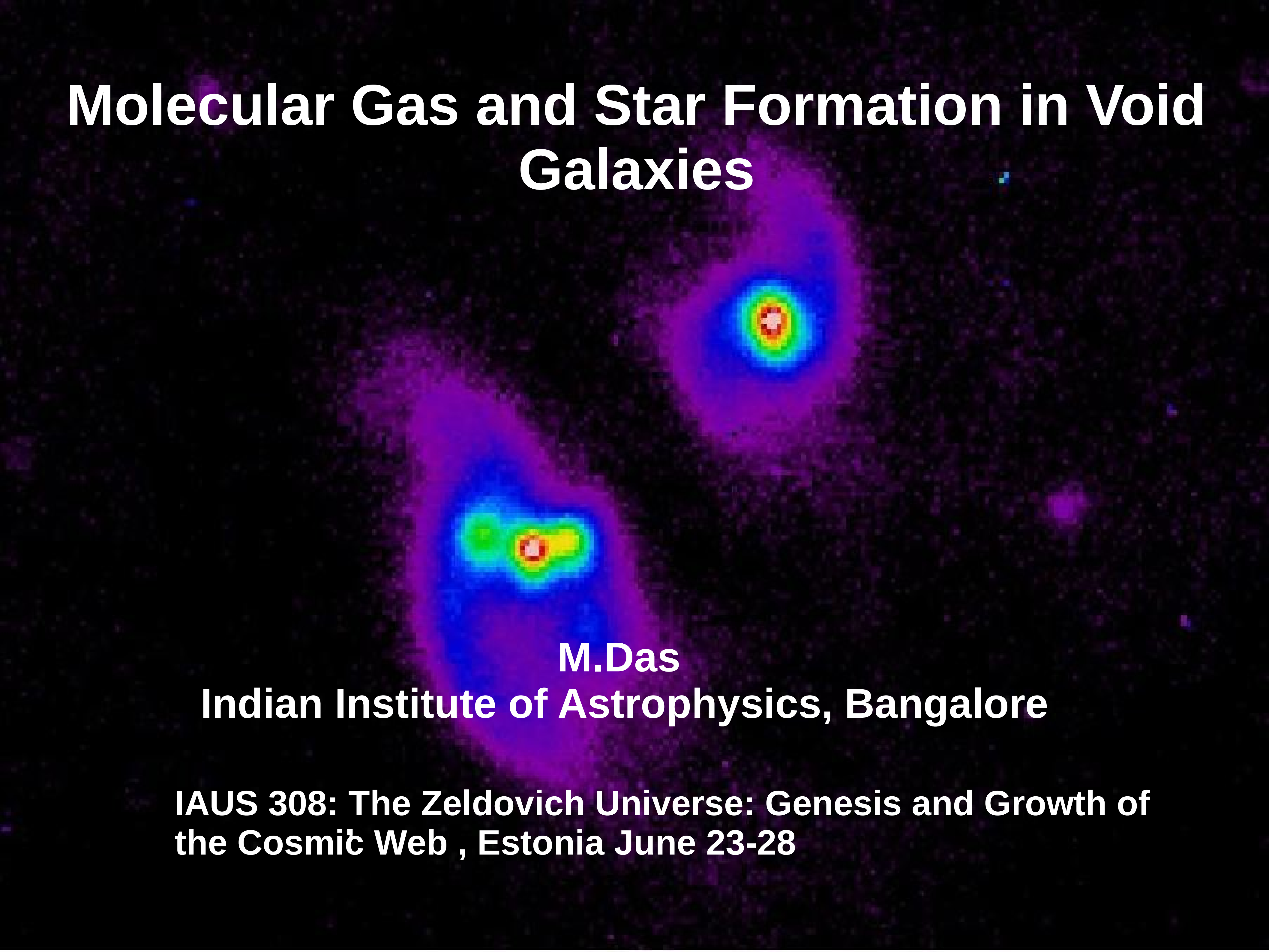

Molecular Gas and Star Formation in Void Galaxies

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IAUS 308: The Zeldovich Universe: Genesis and Growth of the Cosmic Web , Estonia June 23-28

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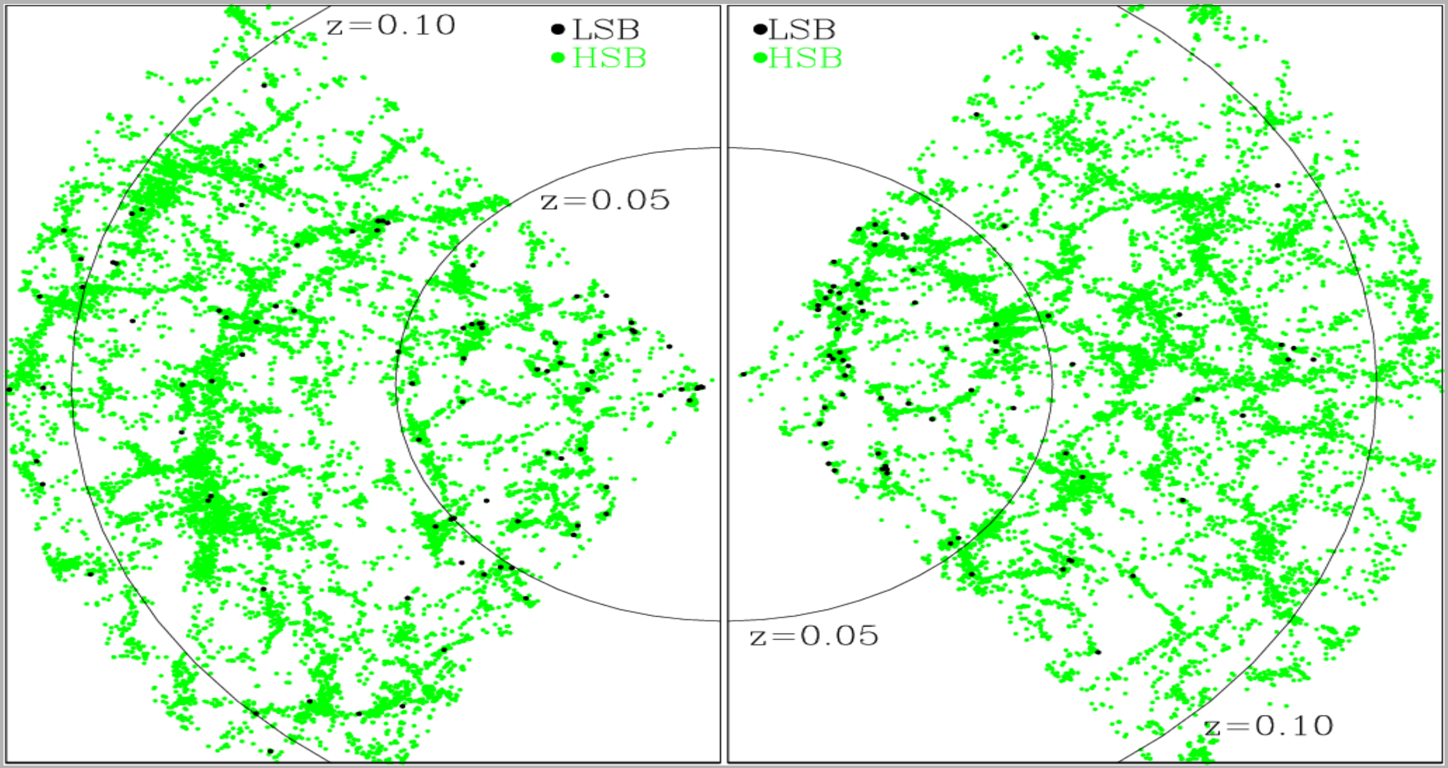
Low surface brightness galaxies near voids

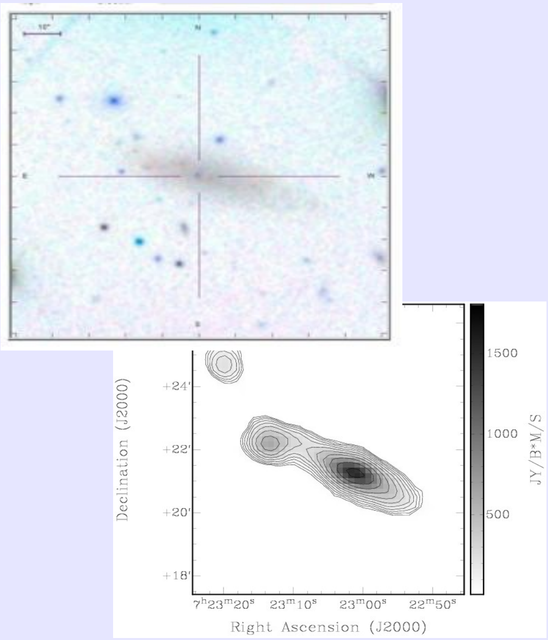
- CDM predicts that voids are populated by low luminosity galaxies such as dwarf spheroidals and low surface brightness (LSB) galaxies. However the detected number is much smaller than observed.
- The large gas rich low surface brightness (LSB) galaxies are usually isolated and lie close to the edges of voids.
- LSB galaxies are dark matter dominated, poor in star formation and have little molecular gas.



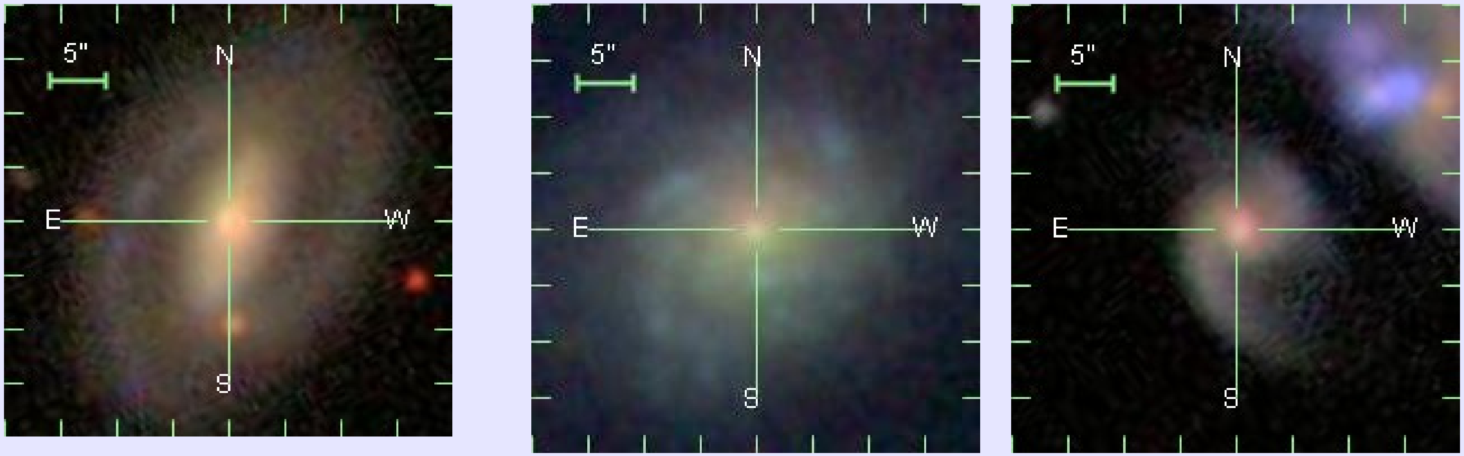
SDSS DR4 map of bright galaxies in green and LSB galaxies in black (Rosenbaum et al. 2009)

Void Galaxies

- They are gas rich, late type disk galaxies that lie within voids. Usually spirals and irregulars; ellipticals less common.
- 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; Szomoru et al. 1997).



