GMRT Low Frequency Observations of Gas Around Void Galaxies

Mousumi Das, Indian Institute of Astrophysics, Bangalore

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Collaborators

K.S. Dwarkanath (RRI, Bangalore)

Preeti Kharb (IIA, Bangalore)

Harsha Raichur (NORDITA)

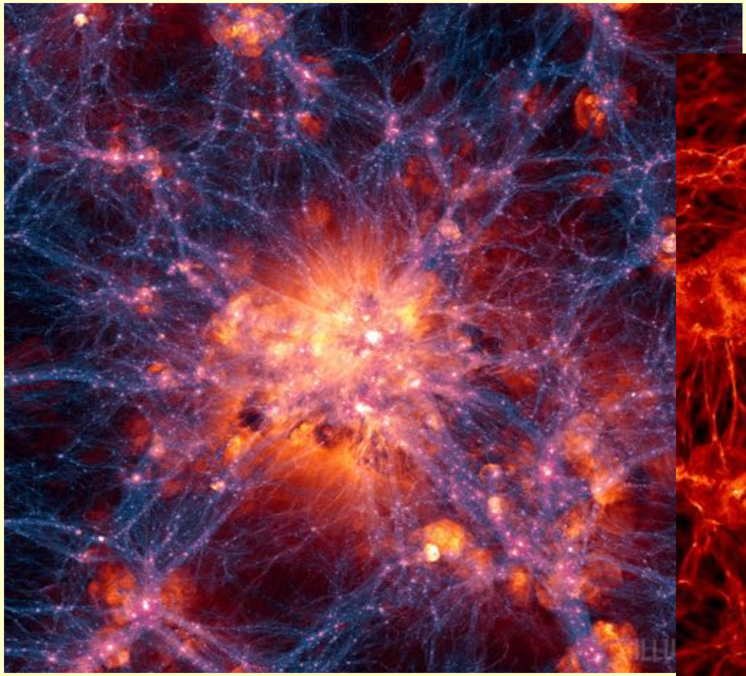
Kanhaiya Pandey (IIA, Bangalore)

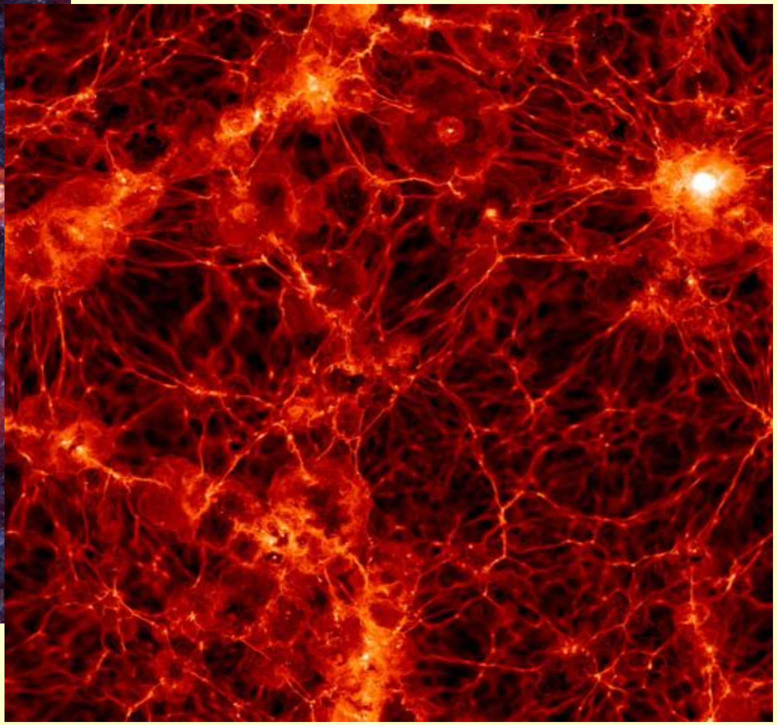
Outline of talk

- Properties of void galaxies
- Cold gas in void galaxies and their star formation rates.
- Low frequency radio emission around void galaxies – searching for diffuse emission at 610 and 150MHz with the Giant Meterwave radio telescope (GMRT).
- X-ray emission around a few void galaxies – signature of hot gas around void galaxies.

Voids

- Our universe is made of matter clustered along walls and filaments with large “empty” regions called voids in between. This foam like distribution of matter and voids is seen in both simulations as well as observations of the large scale structure.





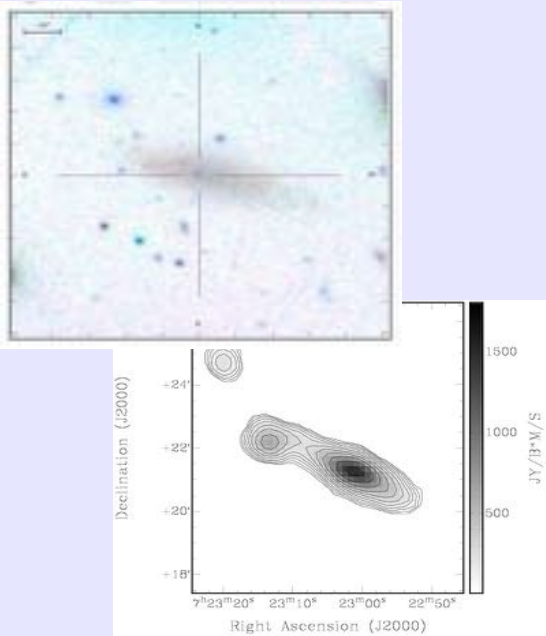
(Haider et al. 2016)

Above : Simulations of cosmic web from the Illutrius simulation showing a cluster (on the left) and void region (on the right).

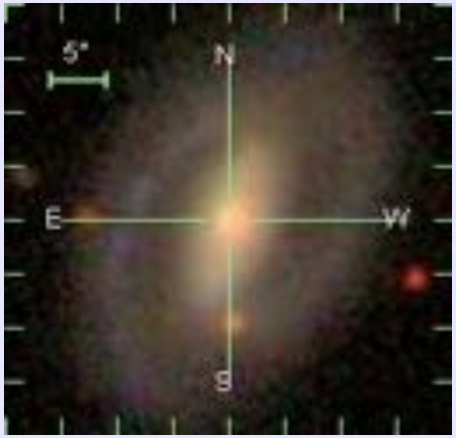
Void Galaxies

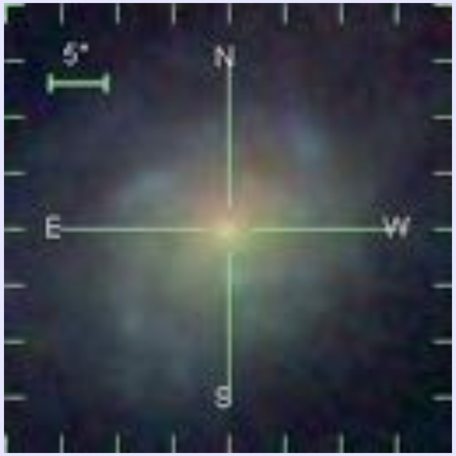
- They are gas rich, late type disk galaxies. Usually spirals and irregulars; ellipticals less common. Stellar masses of order 10^8 to 10^9 solar mass.

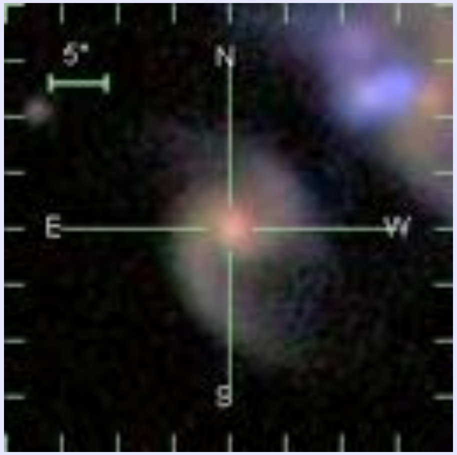
- Relatively blue and show signs of star formation. In the smaller voids the galaxies are usually low luminosity dwarfs or irregulars but the larger voids also have galaxies that show signatures of star formation (Kreckel et al. 2011; Cruzen et al. 2002; Grogin and Geller 2001; Szomoru et al. 1997).



Gas rich dwarf galaxies in the Lynx Cancer void (Chengalur & Pustilink 2013)







SDSS images of some bright galaxies in larger voids : SBS1428+529, VG_06, CG693 - they show star formation and even AGN activity

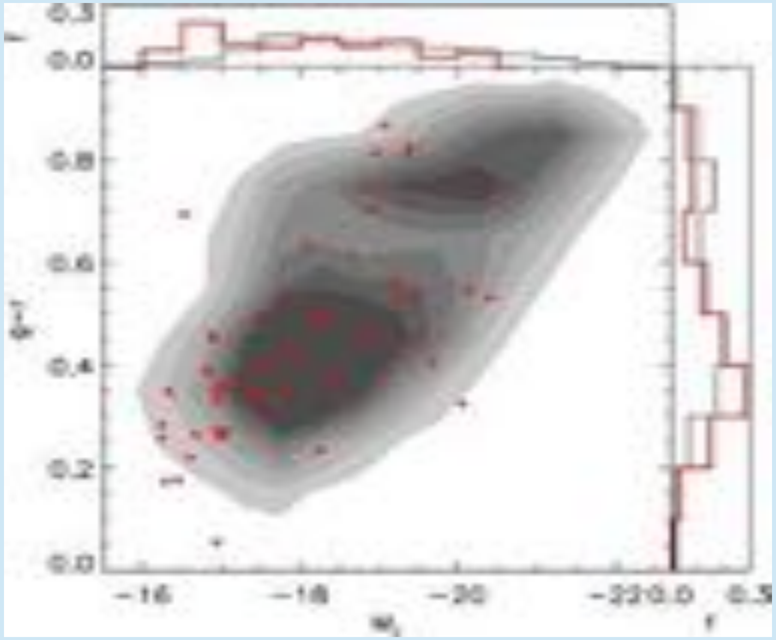
Star Formation in Void Galaxies

In several surveys, void galaxies are found to be blue in color signifying star formation. Hα images and optical spectra also show signs of star formation in the gas rich spirals.

On the color magnitude diagram for galaxy evolution , they fall mainly on the blue cloud. Thus void galaxies are not low luminosity systems as predicted but are **slowly evolving galaxies**.

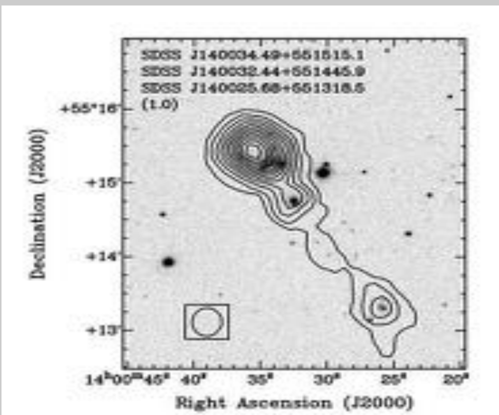
Galaxy in the local void : NGC 6946.

Color magnitude diagram for galaxies in the Void galaxy Survey (Kreckel et al. 2012).

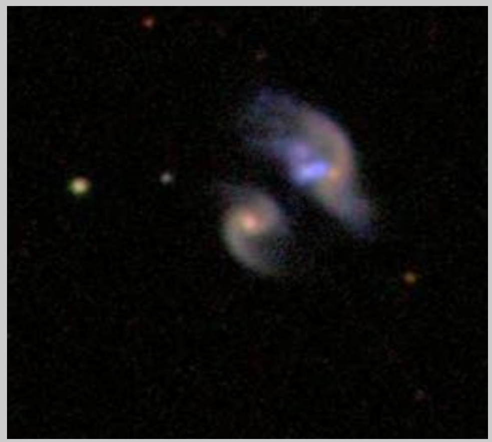


Groups/Interacting Pairs : Signatures of Void Substructure?

