The Extended HI Environment of nearby galaxies.

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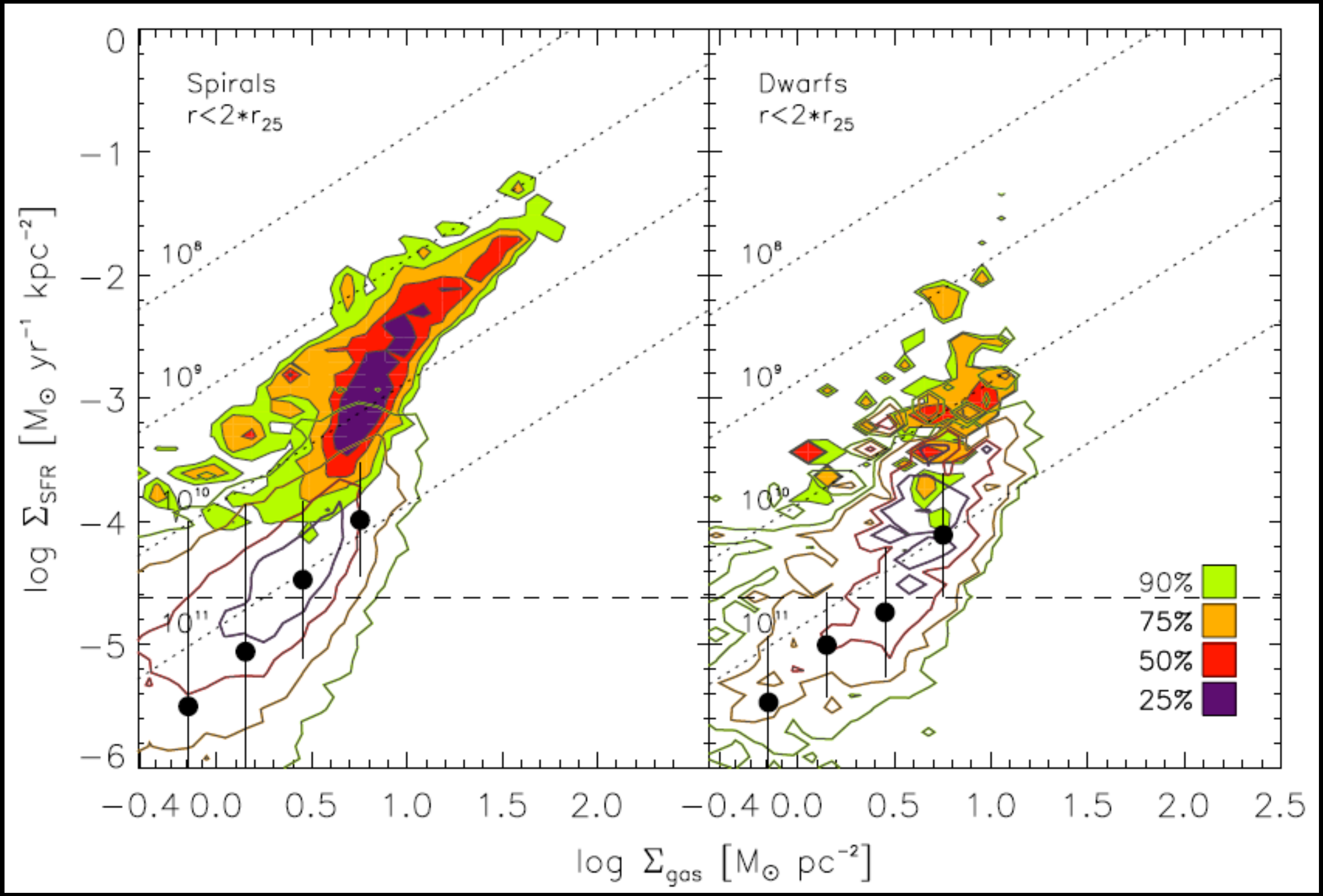
Why study HI?

- While H_2 is the fuel for immediate star formation, HI is the ultimate fuel (maybe HII) and dominates in outer disks.
- It is the easiest component of galaxies to trace kinematics and structure at large radii (better than stars, PNe, or GCs).
- At large radii, HI is the best way to search for past tidal interactions, infall from the IGM, and the effects of the extragalactic radiation field.

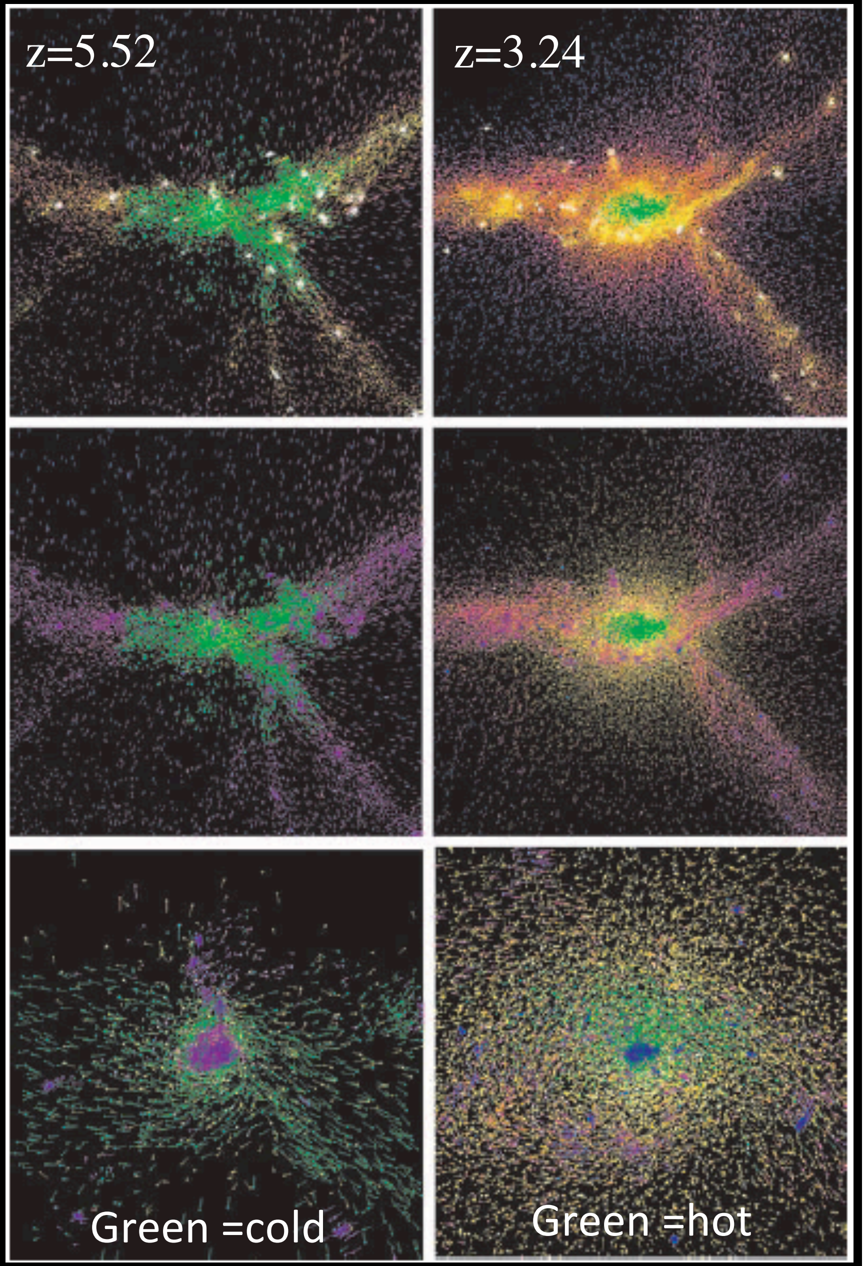
HI traces SF in outer disks



Bigiel et al. 2010

Hot/Cold Flows

- Many simulations predict that gas is accreted by galaxies in two forms (e.g. Birnboim & Dekel 2003, Keres et al. 2005, 2009).
- At z=0, hot mode accretion should be dominant in high mass halos and in high density environments.
- Cold mode should be dominant for $M_{halo} \lesssim 10^{11\text{-}12}\ M_{\odot}$ and in low density environments.
- To find cold mode accretion, must search in low density environments.

