

# A complete CO 2-1 map of M51 with HERA

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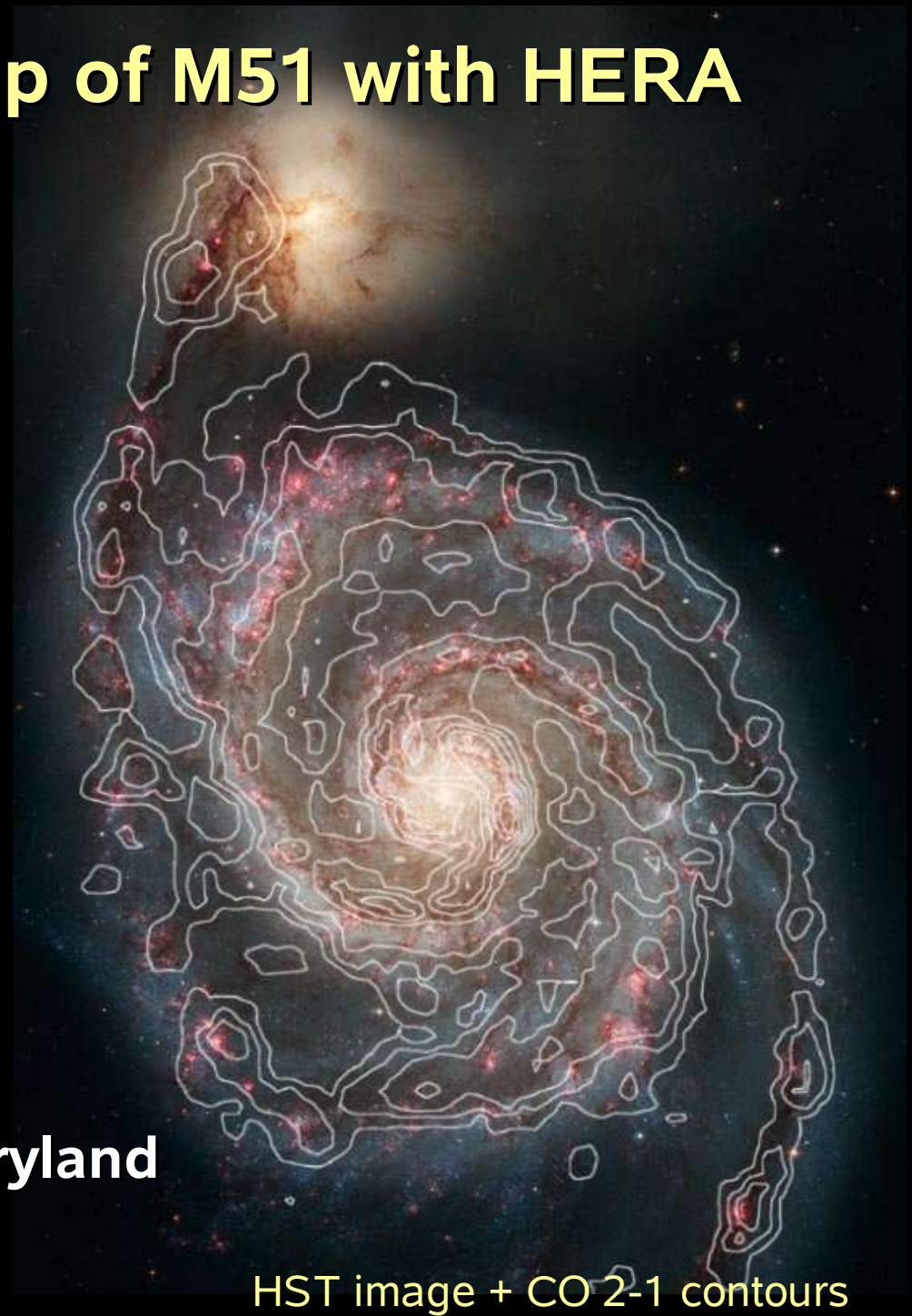
**with**

**Karl Schuster, IRAM**

**Marc Hitschfeld, KOSMA**

**Santiago Garcia-Burillo, OAN**

**Bhaswati Mookerjea, Univ.Maryland**



HST image + CO 2-1 contours

# The CO 2-1 observations

## M51

SA(s)bc  
d=8.4 Mpc  
i=20deg

### IRAM-30m observations:

CO 2-1 @ 11" resol. (450pc)  
18 pixel Heterodyne Receiver Array  
(HERA, Schuster et al. 2004)

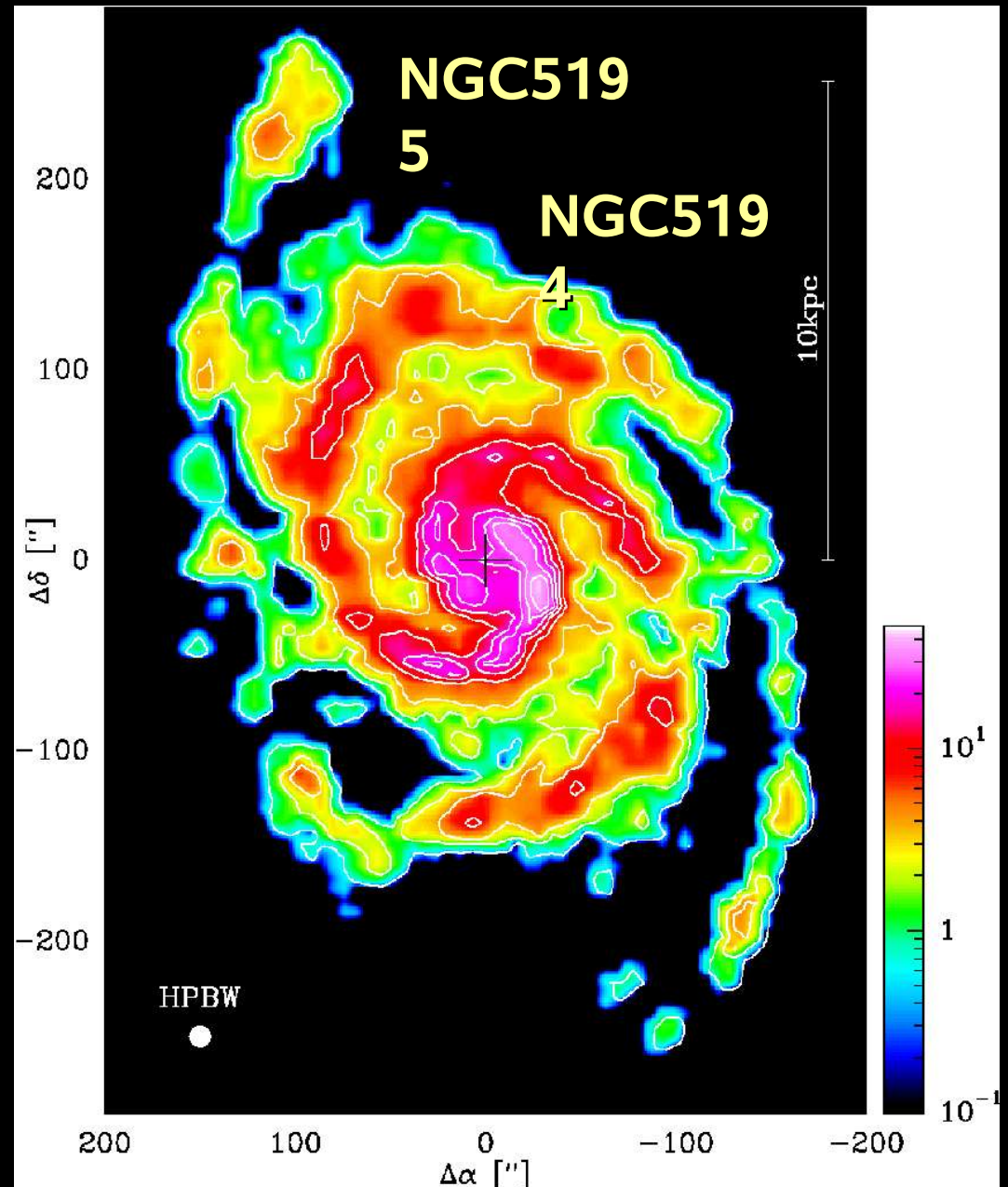
on-the-fly

11' x 11' on a ~6" grid

$B_{\text{eff}} = 52\%$

rms = 18 mK for  $\Delta v = 5 \text{ km s}^{-1}$

$3\sigma$  - limit ( $\Delta v = 5 \text{ km s}^{-1}$ , 11") =  $1.7 \cdot 10^5 M_{\text{sun}}$



# The CO 2-1 observations

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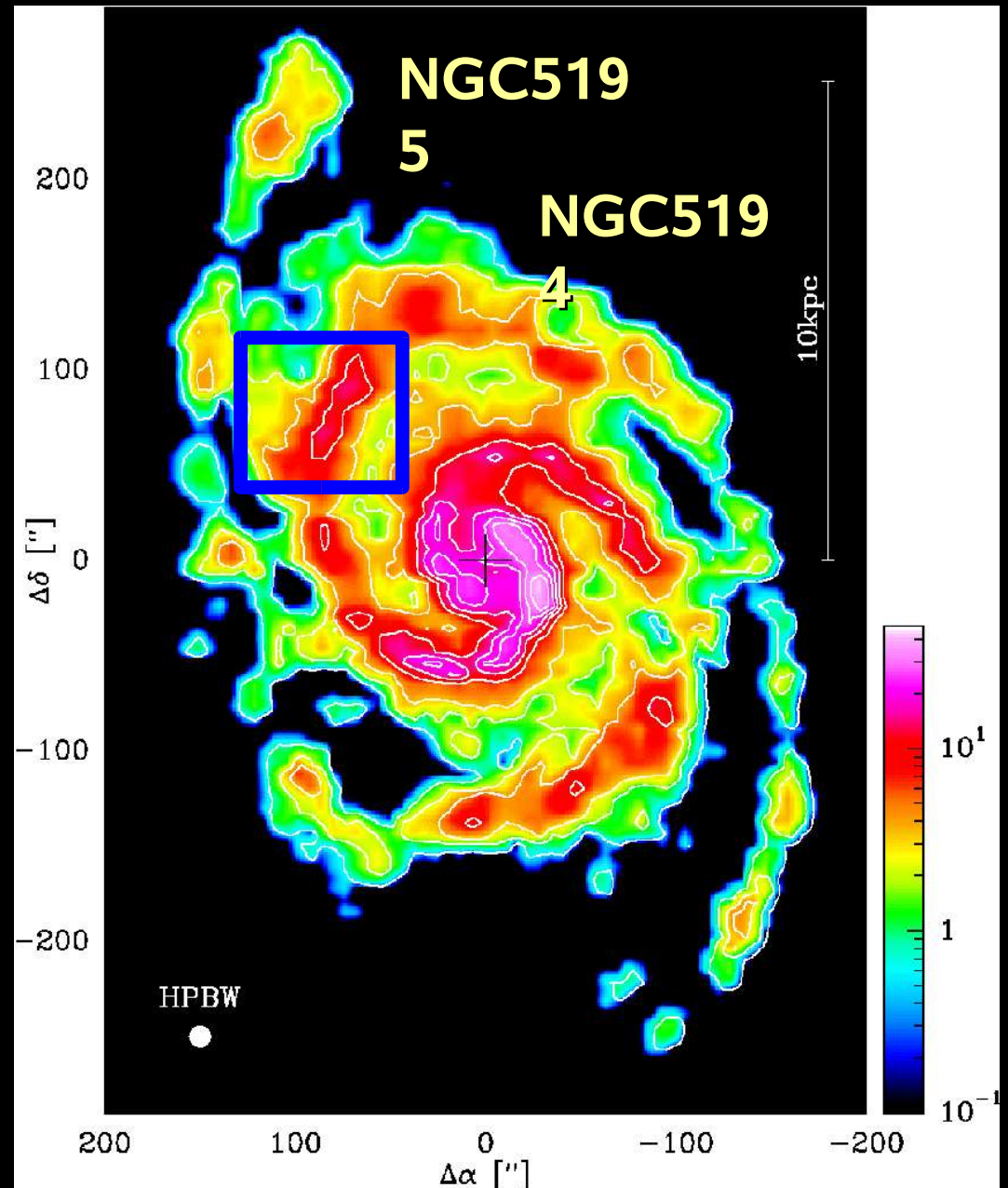
CO 2-1 @ 11" resol. (450pc)  
18ch. array receiver HERA  
+ WILMA autocorrelator

