KAT-7 Science Verification: Using HI Observations of NGC 3109 to Understand its Kinematics and Mass Distribution

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A return to strong radio flaring by Circinus X-1 observed with the Karoo Array Telescope test array KAT-7

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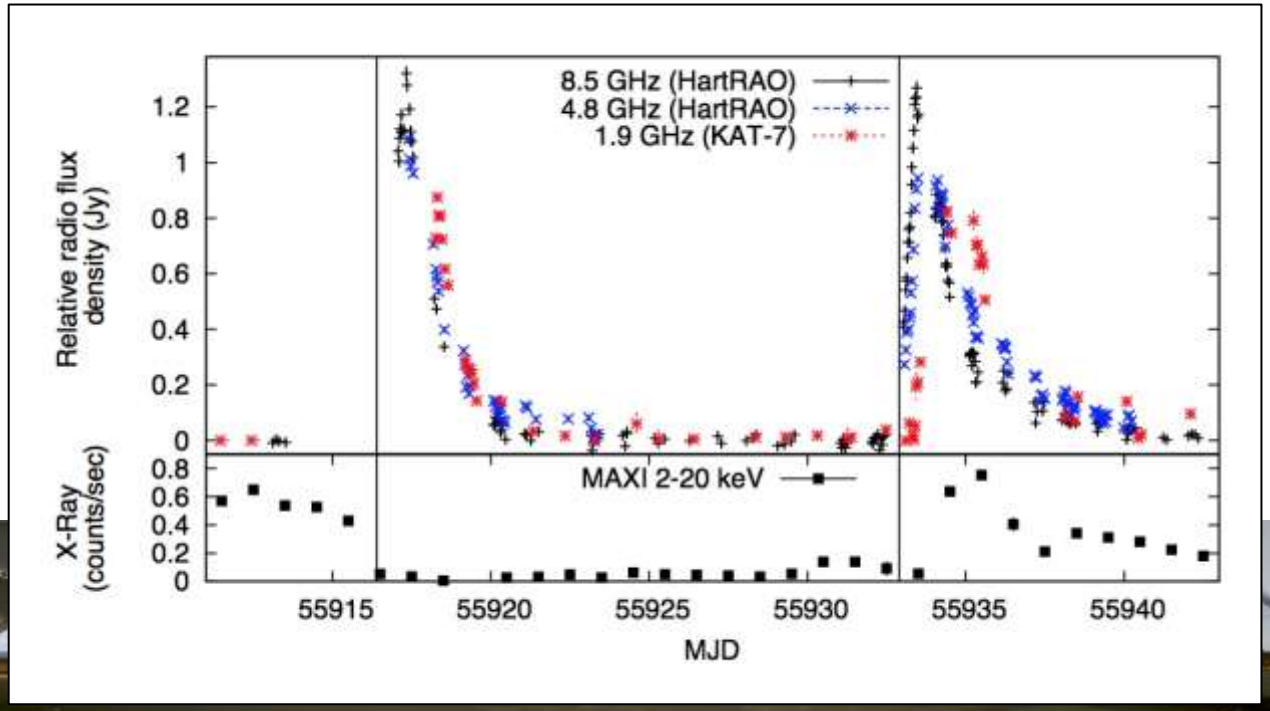
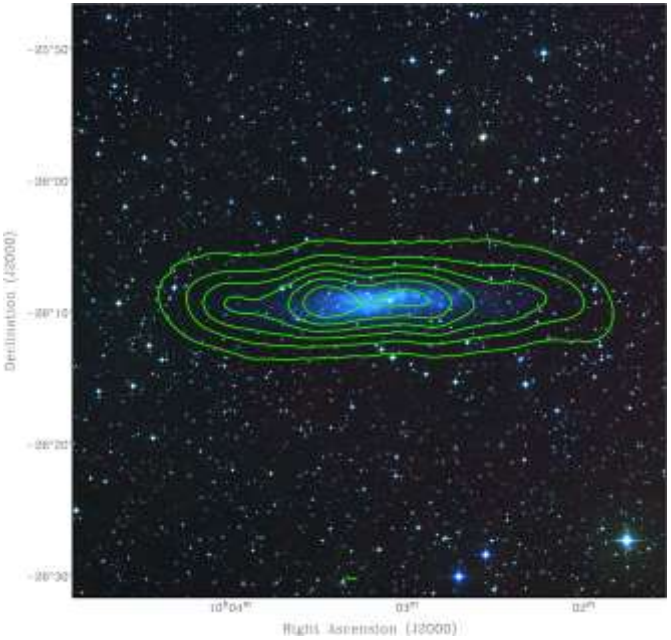
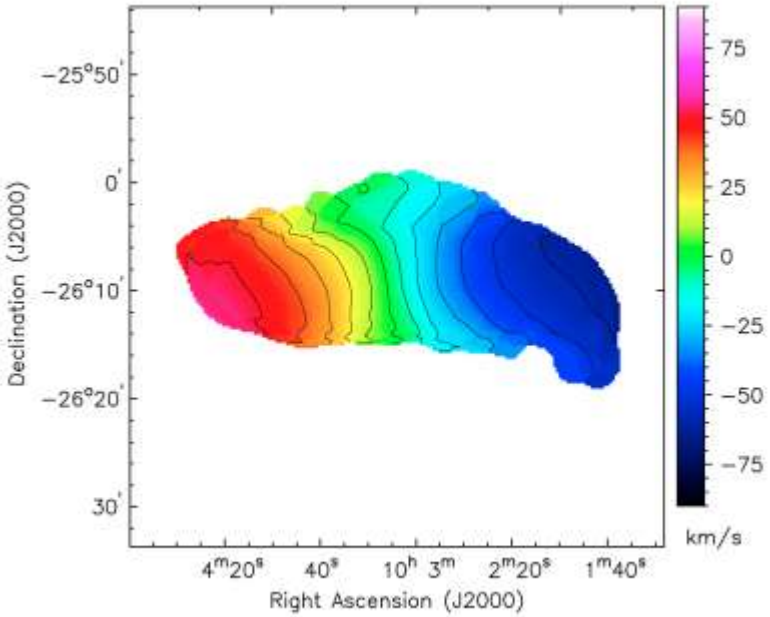


Extra-galactic milestone for South Africa's KAT-7 telescope

- First atomic hydrogen spectral line images of a nearby galaxy

Carnarvon, 14 March 2012. South Africa's KAT-7 telescope, a seven-dish array which is a precursor to the much larger MeerKAT telescope in the Karoo and to the Square Kilometre Array, has reached another major milestone by observing the radio emission from the neutral hydrogen gas (HI) in a nearby galaxy. Hydrogen gas emits radio emission in a spectral line at a very specific frequency of 1420 MHz.





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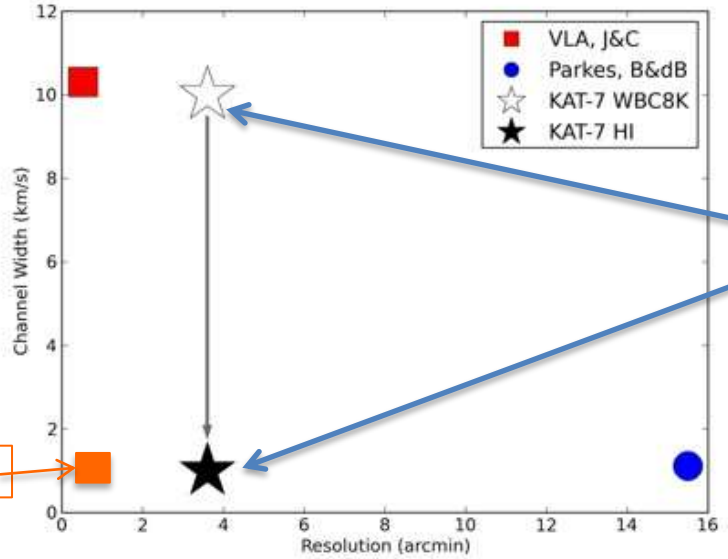


VLA-ANGST

Mode	Bandwidth	Channel width	Velocity resolution at 21cm	Available
Wideband	256 MHz	390.625 kHz	82km/s	Yes
8k Wideband	256 MHz	48.8 kHz	10km/s	Yes
OH Spectral Line	12.5 MHz	1.5 kHz	317m/s	~ Jun 2012
OH Spectral Line	3.1 MHz	381 Hz	80m/s	~ Jun 2012
HI Spectral Line	>= 33.4 MHz	<= 4.8 kHz	<= 1km/s	~ Oct 2012

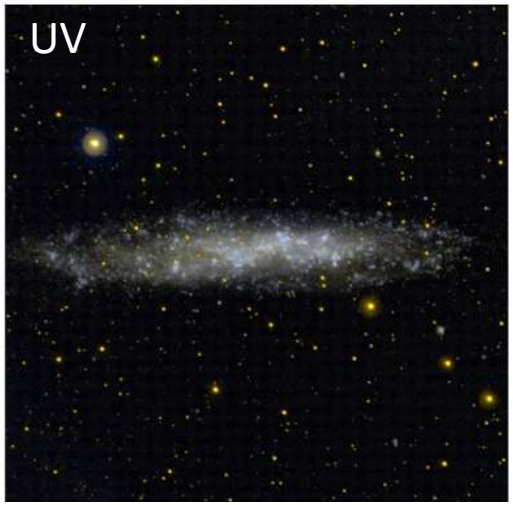
Table 1: Expected correlator modes for KAT-7 to be commissioned before the end of 2012.

