On measuring the Galactic dark matter halo with hypervelocity stars

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ABSTRACT

Hypervelocity stars (HVSs) travel from the Galactic Centre to the dark matter halo of the Milky Way, where they are observed with velocities in excess of the Galactic escape speed. Their trajectories make them a unique probe of the still poorly constrained dark matter component of the Galaxy. In this paper, we present a new method to constrain the Galactic potential with HVSs. The likelihood is constructed by efficiently calculating the local HVS density at any point of the Galaxy by back-propagating the phase space position and quantifying the ejection probability along the orbit. This method is particularly suited to the data from the ESA mission *Gaia*. Therefore, to showcase our method, we applied it to a simulated *Gaia* sample of ∼ 200 stars in Galactic potentials with three different dark matter components, parametrized by a spheroidal NFW profile. We find that individual HVSs exhibit a degeneracy in the scale mass-scale radius plane ($M_s - r_s$) and are able to measure only the combination $\alpha = M_s/r_s^2$, likewise a degeneracy is also present between α and the spheroidal axis-ratio q. When the whole sample is considered, both parameters are nailed down with *sub-percentage* precision (about 1% and 0.1% for α and q respectively) and no systematic bias is observed. This remarkable power to constrain deviations from a symmetric halo is a consequence of the Galactocentric origin of HVSs. To compare our results with other probes, we break the degeneracy in the scale parameters and impose a mass-concentration relation. The result is a competitive precision on the virial mass M_{200} of about 10%.

Key words: Galaxy: halo – Galaxy: Centre – stars: dynamics – methods: numerical

SIMULATED HVS CATALOGUES

1) the ejection distribution that determines how the velocities, positions and masses of our stars are distributed at the moment of ejection from the GC;

2) a survival function that dictates the fraction of HVSs alive after a time *t* post-ejection

3) a gravitational potential under the influence of which the stars trace their orbits.

Ejection rate distribution :

- position, velocity, the stellar mass.

3 pc

$$\mathcal{R}(\boldsymbol{w} = (\boldsymbol{x}, \boldsymbol{v}, m)) = \Gamma \mathcal{R}_H(|\boldsymbol{v}|, m)\, \delta(|\boldsymbol{x}|)\, \delta(\boldsymbol{x} \cdot \boldsymbol{v}), \tag{1}$$

the ejection rate per unit time

zero angular momentum

$$\begin{cases} \mathcal{R}_H(|\boldsymbol{v}|, m) \propto m^{-1.7} |\boldsymbol{v}|^{-1} & \text{if } |\boldsymbol{v}| \leq v_0(m), \\ \mathcal{R}_H(|\boldsymbol{v}|, m) \propto m^{-1.7} |\boldsymbol{v}|^{-6.3} & \text{if } |\boldsymbol{v}| > v_0(m); \end{cases} \tag{2}$$

$$v_0(m) = 1530\ (\mathrm{M}_\odot/m)^{0.65}\ \mathrm{km/s}. \tag{3}$$

Survival function

The probability density function of the variable t_f is found to be equal to

$$f(t_f|m) = -\frac{1}{t_L(m)} log\left(\frac{t_f}{t_L(m)}\right).$$

The function g(t_f , m) is then the corresponding survival function:

$$g(t_f, m) = 1 - \int_0^{t_f} f(t|m)\, dt = 1 - \frac{t_f}{t_L(m)} + \frac{t_f}{t_L(m)} \log\left(\frac{t_f}{t_L(m)}\right), \tag{6}$$

only stars brighter than the 16th magnitude in the G_{RVS} band

total velocity at present time in the Galactic reference frame higher than 450 km/s.

Galactic potential

The last component of the potential is a spheroidal NFW density profile (Navarro et al. 1997) and it models the dark matter halo of the Milky Way,

$$\rho_{\mathrm{NFW}}(x, y, z) = \frac{M_s}{4\pi r_h^3} \frac{1}{(\xi/r_s)(1+\xi/r_s)^2}, \quad \xi^2 = x^2 + y^2 + \frac{z^2}{q^2}. \tag{10}$$

Table 1. Choice of the NFW scale parameters M_s, r_s and axis-ratio q for the three fiducial haloes used in this work to model the dark matter distribution of the Galaxy.

