Using the local escape velocity to determine the mass of the Milky Way

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The RAdial Velocity Experiment (RAVE) is currently measuring radial velocities, metallicities and abundance ratios for many thousands of stars in the southern hemisphere. We analyse the high velocity RAVE stars in order to better constrain the local Galactic escape speed. By inspecting cosmological simulations we show that previous analyses may be subject to bias due to the underlying assumptions regarding the shape of the tail of the velocity distribution. We conclude that $497 < v_{esc} < 612$ km/s (90% confidence). This measurement of the local escape velocity pins down the potential at the solar radius and can be used to provide an estimate of the total halo mass. Although this procedure is model dependent, we find that there is good agreement between various halo models with values ranging between $M_{\rm vir} = 1.01^{+0.70}_{-0.37} \times 10^{12} M_\odot$ and $M_{\rm vir} = 1.45^{+1.08}_{-0.52} \times 10^{12} M_\odot$ (90% confidence).

Motivation

The existence of a dark halo around the Milky Way has been known for many years, but the question of how this halo is composed is a significant issue in astronomy. One vital tool which can be used to tackle this problem is the escape speed (v_{esc}), i.e. the velocity that a star requires to escape the local gravitational field of the Milky Way. If we are able to determine v_{esc} at the solar neighbourhood we can obtain important constraints on the extent of the dark halo.

Analysis techniques

But how do we constrain v_{esc} given a sample of stellar velocities? Following the seminal work of Leonard & Tremaine (1990) we note that asymptotically the distribution function should follow ε^k as $\varepsilon \to 0$, where the energy (ε) is simply the sum of the kinetic energy and the potential energy (given by v_{esc}). Therefore we can obtain the expected velocity distribution as a function of two parameters, k and v_{esc}. Using Bayesian analysis we can constrain k and v_{esc} for a sample of observed velocities.

However, what do we know about the parameter k? This represents the 'shape' of the distribution function, e.g. $k \sim 2.5$ (Hernquist profile), $k \sim 1.5$ (for violent relaxation). Ideally we would like to simultaneously constrain both k and v_{esc}, but we do not posses enough high-velocity stars to do this at present.

We overcome this problem by analysing a suite of 4 cosmological simulations (Abadi et al. 2006). While the dark matter particles take values of k similar to the above predictions, the stellar particles take larger values (see Fig. 1). Therefore previous studies, which have adopted low values for k, may be introducing a bias into their v_{esc} constraints. For our work we adopt a uniform prior on $k \in (2.2, 4.2)$.

