PROCEEDINGS OF SCIENCE

Continuum and HI surveys working together

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SKA1 will offer an enormous improvement in observational capabilities for radio astronomy. The astronomical community is very eager to exploit these new possibilities, so much so that the ambitions for using SKA1 far exceed what is possible given the available observing time. An obvious strategy to alleviate this problem is to try to define commensal surveys, i.e. observing programs from which the same data serves a number of (even very) different science topics. The community is aware of the large potential benefits of this approach and many groups are actively discussing how to define the best commensal observing strategies. This, turns out, is not a trivial exercise unless one has some kind of quantitative measure that defines what an optimal combination of survey strategies is. In this paper, we discuss a possible approach, from the HI science point of view, to quantitatively investigate how one can optimally combine different surveys.

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PoS(EXTRA-RADSUR2015)035

1. Introduction

The first phase of the Square Kilometre Array (SKA1) will give tremendous improvements in observational capabilities for radio astronomy. In addition, the current plans are that a large fraction of the observing time will be devoted to very large surveys, involving large groups of the community. Both these factors will bring an important change in how radio astronomy is done. The quality and sensitivity of the data will be much better than what we are used to, while also the amount of data will be very much larger that what the radio astronomical community is used to handle. The scale of things will change. This implies that many research topics that currently are difficult to address will become accessible which, in turn, will bring important progress in radio astronomy, and astronomy in general. This is, of course, the main reason that SKA1 will be built.

The community is very excited about this prospect and many plans for using SKA1 are already being conceived by many groups. In fact, the community is so motivated to use SKA1 that the sum of all the ambitions appears to be much larger than what in the end we will be able to do with SKA1. This is, by itself, not necessarily a bad thing, because it means that for SKA1 we will able to select the most interesting and relevant issues from a large pool of science topics.

To be a bit more specific: it is likely that for each of the two components of SKA1 (SKA1-Low and SKA1-Mid) about 5000 hrs per year will be available for all surveys combined. This would mean that if, e.g., one would divide the observing time more or less equally over all possible research areas (e.g., HI, continuum, transients, pulsars, magnetism, cosmology,...) not even 1000 hrs per year would be available for each research field on SKA1-Mid. Looking at the long list of surveys one could possibly do with SKA1 [1], and the large amount of observing time of each of these surveys, this is by far not enough to satisfy all ambitions within a reasonable time frame.

The obvious thing to do is, of course, to try to define commensal surveys, i.e. observing programs from which the same data can serve a number of (even very) different science topics, in very different ways. Such an approach would potentially increase the efficiency and output of SKA1 by a large factor. The community is aware of the large potential benefits of this and many groups are actively discussing how to define the best commensal observing strategies. This, turns out, is not a trivial exercise unless one has some kind of quantitative measure that defines what an optimal combination of survey strategies is. In this paper, we discuss a possible approach, from the HI science point of view, to quantitatively investigate how one can optimally combine different surveys. In addition, we will show that there is great potential for commensal continuum and HI surveys, by giving an example where this may be realised in the actual world. Before we discuss this in more detail, we first give, in order to give the continuum community some background, a brief overview the main HI science topics one can investigate with SKA1 and what the current thinking is of the HI community what the layout of the HI surveys could be.

2. HI science with SKA1: the opportunities

To state it boldly: the observational limits of radio telescopes for interferometric HI work have not fundamentally improved since 1980 when the VLA, still the most sensitive interferometer for HI work, became operational. Significant improvements in correlator capacity have occurred, but the sensitivity for HI work of the VLA is currently only slightly better than in 1980. This means that the HI community is very eager to exploit the power of SKA1. To give an idea what the impact of SKA1 can be, it is perhaps best to compare the capabilities of SKA1 with what is possible with current, or near-future, instruments. Compared to the JVLA, SKA1-Mid will be about a factor 30 faster in terms of observing time. To illustrate the impact of this: one important HI project which is currently being undertaken on the JVLA is the CHILES survey [2]. This project uses a 1000 hr (!!) integration on a single field (the COSMOS field) for which a large set of additional data is available to provide resolved images of the neutral hydrogen in galaxies from $z = 0$ out to redshift $z = 0.45$. The aim of the project is understanding galaxy evolution across cosmic time and testing predictions of cosmological simulations. Given the very large amount of observing time, and the pressure on the JVLA to use the telescope for other programs, it will take several years before all data for this project will be taken (the project is about 5 years under way and it is about half way). In contrast, depending somewhat on redshift, SKA1-Mid could do the same project in about a factor 30 less observing time, i.e. about 30 hr, and the observations could be done in less than a week. In addition, the field of view of SKA1-Mid is four times larger than that of the JVLA, meaning that the survey volume is equally larger.

