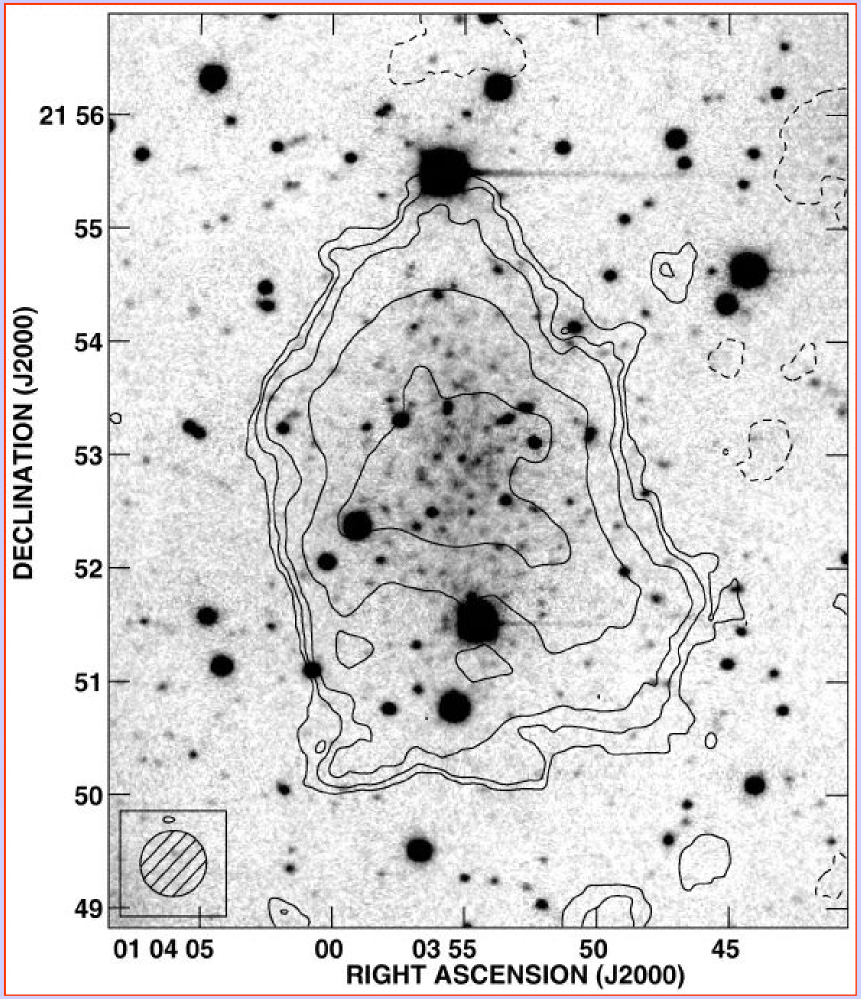
Pressure Modulated Star Formation

Leo Blitz
Erik Rosolowsky
Tony Wong

Some Things We Know About HI

- The HI distribution is generally more extended than the stars. Sometimes much more.
- There are galaxies with HI, but no star formation.
- Unlike the stars, the HI often has a flat or nearly flat surface density distribution. (Why?)
- The velocity dispersion of the HI remains ~constant in the outer parts of galaxies and from galaxy to galaxy. (Why?)
- The outer reaches of HI in disk galaxies are thin. (Why?)

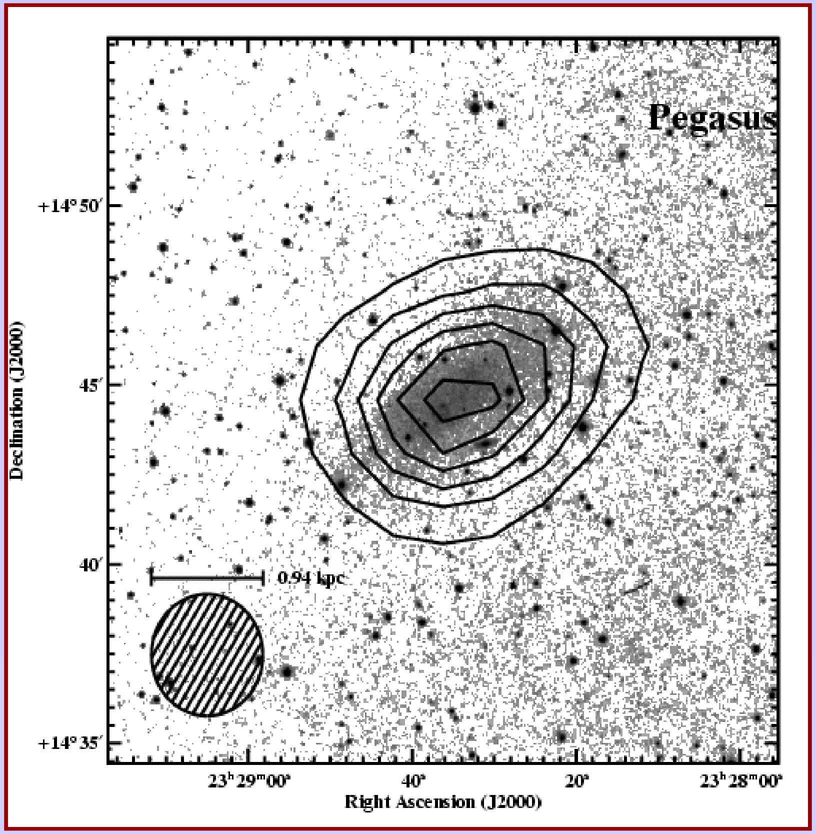
LGS 3



Here's a galaxy with HI and no Star Formation (and no H_2)

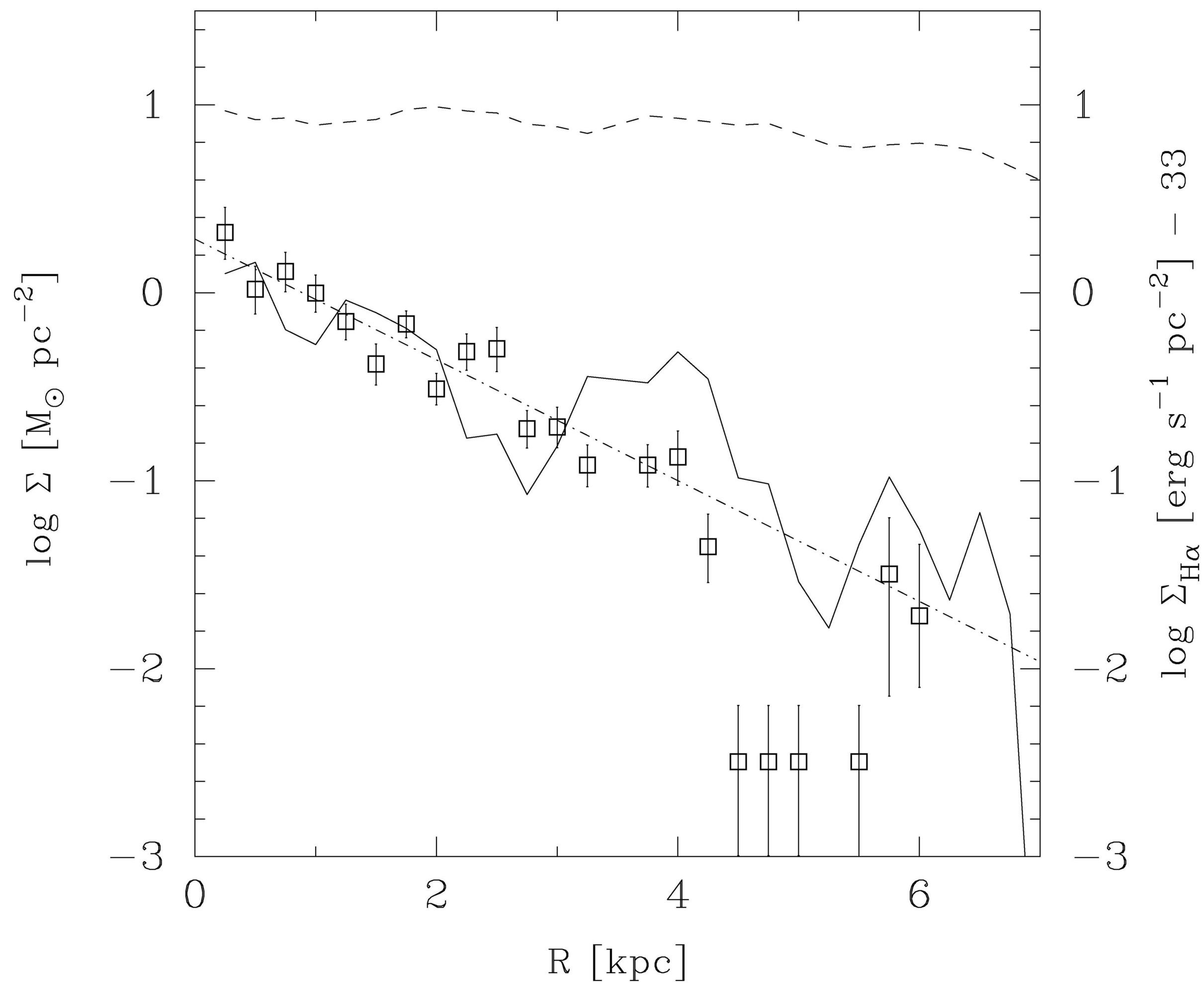
Young & Lo 1997

Pegasus



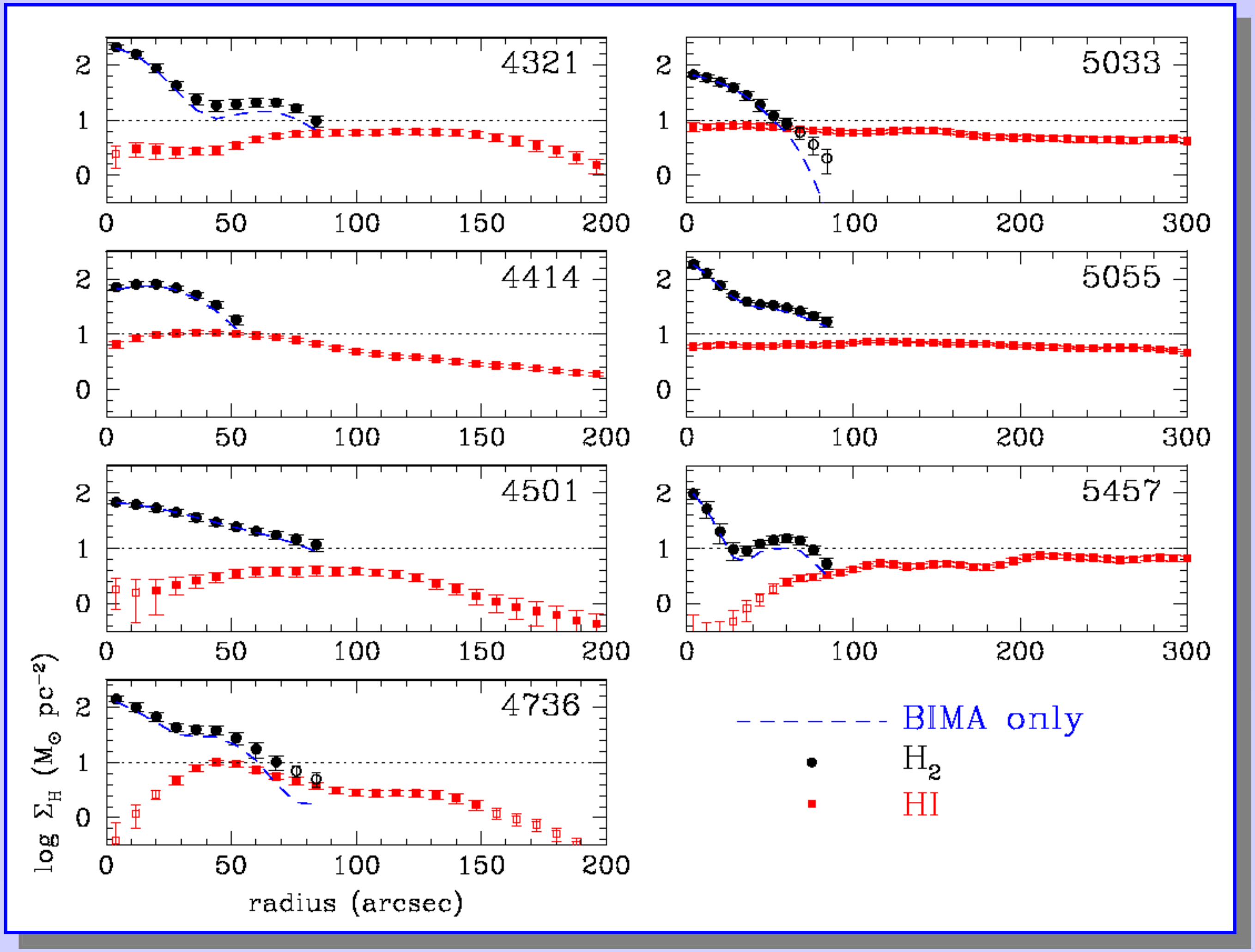
$$\nabla V \sim 4\, kms^{-1}\, kpc^{-1}$$

M33 HI and Stellar Surface Densities

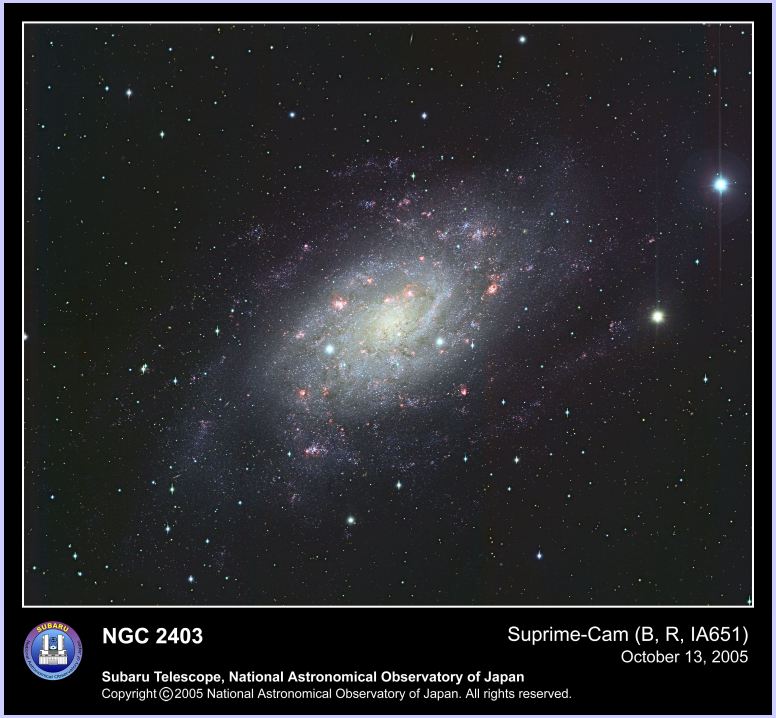


Radial Profiles

Comparison of radial CO and HI profiles in 7 CO-bright galaxies confirms the tendency for H_2 to be more centrally concentrated than HI.



