The Extended Radio Emission around Isolated Galaxies in Voids

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The Meter Wavelength Sky II,
NCRA march 18-22, 2019

Image credit : IllustrisTNG Simulations (Martizzi et al.)

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Outline of talk

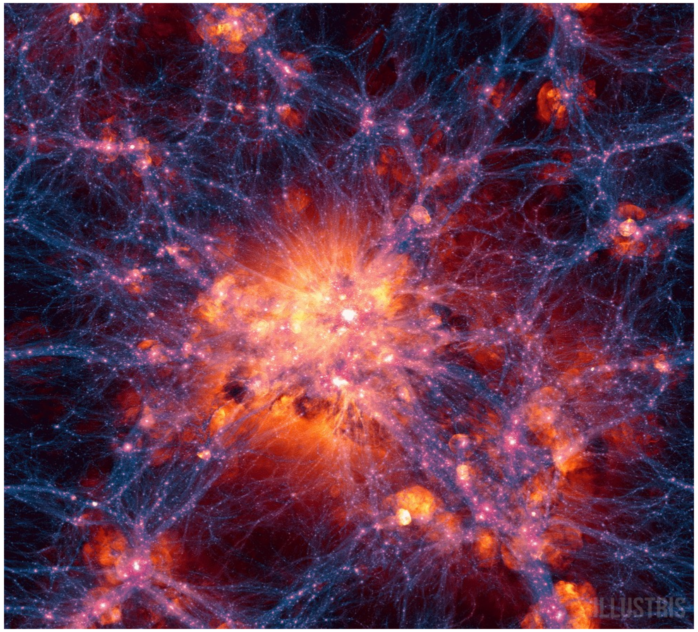
- **Properties of void galaxies**
- **Why study void galaxies?**
- **tSZ detection from star formation using void galaxy sample**
- **Radio (GMRT) observations and galaxy sample**
- **Low frequency radio emission around AGN/starburst activity in nearby voids (610, 325 and 150MHz)**
- **The extended Hot, X-ray emitting gas around CG693**

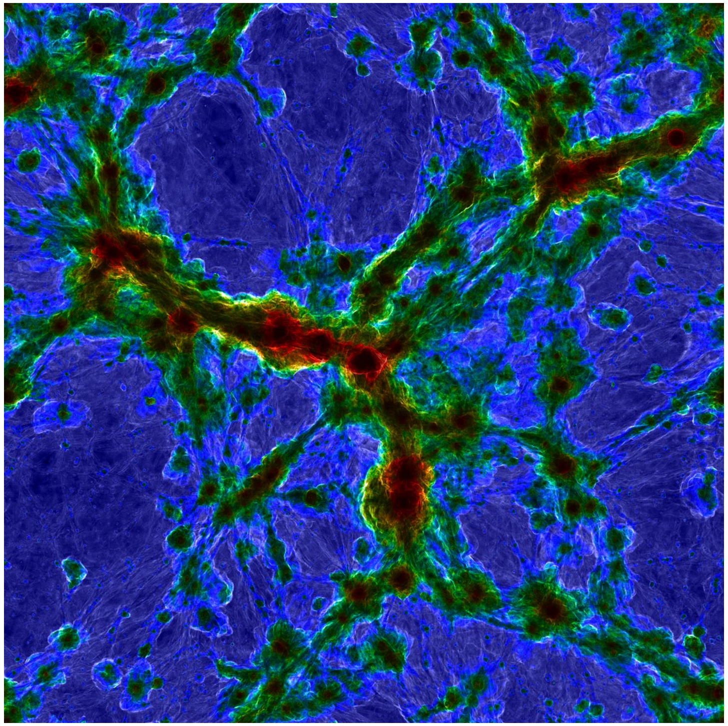
Voids

- **Our universe is made of matter clustered along walls and filaments with large "empty" regions called voids in between. Voids and filaments clearly detected in simulations.**
- **The voids have filaments is seen in both simulations as well as observations of the large scale structure.**

Above : IllustrisTNG Simulations of the cosmic web showing a void region (Martizzi et al. 2019)

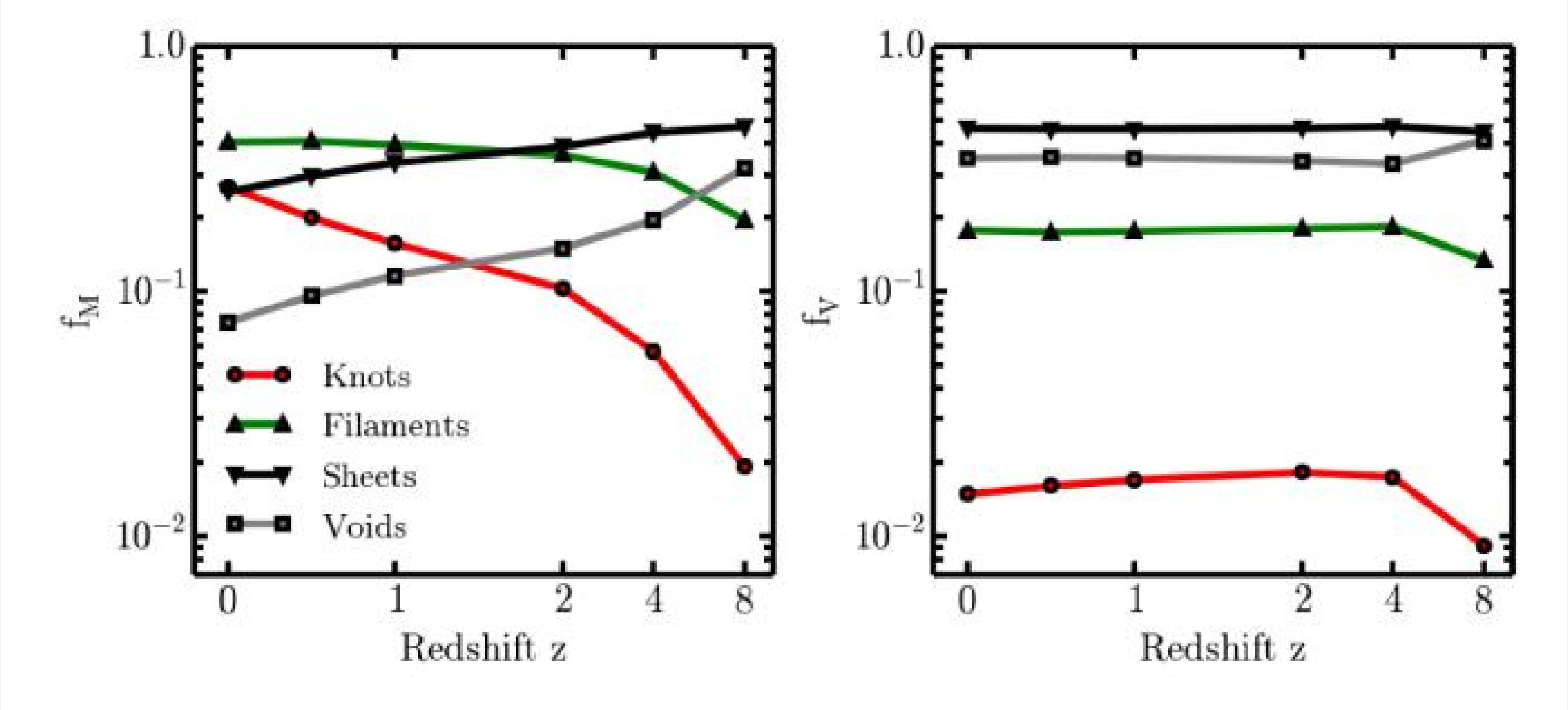
A Cluster : Illustris Simulation (Haider et al. 2016)





Simulations of Mass in voids

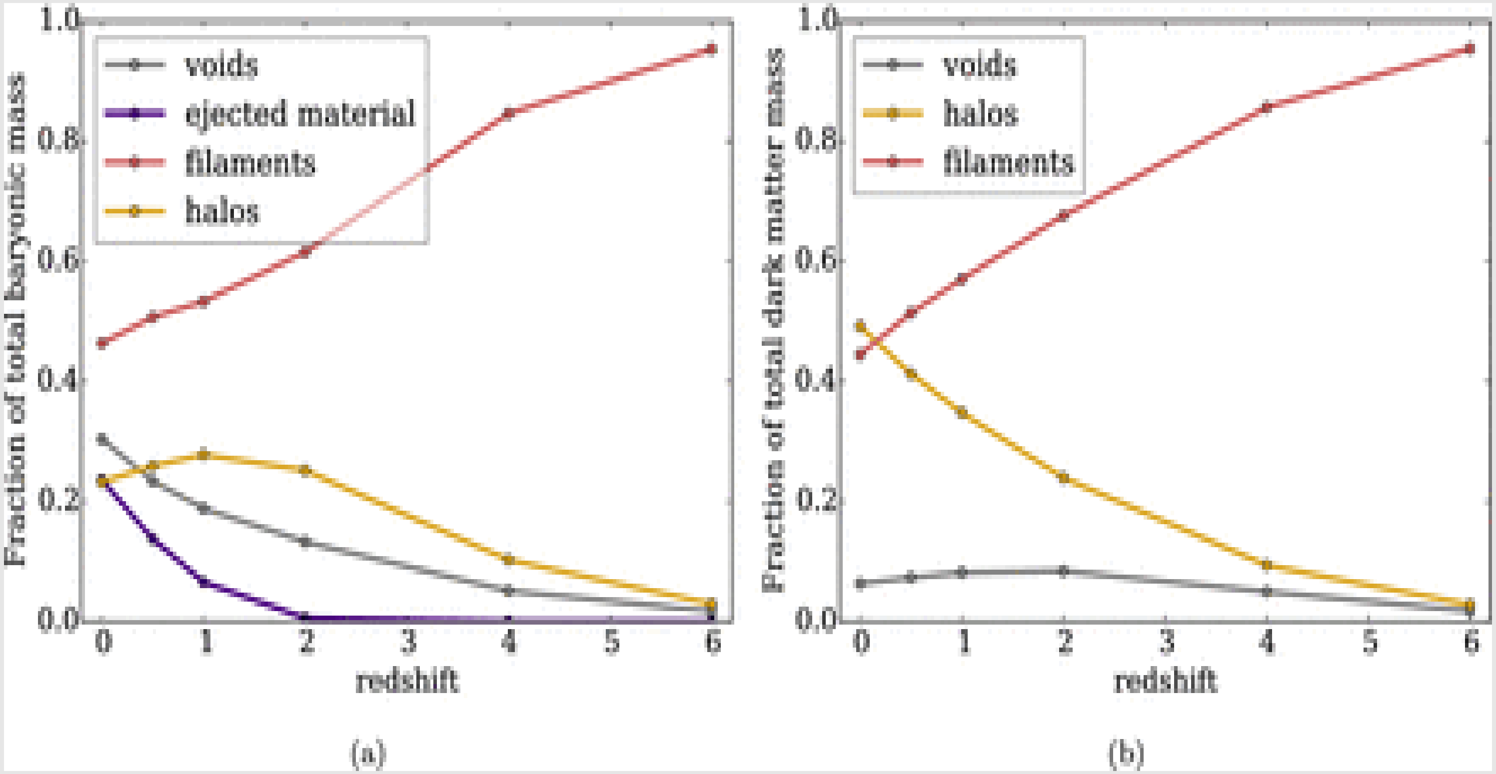
- **Mass moves away from the low density regions in voids. In the process smaller subvoids merge to form larger voids. The hierarchical structure and expansion leads to filaments in voids (Aragon-Calvo & Szalay 2012, Paranjape et al. 2012).**
- **At lower and lower z the mass in voids decreases. Most of the baryonic mass is in filaments. But most of the volume is occupied by voids.**



Martizzi et al. IllustrisING 2019

Simulations on gas in voids

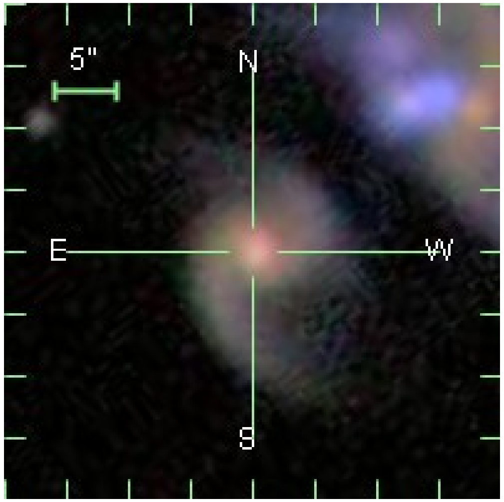
- Cosmological simulations such as the *Illutris* show that the hot gas in voids increases at lower z (Haider et al. MNRAS, 2016).
- The gas could arise from AGN feedback at the void walls.
- Some of the gas can come from star formation and AGN activity **from within the voids themselves.**

