Splashback radius as a physical boundary of clusters

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galaxy cluster Abell 85
SDSS/Chandra X-ray observatory
"Virial" radii:

\[ M_\Delta = \frac{4\pi}{3} \Delta \rho_{\text{crit}}(z) R_\Delta^3 \]

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

\[ R_{200} : R_{500} : R_{2500} \approx 0.3 : 0.6 : 1.0 \]

\[ R_{\text{vir}} \approx R_{100} \text{ at } z \approx 0 \]

\[ R_{\text{vir}} \approx R_{200} \text{ at } z > 1 \]
standard $R_\Delta$ definitions do not correspond to any distinct feature in the cluster profiles (i.e. equilibrium is maintained beyond them)

example: Jeans equation implies that velocity dispersion and mass profiles in equilibrium should be related as

$$M(<r) \approx \eta_\sigma \frac{\sigma^2_r}{G} r$$

![Graph showing no sharp change of $\eta_\sigma$ at any of the commonly used $R_\Delta$](image)

$R_{\Delta c} - \Delta$ is defined wrt $\rho_{\text{crit}}$

$R_{\Delta m} - \Delta$ is defined wrt $\rho_{\text{mean}} = \Omega_m \rho_{\text{crit}}$

a sharp feature can be seen in the outskirts of clusters in simulations in the density distribution

evolution of density field of dark matter in a region where a galaxy cluster-sized object forms $z = 49.0$
in a numerical simulations of cluster formation in a cold dark matter (CDM) model with cosmological constant

animation by B. Diemer and P. Mansfield
www.benediktdiemer.com/visualization/movies
sharp density drops in the outskirts are predicted in simple models of cluster collapse

they are formed by the recently accreted matter that passed through halo just once and "splashed back" to the first apocenter.

Such density drops were predicted by the secondary infall models for both dark matter and gas (e.g., Gunn & Gott '72; Fillmore & Goldreich '84; Bertschinger '85; Lithwick & Dalal '11; Vogelsberger et al. '11; Adhikari et al. '14; Shi '16)

radial velocity-radius diagram and density profile predicted in such models for initial density peaks of different ellipticity; e=0 is spherically symmetric peak [Lithwick & Dalal 2011]
Sharp steepening of the density profiles in the outskirts of halos as a function of peak height and mass accretion rate


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

\[ \sigma(M) = \sigma(R[M]) = \frac{1}{2\pi^2} \int_0^\infty k^2 P(k) |\vec{W}(kR)|^2 dk \]

\[ \delta_c = 1.686 \]

\[ z_i, z_{i+1} = 0 \]

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shapes of 3d splashback shells of individual CDM halos

splashback shells modelled using Penna-Dine (2007) surfaces:

\[ r(\phi, \theta) = \sum_{i,j=0}^{P-1} \sum_{k=0}^{1} c_{ijk} \sin^{i+j} \theta \cos^k \theta \sin^i \phi \cos^j \theta \]

Their shape is characterized by the “asphericity” and “ellipticity” parameters:

(for sphere: \(A_{sp} = 0, E_{sp} = 0\))

and by the radius of a sphere of equivalent volume:

\[ A_{sp} = 1 - \frac{S_{sp}}{(36\pi V_{sp}^2)^{1/3}} \quad E_{sp} = \frac{d_{sp}}{c_{sp}} - 1 \]

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

splashback shells typically have non-ellipsoidal ("snowball") shapes

ellipsoids live in this band

What about gas?

Gas density and pressure drops at the splashback radius are predicted by simulations (Ryu et al. ‘03; Molnar et al. ‘09; Aung, Lau, & Nagai in prep., Lau et al ‘15), but two different physical boundaries in gas distribution are predicted: splashback and outer shock at much larger radii (originated via bow shocks driven inside out during the last major merger).

Beware of some confusion in terminology in the literature: Hurier et al.’18 interpret pressure drop indicated by SZ observations of A2319 as due to “virial shock” but in recent literature this would be called a “splashback shock”.
First detection of splashback in gas pressure profile?

Hurier, Adam & Keshet 2018 (arXiv/1712.05762)

Planck SZ observations of Abell 2319 (~7-10' resolution, $R_{500c} \sim 17'$)

sharp decrement drop at $2.9 \pm 0.05$ $R_{500c}$ $\sim 1.1 R_{200m}$ exactly where splashback is expected
splashback radius detected (?)

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

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


clear signature of splashback in the radial distribution of galaxies in cclusters …but at a smaller than predicted radius???

possible systematic effects (Bush & White 2017; Zu & Mandelbaum 2017)

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

corresponding logarithmic slope

radius from the cluster center
first detection of the splashback in mass distribution using weak lensing measurements in the Dark Energy Survey (DES)

Chang, Baxter et al. 2017, arXiv/1710.06808
cf. also lower limit on Rsp by Umetsu & Diemer ‘17

profile probed by weak lensing

\[ \Delta \Sigma(R) = \overline{\Sigma}(R) - \Sigma(R) \]
splashback radius and galaxy quenching

The difference between profiles of red (quenched) and blue (star-forming) galaxies indicates that most accreted galaxies in clusters stop forming stars before they reach first apocenter of their orbit


stacked surface density profiles of galaxies of different luminosity around redMaPPer clusters of richness >20 + profiles of the reddest and bluest quartiles
splashback shell can be thought of as a physical boundary of clusters, 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 in average ("stacked") profiles


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

or for individual simulated halos


splashback shells have aspherical, “potato” shapes and extend to ~0.8-1.5 \( R_{200m} \), enclosing density contrast of ~50-400. These numbers depend on mass accretion rate and peak height of halos, and mildly on cosmology. (Diemer & Kravtsov 2014; More+ 2015; Mansfield+ 2017, Diemer+ 2017)

Gas density and pressure are predicted to have sharp drops at the splashback shell

(Aung, Lau & Nagai, in prep.)

signature of splashback was recently detected in galaxy surface density profiles and now also in mass density profiles probed via weak lensing, and likely in the gas pressure profiles.

Hurier et al. 2018 (arXiv/1712.05762)
implications

- Environmental effects of clusters on galaxies can be manifested to larger radii than commonly used $R_\Delta$.

- A sharp and detectable feature is predicted in the distribution of matter and galaxies (as well as gas density and pressure) in the outskirts of clusters.

- For clusters of a given mass radius of splashback (i.e., a physical scale) is predicted as a function of cosmology and cluster redshift.

- Potential for measurement, studies of environmental effects, tests of modifications of gravity and self-interaction cross-section of dark matter.
splashback radius and mass vary as a function of halo mass, mass accretion rate, and cosmology

cf. also Diemer & Kravtsov 2014, Adhikari et al. 2014;
Mansfield, Kravtsov & Diemer 2017, Diemer et al. 2017

For typical cluster mass accretion rates splashback is predicted to be located at $R_{sp} \sim 0.9 - 1.2 R_{200m} \sim 2.6 - 3 R_{500c}$
splashback radius, mass, and enclosed density contrast vary as a function of peak height, mass accretion rate and cosmology


dependence on cosmology

dependence on operational definition of splashback using apocenters of particle trajectories

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