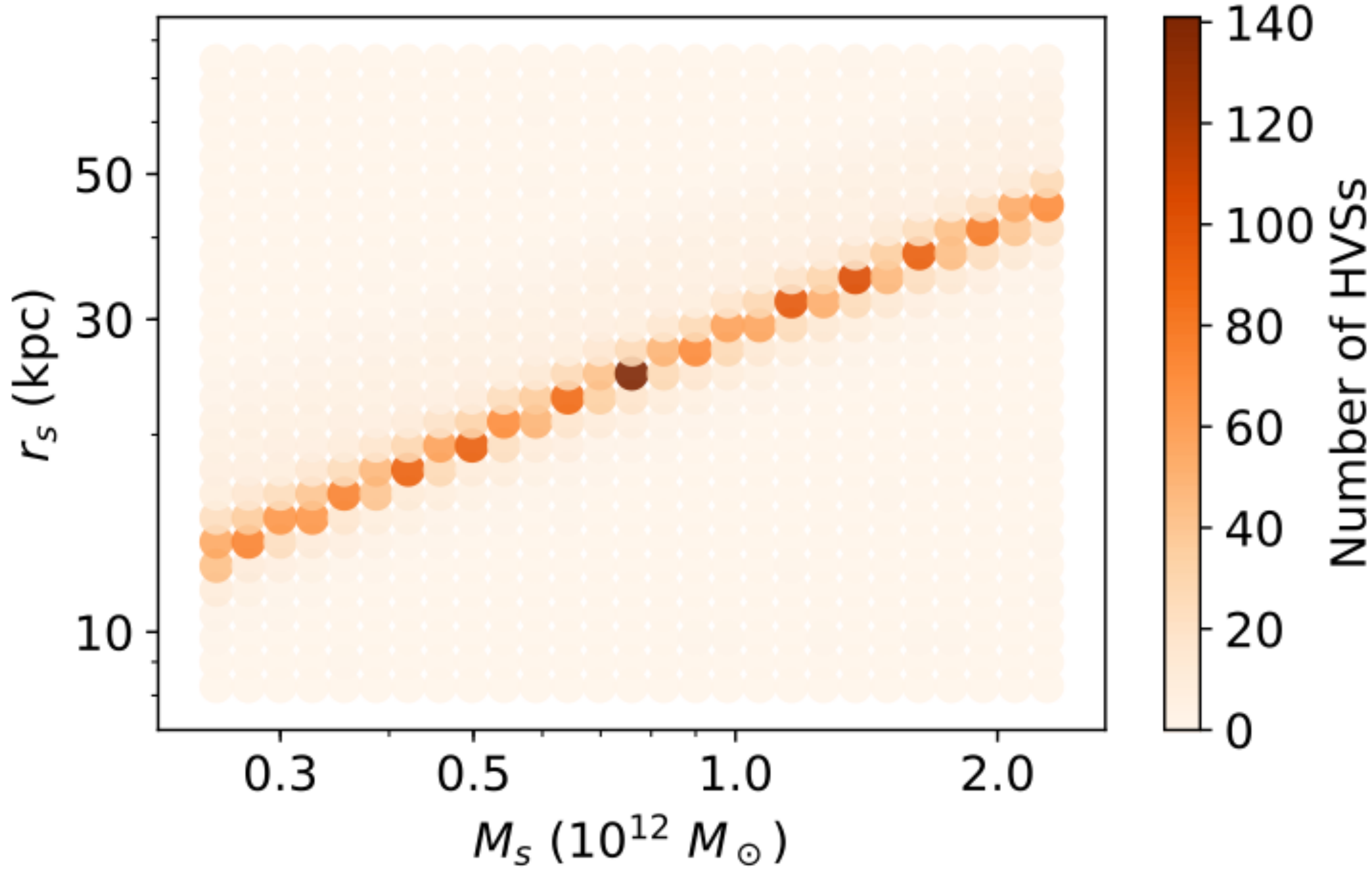
Model	M_s	r_s	q	
A	0.76×10^{12} M$_\odot$	24.8 kpc	1	195
B	0.76×10^{12} M$_\odot$	24.8 kpc	3/2	192
C	1×10^{12} M$_\odot$	20.0 kpc	1	211