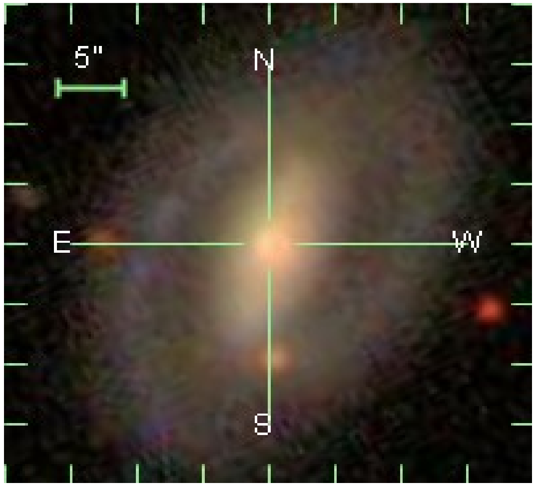


Haider et al. 2016; Illustris Simulations

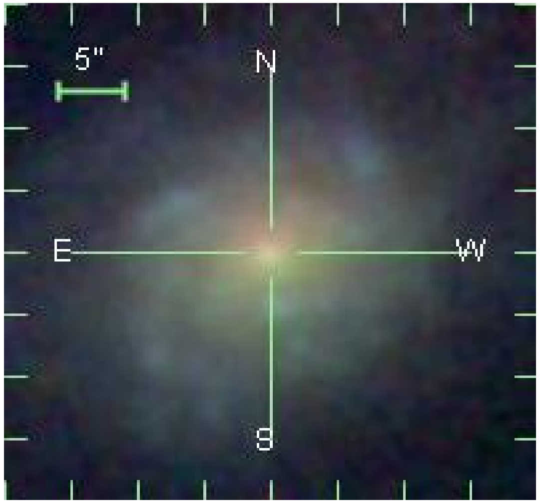
Void Galaxies

- They are gas rich, late type disk galaxies and usually spirals and irregulars. Ellipticals less common. Stellar masses of order 10^7 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 (Kreckel et al. 2011; Cruzen et al. 2002; Grogin and Geller 2001; Szomoru et al. 1997).





SDSS images of some bright galaxies in larger voids : SBS1428+529, VG_06, CG693-692



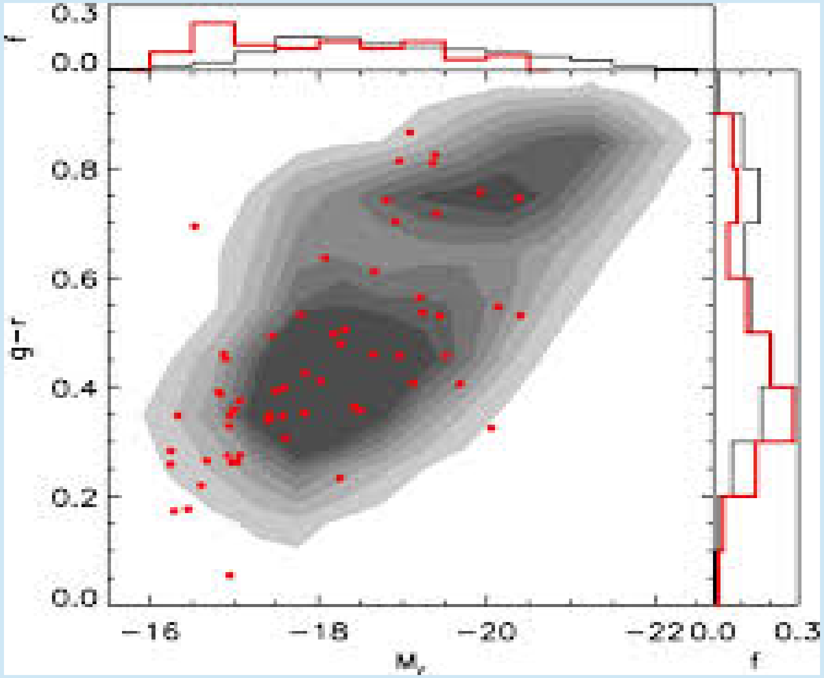
Star Formation in Void Galaxies

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).

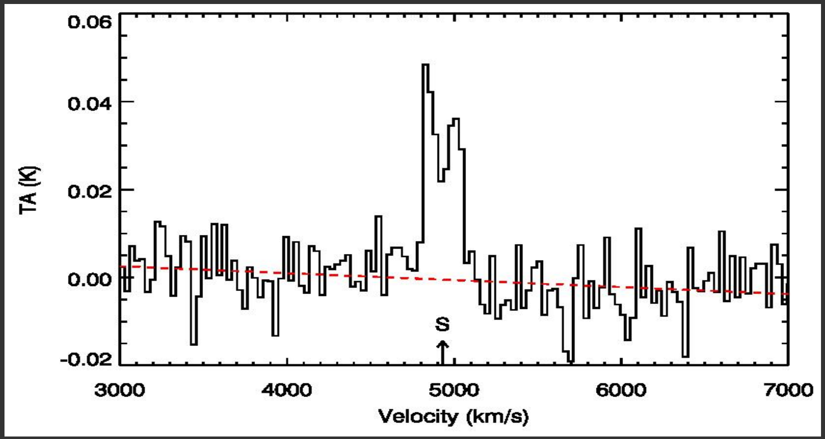


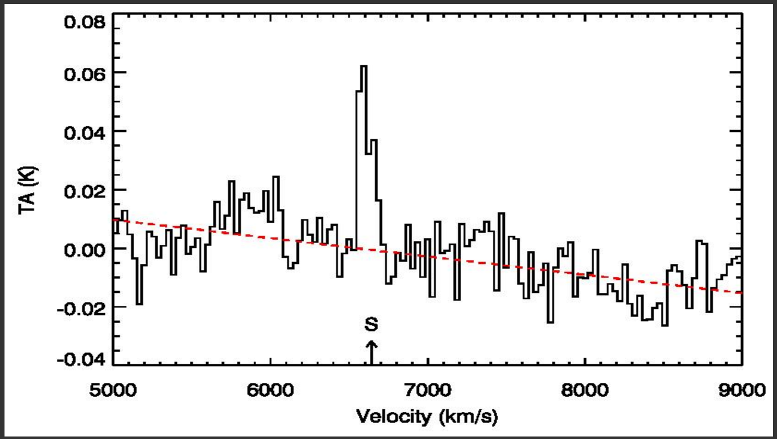
Cold Gas in voids galaxies : CO(1-0) Detections

(Das et al. 2015)

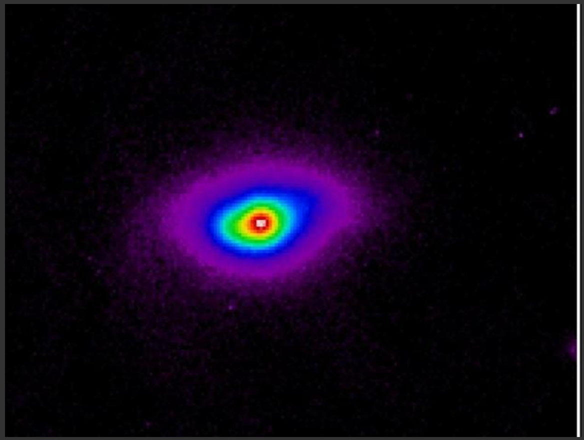
SBS1325+597 (VGS_34)

SDSS1538+3311 (VGS_57)

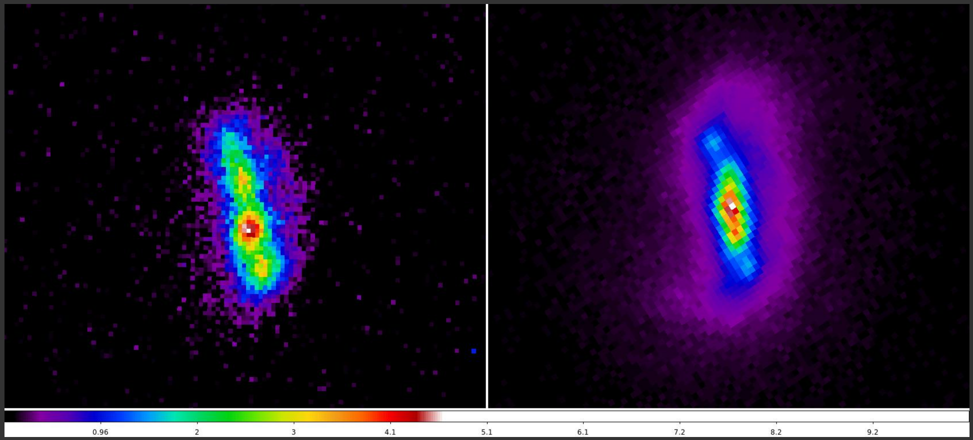




HCT I band image

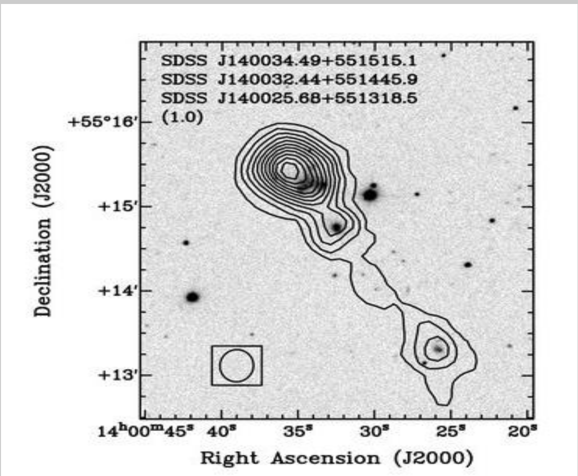


HCT Hα image (left) and SDSS g image (right)



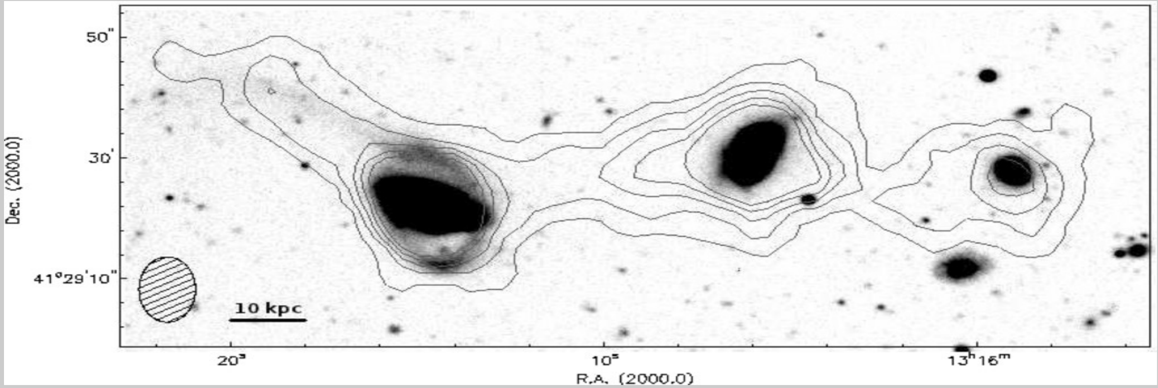
Groups/Interacting Pairs : Signatures of Void Substructure?

