Measuring the shape of the outer halo of the Milky Way with astrometric techniques

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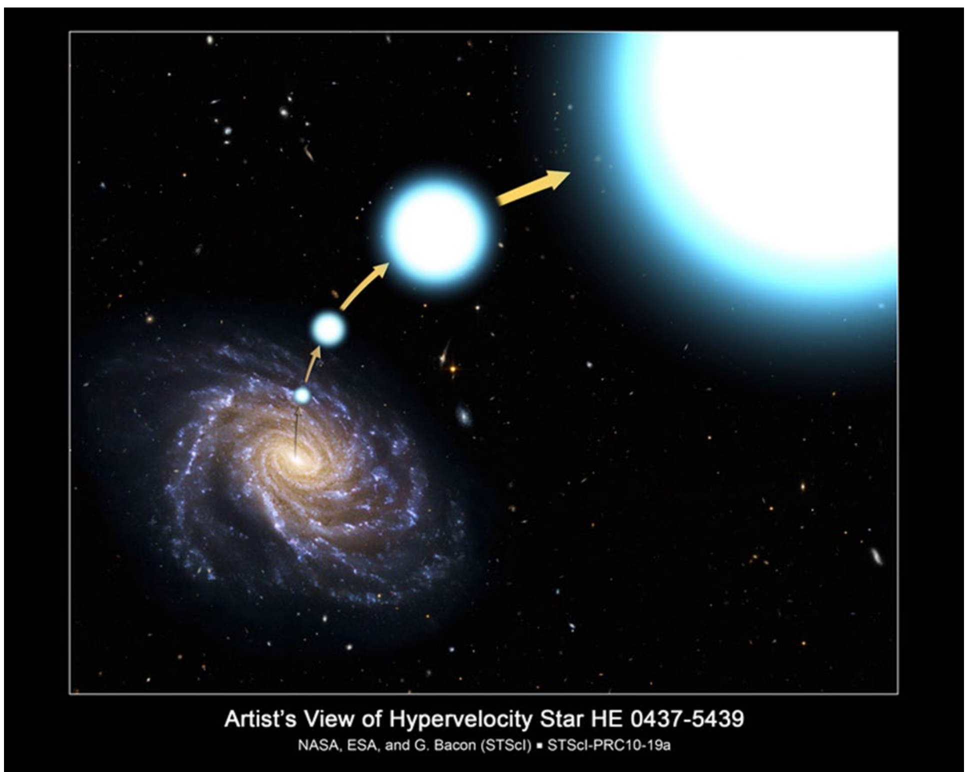
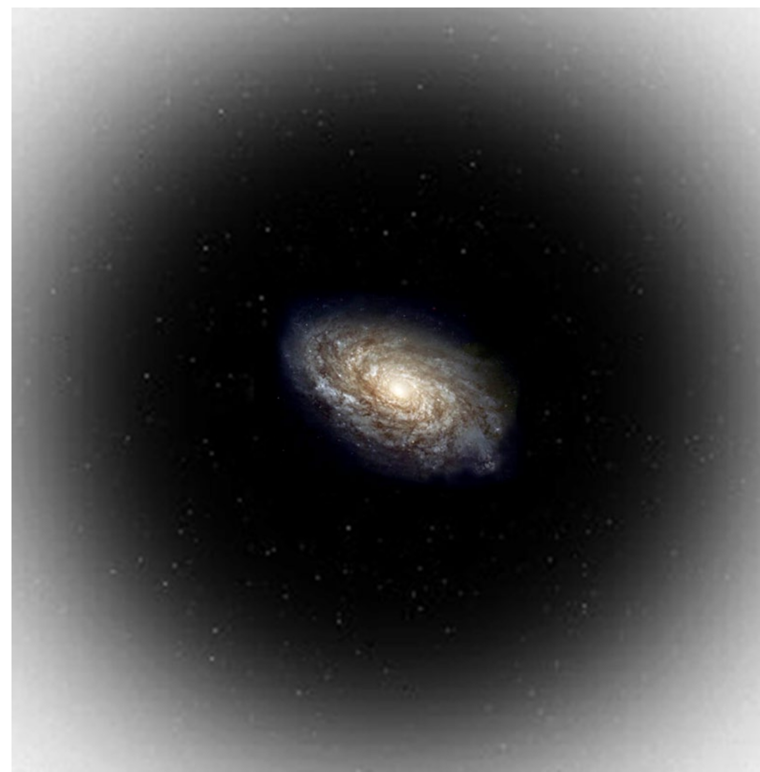
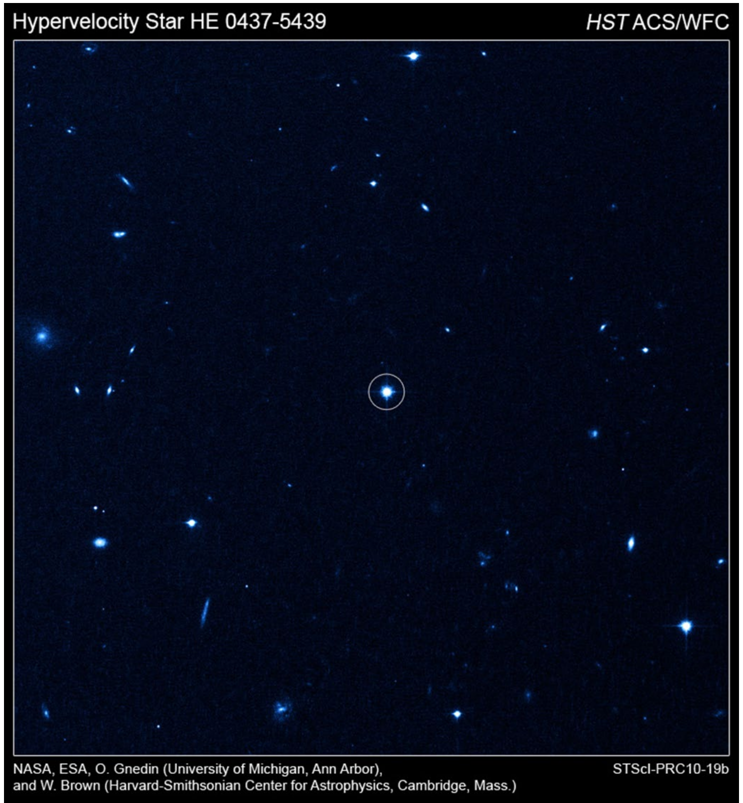
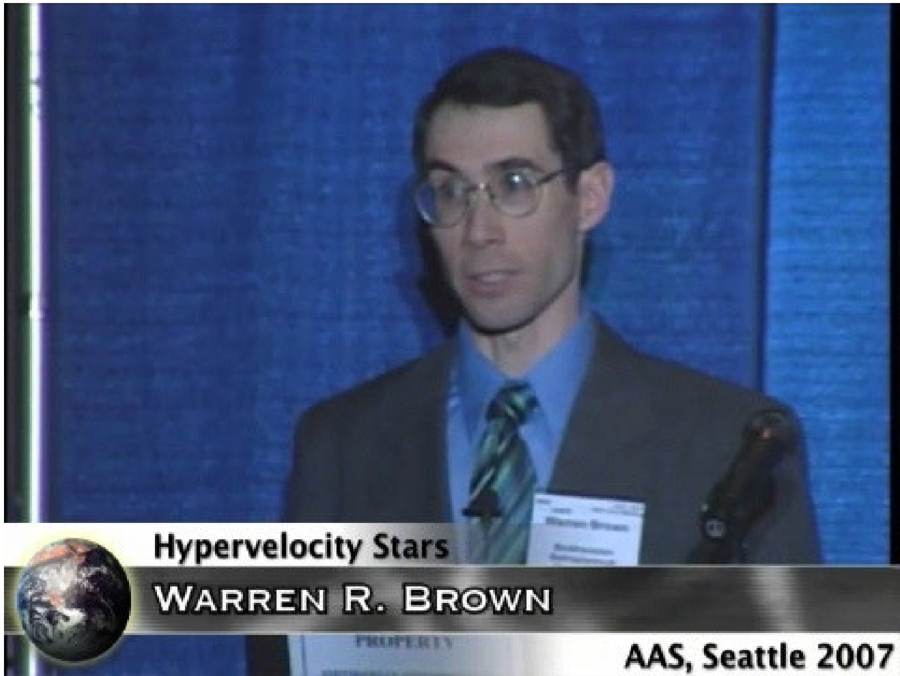