position switched on-the-fly  
11' x 11' on a ~6" grid

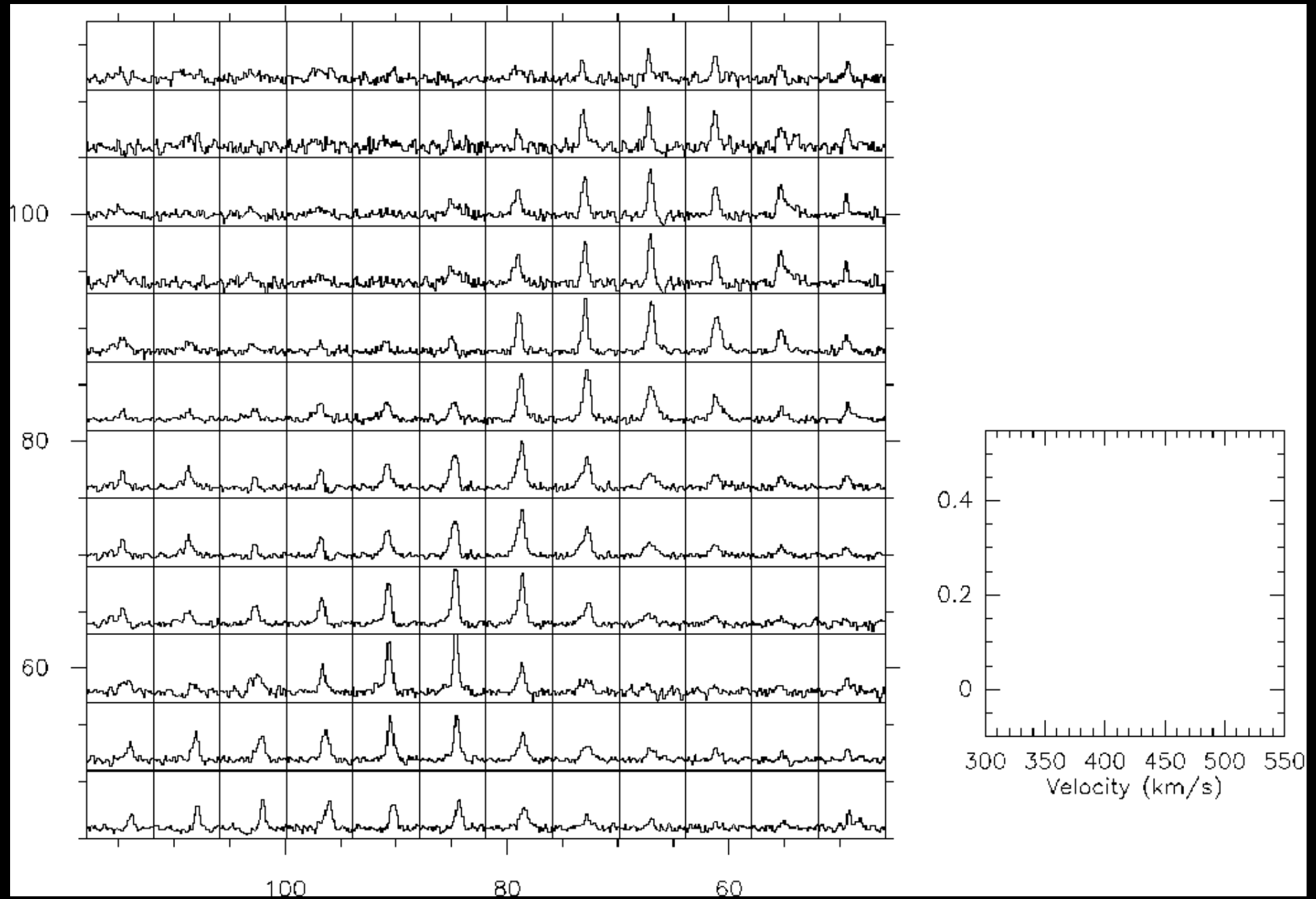
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# The CO 2-1 observations



# Questions to be addressed here:

How are molecular and atomic gas related to the star formation activity ?

Compare to two empirical laws commonly found in spirals:

## 1. The Schmidt Law

star formation rate proportional to a power of the total gas surface density

## 2. The Toomre criterion for stability

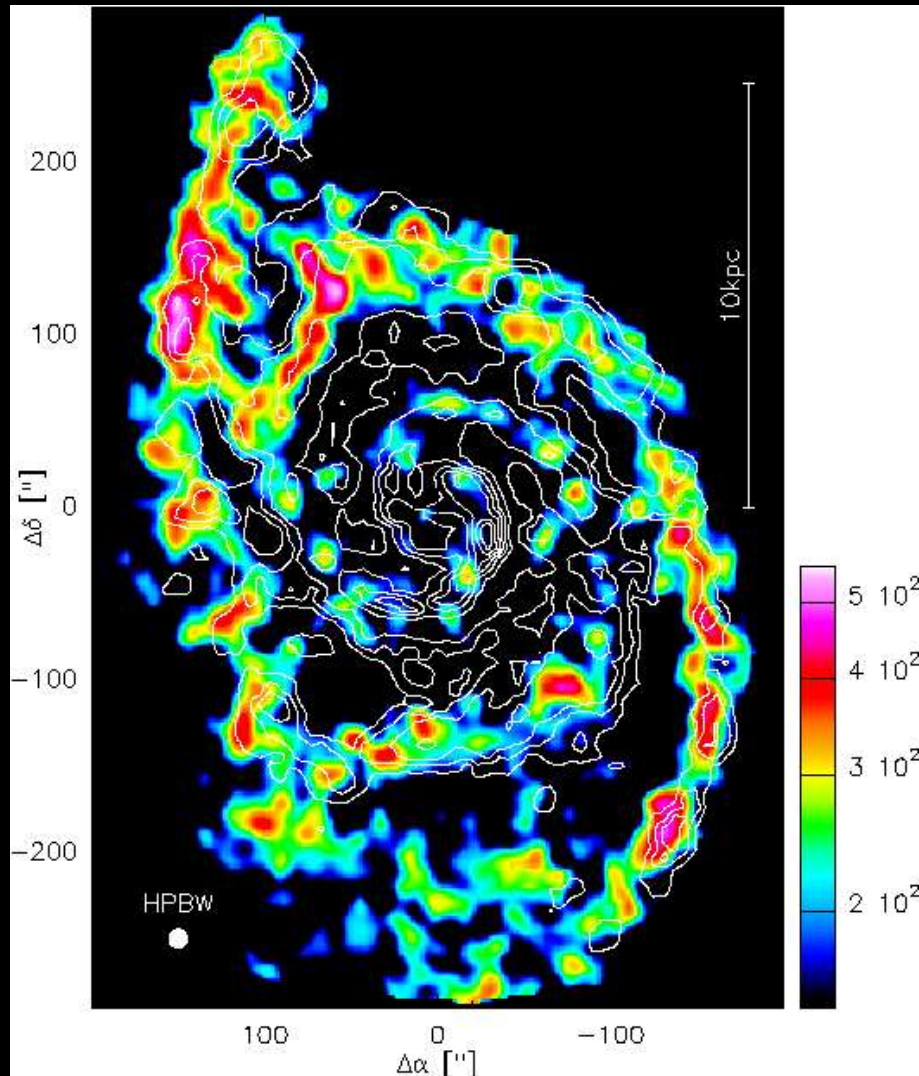
clouds form only above a critical gas density governed by gravitation ?

# Overview:

1. Maps of CO, HI, and 1.4GHz Radio Continuum  
Derivation of  $H_2$ , HI, and total gas surface densities  
Derivation of the star formation rate per unit area
2. Radial distributions of  $H_2$  and HI
3. Schmidt law
4. Toomre criterion for gravitational stability
5. Formation of molecular clouds in the spiral arms
6. Mass distribution of 'clouds'

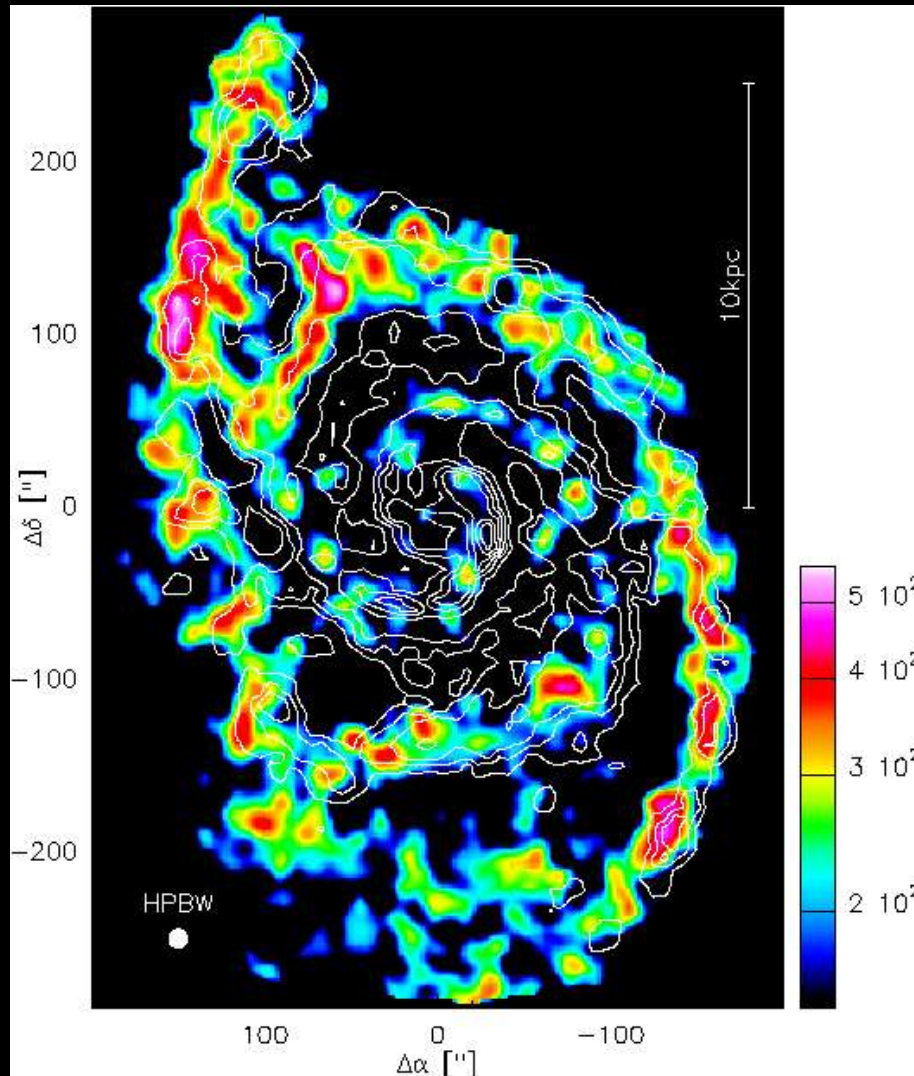
Schuster, Kramer et al. A&A, submitted  
Hitschfeld, Kramer et al. in prep.

