1 The Hector Galaxy Survey Science Case

The ATAC Chair has granted an extra two pages for this proposal to outline the big picture of the full Hector Galaxy Survey (Hector-GS) as well as the focus of the 2023A semester. Hector commissioning is now in its final stages, and has taken longer than expected due to exceptionally poor weather in both semesters of 2022.

1.1 The Hector Galaxy Survey Overview

What is the physical basis for the diversity of galaxy properties in the local Universe? This is the overarching question driving the Hector-GS. The answer lies in connecting the internal properties of galaxies to the detailed role of their environment. For the Milky Way, accretion from and interactions with satellite galaxies have shaped our galaxy. In extragalactic studies there has been a paradigm shift from local and global density-based environment properties to defining environments based on both large-scale structure (filaments, walls, nodes) and where galaxies sit in velocity space. The unique capabilities of the Hector instrument will enable us to tackle this question with data that cannot be obtained with any other survey. The large survey size and spectral resolution, which is a factor of two better than any comparable instrument, will allow us to explore galaxy properties across the stellar mass function with exquisite environmental characterisation. The Hector-GS plans to observe 15,000 galaxies over 6 years, providing a groundbreaking data set that maximises the science productivity of the remaining life of the AAT.

The legacy of the Hector-GS will lie not only with the vast and rich data set that the survey will produce, but also in unique science that cannot be accomplished with any other instrument in the world. SAMI [10, 5, 12] and MaNGA [8] have been the largest IFS surveys to date. However, they lack a combination of the higher spectral resolution that allows stellar kinematics to be measured in a larger fraction and broader diversity of galaxies; the broad range in halo masses required to test the influence of the environment, including mapping the large cluster halos out to higher cluster radii; larger IFUs to get resolved spectra of galaxies to a larger galaxy radius; and a larger sample that will allow the key drivers of galaxy evolution to be statistically determined by sub-dividing the sample in physical parameter space with sufficient statistical accuracy.

The Hector-GS has optimised the science synergies with other large Australian projects. For example, the ASKAP WALLABY [17] and DINGO (https://dingo-survey.org/) surveys will combine their HI data with the Hector-GS to link gas accretion mechanisms and total gas masses from the inner galaxy to the scales probed by HI observations. A group of simulators are already active in the Hector science team, focused on a range of fundamental questions that can be addressed with the Hector-GS regarding the impact of large-scale structure on galaxy evolution. In addition, the Hector-GS regions have been selected to be within the ESO 4MOST WAVES North and South sky areas, which will provide exquisite environmental metrics to confirm the place of our galaxies within local and large-scale structures as well as their kinematic flows (https://wavesurvey.org/).

The Australian community selected the Hector instrument as the next dark-time instrument for the AAT. Membership of the Hector science team is open to all astronomers working in Australia - in some cases with contributions that are not telescope nights. The data will deliver a vast array of science opportunities to the already 65-strong Australian Hector team, drawn from across the country from 8 Universities and the CSIRO as well as KASI in Korea. The team builds from the SAMI IFS team and is expected to outgrow the 140-strong SAMI team.

Here, we request 12 nights from the common pool. The Hector Galaxy Survey science goals are built on a complete statistical sample of 15,000 galaxies, a number carefully set by predictions from simulations and experience with the SAMI data. To complete the full Hector survey on the planned 6-year timeframe requires 100 nights per year. We aim for a minimum of 90 nights per year and a target of 100. Due to the poor weather so far, we aim for 50 nights in the next Semester to stay on-track. Further justification of the survey size is given in section 1.3 below. We have reserved 38.5 nights from four institutions participating in Hector this semester, so we require 12 more to reach our minimum target. We seek these additional nights from the common pool, noting that some Hector institutions (Swinburne, UNSW) have chosen not to reserve Hector nights and instead contribute through the pool, while ANU and UQ have put enough nights into the pool to apply for further Hector nights.

