Nuclear Activity in Low Surface Brightness Galaxies

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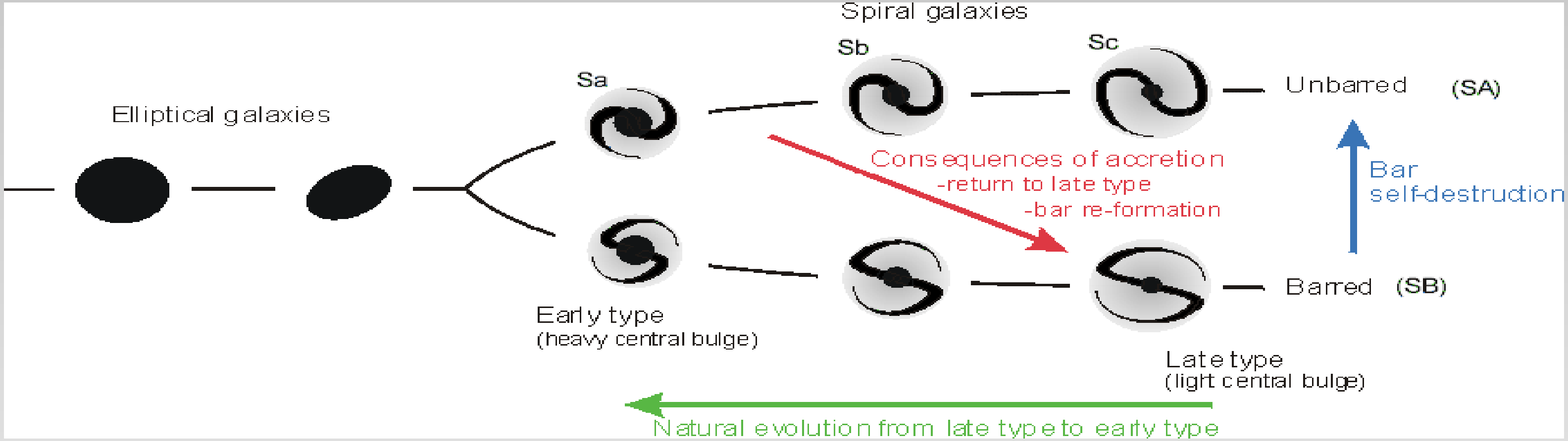
Revisiting the Hubble Sequence



- As we move to the right side i.e. late type spirals, the bulges become relatively smaller and the spirals less tightly wound.
- The late type spirals are also less luminous than earlier type galaxies.
- They appear to be more dark matter dominated than early type galaxies.
- They are also generally less evolved.

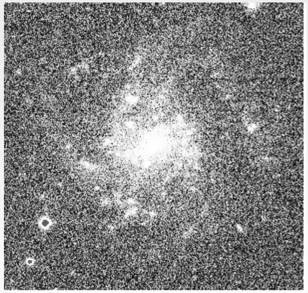
Low Surface Brightness Galaxies

- LSB galaxies are spiral galaxies with diffuse stellar disks but massive HI gas disks.
- They are poor in star formation and low in metallicity. Overall, they are poorly evolved compared to bright galaxies.
- They are more dark matter dominated than early type spirals.

UGC 6614

Malin 2

UGC 1230



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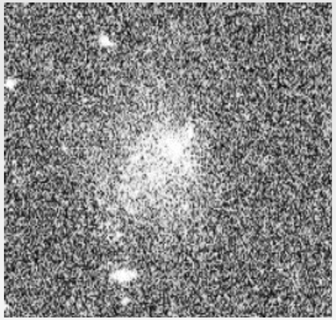

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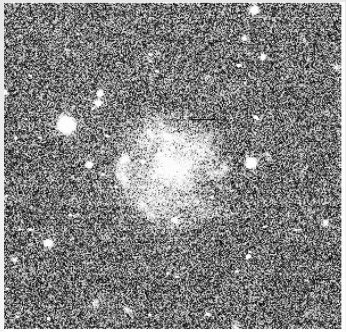
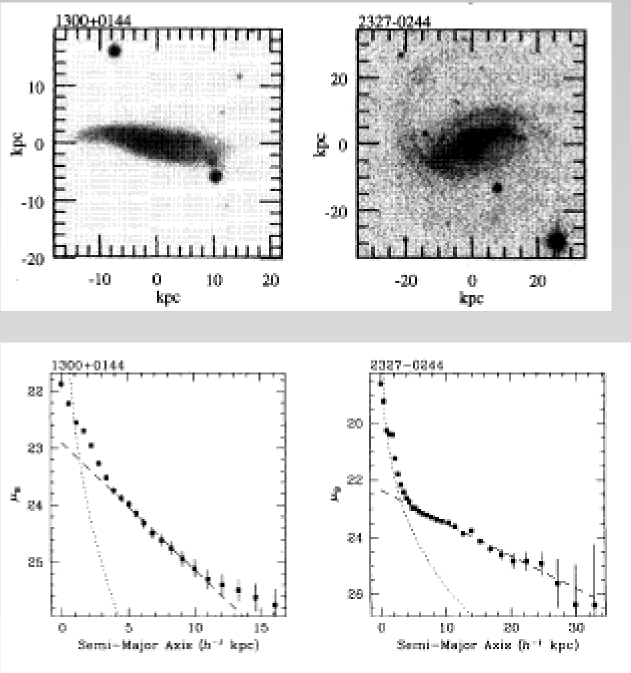


UGC 9024

Bothun's Gallery of LSB galaxies

Low Surface Brightness Disks

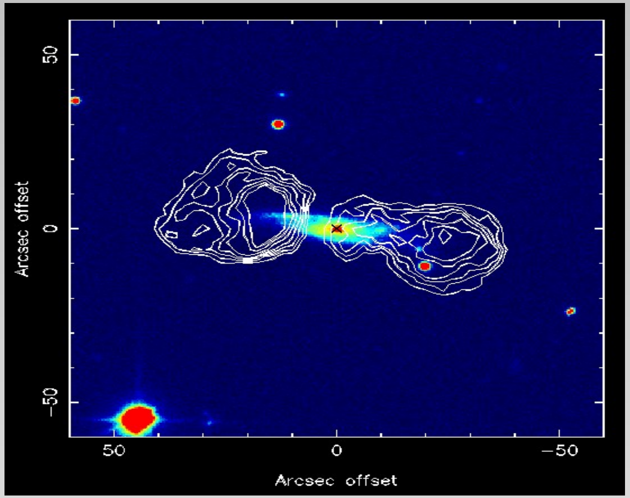
- LSB galaxies have faint stellar disks and massive HI disks. They are poor in disk star formation and low in metallicity.
- They are defined by the extrapolated disk brightness. Hence may sometimes have prominent bulges but very faint disks.
- They are dark matter dominated sometimes even in their inner disks.
- There are both giant and dwarf LSB galaxies.
- The formation and evolution of LSBs still not well understood. The GLSBs are often isolated and at the edge of voids.