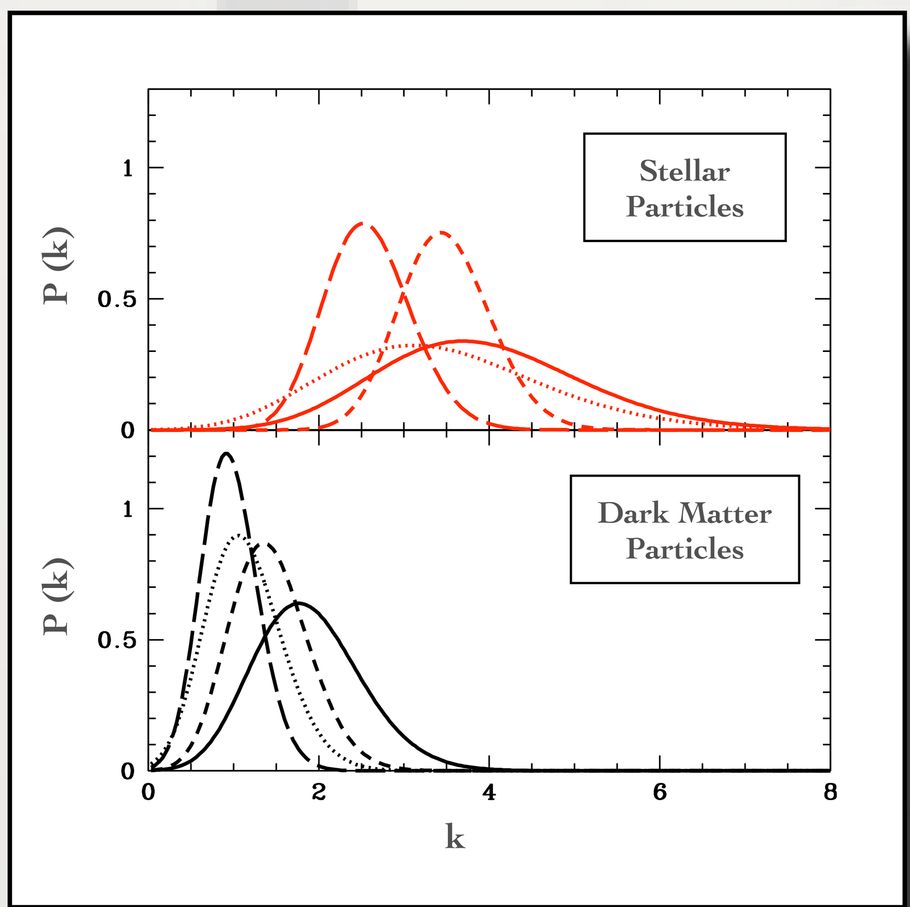

Fig. 1

The probability distribution for the parameter k, as predicted from cosmological simulations (Abadi et al. 2006). While the value of k for the dark matter particles follows the expected trends (i.e. $k \in [0.5, 2.5]$), the behaviour of the stellar particles shows a clear offset. It is important that this information is incorporated into the adopted prior for k.

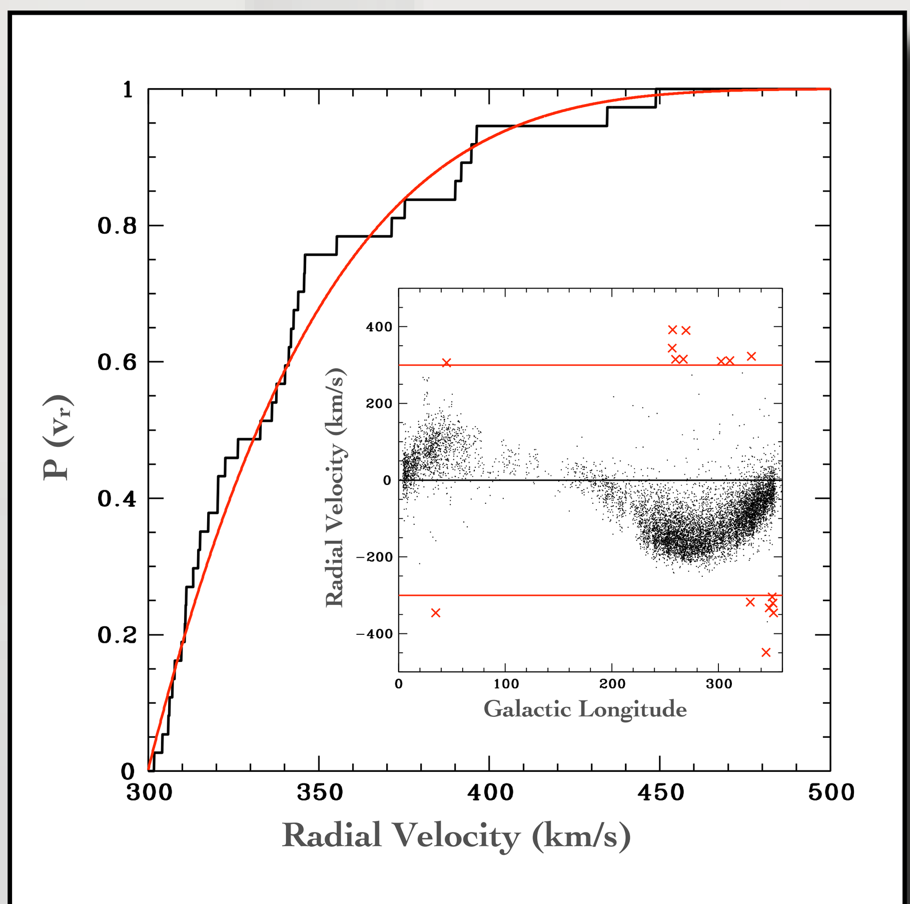

Fig. 2

The cumulative radial velocity distribution of our final dataset of 37 high-velocity stars. The red curve denotes the best fit from our likelihood analysis (see Application of Method). The inset shows the radial velocity of RAVE stars as a function of Galactic longitude. Note how the signature of the disc is clearly visible. The red crosses denote the RAVE stars in our high-velocity dataset.

Application of method

Our observed sample of high velocity stars utilises the RAVE survey (www.rave-survey.org), which is an ambitious project to measure radial velocities and stellar parameters for up to a million stars in the Southern hemisphere. The catalogue already contains over 100,000 stars; clearly, with such a vast number of high precision radial velocities, the RAVE survey will enable us to determine v_{esc} to unprecedented accuracy. In order to improve our statistics we incorporate two archival datasets (Beers et al. 2000; Nordström et al. 2004). Our final sample contains 37 stars with radial velocities greater than 300 km/s (Fig. 2), which is a huge improvement on previous studies. After applying the above Baysean analysis we obtain the results shown in Fig. 3. We find $497 < v_{esc} < 612$ km/s (90%).