Wong & Blitz 2002


NGC 2403
Suprime-Cam (B, R, IA651)
October 13, 2005
Subaru Telescope, National Astronomical Observatory of Japan
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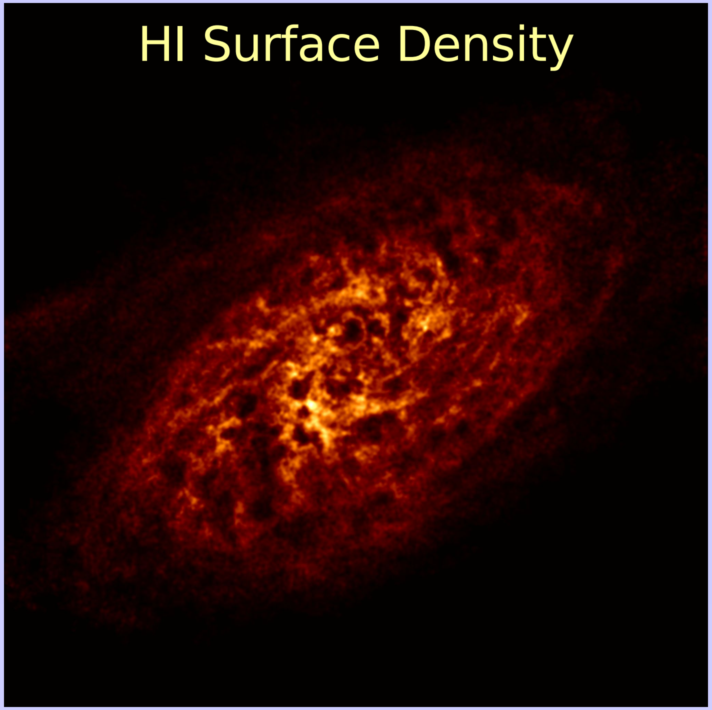
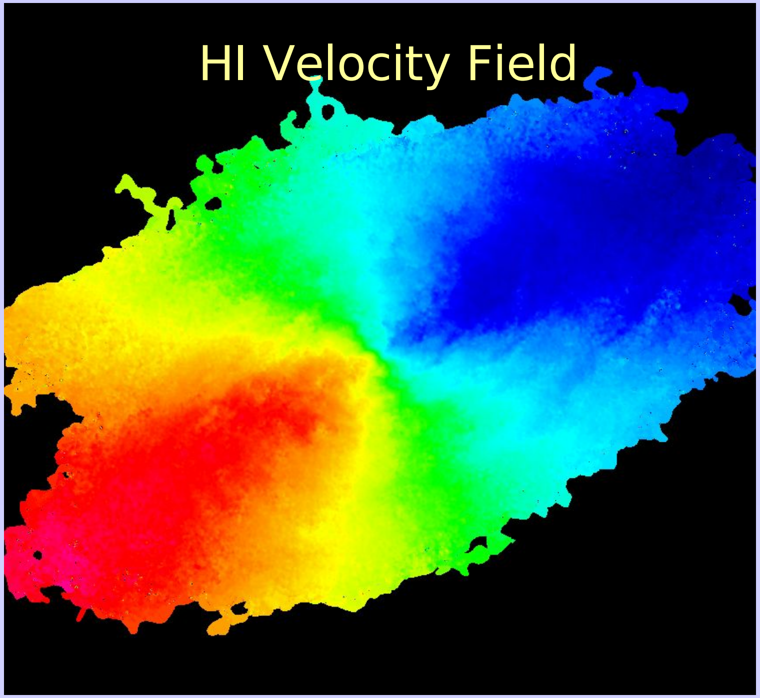
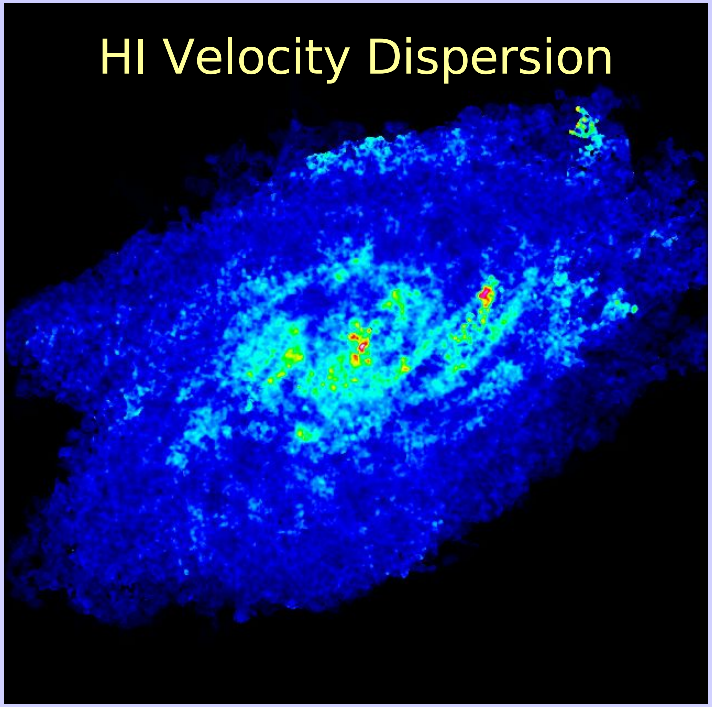
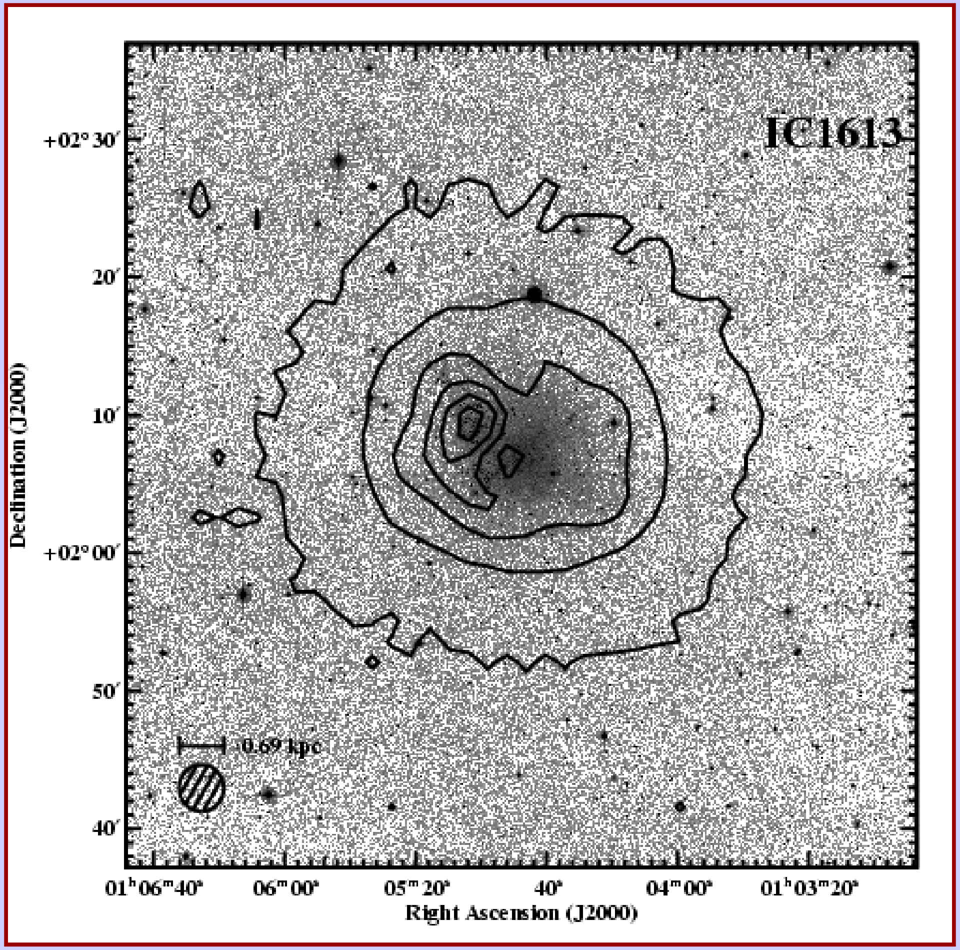
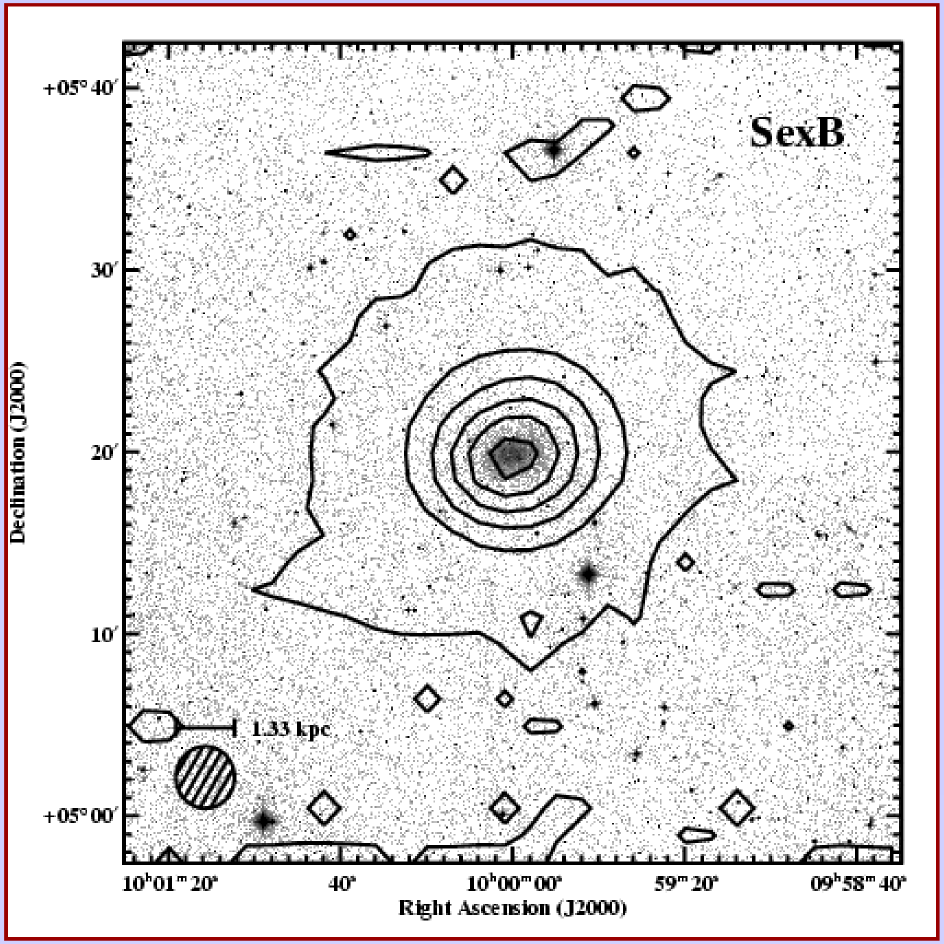

HI Surface Density


HI Velocity Field


HI Velocity Dispersion

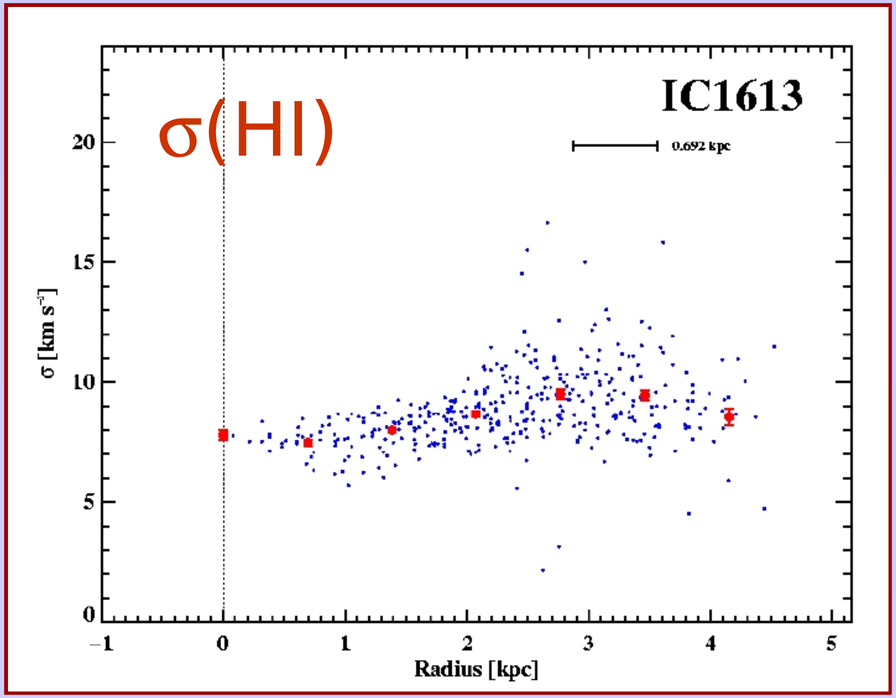
HI in Two Local Group dIrrs

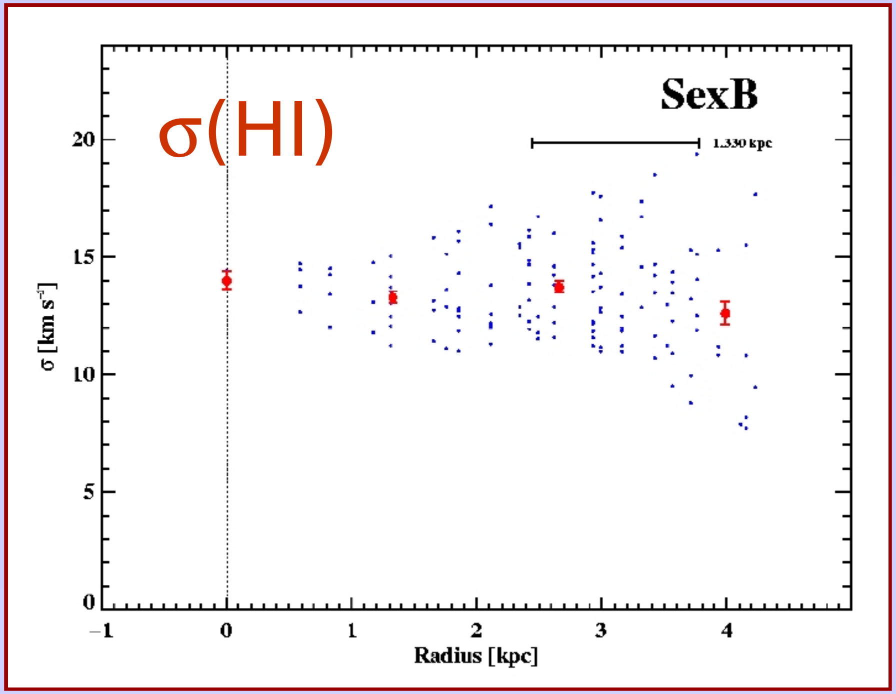




The gas in these two galaxies is pressure rather than rotationally supported.

