Radial Gas Distributions and the Gas Depletion Time Problem

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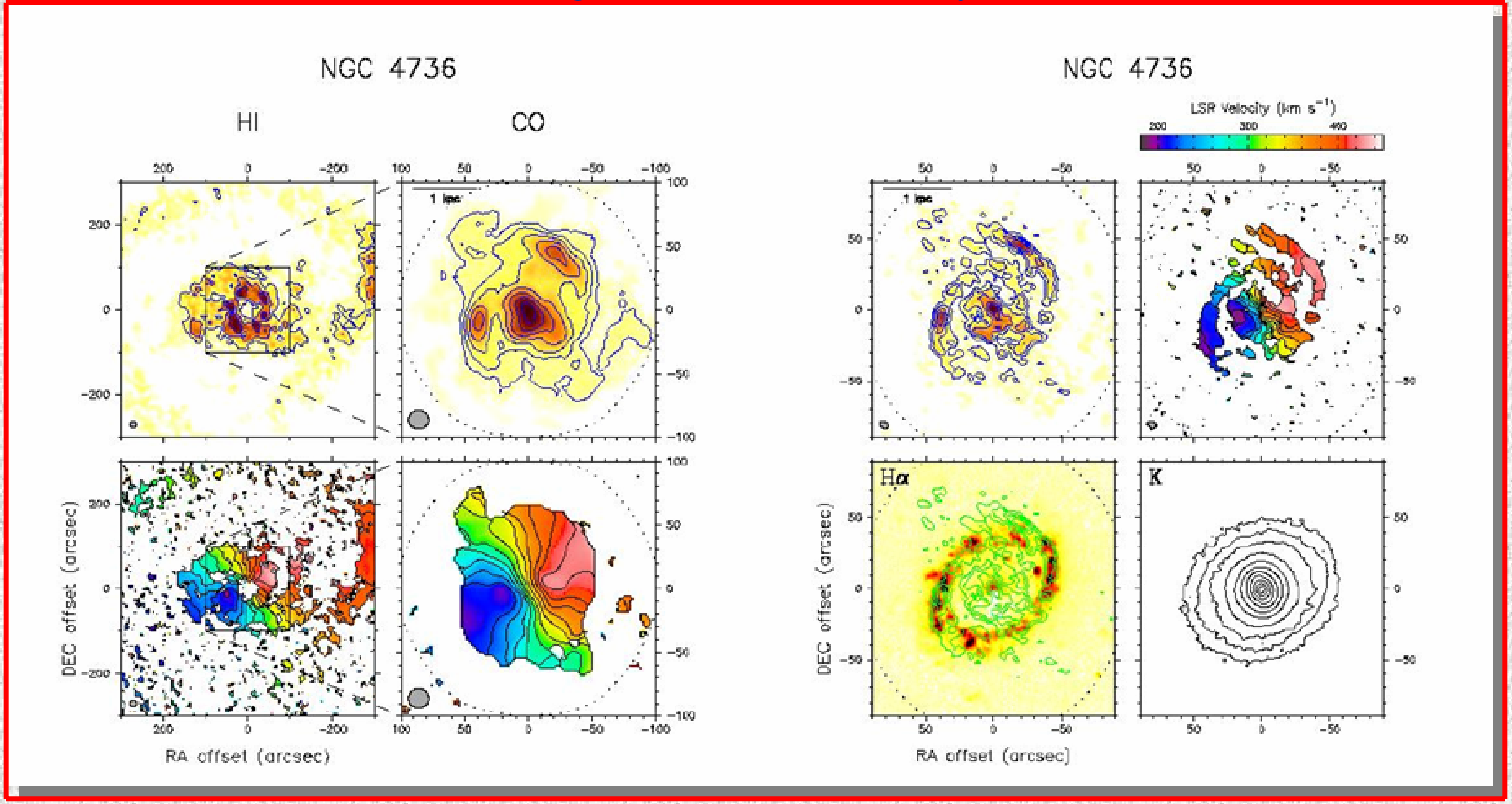
Consider Gas Depletion Times

Atomic, molecular gas and star formation in M94



Wong & Blitz 2002

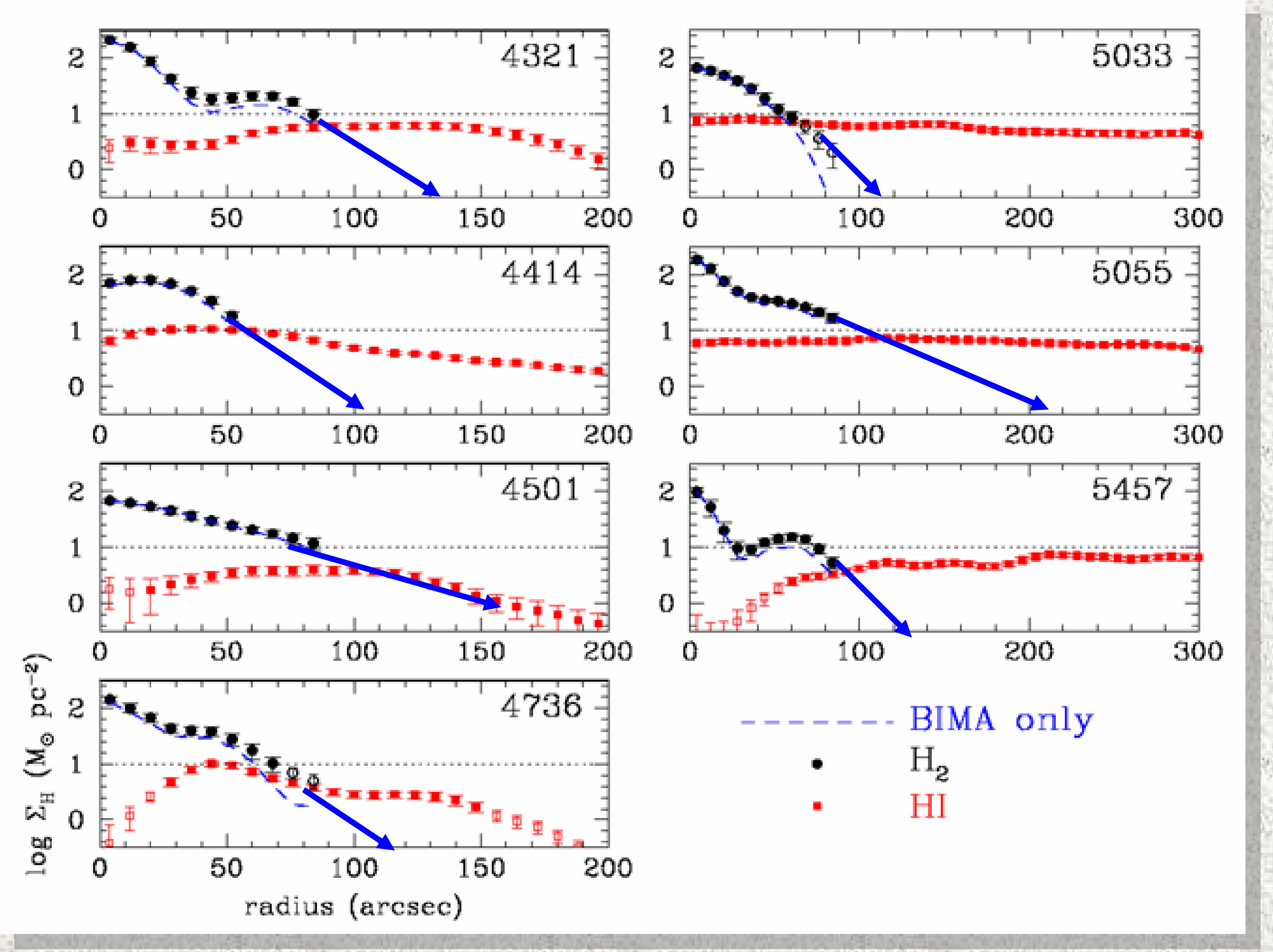
Radial Surface Density Profiles

HI roughly constant with R;

Saturates at ~8-10 $M_\odot pc^{-2}$

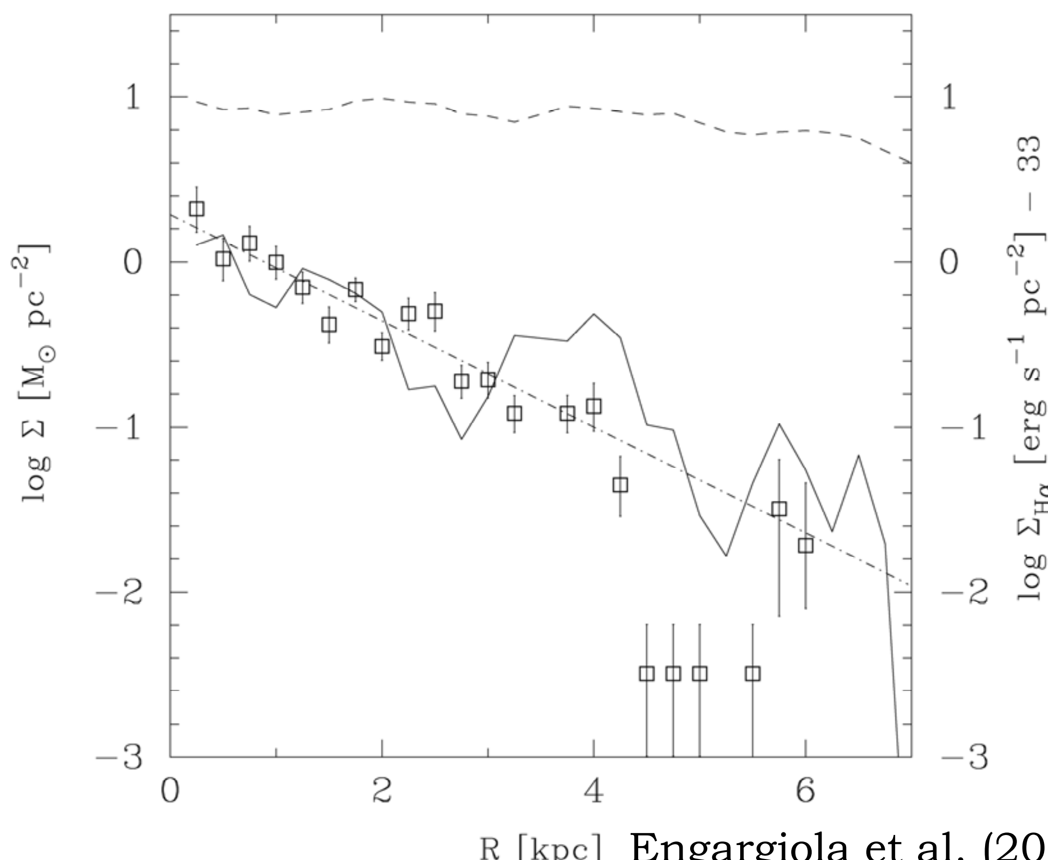
CO is monotonically decreasing (almost)

