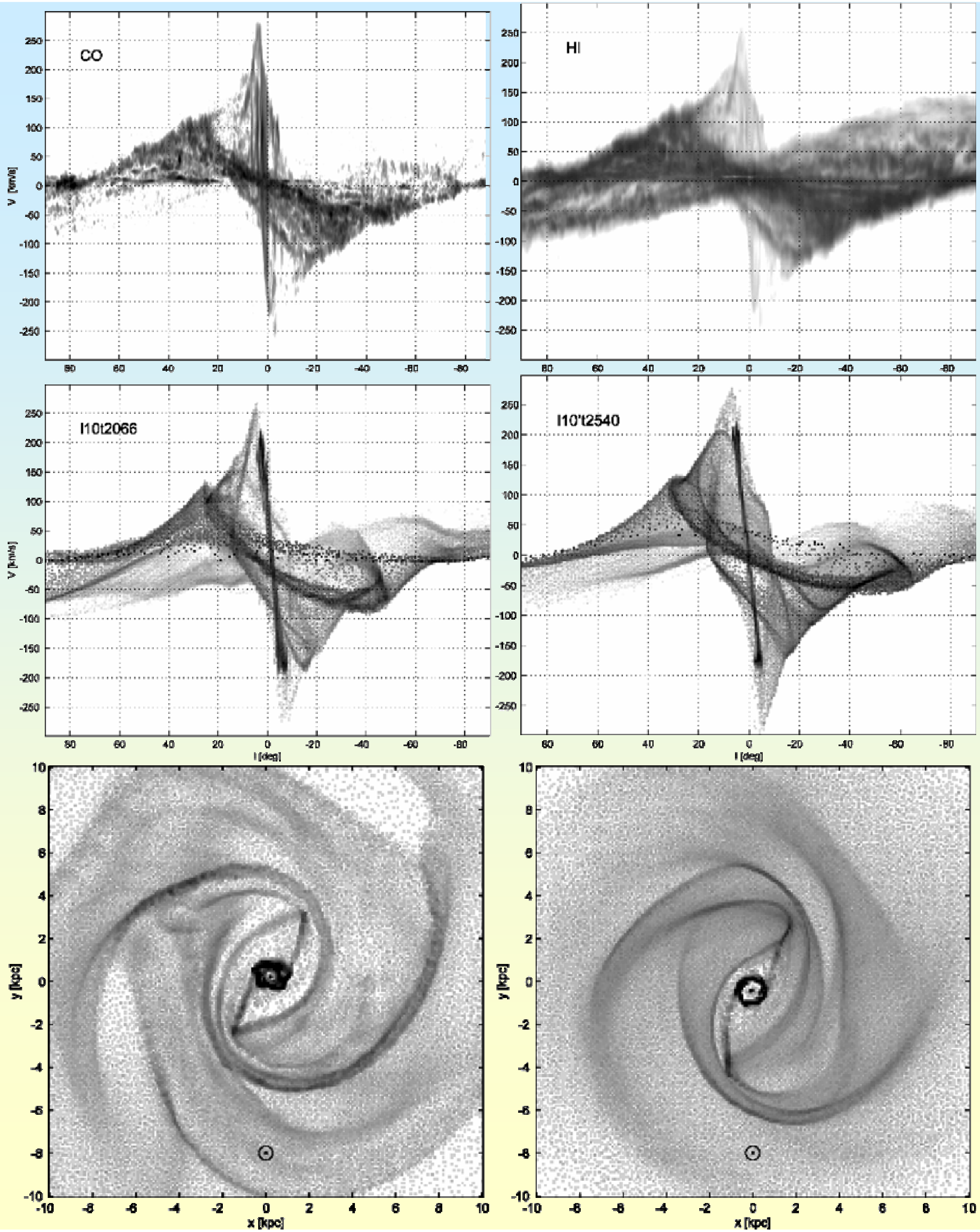
The center of the bar wanders

Gas flow asymmetric non-stationary

→ Transient

3kpc arm is a spiral round the bar

Parallelogram interpreted as leading dust-lanes



Bania's clump and V-elongated features near l=55° are gas lumps crossing the dust-lane shocks