Scientific Interest of NGC 3109

Table 1. Optical parameters of NGC 3109 (DDO 236).

Parameter		
Morphological type	SB(s)m	
Right Ascension (J2000)	$10^{h}\ 03^{m}\ 06.7^{s}$	
Declinaison (J2000)	$-26^{o}\ 09'\ 32''$	
Distance Modulus $(m-M)_0$ (mag)	25.57 ± 0.02	
Distance (Mpc)	1.30 ± 0.02	
Scale (pc arcmin^{-1})	378	
Isophotal major diameter, D_{25}	$14.4'$	
Holmberg radius, R_{HO}	$13.3'$	
Total apparent B magnitude	10.27	
Corrected apparent B magnitude	9.31	
Absolute B magnitude	−16.26	(2)
Exponential disk parameters:		
Central surface brightness, $B(0)_c$	23.17	(3)
Scale length, α^{-1} (kpc)	1.2	(3)

* no correction for intrinsic flattening
(1) de Vaucouleurs et al. (1991)
(2) Soszyński et al. (2006)
(3) Carignan (1985)
(4) Jobin & Carignan (1990)



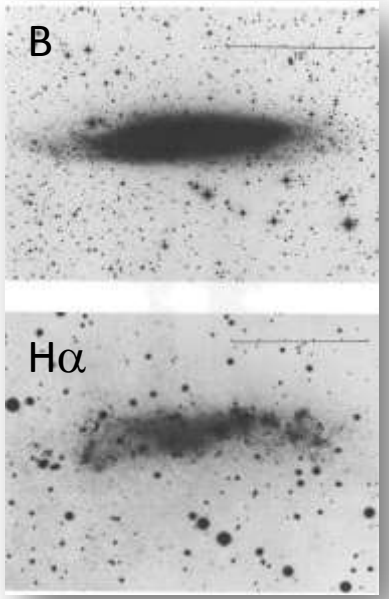


Table 2. Cepheids distance estimates for NGC 3109.

Reference	(Mpc)
Soszyński et al. (2006)	1.30 ± 0.02
Pietrzyński et al. (2006)	1.28 ± 0.03
Musella, Piotto &Capaccioli (1997)	1.36 ± 0.10
Capaccioli, Piotto & Bresolin (1992)	1.26 ± 0.10
Mean Cepheids distance	$< 1.30 \pm 0.04 >$

Scientific Interest of NGC 3109

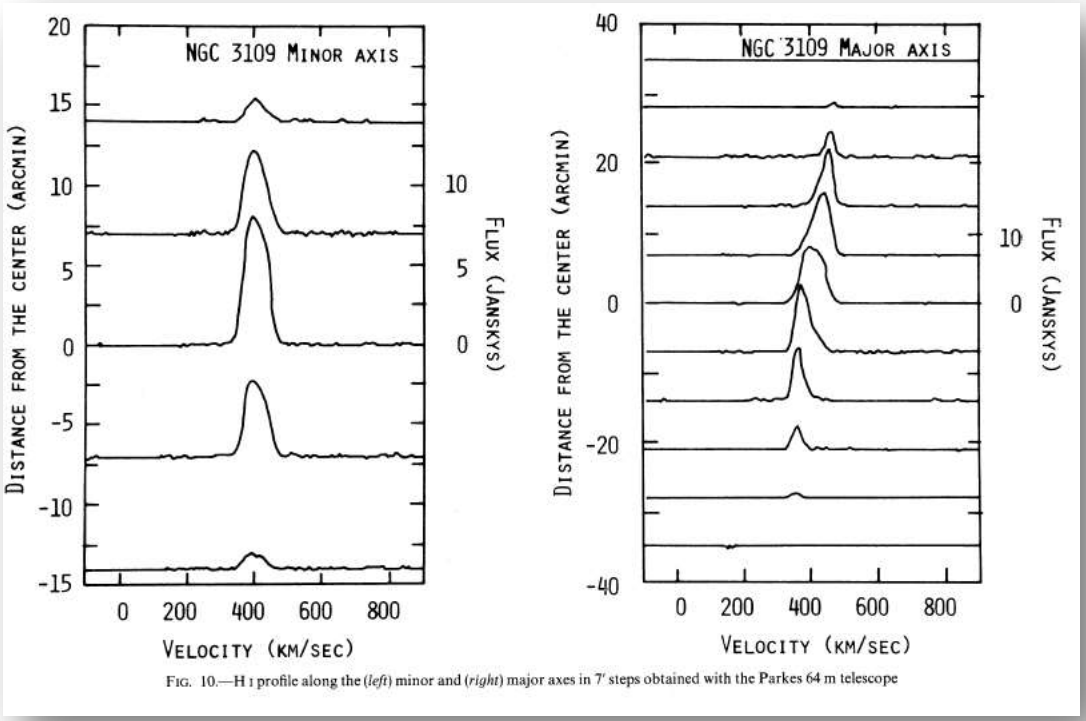


Fig. 10.—H I profile along the (*left*) minor and (*right*) major axes in 7′ steps obtained with the Parkes 64 m telescope

Parkes: Carignan 1985

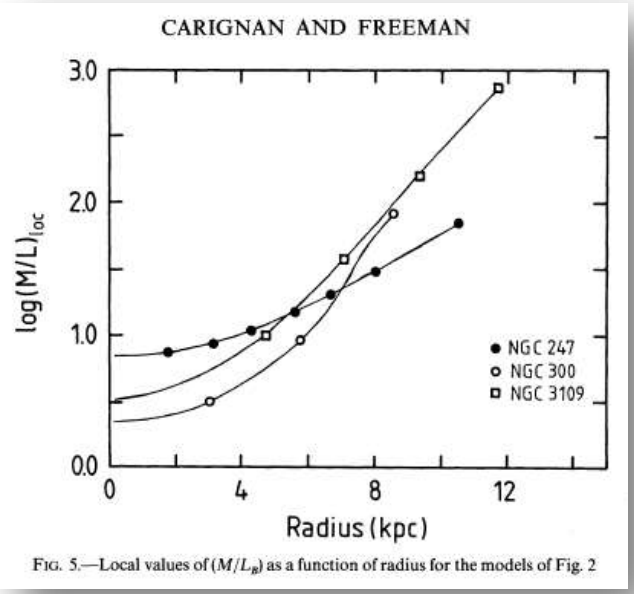
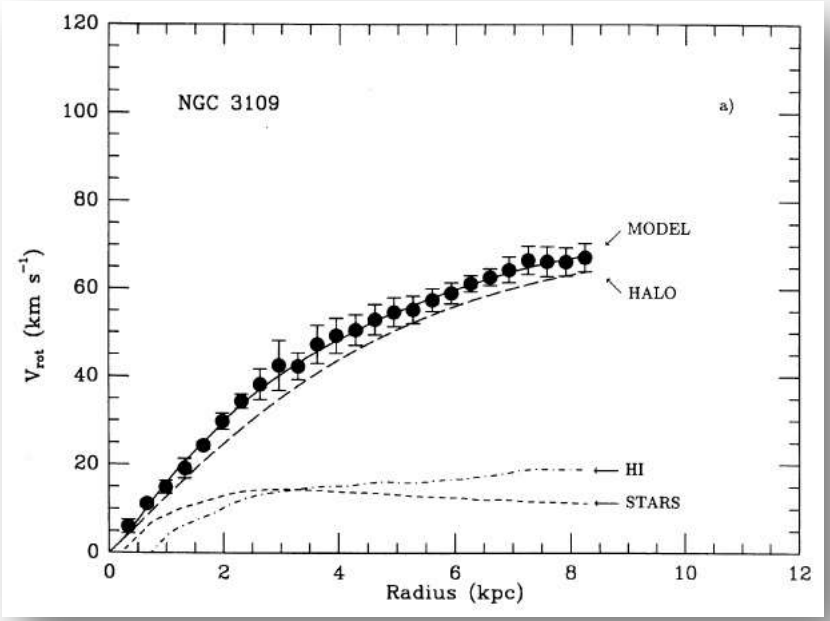
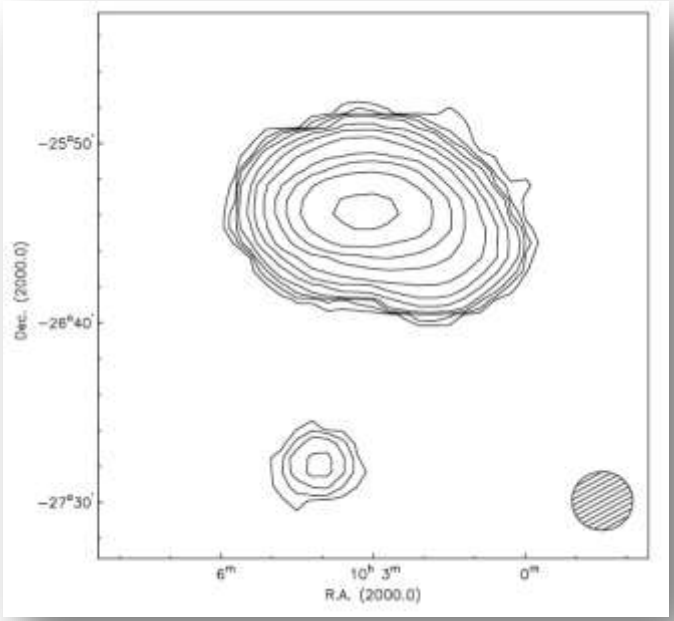