Kreckel et al. 2011



CG693-692 : Interacting pair in Bootes void

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

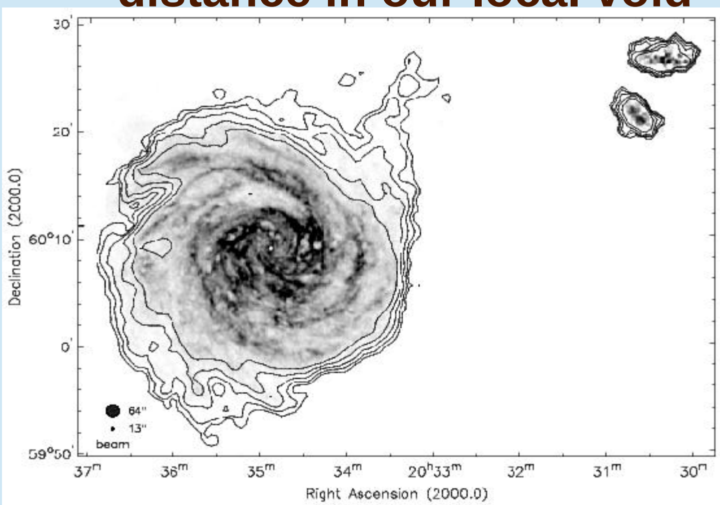


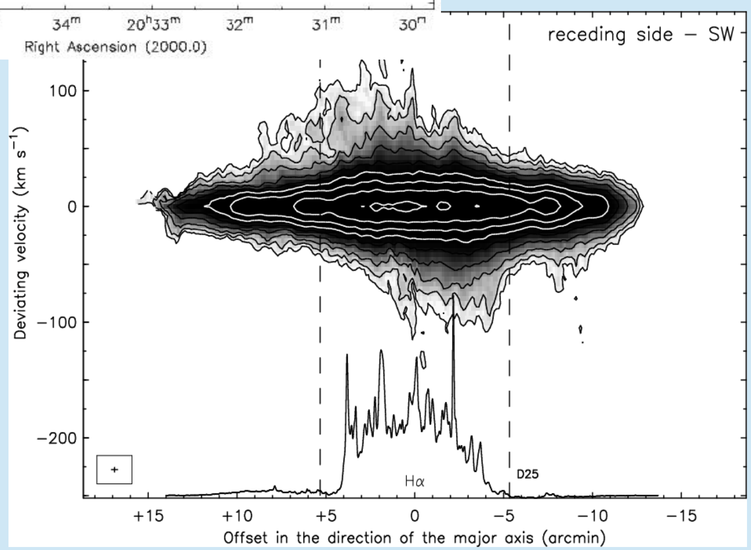
There are many examples of interacting pairs, polar ring galaxies and even small groups of galaxies residing in voids.

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.

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.

1. They could be interacting with close neighbors 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).

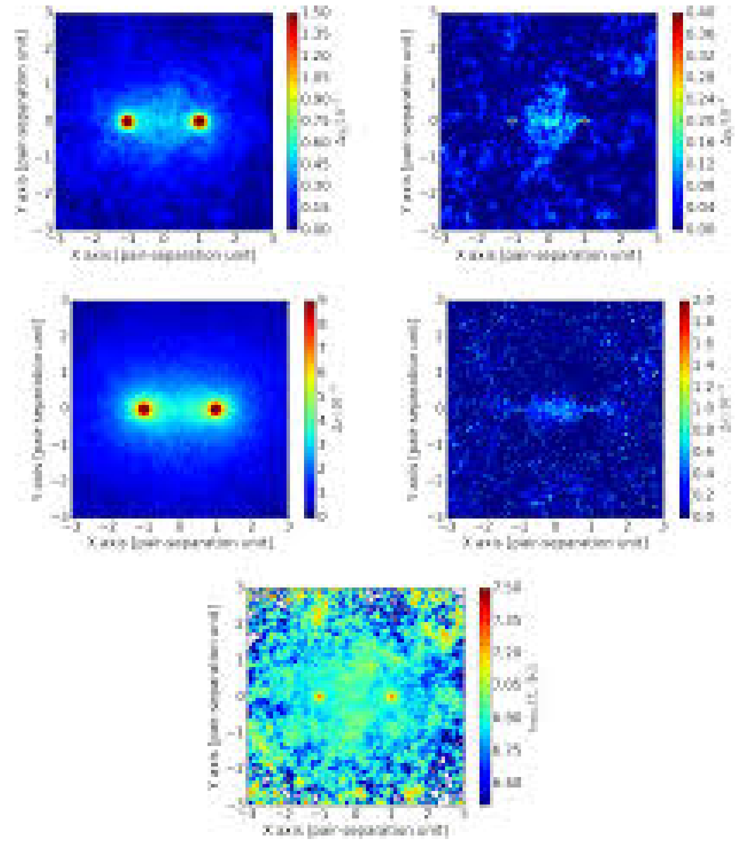
(Boosma et al.)

Why Study void galaxies ?

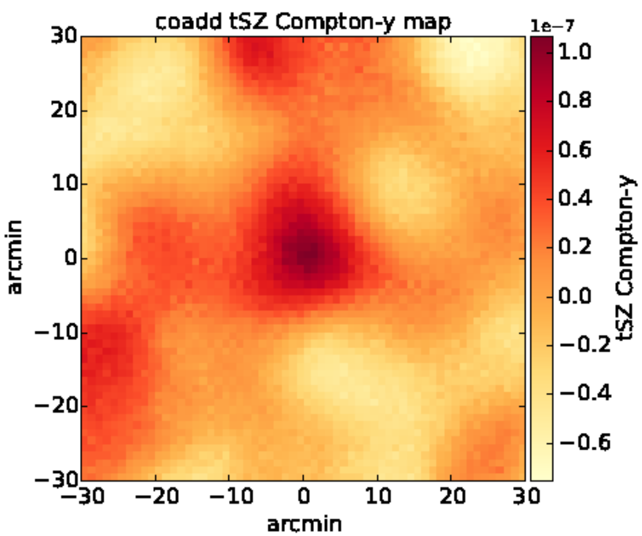
- Void galaxies trace the substructure within voids, (Sahni et al. 1994, Aragon-Calvo et al. 2010). The galaxies lie on filaments or in small groups inside the voids or close to the walls.
- They represent the growth of mass within voids which can be due to gas flow along filaments and mergers of subvoids (Kreckel et al. 2012).
- **Allows us to study the evolution of isolated galaxies, that grow through gas accretion and star formation (Das et al. 2015).**
- **We can explore circum-galactic medium (CGM) around small galaxies (their under dense environment means less confusion).**

Using Planck tSZ maps to study hot gas around galaxies

- The tSZ effect has been used to detect hot gas around clusters, filaments between clusters and filaments between superclusters (Planck 2013).
- The Planck tSZ map can also detect diffuse, hot gas between massive, bright galaxies (Tanimura et al. 2018) and is important for tracing the filaments of WHIM in cosmic web.
- The hot gas around the massive galaxies is due to AGN feedback (Ruan et al. 2015) and traces the circum-galactic medium (CGM) around galaxies.



Tanimura et al. 2018

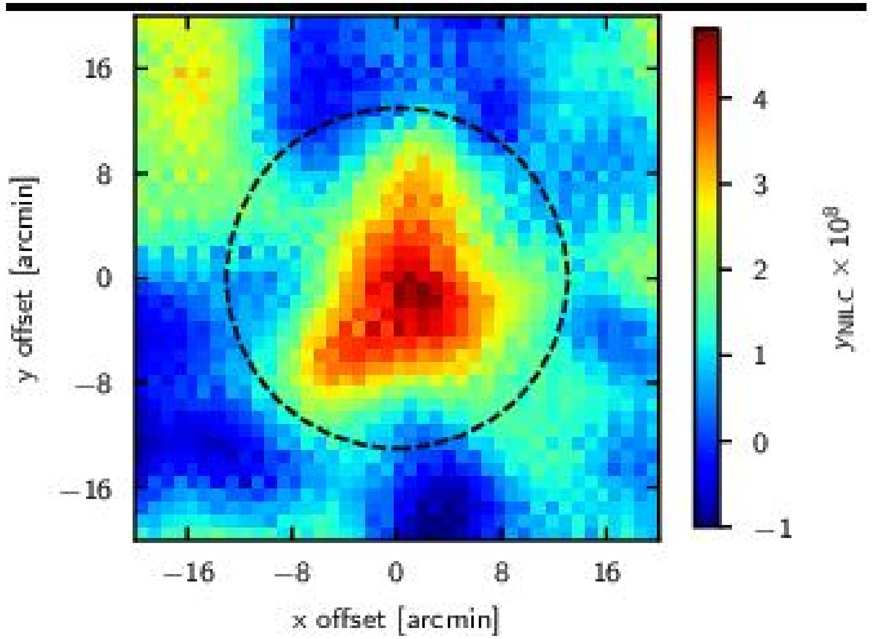


(Ruan et al. 2015)

Using Planck tSZ maps of void galaxies to study hot gas around isolated galaxies

- The hot CGM around small galaxies is difficult to detect because of confusion. But void galaxies are isolated and hence ideal for such a study.
- We stacked ~20,000 void galaxies with $M>10^9\ M_{sun}$ and $z<0.11$ using Planck tSZ maps. We obtained a 3.2 sigma detection.
- The tSZ signal is due to stellar feedback from the star formation in these isolated galaxies.

M82 Stellar feedback : Image Credit is Hubble Space telescope



(B.Singari, T.Ghosh, M.D. Y.Ma, Tanimura, 2019, ApJ, submitted)

What is the morphology of the warm/hot gas in voids and where does it come from?

- The hot gas gas can come from AGN outflows in clusters embedded in the void walls.
- Also galaxies within voids can produce outflows associated with AGN activity and star formation.
- We can explore diffuse emission in voids using low frequency radio observations.
- X-ray emission will trace the hot gas.

Low frequency radio observations of Bootes void galaxies with GMRT

- We have done 610 and 240 MHz observations of the radio emission around the 4 bright AGN host galaxies in the Bootes void. Observations were done in November, 2014. Total observing time was 14 hours for 4 galaxies : CG692-693, SBS1428+5255, Mrk845, IZw81.
- Also uGMRT observations of 4 isolated void galaxies that have TGSS emission. Observations in 2017, approx. 8 hours for 4 galaxies : UGC00749, UGC10514, UGC11717, MRK306.

Goals of low frequency radio study : to detect extended low frequency emission in and around AGN in void galaxies (235, 610MHz)

- To study emission associated with star formation/and or AGN activity around galaxies using low frequency (610M/325/235 MHz) radio continuum observations.
- Compare with hot gas associated with AGN activity or high mass star formation using X-ray emission.
- Identify regions to search for filaments in voids that can be done with more sensitive arrays such as the SKA.

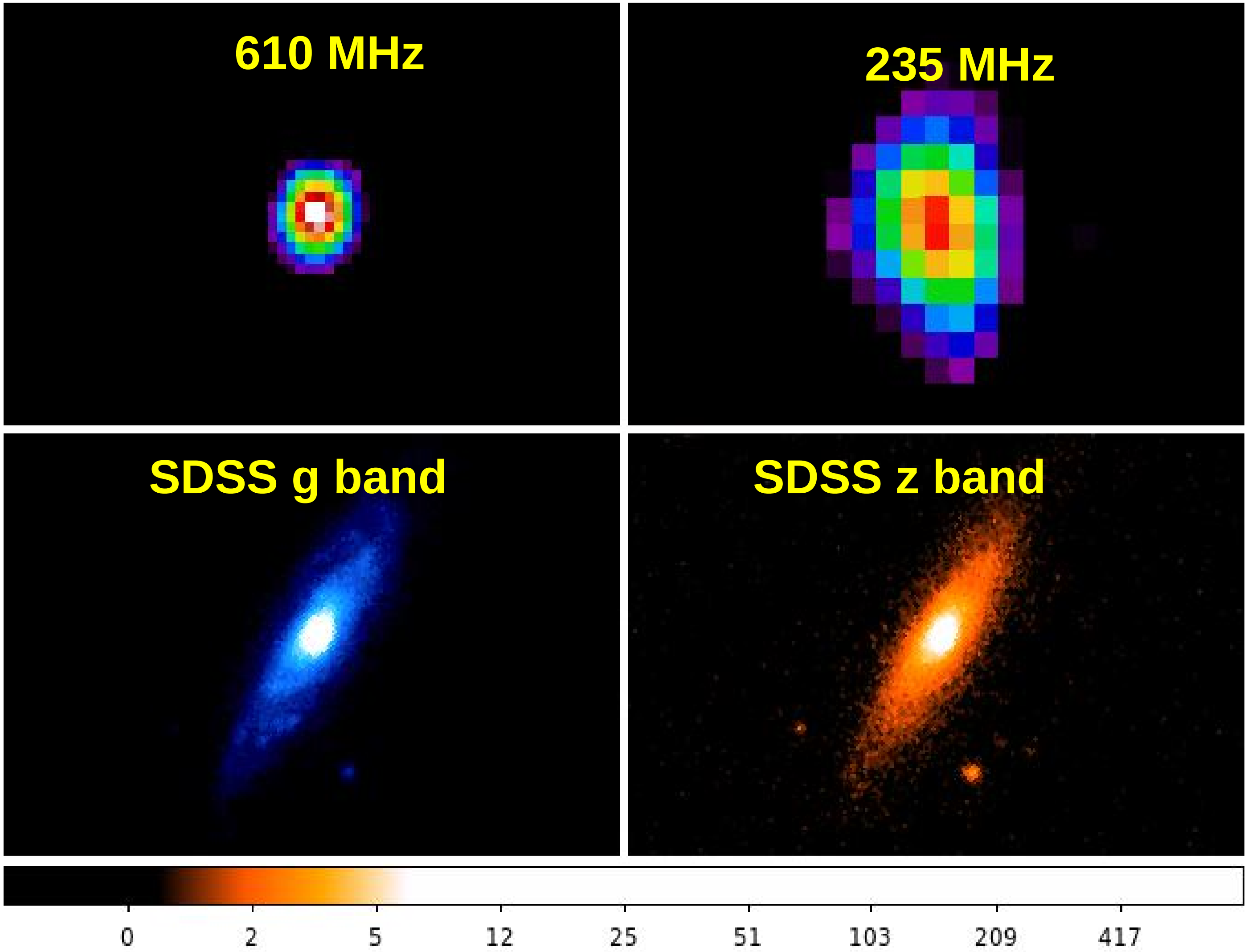
We selected galaxies within one of the largest nearby voids – **the Bootes void.**

Overview of the Bootes void galaxies

- Size is ~ 60 Mpc across (15 degrees), mean redshift ~0.05.
- About 28 galaxies reported in literature. Generally HI rich, late type spiral galaxies.
- AGN fraction (Seyferts, LINERS) high - about 20% compared to 3% for galaxies in other voids.
- A significant fraction are bright and star forming (Cruzen et al. 1997; Szomoru et al. 1996); several are in pairs or triplets. But overall region is very under dense.