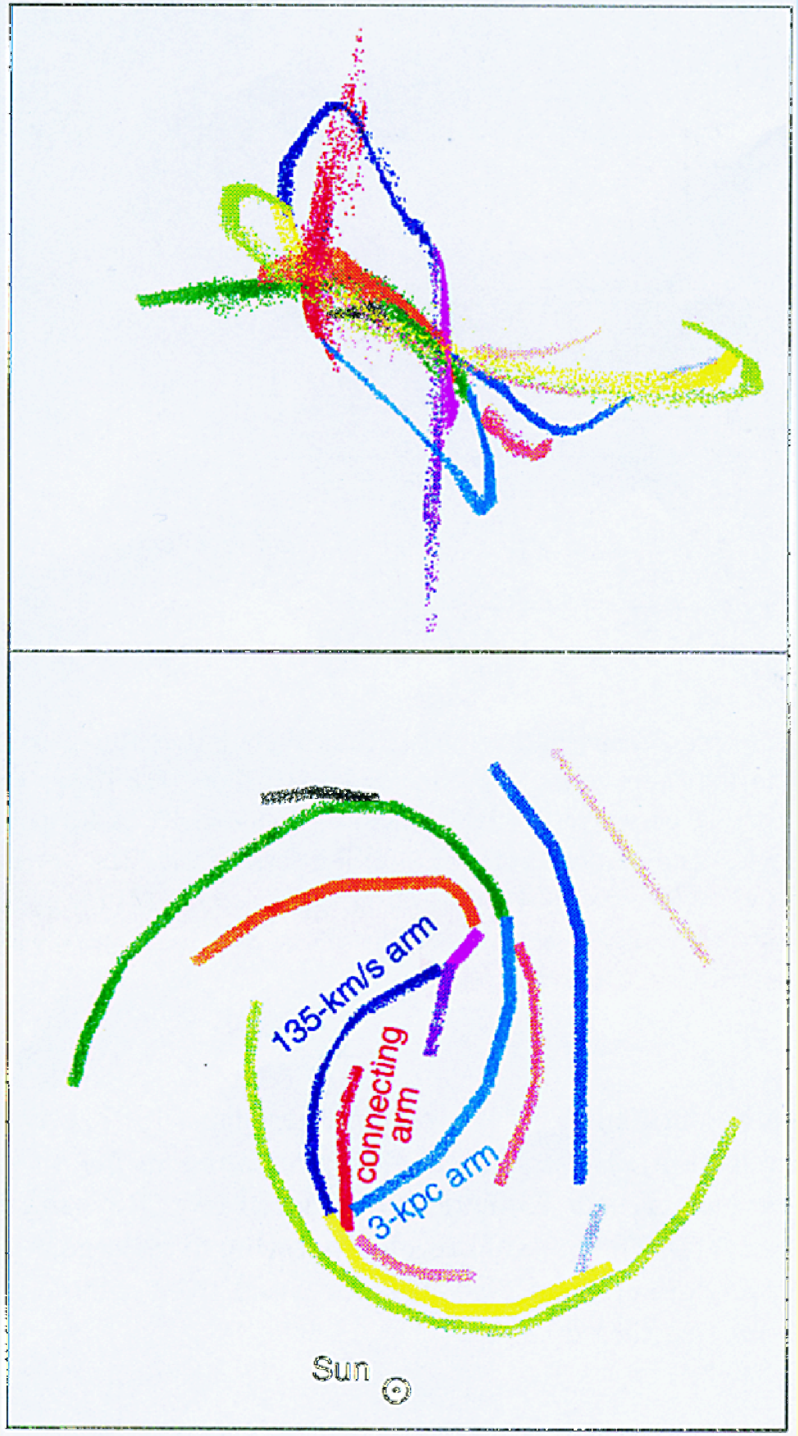
Inclination of the bar 25°

Corotation radius 4.5 kpc

b/a = 0.6

Other features:
inclined plane in the center

strong m=1

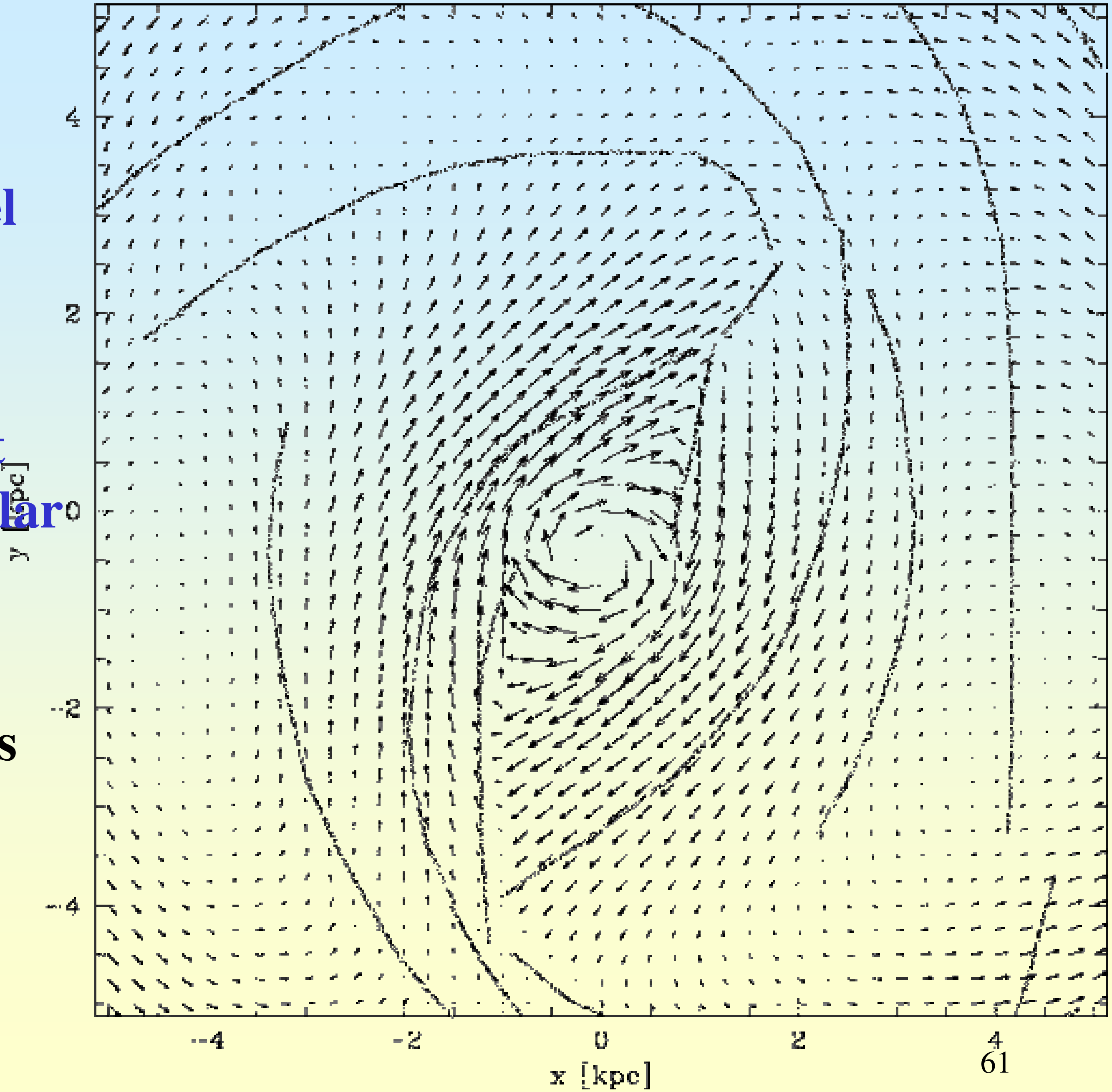


Fux (1999)

Velocities above the circular model

The region around 3kpc arm is subject to strong non-circular motions

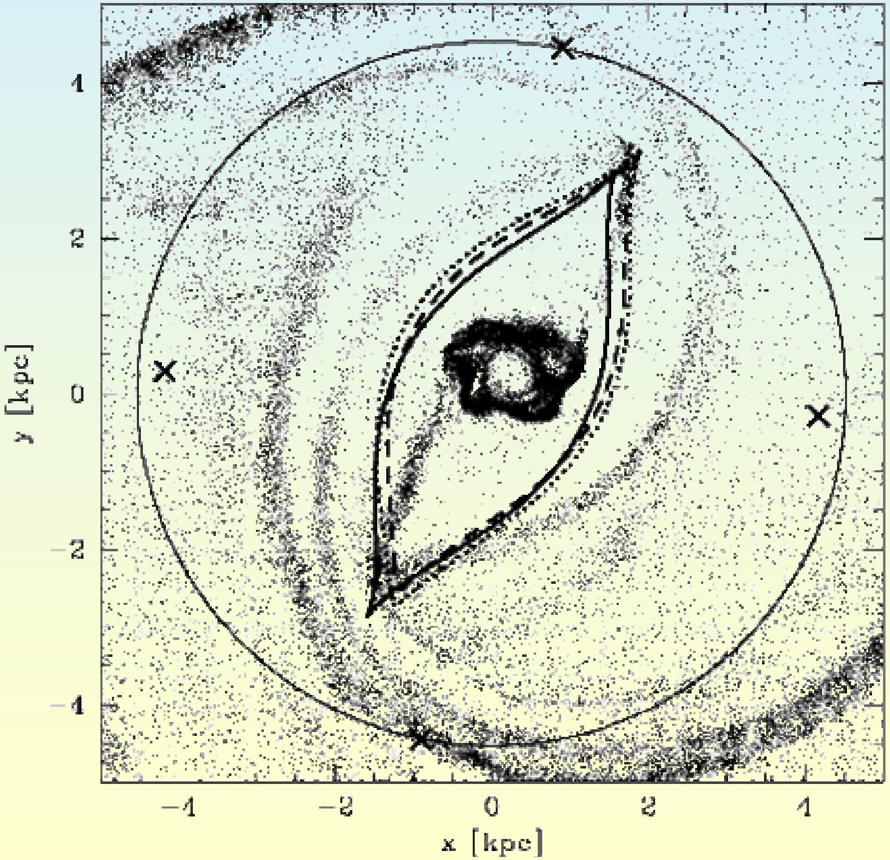
Strong asymmetries

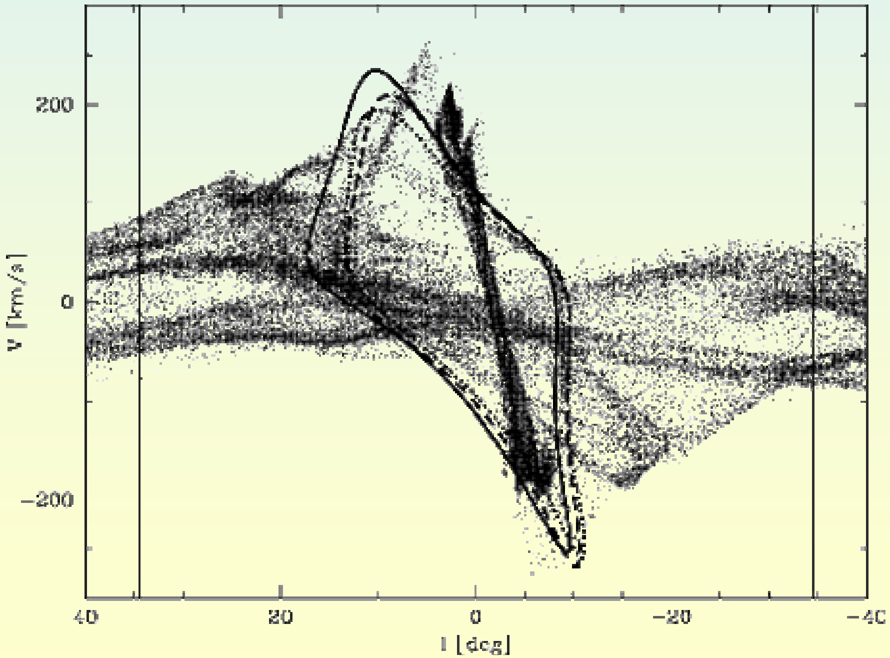


Interpretation of the central l-V diagram from Fux (1999)