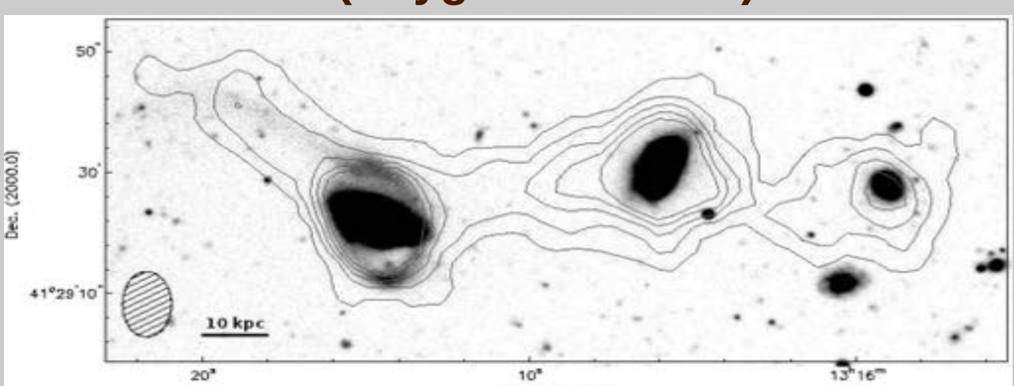
Kreckel et al. 2011



CG693-692 : Interacting pair in Bootes void



Triplet interacting system in a nearby void (Beygu et al. 2013)

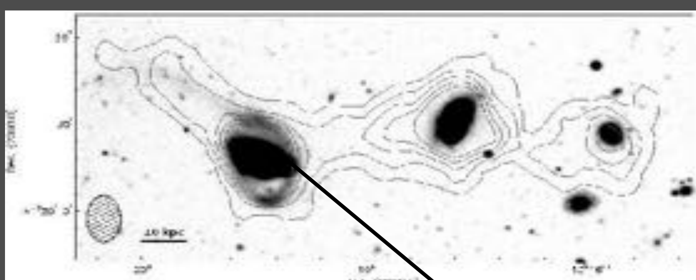


There are many examples of interacting pairs, polar ring galaxies and even small groups of galaxies residing in voids.

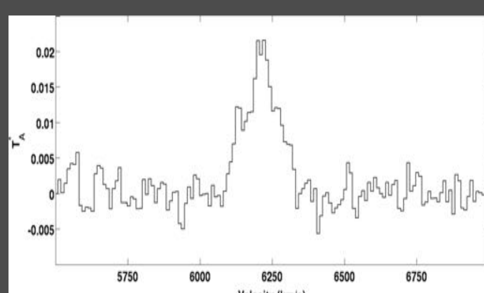
These galaxies may have formed when smaller voids evolved to form larger voids. This merging process can lead to the formation of filaments within larger voids – thus creating a void substructure.

Cold Gas in Void galaxies

- Void galaxies have large HI masses (Szomoru et al. 1996; Kreckel et al. 2012) but their molecular gas (H_2) content is not well studied.
- Early studies of a few Bootes void galaxies detected CO emission from 4 galaxies (of which 2 are very strong). Recent detection was from a interacting system in a nearby void (VGS_31 system, Beygu et al. 2013).

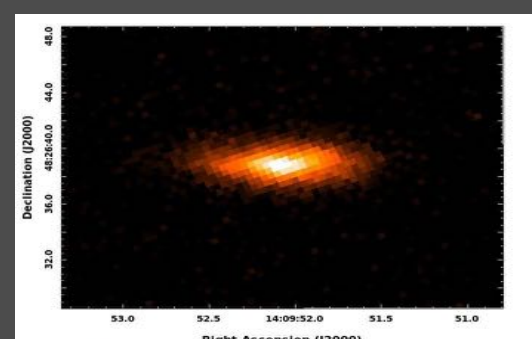


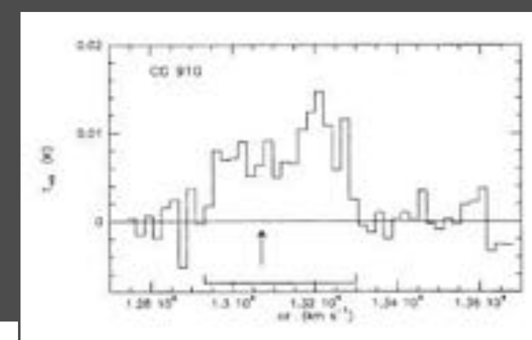
CO(1-0) detection in interacting galaxy triplet system VGS_31



Beygu et al. 2013

CO(1-0) detection in the isolated galaxy CG910 in the Bootes void



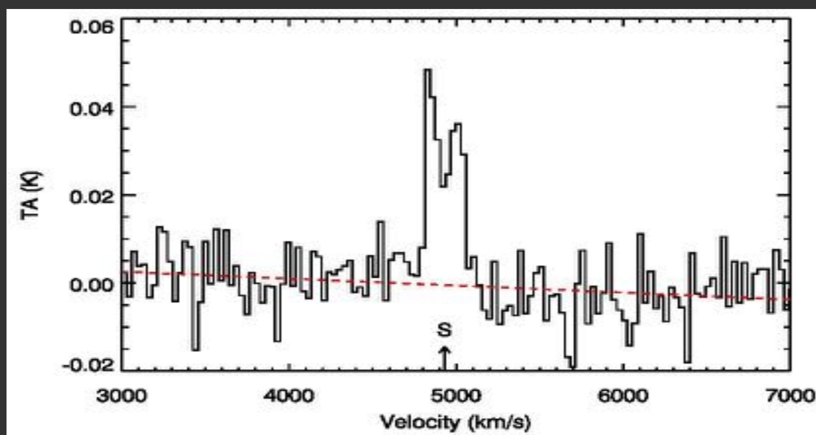


Sage et al. 1996

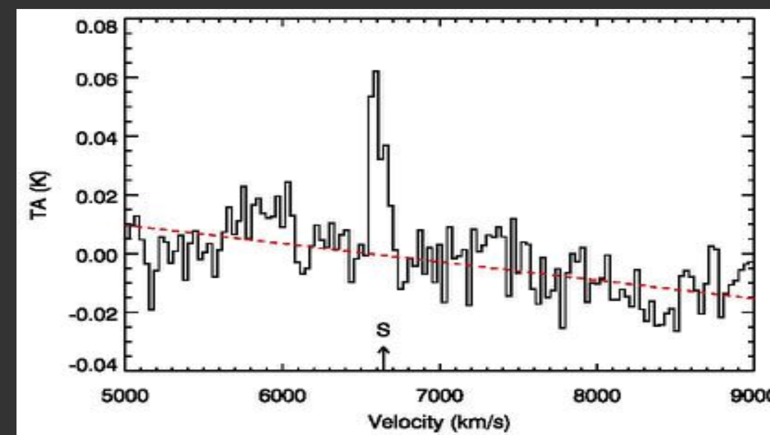
CO(1-0) Detections using NRO

(Das et al. 2015)

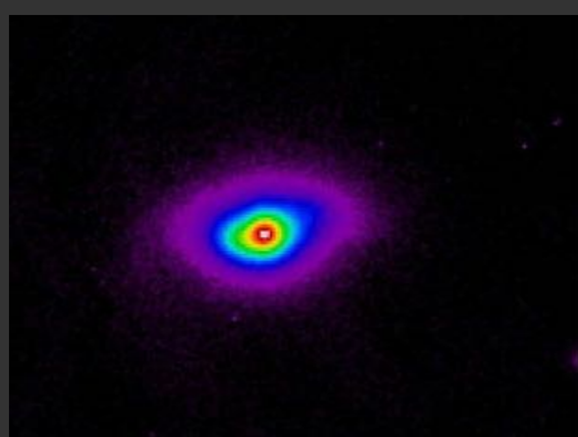
SBS1325+597 (VGS_34)



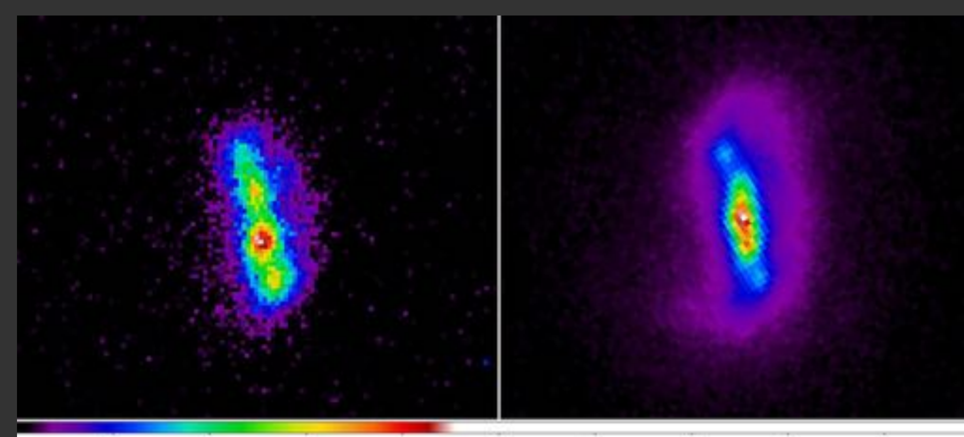
SDSS1538+3311 (VGS_57)



HCT I band image



HCT Hα image (left) and SDSS g image (right)

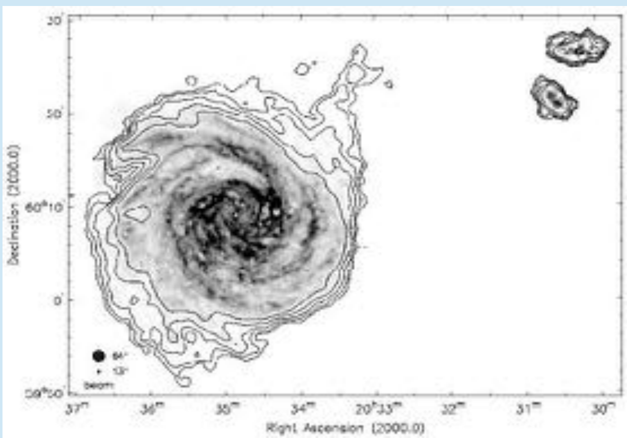


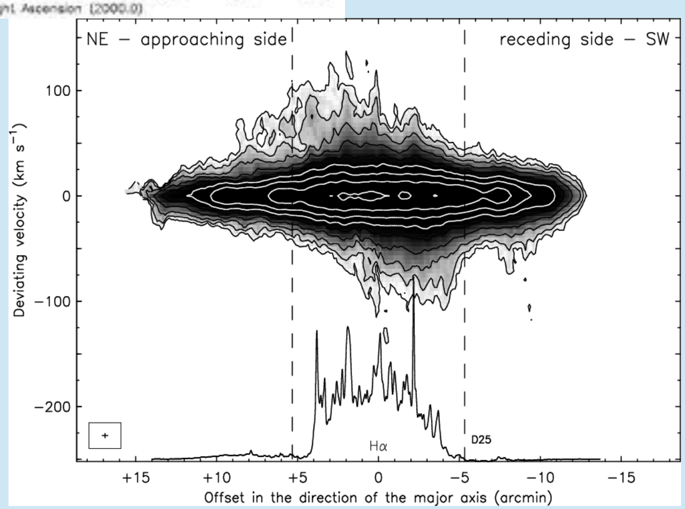
Molecular Gas, HI and star formation rates in void galaxies

- Molecular gas (H_2) has been detected in voids and is not rare (Das et al. 2016). Neutral hydrogen (HI) is also found in void galaxies and the gas masses are comparable to normal spirals.
- The H_2 gas is centrally concentrated and associated with star formation. The HI disk is usually more extended compared to normal galaxies.
- The star formation rates (SFR) and efficiencies are moderate and sometimes comaprable to normal galaxies
- **Overall, void galaxies are slowly evolving, gas rich galaxies (e.g. Kreckel et al. 2012; Grogin et al. 2002).**

What triggers star formation in void galaxies?