1.2 Key Science Goals

(A) **How is the accretion of gas and angular momentum (spin) influenced by the local and global environment?** Cosmic structures over the mega-parsec scale, such as cosmic filaments and clusters where they intersect, strongly constrain the flows and thermodynamics of baryons in their vicinity. Simulations and theory predict that this impacts the accretion onto galaxies and, therefore, their spin, structure and, more generally, their dynamics. The world-leading Australian surveys WALLABY and WAVES (2023+) will map galaxies and their peculiar velocities in the local Universe with unprecedented detail. They will locate the Hector galaxies both in 3D space and dynamically within cosmic flows, permitting the most extensive analysis of correlations between large-scale structure morphology and galaxy-scale dynamics.

SAMI demonstrated the feasibility of such studies through the first detection of the alignment of galaxy spins with filaments [31], but the limited statistical power capped the significance of the results at $\approx 2\sigma$. It also precluded any analysis of cosmic walls, any multivariate analysis (field filaments, filaments in groups, filaments into clusters) and any detailed analysis of the corresponding kinematic disturbances in the outer parts of galaxies. With its increased sampling, wider field of view and wider coverage of clusters up to $2\,R_{\rm vir}$, the Hector-GS will allow for a deep analysis of how filament/wall, filament/group and filament/cluster interactions impact galactic inflows, spin and structure. Such studies are very timely. Modern simulations predict, for instance, that cluster outskirts ($0.75 - 2\,R_{\rm vir}$) are regions of multiple transitions, strongly impacting the structure of galaxies. It is where satellite galaxies are expected to progressively align their orbit and spin to the central galactic plane, while aligned to the nearby cosmic filament at outer radii [30, 29]. While the orbit transition was detected in the SDSS [32], the spin counterpart requires the power of the Hector-GS.

(B) **Tracing the mass accretion and dynamical evolution of galaxies through utilising Hector's spectral resolution.** The SAMI Galaxy Survey was the first to clearly demonstrate the impact of the environment on the stellar-dynamical properties of galaxies. The largest dynamical changes are detected in the most massive galaxies ($\log(M_\star/M_\odot) > 11$) in the most extreme environments. Between $9.5 < \log(M_\star/M_\odot) < 11$ the dynamical transformation as a function of both mass and environment is significantly smaller [9, 11, 28]. In this regime a factor of > 5 increase in sample size is paramount to understanding what physical processes determine a galaxy's morphology and dynamical structure. Nonetheless, the highest impact science is expected to come from the mass regimes currently out of reach of SAMI. Towards low stellar mass, there are hints that galaxies become more dispersion dominated [see also 13, 26, 2, 3], but this mass regime is currently below SAMI's spectral resolution. The higher spectral resolution of Hector will enable stellar kinematic measurements on a broader range of galaxies than any other survey. Similarly, for the most massive galaxies in extremely dense cluster environments, SAMI's current bundle size restricts measurements to the very core of these galaxies, while the vast majority of accreted material and transformation is predicted to take place at larger radii [$> 2R_\mathrm{e}$; 25, 4, 24]. It is in these low and high-mass regimes where the Hector-GS will lead to a breakthrough.

Hector will also revolutionise our ability to measure high-order kinematic signatures that offer a complementary yet unique insight into the orbital structure of galaxies. Measurements from SAMI have resulted in well-cited results for high stellar mass galaxies [27], but the Hector-GS will probe the stellar kinematics of the low-stellar mass population in large numbers for the first time. Detailed Schwarzschild's orbit-superposition models [23] have now demonstrated that high-order kinematic signatures detect unique orbital substructures, and cosmological hydrodynamical simulations show that high-order signatures are the best probes of determining the amount of ex-situ versus in-situ material in galaxies [22]. The Hector-GS will yield an unprecedented number of galaxies ($N \sim 4000$) where high-order kinematics can be measured, across stellar mass, morphology, and environment, enabling detailed comparisons to simulations [e.g. 19, 22] that relate galaxy formation models to the stellar kinematics, to unravel the formation paths of galaxies as drivers of their present-day physical properties.