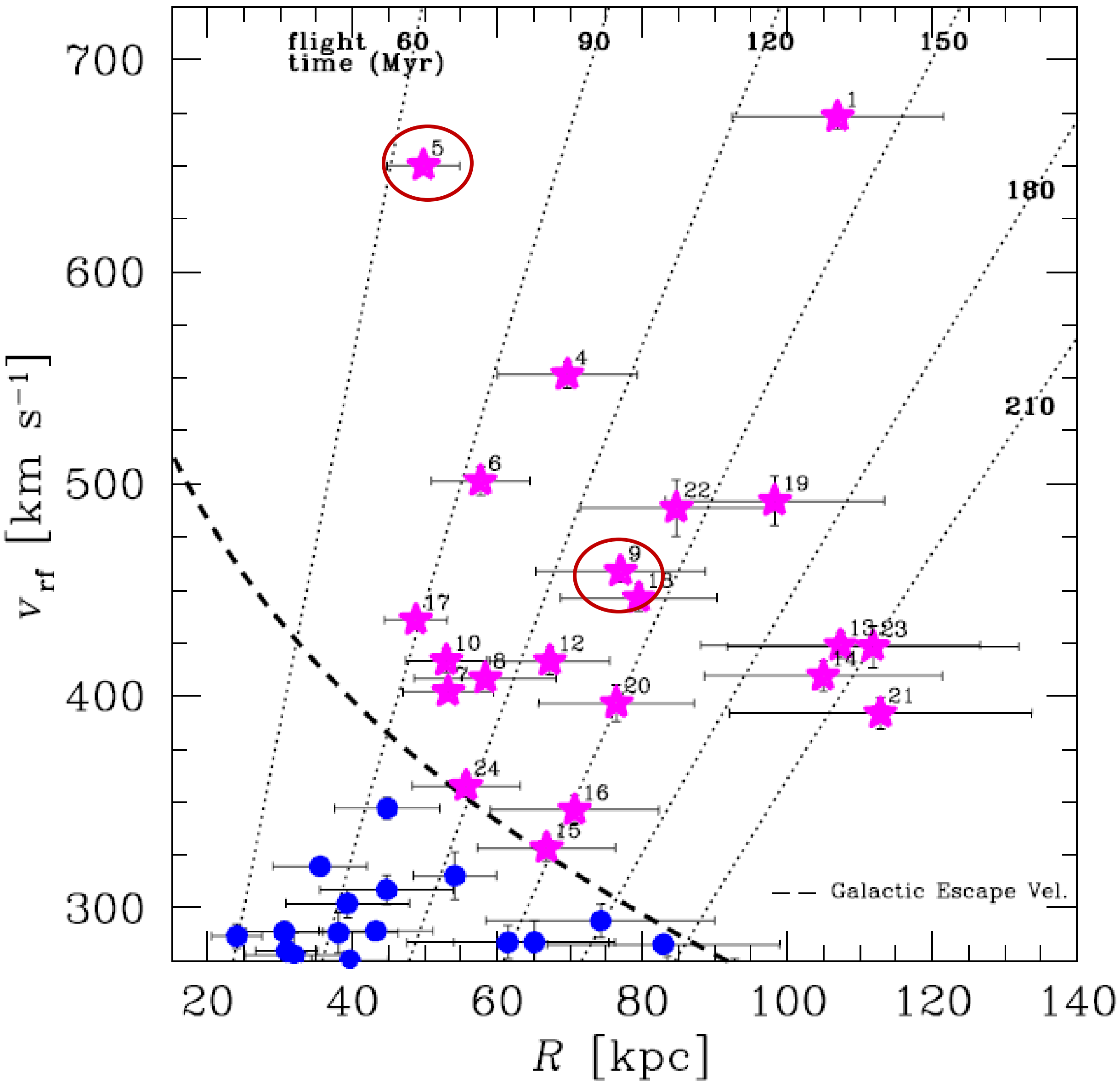
Hypervelocity Stars

- Discovered in 2005 by Warren Brown
- More than 20 are now known, over 800 candidates
- Move with radial velocity +400 to +800 km/s, escaping the Galaxy





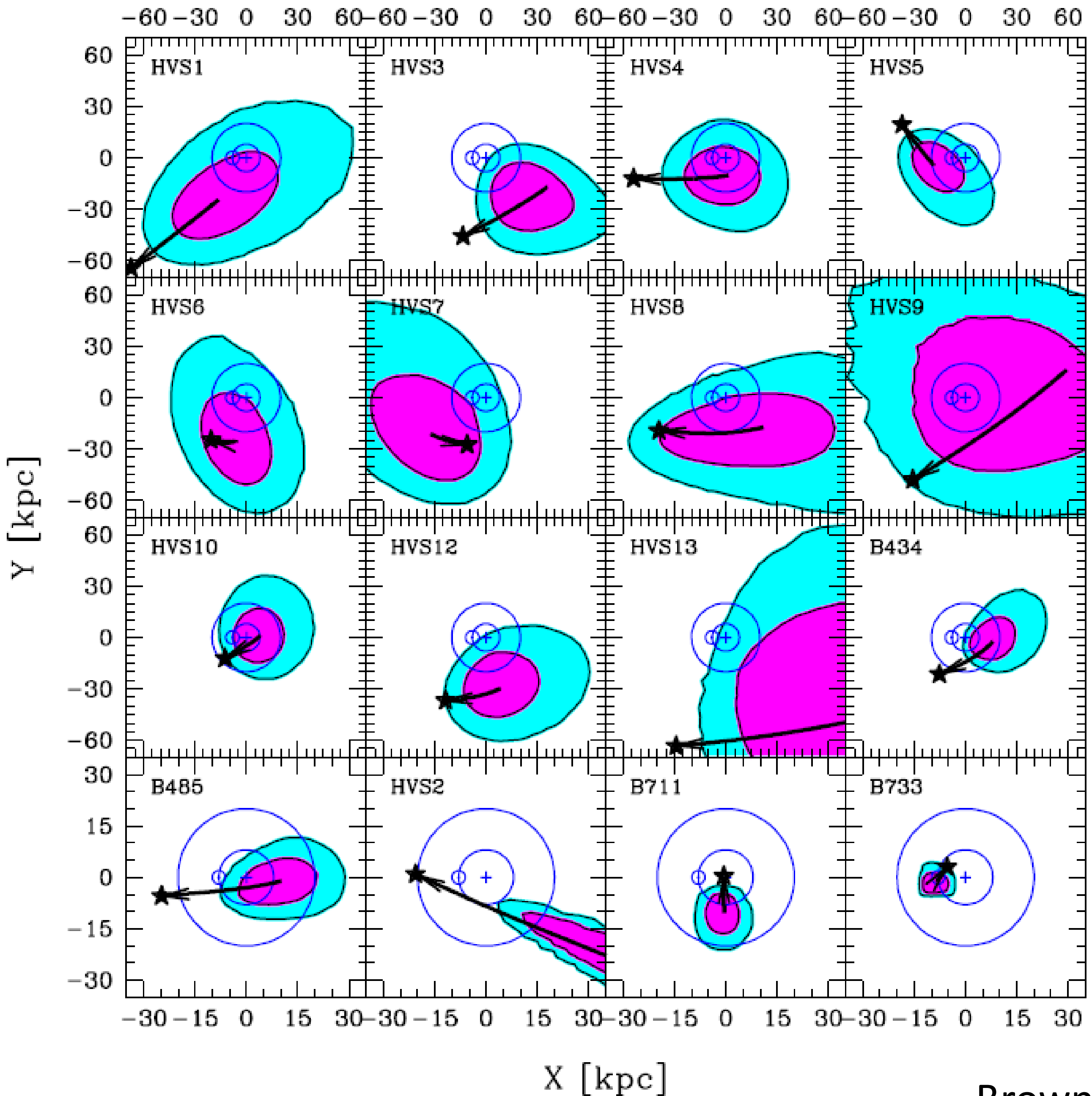
Some HVS escape the Galaxy, some are gravitationally bound



