

Exploring the stellar streams and satellites around the giant low surface brightness galaxy Malin 1

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ABSTRACT

Context. Giant Low Surface Brightness galaxies (gLSBGs), such as Malin 1, host extended stellar and gaseous discs exceeding 100 kpc in radius. Their formation and evolution remain debated, with interactions with satellite galaxies and accretion streams proposed as key contributors. Malin 1 presents multiple nearby and distant satellites. Additionally, it exhibits two giant stellar streams, the largest extending 200 kpc in projection, likely related to past interactions.

Aims. We investigate the orbital dynamics of Malin 1's satellites and their possible connections with the observed stellar streams, testing their nature with different formation scenarios.

Methods. We constructed gravitational potentials for Malin 1 using optical and HI rotation curve data, incorporating stellar, gaseous, and dark matter components. We explored a wide orbital parameter space to determine whether the candidate progenitors of the stellar streams could have originated from past interactions, testing both Navarro-Frenk-White (NFW) and the pseudo-isothermal (ISO) halo profiles.

Results. Among several explored scenarios, some produced bound orbital solutions. The ISO halo model, with mass of $M_{\text{virial}} \approx 2.6 \times 10^{12} M_{\odot}$, favours bound satellite orbits more than the NFW model, that has a lower mass of $M_{\text{virial}} \approx 1.4 \times 10^{12} M_{\odot}$. These orbital models show that the giant stellar streams could be substructures of some satellites galaxies located along their leading and trailing orbital trajectories. Furthermore, our analysis indicates that the most distant Malin 1 satellite (eM1) could have reached its orbital pericentre ~ 1.6 Gyr ago, while the nearest companions could have interacted as early as ~ 100 Myr ago. At the same time, one of the closest companions would still be under a strong interaction. Another close companion displays both leading and trailing arms in a radial orbit, although it also shows a polar orbit. Furthermore, we identify some unbound orbital solutions that could link some satellites with streams.

Conclusions. The observed alignment of satellites and streams indicates that past interactions likely shaped aspects of Malin 1's morphology. Our orbital modelling constrains possible progenitors of the observed stellar streams and their orbital histories, providing new insights into the dynamical evolution of gLSBGs. Our findings are consistent with results reported very recently by other studies using Malin 1 kinematic data.

Key words. gravitation – galaxies: evolution – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: spiral

1. Introduction

Disney (1976) suggested the possibility that there are galaxies with a surface brightness (SB) lower than the empirical limit proposed by Freeman (1970), which defined the characteristic central surface brightness of disc galaxies as being around $21.65 B \text{ mag arcsec}^{-2}$. This threshold was based on observations of high-surface-brightness spirals and was initially thought to represent a universal feature of disc galaxies. Since then, the discovery rate of low surface brightness galaxies (LSBGs) has been boosted by advances in observational techniques and deeper sky

surveys, leading to a growing recognition of their importance in galaxy formation and evolution (Du et al. 2020).

In general terms, LSBGs exhibit a central surface brightness fainter than $23.5 B \text{ mag arcsec}^{-2}$ (Impey & Bothun 1997). These galaxies display poor star formation rates, a low metallicity, and extended HI gas discs, characteristics shared with giant low surface brightness galaxies (gLSBGs), which appear as massive systems typically existing in isolation and have sizes larger than that of the Milky Way up to the 25th isophote (Das 2013).

Malin 1, one of the most iconic gLSBGs due to its immense size and faintness, was discovered serendipitously by Bothun et al. (1987). This particular gLSBG has a bar structure and

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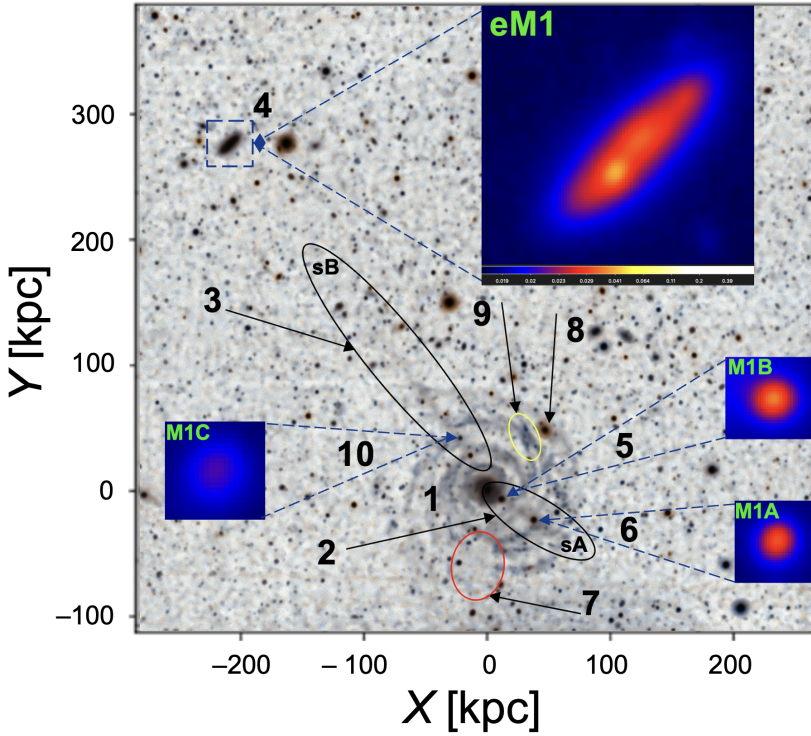


Fig. 1. Malin 1 system g and r band image from the Magellan/Clay telescope (Galaz et al. 2015). The equatorial coordinates have been converted into X, Y in kiloparsec units, adopting an angular scale of $1.557 \text{ kpc per arcsec}^{-1}$, and the origin is centred at Malin 1. The colour-map scale for the sub-panels uses arbitrary units and is shown in panel 4. Labels mark the following: 1. Malin 1. 2. Proposed stream A (sA), possibly linking Malin 1A, Malin 1B, and Malin 1. 3. Proposed stream B (sB), aligned in projection with exo-Malin 1, Malin 1C, and Malin 1. 4. The satellite galaxy SDSS J123708.91+142253.2 (Reshetnikov et al. 2010), referred to here as exo-Malin 1 (eM1) at coordinates $X, Y = (-211, 277) \text{ kpc}$, separated $\sim 350 \text{ kpc}$ from Malin 1. Note the offset between the brightness peak and the geometrical centre (zoom-in). 5. Malin 1B (M1B). 6. Malin 1A. Both, Malin 1B and 1A are compact ellipticals, and interacting galaxies (Saburova et al. 2022). 7. Cavity, a low stellar density region displaying an apparent gap between the spiral arms (red ellipse). 8. A distant background galaxy ($z=0.3639$). 9. The yellow ellipse indicates clumps within the spiral arms; their structure suggests regions of star formation or newly formed star clusters, based on VLT-MUSE observations (Junaïs et al. 2024). 10. A UDG candidate (Ji et al. 2021), with VLT-MUSE data (Junaïs et al. 2024) showing a young star formation region with redshift $z = 0.08292$. It is $\sim 47 \text{ kpc}$ from Malin 1 centre, and we refer to it as Malin 1C (M1C).

shows a LINER nucleus (Barth 2007). Evidence indicates that the bar resulted from several star formation events, and along with the discovery of compact sources, the same evidence points to a possible double nucleus system (Johnston et al. 2024). Ogle et al. (2016, 2019) reported the discovery of a large sample of the most optically luminous, largest, and most massive spiral galaxies in the Universe, called super spirals, that could be analogous to Malin 1; however, Malin 1 is still the largest stellar disc known (Ogle et al. 2016, 2019), but it has a much lower star formation rate of $\sim 1.2 M_{\odot} \text{ yr}^{-1}$ than those observed in typical super spirals (Lelli et al. 2010; Junaïs et al. 2024).

Malin 1 also presents HII regions, a radial decrease in the surface density of the star formation rate, reduced metal content, and flattening in the outer disc (Junaïs et al. 2024). These characteristics provide clues about the development of the disc, with the most likely scenario involving the accretion of pre-enriched gas from a previous merger (Junaïs et al. 2024; Zhu et al. 2018). Furthermore, the galaxy is characterised by a low dust content and a minimal presence of molecular gas (Gerritsen & De Blok 1999; Galaz et al. 2022; Junaïs et al. 2024; Galaz et al. 2024).

Moreover, an optical map has revealed a cavity in the southern part of Malin 1, between the arms (Galaz et al. 2015). This cavity could be due to feedback from star formation, as the HI map shows a nearby asymmetric substructure (Lelli et al. 2010), or the action of supernova-driven winds expelling gas, similar to phenomena observed in other galaxies such as the Hoag galaxy (Bannikova 2018), the Fireworks galaxy (Blair et al. 2019), NGC 1300 (Maeda et al. 2022), or the gLSBG UGC 1382 (Saburova et al. 2022). A northern warp in the HI disc shows axis asymmetry, possibly due to the accretion of a paired system of two gas-rich satellite galaxies. This could be evidence of ongoing interaction (Saha et al. 2021).

Studies have revealed that Malin 1 interacts with at least two companion galaxies, identified as Malin 1B and the SDSS J123708.91+142253.2 (Reshetnikov et al. 2010; Galaz et al. 2015) – the latter is also referred to as exo-Malin 1, a

designation initially introduced by Bustos Espinoza et al. (2024b,a), or eM1 for brevity. Both galaxies are associated satellite galaxies. In addition, Malin 1A is part of the Malin 1 system and, together with Malin 1B, is classified as a compact elliptical (Saburova et al. 2022). A recent study by Junaïs et al. (2024) identified several $H\alpha$ regions, including Malin 1C, which is part of the Malin 1 galaxy and may be an ultra-diffuse galaxy (UDG) that interacts with the core galaxy (Ji et al. 2021). Malin 1C has possibly been stripped of gas and outlying stars by tidal interactions (Kazantzidis et al. 2004). Malin 1B and exo-Malin 1 are situated at distances of 14 and 350 kpc towards the south-east and north-west, respectively (Reshetnikov et al. 2010). These objects, along with others, are illustrated in detail in Fig. 1.

According to Saha et al. (2021), exo-Malin 1 may play a role in star formation within the central bar, while the accretion of Malin 1B could bolster star formation in the arms and bulge (Saha et al. 2021). As noted by Saburova et al. (2023) and Peñarrubia et al. (2006), extended discs in gLSBGs could develop through minor mergers involving gas-rich satellites, and this scenario is possibly applicable to exo-Malin 1, Malin 1B, Malin 1A, and Malin 1C.

Tidal stellar streams exemplify the continuous merging and accretion of galaxies, a key process in the formation of structures within the Universe (Niederste-Ostholt et al. 2012). Several well-studied examples have illustrated the remnants of disrupted dwarf galaxies and their tidal debris. The Sagittarius stream, which originates in the dwarf galaxy of Sagittarius, demonstrates that progenitors can lie several to tens of degrees away from their associated streams (Niederste-Ostholt et al. 2012; Bonaca et al. 2021). Similarly, a vast stellar stream extending more than 500 kpc has been identified on the outskirts of the Coma cluster. The stream likely formed from the destruction of a dwarf galaxy, and it provides key insights into the gravitational potential of the cluster (Román et al. 2023). The spatial relationship between a satellite and its debris depends on its orbital phase. Near the apocentre, the material tends to accumulate into

overdensities, while near the pericentre, the tidal stream stretches along the orbit and compresses perpendicular to its motion due to its acceleration and host tidal field (e.g. [Niederste-Ostholt et al. 2012](#); [Smith et al. 2013](#); [Blaña et al. 2015](#)).

Analysis of the luminosity of the stream progenitors suggests that they were absorbed during relatively early formation periods ([Vera-Casanova et al. 2022](#)). Moreover, recent studies of the giant spiral galaxy Malin 2 have revealed faint tidal structures surrounding the main host ([Junais et al. 2025](#)), suggesting that tidal interactions and mergers may be common processes in ultra-low surface brightness systems.

Various hypotheses have been developed here regarding the origin of gLSBGs. According to [Noguchi \(2001\)](#), gLSBGs evolved from standard spiral galaxies through dynamic changes over time. Their formation is influenced by environmental factors, including large galaxies in voids that feature conventional bulges coupled with extensive LSB discs ([Hoffman et al. 1992](#)). Within the hierarchical formation paradigm, mergers between a central galaxy and its satellite companions may explain the considerable size observed ([Peñarrubia et al. 2006](#)). Although the origins and properties remain partially unknown, some cosmological simulations point to these alignment-driven mergers as the key to such large-scale development ([Zhu et al. 2023](#)). Moreover, [Zhu et al. \(2018\)](#) identified that a significant fraction of the cold gas at redshift zero originated from the cooling of the hot halo gas, a process triggered by the merger of a pair of interacting galaxies.

The Lambda cold dark matter (Λ CDM) cosmology theory suggests that the disruption of satellite galaxies is a frequent process in the lifetime of massive galaxies ([Martínez-Delgado et al. 2023](#); [Miro-Carretero et al. 2024](#)). The extended size of the gas and stellar disc might result from the impact of two or more galaxies merging. This formation mechanism aligns with the existing theories of formation of gLSBGs ([Zhu et al. 2018](#)). As [Román et al. \(2023\)](#) pointed out, such giant faint stellar streams may exist in galaxy clusters and groups according to Λ CDM. So the presence of streams in the Malin 1 system could be evidence that not all gLSBGs are isolated, in contrast to [Das \(2013\)](#), who argued that gLSBGs are usually isolated, often near the edges of voids, and that their lack of interactions contributes to their slow evolution. Research involving cosmological simulations ([Zhu et al. 2018](#)) illustrates that smaller galaxies, often termed intruders, can interact with larger galaxies, leading to the formation of a gLSBG that shares notable similarities with Malin 1. Similarly, [Mapelli et al. \(2008\)](#) proposed that stimulated accretion might explain the exceptionally large disc size of Malin 1. Additionally, [Zhu et al. \(2018\)](#) indicated that a collision involving three galaxies could produce a gas-rich gLSBG.

This paper investigates Malin 1 and its surroundings. We analysed possible orbital configurations of its satellite galaxies, including both leading and trailing segments, to comprehend their impact on its structure, kinematics, and evolutionary progression.

The structure of this article is as follows. In Sect. 2 we describe the observed substructures. Section 3 details the modelling approach for the Malin 1 system. Section 3.1 provides the observational data and associated constraints. In Sect. 3.2 we discuss the gravitational potential of Malin 1, and Section 3.3 outlines scenarios to explore progenitor candidates of the stellar streams, including initial setups. In Sect. 4 we evaluate the results, and in Section 5 we discuss and interpret our findings. The conclusion is found in Section 6. Finally, two appendices provide a summary of the optimal parameters and describe how prior knowledge is integrated into our model.

Table 1. Properties of the Malin 1 galaxy.

