The splashback boundary of galaxy clusters in mass and light and its implications for galaxy evolution

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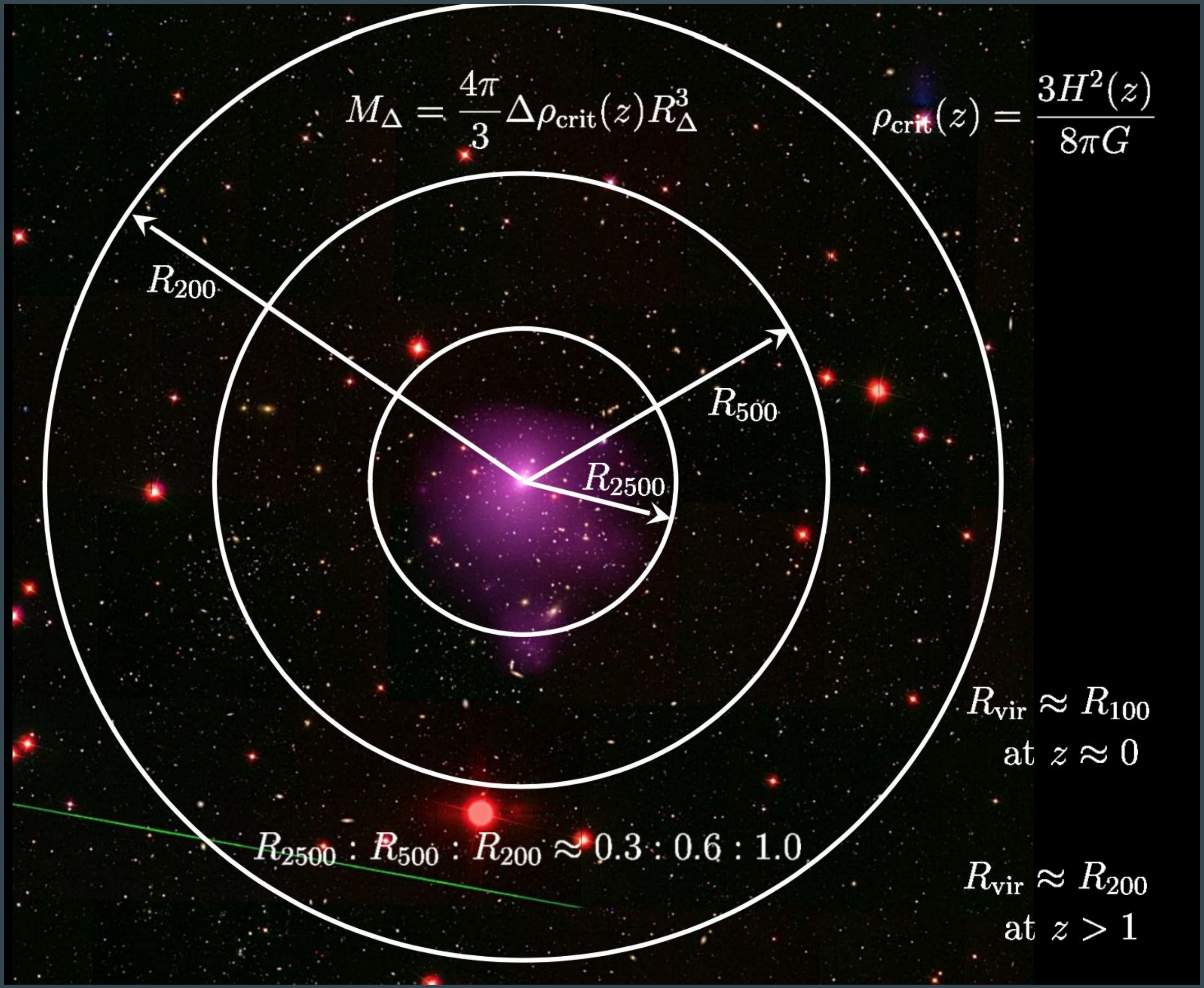
(DES collaboration) (SPT collaboration) (ACT collaboration)

https://arxiv.org/abs/1811.06081 (accepted to MNRAS); 2019 paper in preparation
Based on ~400 public cluster sample from ACT+SPT
Ongoing analysis of 1000+ SZ-selected clusters from DES+ACT+SPT