Radial velocity translated to the Galactocentric frame.

For most HVS the flight time from the Galactic center to the current position is shorter than their main-sequence lifetime.

Brown 2015



Do they come from Galactic Center?

Probably

Probability of ejection from a region from the Galactic plane, based on astrometric proper motions with ACS and WFC3 cameras on HST 2006-2012

For 13 of 16 stars, origin is consistent with ejection from the Galactic center, but the uncertainty is large

Brown, Anderson, OG et al. 2015

The fastest HVS

Koposov et al. 2020: V = 1750 km/s

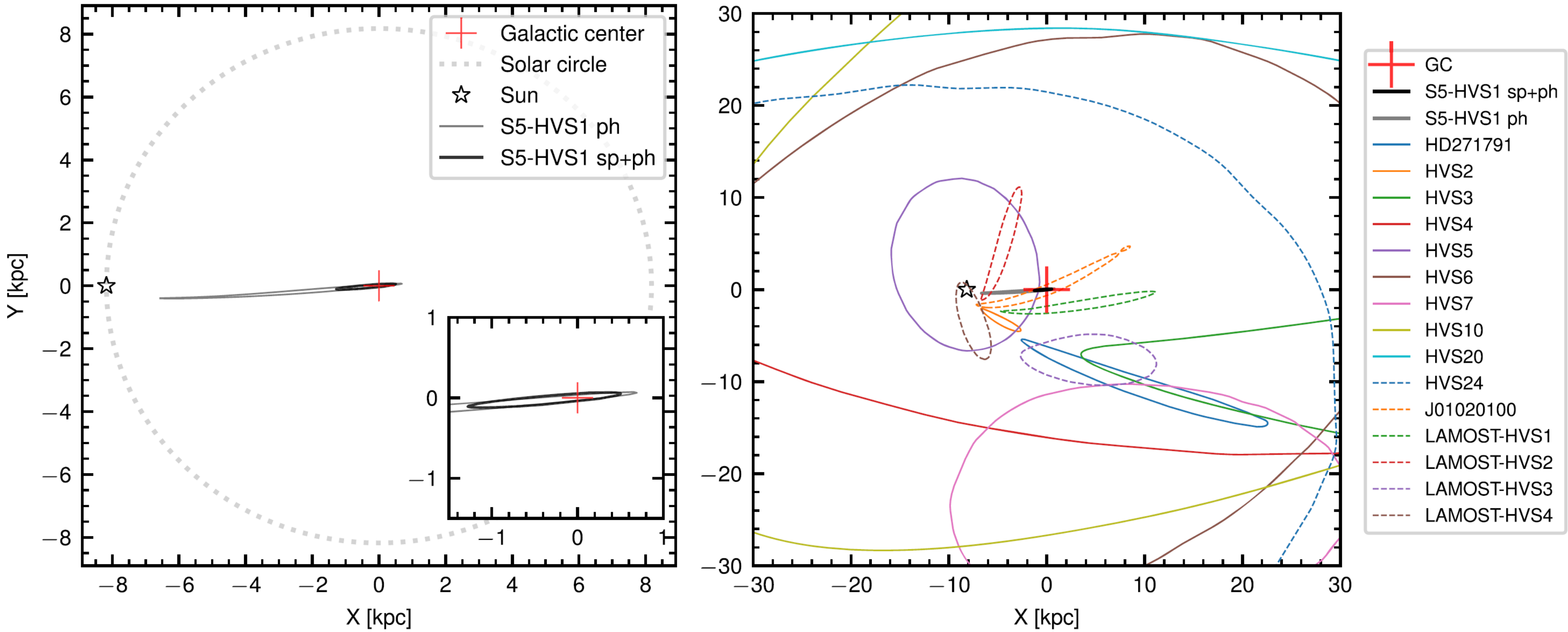
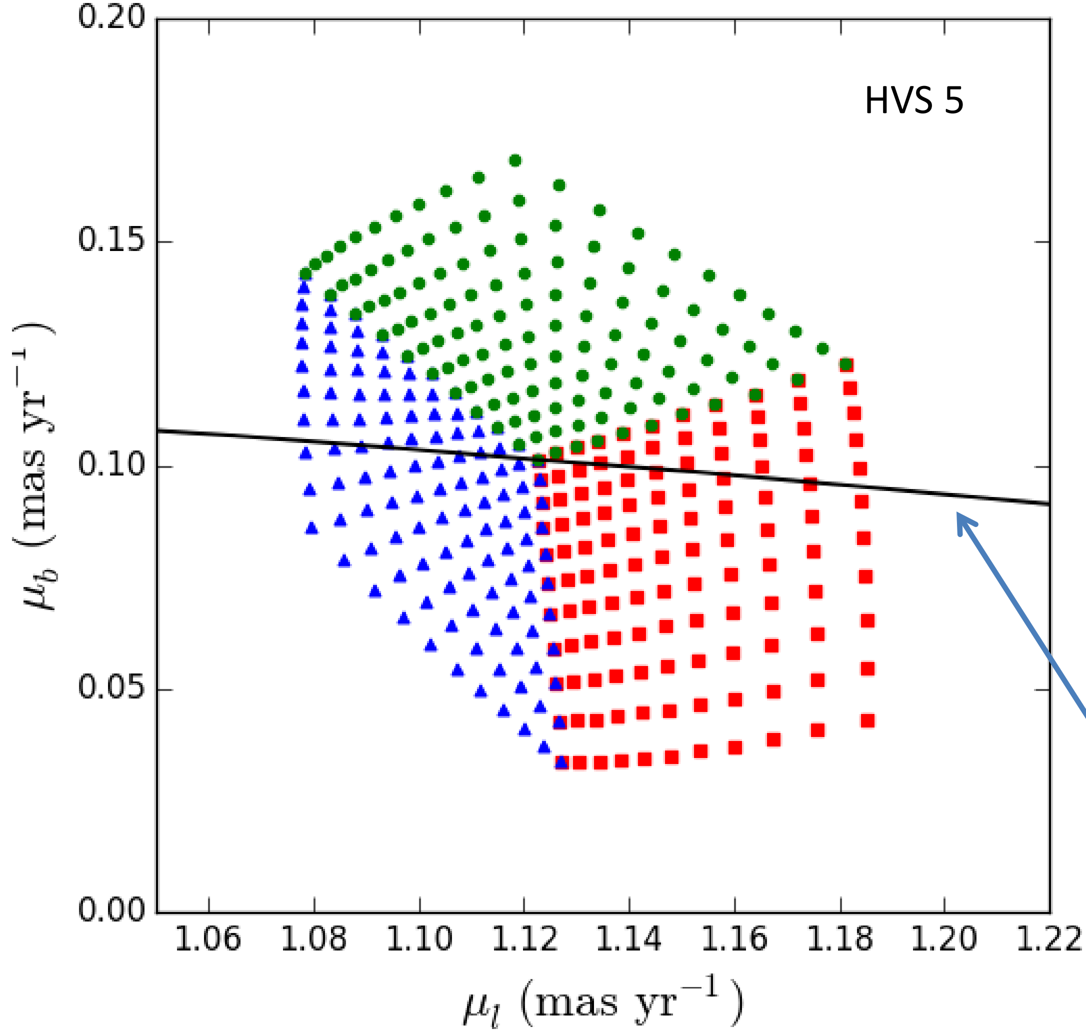