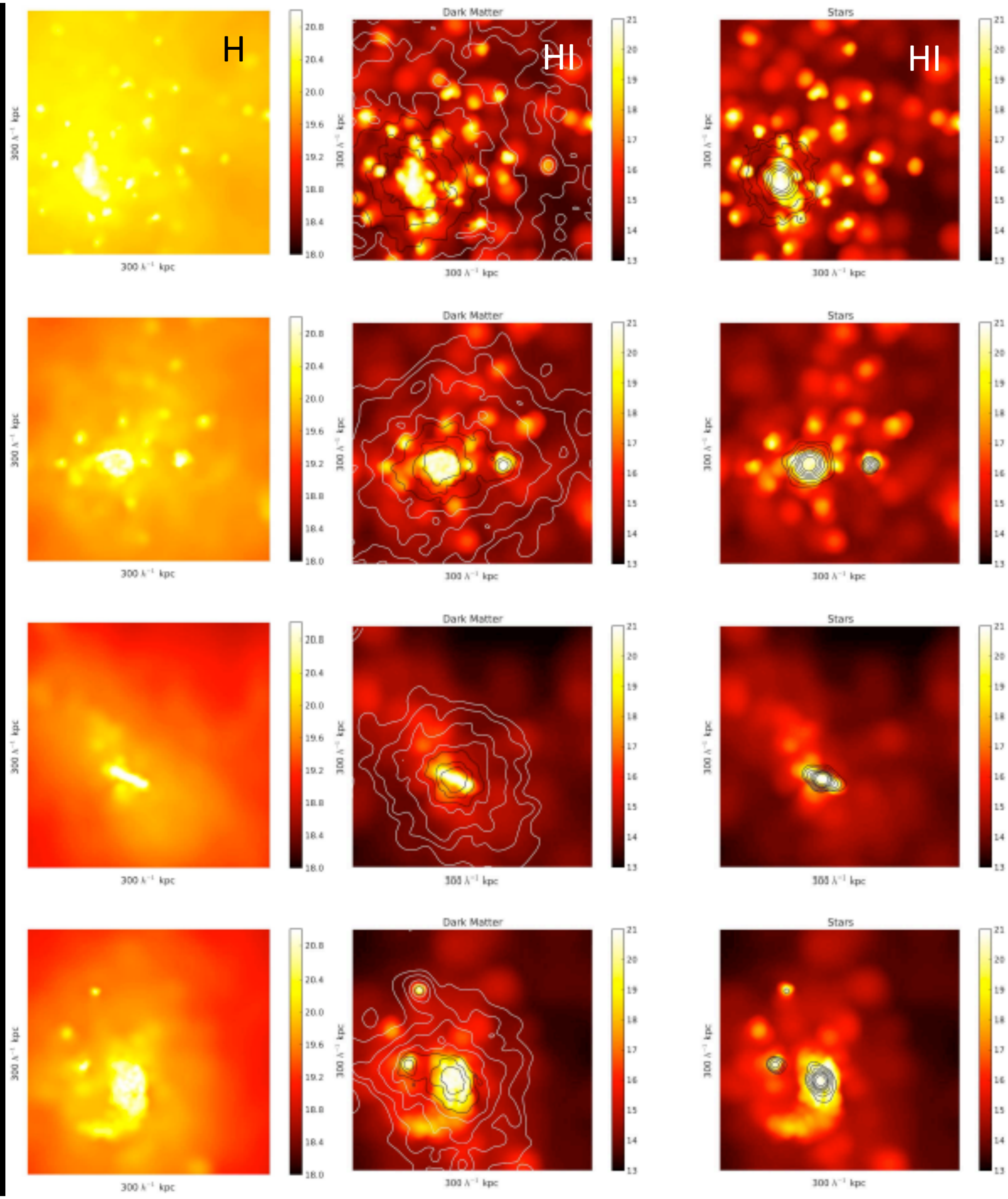


Keres et al. 2005

Hydrogen around galaxies

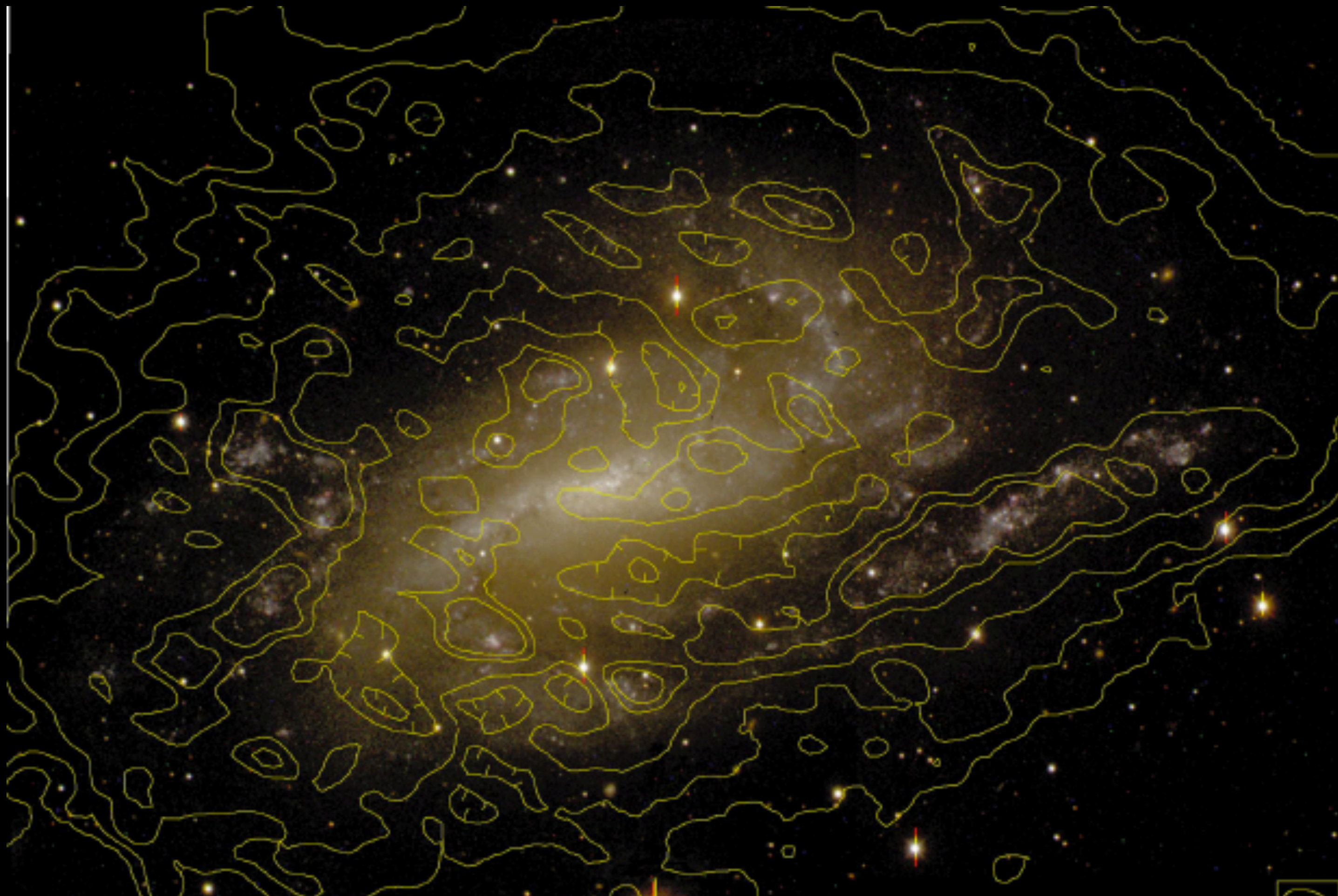
- Some of HI is condensed at high N_{HI}, the rest is diffuse with low N_{HI}.
- Low N_{HI} filaments have sizes of ~ 25 kpc.
- These HI filaments would be seen as Lyman limit systems in absorption.
- This HI can be detected in emission with current radio telescopes and sufficient time.

Popping et al. 2009



Starting at $N_{HI} \sim 10^{20}$ cm^{-2}
and progressing to $N_{HI} < 10^{17}$ cm^{-2}

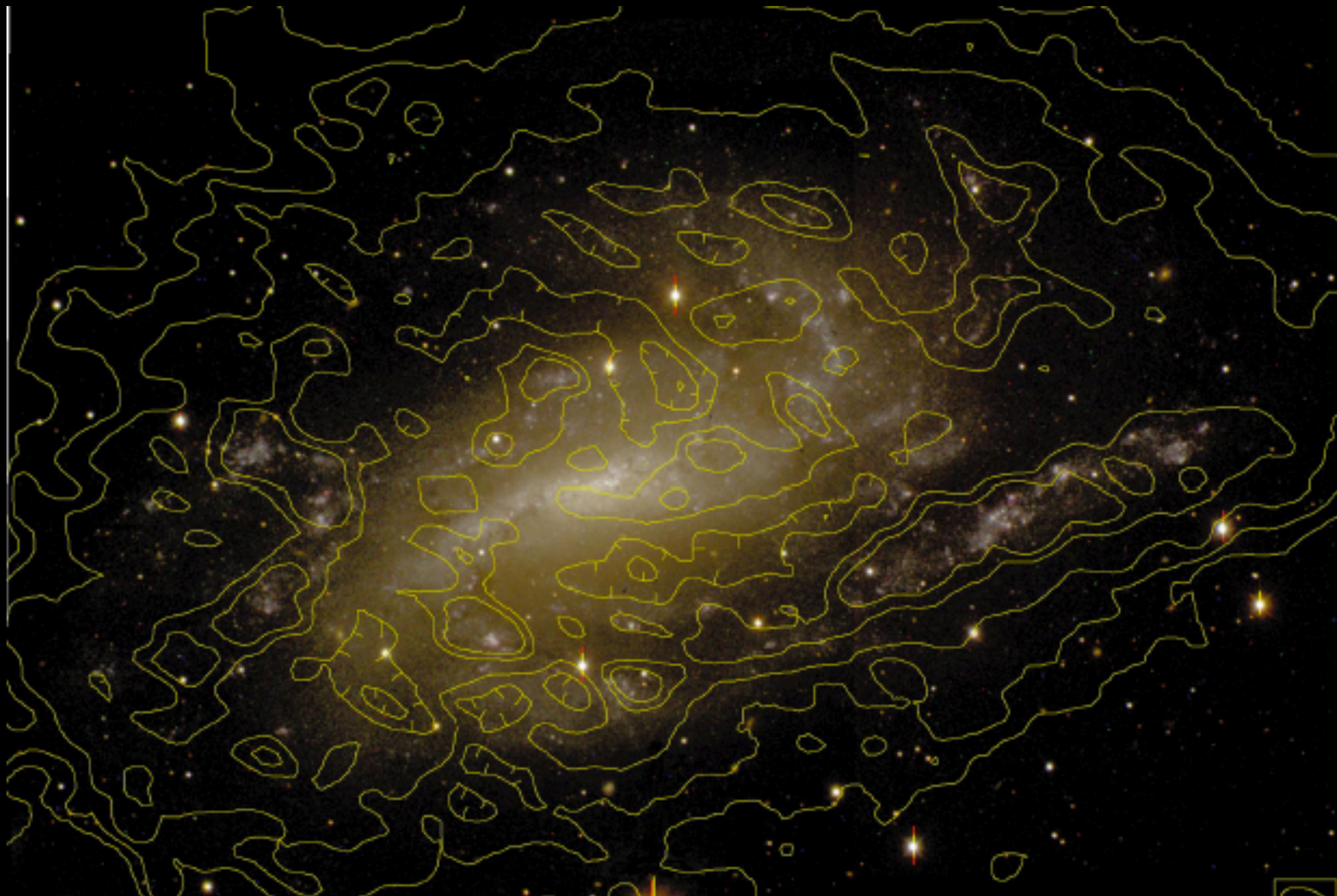
Extent of HI disks



For NGC 925, the HI disk at $N_{HI} \sim 10^{20}$ cm^{-2} extends 1.2x further than the optical disk (R_{25}).

Pisano et al. 1998,2000

Extent of HI disks



For a large sample of spiral galaxies, Broeils & Rhee (1997) found $R_{HI}/R_{25} = 1.7 \pm 0.5$.

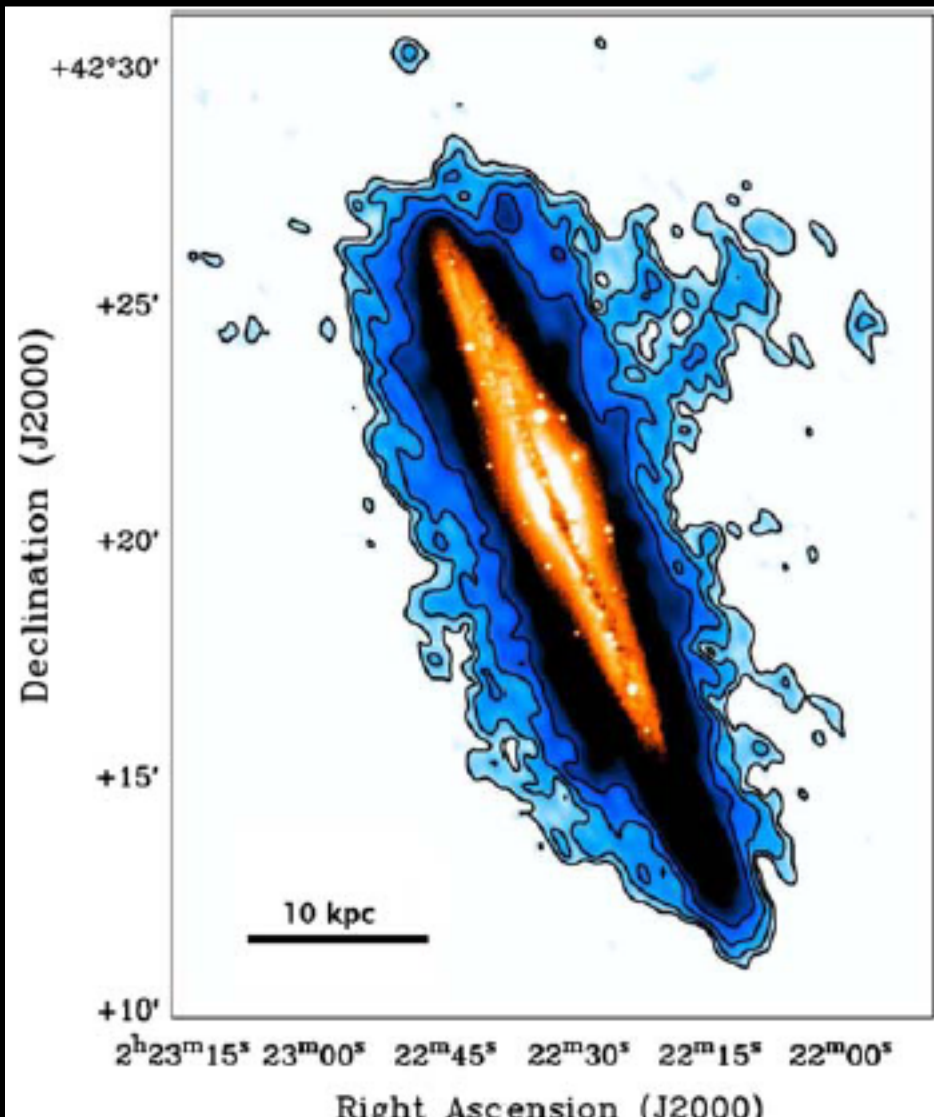
Pisano et al. 2000

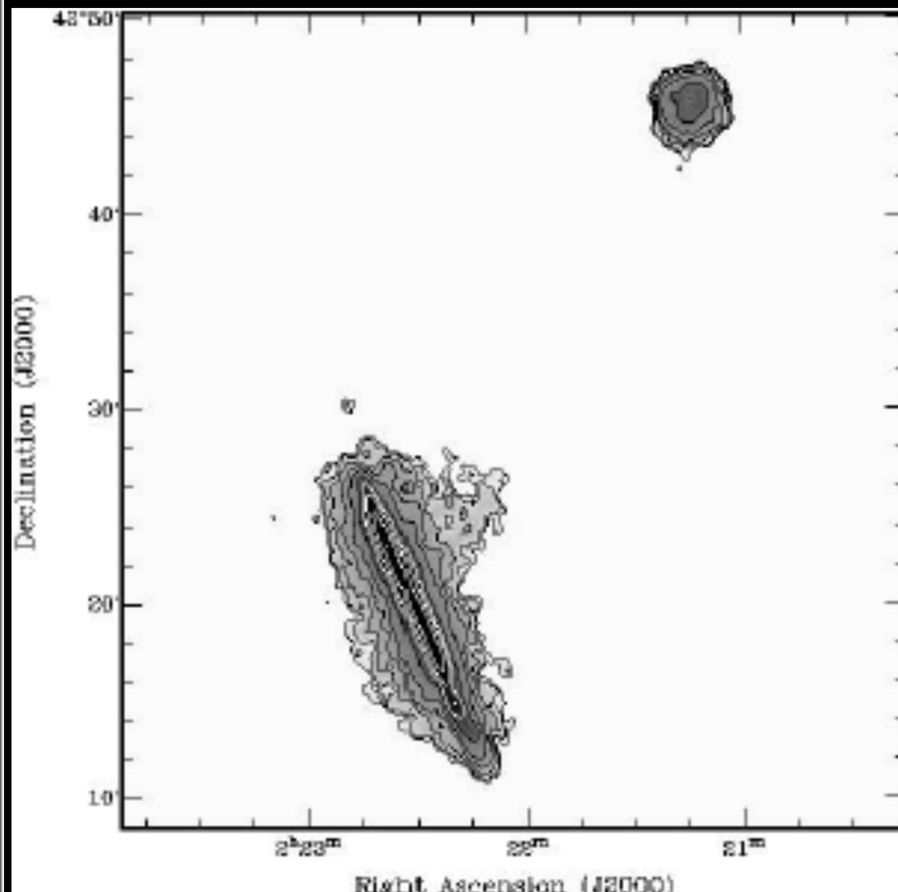
NGC 2915: an extended HI disk

Some galaxies, however, extend 4-5 times further in HI.

