Dwarf Galaxies: From the Deep Universe to the Present
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Cosmic Web Research: Where are the Missing Dwarf Galaxies and the Inter-Galactic HI Clouds

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Abstract. We know that the observed HI (and H_2) content cannot explain the SFR observed in galaxies. The only way galaxies can sustain that SFR is by accreting HI-rich dwarf galaxies or Inter-Galactic HI clouds. However, no observation to detect those accretion events has been conclusive so far. Instruments having the necessary sensitivity (e.g. GBT) lack the necessary spatial resolution and those with the proper resolution (e.g. VLA) lack the sensitivity. I will show that both are necessary to detect those illusive HI clouds. The SKA precursor MeerKAT is starting its operation as we speak and will start the Large Survey Programs at the end of 2018. FAST has started its observations in drift scan mode with CRAFTS (Commensal Radio Astronomy Fast Survey). In the near future (2019-20), the best combination to study low column density HI will be to combine the sensitivity of FAST with the spatial resolution of MeerKAT.

Keywords. galaxies: dwarf, galaxies: ISM, intergalactic medium, cosmology: observations.

1. Introduction

How do galaxies accrete the gas necessary to sustain the observed Star Formation Rates, which are much higher than expected from the gas observed in galaxies, which has consumption timescales of ∼1-2 Gyr? Even the expected contribution from minor mergers and left-over gas in the halos of galaxies fall one order of magnitude lower than what is needed (Sancisi *et al.* 2008). Thus gas **must be accreted** from the IGM.

In this paper, I will concentrate on the radio (HI) side and not on the optical (e.g. Ultra Faint Dwarfs - UDFs) searches such as in the Dark Energy Survey (Drlica *et al.* 2015) or with instruments like Dragonfly (Abraham & van Dokkum 2014). As shown in Figure 1, those cameras can now detect with broadband photometry (e.g. g-band) the faint optical disks to radii close to those reached in HI at a level of $\sim 10^{20}$ cm^{-2}, the level of recent surveys such as THINGS (Brinks *et al.* 2009). Before, such large radii were only reached in emission line work, such as in this deep Fabry-Perot observation of NGC 7793 (Dicaire *et al.* 2008), shown in Figure 2.

2. Reaching lower column densities, N_{HI}

The interaction of galaxies with their environment, the Inter Galactic Medium (IGM), is a very important aspect of galaxy formation. One of the most fundamental, but unanswered questions in the evolution of galaxies is how gas circulates in and around galaxies and how it enters the galaxies to support star formation. We have several lines of evidence that the observed evolution of star formation requires gas accretion from the IGM

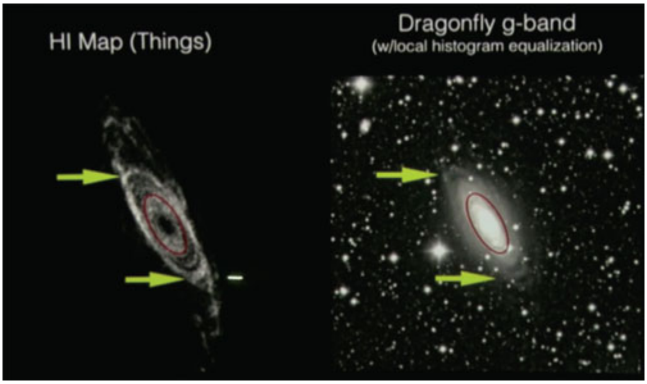

Figure 1. Comparison of the HI disk (THINGS) to the optical disk in the g-band using the Dragonfly camera for the galaxy NGC 2841.