roughly exponential



Wong & Blitz 2002

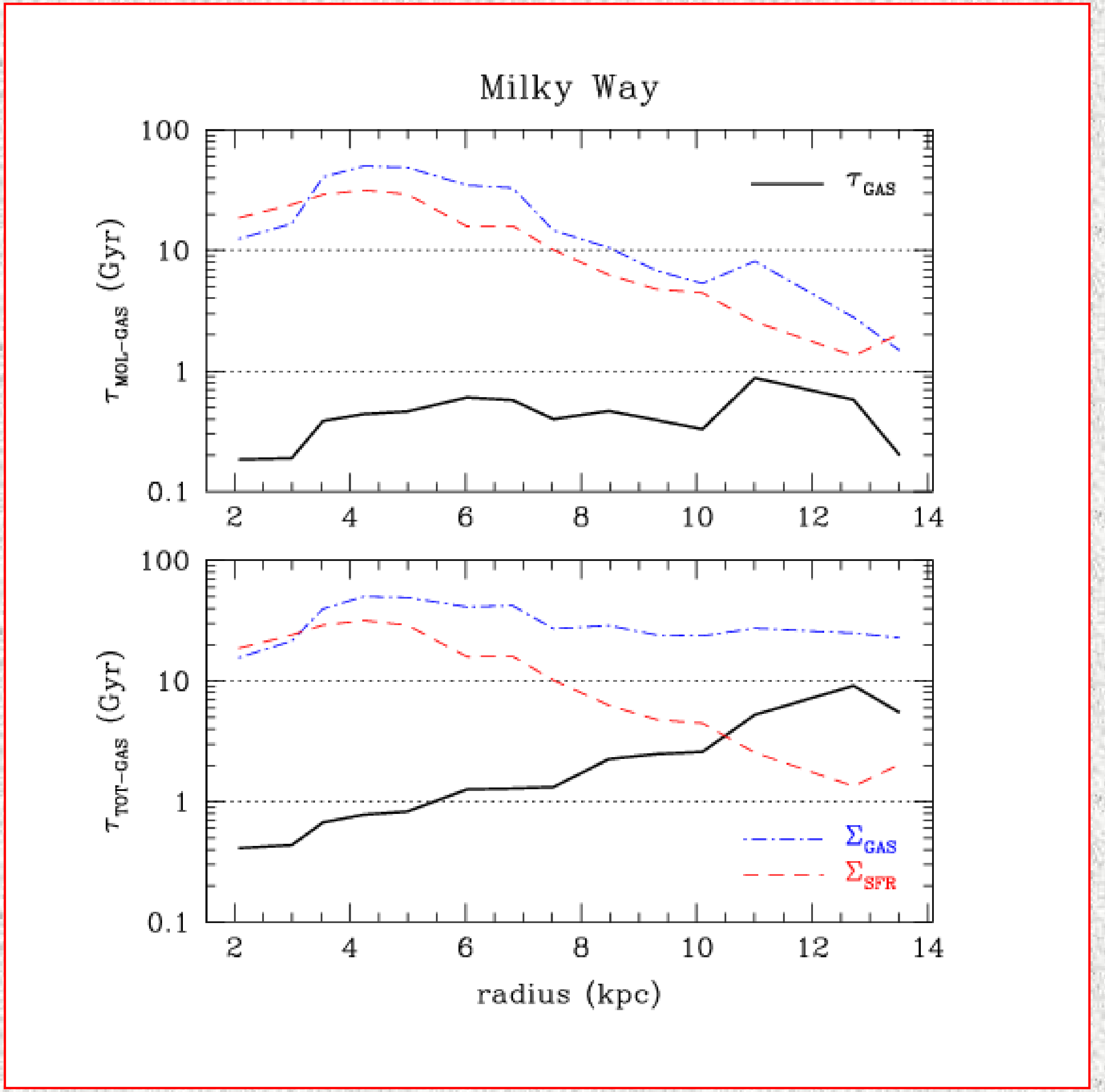
M33 HI and Stellar Surface Densities



Engargiola et al. (2003)