HI Velocity Dispersions in Two Local Group Dwarf Irregulars





Some things we know about star formation:

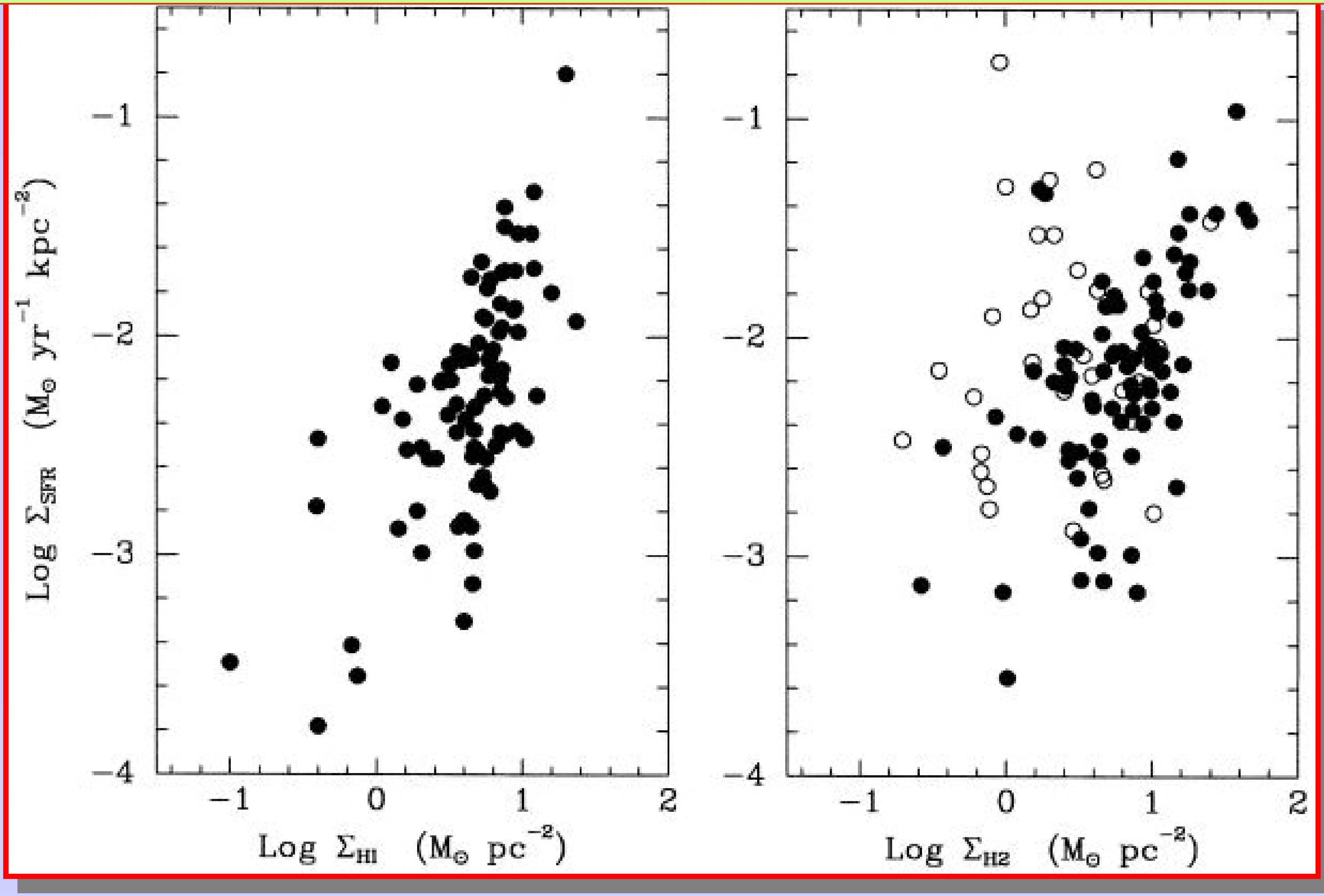
- *All star formation takes place in molecular clouds; most in GMCs*
- *No exceptions*

We know this observationally: all of the most recent star formation takes place in molecular clouds.

We know this from theory: To get a stellar mass forming from a Jeans instability ($\lambda_J{}^2 > \pi c^2/G\rho$) *requires densities and temperatures found only in molecular clouds.*

Star Formation Rate as a function of HI and H_2

Kennicutt's Paradox

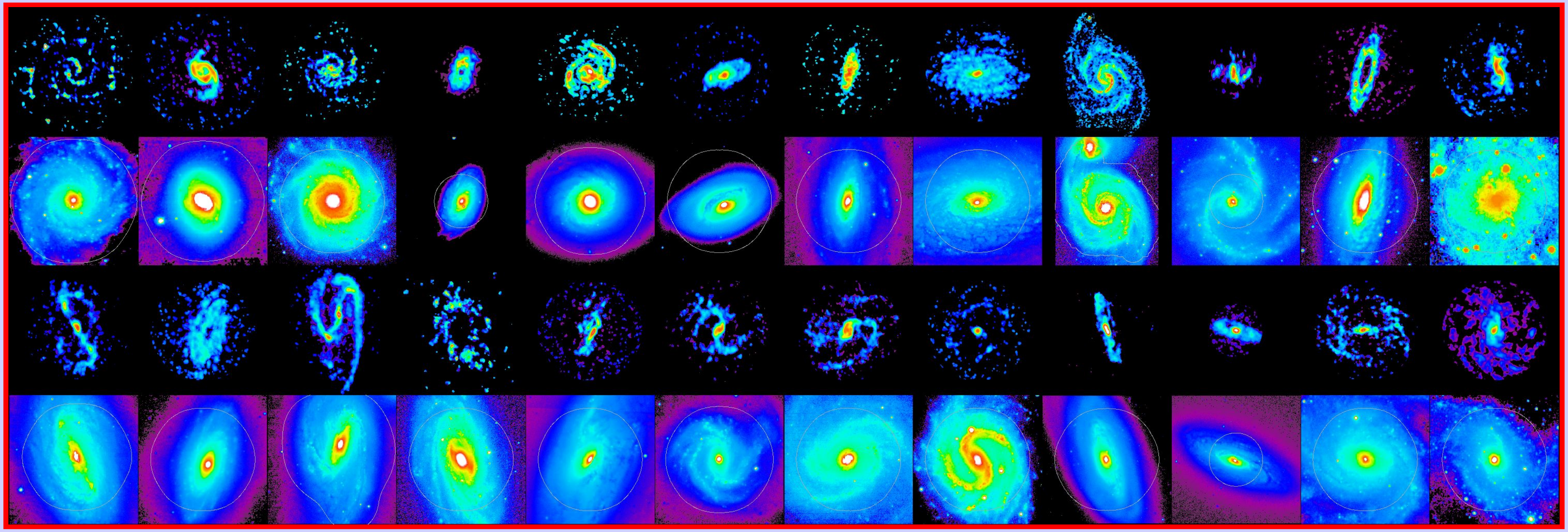


Kennicutt 1998

Largely from global HI and CO observations;
Assumes a constant value of A_V = 1mag

BIMA SONG

Molecular gas (CO; first, third rows)
Optical emission (second, fourth rows)
From 24 of 44 BIMA SONG galaxies



Helfer et al. 2003

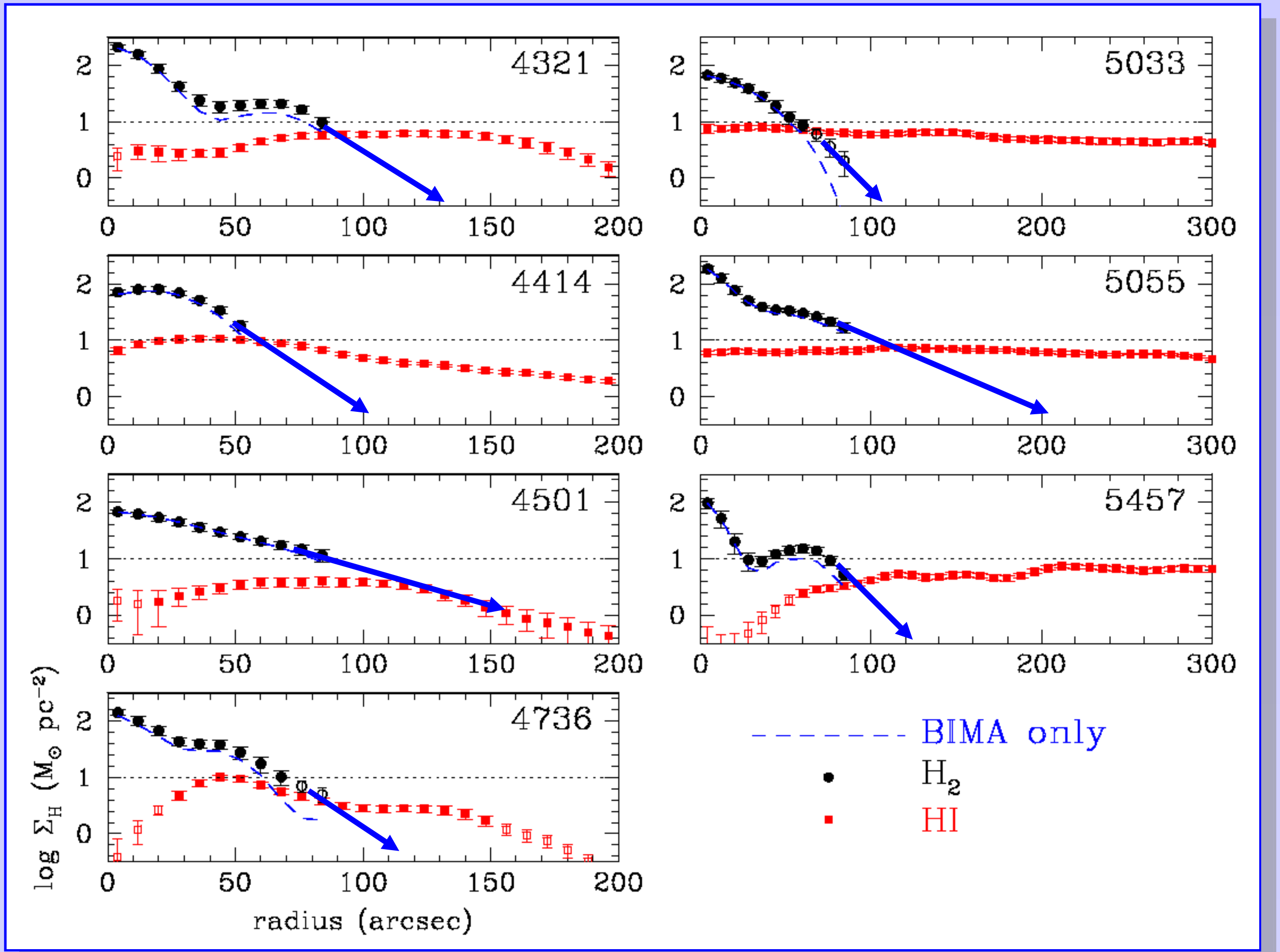
Radial Surface Density Profiles

HI roughly constant with R;

Saturates at ~10 M pc^{-2}

CO is monotonically decreasing (almost)

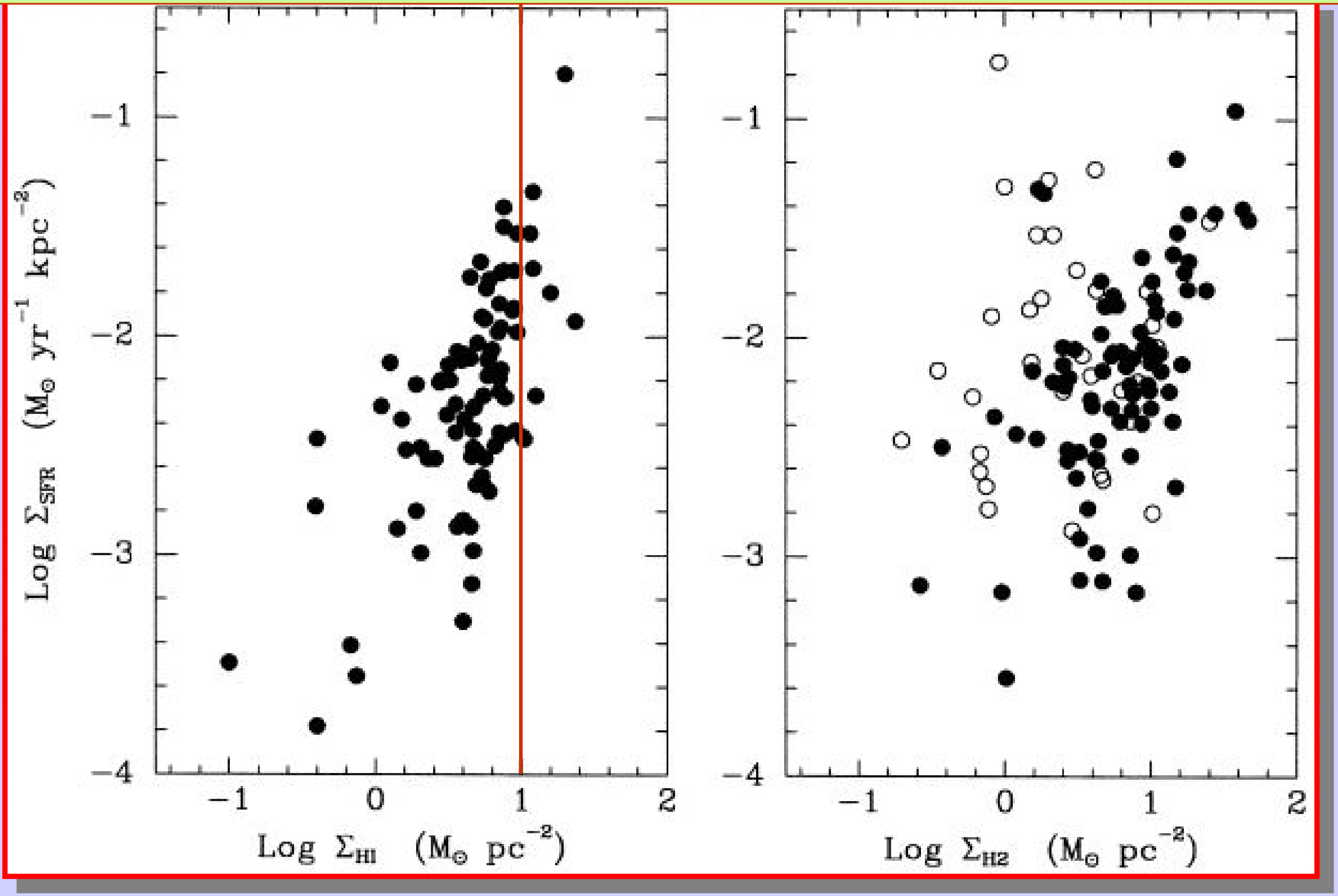
roughly exponential



Wong & Blitz 2002

Star Formation Rate as a function of HI and H_2

Kennicutt's Paradox



Kennicutt 1998

Largely from global HI and CO observations;
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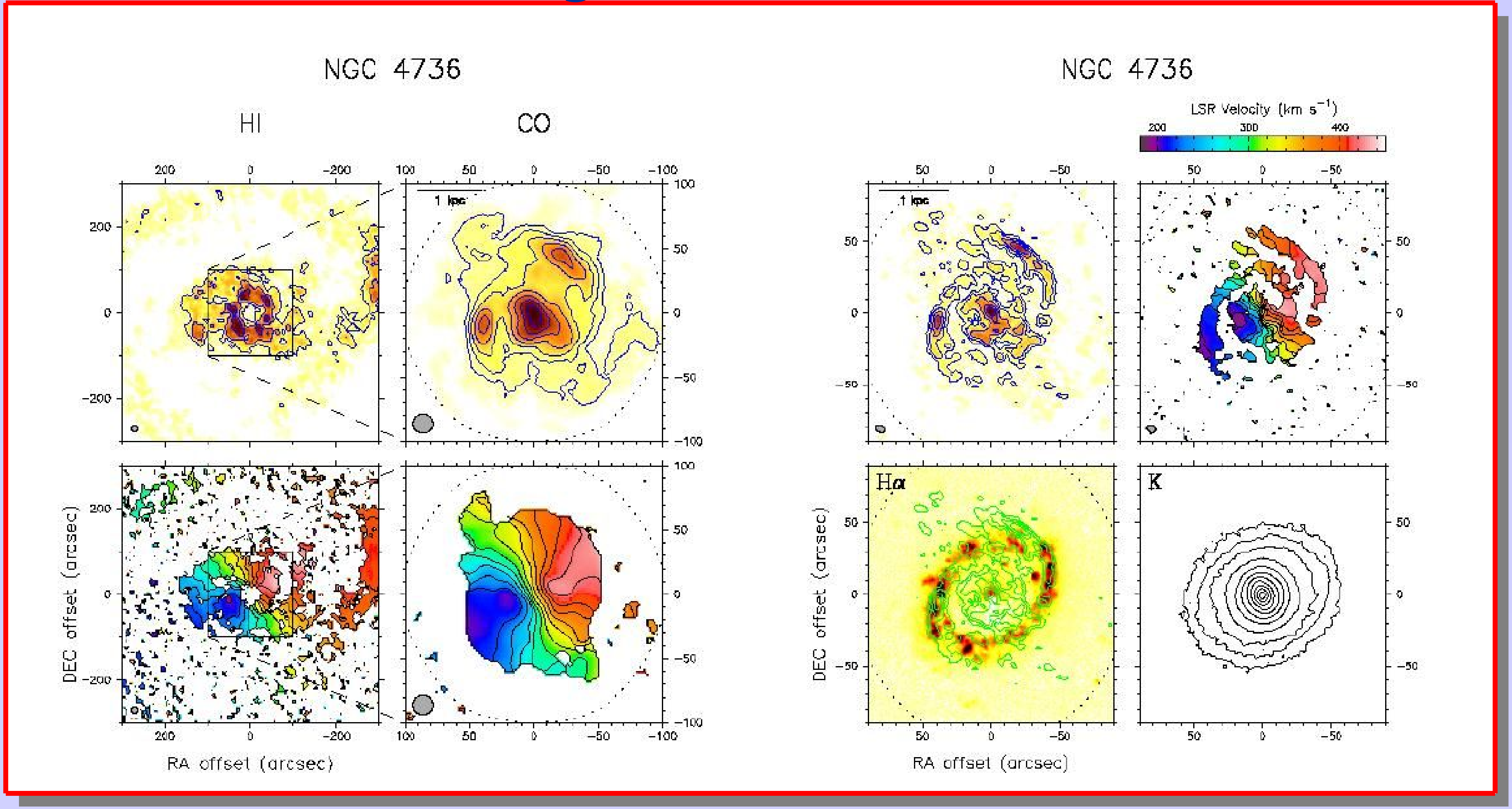
From BIMA SONG