NGC6946 : interacting at a distance in our local void





The position velocity plot of HI gas along the galaxy minor axis. Off axis gas is at abnormal velocities.

(Boosma et al.)

1. They could be interacting with close neighbours or with HI dominated galaxies that we do not see in optical images.

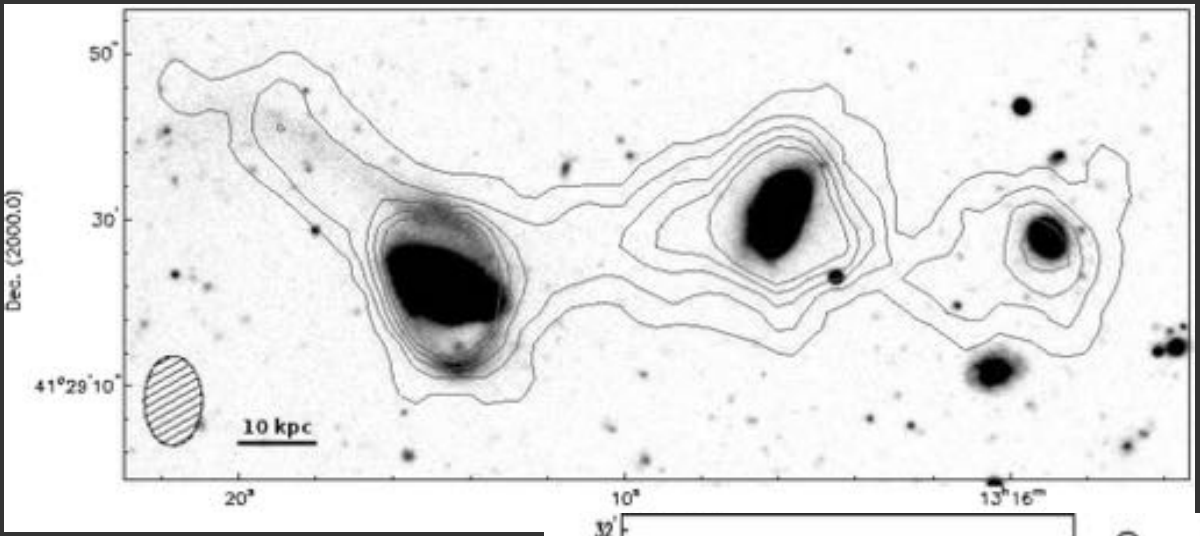
2. Gas accretion onto galaxy disks – the cold gas accretion makes the disks unstable and results in star formation.

3. The merging of sub-voids can result in galaxy interactions and increased gas accretion (e.g. Polar ring galaxy in void wall).

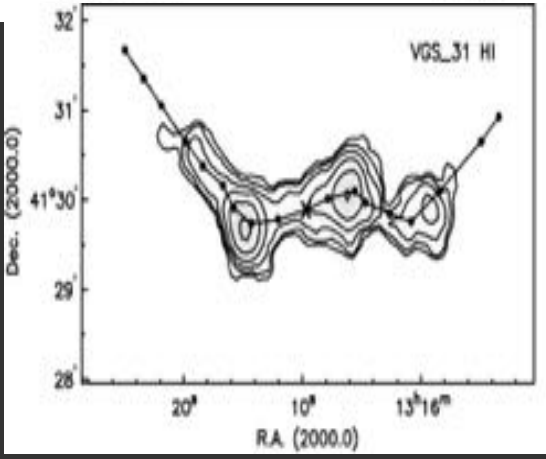
Gas Flow along Void Substructures ?

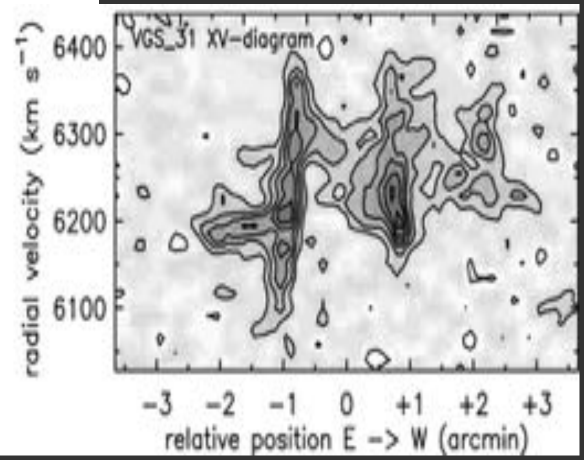
There could be gas flowing along the void filaments that accrete onto galaxies. This may trigger star formation as well as cool the gas disks and results in star formation. As a result the galaxies grow in mass and evolve.

Gas accreting onto galaxies will appear as abnormal velocities in the HI position velocity plots . It has been detected in VGS_31 system (left and below) and in the Local Void galaxy NGC6946.



(Beygu et al. 2013)



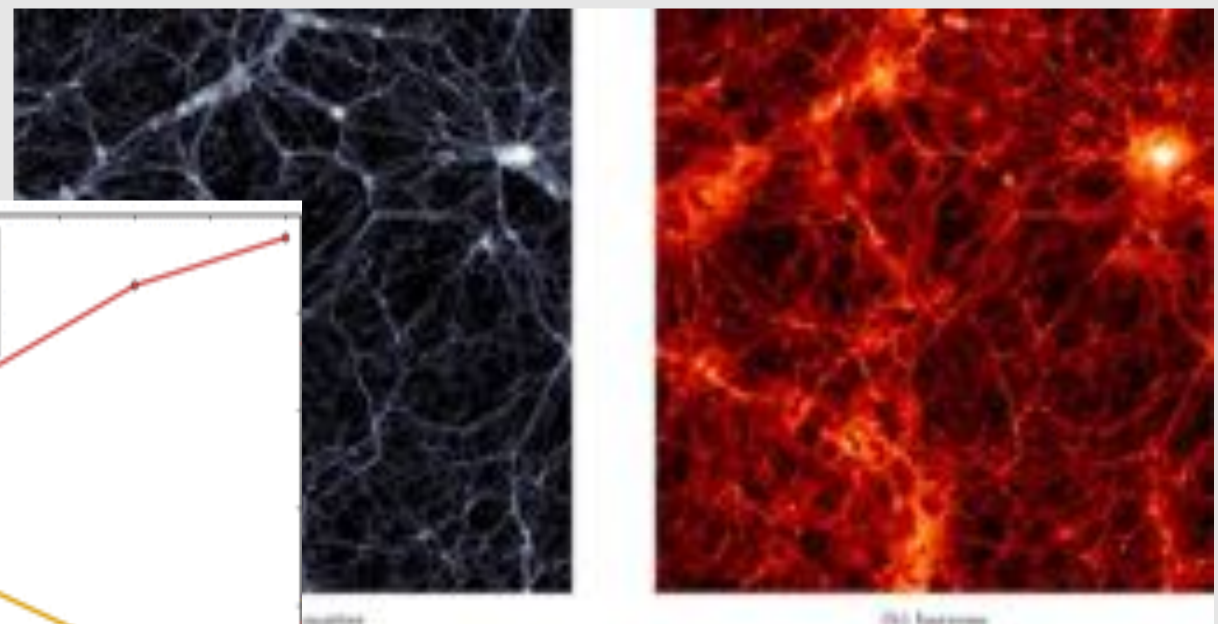


Why study void galaxies.....

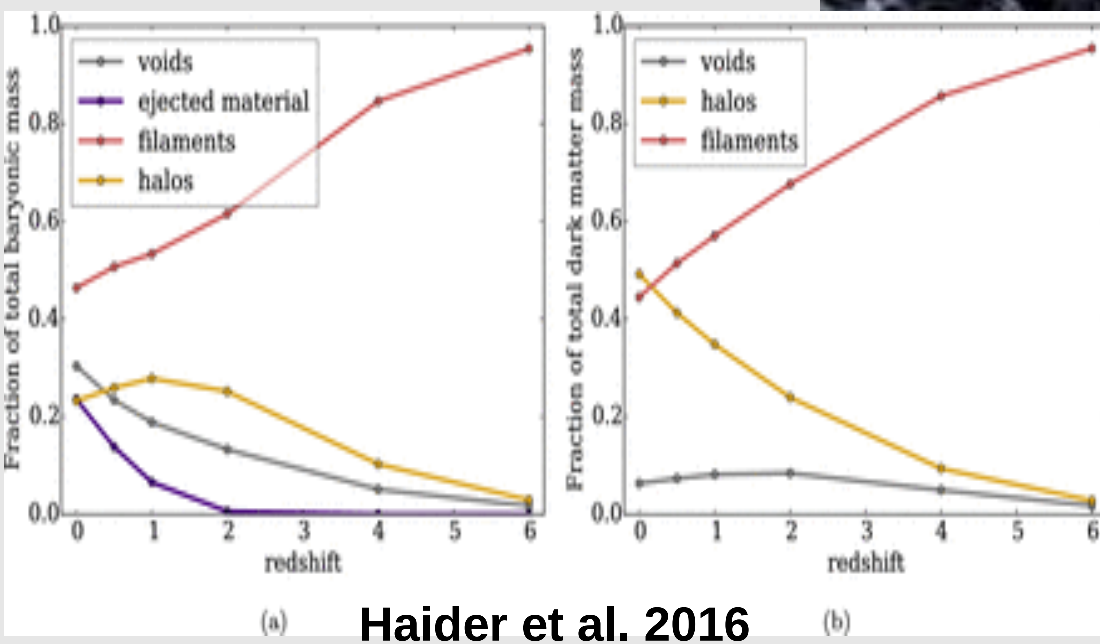
- Void galaxies are an opportunity to study star formation and galaxy evolution in the most isolated regions in our Universe.
- Can be used to probe **diffuse gas** in voids.
- Also probe the void substructure - does it exist and how is it traced by galaxies (e.g. Alpaslan et al. 2014; kreckel et al. 2012)? Is there gas accretion onto galaxies from filaments in the IGM.
- Probe the magnetic field in isolated regions (primordial field).

Recent simulations on gas in voids

- Recent cosmological simulations using the *Illutris* code have shown that a significant fraction of the baryon content at z=0 lies in the form of diffuse gas in voids (Haider et al. MNRAS, 2016).
- The gas could arise from AGN feedback at the void walls.
- In this study we examine whether some of the diffuse gas in voids can come from star formation and AGN activity **inside voids.**



Haider et al. MNRAS (2016)



Haider et al. 2016

Goals of low frequency radio study : to detect diffuse gas in voids (150, 235, 610MHz)

- To study diffuse emission associated with star formation/and or AGN activity around galaxies using low frequency (610M/ 235 MHz) radio continuum observations.
- Compare with hot gas asscociated with AGN activity or high mass star formation using X-ray emission.
- Identify regions to search for filaments in voids, probe proimordial magnetic fields and the missing baryon problem.

Low frequency radio observations of galaxies in the Bootes void with the GMRT

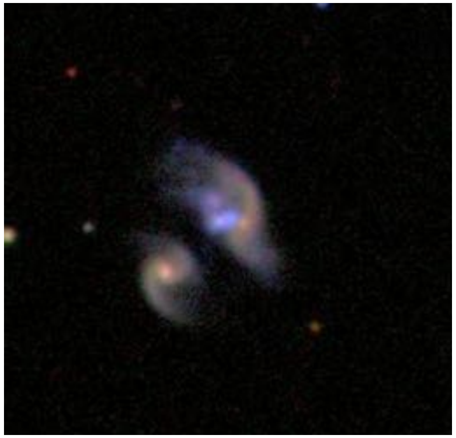
- We have done 610 and 240 MHz observations of the radio emission around the 5 bright AGN host galaxies in the Bootes void. We use 150 MHz images (TGSS ADR; Intema et al. 2016) as well.
- Observations were done in November, 2014 over 2 days. Total observing time was 14 hours for 4 galaxies : CG692-693, SBS1428+5255, Mrk845, IZw81.This is ongoing work, we present results for first day data.