Background

Mass and boundary of dark matter halos



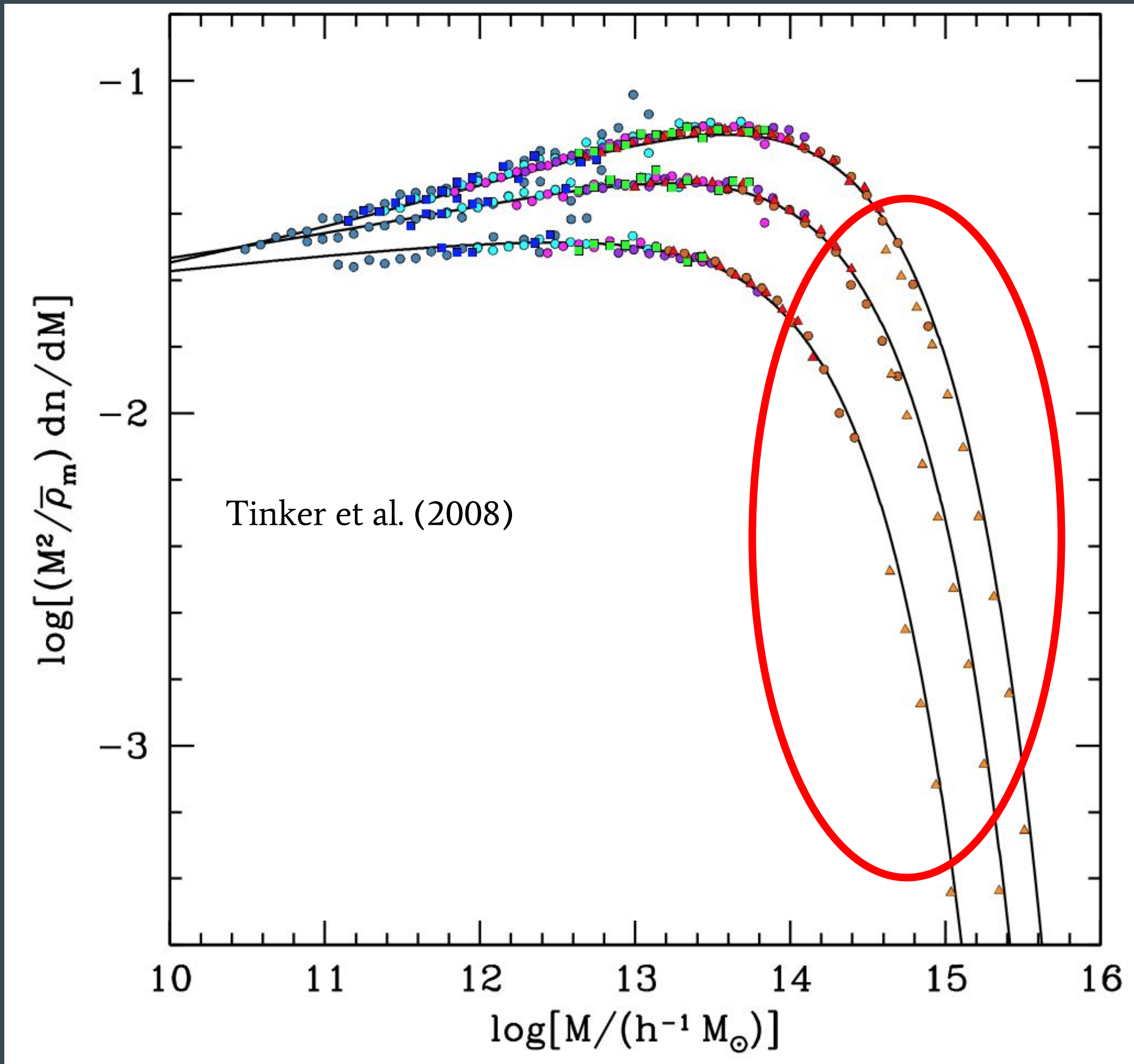
Credit: Andrey Kravtsov

However, M_Δ and R_Δ are subject to pseudo-evolution due to the decrease in the reference density (ρ_c or ρ_m)

Haloes continuously accrete matter; there is no radius within which the matter is fully virialized

$\Rightarrow$ where is the physical boundary of the halos?

Cosmology with galaxy clusters



Galaxy clusters live in the high-mass tail of the halo mass function
⇒ very sensitive to the growth of the structure (Ω_m and σ_8)

Thus, it is important to accurately define/measure the mass of the cluster

Preliminary work by Diemer et al. illuminates that the mass function becomes more universal against redshift when we use so-called “splashback radius” as the physical boundary of the dark matter halos