For nearby galaxies, the situation is similarly dramatic. One of the main high-resolution surveys available on the HI in nearby galaxies is the THINGS survey [3] performed with the JVLA. This survey has given the most detailed view to date of the HI, and it's relation to e.g. star formation, in (about 30) nearby galaxies and is arguably one of the most successful HI projects of the last decade (e.g. in terms of publications and citations). This required substantial amounts of observing time ($\sim$ 30 hr per galaxy) plus there was the usual complication that the observations had to be spread over a large period due to the different array configurations of the JVLA required to make high-fidelity images. With SKA1-Mid it takes only 1 hr of observation to reach the same sensitivity while one has the practical advantage of not having to spread the observations over several array configurations.

A final example of recent work that had significant impact are the ultra-deep HI observation of nearby galaxies like those of NGC 891 [4] and NGC 6946 [5]. These observations revealed that the thin HI disks of spiral galaxies are embedded in a thicker, lagging halo of atomic hydrogen which may play an important role in the life cycle of the gas in spiral galaxies. These observations required integrations of a few hundred hours with the WSRT, i.e. the observations had to be spread over a period of at least a month. The same sensitivity can be reached with SKA1-Mid in about an hour.

From the above examples it is clear the sensitivity, as well as in resolution and field of view, of SKA1-Mid is much better compared to current facilities. This will allow us to probe the HI in galaxies deeper and with higher resolution, but it also means that in particular the scale of projects that are feasible to undertake is very much larger. SKA1-Mid will open up completely new observational parameter space for extragalactic HI studies.

3. The plans for the HI surveys

The international HI community has been actively discussing, in quite an organised manner, for a number of years now how to best use the opportunities offered by the SKA Pathfinders and SKA1. This is happening under the guidance of the SKA HI Science Working Group, but also

PoS(EXTRA-RADSUR2015)035

through the PHISCC (the Pathfinder HI Survey Coordination Committee), a self organised body founded in 2009 of which all relevant HI research groups and individuals are member. Below, we give a brief summary of the main science topics identified by the HI community.

3.1 Resolved HI kinematics and morphology of galaxies out to $z \sim 0.8$

The main aim of this topic is to use HI observations to study galaxy *evolution*. Except for a few cases [2,6,7], HI work has been limited, for emission studies due to the lack of sensitivity, to the relatively local Universe. However, with SKA1 this is really going to change, and finally one can use HI for studying galactic structure at reasonable redshifts, out to look-back times of about 8 Gyr. The main topics can be summarised as:

- studies of the environment: the baryon cycle of galaxies; gas inflow into and removal of gas from galaxies; the gaseous interface between galaxies and the IGM
- studies of the mass properties of galaxies: the HI mass function as a function of environment and redshift; relation between dark and baryonic matter
- angular momentum and kinematics: scaling relations between properties of galaxies, evolution and origin of the (baryonic) Tully-Fisher relation

