- **Scientific Justification**

Section 1

The Need for New Milky Way Halo Models and the Role of the Magellanic Clouds

Astronomy has entered an era of high precision astrometry. Data from the *Hubble Space Telescope (*HST*),* the *James Webb Space Telescope (*JWST*),* and survey missions, such as *Gaia* and *LSST* have/will be used to identify substructure about the Milky Way (MW) and measure their kinematics with unprecedented accuracy. For example, the recently approved HST Large Cycle 24 program GO-14734 (PI Kallivayalil; Co-I Besla) will result in first epoch imaging to lay the foundation for proper motion measurements for *all* satellite galaxies of the MW (precision of ~0.05 mas/yr, or ~10 km/s). High accuracy, 6-D phase space information of halo tracers (satellites, globular clusters, stellar streams) over a wide range of Galactocentric distances is thus imminent. When combined with detailed models of the MW's halo potential, such measurements become high-precision tools to constrain the dark matter mass distribution about the MW and compute accurate orbital histories of satellites/streams, revealing the MW's assembly history.

Facts

There is, however, a problem with all existing MW models. HST proper motions imply that the MW has recently captured a pair of massive, high-speed satellites: the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) (Besla+2007; Kallivayalil, van der Marel, Besla+2013). These galaxies are cosmologically expected to contribute ~2 x 10^{11} M⊙ of dark matter to the MW halo (Besla+2012,2010). This is roughly ~20% of the total expected mass of the MW (Boylan-Kolchin, Besla+2011). <u>Thus, the Clouds are not small galaxies</u>. Indeed, the stellar disk of the LMC has a radius that is ~ half its current separation to the MW!! (Besla+2016; Fig. 1). As such, the Clouds cannot be treated as simple point mass tracers of the halo potential – rather, such massive satellites will *contribute* to the dark matter distribution of the MW, changing the shape of the potential in a non-symmetrical, time evolving manner. This effect has not yet been accounted for in existing models of the MW, but has the potential to perturb the kinematics of *all* tracers of the halo potential.

Problem

Synopsis

<u>We propose to create needed N-body models of the LMC+SMC+MW system with mass resolution 3 orders of magnitude higher than any created to date (10^9 particles).</u> By applying a basis expansion method, we will extract the shape, density and potential of the dark matter halo in the simulated combined MW+LMC+SMC system as a function of time and radius. These simulations will be the <u>*first of their kind*</u>, accounting for our new understanding of both the large mass and HST proper motions of the Clouds. Our solutions for the time evolving potential of the MW will be released to the community, providing necessary tools to interpret existing and upcoming astrometric data sets from HST*,* JWST and *Gaia,* and facilitate the orbital analysis of new substructure as it is discovered. This program is thus both critical and timely.

Section 2

The Magellanic Clouds will Perturb the Orbits of all Halo Tracers

Existing methods to model the motions of satellites galaxies about our MW assume that these satellites exert minimal gravitational forces on their host or on other orbiting objects. This assumption breaks down if the total mass of the satellite is a significant fraction of the host's mass – this is true of the Magellanic Clouds. These massive satellites have been shown to induce warps in the MW's galactic disk (Laporte, Gomez, Besla+2016) and change the orbital barycenter of the MW-LMC/SMC system by tens of kpc (Gomez, Besla+2015; Patel, Besla+2017a). For example, simple orbital integration schemes that include the LMC as an analytic potential, reveal that the orbital plane of the Sag. dSph satellite can tilt owing to this effect (Fig. 2, red vs. green orbit). This tilt will manifest in the properties of the Sag. Stream, the debris of stars stripped from the Sag. dSph. However, triaxial halos can produce a similar effect. Neglecting the LMC when modeling the orbits of satellites and streams will force *artificial* shifts in the gravitational potential, which can be misinterpreted as intrinsic properties of the MW's halo.

Missing in existing orbit integration schemes is the response of the MW's halo to the presence of the Clouds and the distortions to their dark matter distribution caused by the tidal field of the MW. Weinberg (1998, 2000) illustrate that wakes generated in the dark matter halo of the host by orbiting satellites can greatly augment the perturbative effects of the satellite, e.g. by amplifying bending modes in the host's disk. *Such effects cannot be captured without high-resolution N-body simulations, such as those proposed here.*

Section 3 **The Combined LMC+SMC+MW Dark Matter Halo is not Oblate, Prolate or Triaxial!!**

Preliminary low-resolution N-body simulations (40 million particles), including the LMC alone, reveal that the resulting 3D dark matter distribution of the combined system will *not be ellipsoidal (oblate, prolate or triaxial),* as conventionally assumed by *all* existing MW models (see Fig. 3). Instead, the shape of the halo changes markedly as a function of radius, in a non-symmetrical, time-evolving manner. No existing analytic halo potential can mimic this combined structure – we must develop new models.