Background

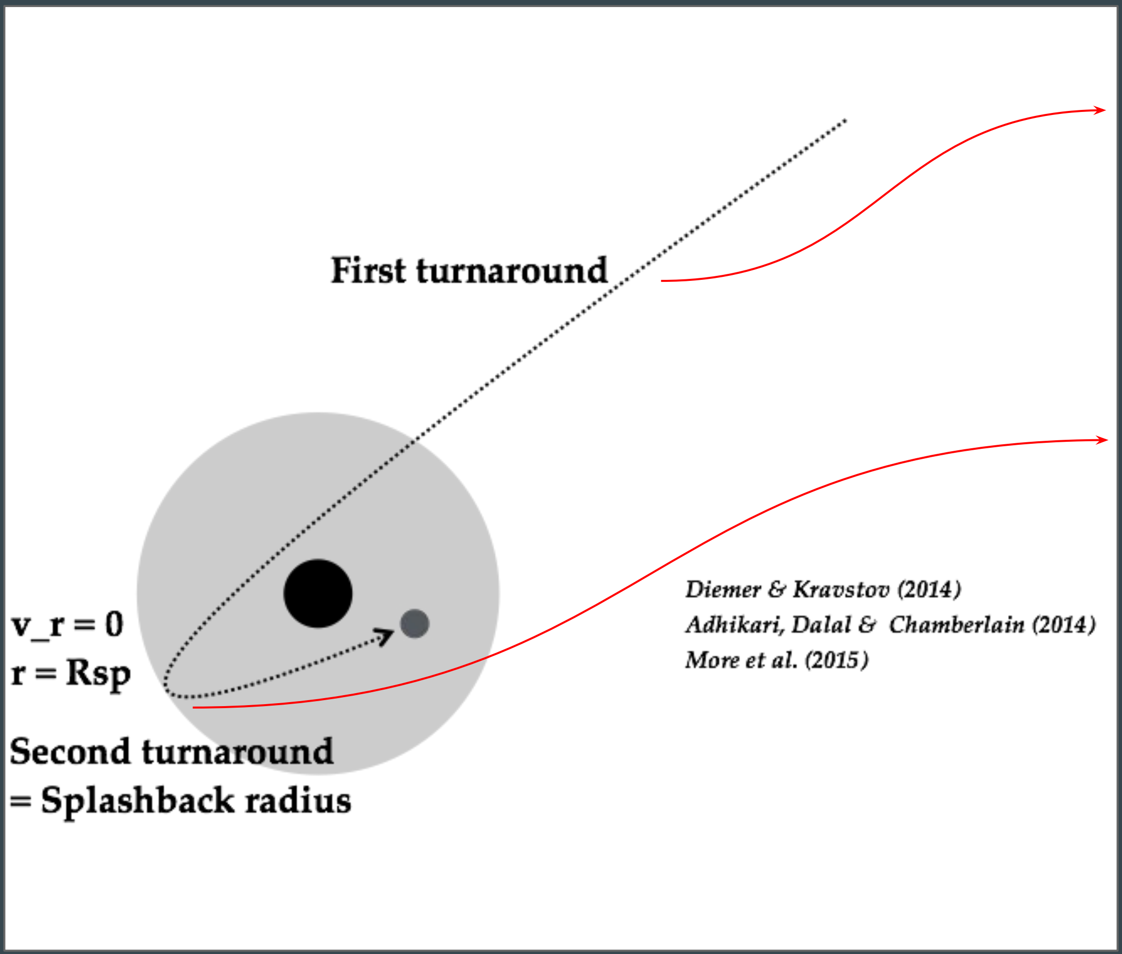
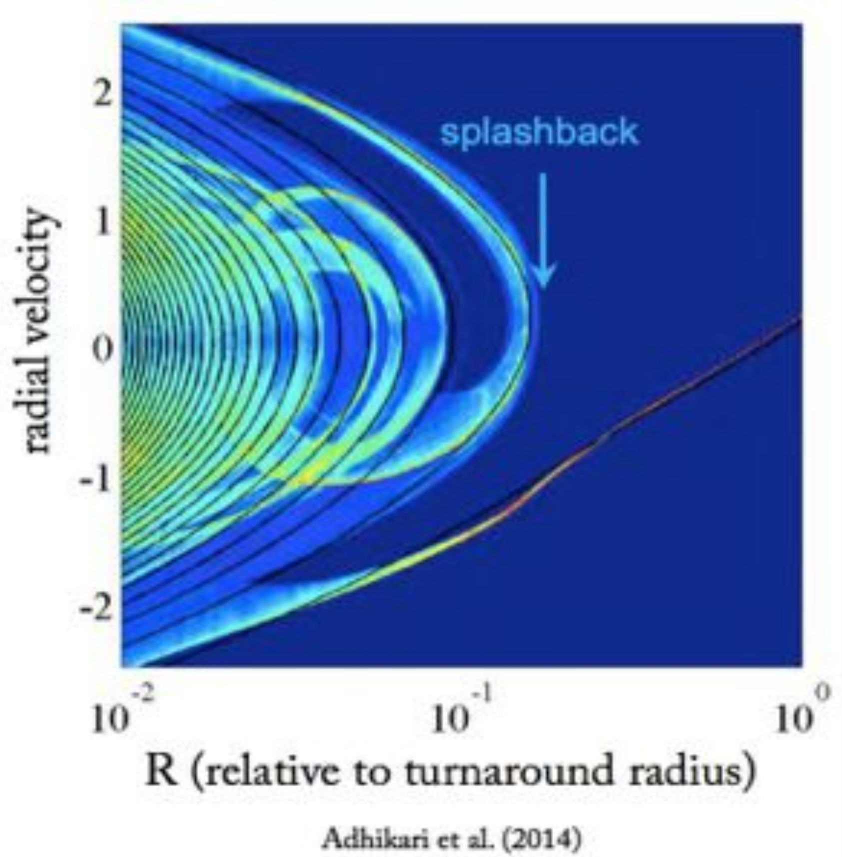