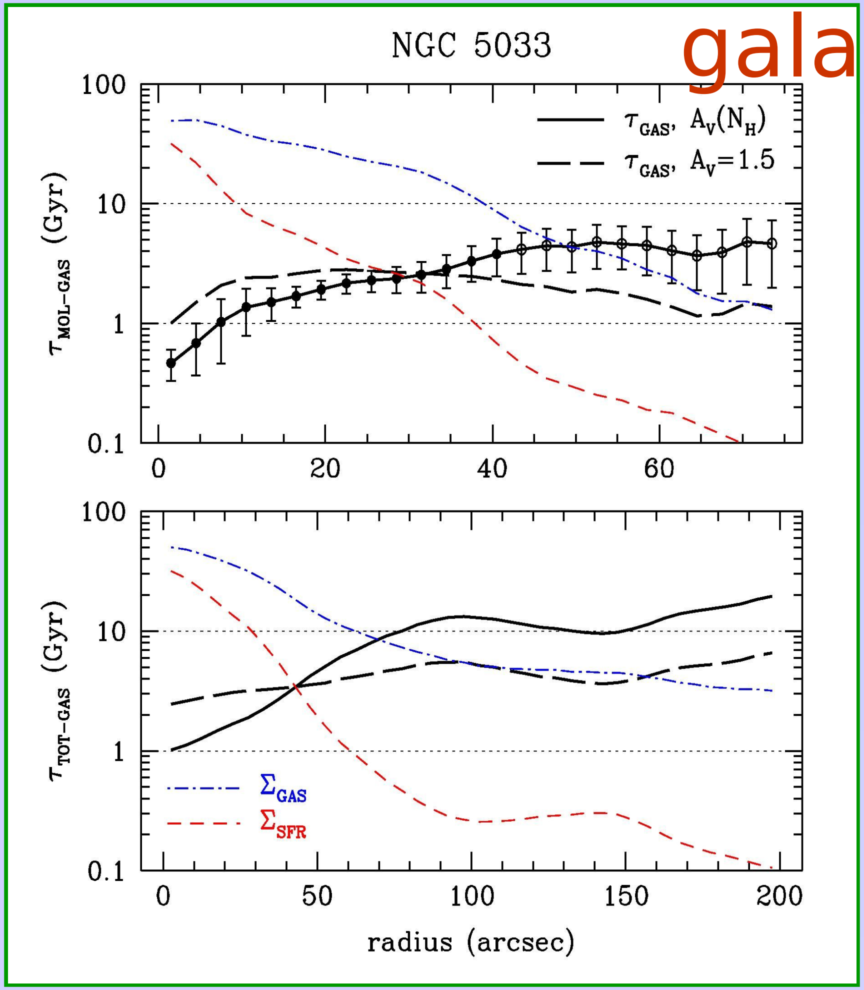
Atomic, molecular gas and star formation in M94

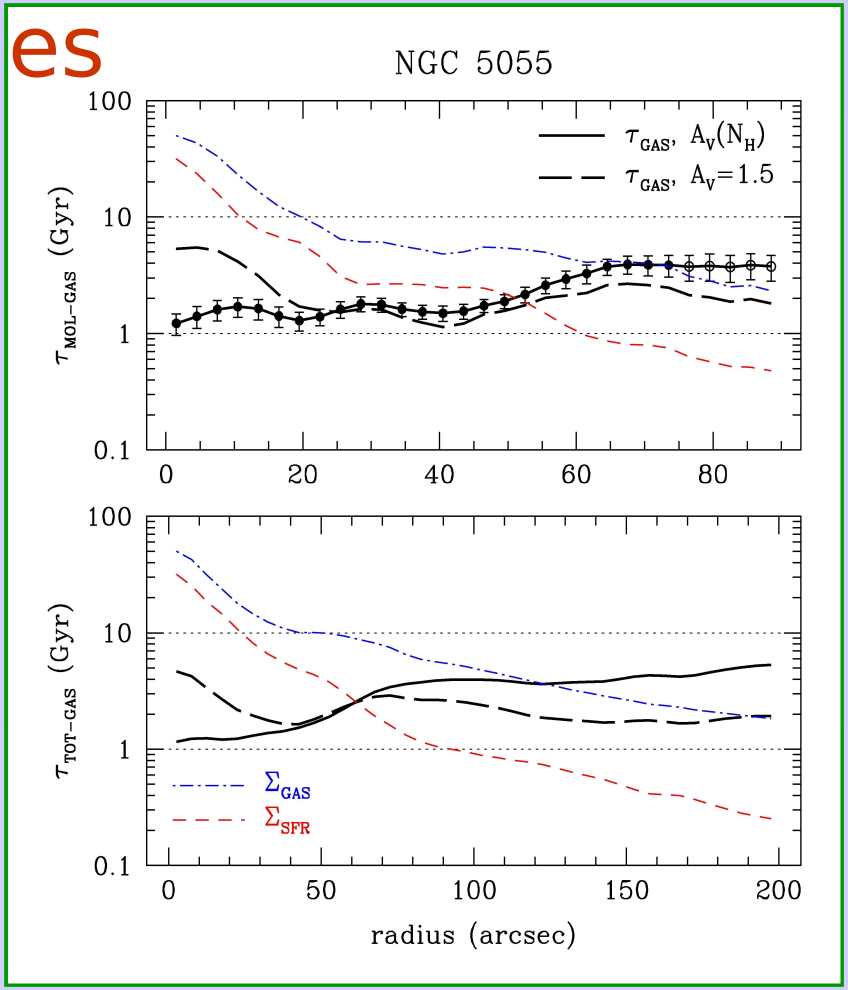


Wong & Blitz 2002

Molecular Gas Depletion Time

molecule – rich galaxies





Wong & Blitz 2002

Molecular Gas Depletion Time

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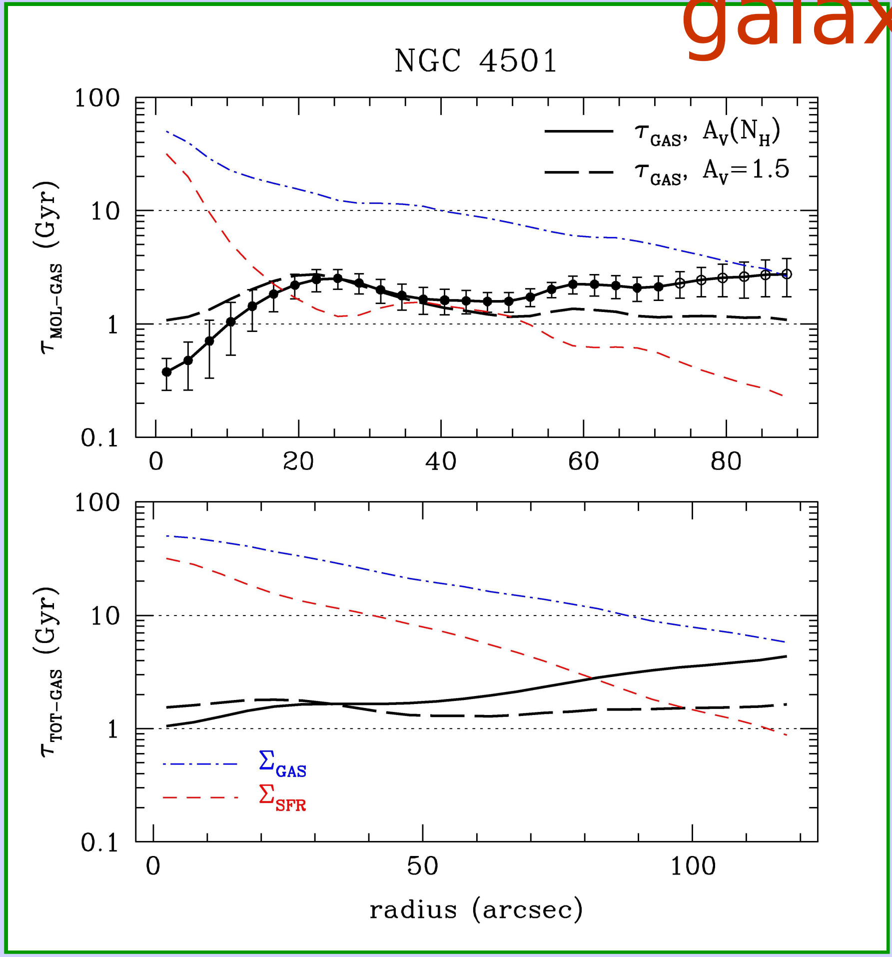

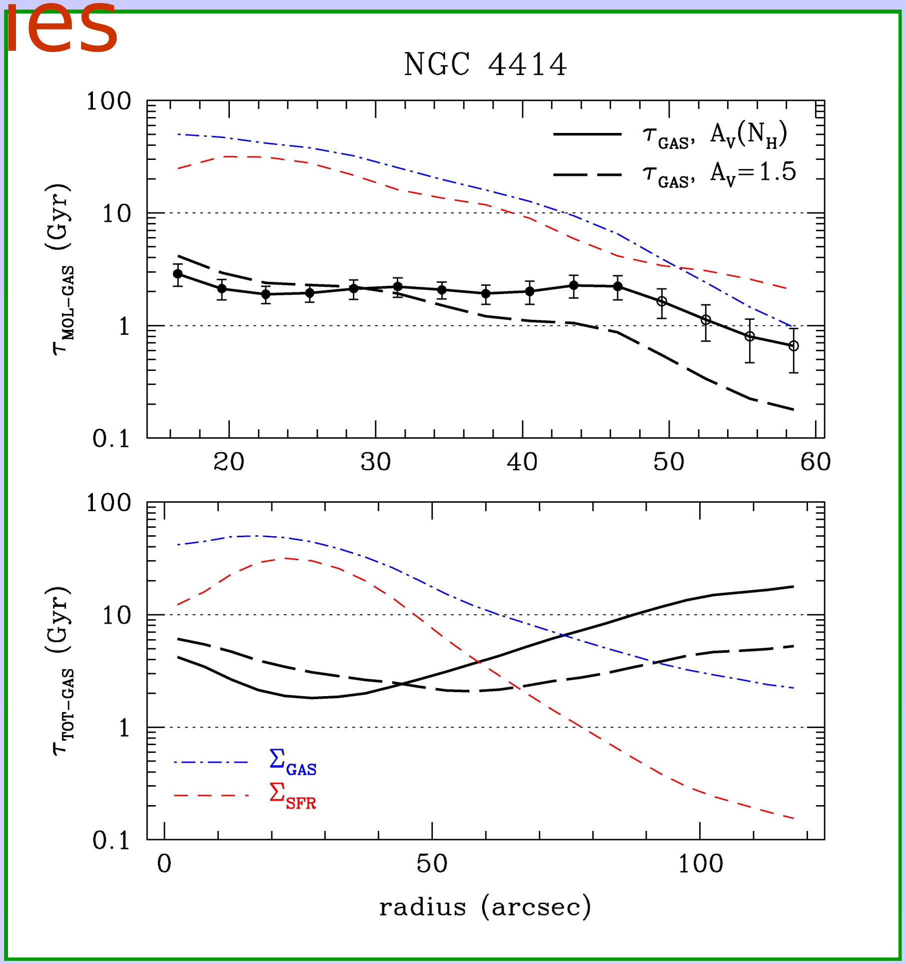

Wong & Blitz 2002

Implications

- *Since molecular gas depletion times are generally less than a Hubble time, suggests that H_2 must form from HI.*

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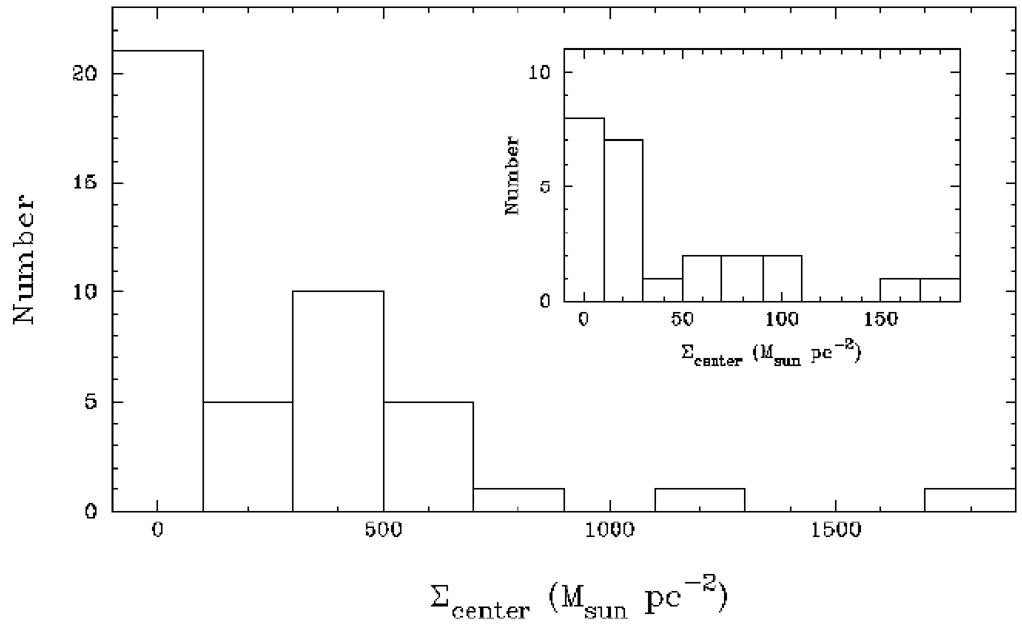
BIMA SONG central H_2 surface densities within central 6” ~ 350 pc

