Investigating the shape of the Milky Way Dark Matter halo with hypervelocity stars in view of future astrometric missions

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Outline

Project aim: Estimating the precision needed by future astrometric missions to distinguish between different Milky Way dark matter halo shapes.

Tool: Hypervelocity stars (HVSs).

Method: Numerical simulations of HVS kinematics in dark matter halos with different shapes.

- Introduction
- The project
- Next steps
Milky Way dark matter halo

Flat rotation curves of spiral galaxies like the Milky Way (MW) (Rubin & Ford 1970):

→ deviation from the velocity profile expected from the distribution of visible matter;
→ evidence of unseen surrounding matter.

A dark matter (DM) halo can reproduce the asymptotic behavior of the rotation curves of disc galaxies (Ostriker & Peebles, 1973).
Milky Way dark matter halo

ACDM scenario: existence of DM halos surrounding the MW and the external galaxies.

- **Triaxial**: $a \neq b \neq c$
- **Prolate**: $a = b < c$
- **Sphere**: $a = b = c$
- **Oblate**: $a = b > c$
Milky Way dark matter halo

--------------- Numerical simulations ---------------

- Collisionless N-body simulations: triaxial or near-prolate halos. (e.g., Vera-Ciro et al. 2011)

- Hydro-dynamical simulations: baryonic dissipation changes the shape of DM halos.
  → round or oblate at the center, triaxial at intermediate radii, and prolate at large radii (e.g., Zemp et al. 2012).

--------------- Observations -------------

Halo stars and tidal streams as tracers of the Milky Way DM halo mass profile:

- Spherical (Ibata et al. 2001)
- Oblate (Loebman et al. 2014)
- Prolate (Helmi 2004)
- Triaxial (Law & Majewski 2010)

Hypervelocity stars

The existence of HVSs was:

- **predicted by Hills (1988)**
  1) super-massive black hole (SMBH) ejection origin;
  2) $v > v_{\text{escape}}$;
- **confirmed by Brown (2005)**

Current sample: $\sim 20$ HVSs;
- heliocentric radial velocity in the range $\sim 200 - 1000$ km/s;
- distance from the Sun in the range $\sim 10 - 100$ kpc.

(Gnedin et al., 2005; Fragione & Loeb, 2017; Contigiani et al., 2019)

$\Rightarrow$ **Statistical approach**: investigate the constraining power of a sample of HVSs on the MW DM halo shape.
Astrometric missions

Relevance of HVS high-precision proper motions to put constraints on the DM halo shape:

- **Boehm et al. 2017**: proposal for an ESA medium size mission (*Theia*).
- **Malbet et al. 2019**: white paper for the next planning cycle of the ESA Science Programme.

→ *Gaia* proper motion precision: $40 - 150 \mu\text{as/yr};$

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Proper motion

Apparent motion of a star on the plane of the sky.

\[
\mu \left[ \frac{\text{as}}{\text{yr}} \right] = \dot{\theta} = 4.74 \frac{v_{\text{tan}} [\text{km/s}]}{d [\text{pc}]}
\]

proper motion + radial velocity → star 3D velocity
A numerical code for HVSs trajectories

1) Generation of the initial distribution of ejection velocities according to the Hills mechanism;

Starting point for the orbit integration:

\[ r_{\text{influence}} = 3 \text{ pc} \]
(Genzel et al. 2010)

2) Computation of the travel time of each star;

\[ t_{\text{age}} + t_{\text{travel}} < t_{\text{ms}} \]
\[ (m_* = 4 \text{ M}_\odot \rightarrow t_{\text{ms}} = 160 \text{ Myr}) \]
3) integration of the orbit of each star through the solution of the equations of motion in a given gravitational potential, described as the superposition of the following components:

- the SMBH: \[ \Phi_{BH}(r_{GC}) = -\frac{G \, M_{BH}}{r_{GC}}, \]

- the bulge (Hernquist 1990): \[ \Phi_b(r_{GC}) = -\frac{G \, M_b}{r_{GC} + r_b}, \]

