SHORT TITLE OF PROPOSAL: Pisces Overdensity - the Nexus of the Galactic Accretion

Observing Period: 2025B & 2026A (and 2026B & 2027A)

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DATA FOR THE PROPOSAL *Proposal page 1*

Title: Pisces Overdensity - the Nexus of the Galactic Accretion. Disentangling the Magellanic wake, the Magellanic stream and the trailing arm of the Sagittarius dwarf.

Scientific field: Galactic structure and dynamics, dark matter, dwarf satellites

Abstract: (max 2,000 characters)

We propose to use the low-resolution mode of the WEAVE spectrograph on the WHT to carry out a comprehensive spectroscopic campaign of a region of the outer Galactic halo known as the Pisces Overdensity. The Pisces Overdensity is a portion of the Northern Celestial hemisphere, both slightly above and below the equator (Dec=0) around RA=0. Most recently, it has been demonstrated that the Pisces Overdensity coincides with the predicted location of the outer portion of the so-called Magellanic Wake, a large sub-structure produced in the Galactic halo as a result of the infall of a heavy Magellanic System of galaxies. In the last few years, two additional structures have been claimed in this region of the Galaxy: the oldest wrap of the trailing debris from the Sgr dwarf galaxy and the Magellanic stellar stream. This Proposal takes advantage of the lucky overlap of the three major (yet poorly understood) outer halo sub-structures in the same area of the sky. This is truly a case of getting three science questions answered for the price of one! We will map out the velocity signature of the Magellanic wake and thus detect for the first time an unambiguous sign of the Dynamic Friction, putting strong constraints on the mass of the Magellanic Family. We will pin down the oldest tidal debris of the Sgr dwarf and therefore finally answer the question of the initial mass of the third largest satellite of the Milky Way. And last but not the least, we hope to uncover the Magellanic stellar stream, the elusive target of a relentless 50-year long hunt.

Note that this area of the sky is mostly outside of the main WEAVE Galactic Archaeology survey footprint; additionally, our main targets are predominantly distant Red Giant Stars requiring a targeting strategy distinct from that employed by the WEAVE GA survey.

TABLE OF OBSERVING TIME REQUESTED *Proposal page 2*

1. **WHT**	**WEAVE**	**MOS**
5 nights	2 Dark, 3 Grey	Clear
Maximum seeing: 1”	Semesters: 2025B, 2026A, 2026B, 2027A	Optimal dates: Aug/Sep/Oct
Impossible dates: Feb/Mar/Apr/May		

Comments: We request 35 WEAVE pointings to be observed with 60min on source per pointing. Assuming overheads of 12 m per pointing, this translates into 42h total time. If we consider 8.5h a night, the time request is 5 nights, of which 2 in dark and 3 in grey. See Objectives and Technical Feasibility for considerations on the exposure time in relation to the precision we want to achieve in the observables.

SCIENTIFIC JUSTIFICATION:

Background:

The Magellanic Clouds and the “wake”

In the last decade our view of the Large and Small Magellanic Clouds (LMC and SMC) has been dramatically transformed. We have uncovered a large population of faint Magellanic Satellites (e.g. Koposov et al. 2015; Kallivayalil et al. 2018; Fritz et al. 2019), mapped out a vast network of extended stellar debris around the Clouds (e.g. Belokurov et al. 2016; Deason et al. 2017; Mackey et al 2018; Navarrete et al. 2019) and placed the first tangible constraints on the mass of the Magellanic Clouds (MCs) using the perturbations the Magellanic System induces on stellar streams in the halo of our Galaxy (e.g. Erkal et al. 2018, 2019; Koposov et al 2019). **Equally recent is our realization of the scale of damage the MCs are inflicting on the Galaxy.** The implications of the arrival of a massive (Penarrubia et al 2016) LMC on a highly eccentric and rapidly evolving orbit (Besla et al 2007; Kallivayalil et al. 2013) are many fold. First, in response to the interaction with a massive satellite, the barycenter of the Milky Way should move (Gomez et al 2015). Second, the MC fly-by will violently disturb the Galactic disc (both stellar and gaseous), warping and heating it out of equilibrium (Laporte et al 2018). Finally, the giant satellite will gravitationally focus Dark Matter particles directly behind it, as it sinks to the centre of the Milky Way due to dynamical friction (Garavito-Camargo et al. 2019). *This ``wake'' ought to have an observable stellar counterpart, composed of MW halo stars at distances beyond 50 kpc.*

Beyond 50 kpc: the realm of Sgr?

