Momentum-driven Winds from Galaxy Nuclei

Rachael C. McQuillin[1] & Dean E. McLaughlin
Astrophysics Group, Keele University, Keele, Staffordshire, ST5 5BG
[1]r.c.mcquillin@epsam.keele.ac.uk

Introduction

The M-σ relation between supermassive black hole (SMBH) mass, M_{SMBH}, and the velocity dispersion of their host galaxy's bulge, σ, is widely accepted as the result of self regulated feedback from the SMBH (Fabian 1999; Silk & Rees 1998; King 2003, 2005; Murray et. al 2005). Figure 1 shows the scaling $M_{SMBH} \propto \sigma^4$ using data compiled by Marconi & Hunt (2003).

A simple explanation for this correlation is that super-Eddington accretion onto a growing SMBH at the centre of a gaseous protogalaxy drives a wind back into the galaxy, which sweeps up ambient gas into a "supershell." At least initially, the wind cools efficiently by inverse Compton scattering (King 2003), and so the shell is momentum-driven. In this case, the thrust on the shell from the SMBH wind is simply

$$\frac{dp_{wind}}{dt} = \frac{L_{Edd}}{c} = \frac{4\pi G}{\kappa} M_{SMBH} \qquad (1)$$

and the motion of the shell is given by

$$\frac{d}{dt}\left[M_g(r)\, v\right] = \frac{4\pi G}{\kappa} M_{SMBH} - \frac{GM_g(r)}{r^2}\left[M_{SMBH} + M_{DM}(r)\right] \qquad (2)$$

Here $M_{DM}(r)$ is the mass of dark matter within radius r in the galaxy; $M_g(r) \equiv f_g \times M_{DM}(r)$ is the mass of the shell at radius r; and v(r) is the velocity of the shell.

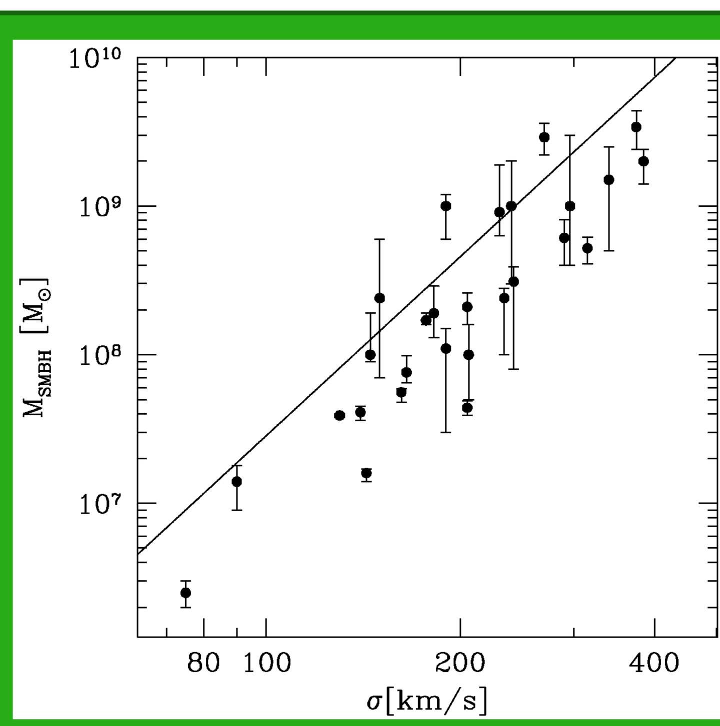

Figure 1 – SMBH mass versus bulge velocity dispersion, from data compiled by Marconi & Hunt (2003). The solid line is Equation (3), the M-σ relation from King (2003, 2005).

In this scenario, there is a critical SMBH mass, denoted M_σ, above which the outwards force of the wind on the shell may overcome the inwards gravitational pull of the SMBH and the dark matter. For the case that the galaxy halo is a singular isothermal sphere with velocity dispersion σ_0, King (2003, 2005, 2010) estimates

$$M_\sigma = \frac{f_g\, \kappa\, \sigma_0^4}{\pi G^2} = 4.56\times10^8\, \sigma_{200}^4\ \mathrm{M_{sun}} \qquad (3)$$

where $\sigma_{200} \equiv \sigma_0/(200\ \mathrm{km\ s^{-1}})$. The idea is that, once an SMBH in a halo with a given σ_0 has grown to this critical mass, the momentum-driven feedback from it can clear the galaxy of all ambient gas, choking off further star formation and SMBH growth and freezing in an M_{SMBH}–σ relation. The relation implied by Equation (3) is shown as the solid line in Figure 1, where, with no free parameters other than an assumed global gas fraction of f_g=0.16, it comes remarkably close to the data.