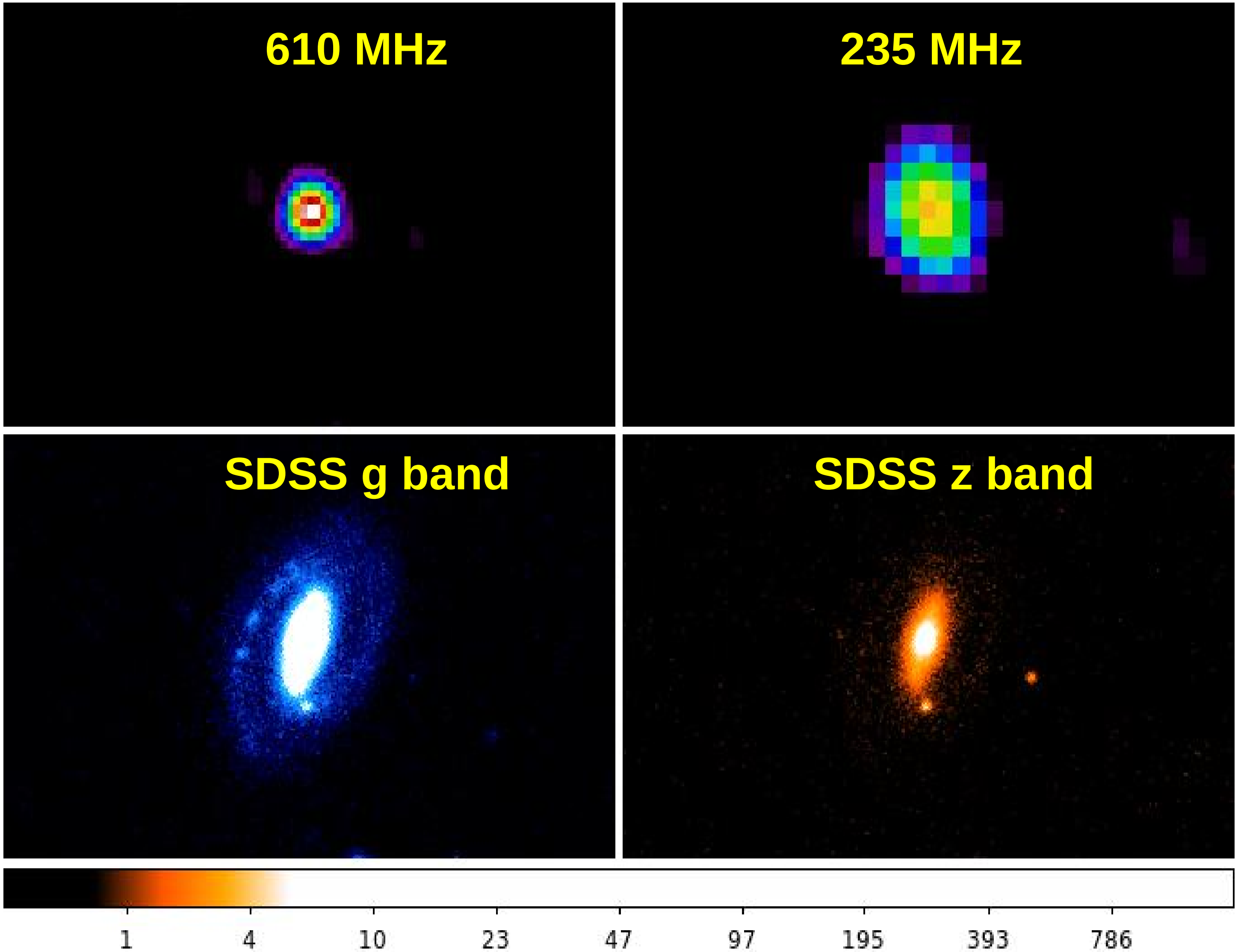
Examples of Bootes void galaxies

610-235 MHz emisison around MRK845



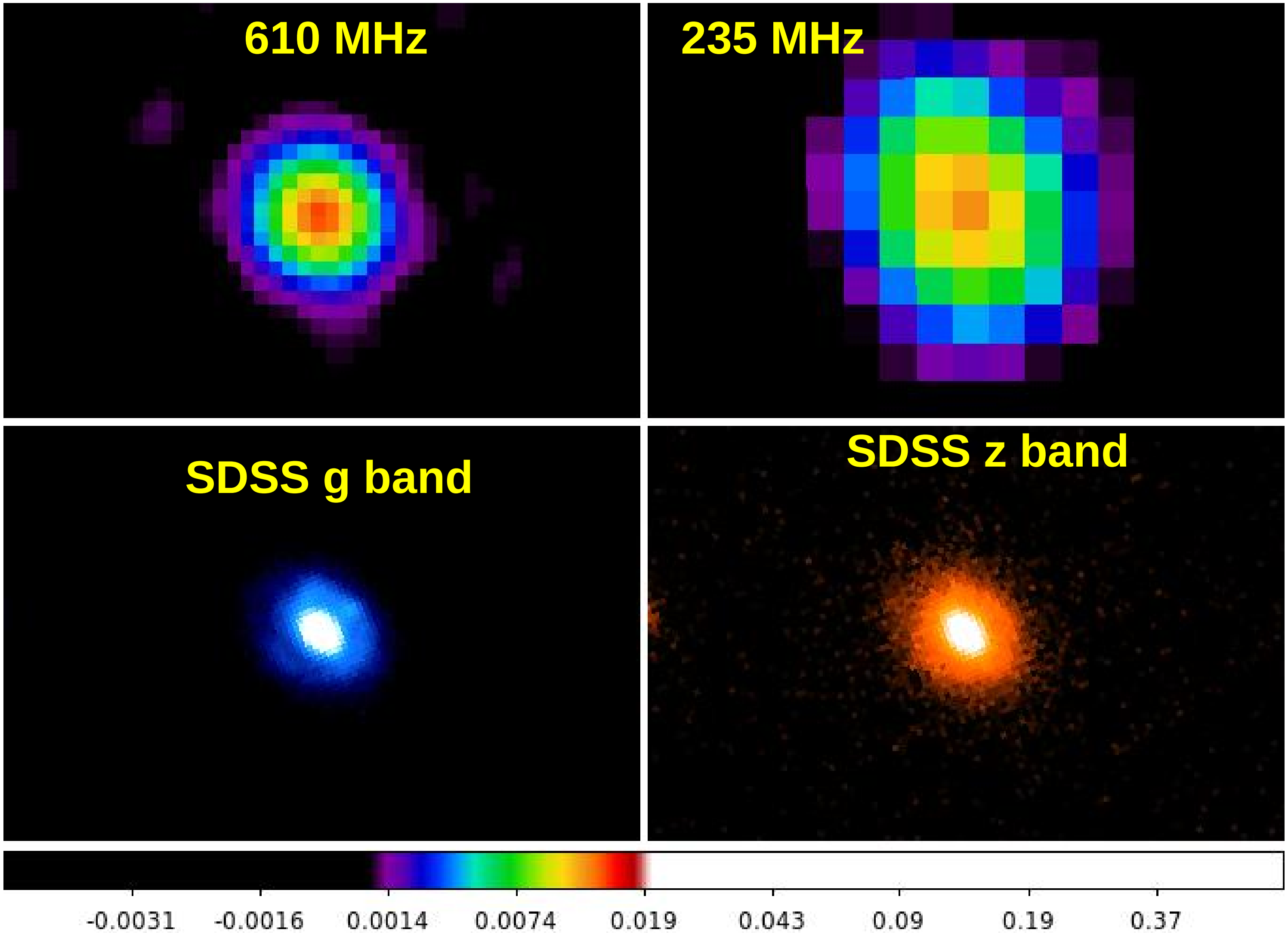
Mrk845 is an emission line galaxy with Sy2 type AGN. Flux at 610MHz is 3.4mJy .
It has been detected in ROSAT and has an X-ray flux of LogLx=43.7.
Emission extended at 240 MHz, detected in TGSS ADR 150 MHz.

610-235 MHz emisison around SBS1428+529



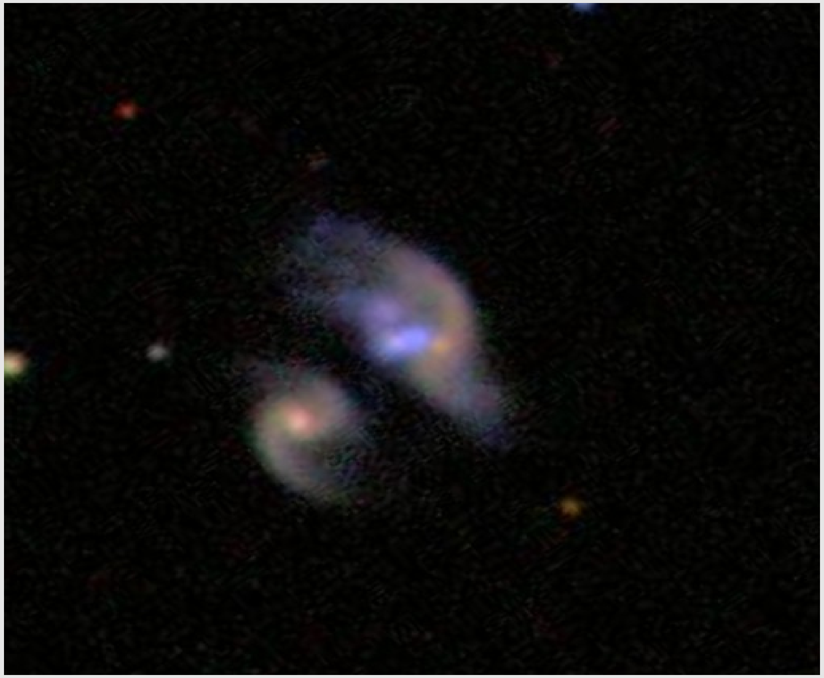
SBS1428+429 has a Sy2 type AGN. It is an isolated spiral galaxy and has a regular disk structure. Flux at 610Mhz is 5.1mJy. It has been detected in ROSAT and has weak X-ray flux. Not detected in TGSS.

610-235 MHz emisison around IZW081



It is a small disk galaxy with a Sy2 type AGN. It is the only AGN host galaxy that lies along a filament. Flux at 610Mhz is 4.3 mJy. Not detected in TGSS 150 MHz map. No x-ray emission.