Meurer et al. 1996

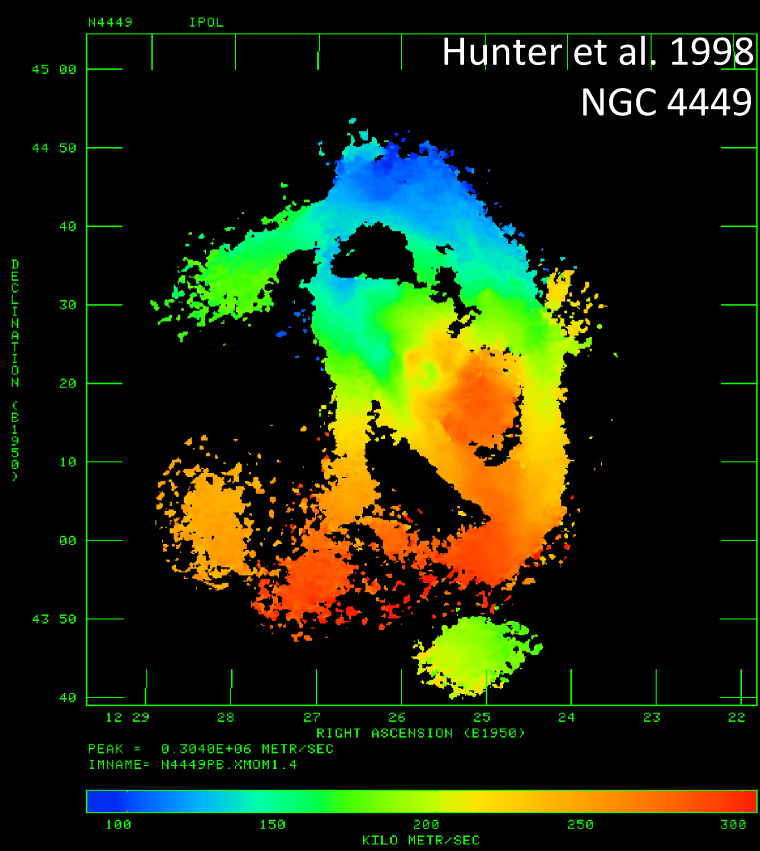
Signatures of accretion or tidal interactions?

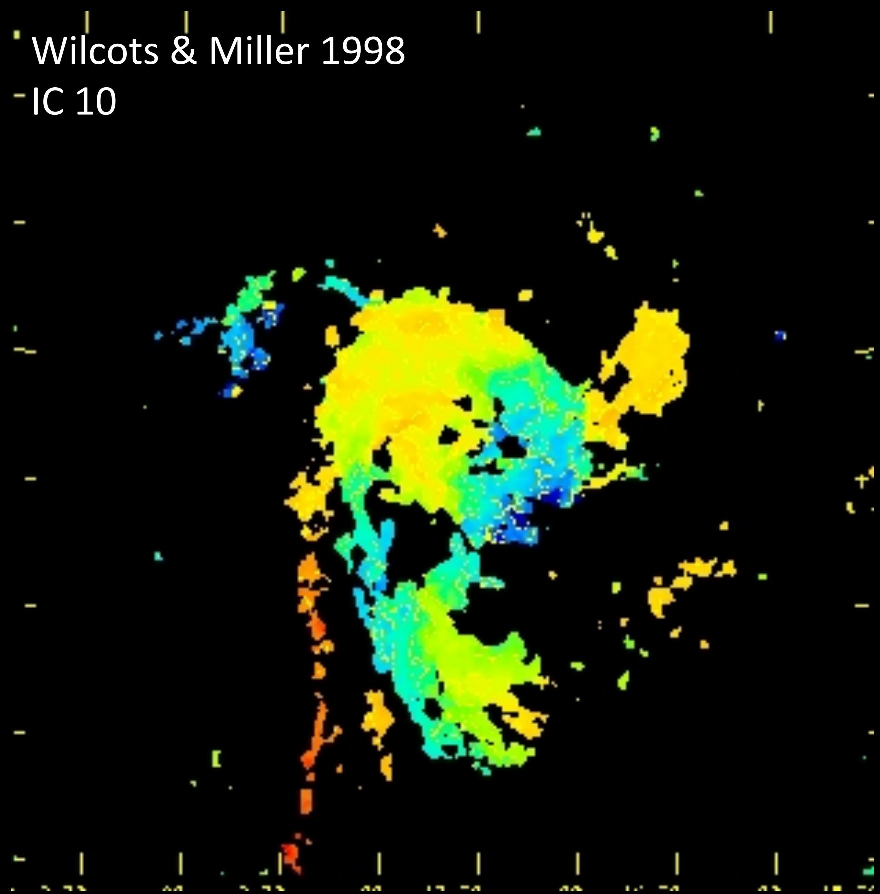




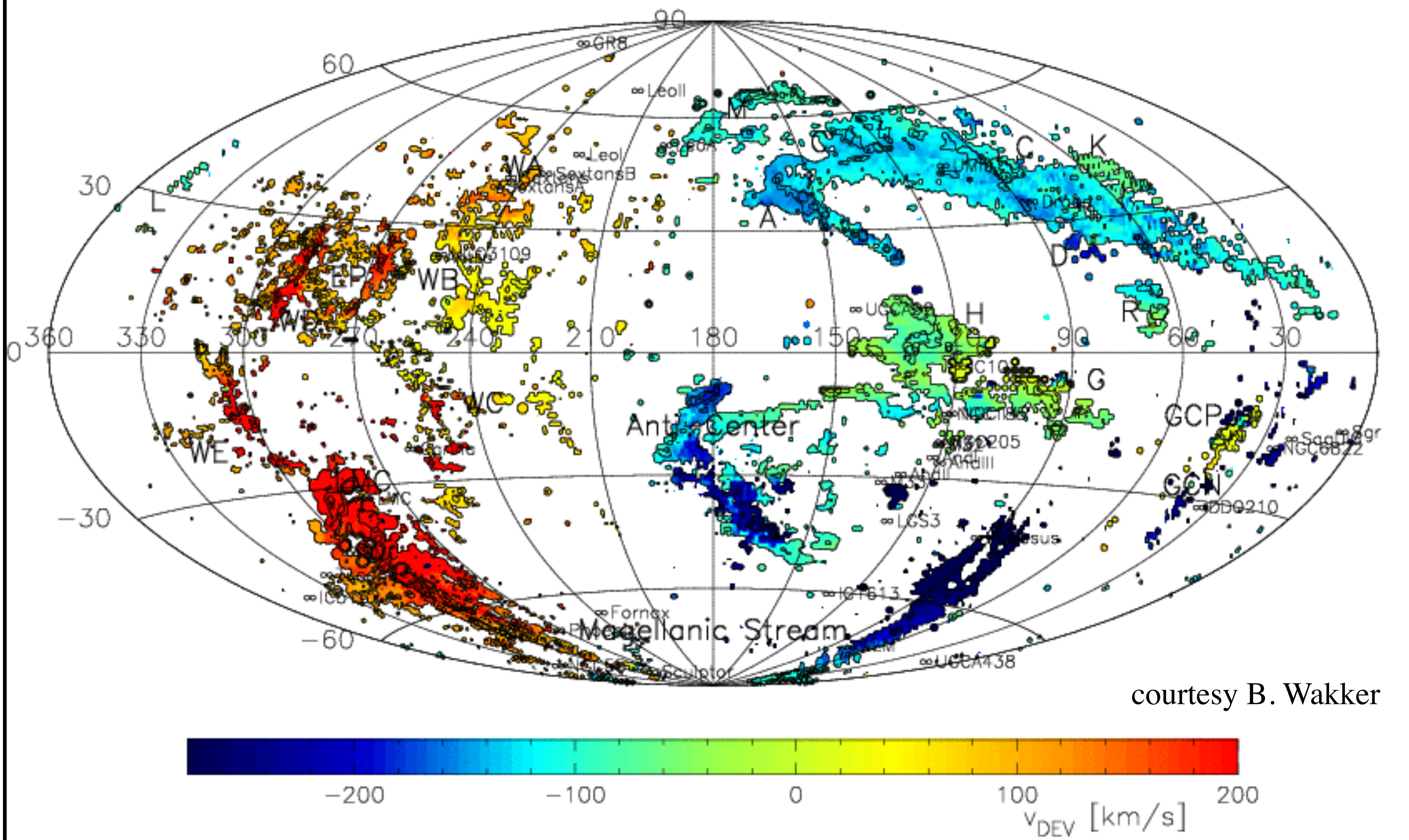
Oosterloo et al. 2007

Signatures of accretion or tidal interactions?



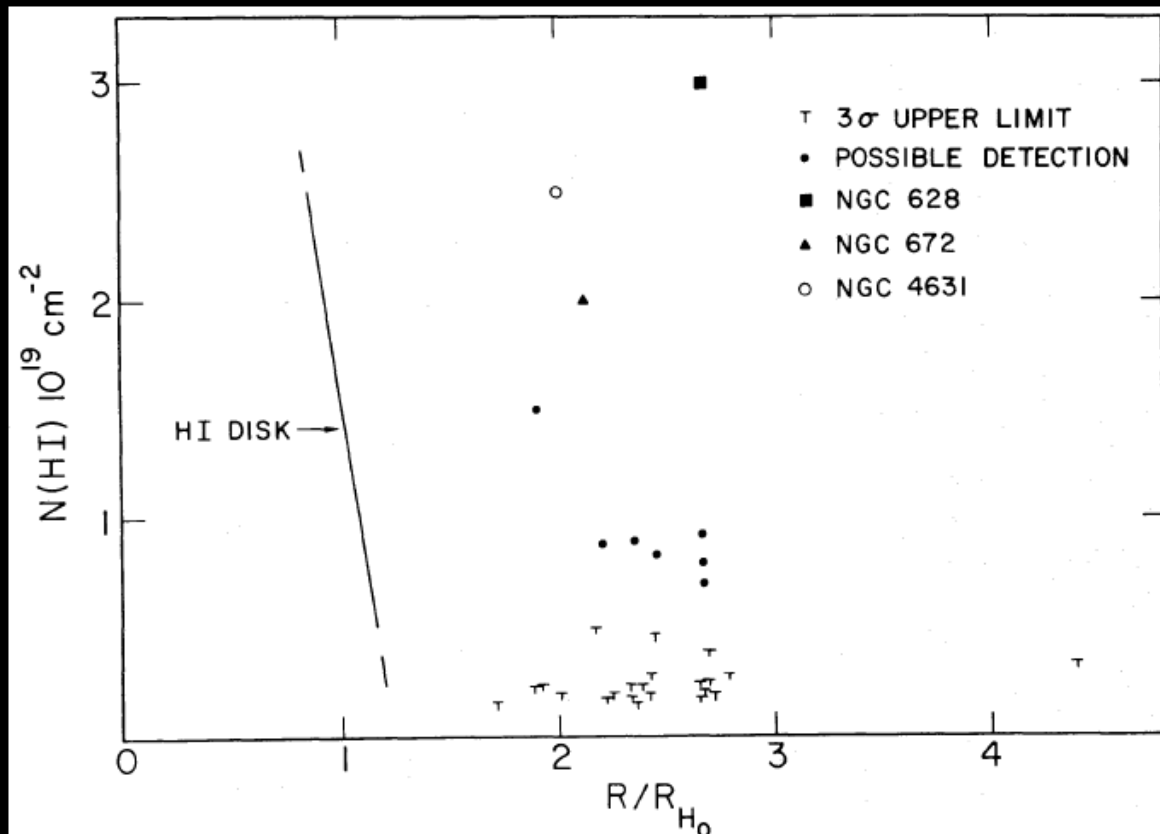


Milky Way High Velocity Clouds (HVCs): remnants of galaxy formation?