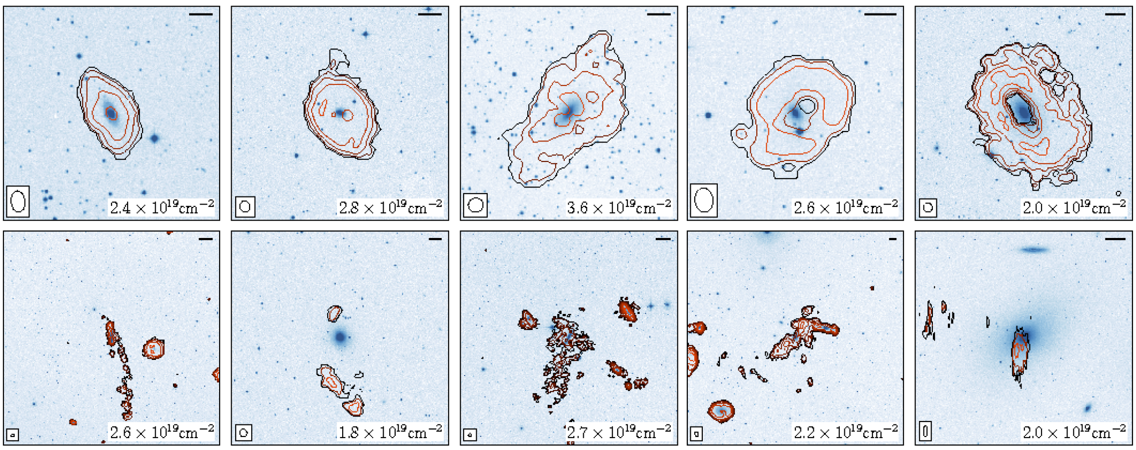

Figure 1: HI structures observed in early-type galaxies as part of the ATLAS^{3D} project [8]. The top row are early-type galaxies that are found in environments of low galaxy density, while the bottom row are objects found in higher galaxy density (but still outside clusters).

An important aspect is that with SKA1 one will be able to spatially resolve the objects so that one not only can consider global quantities, but also the morphological and kinematical structure of galaxies. Figure 1 illustrates the importance of this. Shown are the HI structures found around early-type galaxies in the ATLAS^{3D} survey [8]. The top row are early-type galaxies that are found in environments of low galaxy density, while the bottom row are objects found in higher galaxy density (but still outside clusters). While the optical images of the galaxy do not reveal any signatures of interactions or accretions, the HI data show a strong signal. The HI around galaxies in denser field environments are clearly distorted, likely due to galaxy-galaxy interactions, while

PoS(EXTRA-RADSUR2015)035

those in the top row are all nice, undisturbed regularly rotating gas disks. Interactions between galaxies are an important factor for galaxy evolution and the example shows that HI observations can provide a sensitive tool for investigating this. One of the main aims of the HI projects planned for SKA1-Mid is to perform similar studies at higher redshift to understand the role of interactions in the evolution of galaxies.

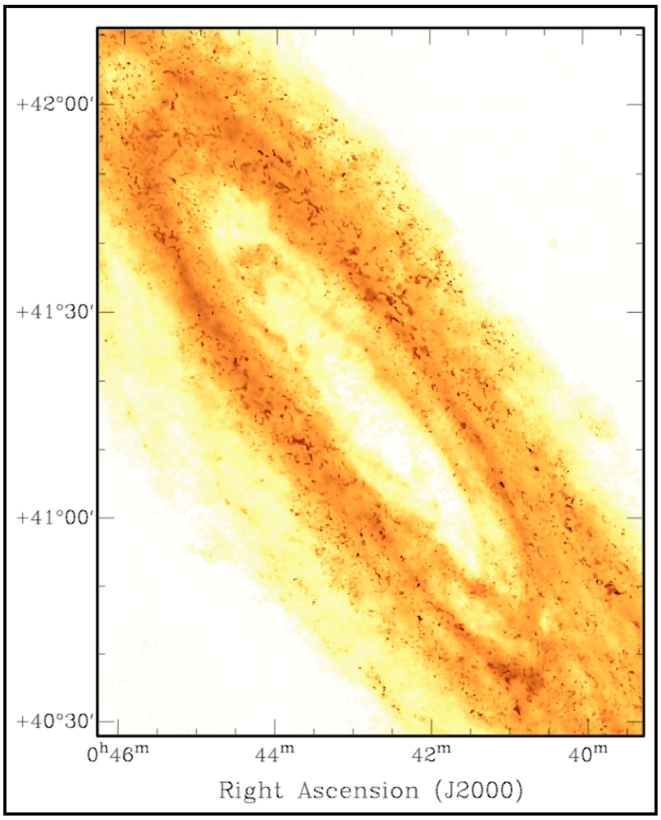

Figure 2: HI image of M31, as observed with the WSRT [9] showing exquisite detail in the HI disk . Due to the vicinity of M31, even the limited spatial resolution of the WSRT detects structures down to linear sizes of 100 pc. SKA1-Mid will be able to image galaxies in similar detail out to distances ten times larger than M31.