Property	Value
Morphology	SB0/a ^a
D_L [Mpc]	377 ± 8 ^b
M_V [mag]	-22.9 ± 0.4 ^c
$\mu_{0,B}$ [mag arcsec ⁻²]	~ 28.0 ^d
$\mu_{0,V}$ [mag arcsec ⁻²]	~ 25.5 ^e
$M_{H I}$ [$10^{10} M_\odot$]	$4 - 7$ ^f
AGN	LINER ^g
α (J2000)	$12^h 36^m 59.35^s$ ^h
δ (J2000)	$+14^\circ 19' 49.16''$ ^h
z	0.0827002 ^h
$V_\odot$ [km s ⁻¹]	24775 ± 10 ^h
D_{opt} [kpc]	~ 220 ⁱ
i	$38^\circ \pm 3^\circ$ ^j

Notes. ^(a)Barred lenticular galaxy with faint spiral arm features ([Lelli et al. 2010](#)). ^(b)[Lelli et al. \(2010\)](#). ^(c)[Pickering et al. \(1997\)](#). ^(d)[Galaz et al. \(2015\)](#). ^(e)[Impey & Bothun \(1997\)](#). ^(f)[Pickering et al. \(1997\)](#); [Lelli et al. \(2010\)](#). ^(g)[Barth \(2007\)](#). ^(h)Equatorial coordinates, redshift, and velocity from [Reshetnikov et al. \(2010\)](#). ⁽ⁱ⁾Optical and H I diameter, scaled to the Milky Way ([Moore & Parker 2006](#)). ^(j)[Lelli et al. \(2010\)](#).

For our calculations, we used a flat Λ CDM cosmology with H_0 set at $70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$. This resulted in a projected plate scale of $1.557 \text{ kpc arcsec}^{-1}$ and a luminosity distance to Malin 1 of 377 Mpc.

2. Observed substructures in the Malin 1 system

This section presents a summary of the features identified in the optical image of Malin 1 ([Galaz et al. 2015](#)). The environment of Malin 1, observed in the g and r bands with the 6.5 m *Magellan/Clay* telescope, is shown in Fig. 1, and the listed substructures are indicated by arrows that follow the same numbering. The essential characteristics are listed in Table 1. Among the relevant properties of the Malin 1 system, the following are noteworthy:

- 1. Malin 1: the gLSBG comprises a dual structure: a central bulge-bar and HSB disc resembling a Sa/SB galaxy with a radius under 10 kpc, and an extended, gas-rich outer LSB region with an optical diameter of 240 kpc ([Barth 2007](#); [Moore & Parker 2006](#)). This last component features the most extensive known stellar disc, reaching a surface brightness of approximately $28.0 B \text{ mag arcsec}^{-2}$ ([Galaz et al. 2015](#); [Boissier et al. 2016](#)). The galaxy also possesses a large HI gas reservoir with a mass $4-7 \times 10^{10} M_\odot$ ([Pickering et al. 1997](#); [Lelli et al. 2010](#)). It also has a high specific angular momentum ([Di Teodoro et al. 2023](#); [Boissier et al. 2016](#); [Salinas & Galaz 2021](#)), and an extended flat rotation curve ([Lelli et al. 2010](#); [Pickering et al. 1997](#)), all of which suggest the presence of a vast dark matter (DM) halo ([Mo 2010](#)).
- 2. Stream A (sA): as noted by [Galaz et al. \(2015\)](#), it is a possible stellar stream that may be associated with two galaxies: Malin 1B, positioned at ~ 14 kpc from the centre of Malin 1 (marked as point 5), and (more likely) Malin 1A, which sits in the middle of the stream at ~ 45 kpc from Malin 1 centre (marked as point 6), both in the south-west direction.
- 3. Stream B (sB): the largest ellipse shown in Fig. 1 outlines a structure found in [Galaz et al. \(2015\)](#) with an elongation that suggests a stellar stream, a jet, or a diffuse region ([Boissier et al. 2016](#)). Here, we call this stellar stream

- candidate Stream B. sB is significantly extended, reaching up to 200 kpc from the centre of Malin 1 in the direction of the satellite exo-Malin 1. If this extended feature corresponds to a stellar stream, then it could have formed from material – either stellar or gaseous – tidally stripped from a satellite galaxy. Here, we explore progenitors that could have had past encounters with Malin 1, removing material from the satellite, producing the stream-like structure.
- 4. exo-Malin 1 (eM1): this galaxy has a total luminosity of $9.47 \times 10^9 L_{\odot}$. While it shows an elongated morphology, it is unclear if this corresponds to an early-type galaxy or a disc structure. It shows evidence of emission lines of H α , H β , and OII, so it is likely a star-forming disc galaxy (SDSS SkyServer 2024; Lintott et al. 2011). Its redshift of $z = 0.083082$ and projected distance of 350 kpc makes it a Malin 1 satellite candidate, that may have interacted in the past (Reshetnikov et al. 2010). This interaction could explain the formation of the extended low surface brightness (LSB) disc or serve as a catalyst for the emergence of the suspected stream B (Galaz et al. 2015). Additionally, the zoom-in image of eM1 (see point 4 in Fig. 1), shows that the peak of the surface brightness is shifted from the geometrical centre. This off-centre, found in this study, could indicate that exo-Malin 1 has experienced past interactions that could involve Malin 1. Further discussion on this can be found in the Section 5. Moreover, it is very intriguing that eM1 appears to align on the sky with the stream B along an almost straight line towards the centre of Malin 1.
 - 5. Malin 1B (M1B): Reshetnikov et al. (2010) recognised it as a galaxy interacting with Malin 1 (point 5 in Fig. 1). Furthermore, Saha et al. (2021) identified its interaction specifically with the central area of Malin 1, implying it might be responsible for initiating recent star formation in the galaxy (Saha et al. 2021). The possibility that stream A is concurrently connected with Malin 1B (Reshetnikov et al. 2010) and/or Malin 1A (Saburova et al. 2022) supports the hypothesis of a past merger. Malin 1A and Malin 1B, both compact ellipticals (Saburova et al. 2022), could have experienced tidal stripping, potentially explaining their compact nature. If further stripping occurs, they might evolve into objects similar to ultra-compact dwarfs (UCDs), as suggested by Bekki et al. (2001). Moreover, such tidal shaping of satellite galaxies has been shown to operate on mass scales of magnitudes of orders of difference (Blaña et al. 2025). Meanwhile, Malin 1C's classification remains unclear: It could be either a UDG (Ji et al. 2021) or a young star-forming region (Junais et al. 2024), possibly linked to past interactions.
 - 6. Malin 1A (M1A): this object was identified as another compact elliptical, which are typically located close to larger galaxies and prone to tidal interactions and stripping (Saburova et al. 2022; Johnston et al. 2024). M1A has undergone significant tidal encounters with Malin 1, leading to the depletion of nearly all their gas (Kim et al. 2020).
 - 7. Cavity: a cavity in the southern region of the observed LSB disc indicates a reduced stellar density, displaying an apparent gap between spirals. Furthermore, irregularities in the HI gas distribution observed in the HI data are also noted (Lelli et al. 2010). Its origin is unknown: it could be the result from a local gas depletion, dust extinction, or satellite interactions.
 - 8. Galaxy SDSS J123657.22+142021.1: a background galaxy at a high redshift ($z = 0.364$) beyond Malin 1, and a broad-line galaxy (Abazajian et al. 2009).

- 9. HII regions: identified using VLT-MUSE, such as the one highlighted by a yellow ellipse, indicate recent star formation activity (Junais et al. 2024).
- 10. Malin 1C (M1C): reported as a star forming (H α) blob candidate using VLT-MUSE observations (Junais et al. 2024), with signatures of H α emission and at a redshift similar to Malin 1 ($z = 0.08292$). It is positioned at a projected distance of 46.75 kpc from Malin 1, forming part of the Malin 1 surroundings. Fig. 1 shows a colour-enhanced image of M1C. MUSE H α emission line has a relative mean velocity of 54 km/s from Malin 1 systemic velocity, being likely bound to Malin 1 and with a velocity dispersion higher than 90 km/s Junais et al. (2024, private communication). This high velocity dispersion could also mean that the system corresponds to a dwarf galaxy. Moreover, the nature of H α blobs are still debated, with tidal remnants, stripped clouds, or UDGs as candidates Ji et al. (2021). Moreover, M1C appears aligned with the stream B, which would be a natural consequence if this is the core of the stream that is being tidally disrupted. Current orbital configurations significantly influence tidal stream arrangements, impacting both the leading and trailing arms, and possibly affecting the remnant bound core. This effect is supported by various simulation studies (see Fig. 1 in Niederste-Ostholt et al. 2012).

3. Modelling the Malin 1 system

Here we describe in detail how we modelled the gravitational potential of Malin 1 and the possible orbits of its satellites and streams. The gravitational potential and orbital models are constrained by observational data, such as the surface brightness profile, rotation curve, and line-of-sight velocities.

3.1. Observational data and constraints

For the photometric modelling, we considered different surface brightness (SB) band data observations of Malin 1: *HST*/F814W for the central area, within <15 kpc (Barth 2007), and the *r* and *g* bands for the extended disc, reaching 100–120 kpc in radius (Moore & Parker 2006; Reshetnikov et al. 2010; Saha et al. 2021). In the analysis, we also used the SB profile of the *R*-band as explained in Lelli et al. (2010). Analysis was conducted on the HI rotation curve data (Pickering et al. 1997; Lelli et al. 2010), taking into account the stellar, gaseous, and DM mass components. Furthermore, the inner part of the rotation curve, dominated by the bulge/core and HSB disc, would be constrained by incorporating existing kinematic data of the central region, such as long-slit spectroscopy (Junais et al. 2020), MUSE observations (Johnston et al. 2024; Junais et al. 2024; Saburova et al. 2022).

In addition, the sky coordinates of the stellar streams, measured with respect to the centre of Malin 1 as the inertial reference frame, were derived from the deep photometric maps of Galaz et al. (2015), who report a ~200 kpc stream that extended towards exo-Malin 1. We also carried out a visual inspection of these maps, guided by surface brightness enhancements relative to the background, to select representative coordinates *x-y* points along both streams, which were then used as observational constraints in our orbital modelling. The *x*-axis aligns with the right ascension (α) and increases leftward on the sky plane. The *y*-axis aligns with the declination (δ) and increases northward (upward) in the plane of the sky. The statistical accuracy of each

Table 2. Line of sight velocity V_{los} , and related properties of *Malin 1* and associated galaxies.

Galaxy ^a	V_{los} [km s ⁻¹] ^b	Petro. radius [kpc] ^g	Luminosity [$L_{\odot}$] ^h	γ_{band} [$M_{\odot}/L_{\odot}$] ^l	$M_{\star}$ [$M_{\odot}$] ^o
M1	0 ± 1 ^c	5.6 ± 0.2	$(1.07 \pm 0.06) \times 10^{11}$ ⁱ	3.3 ± 0.4 ⁱ	$(1.4 \pm 0.3) \times 10^{11}$ ^p
eM1	132 ± 37 ^d	5.2 ± 0.4	$(5.6 \pm 0.3) \times 10^9$ ^d	0.9 ± 0.2 ⁿ	$(5.0 \pm 0.9) \times 10^9$
M1B	65 ± 22 ^d	2 ± 2	$(2.6 \pm 0.7) \times 10^9$ ^d	3.4 ± 0.6 ^m	$(8.8 \pm 1.7) \times 10^9$
M1C	54 ± 27 ^e	1.5 ± 0.5	$(1.3 \pm 0.2) \times 10^8$ ^j	0.9 ± 0.2 ⁿ	$(1.2 \pm 0.3) \times 10^8$
M1A	54 ± 27 ^f	2 ± 2	$(1.12 \pm 0.15) \times 10^9$ ^k	3.4 ± 0.6 ^m	$(3.8 \pm 0.7) \times 10^9$

Notes. ^(a)Galaxy abbreviations defined in Table 5 and Fig. 1. ^(b) V_{los} velocity of the satellite with respect to the Malin 1 system. ^(c)M1 centre with dispersion from the projected angular scale (Galaz et al. 2015). ^(d)Reported by Reshetnikov et al. (2010). ^(e)Junais et al. (2024) and private communication. ^(f)Our estimation based on both M1A and M1C having approximately the same distance from the M1 centre. ^(g)Radius where surface brightness is 20% of the average within it (Petrosian 1976; Psychogios et al. 2016); data from SDSS SkyServer (2024). ^(h)Luminosity in Solar units. ⁽ⁱ⁾This work: averaging isothermal and NFW profiles. ^(j)UDG in r -band (SDSS SkyServer 2024). ^(k)cE in r -band (SDSS SkyServer 2024). ^(l)Mass-to-light ratio in solar units (Bell & De Jong 2001). ^(m) γ value for cE (Bell & De Jong 2001). ⁽ⁿ⁾ γ value for LSB or UDG (Bell & De Jong 2001). ^(o)Stellar mass. ^(p)This work: stellar mass estimation within $r < 100$ kpc, averaging models with ISO and NFW profiles.

coordinate x and y was enhanced by using the projected angular scale and the median seeing of 0.8 arcsec (Galaz et al. 2015), given a confidence level of ± 1.25 kpc. For the distance r measured from the centre of Malin 1, error propagation was used (see Fig. A.1 and Table A.1).

Moreover, the line of sight velocity of the satellite, with respect to the Malin 1 system, denoted V_{los} and cited from various sources (Dey et al. 2019; Cook et al. 2023; Reshetnikov et al. 2010; Saburova et al. 2022; Galaz et al. 2015; Junais et al. 2024; Johnston et al. 2024), along with other likelihood-associated satellite galaxies, is listed in Table 2.

3.2. Malin 1 gravitational potential

To investigate the dynamics of the Malin 1 satellites and streams, we need to model the gravitational potential to calculate the orbits. For this, we proceed with the modelling process in two steps.

First, we construct a model of the surface brightness profile of Malin 1 using the photometric data described in Section 3.1. This model represents the main Malin 1 substructures described in Section 2: the bulge/bar and the HSB and LSB discs. We adopted photometric models that offer analytical solutions for their potentials, which allow for quick orbital calculations and a large parameter space exploration. Therefore, we used the Miyamoto-Nagai (MN) model proposed by Miyamoto & Nagai (1975), where its potential relates to the density through the Poisson equation and is defined as:

$$\Phi_{MN}(R, z) = -\frac{GM}{\sqrt{R^2 + \left(a + \sqrt{Z^2 + b^2}\right)^2}}, \quad (1)$$

where a and b are the radial and vertical scale lengths, M is the mass, $R = \sqrt{X^2 + Y^2}$ is the cylindrical radius, X, Y, Z , and $r = \sqrt{R^2 + Z^2}$ is the spherical radius. We note that when $a = 0$, the potential Φ_{MN} simplifies to the Plummer profile (Plummer 1911). For photometric modelling, we fit the total luminosity of each component L_x . The luminosity can be converted to stellar mass $M_{\star} = \gamma_{\text{band}} L_{\text{band}}$, where γ_x is the stellar mass-to-light ratio in a band. In our analysis, we used a Plummer profile to model the bulge/bar of Malin 1 and two MN models for the components of the HSB and LSB disc. We also tested replacing the spherical bulge model with a triaxial bar model Long & Murali (1992) using the Plummer luminosity and scale lengths from

Saha et al. (2021), finding similar main orbital properties. Given that the MN profile becomes a Kuzmin profile if a face-on disc is integrated along the line-of-sight (los) (Binney & Tremaine 2008), we used this simplified profile to fit the surface brightness profiles.