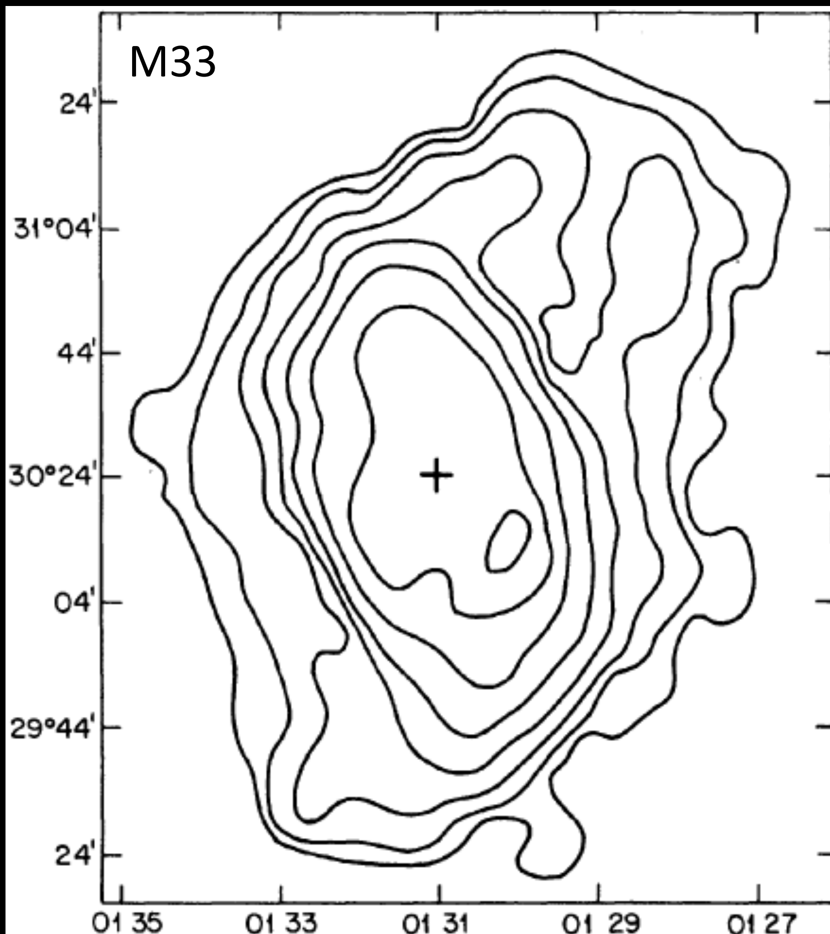
courtesy B. Wakker

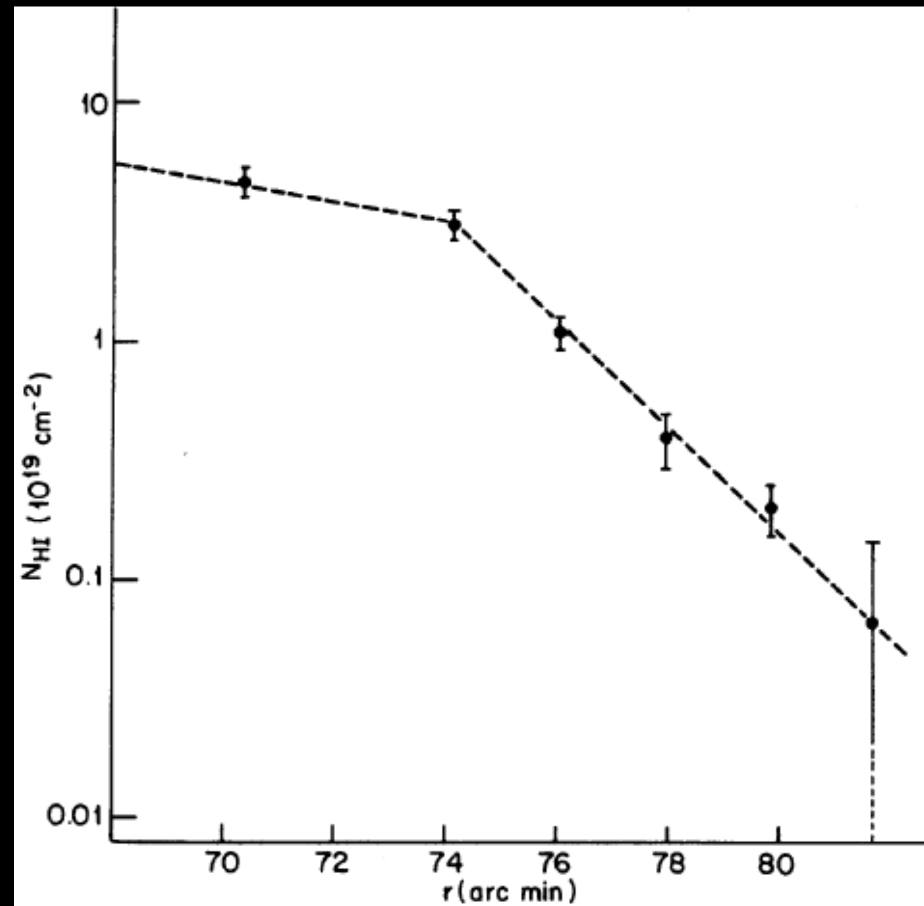
Edges of HI disks



- Briggs et al. (1980) used Arecibo to look beyond the edge of the HI disk down to $N_{HI} \sim 3x10^{18}$ cm^{-2} around 13 galaxies.
- Detected low N_{HI} gas around 3 galaxies related to tidal interactions or HVCs.

Edges of HI disks

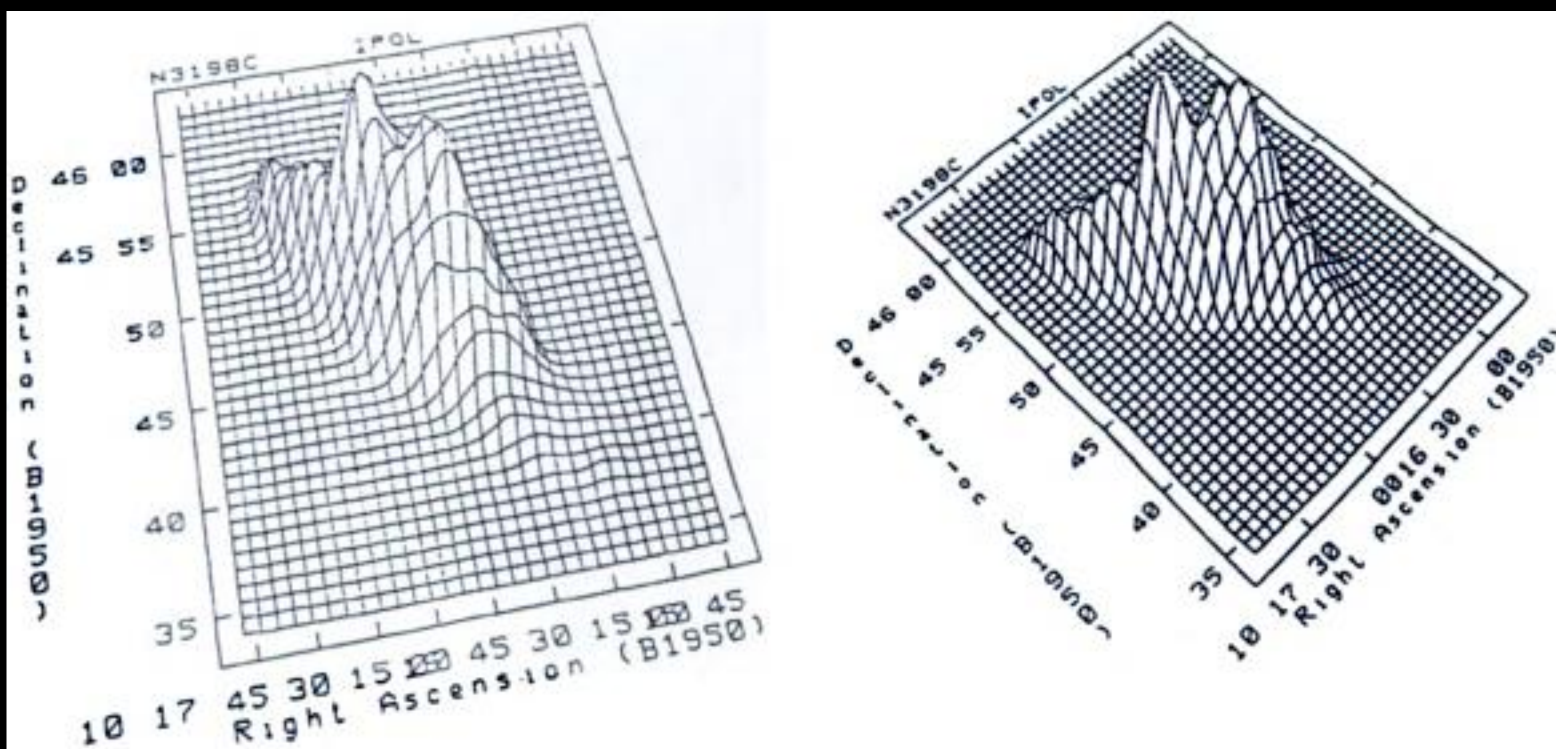




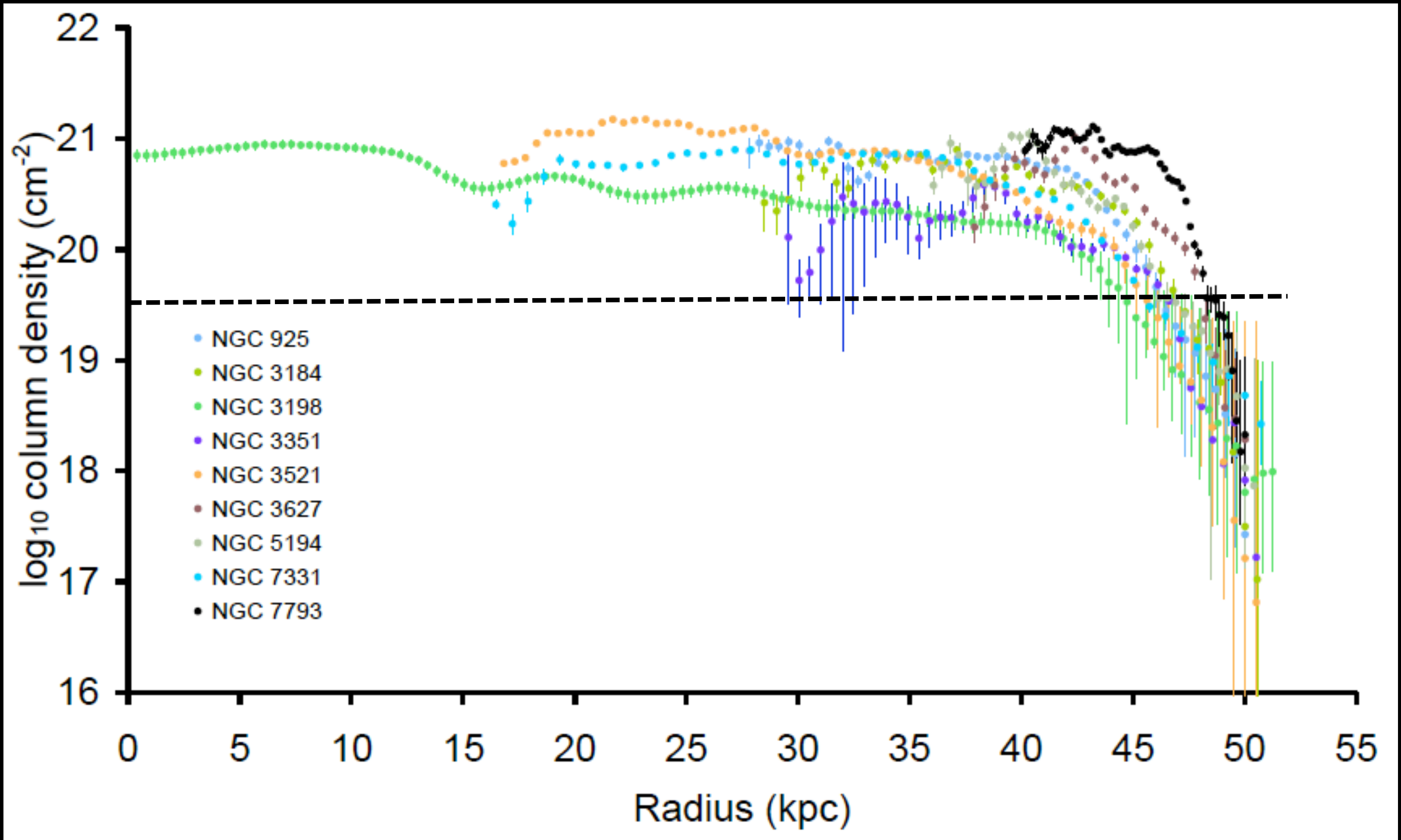
Corbelli et al. (1989) found a similar edge to the HI disk of M33.

Edges of HI disks

- van Gorkom (1993) found a sharp edge to the HI disk of NGC 3198 with $\sigma \sim 4\text{x}10^{18}$ cm^{-2}.
- Maloney (1993) explained it as ionization by the intergalactic radiation field at $N_{HI} \sim 3\text{x}10^{19}$ cm^{-2}.



Edges of HI disks



N_{HI} is mostly flat with r. Starts to drop at large r then gets ionized and plummets.