Fig. 5.—Local values of (M/L_B) as a function of radius for the models of Fig. 2

Carignan & Freeman 1985

Scientific Interest of NGC 3109





VLA: Jobin & Carignan 1990

Multibeam: Barnes & de Blok 2001

Scientific Interest of NGC 3109

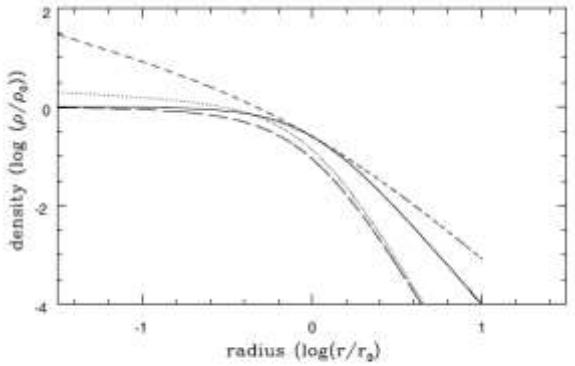
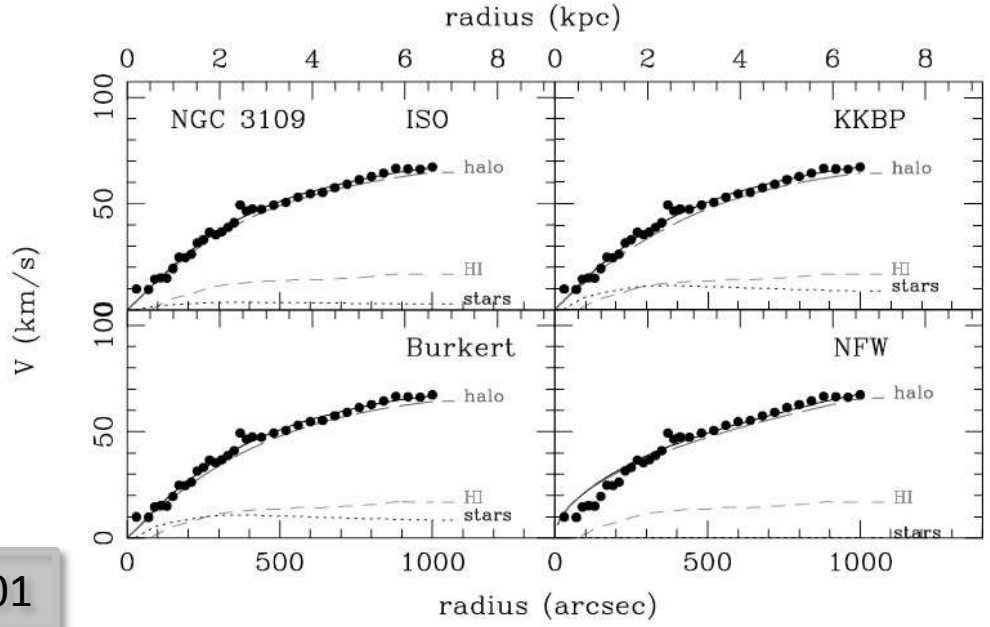
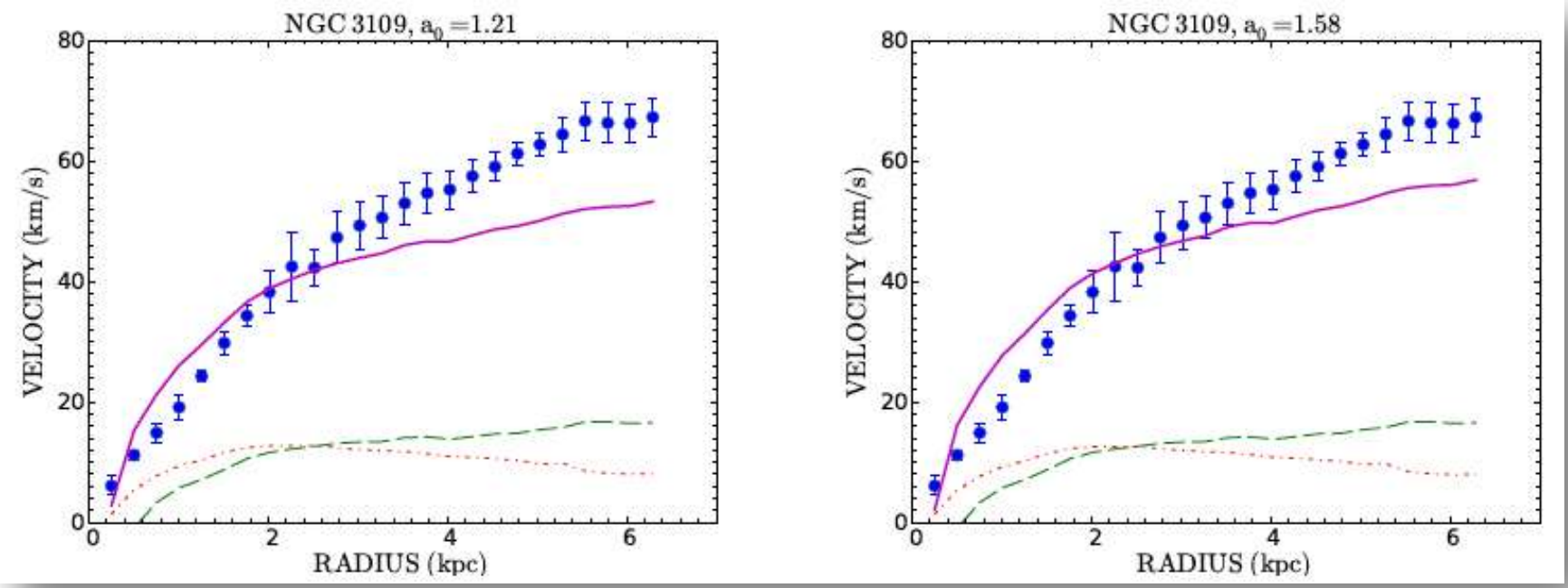


FIG. 5.—Density profiles of the four models: pseudoisothermal sphere (*solid line*), KKBP (*dotted line*), Burkert (*long-dashed line*), and NFW (*short-dashed line*).



Blais-Ouellette, Amram & Carignan 2001

Scientific Interest of NGC 3109



MOND: Randriamampandry 2013, Msc thesis, UCT

KAT-7

CASA (*Common Astronomy Software Applications*; McMullin et al. 2007) is the standard data reduction package being used for the reduction of the KAT–7 data and is anticipated to be used for MeerKAT.

Table 3. KAT-7 specifications.

Parameter	Value
Number of antennas	7
Dish diameter	12 m
Min baseline	26 m
Max baseline	185 m
Frequency range	1200 - 1950 MHz
Max instantaneous bandwidth	256 MHz
Polarisation	Linear H & V
T_{sys}	26 K
Aperture efficiency	0.65
System Equivalent Flux Density (SEFD)	1000 Jy
Latitude	-30:43:17.34
Longitude	21:24:38.46
Elevation	1038 m
Digital back-end	ROACH boards

HI observations of NGC 3109

- The KAT-7 observations of NGC 3109 provide a unique opportunity to simultaneously:
  - achieve HI spectral-line verification, and
  - get an original scientific result.
- It complements:
  - the high spatial resolution (~10”) but small FOV (~30’) of the VLA ANGST data (Ott et al. 2012)
  - the high sensitivity (~10^{17} cm^{-2}) but low spatial resolution (~15’) HIPASS data (Barnes & de Blok 2001).