Most galaxies have central H_2 surface densities one or more orders of magnitude higher than the mean for Galactic GMCs



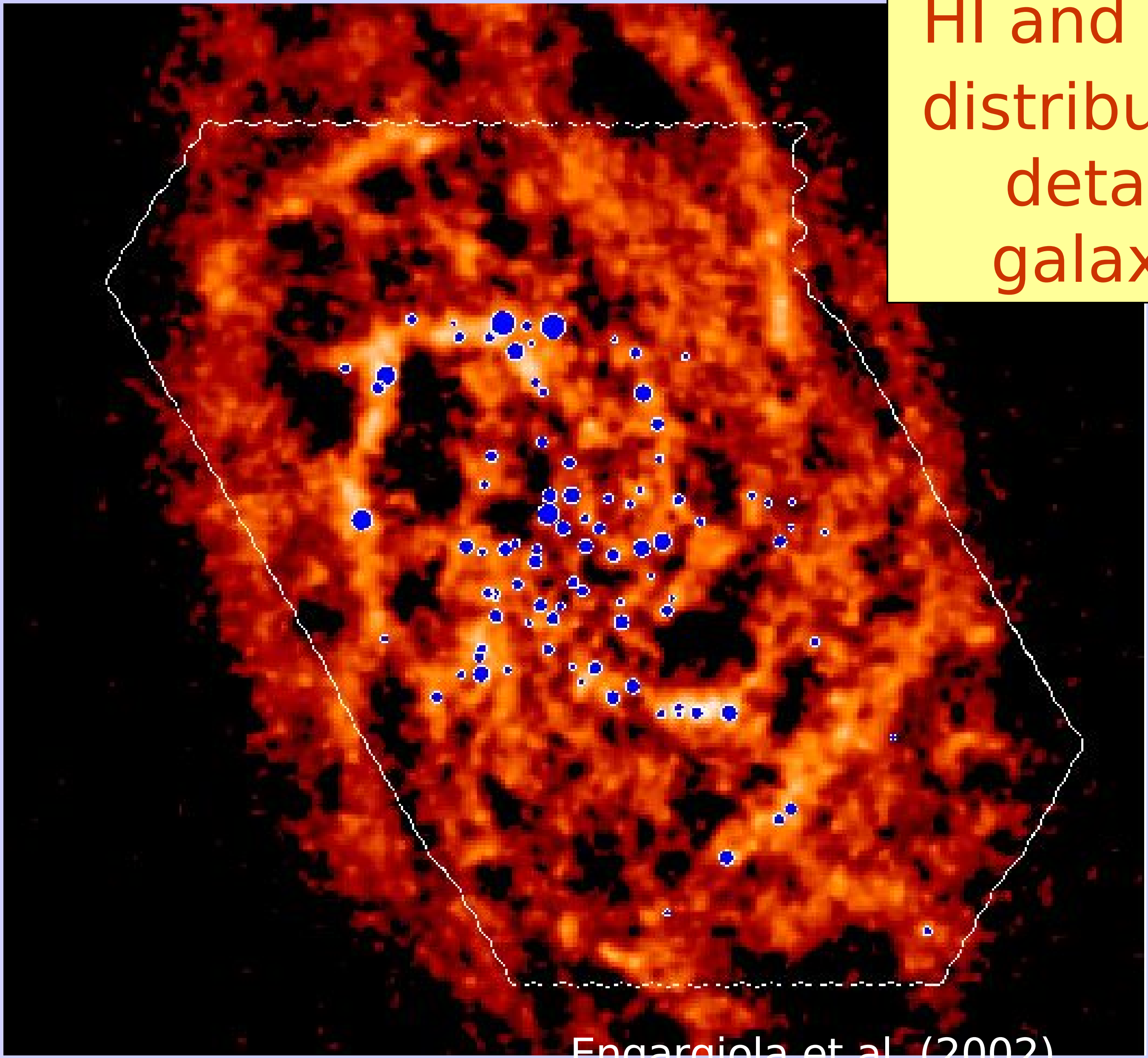
In these inner regions of galaxies, the H_2 cannot form from the HI; there simply isn’t enough of it.

Implications

- *Since molecular gas depletion times are generally less than a Hubble time, suggests that H_2 must form from HI (but this cannot true for GMCs everywhere in galaxies).*
- *If so, then there must be mechanisms to get HI from outer reaches of a galaxy to the central regions (and observational evidence for it).*
- *But total gas depletion times are also often less than a Hubble time. This suggests, not as strongly, that galaxies are still accreting matter.*

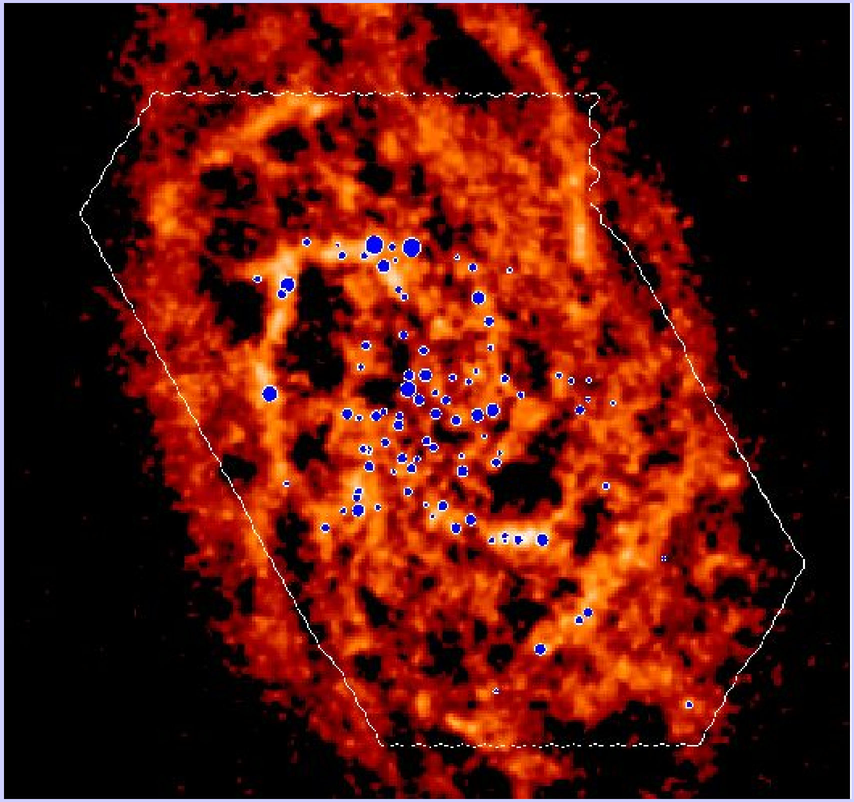
CO on HI in M33

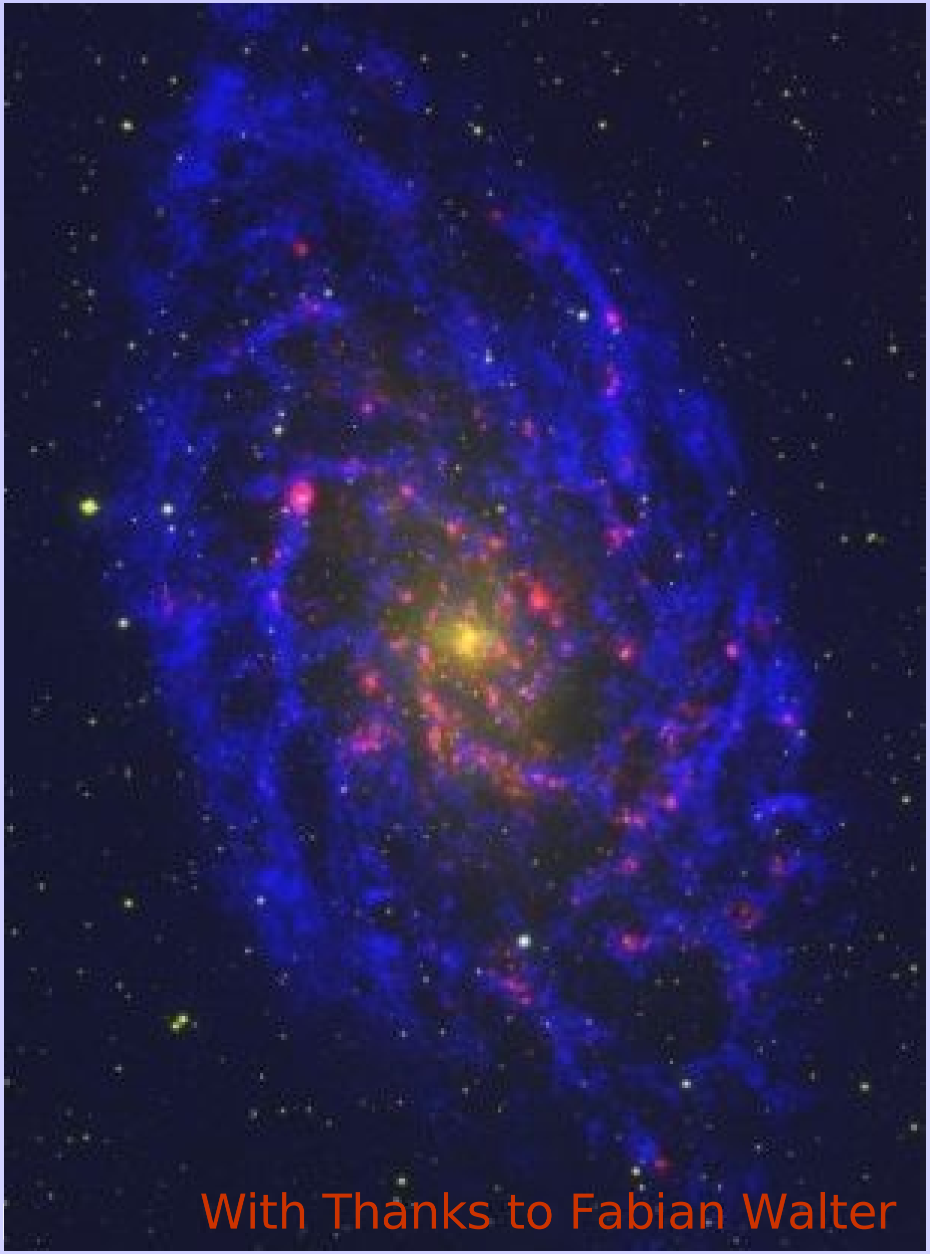
Let's see how HI and H_2 are distributed in detail in galaxies.



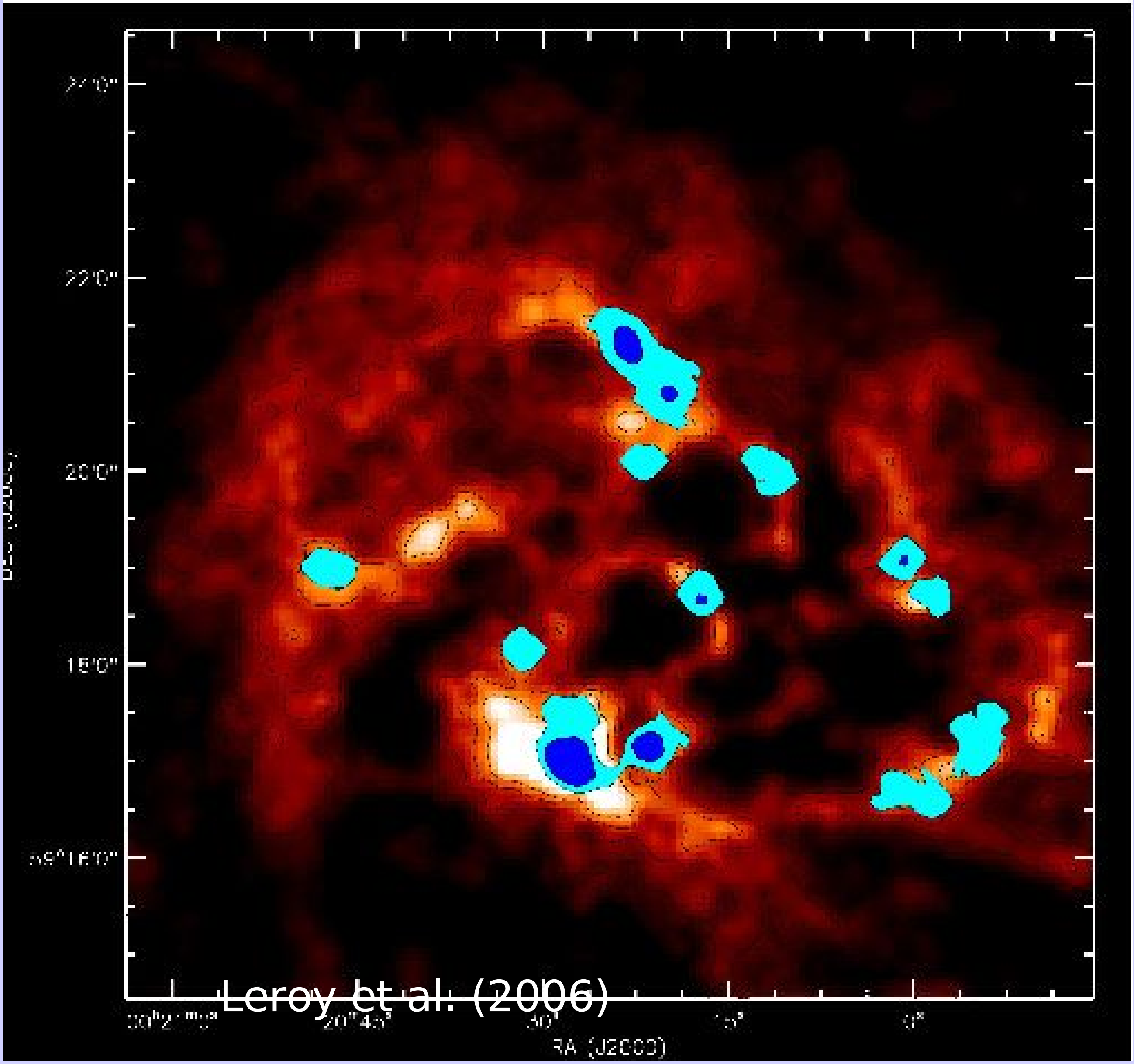
Engargiola et al. (2002)

