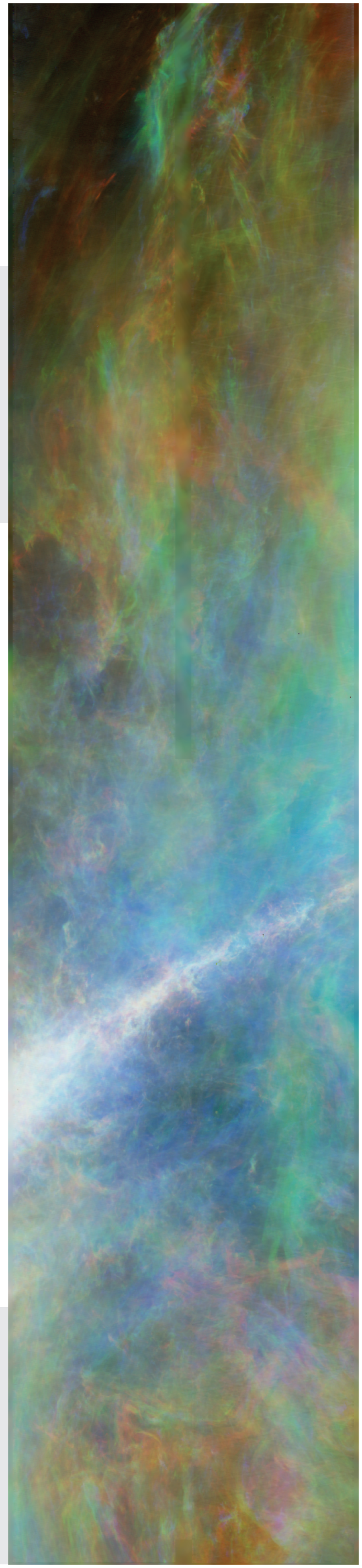
The Cosmic Connection

With the world's largest collecting area, vast physical size, and the multibeam ALFA instrument Arecibo can observe the 21-centimeter transition of the universe's most common element, hydrogen, deeper, faster, and more precisely than any other instrument in the world

we know Our Galaxy is composed of stars, gas, and plasma, but what we *don't know* is how these pieces of our Galaxy flow from one phase into the other through cosmic time



Pictured at right is one half of the first complete picture of the Galactic sky visible to Arecibo (the second half can be seen on the reverse). Red, blue and green represent three of the thousands of velocities we have measured, which trace the dynamics of the Milky Way

Since the first data was released from the Galactic hydrogen survey GALFA-HI, *dozens of groups* have used the data to publish results on connections in the ISM:

By examining long, fibrous hydrogen structures, a student showed that the shape of the the interstellar medium is uniquely tied to its magnetic field, a force known to be critical to the energy balance of the ISM, but with still mysterious properties

A number of projects have used GALFA-HI data to better understand the mysterious dark molecular gas and how the bulk of gas in our Galaxy finds its way into molecular clouds, and thus into stars.

With an eye toward the formation of the Galaxy itself, authors have made detailed maps of the Galaxy's high velocity clouds, thought to be a source of fuel for the ongoing formation of stars in the Milky Way

Small clouds that cascade above the Milky Way's disk may provide key insights into how material is ejected from the Milky Way, and thus maintain the Galaxy we see today

Arecibo is our door to the future of Galactic radio astronomy, providing the quality of data *today* the Square Kilometer Array promises tomorrow

Arecibo's View of the Galactic ISM: The Cosmic Connection

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1. INTRODUCTION

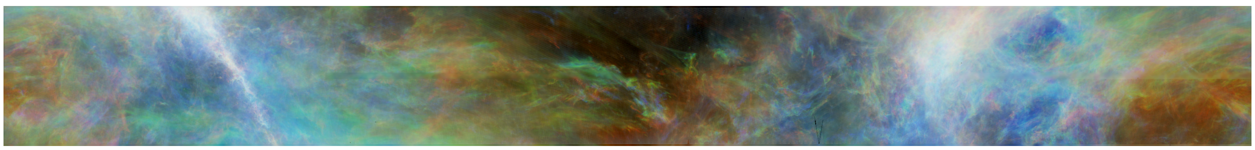

Fig. 1.— A three color image of the entire, completed GALFA-HI sky; 360 degrees in RA by nearly 40 degrees in Dec. Red, blue, and green channels represent -7 to -4 km s^{-1}, -3 to -1 km s^{-1}, and 0 to 3 km s^{-1}, respectively.