In the second step, we fitted circular velocity (v_c) models to the observed gas kinematics to obtain the mass-related parameters. Here we fit the mass-to-light ratio γ under the maximal disc assumption, which means that the stellar components contribute the maximum possible fraction of the observed rotation curve before the DM halo becomes dominant (Binney & Tremaine 2008). For the representation of the dark halo, we implemented two sets of models. One with the Navarro-Frenk-White (NFW) profile (Navarro et al. 1996), which aligns with the Λ CDM model, and another with a pseudo-isothermal (ISO) profile (De Blok & Bosma 2002). Both profiles are widely used to describe the density distribution of DM halos, as has been applied to Malin 1 (e.g. Lelli et al. 2010). NFW assumes that DM halos have a characteristic ‘cuspy’ central density and extend over large distances. The ISO profile, on the other hand, features a flat central core, which implies a constant density at the centre (Mo 2010). These are defined as

$$\Phi_{NFW}(r) = -\frac{GM_h \ln(1 + r/r_s)}{r} \left[\ln(1 + c) - \frac{c}{1 + c} \right]^{-1}, \quad (2)$$

$$\Phi_{ISO}(r) = -4\pi G \rho_0 r_c^2 \left[\frac{1}{2} \ln \left(1 + \frac{r^2}{r_c^2} \right) + \frac{r_c}{r} \tan^{-1} \left(\frac{r}{r_c} \right) \right]. \quad (3)$$

The NFW model defines the concentration parameter $c = r_{200}/r_s$, the virial radius r_{200} , where the mean density becomes 200 times the critical density of the Universe, and the scale radius r_s . On the other hand, in the ISO profile (De Blok & Bosma 2002), the parameter r_c defines the radius of the core and ρ_0 indicates the central density of the DM halo.

In addition, Malin 1 has a very extended HI disc component (Bothun et al. 1987; Pickering et al. 1997). To include this in the gravitational model, we again used a Miyamoto-Nagai model with a mass of $M_{\text{HI}} = (4-7) \times 10^{10} M_{\odot}$ (Lelli et al. 2010), a scale length of $a_{\text{HI}} = a_2$, where we assumed that it has a distribution similar to that of the LSB component and a height of $z_{\text{gas}} = 0.3$ kpc. Furthermore, factors 1.1 for molecular H_2 and 1.4 for helium gas are included (Lelli et al. 2010). Together, these components represent the baryonic mass.

Table 3. Definition of parameters used in the orbital modelling for each scenario.

Parameter	Symbol	Description
Spatial coordinate (los)	Z	Line-of-sight distance of the progenitor candidate relative to the mid-plane of Malin 1 (kpc). A positive (negative) value places the object in front of (behind) the disc along the observer's line of sight.
Tangential velocity	V_{tg}	Magnitude of the velocity component perpendicular to the line of sight (km s^{-1}). Together with the observed los velocity, it defines the full 3D velocity vector of the orbit.
Position angle	PA	Angle measured at the orbit initial condition, indicating the direction of the tangential velocity vector in the plane of the sky, measured counterclockwise from north through east (degrees).
Pericentre	R_{peri}	Minimum galactocentric distance to Malin 1 (r) reached by the orbit (kpc).
Apocentre	R_{apo}	Maximum distance r to Malin 1 reached by the orbit (kpc).
Eccentricity	ϵ	Orbital shape, defined as $\epsilon = (R_{\text{apo}} - R_{\text{peri}})/(R_{\text{apo}} + R_{\text{peri}})$. Circular orbits have $\epsilon = 0$ and highly elongated orbits have $\epsilon \rightarrow 1$.
Posterior probability	$\log(p)$	Logarithm of the posterior probability returned by the MCMC sampling. Larger values correspond to orbital solutions that are statistically more significant.

Notes. The scenarios mentioned are described in detail in Table 5.

3.3. Orbital modelling: Setup, parameters, and methodology

Literature studies on the disruption of satellite galaxies and the formation of stellar streams with N-body simulations typically find that the remaining satellite core has a leading and a trailing component (e.g. [Fellhauer et al. 2006](#); [Smith et al. 2013](#), and references therein). Moreover, satellites and their streams can have different morphologies that depend on the potential of the host and, more importantly, on the eccentricity of the orbit. Very circular orbits can produce ring-like streams or polar ring streams, as observed in the Sombrero galaxy ([Martínez-Delgado et al. 2021](#)). Radial orbits can produce a more diverse morphology depending on the location where the satellite and the streams are observed in their common orbit. For example, a satellite can be preferentially closer to one of its streams, with the trailing stream being closer to the apocentre, and the leading arm could be tidally compressed while entering the host, with the bound core somewhere in the middle of the orbit. (see Fig. 1 in [Niederste-Ostholt et al. 2012](#)).

Our goal is to explore orbital configurations or scenarios that could connect observed stellar streams A and B with the observed satellites in Malin 1, identifying progenitor candidates. Therefore, we are required to consider all detected satellite galaxies near Malin 1 (see Section 2), and to explore the configurations or scenarios that could connect these structures in different ways. Each scenario is also evaluated using two distinct gravitational potentials for Malin 1, the NFW and the ISO DM models (Section 3.2).

For the orbital model of the satellite and stellar streams, we updated the orbital integrator code DELOREAN ([Blaña et al. 2020](#)) with the potentials of Malin 1 and coupled it with EMCEE ([Blaña et al., in prep.](#)) to reconstruct the orbital trajectories of satellites while fitting the position information of the streams. For this, we maximised the likelihood ($p = -\log(\chi^2)$) given by the chi-squared orbit fitted in projection to the stream sky coordinates, shown in Fig. A.1 and Table A.1. Given that the satellite-to-host mass ratio is small ($\lesssim 0.1$), we model the orbits of the satellites and the streams as test particles, where $M_{\text{Satellite}}/M_{\text{Malin 1}} < 0.01$. The input fixed parameters that we

introduce in DELOREAN are the position of Malin 1 and the positions and line-of-sight velocities (v_{los}) of the satellites and the positions of the streams (see Table A.1). The free parameters in each orbit calculation are the los coordinate Z , the tangential velocity V_{tg} , the position angle PA, and the log posterior $\log(p)$. From the posterior sampling, we derived the orbital characteristics: the pericentre R_{peri} , the apocentre R_{apo} , and the orbital eccentricity ϵ , which helped us classify the orbital nature and stability of each solution. More details are provided in Table 3.

The selection of parameter ranges in each orbital scenario is based on a combination of observational constraints and iterative modelling; our general strategy involves the following steps:

- Observational data: we started the process using satellite/stream observational data, specifically the measured projected sky position and line-of-sight velocity for each object.
- Initial parameter space: the orbital solution space was explored by fitting three main free parameters: the line-of-sight distance z , the magnitude of the tangential velocity V_{tg} , and the direction of V_{tg} is aligned with the position angle PA, defined as the angle measured counter-clockwise from North, centred at satellite's observed position. The ranges of initial parameters were established based on physical motivations to restrict search volume and avoid nonphysical results.
- Iterative MCMC refinement: an initial EMCEE run uses wide uniform priors to sample the global parameter space. We then iteratively refined the prior ranges based on the most probable values (identified using the CORNER plots) and repeated the MCMC fitting until the posterior distributions and the resulting orbital paths converged to a robust solution.
- Orbit evaluation: the resulting 3D orbital trajectories were evaluated by checking their consistency against observed features, specifically the stream curvature, direction, and alignment with the disc of Malin 1.
- Best-fit solution: the final, converged parameter distributions derived from the iterative fitting represent the optimised orbital solution for the stream or satellite.

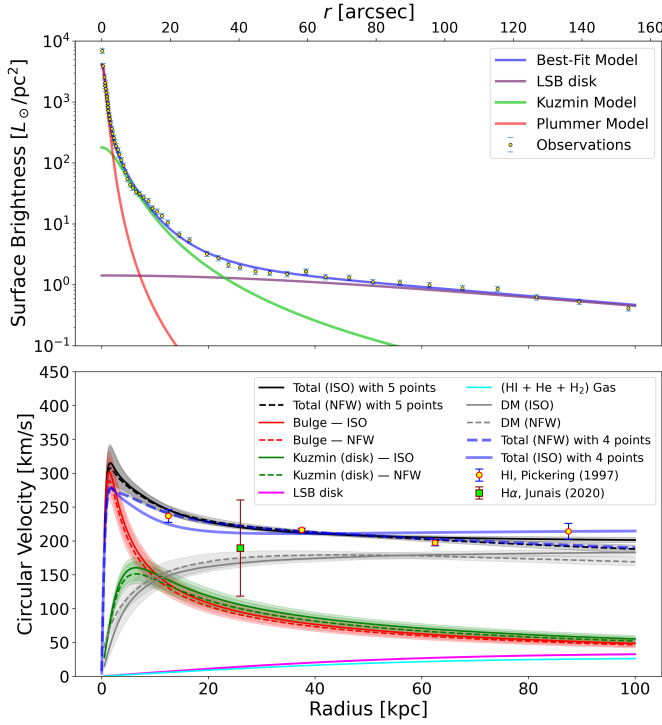


Fig. 2. Top panel: observed R -band surface brightness profile of Malin 1 as a function of the galactocentric radius (Lelli et al. 2010). Overplotted are the best-fit stellar components: a Plummer model for the bulge (red line), a Miyamoto–Nagai (Kuzmin) disc for the inner HSB component (green line), and another Miyamoto–Nagai disc for the extended LSB component (purple line). The total best-fit photometric model is shown in blue. Bottom panel: Observed H I rotation data from Pickering et al. (1997) recalculated in Lelli et al. (2010) (yellow circles) and H α data from Junais et al. (2020) (green square). We show the Malin 1 best model fit: the stellar bulge (red), HSB disc (green), and LSB disc (purple), along with the gaseous disc component composed of H I, He, and H $_2$ (cyan). With gray curves we show the DM halo model cases ISO (solid) and NFW (dashed). The black curves show the total mass model cases for the ISO (solid) and NFW (dashed) halos fitting five data points (four H I and one H α). We also show a test model (blue) fitted to the H I data only that adopts a single γ for the HSB disc and bulge. The shaded regions represent the 1σ confidence intervals from the MCMC posteriors.

4. Results

Here, we first present the results of the mass and potential modelling of Malin 1. This is followed by the results of the orbital modelling of the stellar streams and satellites, considering different satellite-stream scenarios.

4.1. Mass and potential models for Malin 1

In Fig. 2 (top panel), we display the surface brightness profile of the best Malin 1 luminosity model as a function of galactocentric distance. We also show the data points of the r -band, which were converted from the g and r bands (Lelli et al. 2010), revealing a good fit to the main substructures. As expected, the fit produces a Plummer profile that characterises Malin 1’s bulge well, while one Miyamoto–Nagai model (Kuzmin) represents the HSB disc, and the extended disc represents the LSB component, dominating the SB beyond 20 kpc. The MCMC-EMCEE posterior distributions of the luminosities and scale-length parameters are shown in Figure 3. The components of the best fitted models are reported in Table 4, resulting in a luminosity of the inner

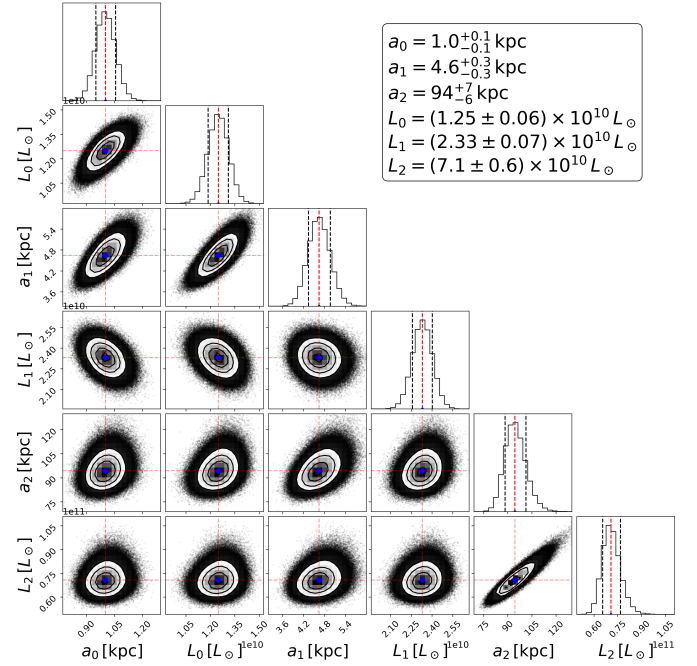


Fig. 3. Parameter posterior distributions for the surface brightness fitting of Malin 1. The scale length parameters a_0 , a_1 and a_2 , and the luminosities L_0 , L_1 , and L_2 are the parameters for the Bulge (Plummer), HSB disc (Kuzmin), and the LSB disc (Kuzmin) components. The histograms are the marginalised distributions for each parameter, with the 16th, 50th, and 84th percentiles (vertical dashed lines) and values shown in the legend.

components of $L_{\text{LSB}} = 3.4 \times 10^{10} L_{\odot}$, while the LSB component has a luminosity of $L_{\text{LSB}}(R < 100 \text{ kpc}) = 2.2 \times 10^{10} L_{\odot}$ within the observed radius of $R \sim 100 \text{ kpc}$.

Following this, we proceed to model the rotation curve data. For this, we used four HI rotation curve data points taken from Lelli et al. (2010). Additionally, there are recent gas kinematic observations from the central region (Junais et al. 2020; Junais et al. 2024; Johnston et al. 2024). We tested the inclusion of these additional observations, considering 17 points: 10 H α , 3 [OII], and 4 H I (see Fig. A.2). However, the gas kinematics of H α and [OII] appear to be affected by non-circular motions, (Saburova et al. 2022; Kataria & Saha 2025). Including them in the fit would bias the mass models, particularly in the innermost kiloparsecs. A more sophisticated triaxial modelling of the stellar kinematics would be required; however, this would mostly improve the modelling in the central region, which is beyond the scope of this work. For this reason, and to ensure consistency with the large-scale dynamical modelling, we adopted a conservative strategy: we excluded the inner H α and [OII] data and retained only the outermost H α point, together with the four H I points. Thus, our final rotation curve fit is based on five data points from robust tracers (four H I + one H α), which are less affected by non-circular motions. This approach balances the use of available kinematic constraints with the need to avoid systematics introduced by disturbed central motions.

The rotation curve modelling requires fitting a DM ISO or NFW halo model, and converting the luminosities to stellar mass profiles. For the latter, we implemented three independent mass-to-light ratio parameters (γ): one for the bulge, another for the HSB disc, and a third value for the LSB disc component. Although physically motivated, introducing this amount of free parameters increases the degeneracy when fitting the

Table 4. Malin 1 model best-fitted parameters.