3.2 High spatial resolution studies of the ISM in the nearby Universe.

This type of work aims to use the high spatial and velocity resolution of SKA1-Mid to probe the ISM in a number of nearby galaxies (covering a wide range of structural properties) and resolve the ISM at the scale of clouds (100 pc or better). Given the column density sensitivity of current radio telescopes, one can study the ISM in external galaxies only on scales larger than about 500 pc. To further understand how the ISM works and can form stars, one has to go to smaller scales. The combination of this kind of work with ALMA observations is very interesting. The idea is to observe about 30 nearby galaxies with integrations long enough to detect the HI disks at a spatial resolution of the order of one arcsecond which would be a significant improvement over the current observational limit of about 5 arcsec. Figure 2 illustrates the amount of detail that will be observable with SKA1- 5 Mid in a typical spiral galaxy in the local Universe. This work also aims to study at high physical resolution the ISM in the Galaxy and in the Magellanic Clouds, both in emission and in absorption.

3.3 HI absorption studies out to the highest redshifts.

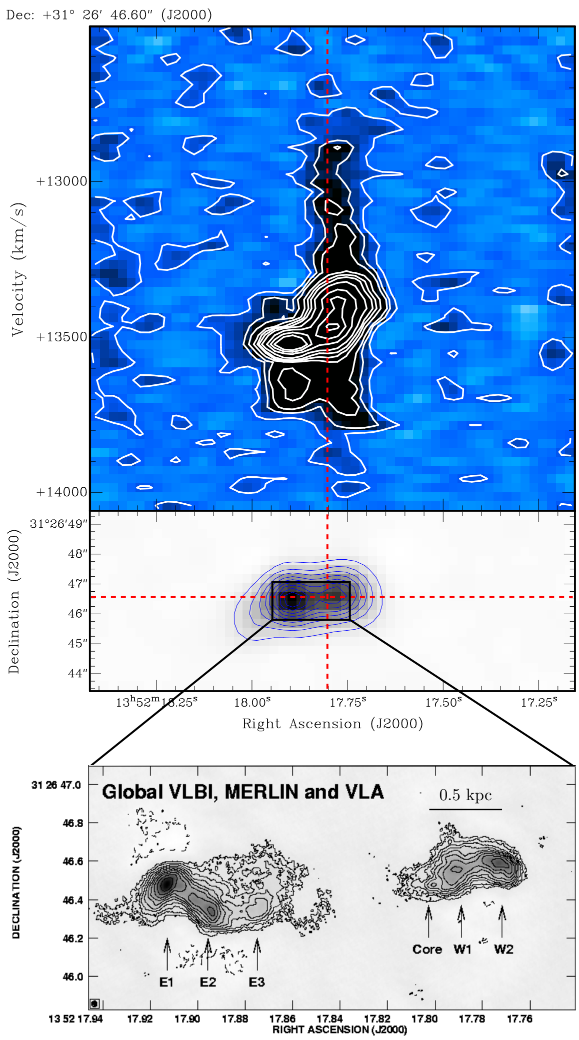

Figure 3: Fast HI outflow detected in the radio galaxy 3C293 [11]. The top panel is a position-velocity plot along the axis of the radio continuum and shows a fast, blueshifted outflow of HI which originates at the western lobe of the radio structure. The bottom panel shows a higher-resolution continuum image of the radio continuum.

Observing HI 21-cm absorption is a unique way to study of cold neutral gas in normal and active galaxies out to the highest redshifts, because the ability to detect HI in absorption depends mainly on the strength of the background continuum. Studies of both the associated HI 21cm absorption as well as intervening HI 21-cm absorption due to objects along the line of sight are planned.

Recent work (e.g. [10]) has shown that the jets of radio loud AGN can interact with the circumnuclear medium which, in turn, can drive a fast outflows of gas, with speeds > 1000 km s^{-1}.

Such outflows may play an important role in the evolution of the galaxy and of the AGN itself. Interestingly, it appears that, despite the large amounts of energy involved, most of the mass in the outflow is in *cold* gas meaning that HI absorption can be an effective method for studying this phenomenon, even out to distances not accessible for HI emission studies. Crucial in the interpretation of the data is that the spatial of the data is high, because this allows to determine where the jet-ISM interaction is occurring (see Figure 3).