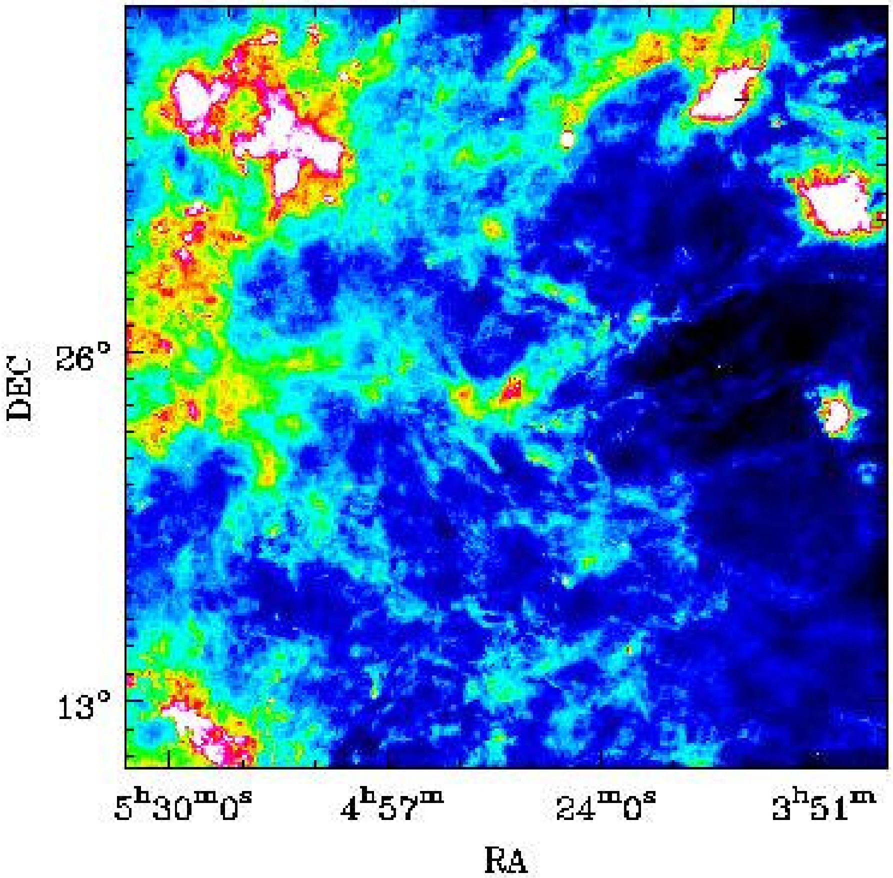
x2 orbits are almost circular

x1 cusped orbits produce the parallelogram

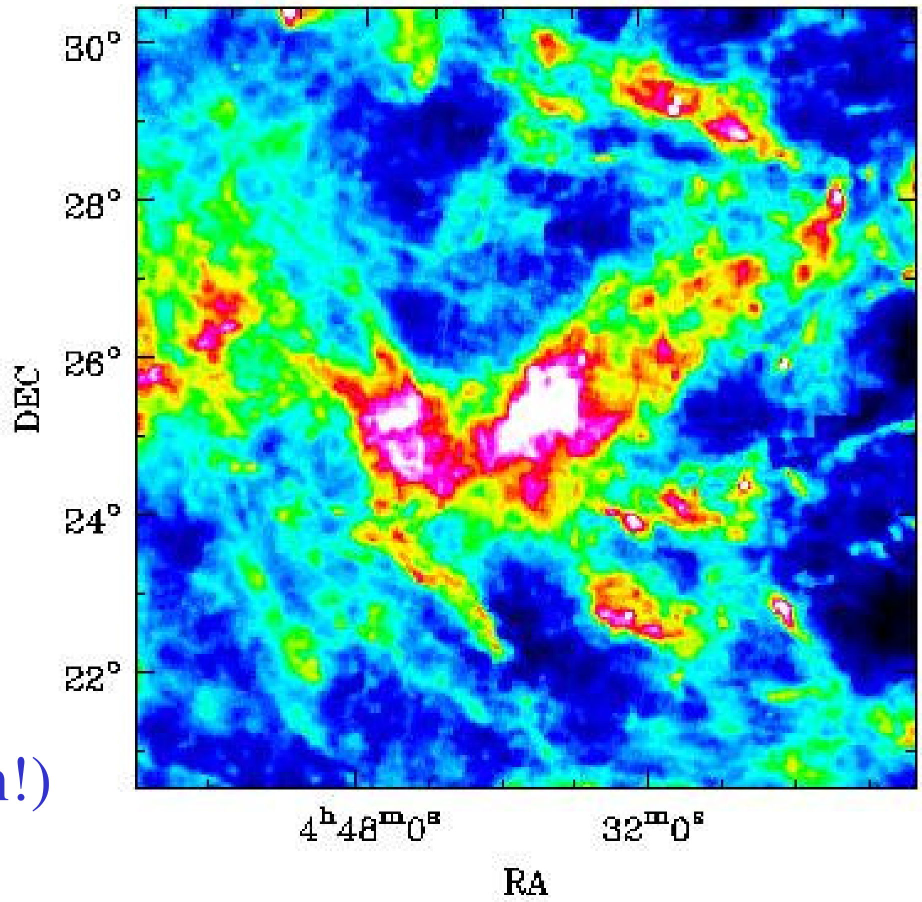




Fractal Structure

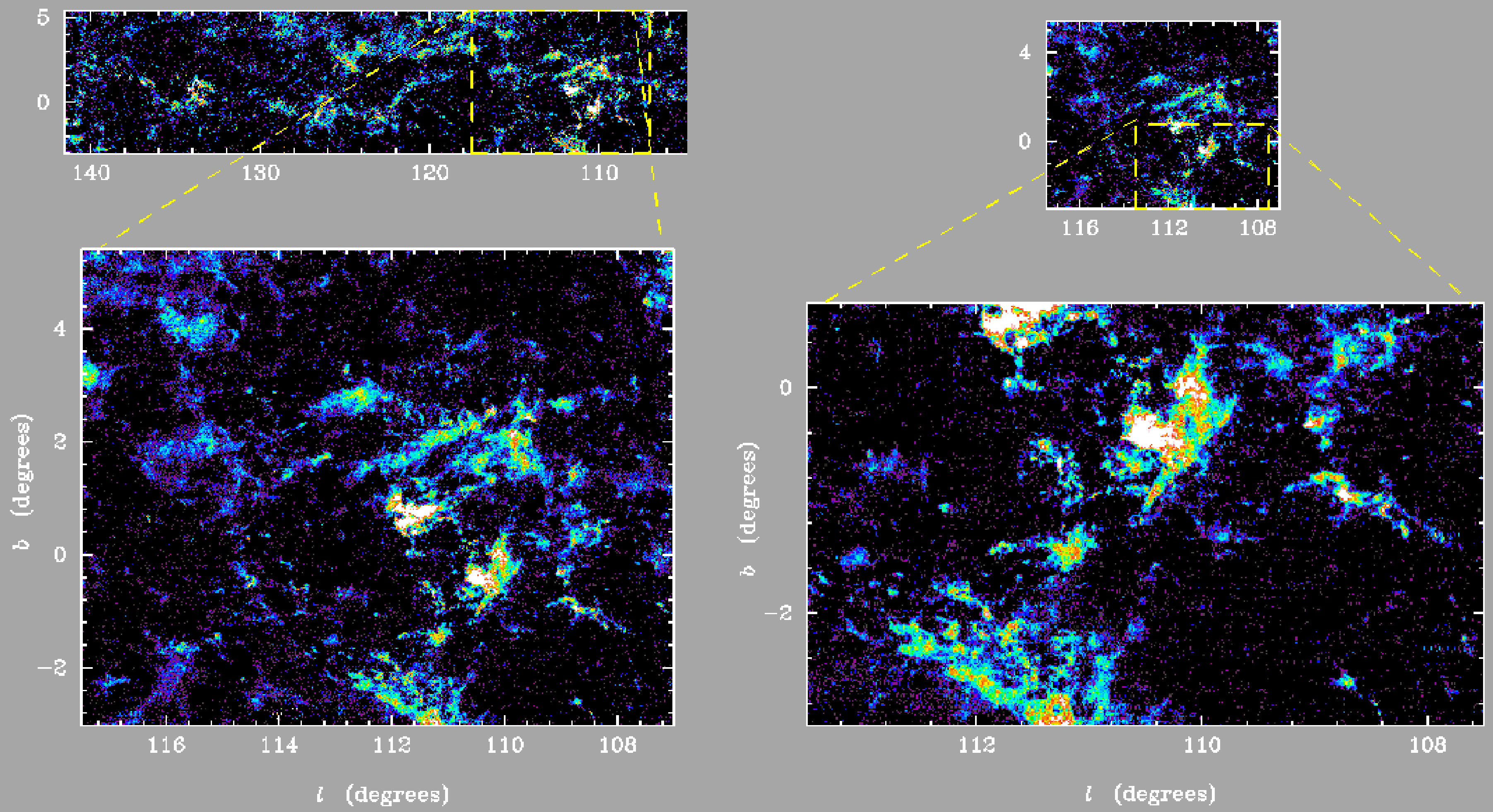


Taurus Molecular Cloud
at 100pc from the Sun



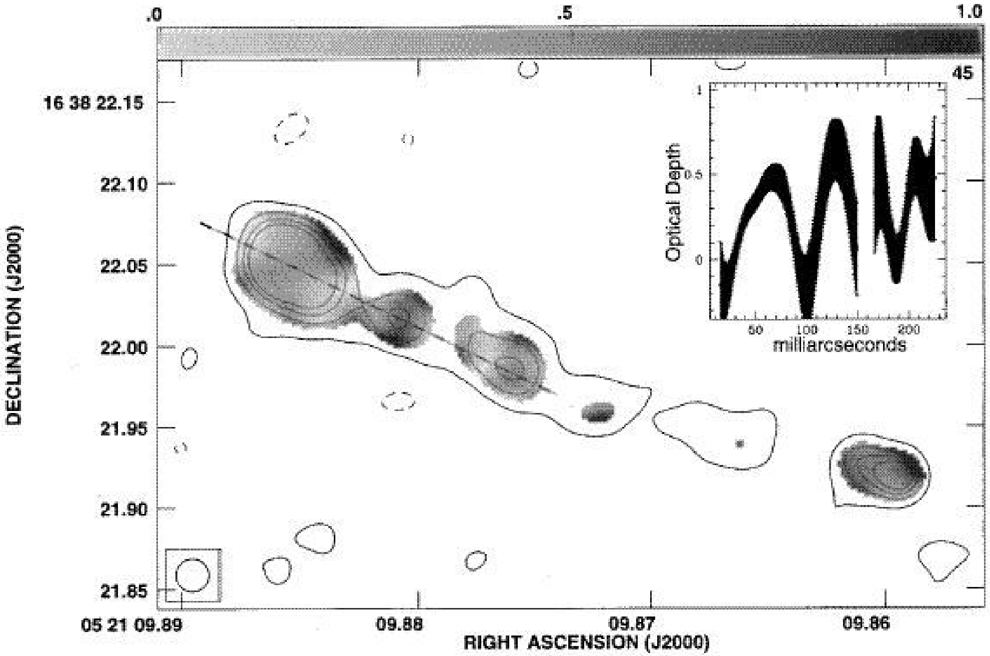
IRAS Emission at 100μ
of heated dust

Self-similar structure
(except for spatial resolution!)