We propose to create a suite of higher resolution simulations than those presented in Fig. 3 (10^9 vs. 10^7 particles), varying the mass of the LMC and MW halos and including the SMC. Our team has a well-established track record of modeling the Magellanic System + MW encounter (Besla+2016; 2013; 2012; 2010; 2007). Higher resolution simulations are critical to resolve the detailed structures induced in the dark matter halo of the MW, such as wakes and resonances generated by the Clouds (e.g. Weinberg 1998).

Next, we must quantify the resulting asymmetric halo structure. The shapes of dark matter halos in cosmological simulations are typically estimated by fitting ellipsoids to the dark matter particle distribution, referred to as the Inertia Tensor Method (Vera-Ciro+2011, Allgood+2006). However, as illustrated in the right panel of Fig. 3, ellipsoids are inappropriate descriptions of the complex structure caused by the motions of extended, massive satellites. Instead, we will apply a basis expansion technique known as the Self-Consistent Field (SCF) method (Hernquist & Ostriker 1992), which allows for an analytic representation of non-idealized dark matter halos. In this scheme, the potential and density of the dark matter halos are expanded in a bi-orthogonal series of spherical harmonics and radial functions. *Using this technique we will accurately quantify the time evolving shape of the dark matter potential of the combined LMC+SMC+MW system for the first time.*

Section 4 **Orbits in Asymmetric Time Evolving Potentials without N-body Simulations**

A major advantage of the SCF method is the ability to precisely represent the potential of a non-ellipsoidal distribution with a low number of terms. As such, we can recreate the full dark matter distribution from the simulation analytically and use it to integrate orbits of halo objects without having to run a full N-body simulation each time.

The ultimate goal of this proposal is thus to compute the SCF expansion at each time step of the simulations (~ every 14 Myr). Once all coefficients are computed for every simulation time step, they are interpolated to create a continuous function. This is the main data product that will be released to the community (per MW + LMC/SMC mass model). The interpolated coefficients are used to analytically reconstruct the density and potential of the combined dark matter distribution (see Fig. 4).

The typical orbital periods for halo objects are of order 1-2 Gyr, whereas the LMC reached its first pericenter about the MW only 50 Myr ago. The expected timescale of distortions to the MW's potential from the Clouds is thus on par with the dynamical times of the substructure used to probe the MW's dark matter halo. We thus anticipate that our new halo models will be of great aid in recovering orbits from observed 6D phase space information for stellar streams, globular clusters and halo stars afforded by *HST, Gaia* & *LSST* (Bovy+2016, Pearson+2015, Watkins+2010; e.g Fig. 5). In particular, with the reconstructed potentials, one can recover the expected orbital histories of halo tracers using HST proper motions, such as for: the fastest satellite (Leo I, Sohn, Besla+2013, GO-12270); satellite-group infall (Crater-Leo Group, GO-14770) satellites on retrograde orbits (Sculptor, GO-12966); the smallest satellites (Ultra-faint dwarfs, GO-14236); and disrupted satellites (Orphan and Sag. Streams, Sohn+2015,2016, GO-13443,12564). With the exceptional precision of HST proper motions these reconstructed orbits will provide the most accurate picture of the assembly history of the MW to date.

Section 5 **To what extent can we consider the MW to be a Virialized System?**

Troublingly, the recent capture of the Clouds (Fig. 3) implies that the MW halo is not virialized. This result would invalidate the use of equilibrium techniques, like Jeans Modeling, to, e.g., constrain the mass of the MW using halo tracers. However, the recent capture scenario of the Clouds affords us with a potential solution – it is possible that the influence of the Clouds has not yet dramatically affected the inner halo (< 30 kpc). We will use the outlined N-body + SCF methods to identify the Galactocentric radii and timescales over which the distortions introduced by the Clouds will affect the kinematics of stars in the halo or the orbits of halo tracers about the MW. Specifically, we will predict perturbations to the 3D velocity dispersion of globular clusters in the MW's outer and inner halo and the corresponding anisotropy parameter induced by a range of LMC/SMC models – this will be directly tested with upcoming HST proper motions (GO-14325, PI Sohn, Co-I Besla).