The interstellar medium (ISM) is a connection. It is the way all material flows from the vast reservoirs of intergalactic and circumgalactic media (IGM & CGM) to the stars in the disk. It is also the way material flows out of stars to enrich the universe with metals, and feedback into the CGM, providing the structure of the disks we know today (Springel & Hernquist 2003). Without the complex interactions between the phases of the ISM, gas would too easily succumb to gravity and form a very different universe than our own. Thus, to understand how our universe came to be the way it is, we must understand the connections in the ISM. We know the ISM has many distinct phases of gas; from hot and ionized to cold and molecular, from outflowing to inflowing, magnetized and shot through with cosmic rays. What we *do not know* is how these phases interact with each other and thereby mediate the processes of Galactic accretion, molecular cloud formation, star formation, cloud destruction, and Galactic-scale feedback. It is *these connections within the ISM* that hold keys to understanding how everything in the universe forms.

One of our earliest and still clearest windows into these processes is the 1420 MHz line of neutral hydrogen. Most of the mass of the ISM resides in HI, and, in most conditions, it all emits in the the 21-cm line. Of particular importance is our ability to capture the dynamical state of the ISM through HI kinematic information, allowing us to probe the rates of flow from one place to another, and one phase to another. Arecibo's massive scale, coupled with the ALFA instrument, gives it an unparalleled grasp of the 21 cm line in our Galaxy, and thus provides an excellent tool to study the connections of the ISM.

In this document I will highlight a few areas where we are already parsing the connections between the different phases and structures of the ISM using Galactic HI data from Arecibo. With the advent of the ALFA instrument, we have been able to conduct a full Arecibo sky survey of Galactic HI: GALFA-HI. Our official survey observations were completed in January 2014, but more are certain to come as we deepen our investigations.

2. Connecting Magnetic Fields to the Bulk of the ISM

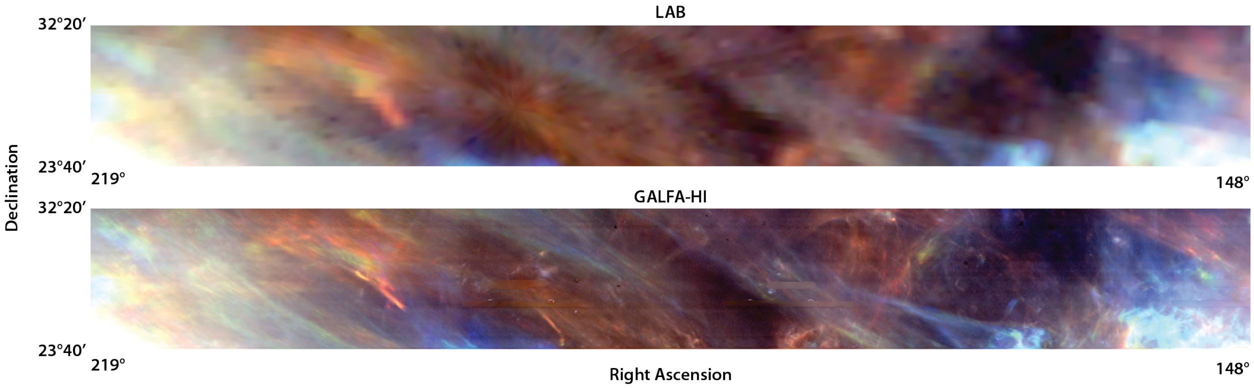

Fig. 2.— A three color image of the high-galactic latitude sky. The top image is earlier data from LAB, the bottom is from GALFA-HI, Red, blue, and green channels represent -7 to -4 km s^{-1}, -3 to -1 km s^{-1}, and 0 to 3 km s^{-1}, respectively. The fibrous magnetized structures in the diffuse HI can only be detected with the resolution and sensitivity provided by GALFA-HI.