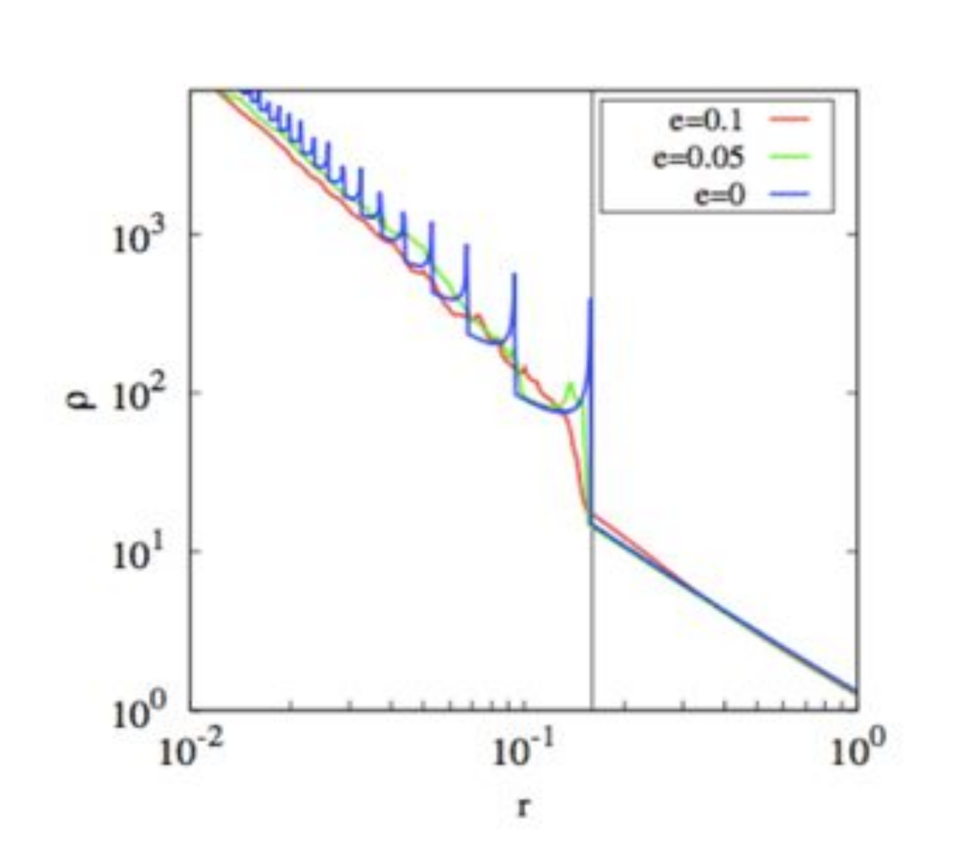
Fig. from Chihway Chang (UChicago)

- Galaxies fall into the cluster potential, escaping from the Hubble flow
- They form a sharp "physical" boundary around their first apocenters after the infall, which we call "splashback radius"

Background

- A simple spherical collapse model can predict the existence of the splashback feature (Gunn & Gott 1972, Fillmore & Goldreich 1984, Bertschinger 1985, Adhikari et al. 2014)





Background

- Galaxy clusters exhibit a sharp decline in density profile around the first orbital apocenters of accreting particles
- Splashback radius, r_{sp}, represents the location of the steepest logarithmic slope and it mostly depends on accretion rate of the matter into the clusters, and mass of the clusters