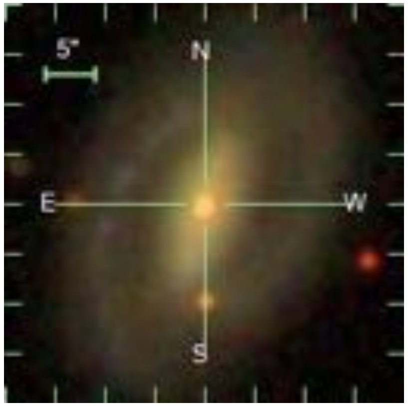
Why Bootes void?

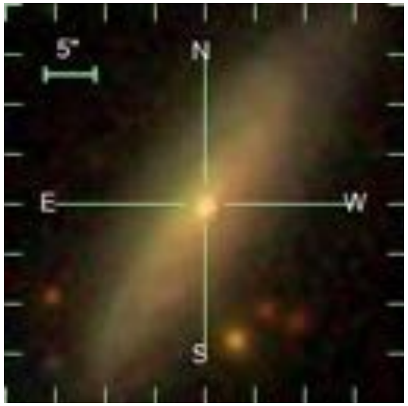
- It appears to be the largest void – 60 Mpc across.
- Has the largest fraction of radio bright and star forming galaxies in nearby voids.
- It has probably evolved from merging of smaller voids – so greater chance of detecting extended gas associated with void galaxies**.**

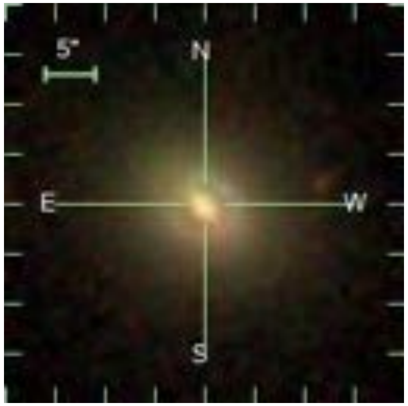
Sample of void galaxies

Galaxy name	redshift
CG 692	0.056
CG 693	0.056
Mrk845	0.046
SBS1428+529	0.044
IZw081	0.052

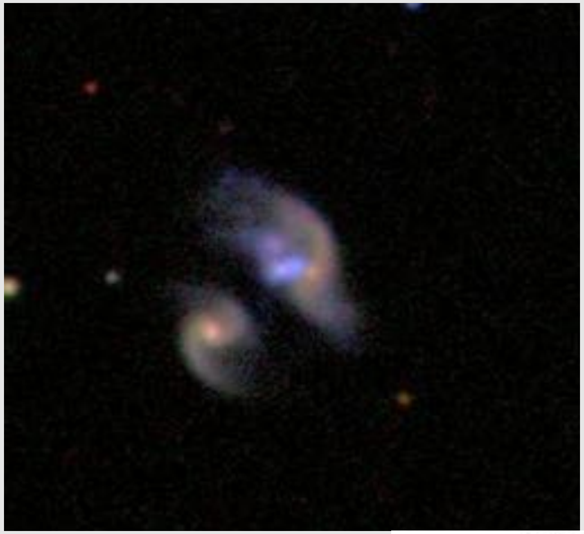




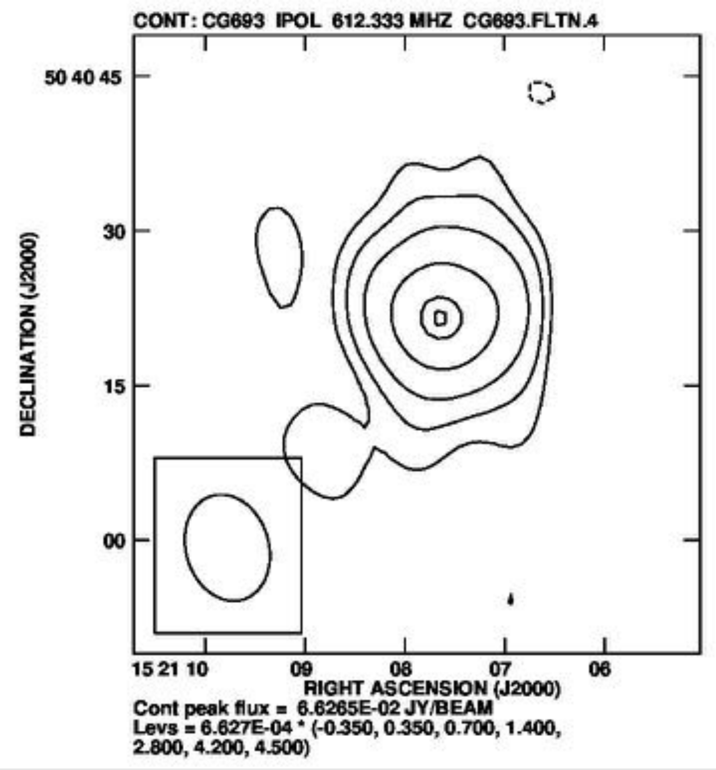




610 MHz emisison around the galaxy pair CG692-693



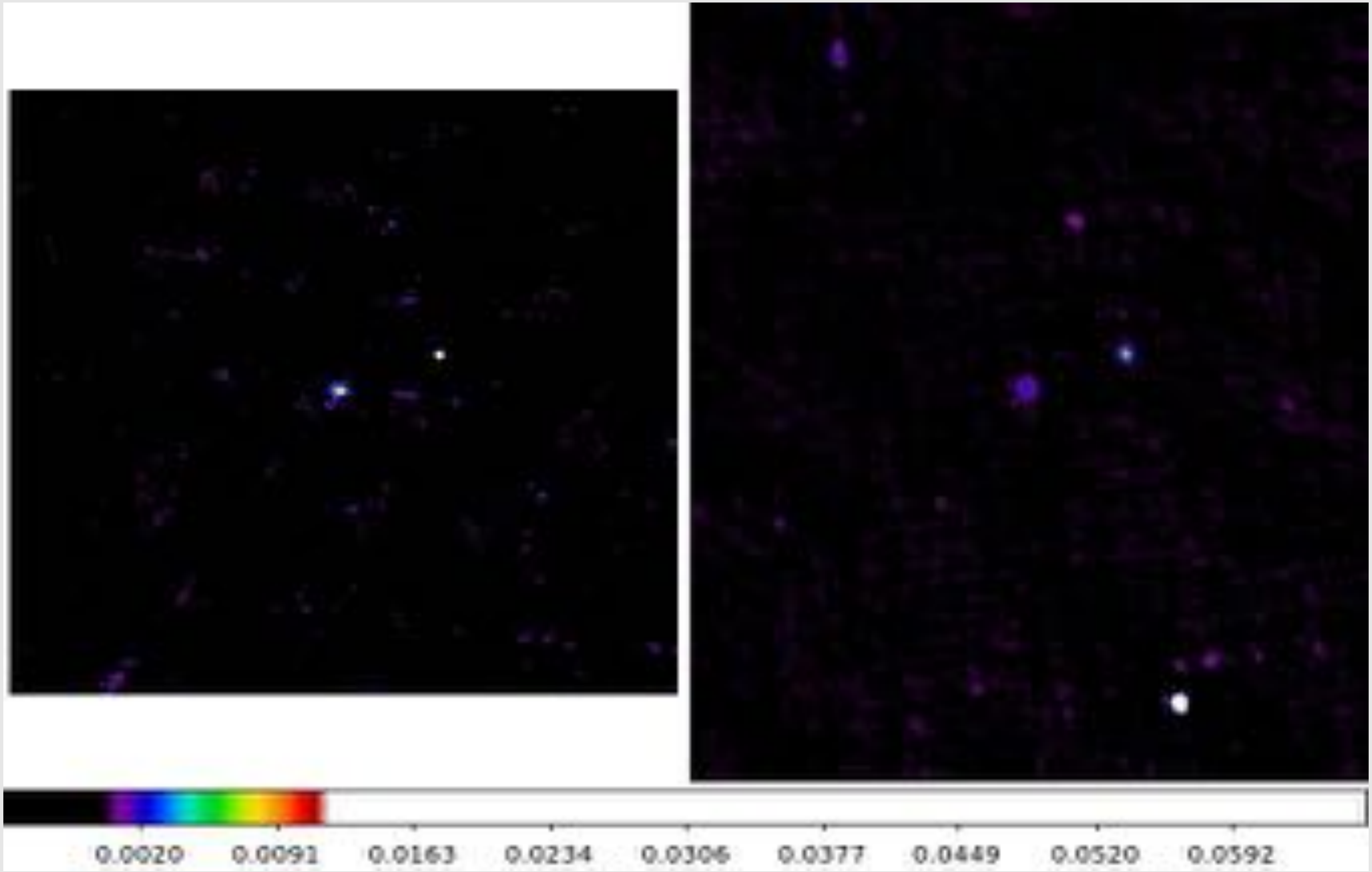
SDSS g band image



610 MHz GMRT image

- CG692-693 is a pair of closely interacting galaxies. CG693 has a Sy1 nucleus whereas CG692 is a star forming galaxy. Bright in X-ray (ROSAT).
- At 610 MHz we detect a total flux ~**5.6mJy** around CG692 and ~0.54mJy around CG693. At 1.4 GHz the flux (FIRST) is ~**9mJy** for CG692 and 2.2mJy for CG693

