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WEAVE–Apertif project: a compound integral-field and HI spectroscopic galaxy survey

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Abstract

The WEAVE-Apertif survey combines spatially resolved optical and HI spectroscopic observations to investigate galaxy evolution using a representative sample of 400 gas-rich galaxies. Utilizing the WEAVE large integral-field unit (LIFU) at the William Herschel Telescope (WHT) and the upgraded Apertif system at the Westerbork Synthesis Radio Telescope (WSRT), this project focuses on the transition of galaxies from the Blue Cloud to the Red Sequence. It aims to provide deeper insights into their star formation histories, kinematics, and environmental influences, while also examining the dark matter content (including total mass and distribution) within galaxies. The synergy of high spectral resolution and broad spatial coverage offered by these instruments uniquely positions this survey to address key questions in galaxy evolution. This report presents the main scientific goals, and current progress of the survey, emphasizing its unique features, such as HI-based sample selection and advanced spectral resolution capabilities.

1 Introduction

The study of galaxy evolution is essential for understanding the formation of large-scale structures in the Universe. Galaxies evolve due to a combination of internal and external processes, including star formation, gas accretion, mergers, and feedback from supernovae or active galactic nuclei. The WEAVE-Apertif survey combines data from the WEAVE spectrograph and Apertif array to explore how galaxies evolve across different environments and cosmic timescales. WEAVE large-IFU (LIFU) mode, installed at the WHT, allows spatially-resolved observations over a 1.3×1.5 arcmin field of view (FoV) with both low- (R∼2,500) and high-resolution (R∼10,000) spectroscopic capabilities, making it ideal for comprehensive studies of galaxy properties (see Jin et al., 2024, for details). The Apertif system (van Cappellen et al., 2022), installed on the WSRT, provides wide-area radio imaging, enabling large-scale neutral hydrogen (HI) surveys at 15 arcsec spatial resolution. The WEAVE-Apertif survey leverages the unique capabilities of these instruments to offer an unprecedented view of the baryonic processes within galaxies, including the interplay between stars, gas, and dark matter.

2 Survey Goals

The survey specifically addresses questions regarding the distribution and dynamics of HI gas, the impact of environmental effects on galaxy morphology, and the processes that drive galaxies from active star-forming states to passive, quiescent ones. This survey also provides insights into the role of gas accretion and depletion, the influence of feedback mechanisms, and the contribution of minor and major mergers in shaping galaxy properties.

The main science goals of the survey include:

- **Investigating the Bimodal Distribution of Galaxies**: The survey aims to understand why galaxies exhibit a bimodal distribution in the color-magnitude diagram (CMD). By studying both the stellar populations and the HI content, WEAVE-Apertif aims to determine the mechanisms responsible for quenching star formation and move from the blue cloud to the red sequence. These include the processes thar drive gas accretion from (minor) mergers and from the IGM, the processes of internal gas depletion by star formation and feedback, and the processes of gas removal by external mechanisms such as ram-pressure and tidal stripping – all this in relation to the evolutionary state of a galaxy's stellar population, the physical state of a galaxy's ISM and a galaxy's local and global cosmic environments.
- **Understanding HI Accretion and Chemo-Dynamical Evolution**: The role of HI accretion in fueling star formation and driving chemical enrichment in galaxies is a central focus. The survey aims to link HI content with metallicity gradients and stellar dynamics to understand how accretion shapes galaxy evolution. This includes understanding how different accretion modes (e.g., cold vs. hot accretion) impact the chemical evolution and star formation efficiency in different types of galaxies. This can be achieved by, e.g., investigating the radial dependence of velocity dispersion for

different stellar populations. The HI morphology helps to assess the global dynamical state of the galaxies (i.e. whether settled or disturbed).

- **Mass Decomposition of Disk Galaxies**: Understanding the distribution of mass, particularly dark matter, within disk galaxies is crucial for testing galaxy mass-assembly. By combining HI kinematics from Apertif with stellar kinematics from WEAVE/LIFU, the survey allows the separation of the different mass components of galaxies and explores how dark matter is distributed in relation to stellar and gaseous components. This allows for a more detailed understanding of galaxy dynamics and the relationship between baryonic and dark matter across different environments.