610 MHz emisison around the galaxy pair CG692-693

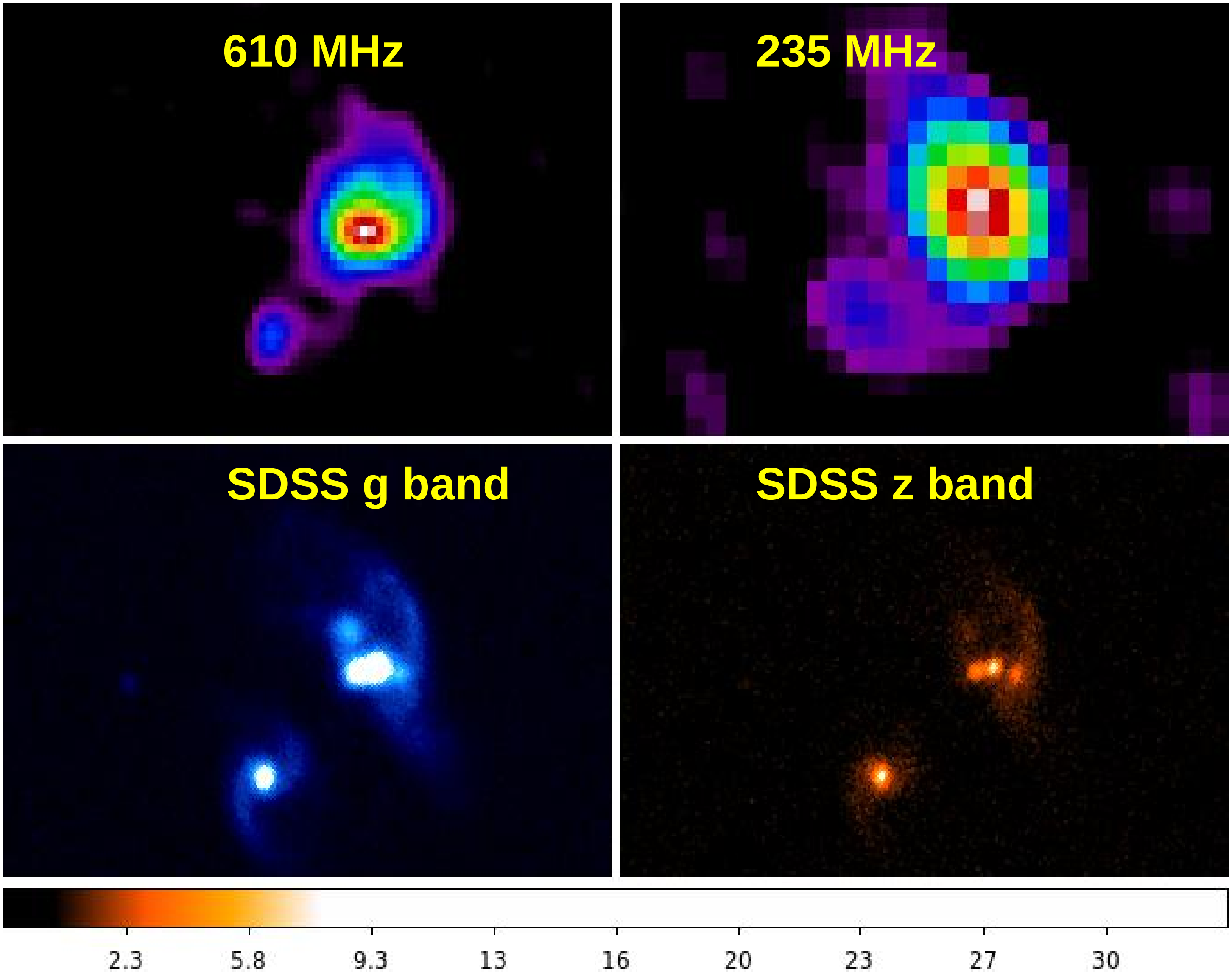


SDSS color composite image

- 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.
- It is just detected in TGSS (Intema et al. 2016).

610-235 MHz emisison around CG692-693 and optical comparison

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.



Spectral Index of the 610-235 MHz emission

- We calculated the spectral index of the 610-235 MHz emission using the peak flux, where $S_{\nu} \sim \nu^{-\alpha}$
- CG692 **α = 1.3**
- MRK845 α = **0.70**
- SBS1428+529 **α = 0.60**
- IZw081 **α = 0.85**

- **The spectral indices are steep and consistent with outflows due to star formation and/or nuclear activity.**

X-ray emission around void galaxies?

Only a few void galaxies have been detected in ROSAT and very few have targeted X-ray observations (Anderson et al. 2007) .

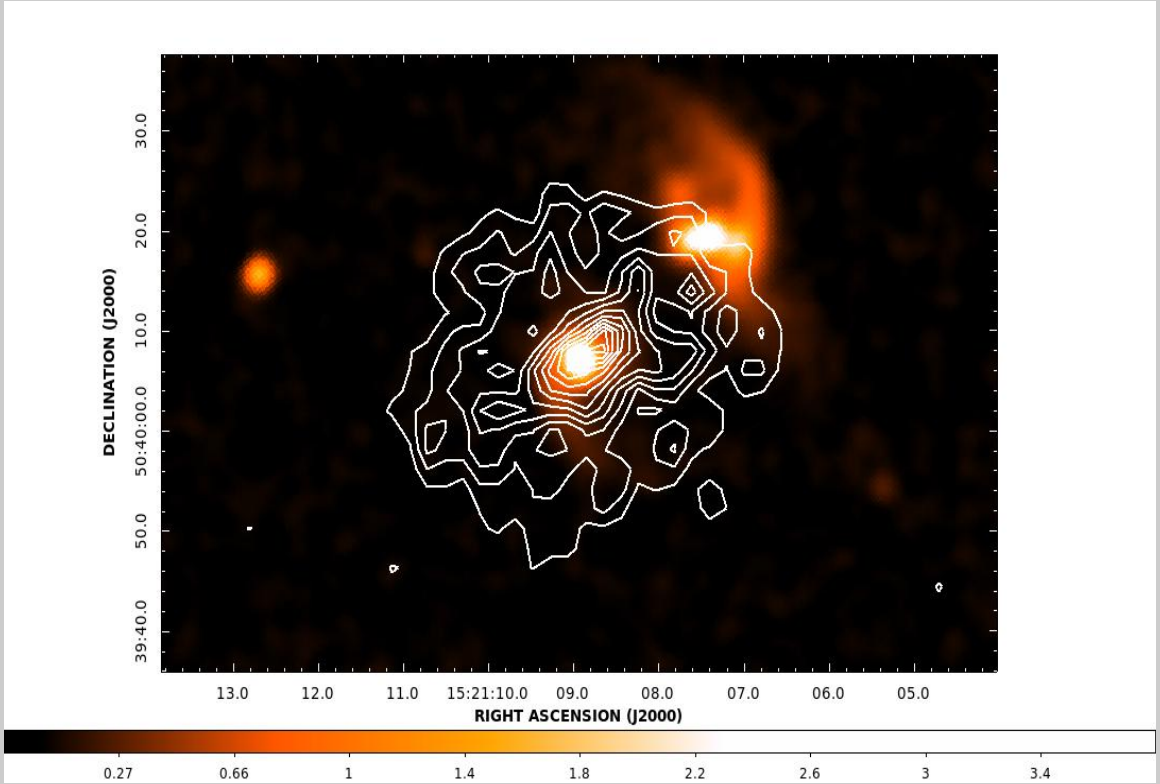
In the Bootes void 5/28 galaxies are detected in X-ray.

But only one galaxy has significant emission – CG693.

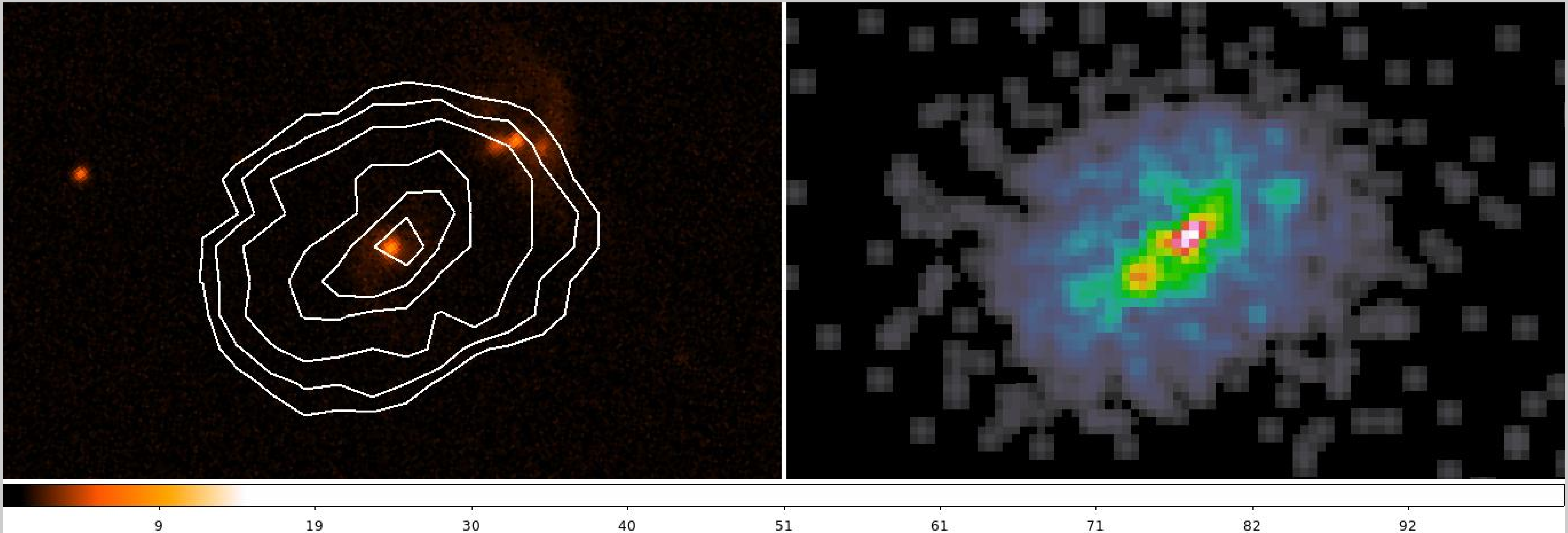
Chandra X-ray emisison around CG692-693

Among the 28 Bootes void galaxies only 3 have been detected and imaged in X-ray. Of them, CG693 has the largest flux in X-ray.
In the Chandra image the emission is concentrated on the Sy1 nucleus in CG693. Extends to twice optical size (~50kpc). Exposure time 18.8 ks. **LogLx=42.9**

The extended emission could be the circum-galactic medium (CGM) around the galaxy and is fed by the AGN.
There is no X-ray emission associated with the star forming companion CG692.