Gas in the center is not always primarily molecular

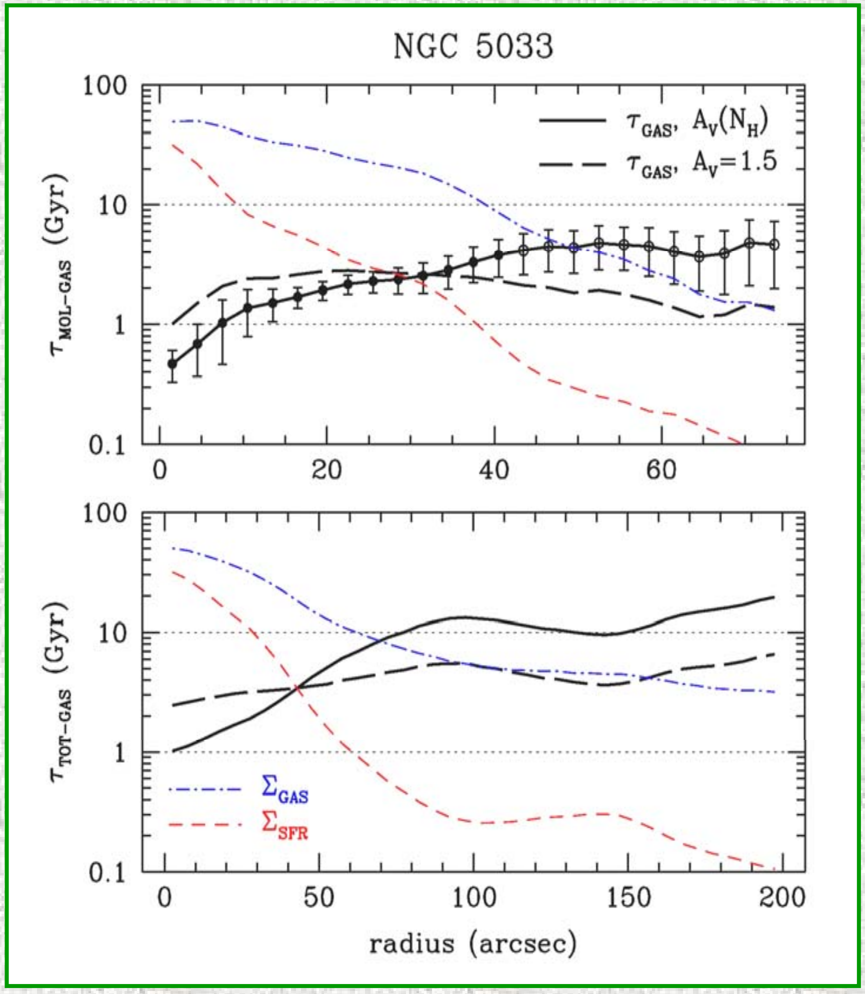
Gas Depletion Time

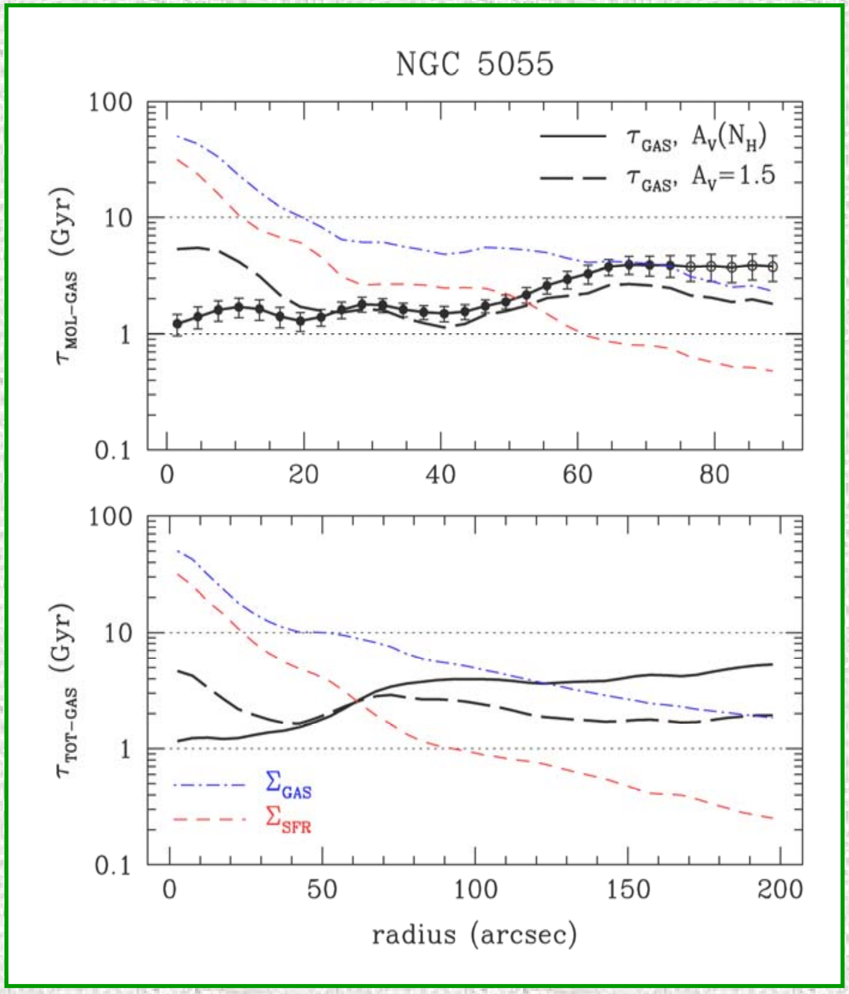


Wong 2001

Molecular Gas Depletion Time

molecule – rich galaxies

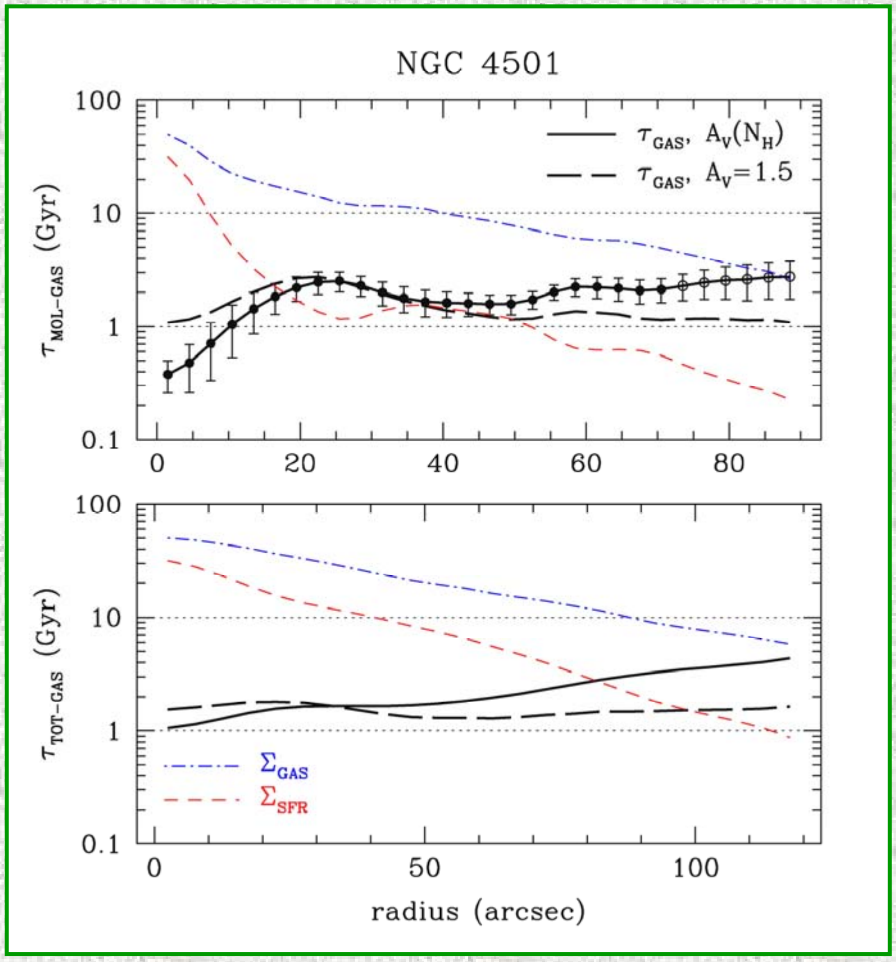


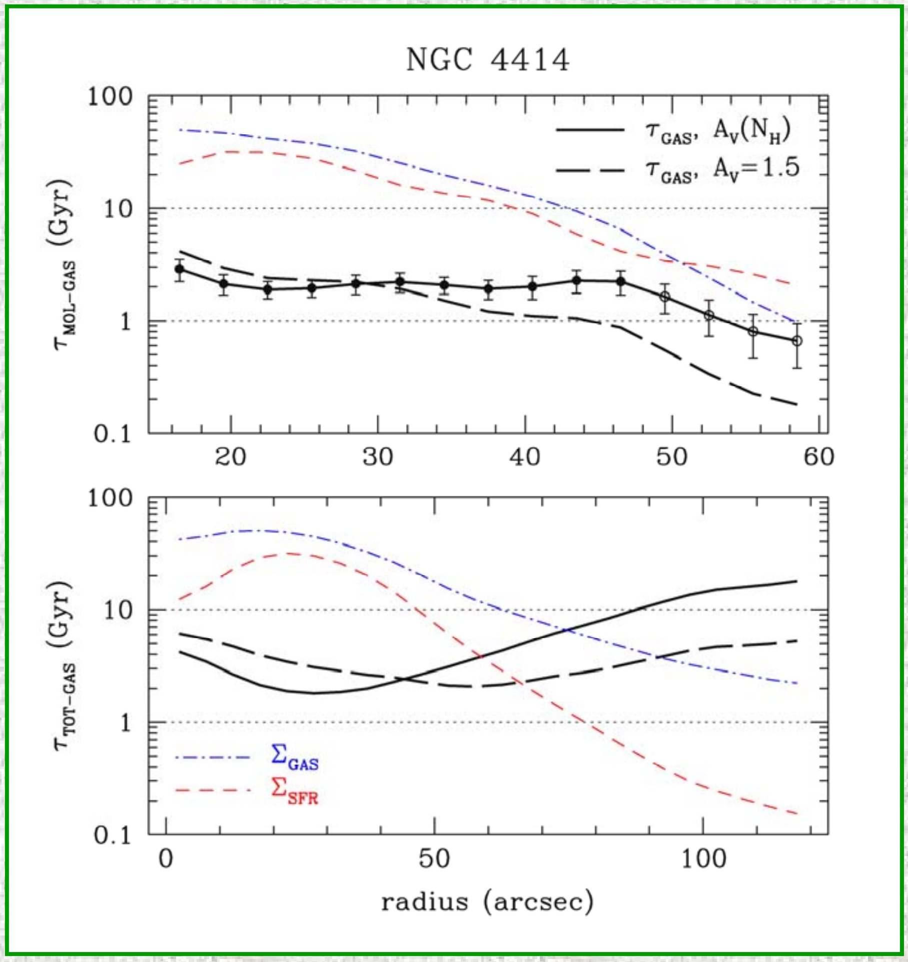


Wong & Blitz 2002

Molecular Gas Depletion Time

molecule – rich galaxies





Wong & Blitz 2002

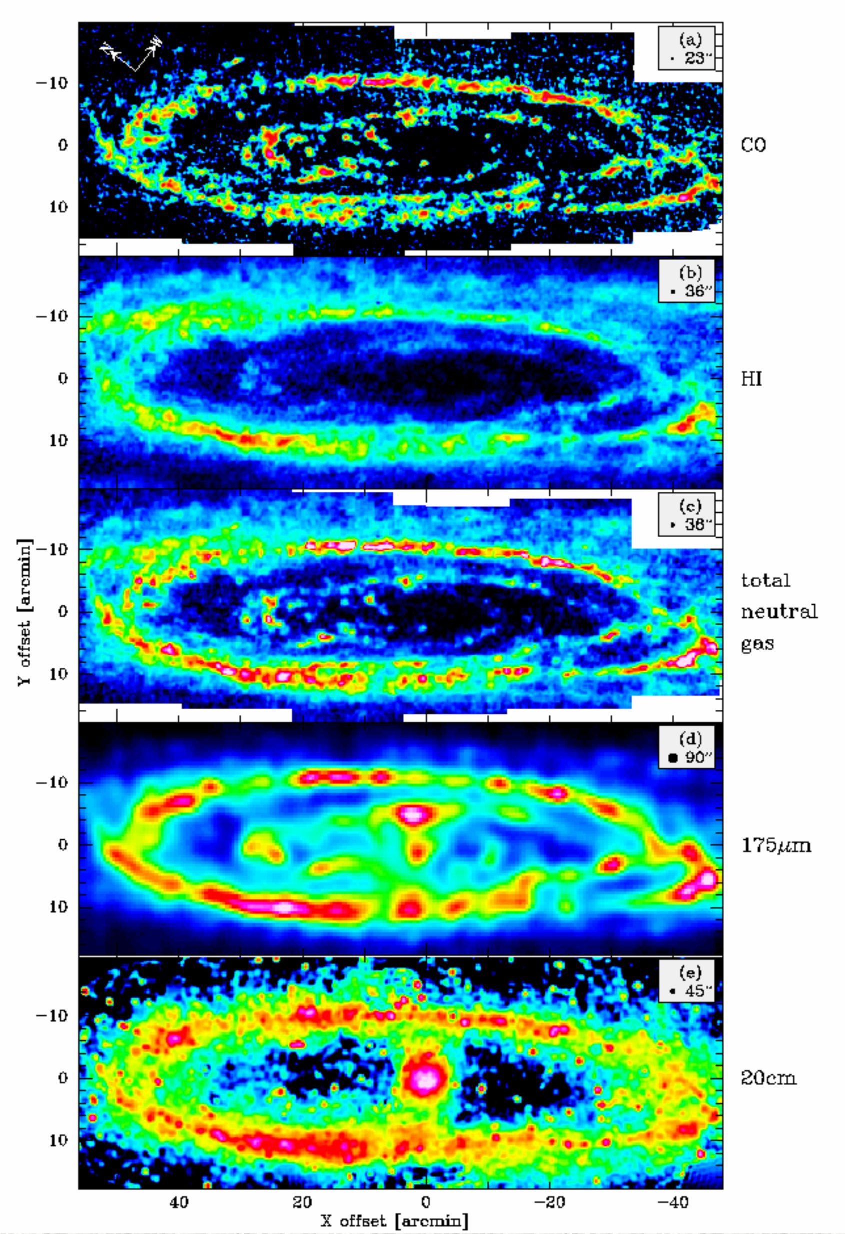
The Gas Depletion Problem

- Do we live in a special era?
- Does the Madau plot imply that we are running out of gas?
  - Problem is not running out of gas; gas is in the wrong phase and wrong place.
  - Star formation rate in disk of MW ~constant for last 5 x 10^9 y.
  - Problem is most severe in galactic centers (scale 5 kpc), but is also a problem in many galactic disks.

Two Standard Solutions

- Infall – Galaxies are still accreting gas from the IGM.
  - This gas will preferentially fall to the outside of galaxies, not to the center where we need it.
  - Primordial infall has not been observed. Evidence weighs against HVCs. No zero metallicity gas has been observed.

M31



If the solution to the gas depletion problem is infall, why isn't it infalling on the most massive galaxy in the local group?