# 1. Distribution of H<sub>2</sub>, HI, and Radio Continuum:

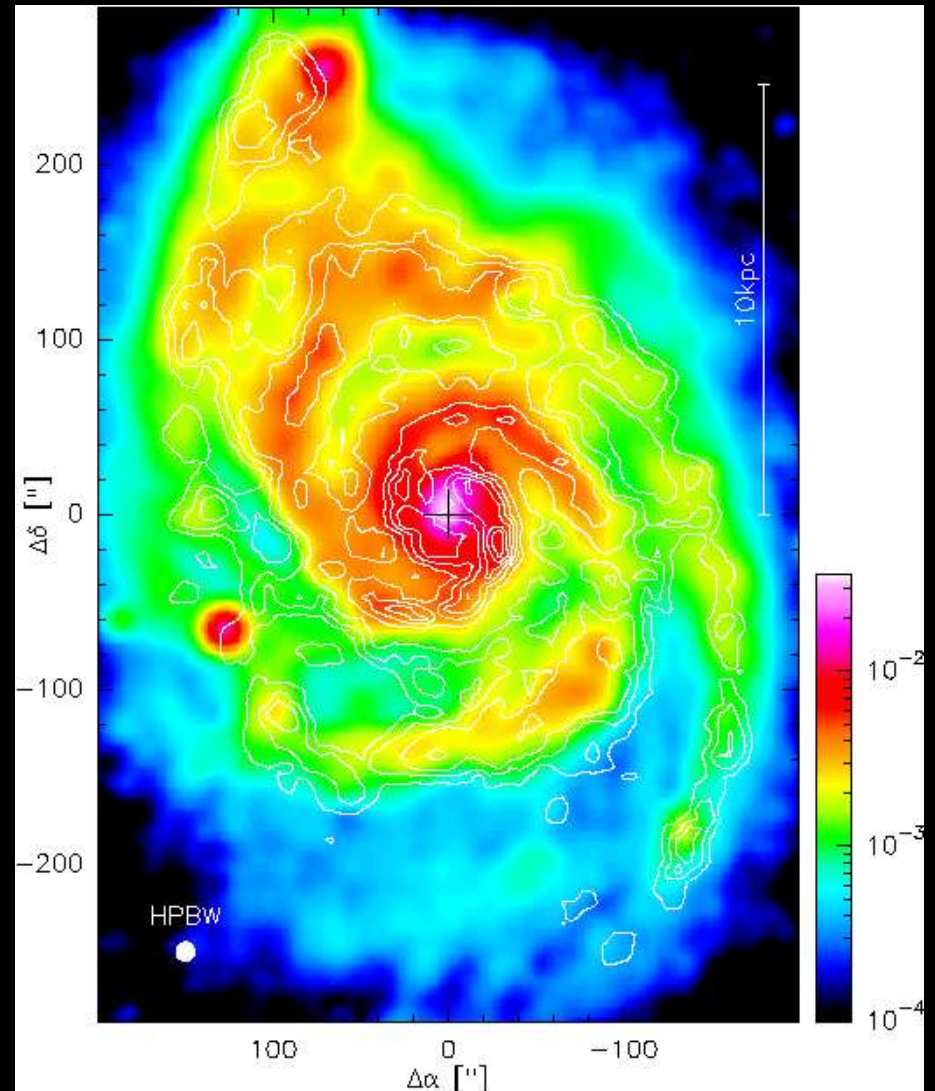


HI intensities (Rots et al. 1990) at 13" resolution + CO 2-1 in contours

# 1. Distribution of H<sub>2</sub>, HI, and Radio Continuum:



HI intensities (Rots et al. 1990) at 13'' resolution + CO 2-1 in contours



Radio Continuum at 1.4GHz at 15'' resolution (Fletcher, Beck et al. in prep.) + CO 2-1 in contours

## 2. Radial averages of surface densities

$$N(H_2) = 0.25 X_{MW} (1/0.8) \int T_{mb}(CO\ 2-1) dv$$

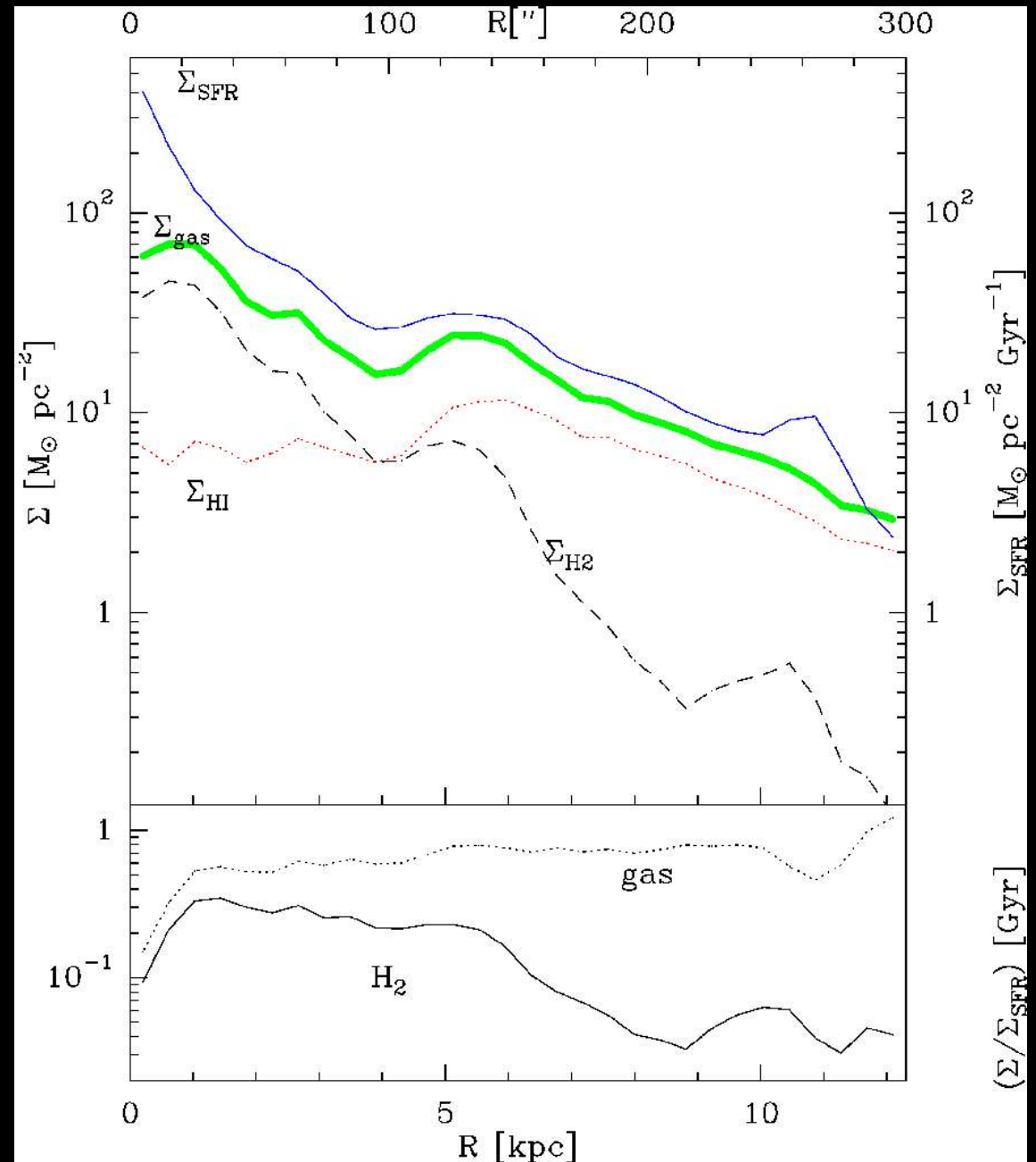
$$\Sigma_{H_2} = 2 m_H N(H_2) \cos i$$

$$\Sigma_{HI} = m_H N(HI) \cos i$$

$$\Sigma_{gas} = 1.36 (\Sigma_{H_2} + \Sigma_{HI})$$

## 2. Radial averages of surface densities:

$\Sigma_{\text{H}_2}$  drops steeply while  
 $\Sigma_{\text{HI}}$  stays rather flat



## 2. Ratio of atomic to molecular gas $\text{HI}/\text{H}_2$

M51:

0.1 at  $\sim 1$  kpc  
to 20 at  $\sim 12$  kpc

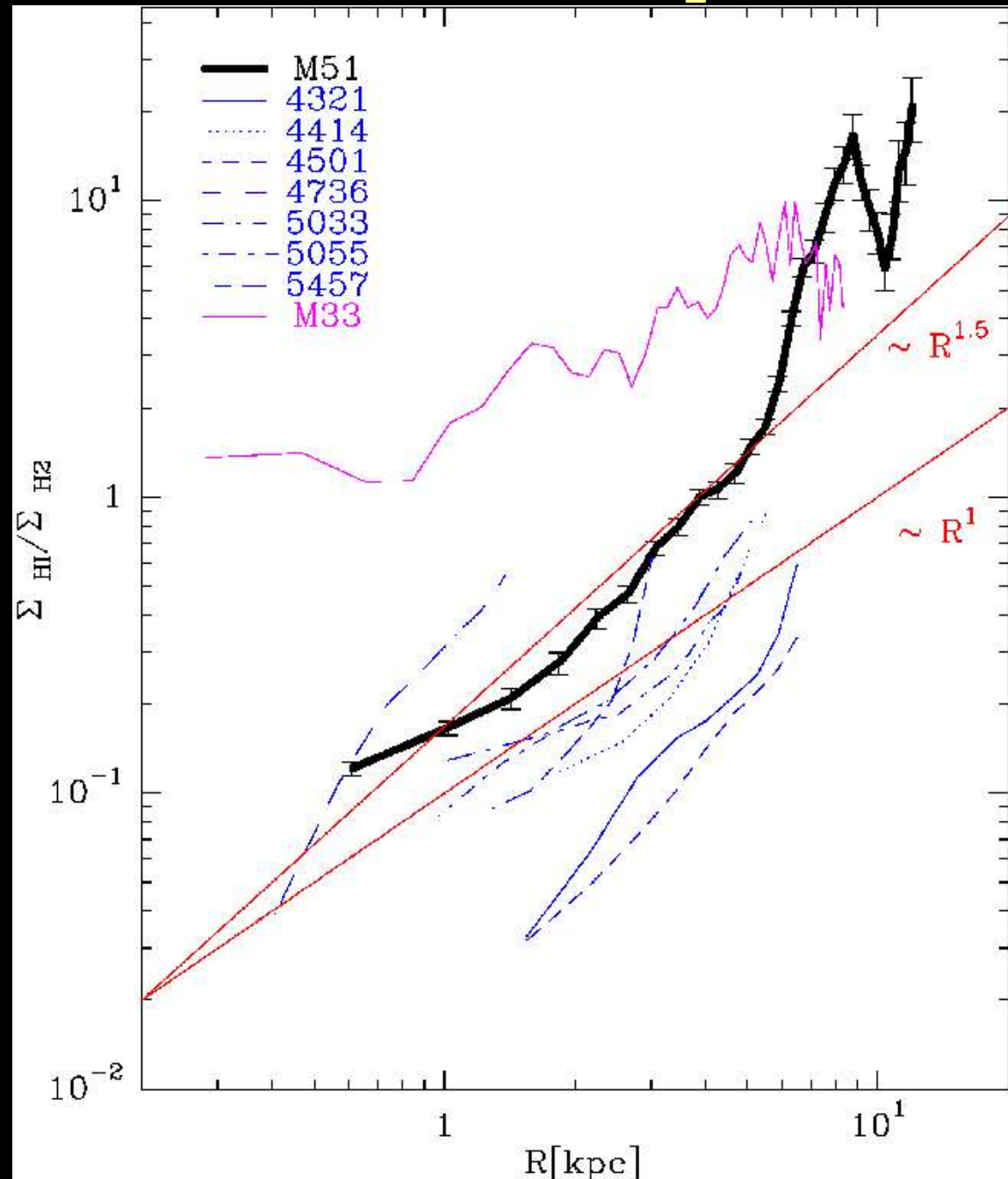
1 at  $\sim 4$  kpc

Other luminous, gas-rich  
spirals:

Wong & Blitz (2002)

M33:

Heyer et al. (2004)



## 2. Radial averages of surface densities:

Star formation rate per unit area:

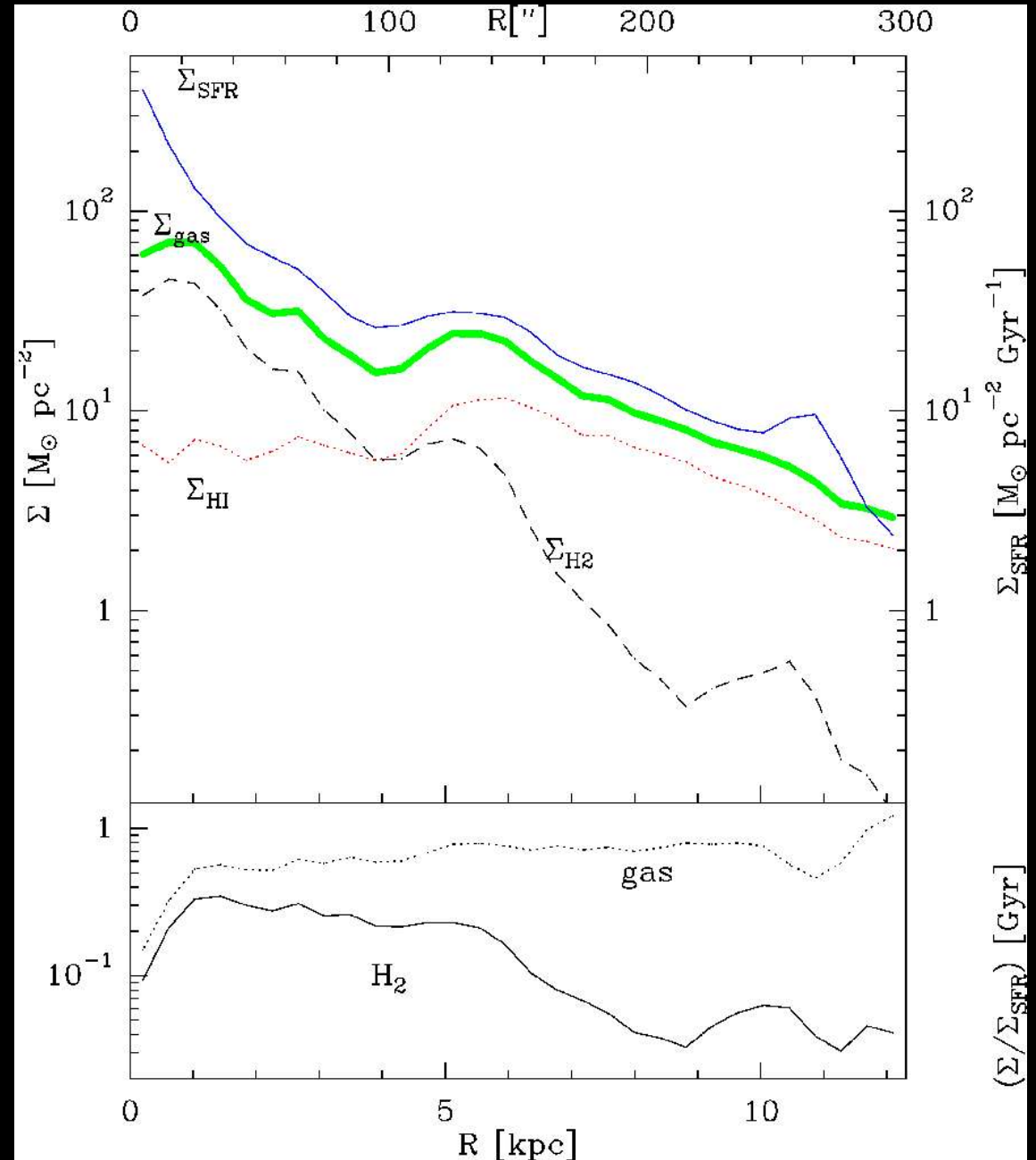
$$\Sigma_{\text{SFR}} = 1.53 \cdot 10^5 S_{1.4}$$

via RC/FIR (Helou et al. 1985;  
Murphy et al. 2005),

and SFR/FIR (Thronson & Telesco  
1986; Yun et al. 2001)

$\Sigma_{\text{SFR}}$  drops from  $100 \text{ Mpc}^{-2} \text{Gyr}^{-1}$   
in the center to 3 at 12 kpc  
distance.

$\Sigma_{\text{SFR}} / \Sigma_{\text{gas}}$  stay almost constant !



# 3. Schmidt Law

$$\Sigma_{\text{SFR}} = 1.1 \Sigma_{\text{gas}}^{1.4}$$

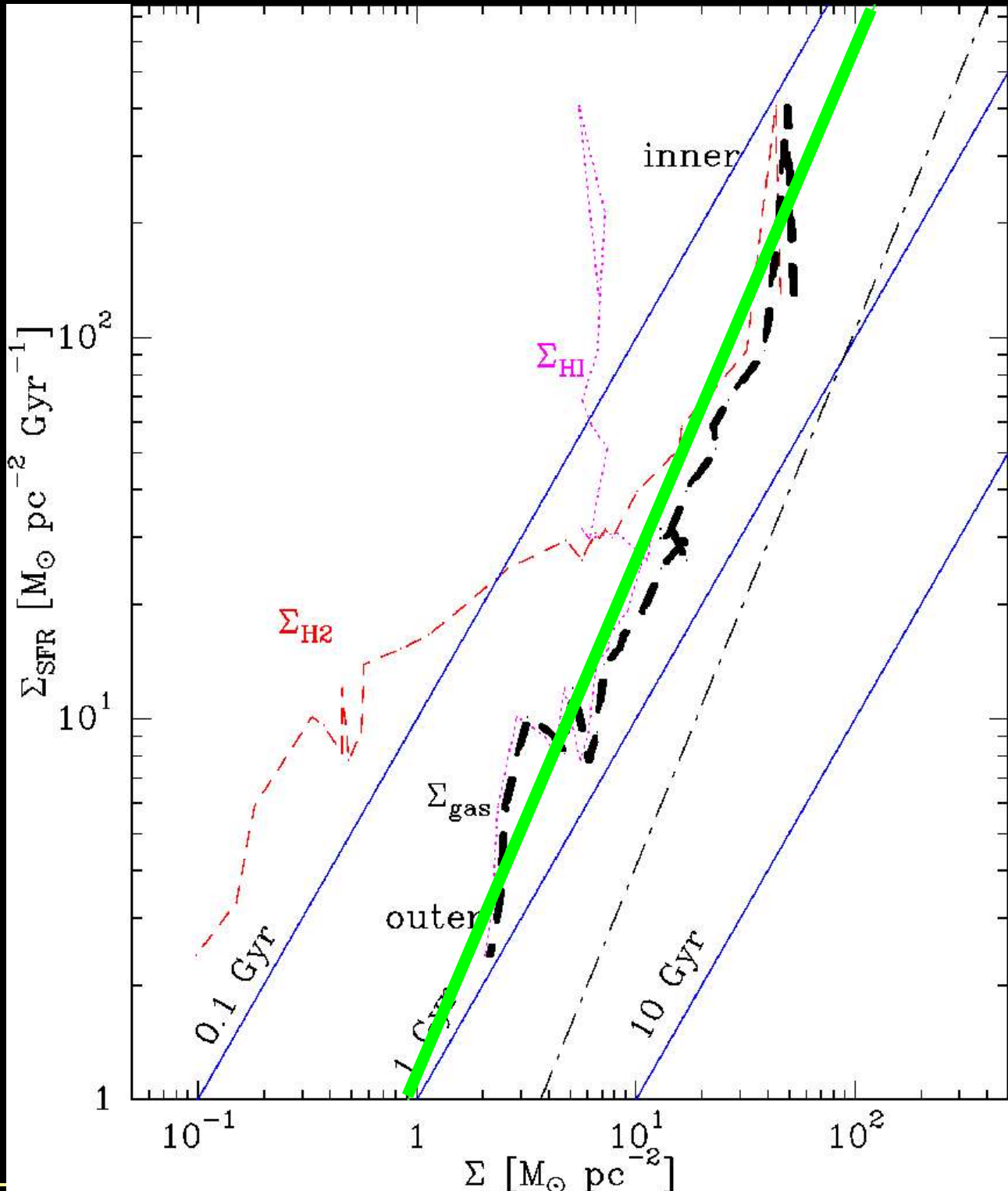
canonical slope found in many spirals (Kennicutt 1998, Wong & Blitz 2002). Note: M33 shows  $n=3.3$  (Heyer et al. 2004)

No linear correlation with  $\Sigma_{\text{H}_2}$  or  $\Sigma_{\text{HI}}$ .

Gas consumption time

$$\tau_{\text{gas}} = \Sigma_{\text{gas}} / \Sigma_{\text{SFR}}$$

varies between 0.1 and 1 Gyr in M51



## 4. Gravitational stability

Axially symmetric disturbances in a differential rotation of a homogeneous, thin gas disk (Toomre 1964):

$$Q_g(R) = \frac{\Sigma_{crit}}{\Sigma_{gas}} = \frac{\kappa \sigma_v}{\pi G \Sigma_{gas}}$$