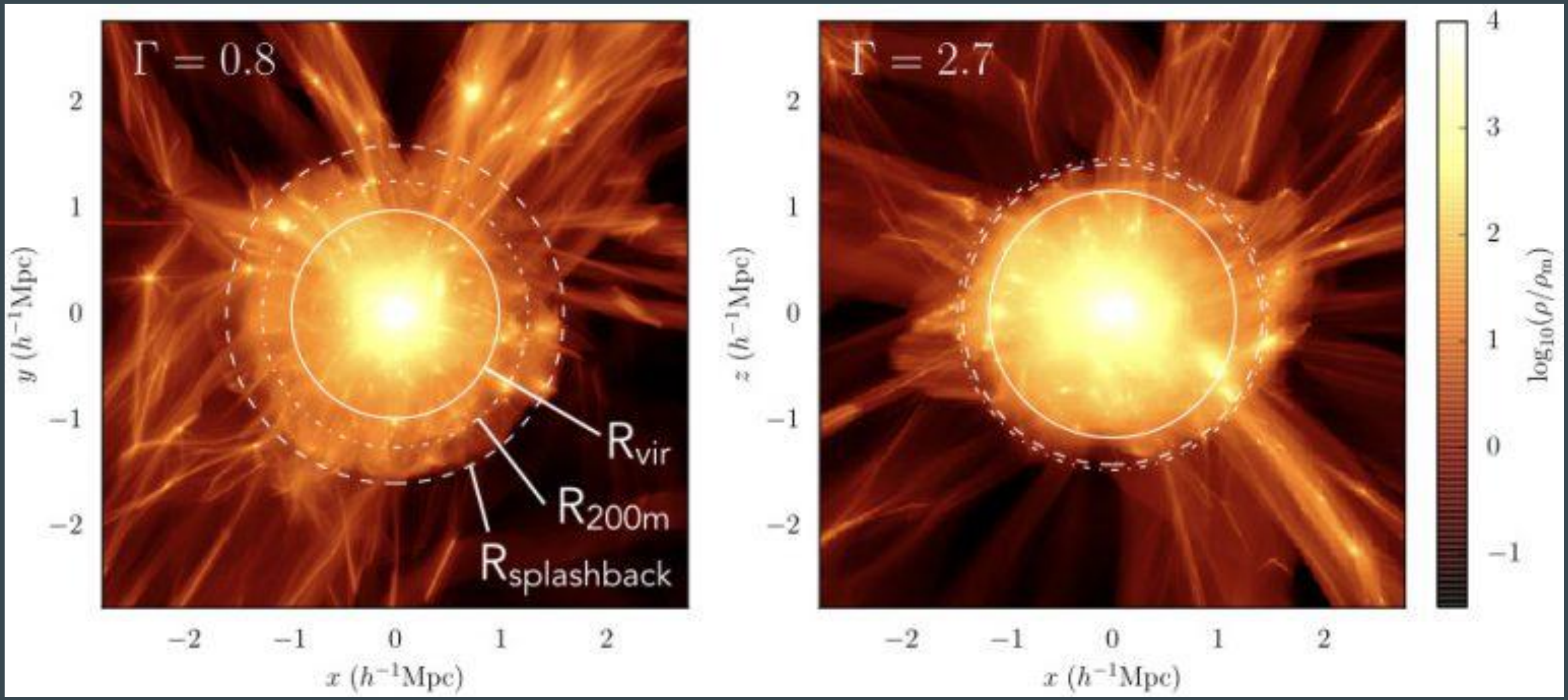


Fig. from More et al. 2015

Background

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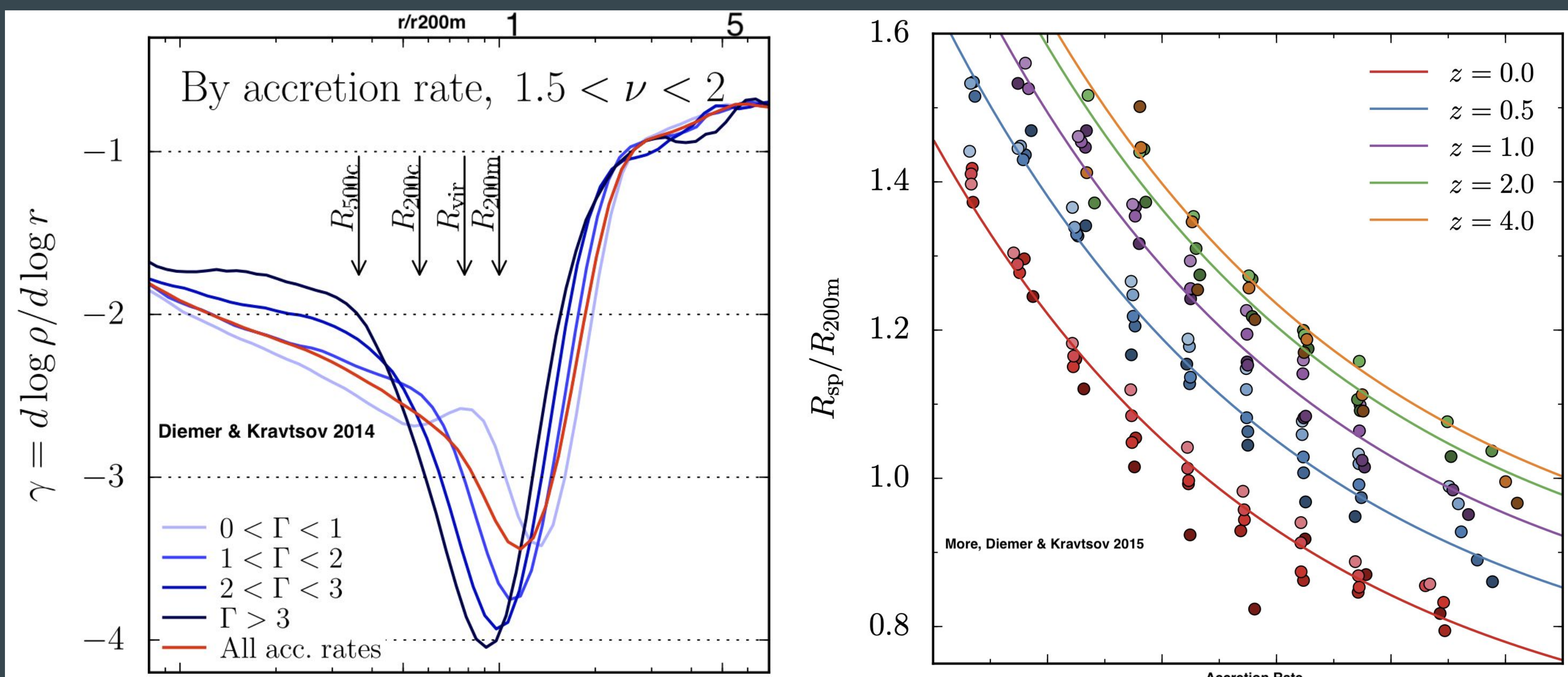