I. Photometric and gas model parameters ^a		
Component	Parameter [Unit]	Value
Bulge	r_{Bulge} [kpc]	1.0 ± 0.1
	L_{Bulge} [$10^{10} L_{\odot}$]	1.3 ± 0.1
HSB disc	z_{HSB} [kpc]	0.3^h
	R_{HSB} [kpc]	4.6 ± 0.3
	L_{HSB} [$10^{10} L_{\odot}$]	2.3 ± 0.1
LSB disc	z_{LSB} [kpc]	0.3^h
	R_{LSB} [kpc]	94^{+7}_{-6}
	L_{LSB} [$10^{10} L_{\odot}$]	$7.1^{+0.6}_{-0.5}$
Gas disc	z_{Gas} [kpc]	0.3^h
	R_{Gas} [kpc]	94^{+7}_{-6}
	M_{Gas} [$10^{10} M_{\odot}$]	8.5 ± 1.0^i
II. Stellar γ :		
	ISO Halo	NFW Halo
γ_{Bulge} [$M_{\odot} L_{\odot}^{-1}$]	$0.90^{+0.16j}_{-0.16}$	$0.90^{+0.16j}_{-0.16}$
III. DM halo parameters:		
	ISO Halo	NFW Halo
R_{vir} [kpc] ^b	282^{+14}_{-14}	231^{+17}_{-15}
M_{vir} [$10^{12} M_{\odot}$] ^c	$2.57^{+0.44}_{-0.38}$	$1.41^{+0.28}_{-0.22}$
ρ_0 [$10^6 M_{\odot} \text{kpc}^{-3}$] ^d	48.7 ± 28.9	6.72 ± 4.77
r_c [kpc] ^e	$3.67^{+1.73}_{-0.85}$	–
r_s [kpc] ^f	–	20.2 ± 6.6
c^g	–	11.4 ± 3.8
χ^2_{reduced}	1.21	2.15

Notes. The results include photometric and gas disk components, stellar mass-to-light ratios (γ), and Dark Matter (DM) halo parameters for both the ISO and NFW models. ^(a)Stellar components modelled with the Miyamoto-Nagai potential (Eq. 1), where z_h is the scale height, R_d is the scale length, and M_d is the mass. ^(b)Virial radius, R_{200} . ^(c)Virial mass, M_{200} . ^(d)Central density for the ISO model (ρ_0). ^(e)Bulge radius (r_c) for the ISO model. ^(f)Scale radius (r_s) for the NFW model. ^(g)Concentration parameter $c = R_{\text{vir}}/r_s$ for the NFW model. ^(h)Parameter fixed during fitting. ⁽ⁱ⁾Estimated error based on H I flux uncertainty. ^(j)Fixed value based on stellar population synthesis models Lelli et al. (2010); the quoted uncertainty is the estimated systematic error.

rotation curve. Therefore, for our fiducial modelling we followed Lelli et al. (2010) and adopted $\gamma_{\text{LSB}} = 0.90 M_{\odot} L_{\odot}^{-1}$ as a fixed LSB value, and fitted γ_{Bulge} and γ_{HSB} for ISO halo models and NFW models. In addition, we chose a prior distribution strongly constrained by colour information and stellar population models from Bell & De Jong (2001) and other γ constraints in Malin 1 (Junais et al. 2020). The resulting posterior distribution of the models that used the ISO halo is shown in Fig. 4, and NFW in Fig. C.1. We also tested the degeneracy of γ_{LSB} by fixing the value of $\gamma_{\text{Bulge}} \approx 3.8 M_{\odot} L_{\odot}^{-1}$, $\gamma_{\text{HSB}} \approx 1.5 M_{\odot} L_{\odot}^{-1}$ based on previous work (Junais et al. 2020, see their Fig. 9), leaving γ_{LSB} as a free parameter, obtaining a range $\approx 0.86\text{--}0.90 M_{\odot} L_{\odot}^{-1}$ in concordance with Lelli et al. (2010). Furthermore, we also tested using a mass-to-light value for the bulge and disc region $\gamma_{\text{Bulge}} = \gamma_{\text{HSB}} = 3.4 M_{\odot} L_{\odot}^{-1}$, finding results consistent with Lelli et al. (2010). The best parameters are reported in Table 4, showing γ for each stellar component, along with the corresponding DM halo parameters for both the ISO and NFW models.

In general, we find that the bulge region has systematically higher γ values than the HSB disc component. The

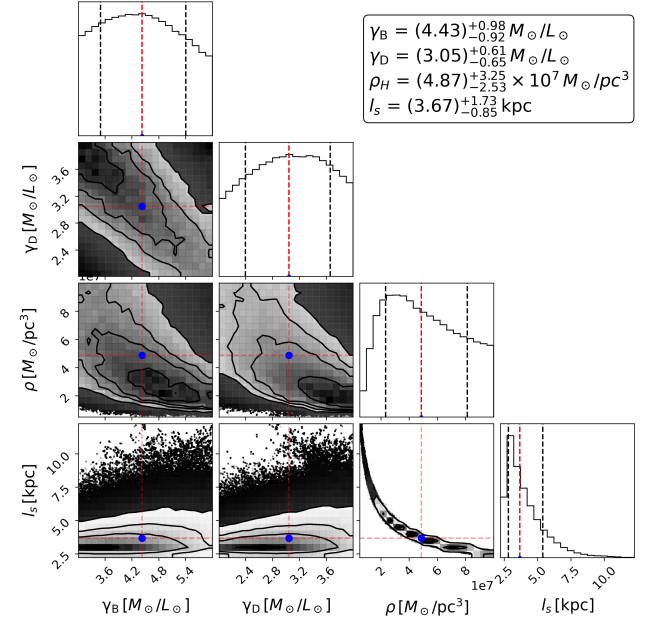


Fig. 4. Posterior distributions of the mass-to-light ratios for the bulge, HSB disc, and the ISO DM halo parameters: central density (ρ_{Halo}) and the core radius (r_c). Diagonal panels show the marginalised distributions with the 16th, 50th, and 84th percentiles indicated by dashed lines. Contour plots display parameter covariances. The legend reports the best-fit values with 1σ uncertainties. The ISO model provides robust fits, with maximum-a-posteriori values (blue points) close to the medians.

rotation curves of the best ISO and NFW models are shown in Figure 2 (bottom panel). The decomposition also shows the contribution of different mass components: stellar bulge, HSB/LSB discs, and the gaseous disc (HI, He and H_2). Both the high- and low-surface brightness (HSB and LSB) regions of the disc are considered. The figure further compares the performance of the two halo parametrizations, highlighting the differences between the NFW and ISO models. Figure 3 illustrates the optimised EMCEE fit parameters for the surface brightness model, while Figure 4 shows the equivalent parameters for the rotation curve model. The data compiled for the two profiles is presented in Table 4. The model with the ISO DM profile provides better fits of the rotation curve, as shown by the reduced (χ^2) of the MCMC. This is due to the flat rotation curve behaviour of the isothermal profile, while the NFW halo drops faster at the same distances and similar masses. Moreover, we also find that the models with NFW produce higher values of γ than the ISO models. This is due to the cuspy nature of the NFW dark halo model, which introduces more mass in the centre, forcing the stellar mass to have lower γ . This results in NFW halos having virial masses of $1.4 \times 10^{12} M_{\odot}$ and lower than the ISO models with $2.6 \times 10^{12} M_{\odot}$. Furthermore, our test with equal central γ result in more massive ISO halo models with $3.7 \times 10^{12} M_{\odot}$.

Given that the differences between the potential models with ISO and NFW haloes are larger than the differences within each halo model profile, we proceed to use both sets of models to consider the uncertainties in the potential that are used to explore the orbital scenarios in the following section.

4.2. Scenarios connecting possible progenitor satellite candidates and stellar streams

Our goal is to search for orbital solutions of satellite galaxies that can overlap with the stellar streams. From these we

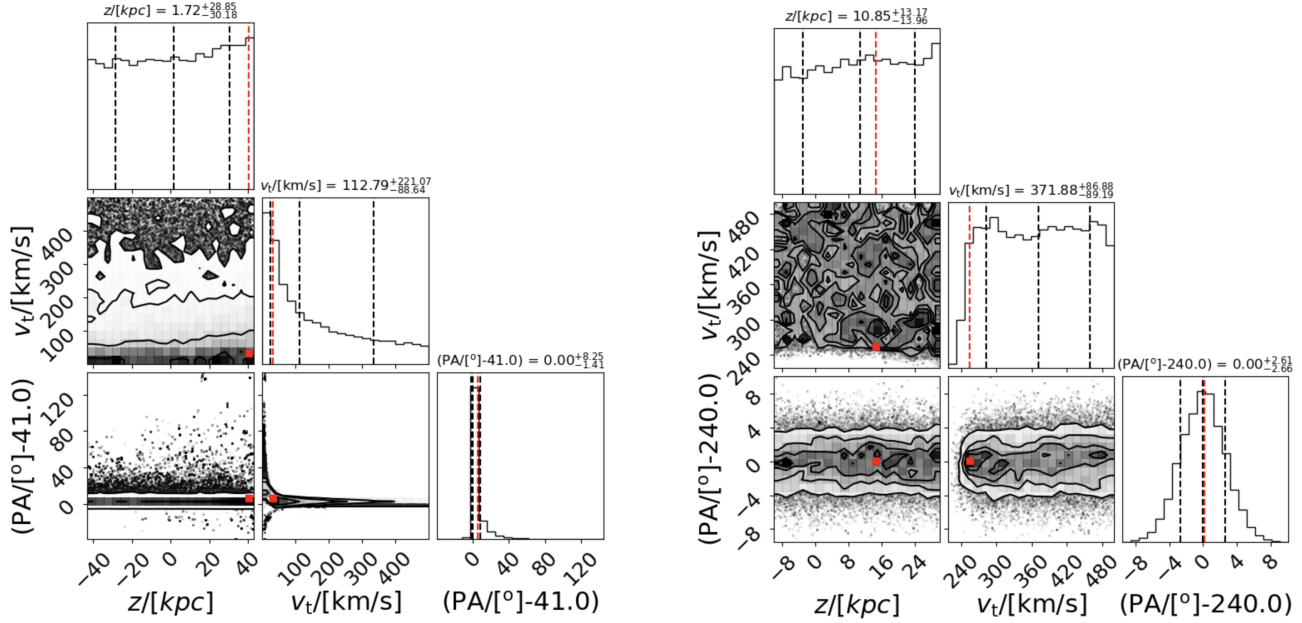


Fig. 5. Corner plots of the posterior distributions of orbital parameters (z , v_t , and PA offset) obtained with *emcee*. Left: Scenario I-a (radial orbit, ISO halo). Right: Scenario IV-a (polar orbit, ISO halo). Diagonal panels show marginalised 1D distributions with dashed lines marking the median and 1σ uncertainties. Off-diagonal panels show 2D covariances with 68 and 95% confidence regions. These two scenarios illustrate contrasting orbital families (radial versus polar) within the ISO halo parametrization.

focus on radial orbits that reach the central regions of Malin 1 where the satellites could have experienced the most intense tidal forces. We also considered polar orbital solutions, similar to those observed in the Sombrero galaxy (Martínez-Delgado et al. 2021), where the satellite has near circular orbits while being tidally stripped.

We defined five scenarios that depend on what satellite is assumed to be the progenitor, and two subcases (a and b) that depend on what combinations of the streams are assumed to be associated with each satellite. These are summarised in Table 5. For many scenarios and cases, we found radial and polar orbital solutions. In addition, we tested two different DM potentials (NFW and ISO) for each scenario.

Following our procedure to constrain the regions where the best orbits are found (see Section 3.3), we converge to the parameter ranges reported in Tables B.1 and B.2 where we justify each. Table 6 reports the Best-fit posterior probabilities (p) for all the scenario models. The investigation consists of millions of orbits per scenario, resulting in a comprehensive analysis of ~ 130 million orbits in total to explore the parameter space. Here, we highlight the solutions that most accurately correspond to the observational data and adhere to physical constraints, such as having bounded orbital solutions. However, unbound solutions were also found. Here, we proceed to describe each scenario in detail:

In the following, we discuss each scenario and the main orbital properties obtained from the modelling. In general, we managed to identify orbital solutions that have a radial behaviour, and orbits with a more circular morphology that due to the satellite configurations produce polar-like orbital solutions perpendicular to Malin 1 LSB disc. Furthermore, we identified scenarios where the orbital solutions that are gravitationally bound (I-a, II-a, II-b, IV-a, and V-a), and unbound (I-b, III-a, III-b, IV-b, and V-b). These correspond to the following:

- Scenario I-a (Radial and Polar): eM1 + sB.

We constrain the current tangential velocity of the candidate progenitor eM1 by computing various orbits backward in

Table 5. Scenarios defining orbital configurations.

Scenario	Case	Combinations
I	a	eM1 + sB
	b	eM1 + sA + sB
II	a	M1C + sB
	b	M1C + sA + sB
III	a	M1B + sB
	b	M1B + sA + sB
IV	a	M1A + sA
	b	M1A + sA + sB
V	a	sA
	b	sB

Notes. Scenarios defining orbital configurations that connect a specific satellite galaxy as the progenitor candidate for a single or both streams (cases a and b). Scenario V assumes that the stream is the disrupted progenitor. Each scenario has been evaluated using two halo models (NFW and ISO). Abbreviations: M1 = Malin 1, sA = Stream A, sB = Stream B, eM1 = Exo-Malin 1, M1A = Malin 1A, M1B = Malin 1B, M1C = Malin 1C.

time. The stellar stream sB appears spatially connected to the central region of M1 and the offset position of eM1 (as initially noted by its position relative to labels 3 and 4 in Fig. 1). Figure 5 left panel illustrates the posterior distributions for the orbital parameters of Scenario I-a, showing the 1σ uncertainties derived from the MCMC samples. Figure 6 illustrates two representative solutions of Scenario I-a: (a) a radial orbit (using the ISO DM potential) and (b) a polar orbit (using the NFW DM potential). The uncertainty bands 1σ shown in the temporal and kinematic evolution panels (iii and vi) were derived from 300 MCMC samples. Radial Orbit: the best-fit radial orbit, integrated over $[-13.0, 20.0]$ Gyr, demonstrates