The stellar halo beyond 50 kpc is poorly characterized: here, tracers are scarce and only three significant substructures have been discovered: the Sgr stream, the Outer Virgo overdensity (OVO) and the Pisces Overdensity (see below). The Sgr stream in particular, is considered to be the dominant contributor at these large distances. *While the Sgr stream has now been mapped in some detail, the presence of this large substructure complicates any potential detection of the “wake” in the outer stellar halo.* Moreover, it is not clear that the OVO and Pisces Overdensity are in fact distinct from the Sgr stream. Indeed, the location of Pisces (RA ~ 0 deg, Dec -10 deg) intersects both the Sgr trailing arm *and* the Magellanic Stream predicted from tidal models of the clouds. Thus, this distant substructure could have multiple, overlapping, origins.

The Pisces Overdensity

The Pisces Overdensity is an excess of stars in the outer halo, which covers an area of at least 25 x 5 deg^2 (Sesar et al. 2007; Watkins et al. 2009; Nie et al. 2015; Belokurov et al. 2019). The overdnesity was discovered from an excess of RR Lyrae and blue horizontal branch (BHB) stars, and appears as a broad and long plume of stars stretching from 40 to 110 kpc with a steep distance gradient. On the sky, Pisces' elongated shape is aligned with the Magellanic Stream (see Fig.1).

Spectroscopic follow-up of stars in this overdensity are scarce, with only a handful of stars with measured radial velocities (e.g. Kollmeier et al. 2009; Sesar et al. 2012). Most recently, Belokurov et al. (2019) showed that the velocity distribution of a small sample of distant BHB stars coincident with this plume has a broad velocity distribution with a bias towards negative radial velocities: *exactly the signature predicted for the Magellanic wake in this region of the sky.*

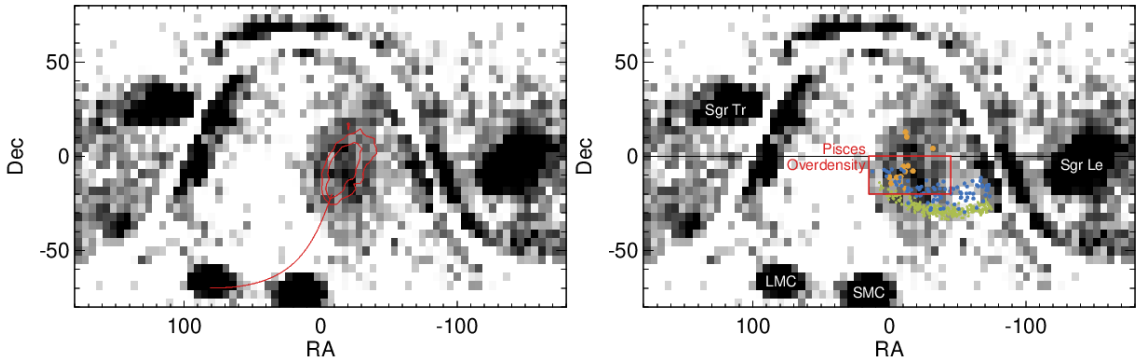

Fig 1: Density of distant (50<D[kpc]<100) EDR3 RGB candidates in equatorial coordinates. Apart from the LMC and SMC at the bottom, three obvious over-densities are visible: the apo-centric pile-up of the Sgr dSph trailing debris at 90 < RA/deg < 160, the Sgr Leading apo-centre + Outer Virgo Overdensity (OVO) at -180 < RA/deg < -140 and the Pisces cloud of stars at -40 < RA/deg < 10. Left: The past orbit of the LMC is shown by the red solid line, while red contours give the density of stars with 65<D/kpc<100 in the Magellanic wake model (see Belokurov et al 2019, Erkal et al 2020). Right: Black solid line gives the boundary of the WEAVE GA LRhighlat survey. Red rectangle is the area covered in this Proposal. Yellow filled circles are the detections of suspected Magellanic Stream from Zaritsky et al (2020). Blue (green) small filled circles are the old trailing Sgr debris with (without) the LMC from the model of Vasiliev et al (2020). The region of the Galaxy studied in this Proposal is the only large structure in the outer halo whose nature remains unknown to date.