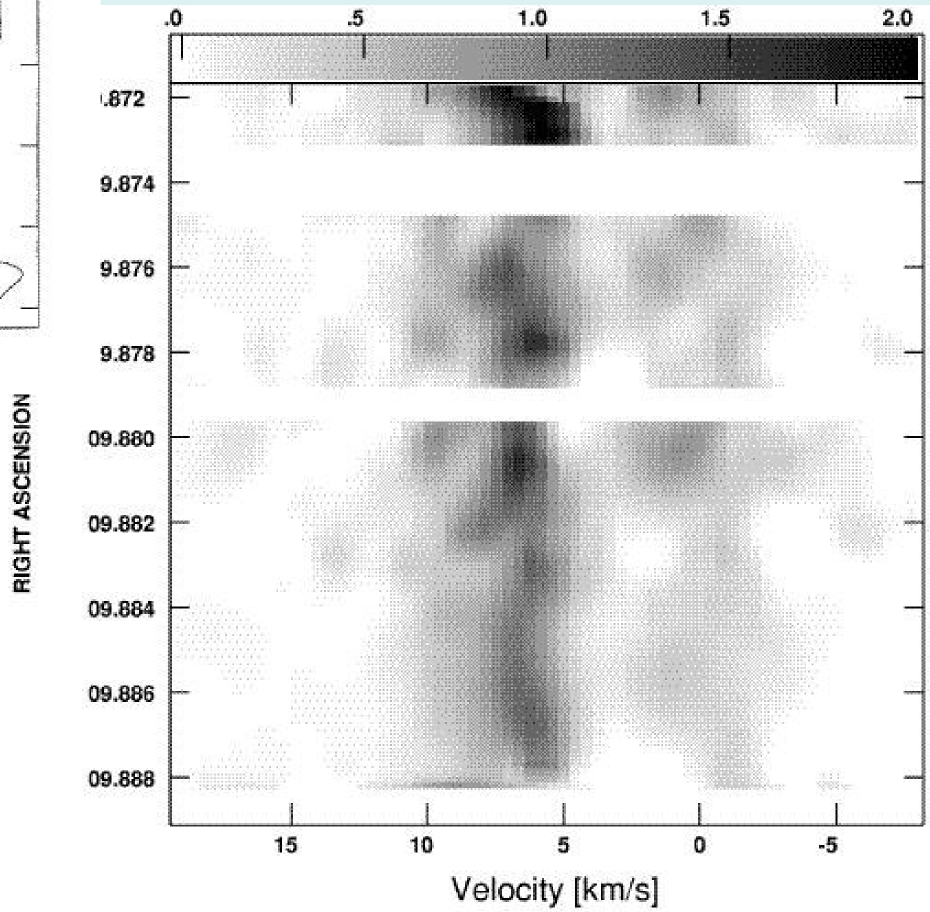


CO mapping with FCRAO of 2nd quadrant (Mark Heyer et al)

Clouds mapped in HI 21cm absorption



3C138



10 AU

VLBA, or VLBI
(Davis et al 96, Faison et al 98)

Fractal Structure – Scaling Laws

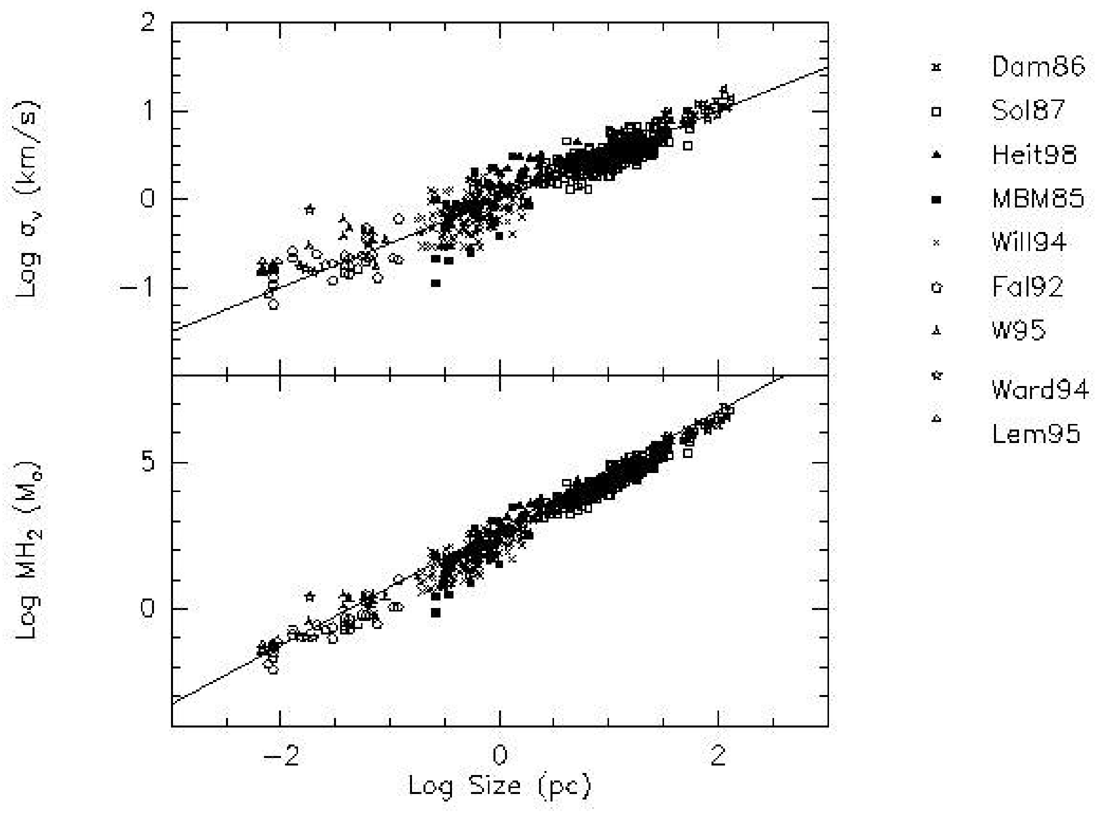
Self-similarity -- relations from Larson (1981)

Relations between size and linewidth $\Delta V \sim R^q$ $0.3 < q < 0.5$

Virialisation at all scales
$\Delta V^2 \sim M/R$
(debate at small scale, where there is no good mass tracer)

Size-Mass **$M(r) \sim r^D$**
$1.6 < D < 2$

Density decreases as $\sim R^{-\alpha}$
$1 < \alpha < 1.4$



Formation by Jeans recursive fragmentation ?

