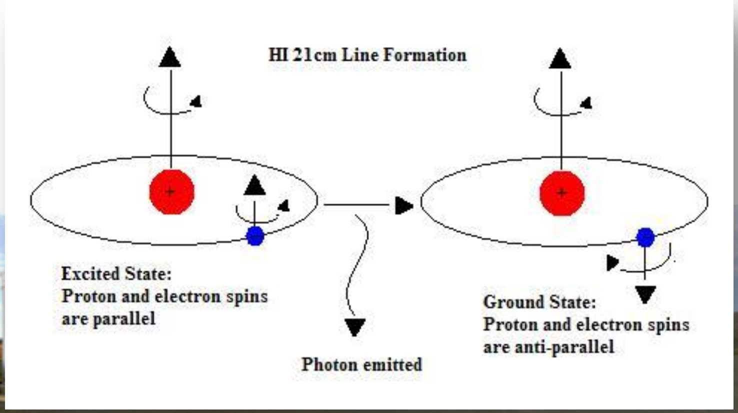
SKA AFRICA
SQUARE KILOMETRE ARRAY

Extragalactic Astronomy

Lecture 3: Interstellar Matter
Neutral Hydrogen (HI), Ionized Hydrogen (HII), Molecular Hydrogen (H_2)

Neutral Hydrogen (HI)

- The gaseous component is important because:
  - Stars form in this component
  - Stellar evolution rejects enriched gas
  - This emission line allows us to trace the potential
- HI line at 21 cm



- The hydrogen atom can be in 2 states in its ground level distinguished by their spin-orbit coupling
- Parallel spins have a higher energy than anti-parallel spins
- The decay produces the emission of a photon at 1420.40575 MHz

Neutral Hydrogen (HI)

$$M(HI)/M_\odot = 2.356 \times 10^5 D^2 \int S_\nu dV_r$$

- S_ν = radio flux in Jy
- V_r = velocity in km/sec
- D = distance in Mpc

- HI is optically thin, such that the HI mass can be measured from the flux measured within the beam

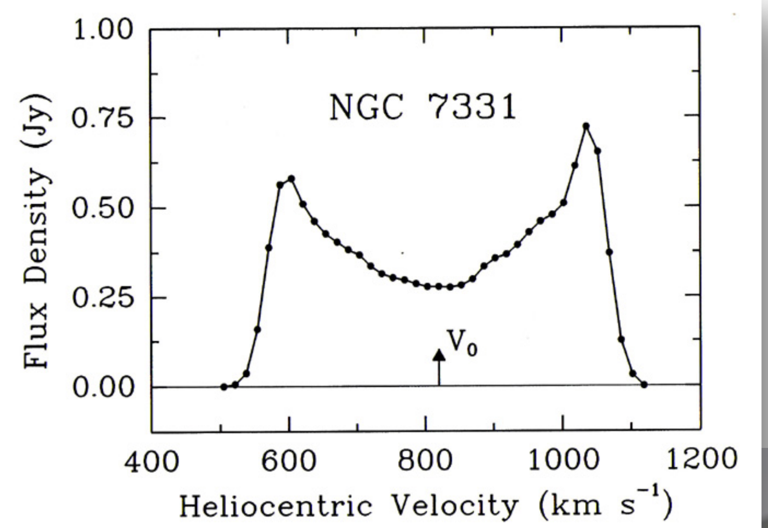
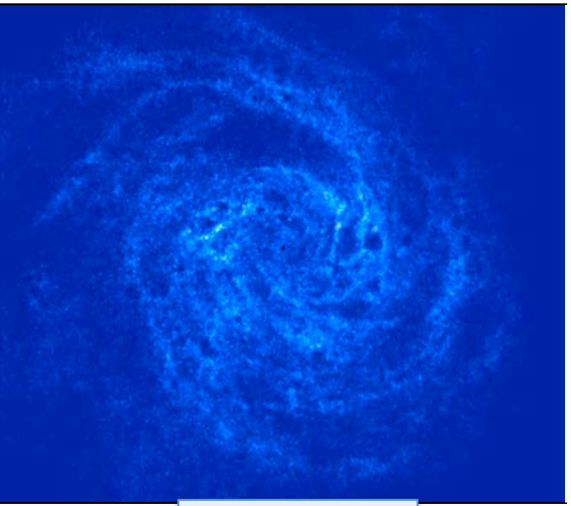
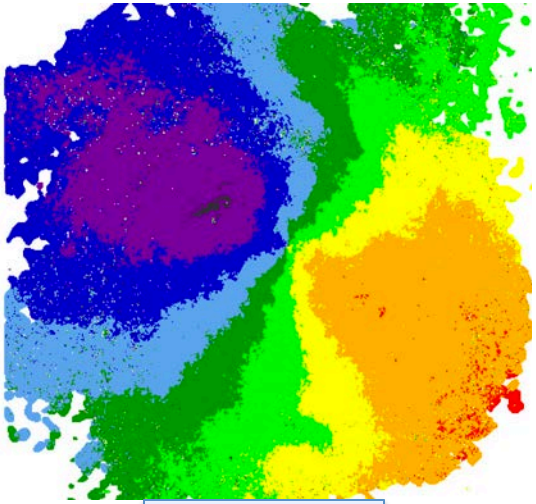


Fig5.22 (K. Begeman) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

HI data cube



MOM 0



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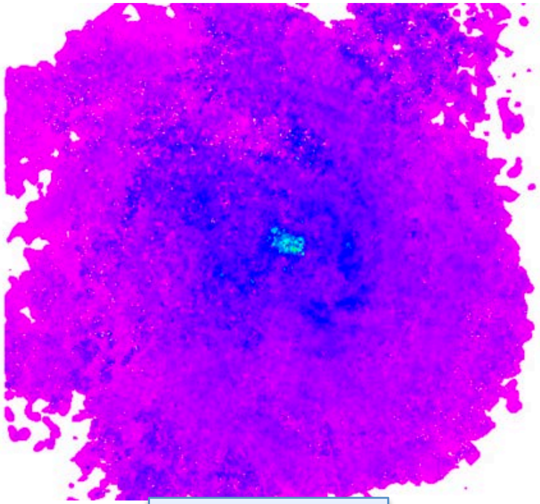
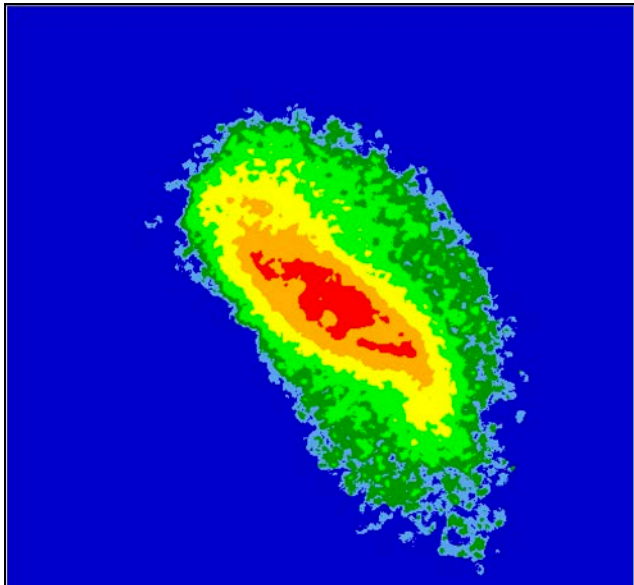


MOM 2

NGC 6946

HI data cube



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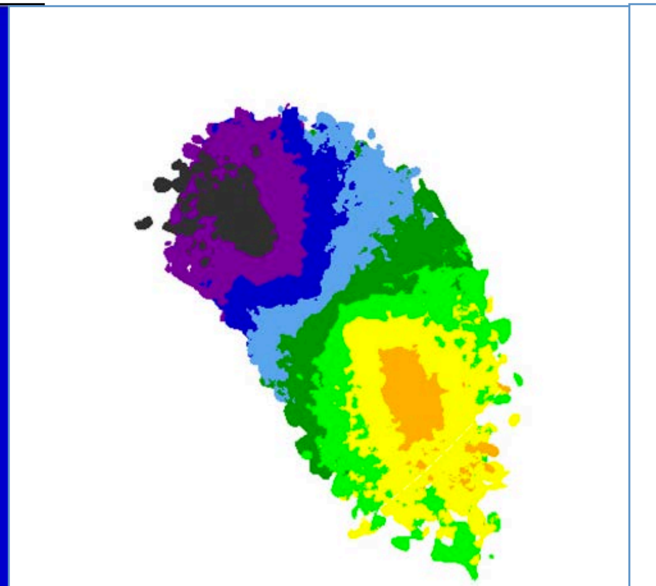
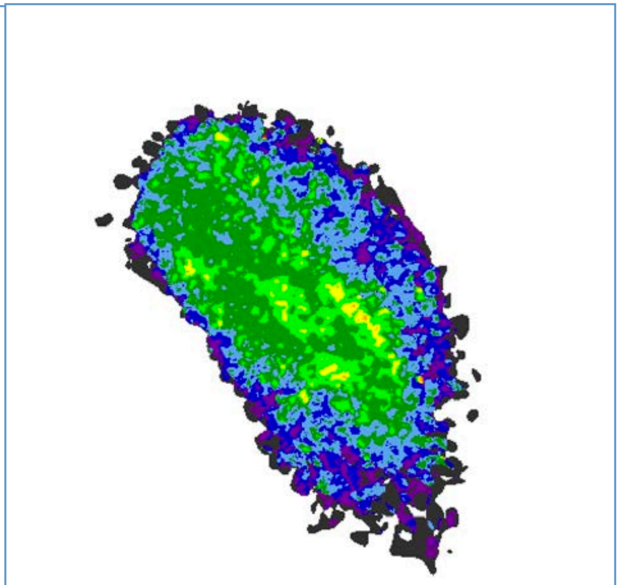
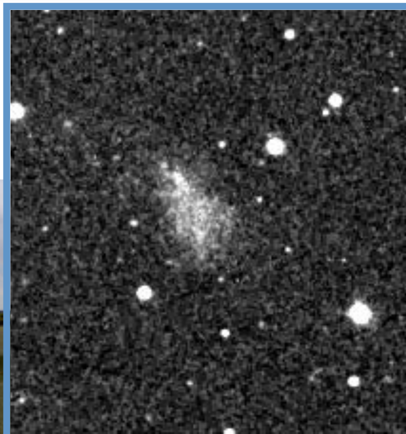


MOM 1



MOM 2

DDO 154

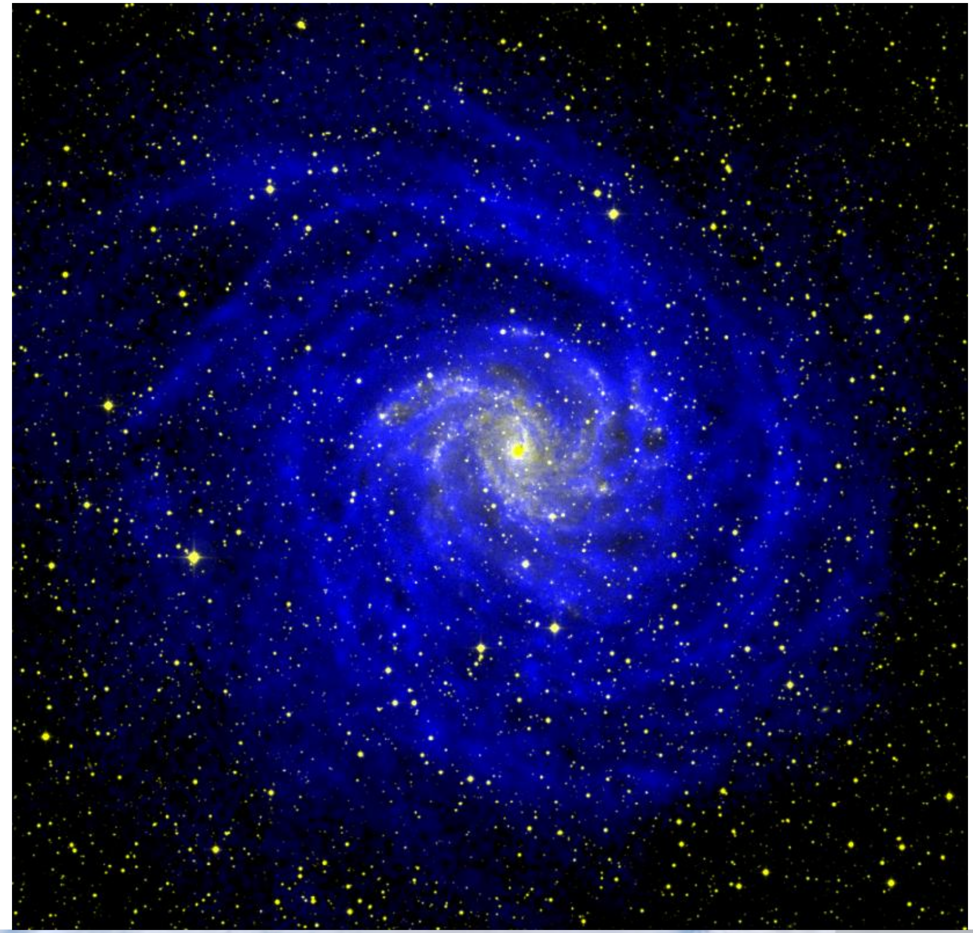


Neutral Hydrogen (HI)

NGC 6946

Radio: WSRT & DRAO

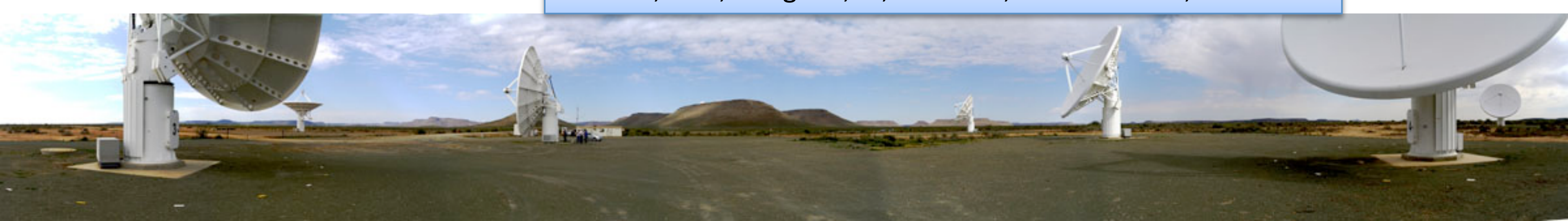
Carignan et al. 1990



Neutral Hydrogen (HI)

NGC 2915-BCD
Optique: AAT
Radio: ATCA

Meurer, G.R., Carignan, C., Beaulieu, S. & Freeman, K.C. 1996



Neutral Hydrogen (M31)

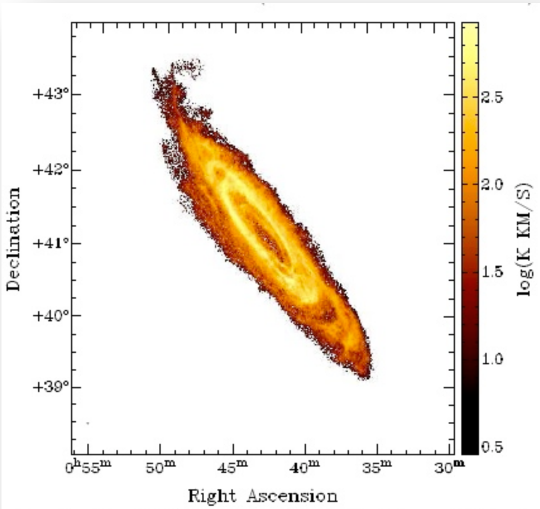


FIG. 4.— Total HI distribution of Messier 31. The small ellipse in the bottom-left corner displays the angular size of the synthesized beam ($\sim 1' \times 1.5'$).

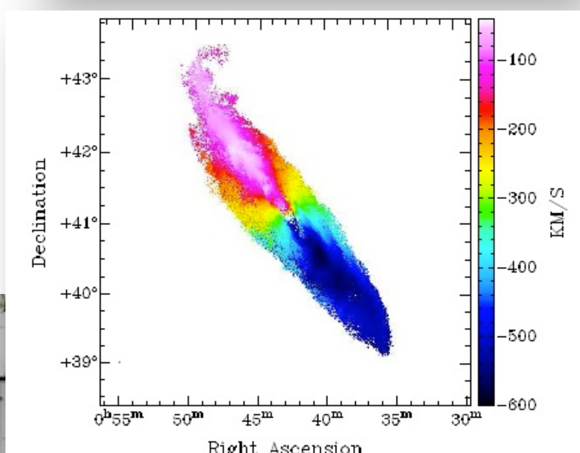


FIG. 8.— Velocity field of M31 used for the titled-ring model analysis.

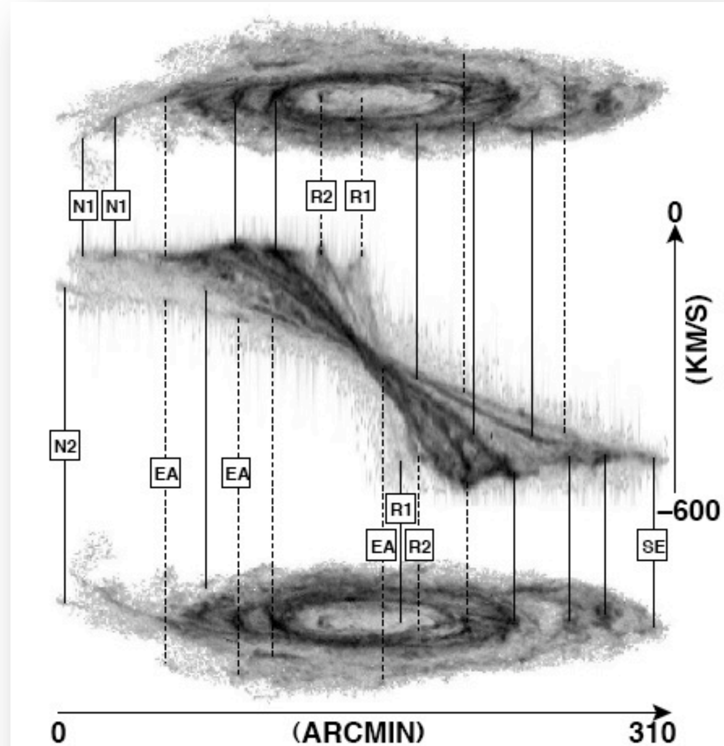
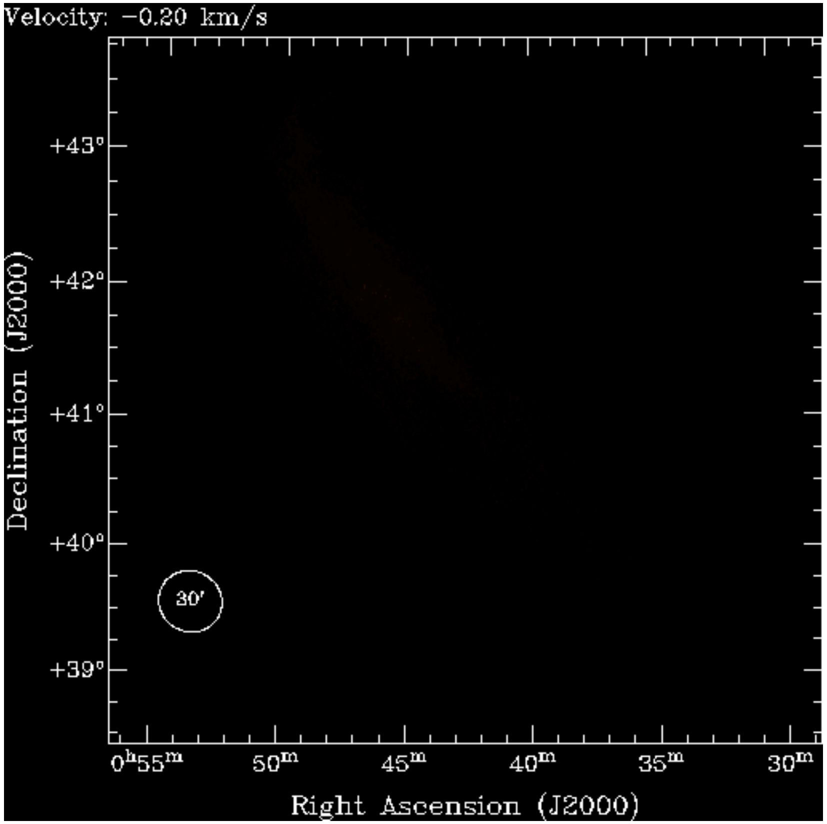
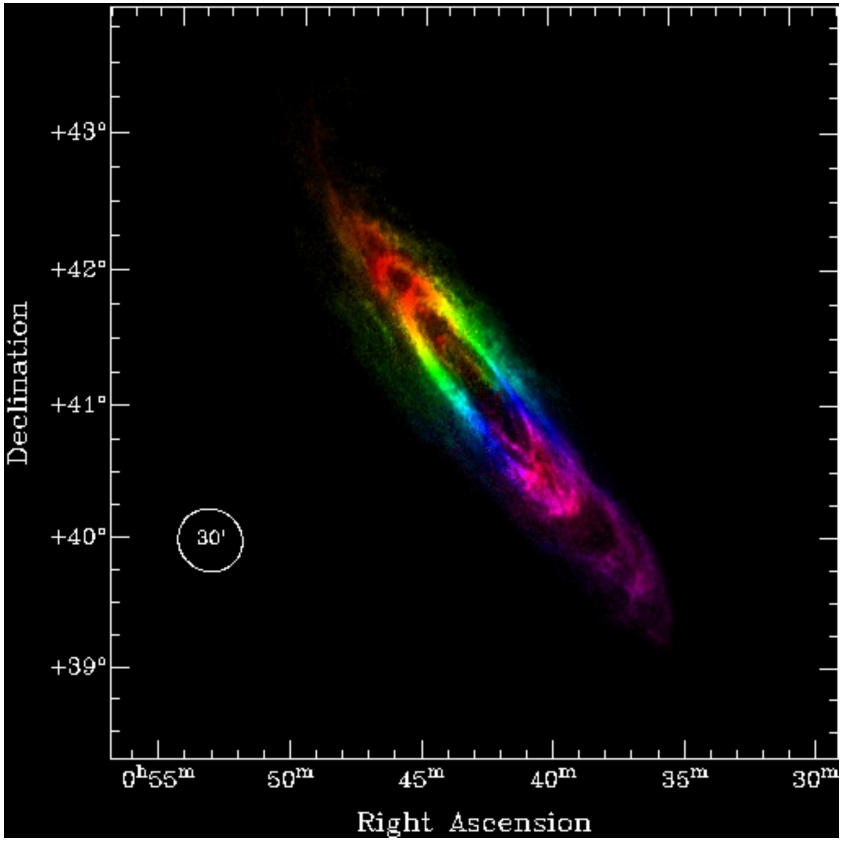


FIG. 5.— 3D view of the HI datacube of M31. The middle panel

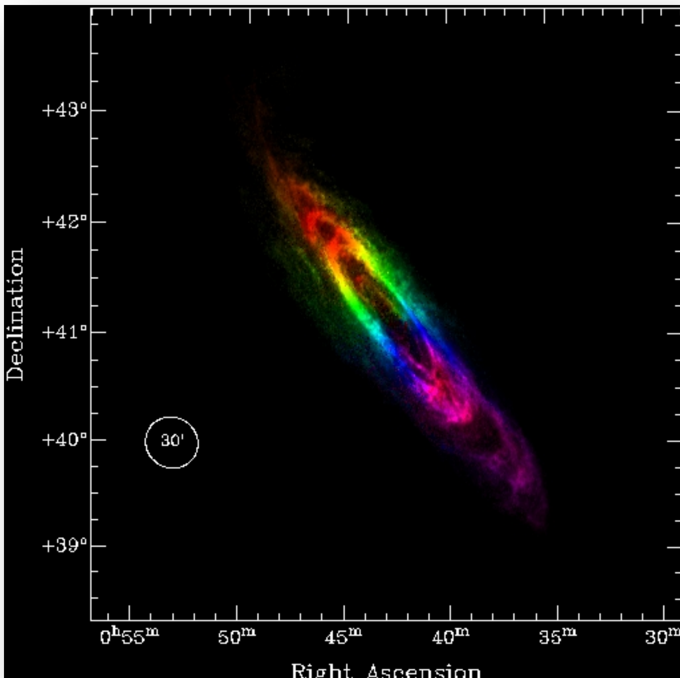
M31: Chemin, Carignan, Tyler 2009

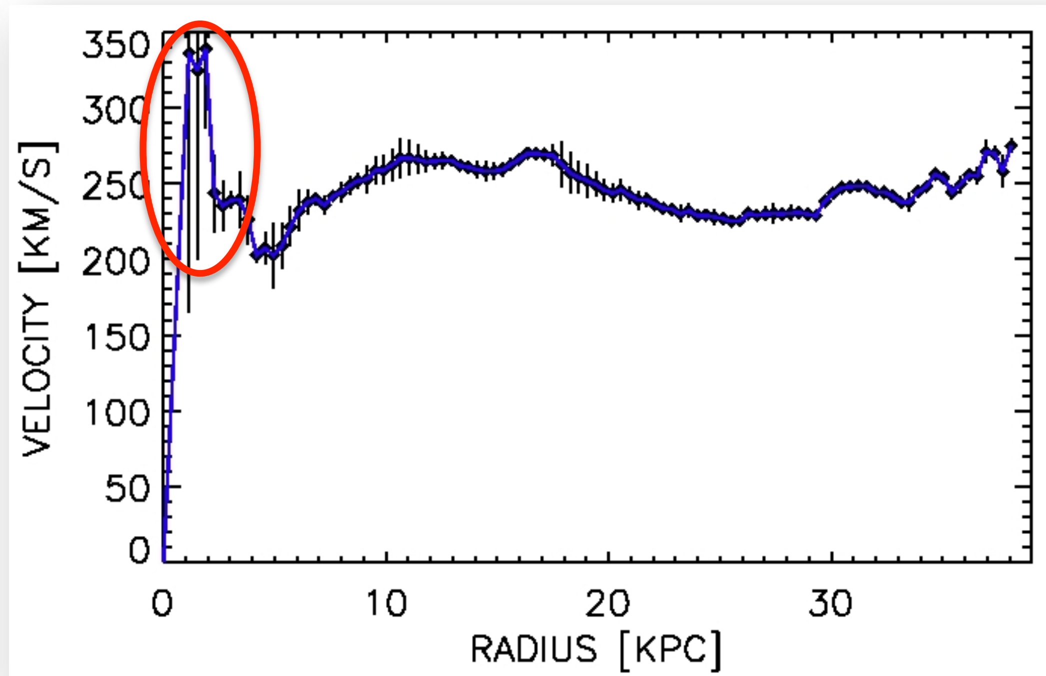
Neutral Hydrogen (M31)