- the disk (Miyamoto & Nagai 1975):
  \[
  \Phi_d(R_{GC}, z_{GC}) = -\frac{G \, M_d}{\sqrt{R_{GC}^2 + (a_d + \sqrt{z_{GC}^2 + b_d^2})^2}},
  \]
A numerical code for HVSs trajectories

- the DM halo (Navarro et al. 1996, Vogelsberger et al. 2008):

\[
\Phi_h(\tilde{r}) = -\frac{G M_{200}}{f(C_{200})} \frac{\ln \left(1 + \frac{\tilde{r}}{r_s}\right)}{\tilde{r}}, \quad \tilde{r} = \frac{(r_a + r_{GC}) r_E}{r_a + r_E},
\]

\[
r_E = \sqrt{\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2}}, \quad f(x) = \ln \left(1 + x\right) - \frac{x}{(1 + x)}
\]

\[
a^2 + b^2 + c^2 = 3; \\
q_y = b/a; \\
q_z = c/a.
\]

AG et al. (in prep.)
Investigating the DM halo shape with HVSs

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A numerical code for HVSs trajectories

4) generation of HVS mock catalogs.

Galactocentric reference frame

<table>
<thead>
<tr>
<th>r [kpc]</th>
<th>θ [°]</th>
<th>φ [°]</th>
<th>Vrad [km/s]</th>
<th>Vtan [km/s]</th>
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Heliocentric reference frame

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<th>l [°]</th>
<th>Vd [km/s]</th>
<th>μl [mas/yr]</th>
<th>μb [mas/yr]</th>
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</table>

AG et al. (in prep.)
Investigating the DM halo shape with HVSs

Statistical analysis

AG et al., (in prep.)

- spheroidal DM halo: \( q_y = 1, q_z = [0.7 - 1.4] \);
- generation of mock catalogs for \( q_z = 0.7, 1, 1.4 \);
- two sample K-S test: spherical Vs. oblate (prolate);

\[ \text{positions & velocities, cartesian & spherical coordinates} \]
\[ \text{galactocentric & heliocentric reference frame.} \]

- **Galactocentric tangential velocity**: \( p - \text{value} < 5\% \)

\[ \Rightarrow \text{key variable to distinguish a spherical DM halo from an oblate (prolate) halo.} \]
Spherical-oblate: 
\[ p - \text{value} \sim 10^{-13} \]

Spherical-prolate: 
\[ p - \text{value} \sim 10^{-14} \]

Galactocentric tangential velocity distribution in the prolate (blue), spherical (green), and oblate (yellow) DM halo case.

**AG et al. (in prep.)**
Statistical analysis

- The **initial conditions** (i.e., the direction of the velocity and the age of the star at the ejection) are fixed.

- The **axis ratio**, $q_z$, changes in each simulation.

Randomizing the initial conditions

⇒ the smallest deviation from the spherical shape ($q_z = 1$) that can be significantly detected ($p$-value < 5%) varies from simulation to simulation.
Statistical analysis

Under the null hypothesis, the p-value is uniformly distributed over the interval [0,1].

⇒ Cumulative distribution: $f(x) = x$;

Procedure:

1) Generate a high number of mock catalogs for different $q_z$ values

⇒ 5000 mock catalogs: $q_z = 0.7, 0.8, 0.9, 1, 1.1, 1.25, 1.4$

2) Compare them with 1 mock catalog generated in a given gravitational potential

⇒ 1 mock sample generated in a spherical DM halo.
3) Obtain a p-value distribution for each shape of the DM halo:

3.1) Obtain a p-value distribution for each shape of the DM halo:

\[
\text{Cumulative distribution}
\]

\[
\text{Fraction vs. pvalue}
\]

\[
\text{Log}_{10}[\text{pvalue}]
\]

\[
q_z = 1.4, \quad q_z = 1.25, \quad q_z = 1.1, \quad q_z = 1, \quad q_z = 0.9, \quad q_z = 0.8, \quad q_z = 0.7
\]

\[
y = x
\]

\[
\text{AG et al. (in prep.)}
\]