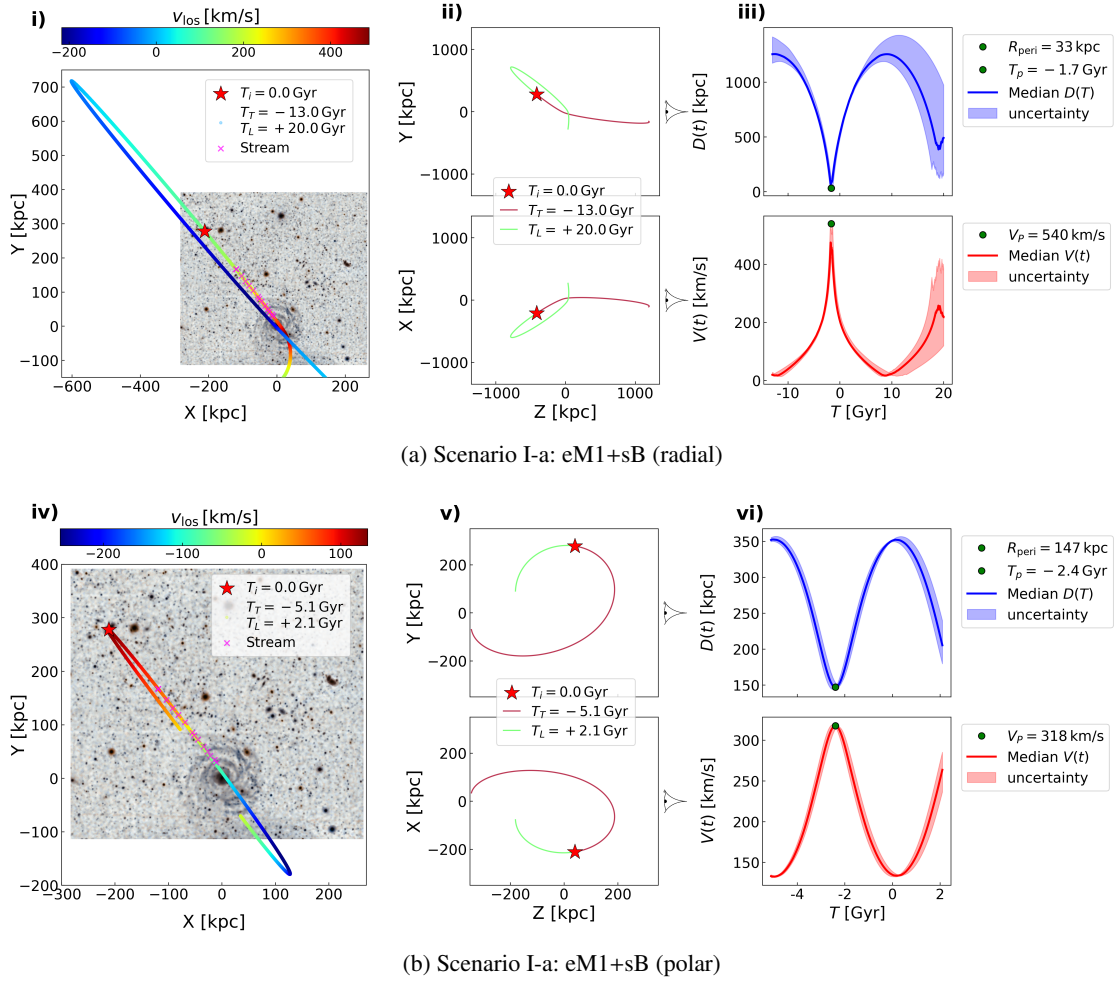


Fig. 6. Best-fit integrated orbits for the eM1+sB model, comparing the two highest-likelihood orbit classes: (a) Scenario I-a (radial) and (b) Scenario I-b (polar). The uncertainty bands in panels iii and vi were derived from the 300 MCMC samples with the highest posterior values. Spatial projections (Panels i and iv): The integrated orbit (coloured line) is overlaid on the optical image of Malin 1 and its environment (Galaz et al. 2015). The orbit is colour-coded by the line-of-sight velocity (v_{los}). The red star marks the progenitor (eM1) at $T_i = 0.0$ Gyr (present), and the magenta cross denotes stellar stream markers (sB). The T_T (Trailing) and T_L (Leading) stream times are marked with dots along the orbit. Orbital projections (Panels ii and v): The Z-Y and Z-X orbital planes are shown for the orbits. The origin $X, Y = (0, 0)$ kpc is the Malin 1 centre. The observer is conceptually located to the right (positive Z and X directions, as indicated by the eye icon). The legends indicate the Trailing (T_T) and Leading (T_L) integration times and colours used for the orbit segments. Temporal and kinematic evolution (Panels iii and vi): The top sub-panels show the orbital distance $D(t)$ (blue) and the bottom sub-panels show the velocity $V(t)$ (red) as a function of time T . The solid line is the median orbit, and the shaded regions indicate the 1σ uncertainty. The green circle marks the maximum a posteriori pericentre (distance R_{peri} and time T_p) and pericentre velocity (V_p), determined as the median of the extrema across all MCMC samples. Scenario-specific parameters: I-a (radial, ISO DM): Best orbit integrated over $[-13.0, 20.0]$ Gyr. Pericentre passage: $R_{\text{peri}} \approx 33$ kpc at $T_p \approx -1.6$ Gyr, with $|V_p| \approx 540$ km/s. Max $\Delta V_{\text{Los}} \approx 650$ km/s. $z \sim -412$ kpc, $v_t \sim 153$ km/s, PA $\sim 40^\circ$, apocentre $R_{\text{apo}} \sim 1194$ kpc and eccentricity $\epsilon \sim 0.68$. This orbit is consistent with sB being the trailing part of eM1. I-b (polar, NFW DM): Best orbit integrated over $[-5.1, 2.1]$ Gyr. Pericentre passage: $R_{\text{peri}} \approx 147$ kpc at $T_p \approx -2.4$ Gyr, with $|V_p| \approx 318$ km/s. Max $\Delta V_{\text{Los}} \approx 350$ km/s. $z \sim -40$ kpc, $v_t \sim 33$ km/s, PA $\sim 47^\circ$, apocentre $R_{\text{apo}} \sim 354$ kpc and eccentricity $\epsilon \sim 0.09$. This orbit, which assumes an NFW DM profile, is also consistent with sB being the trailing part of eM1.

a close passage consistent with the formation of sB as the trailing tidal segment of eM1. The pericentre passage occurred at $P \approx 33$ kpc at $T_p \approx -1.6$ Gyr, with a velocity of $|V_p| \approx 548$ km/s. This orbit yields a large line-of-sight velocity variation ($\Delta V_{\text{Los}} \approx 650$ km/s), which is consistent with the velocity spread expected for a plunging orbit. This solution reveals that eM1 could be a backplash satellite with a long orbital period. N-body simulations have shown that depending on satellite and stream location along the orbit, the leading or trailing streams can be stretched or diluted along the orbit producing apparent gaps between the satellite and the stream (e.g. Smith et al. 2013). Future follow-up deeper observations and simulations will further investigate

this scenario. Polar Orbit: the best-fit polar orbit, utilising the NFW potential, links eM1 and sB via a more distant pericentre: $P \approx 147$ kpc at $T_p \approx -2.4$ Gyr, with $|V_p| \approx 318$ km/s. Despite the larger pericentre, the orbit's alignment is still consistent with sB being the trailing component of eM1. The lower $\Delta V_{\text{Los}} \approx 350$ km/s is characteristic of the shallower tidal interaction experienced in the cuspy NFW potential. Both Scenarios I-a Radial and Polar, are statistically viable solutions, with Scenario I-a Polar offering a higher posterior probability, as discussed in detail in Section 4.3.

– Scenario I-b: eM1 + sB + sA.

In our search for a radial orbit that could simultaneously fit both streams, a solution was not possible. Instead, we

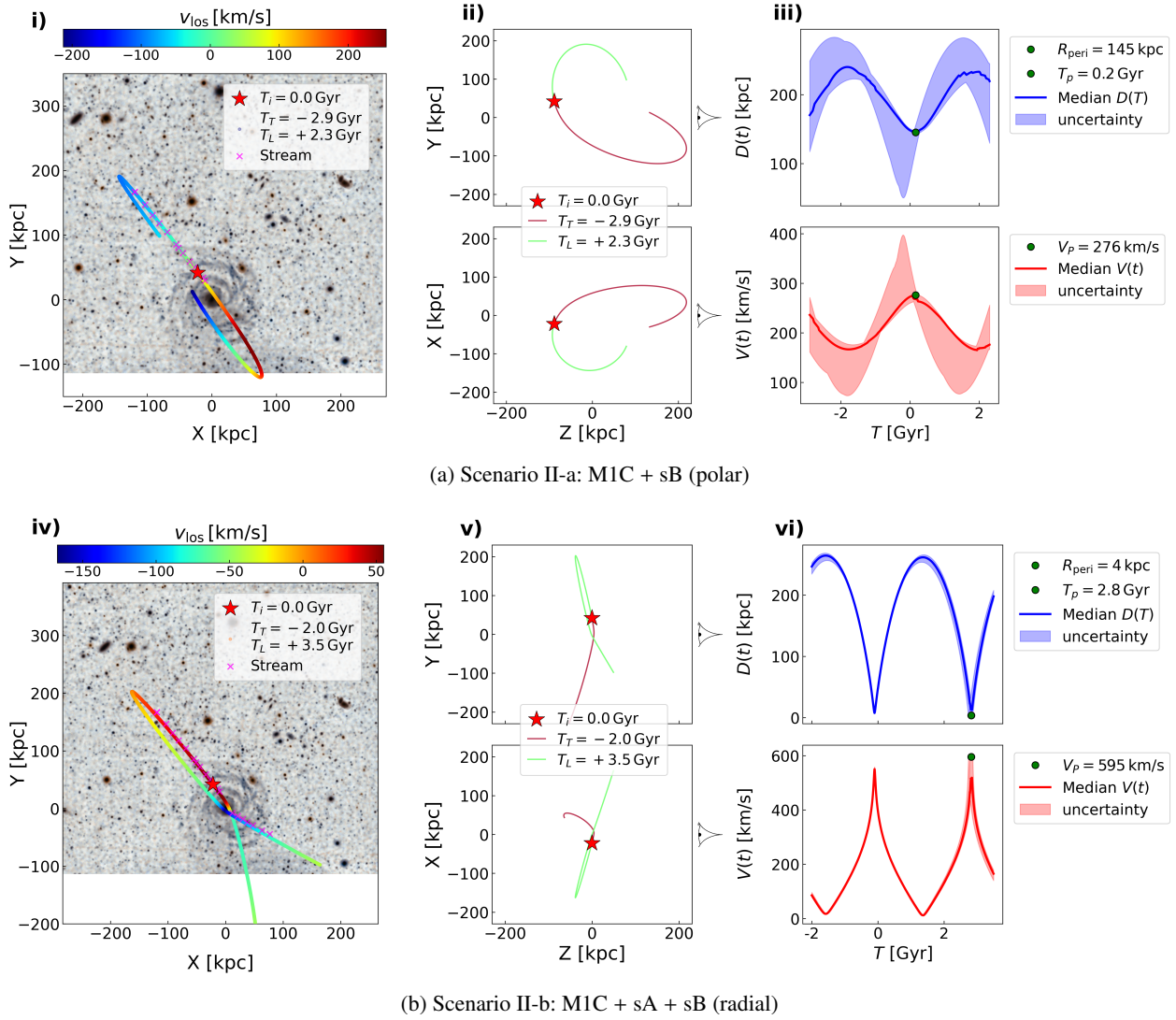


Fig. 7. Best-fit integrated orbits for the progenitor M1C and two scenarios. Panel a corresponds to Scenario II-a ($M1C + sB$) in panels i, ii, and iii. Panel b corresponds to Scenario II-b ($M1C + sA + sB$) in panels iv, v, and vi. The uncertainty bands (iii, vi) use the 300 highest-posterior MCMC samples. Panels i and iv (Spatial): integrated orbit (colour-coded by v_{los}) overlaid on Malin 1's optical image. The red star is the progenitor (M1C) at $T_i = 0$, and the magenta cross marks stream components. Panels ii and v (Orbital): $Z - Y$ and $Z - X$ orbital planes. The observer is to the right (positive Z and X). Panels iii and vi (Evolution): Top: orbital distance $D(t)$ (blue); Bottom: velocity $V(t)$ (red). The green circle marks the maximum a posteriori pericentre (R_{peri} , T_p) and velocity (V_p) from the MCMC sample extrema. Scenario-specific parameters: II-a ($M1C+sB$, radial, ISO DM): integrated over $[-2.9, 2.3]$ Gyr. $R_{\text{peri}} \approx 145.0$ kpc at $T_p \approx 0.2$ Gyr, $|V_p| \approx 276$ km/s. Apocentre $R_{\text{apo}} \sim 250$ kpc and eccentricity $\epsilon \sim 0.82$. This solution is *unbound* and dynamically disfavoured. II-b ($M1C+sA+sB$, radial, ISO DM): integrated over $[-2.0, 3.5]$ Gyr. $R_{\text{peri}} \approx 3.0$ kpc at $T_p \approx 2.8$ Gyr, $|V_p| \approx 598$ km/s. $R_{\text{apo}} \sim 1530$ kpc and eccentricity $\epsilon \sim 0.56$. The leading pericentre passage occurred 2.9 Gyr ago (first passage) and 0.33 Gyr ago (leading arm/second passage). Significantly, this is the only solution found that dynamically links two separate streams (sA and sB) via a common progenitor (M1C).

found a highly eccentric orbit that apparently is unbound from Malin 1. The pericentric passage is elevated, occurring at 694 kpc with a velocity of 933 km/s, which happened 500 Myr ago. This high-energy orbit (shown in panel i) of Fig. D.1) suggests that the progenitor eM1 is currently escaping the gravitational potential of Malin 1.

– Scenario II-a: M1C + sB.

This scenario explores M1C as the progenitor of sB, suggesting that sB contains stellar remnants and potentially undetected gas once linked to M1C. The probable orbit, shown in panel a Fig. 7 and integrated over $[-2.9, 2.3]$ Gyr, experienced its pericentre passage approximately 0.2 Gyr ago. Key Finding: the orbit is bound (as seen in the distance-time plot) and polar to Malin 1. It exhibits a moderate

dynamic interaction, with line-of-sight velocities reaching $\Delta V_{\text{los}} \approx 400$ km/s. This bound outcome is in agreement with the successful bound solution found in Scenario II-b.

– Scenario II-b: M1C + sA + sB.

This setup explores a crucial dynamical link: the possibility that both stellar streams, sA and sB, may be composed of stellar remnants originating from a single progenitor, the companion M1C. This model assumes a highly tidally disruptive system where the leading and trailing arms of the progenitor connects both streams, as suggested by previous numerical studies of satellite galaxy tidal evolution (e.g. Niederste-Ostholt et al. 2012). Figure 7 shows the best-fit radial orbit solution, integrated over $[-2.0, 3.5]$ Gyr using the preferred ISO DM potential. Key Findings: this is the

only solution found that successfully links two separate streams (sA and sB) via a common progenitor (M1C). The orbit is highly radial and plunges deep into the Malin 1 potential well. The model predicts an extremely close pericentre passage at $P \approx 3$ kpc, occurring 2.8 Gyr in the leading component (T_L). The current position of M1C places it on this highly energetic orbit, with a predicted pericentre velocity of $V_p \approx 598$ km/s. The temporal evolution (Fig. 7, panel iii) indicates that the stream sA is linked to an earlier passage of M1C approximately 0.33 Gyr ago, while stream sB is associated with the subsequent passage. This scenario requires significant tidal stripping due to the very small pericentre radius.

– Scenario III-a: M1B + sB.

We investigate the possibility that M1B is the progenitor of the stellar stream sB. The best-fit orbit, shown in Panel iv), Fig. D.1, suggests a highly eccentric association ($\epsilon \sim 0.88$) with a pericentre of $P \sim 7$ kpc and a velocity of $|V| \sim 707$ km/s occurring ~ 0.01 Gyr ago. Key Finding: this close, high-velocity encounter is dynamically possible but results in an *unbound* orbit, making it dynamically disfavoured as the progenitor.

– Scenario III-b: M1B + sB + sA.

This situation seeks M1B as the progenitor of both sB and sA simultaneously. Key Finding: it was not possible to find a single fitting orbit to connect both streams, and the best solution found was an apparently unbound orbit, which is shown in panel ii) of Fig. D.1. The pericentre passage occurred relatively recently, 20 Myr ago, at 32 kpc with a very high velocity of ~ 705 km/s.

– Scenarios IV-a: M1A + sA and V-a: sA.