(C) **Directly identifying feeding and feedback in galaxies**. The Hector-GS will evaluate the balance of gas supply for star formation in all environments by imaging outflows from kinematic signatures and emission-line diagnostics of shocks and AGN. While a small number of galaxies in the SAMI survey had the right size and orientation to identify galactic winds and outflows [15, 16, 18], the larger IFU imaging fibre bundles, called 'hexabundles', and the Hector survey strategy will allow for the gas kinematics to be traced to higher effective radii within each galaxy. This, in turn, better captures the velocity structure, including the maximal rotational velocity, and the subtle signs of inflows, outflows and re-accretion at large radii for a much larger fraction of emission-line galaxies. Our modelling has shown that the higher spectral resolution in the blue will enable multi-component line fitting and distinguishing of AGN outflow signatures in the [OIII]500.7nm emission line, which are ambiguous with the lower resolution IFS surveys.

(D) **Testing the origin of gas and its influence on star formation in galaxies.** The kinematic misalignment of gas and stars is a key tracer of the origin of gas and the impact of gas accretion and mergers on star formation and the build-up of mass. It has been shown with SAMI [6] that the larger IFU size in Hector is needed to map the merger signatures and in-coming accretion from larger radii that is necessary to constrain galaxy formation models.

The broad interests of the Hector Science team met by this survey also include i) spatially resolving star formation rates, metallicities and stellar ages; ii) tracing galaxy star formation histories from stellar populations; iii) separating the formation histories and mechanisms for the disk and bulge components of galaxies and much more.

1.3 Survey Design and Target Selection

Sample Size Justification: The need for 15,000 galaxies has been carefully set by simulations of the highest impact Hector Science goal and based on experience with the SAMI data.

A unique high-priority science goal for Hector is the correlation of the angular momentum of galaxies with their formation position within large-scale structure. While the SAMI survey detected the first signature of galaxy spin alignments with cosmic filaments [31], the significance of the detection was limited to $\approx 2\sigma$ and precluded more detailed analysis. Based on predictions from simulation, it was remarkable that the faint spin-alignment signal at $z < 0.1$ was recovered above the 95% confidence interval, especially considering the relatively low number of galaxies (N=1418) in the sample [31]. However, as outlined in key science goal (A), the limited number of galaxies in SAMI makes it impossible to detect spin-alignment trends within galaxy sub-populations, nor does it allow for a detailed analysis of galaxies near cosmic walls, any multivariate analysis (field filaments, filaments in groups, filaments in clusters), or any detailed analysis of the corresponding kinematic disturbances in the outer parts of galaxies.

We have determined that 15,000 galaxies observed over a wider area, such as the WAVES regions, will be essential to recover the 3D alignments of galactic spins in all cosmic structures, particularly near filaments and walls. While SAMI and MaNGA combined already observed 13,000 galaxies, the environmental statistics are insufficient to carry out the proposed science goal (A) as the SDSS regions lack the required redshift completeness.

Furthermore, understanding the broader science goals in section 1.2, relies on sub-dividing the galaxy sample by stellar mass (4 bins from $10^{7.5}$ to 10^{12} $\mathrm{M}_\odot$), morphology/colour (kinematic morphology - fast/slow rotators - and shape - elliptical, spiral, S0), local and global environment (position within local densities e.g. isolated galaxies, group members and radius of a galaxy within a cluster, and position within large-scale flows e.g. distance to filaments). The Hector Galaxy Survey aims for 180 galaxies per bin when subdividing into these 4 x 5 x 4 bins (requiring 15,000 galaxies) in stellar mass x environment x morphology/colour which will differentiate at the $\sim 15\%$ level between environmental influences on gas accretion and the resulting star formation and angular momentum build up in galaxies.