The bulk of the mass of the Galactic interstellar medium resides in its atomic component, more than is found in the molecular gas, and vastly more than in the ionized gas. While this gas is largely neutral, magnetic fields play a critical role. The neutral atomic medium's weak ionization, provided by cosmic rays and metal ions, means that this phase acts as a plasma and is "flux frozen", moving as one with magnetic field lines. At the typical magnetic field strengths measured in these clouds, the magnetic energy density is comparable to any other energy density in the system, and dwarfs the thermal pressures of the ISM. Unfortunately, it is difficult to trace field strengths and topologies in the neutral gas. Most mechanisms like synchrotron emission and rotation measure trace the electron density of the magneto-ionic medium, and methods like Zeeman splitting are too observationally expensive to observe in high resolution across the sky. Starlight polarization, caused by the magnetically aligned dust that suffuses the neutral medium, is an excellent tracer of magnetic field orientation, but it is sparse. Furthermore, we do not know how the magnetic fields traced this way relate to the kinetic structure of the ISM, as we measure it in the HI emission spectra.

We made an enormous breakthrough in understanding the neutral-magnetic connection when we looked at the first GALFA-HI images. We found a collection of HI fibers: faint, streaky parallel structures criss-crossing the high-latitude sky, with extraordinarily high aspect ratios over enormous stretches of sky. These structures had never been detected before: *only Arecibo, with its huge sky coverage, amazing sensitivity, and resolution could detect these weak features.* It soon became apparent that these elongated clouds might well have some relation to magnetic fields: by eye, there seemed to be a connection to the starlight polarization orientation.

Recent work Clark et al. (2014) confirmed this suspicion by constructing a new algorithm, the Rolling Hough Transform (RHT), to detect and characterize these fibers. Furthermore, the work showed that in certain circumstances the RHT can be used to measure the magnetic field strength of the neutral ISM, providing a new method beyond the known techniques for magnetic field strength measurement. It was also shown that the fibers were likely a feature of the local cavity wall, and thus may have been created by an interaction between the hot ionized medium, in a supernova blast wave, and the magnetized neutral ISM. It is possible this ropey mesh of ISM seen so clearly in these fibers dictates how the feedback from massive stars impacts and drags on the bulk of the gas, which is a clue to some of the hardest problems in how star formation interacts with Galaxy formation through feedback.

This investigation has opened a much larger door than just our understanding of magnetic fields. It marks perhaps the first time we have been able to harness the shapes of the ISM using statistical methods to measure underpinning physical quantities. We hope to develop more methods like the RHT to get at the physics of the other processes that shape the ISM.

3. Connections and Transitions within the Neutral Atomic Media

The multiphase nature of diffuse, neutral gas is a result of the interplay between heating and cooling processes in the ISM. Measuring the physical properties and the mass distribution of HI in its various phases, including the cold neutral medium (CNM), warm neutral medium (WNM) and thermally unstable medium (UNM), is essential for constraining the dominant dynamical and radiative processes at play.

Observational measurements of the temperature and density of HI in the ISM require both emission and absorption information along a line of sight. For example, the Millennium Arecibo 21 Centimeter Absorption-Line Survey (Heiles & Troland 2003, HT03) used 21-cm emission and absorption line pairs along 79 lines of sight to statistically constrain the temperature and density distributions of cold, neutral gas. This study revolutionized our understanding of physical state of the neutral ISM. However, in the case of the WNM, extremely high sensitivity is necessary to detect its characteristically weak and broad absorbing properties, and HT03 suffered from non-uniform, low sensitivity.

To tackle the WNM, several high-sensitivity interferometric absorption line surveys requiring hundreds of hours have been conducted, including 21-SPONGE, a Karl G. Jansky Very Large Array study of 58 sightlines (Murray et al. 2014). Interferometric observations resolve away large-scale emission and are therefore preferable for measuring absorption especially when observing weak radio continuum sources. However, complementary emission observations are equally as important for measuring essential physical properties with these data sets. Given that absorption lines are measured in the direction of arcsecond-scale point sources, emission observations must have as high angular resolution as possible to probe as close to the same spatial scales as possible. In addition, it is prohibitively expensive to obtain sensitive interferometric emission measurements which contain information over the full range of angular scales.

Arecibo provides the most efficient and best resolution complement to all interferometric HI absorption measurements within its field of view, and is therefore essential to ongoing investigations into the physical properties of the ISM phases.