There are, however, some subtleties in this picture that remain to be fully explored. For example, the line in Figure 1 appears to be an upper limit to the data, suggesting that additional momentum-driven feedback from bulge star formation may contribute to establishing the M_{SMBH}–σ relation (Murray et al. 2005; Power et al. 2011). Moreover, numerical simulations show cases of "failed feedback," in which the wind from an SMBH of mass M_σ in an isothermal galaxy halo is not in fact strong enough to clear the galaxy of gas (Nayakshin & Power 2010). Analytical considerations also imply that, in detail, a purely momentum-driven supershell cannot alone do the work to clear the huge masses of gas at large radii in isothermal galaxies, unless M_{SMBH} is many times larger than M_σ (Silk & Nusser 2010).

One solution to these issues may be to rely on the supershell transitioning from being momentum-driven to energy-driven as cooling times change when the shell reaches large galactocentric radii (King 2003; Power et al. 2011). Another, which we focus on here, is to re-visit the motion and the possible escape of momentum-driven shells from more realistic, ***non-isothermal dark matter haloes***.

The Singular Isothermal Sphere

First, Figure 2 shows some velocity profiles satisfying the equation of motion (3) for a momentum-driven supershell in a singular isothermal sphere dark matter halo, which has

$$M_{DM}(r) = \frac{2\sigma_0^2\, r}{G} \qquad (4)$$

Each curve corresponds to a different initial condition for the shell velocity at small *r*. The radial coordinate is scaled by

$$r_\sigma \equiv \frac{G M_\sigma}{\sigma_0^2} = \frac{f_g\, \kappa\, \sigma_0^2}{\pi G} \approx 50\ \mathrm{pc}\ \sigma_{200}^2 \qquad (5)$$

For low SMBH masses, $M_{SMBH} < M_\sigma$ (left-hand panel), every v(r) solution stalls (i.e. v = 0) at some finite radius , and no momentum-driven shell can escape the galaxy. At the "critical" SMBH mass, $M_{SMBH} \approx M_\sigma$ (middle panel) ***some*** momentum-driven shells tend to a non-zero coasting speed at arbitrarily large radius, ***but*** only if they start with extremely high velocities at very small radii. Moreover, the asymptotic coasting speed is well below the nominal "escape" velocity from an isothermal sphere, $v_{esc} \approx 2\sigma$ (shown by the horizontal blue line). It is only for M_{SMBH} at least a few times larger than M_σ (right-hand panel) that some supershells can reach large radii with sufficient speed to escape an isothermal galaxy—and there are still solutions that stall at finite *r*. We conclude that , indeed, the "critical" SMBH mass in Equation (3) does not guarantee the break-out of momentum-driven feedback from a singular isothermal sphere (cf. Nayakshin et al.; Silk & Nusser).