3 Survey Strategy, Sample Selection & Current Status

We aim to obtain a representative sample of 400 galaxies to complete our science goals. The sample will be drawn from the $2200\,\mathrm{deg}^2$ of the sky covered by the Apertif imaging data (Adams et al., 2022), which mapped key large-scale structure surveys (e.g. LoTSS, Lockman, GOODS-N, Elias-N, H-ATLAS, HETDEX, Perseus-Pisces). This set of galaxies intends to span a wide range of HI morphologies, masses and environments, covering the SFR-M_* plane, which is equivalent but more physically motivated than the CMD, to the best of our abilities. Galaxies in our sample will reach $\mu_g = 24$ mag/arcsec^2 within the LIFU's footprint to enable the study of stellar and ionised gas properties beyond the typical surface brightness breaks which are pervasive in disks. This strategy ensures a representative sample for statistical analysis of galaxy properties across the SFR-M_* plane.

WEAVE-Apertif will be conducted as a two-tiered survey:

- **Low-Resolution (LR) Sample**, performed with the LR mode ($R \sim 2500$) of the WEAVE/LIFU, will draw 400 targets from the spatially resolved galaxies imaged by Apertif. These observations will cover the spectral range between $3660 - 9840$ Å and they will offer measurements of the stellar population content and ionised-gas properties for the main sample of 400 objects. They will help us focus on the evolutionary state of galaxies revealed by HI, including members of both the blue cloud and the red sequence, over a broad range of HI content and morphologies, stellar masses, and different environments.

- **High-Resolution (HR) Sample** will follow up a subset of 100 galaxies from the LR sample, with regular HI morphologies, with the HR mode ($R \sim 10000$) of the WEAVE/LIFU. We will take advantage of the dual-arm capabilities of WEAVE to observe simultaneously between $4730 - 5450$ Å and $5950 - 6950$ Å. These observations are aimed at providing detailed kinematic maps of both stars and ionized gas. The data will match the depth of the LR data and will enable the exploration of the internal dynamics as well as constraining the distribution of bary onic and dark matter in disk galaxies.

The full Apertif sample of galaxies has already been observed and the data is currently being processed. At the time of writing, 183 targets have been classified by their HI morphol-

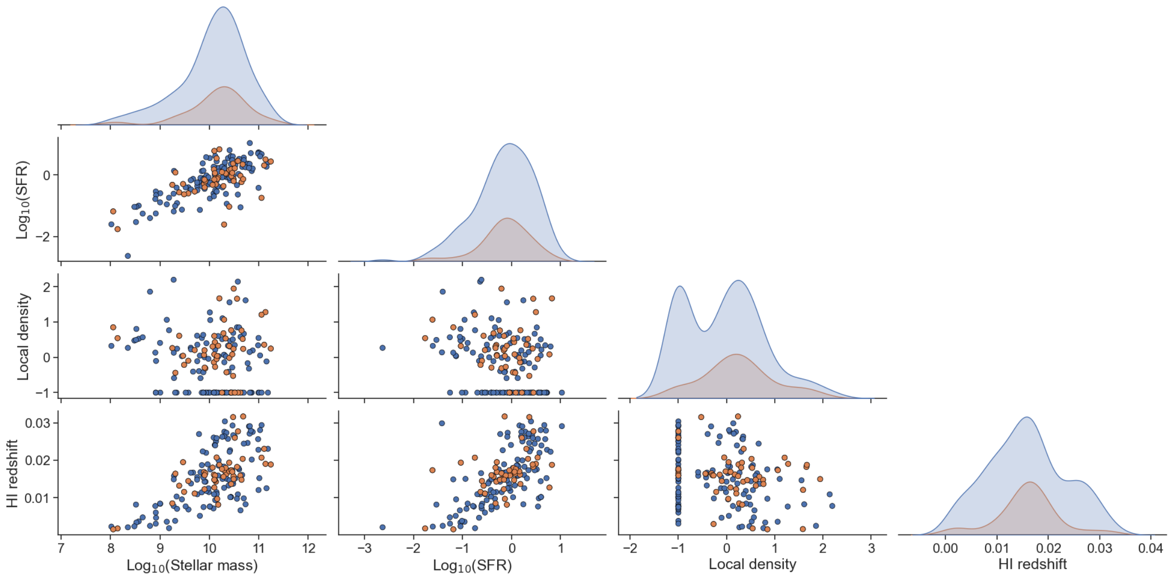

Figure 1: WEAVE-Apertif sample parameter coverage in terms of stellar mass, star formation rate, HI redshift, and local environment (see text for details). Galaxies at local densities of −1 are those in isolation. Blue circles correspond to the full set of Apertif galaxies classified by their HI morphology. Orange circles correspond to the 53 galaxies already observed with WEAVE. Histograms on each row depict the distributions of each sample. They have been smoothed with a Kernel Density Estimation (KDE) algorithm.