HI observations of NGC 3109

- Observational "niche" for KAT-7:
  - Short baselines (26 to 185 m)
  - Low system temperature (26 K)
  - Large FWHM of the primary beam (~1^o)
- KAT-7 is very sensitive to low surface brightness and large scale HI emission → characteristic of the signal expected from NGC 3109

HI observations of NGC 3109

- Mosaic of 3 fields ~uniform sensitivity in a region of 1.5^{o}(EW) x 3.0^{o}(NS)
- Data collected over 13 observing sessions between 2012 November 20 and 2012 December 26 for a median 11 hours/session, total $122^{h}43^{m}56^{s}$, including calibration → ~25 hours/pointing/on source
- 4 sessions with 6 cooled ant.s, 9 with the 7 ant.s

HI observations of NGC 3109

- The c16n7M4k correlator mode was used giving channels of 0.32 km s^{-1} over a flat bandpass of ~1000 km s^{-1} (3/4 of the band), which allowed to collect HI data on background galaxies
- CASA 3.4.0 & 4.0.0 were used for the pre data reduction
- AIPS, MIRIAD & GIPSY for post data analysis
- The testing of the HI line mode led to the discovery of faint, very narrow, internally generated RFI along the signal path (30 out of 3000 channels), eliminated by the insertion of a low-pass filter
- One of the primary goal of the *science verification phase* is exactly to identify these types of problems and correct for them

HI data reduction of NGC 3109

- The 13 sessions were reduced individually
- Data were automatically flagged for shadowing and calibrators below 20^{o} elevation
- Data were interactively flagged as a function of frequency and baseline
- Continuum subtraction was done by selecting line free channels
- Calibration was applied and the three mosaic pointings were then SPLIT from the calibrators
- Data were averaged in time (from 5 to 10 sec.) and spectrally (from 0.32 to 1.28 km s^{-1})
- All 13 data sets were then combined in CONCAT

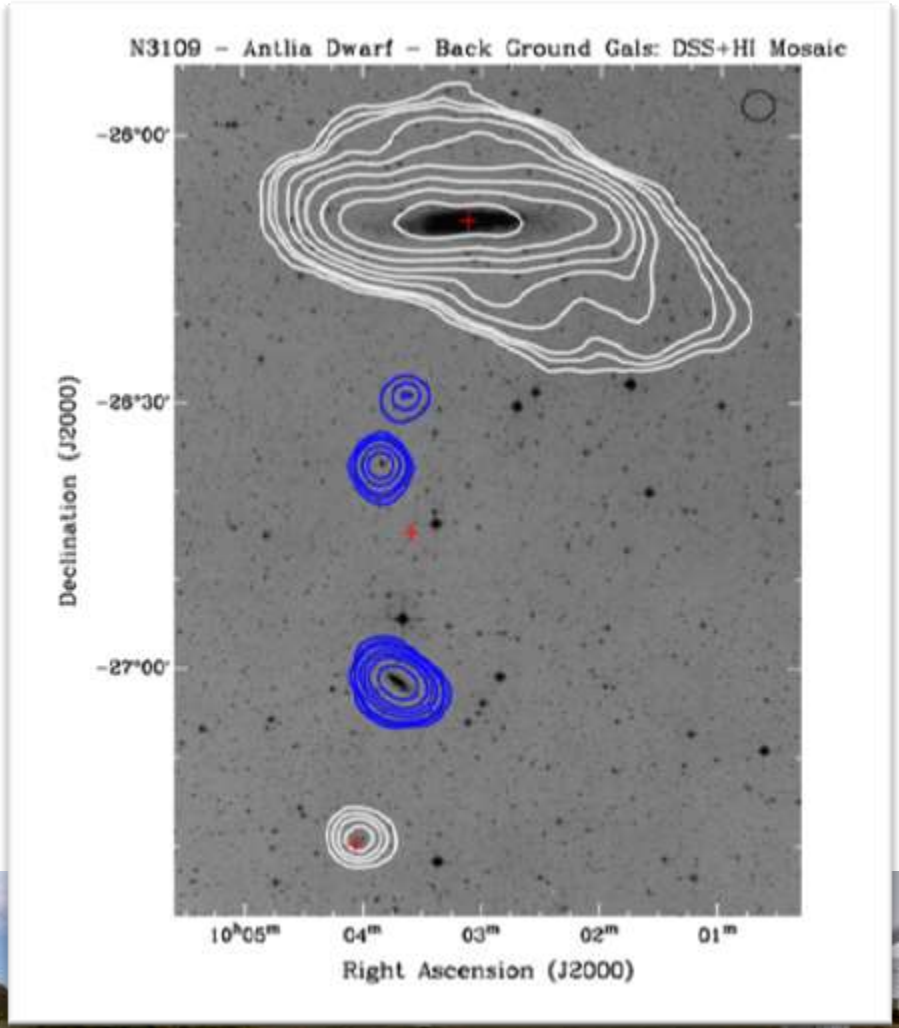
HI data reduction of NGC 3109

- KAT-7 does not use Doppler tracking & CASA does not fully recognized frequency keywords, so special care was taken to produce image cubes with the proper velocity coordinates:
  - Setting MEAS_FREQ_REF and REF_FREQUENCY keywords in the SPECTRAL WINDOW table;
  - Specifying the reference frequency and setting the output frame to optical, barycentric in CVEL, and
  - Specifying the rest frequency again in the task CLEAN.
- The data was imaged using the mosaic mode and the multi-scale clean option

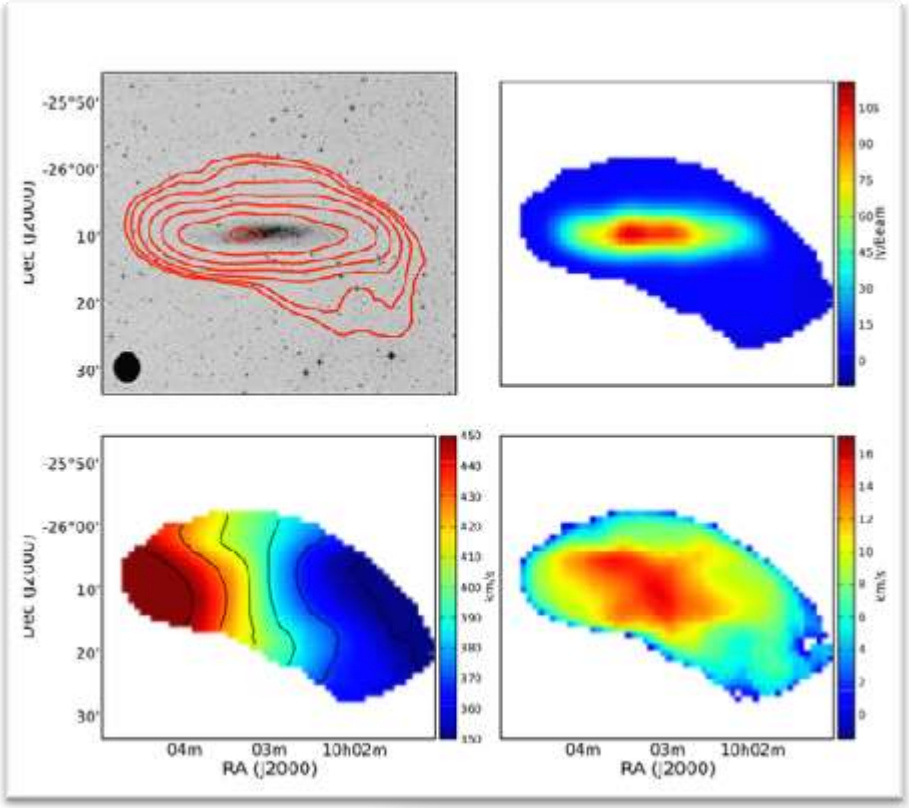
KAT-7 Data on NGC 3109

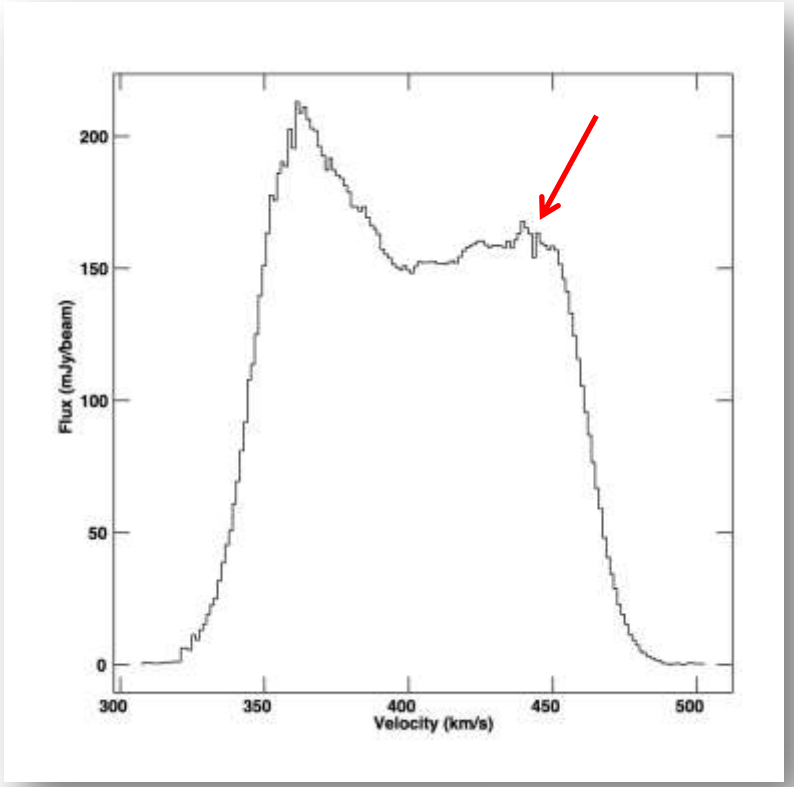
Table 5. Parameters of the KAT–7 observations.