Figure 5. *Left-hand panel:* The constraints on the origin of S5-HVS1 in the Galactic plane. The location of the Sun, Solar circle, and the GC are indicated by a star symbol, grey dotted line, and red cross, respectively. The black contour shows the 90 per cent confidence region of the origin of S5-HVS1 constructed using spectrophotometric distances, while the grey contour shows the constraints if we use less well-determined photometric only distances. Both of these contours contain the GC. The small inset shows the central $2.5 \times 2.5\,\mathrm{kpc}^2$ region around the GC. *Right-hand panel:* 90 per cent confidence regions in Galactic *X*, *Y* for the point of origin of various hyper-velocity stars under the assumption that they come from the Galactic plane. We only included stars with contours that significantly overlap with the $30 \times 30\,\mathrm{kpc}^2$ region shown. The confidence regions for the S5-HVS1 origin are the barely visible grey and black streaks around the GC compared to all other stars.

HVS orbits trace the Galactic potential



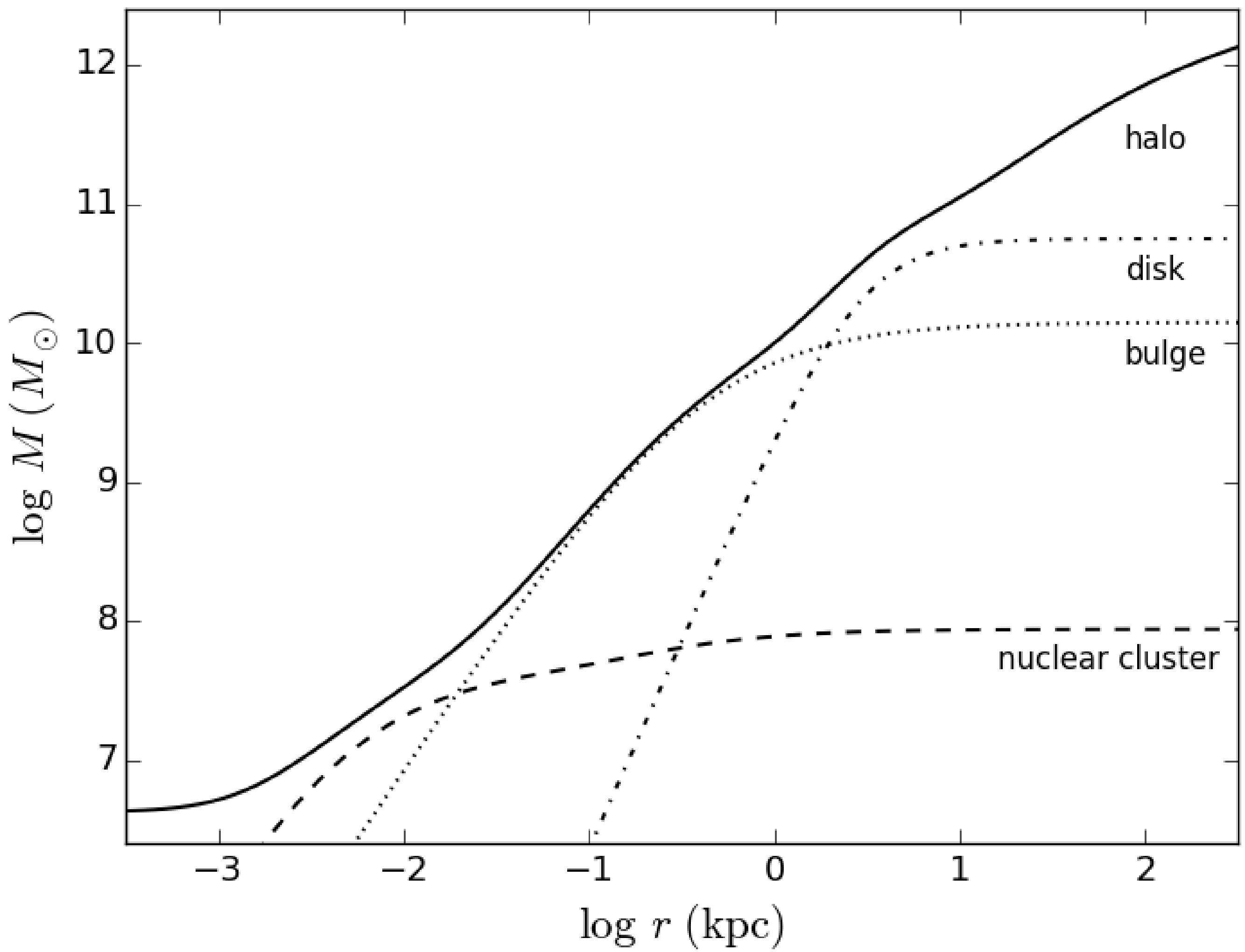
The trajectory from the Galactic center is mostly radial, but with small deflections due to flattened disk and non-spherical dark matter halo

A very accurate measurement of the proper motions (better than 0.1 mas/yr) could constrain the halo shape

Degeneracy between triaxiality and distance uncertainty: requires at least 2 stars to break it

OG et al. 2005

Whether HVS are bound depends on the mass distribution in the Galaxy on all scales

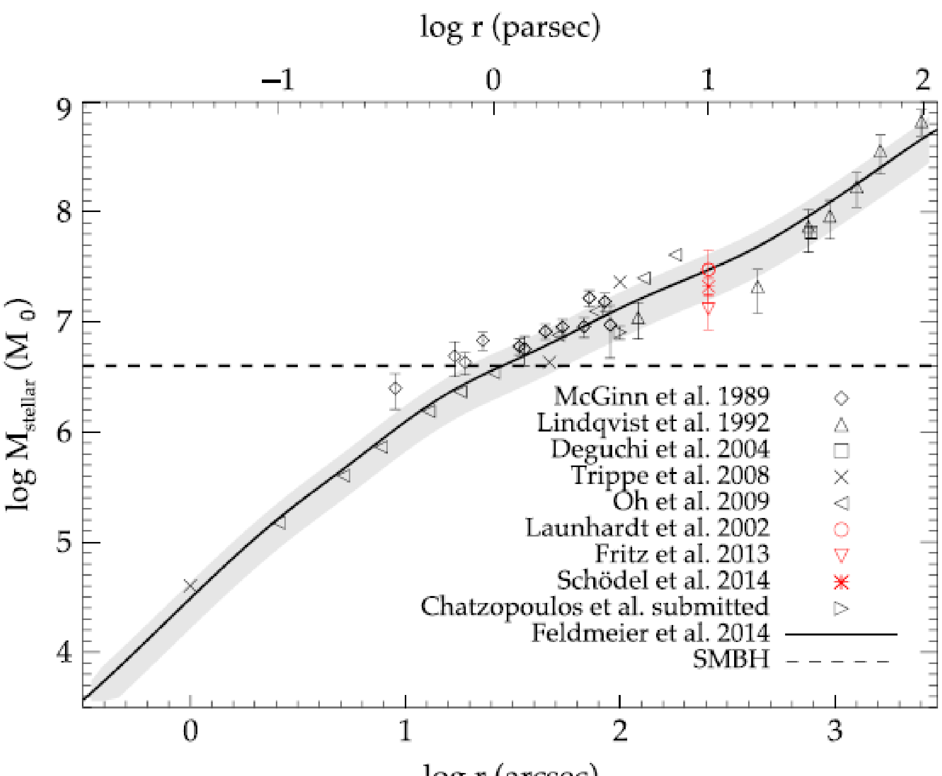


Escape velocity to infinity is 970 km/s from 1 pc, 720 km/s from 1 kpc, 540 km/s from 10 kpc