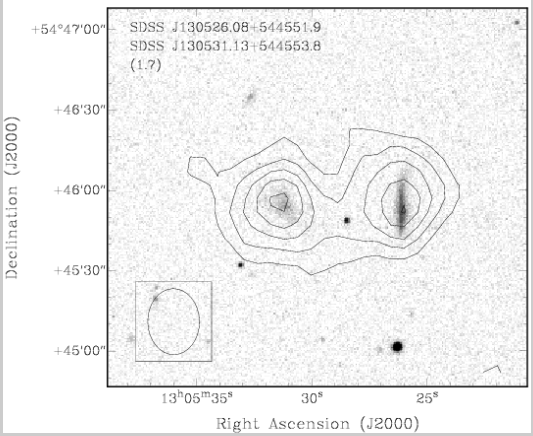
Gas rich dwarf galaxies in the Lynx Cancer void (Chengalur & Pustilink 2013)



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

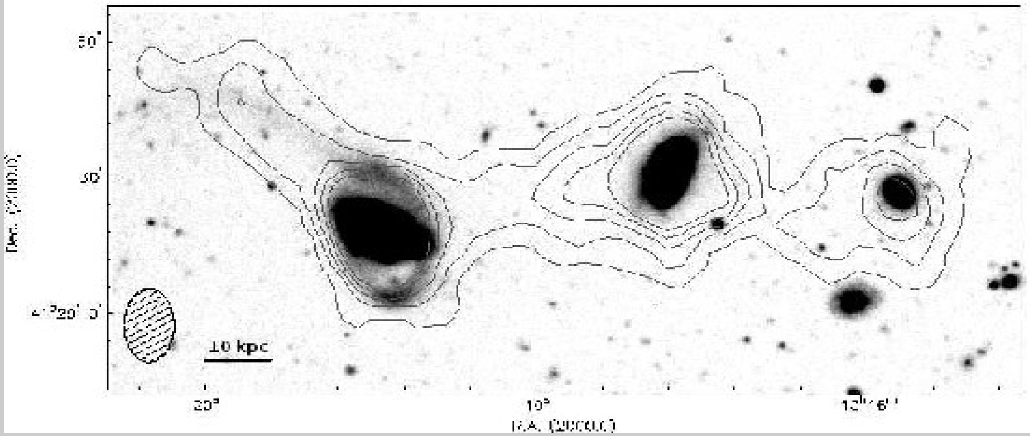
Groups/Interacting Pairs : Signatures of Void Substructure?

Stanonik et al. 2009



CG693-692 : Interacting pair in Bootes void

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



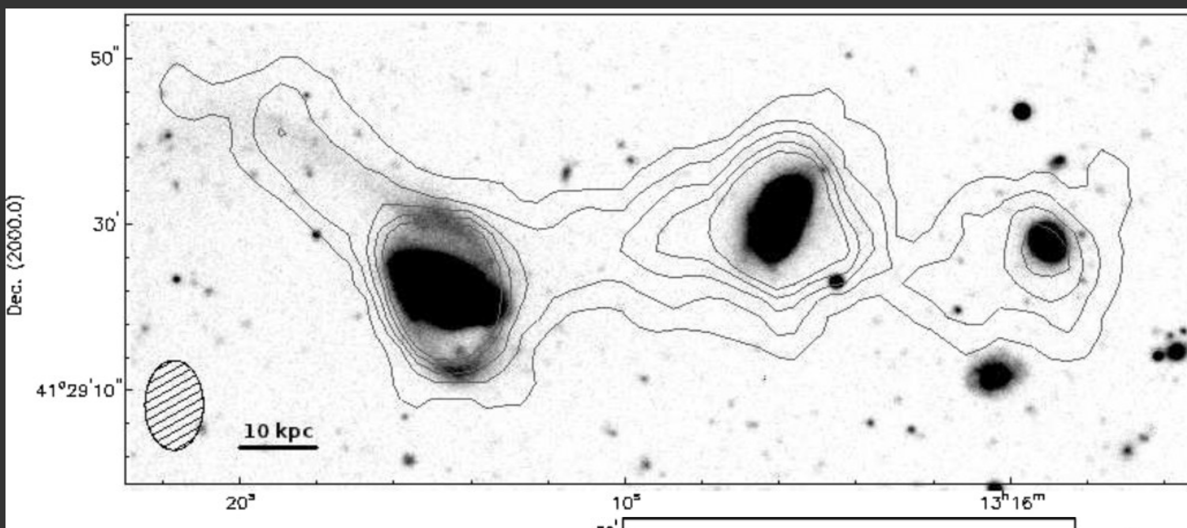
There are many examples of interacting pairs, polar ring galaxies and even small groups of galaxies residing in voids.

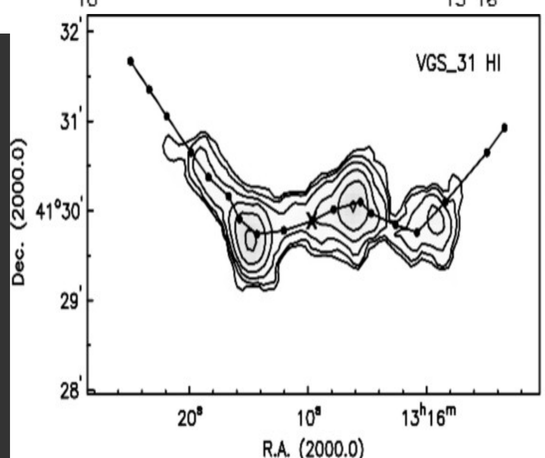
These galaxies may have formed when smaller voids merged to form larger voids. This merging process can lead to the formation of filaments within larger voids – thus creating a void substructure.

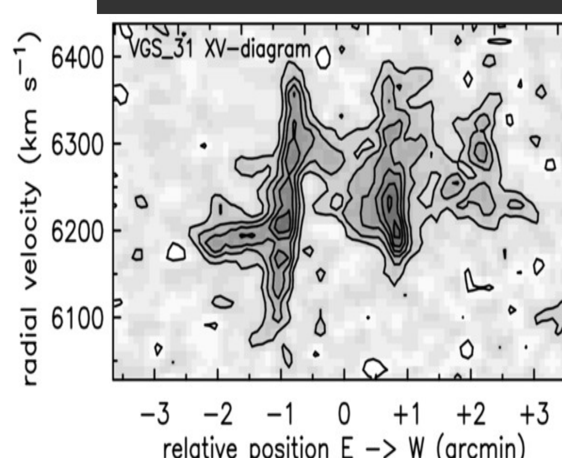
Gas Flow along Void Substructure

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 foremation. As a results 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.







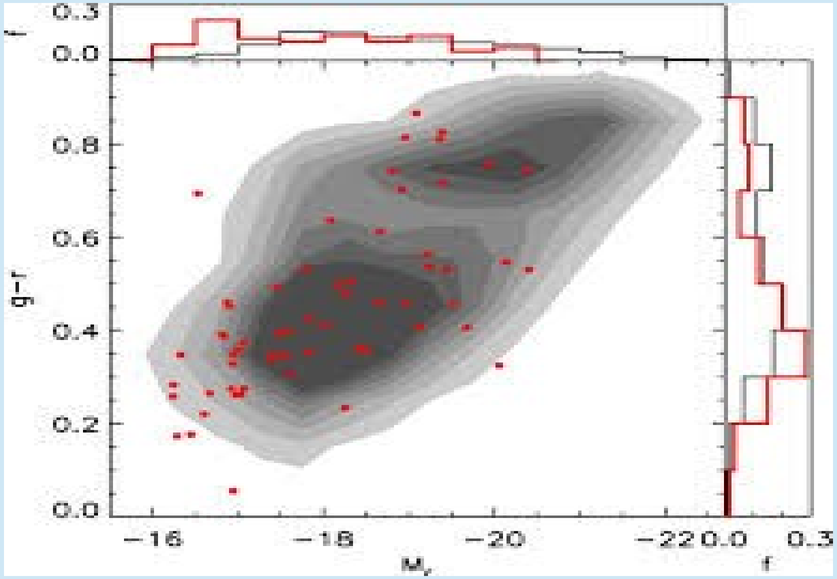
(Beygu et al. 2013)

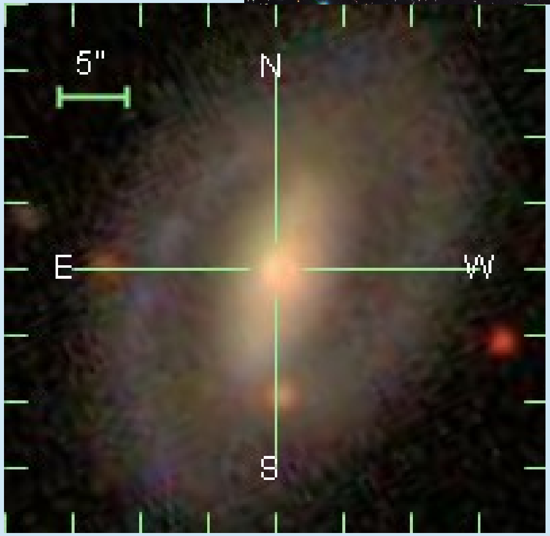
Star Formation in Void Galaxies

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.

When plotted 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.

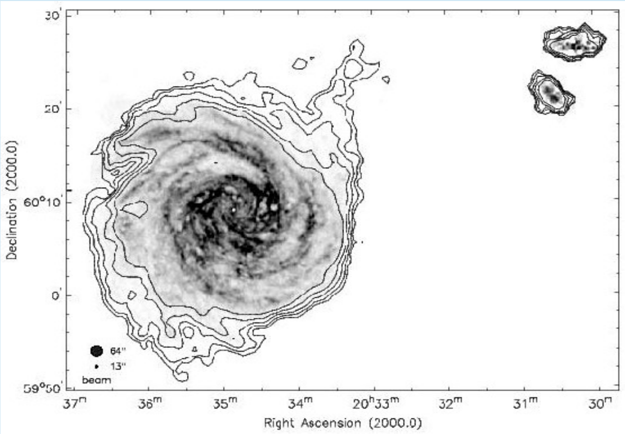
Color magnitude diagram for galaxies in the Void galaxy Survey (Kreckel et al. 2012).