➔a hierarchical fractal

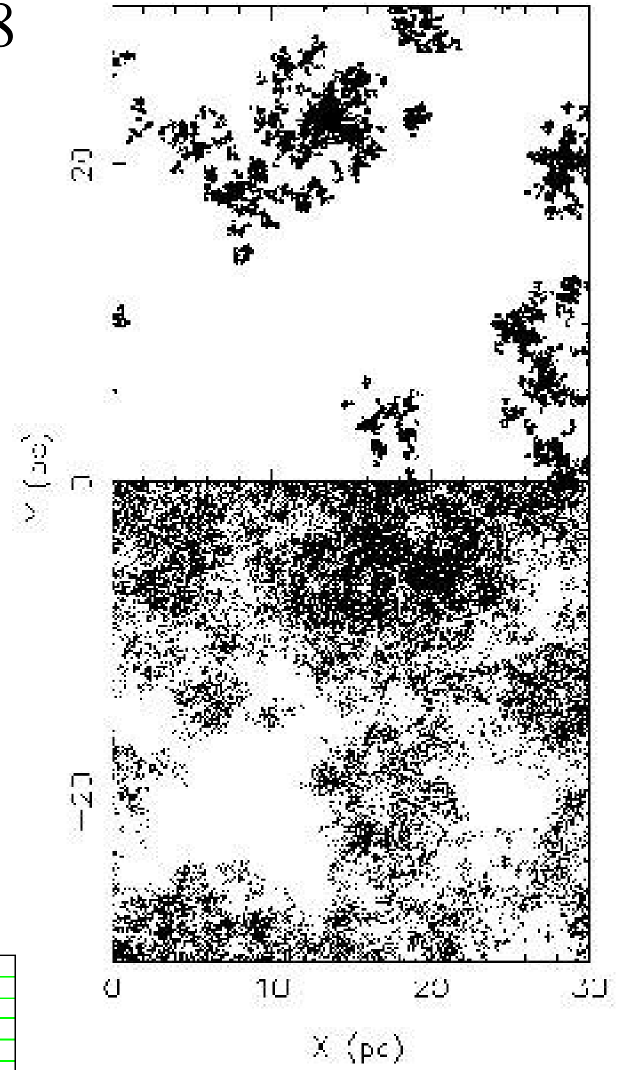
$M_L = N\, M_{L-1}$

$r_L^{\,D} = N r_{L-1}^{\,D}$

$\alpha = r_{L-1}/r_L = N^{-1/D}$

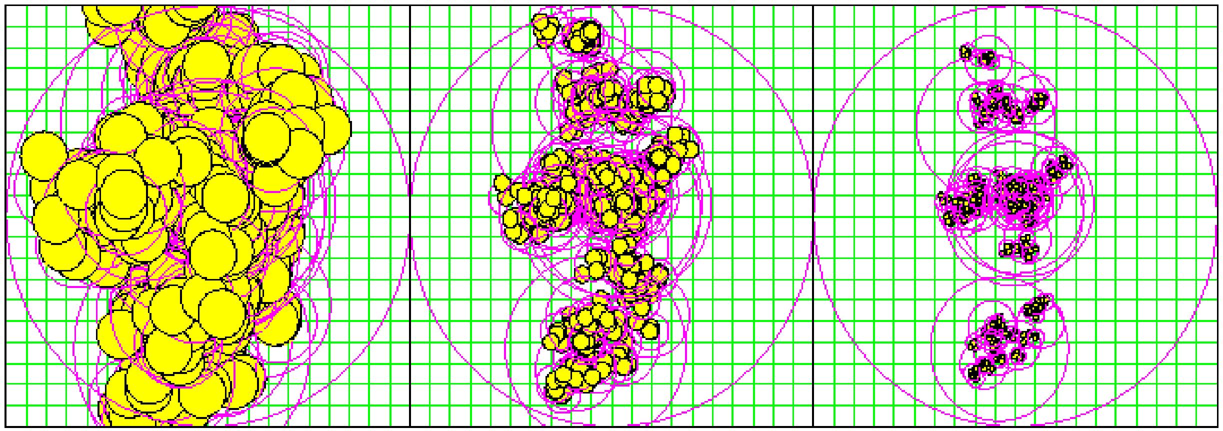
cf Pfenniger & Combes 1994

D=1.8



D=2.2

D=3 D=2 D=1.5

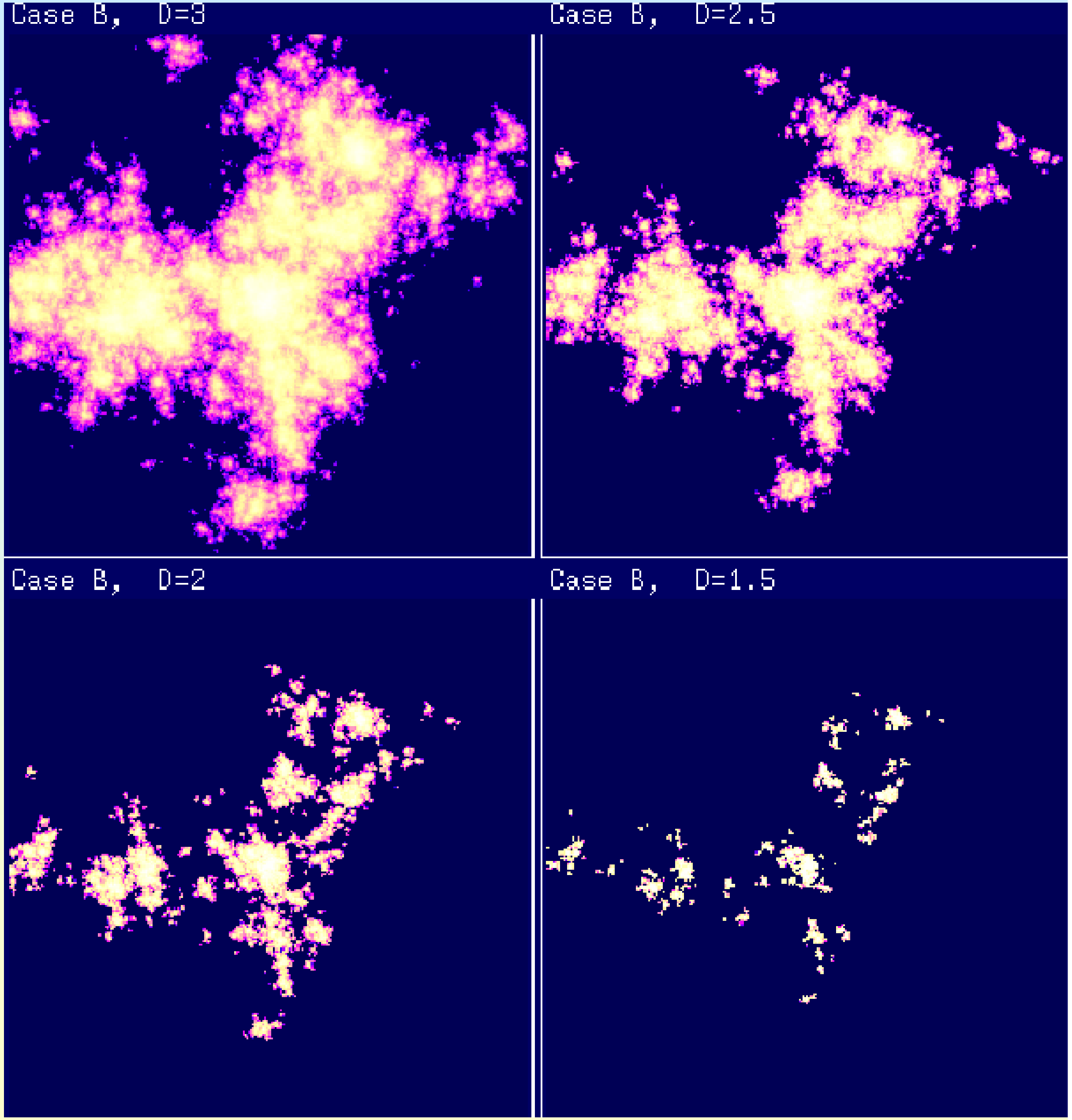


Projected mass
log scale (15 mag)

N=10, L=9

The surface filling factor
depends strongly on D

< 1% for D=1.7



Origin of the heating?

Star formation in the center of the optical disk

Gravitational instabilities in quiet areas
Toomre criterion for stability
self-regulating

Flaring of the plane:

thickness increasing linearly with radius

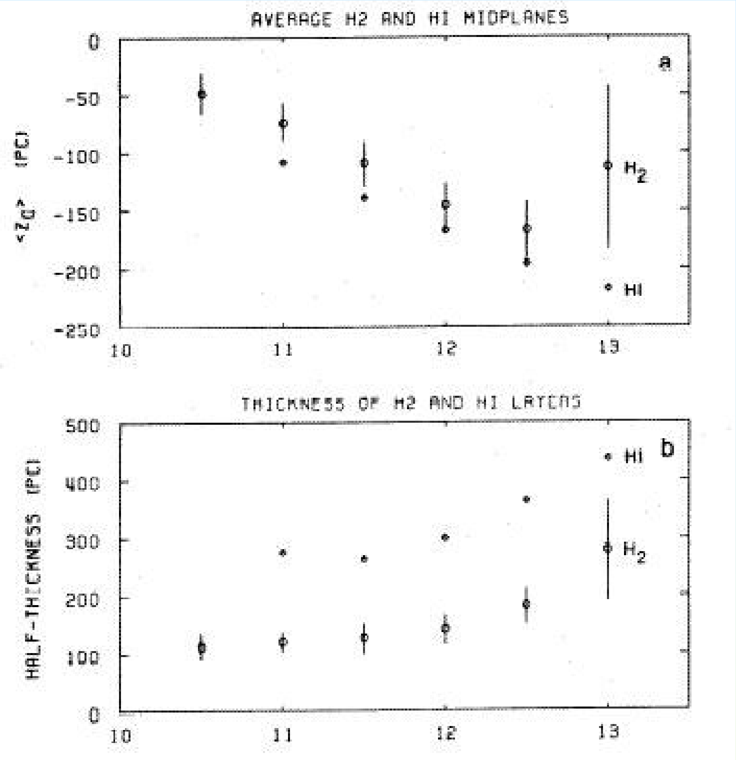
visible in HI, and also in the molecular plane
The total density in the plane is decreasing

Less restoring force, same velocity dispersion
==> increased thickness

Flaring of the HI plane almost linear

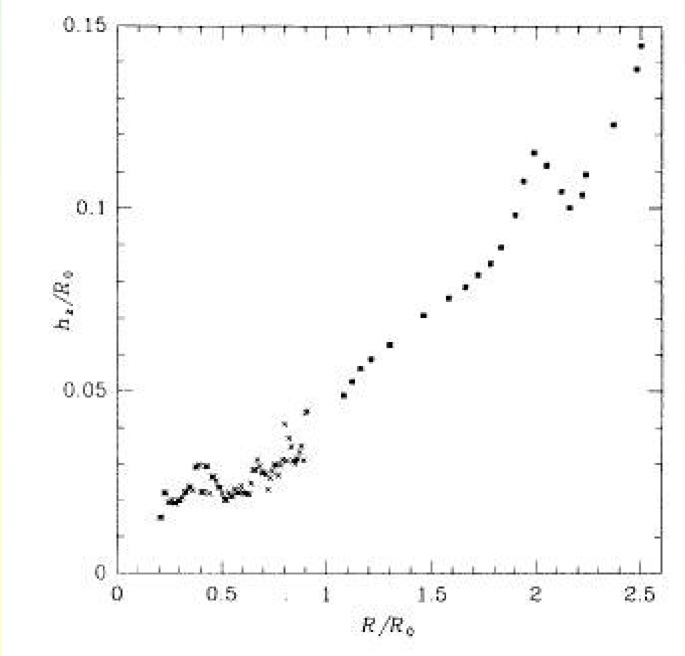
hg = h0 + 0.045 * R

Merrifield (1992)