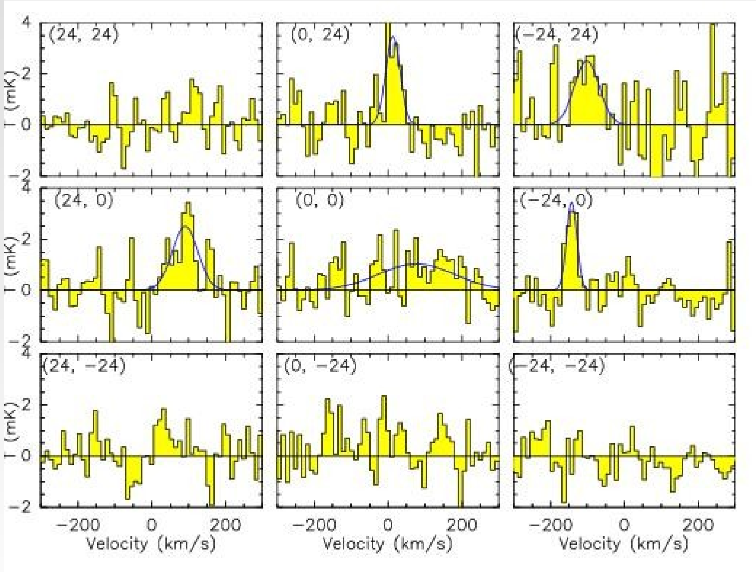
Sprayberry eta al. 1995

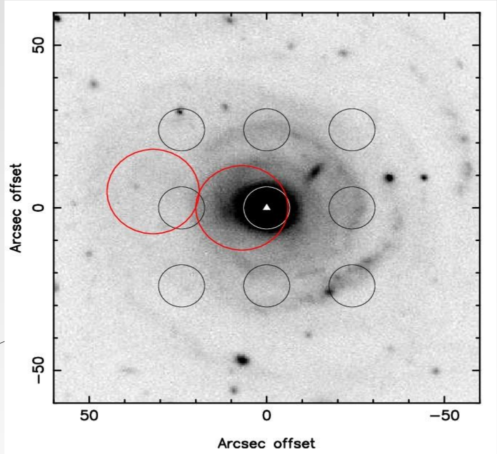
Massive HI Disks

- The HI disks often extend to more than twice the optical disk radius.
- They are often lopsided.
- Generally poor in molecular gas. Very few detections of CO in LSB galaxies.



HI contours on DSS image for PGC045080 (1300+0144) (Das et al. 2007).





HERA CO(2-1) detections from F568-6 (Malin 2) (Das etal. 2010).

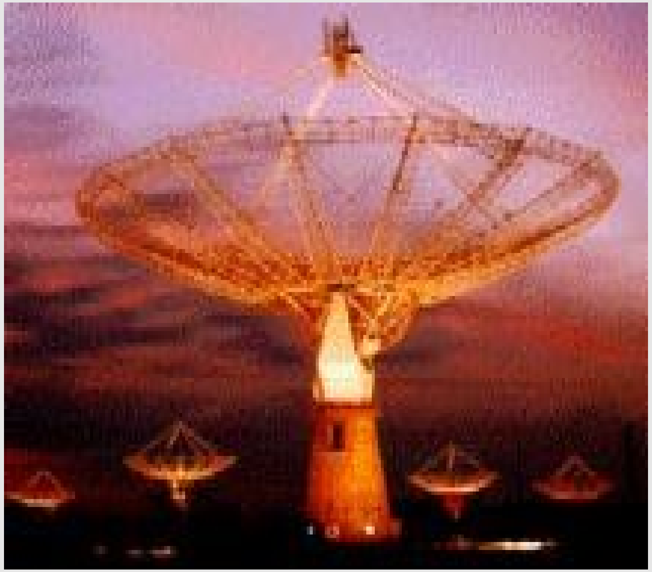
Bulge – AGN Evolution in GLSB galaxies

- Although dwarf LSB galaxies are more populous than giant LSBs (GLSB), the GLSBs are an interesting challenge for galaxy evolution models.
- They often have large bulges and sometime oval distortions that support nuclear activity despite a poor disk star formation.
- Very little is known about their nuclear activity and bulge-AGN connection. In this study we present radio, x-ray and optical studies of the nuclear regions of GLSB galaxies.

GMRT Radio Continuum Observations of Giant LSB galaxies

- We have observed a sample of 8 giant LSB galaxies in radio emission with the GMRT at 1.4 Ghz and 610 Mhz from 2006 to 2008.
- The radio emission can come from AGN activity associated with the nucleus and/or star formation associated with the disk.
- We searched for compact emission at the nucleus. Also extended emission which may be due to radio lobes/jets. We determined the spectral index when possible.

GMRT is an interferometric array of 30 antennae situated near Pune, India.



Galaxy sample

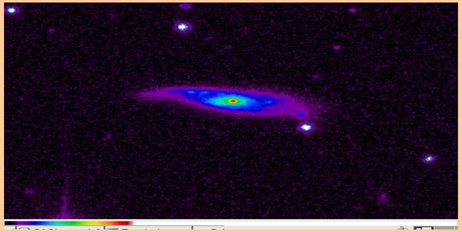
Table 1: **List of Galaxies studied in radio emission**

Galaxy Name	Other Names	Galaxy Type	Distance Mpc
UGC 1378	PGC 007247	(R)SB(rs)a	38.8
UGC 1922	...	S	150
UGC 2936	PGC 014345	SB(s)d	51.2
UGC 4422	NGC 2595	SAB(rs)c	163.4
UGC 6614	PGC 036122	(R)SA(r)a?	93.3
2327-0244	UM 163	SB(r)b pec	136
F568-6	Malin 2	Sd/p	201
1300+0144	PGC 045080	S	176

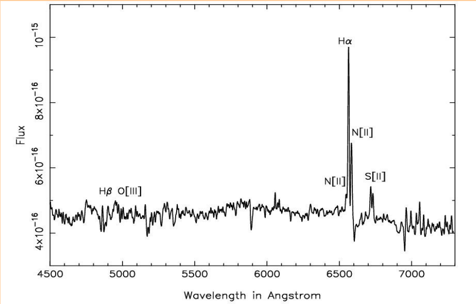
- We studied galaxies that had optically identified AGN. They were all galaxies with fairly prominent bulges but varied morphologies (face on to edge on).
- We also chose galaxies that had been detected in the VLA NVSS survey. But NVSS has a poor resolution of ~45”. Hence high resolution observations were required to examine the morphology. Especially to understand whether the emission is due to AGN activity or star formation.