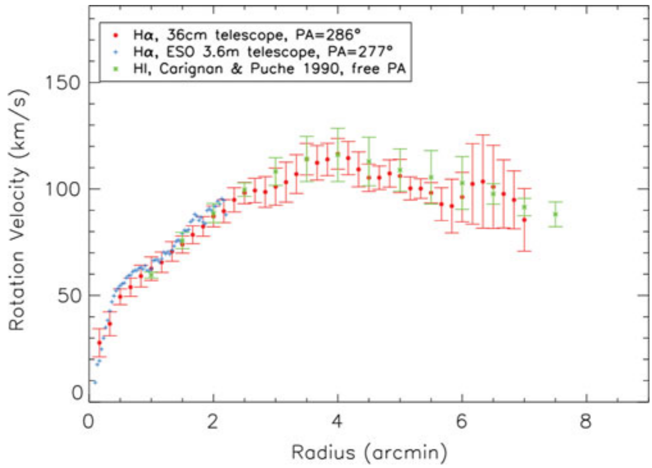

Figure 2. Fabry-Perot Hα rotation curve of NGC 7793 compared to the HI rotation curve.

at all times and on all cosmic scales (Popping *et al.* 2015). The gas is expected to be embedded in an extended cosmic web made of sheets and filaments. Such large-scale gas structures are expected by cosmological numerical simulations, which have made significant progress in recent years (e.g. Nuza *et al.* 2014). Such simulations do not only model the large scale structure of the cosmic web, but also investigate the neutral gas component.

As can be seen in Figure 3, it took more than 25 years to go down 2 orders of magnitude in HI column densities. The first observations at the end of the 70s with the Westertbork Synthesis Radio Telescope (WSRT) were going down to $\sim 10^{21}$ cm^{-2} after 12 hours of observations showing the *thin* HI disk (Sancisi & Allen 1979). About 20 years later, with better receivers and longer integration times, observations started to exhibit the *thick* HI disk at levels of $\sim 10^{20}$ cm^{-2} (Swaters *et al.* 1997). Ten years later with much longer integration (e.g. HALOGAS, 10 × 12 hours), observations started to detect the HI gas in the *halo* at $\sim 10^{19}$ cm^{-2} (Oosterloo *et al.* 2007).

Another problem with high spatial resolution interferometers (e.g. the Very Large Array (VLA), the Australia Telescope Compact Array (ATCA) or the WSRT) is that they may not be able to see gas distributed on scales larger than $\sim 15'$ because of their lack of short spacings. However, lower resolution arrays such as the Karoo Array Telescope

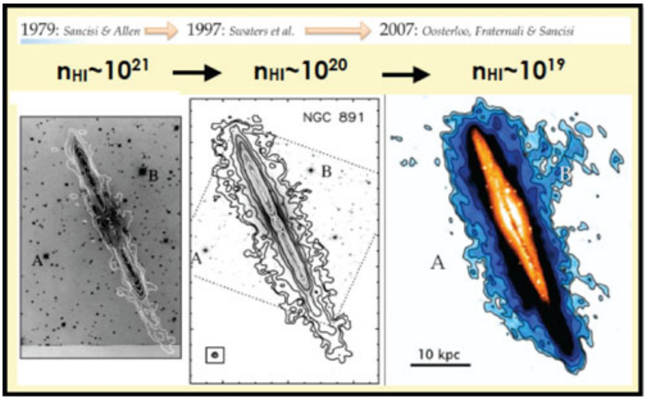

Figure 3. 25 years of HI observations of NGC 891 with the WSRT.