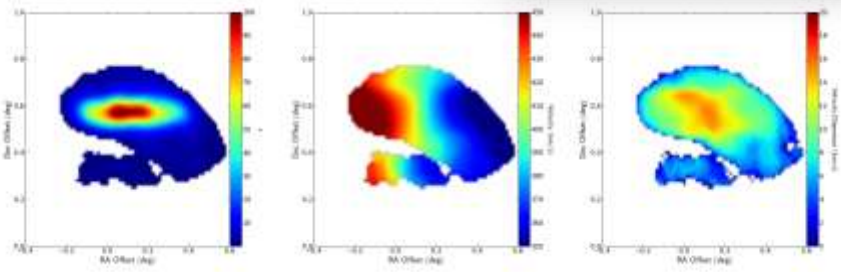
Parameter	Value
Start of observations	20 november 2012
End of observations	26 december 2012
Total integration per pointing	24.75 hours
FWHM of primary beam	58.67′
Total Bandwidth	6.25 MHz
Central frequency	1417 MHz
Channel Bandwidth (4 x 1.526 kHz)	6.1 kHz
Number of channels (4096/4)	1024
Channel width (4 x 0.32 km s^{-1})	1.28 km s^{-1}
Maps gridding	55″ x 55″
Maps size	128 x 256
Flux/bandpass calibrator	3C138
Phase calibrator	0118-317
Robust = 0 weighting function	
FWHM of synthesized beam	212″x 201″
RMS noise	5.6 mJy/beam
Conversion °K/(1 mJy/beam)	0.014
Natural weighting function	
FWHM of synthesized beam	264″x 233″
RMS noise (mJy/beam)	3.7 mJy/beam
Conversion °K/(1 mJy/beam)	0.010
Uniform weighting function	
FWHM of synthesized beam	203″x 196″
RMS noise	9.1 mJy/beam
Conversion °K/(1 mJy/beam)	0.015



KAT-7 Data on NGC 3109







Comparison of the different HI data sets

Table 7. Limiting HI surface densities of the different interferometer studies for NGC 3109.

Reference	atoms cm^{-2}	HI size (arcmin)
KAT-7	1.0×10^{19}	$58' \times 27'$
ANGST, VLA	2.0×10^{20}	$32' \times 08'$
Barnes & de Blok (2001)	2.0×10^{17}	$85' \times 55'$
Jobin & Carignan (1990)	1.0×10^{19}	$40' \times 12'$

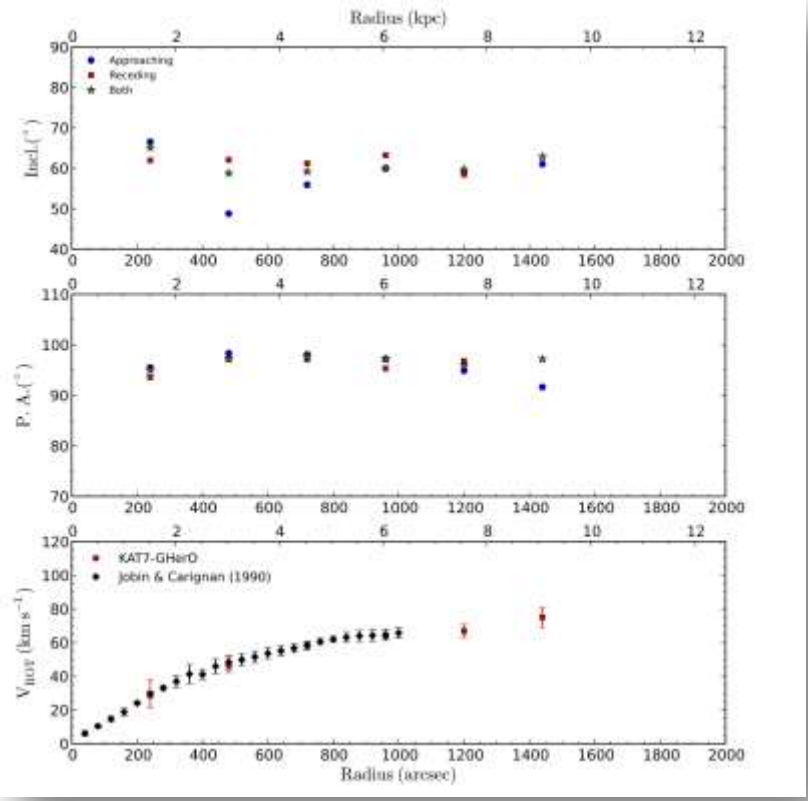
Table 8. Different HI mass estimates for NGC 3109*.

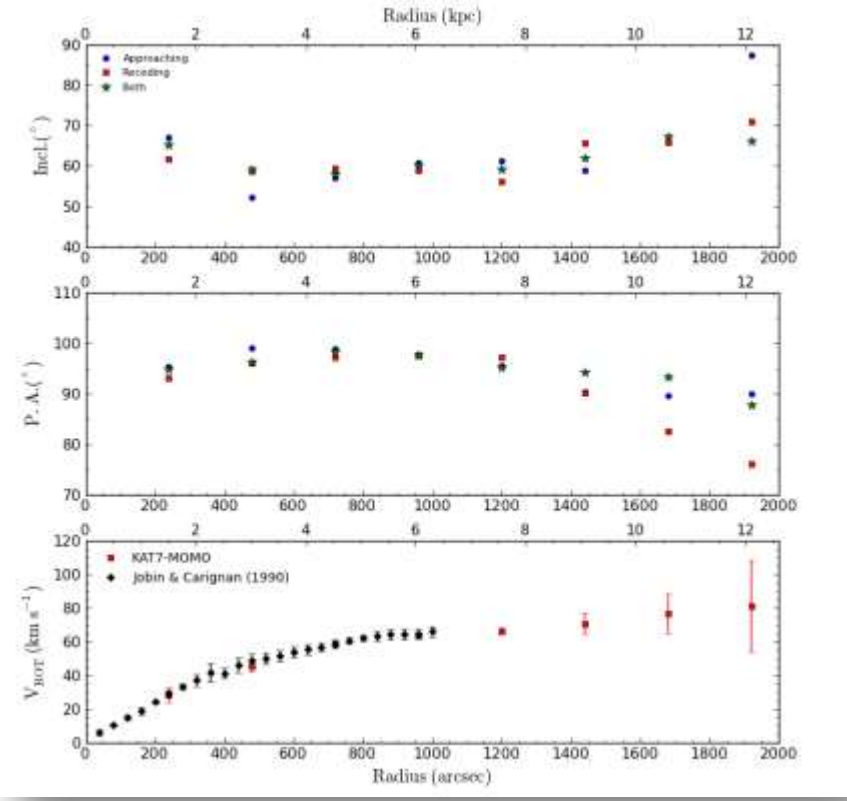
Reference	10^8 $M_\odot$
Aperture synthesis	
KAT-7	4.6 ± 0.5
ANGST, VLA	2.9 ± 0.3
Barnes & de Blok (2001)	4.5 ± 0.6
Jobin & Carignan (1990)	2.9 ± 0.6

* Naturally, all the masses have been corrected to our adopted distance of 1.3 Mpc.

Both the KAT-7 & the HIPASS data detect 40% more flux than the VLA because the VLA lacks the proper short baselines to see scales larger than 15’

Derivation of the RC: Tilted-ring Model





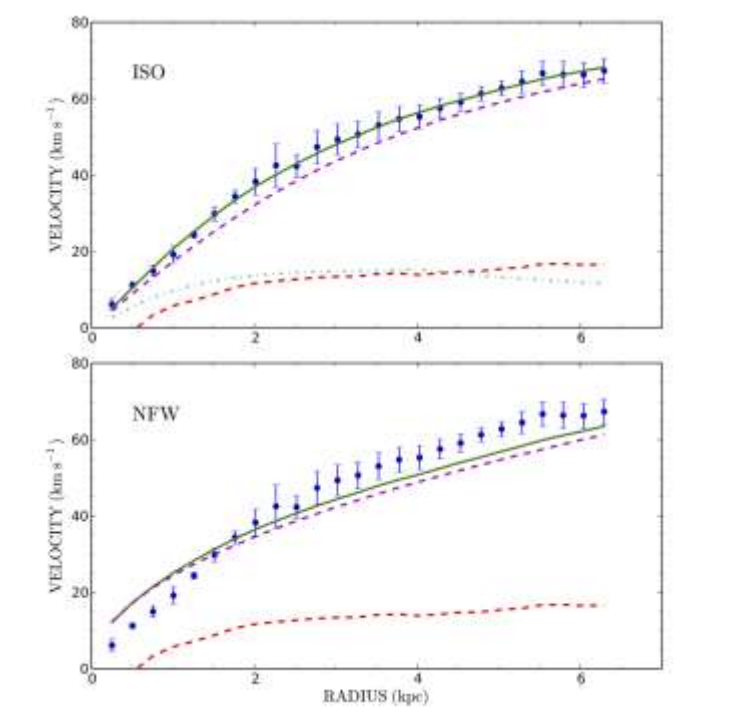
Mass Models Analysis

- Despite the uncertainties on the exact M/L ratio of the luminous disk, Low Surface Density (LSD) galaxies, such as NGC 3109, are clearly DM dominated at all radii
- They can be used to:
  - constrain important properties of DM halos:
    - Characteristic scale density & radius
    - Concentration & virial mass
    - Exact shape of the mass density profile
  - test the results obtained by numerical simulations (ΛCDM – NFW 1996, 1997)
  - test alternative gravity theory (e.g. MOND – Milgrom 1983)