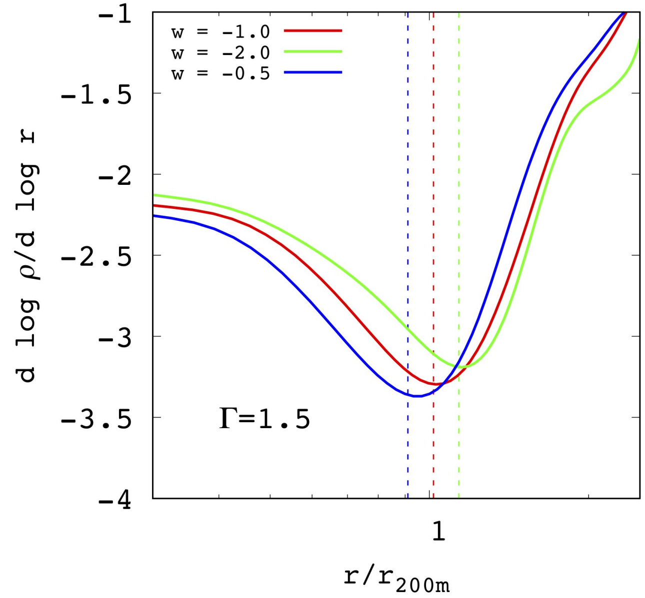
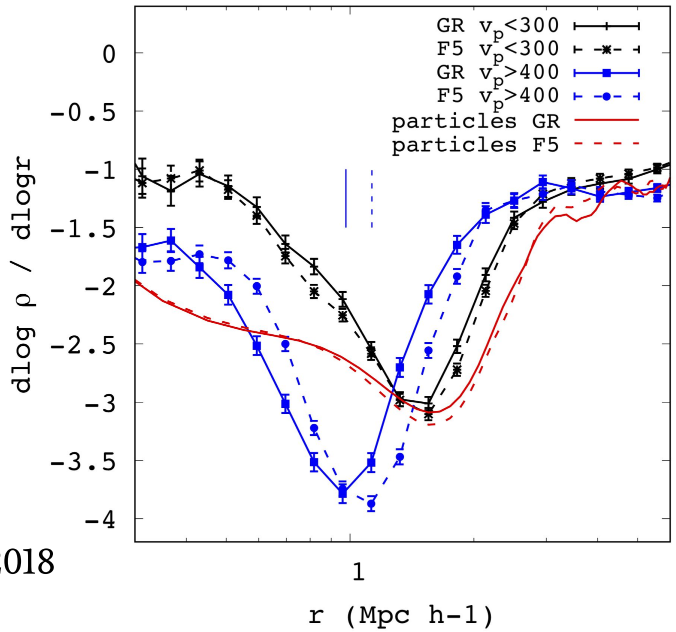


Background

- Furthermore, splashback feature also depends on the cosmology (w), gravity and SIDM etc.