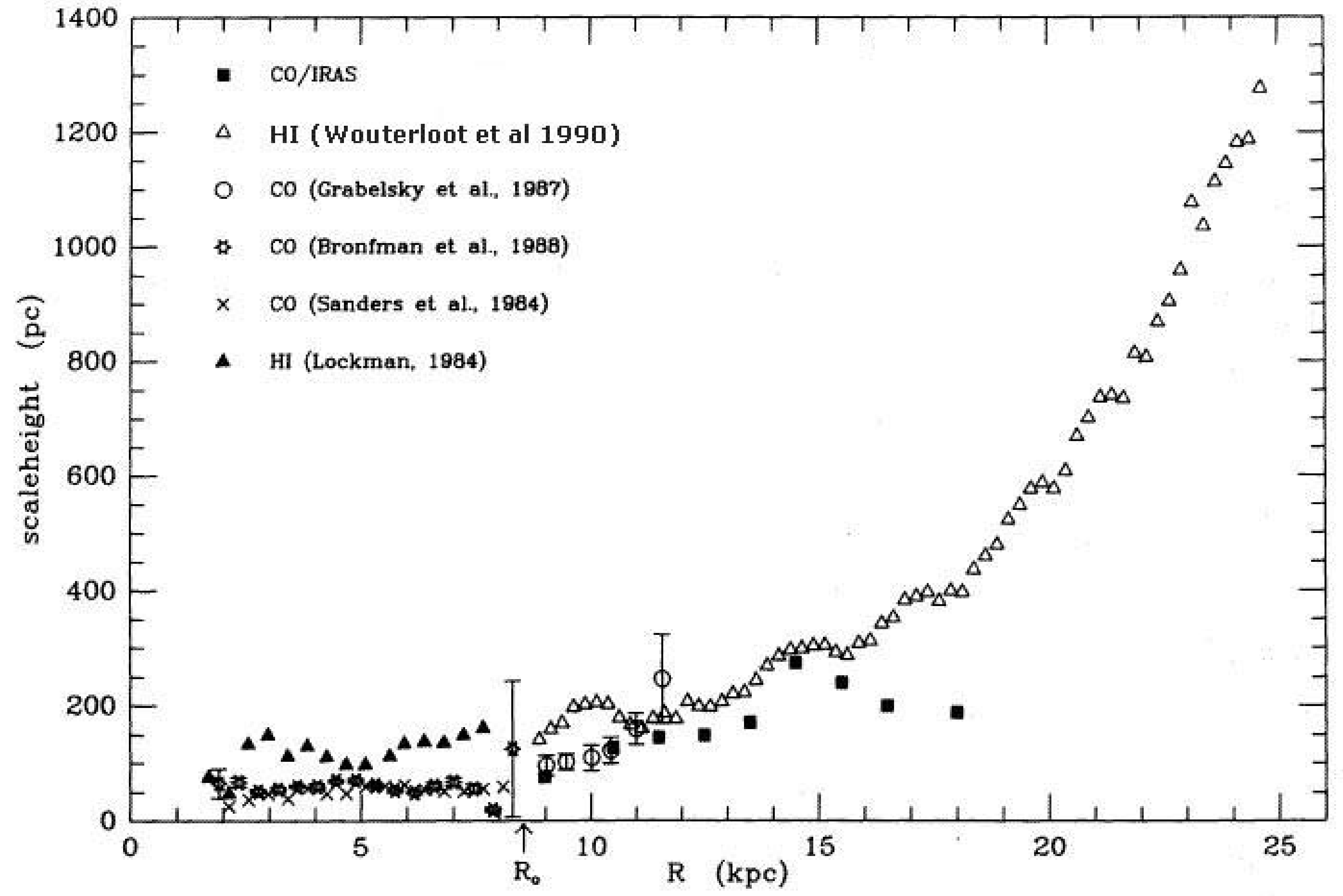


The CO/H_2 follows the flare, and also the warp

Grabelsky et al (1987)



HI and H_2 Flaring



Warping of the plane

Spectacular in HI
Asymmetrical (only one side)

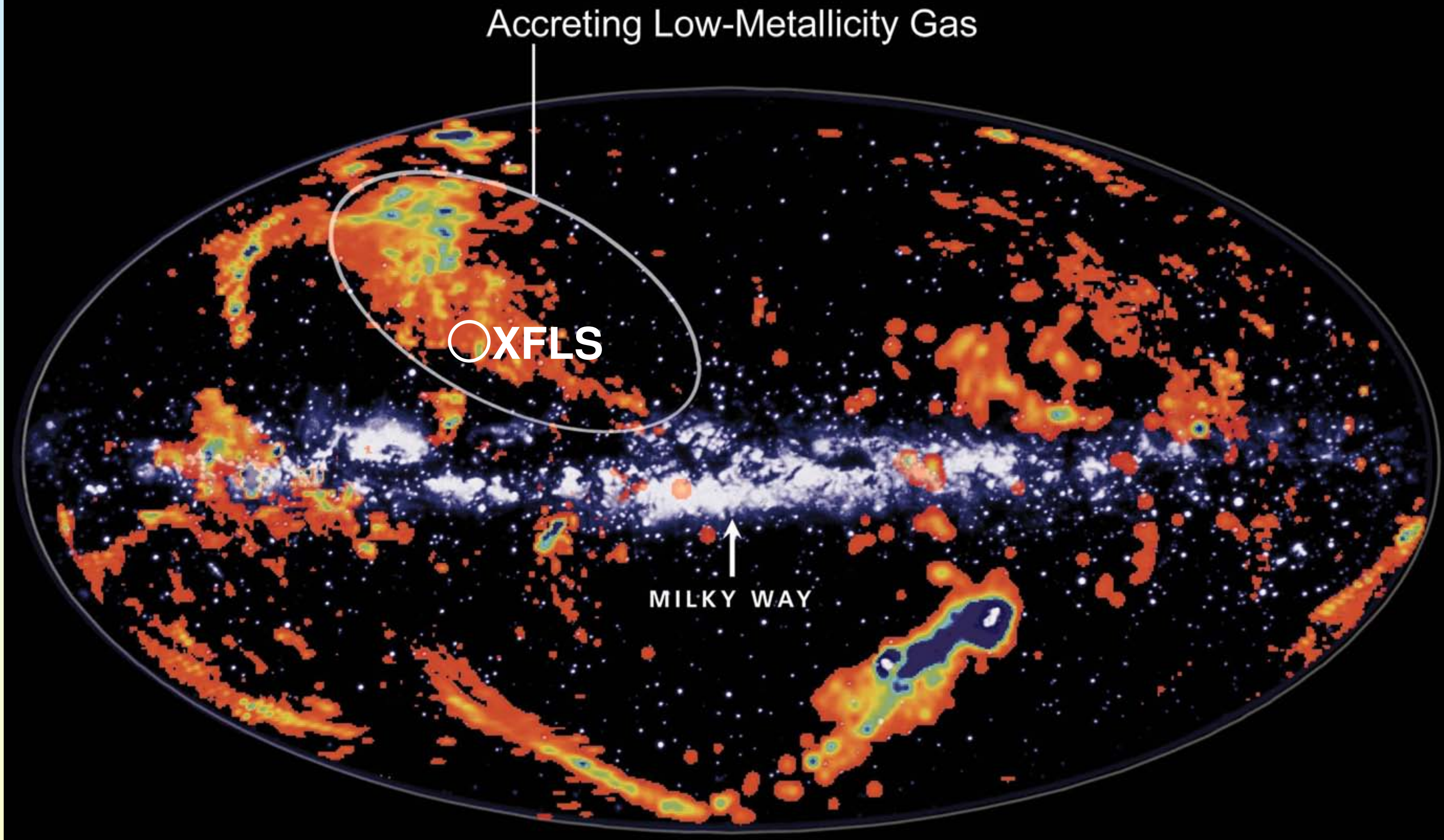
Corrugations (larger amplitude than h_g)