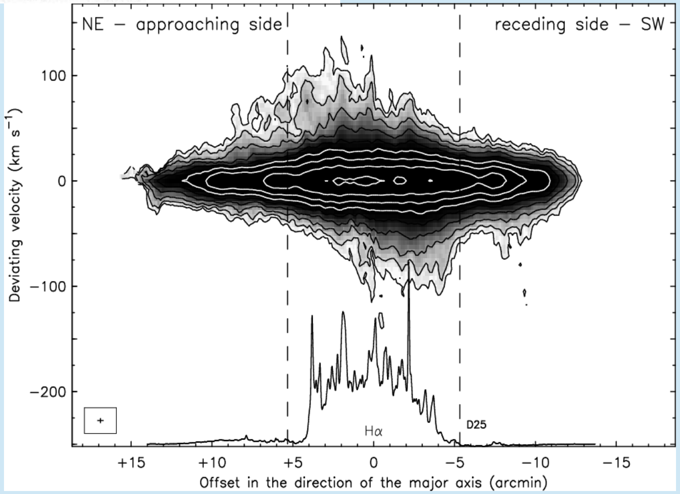


What triggers star formation in void galaxies?

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 neighbours or with HI dominated galaxies that we do not see in optical images. The interactions trigger the star formation.

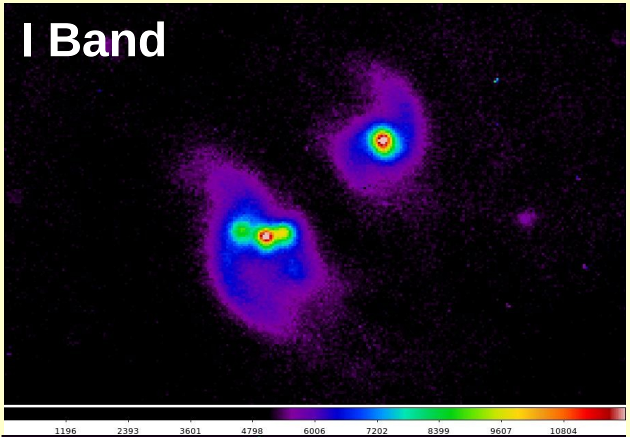
2. Gas accretion onto galaxy disks can shock gas and trigger star formation. Or cold gas accretion makes the disks unstable and results in onset of star formation.

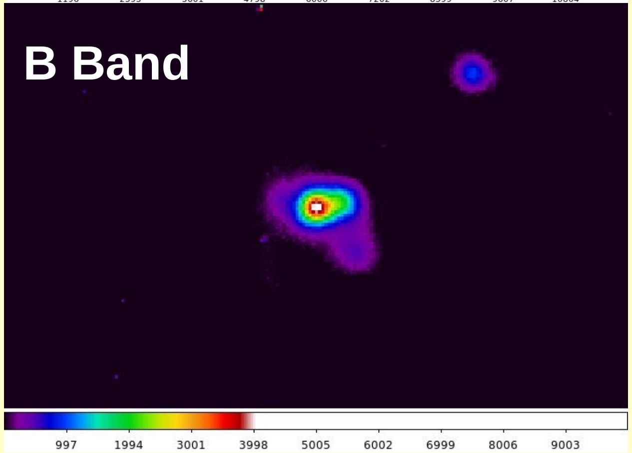
3. Void merging can result in more gas accretion (e.g. Polar ring galaxy in void wall).

Signatures of more evolved void galaxies: bulges and AGN

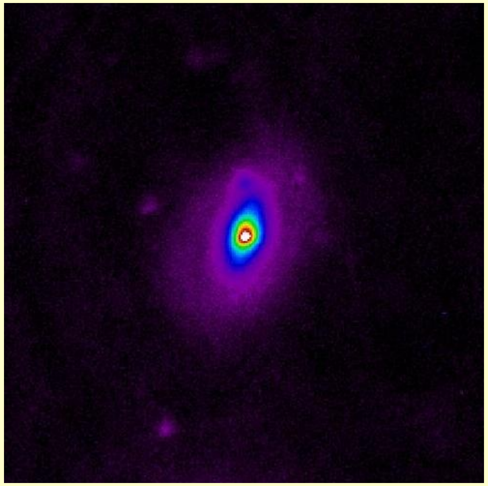
- Star formation will result in gas infall and the growth of bulges and AGN. The Bootes void has examples of more evolved void galaxies that show AGN-bulge evolution.

CG692-CG693

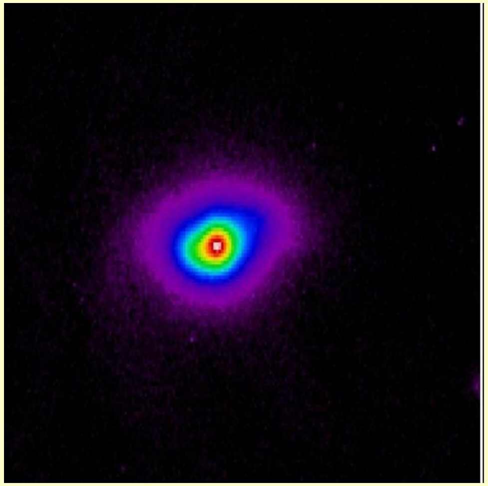




SBS 1428+529



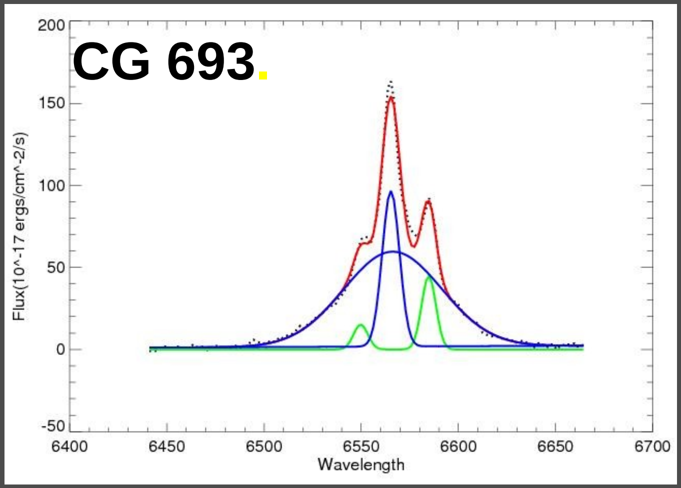
SBS1325+597

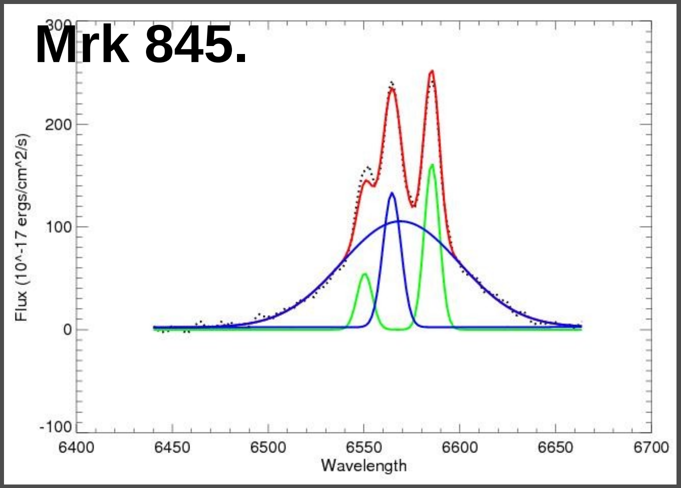


AGN and Black Hole Masses in Void galaxies

- Bulges appear less prominent in void galaxies and .AGN are not common.
- However, of the few that have AGN, the black hole masses are a few times 10^7 solar masses and and show activity simialr to galaxies in normal environments.

The spectral decomposition of the Halpha line in CG693 and Mrk845. The black hole mass lies on M-σ relation

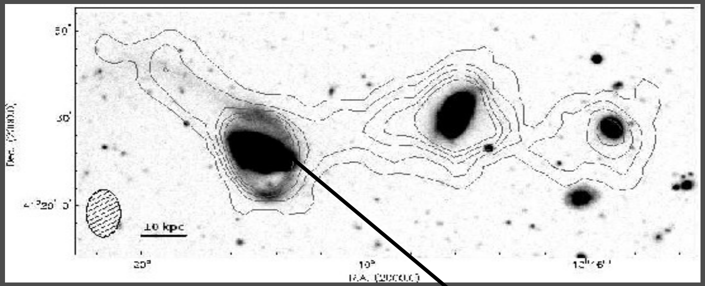




(Subramanium et al. In preparation).

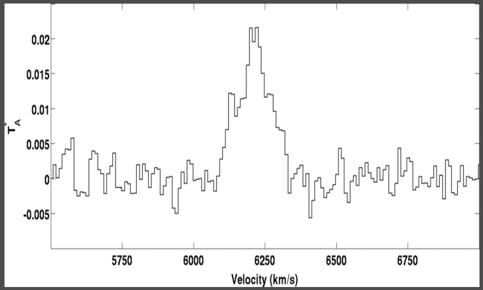
Cold Gas in Void galaxies

- 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).
- The detected galaxies all had high far infrared fluxes or showed signatures of star formation associated with interactions.

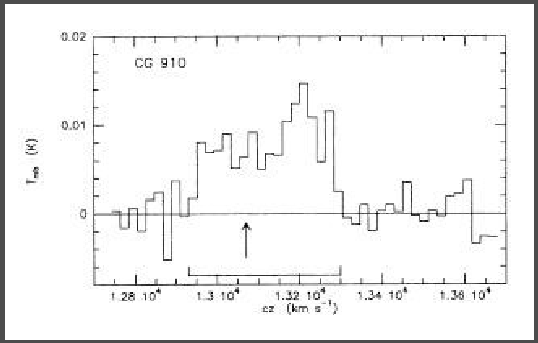


The molecular gas masses are in the range 10^7 to 10^8 solar masses. Suggests that the larger void galaxies have significant gas and dust.

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

Goals of Our Study : Molecular Gas and star formation in void galaxies

- Detection of molecular gas in void galaxies. Is molecular gas common in these galaxies? Or are they usually devoid of H_2? What are the molecular gas masses?
- What is the H_2 gas morphology? Are there signs of gas accretion?
- Are disky void galaxies similar to low surface brightness galaxies (LSB galaxies are low in star formation, low metal content and dark matter dominated)?
- Is the star formation in void galaxies different from nearby field galaxies? What triggers the star formation in the isolated void environment?

The Observations

Nobeyama Radio telescope

Sample galaxies were observed in April 2013 with the 45m Nobeyama telescope. In March 2014, we observed again but due to poor weather conditions, we could not obtain any more data.

Hmalayan Chandra telescope

Three of the sample galaxies that were detected in CO by NRO were mapped in Halpha emission with HCT. The other two were too far for our Hα filters.

CARMA

We observed the Bootes void galaxy CG910 with CARMA in May 2014 as a pilot study for mapping CO emission in void galaxies.