We explore two distinct possibilities for the origin of stellar stream sA: first, that its progenitor, M1A, is still a visible component (Scenario IV-a), and second, that the progenitor was completely tidally disrupted, leaving only sA as a remnant (Scenario V-a) (Deason et al. 2023; Panithanpaisal et al. 2021). Figure 8 illustrates the best-fit orbits for both cases. Scenario IV-a: M1A as Progenitor (Fig. 8, up panels). The best-fit orbit, integrated over $[-1.4, 1.7]$ Gyr and characterised by low eccentricity ($\epsilon \sim 0.08$), successfully connects M1A with the observed leading and trailing segments of sA. Key Finding: this represents a tight polar solution for the M1A progenitor, with the first passage occurring 1.4 Gyr ago at a pericentre of approximately $P \sim 15$ kpc, resulting in a maximum line-of-sight velocity variation of $\Delta V_{los} \approx 400$ km/s along the orbit. This scenario establishes a kinematic link between M1A and sA. Scenario V-a: Disrupted Progenitor (Fig. 8, bottom panels). This hypothesis models sA as the remnant of a completely destroyed progenitor. The best-fit orbit, integrated over $[-1.3, 0.7]$ Gyr, requires the progenitor to have undergone an extremely close pericentre passage, occurring 1.2 Gyr ago at $P \sim 3$ kpc with a high velocity of $|V_p| \approx 493$ km/s. Key Finding: the extremely small pericentre strongly supports the possibility of complete tidal disruption. Intriguingly, the proximity of the solutions (similar time frames and dynamics) suggests that the orbital characteristics of sA are strongly constrained by the streams regardless of the progenitor's current status (intact M1A versus destroyed progenitor).

– Scenario IV-b: M1A + sA + sB.

This situation posits M1A as the single progenitor for both stream sB and stream sA. Key Finding: it was not possible to find a single fitting orbit to connect both streams simultaneously. Moreover, the best solution found was an apparently

Table 6. Best-fit posterior probabilities (p) for all modelled scenarios.

Scenario	Orbit	B/U	DM Model	$\log(p)$	p
I-a	Polar	B	ISO	-0.0934	0.911
IV-a	Polar	B	ISO	-0.1057	0.900
V-a	Radial	B	NFW	-0.1056	0.900
V-b	Radial	U	ISO	-0.1166	0.888
V-a	Radial	B	ISO	-0.1216	0.886
I-a	Radial	B	ISO	-0.1226	0.885
III-a	Radial	U	NFW	-0.1319	0.877
IV-a	Polar	B	NFW	-0.1528	0.858
III-a	Radial	U	ISO	-0.1564	0.855
I-a	Polar	B	NFW	-0.1769	0.838
II-a	Polar	B	ISO	-0.2471	0.781
I-a	Radial	B	NFW	-0.2895	0.749
II-b	Radial	B	ISO	-3.0291	0.048
II-b	Radial	B	NFW	-4.4240	0.012

Notes. The probabilities are categorized by orbital configuration and Dark Matter (DM) halo model. Solutions are sorted by decreasing posterior probability. The column B/U denotes the gravitational status of the best-fit orbit: B for Bound and U for Unbound.

unbound orbit, which is shown in panel iii), Fig. D.1. This high-energy orbit had a pericentre passage 0.1 Gyr ago at 24 kpc with a velocity of ~ 814 km/s.

– Scenario V-b: sB (Disrupted Progenitor).

We investigate the possibility that sB's progenitor has been completely destroyed by the tidal forces of Malin 1 (Deason et al. 2023; Panithanpaisal et al. 2021). The results are shown in panel v), Fig. D.1. The required passage to generate sB has a eccentric $\epsilon \sim 0.60$, occurring 33 Myr ago, with a pericentre of $P \sim 11$ kpc and a high velocity of $D \sim 916$ km/s. Key Finding: This small pericentre strongly indicates that complete tidal disruption is plausible. Intriguingly, the current position and trajectory of the modelled stream sB in this scenario point dynamically towards the position of the other progenitor candidate, eM1.

For a complete visualisation of the unbound solutions, see Appendix D.

4.3. Evaluating orbital solutions

We illustrate three representative posteriors in the main text, chosen to span both halo parametrizations (ISO and NFW) and two orbital families (polar and radial). The strongest evidence for the origin of Malin 1 streams comes from models dominated by the ISO (cored) DM halo, which features slightly more frequently among the top-ranked posterior probabilities (Table 6). To illustrate the spectrum of successful fits, we highlight three representative solutions.

1. Scenario I-a, polar, ISO: this case provides the statistically strongest evidence among all solutions ($\log p = -0.0934$, $p \approx 0.911$) and produces a clean posterior distribution with a narrow position angle (PA). Key Finding: This demonstrates the high viability of polar orbits when modelling the interaction of eM1 and sB within a cored halo potential.
2. Scenario IV-a, polar, ISO: with $\log p = -0.1057$ ($p \approx 0.900$), this solution is slightly less statistically favoured but achieves a more radial plunge. Key Findings: in a cored halo, this radial increase offsets the weaker inner density slope, yet

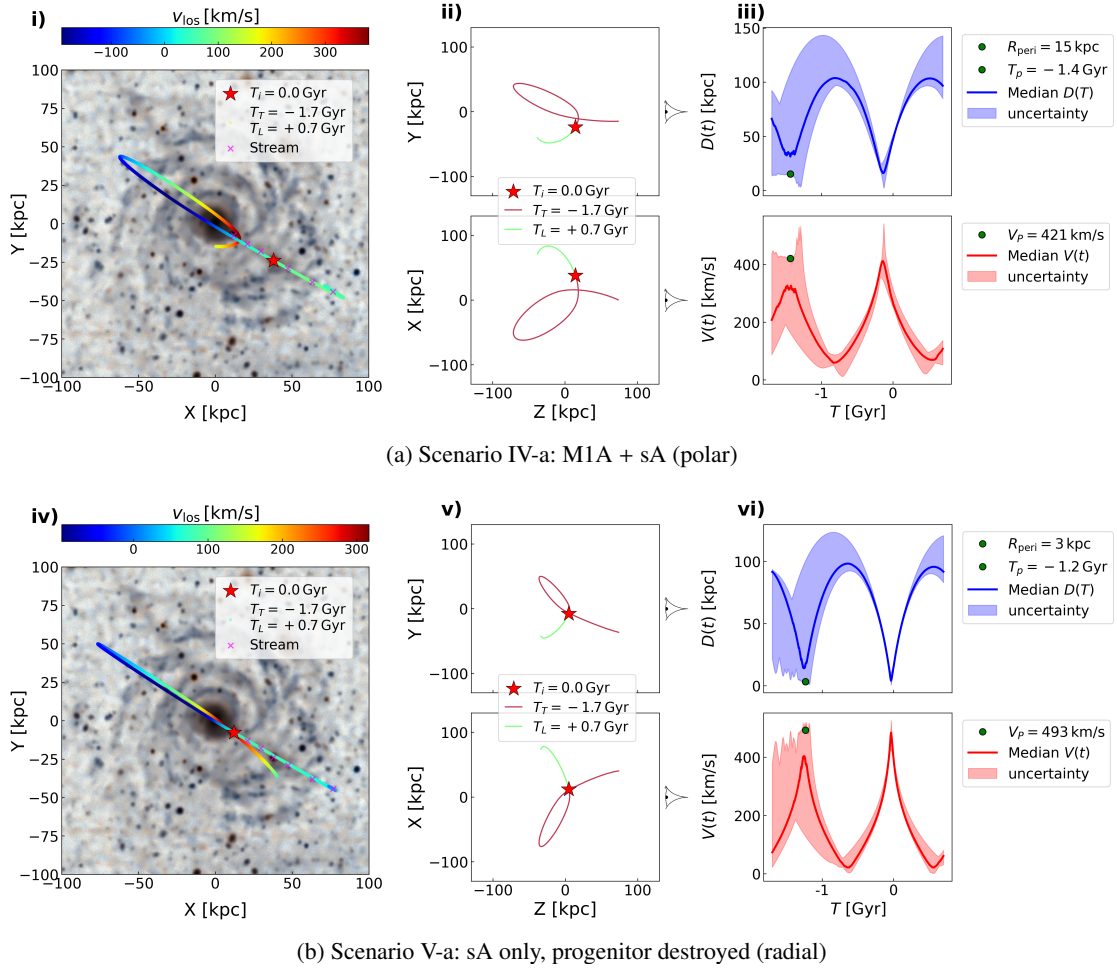


Fig. 8. Best-fit integrated orbits for the stream sA, comparing the two most likely scenarios: (a) Scenario IV-a (M1A progenitor, ISO DM) and (b) Scenario V-a (sA progenitor destroyed, NFW DM). The 1σ uncertainty bands in panels (iii) and (vi) were derived from 300 MCMC samples. Spatial projections (Panels i and iv): Optical image of Malin 1 with the integrated orbit (coloured line) overlaid. The orbit is colour-coded by the line-of-sight velocity (v_{los}). The red star marks the progenitor (M1A/sA) at $T_i = 0.0$ Gyr (present), and the magenta cross denotes the stellar stream (sA). The T_T (Trailing) and T_L (Leading) stream times are marked with dots. Orbital projections (Panels ii and v): $Z - Y$ and $Z - X$ orbital planes. The origin $X, Y = (0, 0)$ kpc is the Malin 1 centre. The observer is conceptually located to the right (positive Z and X directions, as indicated by the eye icon). The legends indicate the Trailing (T_T) and Leading (T_L) integration times and the colours used for the orbit segments. Temporal and kinematic evolution (Panels iii and vi): orbital distance $D(t)$ (in blue; top sub-panels) and velocity $V(t)$ (in red; bottom sub-panels) as a function of time T . The solid line is the median orbit, and the shaded regions indicate the 1σ uncertainty. The green circle marks the maximum a posteriori defined pericentre (distance R_{peri} and time T_p) and pericentre velocity (V_p), determined as the median of the extrema across all MCMC samples. Scenario-specific parameters: IV-a (M1A+sA, polar, ISO DM): Best orbit integrated over $[-1.7, 0.7]$ Gyr. Pericentre passage: $R_{\text{peri}} \approx 15$ kpc at $T_p \approx -1.4$ Gyr, with $|V_p| \approx 421$ km/s. Max $\Delta V_{\text{LoS}} \approx 400$ km/s. This represents a tight polar solution for the M1A progenitor. V-a (sA only, radial, NFW DM): best orbit integrated over $[-1.7, 0.7]$ Gyr. Pericentre passage: $R_{\text{peri}} \approx 3$ kpc at $T_p \approx -1.2$ Gyr, with $|V_p| \approx 493$ km/s. Max $\Delta V_{\text{LoS}} \approx 400$ km/s. This model shows a very close radial passage that leads to the complete destruction of the progenitor (sA). The proximity of the solutions (same time frame, similar velocities and geometry) suggests that the orbital characteristics of sA are strongly constrained by the streams regardless of the progenitor's current status (M1A intact versus sA destroyed).

still yields enough tidal stripping at pericentre to generate Stream A (sA).

3. Scenario V-a, radial, NFW: our baseline disruption solution, statistically related to Scenario IV-a ($\log p = -0.1056$, $p \approx 0.900$), has a small pericentre ($R_p \approx 9$ kpc) and $V_p \approx 437$ km s $^{-1}$. Key Finding: in a cuspy (NFW) halo, such close high-velocity conditions strongly favour the necessary tidal stripping to explain the complete disruption of the progenitor and are highly consistent with the observed Stream A (sA).

We conducted a thorough orbital analysis that spans a wide 40 model combination, covering the full spectrum of physically plausible configurations for DM halos (cusp versus core) and orbital geometries (polar versus radial). Although Table 6 catalogues only the best-fit posterior probabilities (p) discovered

during our search, the solutions presented encompass the most representative and dynamically relevant scenarios. We focus on this subset of solutions, as they successfully reproduce the observed stream track and line-of-sight velocity gradient, including complex cases where a single progenitor is fitted to multiple data sets. This is the Scenario II-b case, in which we used two different sets of data that could be the cause of a small posterior probability (see Table 6).

Using both NFW and ISO DM models, we found that bound orbital solutions were more likely under the ISO profile. This is supported by our maximum likelihood analysis, where the ISO model yielded systematically higher log-likelihood values in both the radial and polar scenarios, see Table 6. This outcome likely arises because the ISO profile predicts a more extended

mass distribution at large radii (Fig. 2, bottom panel), which better accommodates the gravitational constraints required by the satellite orbits. These findings are consistent with the results of Lelli et al. (2010), who also uses ISO profiles to fit rotation curves, despite the general similarities with NFW-based models.

In Bayesian terms, the values $\log(p)$ reported in Table 6 represent the logarithm of the posterior probability, combining the likelihood of the model with the prior distributions. Since we maintained consistent prior choices across both the ISO (cored) and NFW (cusped) DM halo models, the systematic trend towards higher $\log(p)$ values for the ISO halo solutions reflects a quantitatively better fit to the available kinematic and spatial data. This evidence strongly suggests that a cored DM profile is more compatible with the observed orbital solutions of the Malin 1 streams.

It is important to note that the posterior probabilities in Table 6 depend on the specific data sets used to constrain the models. For example, scenarios in which the progenitor must simultaneously satisfy the constraints of two distinct data sets, such as Scenario II-b ($M1C + sA + sB$), incur a significant penalty in their marginalised likelihood, which is reflected in a lower overall $\log(p)$. Despite this statistical demerit, such solutions are of high physical significance, as they demonstrate the orbital ability of a single progenitor to reproduce multiple stellar features.

5. Discussion

5.1. Satellite galaxies and stellar streams

Studies have shown a possible connection between the tidal formation and evolution of compact elliptical satellites and their host spiral galaxy, such as M32 and the Andromeda galaxy stream (Ibata et al. 2004; Fardal et al. 2006). This supports the hypothesis that the compact elliptical satellites M1A, M1B, and possibly M1C, could also be identified as progenitors of streams A and B as they are tidally processed. Similar findings have been reported for other galaxies, for instance the giant galactic tail *Kite*, which extends over more than 350 kpc (Zaritsky et al. 2023), and the previously mentioned ~ 500 kpc giant stream in the Coma cluster (Román et al. 2023). Both features support the presence of such large-scale streams.

In our study, we identify, among others, a possible orbital solution that connects almost linearly in projection the stream sB with eM1 and Malin 1. Moreover, the central region of eM1 appears off-centre (Fig. 1 - point 4), with an ongoing star formation, which would be naturally explained if it had a fly-by through Malin 1. Such phenomena are often observed in galaxies that undergo gravitational interactions, resulting in an off-centre core or a lopsided disc (Mao et al. 2021). Moreover, we are able to identify radial and polar orbital configurations for eM1. The radial configuration (panel i, Fig. 6) had a ~ 33 kpc pericentre passage ~ 1.6 Gyr ago, being now moving away from Malin 1. More interestingly, the apocentre of this orbit happened 13 Gyr ago, implying that this satellite could be on its first infall. We also estimated that the Jacobi tidal radius of eM1 at the pericentre was between ~ 9 – 12 kpc depending on the stellar and DM range. This would again naturally explain the observed internal disturbed morphology. Conversely, the polar configuration reaches a more distant pericentre of 150 kpc, resulting in larger tidal range radii (~ 30 – 70 kpc) and suggesting only mild tidal stripping. Furthermore, while polar configurations have been observed in systems such as the Sombrero galaxy (Martínez-Delgado et al. 2021), the radial interaction is physically analogous to the dramatic tidal

stripping seen in the M31-M32 system (Fardal et al. 2006). Consequently, the radial orbit represents a more efficient mechanism for fueling the observed stellar streams and establishing eM1 as the primary progenitor of the sB stellar component.