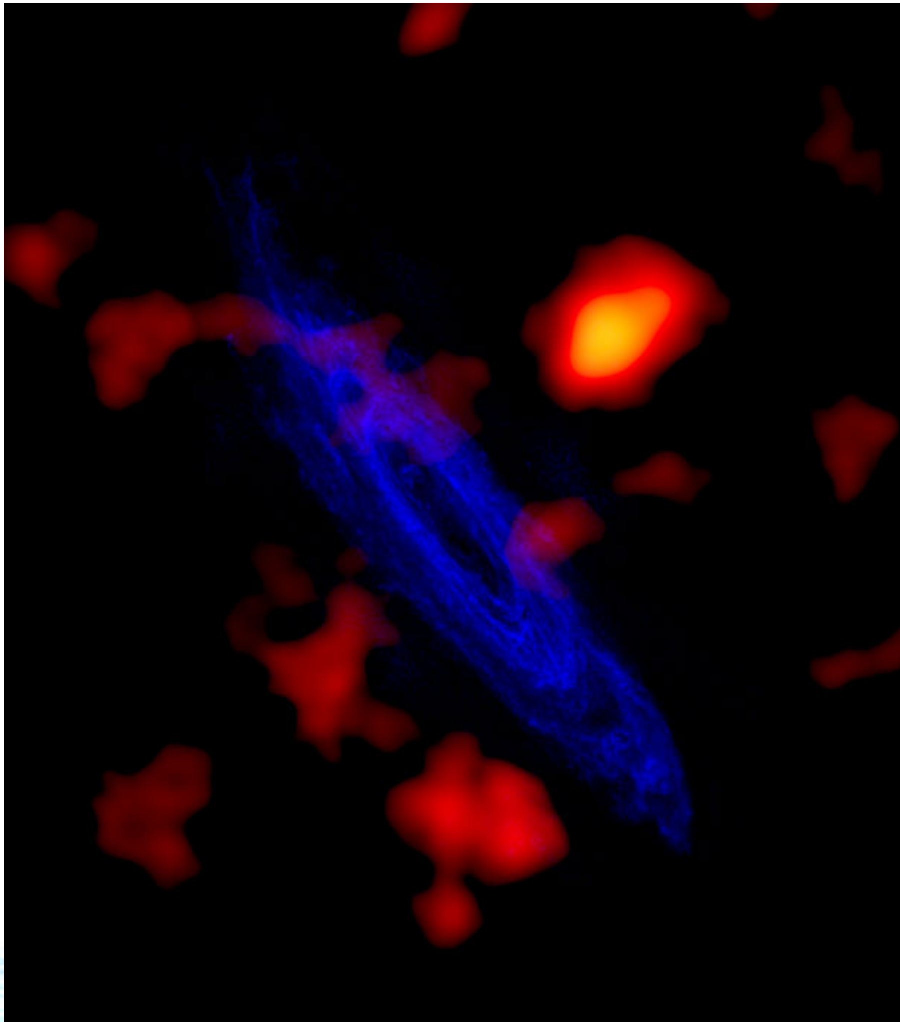
Neutral Hydrogen (M31)





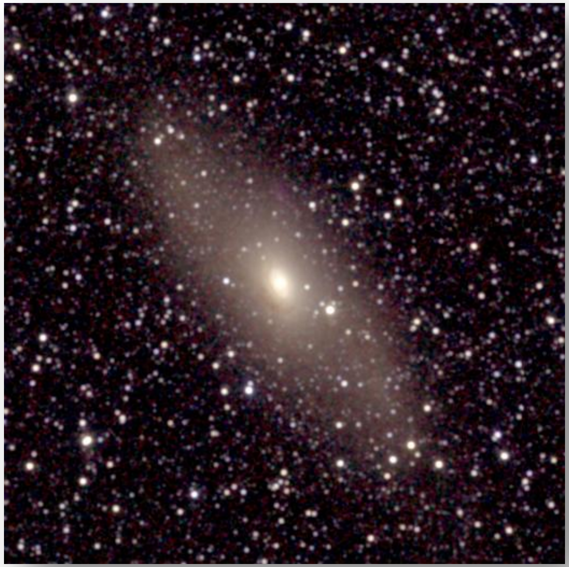
Chemin, Carignan, Tyler 2009

Neutral Hydrogen (M31)

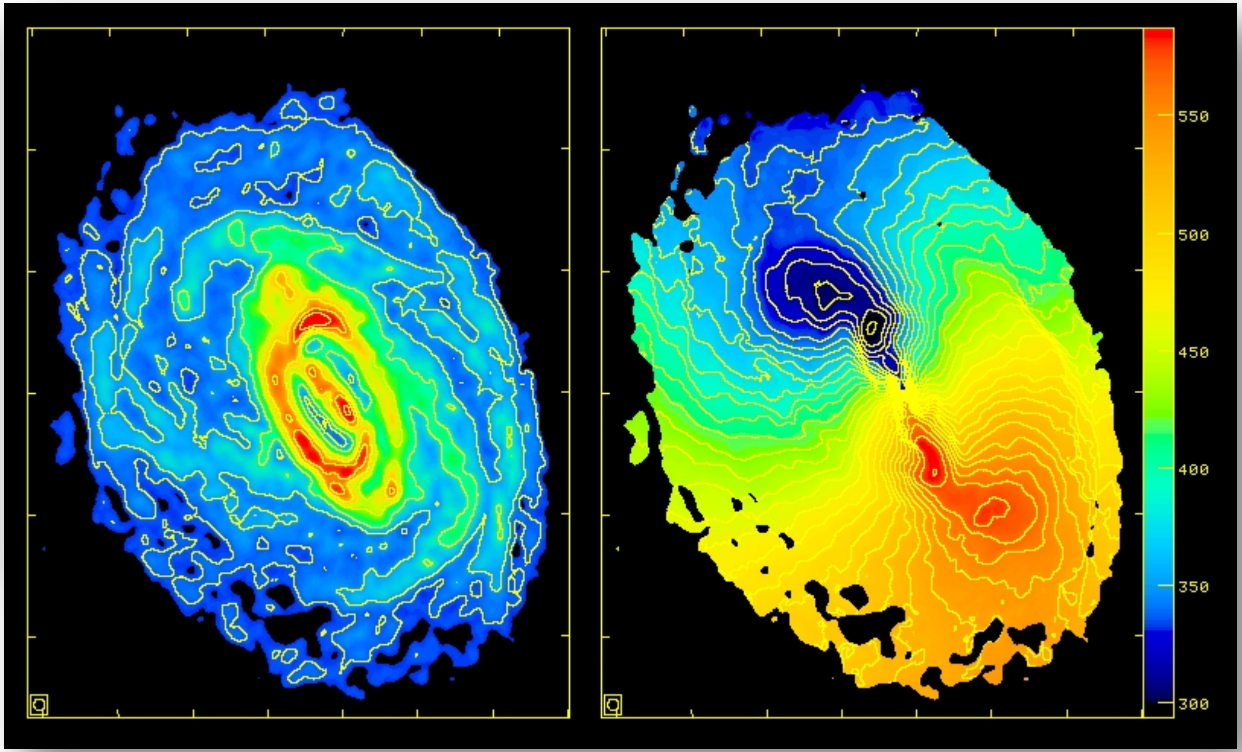


Thilker et al. 2004

Neutral Hydrogen (ZoA)

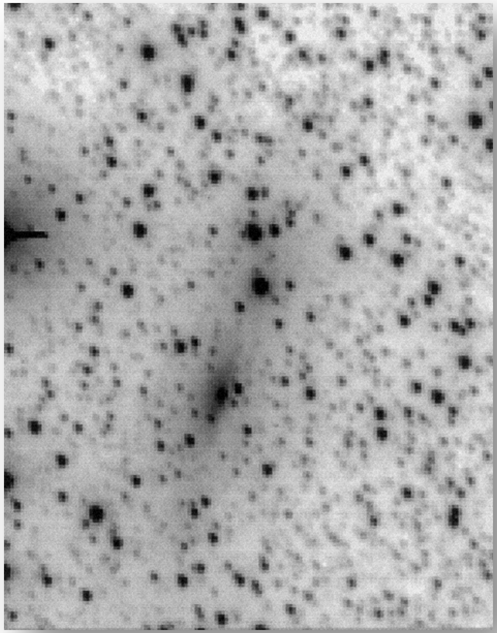


2MASS image

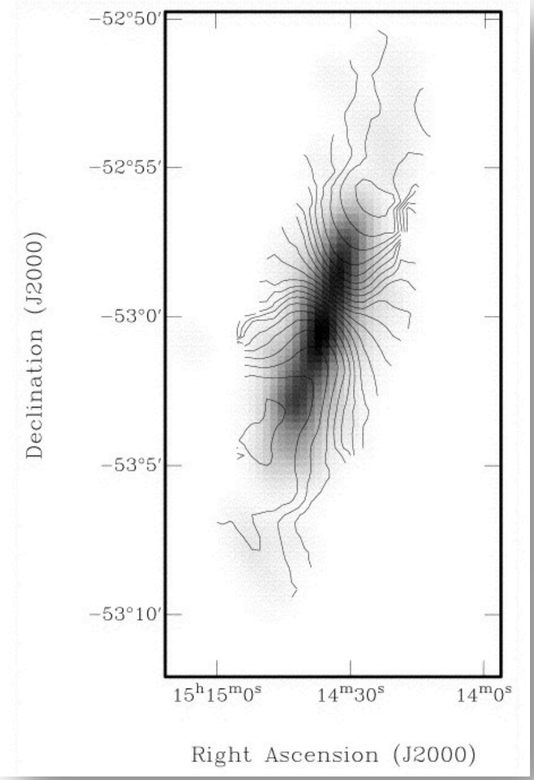


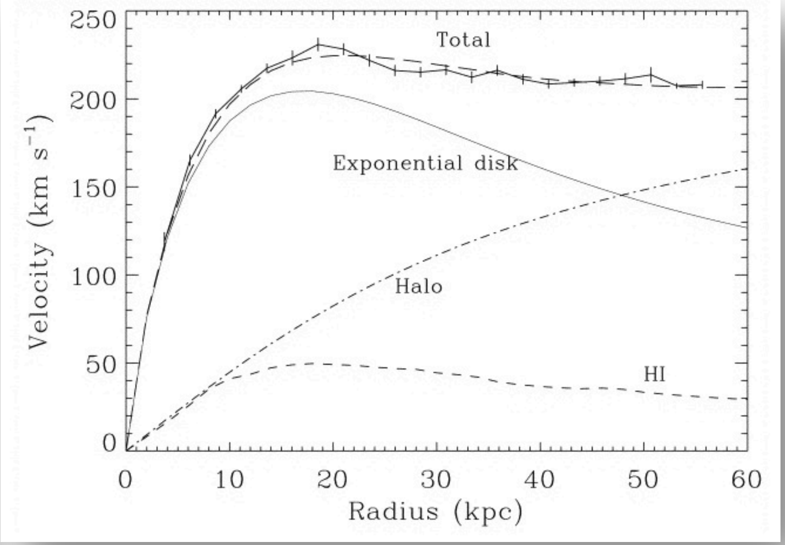
Galaxie Circinus – ATCA data

Neutral Hydrogen (ZoA)



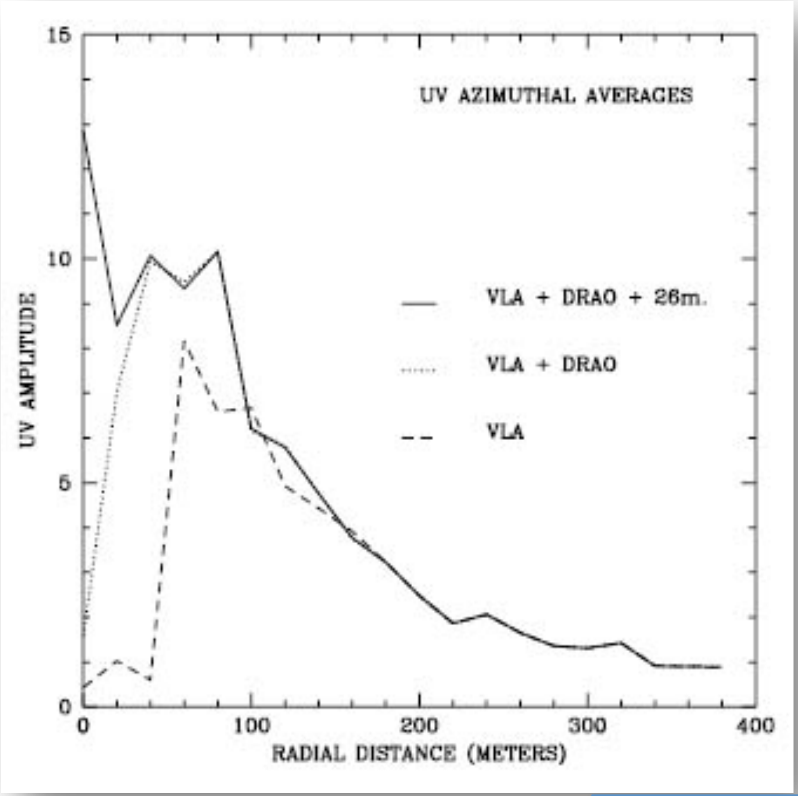
J1514-52





Staveley-Smith et al. 1998

Neutral Hydrogen



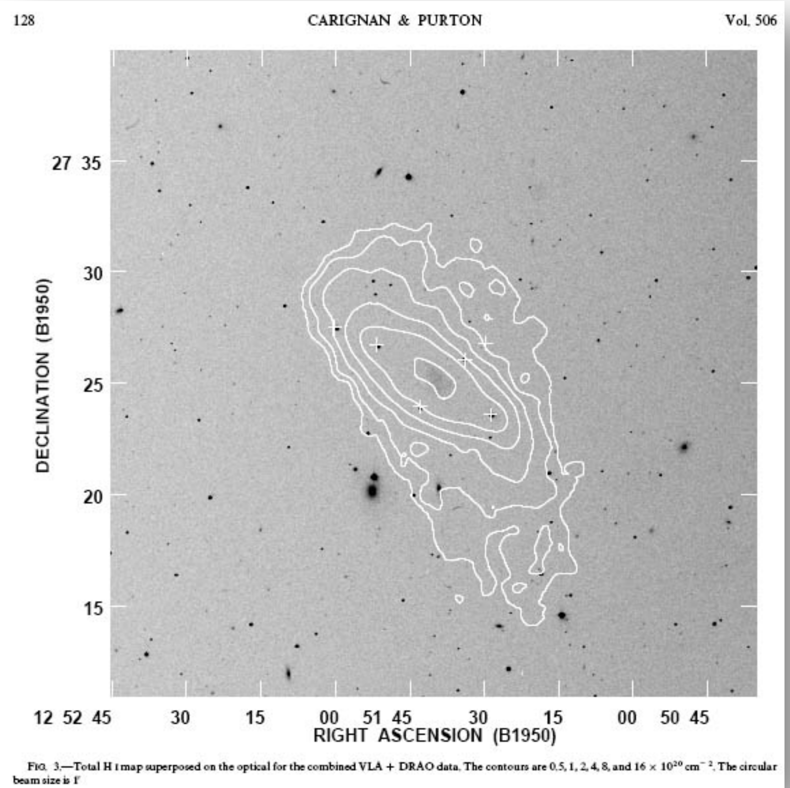
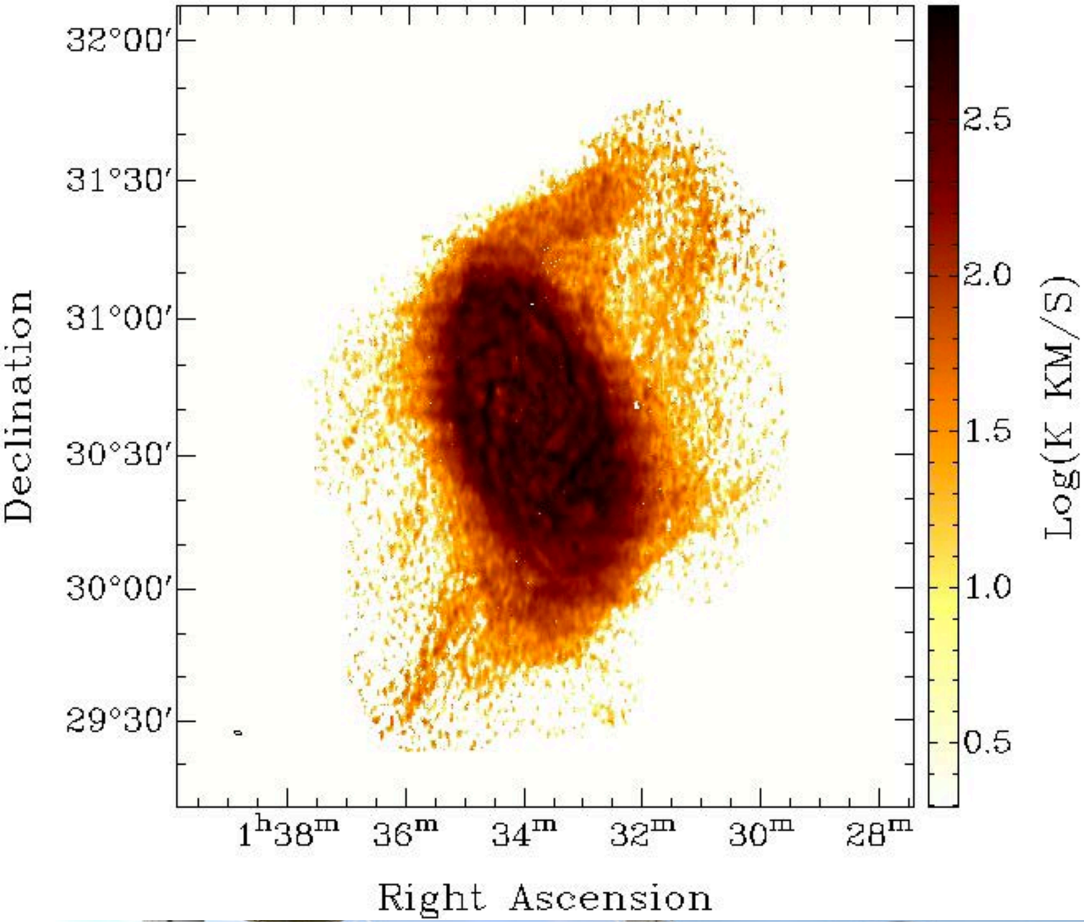


FIG. 3.—Total H I map superposed on the optical for the combined VLA + DRAO data. The contours are 0.5, 1, 2, 4, 8, and 16 × 10^{20} cm^{-2}. The circular beam size is 1′

Carignan & Purton 1998

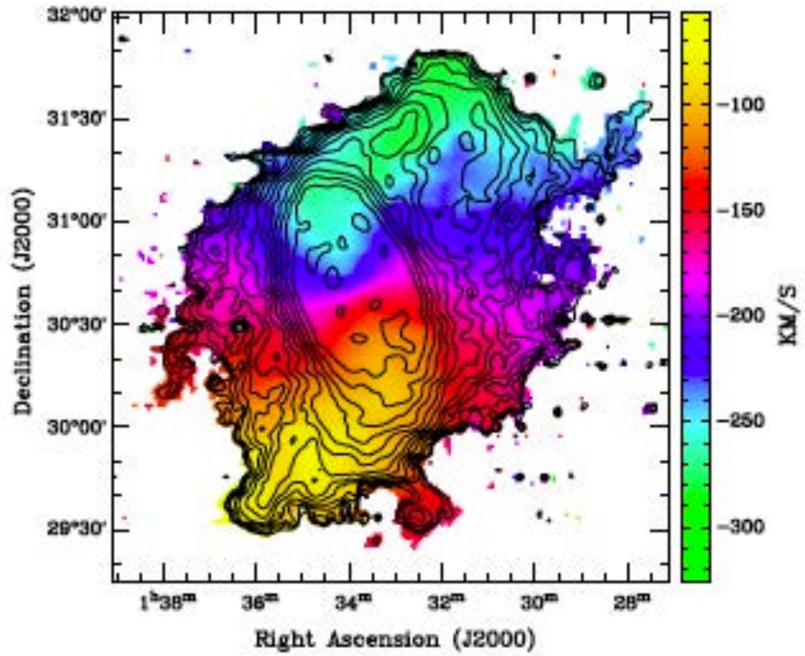
Spacings vs Scales (M33)

M33 DRAO HI



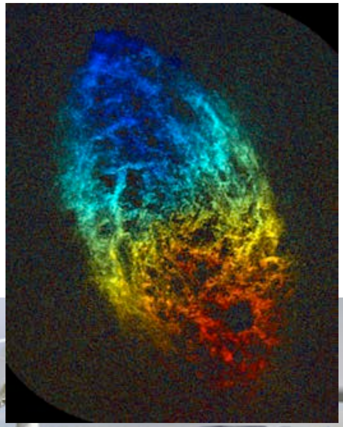
Kam, Chemin & Carignan, in prep.

M33 Arecibo HI



Putman et al. 2009

M33 VLA HI



Thilker, Braun, Walterbos

Neutral Hydrogen

Figure 1. Aerial view of the KAT-7 array in the Northern Cape's Karoo desert, South Africa.

Some KAT-7 HI results

The Astronomical Journal, 146:48 (20pp), 2013 September doi:10.1088/0004-6256/146/3/48

KAT-7 SCIENCE VERIFICATION: USING H I OBSERVATIONS OF NGC 3109 TO UNDERSTAND ITS KINEMATICS AND MASS DISTRIBUTION

C. Carignan[1,3], B. S. Frank[1], K. M. Hess[1], D. M. Lucero[1], T. H. Randriamampandry[1], S. Goedhart[2], and S. S. Passmoor[2]
[1] Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa; ccarignan@ast.uct.ac.za
[2] SKA South Africa, The Park, Park Road, Pinelands, 7405, South Africa
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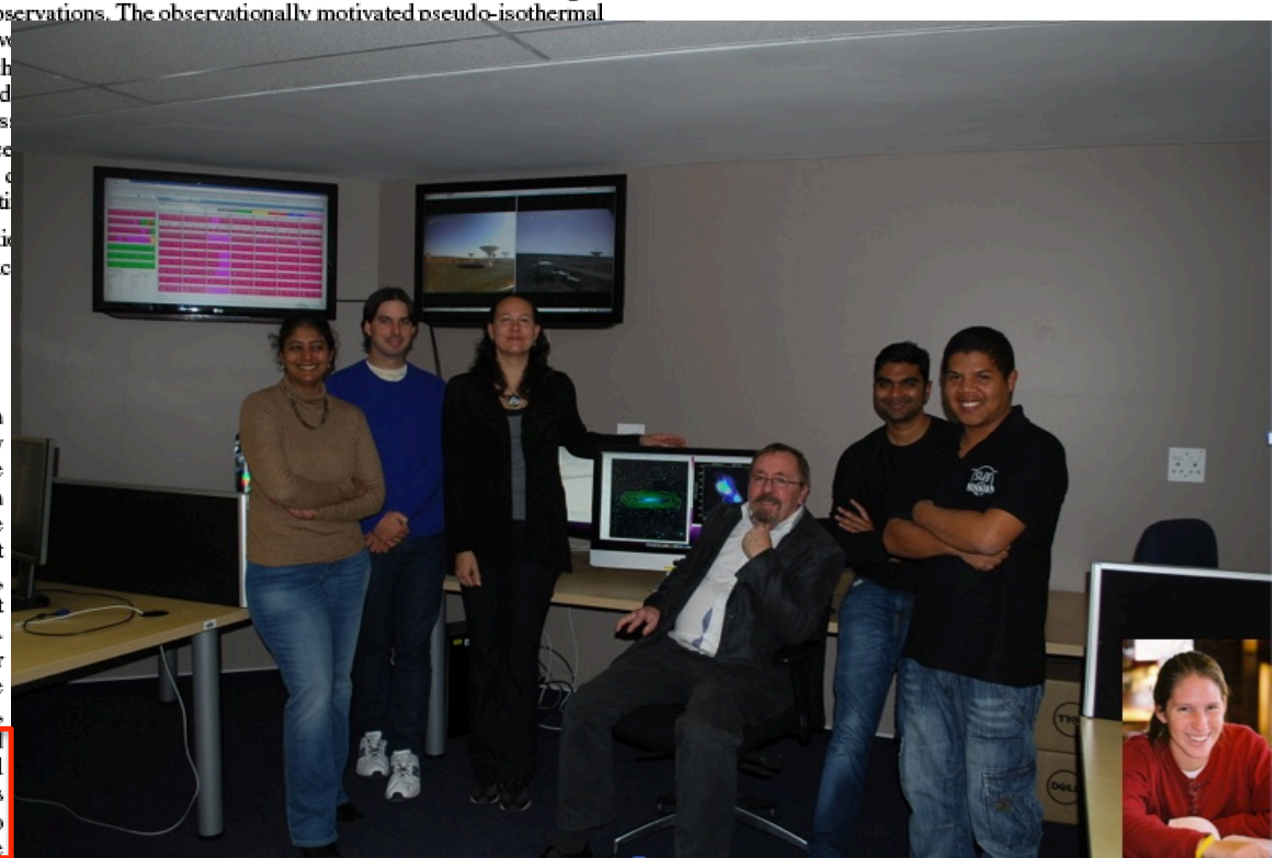
ABSTRACT

H I observations of the Magellanic-type spiral NGC 3109, obtained with the seven dish Karoo Array Telescope (KAT-7), are used to analyze its mass distribution. Our results are compared to those obtained using Very Large Array (VLA) data. KAT-7 is a pathfinder of the Square Kilometer Array precursor MeerKAT, which is under construction. The short baselines and low system temperature of the telescope make it sensitive to large-scale, low surface brightness emission. The new observations with KAT-7 allow the measurement of the rotation curve (RC) of NGC 3109 out to 32′, doubling the angular extent of existing measurements. A total H I mass of $4.6 \times 10^8\ M_\odot$ is derived, 40% more than what is detected by the VLA observations. The observationally motivated pseudo-isothermal dark matter (DM) halo model can reproduce the observ
Frenk-White DM model gives a much poorer fit to th
reduced the discrepancy between the observed RC and
is done at the expense of having to use unrealistic mas
for the MOND *universal* constant a_0. Different distance
kinematics, in view of the small errors on these two
studied recently, the present result for NGC 3109 conti

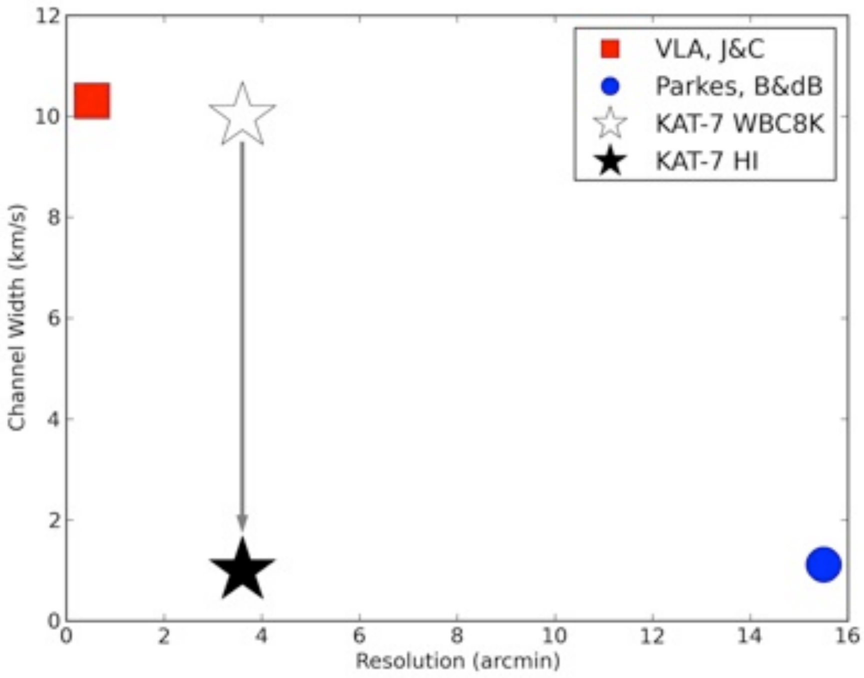
Key words: dark matter – galaxies: halos – galaxi
kinematics and dynamics – techniques: interferometric

1. INTRODUCTION

On 2012 May 25, South Africa was awarded the construction of the mid-frequency array of the Square Kilometer Array (SKA), while Australia will build the low-frequency array. The SKA will consist of an ensemble of 3000 ∼15 m dishes of which 80% will constitute the core portion in the Karoo desert while the remaining antennae will extend all the way to the eight African partner countries, namely Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia, and Zambia. It is expected that the full SKA will be completed around 2025. A precursor array of 64 dishes, MeerKAT, is already under construction by South Africa and should be ready for science operation in 2016. In preparation for these two large projects, a pathfinder array comprising 7 dishes, KAT-7, was completed in 2010 December. While its main purpose is to test technical solutions for MeerKAT and the SKA, scientific targets such as NGC 3109 have also been observed during commissioning to test the H I spectral line mode. In this paper, we compare more



HI observations of NGC 3109



NGC 3109

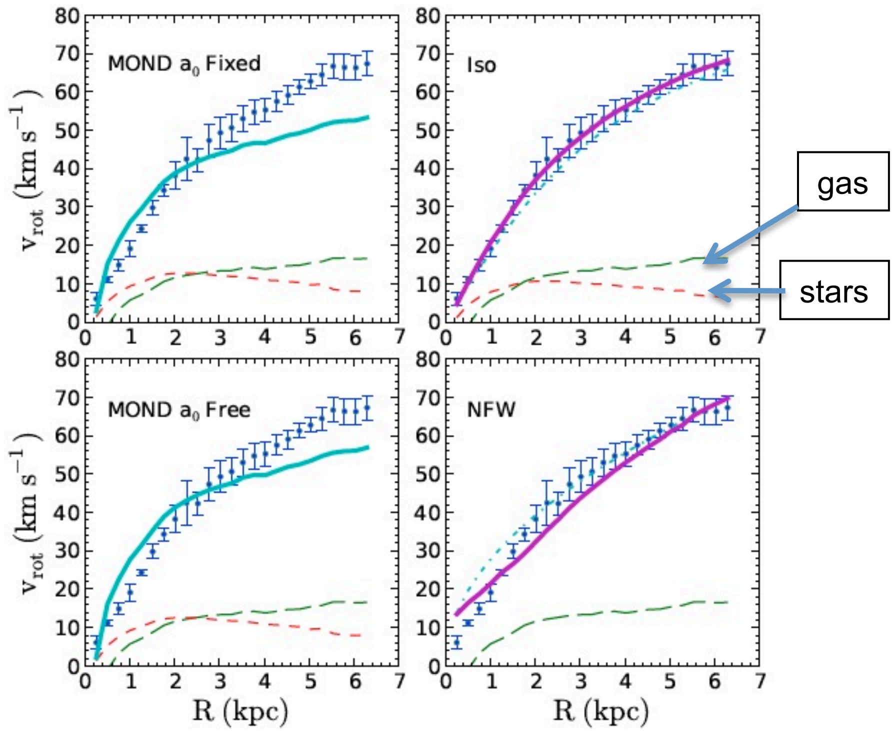


Figure 11: Rotation curve fit for NGC 3109, symbols are the same as in Figure 1.