CO on HI in M33

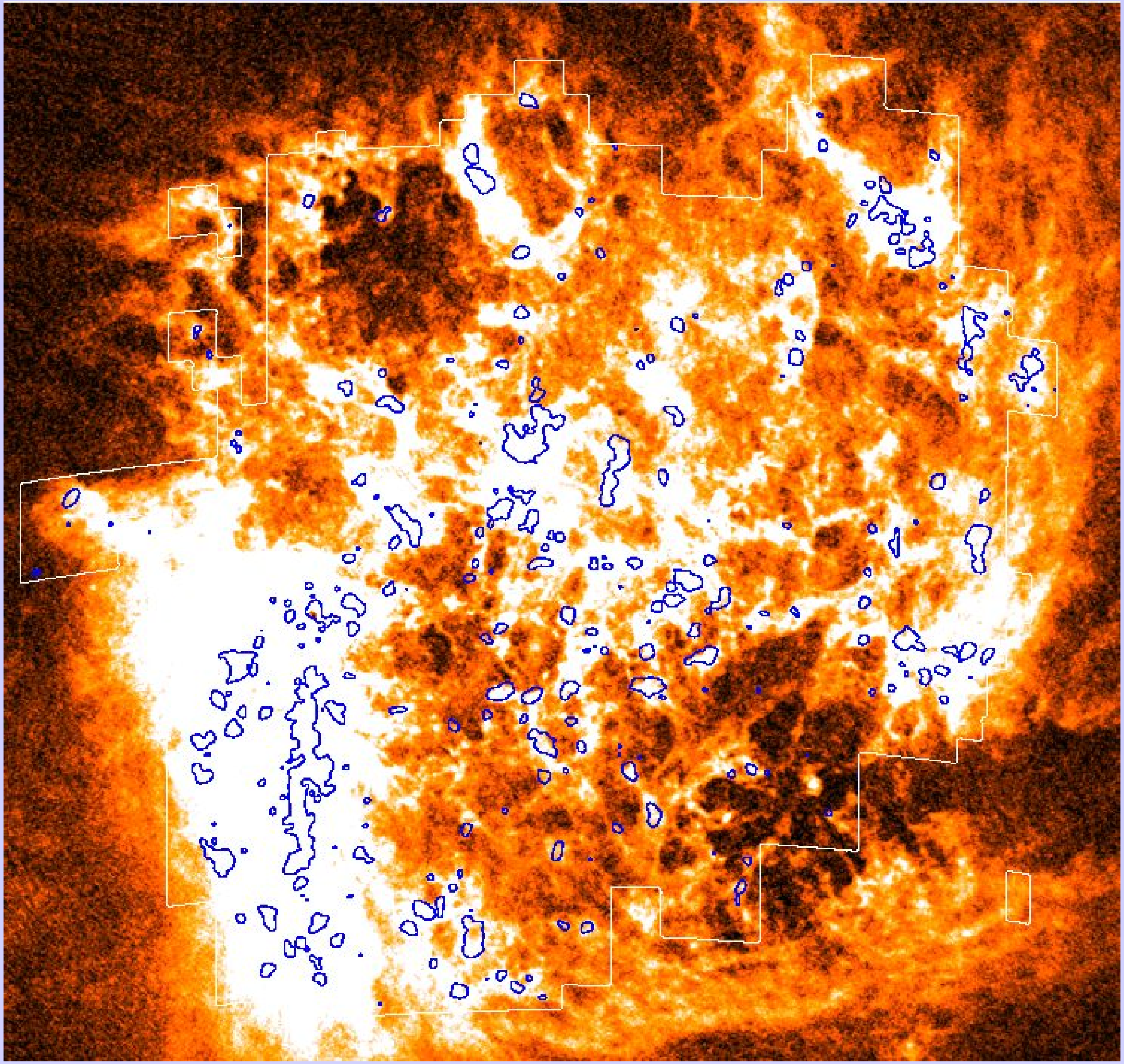




CO on HI in IC10



CO on HI in the LMC

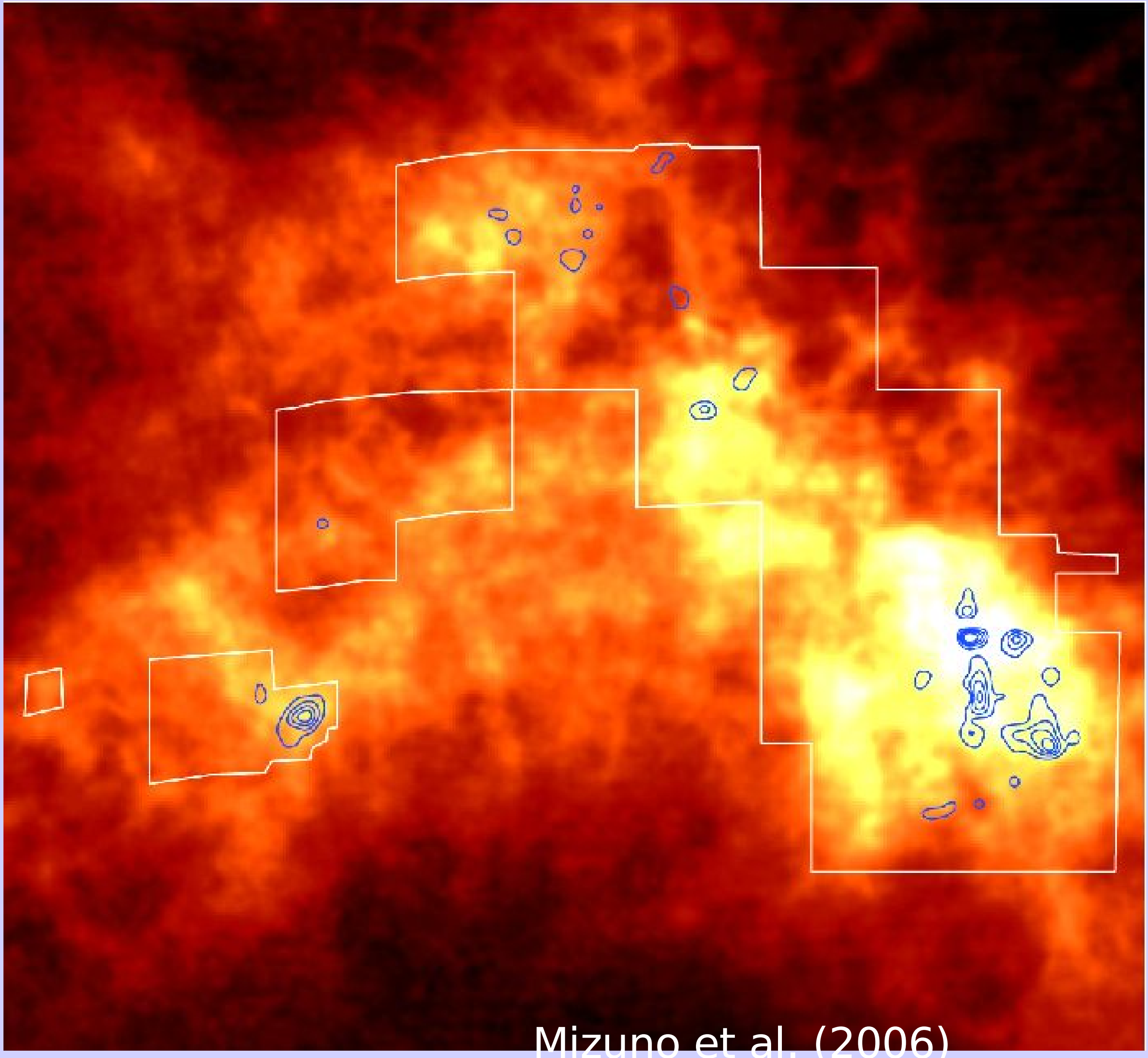


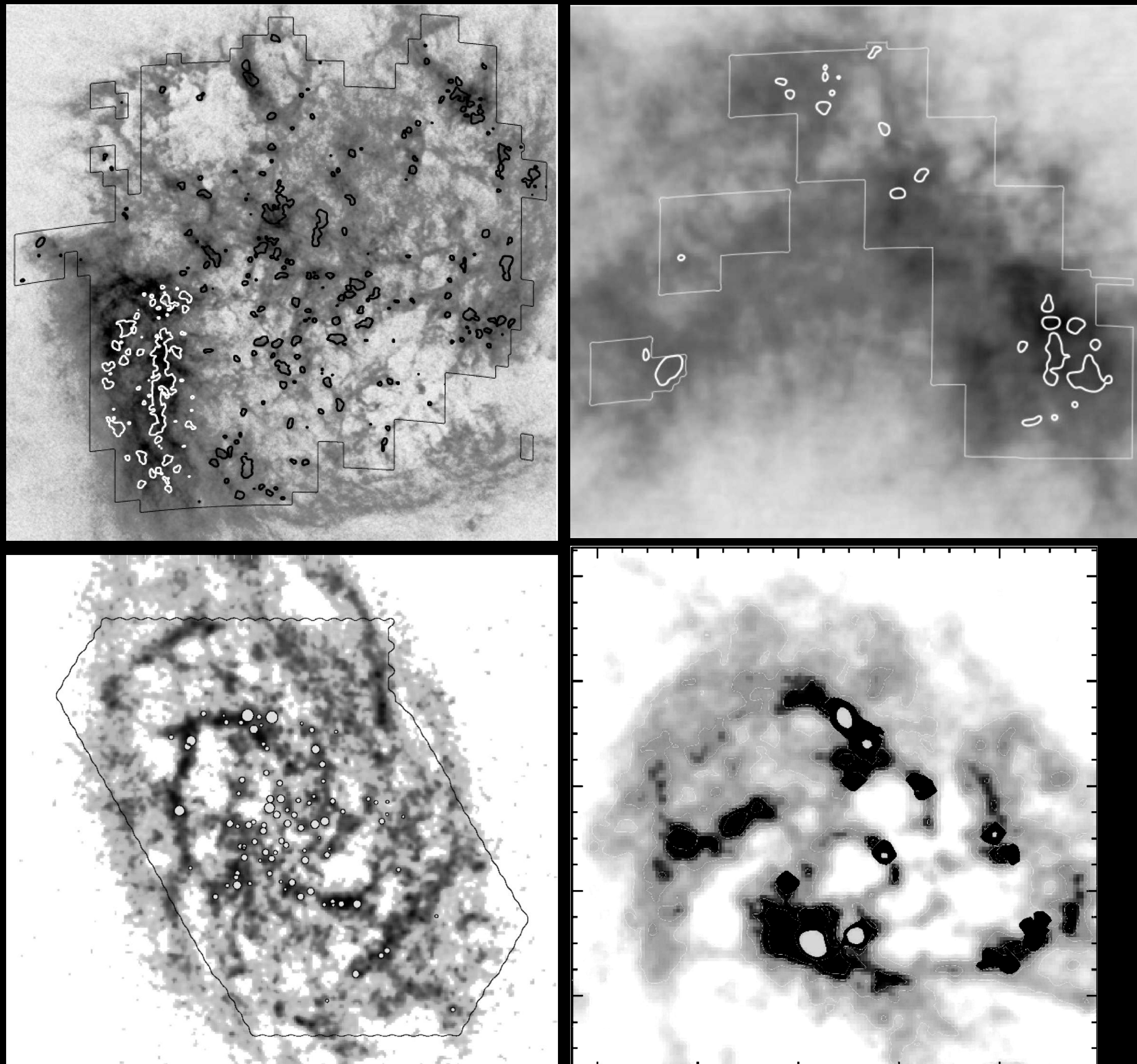
Total molecular mass

(10 % of HI)~ 7×10^7 M

HI : Kim et al. (1998), CO: Fukui et al. (2001)

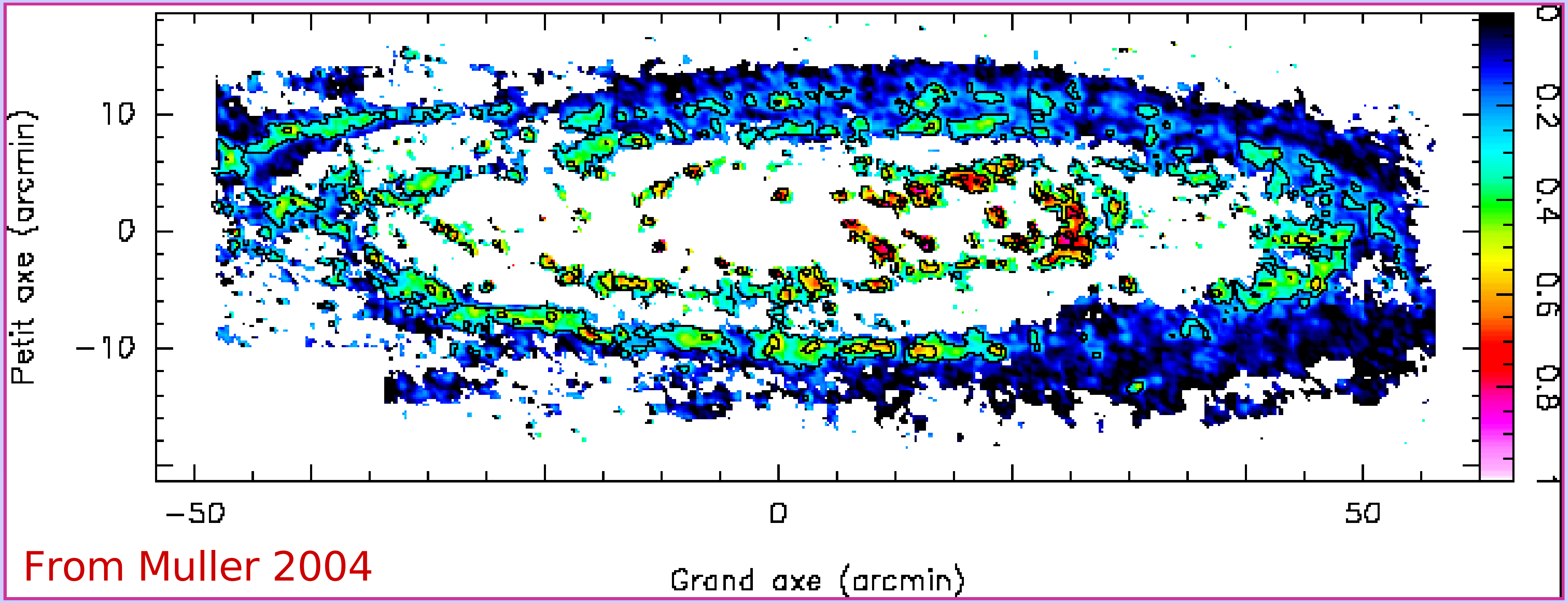
CO on HI in the SMC





HI Filaments in Nearby Galaxies

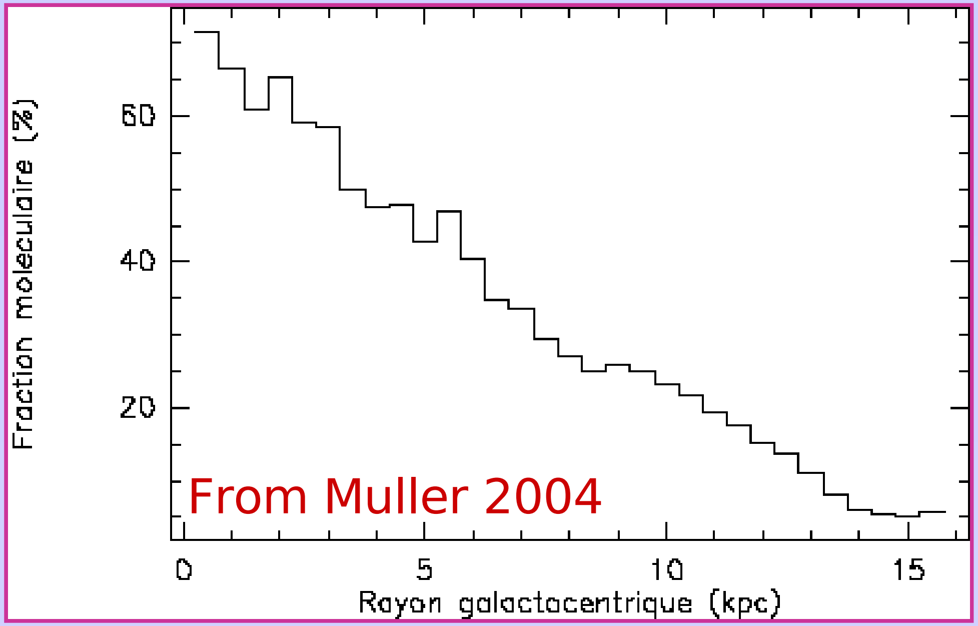
- The filaments seem to have gotten there first.
  - *Molecular cloud formation seems to require first the formation of cloudy filaments.*
  - *Filaments sometimes formed by gravity, sometimes by explosions.*
  - *Then the filament (cloud) has to decide what fraction becomes molecular (and thus star forming.*
  - *Pressure, then, determines what the molecular abundance is in a filament.*



From Muller 2004

Molecular Fraction $\frac{2N(H_2)}{N(HI)+2N(H_2))}$

Why is it that in the inner regions where there is little HI, the gas is still mostly H_2?