Extended Emission in PGC045080

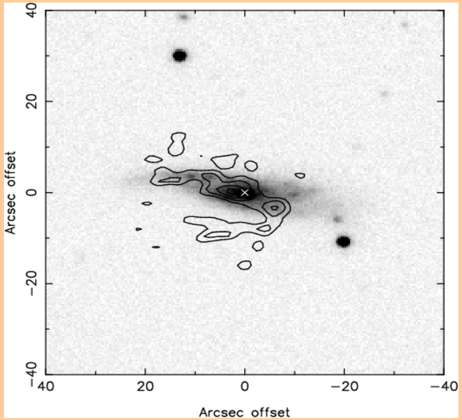
- We detected extended radio emission from the GLSB this galaxy (D~176Mpc). The galaxy is highly inclined and has a lopsided massive HI disk.
- The optical spectrum shows possibly a LINER nucleus. There maybe disk star formation mixed with AGN emission.
- The radio maps at 1420, 610 and 325 Mhz show extended disk emission as well as nuclear emission.



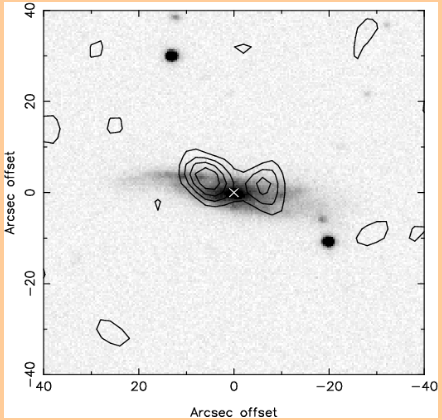
SDSS color image of the galaxy



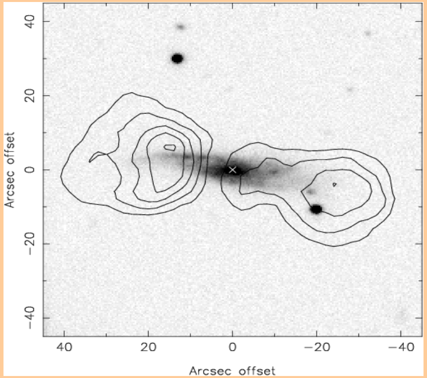
Optical spectrum using HCT



GMRT 1.4GHz radio emission contours overlaid on optical image (beam 4.4")



GMRT 610 Mhz emission contours on optical (beam 7")



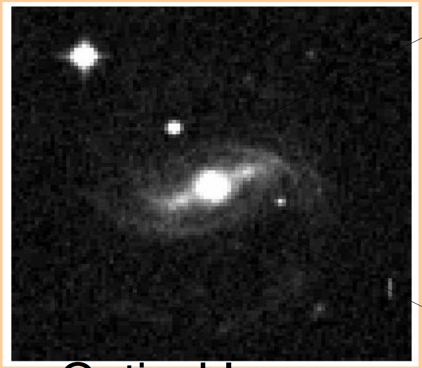
HI contours (beam 14") overlaid on the SDSS optical image of PGC045080

(Das etal, 2007 MNRAS)

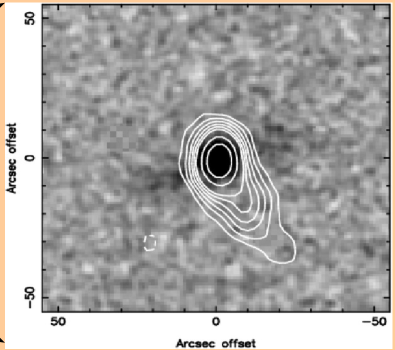
Radio lobes/jets

UM163 (2327-0244)

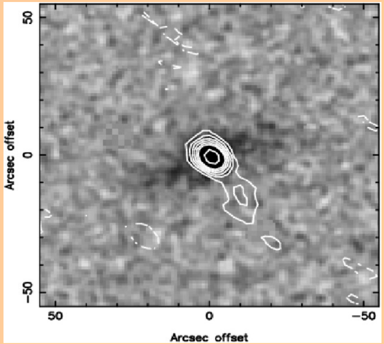
This LSB galaxy has a bar and prominent bulge. It is classified as a Sy1 galaxy. Radio emission at 610MHz shows jet like feature (~22kpc).



Optical Image



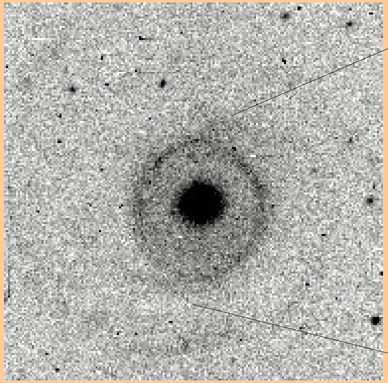
610 Mhz Low resolution



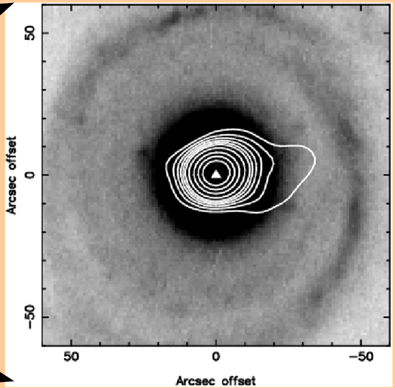
High Resolution

UGC 6614

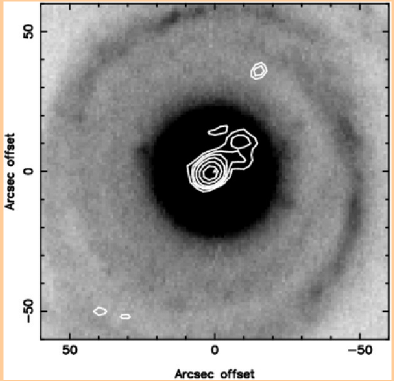
This prototypical giant LSB shows compact radio emission at 110GHz, 1.4GHz. Flat spectrum, At 610MHz there is extended emission. Maybe radio lobe/jet