Neutral Hydrogen

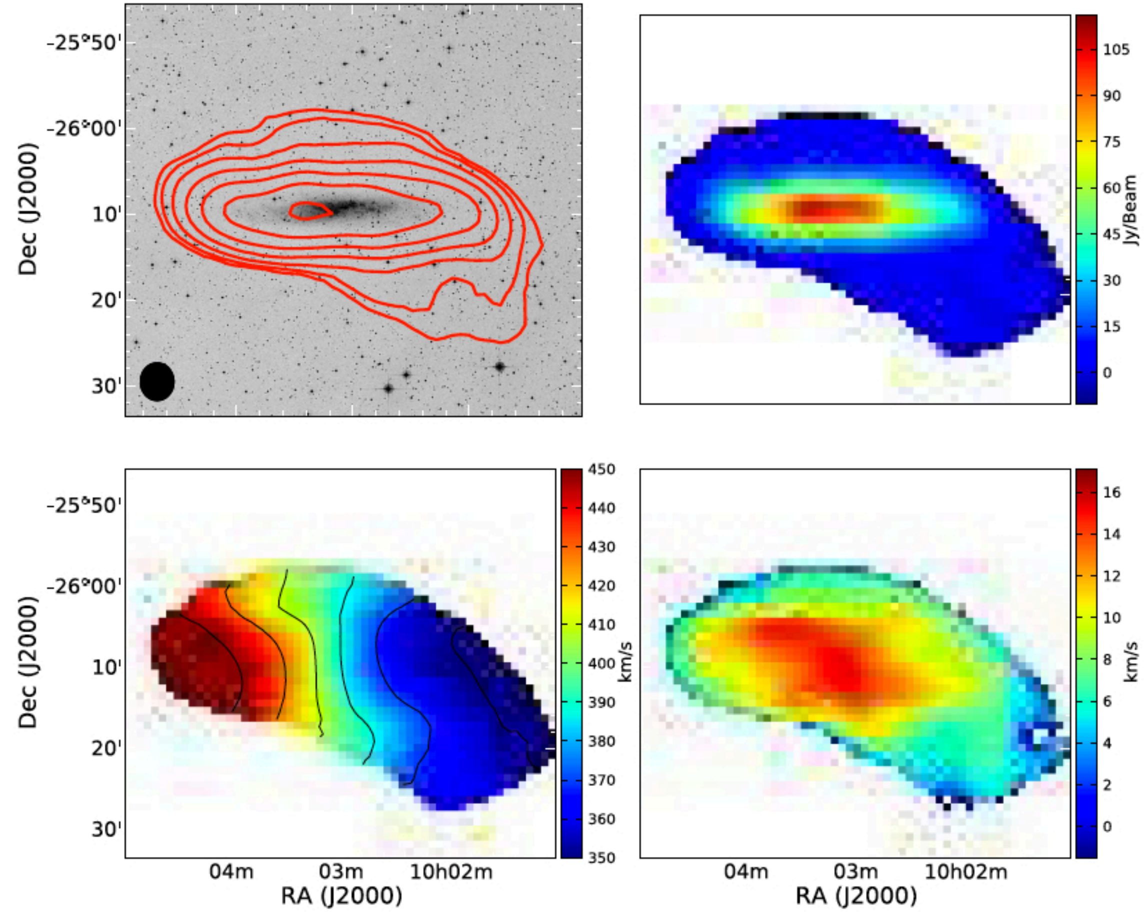
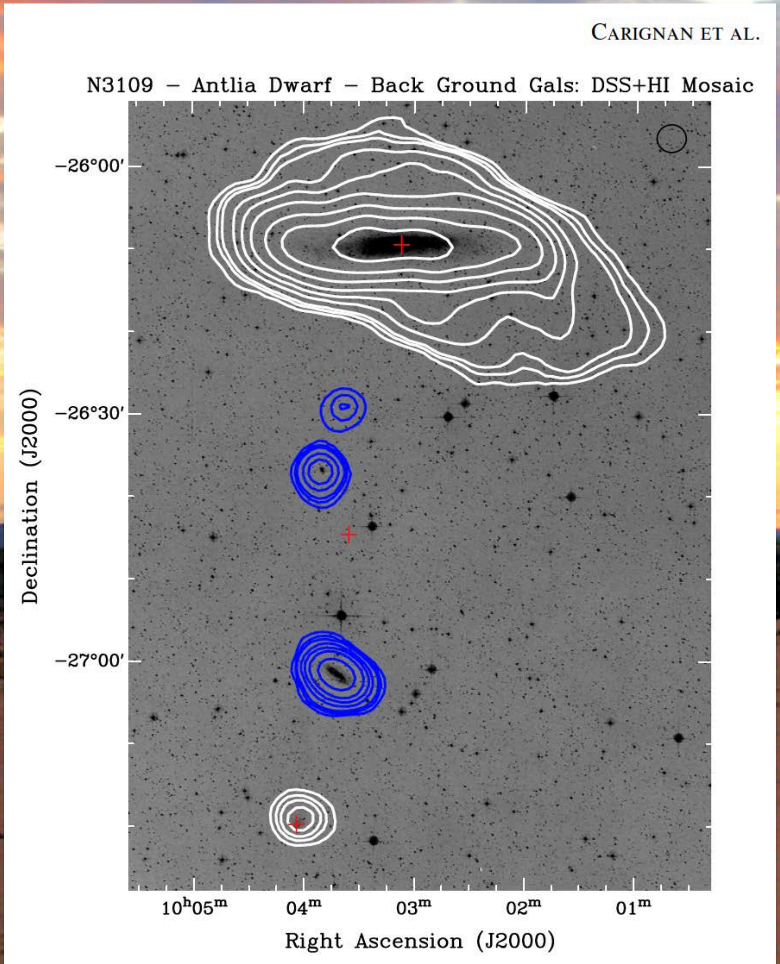
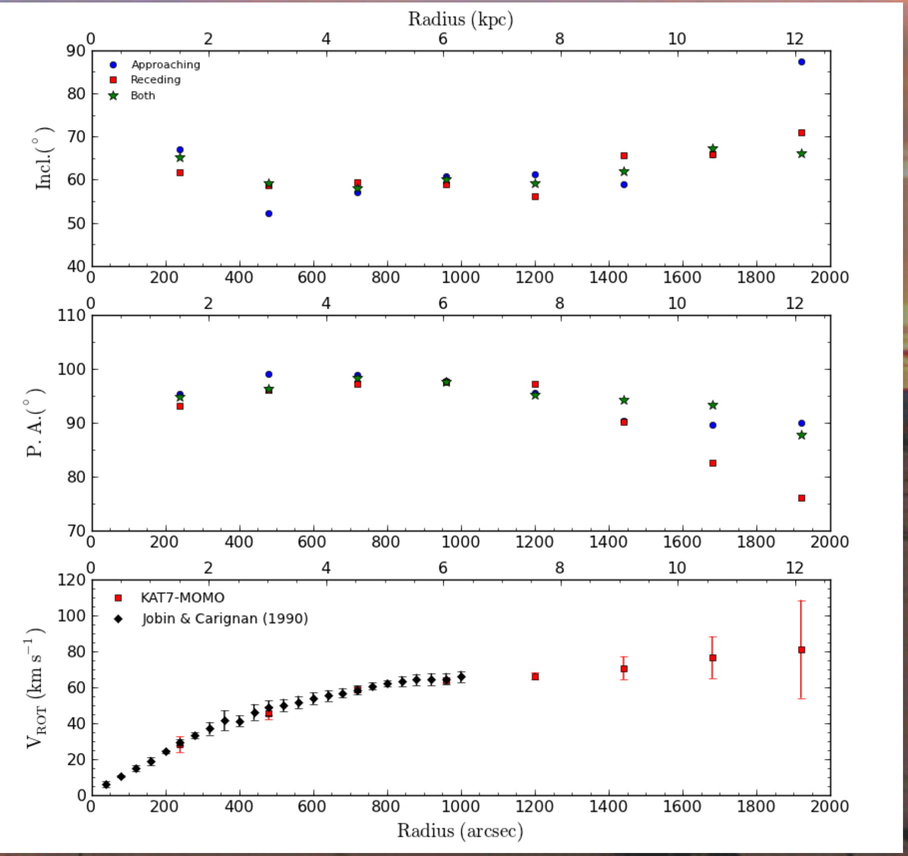


Figure 3. Moment maps of NGC 3109 from the KAT-7 na data cube. (Top-left) Total H I emission map with the synthesized beam in the bottom-left corner. The contours are 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, and 25.6 × 10^{20} atoms cm^{-2}, superposed on a DSS B image. (Top-right) Total H I emission map; (bottom-left) velocity field. The contours are 350, 370, 390, 410, 430, and 450 km s^{-1} ; (bottom-right) velocity dispersion.

Derivation of the RC: Tilted-ring Model





Lowest contour = 1 x 10^{19} cm^{-2}

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HI observations of the nearest starburst galaxy NGC 253 with the SKA precursor KAT-7

D. M. Lucero[1]*, C. Carignan[1], E. C. Elson[1], T. H. Randriamampandry[1], T. H. Jarrett[1], T. A. Oosterloo[2,3] and G. H. Heald[2,3]

[1] Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa
[2] Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands
[3] Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands

ABSTRACT

We present HI observations of the Sculptor Group
tained with the seven dish Karoo Array Telescope (KAT
precursor MeerKAT, under construction. The short bas
the telescope make it very sensitive to large scale, low s
7 observations detected 33% more flux than previous V
parts and in the halo for a total HI mass of 2.1 ± 0.1 ×
HI can be found away from the plane out to projected
and 13-14 kpc at the edge of the disk. However, in the ra
small for a late-type spiral, barely comparable to the op
teractive profile fitting, was used to separate the main di
Full 3D models were generated to check the consistenc
ters. The rotation curve (RC) derived for the HI disk co
parts, as seen in previous optical Fabry-Perot measure
nent, its RC has a very shallow gradient in the inner par
the disk, kinematically lagging by ~100 km s^{-1}. The k
gas are compatible with an *outflow* due to the central s
outer parts. However, the gas kinematics show no evide
WISE data, shows clearly that the star formation rate (
nature of NGC 253.

Key words: techniques: interferometric – galaxies: ind
– galaxies: kinematics and dynamics – galaxies: haloes

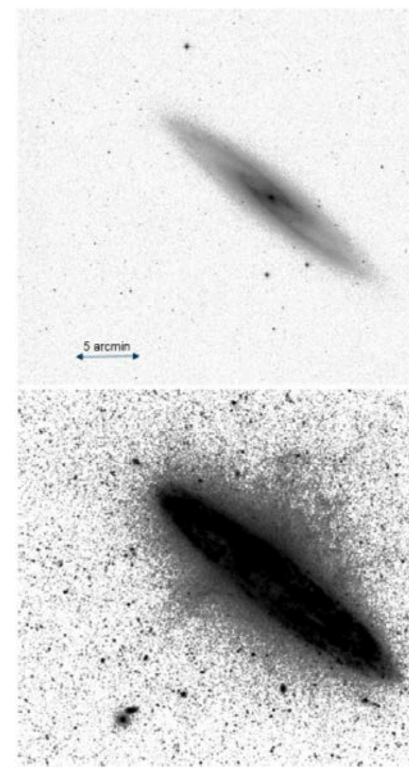
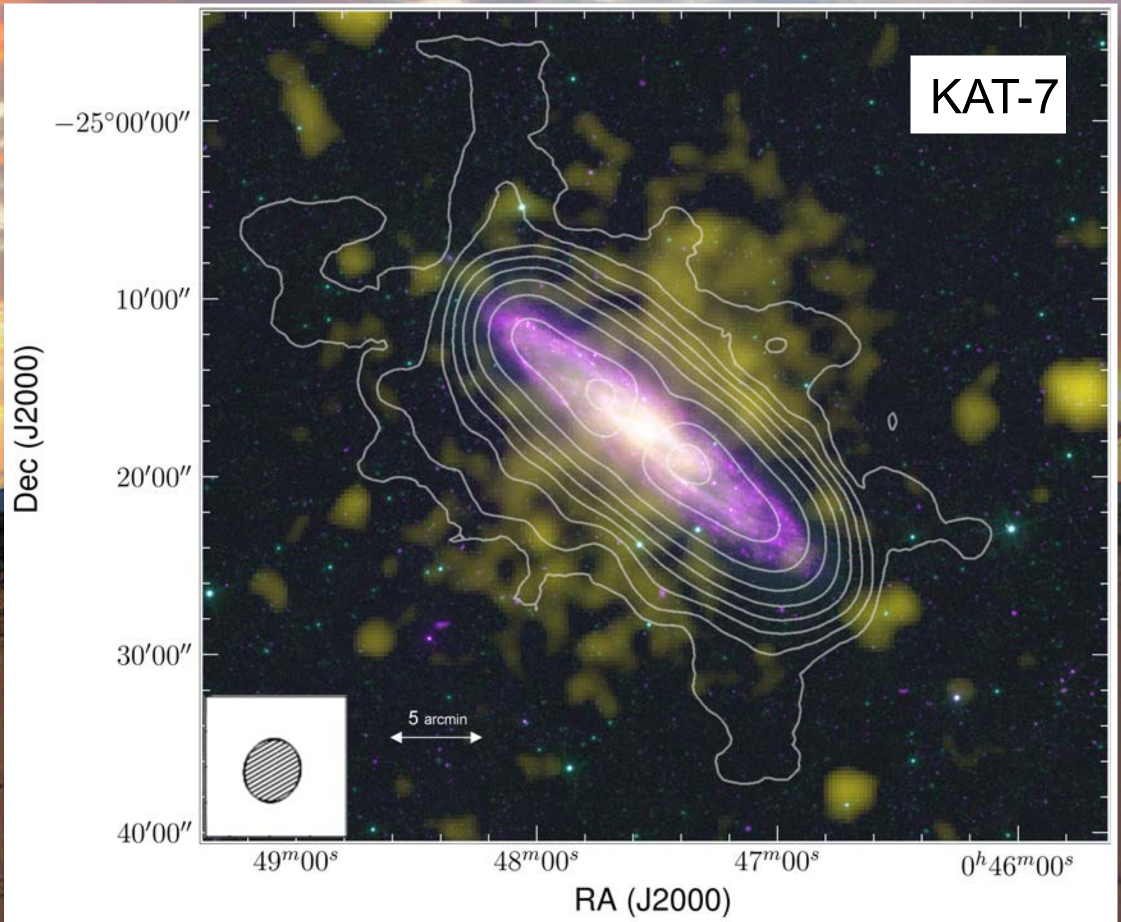
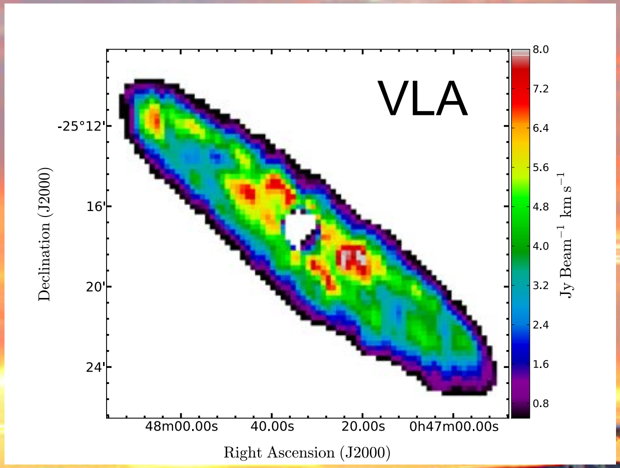
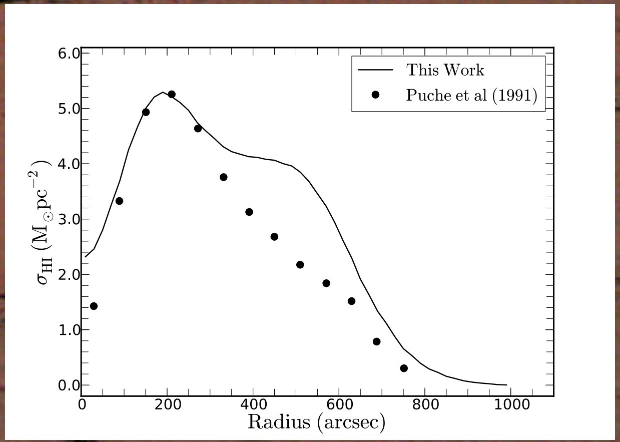


Figure 1. 2MASS K-band (top) and GALEX FUV (bottom)
253.

HI observations of NGC 253



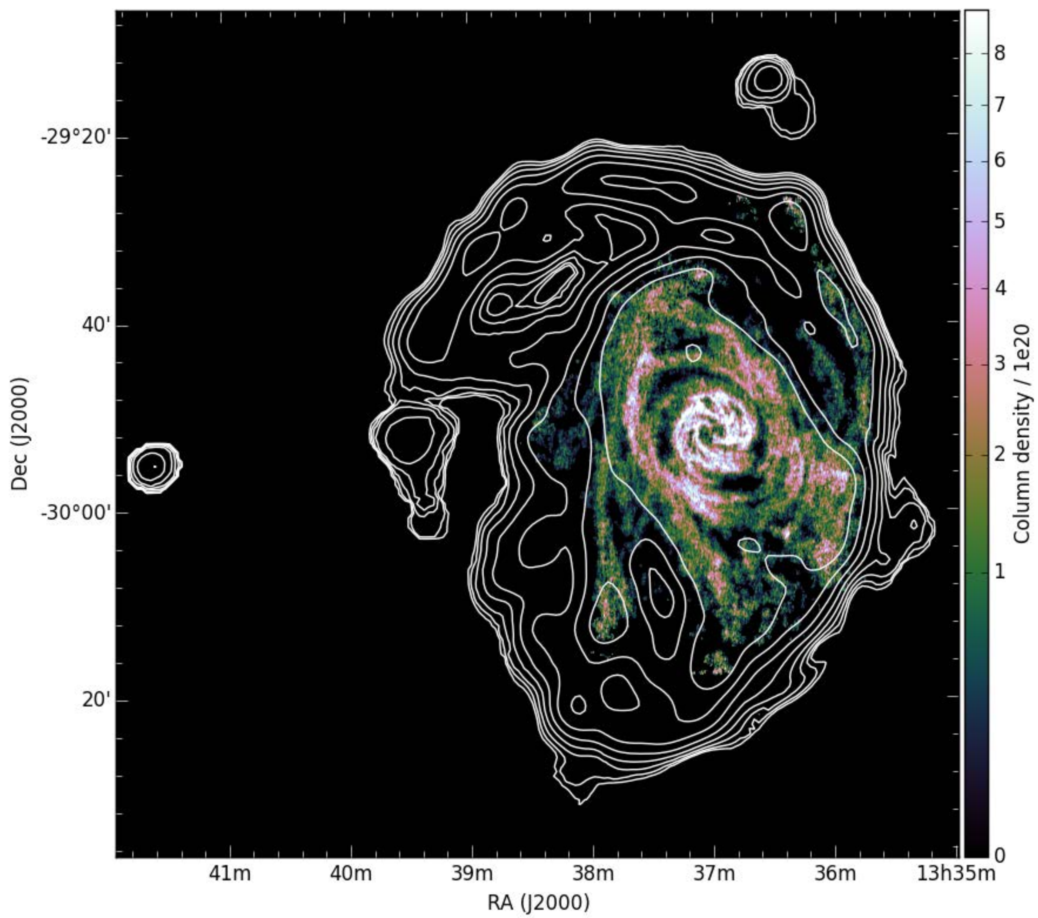




Accretion ? e.g. Wang's talk yesterday

Neutral hydrogen and magnetic fields in M83 observed with the SKA Pathfinder KAT-7

G. Heald[1,2]⋆, W. J. G. de Blok,[1,3,2] D. Lucero,[3] C. Carignan,[3] T. Jarrett,[3]
E. Elson[3], N. Oozeer,[4] and T. H. Randriamampandry[3]
[1] ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA, Dwingeloo, The Netherlands
[2] Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV, Gr
[3] Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 77
[4] SKA South Africa, The Park, Park Road, Pinelands, 7405, South Africa



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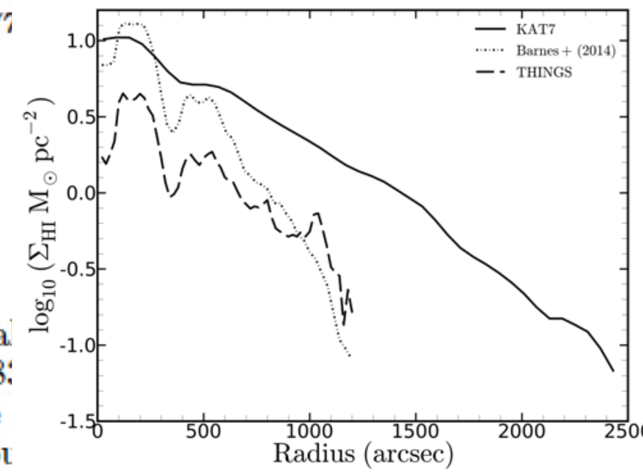
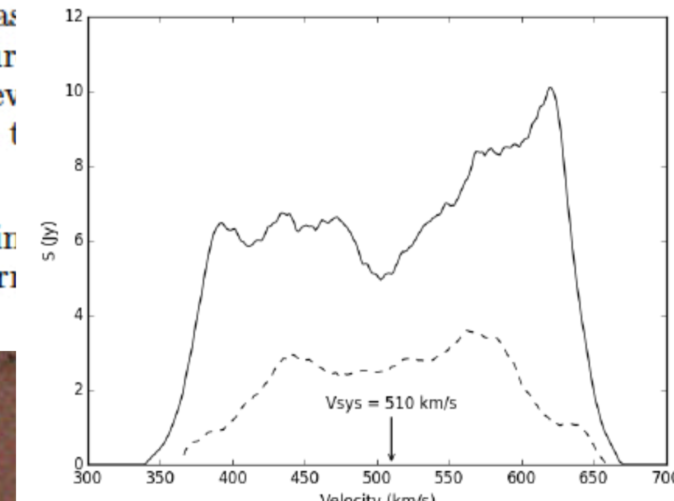
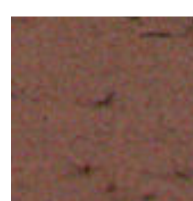






HI in Clusters & groups

KAT-7 SCIENCE VERIFICATION: COLD GAS, STAR FORMATION, AND SUBSTRUCTURE IN THE NEARBY ANTLIA CLUSTER

Kelley M. Hess[1,2,3], Tom Jarrett[1], Claude Carignan[1], Sean S. Passmoor[4], Sharmila Goedhart[4]

Draft version January 11, 2015

ABSTRACT

The Antlia Cluster is the third most nearby cluster to us after Virgo and Fornax, but to date has been poorly studied because of its southern declination and low galactic latitude. The cluster is a dynamically young structure and its locality presents us with a valuable opportunity for detailed study of galaxy and gr … aic completed as part of spectral line commis … ~ 4.2 deg^2 centered on the cluster, and resu … urce catalog to study the neutral atomic gas … T-7 mosaic detects 30 H I cluster members do … s, 20 of which do not

TABLE 1: KAT-7 Observations & Imaging

Observing Parameter	Value
Date of Observations	March - July 2013
Total integration time (7×21 h)	147 h
Total bandwidth	25 MHz
Central frequency	1406.7 MHz
Spectral resolution	6.104 kHz
Flux/Bandpass calibrator	3C138, PKS 1934-638
Phase/Gain calibrator	1018-317
Image Property	
Mosaic area	$\sim$4.2 deg^2
Synthesized beam	$3.7' \times 3.0'$
Velocity coverage	$1159 - 4628$ km s^{-1}
Velocity resolution	15.5 km s^{-1}
Final RMS	0.97 mJy beam^{-1}

HI in Clusters & groups

KAT-7: Cold Gas, Star Formation, Substructure in Antlia 5

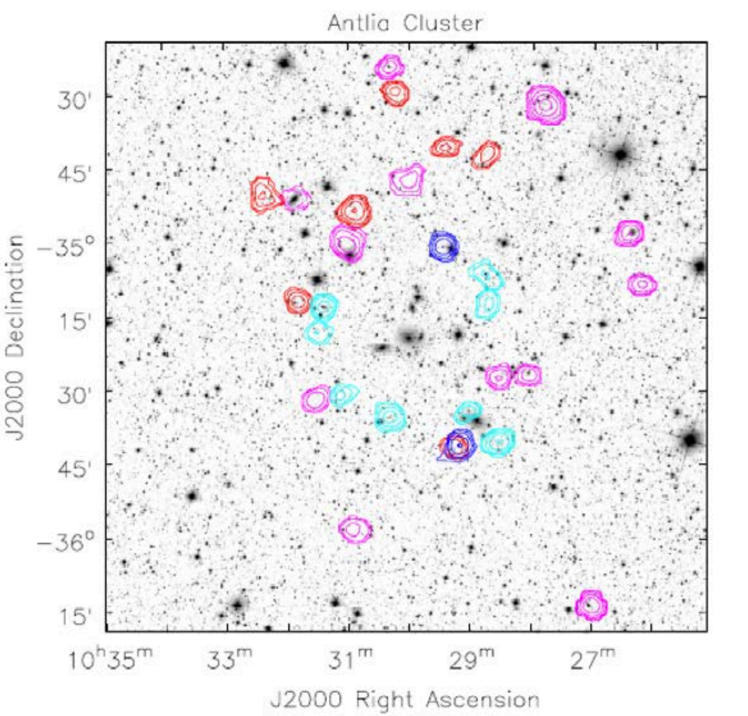
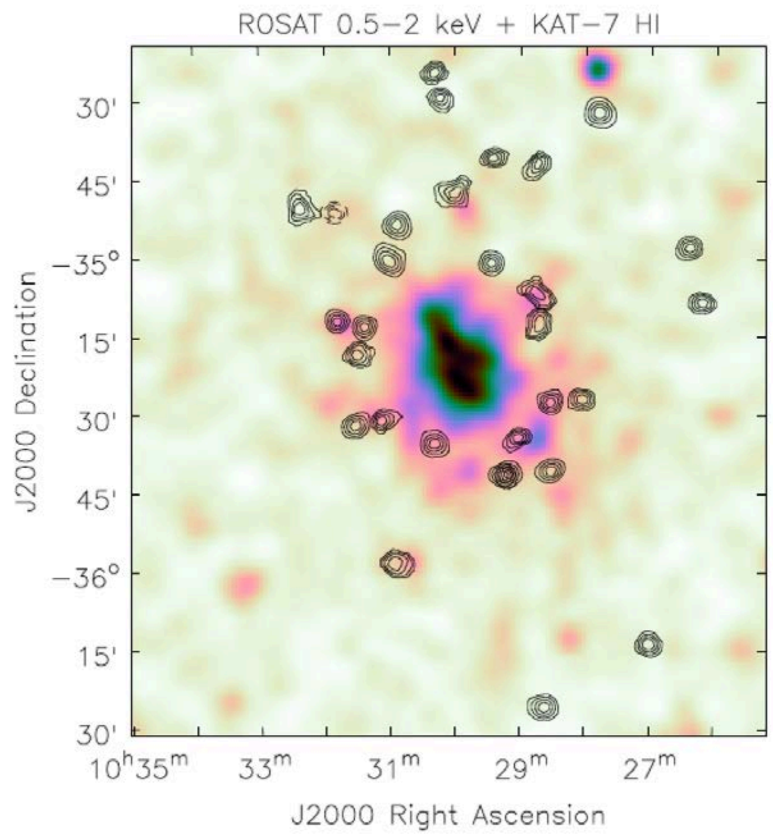


FIG. 1: H I contours on a *WISE* 3.4 μm image. The contours correspond to column densities of 2, 4, 8, 16, 32, 64 $\times \sigma$ listed in Column 6 of Table 2. They are color coded to the systemic velocity of the galaxy relative to the cluster center: dark blue is < 2200 km s^{-1}, cyan is 2200 – 2800 km s^{-1}, magenta is 2800 – 3400 km s^{-1}, and red is > 3400 km s^{-1}. The center of the image coincides with the center of the H I mosaic and the center of the cluster, the massive elliptical galaxy, NGC 3268. Dashed contours represent the negative H I absorption around NGC 3281, northeast of the cluster center.