Sample Galaxies and the Observations at Nobeyama Radio Telescope

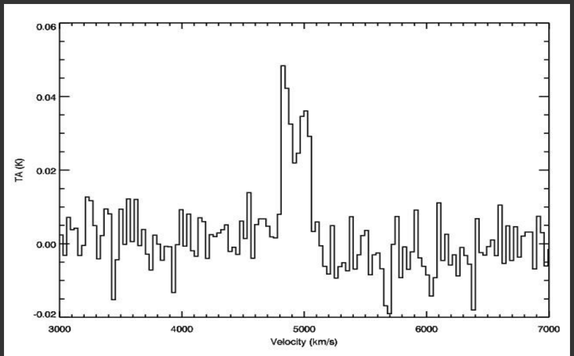
- **We had a sample of 12 spiral galaxies that were from nearby voids and a few from the Bootes void (e.g.Szomoru et al. 1996; Kreckel et al. 2011). The galaxies were selected based on their relatively high IRAS fluxes or strong Hα line emission.**
- **All the galaxies were regular spirals. All 5 appeared to be isolated.**
- **Three of the detected galaxies were imaged in Hα emission. For the other two, we did not have suitable filters.**

Nobeyama CO(1-2) Detection in Void Galaxies

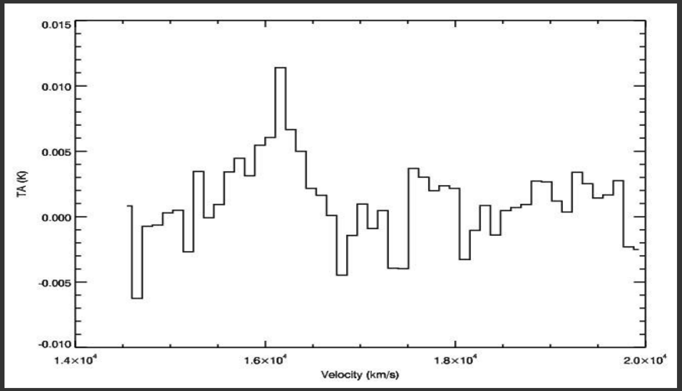
Galaxy	VSYS km/s	Redshift	Type	CO(1-0) Flux K Km/s	Noise (K)	Observing time (hours)
CG 0598	17226	0.0575	HII, Sbrst	5.2±0.1	0.0004	2.5
SBS 1325+597	4956	0.0165	Sm	10.7±0.2	0.0021	1.0
SDSS J143052.33+551440.0	5295	0.0177	....	7±0.2	0.0020	1.25
SDSSJ153821.22+331105	6630	0.022	Sd	6.4±0.2	0.0023	1.5
SBS1428+529	13329	0.0445	Sy2	.....	....	1.5

CO(1-0) Detections

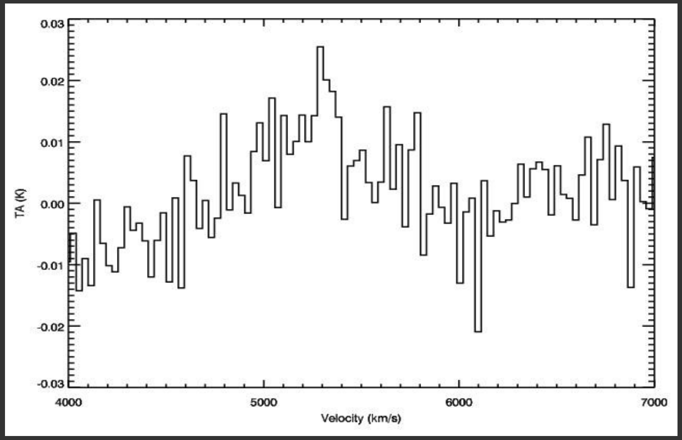
SBS1325+597 (VGS_34)



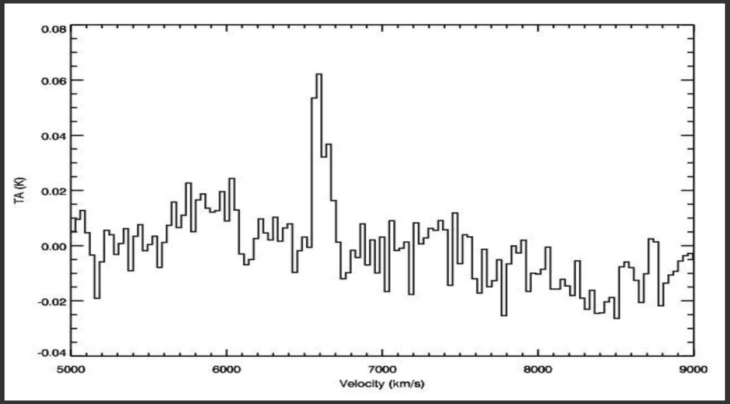
CG 598



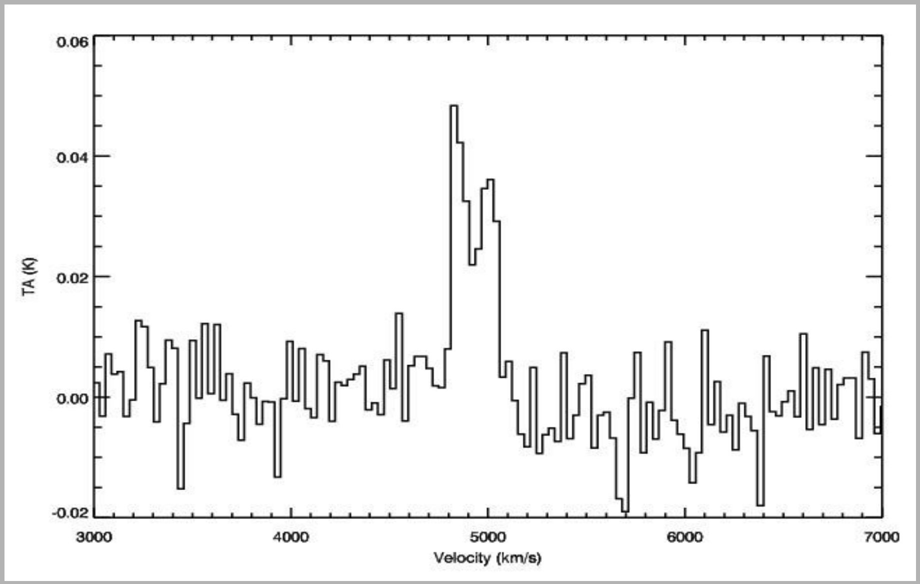
SDSS1430+5514 (VGS_44)

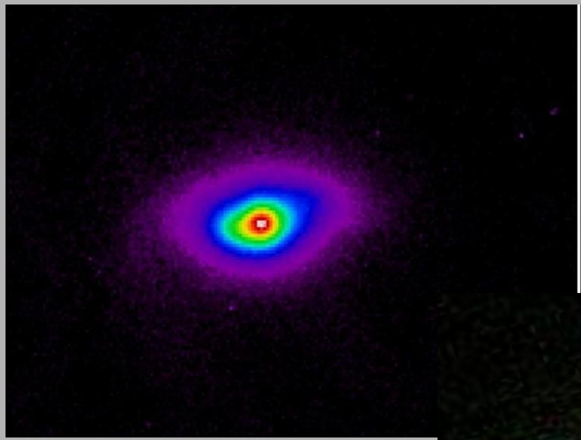


SDSS1538+3311 (VGS_57)



SBS1325+597 (VGS_34)





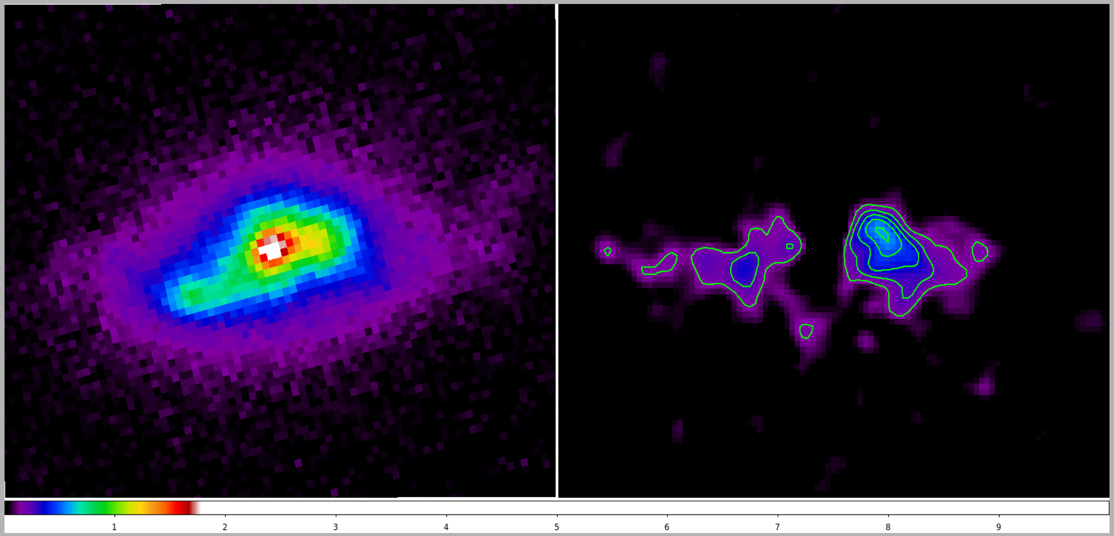
Preliminary HCT I band image

SDSS image of galaxy

- The galaxy has a small optical size of ~10.7kpc at a distance of 70.4Mpc but has a very massive HI disk; M(HI)=23.9x10^8 solar mass (Kreckel et al. 2011). M(H_2)=8.5x10^7 solar mass. The ratio M(H_2)/M(HI) = 0.04 and is low. The molecular gas surface density is moderate – but the total gas mass is high.
- The profile has a prominent double horned structue which shows that the molecuar gas is in a rotating disk. The velocity separation is ~250km/s. Hence the rotation velocity ~125km/s.

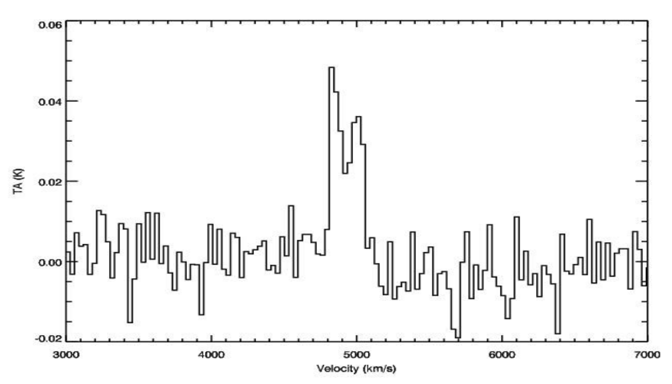
SBS1325+597 : Hα Imaging

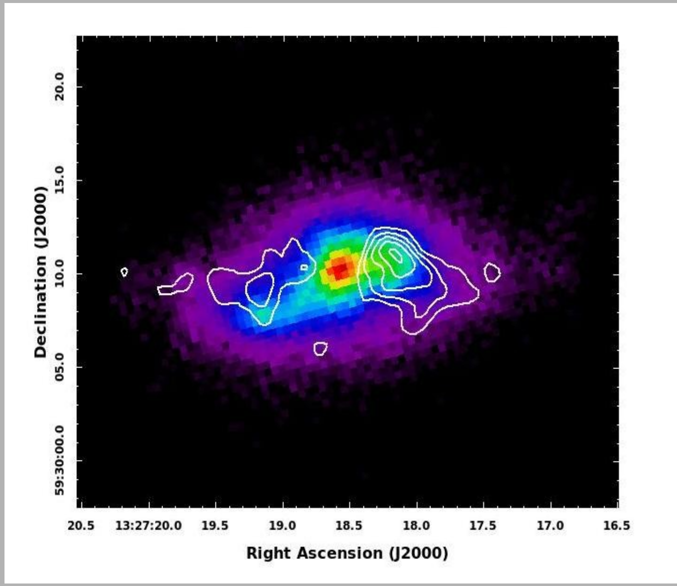
The SDSS B band image (left) and HCT Halpha image (right) of SBS1325+597.