Two Standard Solutions

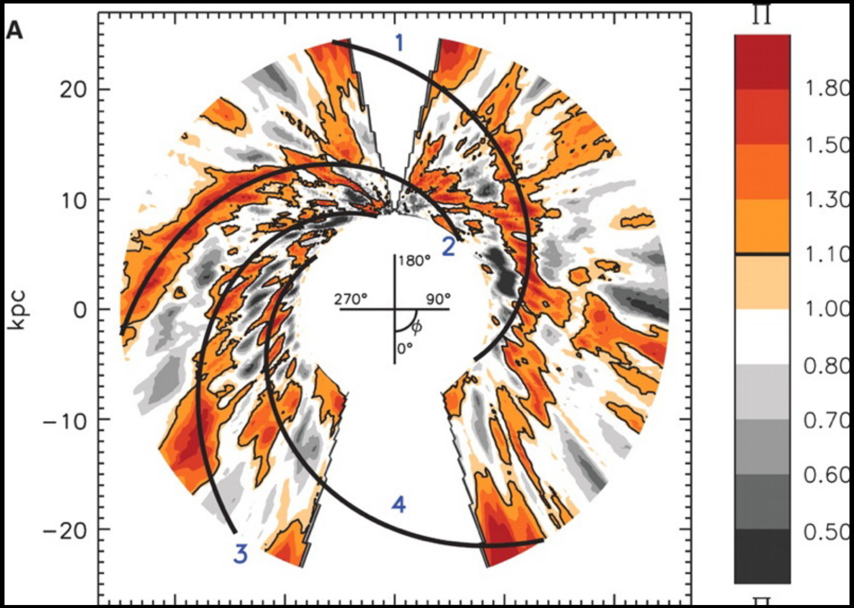
- Infall – Galaxies are still accreting gas from the IGM.
  - This gas will preferentially fall in at large radii of galaxies, not in center where we need it.
  - Primordial infall has not been observed. Evidence weighs against HVCs. No zero metallicity gas has been observed.
- Inflow – Viscosity, angular momentum transfer (spiral arms) brings gas to center.
  - Has not been observed although velocities are 5-7 km s^{-1}, except in bars. The reservoir of HI exists mostly beyond where stellar spiral arms are found.
  - Has small effect at large radii beyond stellar disk.

HI Self-Torque?

1. Outer HI disk fed by satellite accretion
2. HI cools to $Q_{HI} \approx 1$
3. $Q_{HI} \approx 1$ gas forms trailing spirals by swing amplification
4. Trailing spirals transmit angular momentum outward

HI Map of Outer Milky Way

$\delta\Sigma/\Sigma \sim 1$ $\quad m \sim$ several



Levine, Blitz, & Heiles 06

$$t_{\rm inflow} \equiv \frac{R}{\dot{R}} \sim \frac{L_z}{\tau}$$

$$\sim \frac{\Sigma R^3 v_\phi}{m(\delta\Phi)^2 R/4G}$$

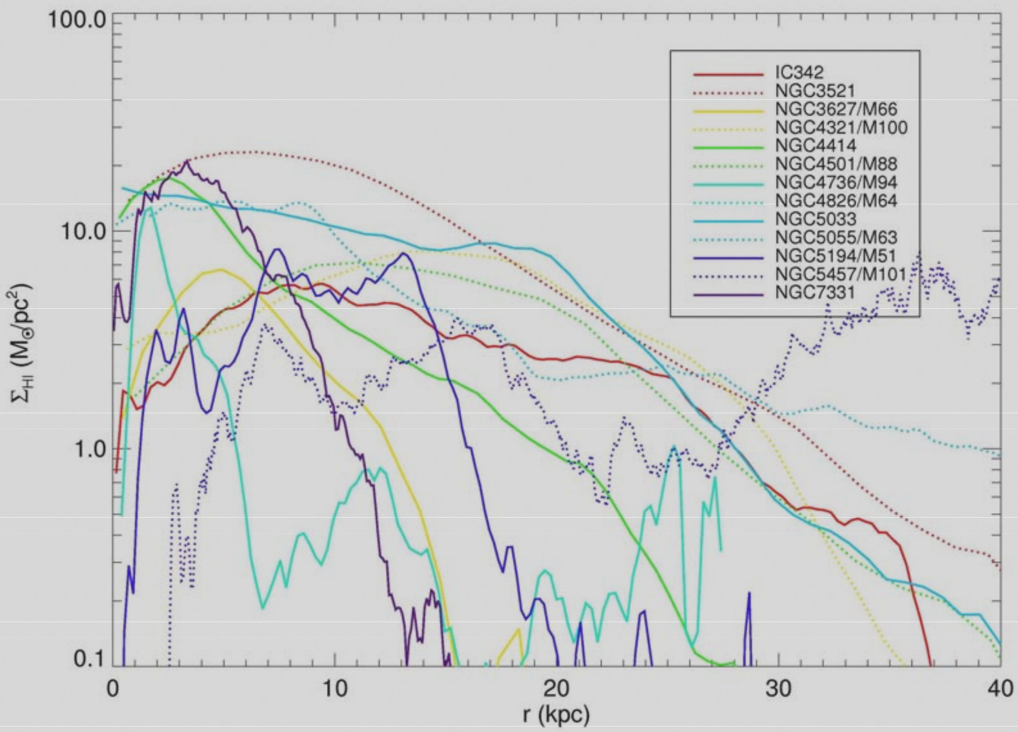
$$\sim 10^{11}\,{\rm yr}\left(\frac{10}{m}\right)\left(\frac{kR}{2\pi}\right)^2 \times$$

$$\left(\frac{\Sigma}{4M_\odot{\rm pc}^{-2}}\right)\left(\frac{4M_\odot{\rm pc}^{-2}}{\delta\Sigma}\right)^2$$

$$\gg \Sigma/\dot{\Sigma}_{\rm SFR} \sim 10^9\,{\rm yr}$$

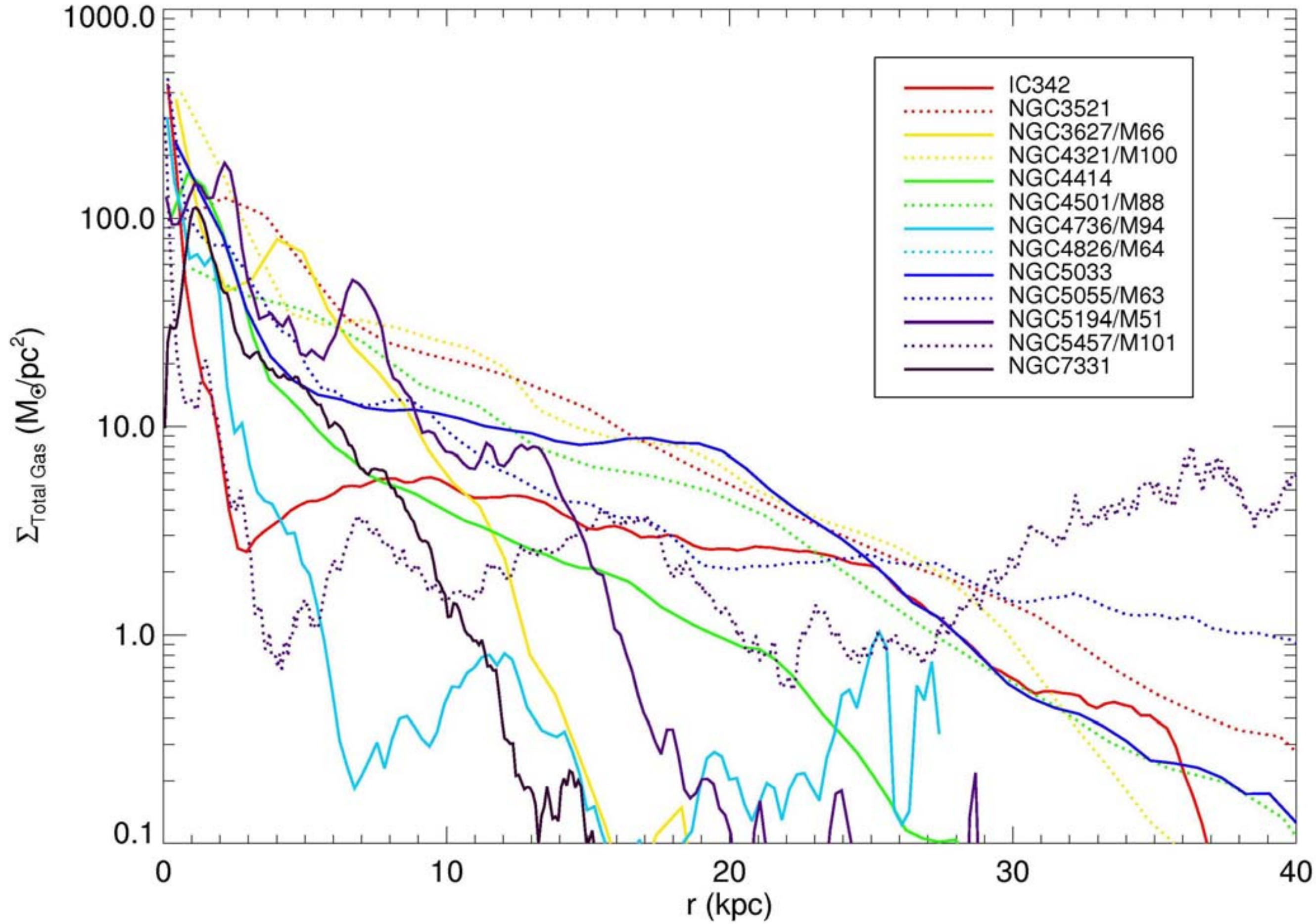
Is there a scaling that makes sense of the different gas distributions in galaxies?

HI radial profiles of 13 Galaxies

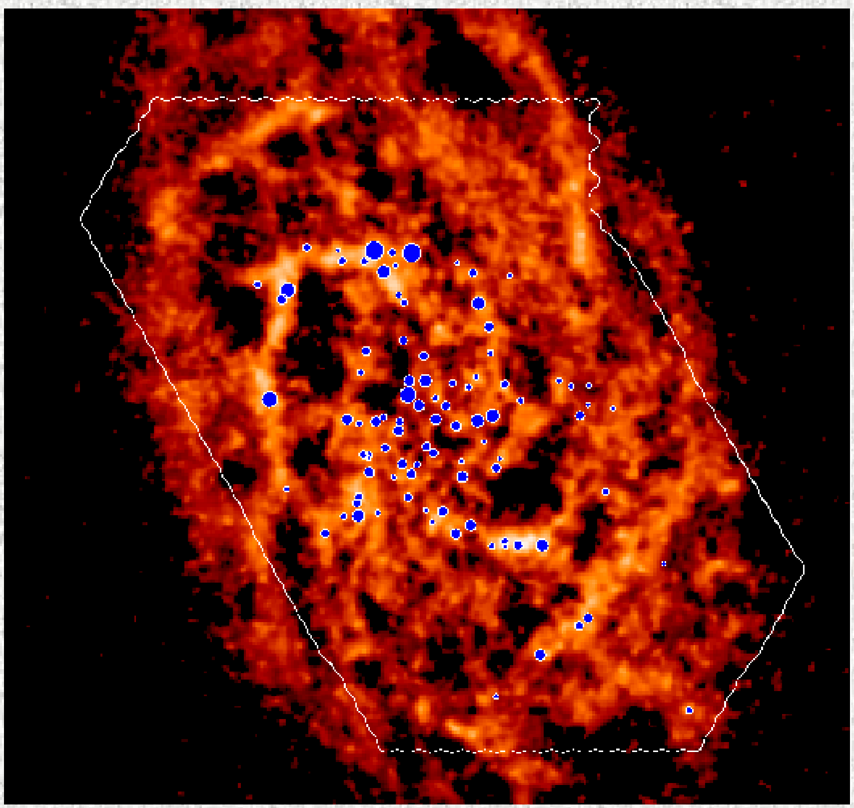


If so, it could help understand evolution of gas in galaxies.