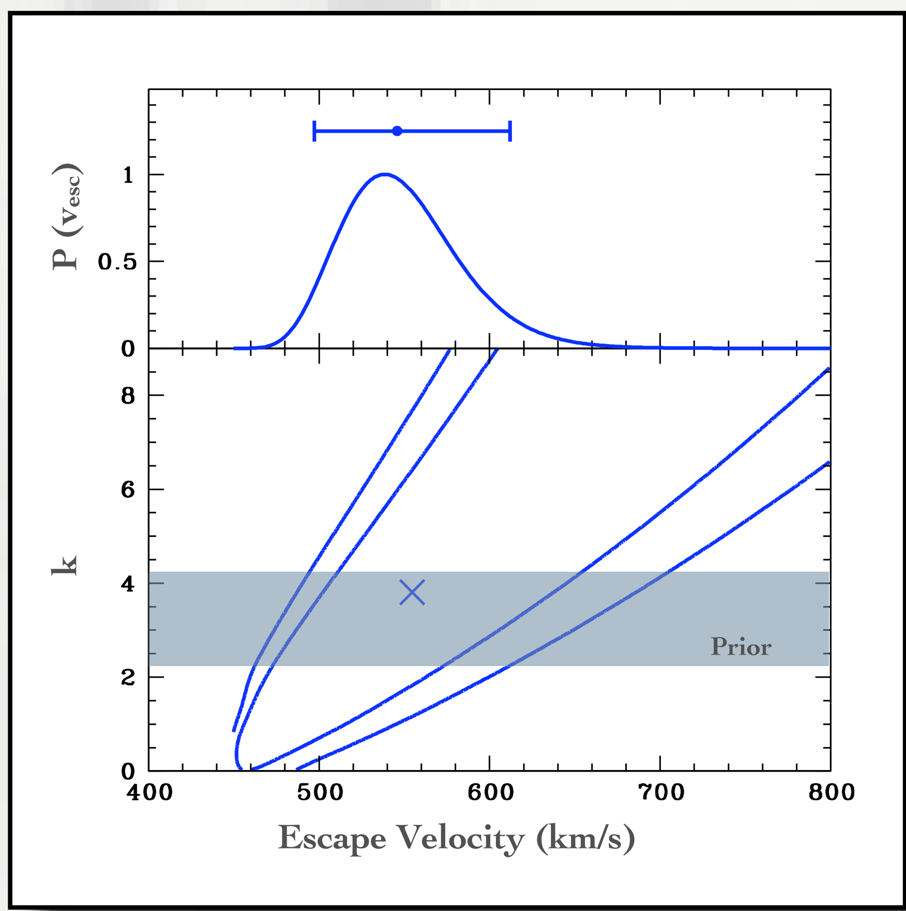

Fig. 3

The lower panel shows the joint likelihood contours for v_{esc} and k. The cross denotes the peak likelihood and the contours represent 10% and 1% of this peak value. We are clearly unable to provide joint constraints given our small sample size, which highlights the importance of adopting an accurate prior for k. After applying our prior for k we obtain the constraints on v_{esc} as shown in the upper panel. The error bar denotes the 90% confidence interval.

The mass of the Milky Way

What can we learn from this value of v_{esc}? One can immediately see that v_{esc} is considerably greater then $\sqrt{2}$ times v_{circ}, which implies that there must be a significant amount of mass exterior to the solar circle. Another simple test one can perform is to model the mass distribution of the Milky Way as a truncated isothermal profile; from this we deduce a truncation radius of 71 kpc.

These simple arguments convincingly demonstrate the existence of a dark halo, but to obtain further precision requires slightly more detailed modelling. We do this by taking three popular halo profiles and include the distributions of baryons in the disc and bulge. We find the following 90% confidence constraints,

NFW halo: $M_{\rm vir} = 1.01^{+0.70}_{-0.37} \times 10^{12} M_\odot$

NFW incorporating adiabatic contraction: $M_{\rm vir} = 1.45^{+1.08}_{-0.52} \times 10^{12} M_\odot$

Wilkinson & Evans (1999) halo: $M_{\rm tot} = 1.40^{+3.01}_{-0.73} \times 10^{12} M_\odot$

Conclusions

We have presented dramatically improved constraints for the local escape velocity. By 2010, the RAVE survey will have $\sim 10^6$ stars. The expected number of high velocity stars (~300 with $v_r > 300$ km/s) will enable a precise determination of v_{esc}. In the pre-GAIA era, the RAVE survey will provide an invaluable resource for scientists wishing to understand our Galaxy.

References:

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RAVE RADIAL VELOCITY EXPERIMENT

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