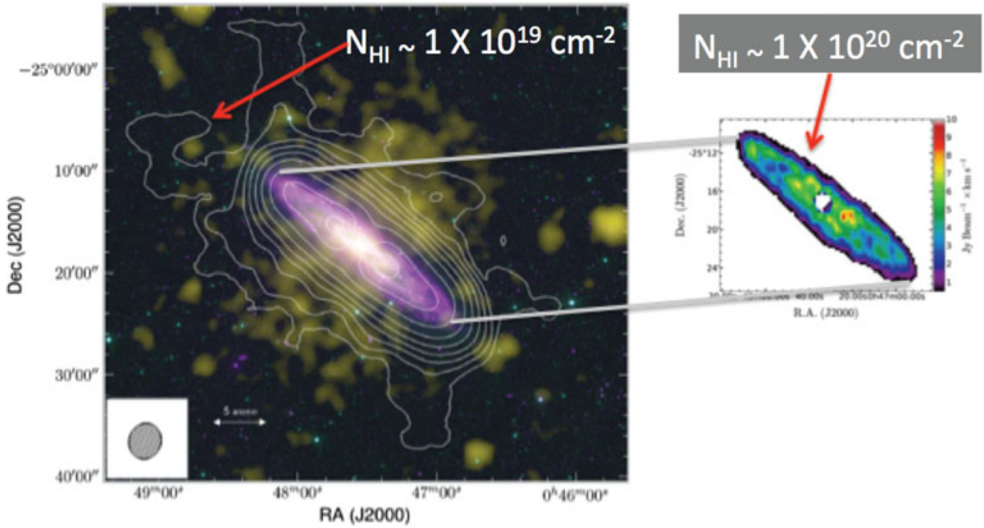

Figure 4. Comparison of a KAT-7 and a VLA HI observation of NGC 253.

(KAT-7) with baselines ranging from 26m to 185m, can be sensitive to those larger scales. This is illustrated in Figure 4 where the VLA (Puche, Carignan & van Gorkom 1991) only detected the HI in the disk while KAT-7 (Lucero *et al.* 2015) could detect the gas in the halo of NGC 253. Figure 5 shows that this starburst Sculptor group galaxy is a texbook case of the *galactic fountain* model. After separating the disk gas from the halo gas, we can see the hot X-ray gas in yellow being ejected from the nucleus, cooling down in the halo and raining back down onto the disk.

3. Cosmic Web Research: at which column densities?

We have just seen in Sec. 2 that densities $\sim 10^{19}$ cm^{-2} allow us to detect the HI in the halos of galaxies (Oosterloo *et al.* 2007; Lucero *et al.* 2015). Which column densities do we have to reach to connect to the HI in the cosmic web between galaxies? This low column density IGM could provide, if accreted, the gas necessary to sustain the observed SFRs. Figure 6 shows cosmological numerical simulations (Popping *et al.* 2009) where it can be seen that the cosmic web HI should be expected at densities around 10^{16}-10^{17} cm^{-2} (dark orange). As seen in Figure 7, simulations of the Circum Galactic Medium

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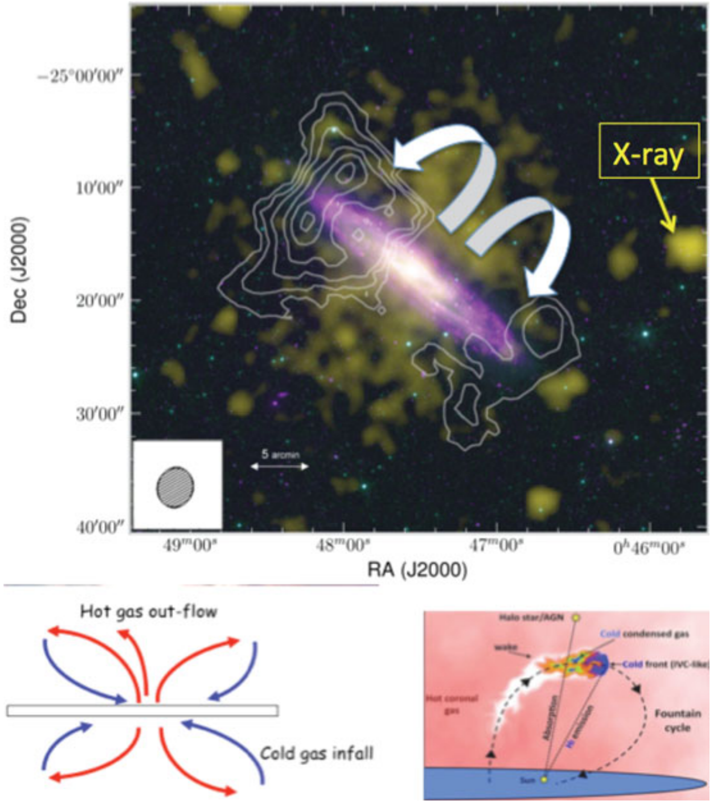

Figure 5. The "galactic fountain" model illustrated in NGC 253 (Lucero *et al.* 2015).