The CO follows the warp

Also observed in external galaxies, in particular M31

CO observed with 2 velocities, at each crossing of the warped plane

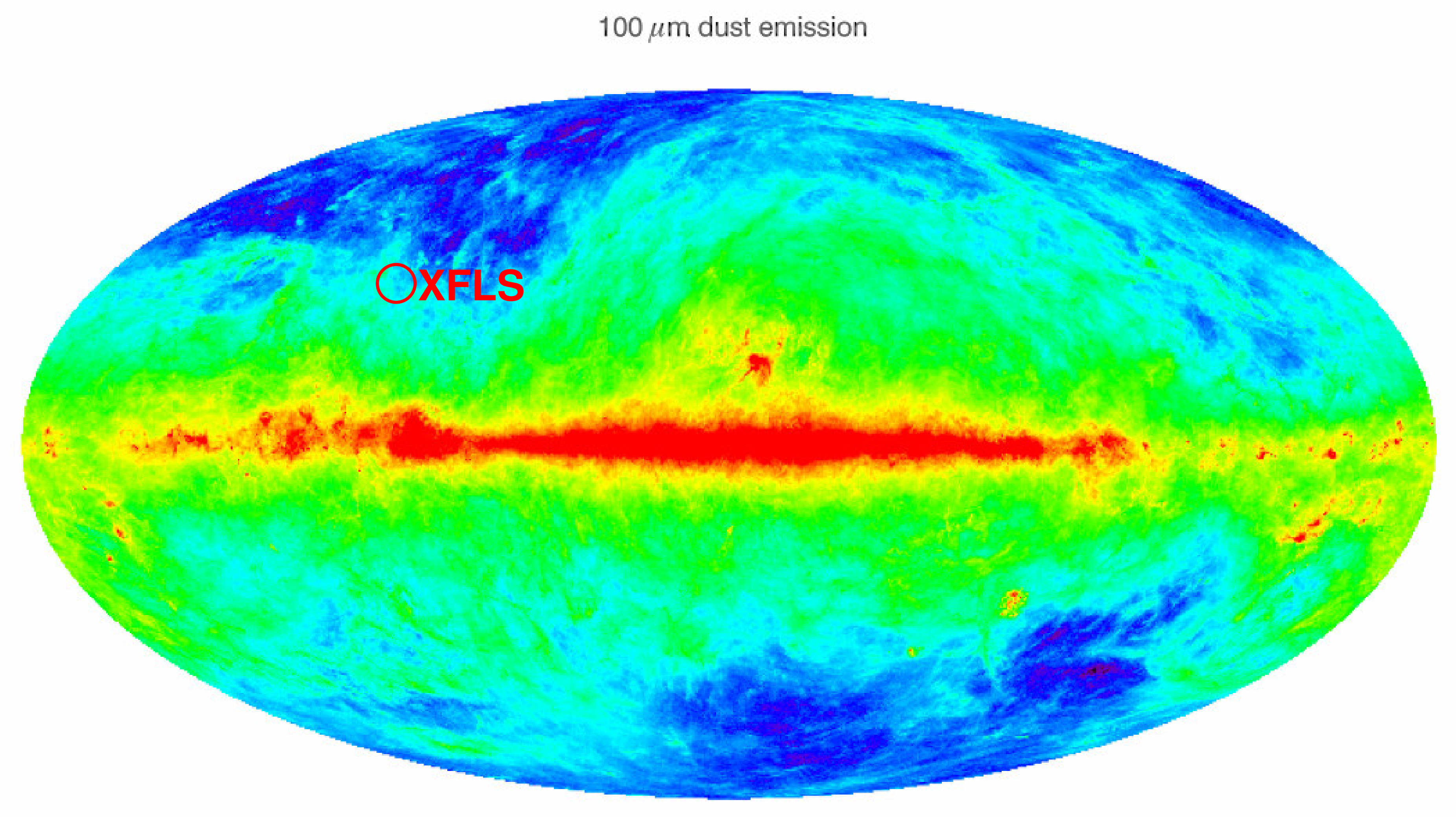
High Velocity Clouds



NASA and B. Wakker (University of Wisconsin-Madison) • STScI-PRC99-46

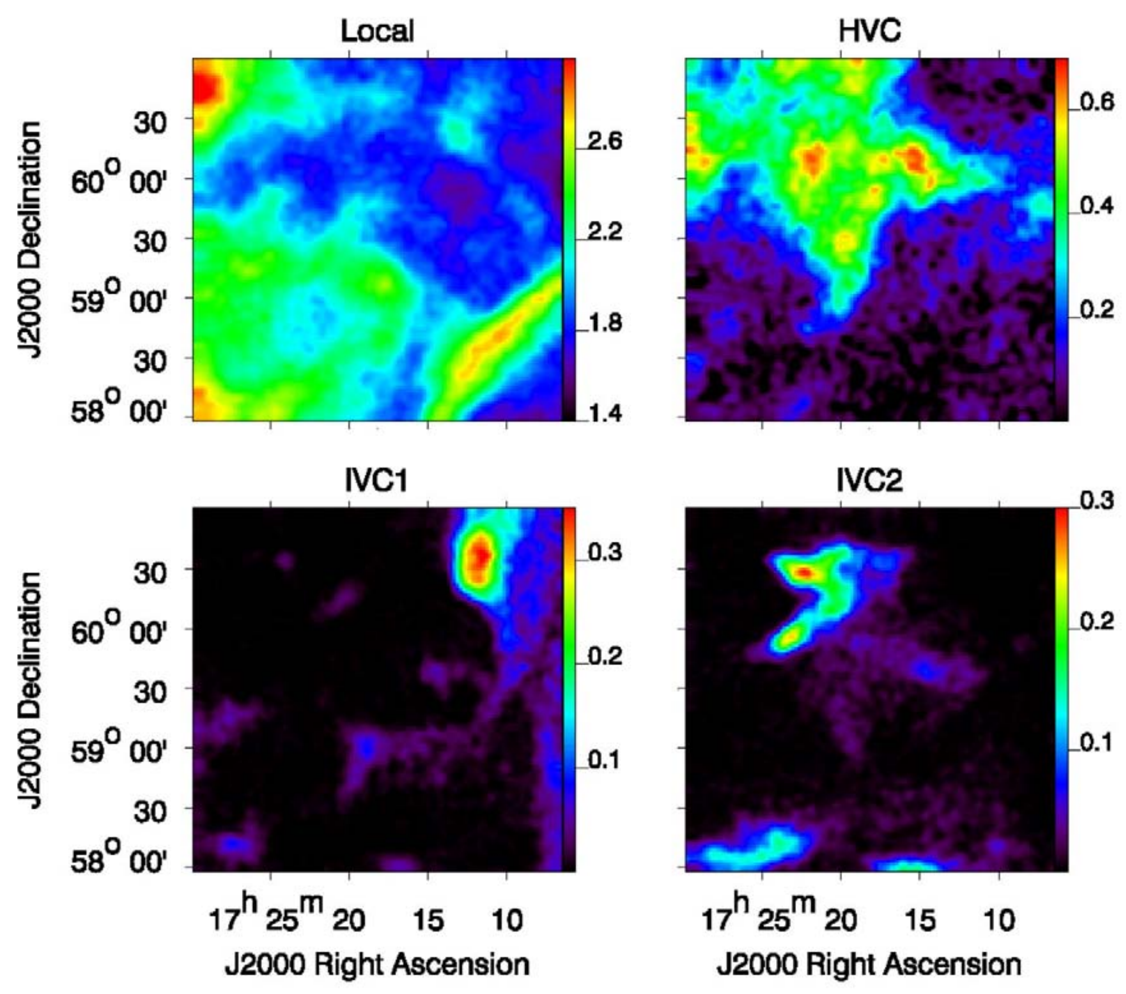
- Observed on 20% of the sky

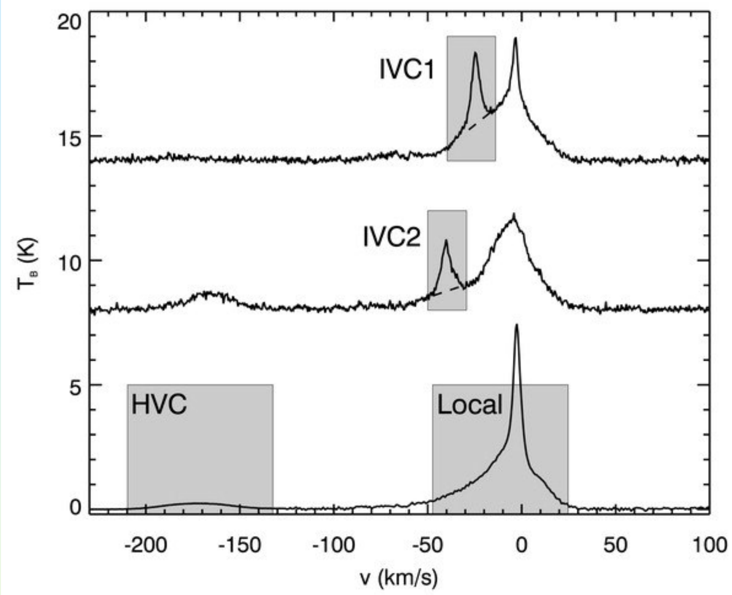
Spitzer Extragalactic First-Look Survey



HI Spectra

HI Maps

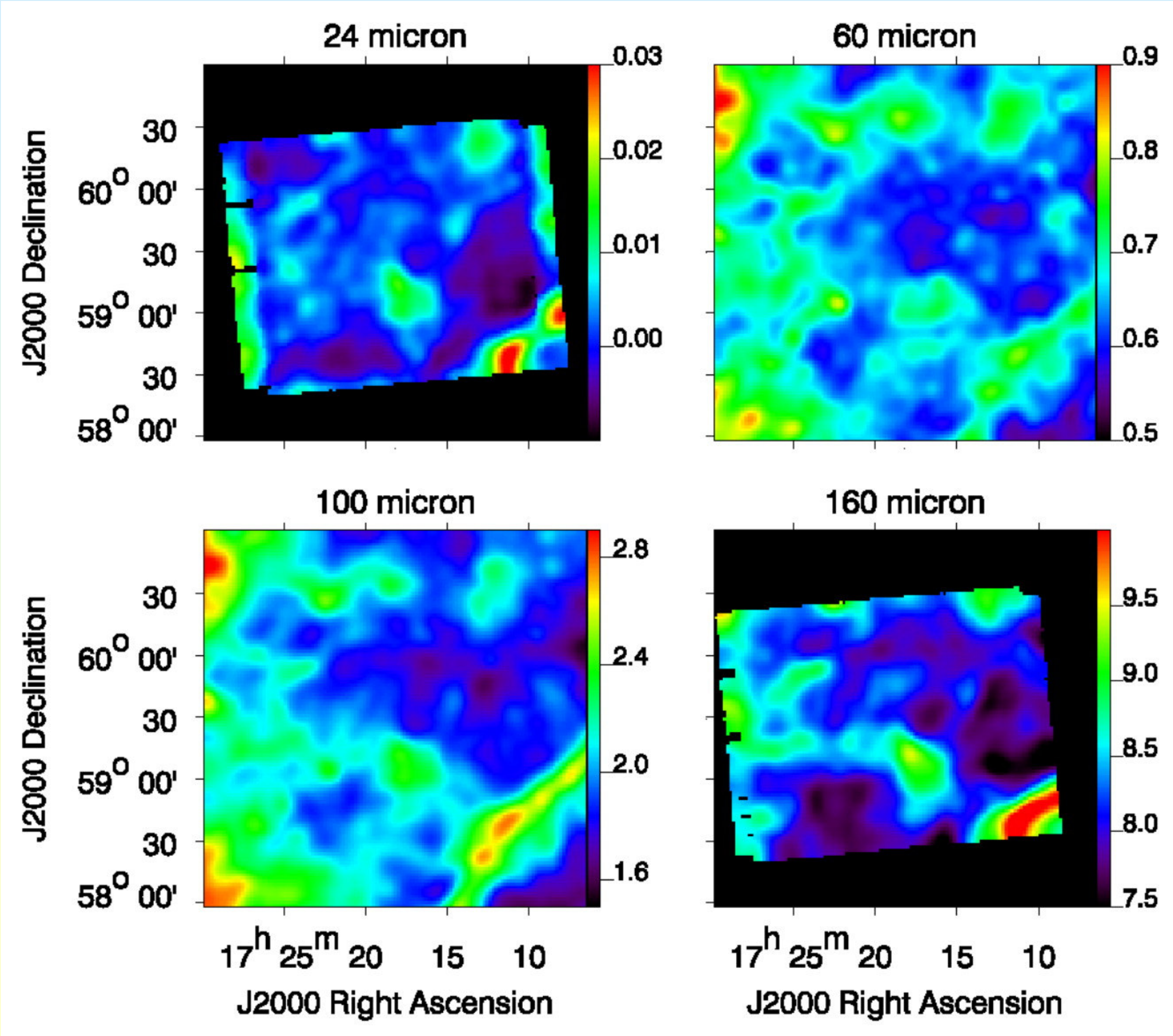




Lockman and Condon 2005

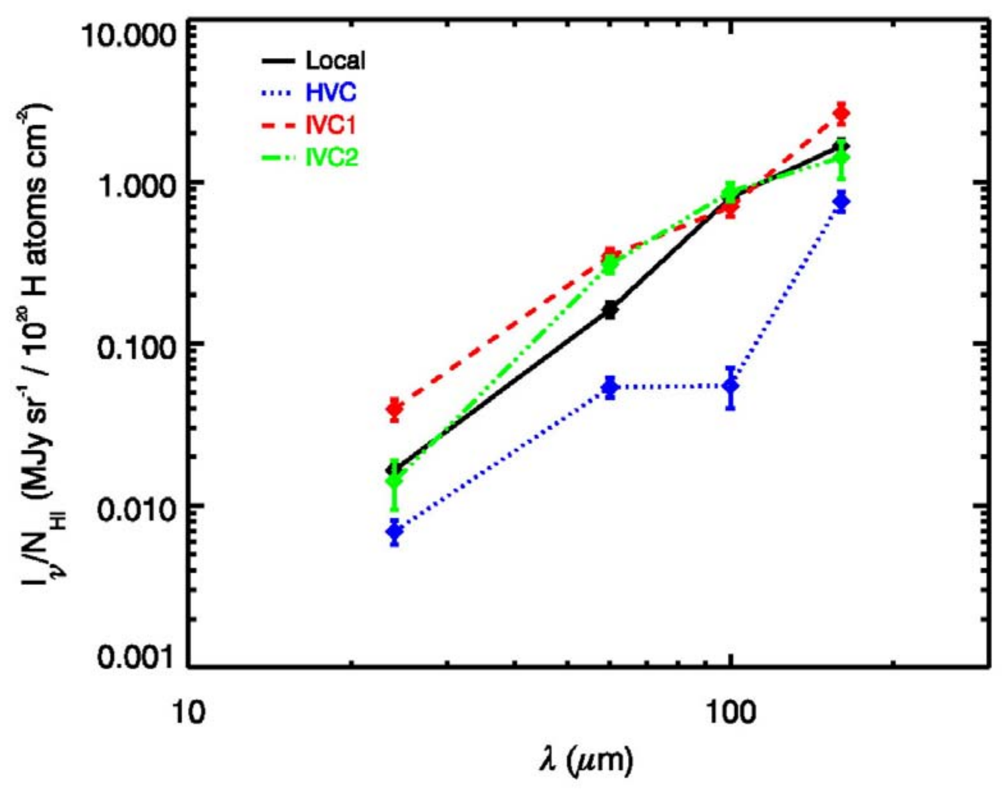
GBT Observations

Spitzer and IRAS Images



Infrared-HI correlation

$$I_\nu (x,y) = \Sigma_i \alpha_\nu^i N_{HI}^i (x,y) + C_\nu (x,y)$$



- Multivariate regression to estimate the infrared emissivity of each HI component.

→ First detection of dust emission in the HVC

  – HVC Emissivity at **100 μm** ~ **10 times smaller** than local gas, but **only a factor 2 smaller** at **160 μm**

⇒ **Colder dust**

Miville-Deschênes et al 2005