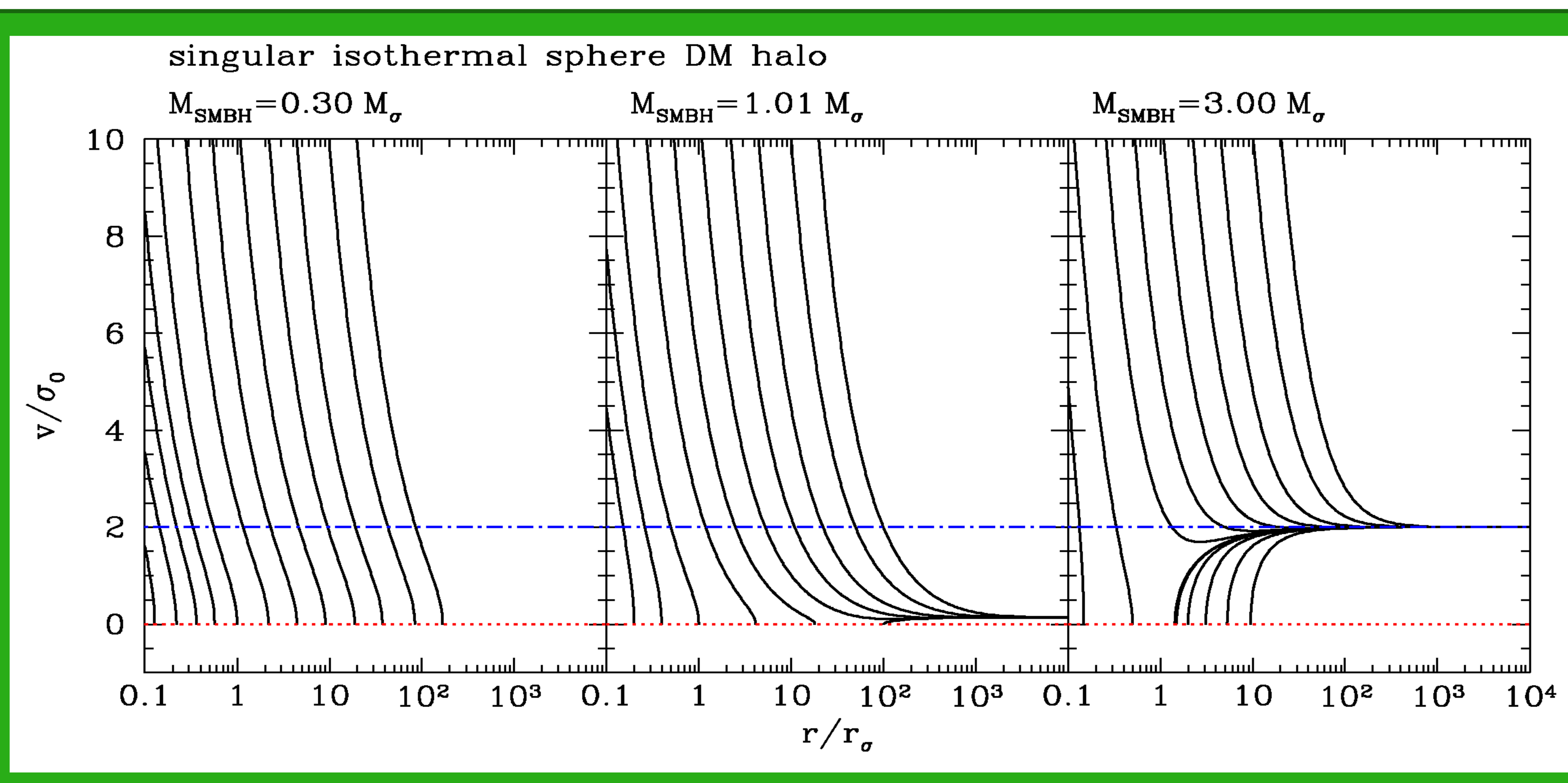

Figure 2 — Families of solutions to the equation of motion for a momentum-driven supershell in a singular isothermal dark-matter halo., for different values of M_{SMBH}. The scale radius r_σ is equal to 50 pc σ_{200}^2 (Eq. 5).

Beyond the Singular Isothermal Sphere

The situation is somewhat different for momentum-driven shells in non-isothermal dark matter haloes—particularly ones with density profiles steeper than r^{-2} at large radii. Here, for analytical convenience, we consider the Hernquist (1990) density profile, which has

$$\rho_{DM}(r) \propto r^{-1}(r+r_0)^{-3} \quad \text{and} \quad M_{DM}(r) = M_{tot}\frac{r^2}{(r+r_0)^2} \qquad (6)$$

where M_{tot} is the total halo mass; r_0 is the radius at which the rotation curve peaks; and we identify a characteristic velocity dispersion as $\sigma_0^2 \equiv V_{c,peak}^2 / 2$. Figure 3 shows solutions for v(r) from Equation (2) in this case, for halo parameters relevant to a Milky Way-sized galaxy. When $M_{SMBH} < M_\sigma$ (left panel) all solutions again stall at a finite radius and purely momentum-driven shells cannot blow out of the galaxy. However, when $M_{SMBH} \geq M_\sigma$ (middle panel and right panel), it ***is*** now the case that ***any*** momentum-driven shell can reach large radius in the galaxy, where it will ***always*** accelerate (because of the steeper-than-isothermal density profile) and eventually exceed the finite escape velocity of the halo (shown in Figure 3 as the broken blue curve in all panels). Thus, the "critical" SMBH mass identified by King (2003, 2005) is sufficient to guarantee the escape of momentum-driven SMBH feedback in a realistically non-isothermal galaxy potential. Figure 4 shows that this conclusion is insensitive to the value of M_{tot} or σ_0 in a Hernquist halo.

