Splashback shells as a physical boundary of dark matter halos

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Cambridge, KICC workshop “Galaxy clusters: physics laboratories and cosmological probes”
\[ M_\Delta = \frac{4\pi}{3} \Delta \rho_{\text{crit}}(z) R_\Delta^3 \]

\[ \rho_{\text{crit}}(z) = \frac{3H^2(z)}{8\pi G} \]

\[ R_{\text{vir}} \approx R_{100} \]

at \( z \approx 0 \)

\[ R_{\text{vir}} \approx R_{200} \]

at \( z > 1 \)

\[ R_{2500} : R_{500} : R_{200} \approx 0.3 : 0.6 : 1.0 \]
$R_\Delta$ definitions are motivated by the spherical collapse model, but do any of these correspond to a halo boundary?

Example: velocity dispersion-mass correlation:

$$\sigma \propto \sqrt{\frac{M}{R}} \propto \rho_{\text{ref}}^{1/6} M^{1/3}$$

Is boundary apparent in the halo density profiles?

\[ \nu \equiv \frac{\delta_c}{\sigma(M, z)} \]

\[ \delta_c = 1.686 \]

\[ \sigma(M) = \sigma(R[M]) = \frac{1}{2\pi^2} \int_{0}^{\infty} k^2 P(k) |\tilde{W}(kR)|^2 dk \]

Density profile with steepening out to 10 Rvir (and more) available in the public Colossus python package: http://www.benediktdiemer.com/code/

Sharp steepening of the density profiles in the outskirts of high-$\nu$ halos

cf. also Adhikari et al. 2014, JCAP

similar trend as a function of halo mass accretion rate

$$\Gamma \equiv \frac{\ln M_{200m}(z_{i+1}) - \ln M_{200m}(z_i)}{\ln a(z_{i+1}) - \ln a(z_i)}$$

$z_i=0.5; \ z_{i+1} = 0$

1.5 $\nu$ 2
Sharp steepening of the density profiles in the outskirts of high-v halos

similar trend as a function of halo mass accretion rate

\[ 1.5 < v < 2 \]

\[ \frac{d \log \rho}{d \log r} = \gamma \]

Sharp steepening of the density profiles in the outskirts of high-$\nu$ halos

similar trend as a function of halo mass accretion rate

what are these density drops?

they are formed by the recently accreted matter that passed through halo just once and has "splashed back" to the first apocenter. Such density drops were predicted by the secondary infall models (e.g., Gunn & Gott ’72; Fillmore & Goldreich ’84; Bertschinger ’85; Lithwick & Dalal ’11; Vogelsberger et al. ’11; Adhikari et al. ’14)

radial velocity-radius diagram and density profile predicted in such models for initial density peaks of different ellipticity; e=0 is spherically symmetric peak (from Lithwick & Dalal 2011)
real CDM halos are messier due to substructure, but fundamentally show the same features

evolution of matter in the vr-r plane for the Via Lactea 2 \(~1 \times 10^{12}\) Msun halo
(Fig 2 of Diemand et al. 2008, ApJL 680, L25)
but these sharp density drops can be seen in density distribution around halos

Density distribution around a massive galaxy cluster (More et al. 2015, ApJ 810, 26)
Identifying splashback shells of individual CDM halos

Mansfield, Kravtsov & Diemer, arXiv tomorrow
cf. also Diemer+, in prep.

\[ r(\phi, \theta) = \sum_{i,j=0}^{p-1} \sum_{k=0}^{1} c_{ijk} \sin^{i+j} \theta \cos^{k} \theta \sin^{j} \phi \cos^{i} \theta \]
SHELLFISH (splashback SHELL Finding In Spheroidal Halos) code will be released tomorrow at:
https://github.com/phil-mansfield/shellfish

Written in Go, but you don’t need to know Go to use it. For any C and python coder, Go syntax is easily readable.

Google search for 'go' shows approximately 7,430,000,000 results in 0.44 seconds.

Go (game) - Wikipedia
https://en.wikipedia.org/wiki/Go_(game)
Go is an abstract strategy board game for two players, in which the aim is to surround more territory than the opponent. The game was invented in ancient China...
Players: 2  Skill(s) required: Strategy, tactics, observation
Age range: 3+  Years active: prior to Zhou Dynasty (1046–256...)