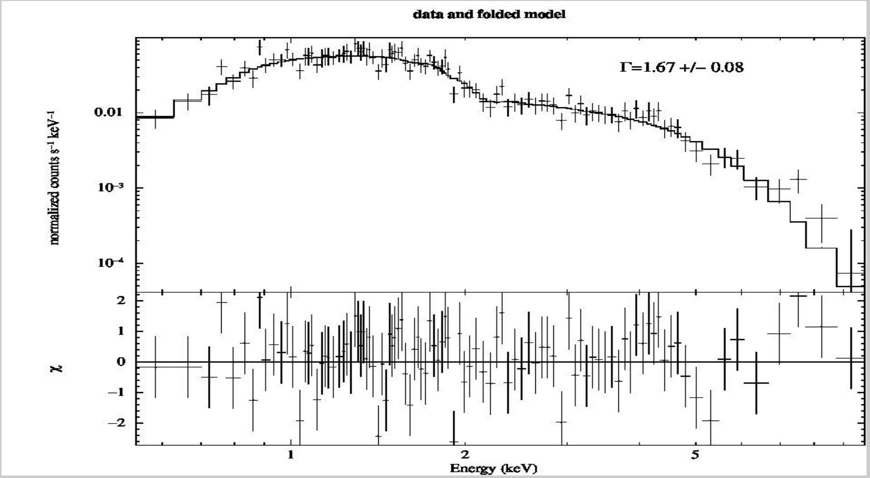


Chandra X-ray emission around CG692-693

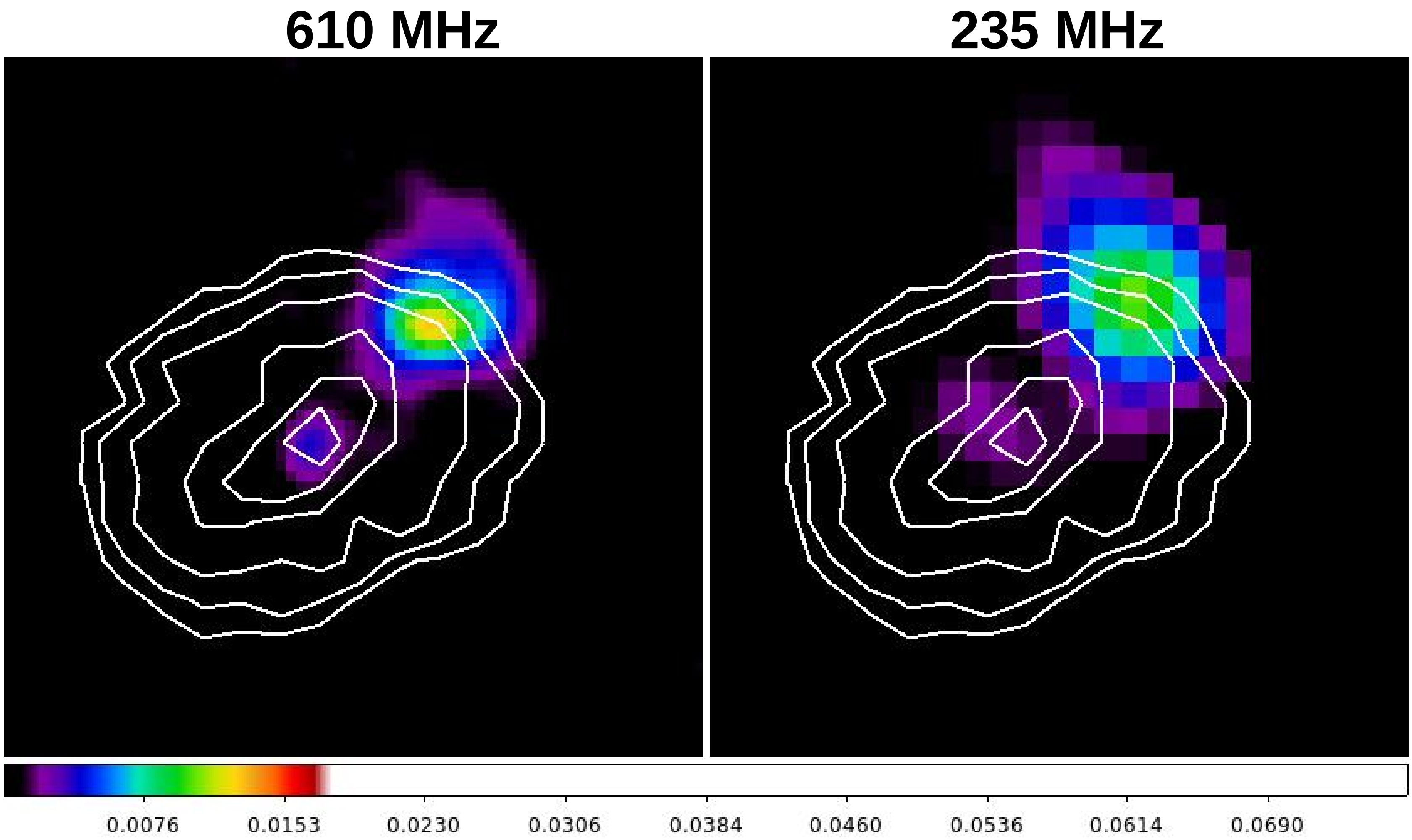


In the Chandra image the emission (0.5 to 7kev) shows some alignment towards CG692. Also some filaments in center.

The spectrum does not have any emission lines.



Comparison of 610, 235 MHz radio and Chandra X-ray emission around CG692-693

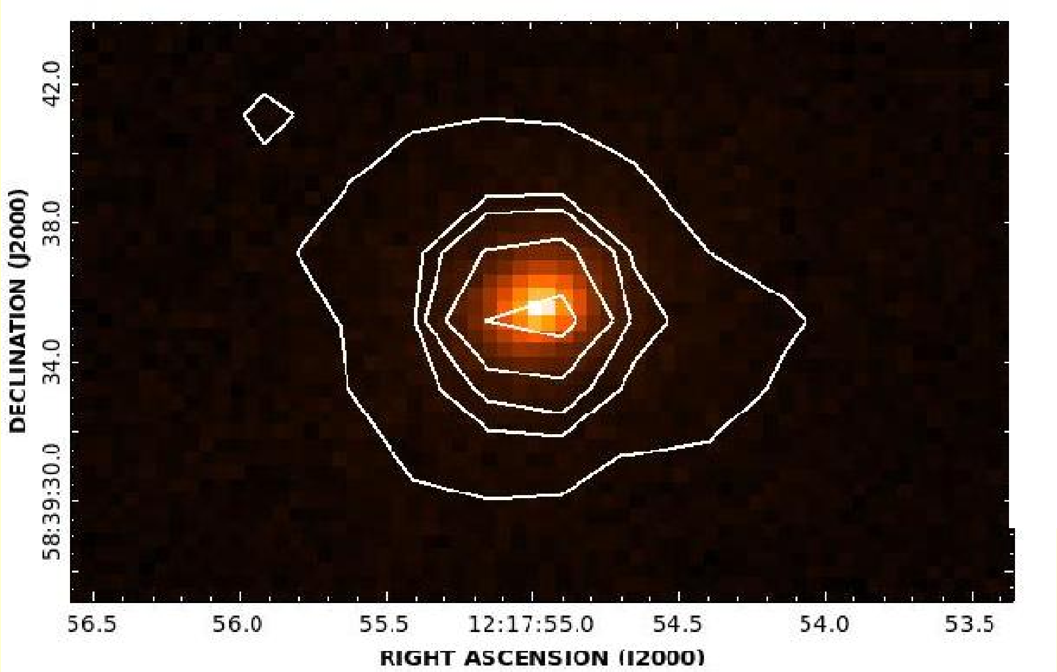


When the X-ray contours are overlaid on the 610 and 235 MHz images, the is a clear distinction. The radio emission is due to star formation but the X-ray is due to the Sy1 activity.

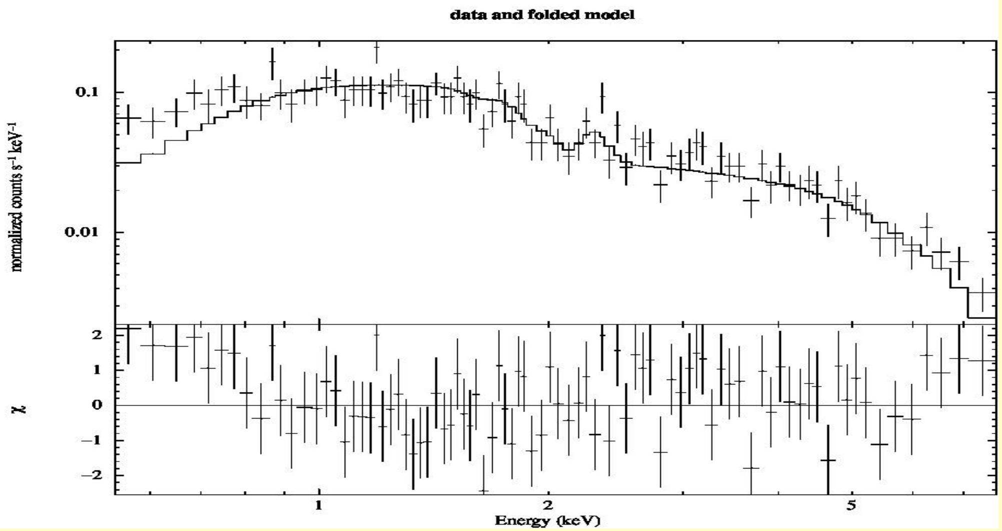
Chandra X-ray emission around Mrk202

- 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 emission in its x-ray spectrum.

Chandra X-ray emssion overlaid on SDSS I band image



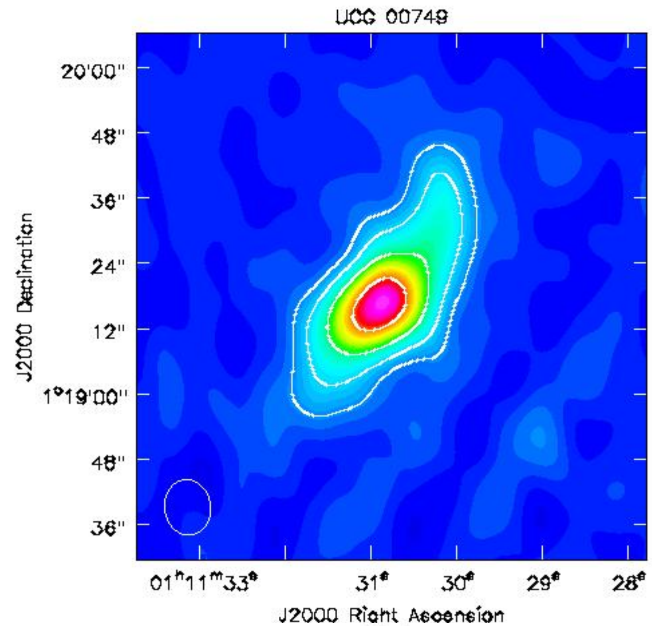
Chandra X-ray spectrum

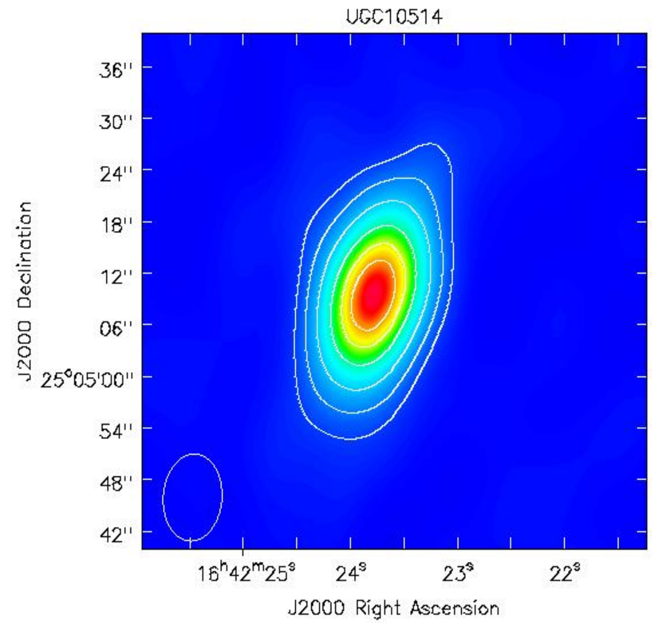


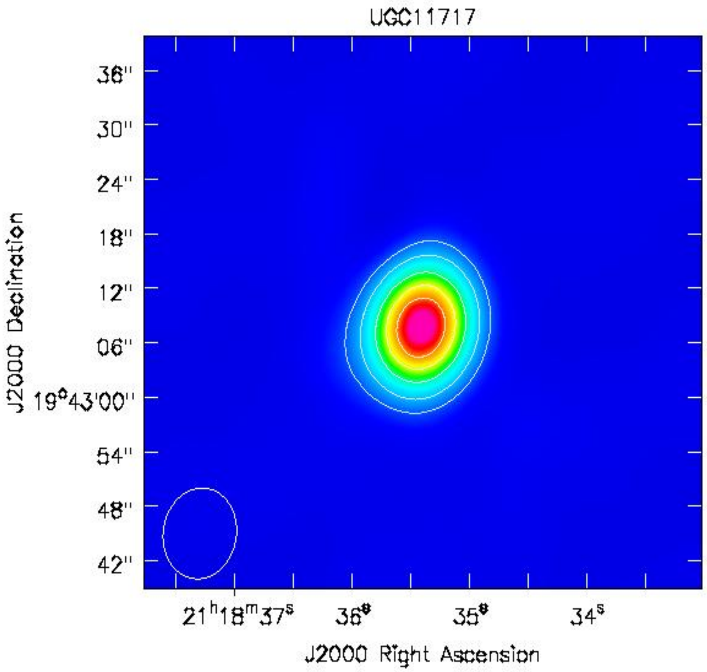
Low frequency observations of star forming void galaxies

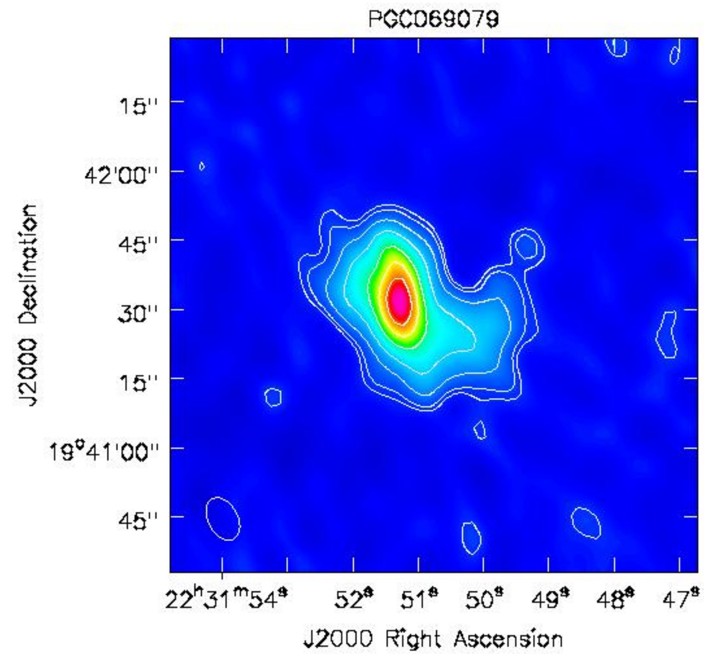
- We have done (250-500)MHz band observations of 4 isolated void galaxies that have been detected in TGSS. Sample from Grogin & Geller (2000) and Kreckel et al. (2012).
- Observations from cycle 32 (2017). A total time of 8 hours.
- We present here only the GSB images