Adhikari et al. 2018



Previous Studies

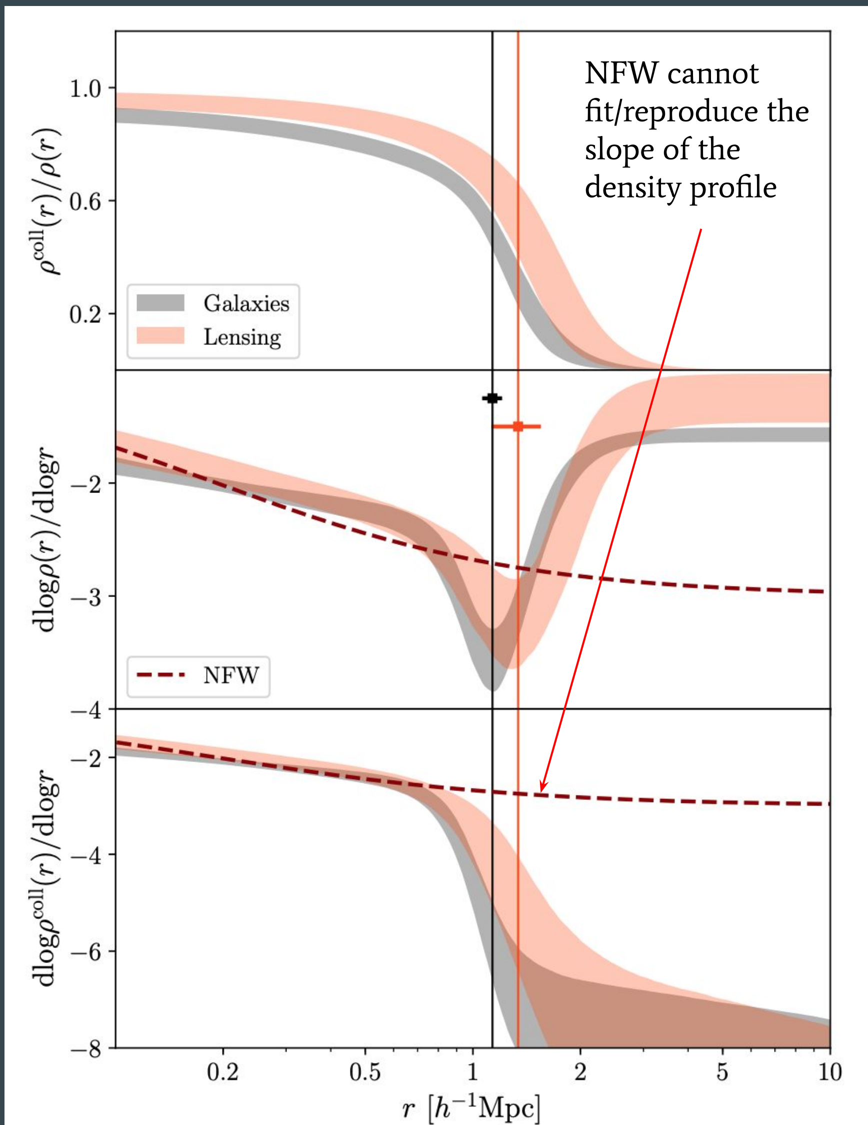
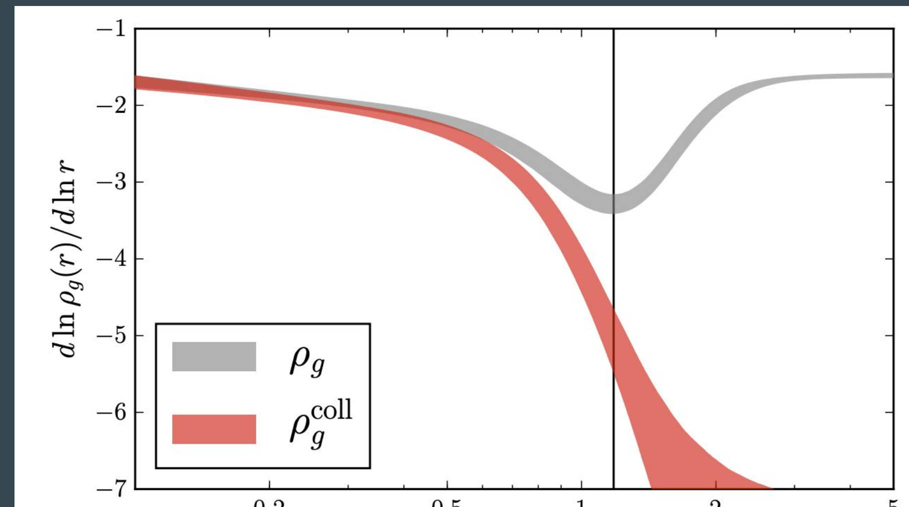