GO Outdoors | Outdoor Clothing | Walking Boots | Winter Jackets
www.gooutdoors.co.uk/
The UK's Biggest Outdoor Stores. Buy waterproof clothing, outdoor clothing, tents, camping equipment and more available at great prices online and in store.
Camping · Tents · Men's · Women's

The Go Programming Language
https://golang.org/
Documentation, source, and other resources for Google’s Go language.
various properties quantifying splashback shells can be defined - e.g., their shape

splashback shells are not ellipsoids

ellipticity and asphericity:

\[ a_{sp}, b_{sp}, c_{sp} \equiv \text{Axes}(I_x, I_y, I_z) \]
\[ E_{sp} \equiv \frac{a_{sp}}{c_{sp}} - 1 \]
\[ A_{sp} \equiv 1 - \frac{S_{sp}}{(36\pi V_{sp}^2)^{1/3}} \]
Equivalent radius of splashback shells

\[ R_{sp} \equiv \left( \frac{3V_{sp}}{4\pi} \right)^{1/3} \]

Splashback radius is defined as the radius of the sphere which has the volume enclosed by the splashback shell.
Splashback radius vs mass accretion rate relation

Mansfield, Kravtsov & Diemer, arXiv tomorrow

\[ \Gamma \equiv \frac{\ln M_{200m}(z_{i+1}) - \ln M_{200m}(z_i)}{\ln a(z_{i+1}) - \ln a(z_i)} \]

- Splashback radii measured for individual halos from 3d density
- Splashback radii measured for stacked density profiles for samples of halos (Diemer & Kravtsov ‘14; More et al. ‘15)
substructure introduces bias in the stacked density profiles

mean density in a shell (the usual way)

using median density in sub-volumes of a shell largely removes contribution of massive subhalos.

three representative halo profiles

\[
\frac{\rho}{\rho_m} 
\]

\[
\frac{d\ln \rho}{d\ln r} 
\]
Splashback radius estimated from the stacked profiles of median density agree with the individual halo measurements.

\[ \Gamma \equiv \frac{\ln M_{200m}(z_{i+1}) - \ln M_{200m}(z_i)}{\ln a(z_{i+1}) - \ln a(z_i)} \]

Mansfield, Kravtsov & Diemer, arXiv tomorrow
Splashback radius vs mass accretion rate relation fits

Mansfield, Kravtsov & Diemer, arXiv tomorrow

\[ \frac{R_{\text{sp}}}{R_{200m}} \propto \Gamma^{\alpha \nu} \]

with log-normal scatter around it (see paper above for details and fit parameters)
Density contrast enclosed within splashback shell vs mass accretion rate relation fits

\[
\frac{\rho_{\text{sp}}}{\rho_{\text{m}}} \propto \Gamma^{\alpha' \nu}
\]

with log-normal scatter around it (see paper above for details and fit parameters)
splashback radius detected (?)

DETECTION OF THE SPLASHBACK RADIUS AND HALO ASSEMBLY BIAS OF MASSIVE GALAXY CLUSTERS

Surhud More 1, Hiroya Miyatake 2,3,1, Masahiro Takada 1, Benedikt Diemer 4, Andrey V. Kravtsov 5,6,7, Neal K. Dalal 8,1, Anupreeta More 1, Ryoma Murata 1,9, Rachel Mandelbaum 10, Eduardo Rozo 11, Eli S. Rykoff 12, Masamune Oguri 9,13,1, David N. Spergel 3,1

arXiv:1601.06063

…but at a smaller than predicted radius???

Stacked surface density profiles of galaxies of different luminosity around redMaPPer clusters

Corresponding logarithmic slope
$$M_\Delta = \frac{4\pi}{3} \Delta \rho_{\text{crit}}(z) R_\Delta^3$$

$$\rho_{\text{crit}}(z) = \frac{3H^2(z)}{8\pi G}$$
splashback shell can be thought of as a physical boundary of halos as it separates matter accreting for the first time from the matter that orbited at least once.

it can be detected around CDM halos statistically

density profiles with splashback can be easily computed using public Colossus code (python):
http://www.benediktdiemer.com/code/

or for individual halos
Mansfield, Kravtsov & Diemer, arXiv tomorrow
SHELLFISH code will be released at: https://github.com/phil-mansfield/shellfish

splashback shells have aspherical, “oval” shapes and extend to ~1-1.5 $R_{200m}$, and enclose density contrast of ~100-200. These numbers depend on mass accretion rate and peak height of halos. Mansfield, Kravtsov & Diemer, arXiv tomorrow

it should be possible to detect and measure splashback in galaxy surface density profiles or mass density profiles probed via weak lensing (possibly gas signature in density or pressure).