610 MHz and FIRST 1.4GHz emisison around CG692-693

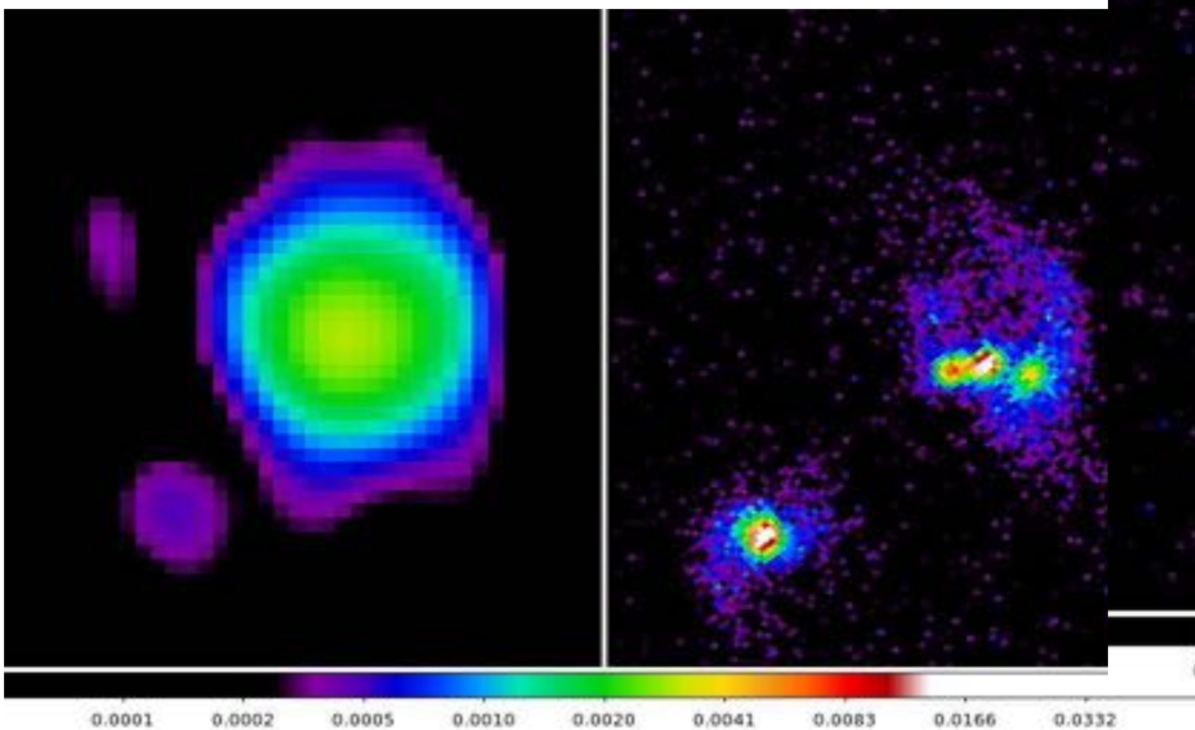


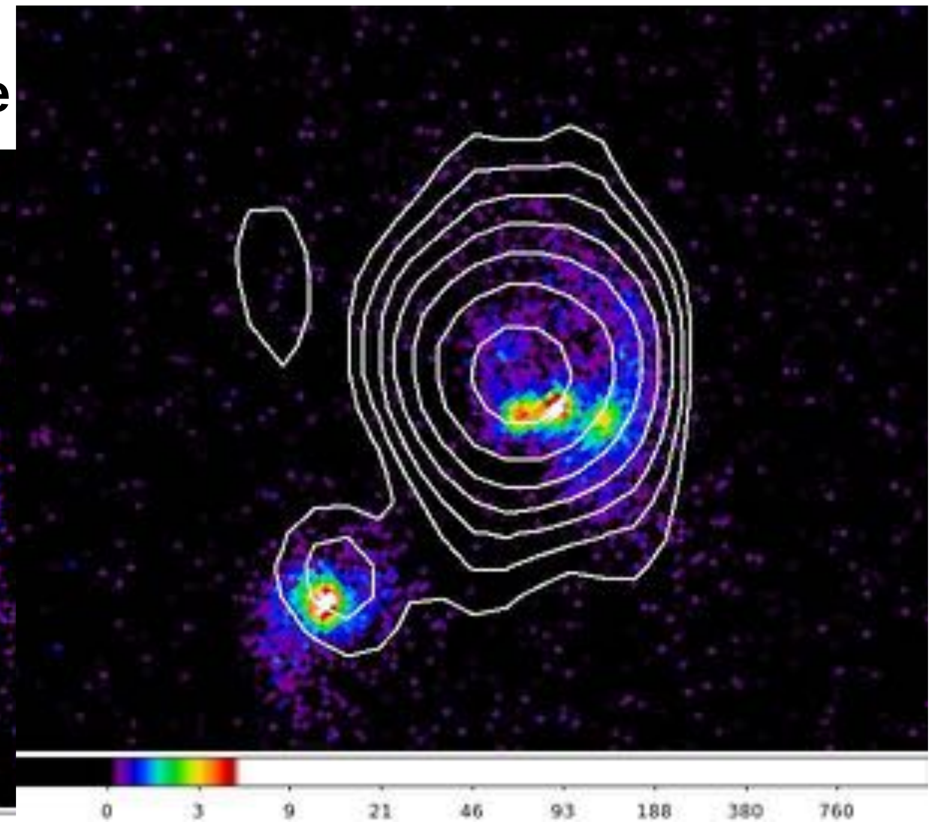
FIRST 1.4 GHz (left) GMRT 610 MHz (right)

610 MHz emisison around CG692-693 and optical comparison

610 MHz contours overlaid on g band image

610 MHz image **SDSS g band image**

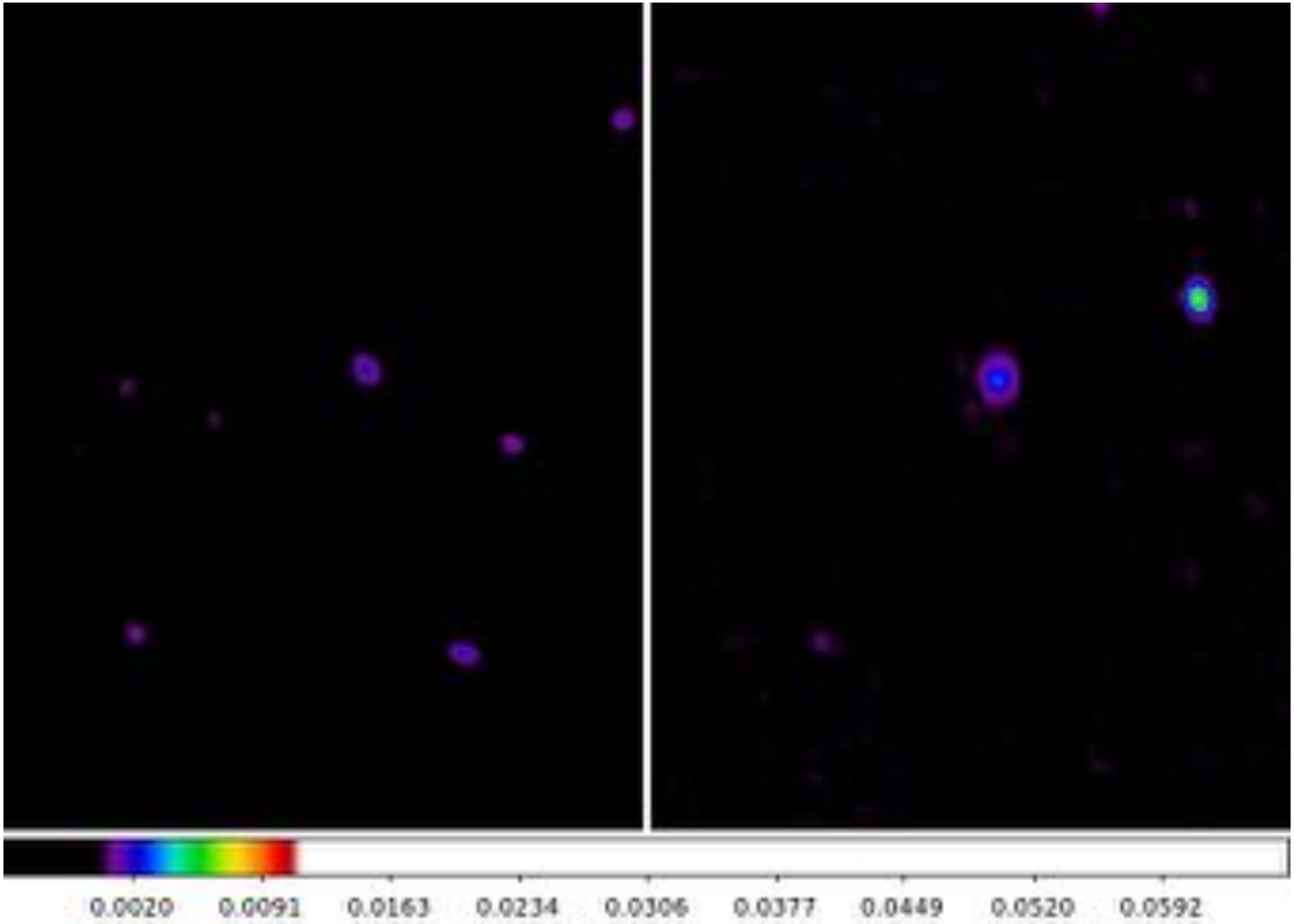




At 610 MHz, CG692 is prominent but the companion CG693 is weak. The emission around CG692 extends well outside the optical radius. CG692 appears to be an interacting system with two nuclei.

240 MHz Image (compared with 610 MHz)

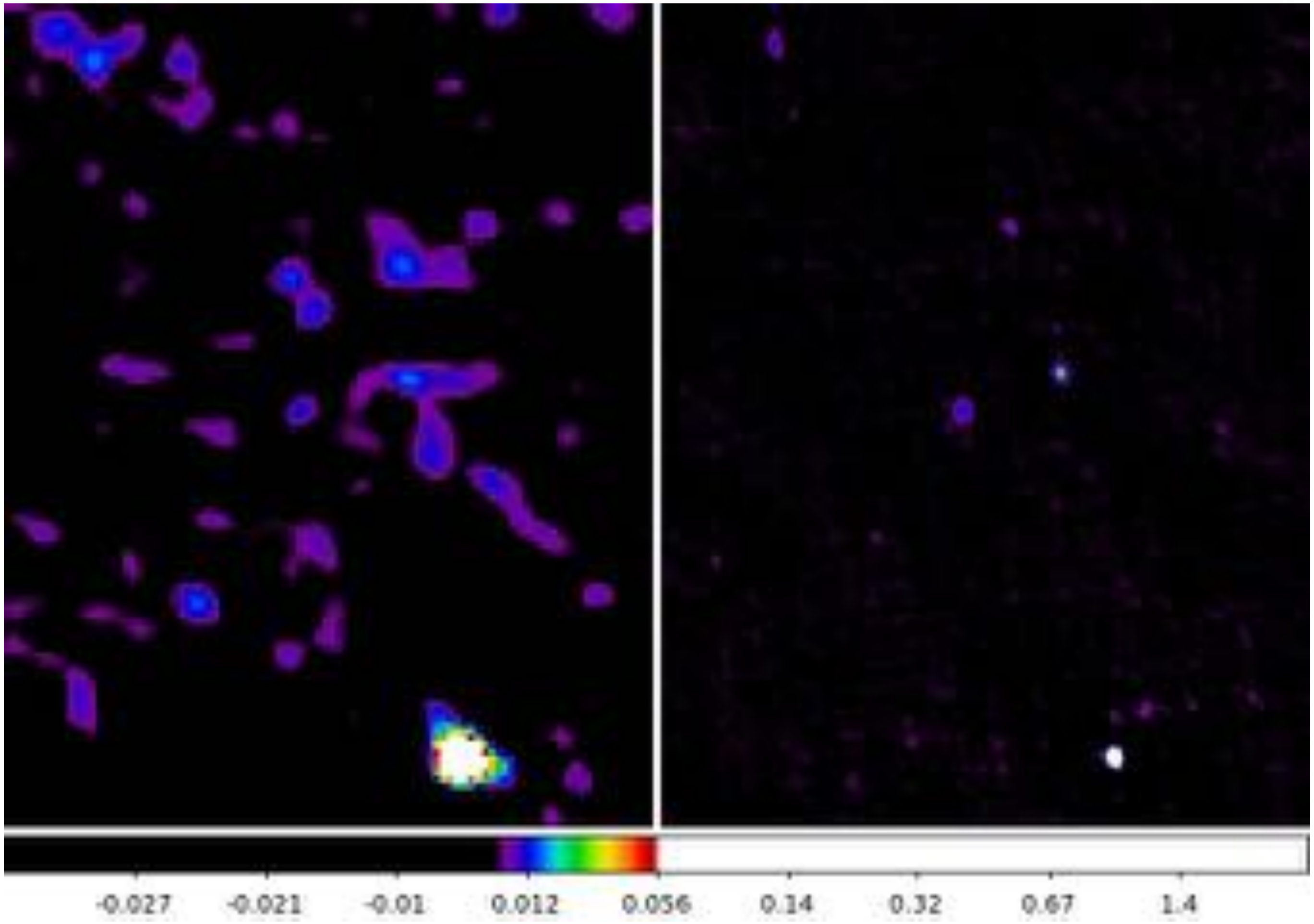
We (just about) detected emission from CG692at 240 MHz. The 235 MHz flux is **1.8mJy**.