However, this is not the final story. Zaritsky et al. (2020) identified potential Magellanic debris in the distant halo from the H3 spectroscopic survey data. The authors found 15 stars that are, in both position and velocity space, in close proximity to the trailing gaseous Magellanic Stream (MS, see Fig. 1). This distribution of debris is predicted from tidal models of the clouds. Remarkably, these stars are also located in a similar region of the sky as the Pisces Plume!

Clearly this distant substructure in the halo lies at the nexus of the most significant accretion events in the MW's (recent) history, and holds the key to disentangling and characterizing these events. The goal of this proposal is to unravel the mystery of the Pisces overdensity, and link it to the critical contributors of the MW halo.

Motivation:

The overarching motivation behind this Proposal is to shed light on the nature of the Pisces Overdensity. But this is not a fishing expedition: we have designed this programme to answer three very specific questions, each closely linked to the two most dramatic events in the recent history of our Galaxy.

To wake or not to wake

Currently it remains unclear whether any part of this region contains the Magellanic wake produced by the "pinching" action of the LMC on the stars in the Milky Way halo. The wake in the Dark Matter halo of the Galaxy must exist for the LMC to experience

Dynamical Friction. The stellar halo wake we are probing is the luminous counterpart to the dark one, and is built up from the stars that were in the halo prior to the LMC's arrival. Consequently, the stellar halo wake is distinct from any accreted sub-structure: i) it does not contain a particular stellar population corresponding to formation in a single satellite system, instead it is a mixture of stars of unconnected metallicities and ages, deposited into the Milky Way previously; ii) while the orbits of the stars in the wake are altered by the interaction with the LMC, the wake's kinematics are unmistakably distinct from that of a generic stellar stream: its velocity dispersion is much larger; it is in fact similar to that of the halo at the same location with an overall shift of the mean of the velocity distribution dependent on the details of the LMC's infall. Therefore, if it can be demonstrated that the Magellanic wake indeed exists, its extent, its shape and the velocity gradient can be modelled to inform our understanding of the interaction between the LMC and the Milky Way.

Note that the stellar halo wake is not the only signature produced by the dance of the two galaxies. A "global" wake is also caused by the reflex motion of the MW induced by the LMC (see e.g. Garavito-Camargo et al. 2019; Erkal et al. 2019; Cunningham et al. 2020). Hints of this global signature have already been reported (Erkal et al. 2020; Peterson & Penarrubia 2020), however, the enormous spatial scale of this global signature precludes an efficient observational investigation following the time constraints of the current Call. Instead, our Proposal focuses on the much more localised structure, namely the pile-up of the stars directly behind the moving LMC, well-aligned with its past orbit. In three spatial dimensions, this trail (or wake) is a giant elongated structure broadly stretching towards the LMC on one end and disappearing into the outskirts of the Milky Way on the other. Beyond a certain distance, however, the cross-section of the wake on the plane of the sky is limited to only 10-20 degrees (see Fig 1) due to the wake's radial orientation. The much-reduced extent of the region of interest makes it viable to conduct a thorough study of the entire outer Magellanic wake.

The oldest Sagittarius tidal debris and the mass of the dwarf

The nearly perfect correspondence between the observed location and the shape of the Pisces Overdensity and the predicted properties of the outer Magellanic wake is truly striking (see Fig 1 of this proposal and Fig. 3 of Belokurov et al 2019). Nevertheless, most recently, new evidence came to light that requires a reassessment of the above interpretation of the Pisces Overdensity, in particular, its connection to the Magellanic wake. Vasiliev et al (2020) recently made a new extremely clean and precise census of the Sgr stellar steam members. Thanks to the available full 6-D phase-space coordinates, they were able to detect a large-scale perturbation of the stream which they demonstrated to be caused by the interaction between the Milky Way, the LMC and the Sgr dwarf. Unfortunately, the original study of Belokurov et al (2019) which presented the new map of the Pisces Overdensity and suggested the connection to the Magellanic wake had to rely on a tiny kinematic sample limited to a single location at the edge of the Pisces Overdensity. Nonetheless, the sample in question is the best we currently have access to. Based on the limited kinematic information available as part of the dataset presented in Belokurov et al (2019) it is impossible to disentangle the exact make of the Pisces Overdensity and establish whether the Sgr stream is contributing a large number of stars to what was assumed to be the Magellanic wake.