Optical Image



VLA 1.4 GHz



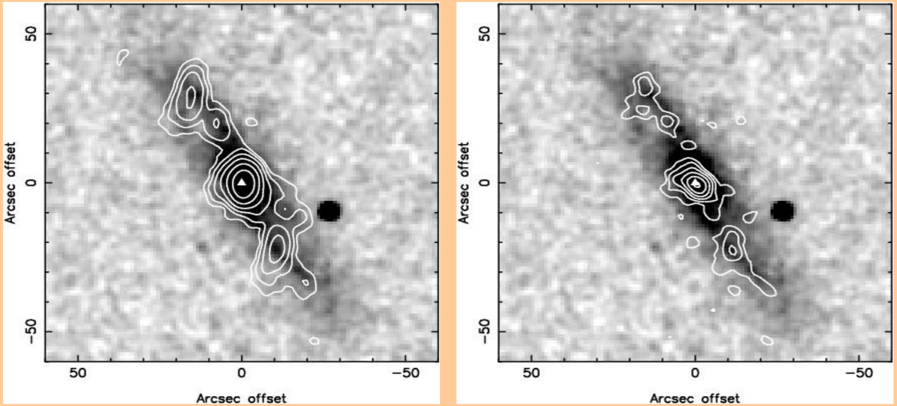
610 Mhz

(Das et al. 2009)

Nuclear and Disk Emission from UGC 2936

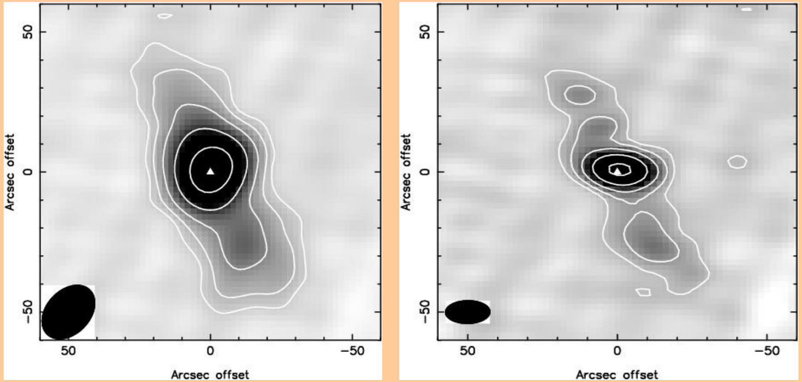
- UGC 2936 is a near edge on LSB galaxy with a large LSB disk and small bulge.
- There is emission associated with AGN but also extended emission. Possibly due to disk star formation.
- This is a rare LSB that shows some disk star formation. Maybe building a bulge (secular evolution).

1280 Mhz Maps



Low and High resolution

610 Mhz Maps

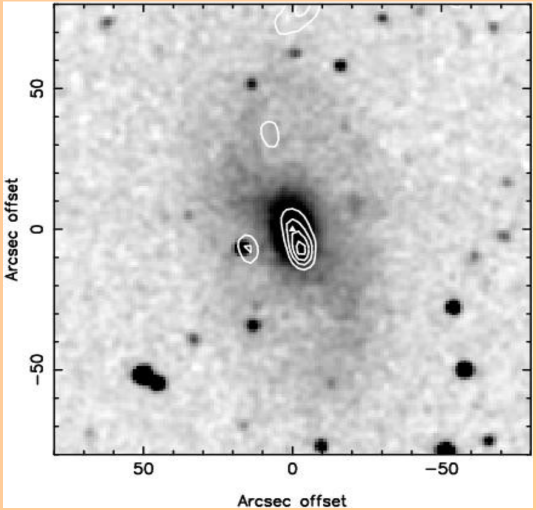


Low and High resolution

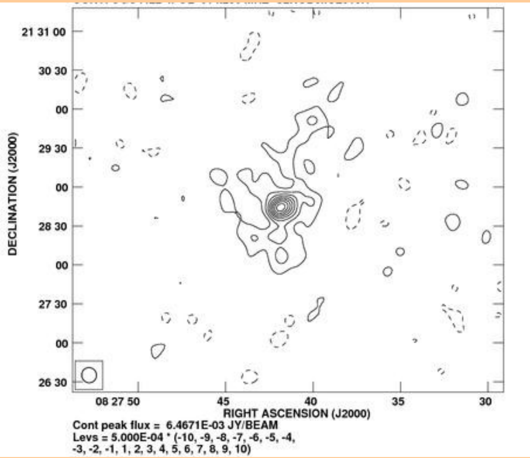
Bulge and Disk Emission

- In the GLSB galaxies UGC 4422 and UGC 1378 we detected radio continuum emission at 610 Mhz associated mainly with the bulge.
- Emission is due to old stellar population in the bulge. At higher resolution compact emission due to AGN activity not detected.
- In UGC4422 some emission is associated with disk star formation as well.

610 Mhz emission from the bulge of **UGC1378**



GMRT 610 Mhz map of radio continuum emission from **UGC 4422**.



Summary of radio observations ....

- A significant fraction of GLSB galaxies have radio emission. However the emission is more centrally concetrated than observed in bright star forming galaxies.
- In some cases radio lobes or jets are detected, especially at lower frequencies.

X-ray Observations of GLSB Galaxies : Chandra and XMM (archive)

- We observed 8 galaxies with Chandra ACIS-S for a total of 30 Ks.
- The were all nearby (<10,000 km/s) GLSB galaxies, having prominent bulges and optically detected AGN.
- We wanted to examine the x-ray properties of these galaxies; search for both compact sources and diffuse emission.
- Galaxy morphologies varied from face on to nearly edge on (ugc2936)

Table 1: **List of Galaxies and exposure times**

Galaxy	Distance (Mpc)	Exposure Time
UGC 1455	67	3.8
UGC 2936	51	2.7
UGC 1378	39	3.5
UGC 1922	150	5.9
UGC 3059	66	3.3
UGC 4422	63	2.9
UGC 11754	63	4.2
UGC 12845	64	3.3

Results of x-ray imaging

- We detected compact emission from the nucleus of 3 galaxies : UGC 2936, UGC1455 and UGC 6614 (XMM archival data).
- The emission is associated with the optical center of the galaxies - hence due to AGN activity.
- UGC 2936 appears to be a Seyfert 2 galaxy and UGC 6614 is a Seyfert1.
- For the non-detections we determined upper limits to the nuclear x-ray luminosities from lowest count rates in the field. They could be LLAGNs at large distances.