(CGM) around M31 and the MW (Nuza *et al.* 2014) predict also that this gas should be found around 10^{16}-10^{17} cm^{-2} (light green).

Is there evidence that some of that CGM is being accreted on galaxies? The closest evidence comes from VLA and Green Bank Telescope (GBT) observations of NGC 2403 (de Blok *et al.* 2014), as illustrated in Figure 8. We know that the large HI cloud is not part of the disk since it is at the systemic velocity but, as can be seen, it is barely resolved by the GBT beam (9.1').

4. Cosmic Web Research: on which scales?

In 2004, a study was made of the IGM in the Local Group, and more specifically between M31 and M33 (Braun & Thilker 2004). In order to get the proper sensitivity $\sim 10^{17}$ cm^{-2} to detect the cosmic web gas between the galaxies, they used the WSRT, not as an interferometer but, as a collection of single dishes. The price to pay was a very large beam of ∼49'. As seen in Figure 9, those observations suggested the presence of a filament of low column density HI between M31 and M33.

However, ∼10 years later, a study with the GBT having a beam of 9.1' (Wolfe *et al.* 2013) showed that in fact the HI between M31 and M33 was in the form of small discrete clouds and not of a large scale filament, which was only the result of the very low spatial resolution of the WSRT observations. As shown in Figure 10, the cosmic web HI is thus more expected to be in the form of discrete clouds than in the form of large scale filaments.

One of the regions well studied for its CGM is the M81 group. A very well-known study with the VLA (Yun, Ho & Lo 2014) showed about 15 years ago the large amount

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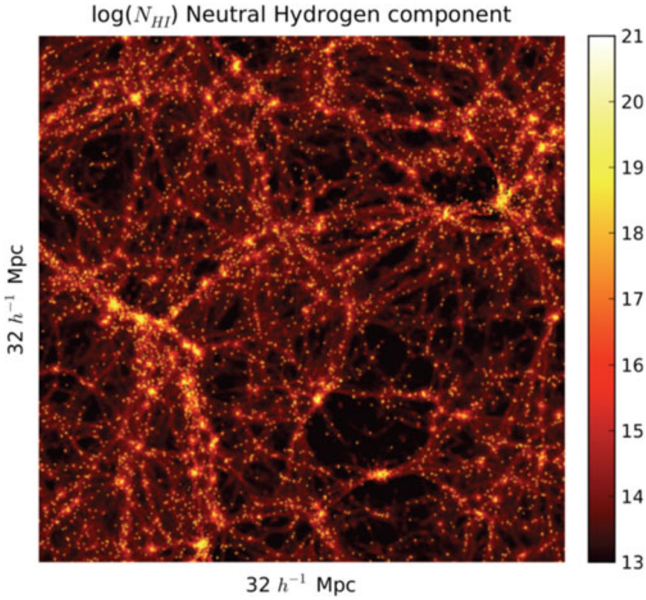

Figure 6. Simulations of the HI component of the cosmic web (Popping *et al.* 2009).