4. Definition of survey parameters

In order to investigate the possibilities for commensal surveys, it is important to understand the parameters that drive the design of HI surveys. Key to this is that much of HI science is driven by column density sensitivity and not by point source sensitivity. This is because only when one can *resolve* the HI structures in and around galaxies, one can try to understand what is going on. Relevant for this is that the typical column density of the HI in galaxy disks is basically the same in every galaxy. This follows from the observed relation between total HI mass ($M_{\rm HI}$) of the HI disks and their diameter of the HI disk ($D_{\rm HI}$), which is found to be of the form [12]

$$M_{\rm HI} = 10^{6.5-6.7}\, D_{\rm HI}^2.$$

The fact that the HI mass is proportional to the square of the diameter implies that the average column density is constant and is at a value of a few times 10^{20} atoms cm^{-2}. Therefore, to be able to image the HI disk of any galaxy from the above equation one can, given a spatial resolution one aims for, estimate how long to observe a galaxy, and this is basically independent of which galaxy you observe. Another way of looking at it is that galaxies of a given HI mass all have the same size. This can be used to compute, given a mass-sensitivity limit, what the ideal resolution should be for the observations.

Resolution is a key aspect of the HI science we hope to do with SKA1-Mid. However, another important aspect is to observe large areas of the sky in order to obtain a statistically relevant number of objects, and to reduce the effects of cosmic variance. So the trade-off between survey parameters like area and depth per pointing is between how many galaxies one can resolve in what detail, out to which redshift one can do this, while maximising the total number of detections of the entire survey. In general, the number of objects detected in a single pointing increases with observing time t as $t^{3/4}$ while it increases linearly with the number of pointings. Therefore, to optimise the number of objects detected in a survey, the strategy should be to integrate per pointing just as long as one needs to detect your type of object at a given redshift and after that, use the remaining observing time to cover as many pointings as possible.

How this works for HI surveys is illustrated in Figure 4 which gives, for three different integration times on SKA1-Mid, the linear resolution of the smallest HI objects one will detect, as function of frequency. Galaxies above the curved lines will be detected and spatially resolved, those that lie below these lines will not be detected. The horizontal lines give the physical extent of a galaxy with an HI mass of $10^{10}\ M_\odot$ and of $10^9\ M_\odot$. As an example, for an integration time of 10 h, a galaxy with an HI mass of $10^{10}\ M_\odot$ will be resolved up to a redshift of about $z = 0.3$, while a galaxy of $10^9\ M_\odot$ up to $z = 0.1$. The characteristic HI mass ('the knee') in the HI mass function is around $10^{10}\ M_\odot$. Therefore, in order to have a reasonable sampling of the galaxy population, one

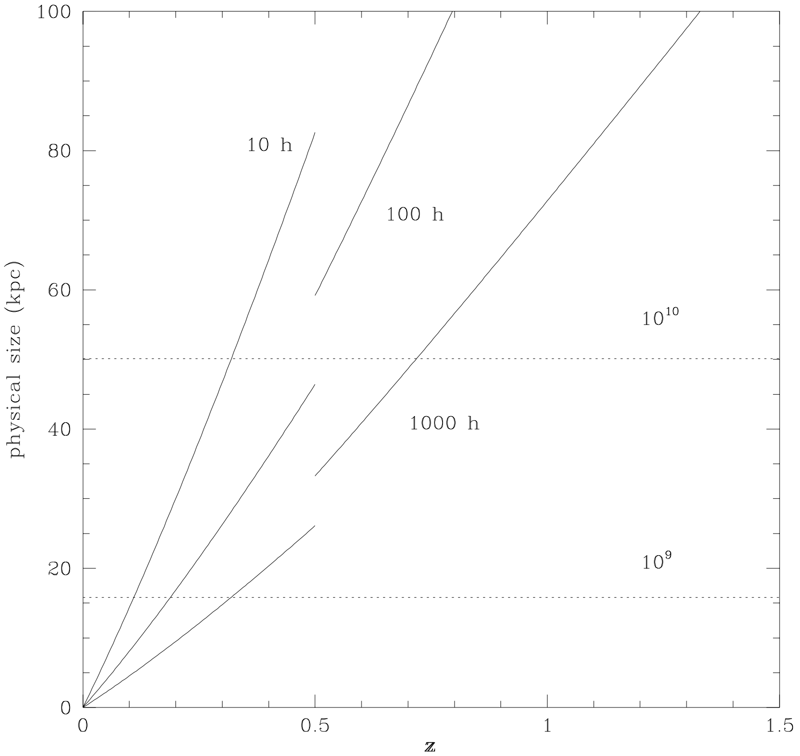

Figure 4: Physical size of the smallest HI detection with SKA1-Mid, as function of redshift. Given are the results for three different integration times (10h, 100 hand 1000 h) for a single pointing. The horizontal lines give the physical extent of a galaxy with an HI mass of 10^{10} $M_{\odot}$ and of 10^9 $M_{\odot}$.