By fitting Gaussian functions to VLA absorption and Arecibo emission in 21-SPONGE, we solve for spin temperature and column density of individual components. Surprisingly, we find fewer components in the UNM than predicted by previous work. This has major implications for the influence of mechanisms that maintain this thermally UNM, including supernovae, turbulence and excitation processes. In addition, we stacked the residuals after removing our Gaussian models and statistically detected a widespread WNM feature with high spin temperature, Ts 7000 K (Murray et al. 2014). This temperature is well above theoretical expectations for this phase (e.g. Ts=2000-4000 K, Wolfire et al. 2003; Kim et al. 2014), and this study shows for the first time that non-collisional excitation of HI must be very important in the diffuse, neutral ISM. Future absorption line observations with the VLA of weaker radio continuum sources, and with complementary HI emission observations from Arecibo, will remain crucial to extending these studies and constraining the temperature, density and excitation of the neutral ISM.

4. Connecting the Diffuse Medium to Molecular Clouds

Molecular clouds are the birth places of all the stars in the universe, but we do not know how they form. One of the greatest impediments to understanding this process is our lack of ability to observationally trace hydrogen from atomic to molecular phase. In a low density regime, the 21 cm line is an excellent tracer of atomic gas. In much denser regimes carbon monoxide, and a number of other molecules, have historically given us our picture of molecular gas. But it has become clear in recent years that there is a huge reservoir of "dark gas", material detected by no clear observational tracer, in densities too low to be detected by CO. Because this gas is dark it is very hard to observe the transition region between atomic and molecular gas and thus trace the process of molecular cloud formation and dissolution.

One way to get around this problem is to use FIR dust emission. Since dust is typically a good tracer of total column density, the difference between FIR emission and HI emission makes a very accurate tracer of the HI-H_2 transition. *Arecibo is uniquely positioned to study this effect, as its beam is almost exactly matched to both major data sets of FIR emission, Planck and IRAS.*

Lee et al. (2012) showed that GALFA-HI data are excellent for the study of the HI-to-H_2 transition in the Galaxy, testing recent analytic model of H_2 formation by Krumholz et al. (2009) with high resolution HI and H_2 column density images of the Perseus molecular cloud. They derived the HI and H_2 column density images using GALFA-HI and IRAS data, and the large coverage and high resolution of GALFA-HI allowed them to probe the HI-to-H_2 transition across the cloud on 0.4 pc scales. The most important prediction from Krumholz et al. (2009) is the existence of the minimum HI column density required for shielding H_2 against photodissociation, and the observed relatively uniform HI column density of $\sim 10^{21}\mathrm{cm}^{-2}$ was in excellent agreement with the prediction for solar metallicity. This result suggests that HI is one of the key ingredients to understand the formation and evolution of molecular clouds.

With an aim of further investigating the relation between molecular clouds and their associated HI envelopes, Stanimirović et al. (2014) recently performed a follow-up study based on Arecibo HI emission and absorption measurements toward 26 radio continuum sources behind Perseus. They decomposed the HI spectra into individual Gaussian components along each line of sight, and estimated the spin temperature, optical depth, and column density of the cold and warm neutral medium (CNM and WNM). In comparison with HT03, they found that the HI envelope of Perseus has the total HI column density and CNM fraction that are higher than those found for random lines of sight through the Galaxy, while the properties of the individual HI components are not atypical. Based on the properties of the CNM and WNM in the vicinity of Perseus, Lee et al (submitted) then examined the impact of high optical depth on the HI column density distribution, and found that H_2 formation is indeed primarily responsible for the observed saturation in the HI column density.

Future work of this kind across a range of molecular clouds will provide insights into HI properties and their roles in the formation and evolution of molecular clouds, and consequently star formation.

5. Connecting HI Structure to Supernova Feedback

The structure of the diffuse ISM is driven by supernovae (SNe). SNe not only produce hot coronal gas in the ISM but also shape the large-scale morphology of the HI gas and drive turbulent motion. Numerical studies to accurately model the energy/momentum deposit from SNe into the ISM are currently underway (Kim et al. 2014; Simpson et al. 2014). But SN types are diverse with varying explosion energies and environments, so that observational studies of SN remnants (SNRs), particularly the old ones visible in HI 21-cm line, are essential to understand the role of SNe in the real ISM.