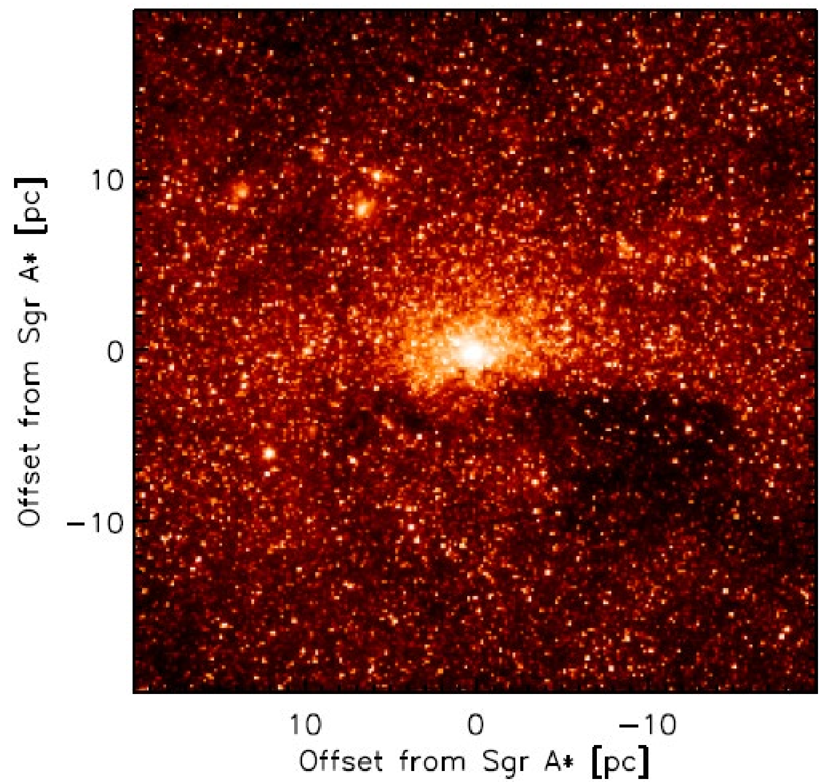
Galactic Nucleus is dense and flattened:

leads to significant deceleration and anisotropic orbits of HVS

- central cluster mass = $2 \times 10^7\ M_\odot$
- half-light radius = 4 pc
- axis ratio *c/a* = 0.7
- density profile $\rho(r) \propto r^{-1.4}$



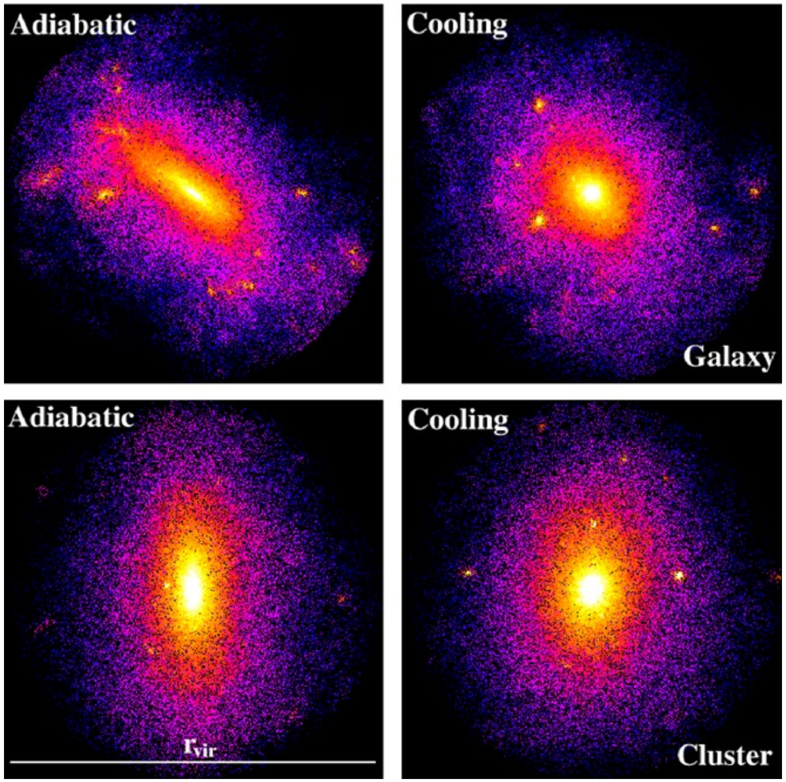
- centered on Sgr A*



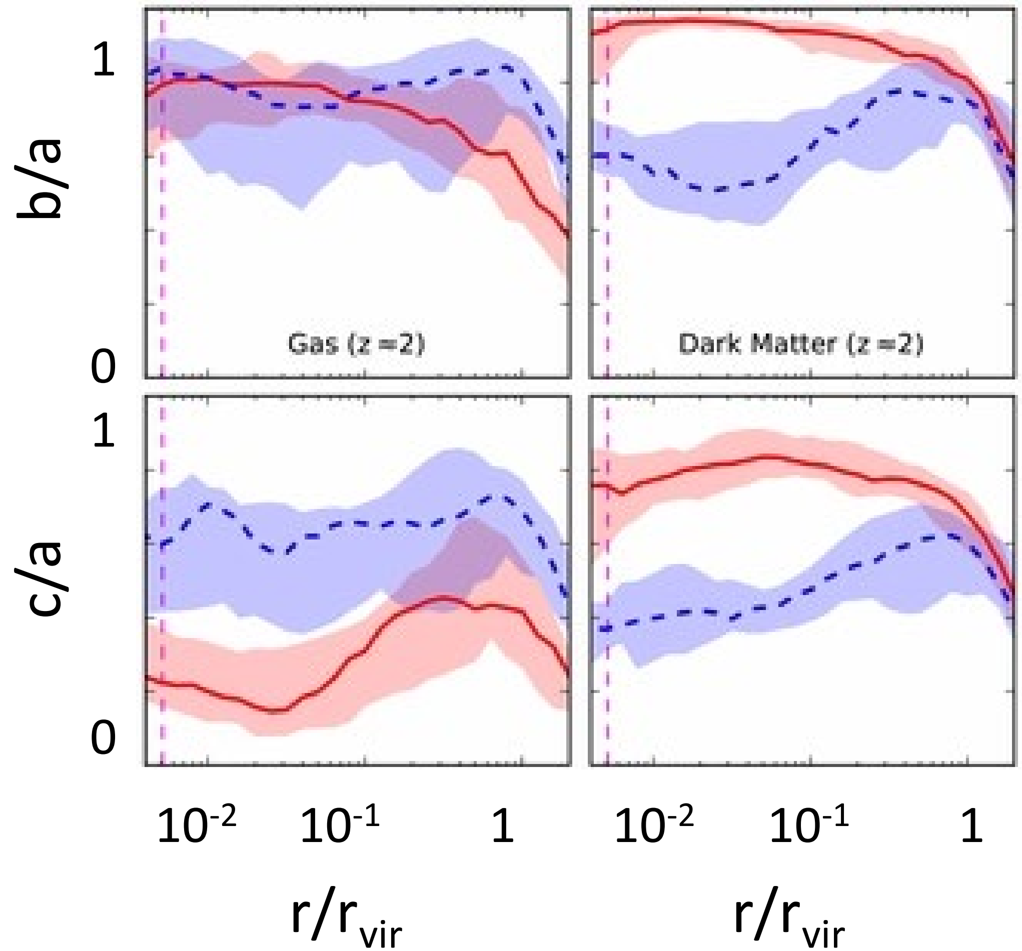
Spitzer/IRAC 4.5 μm
(Schodel et al. 2014)