20 Hess et al.



- 35 new HI detections
- 27 new spectroscopic redshifts
- Allow to study the cluster substructure

HI in the Virgo Cluster Outskirt

HI observations of galaxies in the southern filament of the Virgo Cluster with the SKA Precursor KAT-7 and the WSRT.

A. Sorgho[1*], C. Carignan[1], K. Hess[1,2], T. A. Oosterloo[2,3], J. H. van Gorkom[4], T. Jarrett[1]

[1] *Department of Astronomy, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa*
[2] *Netherlands Institute for Radio Astronomy (ASTRON), Postbus 2, 7990 AA Dwingeloo, The Netherlands*
[3] *Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands*
[4] *Department of Astronomy, Columbia University, New York, NY 10027, USA*

Lowest column density sensitivity in the Virgo region ~8 x 10^{17} cm^{-2}

Parameter	KAT-7	WSRT
Weighting function	Robust = 0	Robust = 0.5
Channel width	15.2 km s^{-1}	16.5 km s^{-1}
FWHM	$4.4' \times 3.1'$	$2.9' \times 0.6'$
Map gridding	$55'' \times 55''$	$5'' \times 5''$
Map size	256 × 256	1232 × 1642
RMS noise	2.5 mJy $beam^{-1}$	0.35 mJy $beam^{-1}$

Table 1: Summary of the KAT-7 and WSRT image cubes.

on of the Virgo cluster using
is Radio Telescope (WSRT).

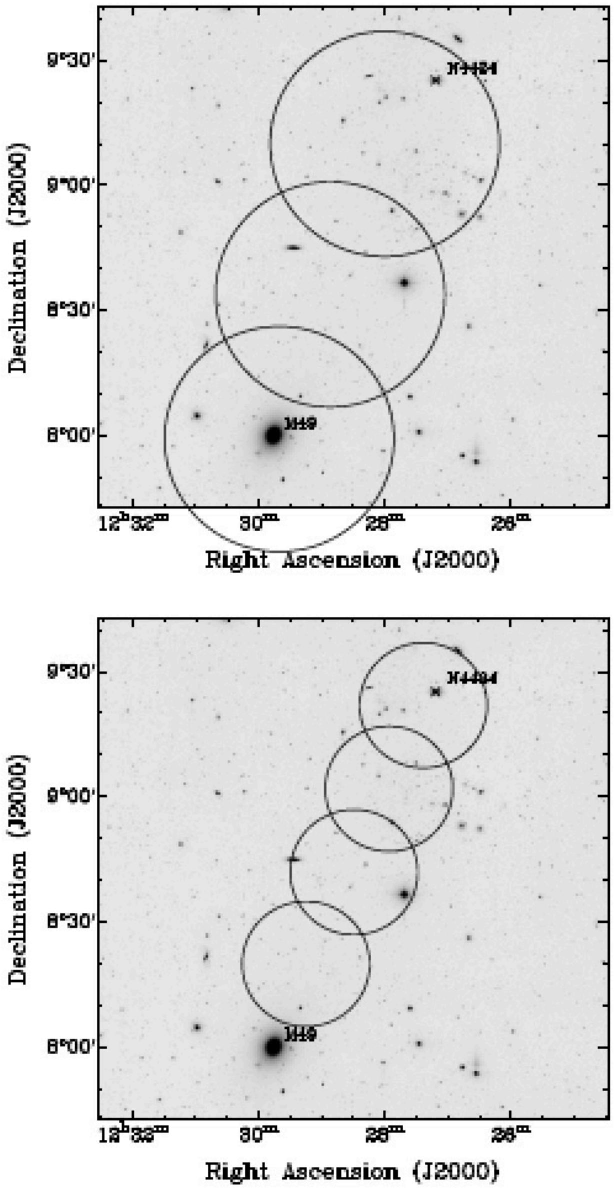
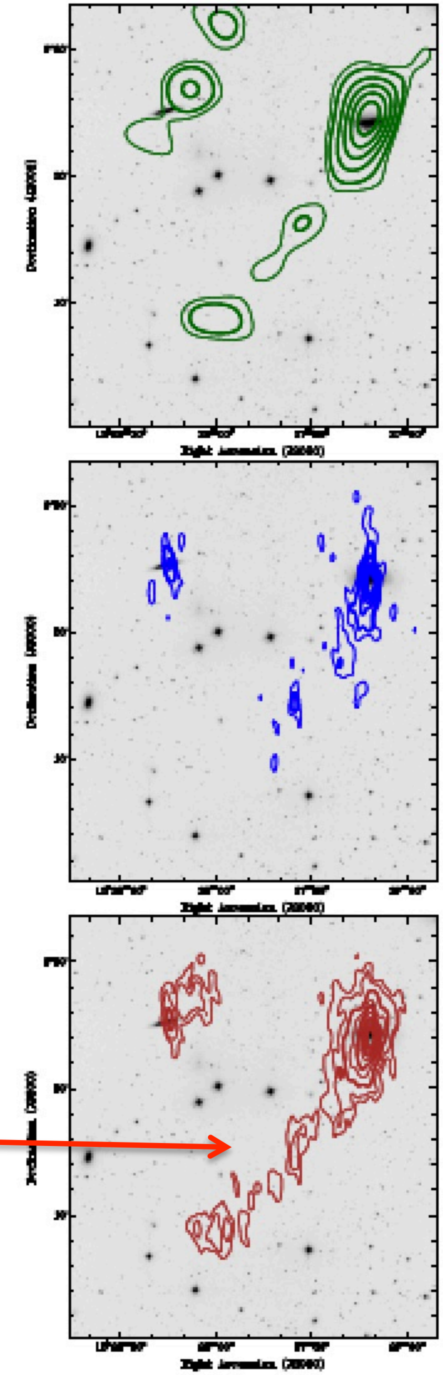
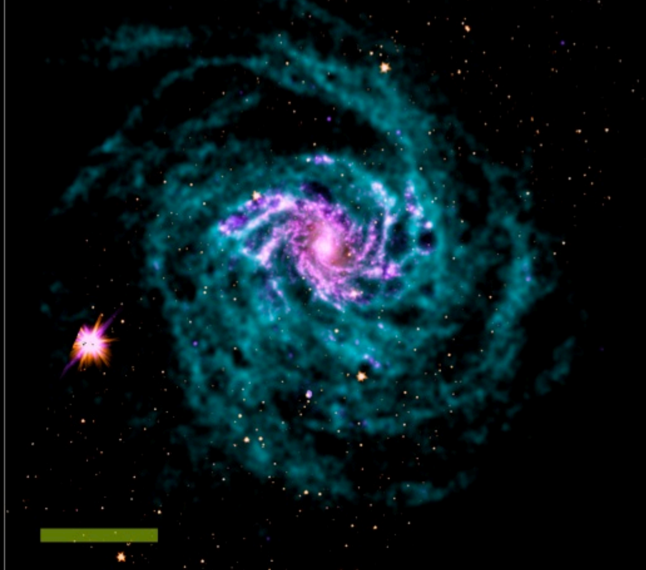


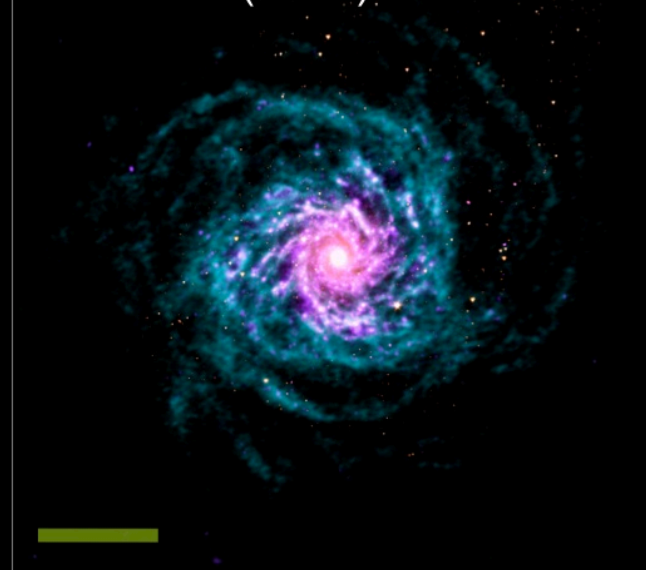
Figure 1. KAT-7 (*top*) and WSRT (*bottom*) primary beams on optical *r*-band grayscale, showing the pointings positions of the observations.



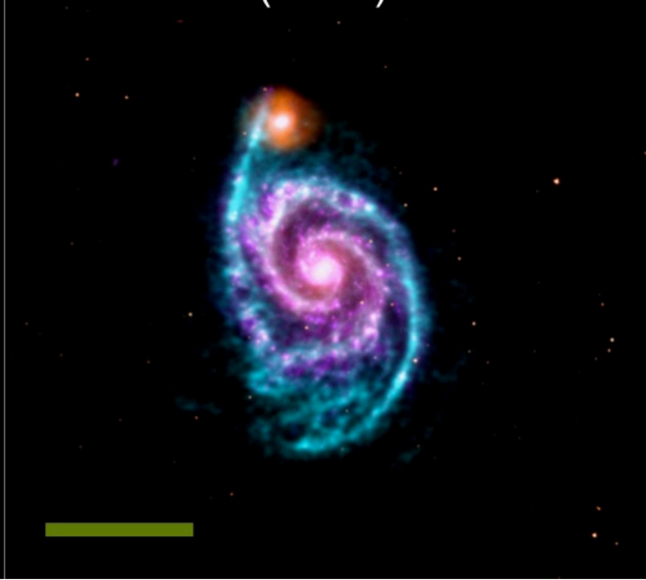
Spiral Galaxies in T*HI*NGS — The *HI* Nearby Galaxy Survey



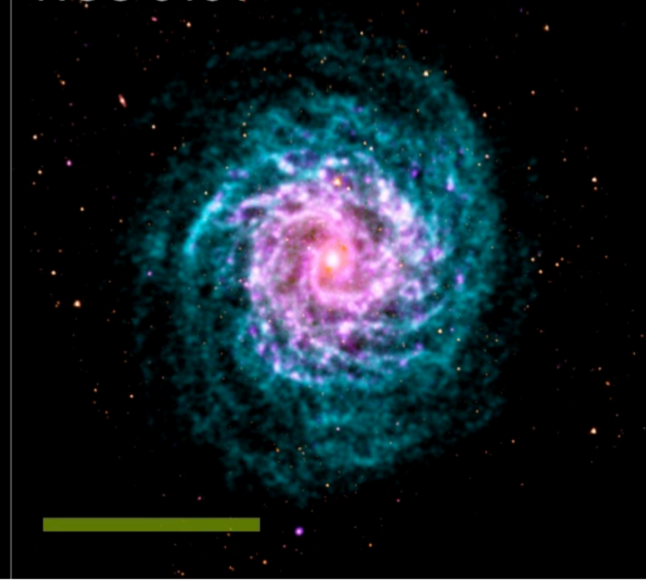
NGC 6946



NGC 628 (M 74)



NGC 5194 (M 51)



NGC 3184

'Face-on' Spiral Galaxies in T*HI*NGS

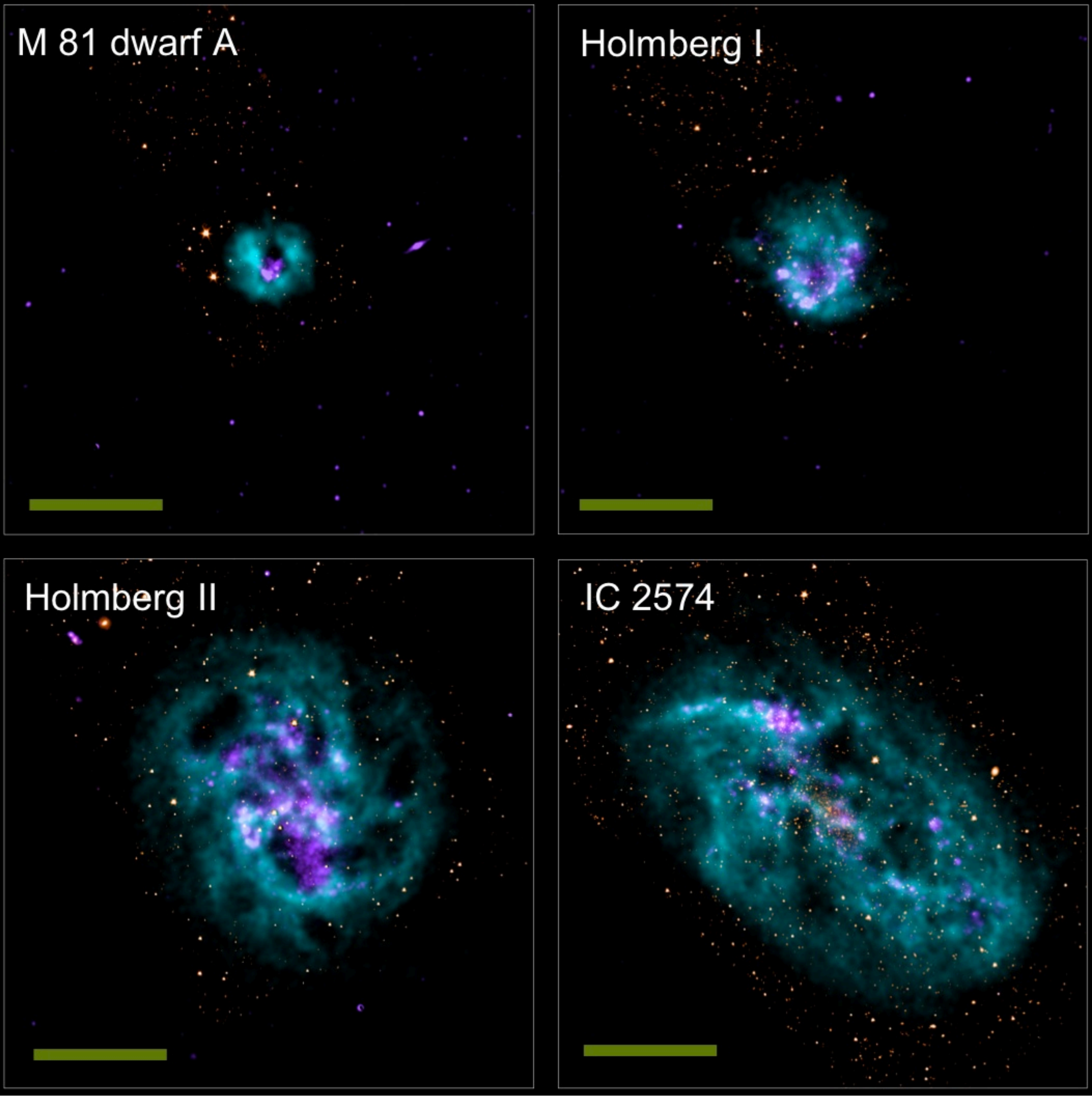
scale:
10 kpc
30.000 light years

Color Coding:

Atomic Hydrogen (HI)
(Very Large Array)
Old stars
(Spitzer)
Star Formation
(Galex & Spitzer)

Image credits:
VLA THINGS: Walter et al.
Spitzer SINGS: Kennicutt et al.
Galex NGS: Gil de Paz et al.

Dwarf Galaxies in T*HI*NGS -- The *HI* Nearby Galaxy Survey



Dwarf Galaxies of the M81 group in T*HI*NGS

scale:
5 kpc
15.000 light years

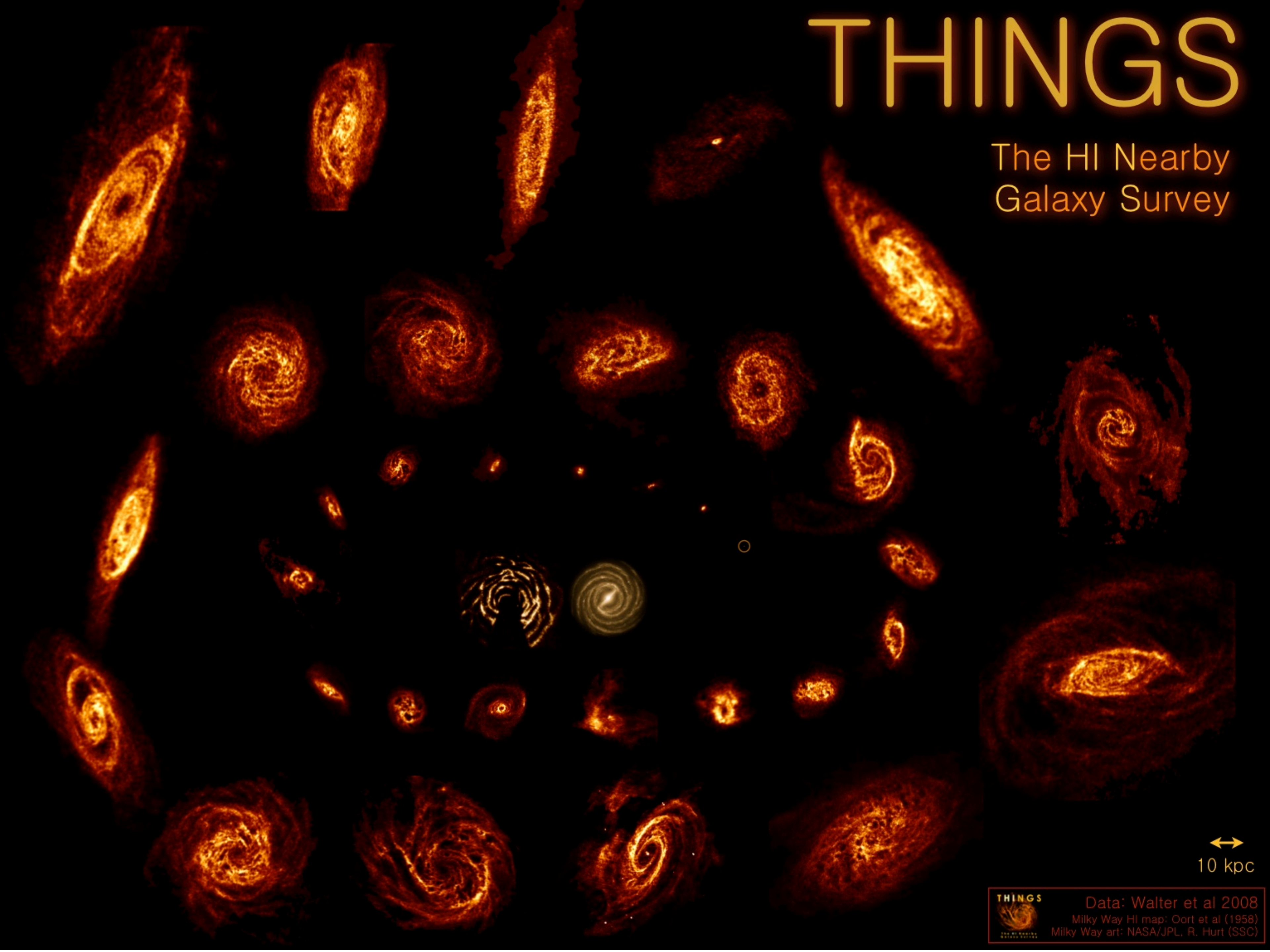
color coding:

Atomic Hydrogen (HI)
(Very Large Array)

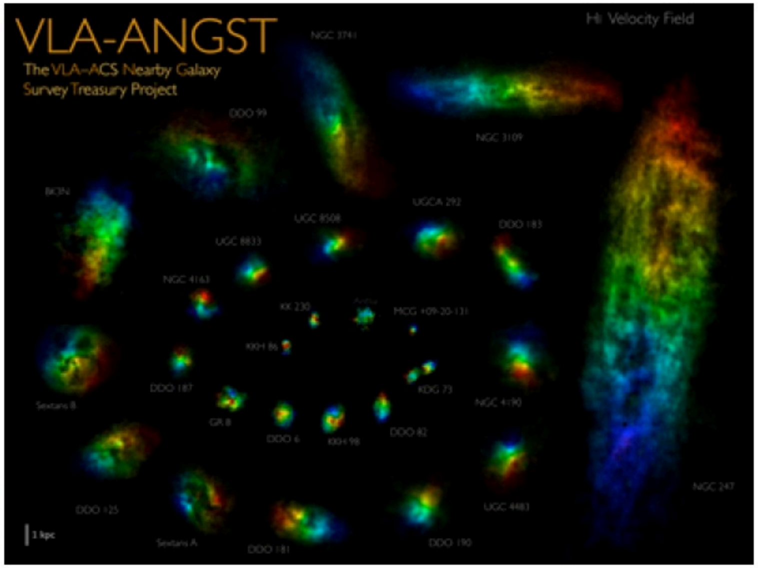
Old stars
(Spitzer)

Star Formation
(Galex & Spitzer)

Image credits:
VLA THINGS: Walter et al.
Spitzer SINGS: Kennicutt et al.
Galex NGS: Gil de Paz et al.

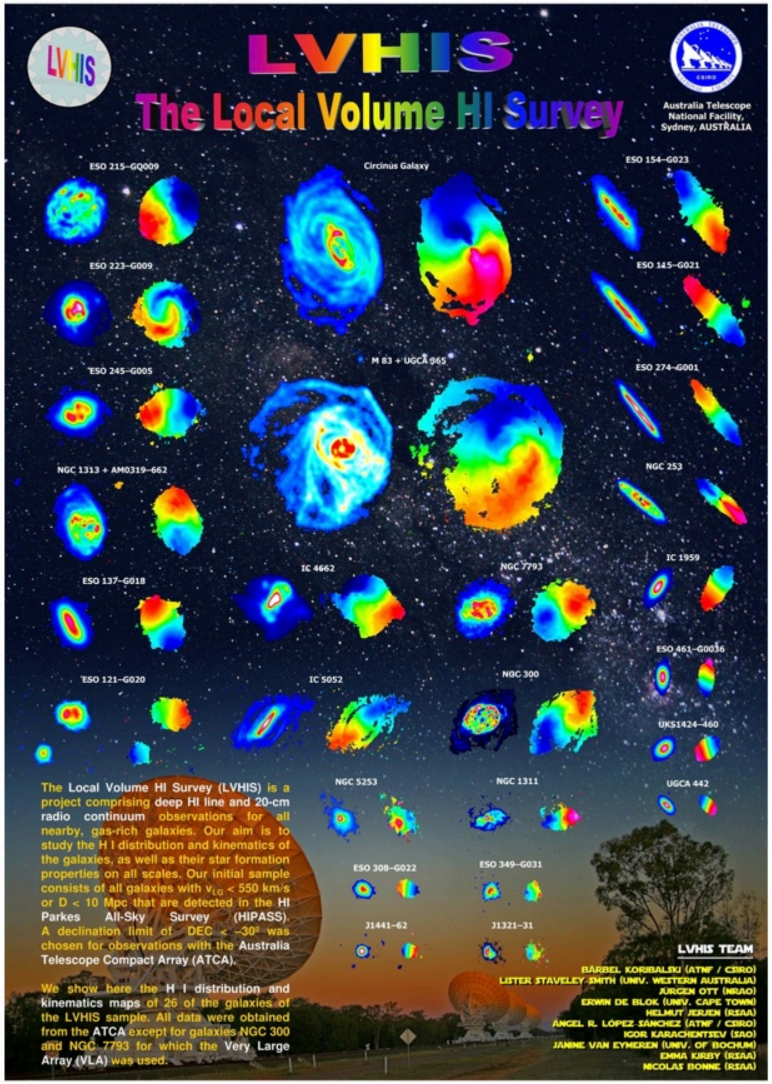

THINGS
The HI Nearby Galaxy Survey
10 kpc
Data: Walter et al 2008
Milky Way HI map: Oort et al (1958)
Milky Way art: NASA/JPL, R. Hurt (SSC)