back-propagating the observed location to the ejection point

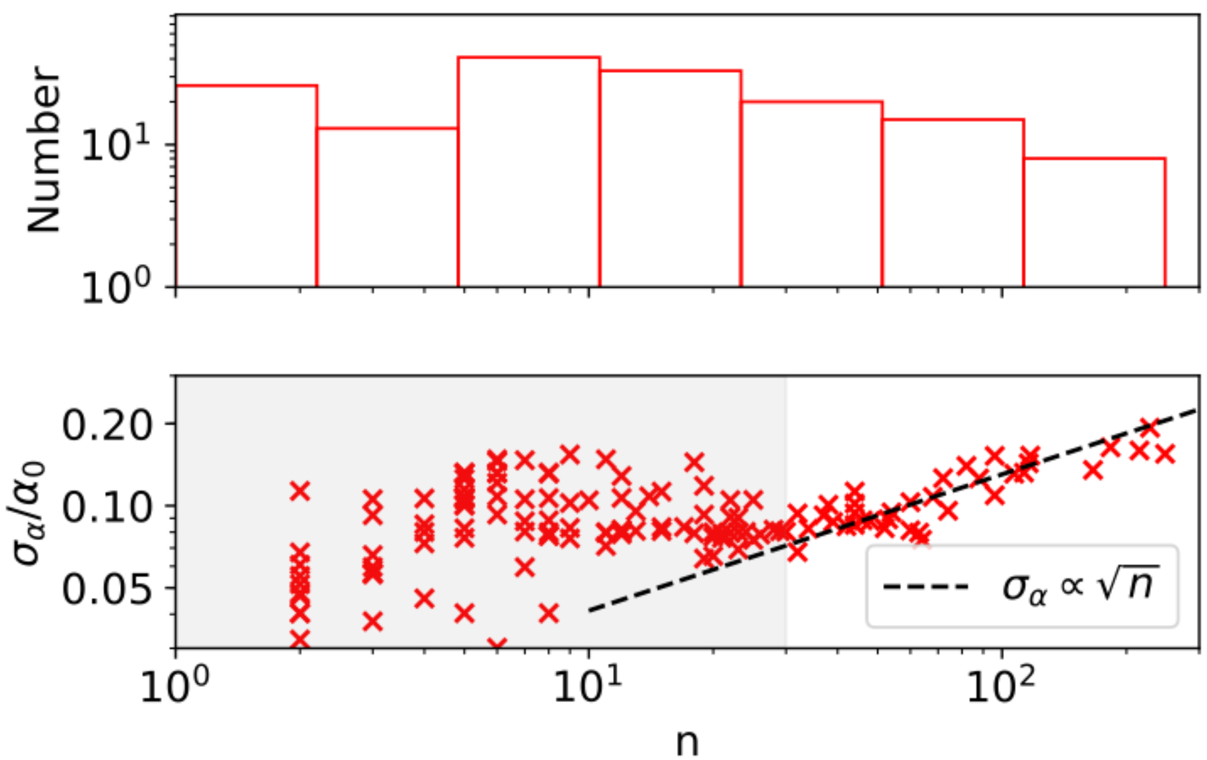
—>the density of HVSs for a given stellar mass and phase-space position