From the Hα flux we obtain a SFR=0.20 solar mass/year (Kennicutt 1998).

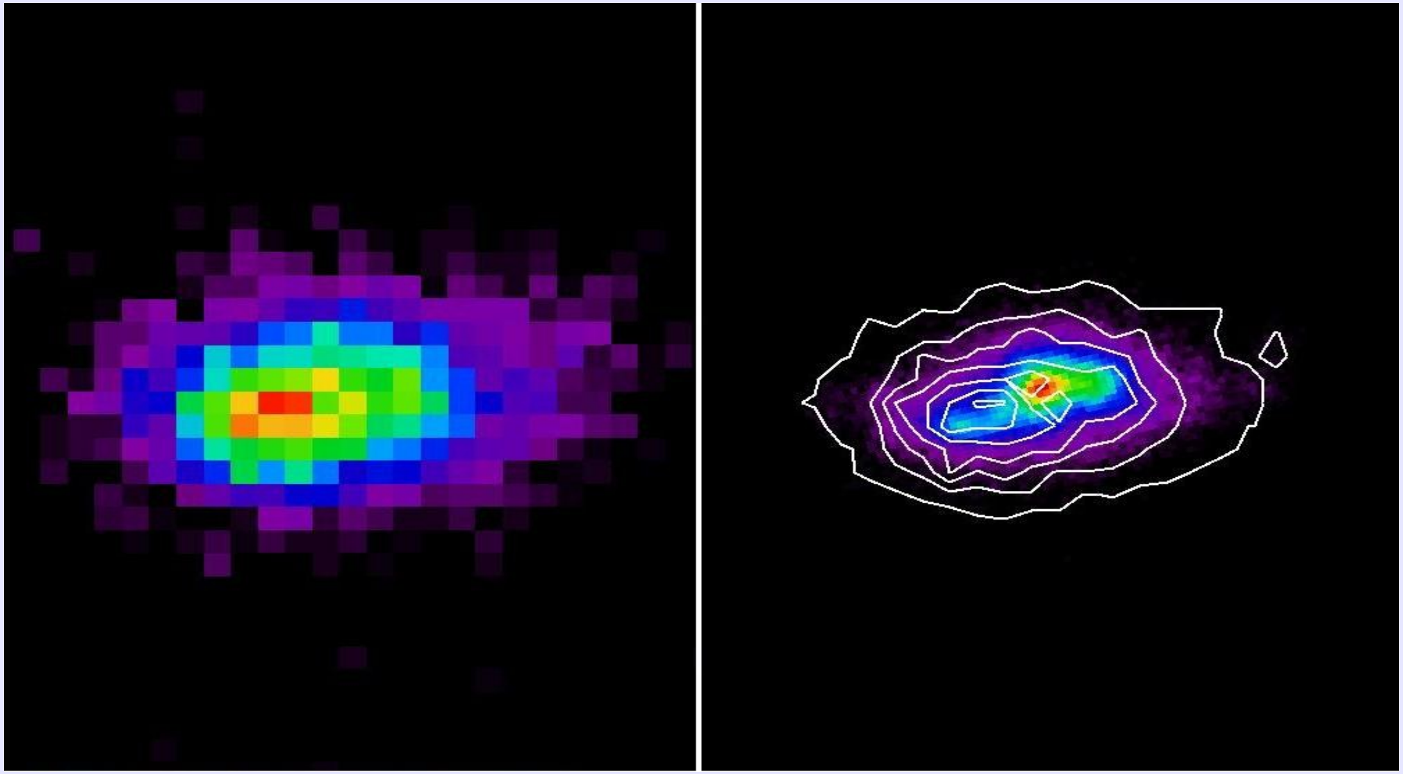
- **The Hα disribution is in a ring about galaxy center. Much like the CO distribution.**



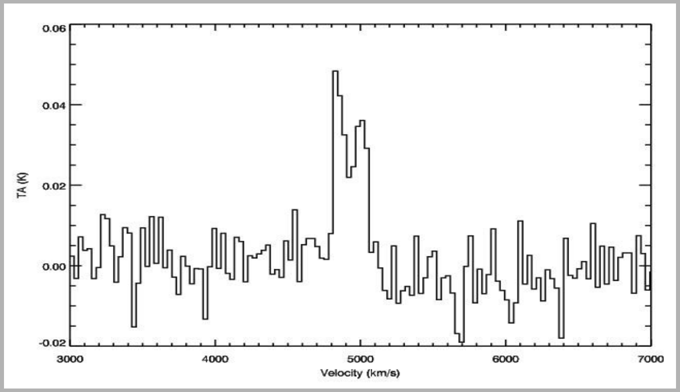


SBS1325+597 : UV emission

The GALEX near UV image shows emission that has a scale slightly larger than the g band image of the galaxy. The peak emission is slightly off from the galaxy center.



SBS1325+597 : dark matter mass

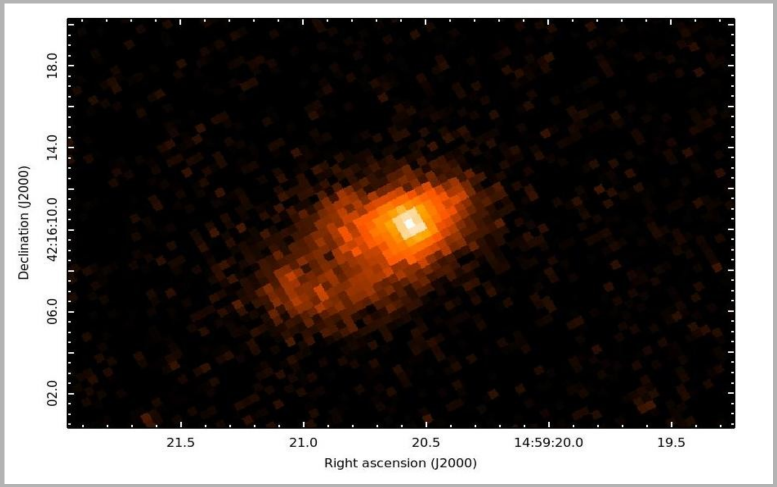


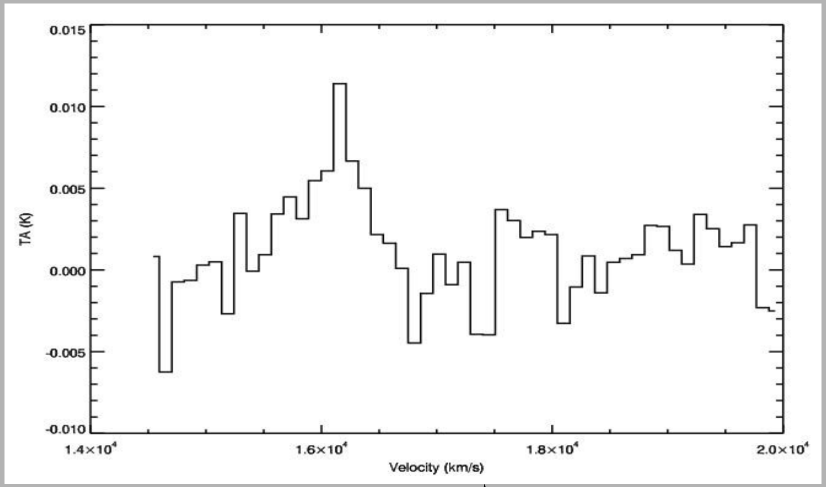
We used the color of the galaxy to determine the mass to light ratio (M/L) in k band. Using the 2MASS flux the stellar mass $2x10^7$ solar mass.

From the CO and HI profile the HI dynamical mass was determined to be $3x10^{10.}$ So baryonic fraction is 9% of dynamical mass.

So dark matter is ~90%.

CG 598 : A galaxy in the Bootes Void



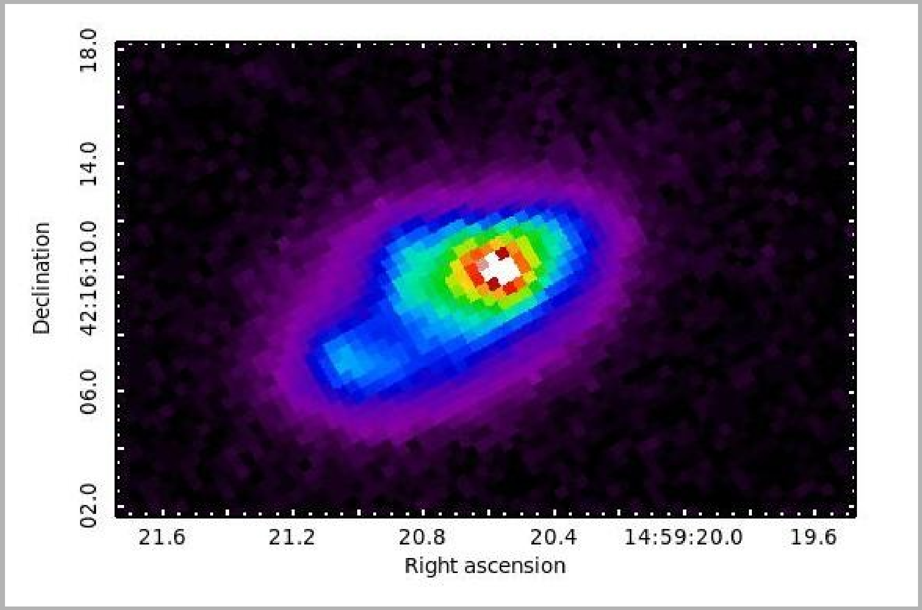


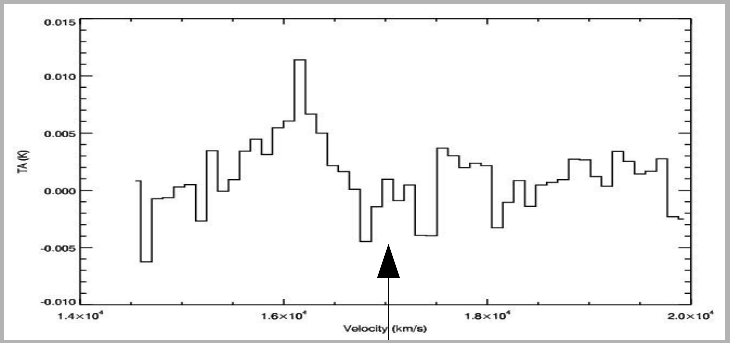
V_0 = 17226 km/s

This is a distant galaxy lying in the Bootes void (z~0.05). It appears disky in all images but not much structure canbe seen, It is however large in optcal size ~52.5kpc.