Survey Design: The Hector-GS field sample will probe a significant range in environmental densities, from the lowest density voids all the way to the centres of low mass clusters. However, the Hector-GS field sample volume does not contain rare massive clusters ($M_{200} > 10^{14.5} M_{\odot}$). To sample the full range in environment density, the Hector-GS will observe an additional 11 galaxy clusters with $M_{200} > 10^{14.5} M_{\odot}$, which have existing high-quality optical *griz*-band imaging from the Dark Energy Survey [DES; 1]. Furthermore, the Hector-GS will go beyond the cluster science possible with SAMI by covering the cluster outskirts out to twice the virial radius. This will bridge the density regimes of field and cluster galaxies. These intermediate density regions are a crucial environment for the morphological transformation of galaxies. Thus, the Hector-GS will be the first IFS survey that truly covers the full range of environmental densities, allowing for the most comprehensive investigation of environment-driven galaxy transformation to date.

The field sample will be in two regions: one in the north galactic cap at $\delta \simeq 0°$ (with known redshifts from SDSS, 2dFGRS and GAMA); and a second at $\delta \approx -30°$ in the south galactic cap (with known redshifts from 2dFGRS). These are the "WAVES North" and "WAVES South" fields that will be observed with (unresolved) single-fibre spectroscopy using 4MOST as part of the upcoming WAVES survey from 2024. The alignment of the Hector Survey to these WAVES fields enables the environmental and large-scale structure information from WAVES which is essential to the key science cases for the Hector Survey. Photometry for the target selection is based on deep optical KiDS imaging.

Target Selection: Target selection for the Hector-GS will follow a similar philosophy to that of the SAMI galaxy survey, using a selection function described by a series of steps in the redshift – stellar mass plane (see [5] for details). To avoid an overabundance of L_*-mass galaxies, we will sparsely select in the mass range $\sim 10^{10} - 10^{11}\,\mathrm{M}_{\odot}$. The final target selection selects 15,000 galaxies at $z \leq 0.1$.

The 2023A semester Hector observations will focus on sub-regions in the WAVES North fields that overlap the GAMA survey. These regions are to be targeted first because they complement the SAMI Galaxy Survey data which partially covered the G09, G12 and G15 fields. Hector will first complete the declination stripes in the G12 and G15 fields that were not included in SAMI. In addition, we will use the Hector instrument to target 9 of the Hector-GS clusters. Enabled by the 2dF Hector Galaxy Redshift Survey, the clusters now also have sufficient redshift coverage for the selection of Hector targets in semester 2023A. Note that the attached table of fields includes the 2dF fields to be observed as part of the reserved time application.

1.4 Hector performance so far

The Hector commissioning time in 2022 has taken very much longer than expected due to poor weather (e.g. Feb-July time was only 20% usable). Nevertheless we have commissioning data on 234 cluster and 54 field galaxies, and that data illustrates the power of the higher resolution spectrograph for achieving our science. Figure 1 demonstrates that Hector is achieving the high spectral resolution that will deliver the unique science discussed in Section 1.2. The [OII] doublet shown in Figure 1 best illustrates this resolution as it is now resolved in the blue arm of the Spector spectrograph. This double line is crucial for gas-phase metallicity and ionisation diagnostics but more importantly, the high spectral resolution Hector is delivering benefits line fitting of every line in the spectra, and no other IFS galaxy Survey (e.g. MANGA, SAMI) has high enough spectral resolution to resolve this doublet and fit detailed lines shapes of other lines.

1.5 Plan for Semester 2023A

The Hector instrument [7] has 19 hexabundles on galaxies in each field and two that image secondary standard stars for calibration. This semester, the Hector-GS aims to target 1115 galaxies in 44 dark/grey nights (of the 38.5 reserved nights, 32 are on Hector galaxy survey targets - the others are on 2dF - plus 12 shared-time nights requested here totals 44 nights), with 2 fields per night and 19 galaxies per field (with weather overhead). Our targets this semester are available all semester but March and July will require more plates changes due to the alignment of RA's, which is less efficient and therefore we prefer the other months. To reach 15,000 galaxies, a future request of 100 nights (2,500 galaxies) per year over 5.5 years is required.