235 MHz (left) and 610 MHz (right)

TGSS 150 MHz compared with 610 MHz

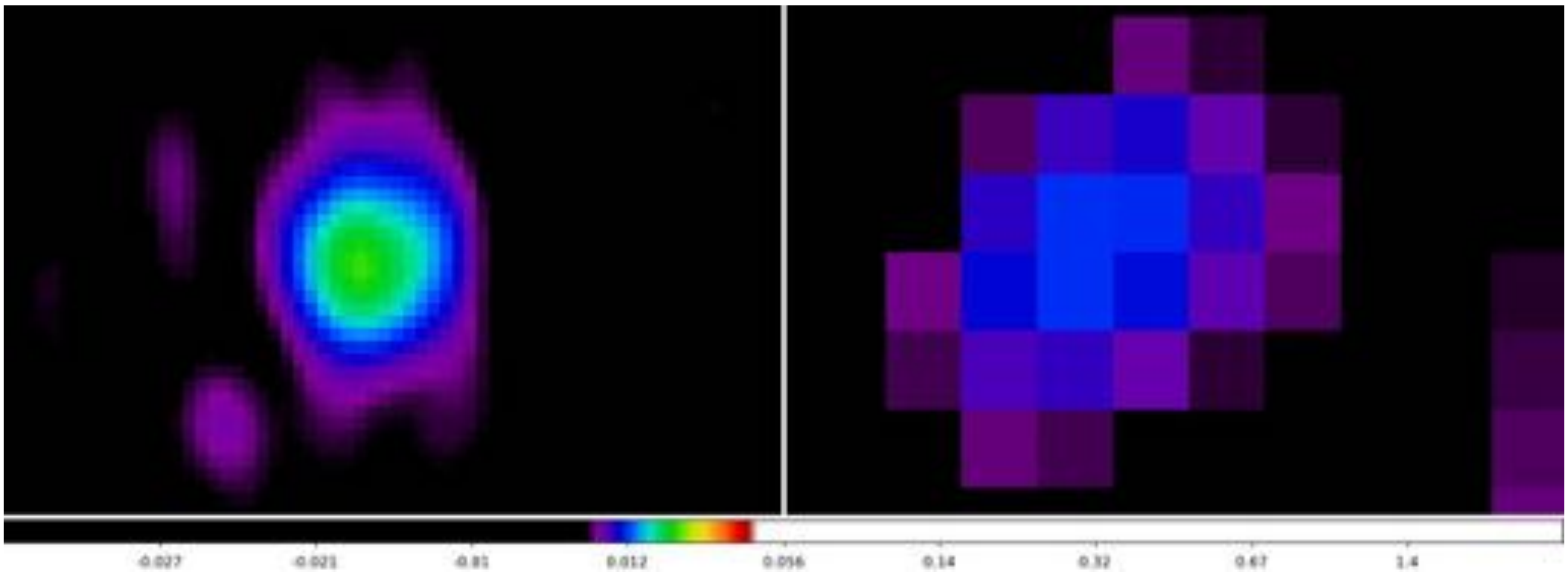
We detected some emission at the same location as CG692at 150MHz in TGSS. But region is noisy and the emission needs to be confirmed with deeper observations.



TGSS 150 MHz (left) and 610 MHz (right)

Comparing with TGSS (ADR) 150 MHz Images : spectral index

The 150 MHZ flux is **13.6 mJy**. We calculated the spectral index (150-610 MHz) and its value is ~ -0.62



150 MHz TGSS Image credit : TGSSADR

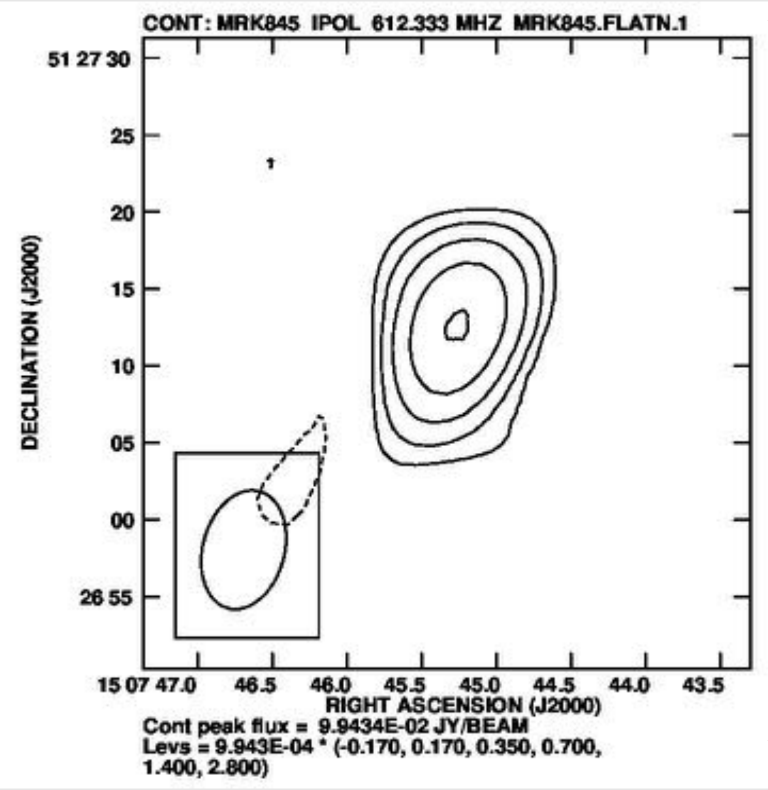
610 MHz emisison around Mrk845

Mrk845 is an emission line galaxy with Sy2 type AGN. It is an isolated spiral galaxy and has a regular disk structure. Flux at 610MHz is 3.4mJy and rms =0.7microJy/bm

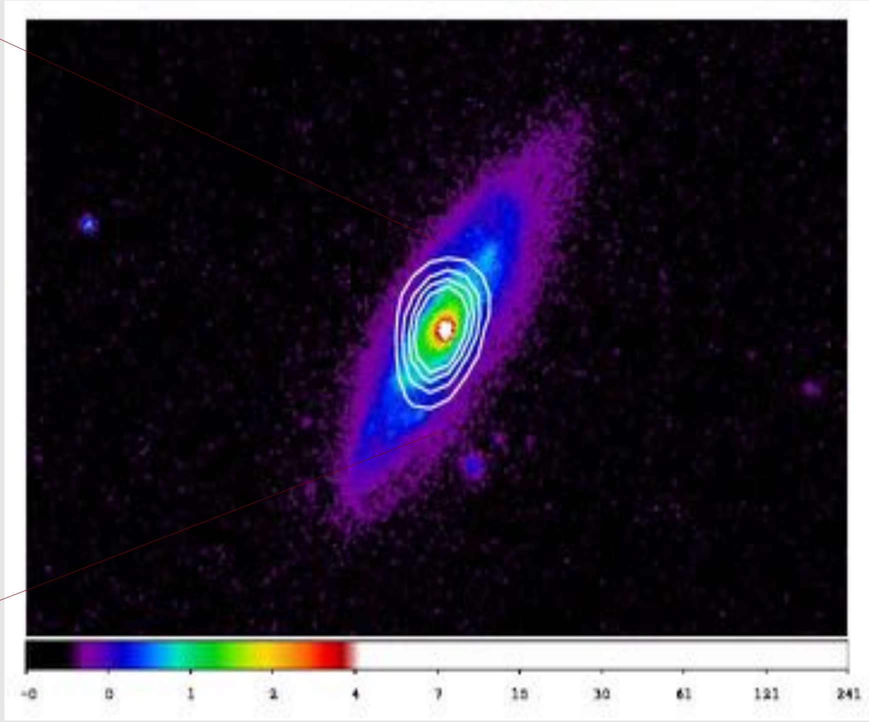
It has been detected in ROSAT and has an X-ray flux of LogLx=43.7.

We are processing the archival Chandra data.

610 MHz GMRT image



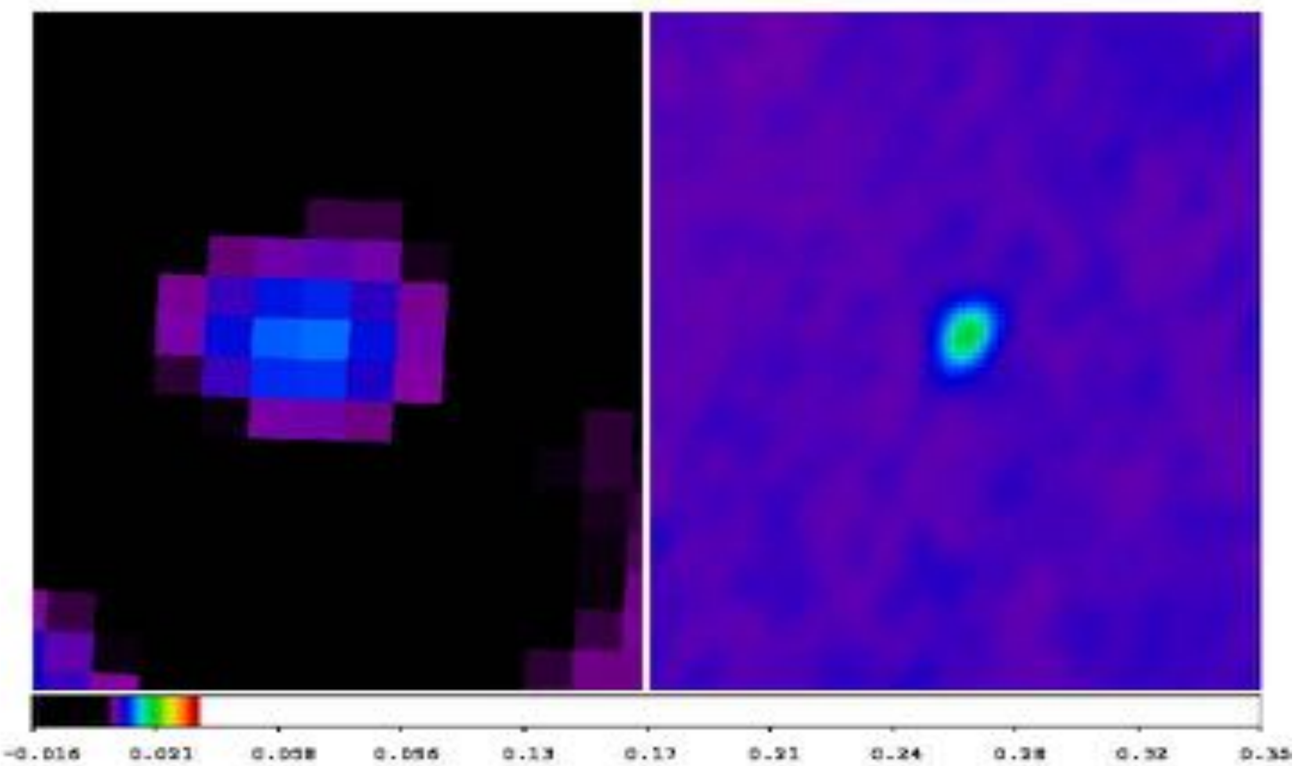
610 MHz contours overlaid on SDSS g band image



TGSS(ADR) 150 MHz emisson around Mrk845

At 150 MHz, Mrk845 is barely detected in the TGSS maps.
Flux is **34 mJy**.