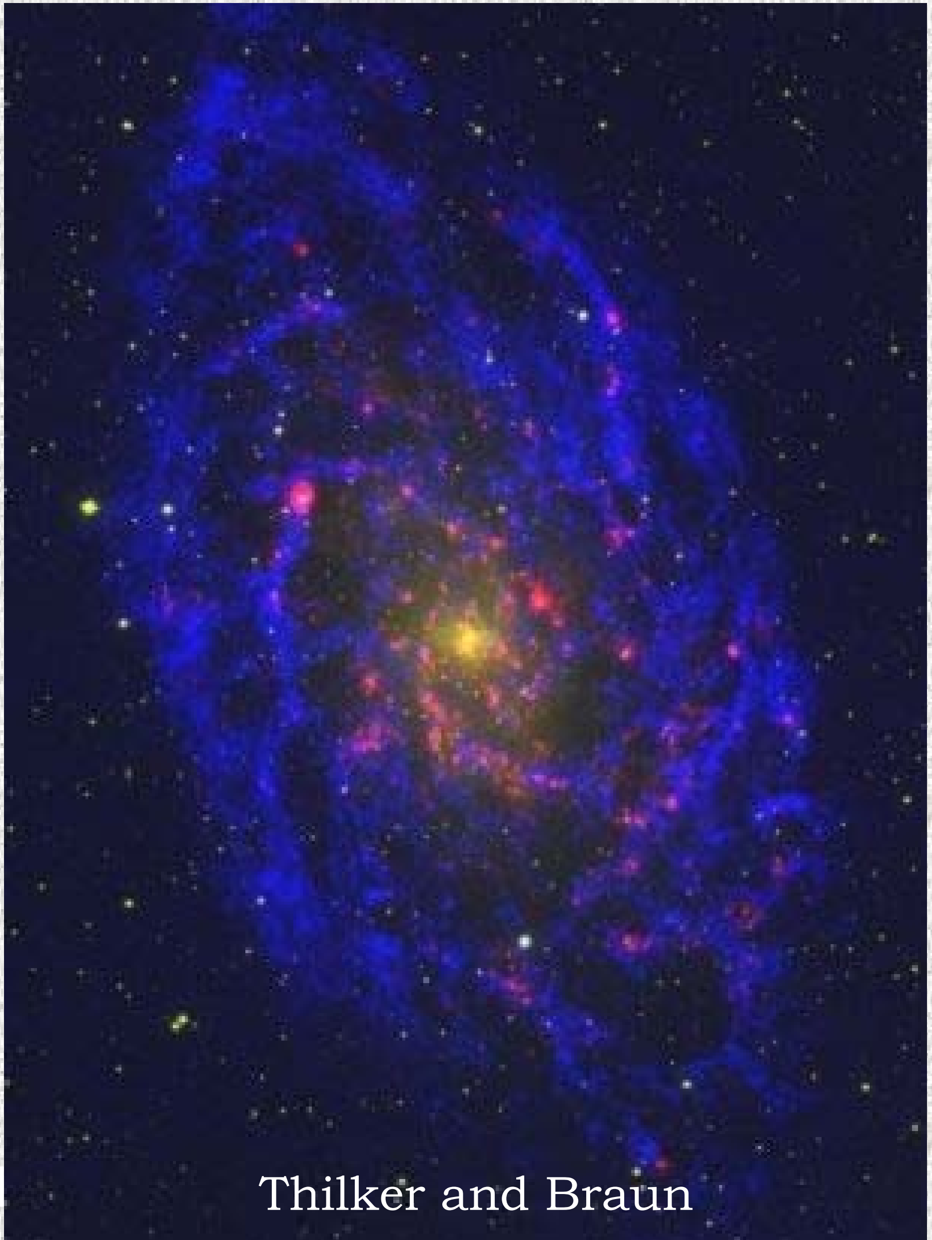
HI + H_2 radial profiles of 13 Galaxies



CO on HI in M33



Engargiola et al. (2003)



The Role of Pressure in GMC Formation

Let's *assume* that

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

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

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

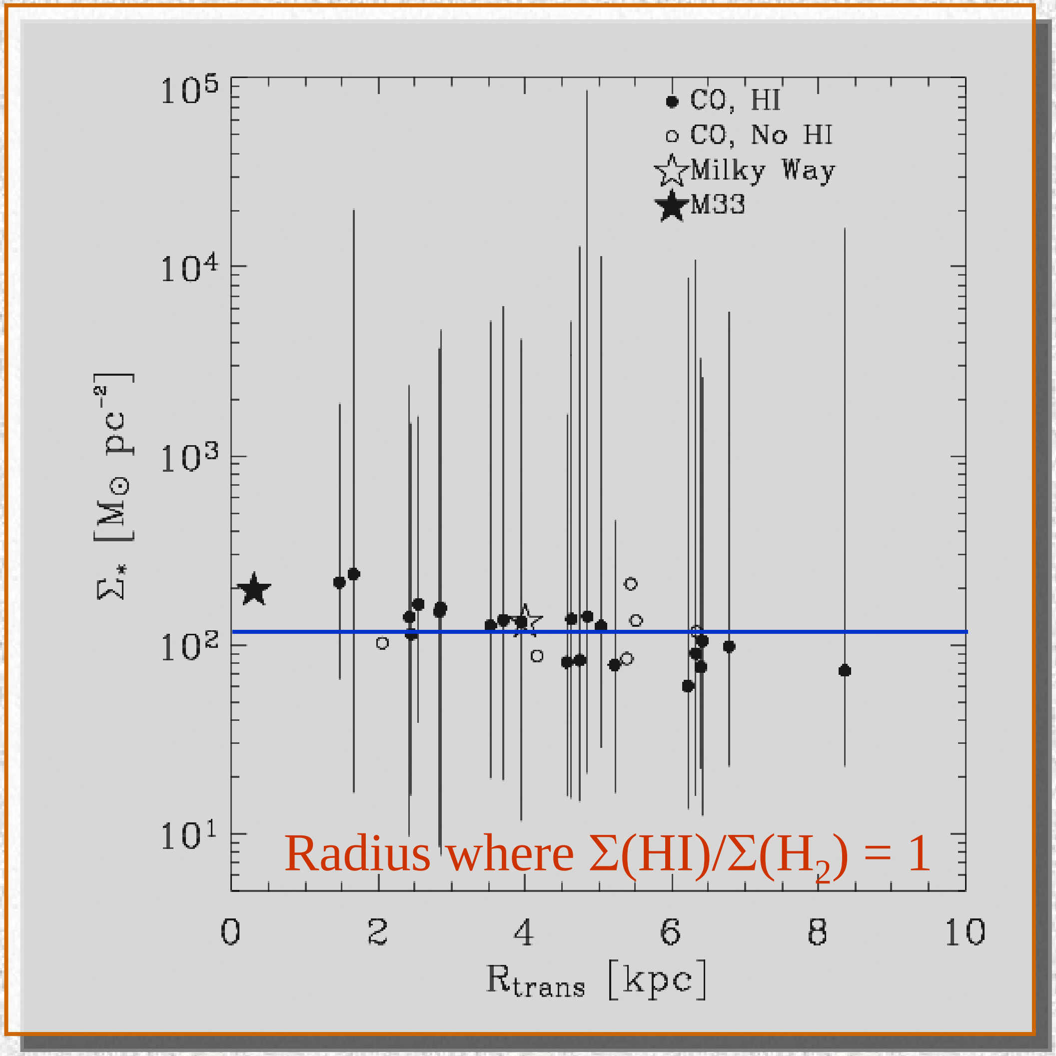
$P_{EXT} = 0.84(G\Sigma_*)^{0.5}\Sigma_g \upsilon_g h_*^{-0.5}$

but, υ_g and h_* are constant in disk galaxies

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

Prediction 2: *f*(Pext) is a well defined function of the four observables, two that vary little, for all galaxies.

28 Galaxies from the BIMA SONG Survey



Blitz & Rosolowsky 2004

22 with measured $\Sigma(HI)$

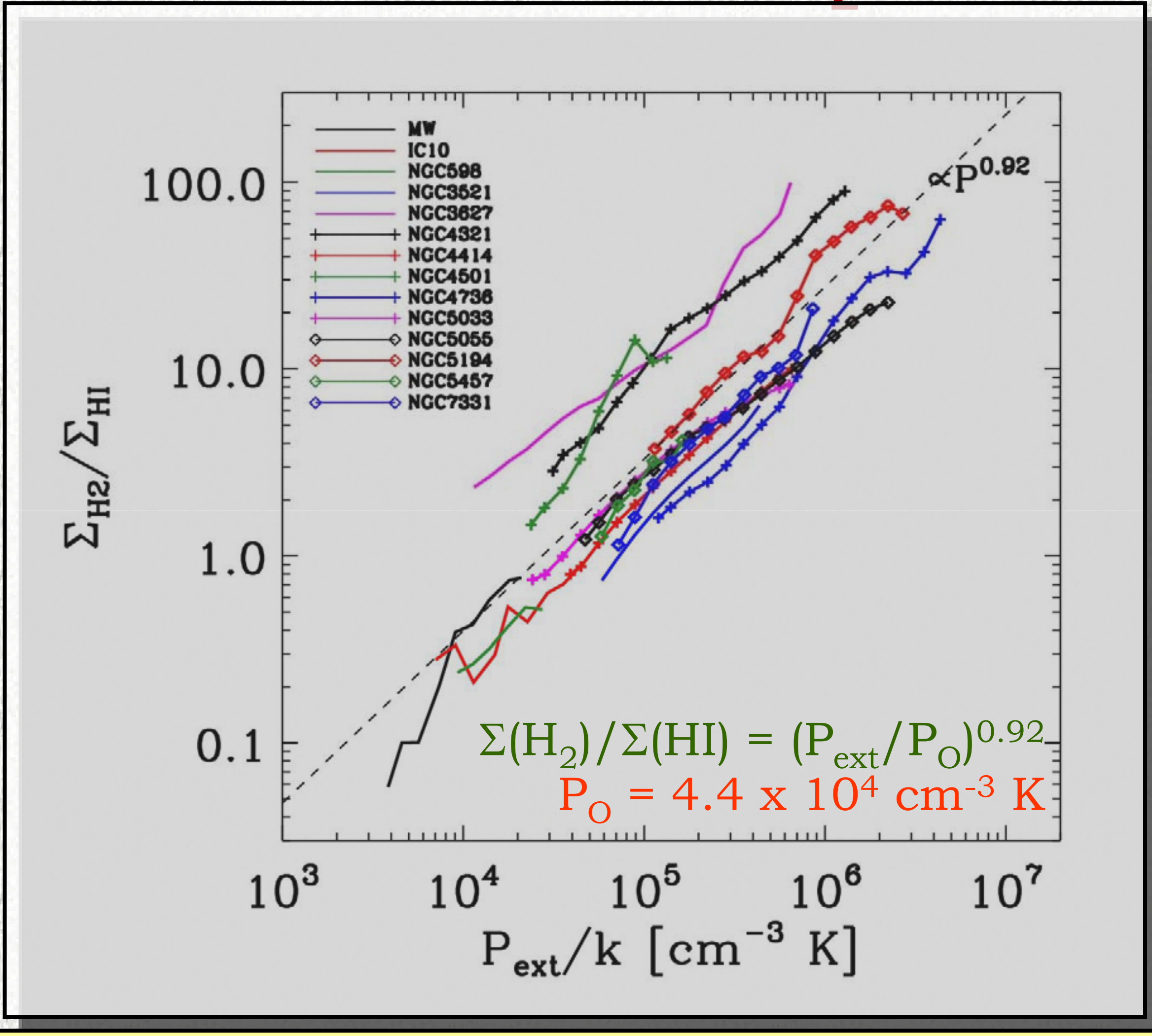
$\langle\Sigma_*\rangle = 120 \pm 10\ M_\odot\ pc^{-2}$