Koo & Kang (2004) noted that, in low-resolution HI surveys, there are small, faint, high-velocity "wing-like" features extending to velocities well beyond those permitted by Galactic rotation and proposed that these forbidden velocity wings (FVWs) may represent the expanding HI shells of old SNRs that are visible only in HI 21-cm line. In the Milky Way, SN explodes at every $\sim$50 years and if we take $\gtrsim 10^5$ yrs as the lifetime of SNRs, there might be more than 2,000 SNRs. But the number of known SNRs in radio continuum and X-rays is only ~ 300 and therefore *most SNRs are missing.*

Follow-up high-resolution, sensitive studies using the Arecibo telescope showed that some FVWs indeed have properties consistent with the SNR hypothesis (Koo et al. 2006; Kang et al. 2012).

Recently-completed I-GALFA survey now provides an opportunity to do a systematic study of FVWs (Koo et al. 2009). The survey has revealed numerous FVWs spaced at every $\lesssim 1°$, some of which are associated with known SNRs (Figure 1). A systematic study of these FVWs and also the ones to be discovered in the over all GALFA-HI survey will be helpful in understanding the role of SNe in regulating the structure and evolution of interstellar HI gas.

6. Connecting the Circumgalactic Medium to the Galactic Disk

Most of the baryonic mass of the Galaxy exists in a very low density, multiphase medium that suffuses the volume within the virial radius of the Milky Way disk (e.g. Werk et al. 2014). We know that the Galaxy is still forming stars, a few every year, and it needs some source of fuel for this processes. What we don't know is how this CGM gets into the Galaxy. Does it come in through a neutral flow, or in a hot phase? Does it connect to the outside of the disk of the Galaxy, or accrete to it's central star forming region?

We know high-velocity clouds are a big part of this story. HVCs have long been known to be bringing neutral gas into the disk, but until recent HI observations with Arecibo, we never had a detailed, sensitive picture of the process.

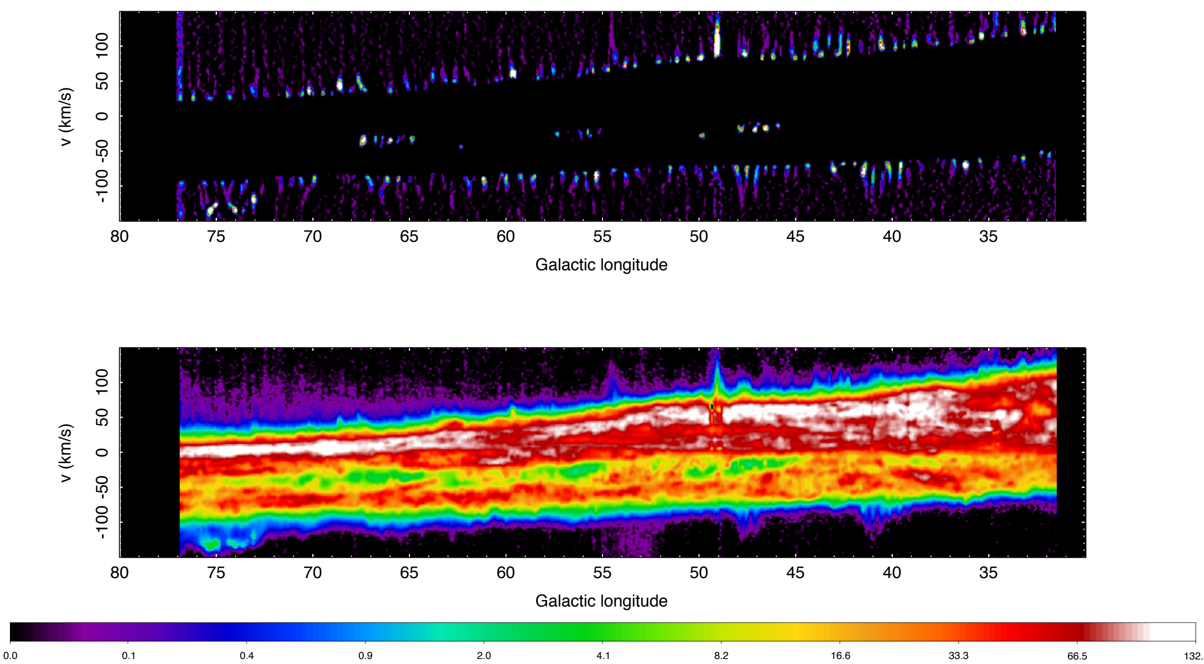

Fig. 3.— Bottom shows a Galacitc longitude-velocity diagram of the Galactic plane at $b = -0.28°$ from the I-GALFA survey. The colorbar shows the range of brightness temperatures in K. Top shows same as the bottom image, but median-filtered.