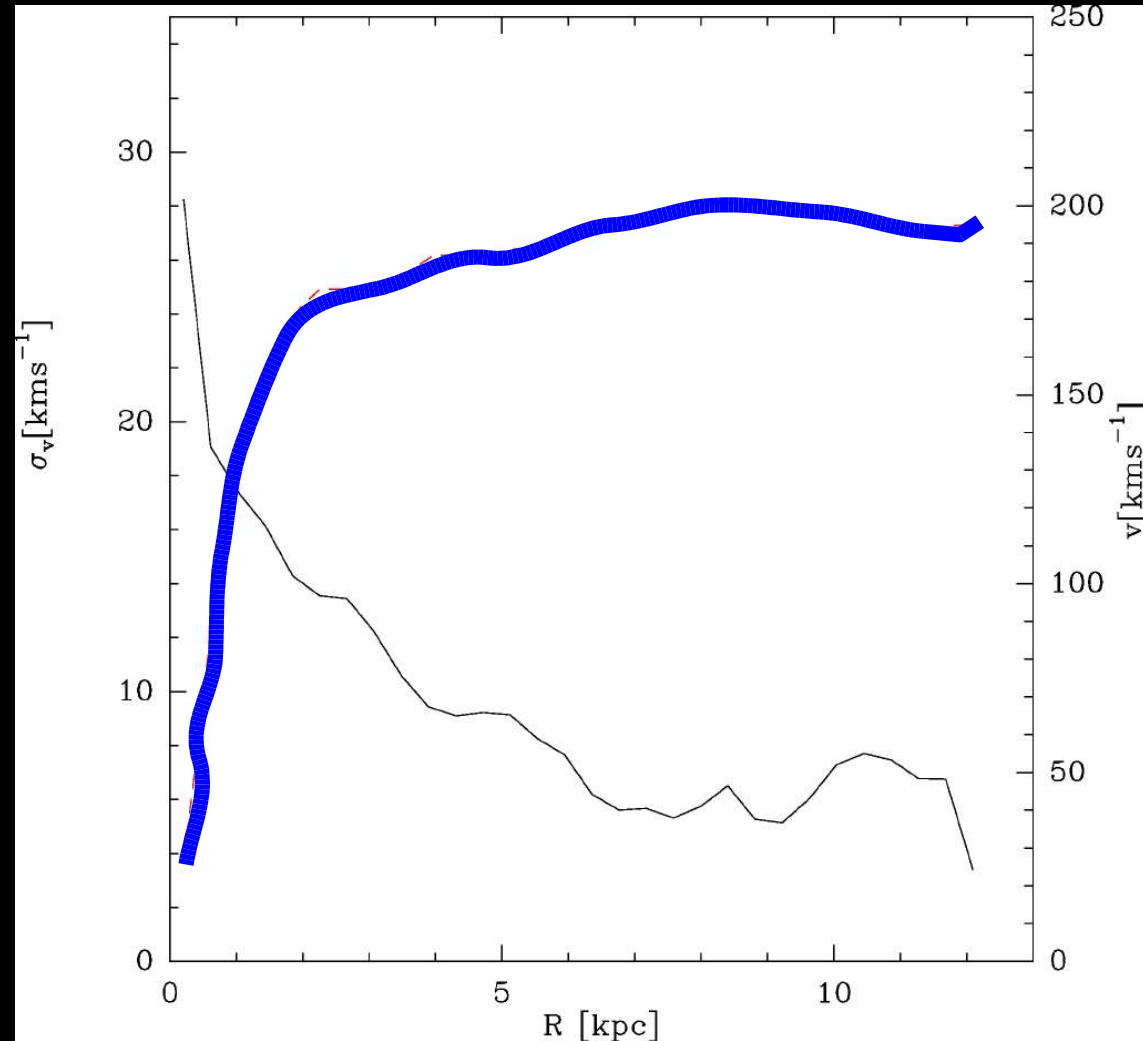
cf. study of Kennicutt (1989) and Martin & Kennicutt (2001)

# 4. Gravitational stability

$$Q_g(R) = \frac{\Sigma_{crit}}{\Sigma_{gas}} = \frac{\kappa \sigma_v}{\pi G \Sigma_{gas}}$$

$$\kappa^2 = \frac{2V}{R} \left( \frac{V}{R} + \frac{dV}{dR} \right)$$

epicyclic frequency



M51 rotation curve from Garcia-Burillo et al. 1993a (cf. Sofue 1996)

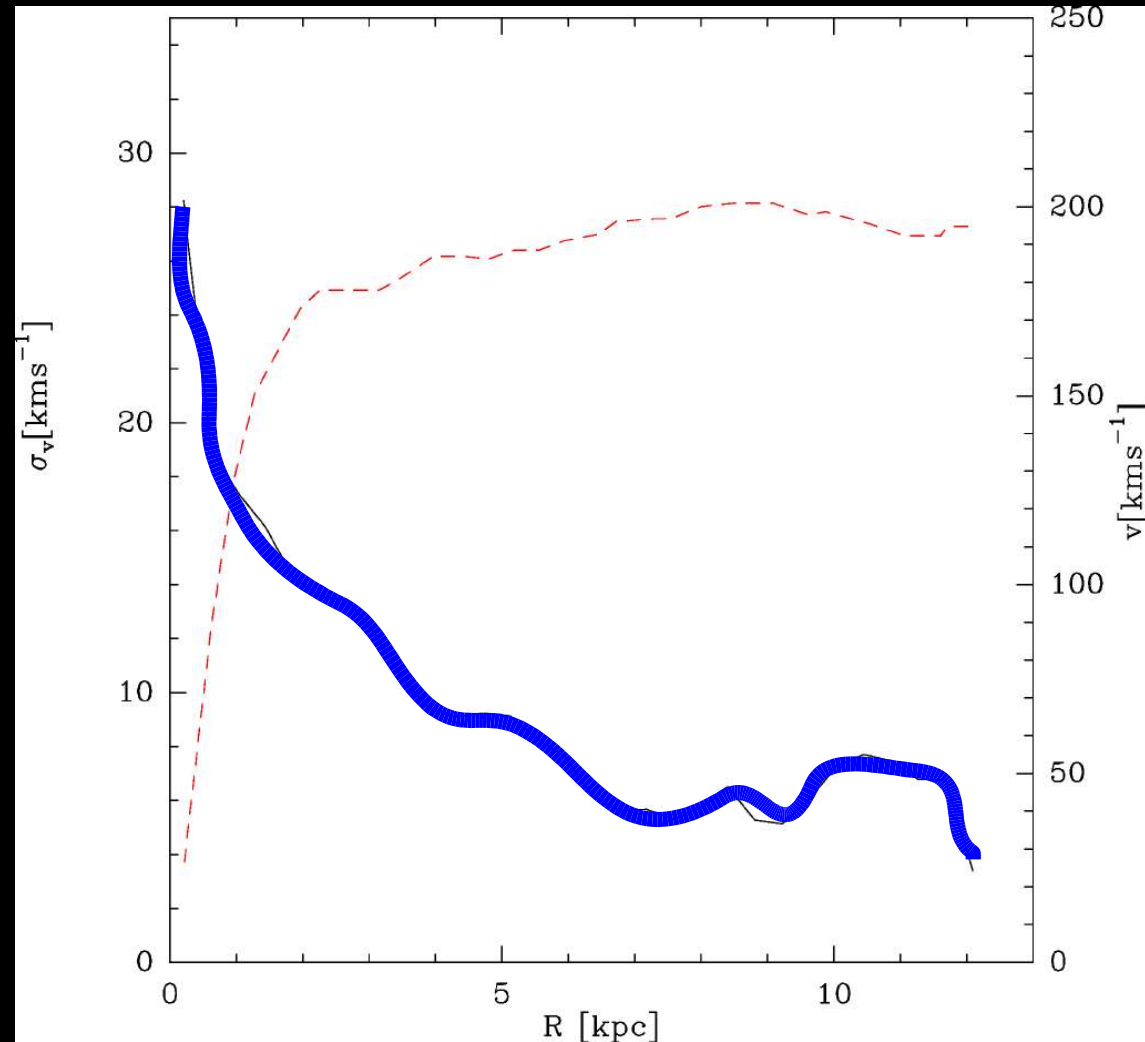
# 4. Gravitational stability

$$Q_g(R) = \frac{\Sigma_{crit}}{\Sigma_{gas}} = \frac{\langle \sigma_v \rangle}{\pi G \Sigma_{gas}}$$

$$\sigma_v = \frac{\Delta v_{eq}}{2\sqrt{2\ln 2}} = \frac{\int T dv / T_{pk}}{2\sqrt{2\ln 2}}$$

measured velocity dispersion

28 kms<sup>-1</sup> in the center to  
6 kms<sup>-1</sup> in the outskirts



# 4. Gravitational stability

$$Q_g(R) = \frac{\Sigma_{crit}}{\Sigma_{gas}} = \frac{\kappa \sigma_v}{\pi G \Sigma_{gas}}$$

$Q_g > 1$  for all radii

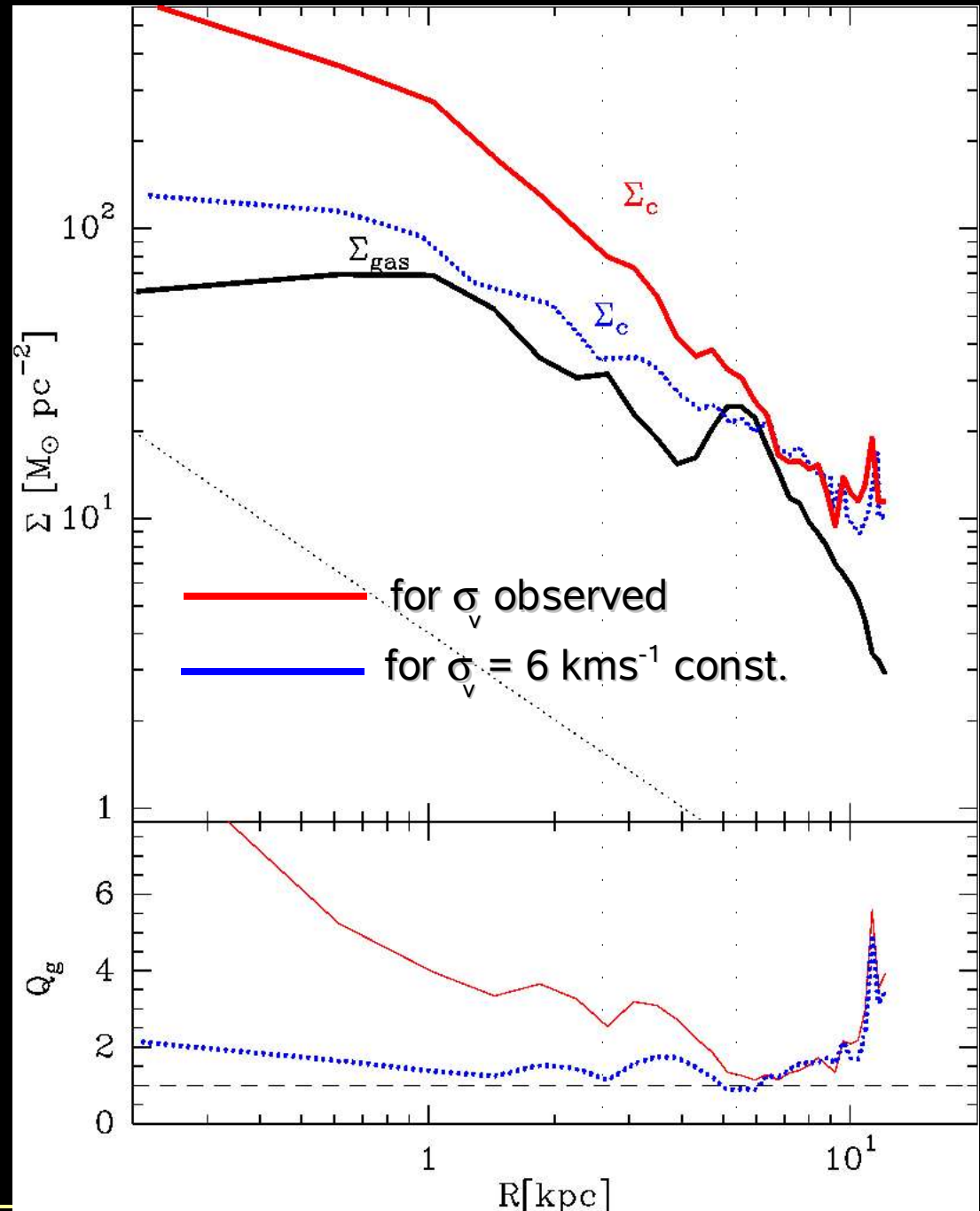
Little evidence for correlation with star formation.

Cloud intrinsic  $\sigma_v$  is smaller

Assuming  $\sigma_v = 6 \text{ km s}^{-1}$  :

$Q_g = 1-2$  almost constant for radii upto 10 kpc.