For 28 galaxies

rms scatter = 40%

This implies that the radius where $\Sigma(H_2)/\Sigma(HI) = 1$ is a proxy for a gravity scaling of the disk at 120 $M_\odot pc^{-2}$

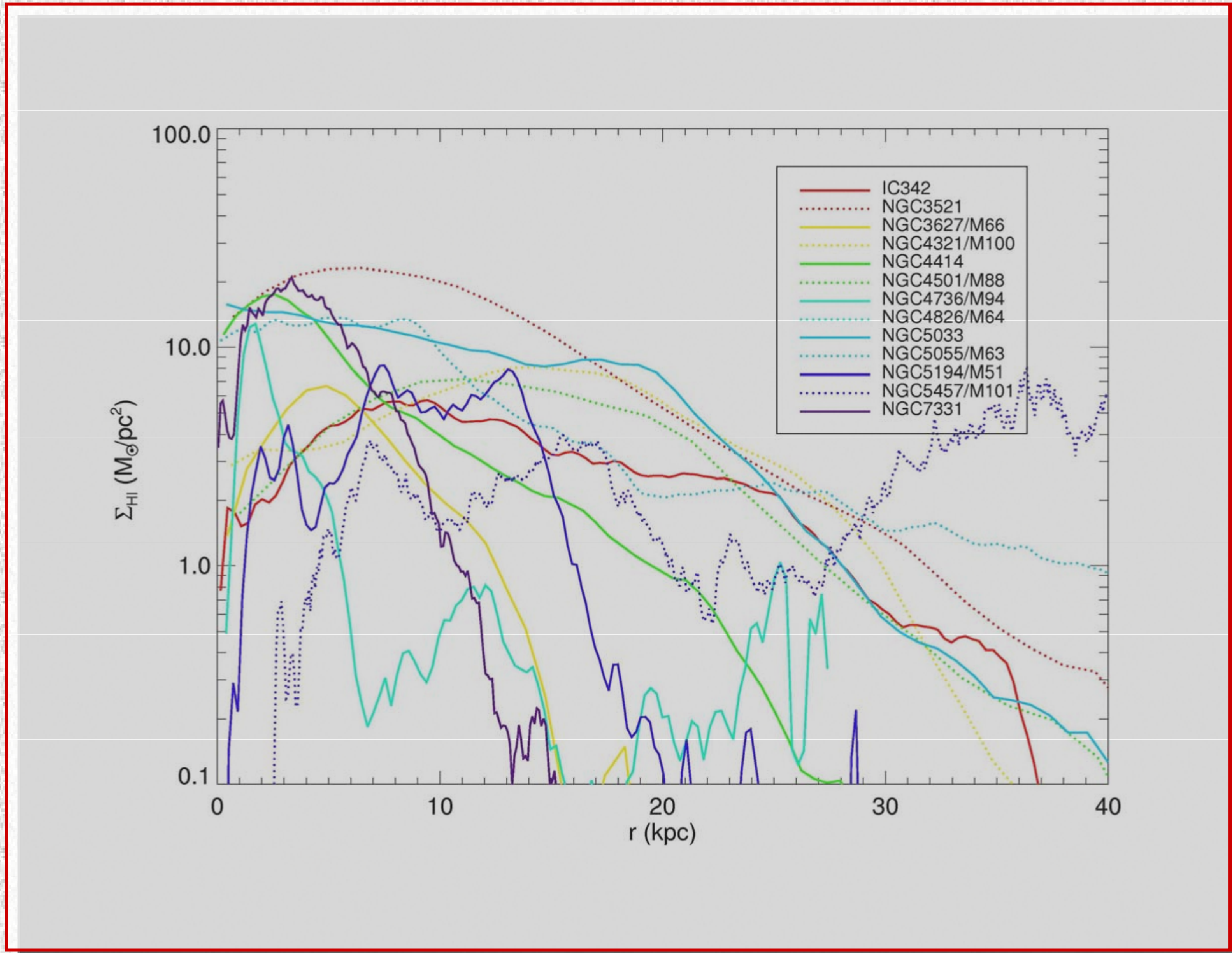
Pressure vs. H_2/HI



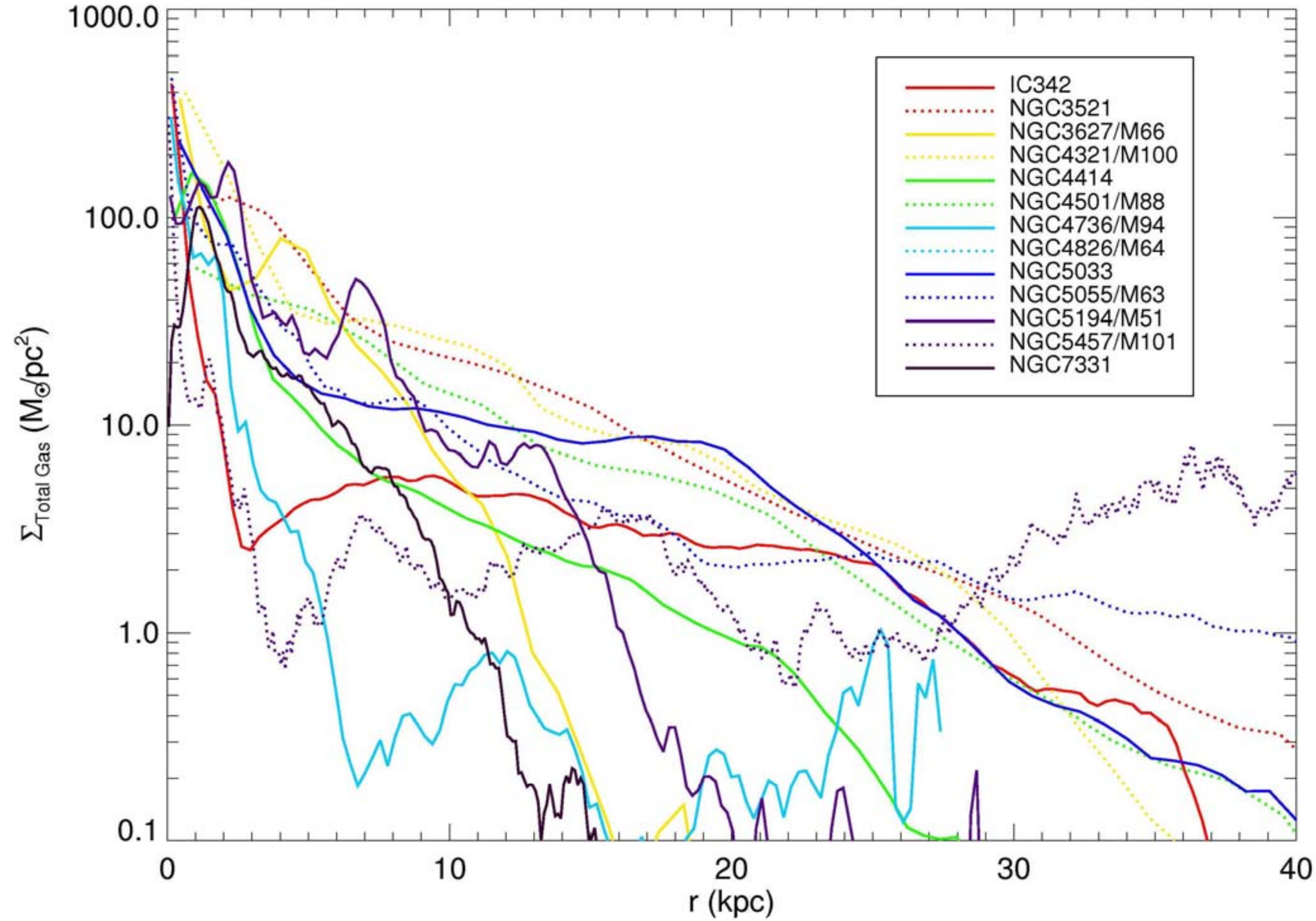
Blitz & Rosolowsky (2006)

P_O is the pressure at the location where $\Sigma(H_2)/\Sigma(HI) = 1$
Occurs is at the same value of Σ_* in *all* disk galaxies.