- Predictions of Cold Dark Matter model match observations of galaxy clustering on scales larger than individual galaxy
- Predictions on galactic scales (density profile, number of satellites) are heavily modified by baryon physics (cooling and feedback)
- Triaxial shape of dark matter halo is least affected by the baryon effects, and therefore is one of the most robust predictions of CDM theory

In the inner regions where baryons dominate mass, halos turn more round. In the outer regions, halo retains the shape acquired from accretion along cosmic filaments.



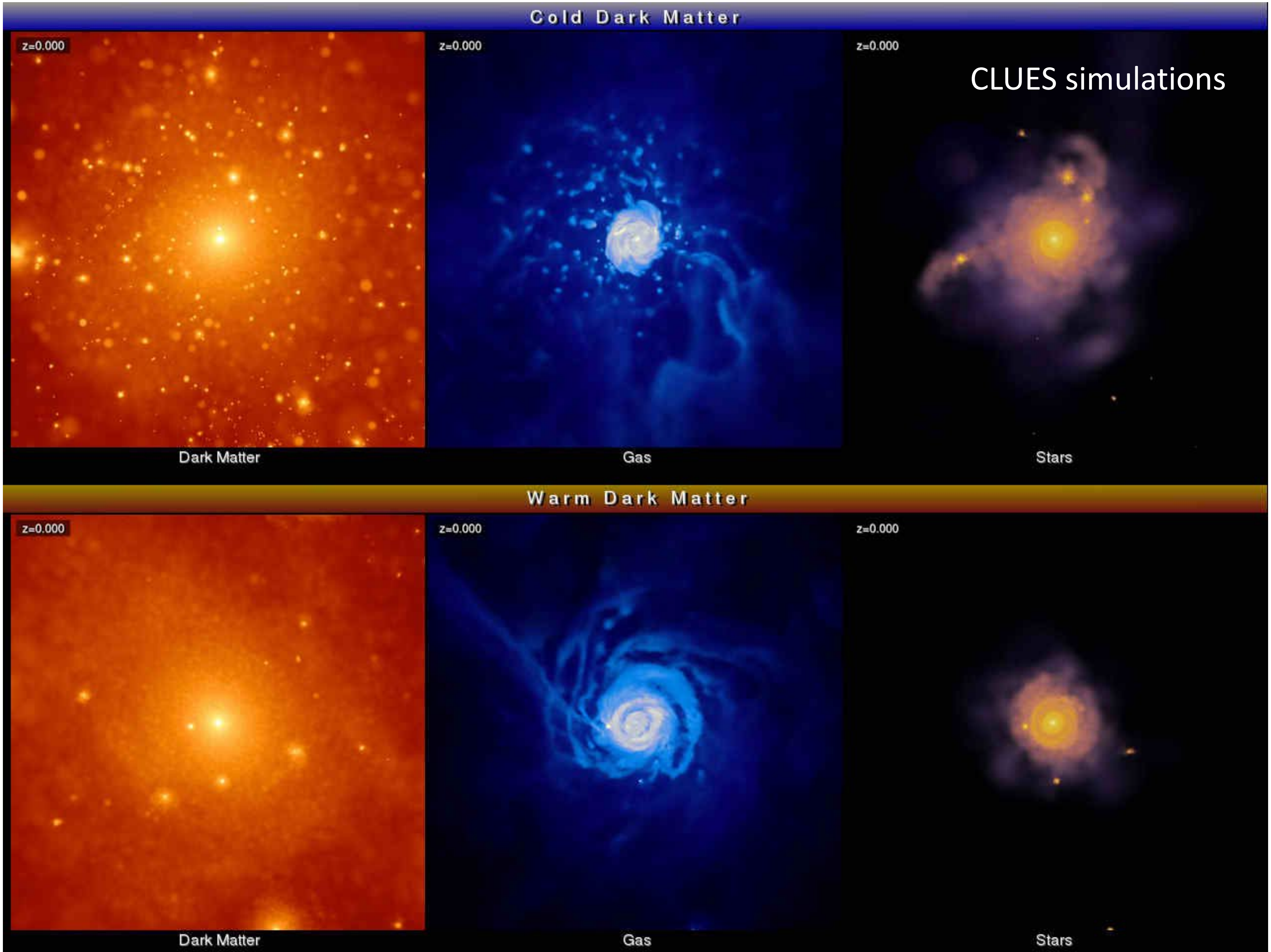
Kazantzidis et al. 2004



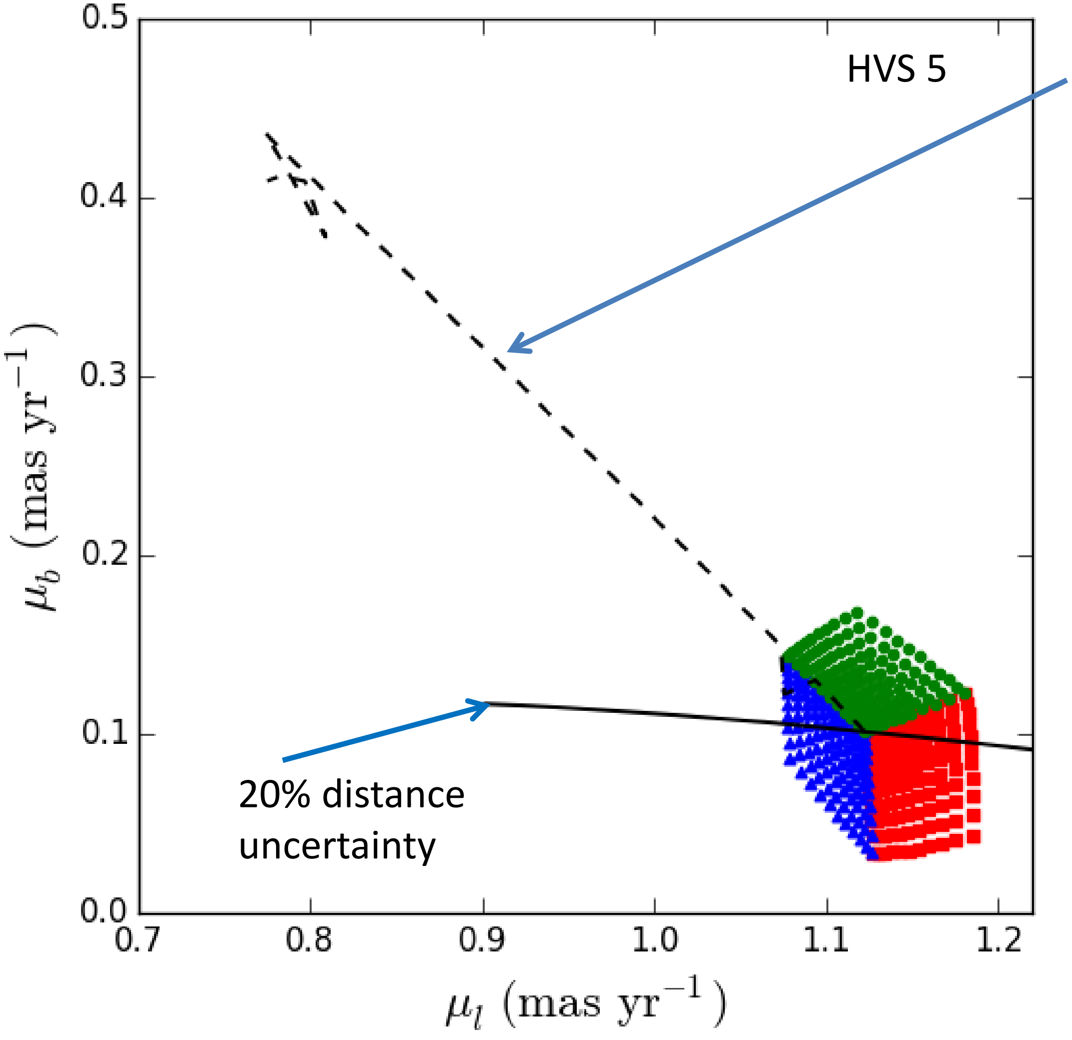
Measurements of halo shape based on tidal streams at 20-50 kpc are uncertain and consistent with spherical