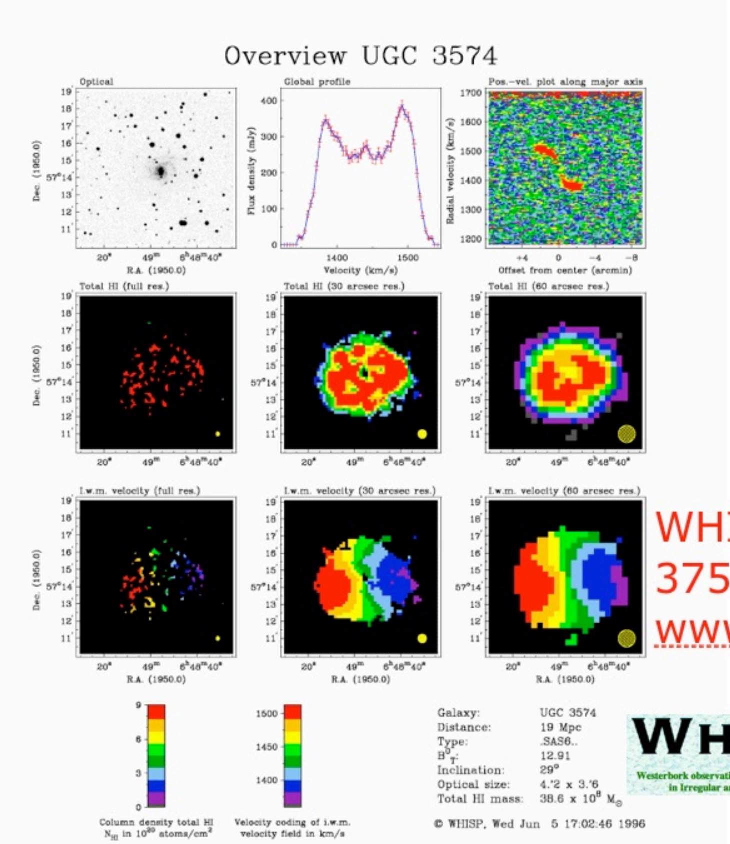
SKA AFRICA
SQUARE KILOMETRE ARRAY



VLA-ANGST:
35 galaxies

LVHIS:
all D<10Mpc galaxies

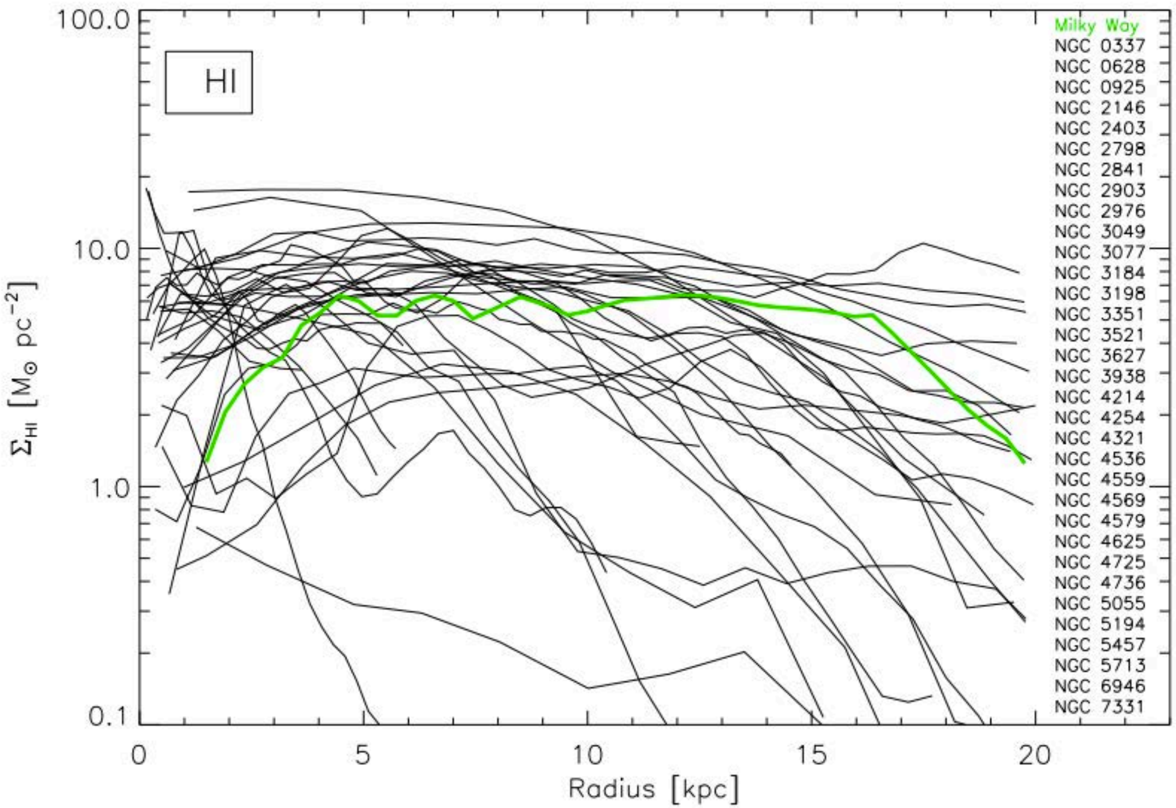




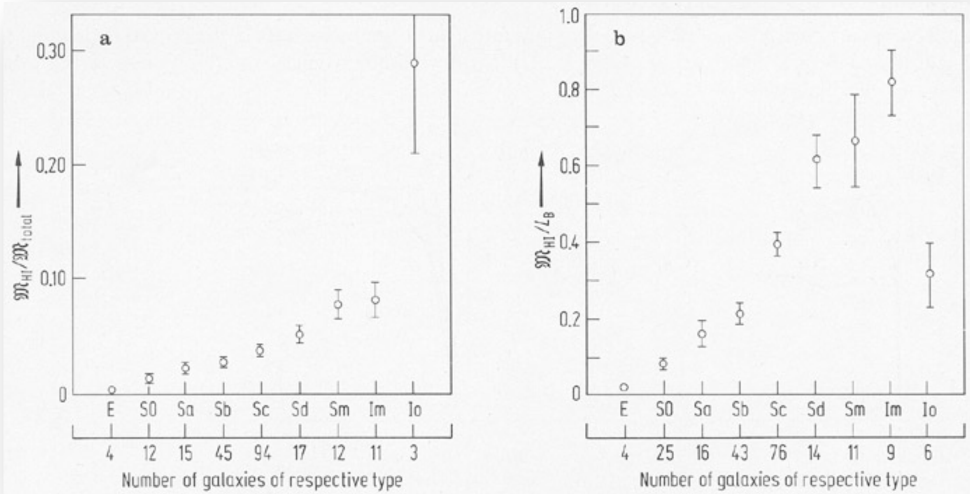
WHISP:
375 galaxies
www.astron.nl/wow

HI vs Optical

Scale length ~ 0.6 ∗ R_{25}
h_{gas} ~ $2h_{optical}$



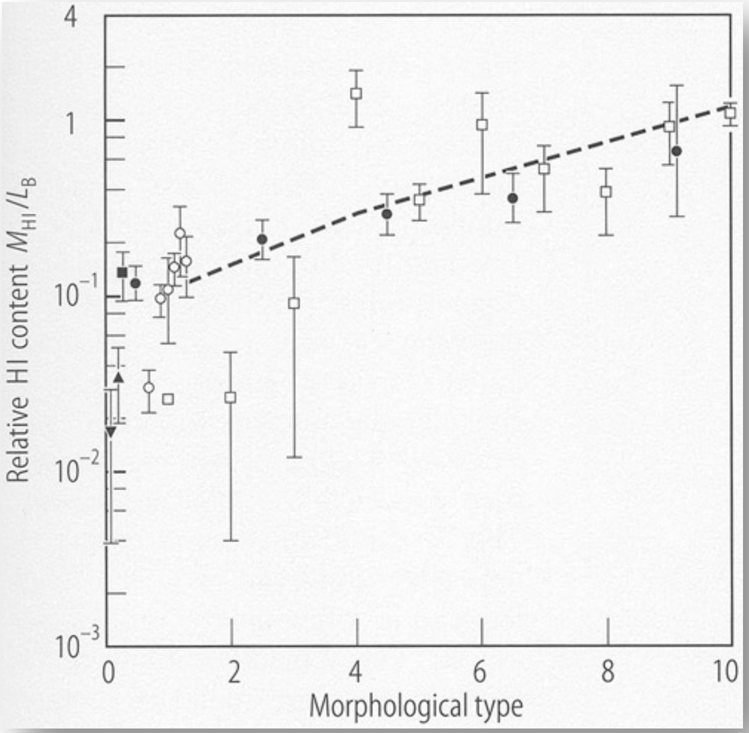
Neutral Hydrogen



- HI content for different types:
  a) Ratio HI mass / total mass
  b) Ratio M_{HI}/L_B

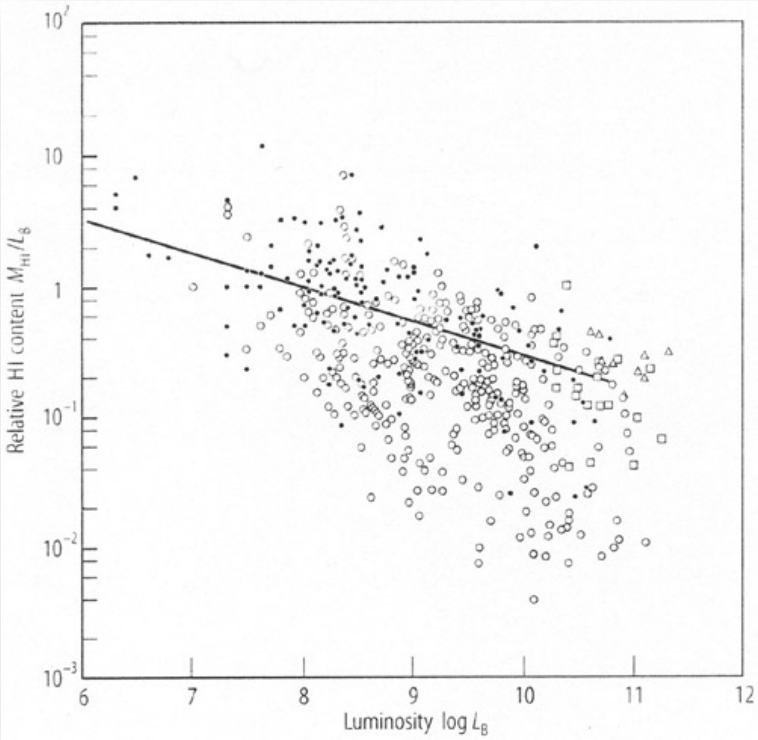
Neutral Hydrogen

- Relative HI content vs morphological types
- M_{HI}/L_B is often used to compare to other galactic parameters

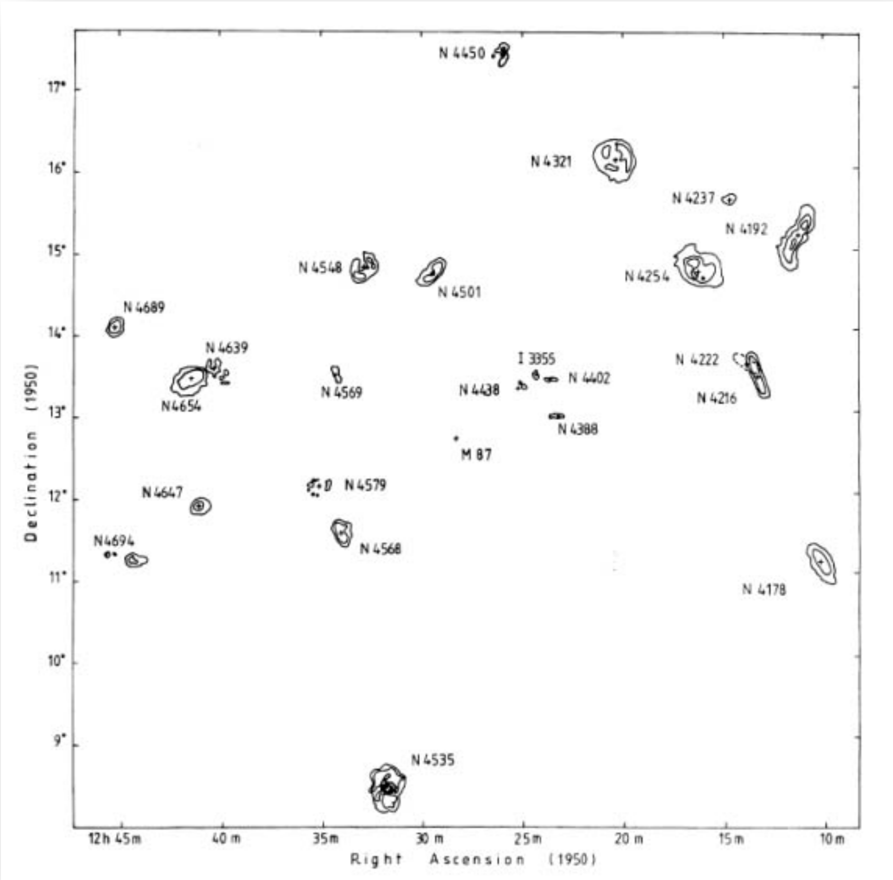


Neutral Hydrogen in clusters

- HI deficiency in the Virgo cluster
- M_{HI}/L_B vs blue luminosity
- A large number of the Virgo cluster galaxies have a M_{HI}/L_B much smaller than expected from their luminosity



Neutral Hydrogen in clusters



- HI survey in Virgo (Cayatte et al. 1994)

- Galaxies close to the cluster center have an HI deficiency caused by *ram pressure* from the inter-galactic medium

Neutral Hydrogen in clusters

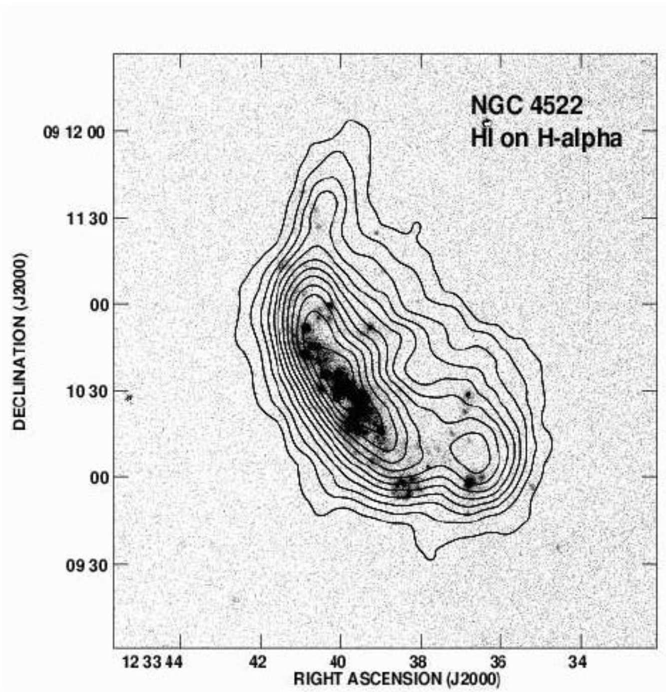


Fig. 13.— HI contour map on Hα greyscale image of NGC 4522. Lowest HI contour level and contour increments are 50 mJy/beam km/s. The spatial distributions of these 2 ISM components are similar on scales ≥15″ ≃1 kpc. There are HII regions associated with each of the 3 major extraplanar HI peaks, and those in the SW are much more luminous. The outermost bright disk HII complex in the SW appears to form a 6″=500 pc diameter bubble.

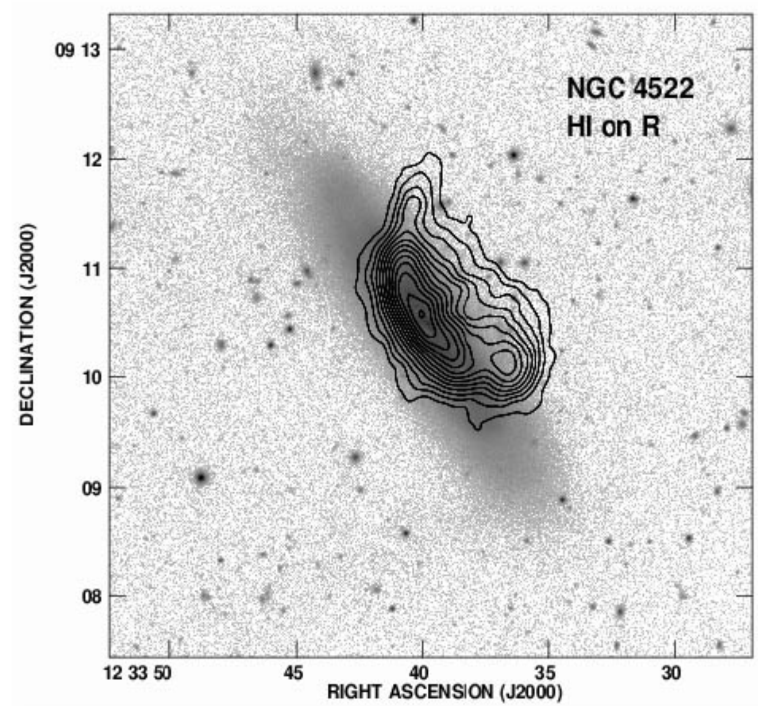


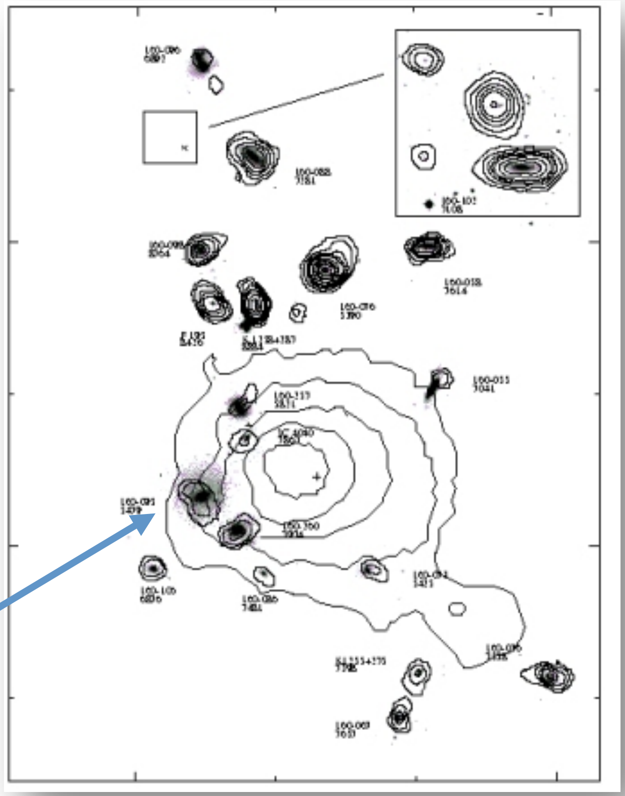
Fig. 3.— HI moment 0 contour map of NGC 4522 on R-band greyscale image from the WIYN telescope from Kenney & Koopmann (1999). Lowest HI contour level and contour increments are 50 mJy/beam km/s. Optical image shown with logarithmic stretch. Note undisturbed outer stellar disk.

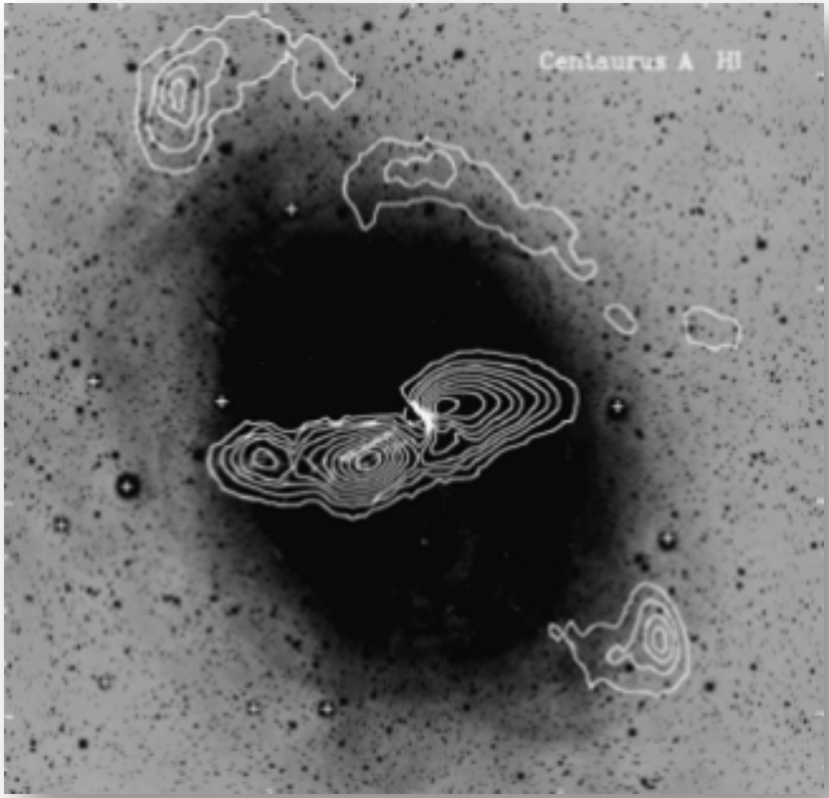
Kenney et al. 2004

Neutral Hydrogen in clusters

Coma

X-ray





page web J. van Goorkom

Neutral Hydrogen in clusters

Outskirts in Coma

IC 842

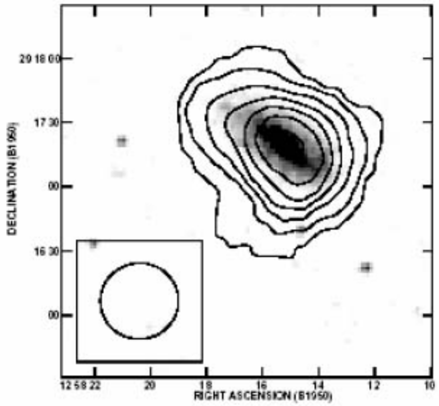


Fig. 17a. HI density distribution of IC 842 superposed on a DSS B-band gray scale image. The contours are 0.3 (2.5 σ),

CGCG 160-058

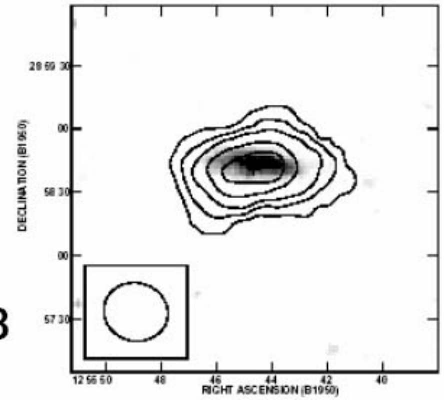


Fig. 6a. HI density distribution of CGCG 160–058, superposed on a DSS B-band gray scale image. The contours are 0.4

And near the Coma core….

NGC 4921

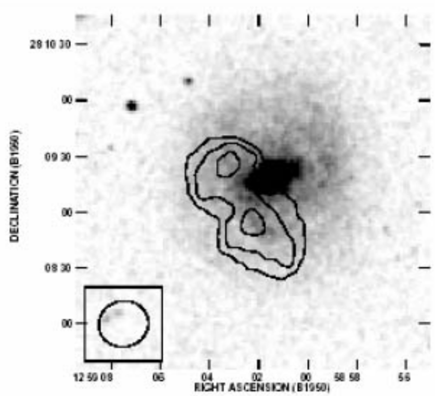


Fig. 16a. HI density distribution of NGC 4921, superposed on a DSS B-band gray scale image. The contours are 0.3 (2.5 σ),

NGC 4848

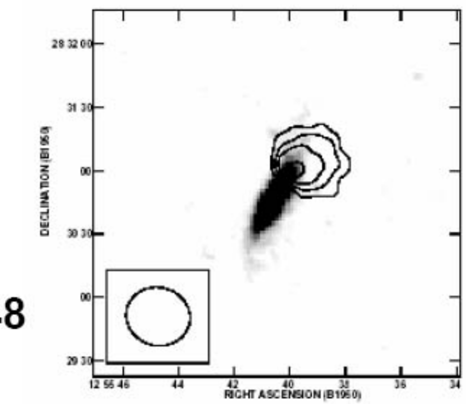


Fig. 4. HI density distribution of NGC 4848, superposed on a DSS B-band gray scale image. The contours are 0.3 (2.5 σ),

Bravo-Alfaro et al. 2001

Morphology Density relation

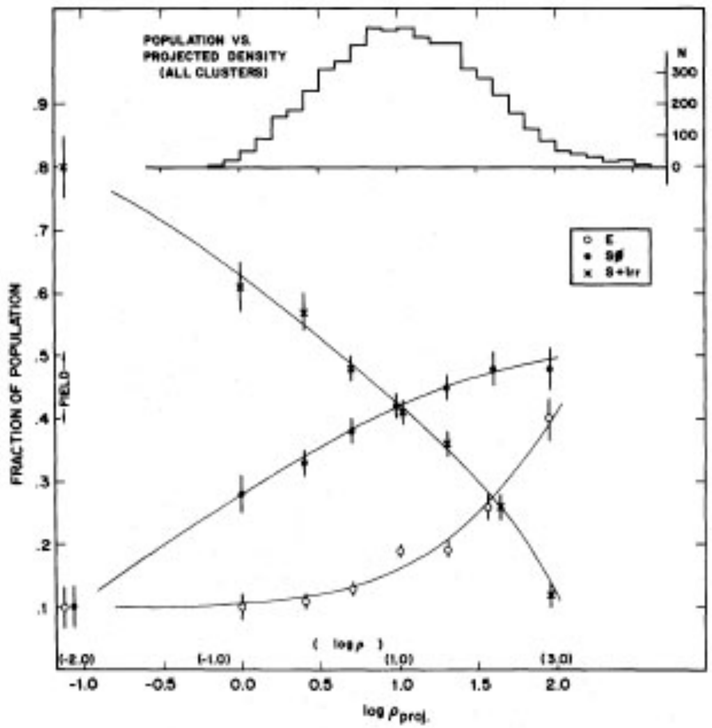
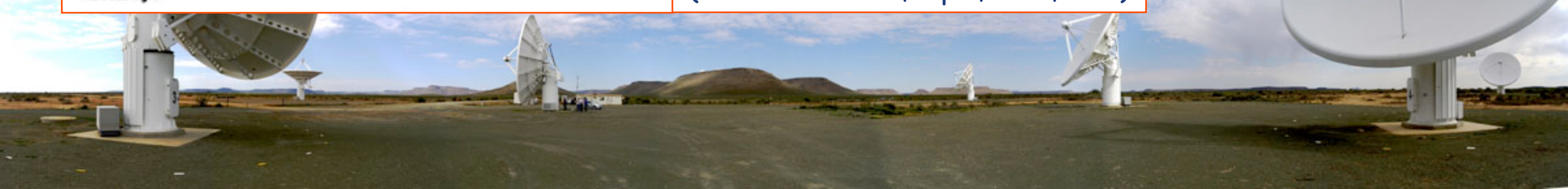


FIG. 4.—The fraction of E, S0, and S+I galaxies as a function of the log of the projected density, in galaxies Mpc^{-2}. The data shown are for all cluster galaxies in the sample and for the field. Also shown is an estimated scale of true space density in galaxies Mpc^{-3}. The upper histogram shows the number distribution of the galaxies over the bins of projected density.