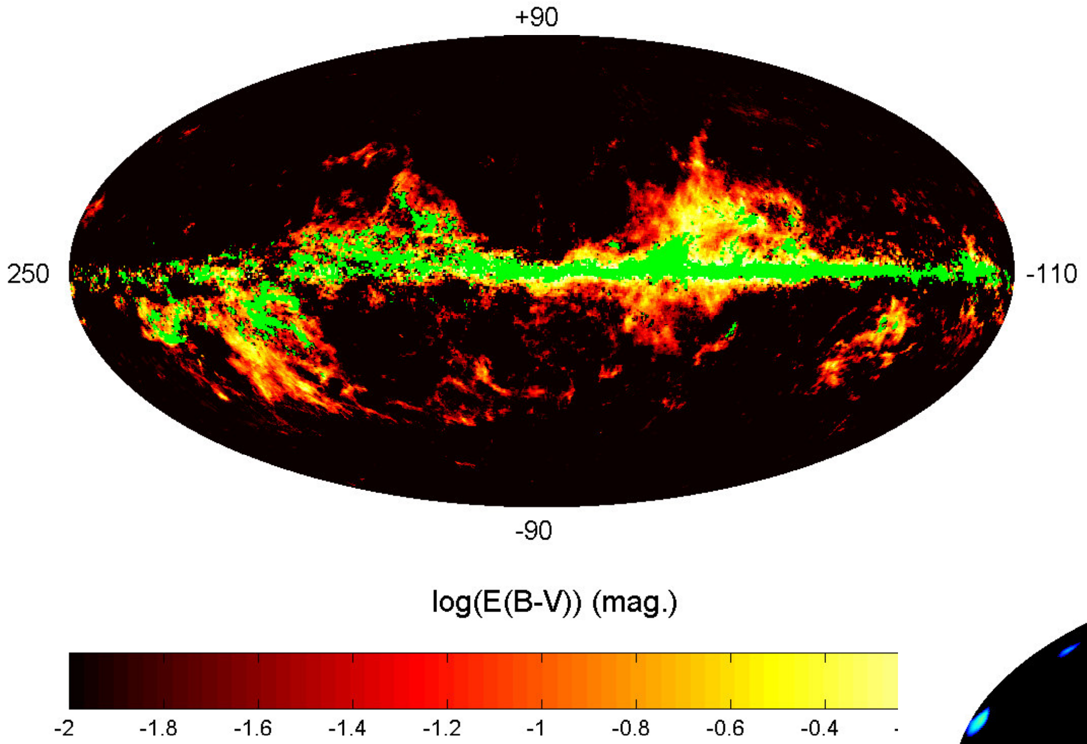
Gamma-ray surveys

In the Milky Way, the detection of gamma-rays of high energy (> 100Mev) is a tracer of all matter

Nucleons (HI, H_2, HII..) interact with cosmic rays to produce pions, that disintegrate in gamma-rays

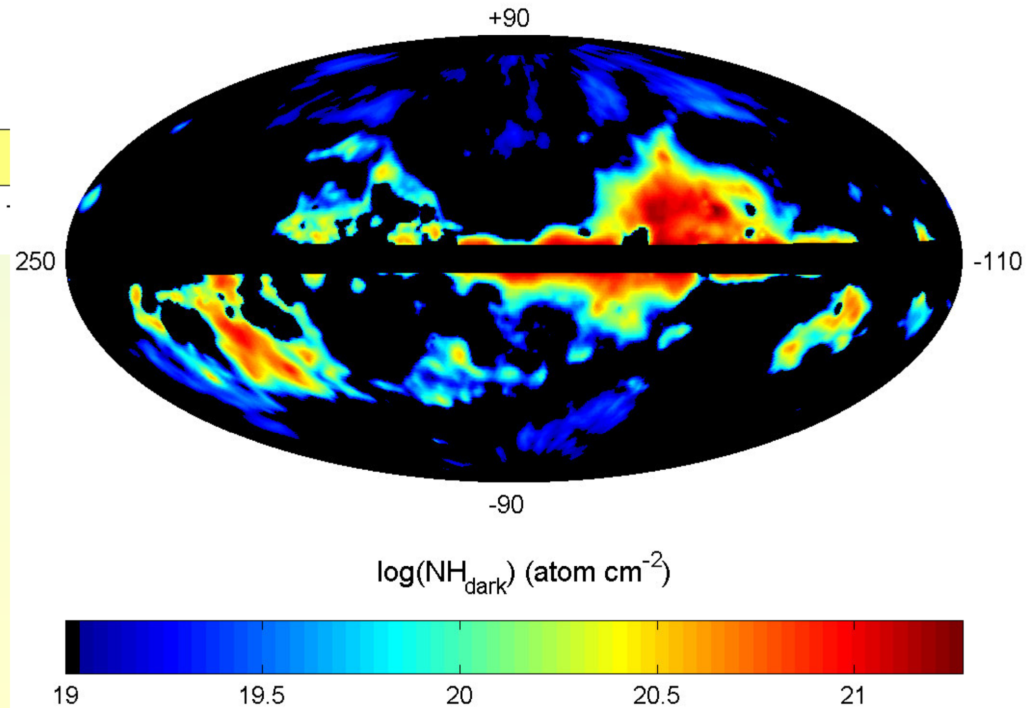
Early surveys showed that the CO/H_2 conversion ratio must not be constant throughout the Galaxy (Wolfendale et al 1977)

γ-rays: Dark gas in the solar neighborhood



Dust detected in B-V
(by extinction)
and in emission at 3mm

γ-Emission associated
to the dark gas



H_2 x a factor 2 (or more)
Grenier et al (2005)

Conclusion: ISM in MW

- **About comparable amounts of H_2 and HI gas in the MW**
- **M(H_2) ~ 2-3 10^9 Mo**

Very different radial repartition

H_2 is centrally concentrated, then in a molecular ring 4-8kpc

HI depleted in the center
and much more radially extended

Repartition in clouds, GMC of 10^6Mo -- H_2 clumpiness

Fractal structure of molecular clouds
same flare and warping