should be able to resolve galaxies with an HI mass down to a few times 10^9 $M_{\odot}$, although where that boundary should precisely lie is a matter of discussion. From Figure 4 one can determine, depending on what mass range and the redshift range one wants to cover, the optimum survey parameters. One can see from Figure 4 that, if one wants to cover the entire redshift range out to $z \sim 0.7$, one will need a set of surveys (a 'wedding cake') varying in depth and area, each aiming for a specific redshift range. For imaging low-redshift galaxies, a short integration per pointing will be sufficient, but the volume covered at low redshift by a single pointing is small and one will need many pointings to obtain a sensible number of detections. On the other hand, for high-redshift detections, one has to integrate very long. However, the physical volume at high redshift covered by a single, deep integration is large and still a reasonable number of detections will be obtained.

4.1 How to make a wedding cake

Given the discussion outlined above, the important question is how to make the best wedding cake: given a certain amount of total observing time, how do we combine a number of surveys, where each survey has a certain area and integration time per pointing, in such a way that the combination of the surveys has an optimal sampling of the population of objects we are interested in. One useful aid for looking into this is to consider the coverage of the $z - M_{\rm HI}$ plane of the combined surveys. An example is given in Figure 5 where, using the reasoning of the previous

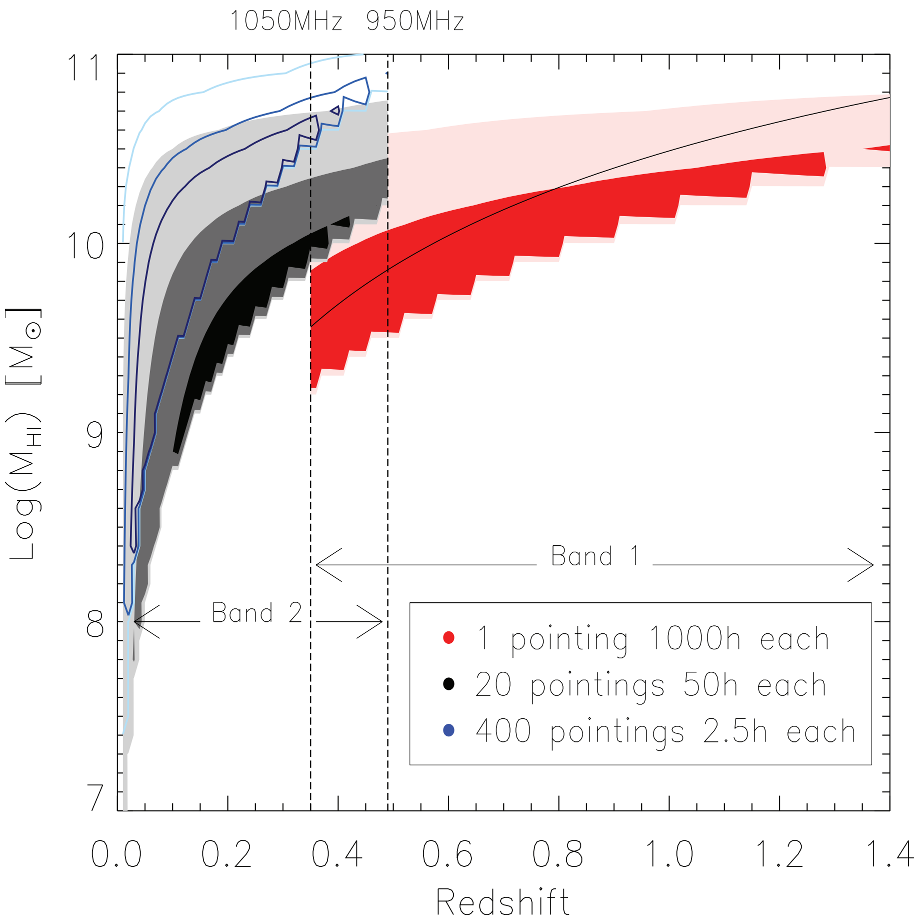

Figure 5: Combined coverage of the $z - M_{\rm HI}$ plane of three fiducial SKA1-Mid surveys, i.e. it shows the region of this plane where at least 1 object will be detected. The shading roughly indicates the number of objects detected. As always, most detections are close to the detection limit.