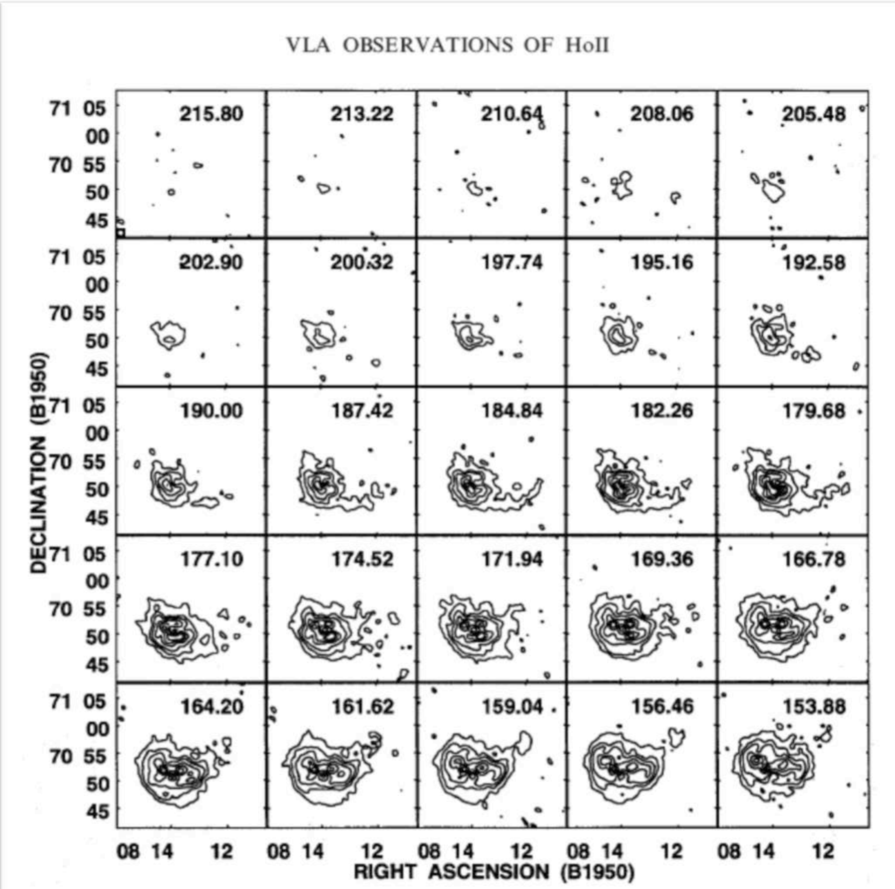
(Dressler 1980, ApJ, 236, 351)

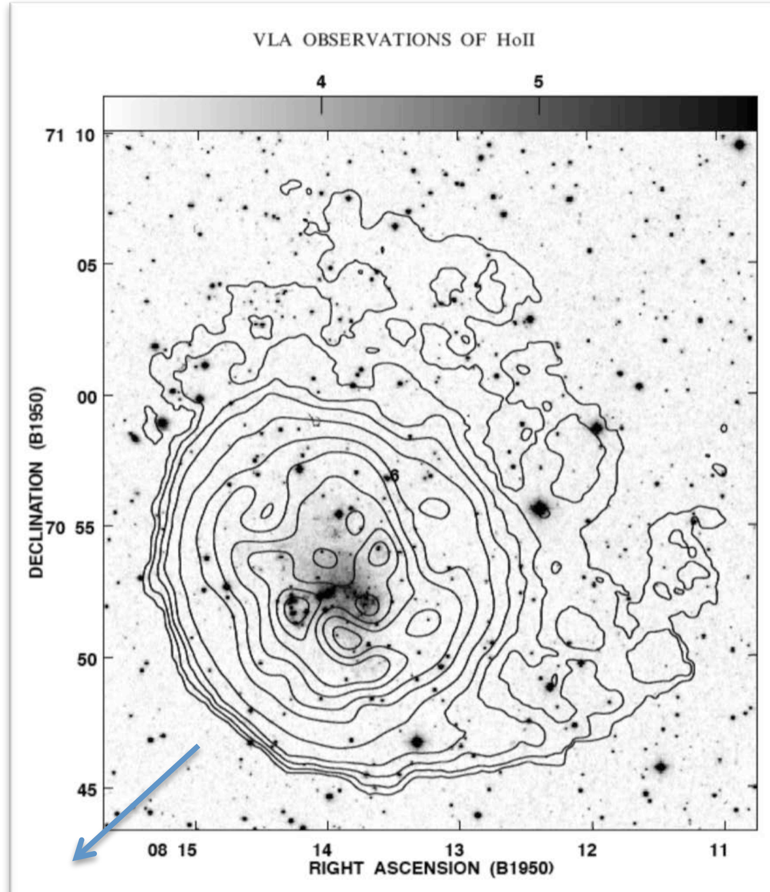
- Proportion E + S0 and Sp + Irr vary as a function of the density of the environment

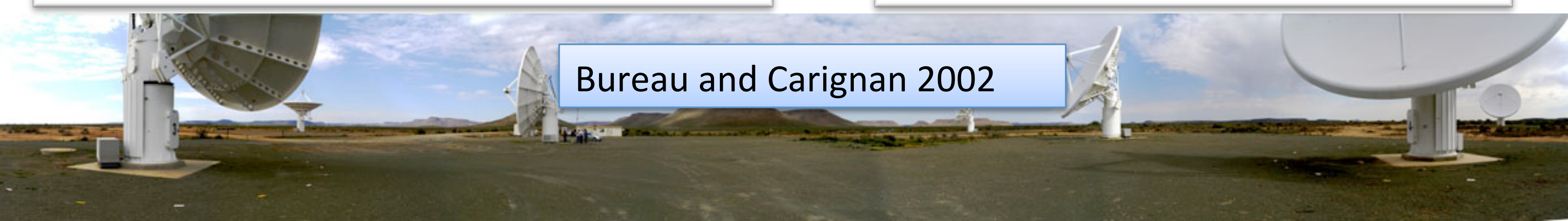
- 2 suggested mechanisms:
  - Mergers: Sp+Sp -> E
  - Ram Pressure from IGM: Sp -> S0



The case of Holmberg II (M81 group)





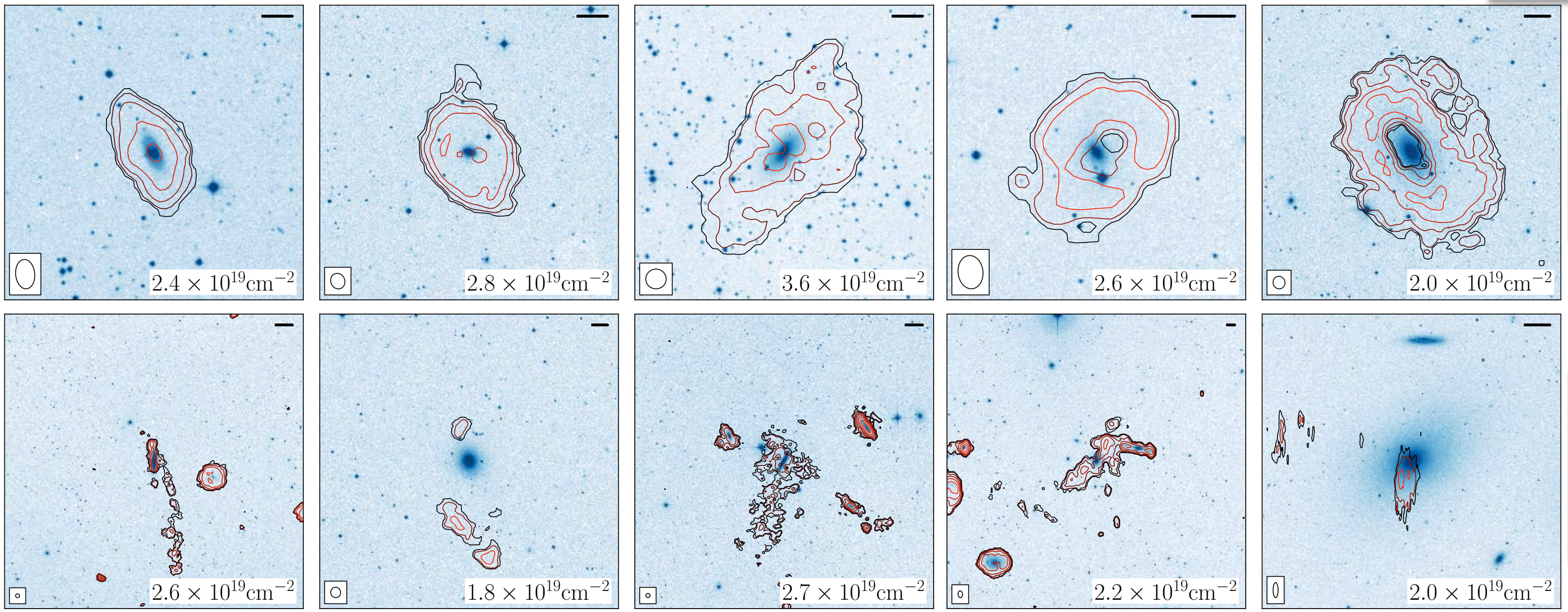


Bureau and Carignan 2002

ATLAS^{3D}

- 166 early-type galaxies, ~2000 hrs Westerbork
- sensitivity: N(HI)~10^{19} cm^{-2}, M(HI)~10^7 $M_\odot$
- 40% detection rate outside Virgo
- 1/4 of all ETGs host HI discs (10^7-10^{10} $M_\odot$)
- show the importance of environment

Serra et al. 2012

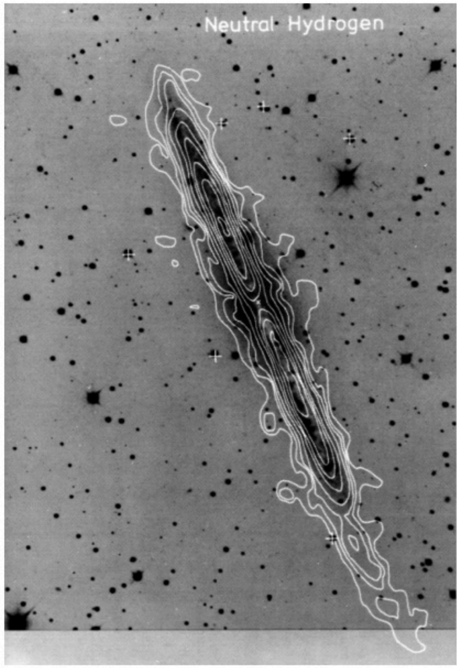


low density

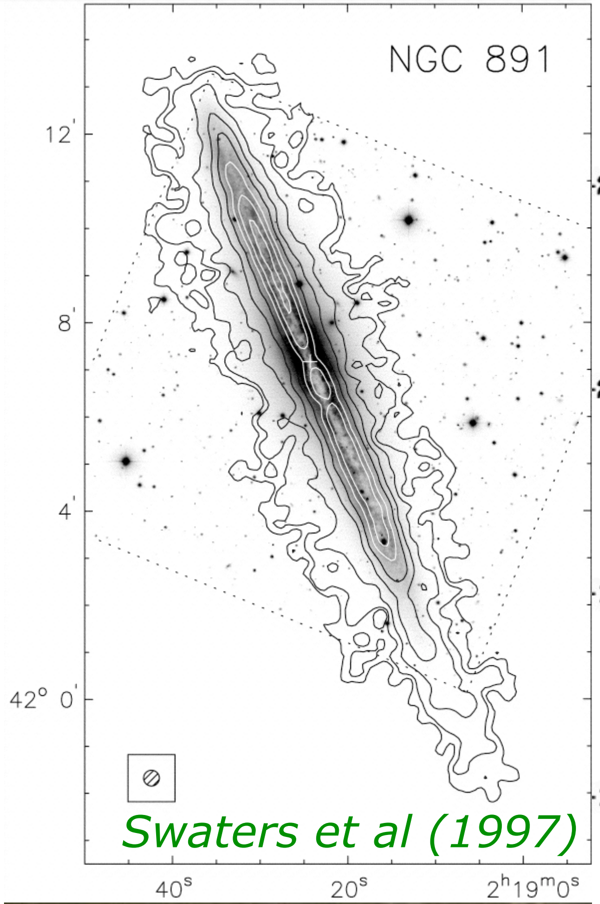
high density (groups)

HI vs z (height)

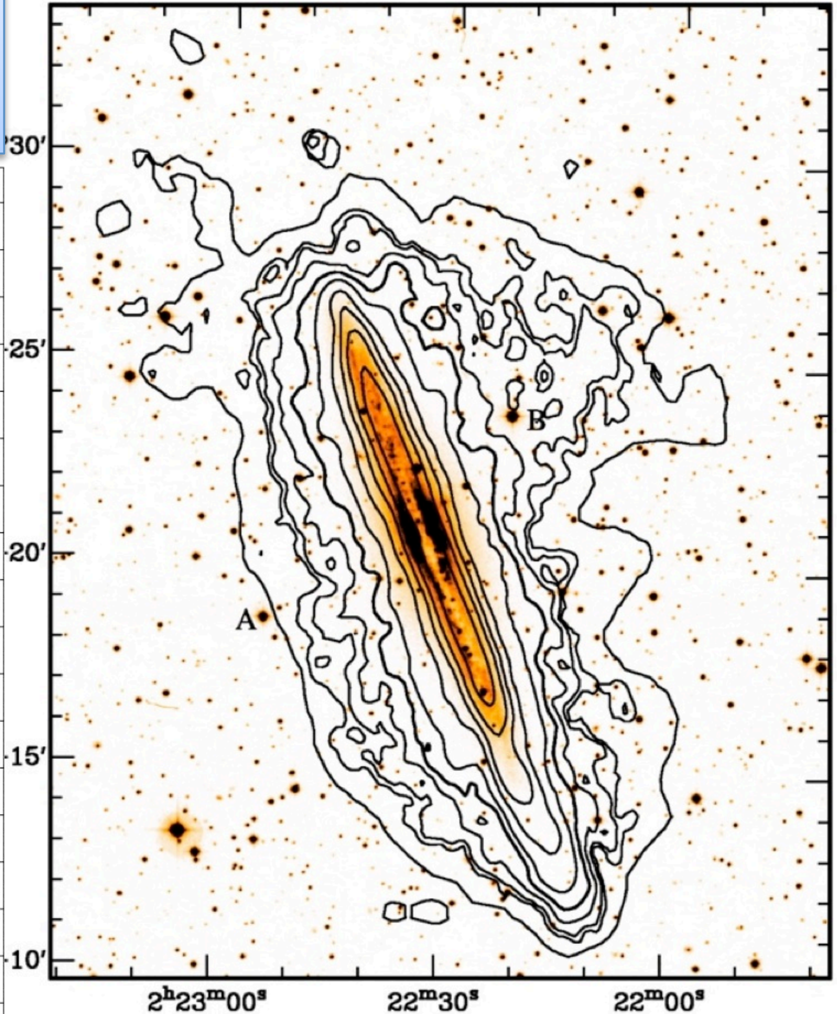
HI is mainly distributed in a **thin** disk, but (sometimes) exhibits a **thick** disk, with much larger scale height



Sancisi & Allen (1979)



Swaters et al (1997)

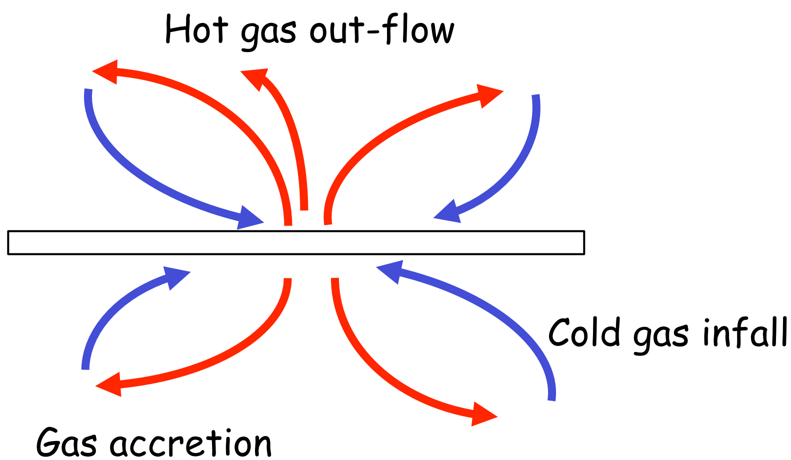


Oosterloo et al (2007)

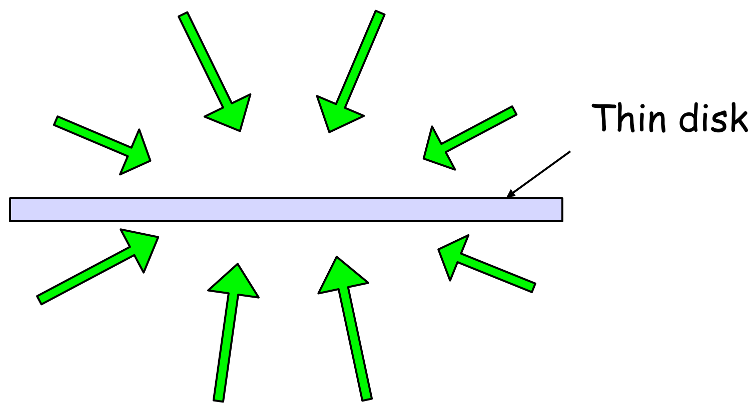
Extra-planar HI

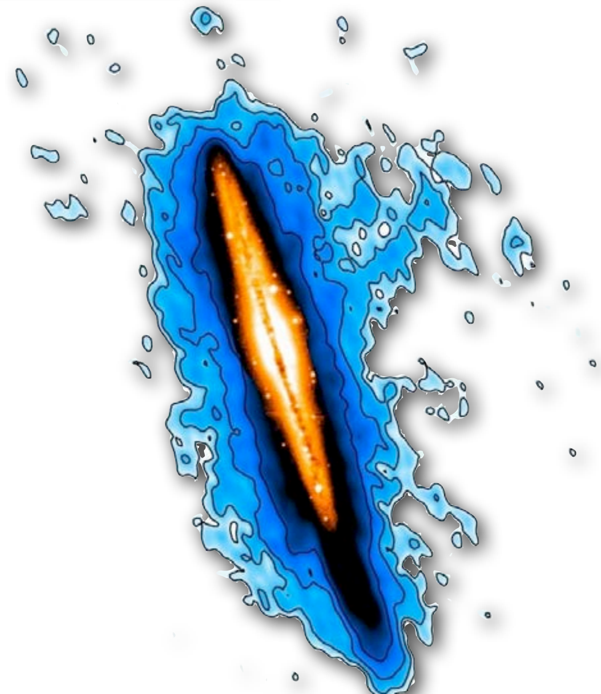
Two components

Galactic fountains



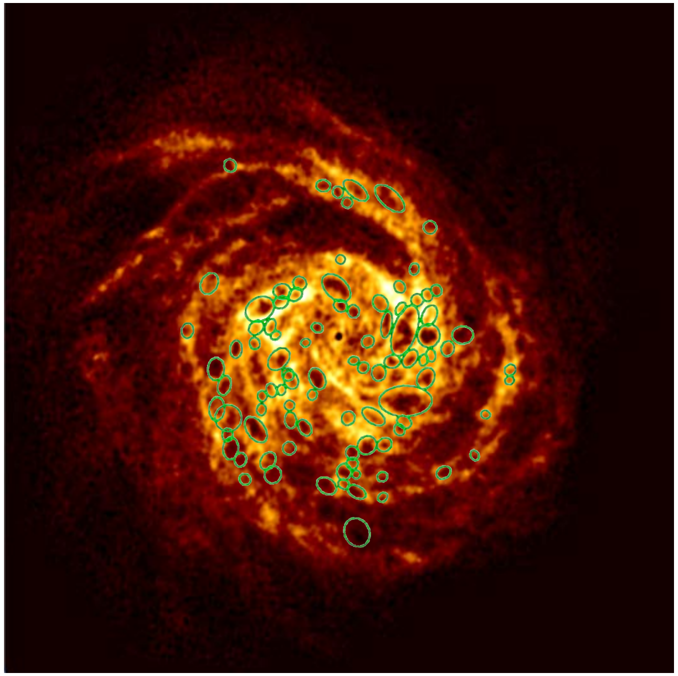
Accretion (HVC)

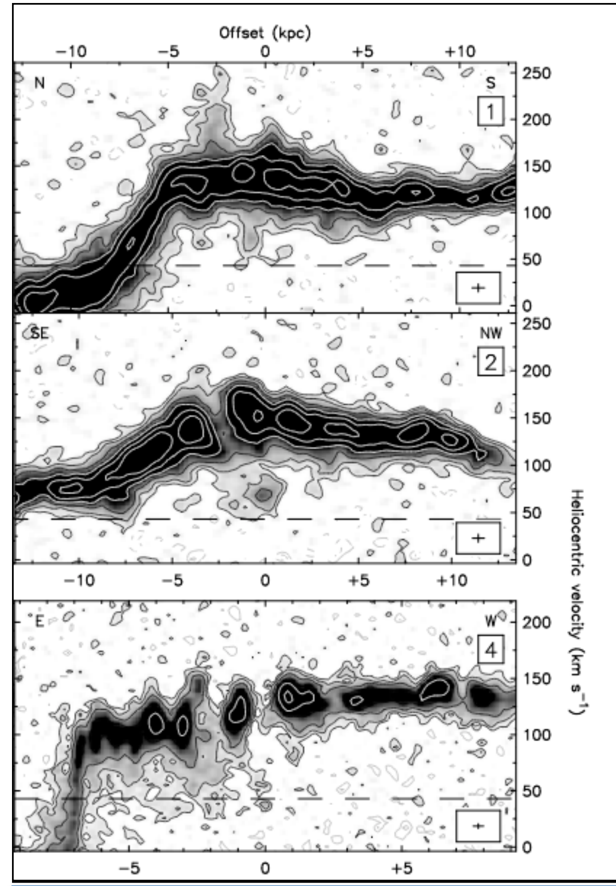




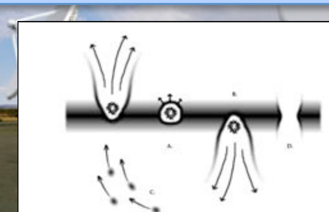
Ultra-deep HI observations reveal significant amount of extra-planar gas (Sancisi+ 2008)

HI vs z (height)



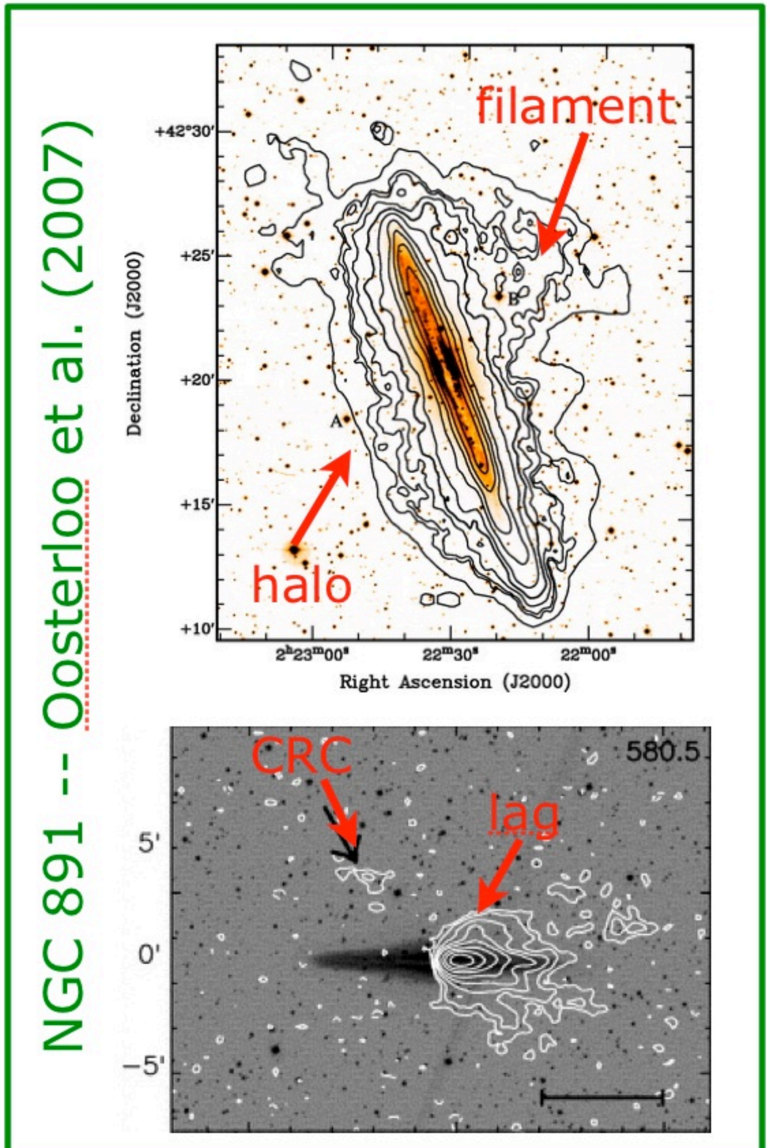


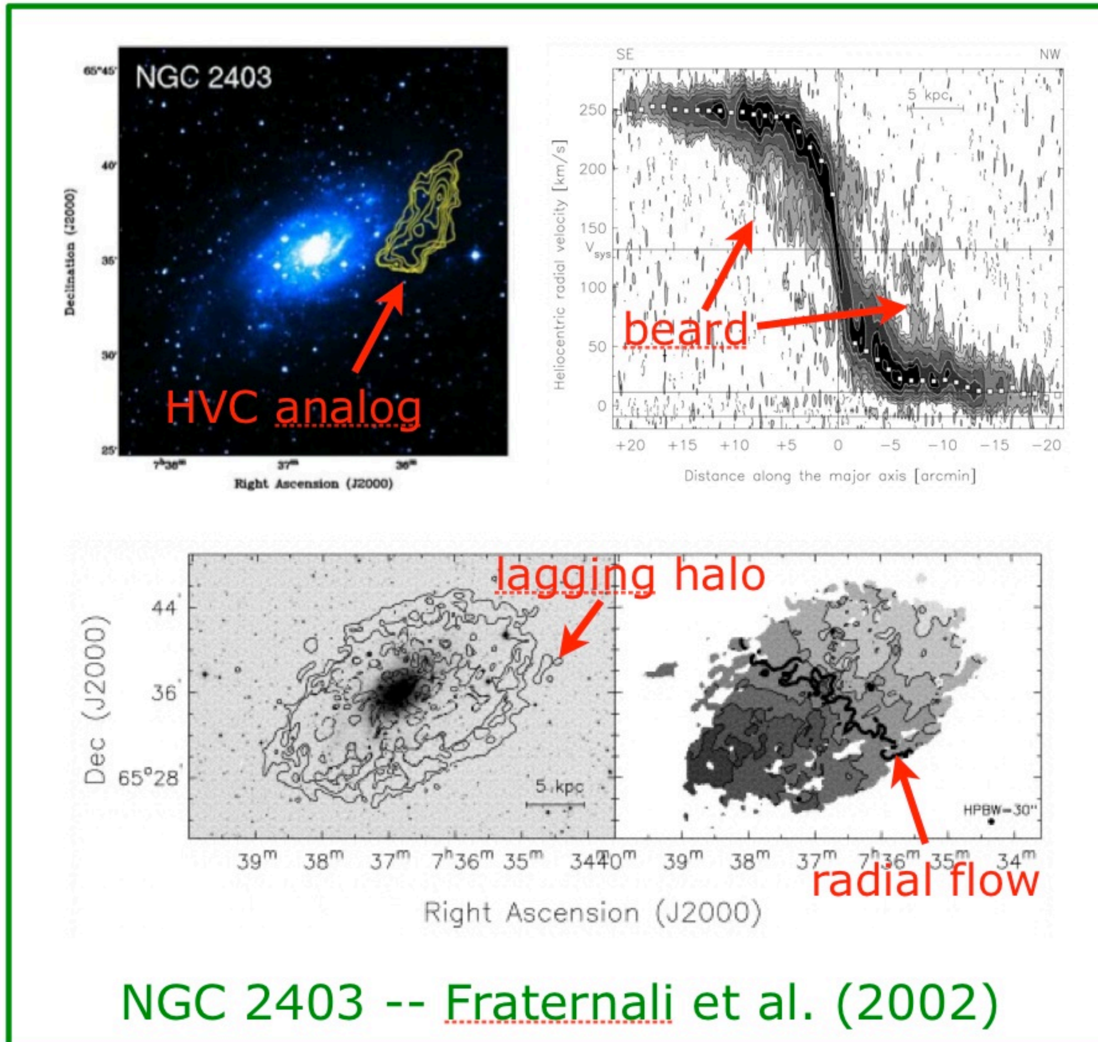
Different phases of galactic fountain



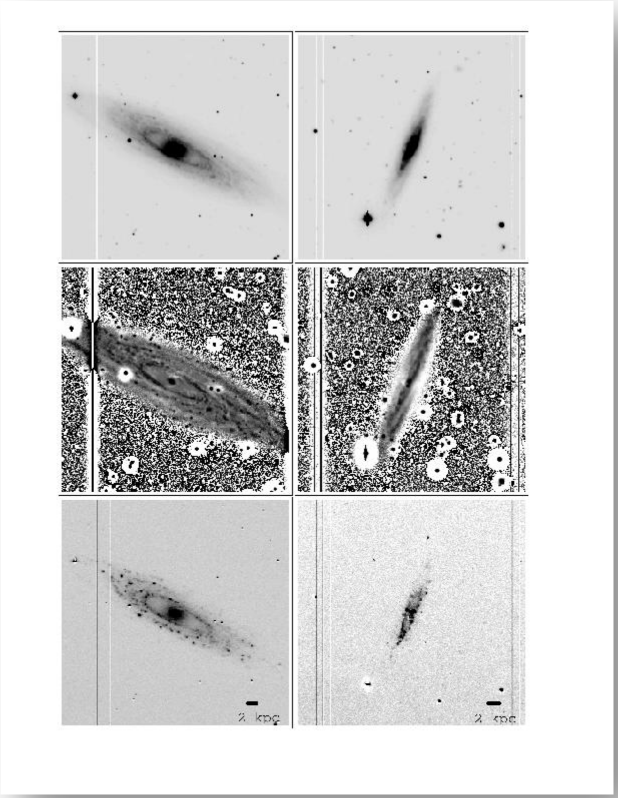
- In face-on galaxies, we can study the vertical motions (σ) of the layer and connections with star formation
- Star formation makes holes, blows gas into the halo, gas rains down, …

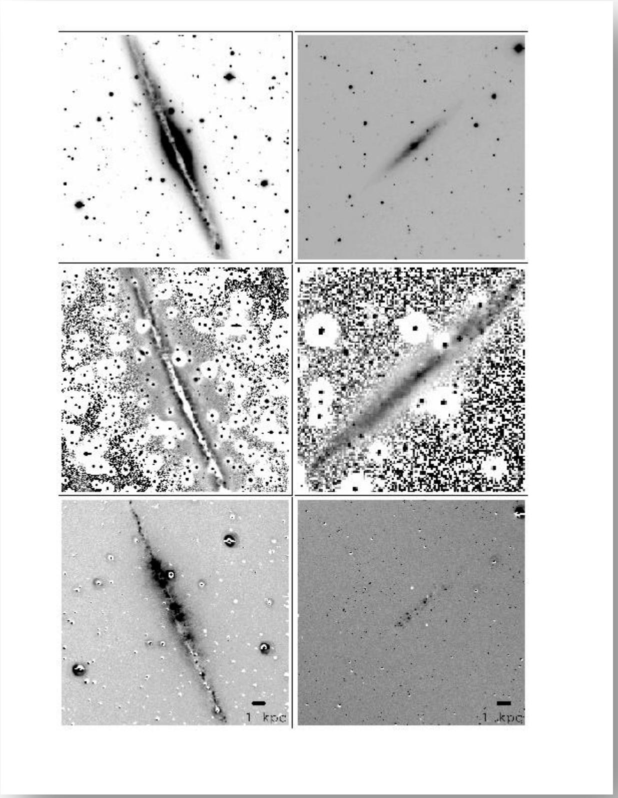
HALOGAS: Scientific motivation: how many nearby spiral galaxies show features like these ?