Targets for 2023A will be chosen from the main Hector survey input catalogue, but be specifically chosen to allow key early science results. They will deliver immediate papers on the following 3 science cases:

(1) **The unexpected dynamics of low-mass dwarf galaxies.** Recent results indicate that both low-mass ($\log(M_{\star}/M_{\odot}) < 9.5$) spirals and spheroidals have unusual low ratios of V/σ as compared to more massive galaxies [13, 26], and break away from fundamental galaxy scaling relations [e.g. Faber-Jackson, $M_{\star} - S0.5$; 2, 3]. Determining the physical cause for low-mass galaxies to be outliers is currently restricted by 1) a bias towards spheroidal galaxies and those with early-type morphology residing in over-dense cluster environments, and 2) limited spectral resolution in the largest IFS surveys (e.g., ATLAS^{3D}, CALIFA, SAMI, and MaNGA). Due to its higher spectral resolution, the Hector-GS will be the first IFS survey to properly measure the stellar dynamics of low-mass galaxies. We will test whether the offset from current dynamical scaling relations is real or whether this is caused by the limited spectral resolution of previous surveys. This semester will prioritise low-mass dwarfs where the spectral resolution in SAMI would be insufficient to measure their low velocity dispersion, with repeat observations to reach the required

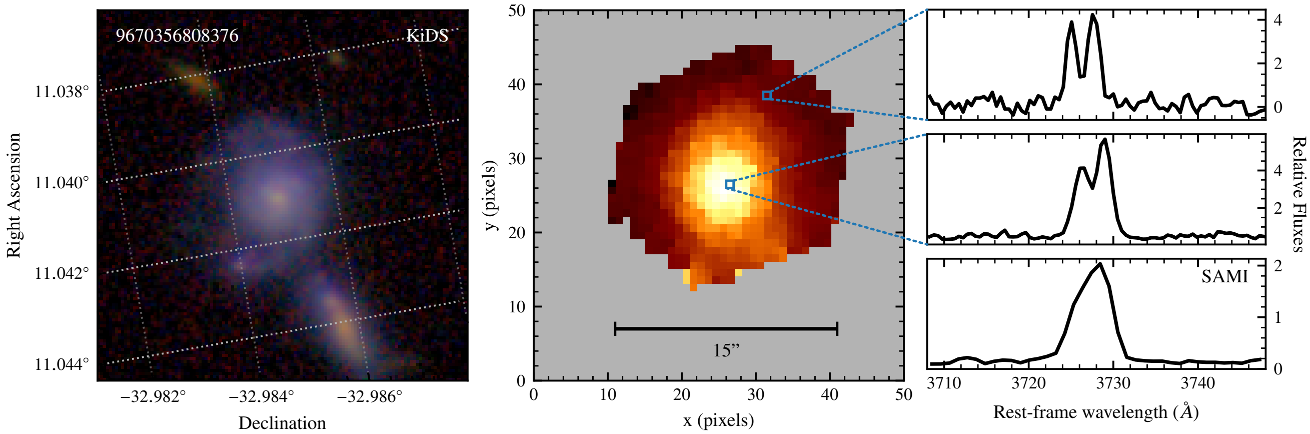

Figure 1: Left panel: ***gri*** **A colour image cutout from the Kilo-Degree Survey (KiDS)** The orientation and size have been matched to the **Hector datacube (Centre)**. The cube from the blue arm of the Spector spectrograph has been collapsed over the wavelength axis to form an image. Using the 61-core hexabundle, this galaxy has been observed out to at a minimum of 2.5 effective radii. **Right panels: Spectral cutouts around the [OII] doublet emission lines.** In the upper panels, we show that the resolved [OII] doublet from Spector is clearly resolved at the centre of the galaxy and right to the outskirts of the hexabundle at $3r_{\rm e}$. The lower panel shows the equivalent window from a SAMI galaxy (CATID 6821), which was not capable of resolving these lines. This unique capability allows more accurate fitting of gas kinematics across the galaxy as well as higher order fitting of the spectral line shapes.

depth (typically 2-3 repeats). Based on the tiling in these fields, this will result in 200 $\log(M_\star/M_\odot) < 9.5$ galaxies in this semester alone.