section, the combined coverage of three fiducial HI surveys is given: a shallow, large-area survey, a medium-deep survey and a deep pencil-beam survey. Each of the three surveys covers a particular region of the $z - M_{\rm HI}$ plane. For each survey, the lower boundary of the region covered is set by the integration time per pointing, as this sets the detection limit of the faintest objects present in the survey. The upper bound is set by the total area (hence volume) covered by the survey. One can see, for example, that the shallowest survey will detect more massive objects at low redshift than the other two surveys. This is because detecting such massive objects does not depend on sensitivity (they are very bright and therefore easy to detect even in short observations), but the physical volume covered by the deeper, but smaller area, surveys is simply too small to contain even one very massive galaxy.

Figure 5 shows that the particular combination of surveys chosen for Figure 5 is clearly not ideal. There is large overlap between the survey of 400 pointings and the one of 20 pointings, while there is also a large discontinuity around $z = 0.35$ in the coverage of the $z - M_{\rm HI}$ of the medium-deep and the deep survey. To improve the situation, one would have to vary the parameters of the survey, for example reducing the area covered by the medium-deep survey but integrating longer

PoS(EXTRA-RADSUR2015)035

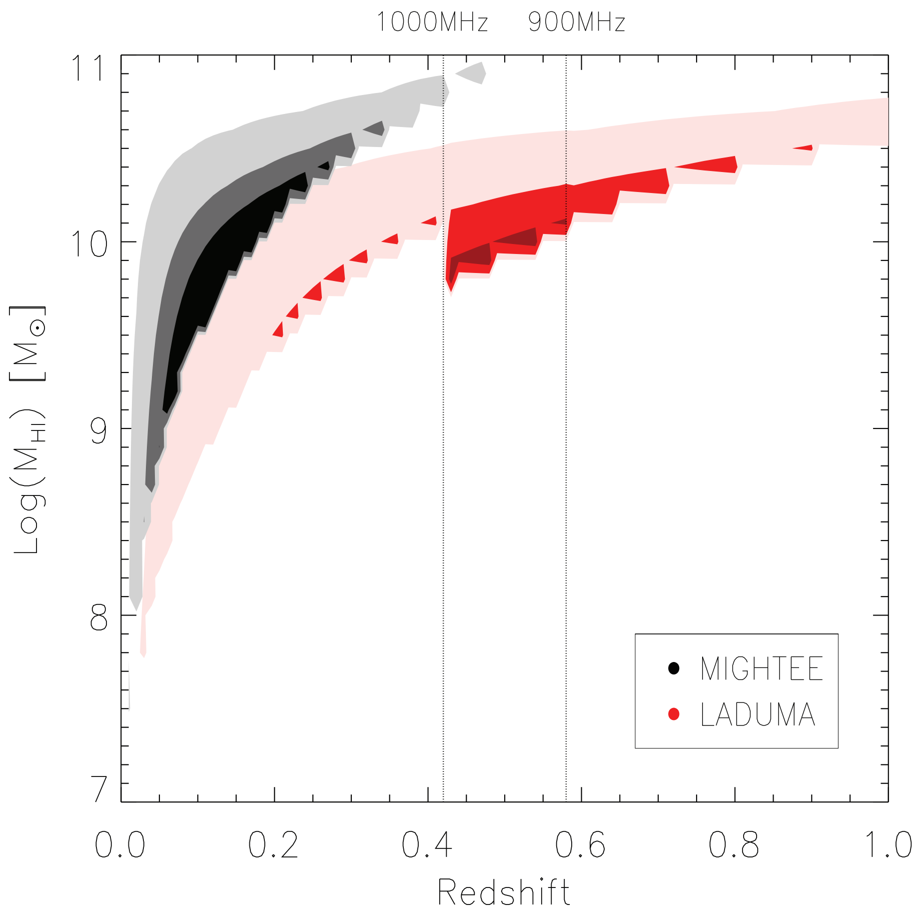

Figure 6: As Figure 5 but now for the combination of the Laduma and Mightee surveys.

per pointing. This would reduce the overlap with the shallow survey as well as the discontinuity in the coverage with the deep survey.