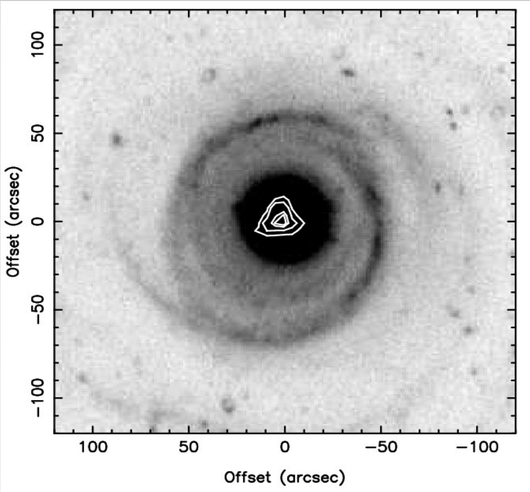
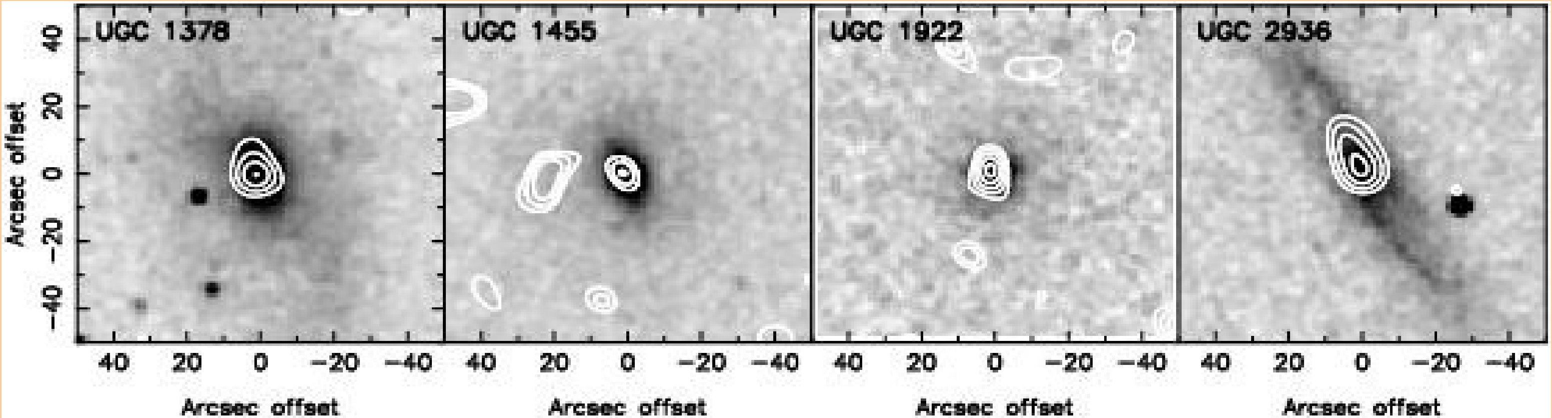


Table 1: **AGN X-ray Flux**

Galaxy	Luminosity of compact sources	telescope
UGC 1455	$1.1 \times 10^{40}\ erg\ s^{-1}$	Chandra
UGC 2936	$1.8 \times 10^{42}\ erg\ s^{-1}$	Chandra
UGC 6614	$1.1 \times 10^{42}\ erg\ s^{-1}$	XMM

Diffuse Emission X-ray Emission

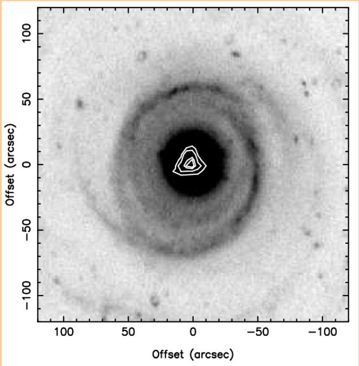
- We searched for diffuse x-ray emission from the 8 galaxies in the Chandra sample. The point sources were removed and the images smoothed. Diffuse emission mainly associated with the bulges.
- The diffuse gas luminosities were estimated. They are approximate values and lie in the range 10^{39} to 10^{40} erg/s. Luminosities are similar to that observed from the bulges of nearby bright galaxies.
- These GLSB galaxies lack star formation. Hence emission is due to old stellar poplation in the bulges.



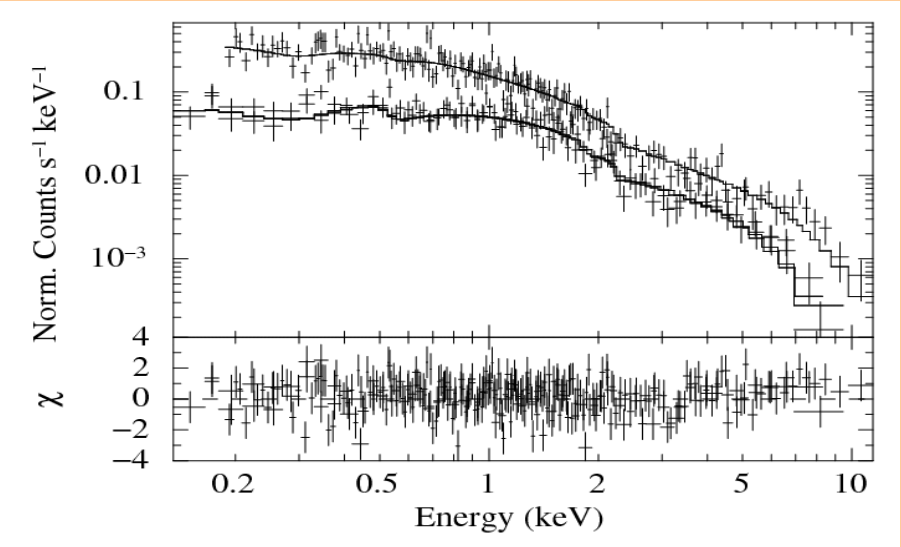
(Das et al. 2009, ApJ)

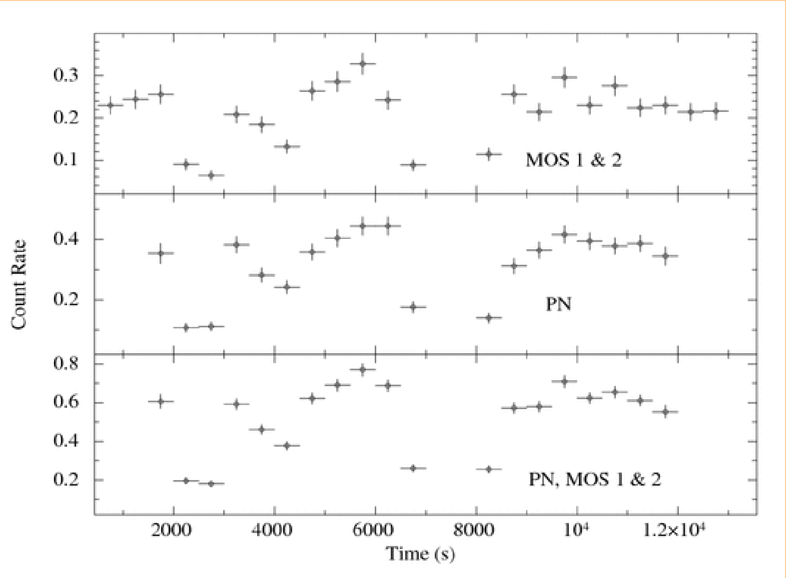
X-ray Spectrum of UGC 6614

(Naik et al. 2010 MNRAS)