Extended Applications: The Combined Halo Potential of M31 and M33

The sensitivity of JWST will soon allow us to measure proper motions for more distant, fainter satellites – such as those about M31. M31 also harbors a massive satellite galaxy, M33. The proper motion of M33 is accurately measured using water masers (Brunthaler+2005). With the recent HST proper motions of M31 (Sohn+2012), our team has reconstructed the orbital history of M33, revealing that it has likely been recently captured by M31 (< 2 Gyr; Patel, Besla+2017a). As such, it is reasonable that the mass of M33 will be close to its cosmologically expected infall mass of $\sim 10^{11}$ M⊙. As in the case of the Clouds, such a massive satellite will induce significant perturbations to the kinematics of M31's satellites. This proposal will thus lay the groundwork to expand the described N-body + SCF technique to the M31-M33 system, allowing us to create the most comprehensive picture of the dynamics of the entire Local Group to date.

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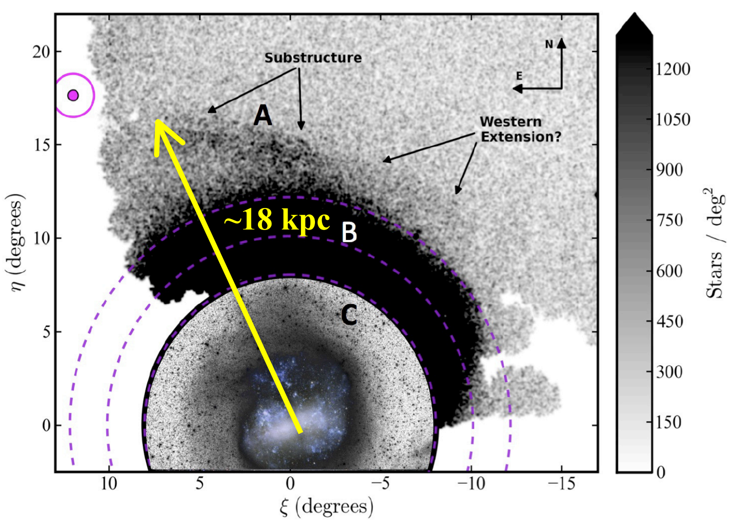

Fig. 1 The Large Magellanic Cloud: A modified version of Figure 1 from Mackey et al. (2015) showing the spatial density of old main sequence turn-off stars in the LMC. The three purple dashed circles indicate angular separations of 8, 10 and 12 degrees from the center of the LMC. At the distance of the LMC 1 degree is ~ 1 kpc, indicating that the LMC's stellar disk extends ~18 kpc in radius (almost half the 50 kpc separation to the MW). The central inset (C) is a shallower image of the LMC from Besla+2016.

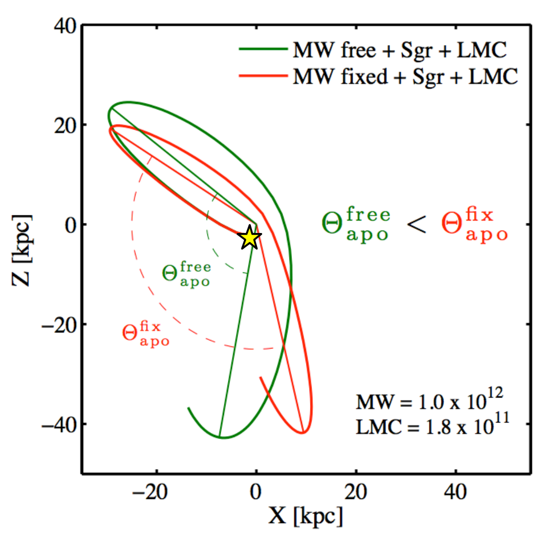

Fig. 2 The orbit of Sag. dSph (Sgr) is plotted over the past 1 Gyr (location today is marked by the star). Orbits are integrated accounting for the gravitational pull of both the MW and a massive LMC. The MW is allowed to respond to the presence of the LMC (green) or kept fixed at (0,0) (red). The angle between the apocenters (Θ_{apo}) of Sag. dSph's most recent two orbits is significantly smaller when the MW responds to the LMC (by ~17°). Its orbital plane also tilts significantly. The Sag. Stream roughly traces the past two orbits of Sag. dSph - the presence of a massive LMC will thus strongly affect the properties of the Stream. Figure adopted from Gomez, Besla+2015.