4) The \( q_z \) for which the cumulative distribution increases linearly is the one compatible with our “observed” sample.
1) Theoretical project

a) Fully triaxial DM halo case:

⇒ $v_{\theta}^{GC}$ & $v_{\phi}^{GC}$ affected by the DM halo shape (loss of axial symmetry);

⇒ use of the 2-D K-S test.

b) Effect of the observational uncertainties on the Galactocentric tangential velocities:

⇒ quantify the **proper motion precision** that is needed to distinguish among different halo shapes.
2) **Observational project**

In collaboration with INAF-Osservatorio Astrofisico di Torino, we plan to:

a) identify new HVS candidates in the Galactic halo in the Gaia (E)DR3;

b) compare the kinematic properties of this sample with that of our mock catalogs in order to constrain the DM halo geometry.
Thanks for your attention!
Bibliography


Fragione, G. & Loeb, A., 2017, New Astronomy, 55, 3238
Bibliography II

Genzel, R. et al., 2010, *Reviews of Modern Physics*, 82, 3121
Wang, Y. et al., 2018, *MNRAS*, 475, 4595
S-stars are stars orbiting around Sgr A* with highly eccentric orbit.

⇒ How did these stars obtain their highly eccentric orbits near the central SMBH?

In their studies of 2006, Ginsburg & Loeb simulated the orbits of the companion stars of HVSs.

→ Typically kicked into a highly eccentric orbit with an eccentricity similar to that observed for the S-stars.

This suggests a possible binary origin for these stars.
Hills velocity distribution: parameter sampling

The parameter sampling is performed as follows:

- the **stellar binary semi-major axis**, \( a \), is randomly chosen according with the probability density function:

  \[
  p(a) \, da \sim \frac{da}{a},
  \]

  in the range \( 0.05 \text{ AU} \leq a \leq 4 \text{ AU} \);

- the **minimum approach distance**, \( b \), is randomly chosen in the range \([1 \text{ AU}; 700 \text{ AU}]\) according with the probability density function:

  \[
  p(b) \, db \sim b \, db;
  \]
Hills velocity distribution: parameter sampling

The probability density function of the semi-major axis is given from observations of large samples of stellar binary systems.

The range of values is motivated by:

$⇒ a < 0.05 \text{ AU}$: ejections only for very small $b$ values, that likely produce a tidal disruption event rather than a HVS;

$⇒ a > 4 \text{ AU}$: very low ejection velocities $→$ stars are very unlikely to reach the Galactic halo.
Hills velocity distribution: parameter sampling

The **probability** density function of closest approach distances, $b$, to Sgr A* is the result of the gravitational focusing.

$\Rightarrow$ the enhancement in the likelihood that two particles will collide, due to their mutual gravitational attraction.

The **range** of values is motivated by:

$\Rightarrow b < 1 \text{ AU}$: tidal disruption events;

$\Rightarrow b > 700 \text{ AU}$: no ejection, the value of 700 AU correspond to the value that gives a zero ejection probability when $a = 4 \text{ AU}$. 
Hills velocity distribution: parameter sampling

The parameter sampling is performed as follows:

- the inclination angle, $i$, between the binary revolution plane and the orbital plane of the center of mass around the SMBH, is randomly sampled in the interval $[0, 2\pi]$ with a uniform probability density function;

- the initial phase, $\phi$ of the binary is randomly sampled in the interval $[0, 2\pi]$ with a uniform probability density function;
Star ejection

The star ejection takes place when the SMBH tidally disrupts a stellar binary.