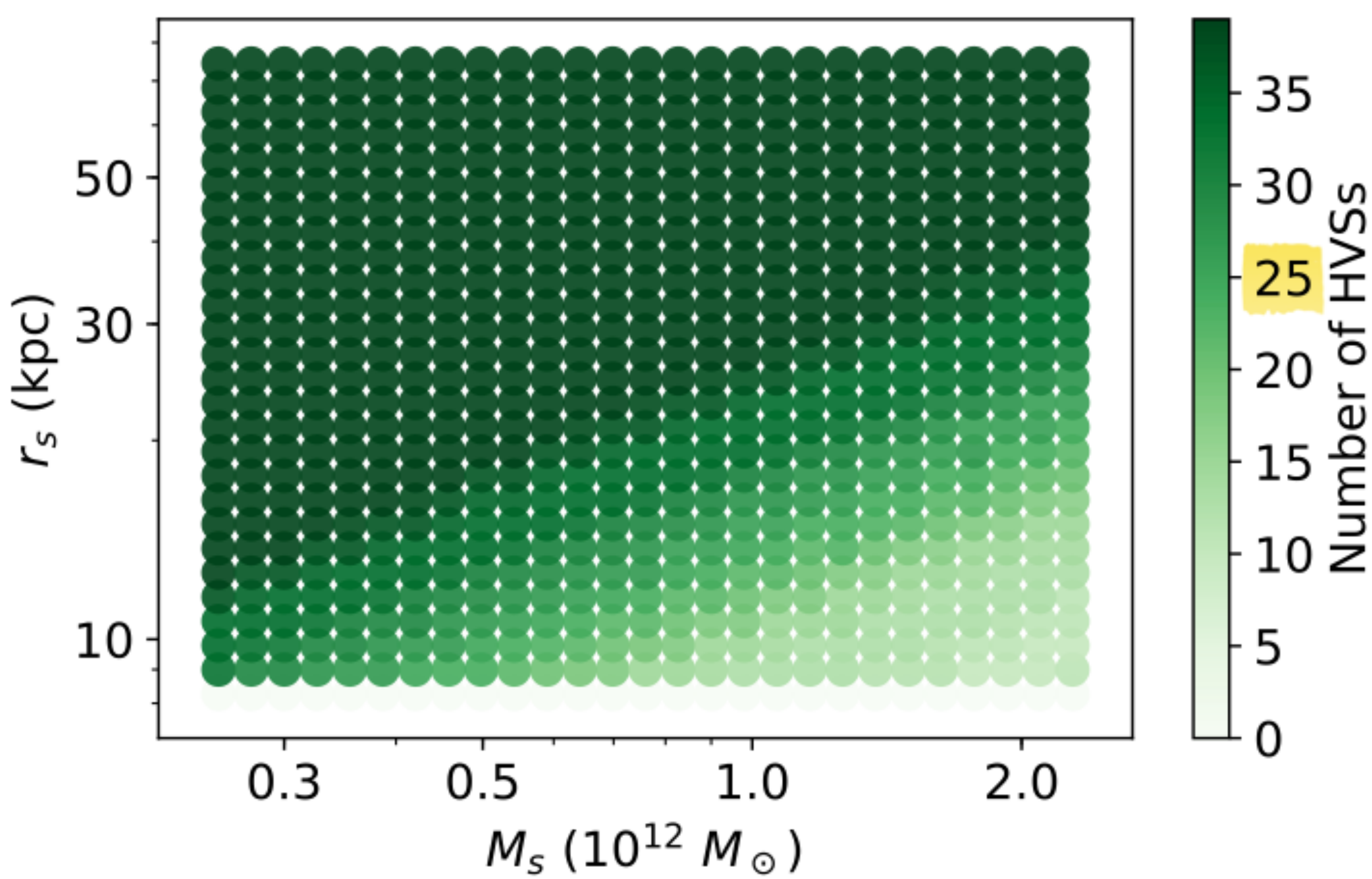
We can then assign for every value of this parameter vector a likelihood to the observation of $N_{\rm HVS}$ HVSs in the configuration space points $\{\boldsymbol{w}_1, \ldots, \boldsymbol{w}_{N_{\rm HVS}}\}$ at a time t:

$$\mathcal{L}(\boldsymbol{\theta}) = \sum_{i}^{N_{\rm HVS}} f(\boldsymbol{w}_i; t|\boldsymbol{\theta}). \qquad (17)$$