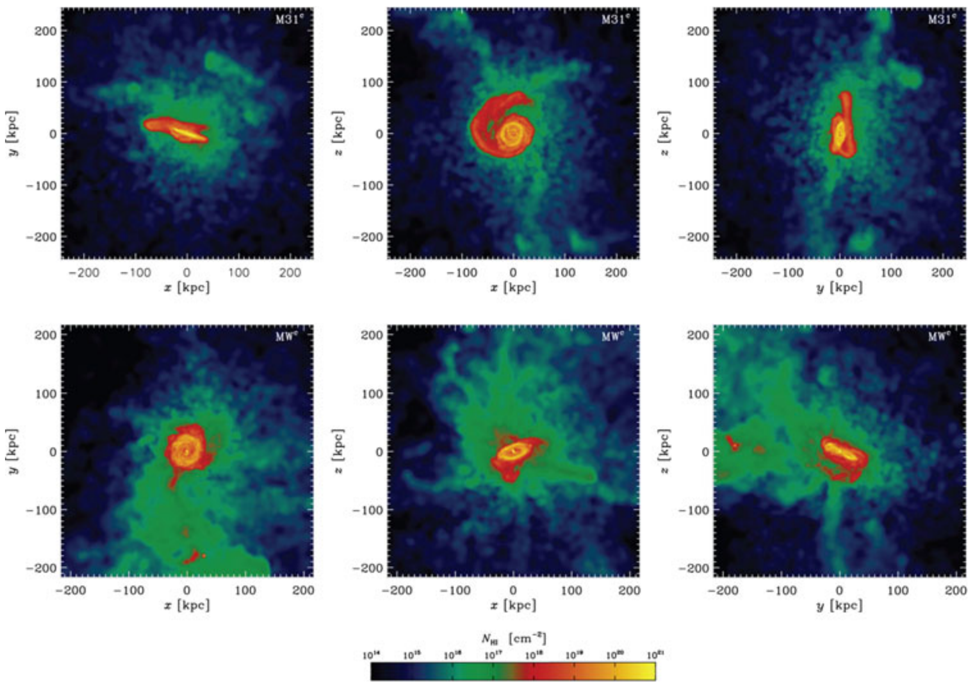

Figure 7. Numerical simulations of the CGM around M31 and the MW (Nuza *et al.* 2014).

of HI gas between M81, M82 and NGC 3070 (Figure 11). Figure 12 goes much deeper and shows the HI clouds between that group of three galaxies and NGC 2976 further south.

So, the lesson learned in the last few years is that, if we want to be able to detect low column density gas, we need both sensitivity and resolution. We can look then at

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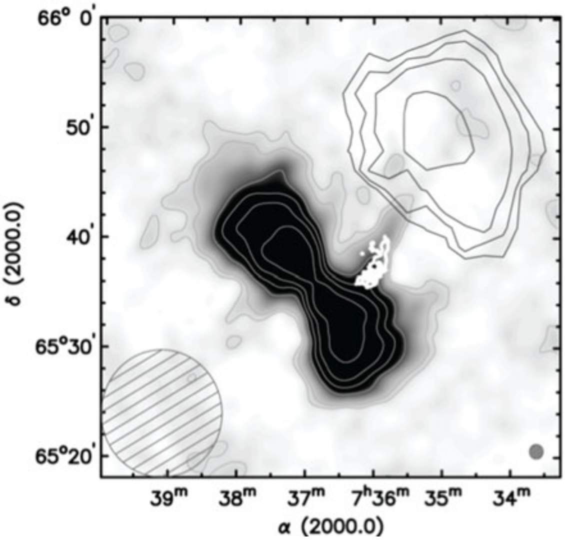

Figure 8. VLA (small cloud) and GBT (large cloud) observations of NGC 2403 (de Blok *et al.* 2014).

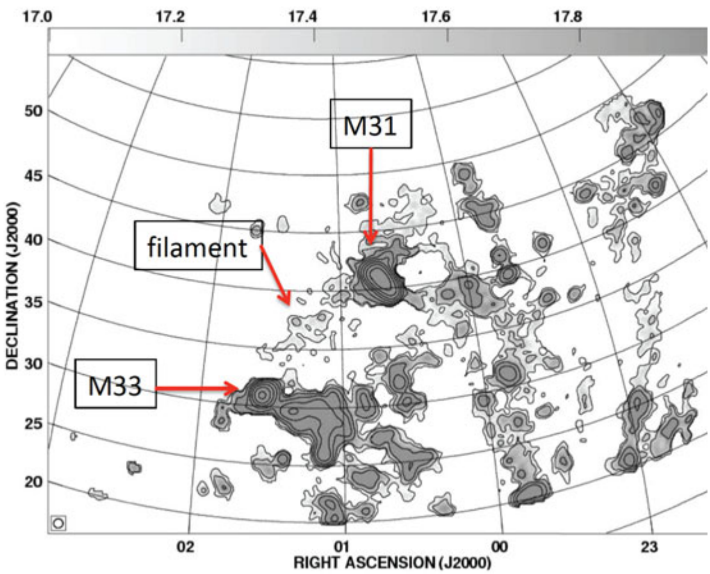

Figure 9. Study of the CGM in the environment of M31 and M33 (Braun & Thilker 2004).