Theory says as halo clouds move through the diffuse halo medium, they form a compressed head and diffuse tail structure (e.g. Quilis & Moore 2001; Gunn & Gott 1972). The morphological details vary according to the speed and density of the cloud, and the density of the halo medium, and thus the structure of the cloud is a probe of the medium through which it moves. Theory (Wolfire et al. 1995) also says that the friction between the infalling cloud and the halo also produces a core-halo structure in *velocity* space—again, just like the observations of some clouds (Figure 5, right panel). Moreover, the numerical simulations reveal stripping effects that result in slower-moving shards and fingers extending off the sides of the cloud.

Observations uniquely show this happening (Figure 5, left panel). A straightforward dynamical model for the drag on the fragments provides quantitative values for the local ambient halo density. Combining this with a hydrostatic halo model, in which density is a well-defined function of z height and Galactic radius, provides a new technique for getting HVC distances (Peek et al. 2007) —which are notoriously hard to measure. With deeper observations of HVC complexes we could hope to use the morphological and kinematic information in these clouds and compare it with simulations to determine the structure of the multiphase halo, one of the few methods able to get at this elusive, but crucial phase of the diffuse universe.

Closer to home, questions of accretion are yet more complex. We have essentially no idea how material from the halo, supplied by HVCs or otherwise, joins up with the disk. One current theory is that neutral material from the Galactic plane is lofted into the lower halo via a star-formation-

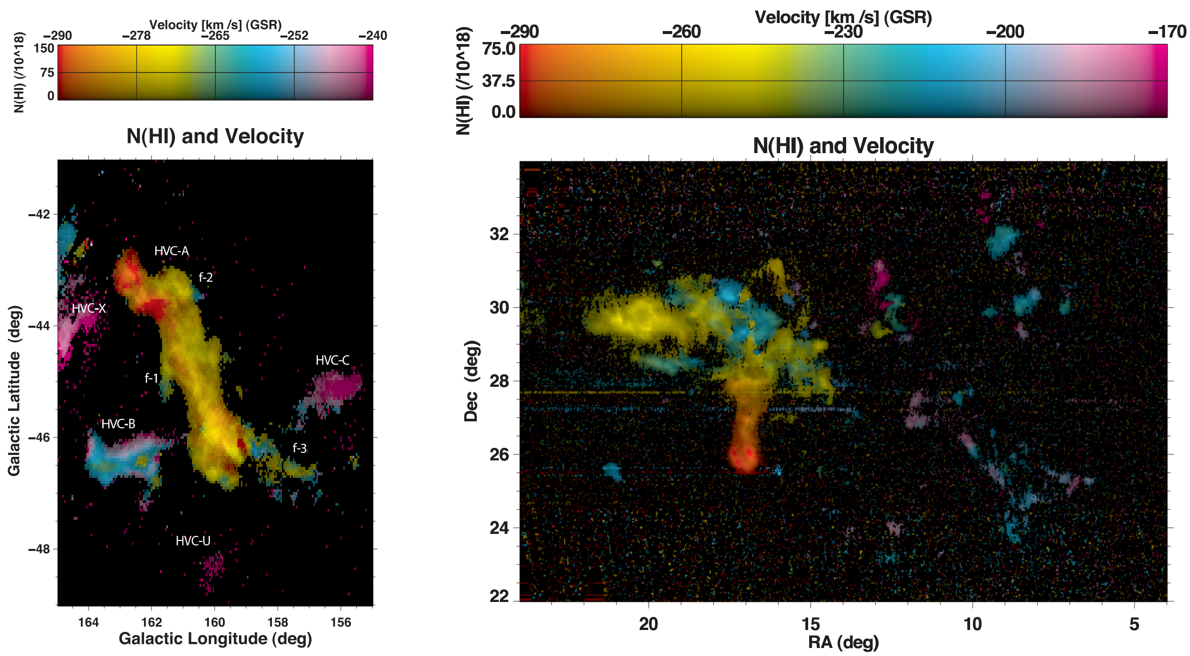

Fig. 4.— *Left:* The HVC and its shards. Color represents central GSR velocity and brightness the total column density. The labelled features were used in the hydrodynamic modelling. *Right:* The HVC showing a clear head-tail velocity difference.