Self-regulation ?  
(Kennicutt 1989)



# 5. Formation of GMAs

Wyse 1985:

HI-interarm-clouds collide to form  $H_2$ -clouds in the arms:

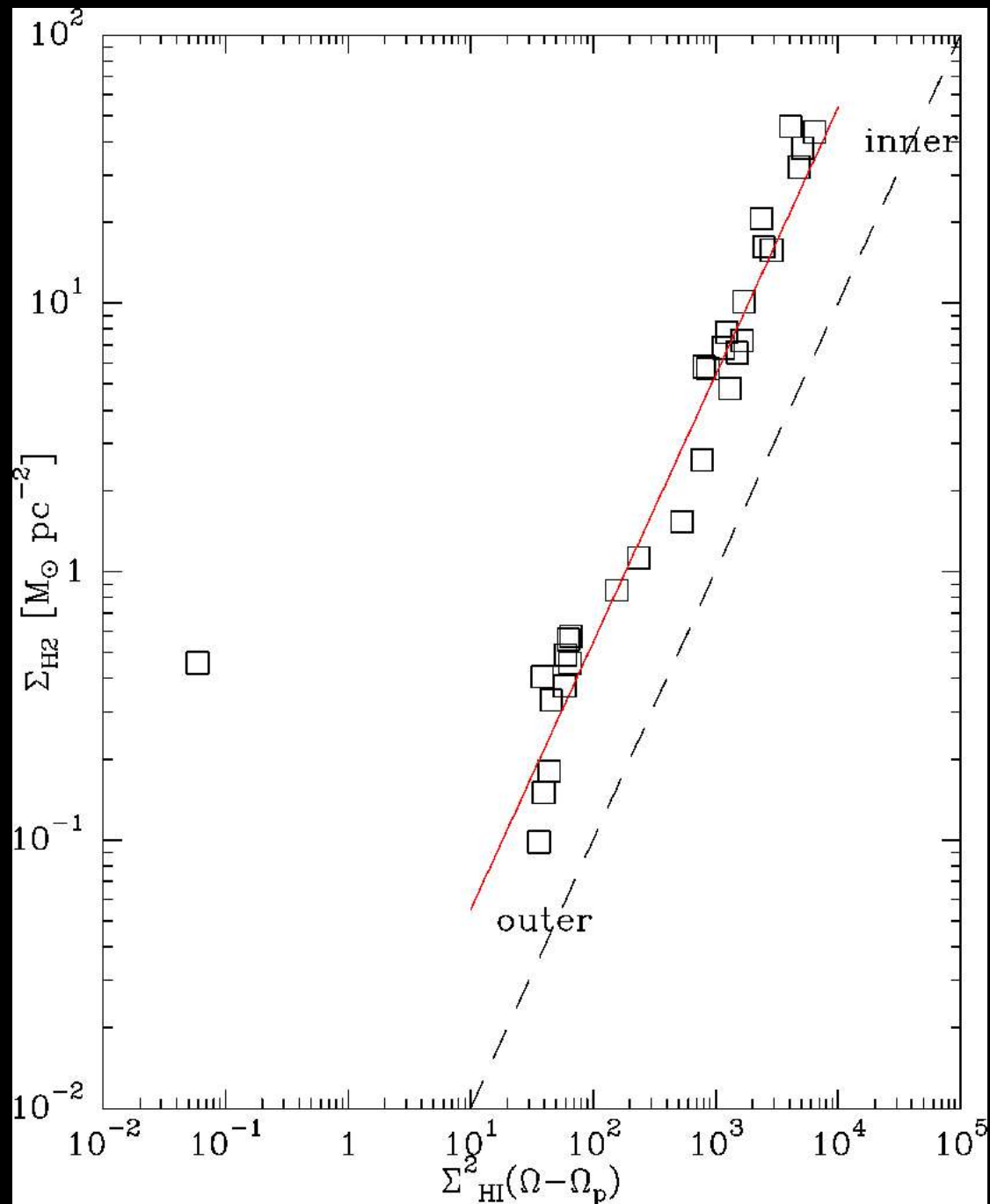
$$\Sigma_{H_2} \propto \Sigma_{HI}^2 (\Omega(R) - \Omega_p)$$

Pattern speed

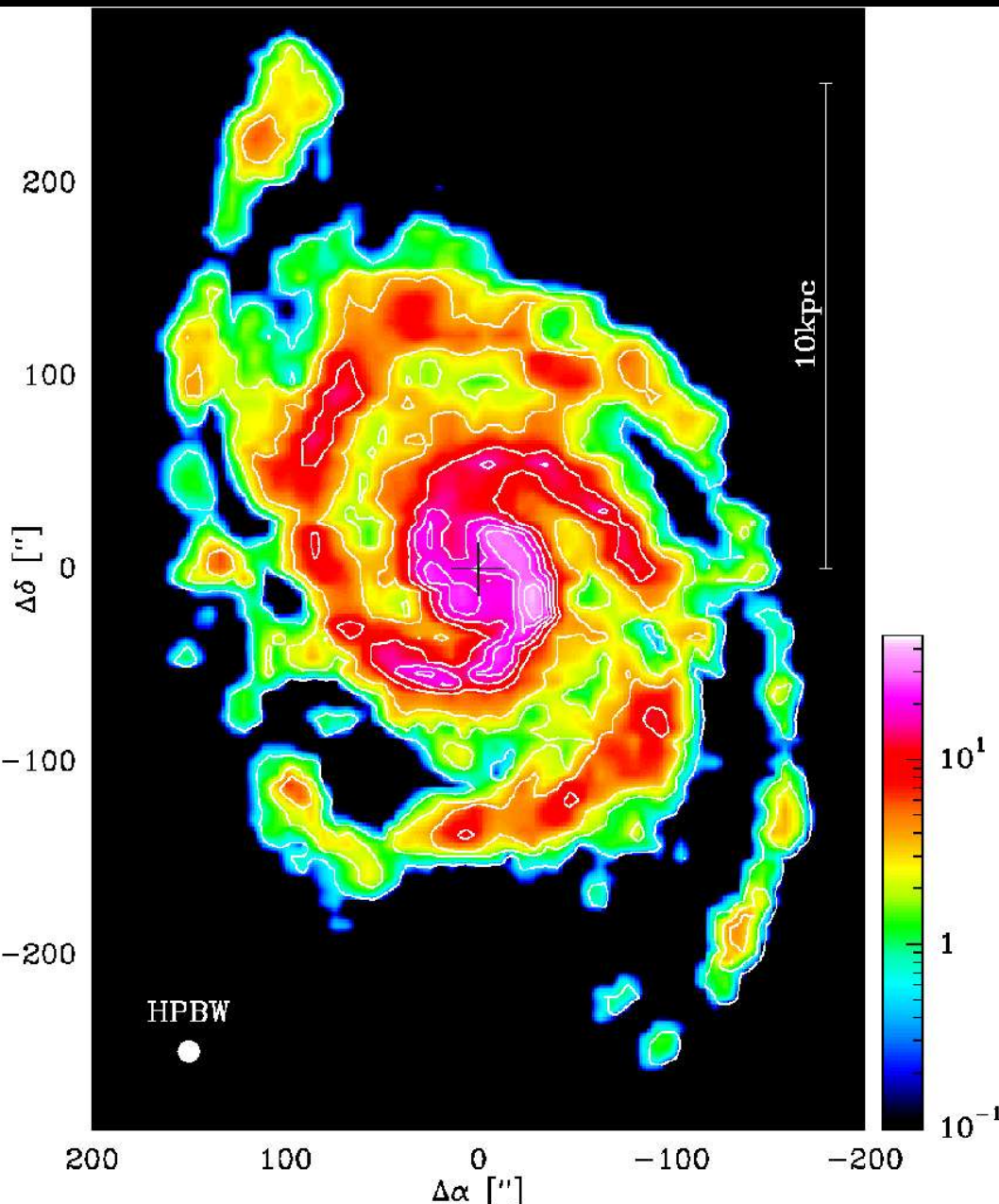
$$\Omega_p = 27 \text{ kms}^{-1} \text{ kpc}^{-1}$$

(Garcia-Burillo et al. 1993b)

Fit to the M51 data results in a slope of  $1.01 \pm 0.54$  confirming the Wyse-approach.



# 6. Giant molecular associations: Properties

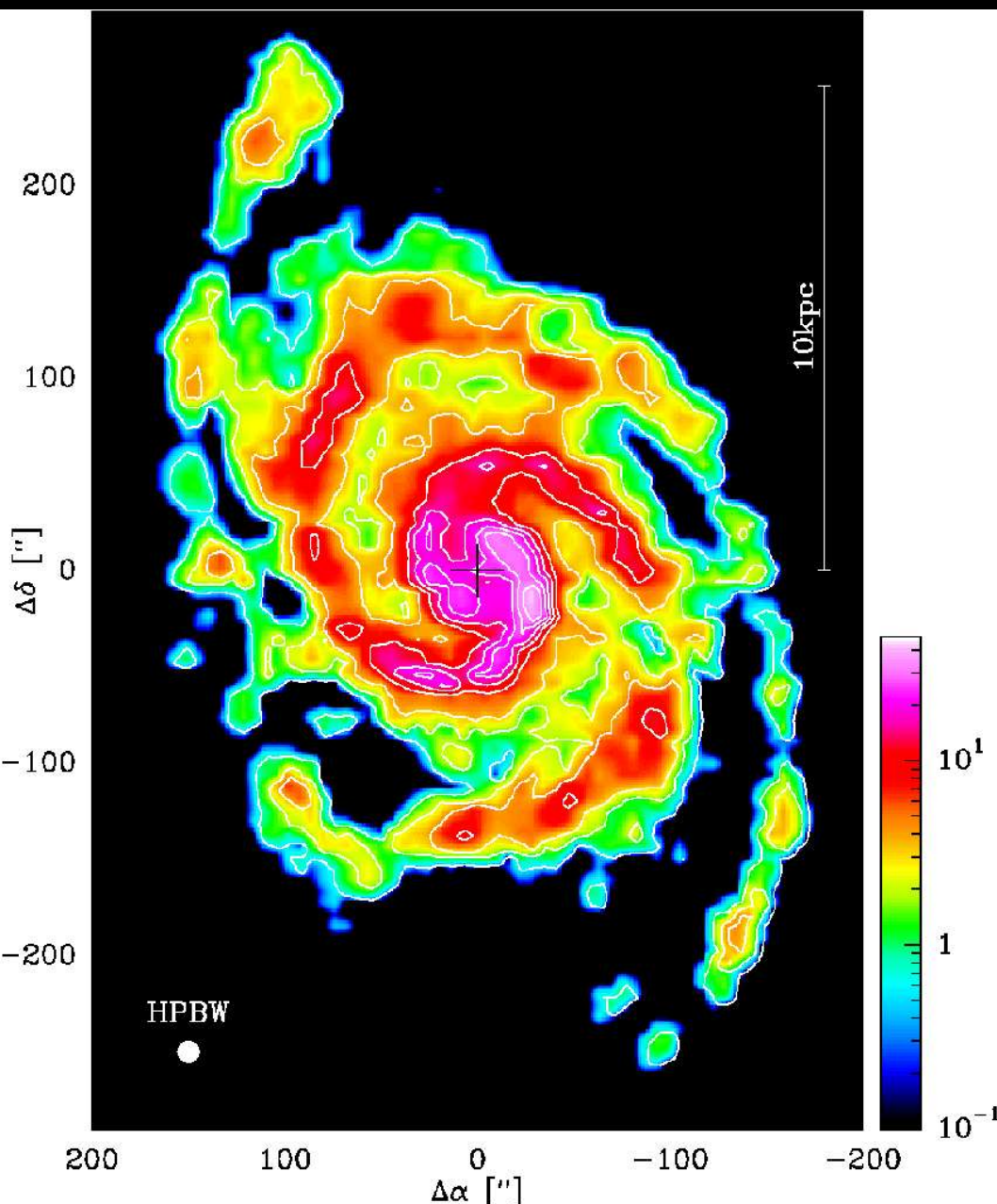


Distribution of 'clouds' in an entire galaxy

Advantages:

- same distance
- almost no contamination

## 6. Giant molecular associations: Properties



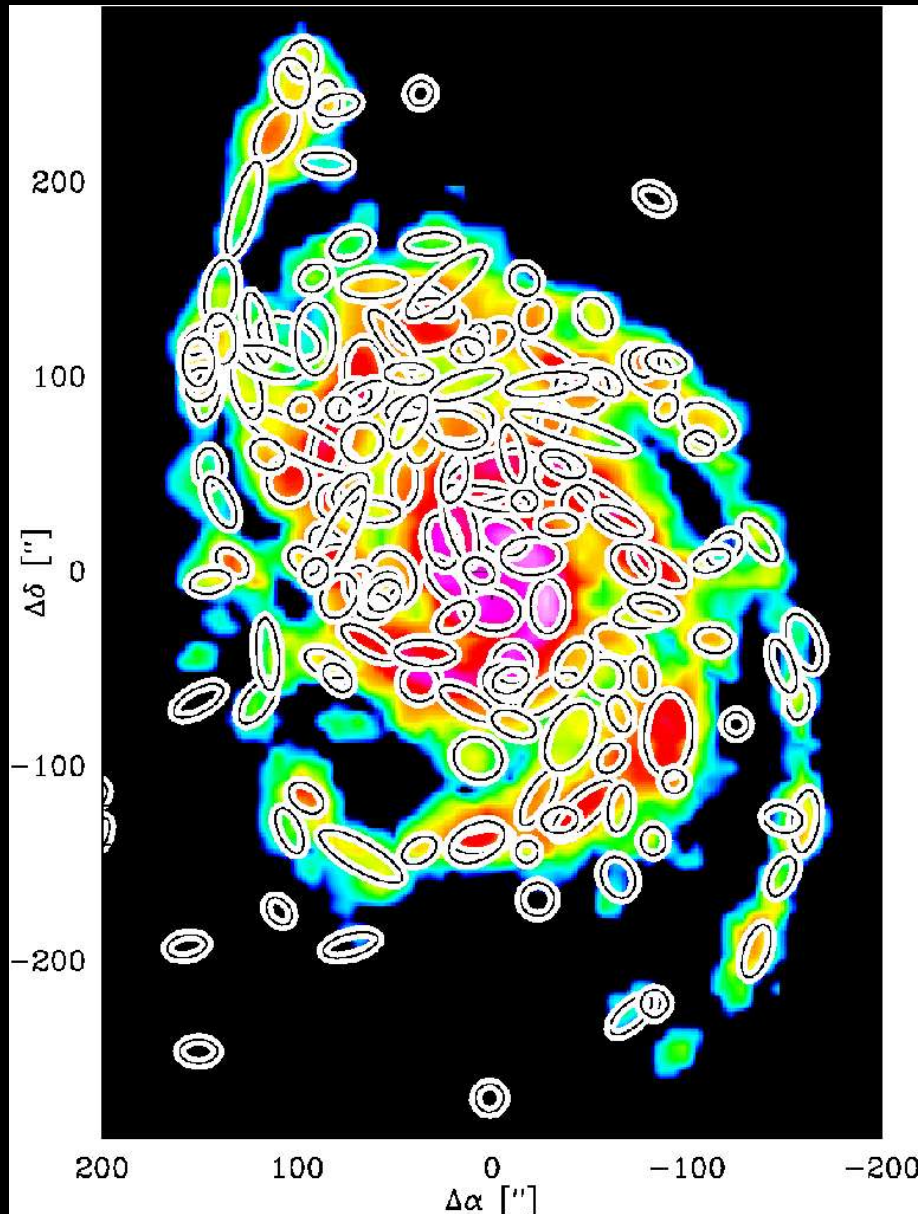
De-composition into GMAs using  
the  $\alpha - \delta - v$  3d-data cube

gaussclumps

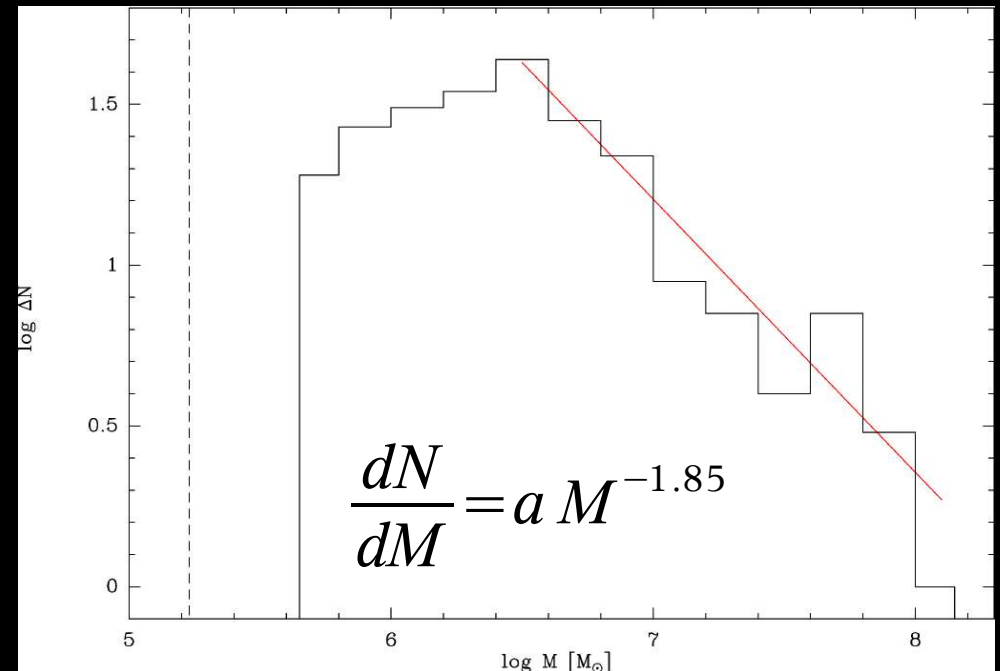
Stutzki & Güsten (1988)

Kramer, Stutzki et al. (1998)

# 6. Giant molecular associations: Properties



De-composition into GMAs using the  $\alpha - \delta - v$  data cube



$$3 \cdot 10^6 < M / M_{\text{sun}} < 10^8$$

## 6. Mass spectra of entire galaxies

	$\alpha$	$\log M_{\text{up}}$	
M33	2.6	6	Engargiola et al. 2003
CenA	2.3	6	Beletsky et al.: Poster #80
Andromeda	1.6	6	Muller: Talk on Wednesday
LMC	1.8	6.3	Fukui et al. 1999
Antennae	1.4	9	Wilson et al. 2003
M51	1.9	8	this talk
<b>Milky Way:</b>			
Inner-Galaxy	1.5	6.5	Scoville et al. 1987
Galactic Ring	1.8	5	Simon et al. 2001
Galactic GMCs	1.6	4	e.g. Mookerjea et al. 2004

# 5. Summary

- $\text{HI}/\text{H}_2$ 
  - $\Sigma_{\text{HI}}/\Sigma_{\text{H}_2} \sim R^{1.5}$  for  $R < 7\text{kpc}$
  - $0.1 < \Sigma_{\text{HI}}/\Sigma_{\text{H}_2} < 20$
- $\Sigma_{\text{SFR}} - \Sigma_{\text{gas}}$  (Schmidt Law)
  - slope  $n = 1.35$  similar to other spirals
- $\Sigma_{\text{crit}} - \Sigma_{\text{gas}}$  (Gravitational stability)
  - good correlation for  $\sigma_v = 6 \text{ km s}^{-1}$  const.:  $Q=1-2$
- Formation of GMAs by collisions of atomic clouds
- Mass distribution of GMAs: slope similar to Galactic GMCs

Schuster, Kramer et al. A&A, submitted  
Hitschfeld, Kramer et al. in prep.

# END

# 5. Outlook

## ■ Complete census of GMAs in M51

very few studies of entire galaxies so far:

cf. Antennae at 19 Mpc by Wilson et al. 2003

M33 at 850 kpc by Rosolowski et al. 2003, Engargiola et al. 2003

- GMA mass spectra
- Stability of GMAs
- Formation of GMAs (Wyse 1986)

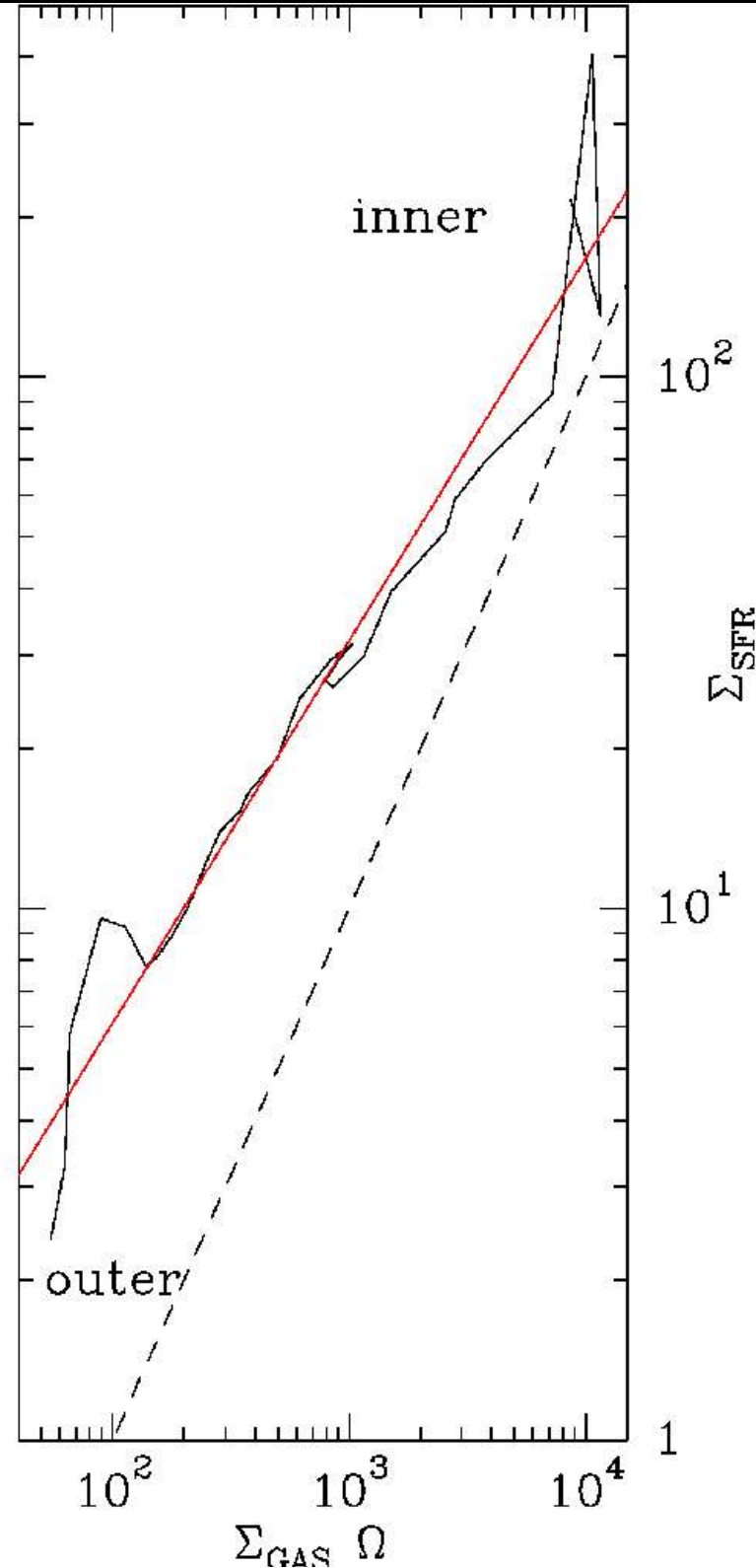
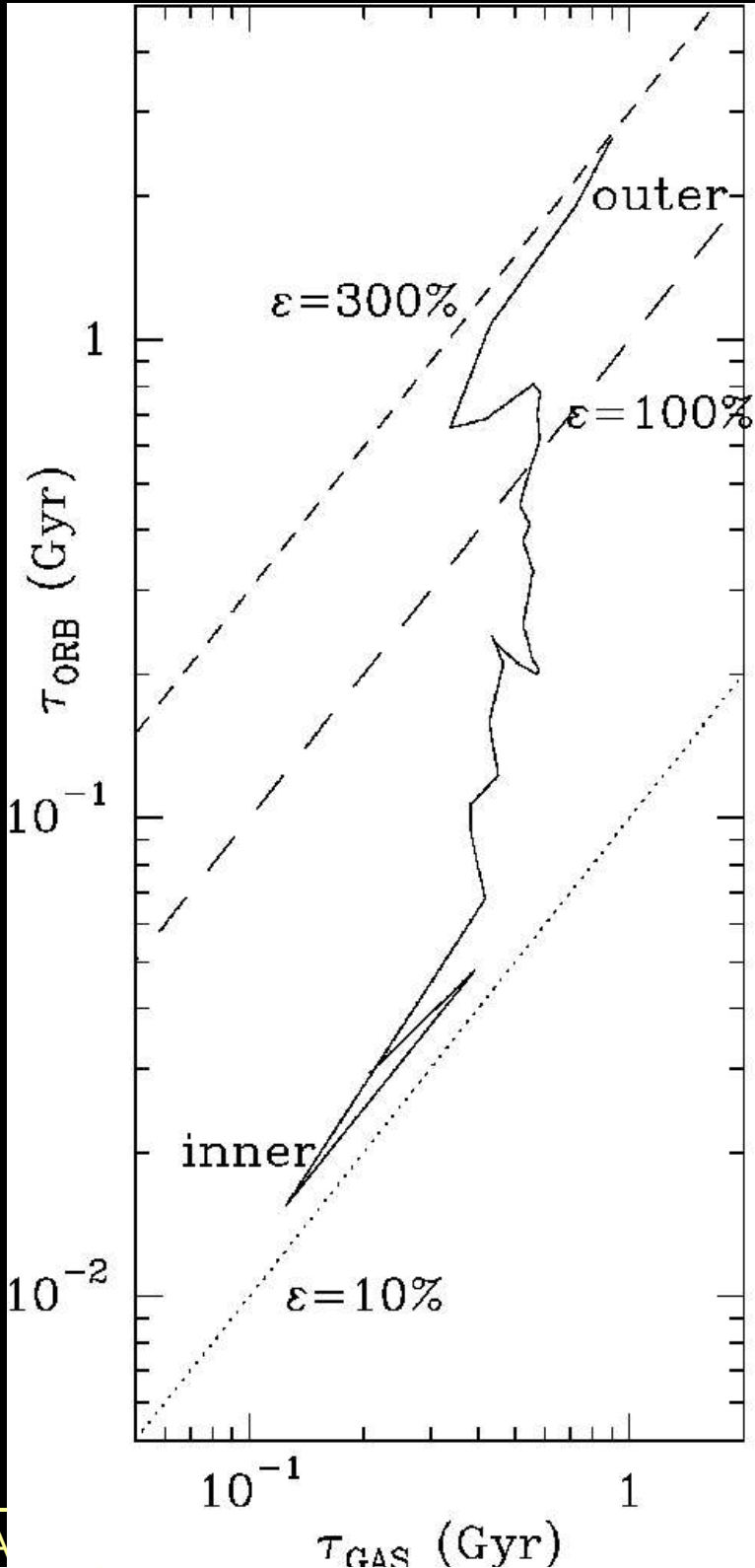
## ■ Gas excitation