325 MHz observations



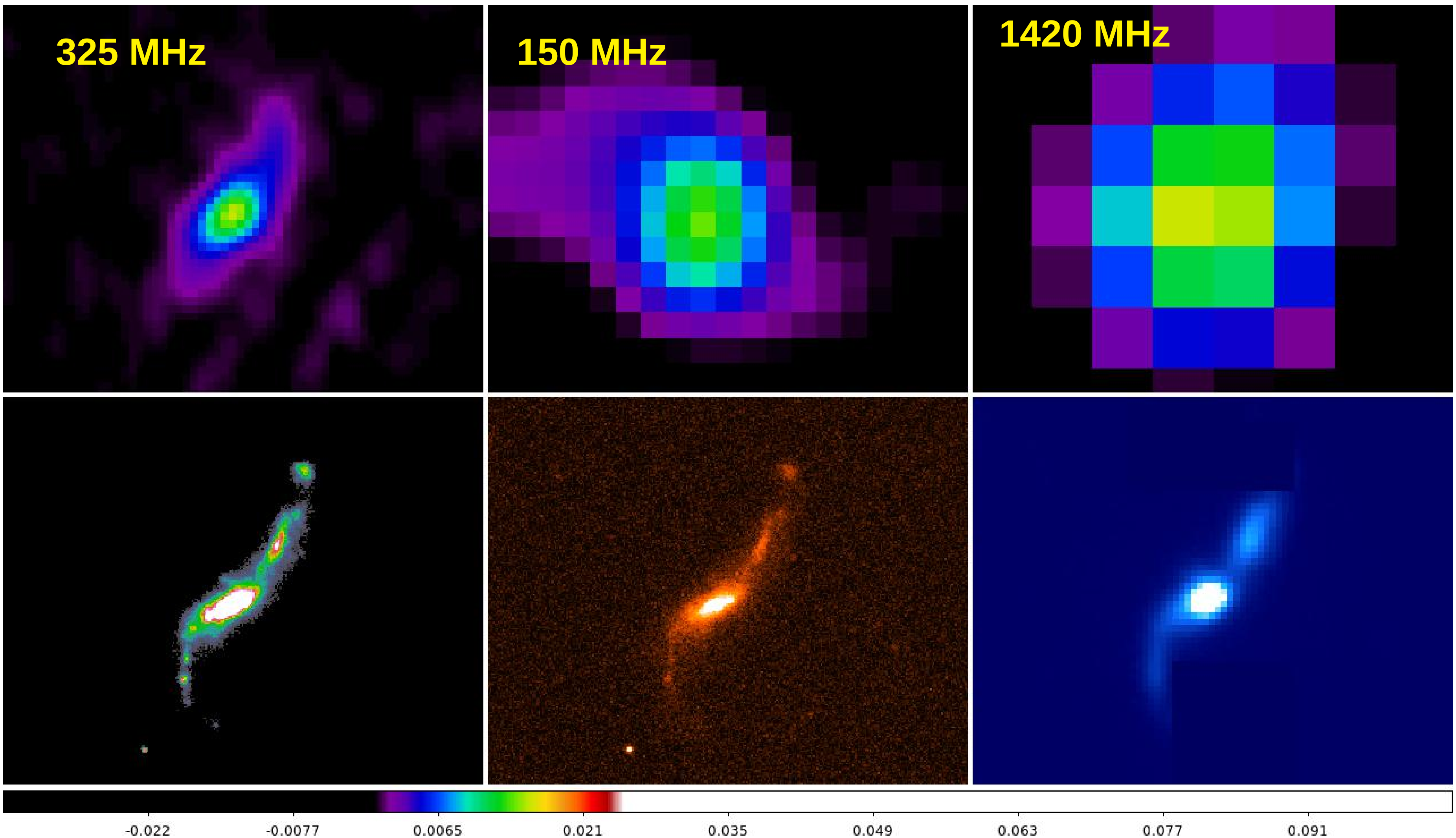






UGC00749

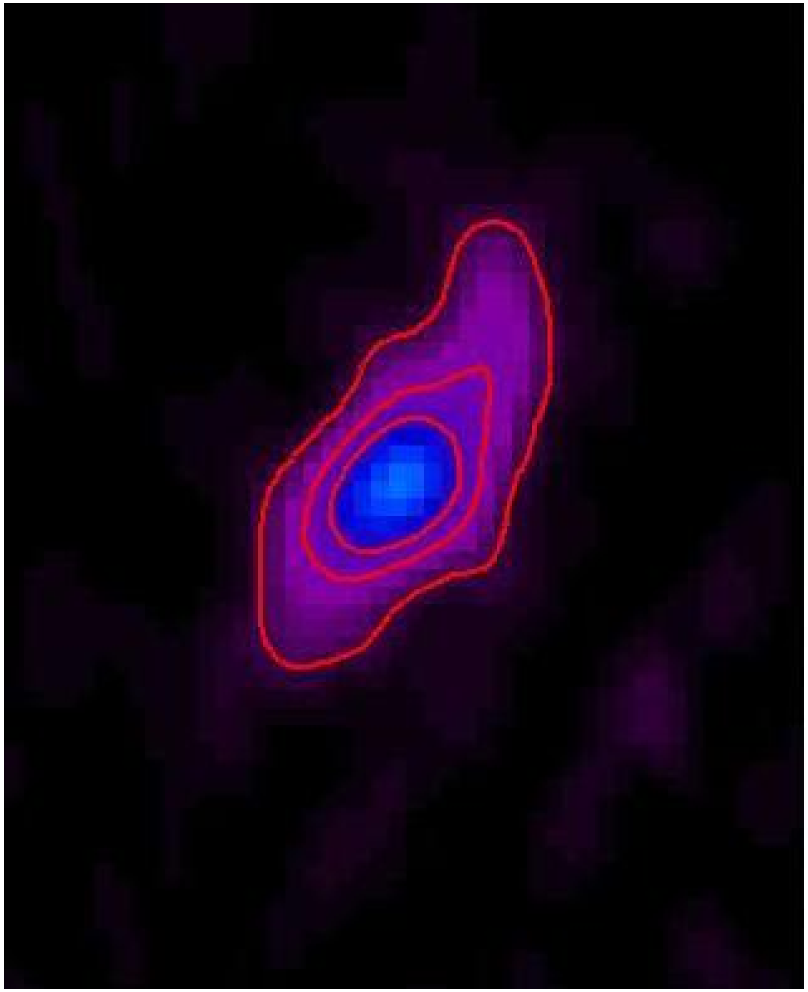
- It is close to edge on, S-shaped star forming galaxy.



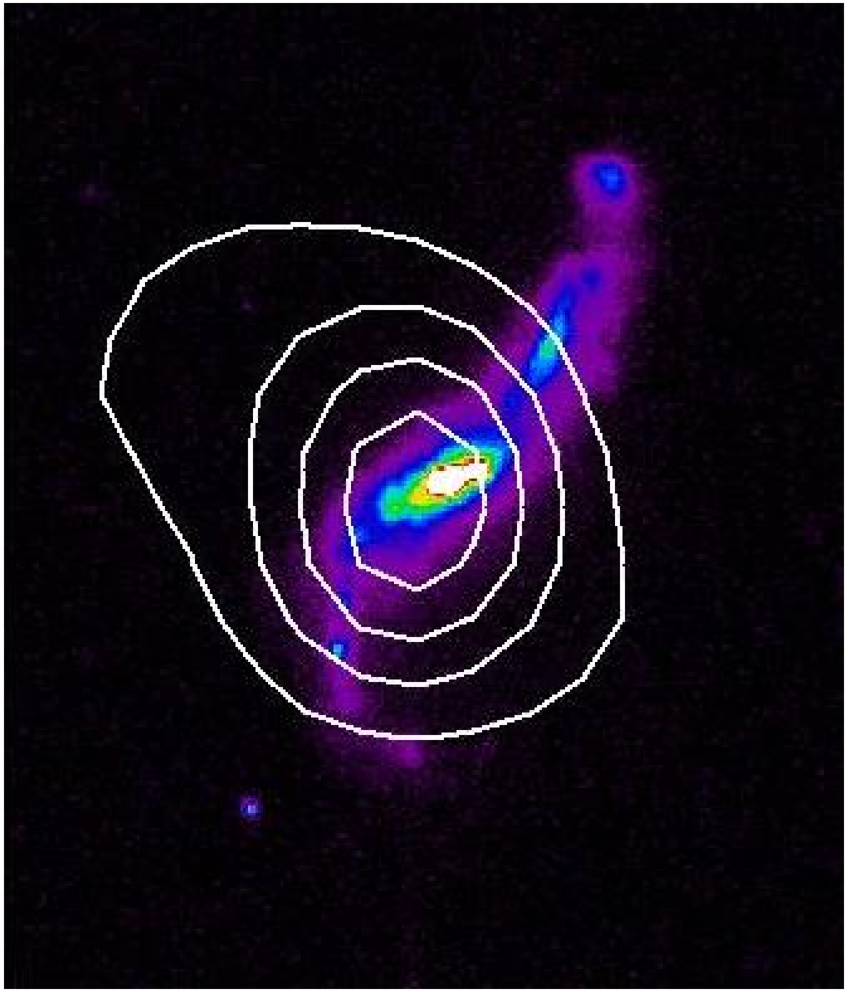
UGC00749

- 325MHz emission mainly along disk. Signatures of 150MHz emission from the galaxy disk that could be due to outflows of height~15kpc.