Note that if the Sgr stars are identified as part of our program they would contribute invaluable new information on the earliest bouts of the Sgr dwarf disruption. Their kinematics and metallicity can be used to place strong constraints on the mass of the Sgr dwarf shortly after its arrival to the Milky Way. This has implications for perturbations of the Galactic disk (Antoja et al. 2018), which can be explained by a massive Sgr kicking the disc in the past (e.g. Laporte et al. 2019; Bland-Hawthorn et al. 2019). In contrast, the Sgr mass *today* is relatively low *(*Vasiliev & Belokurov 2020). The question of how much mass exactly and how quickly was lost from the Sgr dwarf galaxy can be answered by our programme if we can detect the Sgr trailing debris in the area of Pisces Overdensity.

<u>The Magellanic Stellar Stream</u>

To add more complexity to the already messy situation, a detection of a previously unseen (but long sought after) substructure has been reported several months ago, again in the area of the Pisces Overdensity. Zaritsky et al (2020) claimed a detection of the Magellanic stellar stream, the elusive counterpart of the Magellanic gaseous stream. Now, if true, this is a triumph for the models of the tidal disruption of the Magellanic system, such as those e.g. by Besla et al or Diaz et al. In these models, the Magellanic stellar stream typically forms from the material stripped from the SMC rather than the LMC. The tides of the Large Cloud pull the stars from the Small one and the Milky Way's tides scatter these stars around the Galactic halo, tracing a giant arc, crossing the region of interest studied in this Proposal. The existence of this stellar stream was postulated a long ago, but until recently the efforts to pin it down had remained fruitless. If the stream is uncovered (and mapped by our programme), we will be able to understand the orbital path of the Magellanic system. For the vast majority of Galactic satellites, their past orbits can be determined if their proper motions are measured. It is not as simple for the Clouds! This is because the additional (it is not important for other, lower mass satellites of the Galaxy) Dynamical Friction force plays a vital role in reshaping the orbit of the Clouds. However, with the stellar stream in hand, we will be able to reconstruct the orbital evolution of the MCs.

Please note that while both the Magellanic stream and the Magellanic wake have formed in the halo of our Galaxy as a result of the infall of the LMC+SMC system, they are clearly distinct in terms of their stellar populations and their kinematics. The wake is a "pinched" subset of the stellar halo, and thus is a kinematically "hot" mish-mash of stars accreted previously, while the stream is kinematically "cold" and is composed from stars born in the SMC.

The properties of the Magellanic stream hold the clues to the past trajectory of the Clouds in the Milky Way's halo as well as the details of their mutual interaction. Given their high mass, the MCs are bound to play an important role in sculpting the Galaxy. Their recent infall is destroying the equilibrium of the Galaxy and if we still want to be able to model the Gaia + WEAVE survey data to understand the formation and evolution of our Galaxy we must account for this recent, unceremonious and hugely consequential intervention. The proposed study of the candidate Magellanic stream will offer the only direct constraint on the Magellanic orbit.

Objectives:

The focus of our Proposal, the Pisces Overdensity, holds vital clues to the details of the two most recent and most massive accretion events in the Milky Way: the disruption of the Sgr dwarf and the arrival of the Magellanic Clouds. The area of the sky we propose to scrutinize is sizable but our goal of disentangling the three distinct structures that appear to overlap here is achievable using the observing strategy outlined.

- We aim to map the Pisces Overdensity with 35 WEAVE non-contiguous pointings. We need to target distant giants, which are rare, but we estimate we will have about 40 such targets per WEAVE pointing. This will total a sample of 1400 distant giants with line-of-sight velocities precise to 5-6 km/s and metallicities to +/-0.3dex.
- These measurements will be used to discern the origin(s) of the Pisces stars. Field halo ([Fe/H] ~ -2), magellanic stream ([Fe/H] ~ -1), and Sgr stream ([Fe/H] ~ -1.5) stars have distinct chemo-dynamical signatures: we will dissect the sample as a function of metallicity, and use the radial velocity measurements to confirm which component they are related to.
- State-of-the-art models of the MW-LMC-Sgr system (e.g. Erkal et al, Vasiliev et al.), will be used to inform and calibrate our classification of stars in this region of the sky.
- This dataset will also have legacy value: spectroscopic confirmation of distant halo stars are scarce, and we will provide a detailed mapping of a sizeable fraction of the distant halo.

We note that the only WEAVE survey including such distant and faint stars among its targets is the Galactic Archaeology LRhighlat survey, i.e. the survey targeted the Milky Way stellar halo and thick disc at low spectral resolution. However, the area we are proposing for, at DEC < 0 <u>is not part of the GA-LRhighlat survey footprint</u>: the GA-LRhighlat footprint is limited to DEC > 0 due to requirements from one of the other WEAVE surveys GA-LRhighlat is sharing fibres with (WEAVE-LOFAR, which is performing follow-up of LOFAR sources).