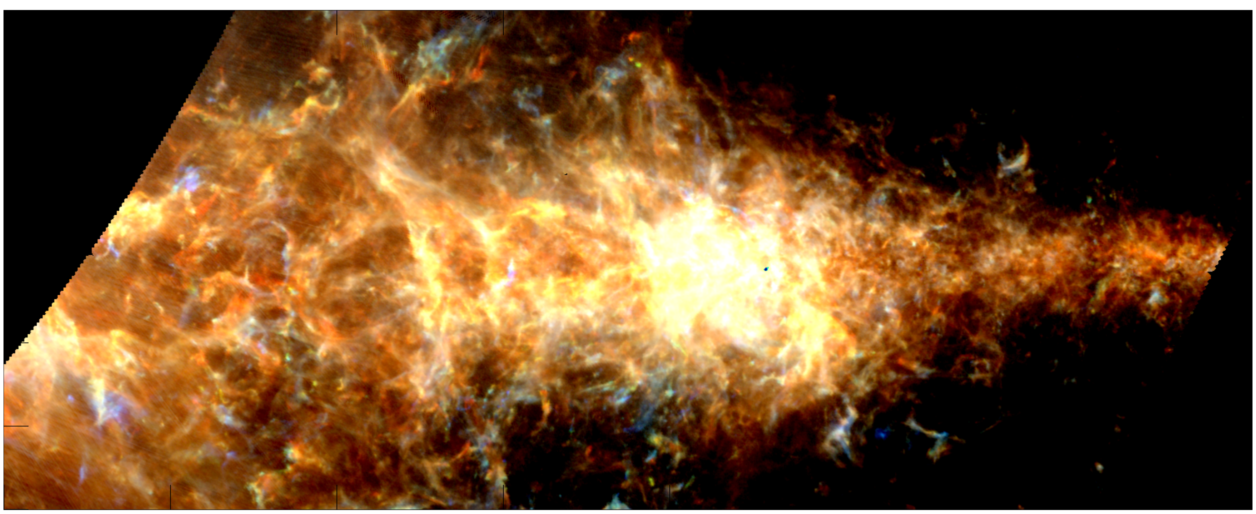

Fig. 5.— The inner Galactic plane from the I-GALFA project, shown here at velocities just beyond the tangent point velocity. Are these small structures related to a Galactic fountain?

driven fountain and hotter material cools onto it before it returns to the disk (Fraternali & Binney 2008). For this to be true, there must be an excess of neutral gas clouds above the plane of the Galaxy associated with regions of enhanced star formation in the plane. Only Arecibo has the sensitivity and resolution to pick up this riot of small clouds and associate them with tracers of star formation. By making this comparison we can perform a critical test of models of Galactic accretion.

7. Arecibo: Our Connection to the Future of ISM Studies with the SKA

The future of radio astronomy is happening through the rapid development of the SKA. And while the effort toward and technologies of the SKA will open up vast new windows into our understanding of the ISM, Arecibo will remain unsurpassed in its unique combination of sensitivity, survey speed, and resolution for years, if not decades, to come. The data we get now from Arecibo will allow us to formulate theories and design experiments appropriate for the SKA era.

We have just this year completed our first all-sky survey of Galactic HI with GALFA-HI. Our early data release was been very popular, with 40 citations since 2011, and increasing citations every year. Our next task is to produce from the completed data set the most exquisite maps of Galactic HI the world has ever known. While that map will have legacy value well into the era of the SKA, there is much more we want to use Arecibo to explore. The ongoing future of Galactic HI with Arecibo will include:

- The development of more robust algorithms to parse the structure of the ISM, and use it to extract information that connects the dominant HI phase of the interstellar medium to all the other phases and processes that shape it
- Zeeman splitting observations of magnetized neutral ISM features, allowing us to more deeply understand ISM magnetization
- Deep HI investigations of molecular regions to understand their interactions with other phases
- A mining of our extraordinarily vast data set using machine learning algorithms to build more sophisticated models for the Arecibo sidelobes and push beyond the current sensitivity limitations
- Investigations of deep fields to probe the structure of the neutral halo, and faint high-velocity clouds
- Ideas as yet undreamed

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