- We used XMM archival data to study the x-ray spectrum of UGC 6614 and its variability. 13.8 Ks observation of the galaxy.
- The nucleus is bright and has a short times scale of variation (few Kseconds) and large luminosity (1.1×10^{42} erg/s).
- We determined the black hole mass in the nucleus using the method of excess variance and its value is 1.2×10^{5} M_{sun}





Summary of X-ray Studies

- We find that the AGN in GLSB galaxies are often X-ray bright.
- Their x-ray variability and position on the L_X-L_R correlation suggests that they have black hole masses that are low compared to brighter galaxies.
- They also show diffuse x-ray that is associated with the old stellar population in the bulge.
- Hence the bulge and nuclear regions in these galaxies follow an evolutionary track similar to bright galaxies. But this bulge – AGN growth appears to be decoupled from disk activity in most cases.

Optical Spectroscopy of GLSB Galaxy Nuclei

(Ramya et al. 2010 MNRAS submitted)

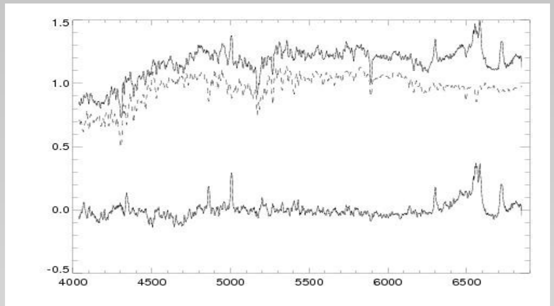
- We did medium resolution optical spectroscopy of 9 GLSB galaxies using the 2m Himalayan Chandra Telescope (HCT) at Leh.
- Nearly all the galaxies had prominent bulges. They are also nearby galaxies; mostly close to face-on.
- All the galaxies had been studied by Schombert (1998) and appeared to have broad Halpha.
- Two grisms used covering wavelengths 3800 to 8350 A^0 and having a spectral resolution of ~$8A^0$

Table 1: **List of Galaxies**

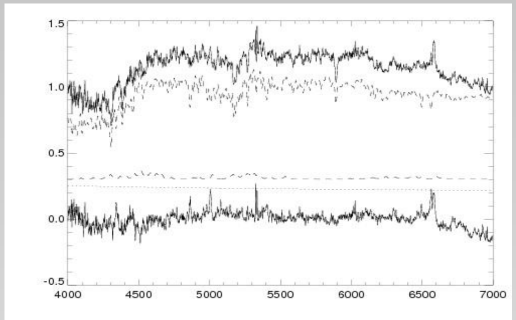
Galaxy	Distance (Mpc)	prominent bulge
UGC 1378	38.8	Yes
UGC 1922	150	Yes
UGC 3968	95.3	Yes
UGC 4219	178	Yes
UGC 6614	93.3	Yes
UGC 6754	103	Yes
UGC 6968	120	Yes
UGC 7357	97.6	No
F568-6 (Malin 2)	201	Yes

HCT (Leh)

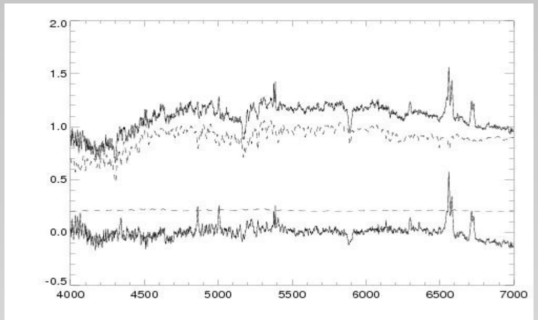
Spectral Decomposition



UGC 6614



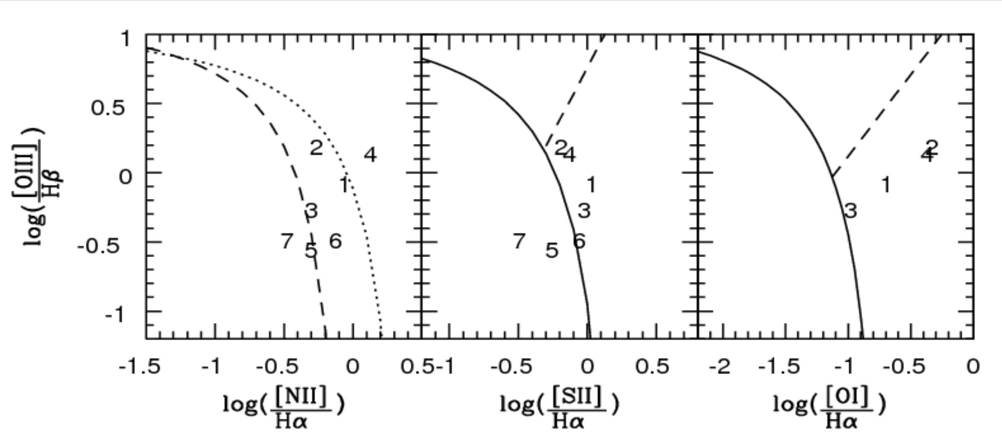
F568-6 (Malin 2)