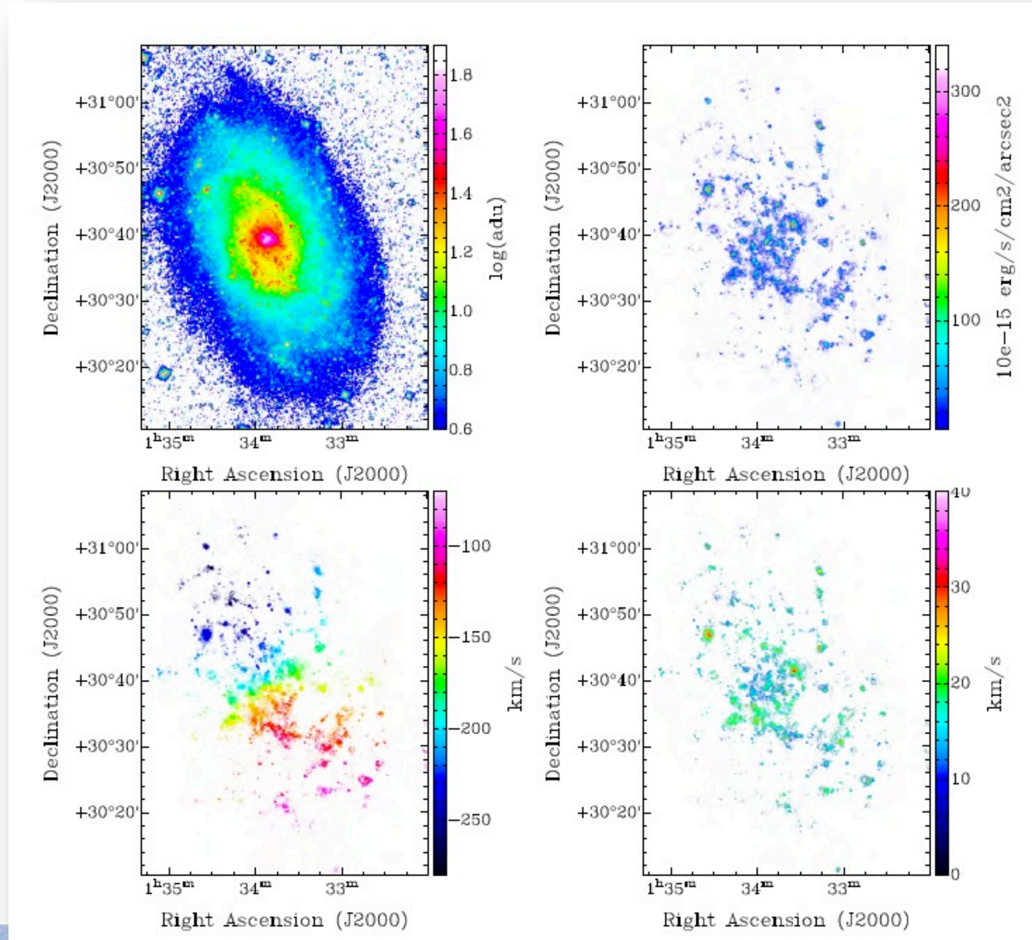


Ionized Hydrogen (Hα)

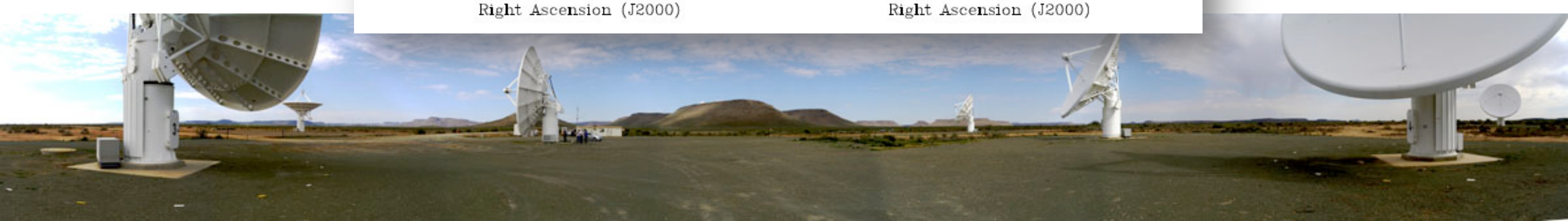




Ionized Hydrogen (Hα)

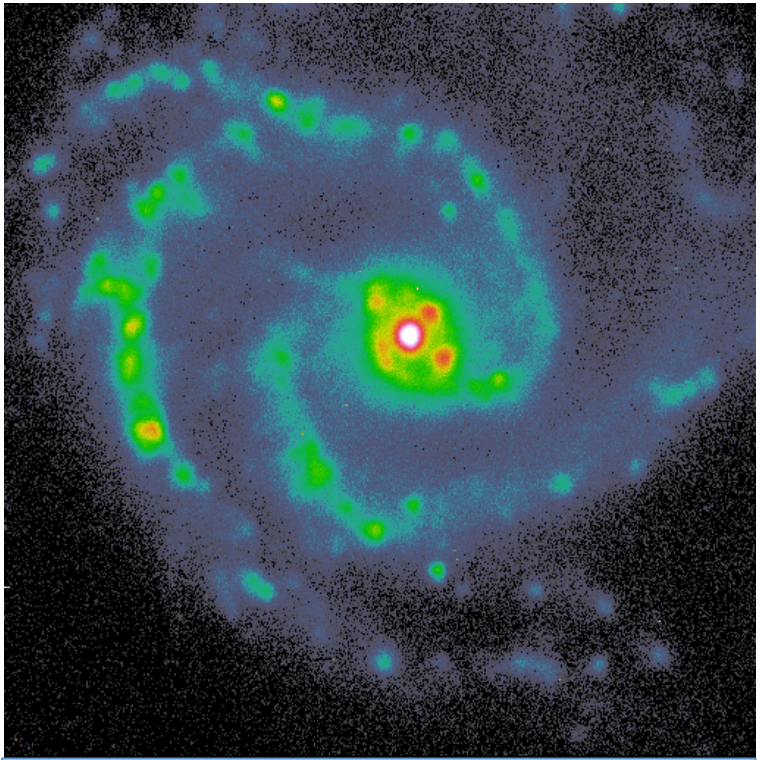


M33



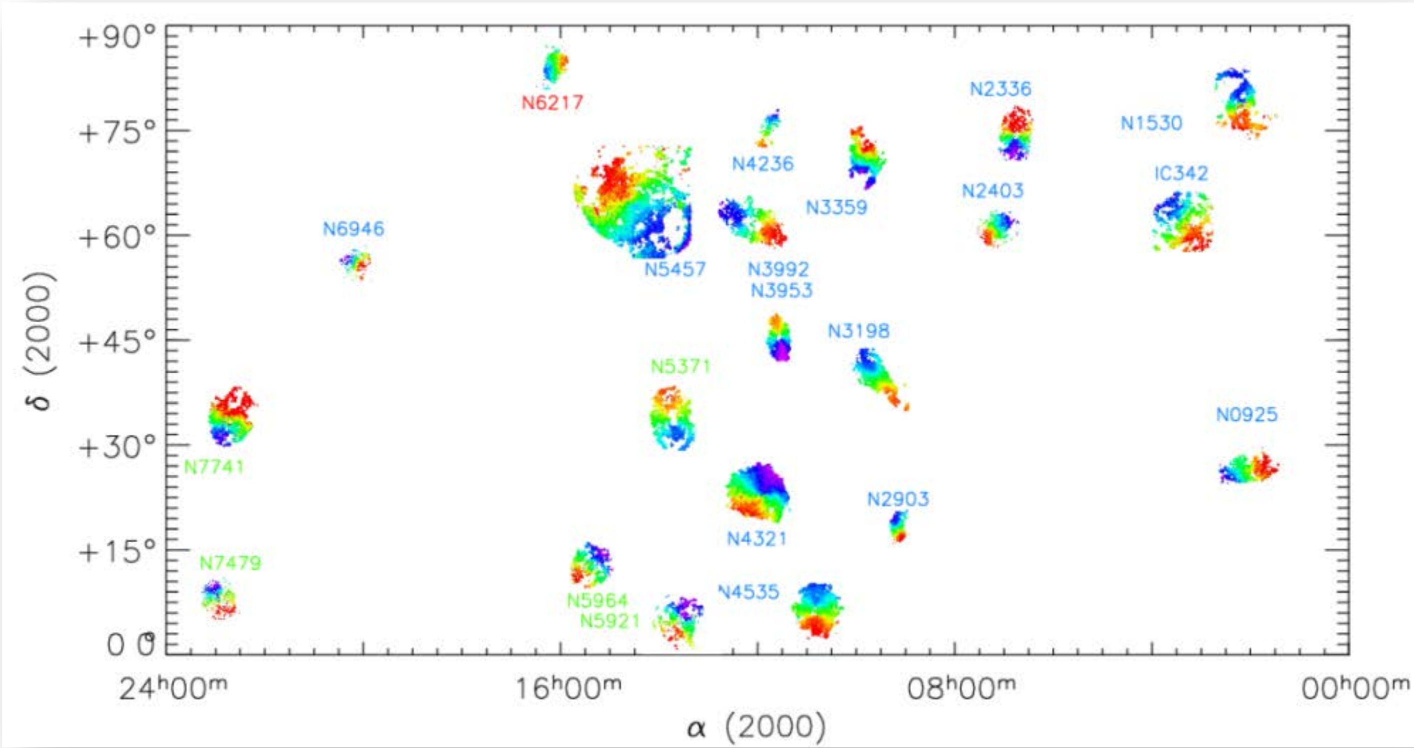
Ionized Hydrogen (Hα)

- OB* and HII regions ionized by those stars trace very well the spiral arms



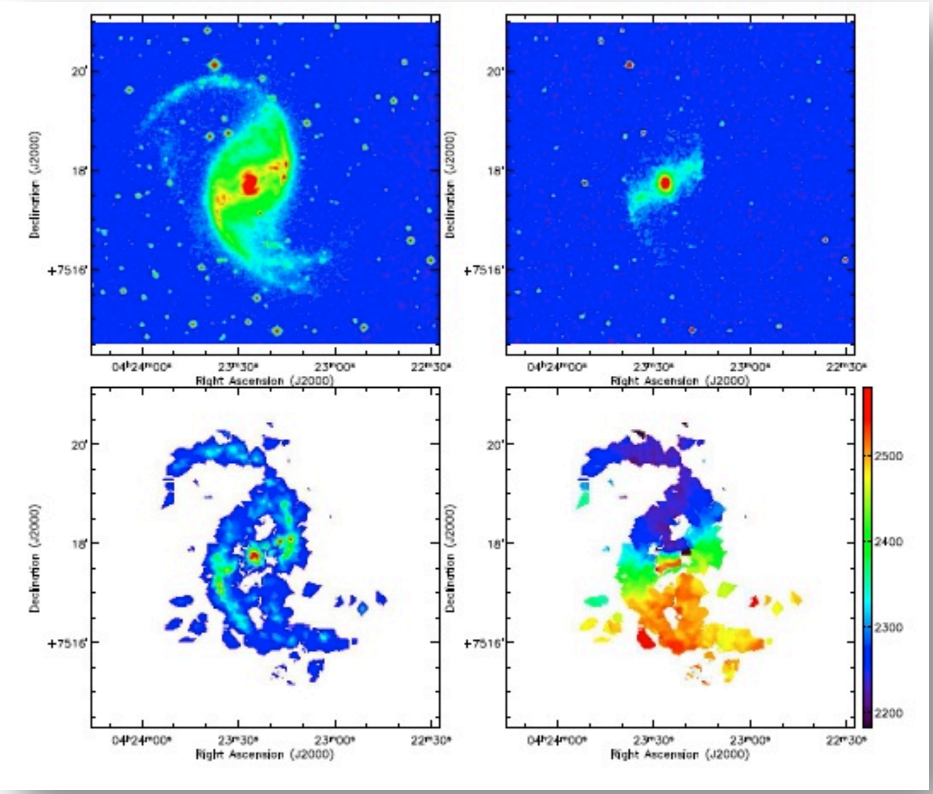
NGC 5427, OB* trace SFR

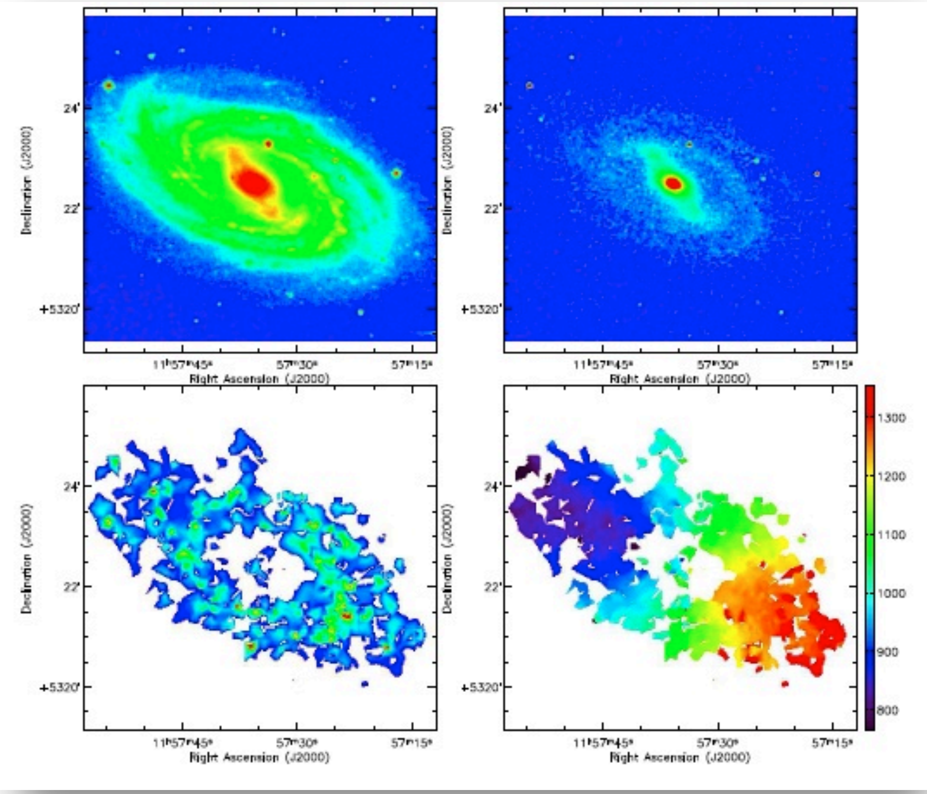
Hα in galaxies



Bhαbar: Hernandez et al. 2005

Hα in galaxies

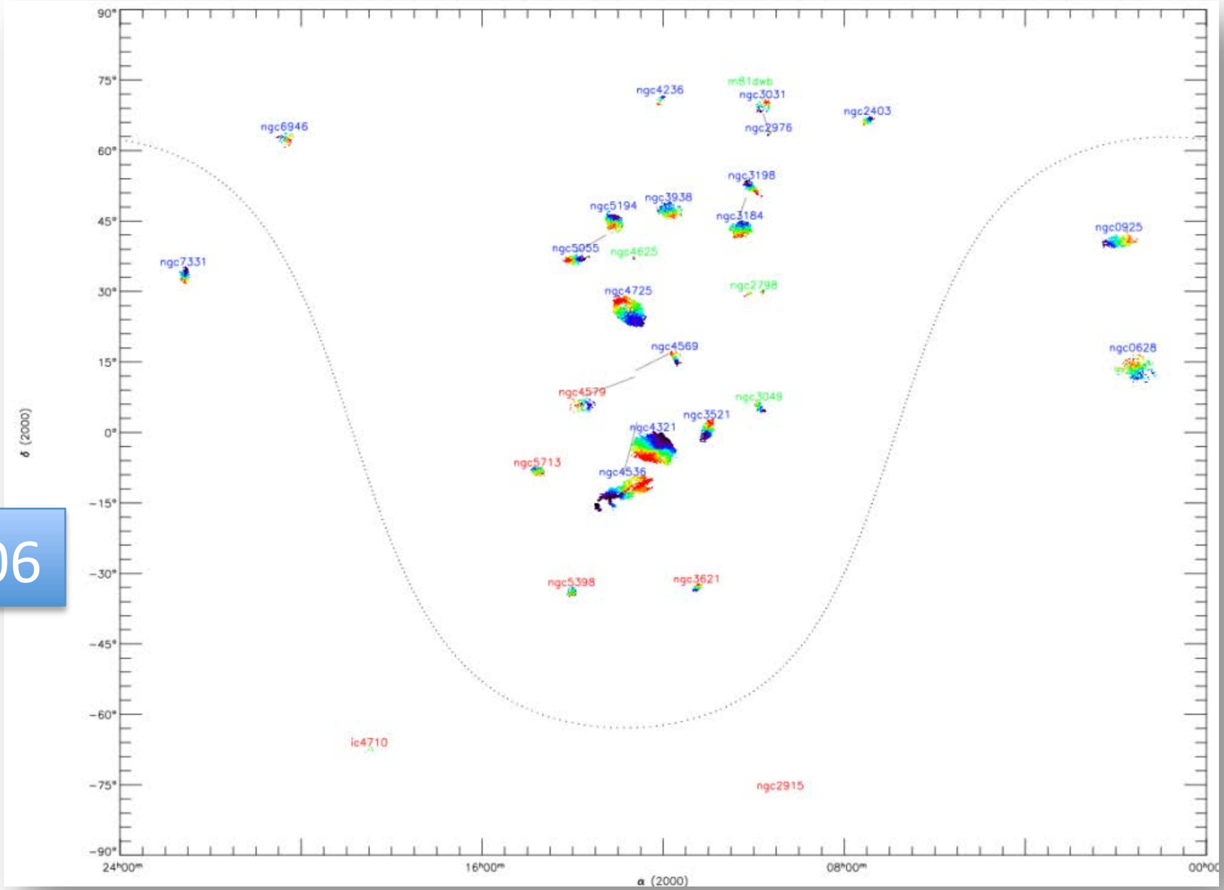




Hernandez et al. 2005

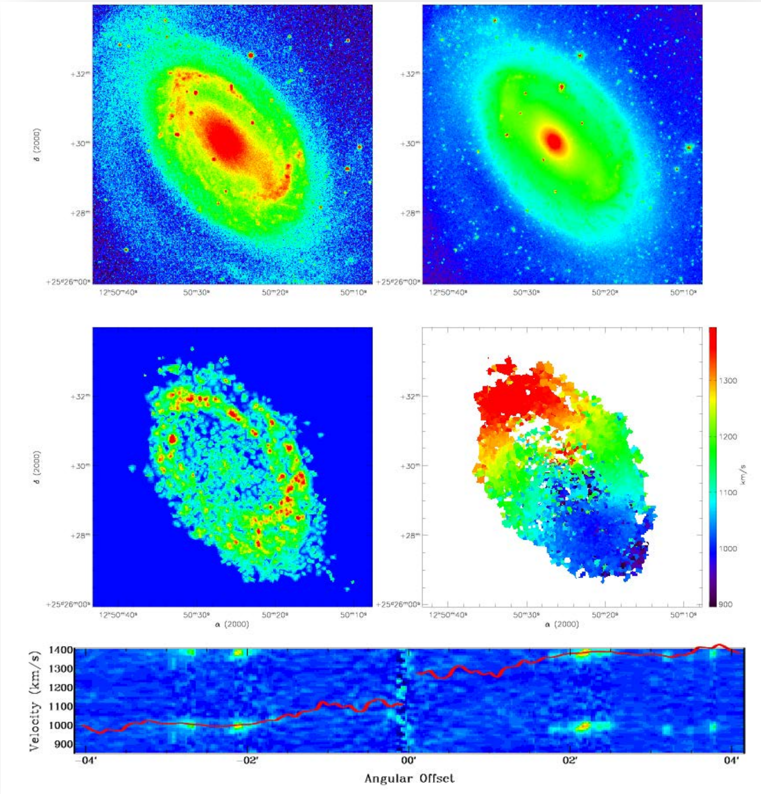
Hα in galaxies

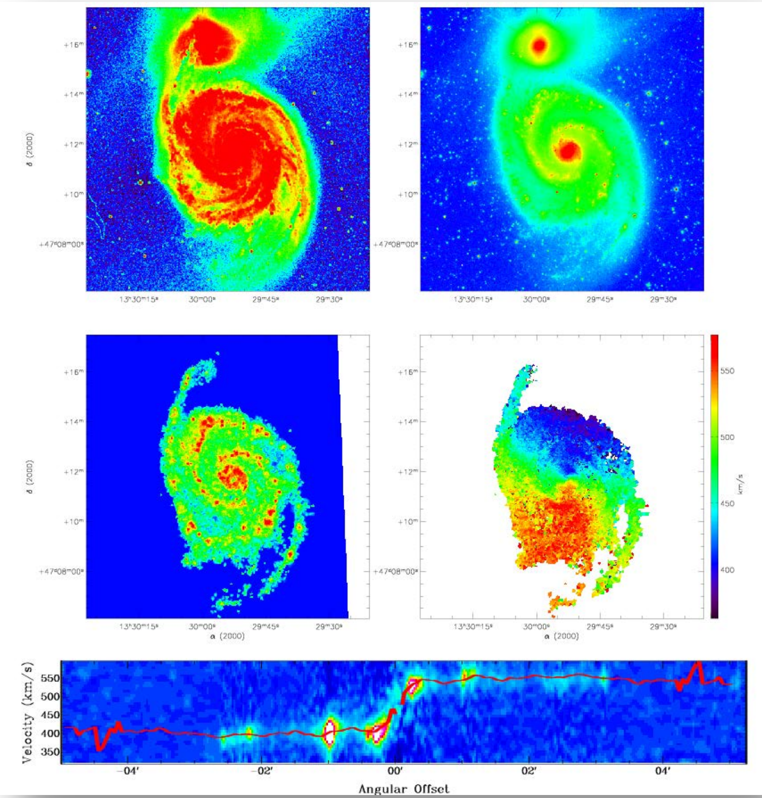
SINGS sample



Daigle et al. 2006

Hα in galaxies

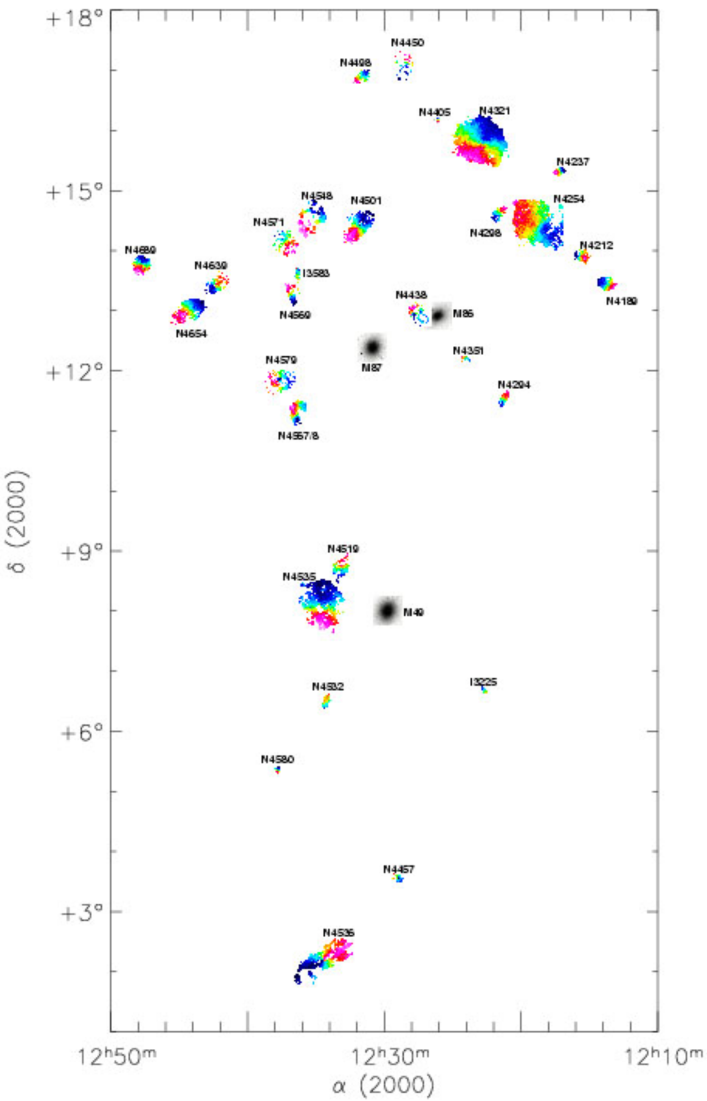




NGC 4725

M 51

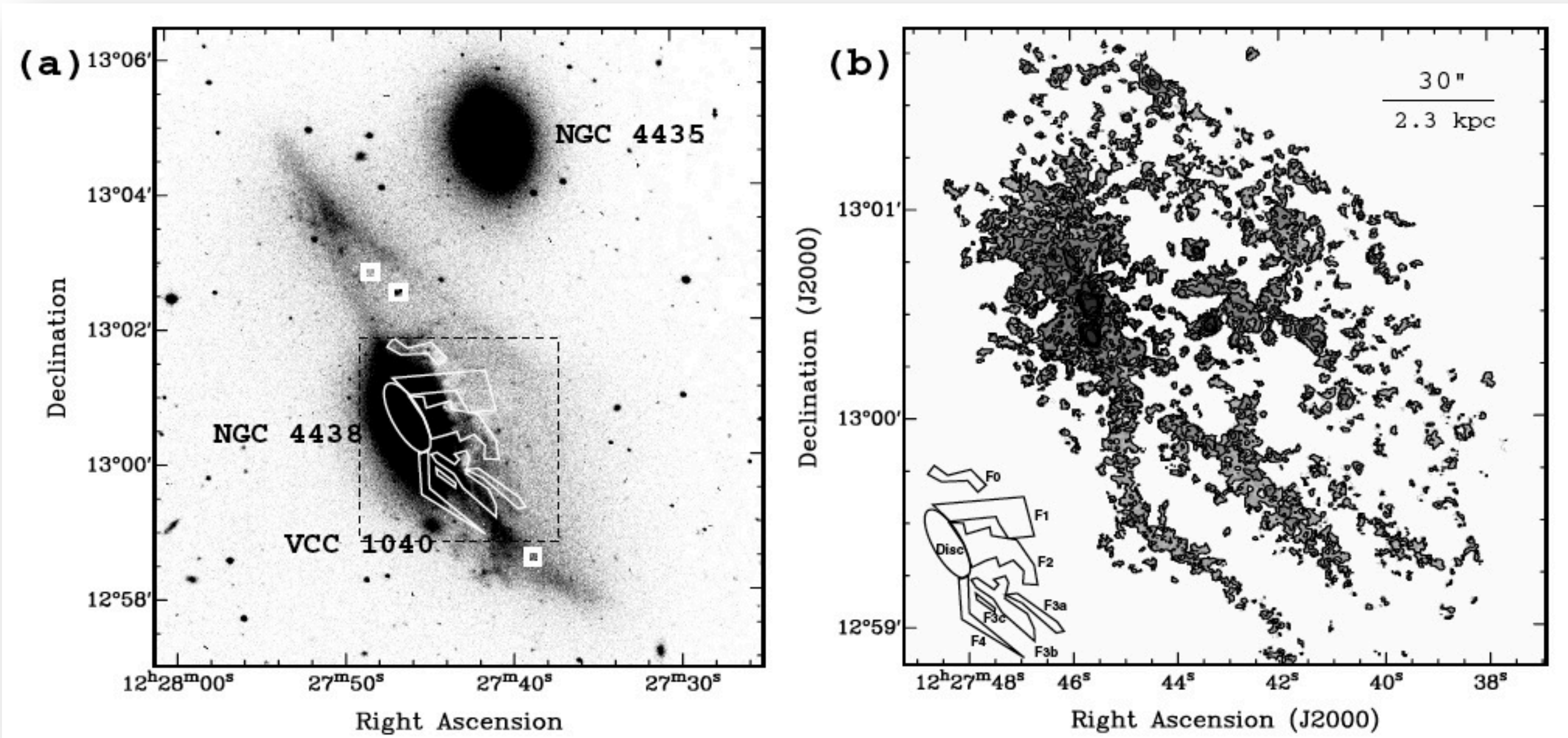
Hα in galaxies



- Galaxies close to the center have lost their gas from ram pressure of the IGM (same situation than in HI)