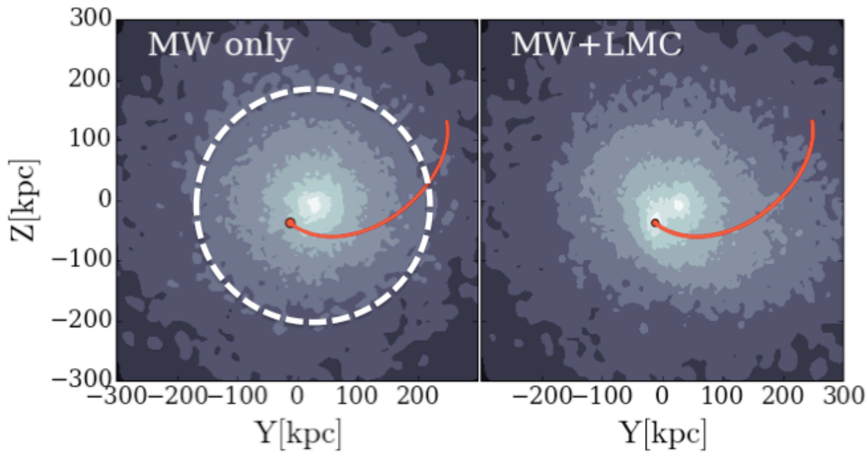

Fig. 3 The Distribution of Dark Matter about the MW: Contours of constant dark matter density from a low resolution N-body simulation of the LMC (total mass of 2.5 x 10^{11} M⊙, which is 25% of the MW mass of 10^{12} M⊙). The red line indicates the orbital trajectory of the LMC, constrained by observations. *Left*: contours using only MW dark matter particles. Contours are roughly spherical, except at >100 kpc where contours deviate from a perfect circle (dashed line). *Right:* contours are made using *both* LMC and MW particles. Contours are **not regular ellipsoids** and change in orientation with radius. To better capture these distortions much higher resolution simulations are proposed (10^9 particles).

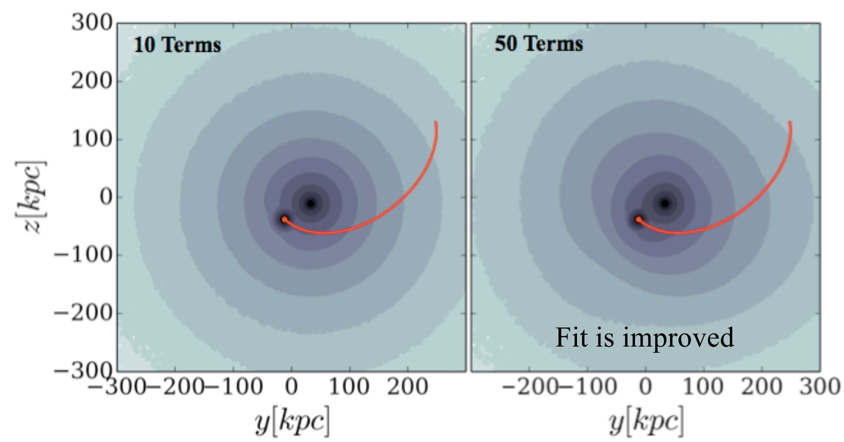

Fig. 4 Maps of the dark matter density, recovered using the SCF method, from the low resolution MW + LMC simulation (Fig. 3), using 10 (left) and 50 (right) coefficients in the MW expansion. We included a separate expansion (5 terms) for the LMC main body in both panels. As the number of terms increases, the match to the real simulation (Fig 3; right) improves.

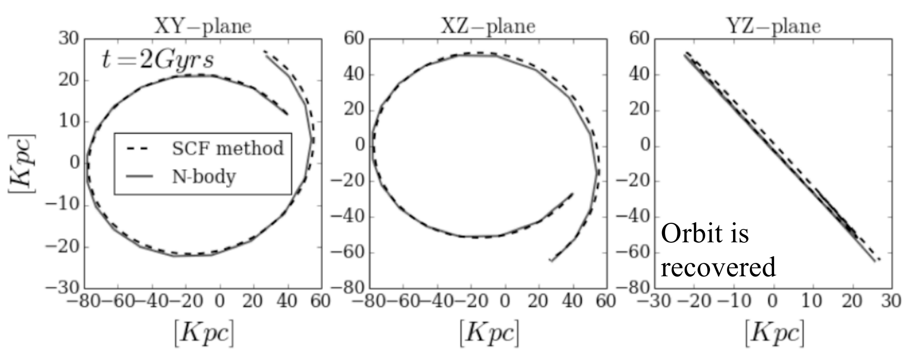

Fig. 5 Recovering Orbital Histories: *Solid line:* Orbit of a dark matter particle tracked throughout the LMC+MW simulation of Fig. 3 in three planes. *Dashed line:* the numerically integrated orbit of the particle using the potential recovered with the SCF method.