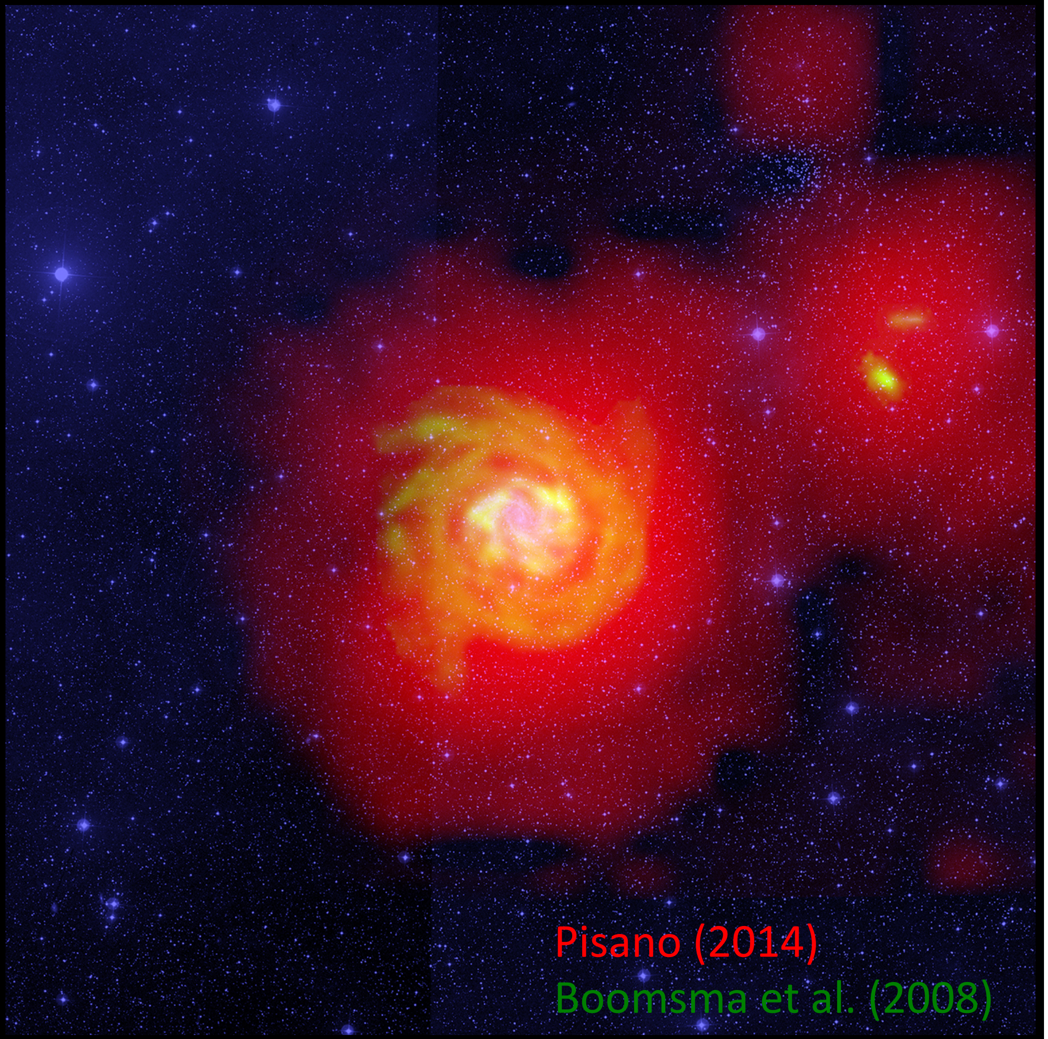
How can we observe low N_{HI} gas in emission?

- Most of the previous HI maps were made with *interferometers* (VLA, WSRT). These are very sensitive to clumpy HI clouds.

- To detect faint, diffuse HI, we need to use a *single-dish* radio telescope (like the GBT).

NGC 6946

- NGC 6946 is a void galaxy in a group. Local galaxy density is 0.07 Mpc^{-3} (Tully 1988)
- Optical in blue, WSRT HI data in green, GBT HI data in red.
- GBT can detect HI down to $N_{HI} = 10^{18}$ cm^{-2}.
- Filament has peak $N_{HI} = 2 \times 10^{18}$ cm^{-2} and FWHM = 48 km/s.
- The filament smoothly connects in position and velocity with NGC 6946 and companions.
- Some emission from filament could be due to stray radiation.
- Filament could be a cold flow, but is more likely to be a tidal stream. No visible stellar counterpart.



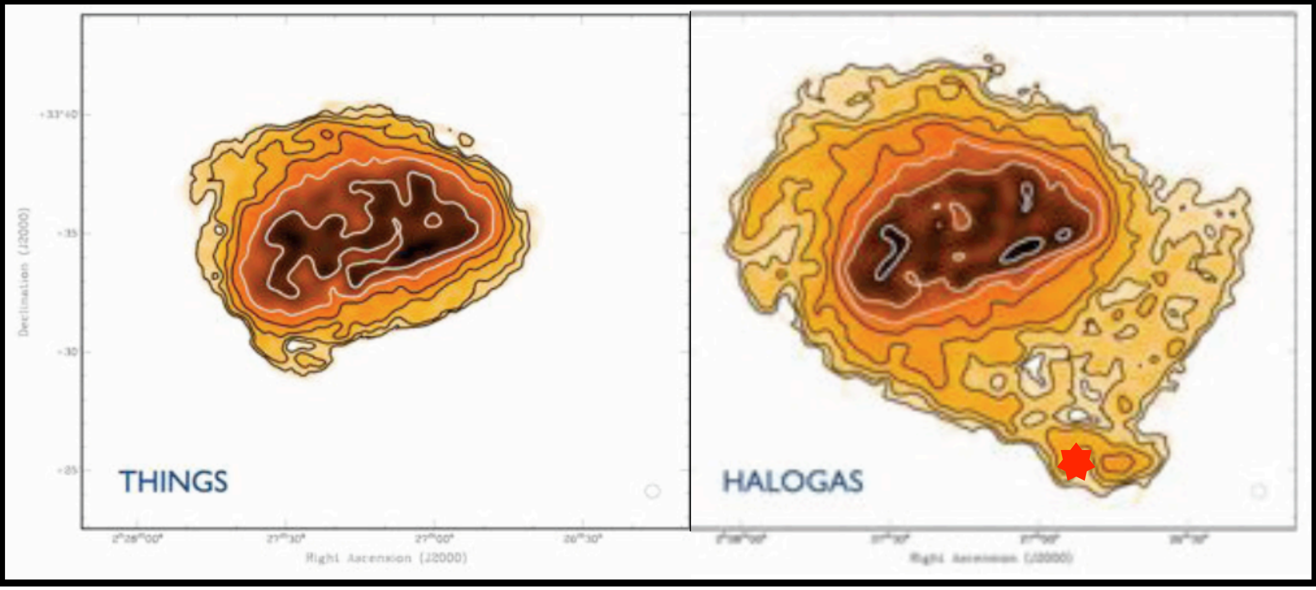
NGC 2403

- A group galaxy with local galaxy density of 0.3 Mpc^{-3}.
- Fraternali et al. 2002 found an anomalous velocity HI cloud in their WSRT data.
- Our GBT data (de Blok et al. 2014) reveal a more diffuse, extended cloud connected spatially and kinematically.
- Not associated with any stellar overdensities, but does point toward a companion.
- This may have a tidal or accretion origin.

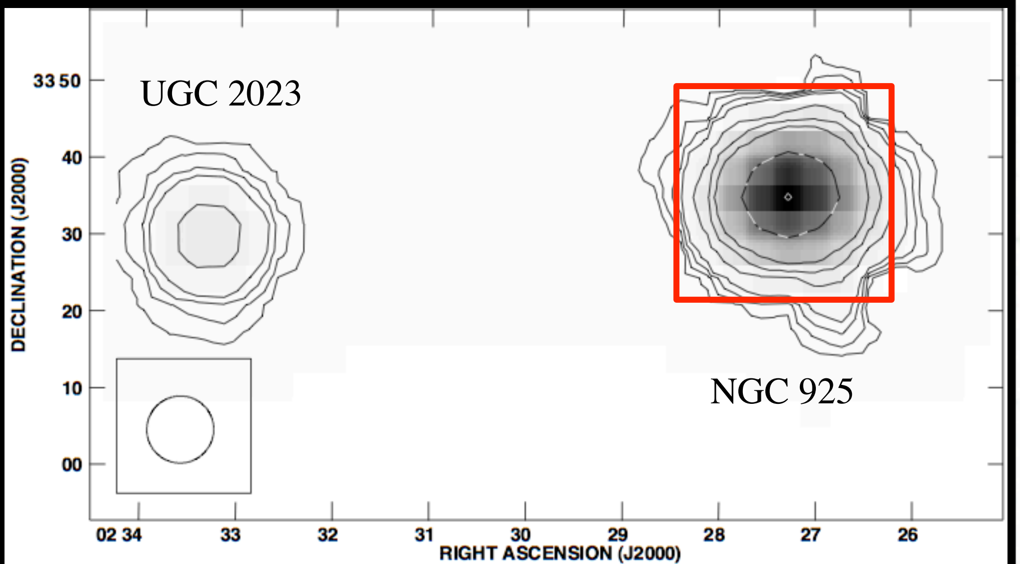
NGC 925

(D ~ 9.3 Mpc)

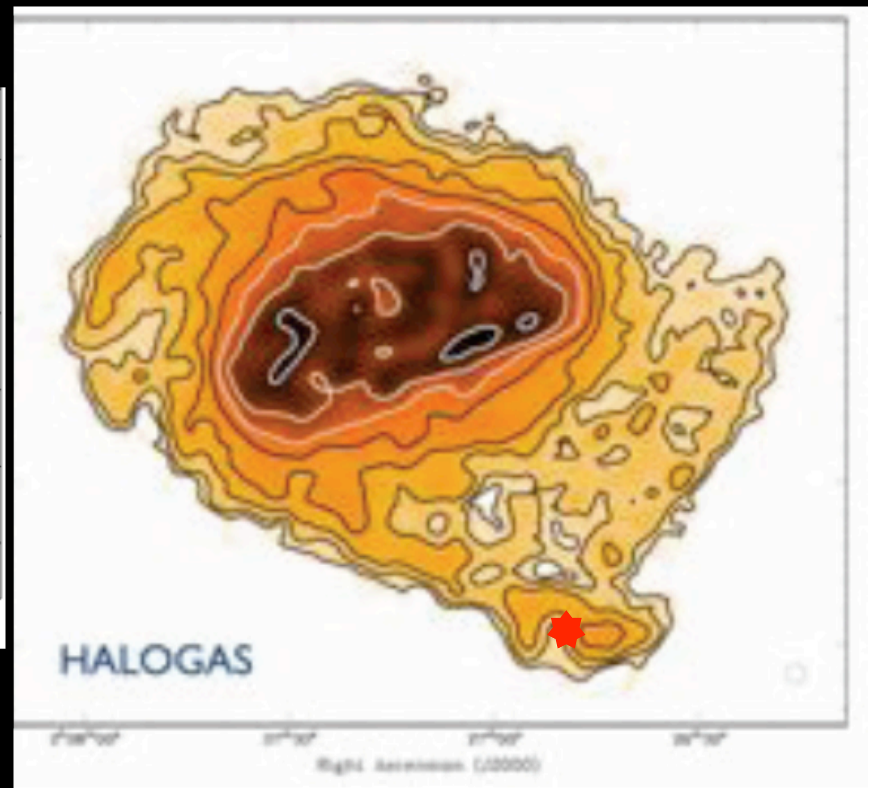
- THINGS data on left is relatively shallow and only shows a hint of asymmetry in NGC 925 HI distribution. Lowest contour at $N_{HI} = 9\times10^{19}$ cm^{-2}.
- HALOGAS (Heald et al. 2011) observations confirm filament seen by Pisano et al. (1998) and show extensive extended HI around galaxy. Clump at end of filament has stars. Lowest contour at $N_{HI} = 1.8\times10^{19}$ cm^{-2}.