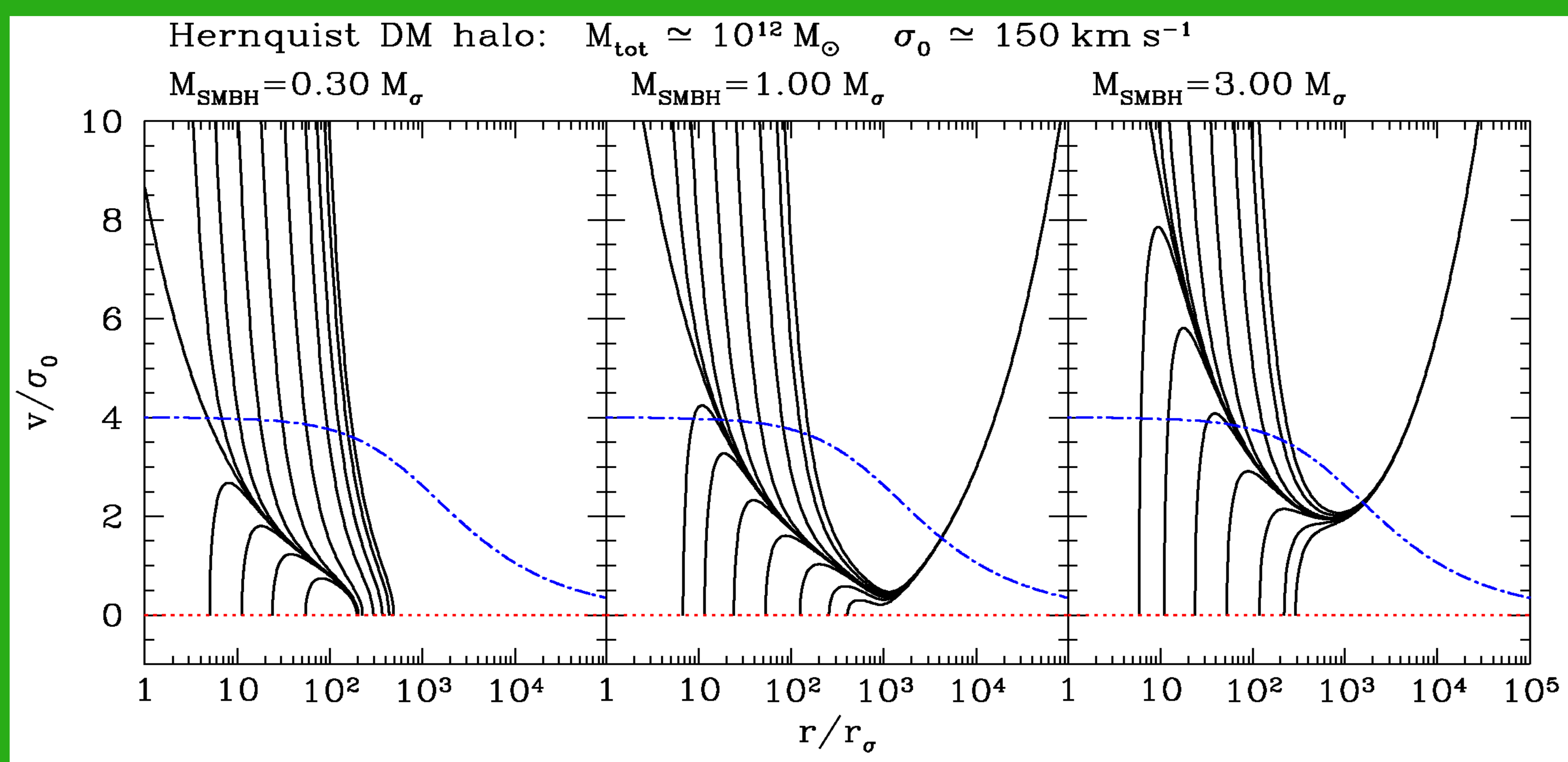

Figure 3 — Families of solutions to the equation of motion for the Hernquist model with a L*-galaxy sized halo. The characteristic radius is r_σ = 50 pc σ_{200}^2. The blue curve shows the escape velocity for the halo.