- The molecular gas mass is $M(H_2)=4.6x10^8$ solar mass, which is quite large. The M(HI) mass is $\sim 3.6x10^9$ solar masses. The gas mass ratio is 0.13. The H_2 gas surface density appears to be high – at least on one side of the galaxy.
- The profile is one sided – the other half of gas emission from the disk is weak.

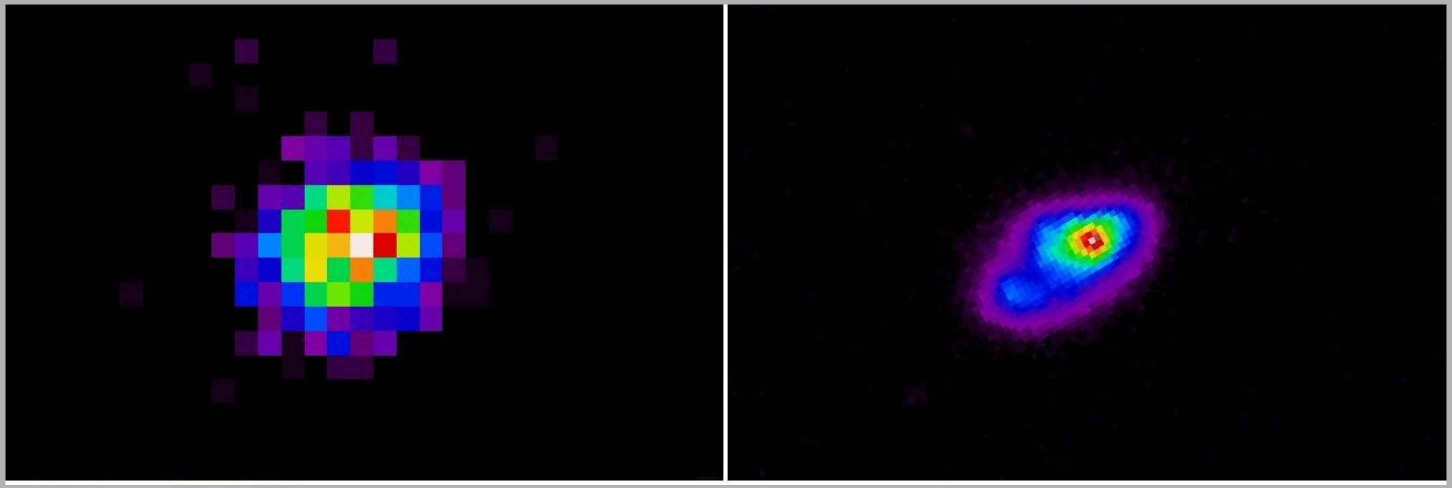
CG 598 : star formation



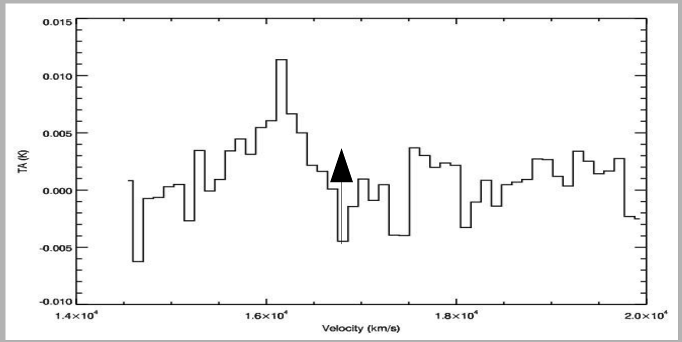


The g- band sdss image shows that the galaxy is accreting a smaller companion. Hence the larger size and off-center H_2 distribution. The interaction leads to clumpy H_2 and star formation.

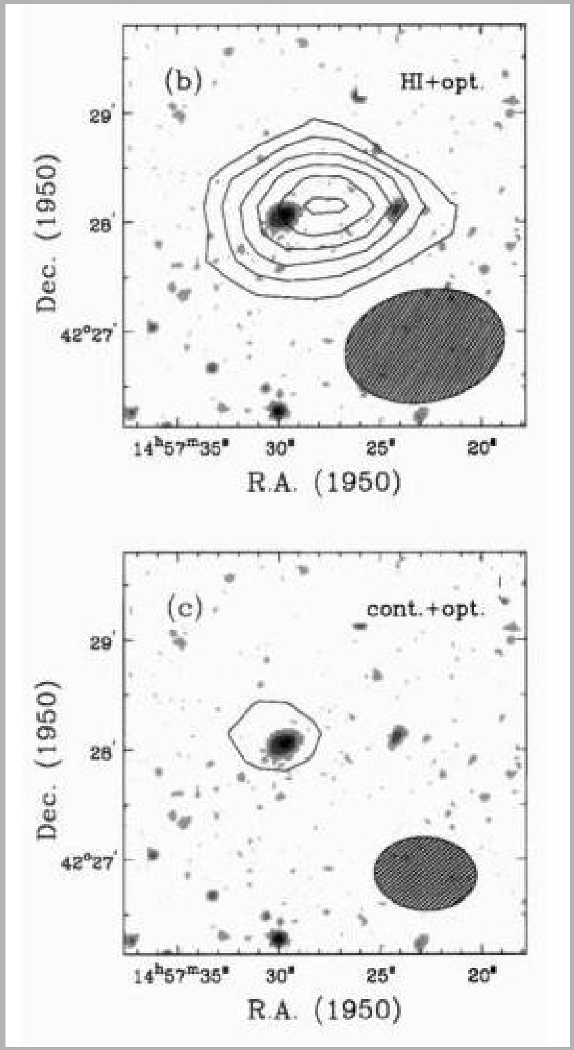
The NUV image superposed g- band sdss image shows that the galaxy has star formation. The rate is 0.17 solar mass yr^{-1}. The size is more extened than optica..



CG 598 : HI and H_2 Gas content



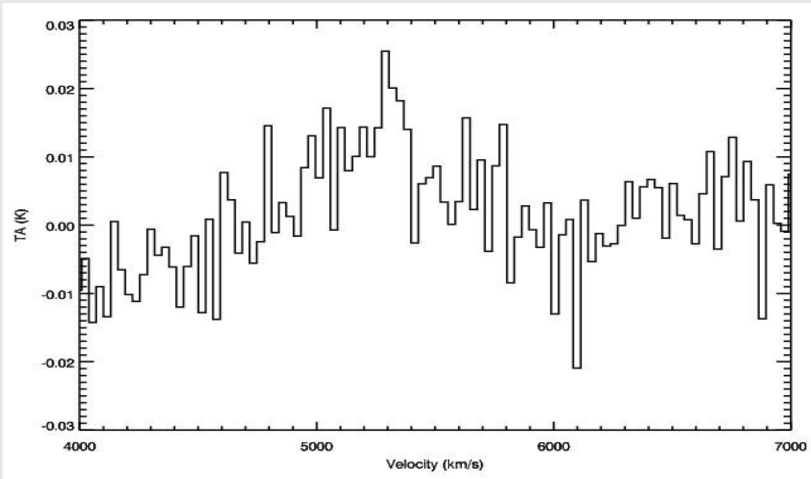
The HI map indicates that the galaxy maybe interacting with another companion galaxy that is further away. .



- However the obvious choice for the interacting galaxy is not at the coreect redshift. Hence there could be another companion galaxy causing tidal interaction.

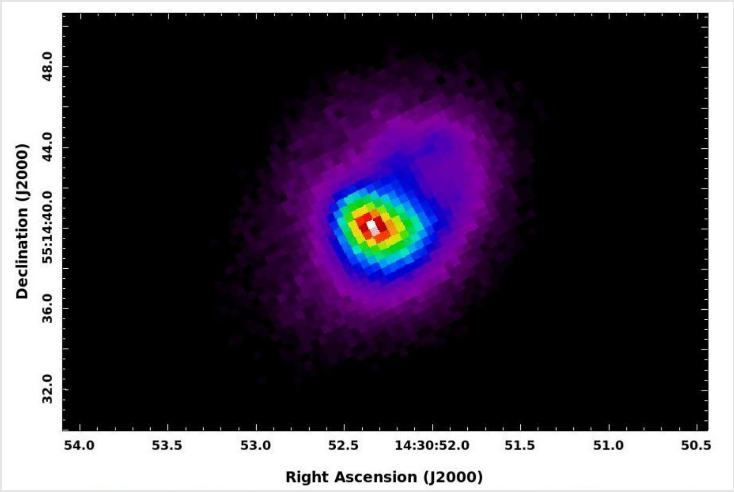
(Szomoru et al. 1996)

SDSS143052.33+551440.0 (VGS_44)



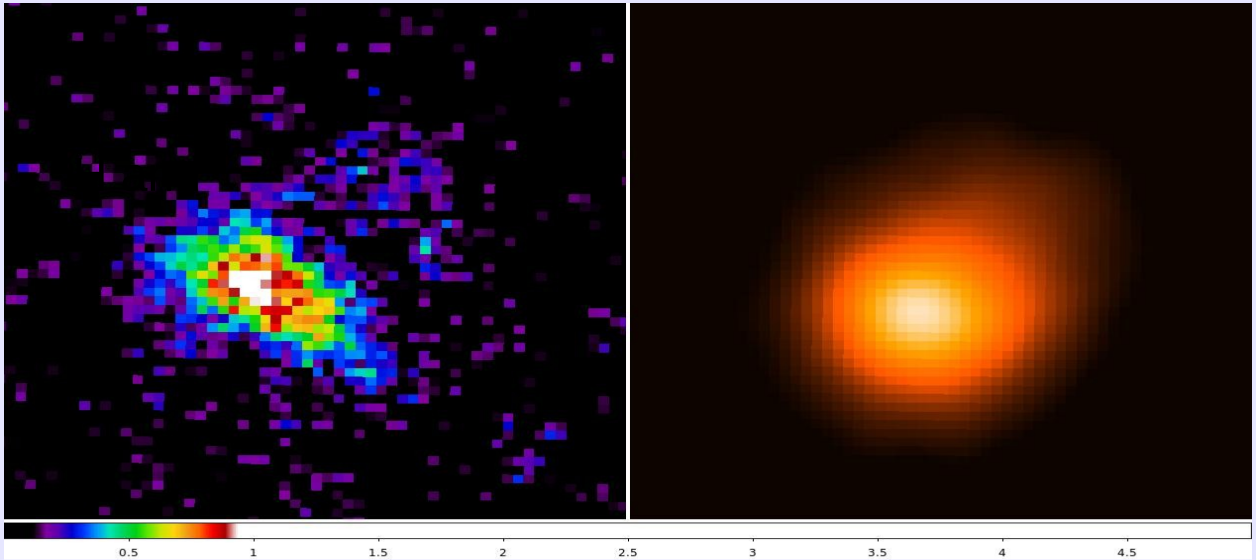
V_0 = 5295 km/s

SDSS g band image)