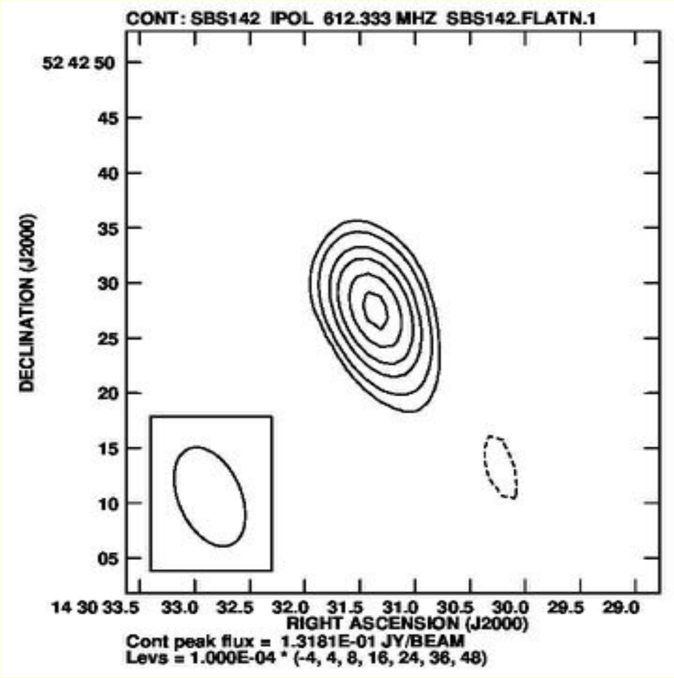
150 MHz TGSS image **GMRT 610 MHz**



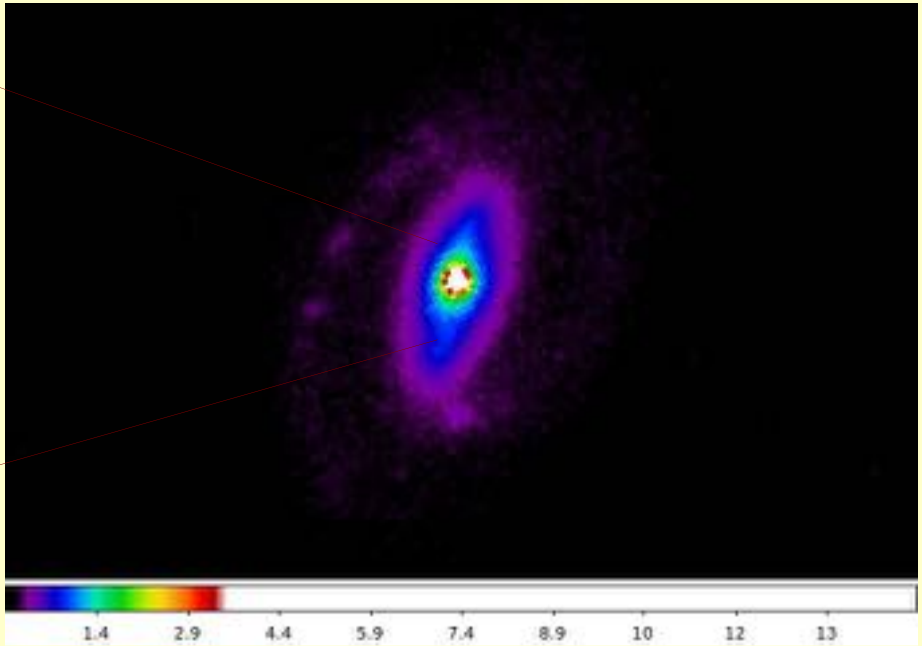
610 MHz emisison around SBS1428+529

SBS1428+429 has a Sy2 type AGN. It is an isolated spiral galaxy and has a regular disk structure. Not detected in TGSS. Flux at 610Mhz is 5.1mJy and rms=100microJy/bm.
It has been detected in ROSAT and has an X-ray flux of LogLx=43.7.
We are processing the archival Chandra data.

610 MHz GMRT image

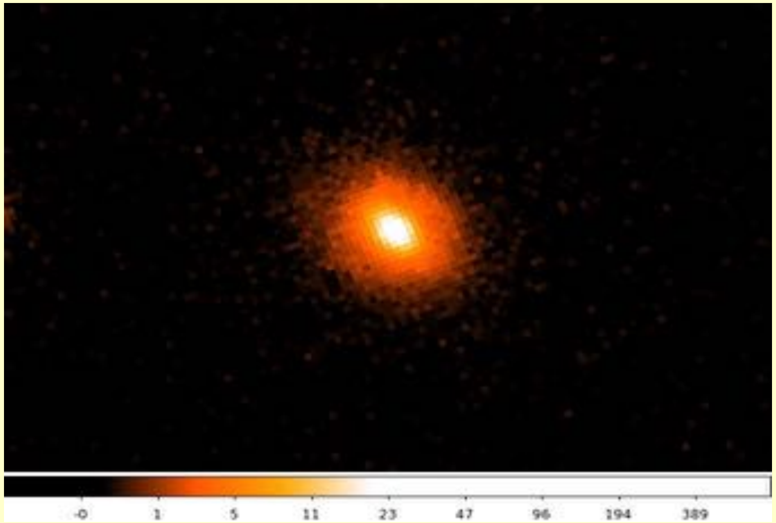


610 MHz contours overlaid on SDSS g band image



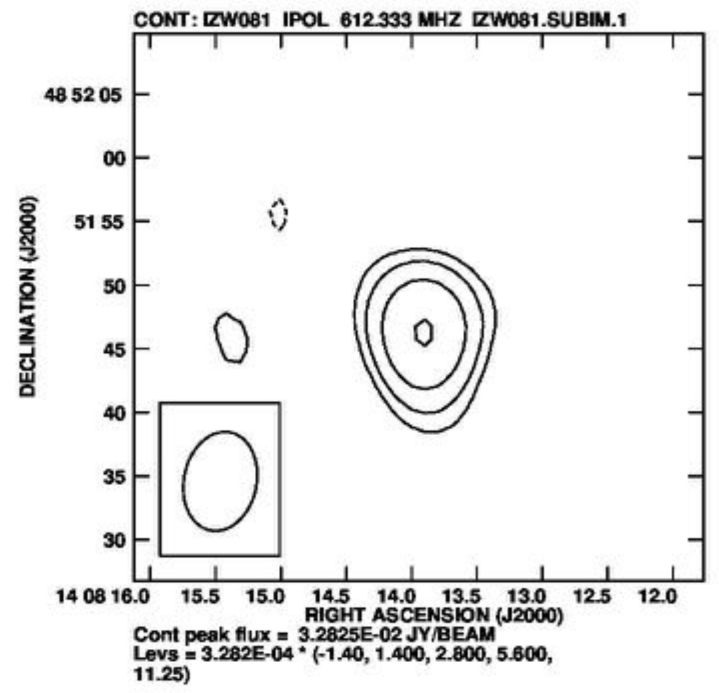
610 MHz emisison around IZw81

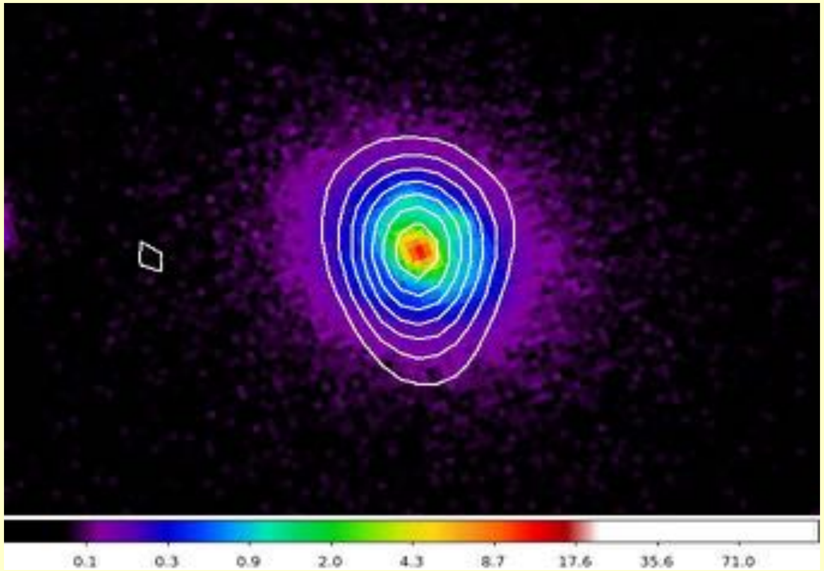
SDSS I band image



It is a small disk galaxy with a Sy2 type AGN. It is an isolated spiral galaxy and has a regular disk structure.
Flux at 610Mhz is 4.3 mJy and rms=102 microJy/bm.

610 MHz GMRT image





610 MHz contours overlaid on SDSS g band image

Magnetic field estimation from radio luminosity of the void galaxies

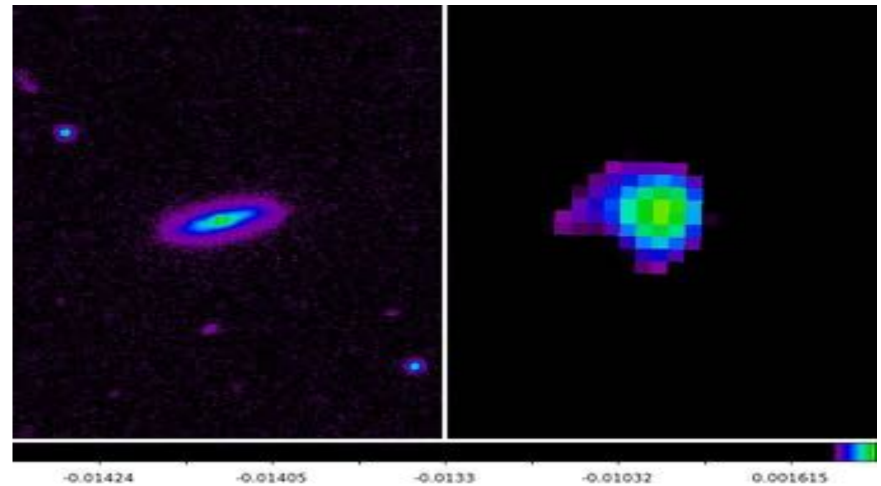
- The radio emission is synchroton emission and associated with a magnetic field **B**.
- If we assume a minimum energy for the radiation then we can get an order of magnitude for the **B**

Galaxy name	size of emitting region (kpc)	L(610) (10^{22}W/Hz)	B(min) (µG)
CG 692	26.2	3.9	2.6
CG 693	8.4	1.5	5.3
Mrk845	13.1	1.6	3.7
SBS1428+529	12.9	2.4	4.2
IZw081	14.5	2.6	3.9

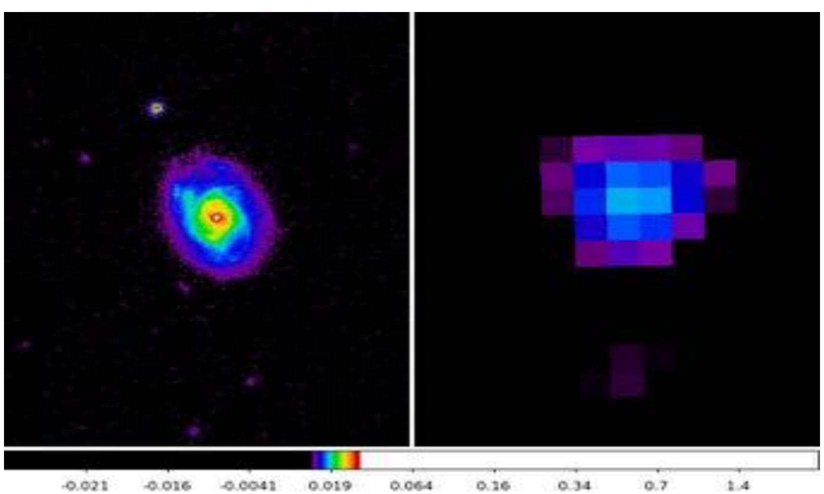
What we have learnt so far ....

- preliminary observations at 610 MHz and TGSS(ADR) images suggest that **star formation rather than AGN activity** can produce low frequency emission from diffuse gas within voids.