NGC 925

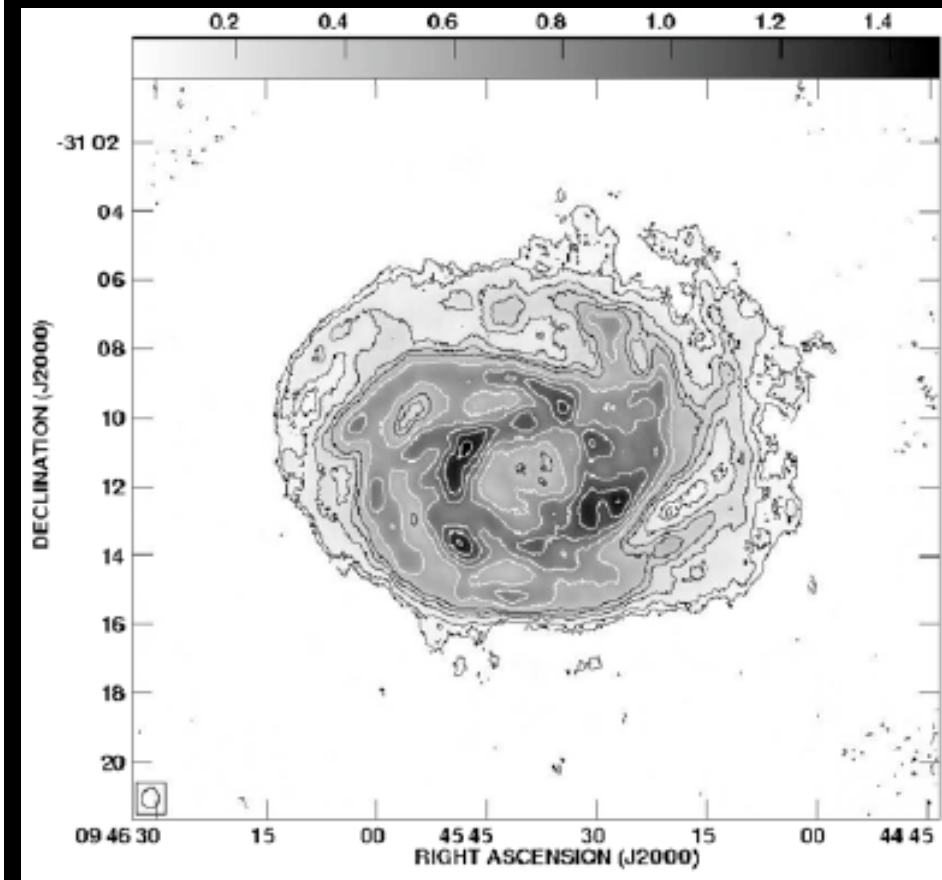


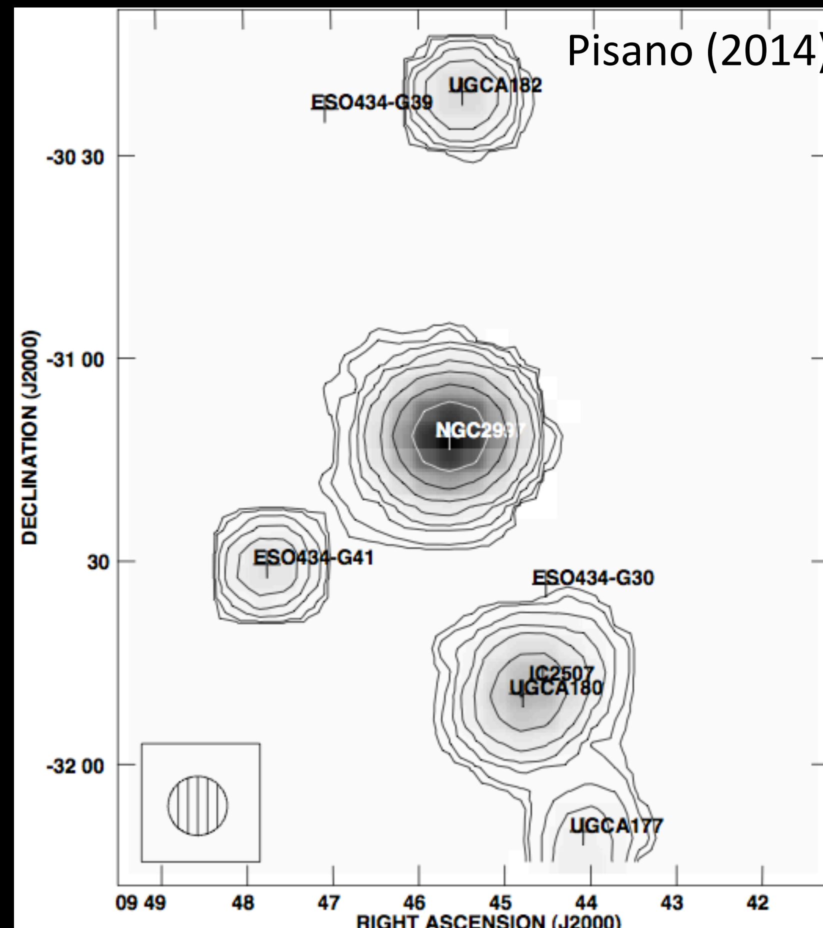
3σ, 20 km/s sensitivity ~10^{18} cm^{-2}.
Can see the tidal features near NGC 925, but no connection with companion.
Absence of low N_{HI} features probably real, but may be due to distance of source.



Contours at 1, 3, 6, 10...600x10^{19} cm^{-2}.
See signs of extended HI around NGC 925, but no filamentary structures.

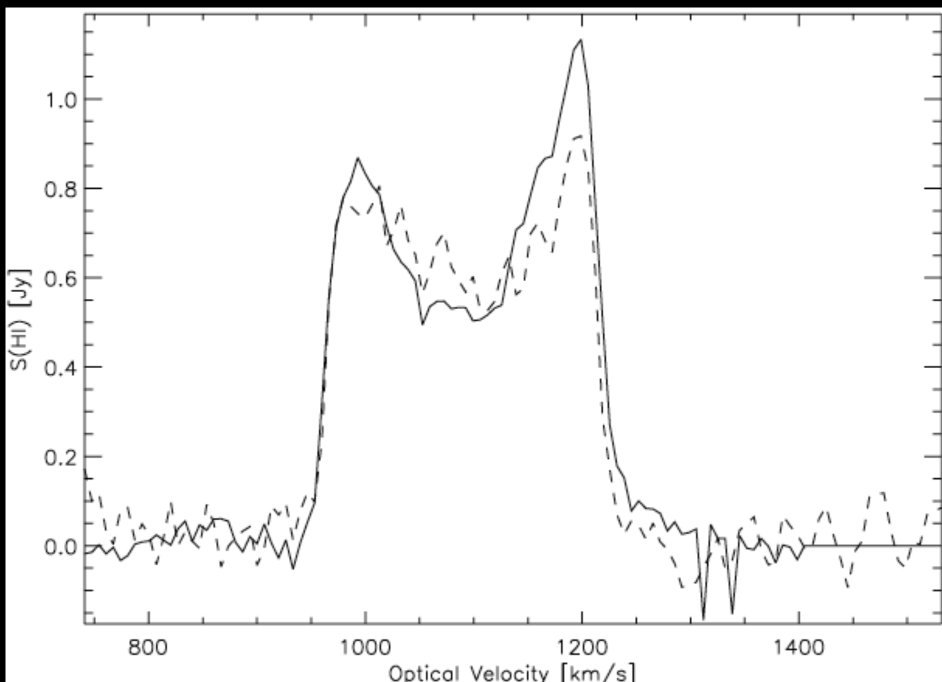
NGC 2997



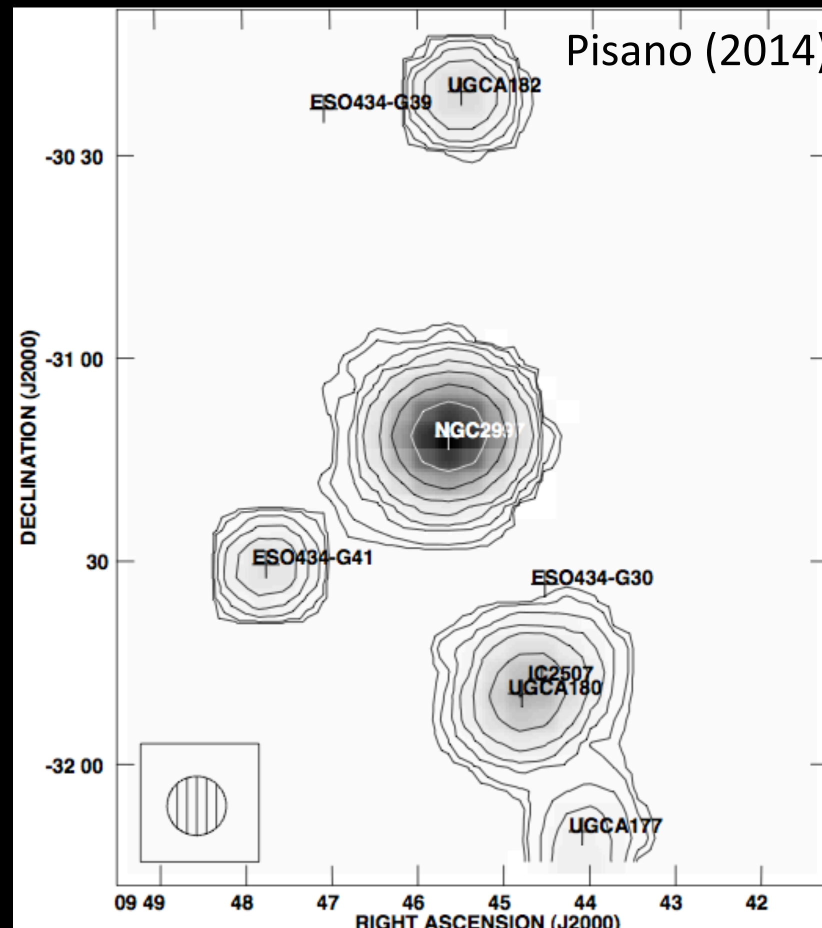


No discrete features at the $N_{HI} = 5x10^{17}$ cm^{-2} level,
but HI covers 23% more area at the 10^{18} cm^{-2} level.

NGC 2997

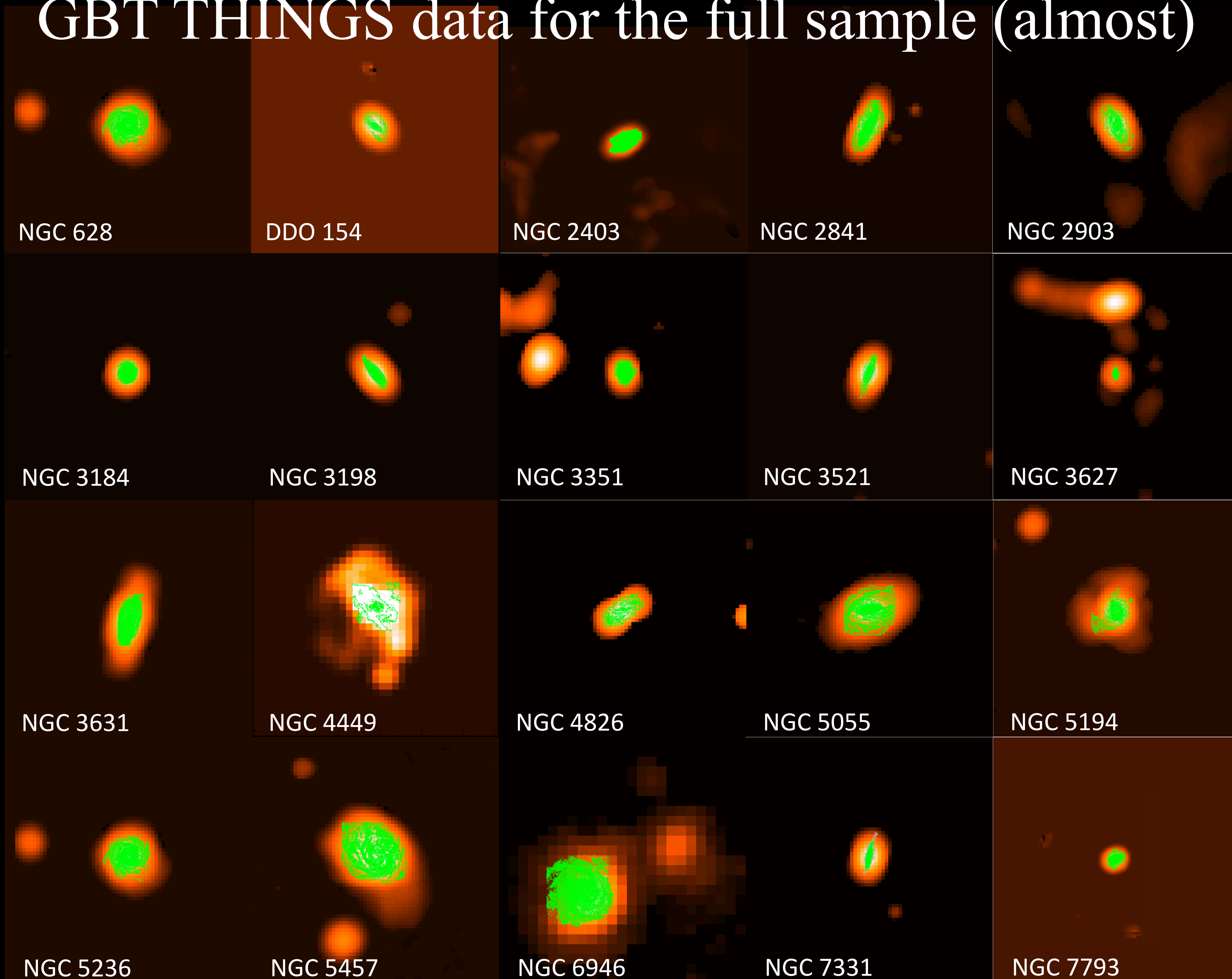


GBT: solid line
GMRT+ATCA: dashed line



The HI flux of NGC 2997 as measured by the GBT agrees within 10% of interferometer data.