From Muller 2004

The Role of Pressure in GMC Formation

Let's *assume* that

$\Sigma(H_2)/\Sigma(HI) = f\,(P_{ext})$ only

$P_{EXT} = (2G)^{0.5}\Sigma_g v_g \{\rho_*^{0.5} + ((\pi/4)\,\rho_g)^{0.5}\}$

but, almost everywhere, $\rho_* >> \rho_g$

$P_{EXT} = 0.84(G\Sigma_*)^{0.5}\Sigma_g v_g h_*^{-0.5}$

but, v_g and h_* are constant in disk galaxies

$P_{EXT} = const\,\Sigma_* \Sigma_g^{0.5}$; $\Sigma(H_2)/\Sigma(HI) = f\,(\Sigma_* \Sigma_g)$

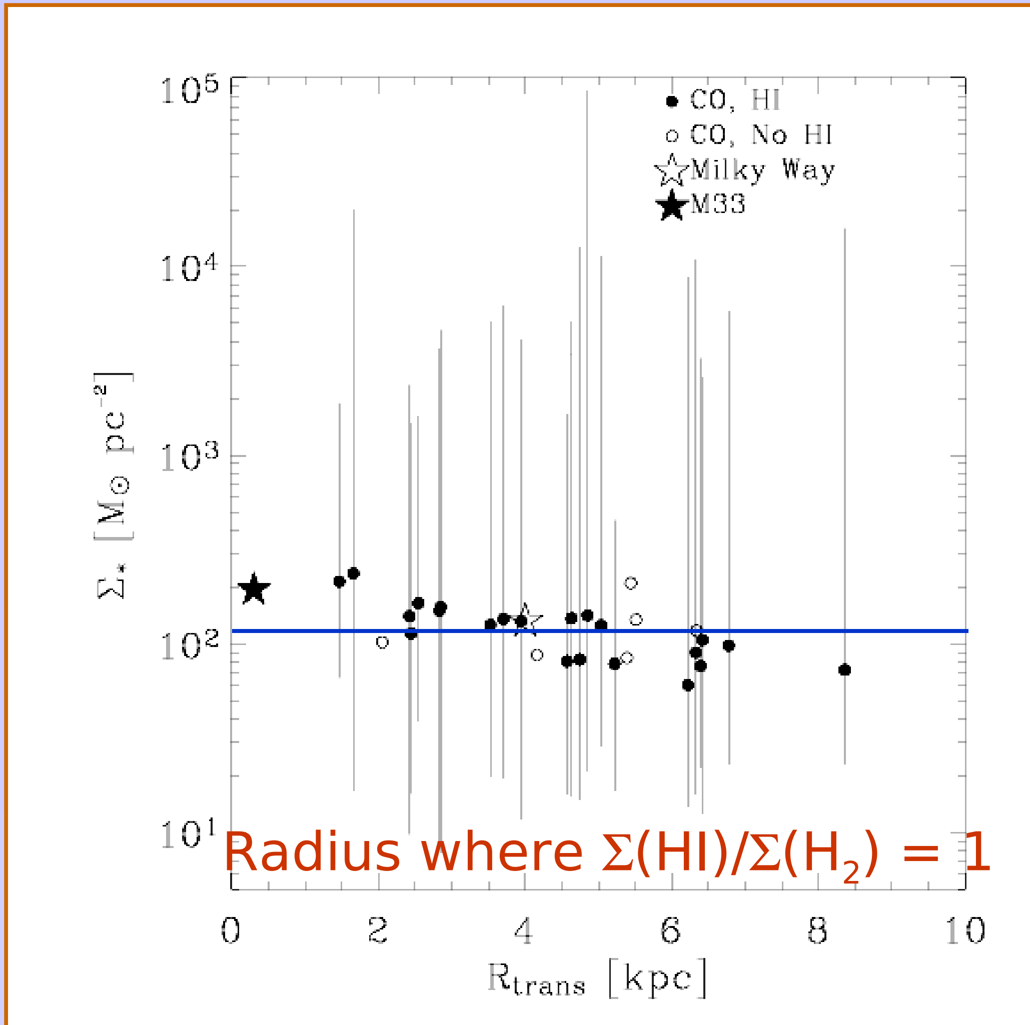
$$\Sigma(H_2)/\Sigma(HI) = f\,[P_{EXT}(\Sigma_* \Sigma_g)]$$

Now, consider when $\Sigma(H_2)/\Sigma(HI) = 1$. By assumption, this occurs for fixed P_{EXT} for all galaxies if there are no other parameters.

But, since Σ_{HI} is ~ 1 x 10^{21} cm^{-3}, then $\Sigma(H_2)/\Sigma(HI) = 1$ occurs at fixed Σ_g for all spiral galaxies, i.e. for $\Sigma_{GAS} = 2 \times 10^{21}$ cm^{-3}.

Prediction: The location where $\Sigma(H_2)/\Sigma(HI) = 1$ occurs is at the same value of Σ_* in *all* disk galaxies.

28 Galaxies from the BIMA SONG Survey



$\langle\Sigma_*\rangle = 120$

+/-10 M pc^{-2}

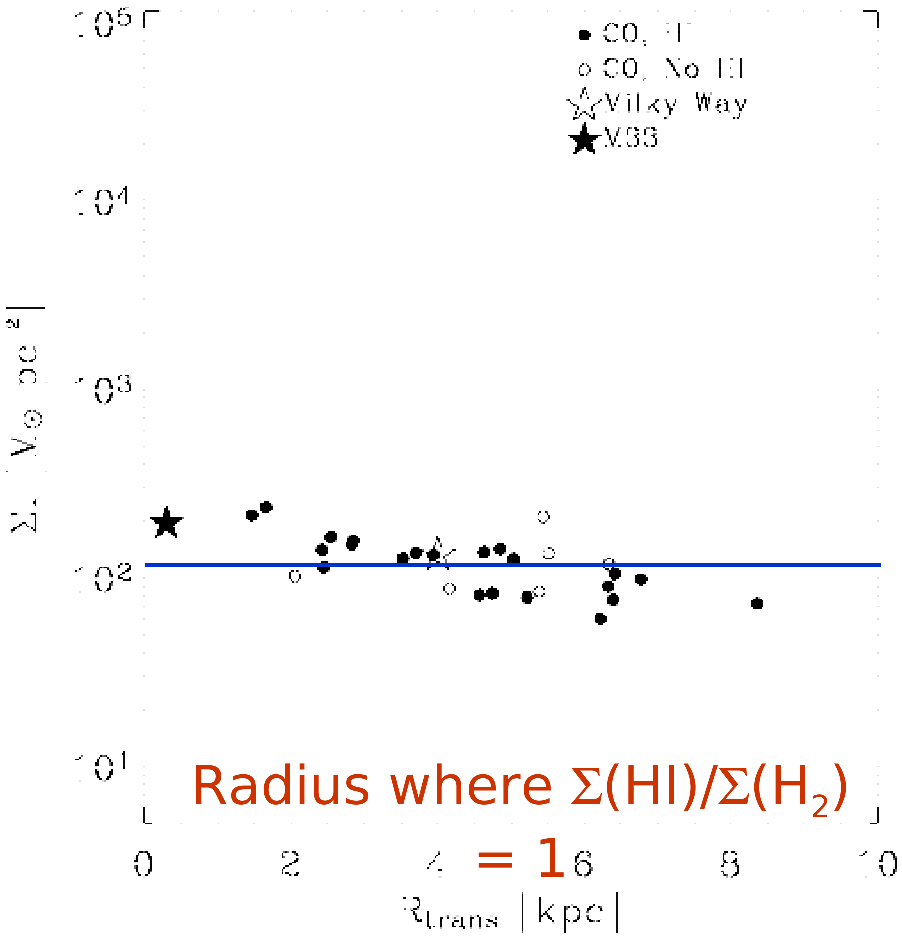
For 28 galaxies

rms scatter = 40%

Blitz & Rosolowsky 2004

22 with measured Σ(HI)

28 Galaxies from the BIMA SONG Survey



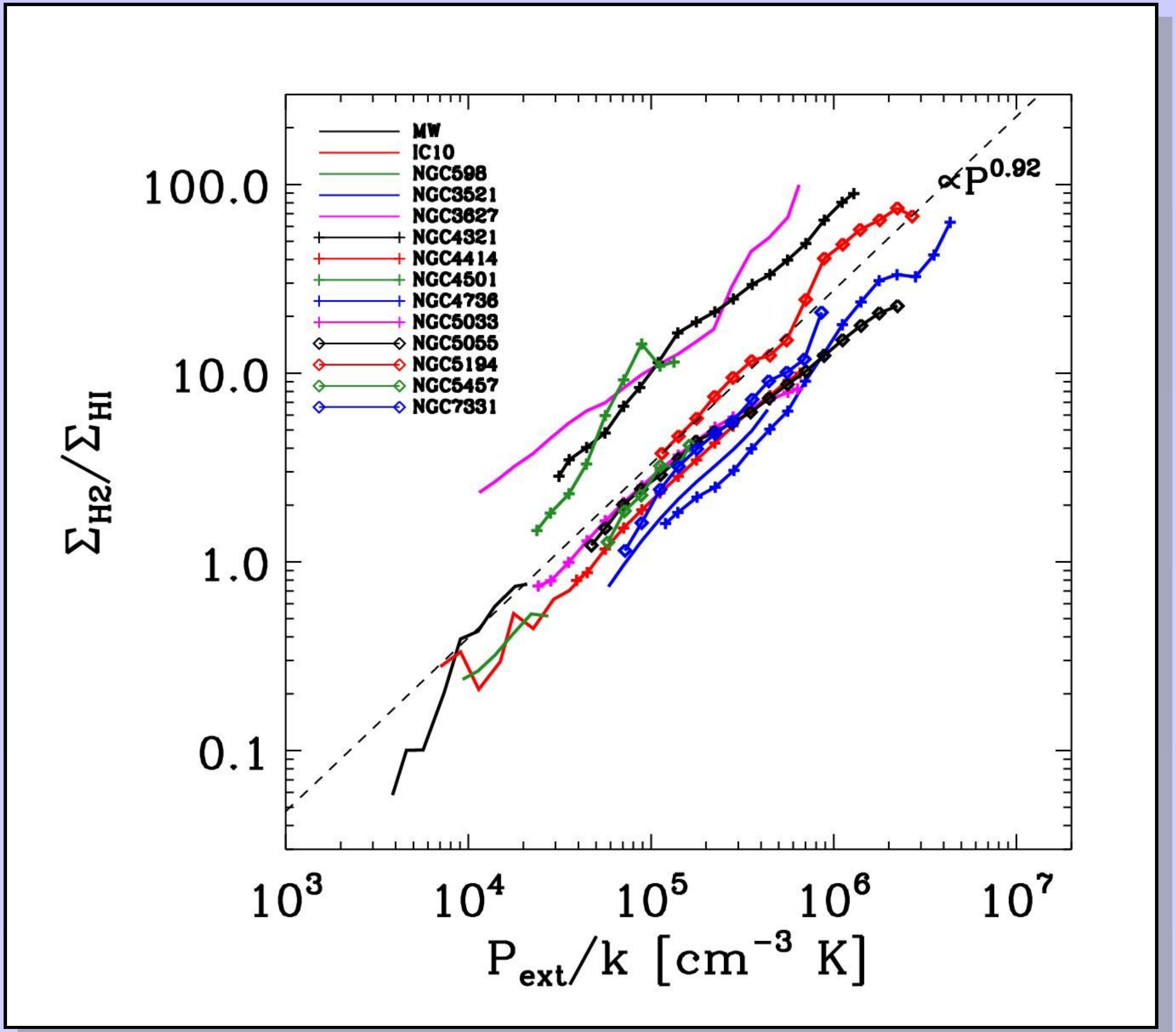
For Milky Way: $\Sigma(H_2)/\Sigma(HI) = 1$ at the peak of the molecular ring (R = 4 kpc)

$\Sigma_*(R\ ) = 35$ M pc^{-2}

$R_* = 3$ kpc

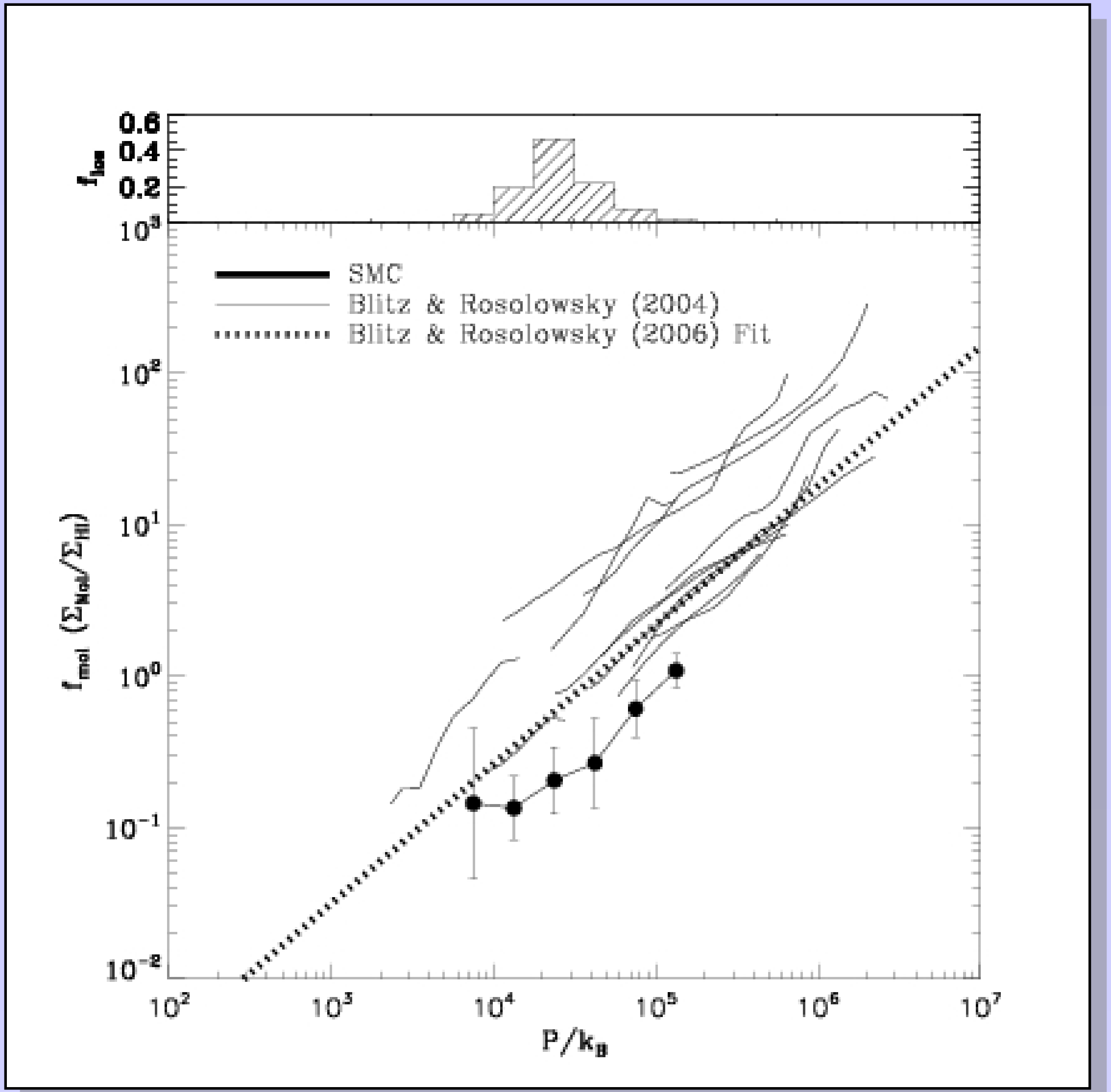
$\Sigma_*(4) = 132$ M pc^{-2}

Pressure vs. H_2/HI



Blitz & Rosolowsky (2006)

Pressure vs. H_2/HI



Leroy et al. (2006)

$$\Sigma(H_2)/\Sigma(HI) = (P_{ext}/P_O)^{0.92}$$

$$P_O = 4.4 \times 10^4 \text{ cm}^{-3} \text{ K}$$

P_O is the pressure at the location where $\Sigma(H_2)/\Sigma(HI) = 1$

Occurs at the same value of Σ_* in *all* disk galaxies.