325 MHz

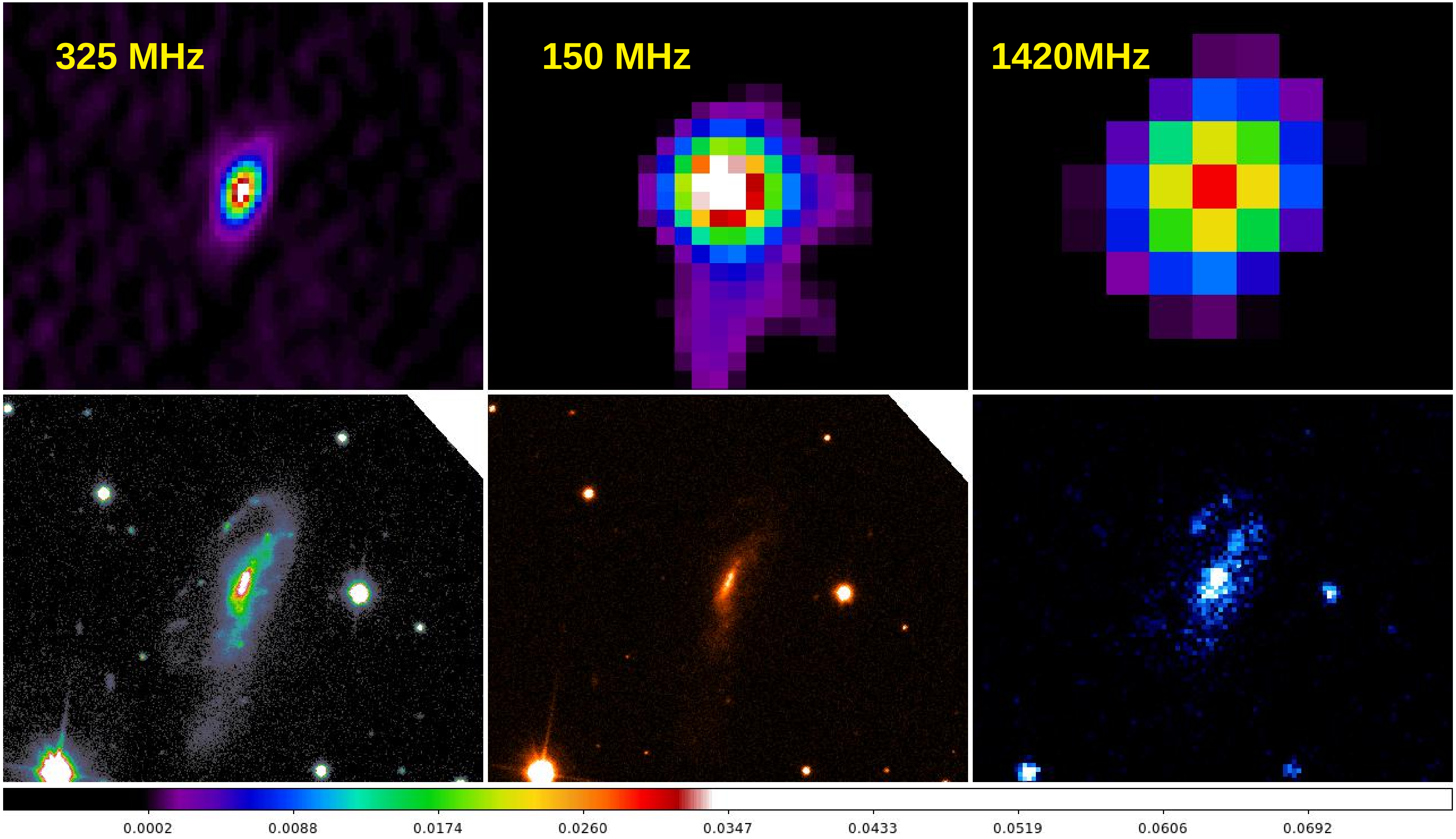


Optical with 150 MHz



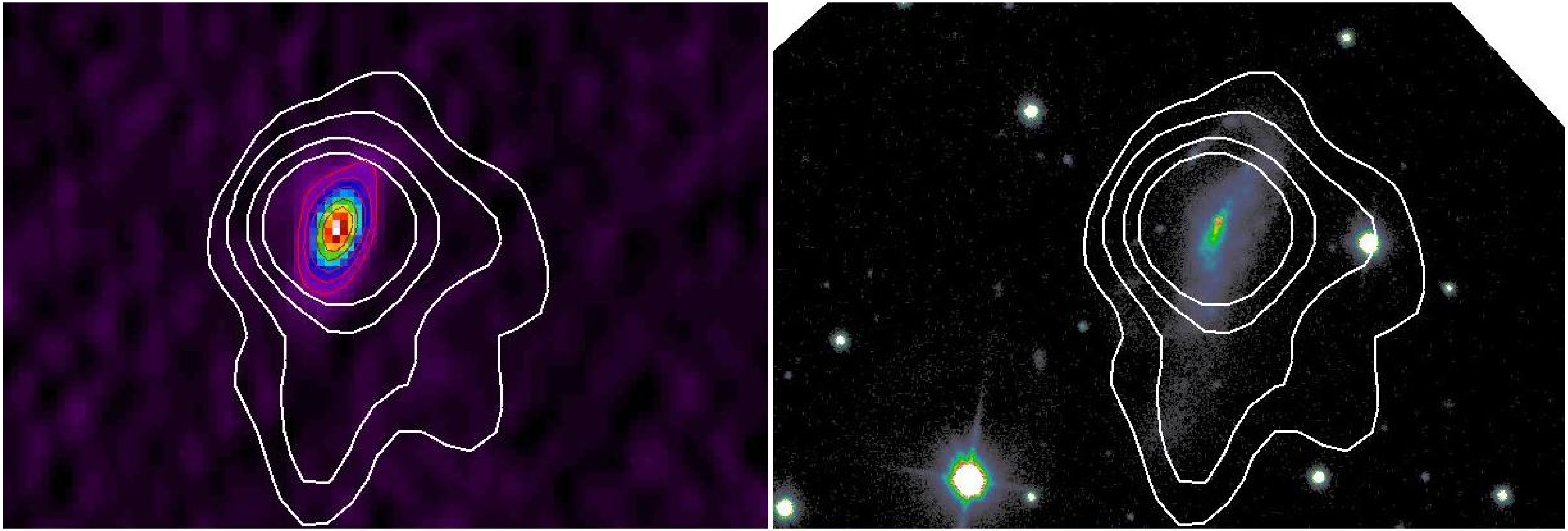
UGC10514

- It is a star forming galaxy with extended, tidal features.



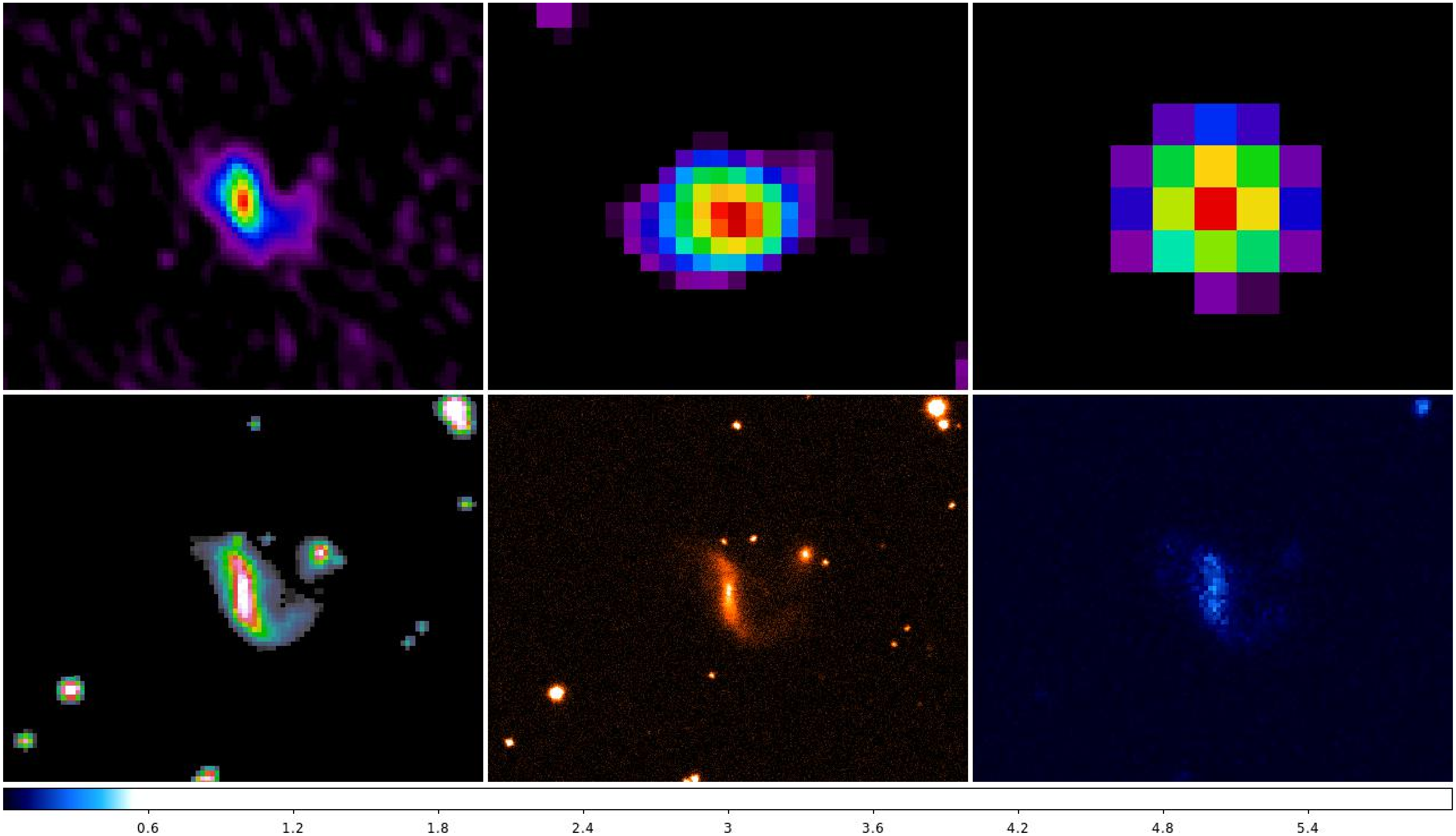
UGC10514

- The 325 MHz emission associated with the disk. But the TGSS 150MHz emission is extended to ~18kpc above disk.
- The low frequency radio traces extended outflows.



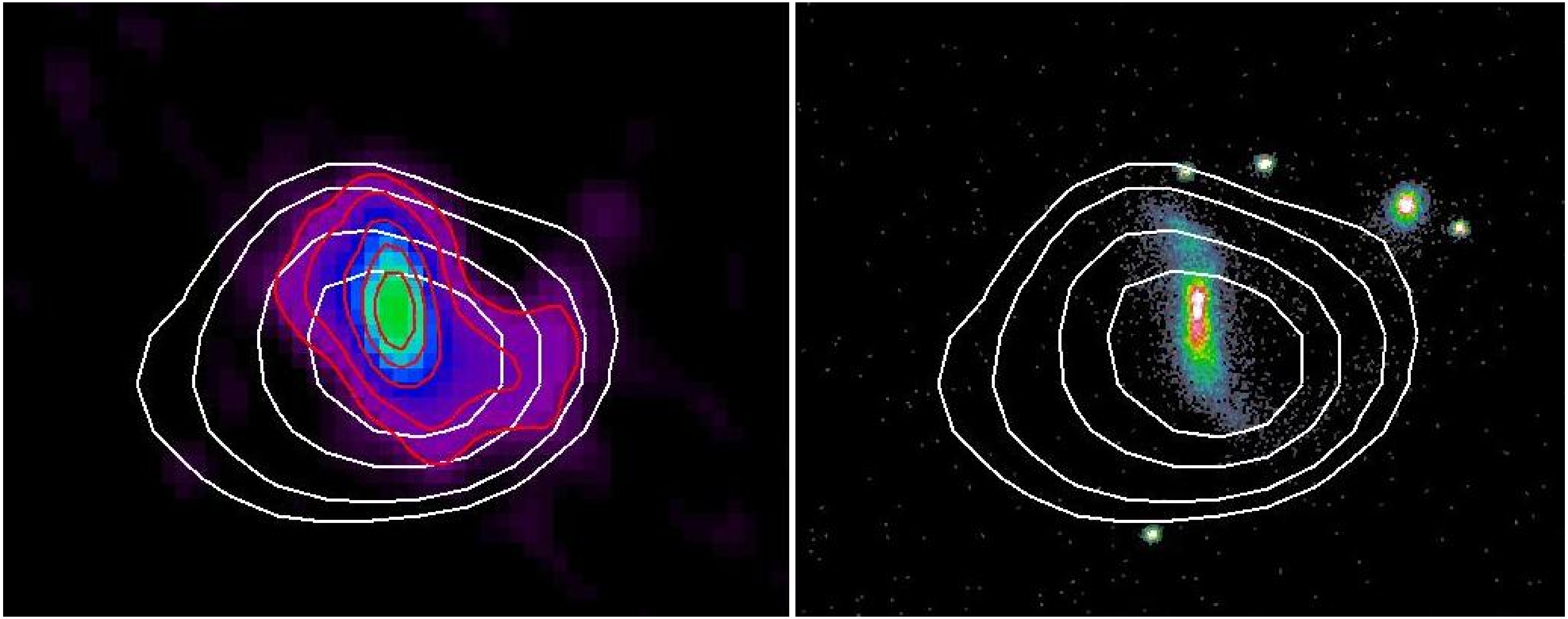
UGC12066 (MRK306)

- It is a closely interacting with companion.



UGC12066 (MRK306)

- The 325 MHz emission is close to the galaxy disk and associated with extended tidal tail. But TGSS 150 Mhz emission is extended and could be due to outflows. Extends out to ~20kpc.



Summary of radio continuum observations around star forming void galaxies

The star forming galaxies have 325MHz emission mainly associated with the disks.

The extended emission due to outflows is best traced with 150 MHz observations.

The radio detection of outflows suggests that there is significant amount of hot as being fed into voids through the void galaxies themselves and not just from the clusters at the void walls.

Our main results

- We have detected tSZ signal from stacking of void galaxies. The emission is due to stellar feedback.
- We have detected low frequency radio emission (610, 235 MHz) around AGN host galaxies in the Bootes void.
- The interacting galaxy pair CG693-692 shows the largest radio and X-ray emission. CG693 has extended (~50kpc) X-ray emission which forms its CGM. It is fed by the Sy1 AGN. CG692 has a radio halo with emission at 1420, 610 and 235 MHz from a cooler CGM.
- We have detected outflows from isolated star forming void galaxies (UGC00749, UGC10514 and MRk306). The emission is more extended at 150 MHz TGSS ADR images. The isolated nature of these galaxies reveals that the 150MHz emission can extend out to ~20kpc.
- Hence 150 or 235 MHz is best for tracing the diffuse emission from star formation around isolated galaxies and determining the outflow extents and morphologies.