An example of a better survey design is the combination of Laduma [13] and Mightee, two surveys planned to be executed on MeerKat. In fact, the origin of Mightee is not that is was designed as an HI survey, but instead a continuum survey. However, given the way the Mightee observations will be done with the full spectral resolution of MeerKat, the data from Mightee can also be used for spectral line work and, in fact, provide a very valuable HI dataset.

Laduma will survey a single field (the Chandra Deep Field South) and will spend a total of 5000 h (!!) on this single field (albeit spread over two frequency settings). Mightee is designed as a continuum survey and will survey an area of 35 deg^2 with shorter integration times per field.

Figure 6 show the combined coverage of the $z - M_{\rm HI}$ plane of the two surveys. It is clear that Laduma, due its deeper integrations, covers a larger redshift range and will also detect fainter objects in the nearby Universe. However, because Laduma only observes a single field, the survey volume at low redshift is relatively small and it will not detect massive HI galaxies in the nearby Universe because they are rare. Mightee, however, because of its larger survey volume at low redshift, fills up this gap and the combined surveys cover a fairly complete mass range out to

$z \sim 0.3$.

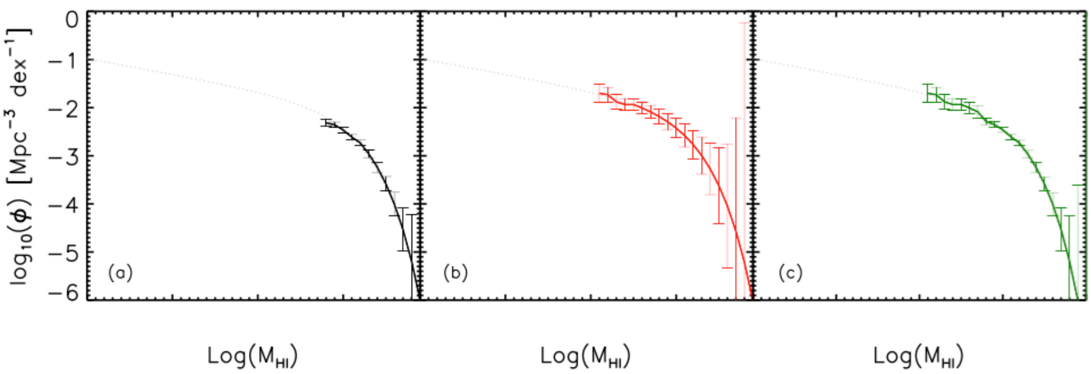

Figure 7: HI mass function as derived from the Mightee survey alone (left), the Laduma survey alone (middle) and from the combination of the two surveys (right). See text for further discussion.

To illustrate the good combination of Laduma and Mightee, in Figure 7 we show the results for if one uses the combination of the two surveys to determine the HI mass function for $z < 0.4$. The left panel of Figure 7 shows the HI mass function as determined from a simulation of the Mightee survey, while the middle panel gives the same but now for the Laduma survey. From the comparison of the two, one can see that from Laduma one can determine the HI mass function down to lower masses, but the error bars for the high HI masses are much larger. This is, of course, what one would expect based on Figure 6. The right panel of Figure 7 gives the HI mass function as determined form the combination of the two surveys and one clearly can see the result is far superior. One can argue that resolved HI kinematics is a more important deliverable of the combination of the two surveys than the HI mass function, but it shows that by combining the two surveys one has a better sampling of the diversity in HI masses than each of the surveys individually and one will be able to do better HI science.

Apart from illustrating how to design HI surveys, the example also shows that there is great potential for commensal science between the continuum and HI surveys. Ironically, the Mightee survey was designed almost entirely with continuum science in mind with little attention to the HI aspects of the survey. It, sort of, fell into place by itself. But for other instruments we may not be so lucky and our discussion here shows that there are quantitive methods to guide the design of commensal surveys and that using such methods may lead to more efficient use of the observing time on SKA1-Mid. It would be wise for the continuum and HI communities to engage in attempts for such a common approach.

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