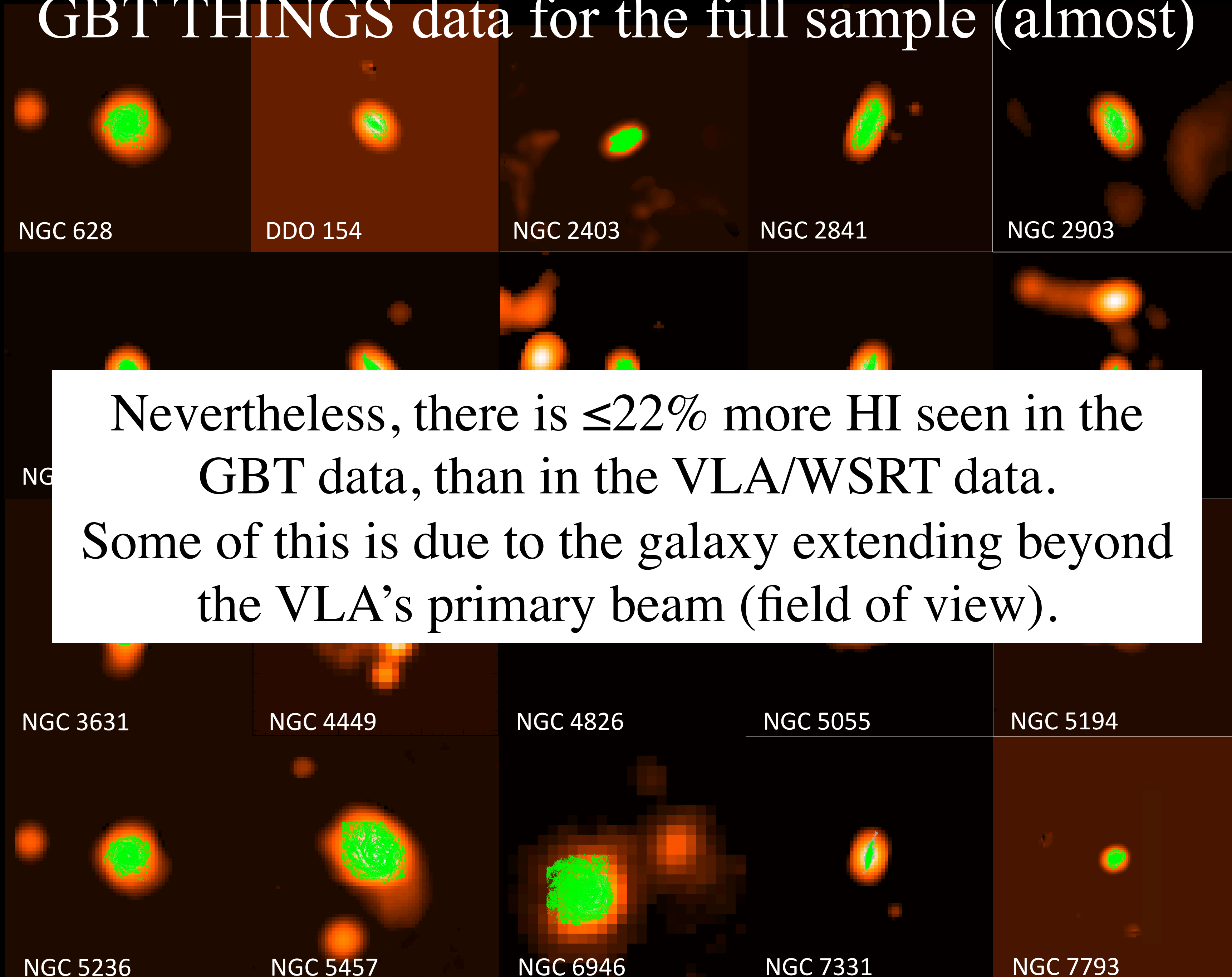
GBT THINGS data for the full sample (almost)



GBT THINGS data for the full sample (almost)

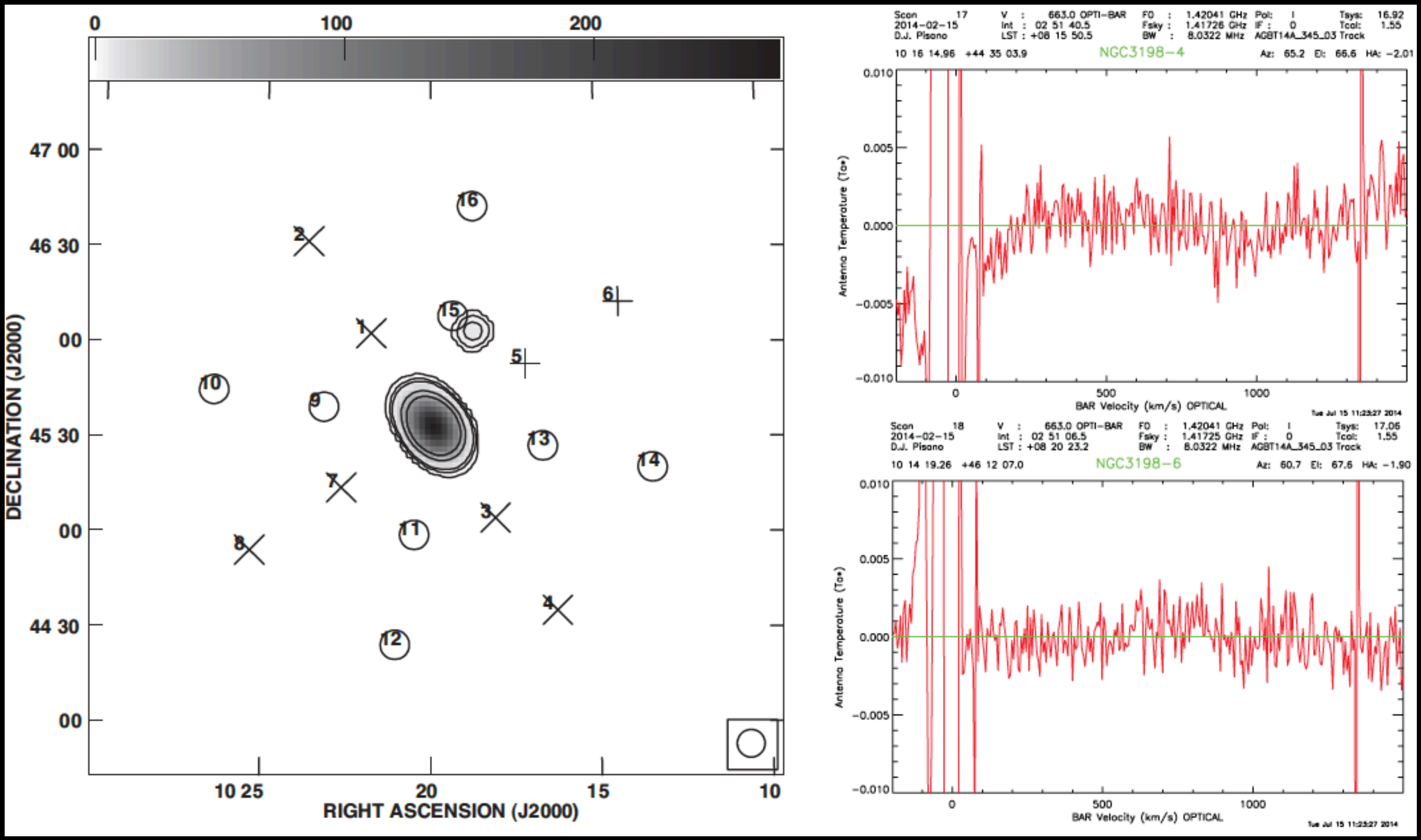
Based on a first look, only those THINGS galaxies undergoing an interaction appear to have diffuse gas features with $N_{HI} \geq 10^{18}$ cm^{-2}.

GBT THINGS data for the full sample (almost)



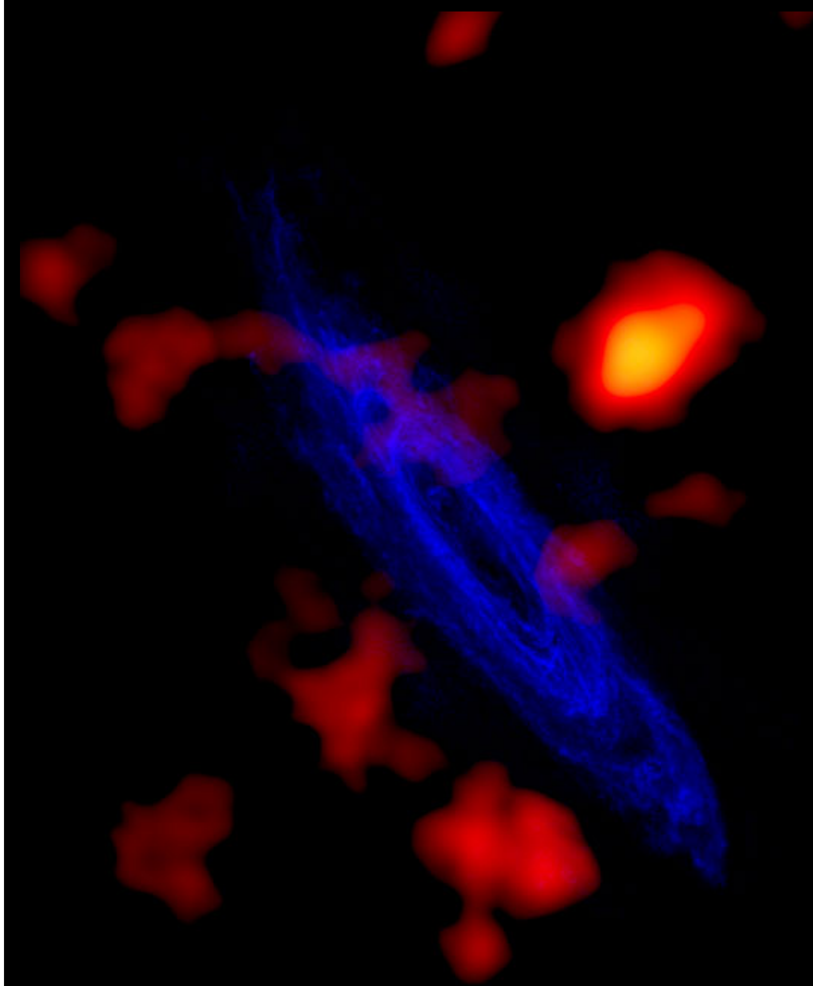
Nevertheless, there is ≤22% more HI seen in the GBT data, than in the VLA/WSRT data.
Some of this is due to the galaxy extending beyond the VLA's primary beam (field of view).

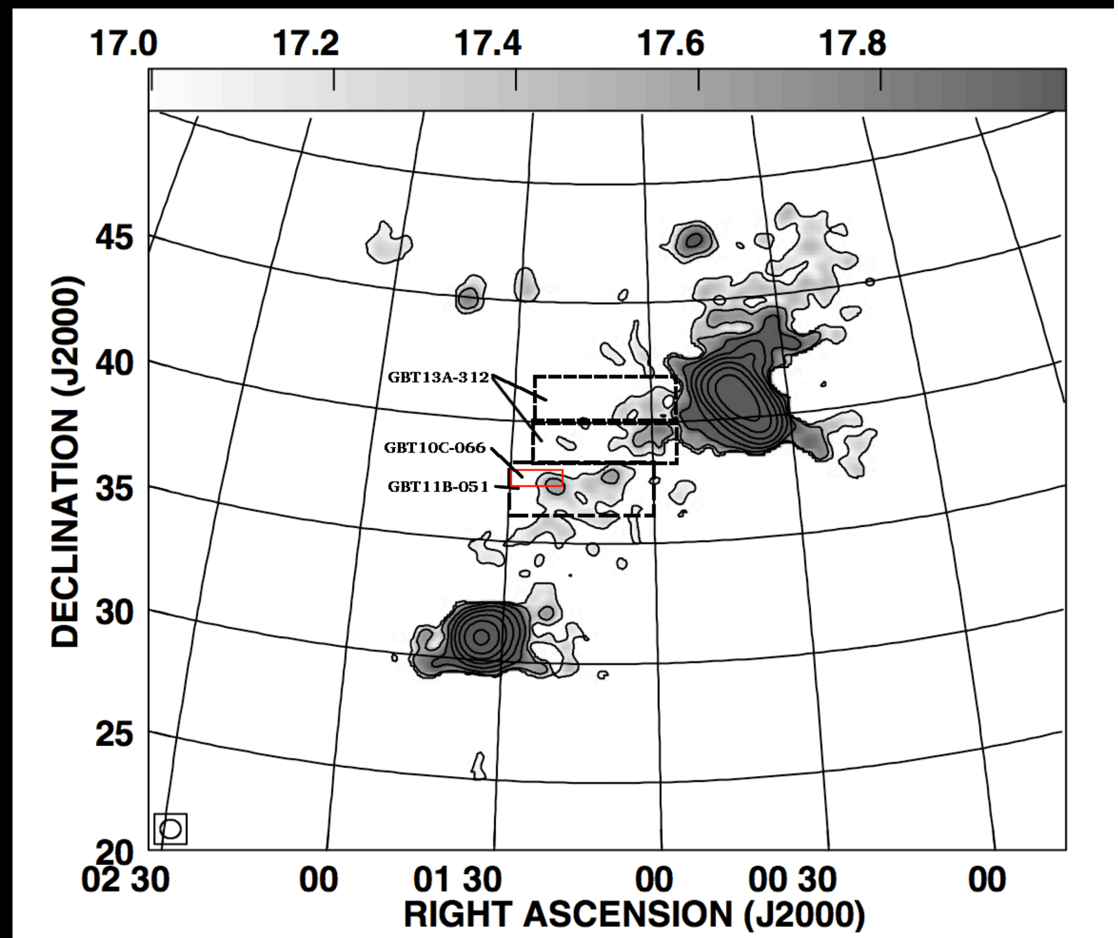
Deep observations of NGC 3198



- Barely any sign of HI at 10^{17} cm^{-2} around 3198 or 2403.