(2) **Inflows and outflow at large radius.** Using SAMI we found that at least $\sim 40\%$ of edge-on star-forming galaxies show evidence for outflows [16]. A more recent analysis using SAMI shows that almost all galaxies have increased velocity dispersion in extra-planar gas, suggesting that winds are much more widespread. Hector can make fundamental steps forward in this area for two reasons. First, the higher spectra resolution in the blue part of the spectrum will allow us to decompose all the spectral lines (e.g. Hβ, [OIII]5007) into multiple components to provide much clearer ionisation diagnostics. Second, the spatial extent of these outflows was limited by the small fibre bundle sizes of SAMI. With the larger fibre bundles of Hector we will probe much further out, tracing the radial decline of the outflows and their ionisation structure. This semester we will intentionally target a set of ~ 40 galaxies with effective radii larger than the SAMI hexabundles and that are preferentially edge-on galaxies where outflows will be more easily detected in ionised gas to the edge of the Hector hexabundles. This number alone will substantially build on the outflows results from SAMI.

(3) **The future fate of ram-pressure affected cluster galaxies:** SAMI targeted galaxies in the central parts of 8 clusters, finding a substantial fraction of recently accreted star-forming galaxies were undergoing outside-in quenching due to the effects of ram-pressure stripping [21]. However, many of these galaxies are only partially quenched, exhibiting ongoing central star-formation. The outstanding question is whether these galaxies are completely quenched at the first cluster core passage, as predicted by [20], or whether the central star formation continues for long periods following pericentric passage. The Hector-GS will address this question by measuring the spatial distribution of star formation in galaxies located in the 1-2R_{200} regions. This region is dominated by two distinct galaxy populations: higher velocity galaxies on their first in-fall into the cluster, and lower velocity “backsplash” galaxies that are close to the turn-around radius after a recent cluster core passage [14]. Comparing the resolved star-forming properties of the first time in-fallers, the backsplash, and galaxies in the central virialised regions will provide a strong empirical constraint on quenching timescales following the accretion of a galaxy onto a cluster. This semester will focus on galaxies located at 1-2R_{200} thereby allowing a complete view to the outskirts of clusters.

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2 Technical Justification

Hector Commissioning Status: The commissioning of Hector has been successful, with "first light" achieved during the first commissioning run: a detection of bright Hα emission lines of 19 galaxies simultaneously in *all* hexabundles. Due to exceptionally poor weather during 2022, not all commissioning tasks were finalised in the first 3 runs of the year and have continued into the latter runs, causing some delay in starting the Hector Galaxy Survey. However, initial data of galaxy fields began in the August and September runs. Those fields have been successfully reduced and the cubing pipeline has produced data cubes for all galaxies, which are now being used by the Hector Science team members and will shortly be science-grade based on improvements to the cubing. The results show that Hector is meeting it's requirements for high throughput and spectral resolution in the new spectrograph. All subsystems (positioner, guider, sky fibre system, magnetic field system and hexabundles) have all been demonstrated successfully and are operational with only minor "icing on the cake" tweeks to be implemented. Intensive training of a team of observers has resulted in 19 fully or partially trained observers in the Hector Science team.