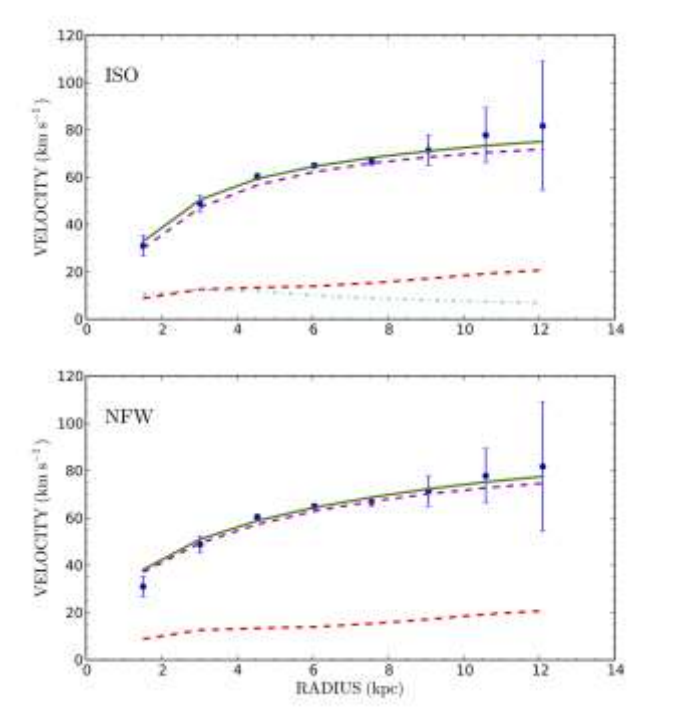
Mass Models Analysis

- The study of the mass distribution of LSD galaxies has generated in the last 15 years the so-called cusp-core controversy:
  - Are RCs of LSD better reproduced by:
    - A cuspy halo as seen in ΛCDM simulations
    - A nearly constant central density core as seen in most high spatial resolution observations
- Nowadays, galaxies are expected to form inside cuspy CDM halos while some physical process could have turned initially cuspy DM halos into cored ones (e.g. Governato et al. 2010)

Mass models: ISO & NFW

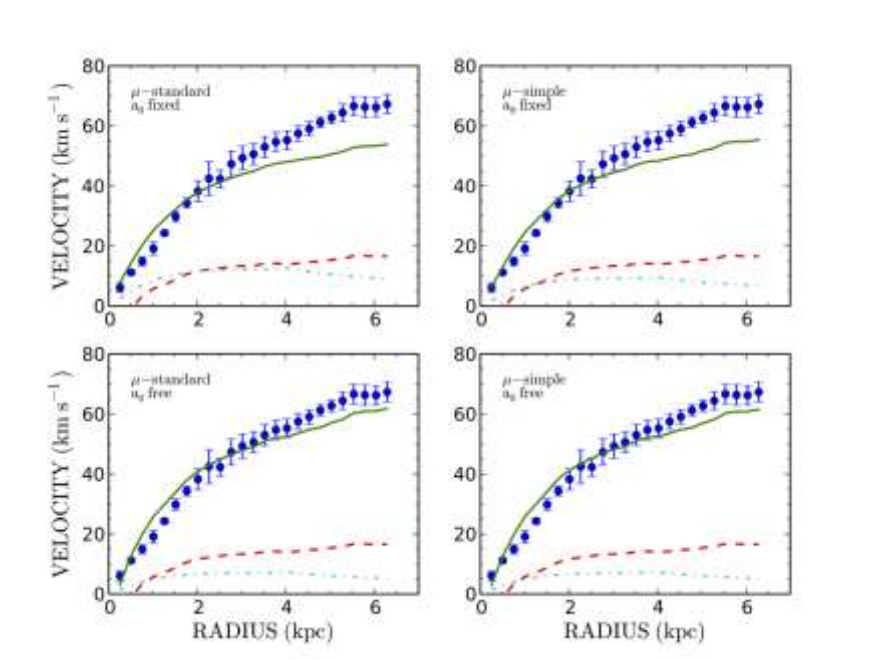


VLA



KAT-7

Mass models: MOdified Newtonian Dynamics (MOND)

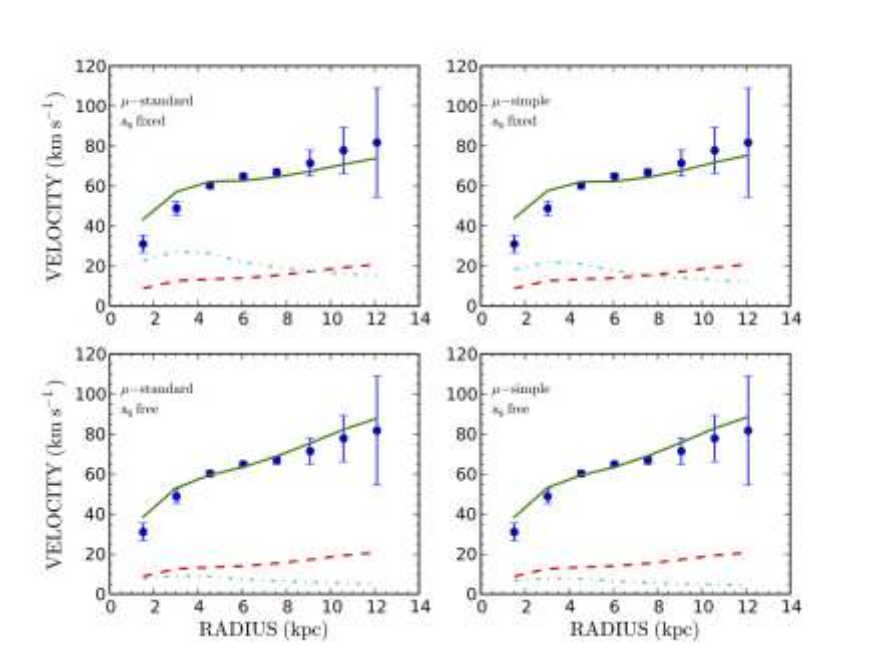


the MOND models of NGC 3109 for the VLA data.

a_0 10^{-8} cm s^{-2}	μ	Parameter	Result
fixed	standard	$(M/L)_I$	0.45
		a_0	1.21
		χ^2	12.01
	simple	$(M/L)_I$	0.26
		a_0	1.21
		χ^2	9.25
free	standard	$(M/L)_I$	0.15
		a_0	2.48
		χ^2	5.50
	simple	$(M/L)_I$	0.15
		a_0	2.07
		χ^2	5.57

VLA

Mass models: MOdified Newtonian Dynamics (MOND)



the MOND models of NGC 3109 for the KAT–7 data.

a_0 10^{-8} cm s^{-2}	μ	Parameter	Result
fixed	standard	$(M/L)_I$	2.61
		a_0	1.21
		χ^2	2.96
	simple	$(M/L)_I$	1.69
		a_0	1.21
		χ^2	3.38
free	standard	$(M/L)_I$	0.29
		a_0	3.48
		χ^2	1.30
	simple	$(M/L)_I$	0.22
		a_0	3.25
		χ^2	1.37

KAT-7

SUMMARY

- A total HI mass of 4.6 x 10^8 M_{sol} is measured for NGC 3109, 40% larger than the value measured by the VLA. This is surely a better estimate of the total mass of NGC 3109 since KAT-7 is sensitive to large scales for which the VLA is not.
- The KAT-7 rotation curve agrees in the inner parts with the VLA data while allowing to extend the rotation data by a factor of 2 out to 32’

SUMMARY

- The observationally-motivated DM ISO model reproduces very well the KAT-7 rotation curve while the cosmologically-motivated NFW model gives a much poorer fit, with a non-physical M/L = 0 for the best-fit NFW model. NGC 3109 has definitely a cored and not a cuspy halo
- While it is clear that having the proper gas distribution has reduced the discrepancies between the observed RC and the MOND models, the unreasonable (M/L) and large a_0 values obtained bring us to conclude that we cannot get acceptable MOND models for NGC 3109
- Besides some elongation of the outer isophotes, already seen in previous observations, no further evidence is found of past encounter and/or interaction between the Magellanic-type spiral NGC 3109 and the dIrr/dSph Antlia.