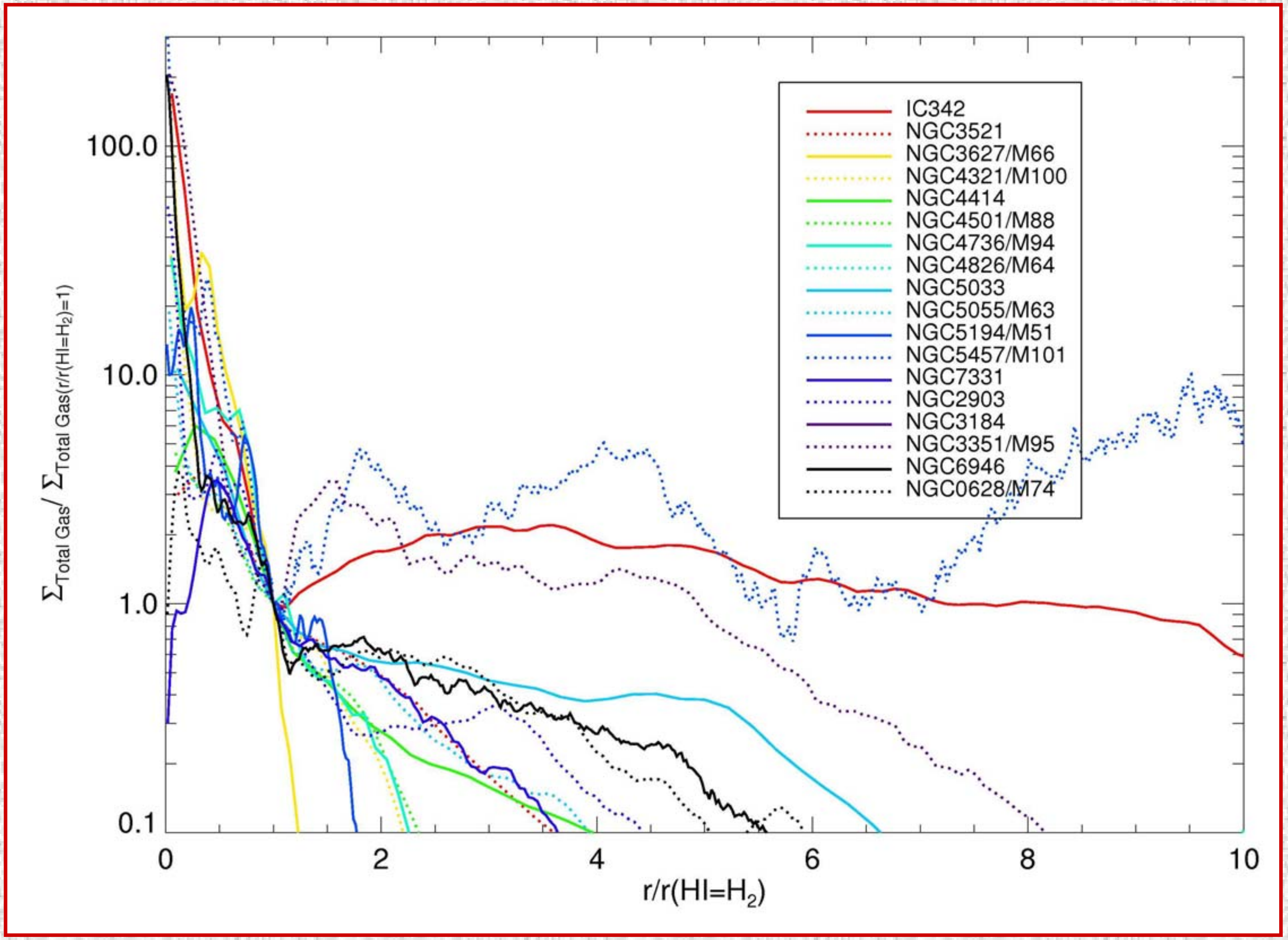
HI radial profiles of 13 Galaxies



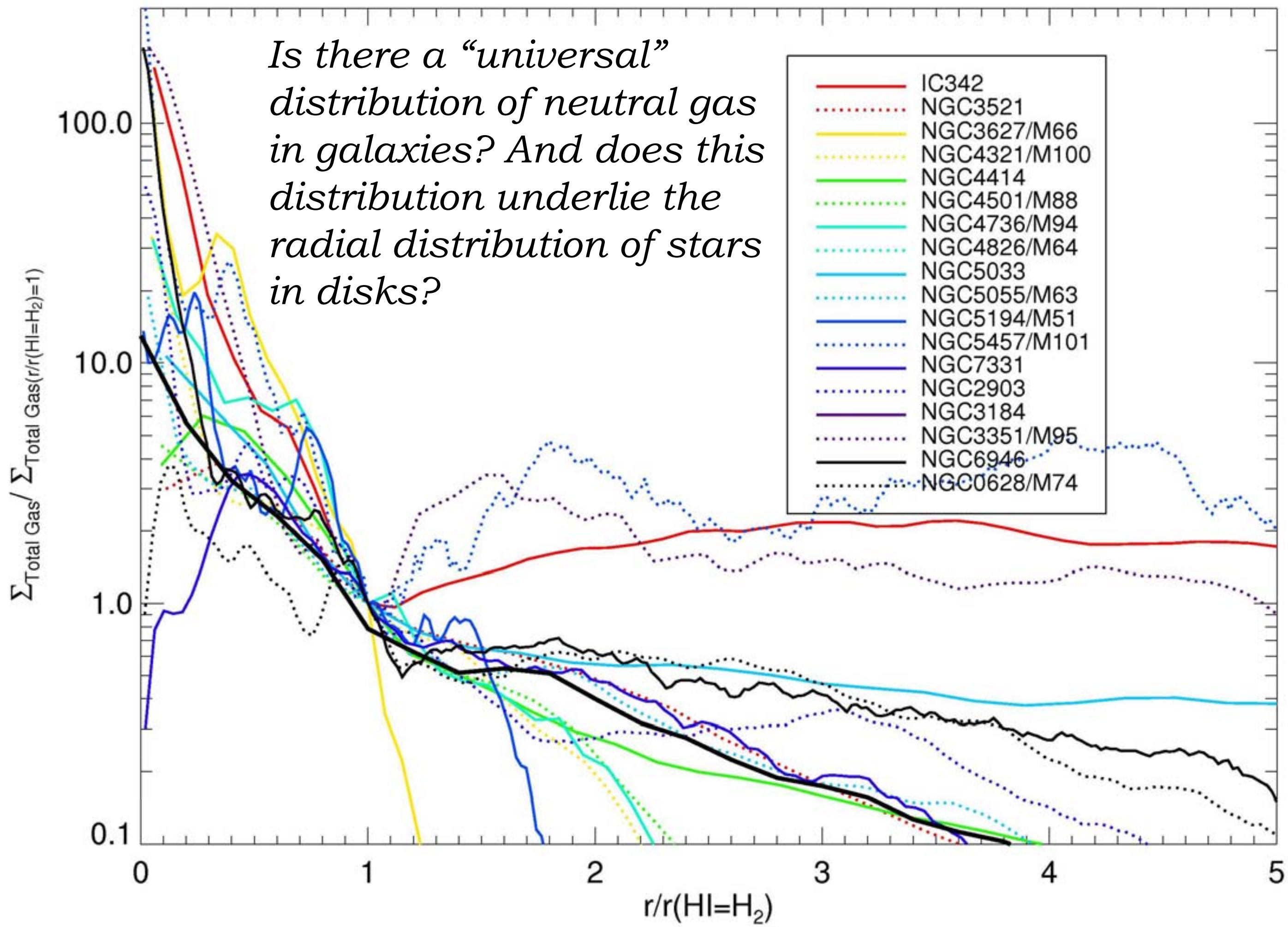
HI + H_2 radial profiles of 13 Galaxies



HI + H_2 *normalized* radial profiles of 18 Galaxies



HI + H_2 *normalized* radial profiles of 18 Galaxies



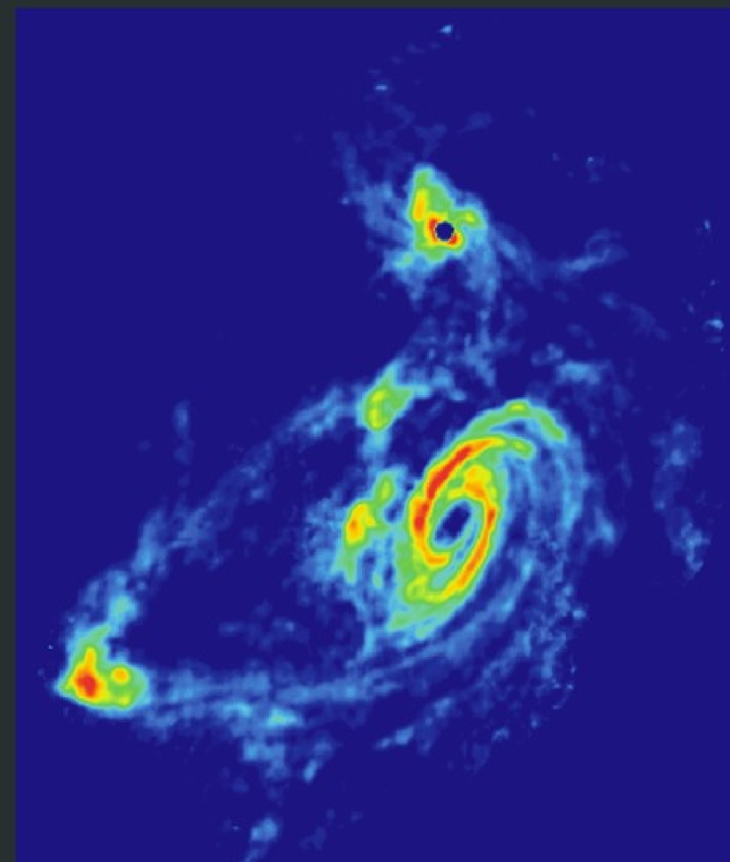
Restatement of Gas Depletion Problem

- How can galaxies retain an approximately self-similar neutral gas distribution for more than a few 10^9 y if the molecular gas is being depleted that fast?
- *Hint: Most galaxies reside in groups.*