Zemp, OG, et al. 2012

Halo triaxiality is a test of dark matter physics. WDM predicts much rounder shape.

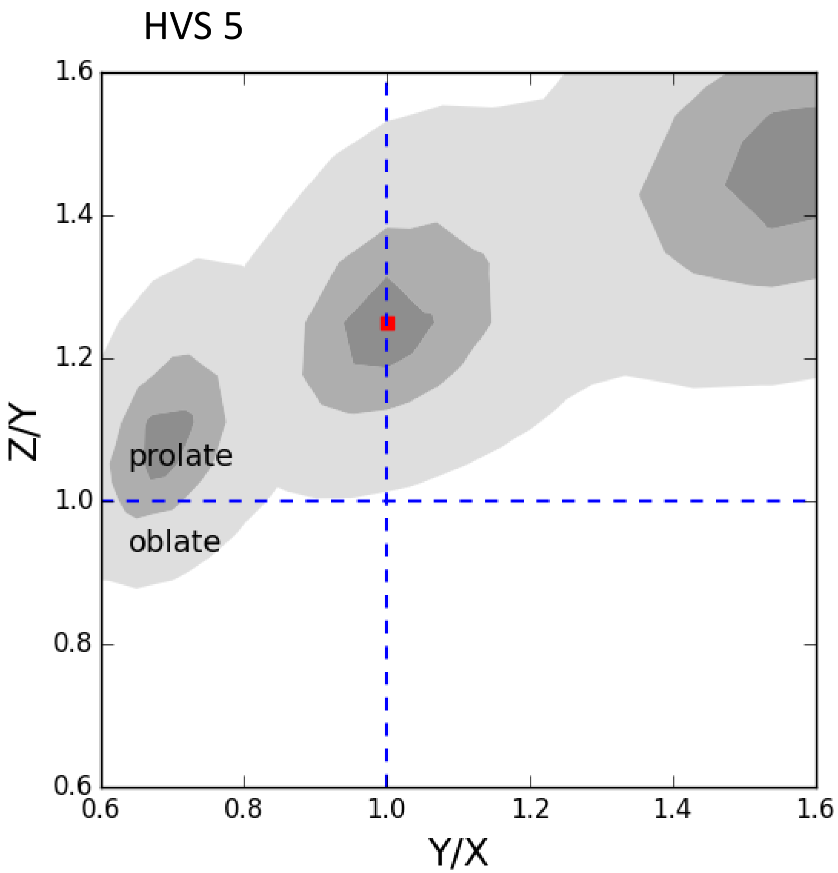


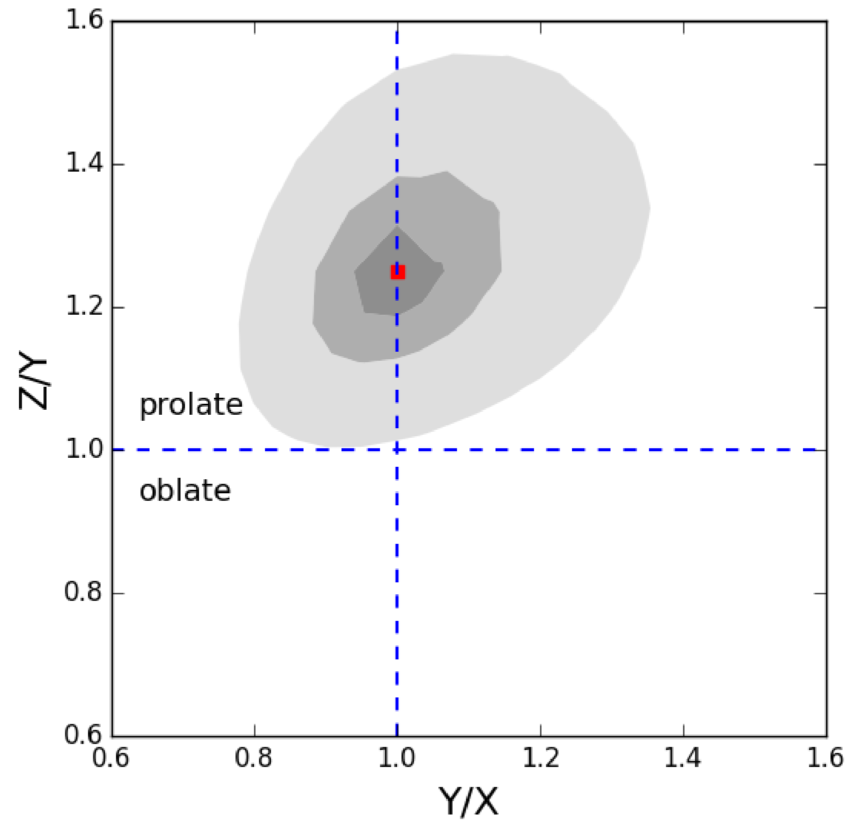
Origin at the Galactic Center is necessary for this test



Ejection from the Galactic disk outside the center results in larger change of the proper motion than halo triaxiality