CONCLUSIONS

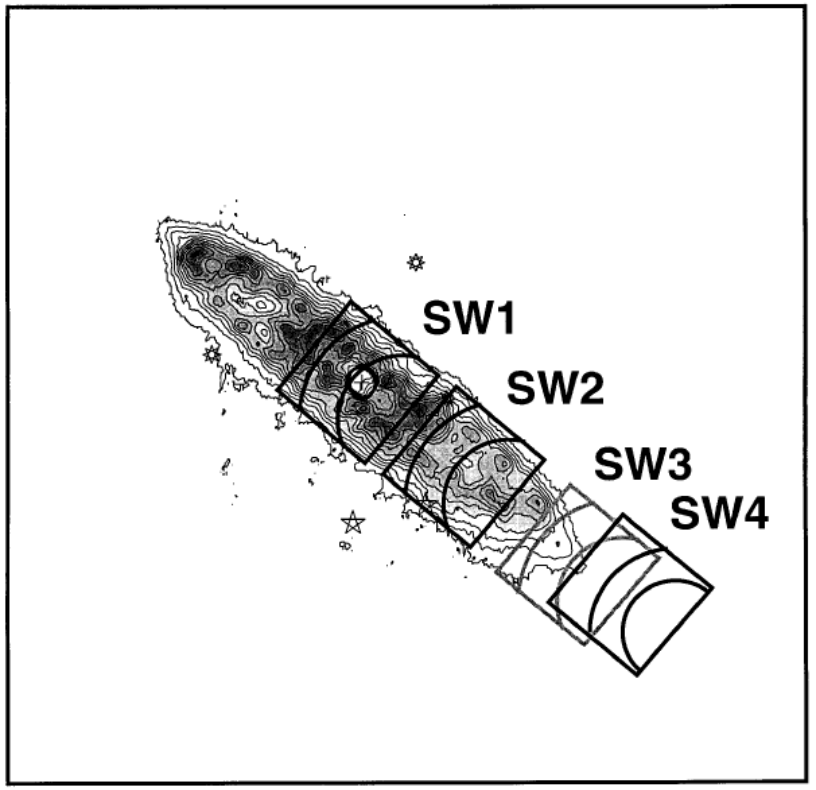
- Those observations with KAT-7 have shown that despite its relatively small size (7 x 12 m), this telescope really has a niche for detecting large scale low surface brightness emission over the ~1^{o} FWHM of its antennae.
- Since KAT-7 was built primarily as a testbed for MeerKAT, any scientific result that can be obtained is a bonus.
- While most of the extragalactic HI sources would be unresolved by the ~4' synthesize beam, many projects such as this one on NGC 3109 can be done on nearby very extended objects such as Local Group Galaxies or galaxies in nearby groups like Sculptor.

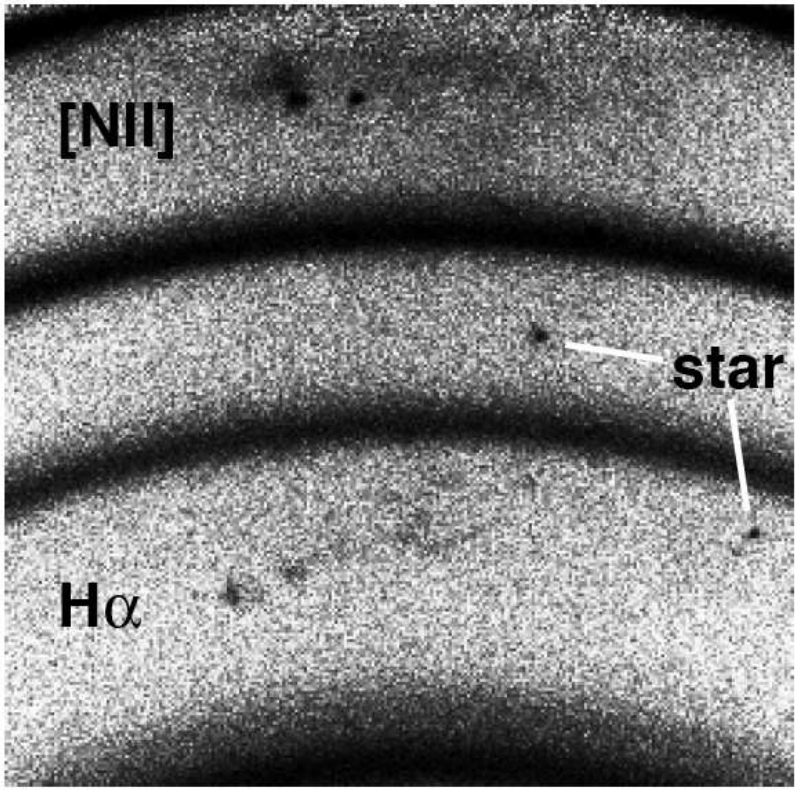
Thank’s

Examples of suitable targets for KAT-7 in HI spectral line mode

- The nearest “starburst” galaxy NGC 253 in Sculptor
- The “merger” NGC 5128 (Centaurus A)
- The Local Group galaxy NGC 6822

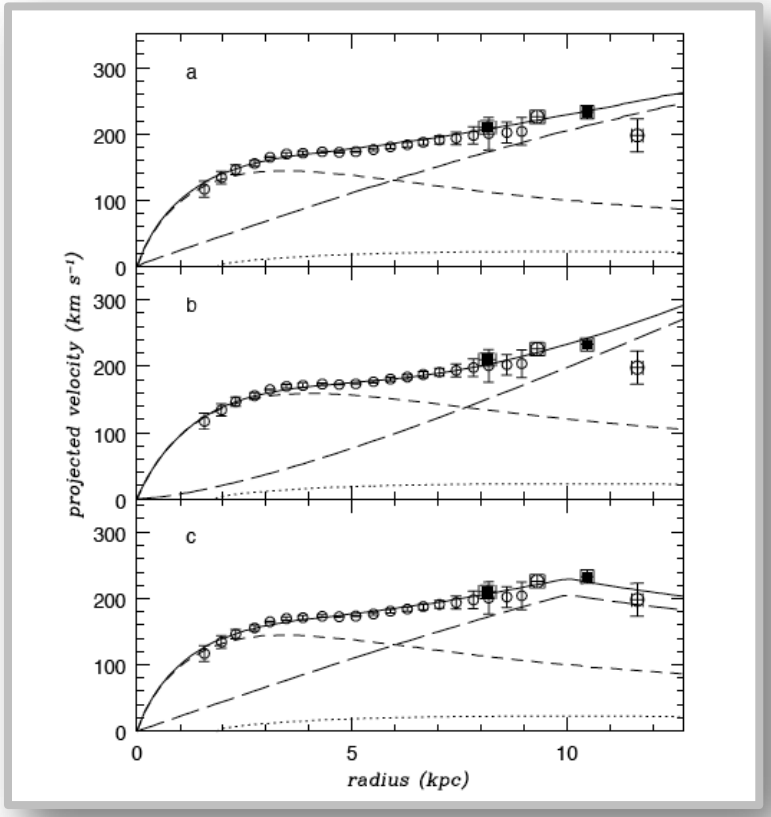
The case of NGC 253 (nearest starburst)