ogy, and of those 53 have been already observed with WEAVE. Figure 1 shows the coverage of parameter space of those targets. The HI morphological classification is done by a group of experts within the team. Stellar masses and star formation rates are computed following the prescriptions in Appendix A of Marasco et al. (2023). Local environmental density are calculated as described in Argudo-Fernández et al. (2015). HI redshifts are derived directly from the Apertif data. In terms of HI morphology, the vast majority of galaxies have either regular or lopsided distributions (not shown). As for the other parameters, observed galaxies populate all regions of the paramter space, currently with some bias towards massive, star-forming galaxies. Our goal is to draw galaxies from Apertif to homogeneously cover this set of parameters.

4 Initial Data and Quality Assessment

The first set of data from the WEAVE/LIFU Science Verification phase has already been obtained, and the quality of the observations has been assessed. Figure 2 showcases the comparison between optical images overlaid with HI iso-density contours for already observed WEAVE-Apertif galaxies. Stellar kinematic maps for a sample of galaxies have been generated using the Advanced Products System (APS) provided by the WEAVE consortium (see

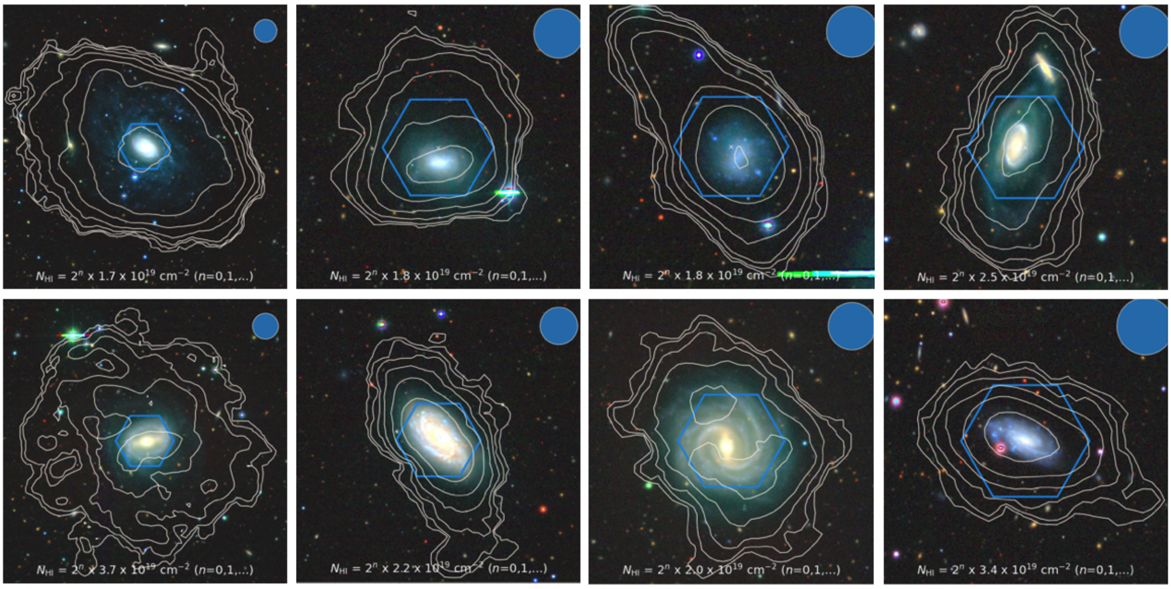

Figure 2: Examples of already observed WEAVE-Apertif galaxies. Apertif HI moment-0images (white), over DECaLS (Dey et al., 2019) color images, and the WEAVE/LIFU footprint (blue).

Fig. 3). The initial results are promising, with the data meeting the expected quality for the low-resolution mode. Nevertheless, there is still room for improvement in the data processing pipeline, particularly for the few HR mode observations taken so far. In addition to the stellar kinematics, emission-line and line-strength diagnostic maps (not shown here) were also generated, providing critical insight into the ionized gas properties of the galaxies. These maps will be essential for understanding the interplay between gas dynamics and star formation.