Star Formation Prescription

Using the relation of Gao & Solomon with FIR as a SF tracer:

$$\Sigma_{\rm SFR} = 0.1\ \epsilon \Sigma_g \left(\frac{P_{ext}}{P_0}\right)^{0.92} \quad M_\odot\ \mathrm{pc}^{-2}\ \mathrm{Gyr}^{-1}$$

Low Pressure

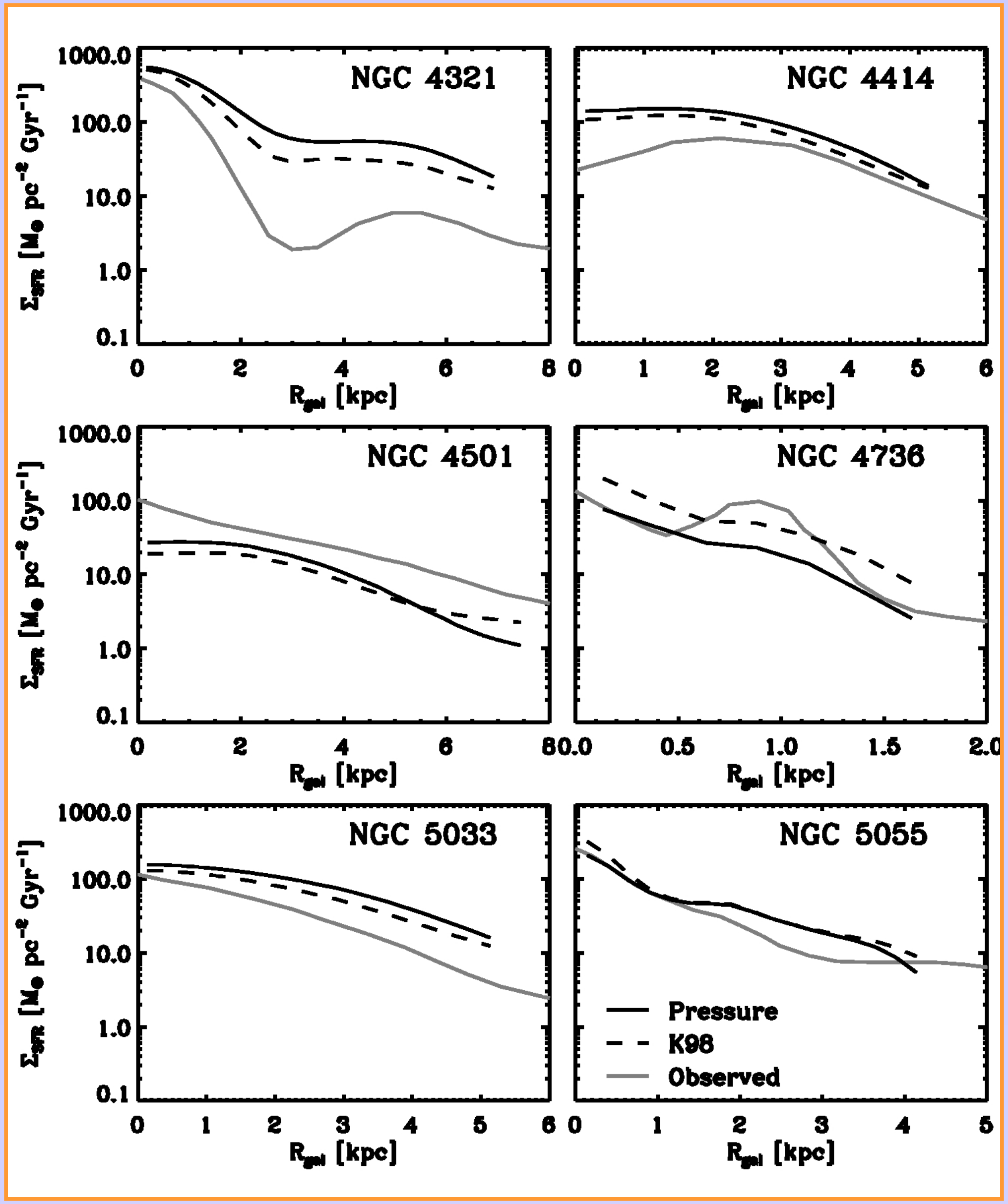
$$\dot{M}_\star = (0.77 \pm 0.07) \left(\frac{M_{\rm H2}}{10^9\ M_\odot}\right)^{1.44} \quad M_\odot\ \mathrm{yr}^{-1}.$$

High Pressure

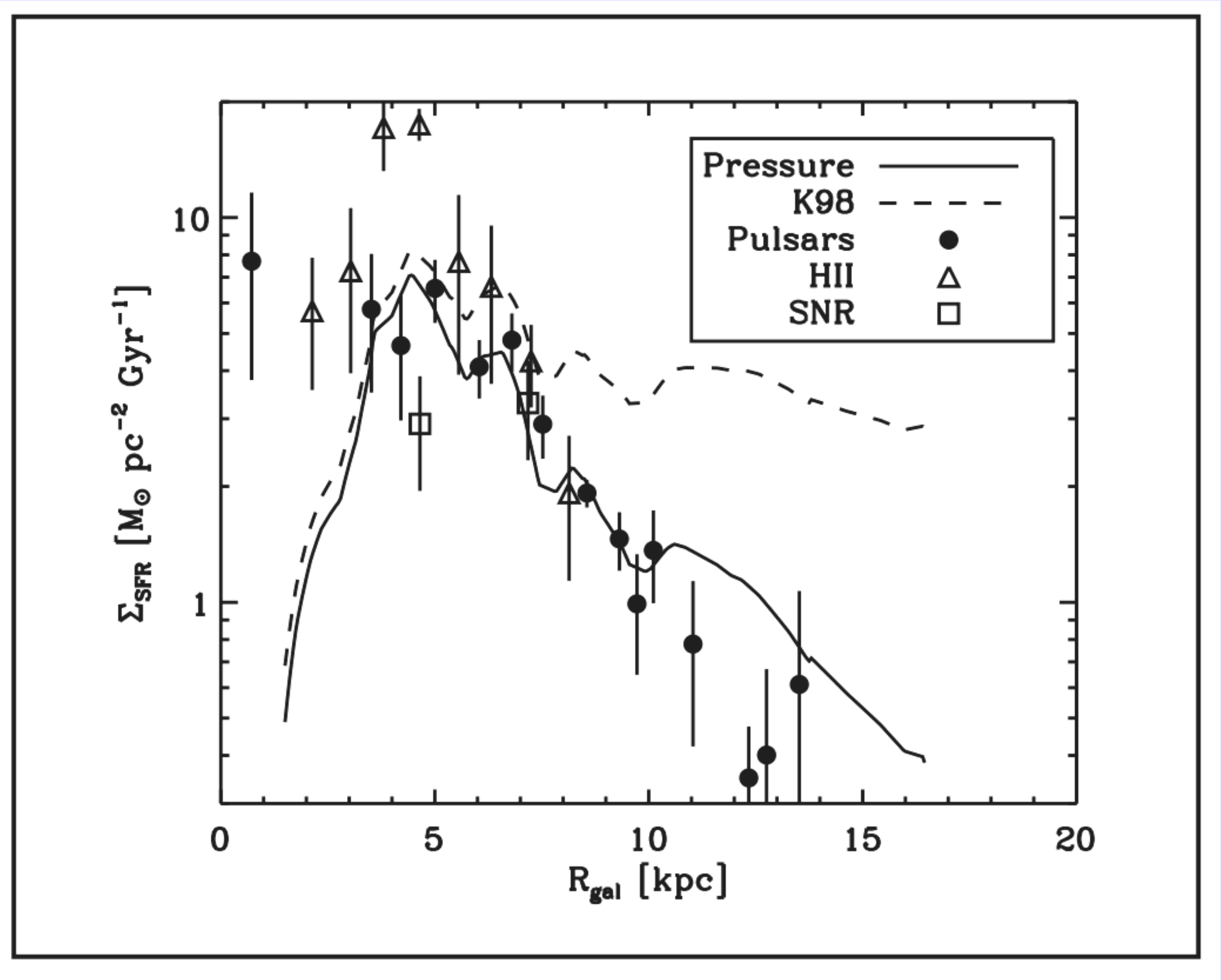
Kennicutt relation:

$$\Sigma_{\rm SFR} = 0.16\ \Sigma_g^{1.4}$$

High Pressure Comparison

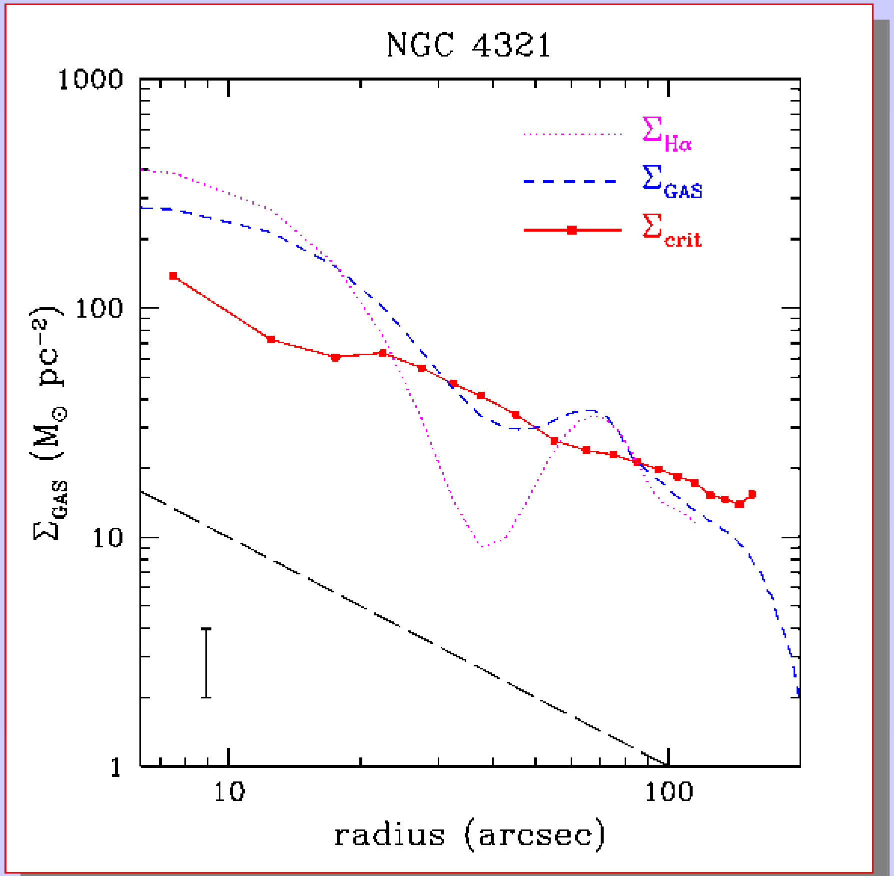


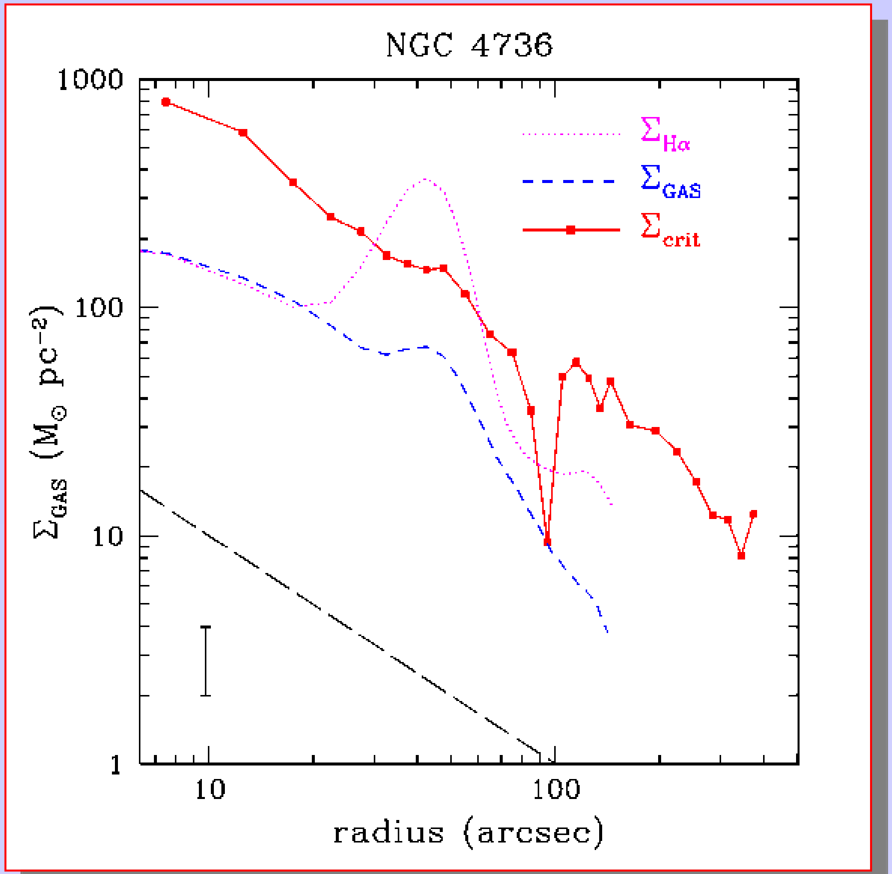
Low Pressure Comparison



The Milky Way

Radial instability of the gas layer





Wong & Blitz 2002

Why is Q_g (i.e. $\Sigma_{crit}/\Sigma_{tot}$) near unity?

$$V_c^2 = 2\pi G \Sigma_{tot} R$$

$$\Sigma_{tot} = \frac{\Omega V_c}{2\pi G}$$

For a Mestel disk with a flat rotation curve

$$\Sigma_{crit} = \frac{\sqrt{2}\,\Omega c_g}{\pi G}$$

For flat rotation curve

$$\mu Q_g = \frac{\Sigma_{crit}}{\Sigma_{tot}} = \frac{2\sqrt{2}\,c_g}{V_g}$$

For $\mu = \frac{\Sigma_{gas}}{\Sigma_{tot}}$

$$Q_g = \frac{2.8 c_g}{\mu V_c}$$

$C_g \sim 7$ km s^{-1}; $V_c \sim 200$ km s^{-1}; $\mu \sim 0.1$ → $Q_g \sim 1$

Based on Wong & Blitz 2002

Summary & Conclusions

1. The question “Do molecular clouds form from HI or H_2?” is ill posed.
2. GMCs form on filaments of pre-existing HI in galaxy disks.
3. The local H_2 fraction and the star formation rate in galaxies depends on the ambient pressure (only).
4. Pressure regulated star formation produces good fits to SF even where HI dominates.
5. There should be better evidence for infall and inflow in galaxies.