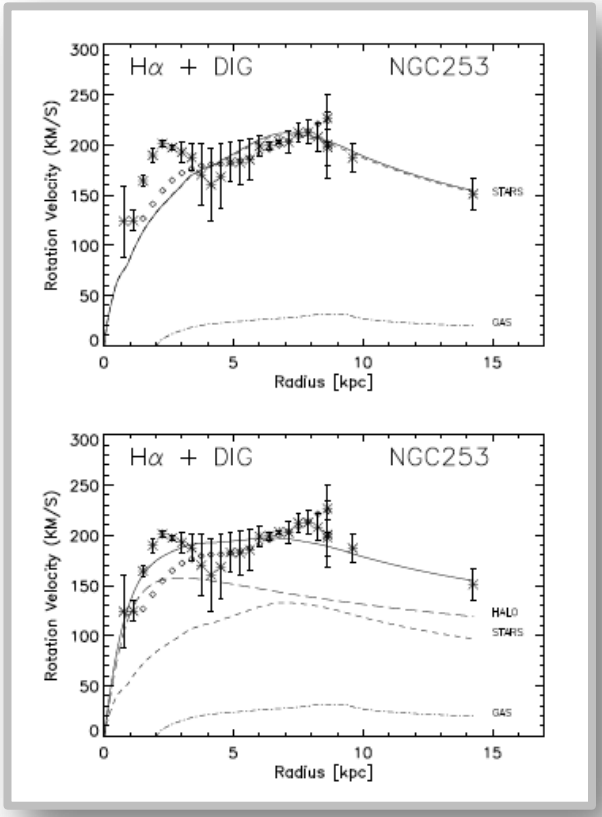


Bland-Hawthorn, Freeman, Quinn 1997

The case of NGC 253

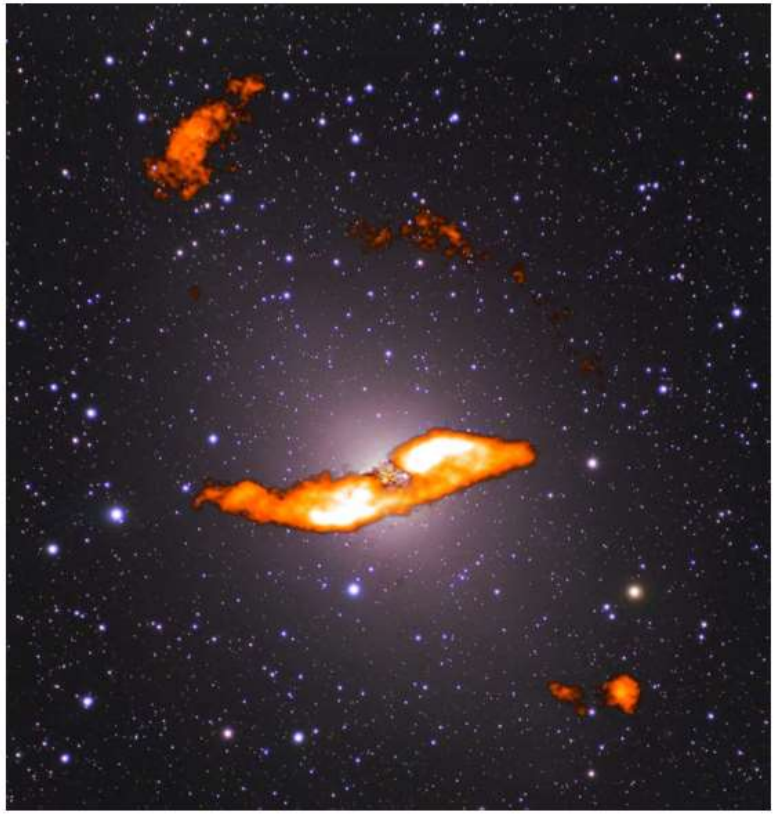


Bland-Hawthorn, Freeman, Quinn 1997

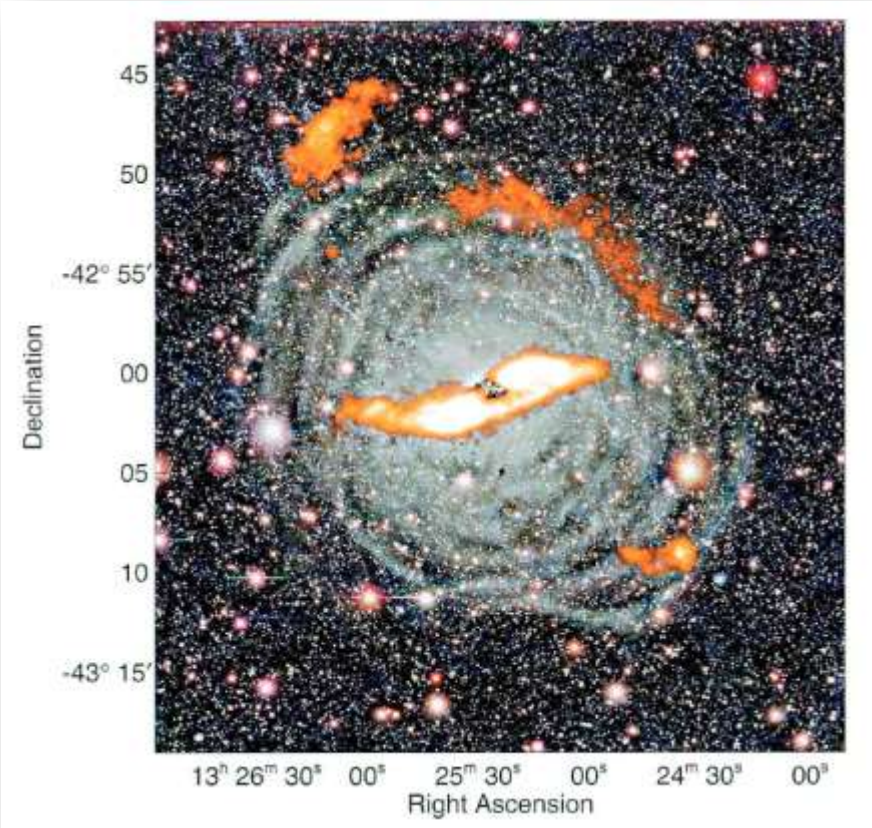


Hlavacek-Larrondo, Carignan et al. 2011

The case of NGC 5128 (Centaurus A)

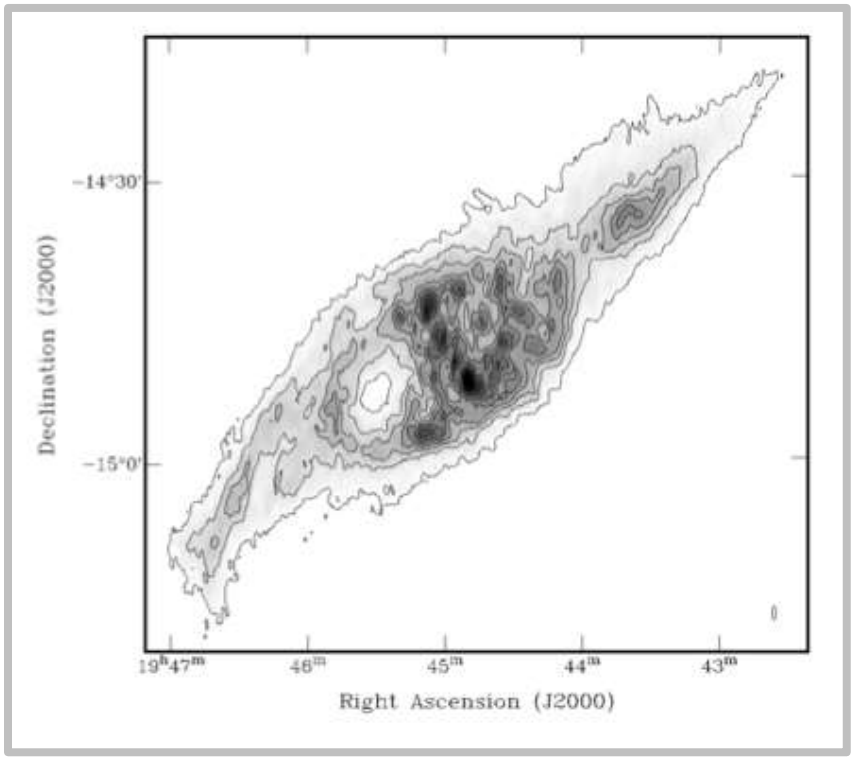


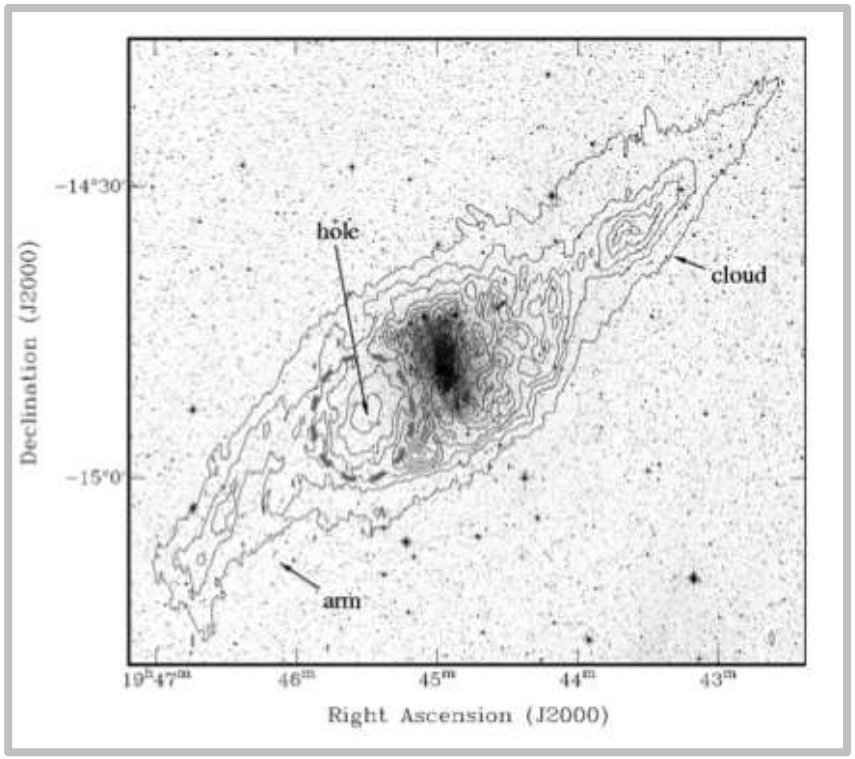
Struve et al. 2010, PASA, 27, 390



Struve et al. 2010, A&A, 515, 67

The case of NGC 6822





De Blok & Walter 2000

Faintest contour: 1 x 10^{20} cm^{-2}