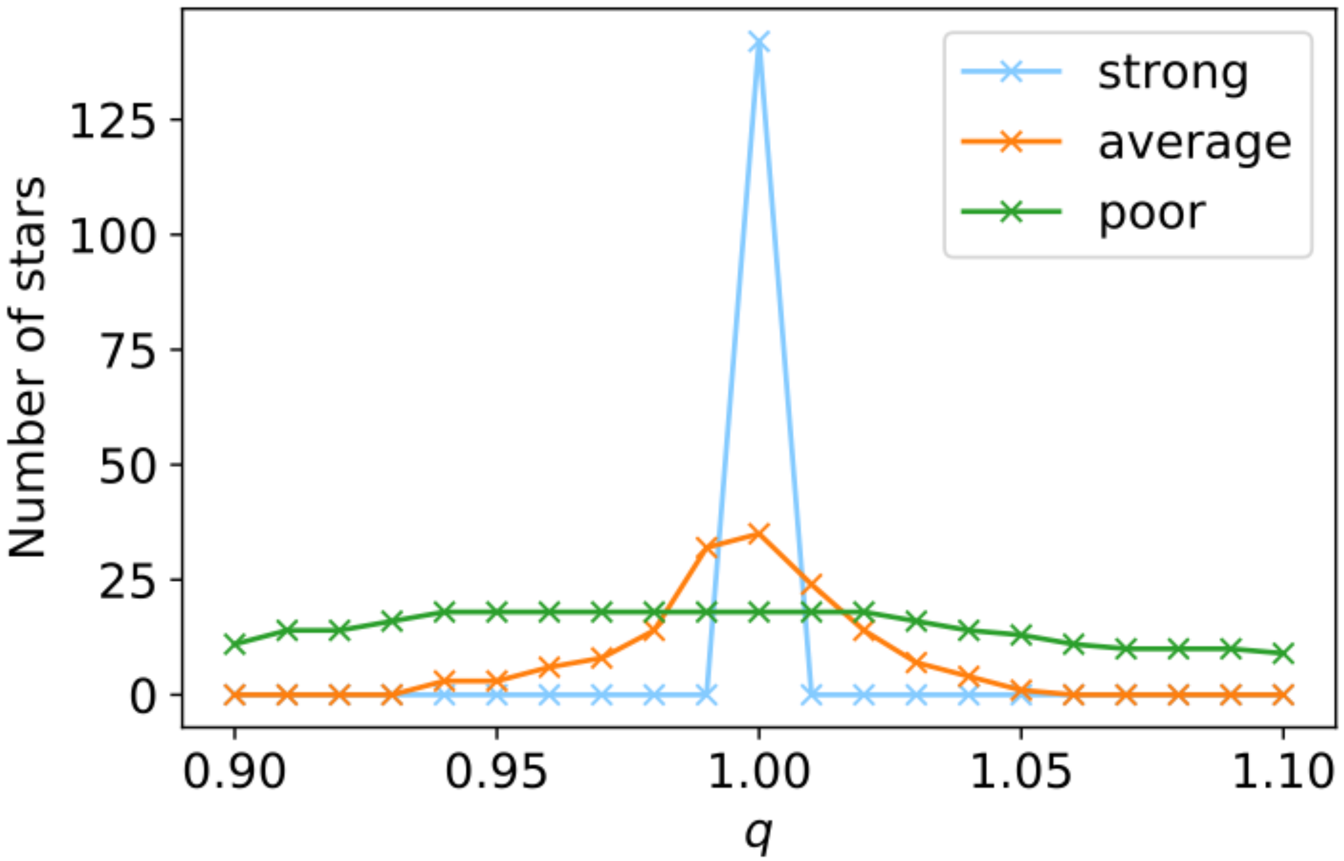
$$\alpha = \frac{M_s}{r_s^2}$$

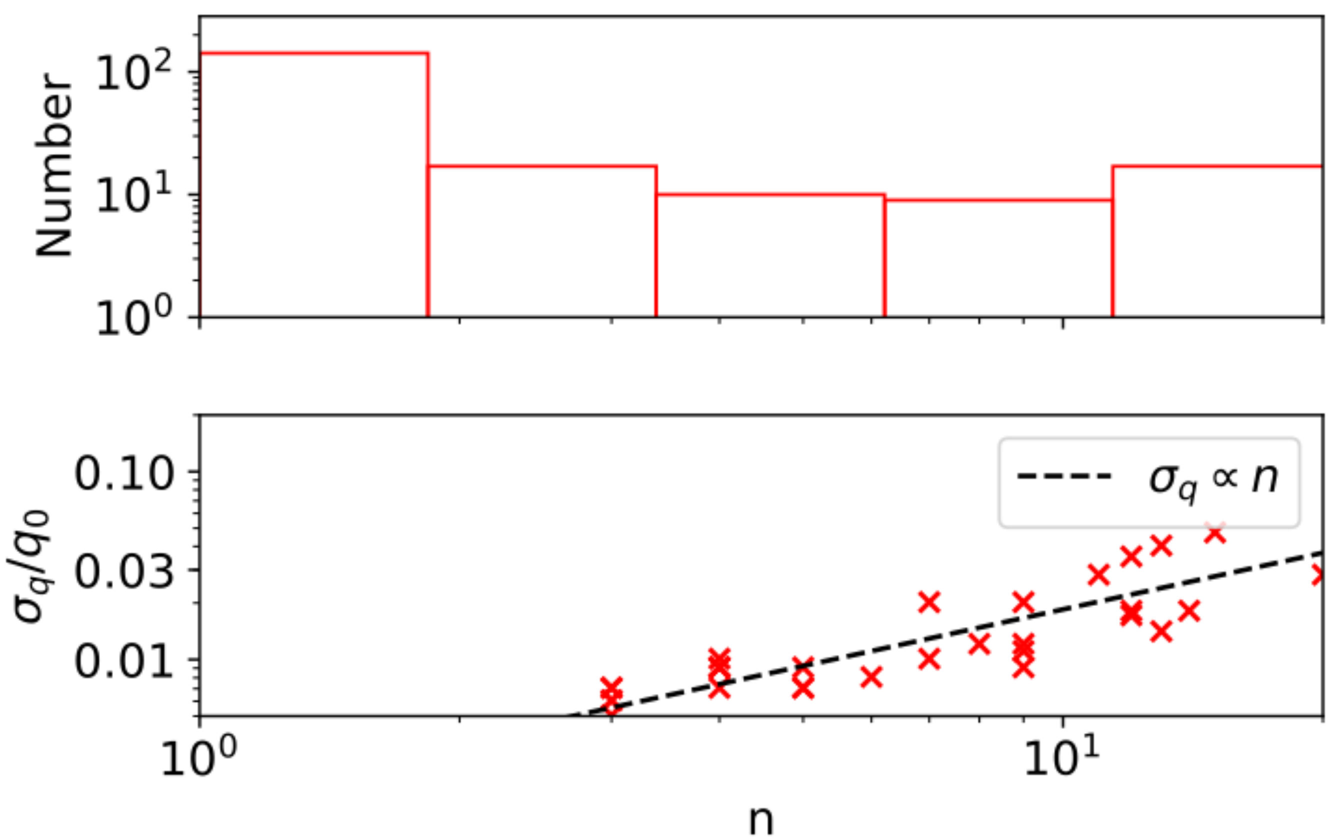




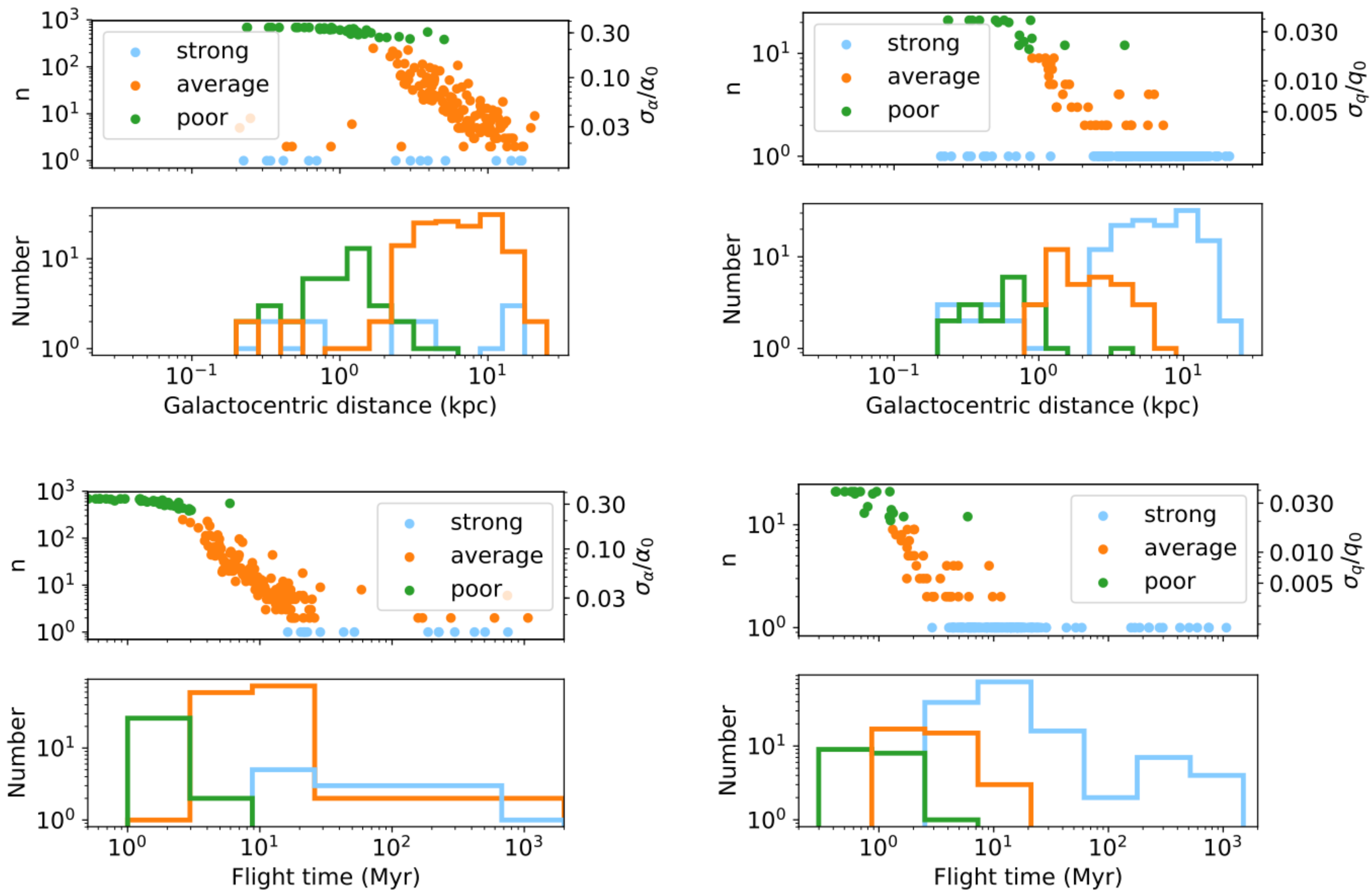
The proportionality constant in $\sigma\alpha(n)$ is found to be equal to $(1.7,1.2,3.3) \times 10^7$ $M_\odot$ kpc^{-2} for halo A, B, C respectively.