HI at the 10^{17} cm^{-2} level in the Local Group

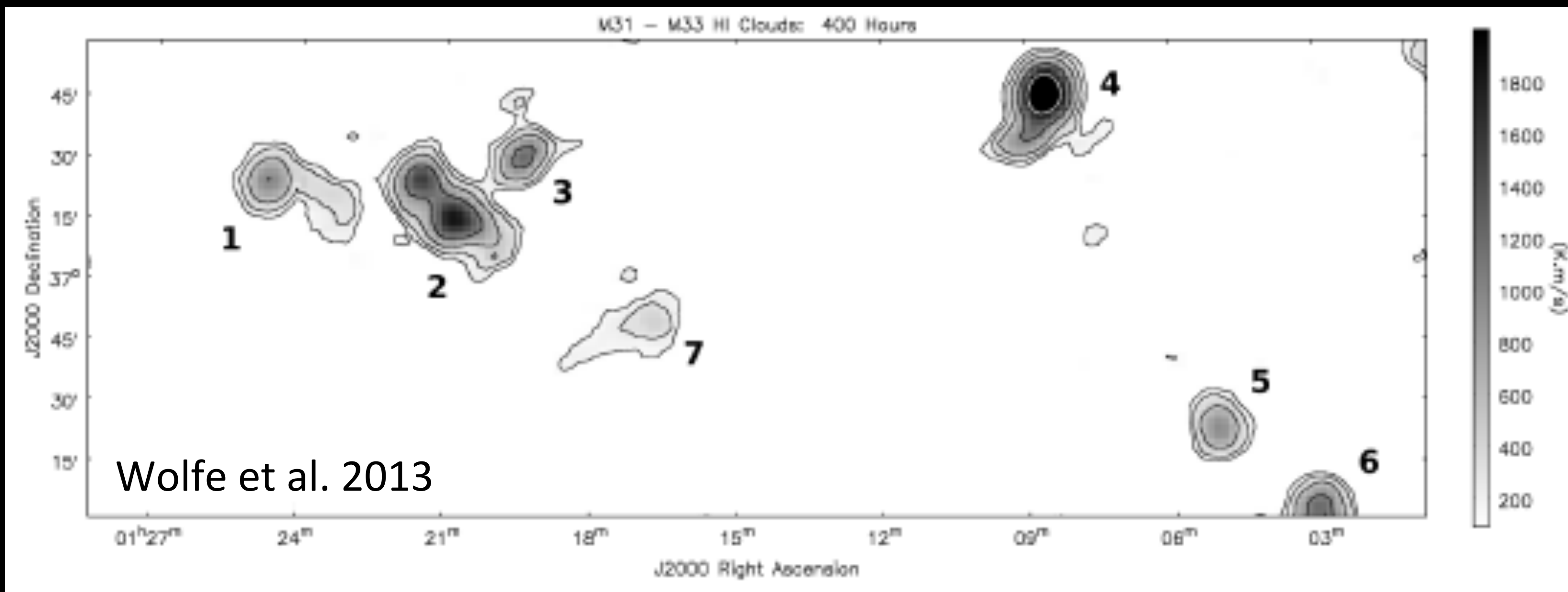




$N_{HI} = 0.5 – 20 \times 10^{18}$ cm^{-2}

Thilker et al. 2004; Braun & Thilker 2004

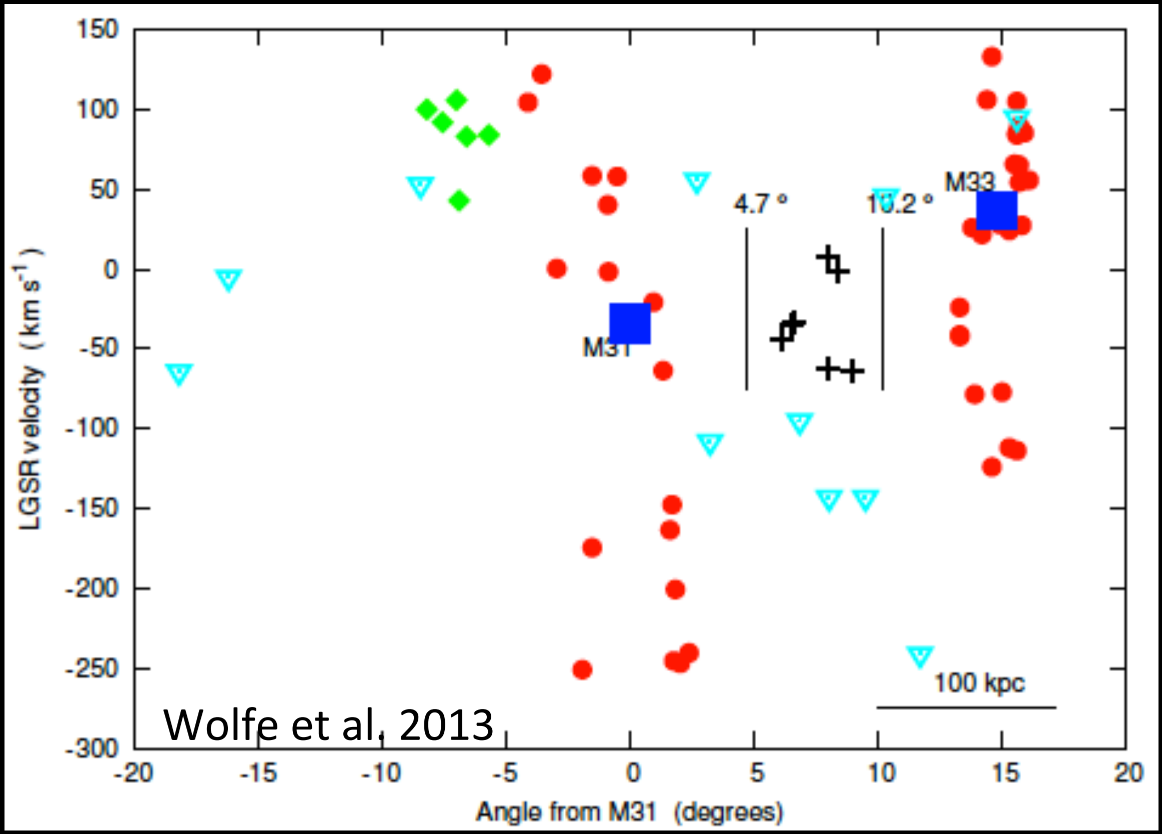
But is this really diffuse?



The GBT data shows that this feature is much clumpier than previous data suggested. We think that they are part of a condensing intergalactic filament.

Cloud #4 may have a stellar counterpart (Martin et al. 2013) and appears to be interacting with the CGM or IGM.

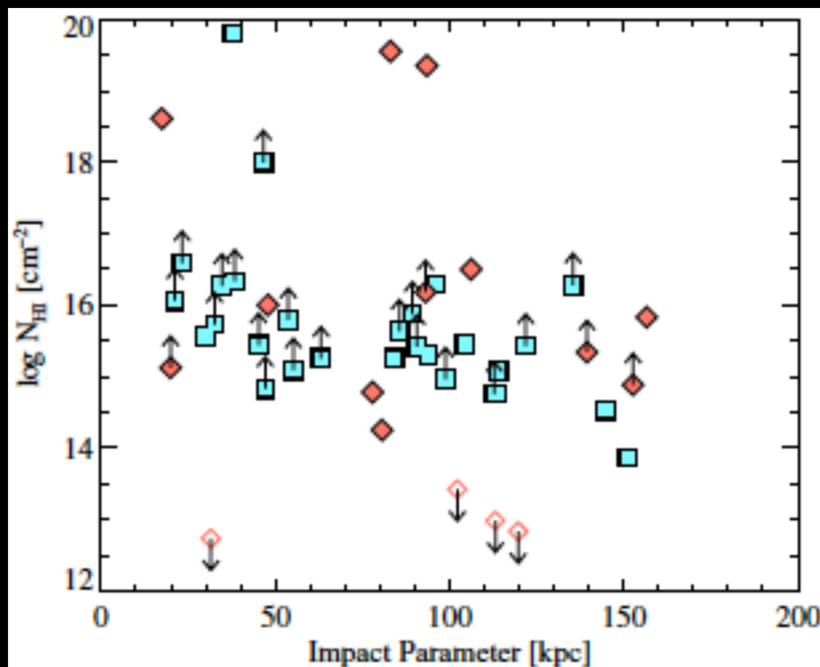
It is not associated with nearby dwarf galaxies.



The clouds are at different velocities than M31's HVCs and its dwarf companions, so they are a different phenomenon.

Below N_{HI}~10^{17} cm^{-2}

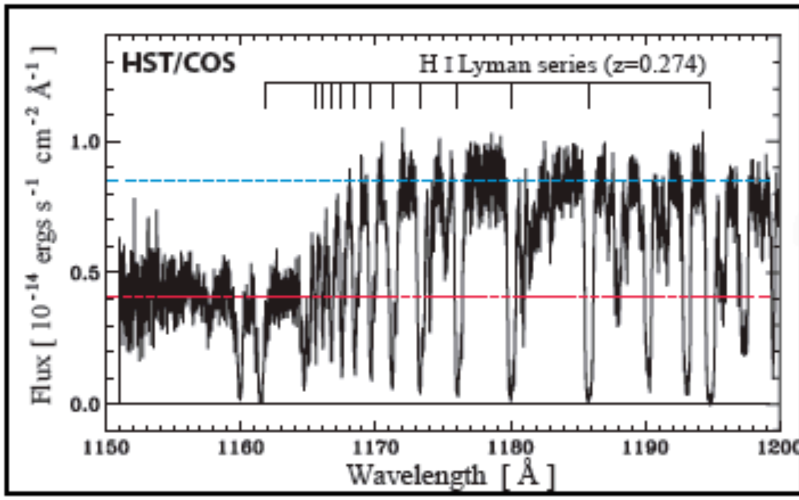
- Below this level, it is extremely time-consuming to map HI in emission.
- COS-Halos probes the CGM around z<0.3 galaxies.
- Diffuse HI ubiquitous in the CGM around star-forming galaxies.

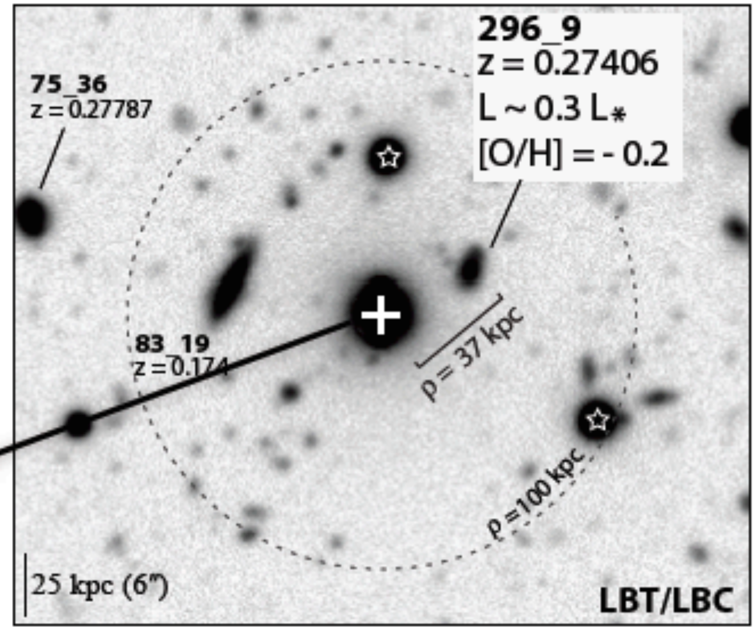


Tumlinson et al. 2013

A probable cold accretion stream at z = 0.274

PG1630+377





- log N(H I)$_{total}$ = 17.06±0.05
- [Mg/H] = -1.71 ± 0.06

The LLS and galaxy are separated by ρ = 37 kpc and Δv ~ 25 km/s.

They differ in metallicity by a factor of ~30.

Ribaudo+ (2011b) astro-ph/1105.5381

courtesy of J.C. Howk

Conclusions

- Disks have nearly flat HI distributions, then decline before a sharp edge around $N_{HI} \sim 3x10^{19}$ cm^{-2} due to ionization.
- Even at high N_{HI}, we see signatures of tidal interactions (or accretion) that are invisible in starlight.
- We see possible signatures of accretion down to $N_{HI} \sim 10^{17-19}$ cm^{-2}, but how to discriminate from tidal debris?
- HI emission detectable at $N_{HI} \sim 10^{17}$ cm^{-2} with single-dish radio telescopes, but not ubiquitous. Need this sensitivity to detect cold flows. ASKAP, MeerKAT, and SKA should help with this.
- At $N_{HI} < 10^{17}$ cm^{-2}, can only see HI in absorption. 100% of sightlines passing within virial radius have Lyman-α absorption due to infall/outflows. Can discriminate via metallicity, but hard to associate with specific galaxies.