LIST OF PRINCIPAL TARGETS

The area to be covered is within the range RA = [-45deg, 15deg], DEC = [-20deg, 0]. We request 35 equally spaced pointings, in a pattern of a rectangle with 7x5 pointings per side.

In each pointing, our main target stars are distant red giants, at d > 50kpc. We estimated a target density of ~40 such distant giants per WEAVE pointing based on the Gaia EDR3 data. Among the ORM facilities, WEAVE is the only instrument that has the necessary multiplex power to follow such a large number of faint targets in one go.

In addition to distant giants, we will also include blue horizontal branch stars and RRLyrae selected to lie in a similar distance range. Although these targets are much rarer than giants, they will be a useful complement, since their distances can be determined more easily.

The rest of the fibres could be filled in following the standard WEAVE GA-LRhighlat standard selection strategy, with a mix of inner and our halo Milky Way stars, if this is deemed reasonable by the TAC. Following this strategy, it will be possible to acquire information also on closer regions of the Milky Way stellar halo in the very complex region being targeted and place it in the context of the results obtained by WEAVE GA-LRhighlat in other regions of the sky.

In order to isolate distant giants, we need to target down to magnitudes as faint as G=20-20.5. See Section Technical feasibility for estimates on the exposure time per pointing.

Technical feasibility (per telescope on which you request time).

We are requesting time for WHT/WEAVE. Since the instrument has not been commissioned yet, we have relied on the results of the analysis of the most recent set of WEAVE simulated spectra, that were produced by the WEAVE project as part of the Operational Rehearsals, with input from the surveys' teams. This is by far the best information available before commissioning and science verification are carried out.

Our targets (selected using the Gaia DR3 colours, magnitudes, parallaxes and proper motions) cover the magnitude range G = 16-20/20 and the accuracy we aim for at the magnitude of the faintest targets is about 5 km/s. WEAVE spectra simulated as part of the project Operational Rehearsal, and analyzed with the pipeline that will be applied to WEAVE survey data (the Advanced Processing system), suggest that we can obtain a precision of ~5-6 km/s (and metallicities to +/-0.3dex) down to G = 20.5 in dark time and down to G ~ 20 in grey time for seeing < 1" in 60min on source per WEAVE pointing.

Our team includes the sub-survey leads of one of the WEAVE GA surveys (the low resolution survey of the stellar halo and thick disc), A. Deason, G. Battaglia, as well as members of the target selection group (G. Battaglia, V. Belokurov, S. Koposov), catalogue submission group (G. Thomas), and quality assurance group (D. Aguado); this implies good knowledge of the expected performance of the instrument and first-hand information on the surveys boundaries and target selection strategies.

A project management plan

The target stars have already been selected.

Phase 2 (i.e. the preparation of catalogues and observing blocks compliant to the WEAVE formats and requirements) will be led by S. Koposov (and assisted by PI and other co-I's).

WEAVE data in open time will be reduced by the Core Processing System and the extracted spectra analysed with the WEAVE Advanced Processing System (APS), where the latter will deliver the observables of interest for this proposal. Hence no issues are foreseen for the data reduction and analysis, since our targets are one of the target types for which the APS pipeline is optimized. Line-of-sight velocities, metallicities and estimates of the abundances of alpha-elements are the standard output of the APS module analyzing late-type stars in low resolution mode, as the targets of this proposal.

All the Co-Is in the proposal are experts in the field of Galactic Archaeology. In particular, within our team, we have the WEAVE Galactic Archaeology Science Team Lead (V. Hill) and the sub-survey team leads (A. Deason, G. Battaglia), catalogue maker (S. Koposov), OB maker (G. Thomas), and quality assurance group representative (D. Aguado) of the GA-LRhighlat survey; this implies a deep knowledge of the procedures and formats needed to go from target selection, to catalogue making and submission, observing blocks configuration, should these tasks fall on the team proposing for the observations.

The expertise in observations and models needed to carry out the analysis of the data is already available within the team. The analysis will be led by A. Deason, V. Belokurov, A. Carrillo, and E. Cunningham.

Any additional relevant information, including results from previous ITP awards.

This program was awarded 5n for the 2023B/24A period, but due to delays to the WEAVE/MOS instrument no data was taken.

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