what MeerKAT will be able to accomplish. In the 2010 call for proposals, the LSP MHONGOOSE, was selected as a "Key Science Program" for MeerKAT. The desired column density limit was 7.5×10^{18} cm^{-2} at 3σ over 16 km s^{-1} at 30" resolution. For the 2010 MeerKAT parameters, this corresponded to a noise of 0.074 mJy beam^{-1} per 5 km s^{-1} channel assuming natural weighting. This would have been reached after 200 hours of observing time per galaxy (including calibration overhead). For the complete sample of 30 galaxies, the total allocated observing time was therefore 6000 hours.

With the new MeerKAT parameters (improved sensitivity of a factor $\sim$4), this noise level will now be reached after 48 hours on-source. Assuming 15% overhead, this becomes

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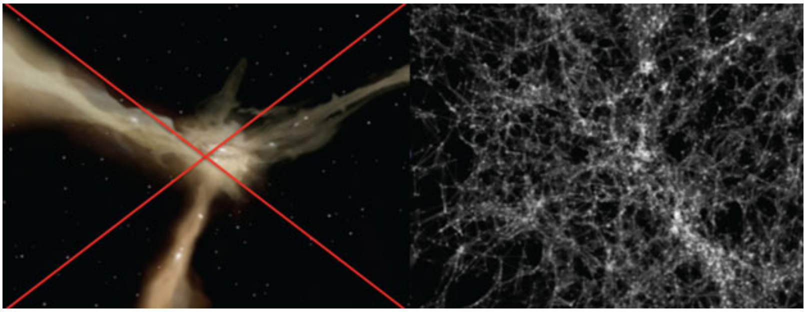

Figure 10. The cosmic web is thought to be more clumpy (right) than in the form of large scale filaments (left).

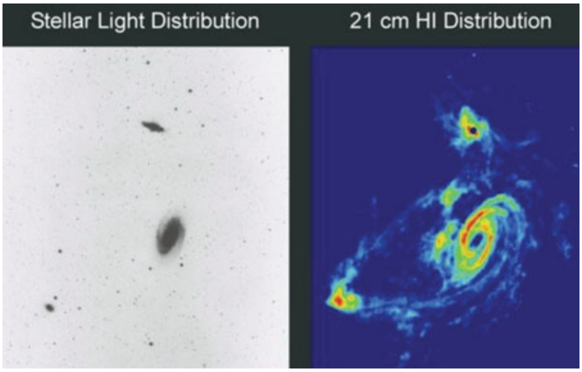

Figure 11. HI in the M81 group from VLA observations (Yun, Ho & Lo 2014).

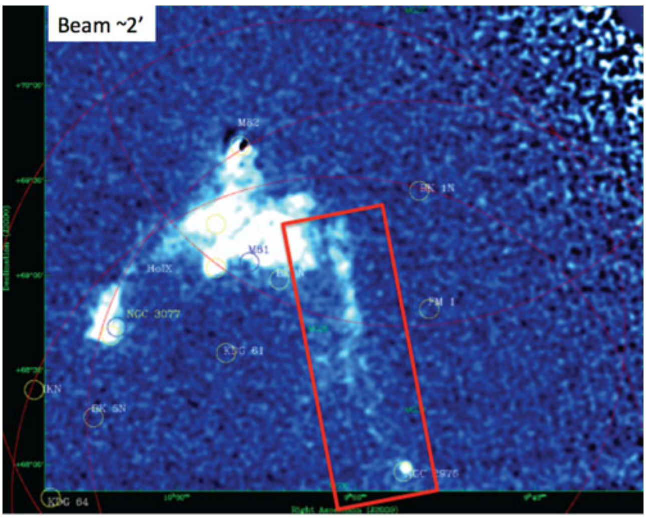

Figure 12. HI in the M81 group from DRAO observations (Sorgho, A. *et al.* 2018, in prep.).

30×55 hours = 1650 hours. With very good data processing, the best sensitivity reached by MHONGOOSE will probably be around 5.0×10^{18} cm^{-2}. We think that the only way to gain another order of magnitude in column density will be to combine the resolution of MeerKAT with the sensitivity of FAST.