UGC 1922

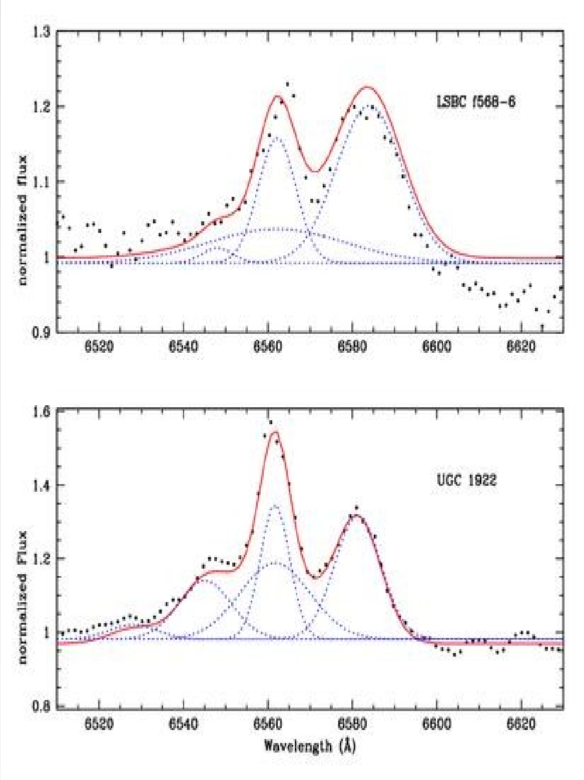
- We removed the stellar light from the nuclear spectra so that the final spectrum is due to only star formation and AGN emission.
- To confirm AGN activity we searched for broad Halpha lines; the broad and narrow components were separated. We also looked for the N[II], S[II], O[III] and O[I] emission lines.
- Determined the oxygen abundances. Close to solar in value for the bulges of these galaxies.

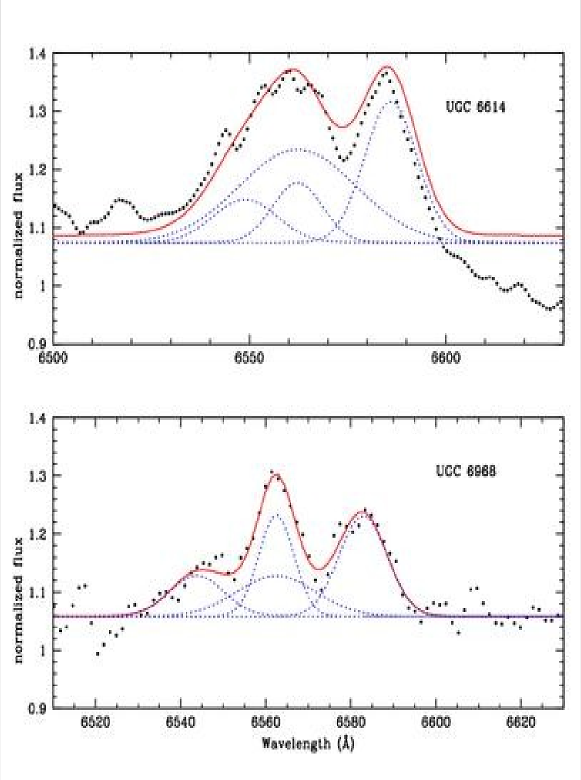
Emission Line Diagnostic Diagram



- Using the emission line diagnostic diagram, 4 of our sample have confirmed AGN emission – **UGC 6614, UGC 1922, UGC 6968 and F568-6 (Malin 2**).
- Of these galaxies, 3 have been detected in molecular gas (UGC 6614, UGC 1922 and malin 2) and at least two show nuclear x-ray emission.
- All 4 galaxies also show nuclear radio emission, possibly associated with AGN activity. Hence the ncuelar activity is visible over a range of wavelengths.

Determination of Black Hole Mass from Halpha line





- We separated the broad and narrow Halpha components for the 4 AGN detections. The broad Halpha fluxes and linewidths were used for deriving the black hole masses using the virial approximation of Green and Ho (2007).

Black Hole Masses

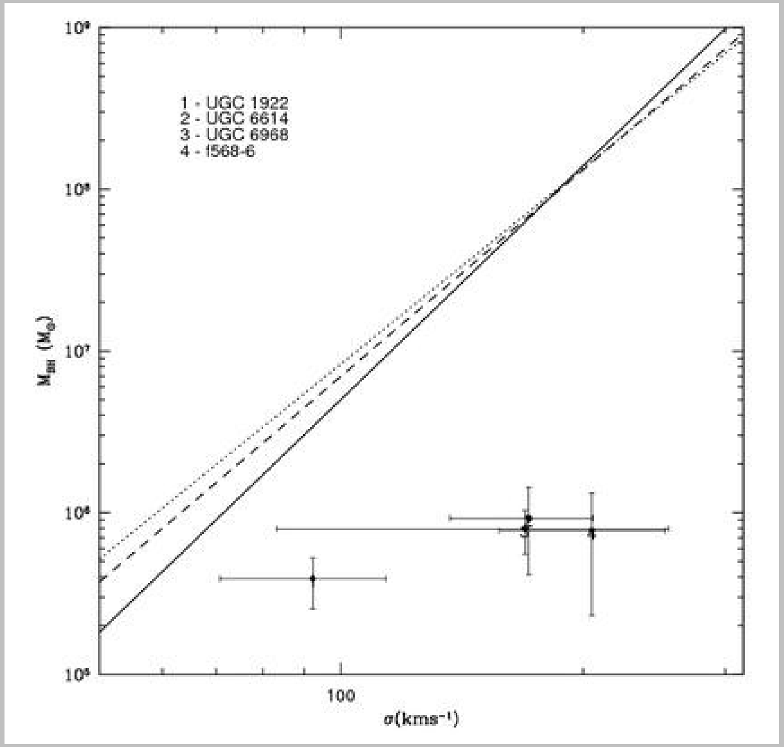
Table 1: Hα Luminositiess and Black Hole Masses for Detected AGN

Galaxy	Hα Broad	Hα Narrow	$L_{H\alpha}$ $\times10^{40}$erg s^{-1}	fwhm km s^{-1}	σ_e km s^{-1}	M_{BH} $\times10^5 M_\odot$
UGC 1922	8.13	4.79	2.21 ± 0.41	855.7 ± 140.7	0.39 ± 0.14	3.9 ± 1.4
UGC 6614	7.47	2.55	0.66 ± 0.10	1568.8 ± 223.3	171.07 ± 34.48	7.9 ± 2.4
UGC 6968	5.33	1.80	0.81 ± 0.19	1616.8 ± 425.7	169.30 ± 86.09	9.2 ± 5.1
F568-6	2.15	0.87	0.91 ± 0.35	1445.8 ± 476.3	205.00 ± 47.82	7.8 ± 5.4

- We find that the nuclear black hole masses for the 4 GLSB galaxies lie in the interval 3 – 9 x10^5 solar mass. This is closer to the intermediate mass black hole (IMBH) range than the SMBH range.
- Masses appear to be low compared to the bulge sizes and galaxy masses.
- The average L_{bol}/L_{Edd} ratio is 0.4 suggests that they are radiating at a considerable fraction of their Eddigton limit.