We also identify another polar-like orbital solution perpendicular to Malin 1 disc, where M1A could be connected to sA (scenario IV-a, panel a) in Fig. 8). In this arrangement, the orbital solution is also radial having an apocentre of ~ 100 kpc and a pericentre of 16.1 ± 1.2 kpc that could have impacted Malin 1 discs, providing a possible trigger mechanism for the active star formation observed in Malin 1 (Lelli et al. 2010; Junais et al. 2024; Junais et al. 2025), and in the central region (Johnston et al. 2024; Kataria & Saha 2025). We note that here we assumed that sA extends along its orbit. Another possibility is that sA could be a tidal arm structure stretching from M1A and aligned towards Malin 1 centre following the Lagrange points. Given that our simplistic orbital analysis cannot reproduce these tidal structures, we leave this for a follow-up N-body study. Furthermore, our attempts to connect the satellite M1B with the streams sA and sB (Scenarios III-a/-b) resulted in unbound solutions due to the satellite's LoS velocity and position near Malin 1 centre, which forces it to have large tangential velocities to reach the streams orbital paths.

The satellite M1C appears to be a $H\alpha$ blob (Junais et al. 2024,¹). In Ji et al. (2021) they propose that blobs in general could be tidal remnants or even progenitors of UDGs, which could be supported by M1C's observed high $H\alpha$ velocity dispersion ($\sim 90 \text{ km s}^{-1}$). We found orbits that could connect M1C to the streams, including an interesting case that connects both streams simultaneously (panel a of Fig. 7). This solution offers a compelling solution already seen in other galactic systems, and would imply that the complete stream (panel b of Fig. 7) could be even longer, extending 500 kpc long at least.

We explored orbital scenarios where we assume that the stellar streams are the disrupted progenitors themselves, as seen in other systems (Deason et al. 2023; Panithanpaisal et al. 2021). In scenarios V-a and V-b we identify possible radial orbital solutions for the streams sA and sB, which could imply recent tidal disruptions. However, solution V-b produces an unbound orbit. We note that in the solution V-a the stream sA appears disconnected from sB, suggesting that it is an independent event. Moreover, the spatial proximity of M1A, sA and M1B also suggests a complex interaction between Malin 1 and this sub-group of satellites.

Finally, we also identified unbound orbital solutions. For example, we attempted to connect eM1 with both stellar streams simultaneously, finding only unbound solutions, as shown by the best-fit trajectories for this configuration (Fig. D.1, panel i). Similar unbound trajectories arise across multiple configurations, including (M1B, sA, sB), (M1A, sA, sB), (M1B, sB), and the sB-only case, as illustrated in panels ii) through v) of Fig. D.1. These unbound solutions could suggest that the mass distribution of Malin 1 is inconsistent with the kinematic states of the satellites, implying that Malin 1 could be more massive than we can estimate by the rotation curve alone. Consequently, given that Λ CDM galaxy formation models show that galaxies are unlikely to have such orbits (e.g. Knebe et al. 2011), we exclude these specific orbital configurations as viable evolutionary paths, implying that the observed stellar streams are likely the result of more constrained, bound accretion events rather than fast unbound encounters.

¹ private communication.

5.2. Satellite interactions and Malin 1 gLSB evolution

Recent high-resolution observational studies of Malin 1 have revealed a complex dynamics and star formation history (Galaz et al. 2015, 2022, 2024; Johnston et al. 2024; Junais et al. 2025; Kataria & Saha 2025), suggesting an active past involving mergers or accretion. Studies have shown in general that examining the formation of tidal streams could provide insight into the timing of major merger events in the main host galaxy (e.g. Martínez-Delgado et al. 2023). Galaz et al. (2024) reported evidence of ongoing star formation in regions of extremely low molecular gas density, while Johnston et al. (2024) identified a possible double nucleus, pointing towards a recent disturbance or merger. This central activity is further supported by the H α emission studies by Junais et al. (2024) and by the presence of high non-circular motions (Kataria & Saha 2025). Within this framework, our semi-analytical orbital analysis explores a wide set of configurations involving Malin 1, the two stream candidates sA and sB, and at least four satellite galaxies – M1A, M1B, M1C, and eM1 – and consistently recovers kinematic signatures that corroborate these high velocity encounters.

These non-circular motions are often attributed to recent events such as stellar feedback and satellite accretion (Saburova et al. 2021). Our derived orbital velocities (e.g., $V_{tg} = 100\text{--}700$ km/s for many scenarios, see Table B.1) are high enough to naturally explain the observed non-circular motions in the inner H α and [OII] components discussed by Kataria & Saha (2025), suggesting that the system's current high-velocity dispersion could be a direct consequence of these high-speed encounters considered in our models.

The observed state of Malin 1 likely reflects a multi-stage assembly process consistent with recent cosmological simulations. For example, Zhu et al. (2018) found a Malin 1 simulated analogue that formed of large diffuse galactic disc driven by the stimulated hot halo gas accretion and the accretion of a pair of intruding gas-rich galaxies in a coherent plane, as found in other simulated gLSBs (Zhu et al. 2023). Our orbital analysis offers a compelling candidate for this process: the temporal coincidence of the eM1 radial passage (approximately -1.6 Gyr) and the M1A encounter (approximately -1.4 Gyr) suggests that these satellites may have acted as intruding galaxies as found in Zhu et al. (2018). This sequential interaction likely catalyzed the dynamical disturbance and subsequent gas inflow necessary to form the observed stellar streams and support the expansive growth of the disc. Consequently, we propose that the morphological state of Malin 1 is the observational legacy of this merger-driven accretion event, which occurred between approximately 1.4 and 1.6 Gyr ago.

The morphological inspection of Malin 1 LSB disc reveals a rich complexity, where we can specifically identify an optical cavity (Fig. 1, Point 7). Additionally, HI observations reveal a warp in the extended gaseous disc, as well as a substructure near the cavity (Pickering et al. 1997; Lelli et al. 2010). Simulations reveal that these types of features can be produced by gravitational interactions with satellite galaxies (e.g. Block et al. 2006; Gordon et al. 2006; Kalberla & Kerp 2009; Kim et al. 2014). Our orbital models indicate that these features are kinematically consistent with recent high-velocity encounters. Our orbital models for M1C reveal two distinct dynamical pathways that explain these structures: a polar configuration (Scenario II-a) with a large pericentre (~ 145 kpc), which aligns with empirical warp models (Binney 2024), and a radial disc-crossing configuration (Scenario II-b) with a tight pericentre (~ 3 kpc) approximately 0.2 Gyr ago. This recent radial passage

provides the gravitational tide strength necessary to drive the formation of the observed stellar streams (sA and sB) and the central disc cavity, positioning M1C as a primary progenitor for these features. Furthermore, the radial encounter of eM1, which occurred ~ 1.6 Gyr ago with a pericentre of ~ 33 kpc, provides a compelling explanation for the larger-scale HI warp and the current kinematic state of the outer disc. Given that the rotation periods in the outer disc are very slow, the cavity at $R \sim 50$ kpc is around $T_\theta = 2\pi R/v_c \sim 1.6$ Gyr. Therefore, the cavity could have already rotated around Malin 1 since the eM1 passage. However, independent of the impactor, we identify the cavity as a potential observational fossil substructure produced in an impulsive gravitational encounter.

6. Conclusions and future work

In this study, we have performed a comprehensive analysis of the stellar streams and satellite surrounding the gLSBG Malin 1. For this we combined deep *R*-band photometry with HI and H α kinematics to determine the gravitational potential of Malin 1 to model the orbital dynamics of its satellites and search for orbital solutions that can connect them with the observed stellar streams sA and sB (Galaz et al. 2015). Our key findings are summarised as follows:

- Massive DM halo: we confirm that Malin 1 is hosted by a massive DM halo (Section 4.1). The MCMC modelling of the rotation curve yielded a virial mass of $M_{\text{vir}} = 1.4^{+0.3}_{-0.2} \times 10^{12} M_\odot$ for an NFW profile and $M_{\text{vir}} = 2.6 \pm 0.4 \times 10^{12} M_\odot$ for a pseudo-Isothermal profile. The latter provides a statistically better fit to the outer rotation curve data.
- Connecting satellite orbits with streams: using our orbital models, we identified viable orbital solutions, which we call scenarios (Section 4.2) connecting the satellite galaxy candidates M1A, M1B, M1C, and eM1 to the observed stellar streams. These scenarios are as follows:
 - Malin 1 interacting with satellite M1A provides a bound orbital configuration, identifying M1A as a plausible progenitor of the stellar stream sA.
 - Interaction models involving the satellite M1B suggest that it is a candidate progenitor for the streams; however, the resulting orbits are unbound or marginally bound implying high-velocity encounters.
 - The orbital connection between the satellite M1C and stream sB can be modelled via a polar configuration. We also identified a radial orbital solution that allows streams sA and sB to simultaneously connect with M1C (Fig. 7), which would imply that the stream is more extended than currently observed.
 - We identified two types of orbits that can connect the distant eM1 satellite with sB, finding radial and polar configurations (Fig. 6). Both solutions result in long orbital periods, with the radial solution allowing stronger tidal interaction with Malin 1 and indicating that eM1 would be on its first infall.

These results indicate that while several satellites could be progenitor candidates of the observed streams and tidal debris, their specific interaction properties (e.g. pericentres, bound versus unbound) vary significantly across the system.

- Types of orbital interactions: our modelling revealed two distinct modes of satellite interaction categorised by orbital geometry and pericentric proximity:
 - Close radial encounters: these represent high-impact trajectories characterised by small pericentres. Notable

examples include the M1C-driven interaction (driving sA and sB) and the sA-only event both occurring at ~ 3 kpc as found by Johnston et al. (2024); Kataria & Saha (2025), as well as the M1A-driven interaction at ~ 15 kpc and the eM1 radial encounter at ~ 33 kpc. These close-range crossings generate the impulsive gravitational forcing necessary to trigger significant tidal stripping and drive the observed morphological evolution of the Malin 1 disc.

- Distant polar orbits: in contrast, we also identified possible polar orbital configurations, similar to the ones observed in the Sombrero galaxy (Martínez-Delgado et al. 2021). These solutions involve the satellites eM1 and M1C connected with the stream sB, and they exhibit larger pericentres of ~ 145 – 147 kpc. These solutions imply weaker interactions with the outer halo of Malin 1 rather than direct crossing events with the HSB, LSB, or both disc components.

The findings of this work provide a viable dynamical framework for understanding the role of ‘nurture’ in the evolution of gLSBGs. To further refine this history, future work will focus on the areas discussed below:

- Spectroscopic analysis: upcoming MUSE and JWST data will be utilised to determine the metallicities and star formation histories of the streams and M1C. This will help distinguish between tidal debris and *in situ* star-forming regions (e.g. H α blobs).
- Simulations: the orbital parameters derived in this study will serve as initial conditions for full N-body hydrodynamical simulations. These will investigate the long-term survival of the streams and the origin of the observed warp and cavity in the outer disc.
- Environmental survey: a broader analysis of the 1 Mpc environment around Malin 1 will clarify the impact of the local cosmic web on the galaxy’s continued growth and satellite accretion history (Bustos-Espinoza et al., in prep.).

These dynamical interactions likewise offer a solid basis for interpreting the recent star formation history of Malin 1. The impulsive gravitational encounters found in our models – especially those characterised by small-pericentre radial passages – are highly effective at driving gas inflows and concentrated star formation, in agreement with recent observational work (Galaz et al. 2022, 2024; Johnston et al. 2024; Kataria & Saha 2025). This implies that the observed central activity and irregular star-forming patches are not random but that they instead arise directly from satellite-driven gas compression and tidal perturbations.

Our dynamical modeling successfully constrains the diverse orbital configurations capable of producing the observed stellar features. Ultimately, this study shows that the environment of Malin 1 is complex, and it could be the result of multiple satellite tidal interactions, providing a key benchmark for the role of hierarchical assembly in the evolution of gLSBGs.

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Appendix A: Stream points

Table A.1 presents the stream points used as prior information for the Monte Carlo Markov chain MCMC-EMCEE method (Foreman-Mackey et al. 2013), identified visually from Fig. 1 (Galaz et al. 2015).

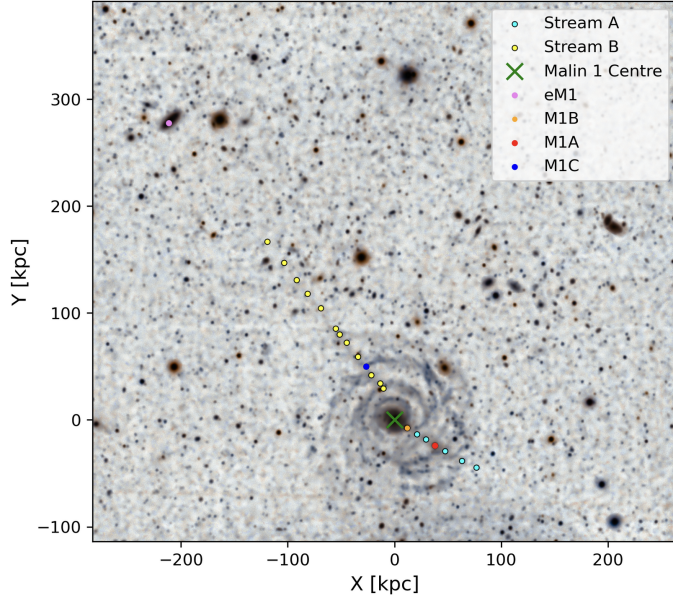


Fig. A.1: Stream points sA (cyan points) and sB (yellow points), and four satellites, M1A (red), M1B (orange), M1C (blue), and eM1 (violet). The centre of Malin 1 is marked with a green cross. Data values are shown in Table A.1.

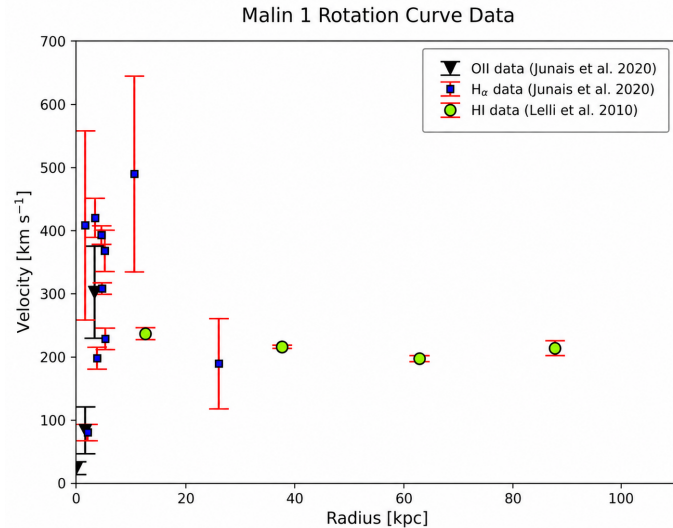


Fig. A.2: Observed Malin 1 rotation curve including H I, OII, and H α data.