Constraints on the axis ratios of triaxial halo from p.m. measurement



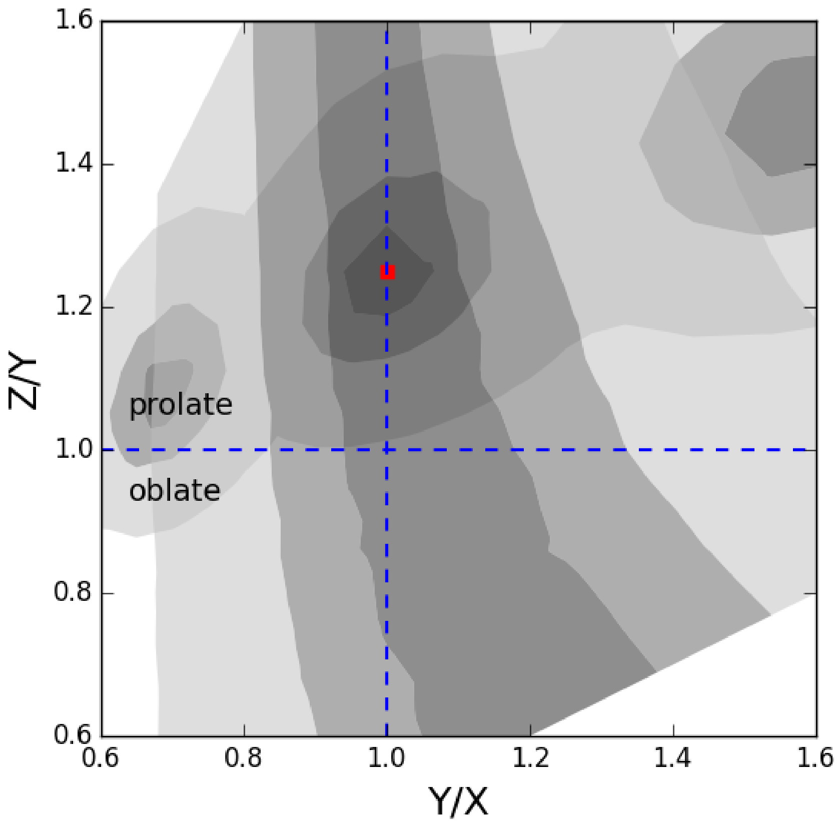


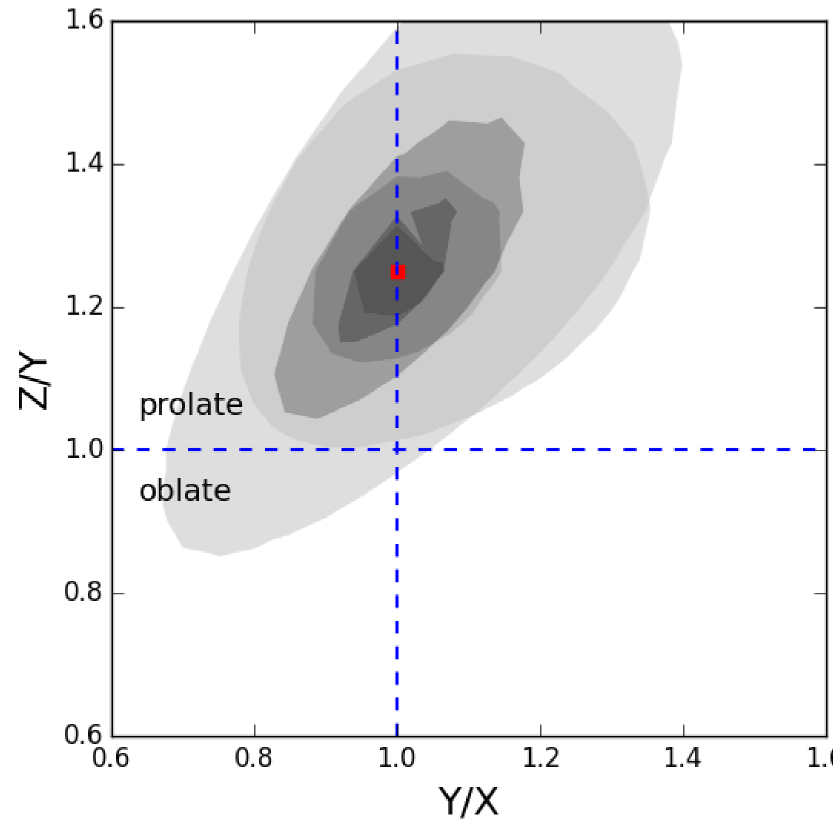
Contours: 0.005, 0.01, 0.02 mas/yr

Determining distance even to 20% breaks the degeneracy in deriving halo axis ratios

Constraints on the axis ratios of triaxial halo from p.m. measurement

HVS 5 and 9





Simultaneous measurements of proper motions for two stars in orthogonal directions on the sky breaks the degeneracy, even if distances are poorly known

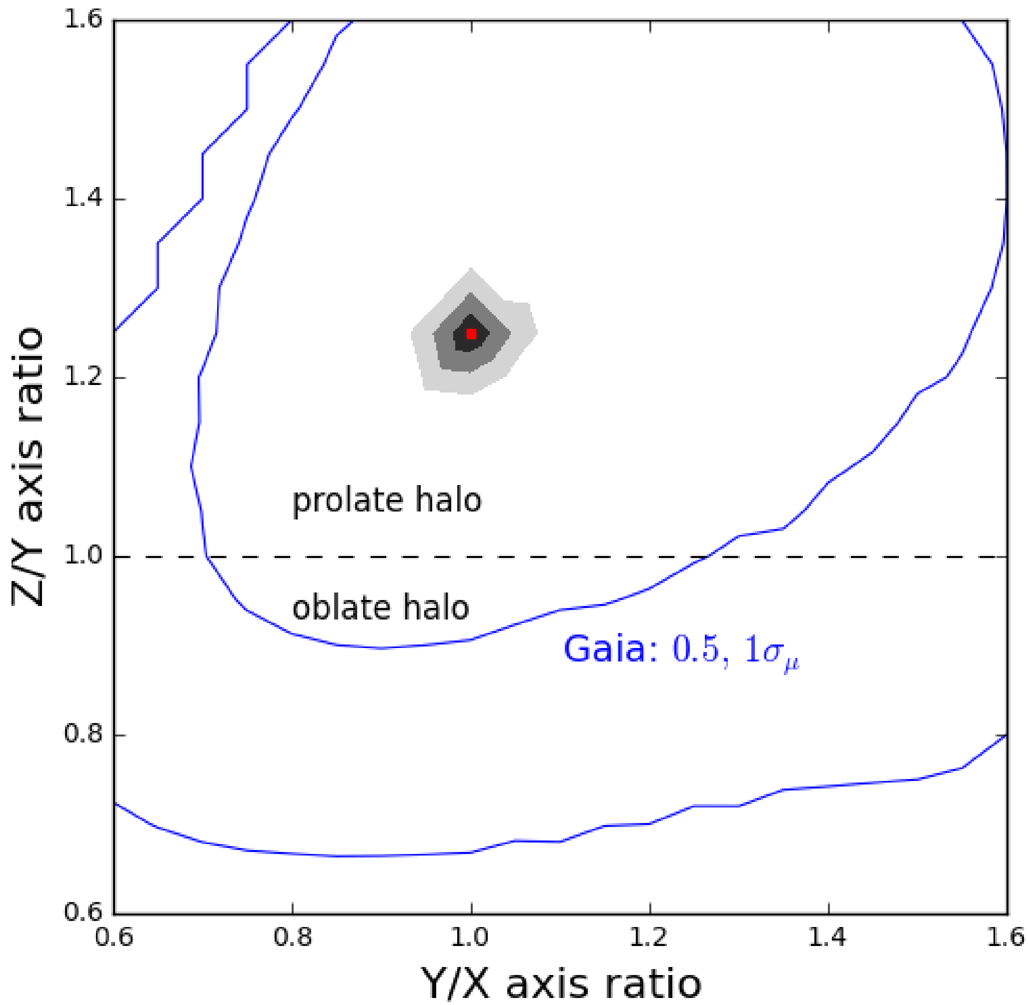
Beyond Gaia

- We need proper motion accuracy of 0.01 mas/yr

- End-of-mission Gaia accuracy for the HVS brightness will be 0.04 – 0.15 mas/yr

- We have established the astrometric frame with HST.
  Future measurements with JWST could improve proper motion accuracy by a factor 2-3

- Future astrometric mission with accuracy at least 10 times Gaia could set the unprecedented constraints on halo shape



1.6
1.4
1.2
1.0
0.8
0.6
Z/Y axis ratio
prolate halo
oblate halo
Gaia: $0.5,\ 1\sigma_\mu$
0.6
0.8
1.0
1.2
1.4
1.6
Y/X axis ratio