The M-σ Relation for the GLSB Galaxies

- We used the CaII triplet lines to derive the velocity dispersion across the bulge.
- Using the BH masses we plotted the M-σ relation for these galaxies.
- Also plotted are the Gultekin et al. (2009), Tremaine et al. (2002) and Ferrarese & Merritt (2000) correlations.
- We find that LSB galaxies lie significantly below the M-σ relation for bright galaxies.

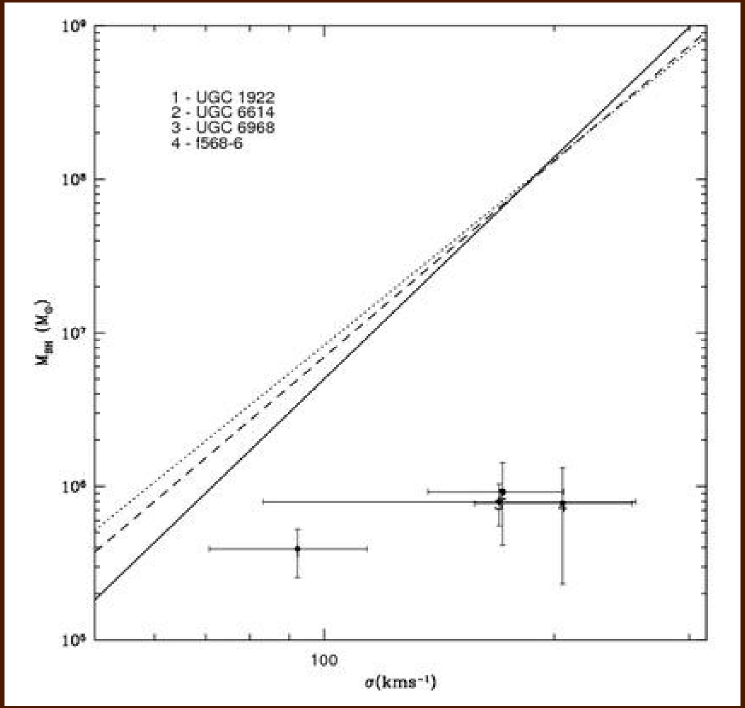


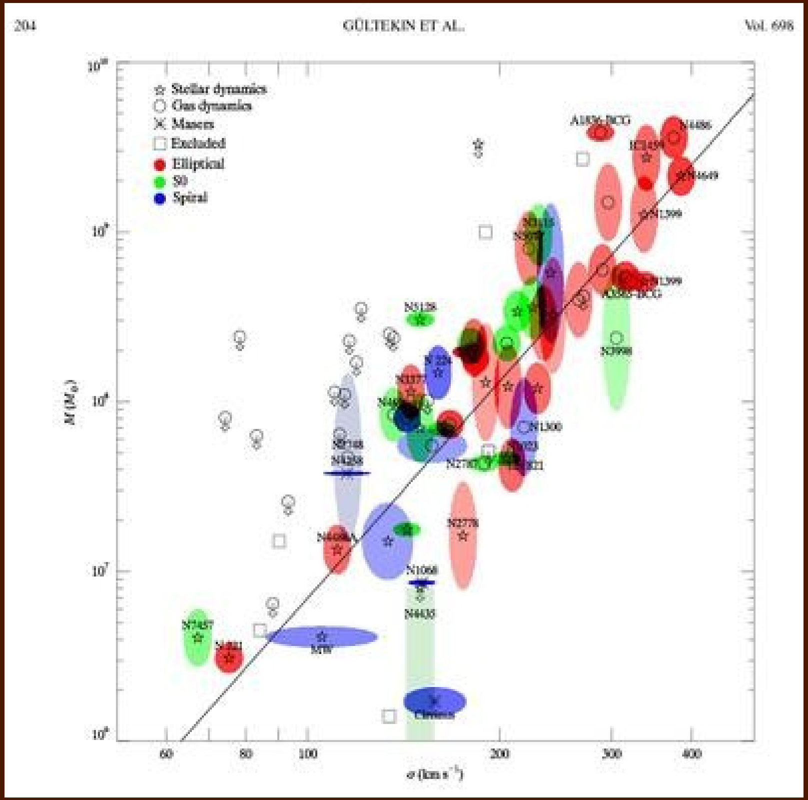
Summary/Discussion of Optical Study

- One of the main results is that we detect relatively low mass black holes in the intermediate mass range in GLSB galaxies. Such IMBHs are usually associated with late type galaxies that do not have such a well developed bulge or with dwarf galaxies.
- In the GLSBs the bulges are well developed and associated with large disks. Hence the low mass is suprising.
- Suggests that the lack of disk activity has resulted in a slower growth of the central BH.
- The galaxies lie below the M-sigma relation for bright galaxies.

M-Sigma for GLSBs compared with other galaxies

- The GLSBs lie below most galaxies and away from the correlation.





Main Conclusions

- The bulges in the extreme late type spiral galaxies, LSB galaxies, can host AGN activity that is visible at optical, radio and x-ray wavelengths even though their halo dominated disks show little star formation.
- In radio emission the nuclei sometimes exhibit a compact core structure associated with extended emission resembling radio jets/lobes. In some cases the emission is only due the old stars in the bulge and in a few cases it is a mixture of AGN activity and disk star formation.
- Thus at radio wavelengths, GLSB galaxies have nuclear properties similar to that observed in brighter spiral galaxies even though thier disks are poorly evolved.

Main Conclusions Continued ...

- In the X-ray domain the emission is again mainly associated with the bulge. Compact X-ray emission associated with AGN activity have been detected in 3 out of the 9 galaxies studied. The x-ray luminosity is relatively high for such weak AGN activity.
- The x-ray spectrum of UGC6614 shows variability similar to Seyfert galaxies. Implies a nuclear BH mass of 1.2×10^5 solar mass.
- Diffuse emission detected from the bulges of a few galaxies - associated with the older stellar population.
- Optical spectroscopy studies detected AGN in 4 GLSB galaxies. The oxygen abundances close to solar in value.
- The broad Halpha emission suggests BH masses 3 -9 $\times10^5$ solar masses which is closer to the IMBH range than SMBH.

Summary

- **Dark Matter dominated systems such as LSB galaxies do show nuclear activity. Their weak AGN activity is visible in the optical, x-ray and radio domain.**
- **The nuclear evolution is coupled to their large bulges. The black hole masses are low compared to bright galaxies and they lie below the M-sigma correlation.**
- **The bulge evolution appears to be decoupled from the disk evolution.**
- **The low BH masses could be due to the lack of disk contribution to the build-up of the central masses in these galaxies.**