5 Follow-Up Observations

The WEAVE-Apertif survey is expected to deliver an unprecedented dataset over the next few years, covering a wide range of galaxy types and environments. However, the optical and HI data obtained through WEAVE and Apertif will be further enhanced by complementary observations, including:

- **Deep Imaging**: High-quality deep imaging observations are planned to provide additional structural information on the surveyed galaxies. These data will help to identify faint features such as stellar streams, tidal tails, and low-surface-brightness disks that may be missed in shallower surveys. We are aiming to reach surface brightness levels beyond 27 mag arcsec^2 in g-band.

- **Cold Gas Mapping**: Observations of cold molecular gas (CO) will complement the HI data, offering a complete picture of the gas reservoir in galaxies. The synergy between

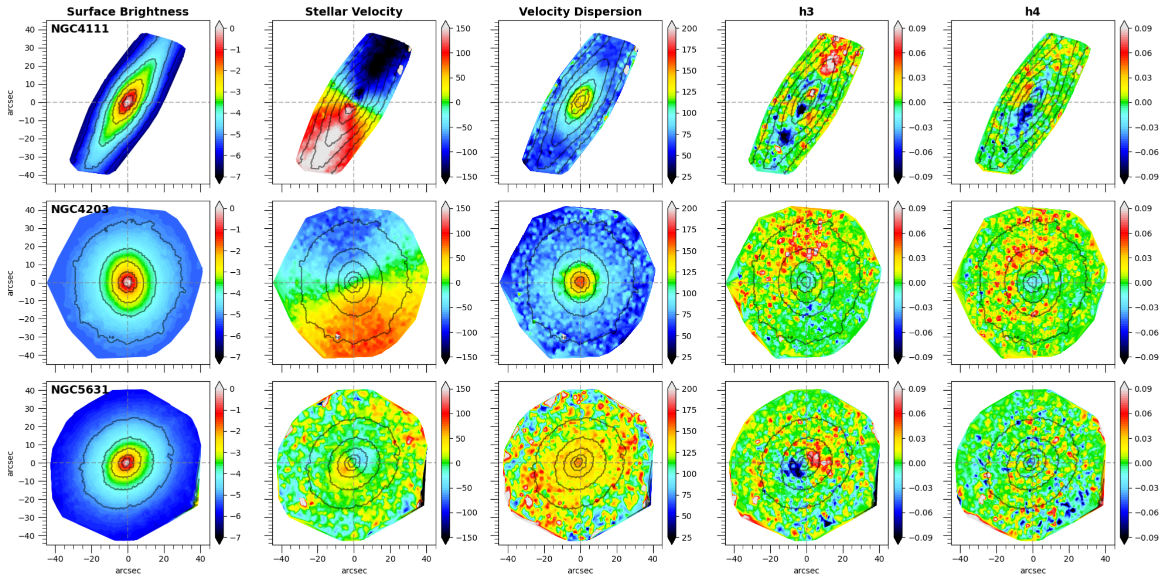

Figure 3: Stellar kinematic maps for three galaxies observed during the Science Verification phase of WEAVE/LIFU, generated using the Advanced Products System (APS). The maps show velocity, velocity dispersion, and Gauss-Hermite higher order moments, highlighting the high quality of the LIFU data.

HI and CO observations will be critical for understanding the fueling of star formation and complete the study of the *baryonic cycle* of galaxies.

6 Conclusions

The WEAVE-Apertif survey represents a major step forward in our ability to study galaxy evolution in detail. The combination of spatially resolved optical and radio 21cm observations will allow the WEAVE-Apertif team to tackle a wide range of scientific questions related to galaxy formation and evolution. The inclusion of deep imaging and molecular gas data will provide a holistic view of the processes driving galaxy evolution, from gas accretion and star formation to quenching and morphological transformation, thus completing the study of the baryonic cycle of galaxies.

The key takeaway messages from this conference proceeding are:

- The synergy between HI and optical IFU observations provides powerful constraints on the processes driving galaxy evolution.

- The survey's focus on HI-based sample selection offers a new perspective on galaxy evolution, particularly in understanding the role of gas in star formation and quenching.

- The initial LR data from the Science Verification phase show promising results, with high-quality stellar kinematic maps that meet the survey's scientific objectives.
- Future observations, including deep imaging and cold gas mapping, will complement the survey data and provide a complete picture of the baryonic processes at play in galaxies.

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