Appendix B: Parameter priors and ranges

Table B.1 defines each orbital parameter: line-of-sight coordinate z , tangential velocity V_{tg} , position angle PA, pericentre, apocentre, eccentricity e , and posterior log-probability. The astrophysical motivation for the parameter ranges is also explained.

Appendix C: MCMC parameter fits

C.1. NFW halo

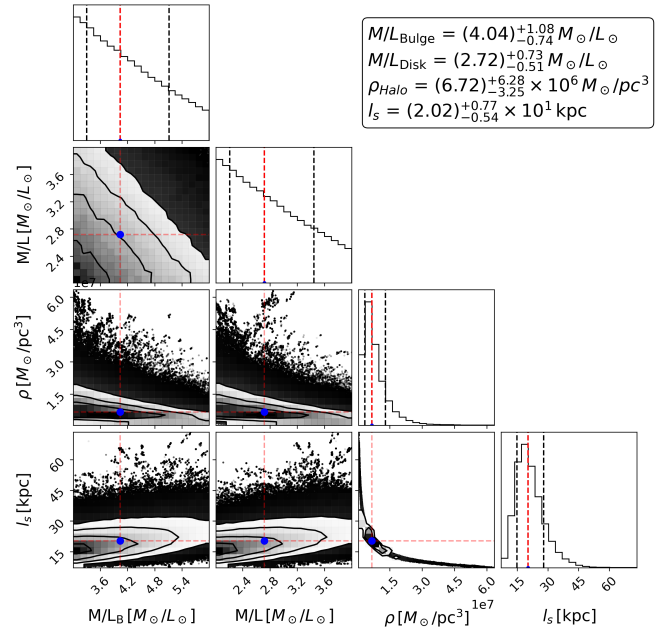


Fig. C.1: Posterior distributions of the mass-to-light ratios for the bulge and HSB disc, together with the NFW DM halo parameters (central density ρ_{Halo} and scale length l_s). Histograms (diagonal) show marginalised distributions with the 16th, 50th, and 84th percentiles. Contours display covariances. Best-fit values with 1σ uncertainties are reported in the legend. In the NFW case, maximum a posteriori (MAP) values deviate from the medians, highlighting weaker convergence compared to the ISO model in the main text.

Appendix D: Unbound scenarios

D.1. Unbound solutions

Representative unbound or disfavoured configurations are shown in Fig. D.1. These include panel i) scenario I-b: eM1+sB+sA, ii) scenario III-b: M1B+sB+sA, iii) scenario IV-b: M1A+sA+sB, iv) scenario III-a: M1B+sB, and v) scenario V-b: progenitor destroyed; these could not satisfy the binding or tidal feasibility criteria. These fail because the total orbital energy is positive ($E > 0$) or because the tidal radius at pericentre exceeds the half-light radius of the progenitor, making tidal stripping inefficient. Such cases help illustrate the explored parameter space but are excluded from the main analysis.

Table A.1: Stream points sA and sB coordinates.

Object	α (J2000)	δ (J2000)	x [kpc]	y [kpc]	r [kpc]
Malin 1	12:36:59.36	14:19:49.4	0 ± 1	0 ± 1	0
sA1: M1B	12:36:58.89	14:19:43.9	12 ± 1	-8 ± 1	14 ± 1
sA2	12:36:58.42	14:19:39.4	21 ± 1	-13 ± 1	25 ± 1
sA3	12:36:58.03	14:19:36.1	30 ± 1	-18 ± 1	35 ± 1
sA4: M1A	12:36:57.62	14:19:32.9	38 ± 1	-24 ± 1	45 ± 1
sA5	12:36:57.12	14:19:28.2	47 ± 1	-29 ± 1	56 ± 1
sA6	12:36:56.78	14:19:26.8	63 ± 1	-38 ± 1	74 ± 1
sA7	12:36:56.47	14:19:24.9	77 ± 1	-44 ± 1	89 ± 1
sB1	12:36:59.98	14:20:07.1	-11 ± 1	29 ± 1	31 ± 1
sB2	12:37:00.02	14:20:12.1	-13 ± 1	34 ± 1	37 ± 1
sB3: M1C	12:37:00.36	14:20:16.8	-22 ± 1	42 ± 1	47 ± 1
sB4	12:37:00.65	14:20:22.6	-27 ± 1	50 ± 1	57 ± 1
sB5	12:37:01.03	14:20:27.6	-34 ± 1	59 ± 1	69 ± 1
sB6	12:37:01.34	14:20:34.4	-45 ± 1	72 ± 1	85 ± 1
sB7	12:37:01.68	14:20:41.3	-52 ± 1	80 ± 1	95 ± 1
sB8	12:37:01.70	14:20:41.6	-55 ± 1	85 ± 1	102 ± 1
sB9	12:37:02.69	14:20:56.4	-69 ± 1	105 ± 1	125 ± 1
sB10	12:37:03.22	14:21:02.9	-81 ± 1	118 ± 1	144 ± 1
sB11	12:37:03.55	14:21:12.2	-92 ± 1	131 ± 1	160 ± 1
sB12	12:37:04.10	14:21:24.8	-103 ± 1	147 ± 1	180 ± 1
sB13	12:37:04.85	14:21:37.8	-119 ± 1	167 ± 1	205 ± 1
eM1	12:37:08.92	14:22:53.3	-211 ± 1	278 ± 1	349 ± 1

Notes. Observational inputs for stream sA (7 points) and sB (13 points) used in the MCMC-EMCEE analysis (Foreman-Mackey et al. 2013). Satellite positions are also included. Spatial locations of these points and companion satellites are illustrated in Fig. A.1. Spatial uncertainties are set by the projected angular scale and median seeing of $0.8''$ (Galaz et al. 2015), corresponding to ± 1 kpc. Radial distance errors are propagated.

Table B.1: Best-fitted parameter ranges and astrophysical motivation for orbital scenarios.

Scenario	z [kpc]	V_{ig} [km s $^{-1}$]	PA [deg]
I-a-Radial: eM1+sB	$-294.43^{+172.90}_{-30.12}$	$250.27^{+162.21}_{-130.54}$	$40.00^{+1.48}_{-0.30}$
I-a-Polar: eM1+sB	$1.72^{+28.85}_{-30.18}$	$112.79^{+221.07}_{-88.64}$	$41.00^{+8.25}_{-1.41}$
II-b: M1C+sA+sB	$0.10^{+2.77}_{-2.52}$	$384.82^{+7.21}_{-10.21}$	$37.00^{+0.56}_{-0.54}$
III-a: M1B+sB	$-0.32^{+9.02}_{-7.80}$	$781.48^{+77.08}_{-73.86}$	$27.00^{+4.03}_{-3.97}$
IV-a: M1A+sA	$10.85^{+13.17}_{-13.96}$	$371.88^{+89.19}_{-89.19}$	$240.00^{+2.61}_{-2.66}$
V-a: sA	$-0.15^{+6.87}_{-6.87}$	$648.41^{+171.08}_{-176.05}$	$-240.00^{+1.56}_{-1.51}$
V-b: sB	$-0.19^{+6.93}_{-6.68}$	$703.99^{+133.72}_{-138.87}$	$37.00^{+0.82}_{-0.86}$

Notes. Refer to Table 6 for the complete tabulated best-fit parameters and Table B.2 for the R_{peri} , R_{apo} , and ϵ ranges. Astrophysical motivation: I-a-Radial: Satellite projected near NE disc; PA limited to quadrant I based on stream direction; negative z assumed. I-a-Polar: Polar orbit; stream as projection of circular orbit; orientation suggests infall from below. II-b: Highly unconstrained distant satellite; wide ranges used for exploration. III-a: Orbit near disc plane on southern side; PA reflects motion direction. IV-a: Stream features suggest decaying retrograde orbit entering from behind disc. V-a: Curvature favors transverse westward orbit; both z signs allowed. V-b: Wide z range tests vertical impact; PA constrained by stream bending.

Table B.2: Best-fit orbital geometry parameters and astrophysical motivations.

Scenario	R_{peri} [kpc]	R_{apo} [kpc]	ϵ
I-a-Radial: eM1+sB	$182.05^{+238.77}_{-72.17}$	$1736.05^{+1681.03}_{-1137.98}$	$0.37^{+0.19}_{-0.10}$
I-a-Polar: eM1+sB	$159.90^{+41.98}_{-17.44}$	$416.76^{+1841.46}_{-63.05}$	$0.11^{+0.34}_{-0.02}$
II-b: M1C+sA+sB	$199.36^{+2.51}_{-2.73}$	$1434.19^{+28.70}_{-40.84}$	$0.35^{+0.01}_{-0.01}$
III-a: M1B+sB	$215.44^{+17.32}_{-13.64}$	$682.37^{+50.86}_{-40.34}$	$0.14^{+0.03}_{-0.02}$
IV-a: M1A+sA	$202.08^{+13.04}_{-12.49}$	$565.20^{+59.18}_{-60.28}$	$0.12^{+0.02}_{-0.02}$
V-a: sA	$211.30^{+7.20}_{-7.67}$	$871.29^{+286.35}_{-226.89}$	$0.21^{+0.07}_{-0.07}$
V-b: sB	$207.23^{+3.69}_{-3.60}$	$944.86^{+223.98}_{-225.36}$	$0.23^{+0.05}_{-0.07}$

Notes. Final best-fit orbital geometry parameters—pericentre (R_{peri}), apocentre (R_{apo}), and eccentricity (ϵ)—for each scenario, corresponding to ISO and NFW dark matter profiles. Astrophysical motivation: I-a-Radial: Satellite projected near NE disc; PA limited to quadrant I based on stream direction; negative z assumed. High eccentricity ($\epsilon \approx 0.37$) and large $R_{\text{apo}} \approx 1.7$ Mpc indicate a loosely bound, highly elongated orbit. I-a-Polar: Polar orbit; stream as projection of circular orbit; orientation suggests infall from below. Nearly circular ($\epsilon \approx 0.11$) with the closest $R_{\text{peri}} \approx 160$ kpc. Apocentre uncertainty is the highest. II-b: Highly unconstrained distant satellite; wide ranges used for exploration. Highly elliptical ($\epsilon \approx 0.35$) with $R_{\text{apo}} \approx 1.4$ Mpc. Low uncertainty on ϵ suggests a robustly elongated shape. III-a: Orbit near disc plane on southern side; PA reflects motion direction. Compact, nearly circular ($\epsilon \approx 0.14$) orbit with moderate $R_{\text{apo}} \approx 682$ kpc, suggesting a tightly bound satellite. IV-a: Stream features suggest decaying retrograde orbit entering from behind disc. This is the most compact orbit overall, with the smallest $R_{\text{apo}} \approx 565$ kpc and very low eccentricity ($\epsilon \approx 0.12$). V-a: Curvature favors transverse westward orbit; both z signs allowed. Moderately eccentric ($\epsilon \approx 0.21$). R_{peri} is well-constrained, but R_{apo} shows large uncertainties. V-b: Wide z range tests vertical impact; PA constrained by stream bending. Moderately eccentric ($\epsilon \approx 0.23$) orbit. R_{peri} is one of the most precisely determined values in the table.

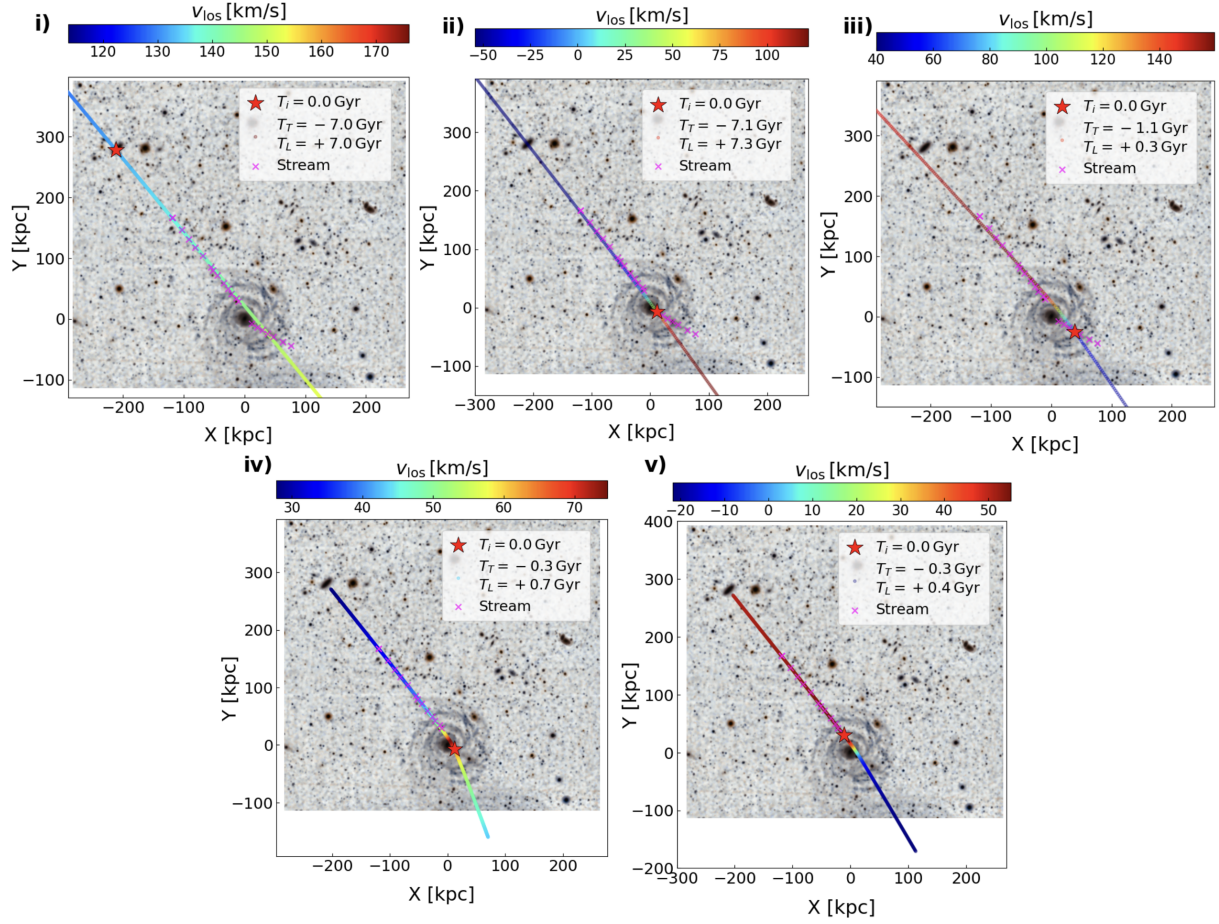


Fig. D.1: Examples of unbound or disfavoured configurations. Panel i) scenario I-b: eM1+sA+sB, ii) scenario III-b: M1B+sA+sB, iii) scenario IV-b: M1A+sA+sB, iv) scenario III-a: M1B+sB, and v) scenario V-b: progenitor destroyed; these fail to satisfy binding or tidal feasibility criteria.