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Figure 13. FAST-MeerKAT & SKA pathfinders Synergies Conference in Pingtang, Guizhou, China on 13-15 June 2018.

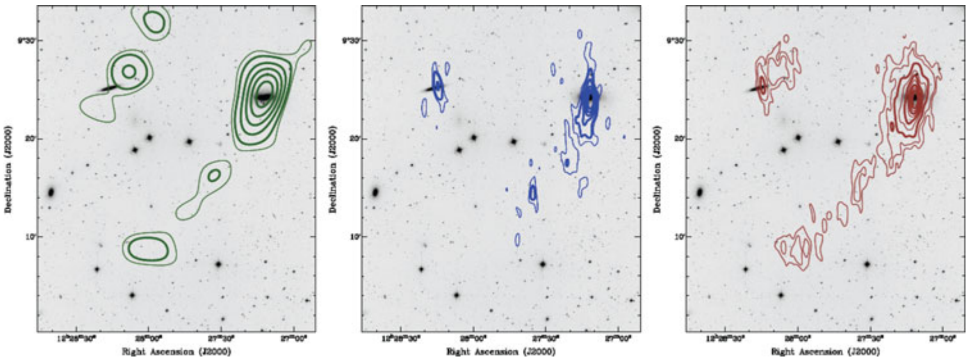

Figure 14. Combining (right) HI observations from KAT-7 (left) & WSRT (middle) in the map plane.

5. Combining HI data from MeerKAT & FAST

On June 13-15 2018, there was a meeting (Figure 13) in the astronomy town of Pingtang in Ghizou province, China, to discuss the possible synergies between the Chinese 500 m single-dish FAST, MeerKAT and the other SKA pathfinders (e.g. ASKAP, APERTIF, ...). As far as HI science is concerned, it was proposed to observe 2-3 spirals in the $\sim 20^0$ common DEC strip ($+0^o$ to $+20^o$) (e.g. NGC 3521 at DEC $\sim 0^o$), where we could reach low column densities much faster by combining FAST & MeerKAT data and probably combine the data in the map (column density) plane as was done by combining KAT-7 and WSRT data for a southern extension of the Virgo cluster (Sorgho *et al.* 2017). This study succeded to reach column density limits of 8×10^{17} cm^{-2} and uncovered the long 60 kpc tail of the galaxty NGC 4424 (Figure 14).

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Table 1. Sensitivities of different past and future telescopes.

Telescope Array(s)	Integration hours	resolution km.s^{-1}	beam arcsecs	sensitivity cm^{-2}	Expected date
VLA (THINGS)	10	5	30	1.0×10^{20}	
WSRT (HALOGAS)	120	5	30	1.0×10^{19}	
KAT-7	100	5	210	1.0×10^{19}	
KAT-7 + WSRT	100	16	210	1.0×10^{18}	
MeerKAT	50	16	90	1.0×10^{18}	2019
SKA_1-MID	100	5	30	7.5×10^{17}	2023
SKA_2	10	5	30	2.5×10^{17}	2030
SKA_2	100	5	30	7.5×10^{16}	2030

6. Conclusion

The SKA precursor MeerKAT has been inaugurated on 2018 July 13 and will start its Large Survey Programmes (LSPs) at the end of 2018. FAST has started its observations in "drift scan" mode with CRAFTS (Commensal Radio Astronomy Fast Survey). An open call for proposals with MeerKAT should be issued before the end of 2018. A similar call for proposals with FAST should be issued at the beginning of 2019. Table 1 compares the sensitivities of past and future instruments.

In the near future (2019–20), the best combination to study low column density HI will be to combine the sensitivity of FAST with the spatial resolution of MeerkAT. The combination of the data from those two telescopes will allow, 4-5 years before SKA1-MID, to do "cosmic web" research to levels $< 5 \times 10^{17}$ cm^{-2}, close to 10^{16} cm^{-2}, densities that would normally only be accessible to the full SKA around 2030. It is at those densities that we expect the galaxies to connect to the sourrounding cosmic web.

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