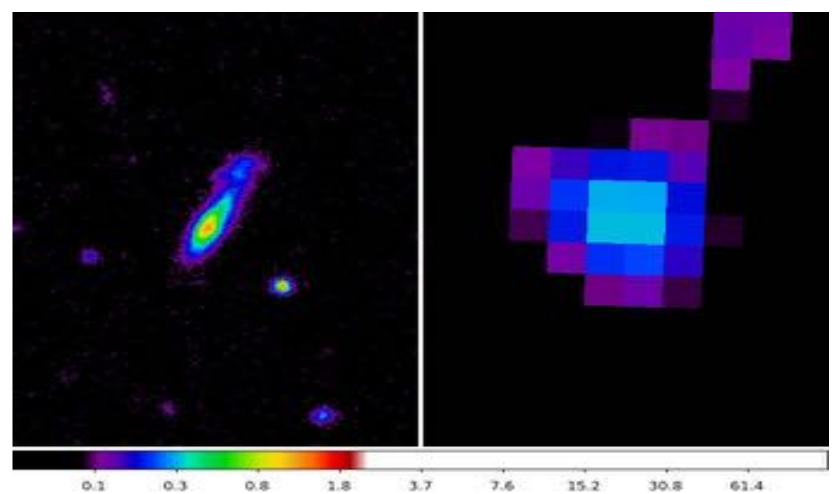
TGSS : 1540+5049



TGSS : CG538



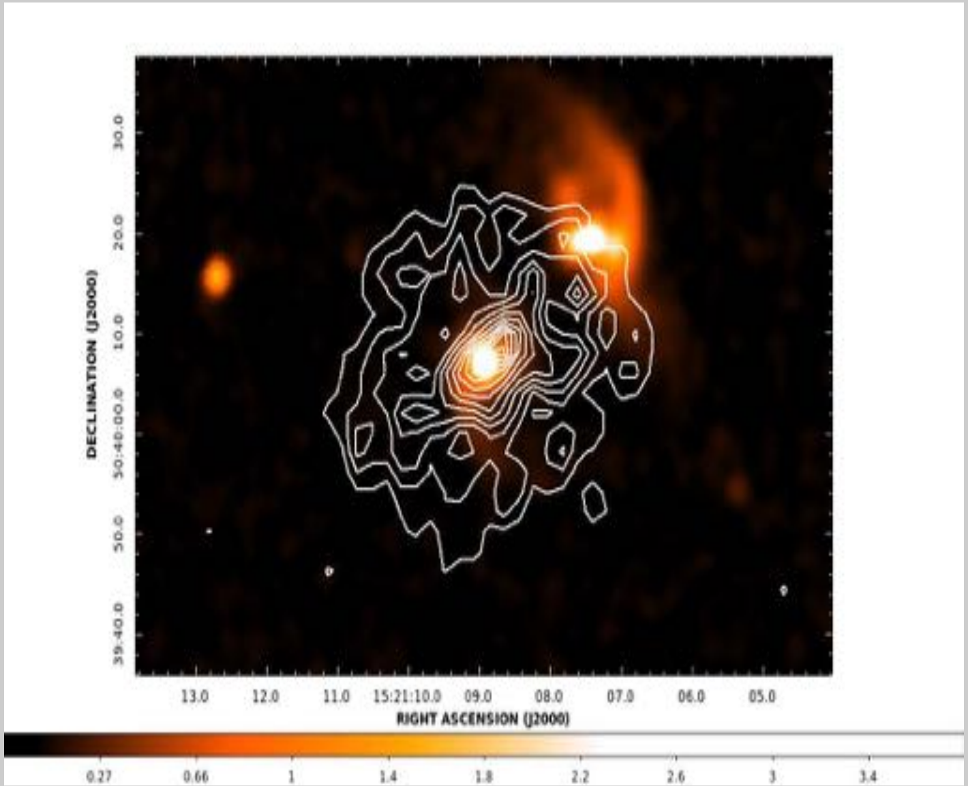
TGSS :IRAS15479



X-ray observations of void galaxies : the hot gas around galaxies

- Only a handful of void galaxies have been studied in X-ray (about 10). Some have been detected in ROSAT and ~4 have Chandra data.
- We have used the x-ray archival data to examine hot gas around these galaxies.
- Work under progress, two galaxies have been done.

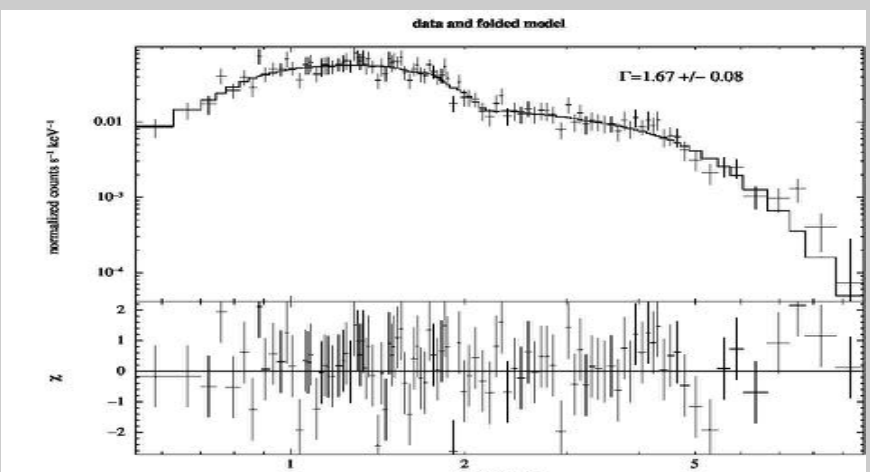
Chandra X-ray emisison around CG692-693

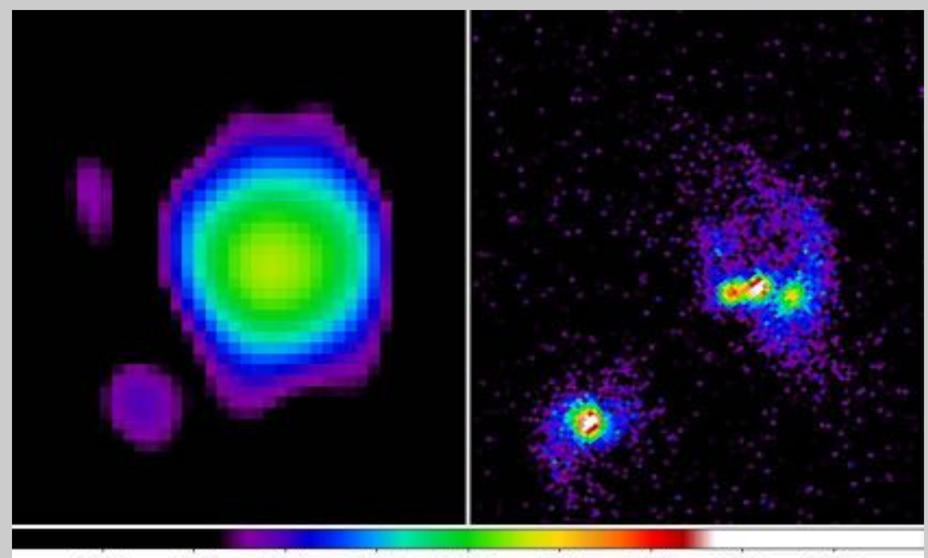


In the Chandra image the emission is concentrated on CG693 and with the AGN (Sy1 nucleus). Extends to twice optical radius (~20kpc). Flux is LogLx=42.9

The extended emission could be the circumgalactic medium (CGM) around the galaxy and is fed by the AGN.

Clearly not associated with the star forming companion CG692.

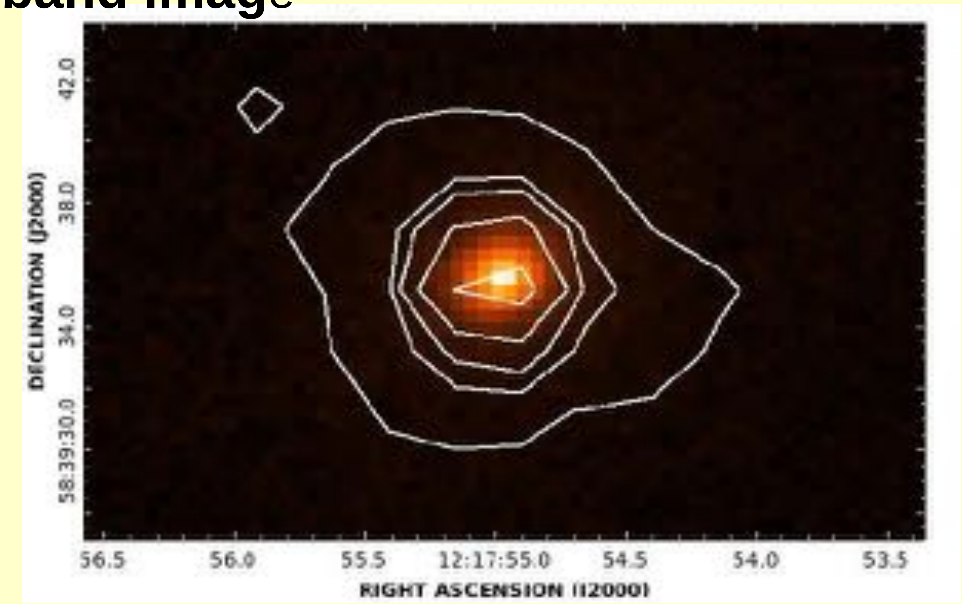




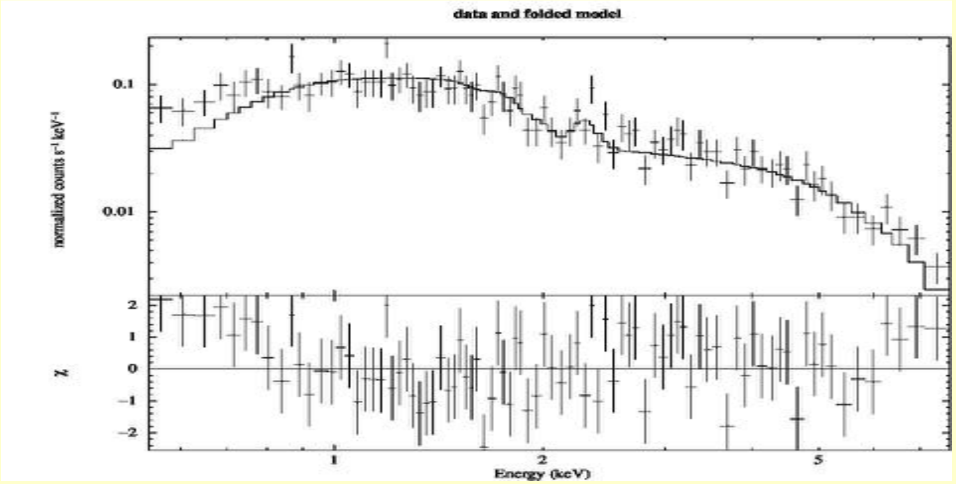
Chandra X-ray emission around Mrk202

- The elliptical galaxy Mrk202 from the Void Galaxy Survey (kreckel et al. 2012) shows broad emission lines in optical spectrum, x-ray emission in Chandra observations and absorption/emission in its x-ray spectrum.

Chandra X-ray emssion overlaid on SDSS I band image



Chandra X-ray spectrum



Our main results

- Our main aim is to detect diffuse gas in voids using radio observations (warm gas) and existing X-ray data (hot gas).
- We detect all 5 galaxies at 610MHz using GMRT. The emission is slightly less than their 1.4GHz fluxes – which could be due to free free absorption.
- We find that the emission associated with star formation is far more extended than that due to nuclear activity. Future low frequency observations should focus on star forming galaxies to map the diffuse gas within voids.
- X-ray emission exists around some void galaxies and may conribute to the WHIM in voids as well as circum-galactic medium (CGM) around galaxies (CG693 and Mrk202).

Our main results

- Our main aim is to detect diffuse gas in voids using radio observations (warm gas) and existing X-ray data (hot gas). We detect all 5 galaxies at 610MHz using GMRT. The emission is slightly less than their 1.4GHz fluxes – which could be due to free free absorption.
- We find that the emission associated with star formation is far more extended than that due to nuclear activity. **These are the galaxies future SKA observations should target to trace the cosmic web in voids.**
- X-ray emission exists around some void galaxies and may conribute to the WHIM in voids as well as circum-galactic medium (CGM) around galaxies (CG693 and Mrk202).