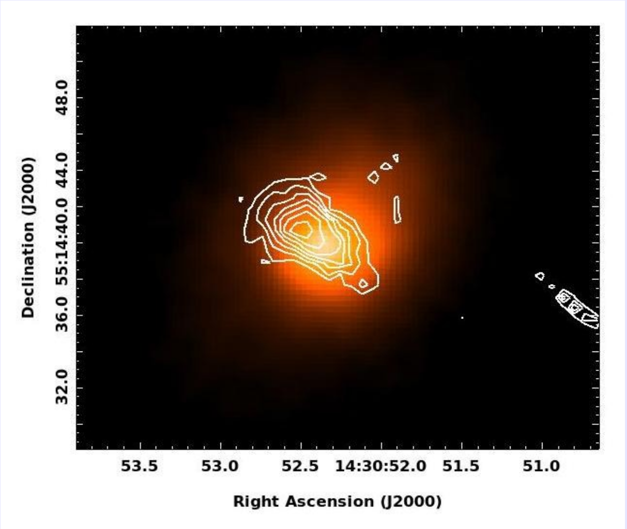
- This is a relatively small galaxy at distance of 76Mpc and has a stellar disk of ~15kpc.
- $M(H_2)=6.6x10^7$ solar mass. The ratio $M(H_2)/M(HI) = 0.13$; this is similar to our Galaxy. The gas surface density appears to be very high – but the galaxy size may be underestimated.
- The profile is one sided – the other half of gas emission from the disk is weak.

SDSS143052.33+551440.0 : Hα Image

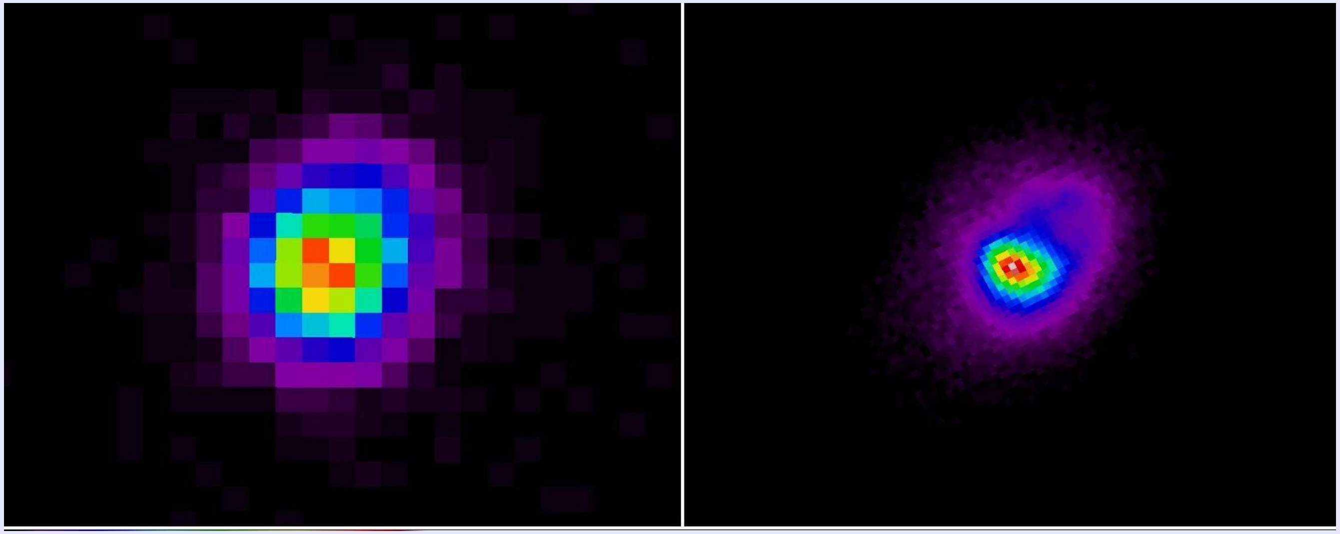


Hα on left and SDSS g band image on right. Emission is little lopsided.

- **The Hα emission gives a SFR=0.60 solar mass/year. This is similar to low luminosity spirals such (e.g. BCDs and LSB galaxies).**

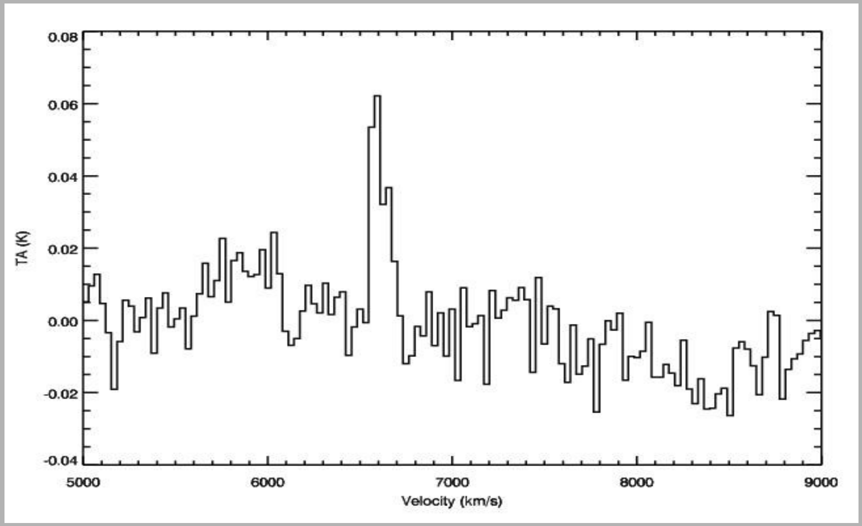


SDSS143052.33+551440.0 : Galex UV

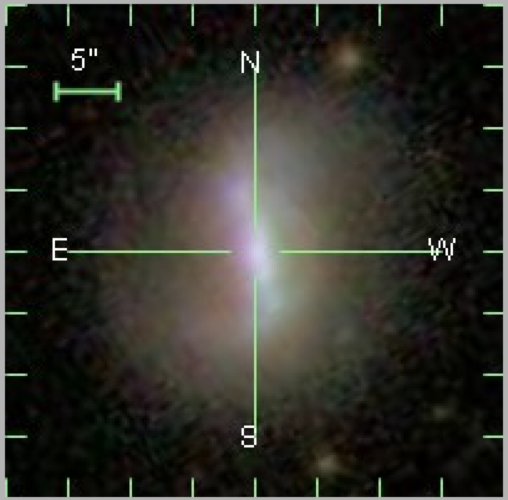


- Thie Galex NUV image is shown on the left and the SDSS g band image on the right.
- The NUV is slightly more extended than the g band emission (which is due to presence of young stars).

SDSSJ153821.22+331105.1 9(VGS_57)



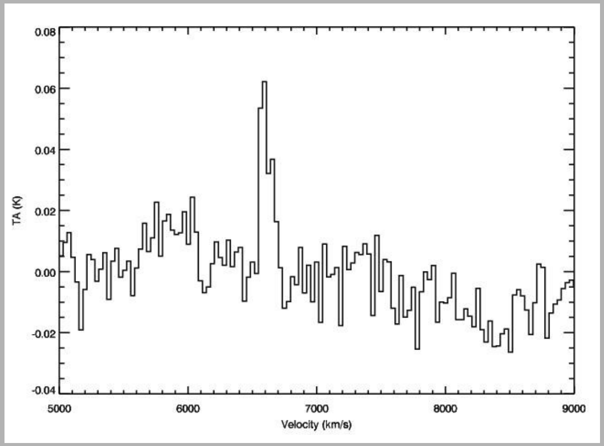
The galaxy is average in size (14.5kpc) but very blue in color and shows active star formation. No sign of interaction.



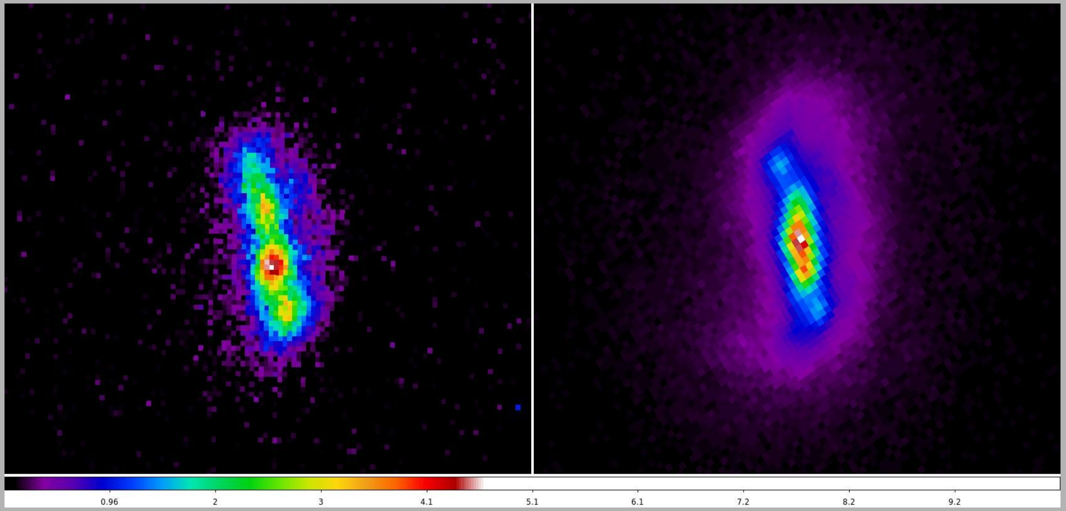
The molecular gas mass $M(H_2)=9.6x10^7$ solar mass and the M(HI) mass is $\sim 6.4x10^8$ solar masses. The gas mass ratio of molecular to HI is 0.15.

The CO(1-0) emission is sharply peaked and has a width ~250km/s which suggests a disk rotation velocity of ~125km/s.
Galaxy appears to have a bar and distinct spiral arms.