The code checks if the binary has been disrupted or not:  
⇒ if the binary total energy in the CM reference frame, $E_{bin}$, is positive, the binary has been disrupted.

$$E_{bin} = \frac{1}{4} M_\star \sum_i (\Delta v_i)^2 - \frac{GM_\star}{a},$$

where $\Delta v_i$ is the difference between the i-th velocity component of the two stars.
Star ejection

Then the code decides which star has been ejected:

\[ \Rightarrow \text{the total energy of both stars is calculated in the SMBH reference frame and the star with positive energy is the ejected one.} \]

The velocity at infinite distance from the SMBH is computed starting from total energy conservation and is:

\[ v_{ej} = \sqrt{v_\star^2 - \frac{2GM_{SMBH}}{b}}, \]

where:

\[ v_\star = \sqrt{\frac{GM_\star}{2a}}. \]
Gravitational potential

Model parameters:

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</tr>
</thead>
<tbody>
<tr>
<td>$4 \times 10^6$</td>
<td>$3.4 \times 10^{10}$</td>
<td>0.7</td>
<td>$10^{11}$</td>
<td>6.5</td>
<td>0.26</td>
<td>$8.35 \times 10^{11}$</td>
<td>18</td>
<td>10.82</td>
</tr>
</tbody>
</table>

AG et al. (in prep.)
The times

\[ N(t) = R \left( t_{ms} - t_{age} \right) \left( 1 - e^{-\frac{t}{t_{ms} - t_{age}}} \right) \Rightarrow \lim_{t \to \infty} N(t) = R \left( t_{ms} - t_{age} \right) \]

AG et al. (in prep.)
For stars with low ejection velocities \( v_{ej} \lesssim 700 \text{ km/s} \), angular velocities are tightly coupled with the radial velocity.

Figures: Left panel: \( q_y = 1, q_z = 1 \); right panel: \( q_y = 0.8, q_z = 1 \).

AG et al. (in prep.)
Sample selection

We select only the stars that at $t_{\text{obs}}$:

1) $r^{\text{GC}} \geq 10 \text{ kpc};$   
2) $v_{r}^{\text{GC}} > 0 \text{ km/s};$

AG et al. (in prep.)
Relevant timescales

**Rate of ejection:** \( R = 10^2 \frac{\text{stars}}{\text{Myr}} \) (Zhang et al. 2013).

**Ejection time:** \( t_{ej} \), uniformly chosen between 0 Myr and \( t_{\text{max}} \).

**Observation time:** \( t_{\text{obs}} \), fixed and equal for each star.

**Travel time:** \( t_{\text{travel}} = t_{\text{obs}} - t_{ej} \).

**Main-sequence lifetime:** \( t_{ms} = 160 \text{ Myr} \), for a 4 M\(_{\odot}\) star.

**Age of the star:** \( t_{\text{age}} \), uniformly sampled between 0 and \( t_{ms} \).

\[ \Rightarrow t_{\text{age}} + t_{\text{travel}} > t_{ms} \rightarrow \text{the star is rejected}; \]

\[ \Rightarrow t_{\text{age}} + t_{\text{travel}} < t_{ms} \rightarrow \text{the star trajectory is computed}. \]
Alternative mechanisms

• 3-body interactions of stars with a stellar mass black hole (SBH) orbiting a SMBH (O’Leary & Loeb 2008).

• 3-body interactions of stars with a binary SMBH can eject single stars as HVSs (Yu & Tremaine 2003);

• 4-body interactions of stellar binaries with a SMBH binary system can eject both single and binary HVSs (Wang et al. 2018).
Wang’s mechanism

A binary BH system in the center of a galaxy:

- SMBH,
- IMBH,

can eject the stars of the stellar binaries in its proximity.

Recent observational constraints on the Galactic BBH:

- $M_{\text{SMBH}} = 4 \times 10^6 M_\odot$;
- $M_{\text{IMBH}} = 10^4 M_\odot$, at $r_{GC} = 0.13$ pc. (Tsuboi et al. 2017)
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Wang’s mechanism

S. Ebagezio, L. Ostorero, AG, (in prep.)

**Aim of the project:**

testing the goodness of the Wang’s mechanism in explain HVSs current observations, given the density of stars near the Galactic center.