q

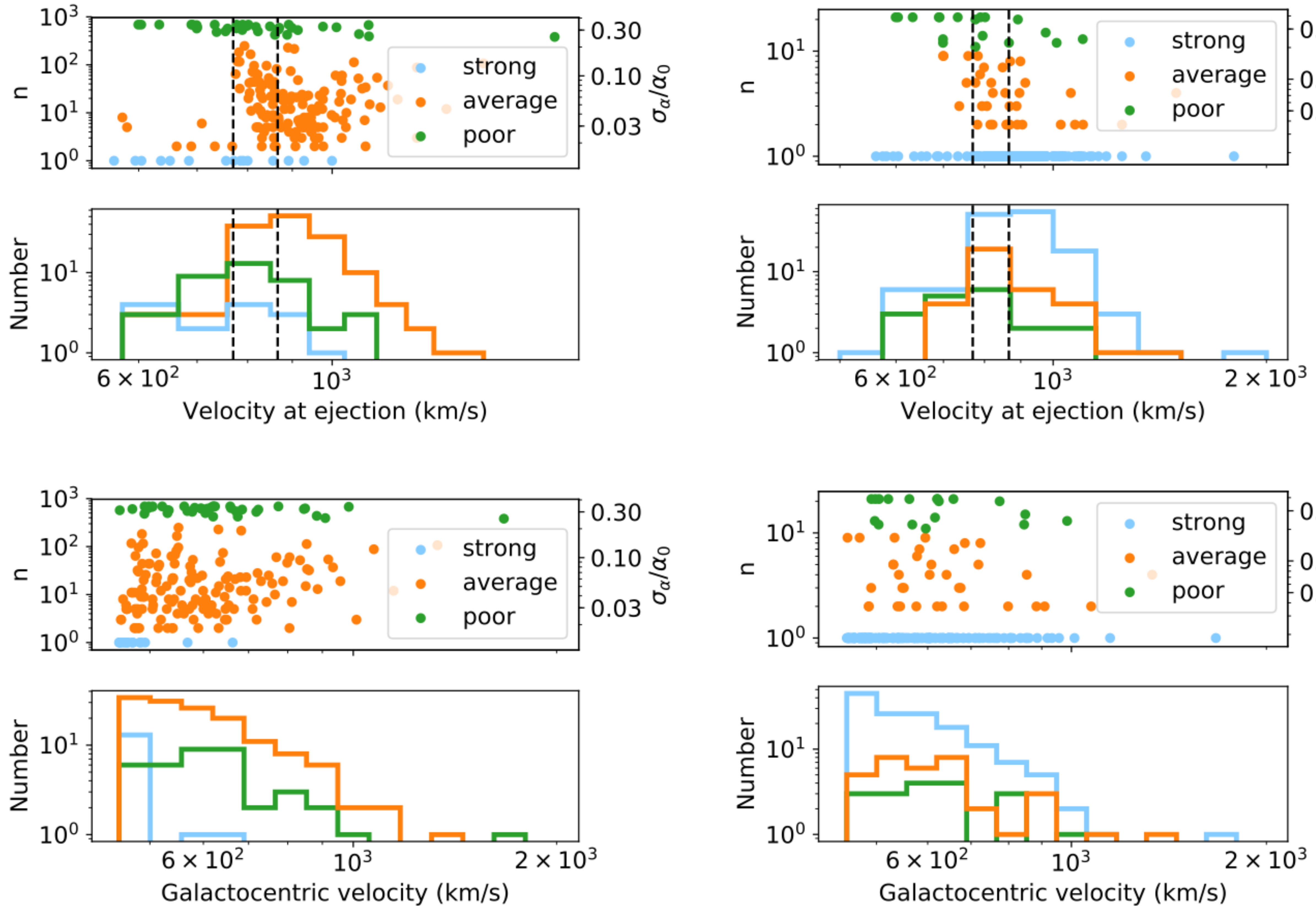




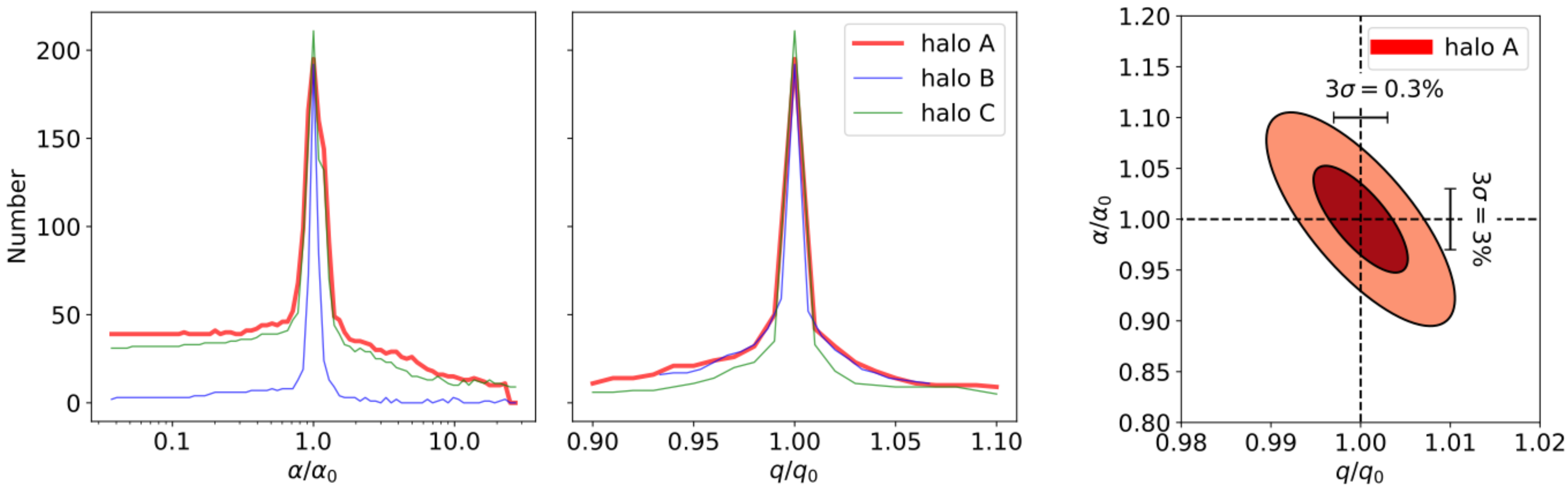
The proportionality constant in $\sigma_q(n)$ is found to be equal to (1.8, 2.3, 2.3) × 10^{-3} for halo A, B, C respectively.



strong
average
poor
n
Number
σ_α/α_0
σ_q/q_0
0.30
0.10
0.03
0.030
0.010
0.005
Galactocentric distance (kpc)
Flight time (Myr)



n
Number
σ_α/α_0
σ_q/q_0
strong
average
poor
Velocity at ejection (km/s)
Galactocentric velocity (km/s)



Number
α/α₀
q/q₀
halo A
halo B
halo C
3σ = 0.3%
3σ = 3%

back-propagating the observed location to the ejection point

—>the density of HVSs for a given stellar mass and phase-space position

$$f(\boldsymbol{w};t|\boldsymbol{\theta}) = \int_0^t dt'\,\mathcal{R}(\boldsymbol{w}'(\boldsymbol{w};t-t'|\boldsymbol{\theta}))\,g(t-t',m). \tag{16}$$

We can then assign for every value of this parameter vector a likelihood to the observation of N_{HVS} HVSs in the configuration space points $\{\boldsymbol{w}_1,\ldots,\boldsymbol{w}_{N_{\mathrm{HVS}}}\}$ at a time t:

$$\mathcal{L}(\boldsymbol{\theta}) = \sum_i^{N_{\mathrm{HVS}}} f(\boldsymbol{w}_i;t|\boldsymbol{\theta}). \tag{17}$$