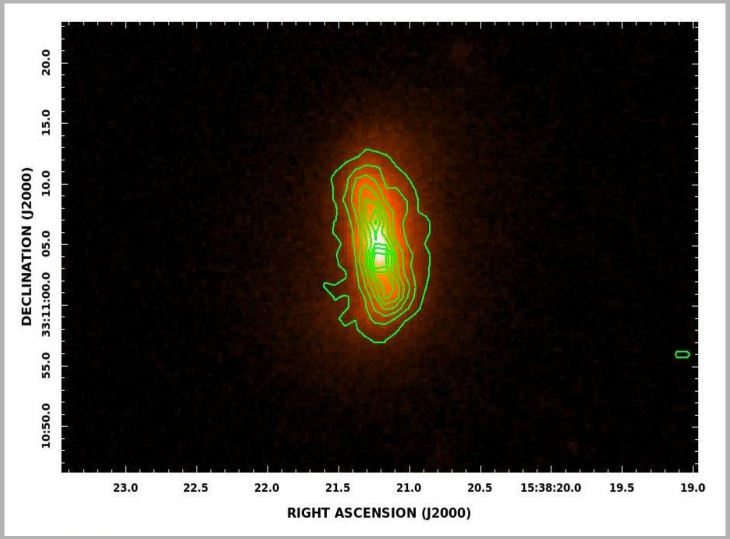
SDSSJ153821.22+331105.1 : Hα image



HCT Hα image and SDSS g image



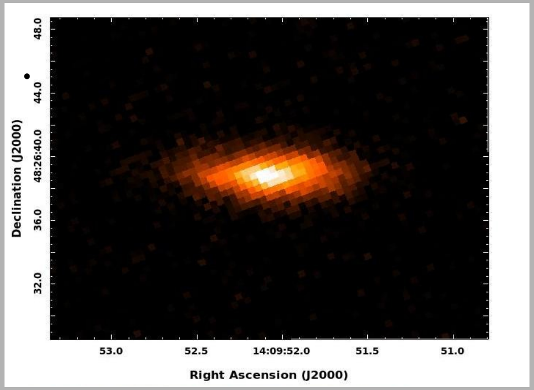
Hα contours overlaid on SDSS z band image

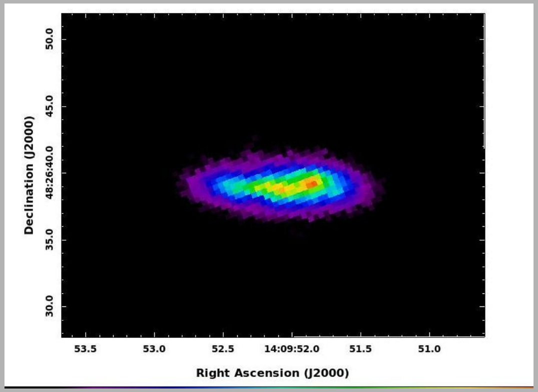


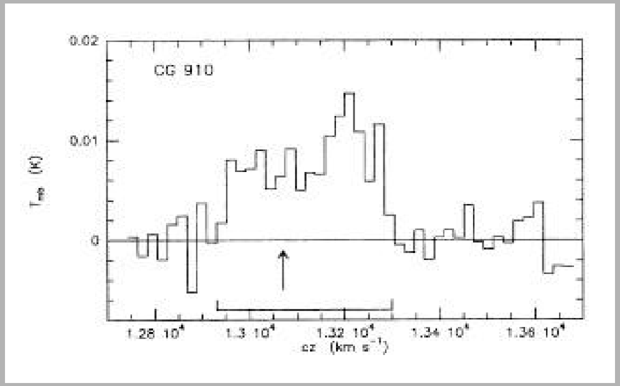
The Hα emission is distributed over the center and inner disk or bar.
The star formation rate is high at SFR=1.0 solar mass/yr.

Mapping the Molecular Gas in CG910

Galaxy is at z=0.044. Relatively isolated.
Disk size 19 Kpc (21”) and is inclinedat 60 degrees.
CO emission has double horned profile, suggest a rotating disk with v=140km/s.
Niuclear emission in radio but optical spectrum suggests star formation rather than AGN activity.





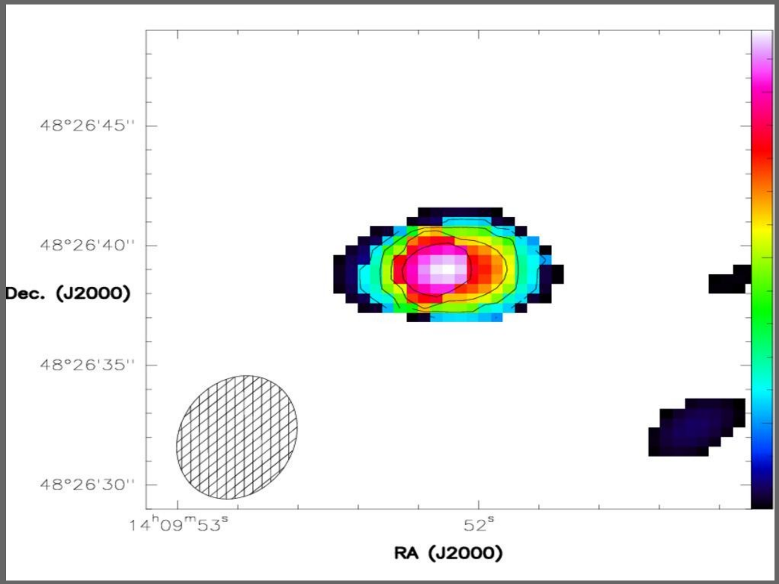


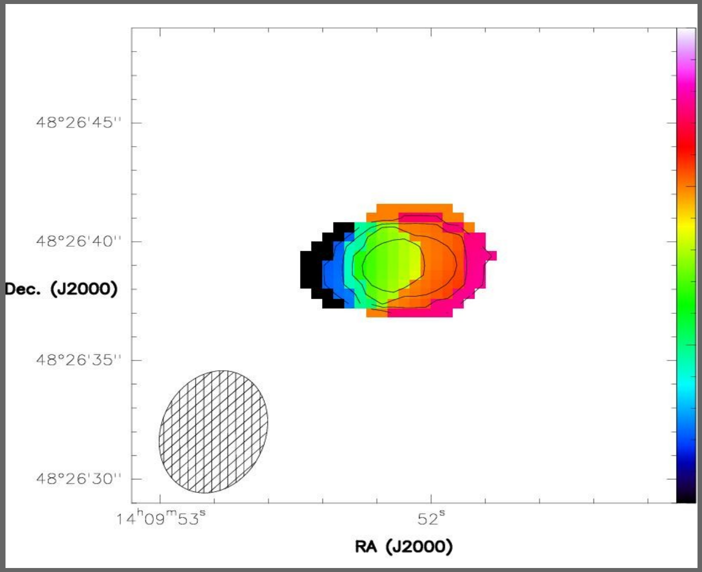
SDSS z and g band image of CG910. The bulge is prominent and disk inclined. Its IRAS flux is high suggeting relatively high star formation. In g band the emission is lopsided.

The IRAM spectrum of CO(1-0) emission (Sage et al. 1997). The mass of molecular gas is 3.8x10^8 solar mass.

CARMA CO(1-0) Map of CG910

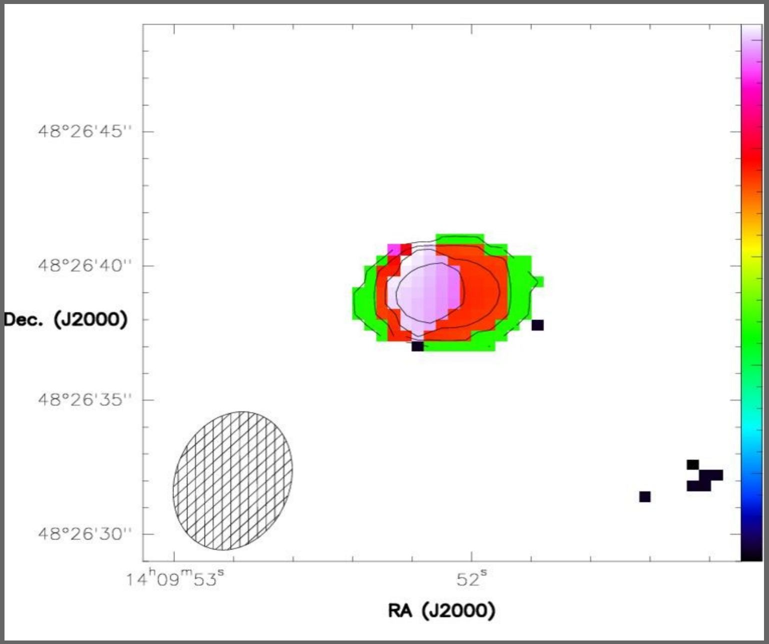
- The CO emission is distributed out to 7 to 8Kpc. Gas surface density is very high.
- Peak emission slightly off-center.
- Velocity field shows signs of gas outflow or may small bar.

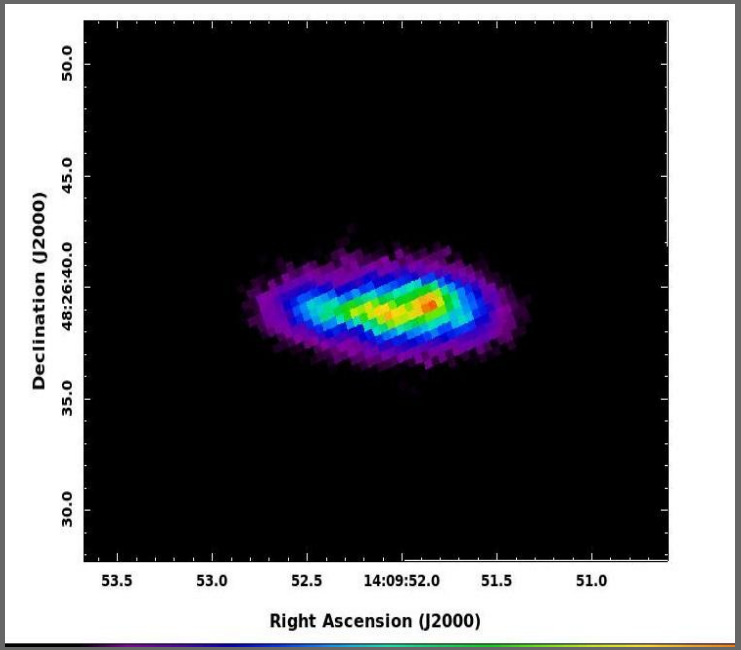




CARMA CO(1-0) Map of CG910 Velocity Dispersion

The CO line width or velocity dispersion is also off-center .
It matches the SDSS g band map of the galaxy which shows offcenter blue emission - due to star formation on one side of the disk .





Summary

- We have searched for CO(1-0) emission from 5 void galaxies with the 45m NRO millimeter telescope. We have detected molecular gas in 4 out of the 5 galaxies. Earlier detections were in 4 other galaxies (Sage et al. 1997 and Beygu et al. 2013).
- We have detected a double horn profile – signature of a rotating disk in the galaxy SBS1325+597. SDSS1530 has acentrally peaked CO emission. Molecular gas masses for our galaxies lie in the range 10^7 to 10^8 solar masses – similar to late type spirals.
- We have mapped the Hα emission in 3 of the detected galaxies. The star formation rates are in the range 0.1 to 1 solar mass/year.
- Thus these star forming void galaxies appear very similar to late type spirals in normal environments.

Star forming void galaxies are evolving, but at a slower rate than normal environment galaxies.

Questions .....

- **Many of the galaxies show offcenter star formation. Can these be signs of accretion or interactions?**
- **We need to understand what triggers this star formation. Is it gas accretion, galaxy interactions or something else?**
- **Are there low luminosity companions that we don't detect?**
- **How important is void substructure for star formation?**