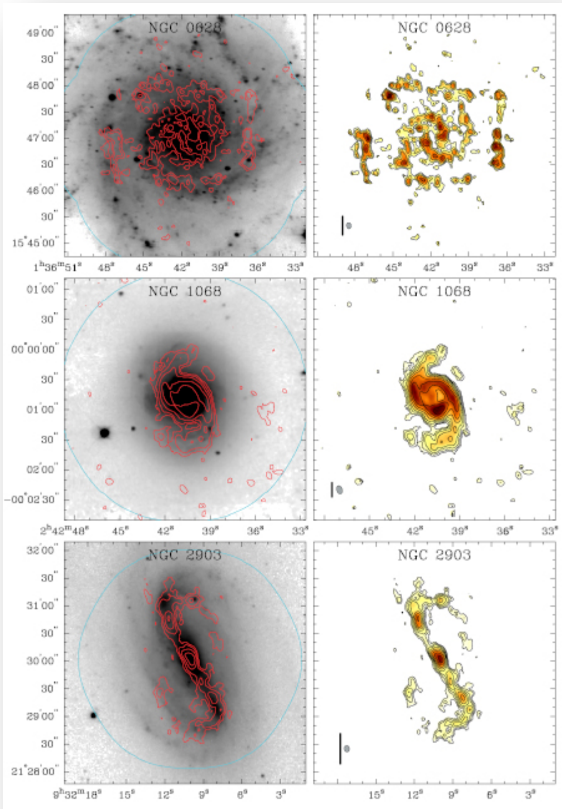
Chemin et al. 2006

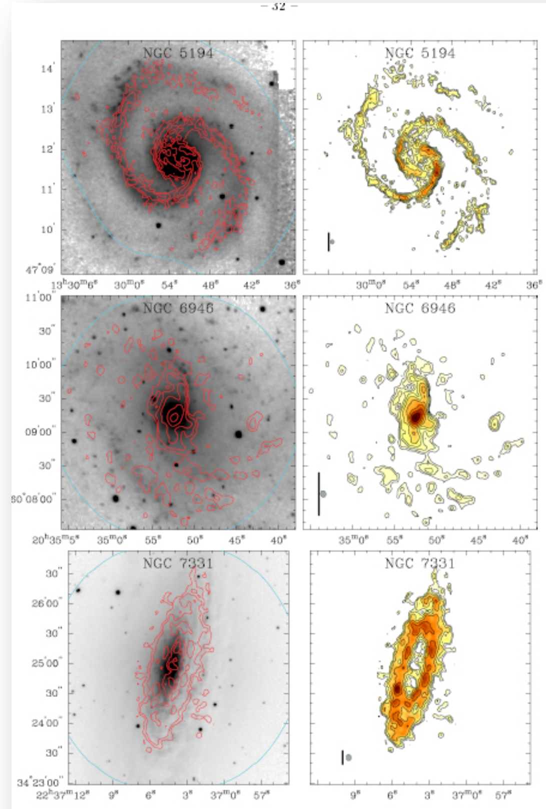
Hα in galaxies



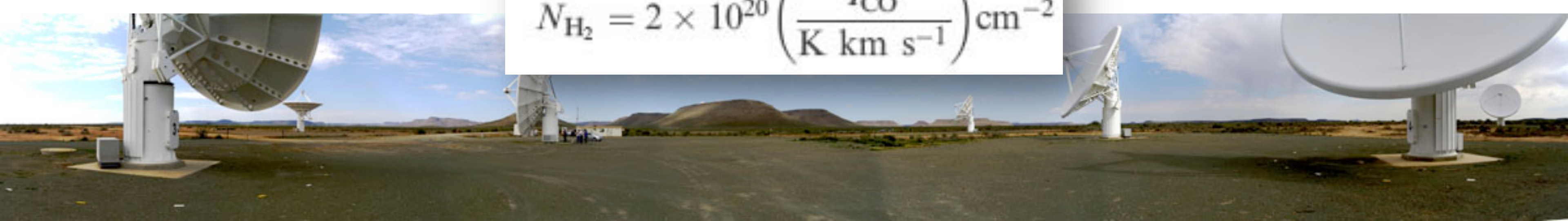
Chemin et al. 2006

H_2 (via CO) in galaxies





$$N_{\mathrm{H}_2} = 2 \times 10^{20} \left(\frac{I_{\mathrm{CO}}}{\mathrm{K\ km\ s^{-1}}} \right) \mathrm{cm}^{-2}$$



H_2 (via CO) in galaxies

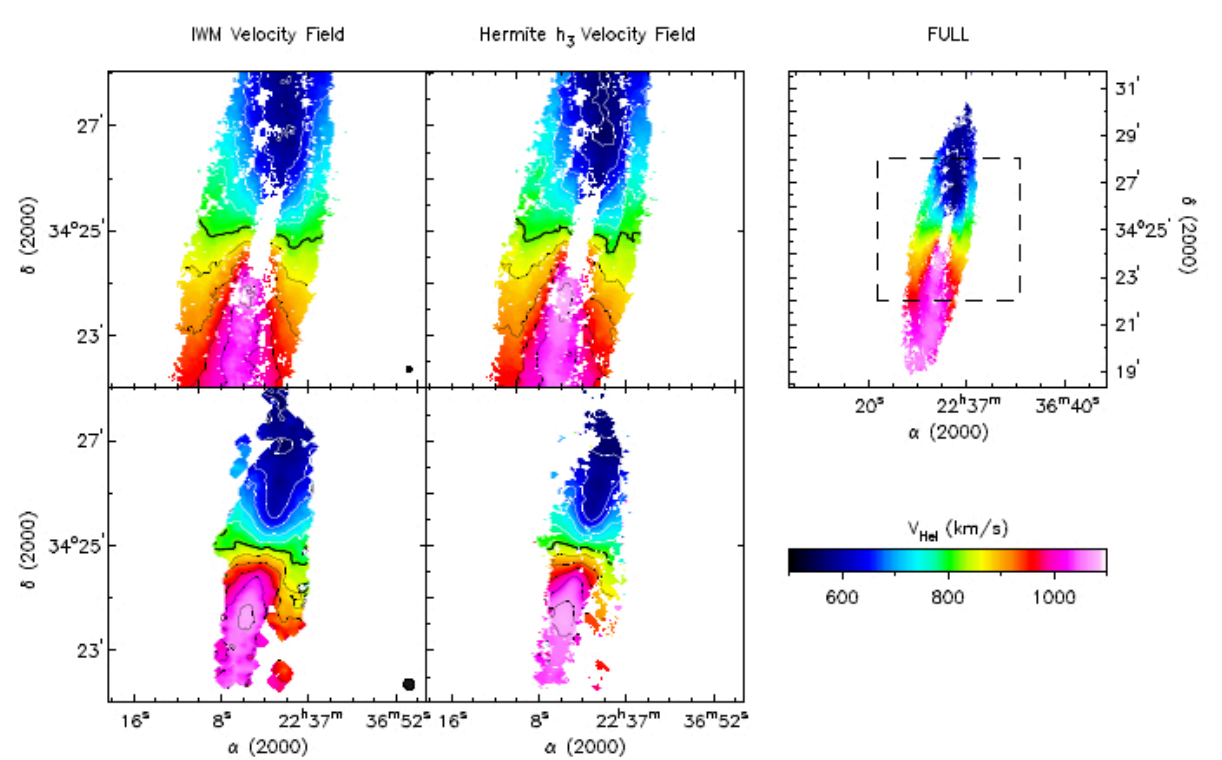


Figure 74: IWM and her$_3$ velocity field multi-panel plots for the THINGS and HERACLES observations, respectively, for NGC 7331. Inset designations are denoted as in figure 6. The contours are plotted for the range $500 - 1100\,\mathrm{km\,s^{-1}}$ in steps of $50\,\mathrm{km\,s^{-1}}$.

Brad Frank's PhD thesis, UCT

H_2 (via CO) in galaxies

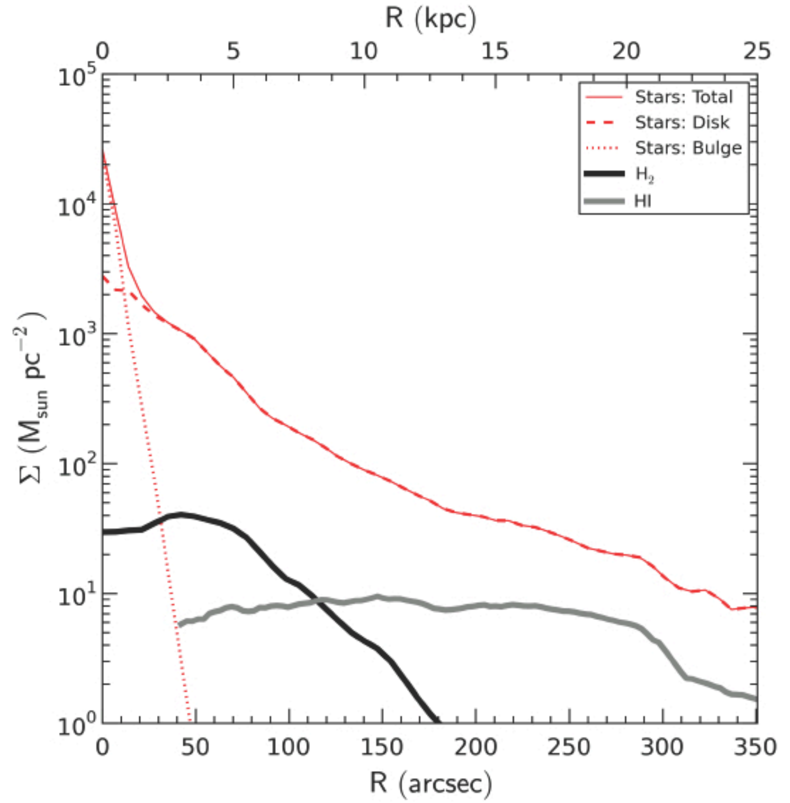
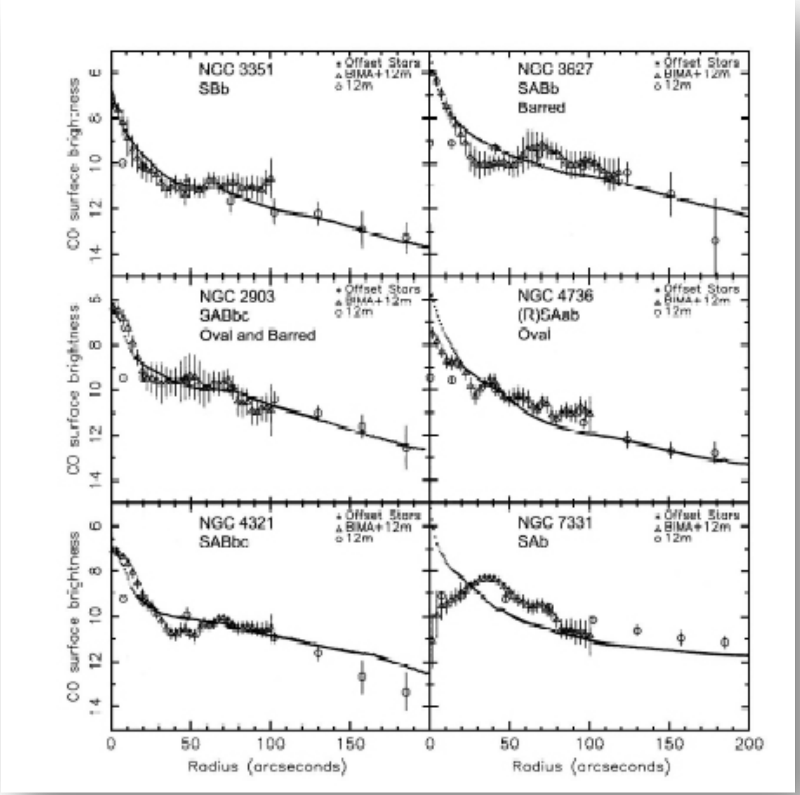
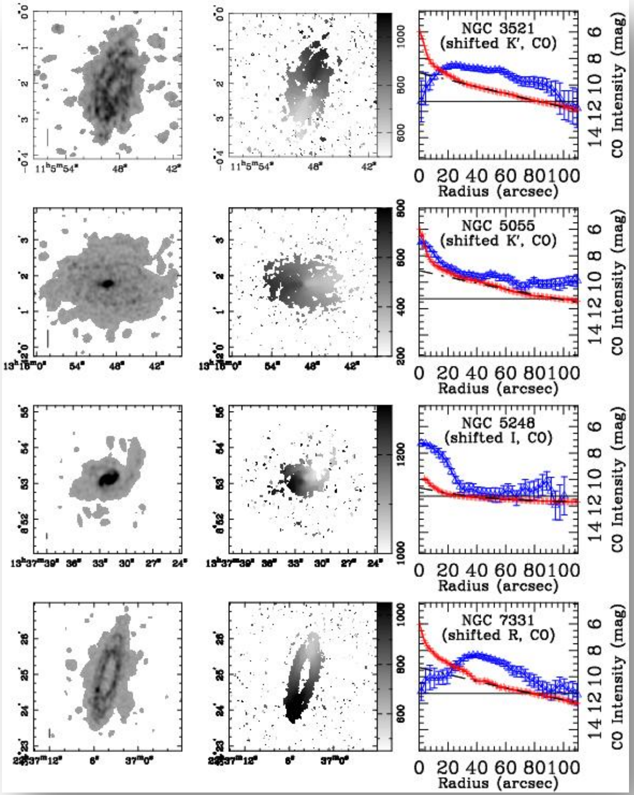


Figure 119: Stellar (red), molecular (black) and atomic (grey) surface densities for NGC 7331. The dashed and dotted red lines correspond to a disk/bulge decomposition of the full stellar surface density.

Brad Frank's PhD thesis, UCT

H_2 (via CO) in galaxies





H_2 (via CO) in galaxies

- CO (H_2) seems to be distributed like the stars
- This is not surprising since stars form in the molecular (H_2) clouds

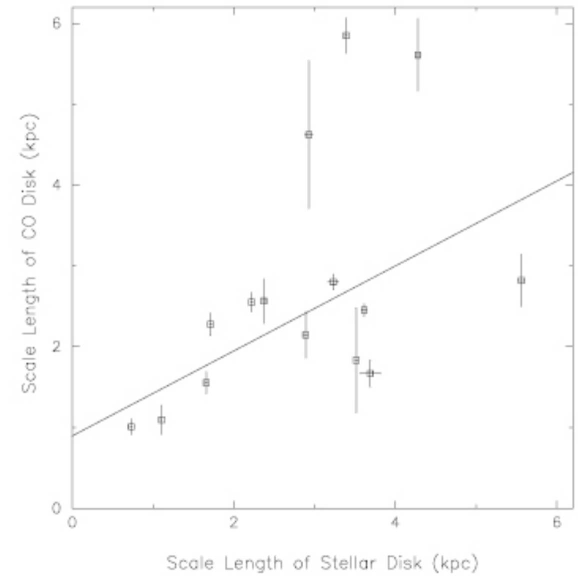
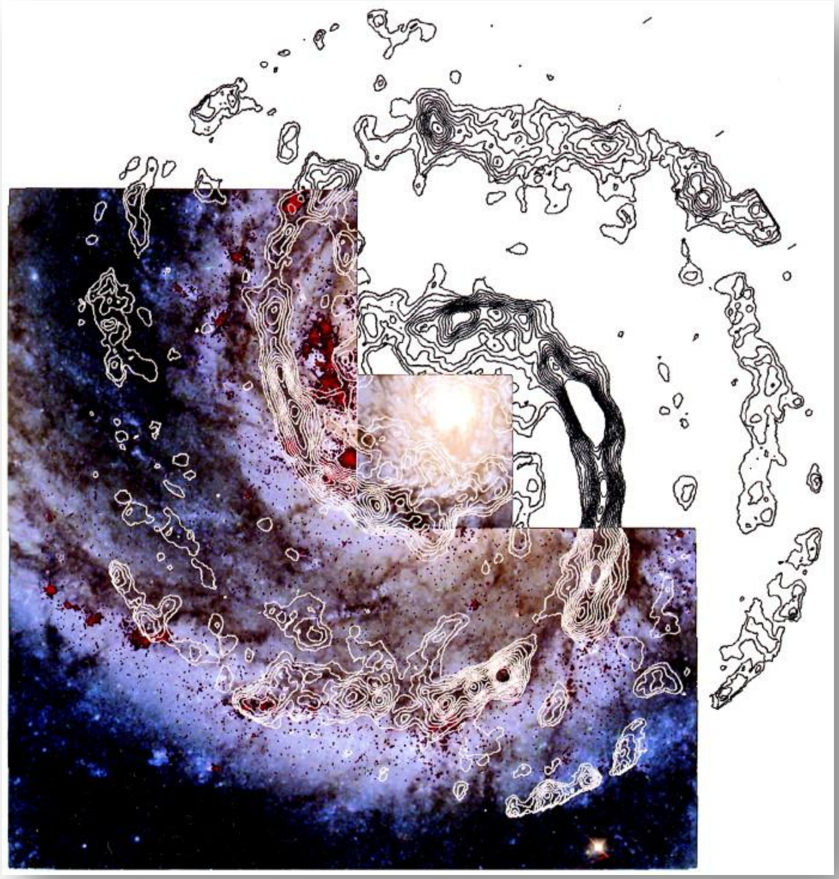


Fig. 5.— Scale lengths of CO and stellar disks. The error bars are the formal one sigma uncertainties in the fitted scale lengths. The CO scale lengths are derived from the fully sampled single dish maps. The solid line represents a linear least-squares fit.

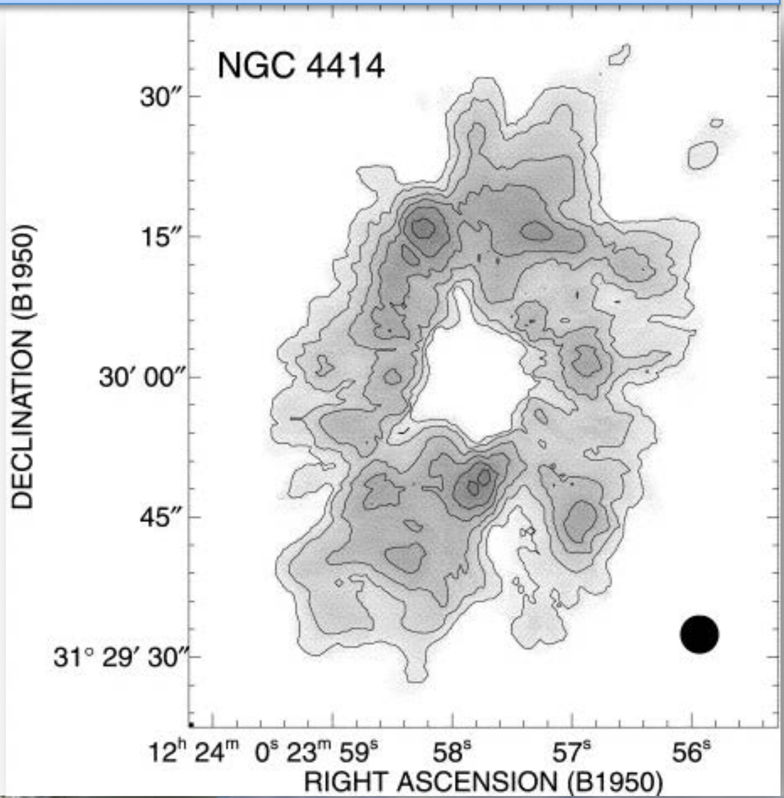
H_2 (via CO) in galaxies

- CO contours superposed on an HST image
- Trace very well the contours of the spiral arms

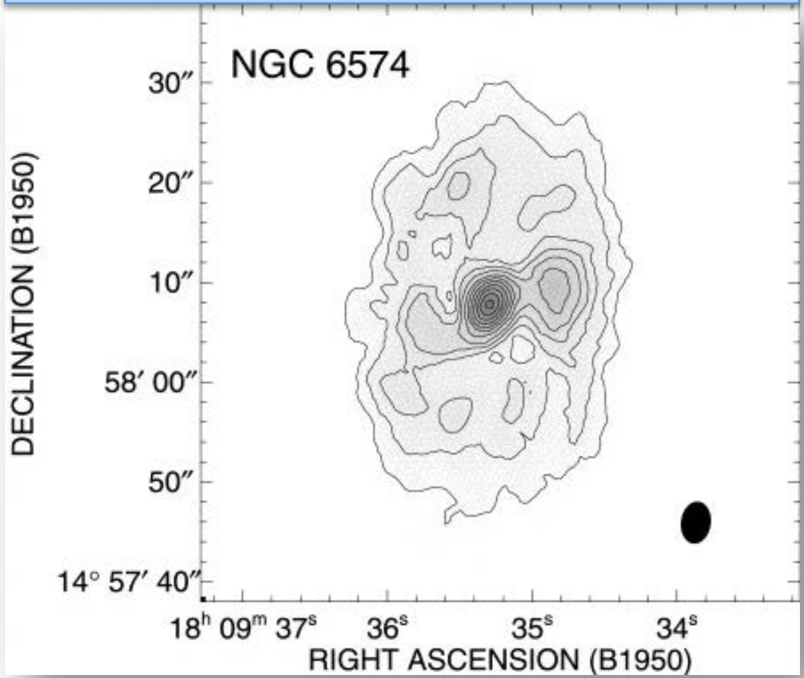


H_2 (via CO) in galaxies

Disk-dominated – normal galaxies



Nuclear dominated – active galaxies



H_2 (via CO) in galaxies

- H_2 via CO is interesting but:
  - the conversion rate H_2/CO may vary as a function of morphological type
  - the conversion rate H_2/CO may vary as a function of the radius in the galaxy
  - cannot be used in dwarf galaxies (e.g. the non-detection of CO in dwarf galaxies doesn't mean that there is no H_2)

Comparison HI, Hα & H_2

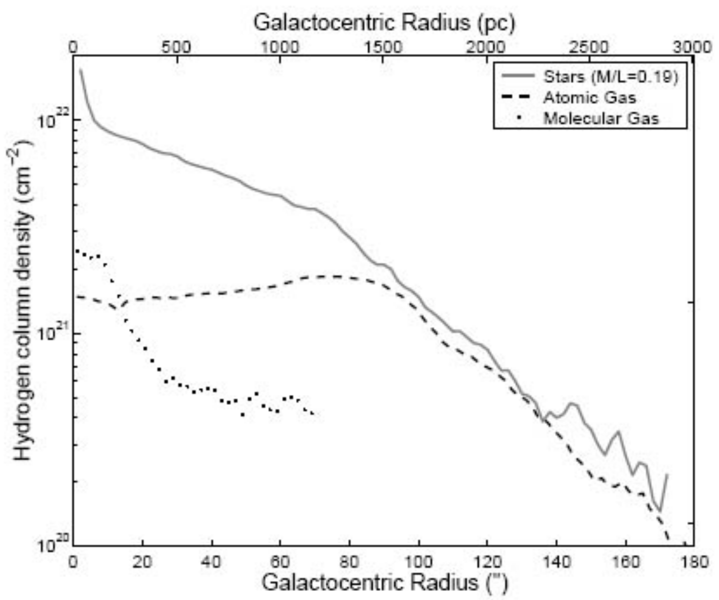


FIG. 6.—Surface densities of the stars and gas in NGC 2976. The H I and H_2 surface densities do not include helium, so the stellar surface densities are divided by a factor of 1.3 to match. Of the baryonic components, the stars dominate the inner disk, but the H I is almost as important in the outer disk. The molecular gas surface density outside 40″ is quite uncertain.

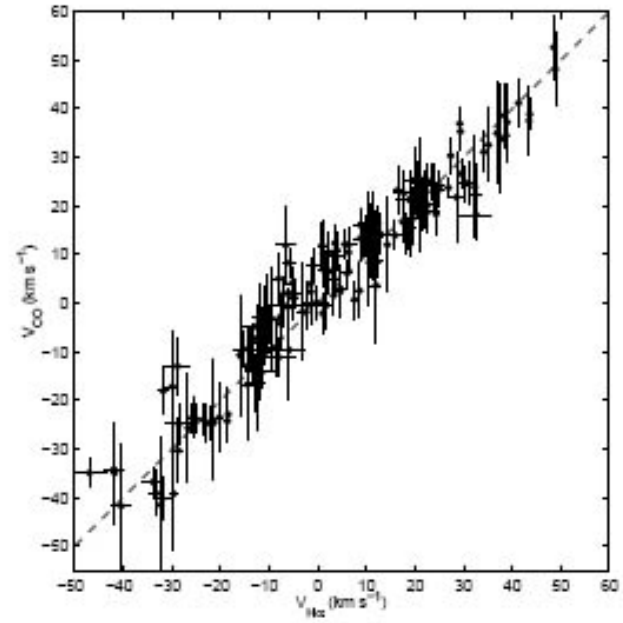
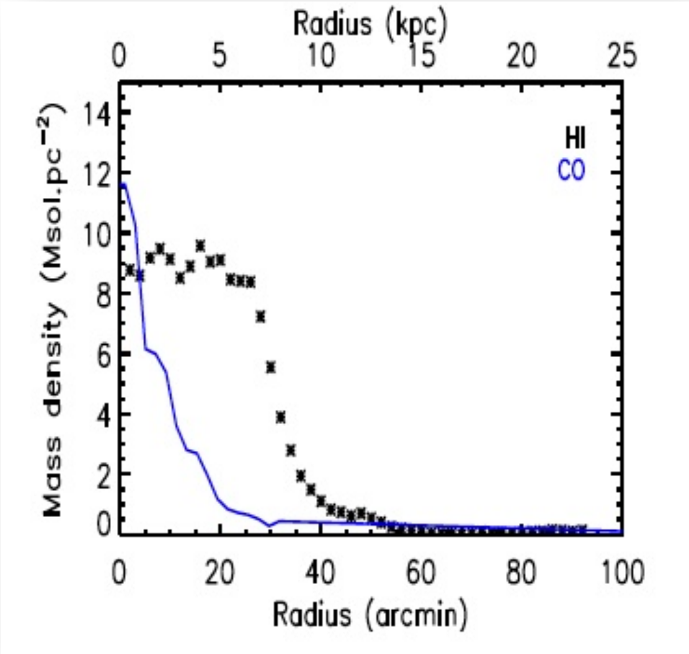
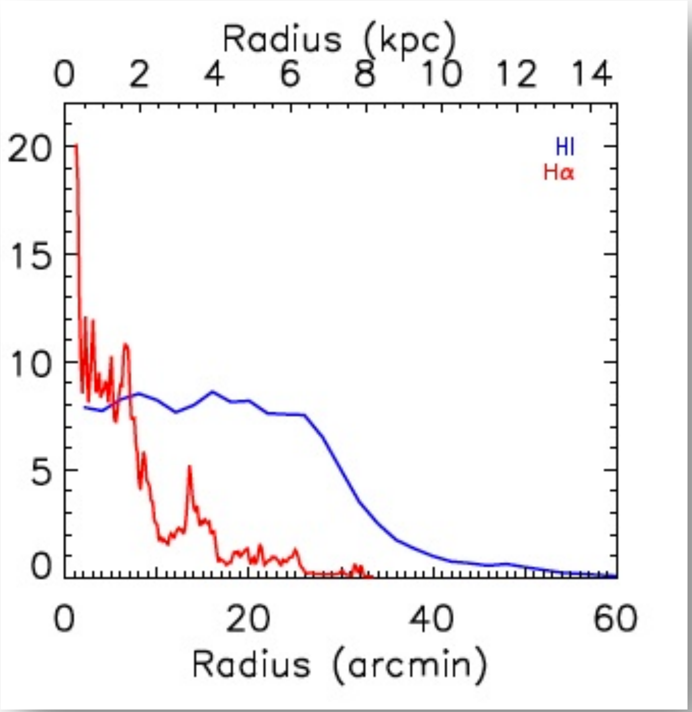


FIG. 12.—Point-by-point comparison of Hα and CO velocities. Although the line $v_{H\alpha} = v_{CO}$ provides a very good description of the data, with remarkably small scatter, there are still small systematic trends visible near the center of the galaxy and at positive velocities.

Simon et al. 2003

Comparison HI, Hα & H_2 in M33





END