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Constraining the Galactic dark matter Halo with hypervelocity stars

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Large uncertainties in shape, orientation, coarseness, mass radial profile and total mass
e.g. Moore+99; Bullock +10; Law & Majewski 10; Vera-Ciro & Helmi 13; Pearson +15; Gibbons, Belokurov & Evans 15;,
A factor of ~6 in mass: is that important?

Wang et al. 15
Testing $\Lambda$CDM

In $\Lambda$CDM, for $> 10^{12} \, M_{\odot}$ Milky Way halos:

Mismatch between the number of low-mass sub-halos predicted and faint Milky Way’s satellites: “the missing satellite problem”

(Klypin +99; Moore + 99)

the most massive sub-haloes predicted do not correspond to any of the known satellites of the Milky Way: “the too big to fail problem”

(Boylan-Kolchin, Bullock, & Kaplinghat 11)

A lighter Halo ($< 10^{12} \, M_{\odot}$) can solve the problem

$\Rightarrow$ halo mass determination within that range can thus be used to test cosmological models
Hyper-velocity stars

So far, a small fraction detected:
- First detection in 2005 (Brown et al.),
- ~20 so far discovered
- Estimated $\sim 10^4$ of all masses out to about 100 kpc (Brown et al. 07)

Current discovery strategy yields biased sample:
- Found spectroscopically (SDSS)
- Targeting the outer halo
- All late B-Type stars ($\sim 3-4$ $M_{\odot}$)
- Only line-of-sight velocities

Brown 2015
HVSs are exceptional tools

- Allow study of Galactic Centre stars, in more accessible part of the sky
- Are alternative dynamical tracers of the Galactic Potential
  (Gnedin et al. 2005 Yu, Q. & Madau, P. 2007)
Origin of Hypervelocity stars

Hills mechanism

Before

SgrA*

Hills 1988

After

Keck/UCLA
Galactic Center Group

S-star cluster at < 0.04 pc from SgrA*

Perets + 07; Antonini & Merritt 13; Madigan + 14
Ejection velocity

We use a **restricted 3-body formalism**, exploiting $m/M \ll 1$

The HVS ejection velocity *analytically* depends on binary mass and separation

$$v_{HVS} \approx \sqrt{\frac{2GMc}{a}} \left( \frac{M}{m} \right)^{1/6}$$

numerical factor here of the order of unity

Given separation and mass distributions $\Rightarrow$ HVS velocity distribution

Sari, Kobayashi & EMR 2010; Kobayashi+ 2012; EMR, Kobayashi & Sari 14
velocity distribution in the halo

Agnostic approach: to define the Galactic Potential only by its escape velocity $V_G$ from the inner Halo (at ~25 kpc)

$$v^2 = v_{ej}^2 - V_G^2$$

shaped by

>$99\%$ probability data do not come from model
Are binary stars in GC different?

late B-type binaries
Star forming regions;
Sana + 13

late B-type binaries in Solar Neighbourhood;
Kouwenhoven+07; Duchene & Kraus 13

K-S test fails to reject that data come from model

EMR+ in prep.
Constraining "$V_G$" range

late B-type binaries
Star forming regions;
Sana + 13

$V_G = 950 \text{ km/s}$

Binary mass ratio distribution, $\gamma$: $f_{\alpha}$

Binary separation distribution, $\alpha$: $f_{\alpha} \propto a^\alpha$
720 km/s < $V_G$ < 780 km/s
note: ~720 km s$^{-1}$ is the escape velocity from the bulge

$\Rightarrow$ For 720 km/s < $V_G$ < 780 km/s
stripe of minima overlaps with observed binary population in star forming regions BUT never overlaps with Solar Neighbourhood data

Lets’ take NWF and de-project the $V_G$ range onto Mass-scale radius plane for values make with a star

…plus the potential for the disc and bulge (Hernquist 1990)
Constraining the Halo mass

$\alpha = -1$ and $\gamma = -3.5$

HVS data suggest a light halo with mass $< 10^{12} \, M_{\text{sun}}$
Conclusions and Caveats

— Massive $> 10^{12} \ M_{\odot}$ Halo & GC binaries not like those observed in either star and non-star forming regions

   OR

— Light $< 10^{12} \ M_{\odot}$ Halo & GC binaries like those observed in star forming regions with $\alpha \sim -1$ and $\gamma \sim -3.5$

   $\Rightarrow$ this would support $\Lambda$CDM

Caveat: the semi-major axis distribution may reflect a selection in binaries that fall into the tidal radius:

if e.g. full loss cone, than a light halo + binaries like in Solar N. is also OK
back-up slides
the Halo mass in simulations

\[ \alpha = -1 \text{ and } \gamma = -3.5 \]
The Universe’s evolution

Understanding the Universe’s evolution is understanding galaxies

An outstanding laboratory: the Milky Way

galaxies are the Universe’s “bricks”
The galaxy formation

- It is traditionally addressed with Simulations + Observations

- Successful field but still many open questions. Let’s consider our own Galaxy:
  - The visible part is hard to reproduce
  - The Dark Halo is poorly constrained and different realisations of the MW give different mass, shape and lumpiness
**Our computational method**

- **Others:** Velocities and trajectories are calculated via 3-body or N-body interactions for a given parameter space (e.g. Brown’s group; Gualandris +)

- **We:** restricted 3-body formalism, exploiting $m/M << 1 \implies$ more efficient method

Sari, Kobayashi & EMR 2010; Kobayashi+ 2012; EMR, Kobayashi & Sari 14
dynamical tracers

e.g. Johnson, Hogg Gibbons, Law & Majewski, Helmi, Wang, Bullock, Ibata, Price-Whelan, Belokurov….
dynamical tracers

Hyper Velocity Stars

Halo Stars

Satellite Galaxies

Sagittarius Stream
Our computational method

We use a restricted 3-body formalism, exploiting $m/M \ll 1 \Rightarrow$ more efficient method than N-body.

Sari, Kobayashi & EMR 2010; Kobayashi+ 2012; EMR, Kobayashi & Sari 14