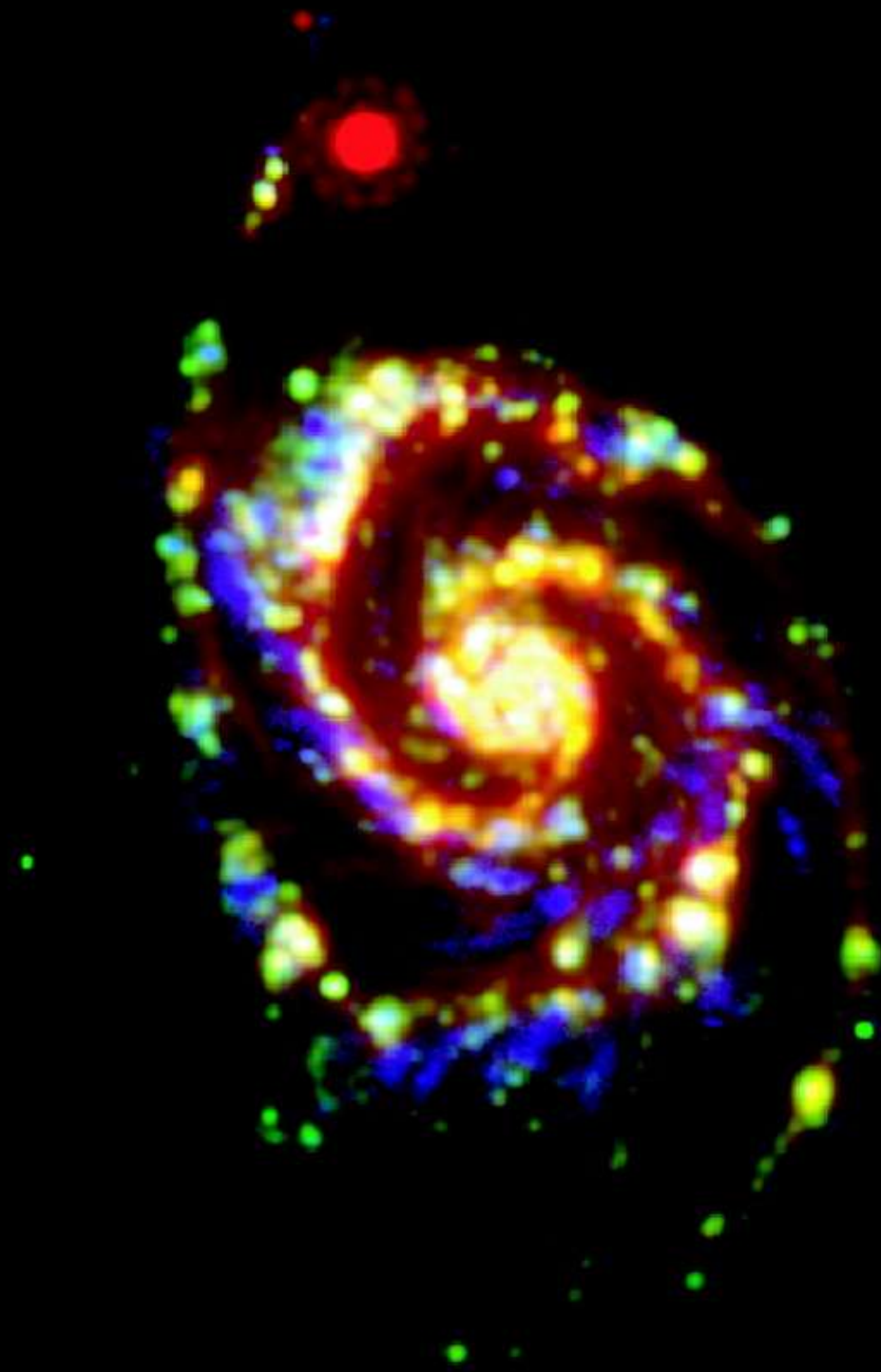
- 2-1/1-0 using BIMA data  
(Helfer et al. 2003; Regan et al. 2001)

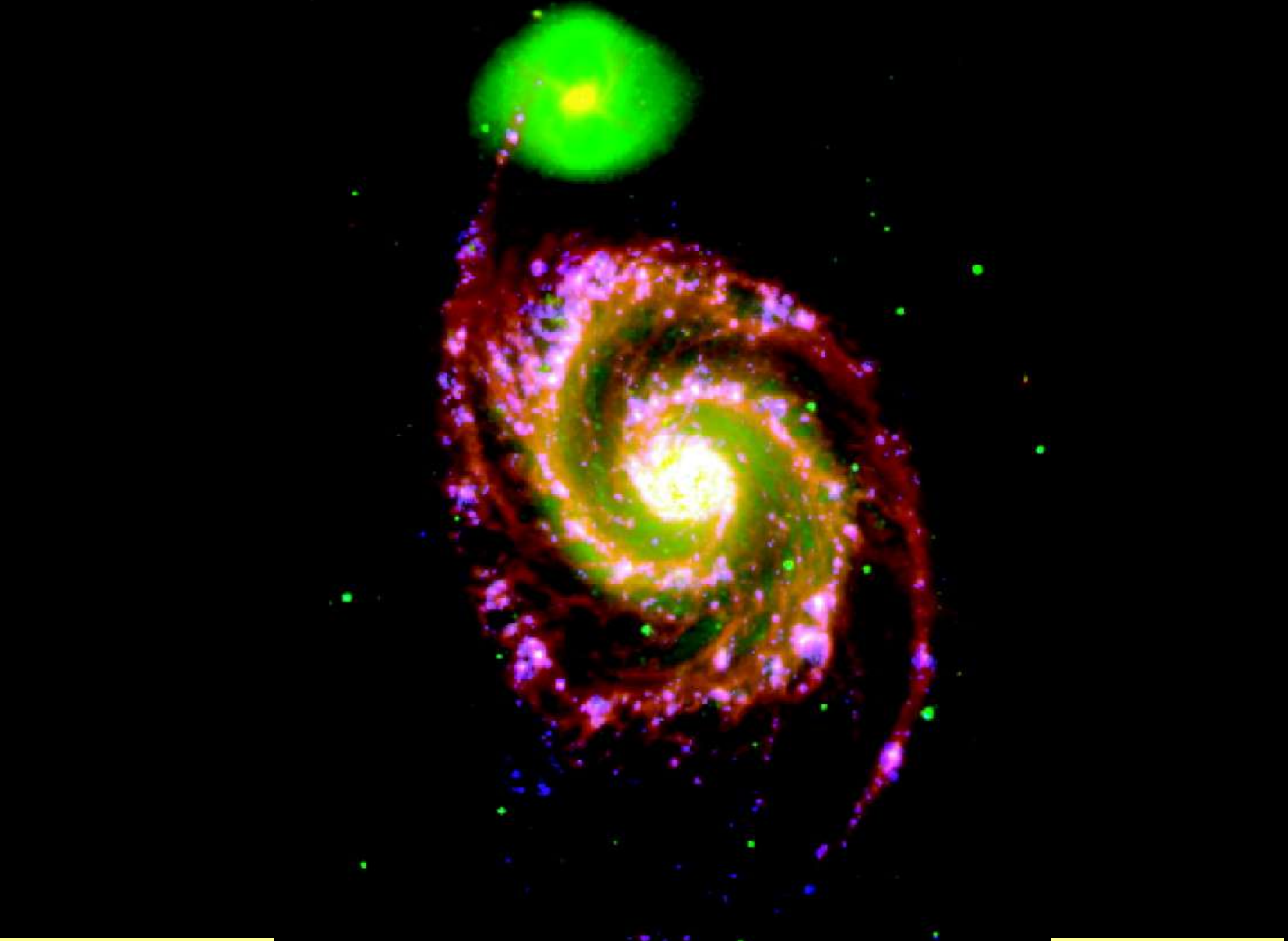
## ■ Dust to Gas correlation

- 850 $\mu$  m SCUBA map of Meijerink et al. 2005
- Spitzer SINGS IRAC & MIPS data of Calzetti et al. 2005

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# The CO 2-1 observations

**M51**

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d=8.4 Mpc  
i=20deg

IRAM-30m CO 2-1 map +  
BIMA CO 1-0 map of  
Helfer et al. (2003),  
Regan et al. (2001)