TIDAL INTERACTIONS IN M81 GROUP

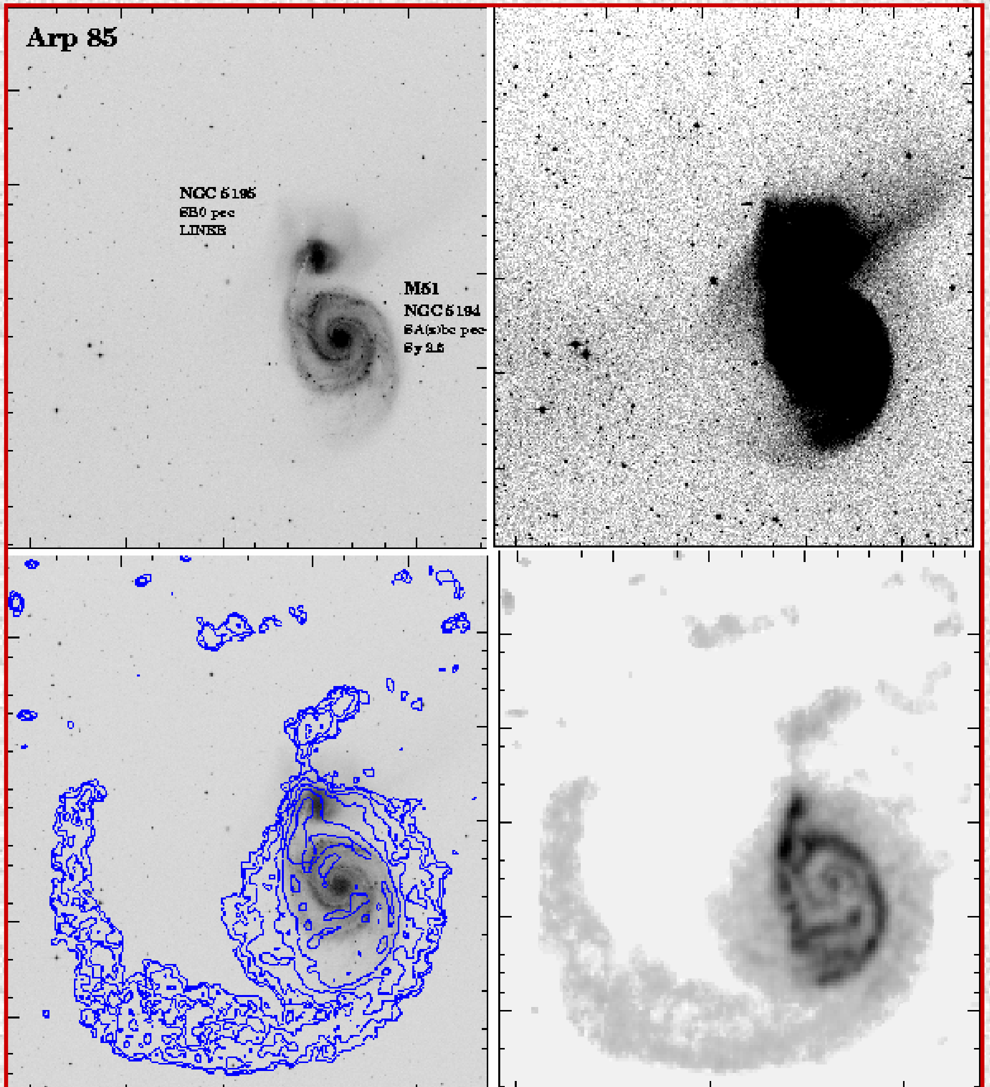
Stellar Light Distribution

21 cm HI Distribution



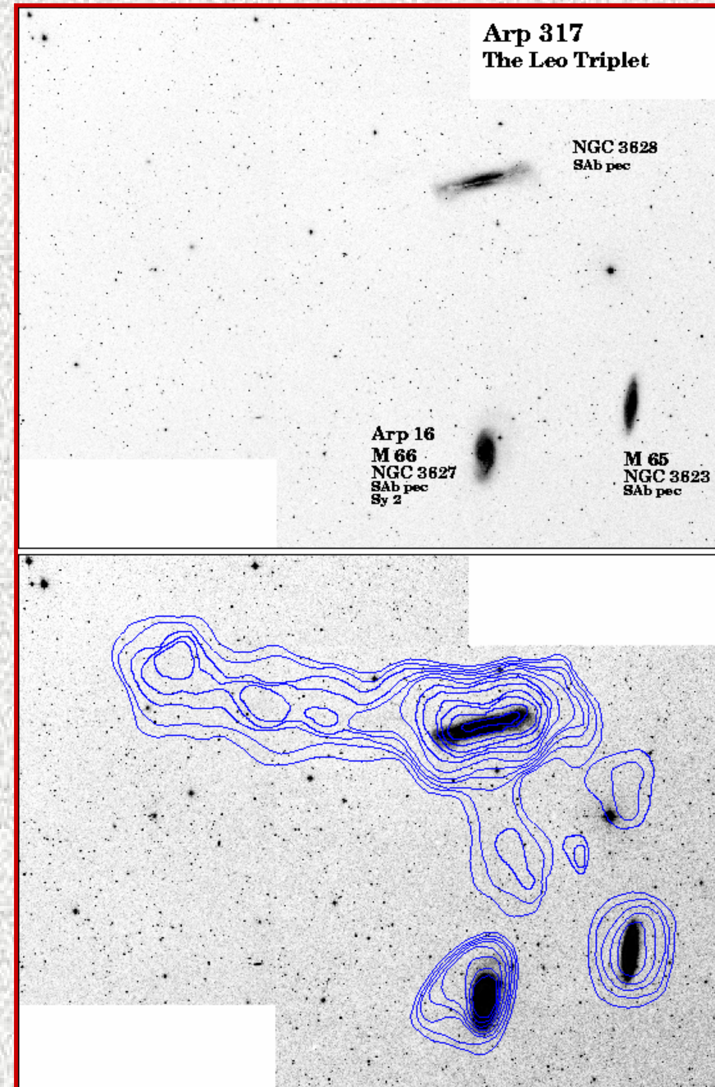
Yun et al. (2000)

M51 Tidal Disruption



Verheijen & Sancisi (2001)

Leo Triplet



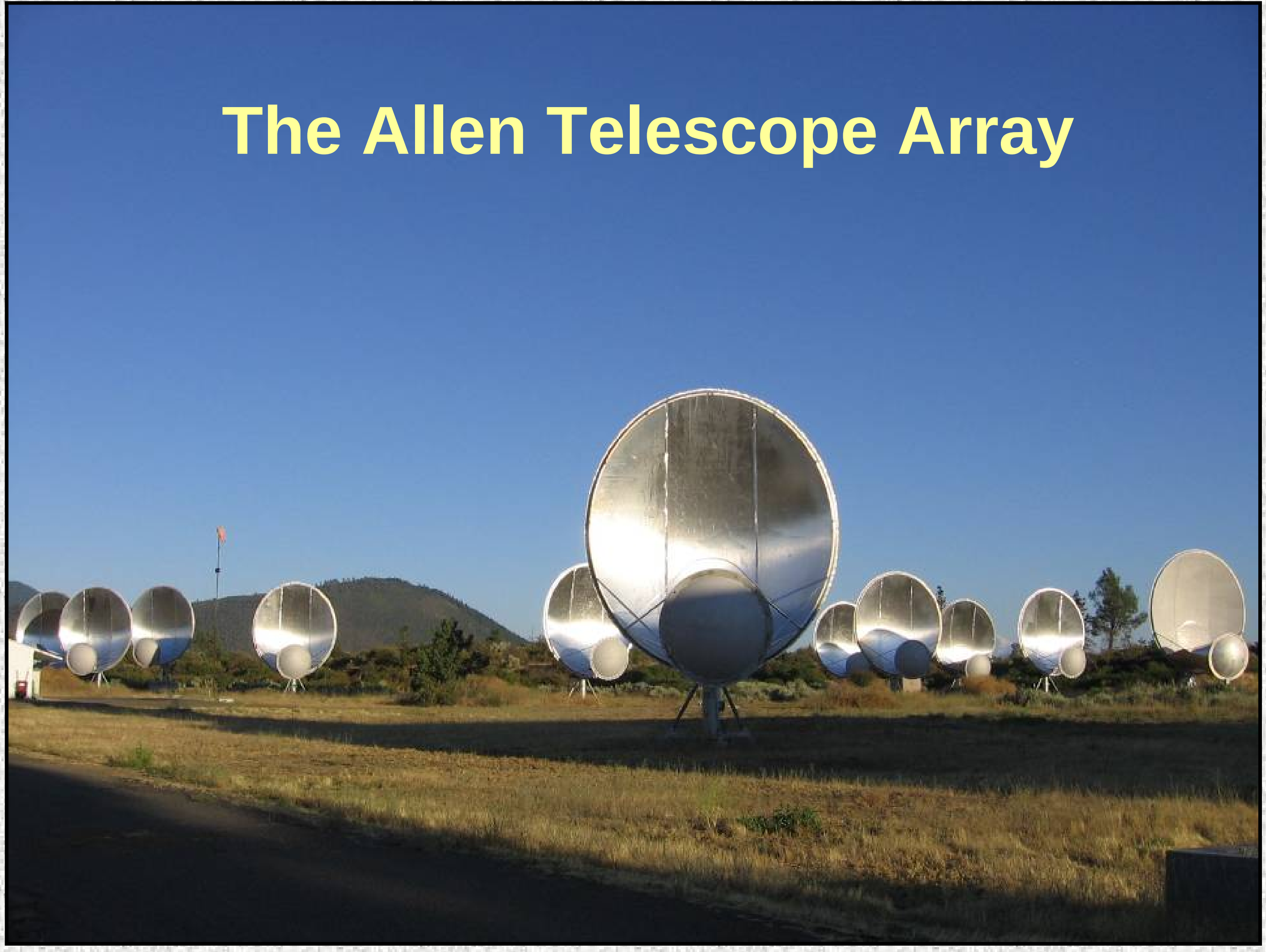
Giovanelli & Haynes (1979)

Suggestion

- Galaxies in groups redistribute their outer HI though out of the plane, distant tidal interactions.
- Half of this gas will lose angular momentum and fall into the central regions and convert HI to H_2 through hydrostatic pressure.
- The H_2, in turn is converted into stars.
- Can use entire reservoir of HI.
- *This is what feeds the normal star formation in galaxies and gets around the gas depletion problem.*
- Explains lack of zero metallicity intergroup gas in Local Group.
- This process is rapid compared to inflow.

Predictions

- Essentially all galaxy groups will contain intercluster gas. This gas will often look as if it is a tidal remnant. Roughly speaking, the mass will be ~10^8 -10^9 $M_\odot$.
- The star formation rate in galaxies is determined, on average, by the mass of intercluster gas divided by the infall (dynamical) time for the gas.
  - However, this SFR will lag the observed amount of gas by the infall time (10^8 – 10^9 y).


The Allen Telescope Array

Summary & Conclusions

1. Is there evidence for a "universal" gas radial profile?
2. GMCs form on filaments of pre-existing HI in galaxy disks.
3. Location where $\Sigma(HI) = \Sigma(H_2)$ (i.e. where $\Sigma_* = 120\ M_\odot pc^{-2}$) may be a fundamentally important scale for star formation in galaxies.
4. The molecular gas fraction is determined by hydrostatic pressure.
5. The gas depletion problem may be solved by tidal angular momentum exchange of the outermost HI gas in groups.