Instrument setup and exposure times: Hector uses two spectrographs simultaneously - AAOmega and Spector (the new Hector spectrograph). In both spectrographs the wavelength range is selected to include [OII]λ3727Å to the [SII] doublet at λ7424Å for our maximum survey redshift of 0.1. Important lines in between are [NII], [OI], [OIII], Mgb, D4000, Fe lines, Hα and the rest of the Balmer series. AAOmega will cover a wavelength range of $3700 - 5700$Å with the 580V grating giving a resolution of $R \sim 1700$ in the blue arm. The 1000R grating on the red arm will cover $6300 - 7400$Å at $R \sim 4500$. Spector has a fixed instrumental resolution of 1.3Å from $3727 - 7761$Å delivering $R \sim 3460$ at 4500Å and $R \sim 5000$ at 6500Å.

Both spectrographs will use the same exposure times because they observe galaxies simultaneously. The exposures are set to achieve S/N sufficient to measure stellar velocity dispersions out to 1 effective radius, and $H\alpha$ emission line out to 2 effective radii. The Hector-GS pipeline allocates galaxies to the different sized hexabundles and different resolution spectrographs based on a formula that has been extensively modelled to optimise the fraction of each hexabundle that will contain useful data for stellar kinematics and/or emission line physics. The median surface brightness of the Hector-GS galaxies is r=22 mag arcsec^{-2} at $1R_e$ and the 90^{th} percentile is at r=23.65 mag arcsec^{-2}. Both Spector and AAOmega will achieve that median at a S/N=20/Å unbinned and the 90^{th} percentile at a S/N=5/Å unbinned (higher with binning) in a 4-hour exposure (see plots from the exposure time calculator as presented in the Hector Science document Fig.10] https://hector.datacentral.org.au/uploads/hec-spc-001-science-case-document-v-1-0-signed.pdf). The throughput of the AAOmega instrument and the fibre cable to AAOmega is well characterised from SAMI. The new front end hexabundles will not change the throughput from SAMI. The Spector spectrograph requires a longer fibre cable which entails a slightly higher loss, but was built to optimise for throughput, giving a similar net throughput (commissioning data is currently being analysed and compared to the modelled integration time calculator).

Observing strategy: One of the Hector hexabundles on each Spector and AAOmega spectrographs will be used to measure a secondary standard star for both flux and PSF calibration. The remaining 19 hexabundles will be on galaxies. Each field of 19 galaxies will be observed in a 7-point dither pattern (previously optimised for SAMI) using 30 minute exposures plus calibration overheads for arcs and flat exposures. We will observe an average of 2 fields per clear night (slightly more in winter and less in summer). The complete Hector-GS aims to target 15,000 galaxies in 100 nights per year for 6 years (38 galaxies per night, then accounting for weather overheads).

In 2023A our targets are available in all months however March and July will have less efficiency because an extra plate change may be required due to the RAs of the targets.

A full observing preparation pipeline exists for Hector, which tiles the fields using a modified Greedy algorithm to maximise tiling for sky coverage, then calculates positions on the field plate, accounting for distortions in the optics and thermal changes. Next, the configuration code sets the 3D rotation of the hexabundles for placement while the collision code optimises positioner magnet placement order and then delivers the observing tile files and plots [7]. We will use the SAMI data reduction pipeline, modified to handle data from the Spector spectrograph, to process all observations. By using a well-established pipeline, we are able to produce publication-quality data cubes immediately after observations take place, allowing rapid turn-around of the data.

A highly qualified team: The Hector Science team has a wealth of experience with observing on the AAT, data reduction of integral field data, and with the instrumentation. This comes from a strong overlap with the SAMI science team members and senior team members who have used many instruments on the AAT. The observing process for Hector is similar to SAMI. 19 observers have been fully or patially trained so far for Hector, ensuring the team can provide two observers per Hector observing run.

Availability of data: The data is available immediately to team members and will be publicly released over time. We anticipate the first public data release 2 years into the survey once the first 5,000 galaxies are observed and quality controlled. The second data release will be at 10,000 galaxies and the final release at the end of the 15,000 galaxy survey.