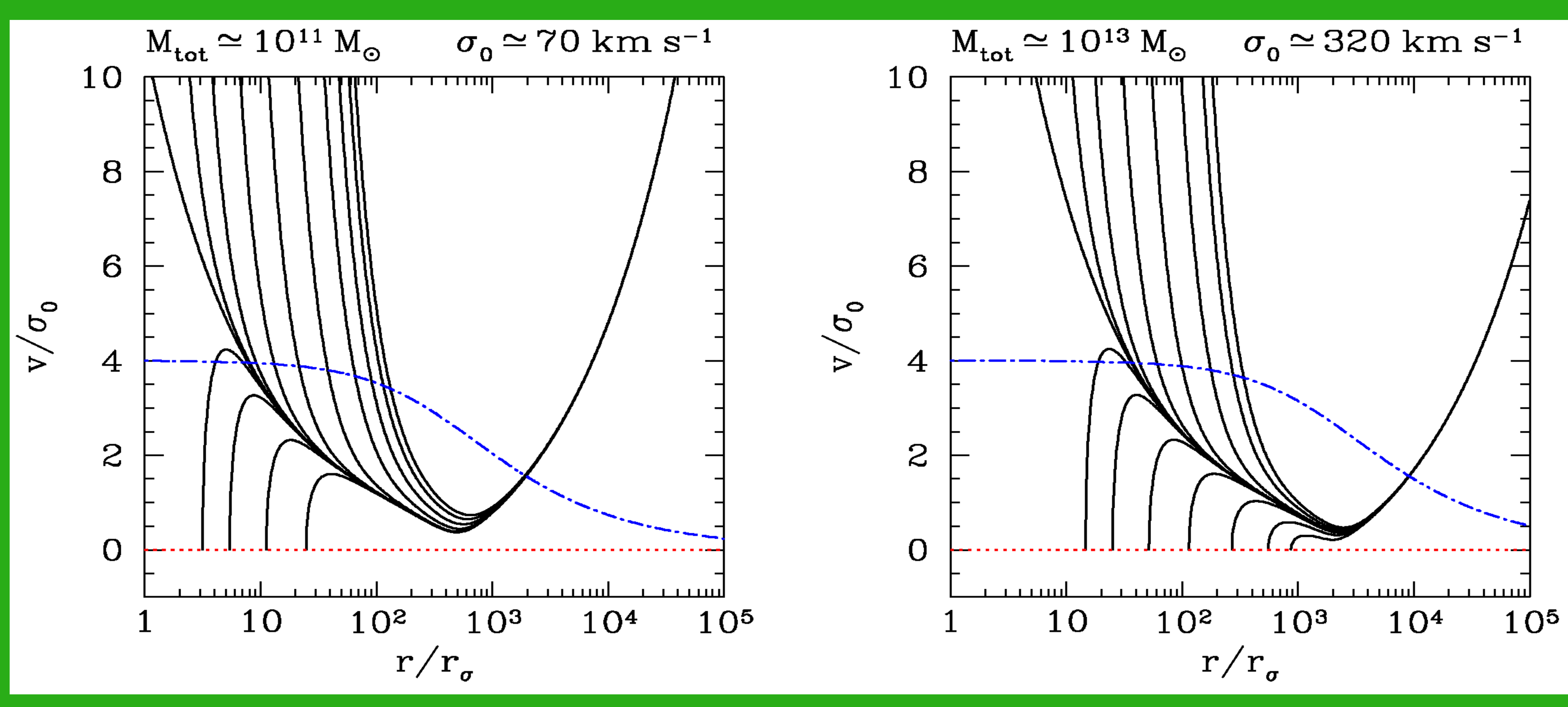

Figure 4 — Families of solutions for the velocity of momentum-driven supershells in Hernquist dark-matter haloes with masses about 0.1x and 10x that of an L* galaxy. In both cases, $M_{SMBH} = M_\sigma$. The radius r_σ = 50 pc σ_{200}^2.

Summary

In agreement with other works, we find that $M_{SMBH} = M_\sigma$ is necessary but not sufficient to allow the escape of a momentum-driven supershell from a singular isothermal sphere, and that escape is dependent upon the velocity of the supershell at small radii. In the case of the Hernquist halo we find that $M_{SMBH} \approx M_\sigma$ still represents a critical mass at which the momentum-driven supershell can escape but, in contrast to the singular isothermal sphere, this escape is independent of the initial velocity of the supershell. Moreover, this result is insensitive to the total halo mass and velocity dispersion.

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