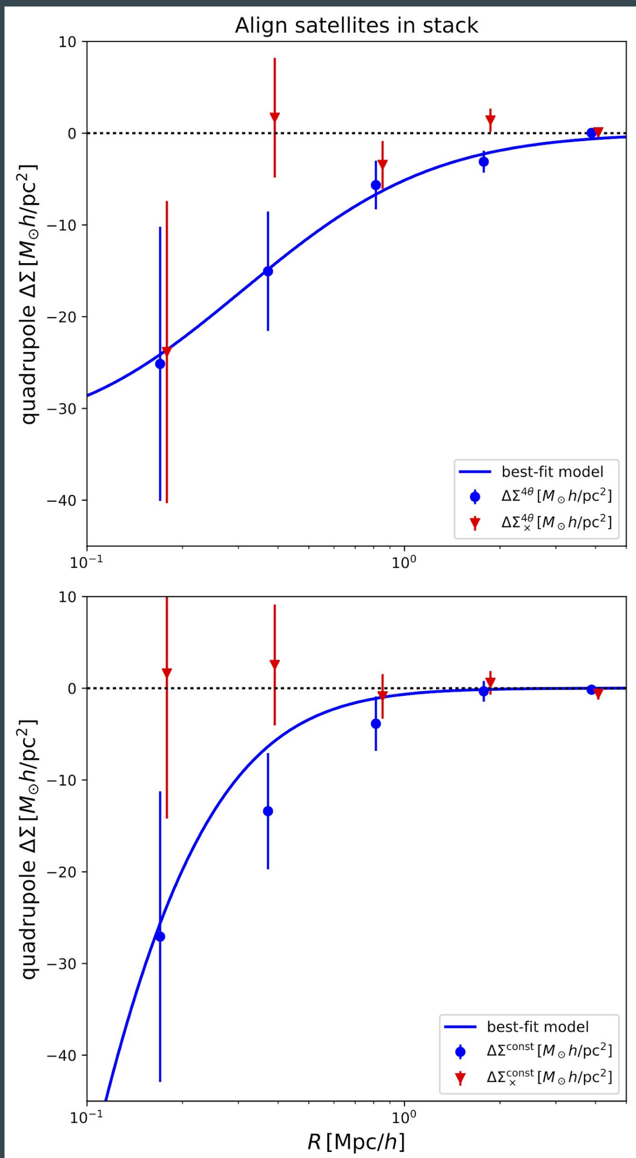
Fig. from Chang et al. 2017



Baxter et al. 2017

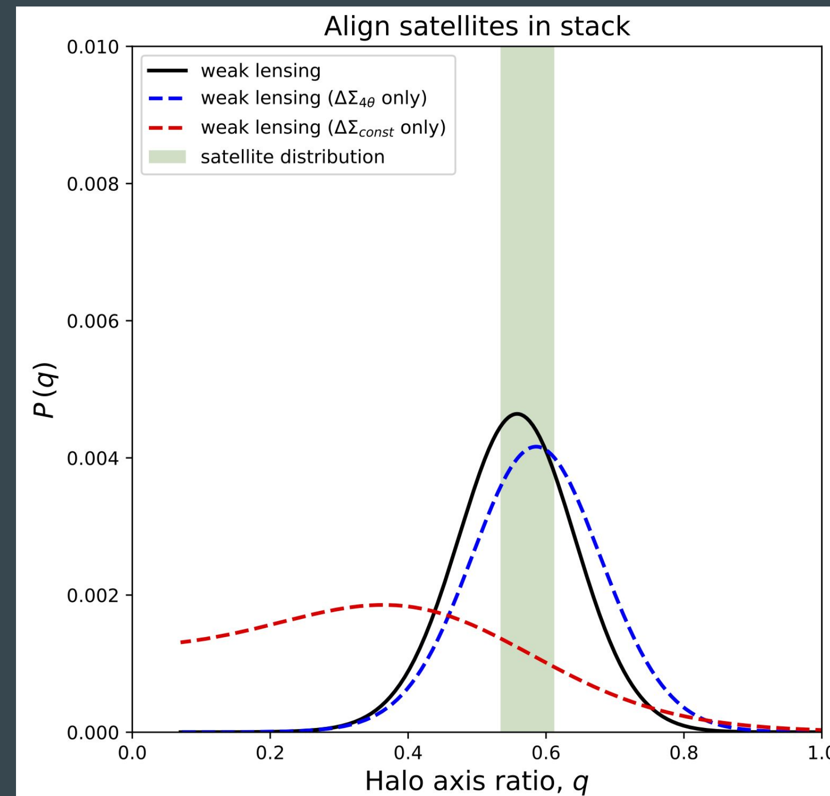
- First detection was reported in More et al. 2016
- Re-analysis with SDSS and DES by Baxter et al. 2017 and Chang et al. 2017, with optically selected clusters (redMaPPer). Detection in lensing also.
- However, the location of r_{sp} is ~20% smaller than the theory

Ellipticity of Galaxy Clusters (Shin et al. 2018)



⇐ quadrupole weak-lensing signal around stacked SDSS RM clusters

Constrained 2-D axis ratio b/a from the lensing (black) and from the satellite distribution (green band) ⇒



The shape and the boundary of galaxy clusters are typically anisotropic

⇒ Splashback feature on the major/minor axes of the underlying halos could tell us about the accretion along the filamentary structure (FUTURE WORK TOPIC)

Optical vs SZ Cluster Samples

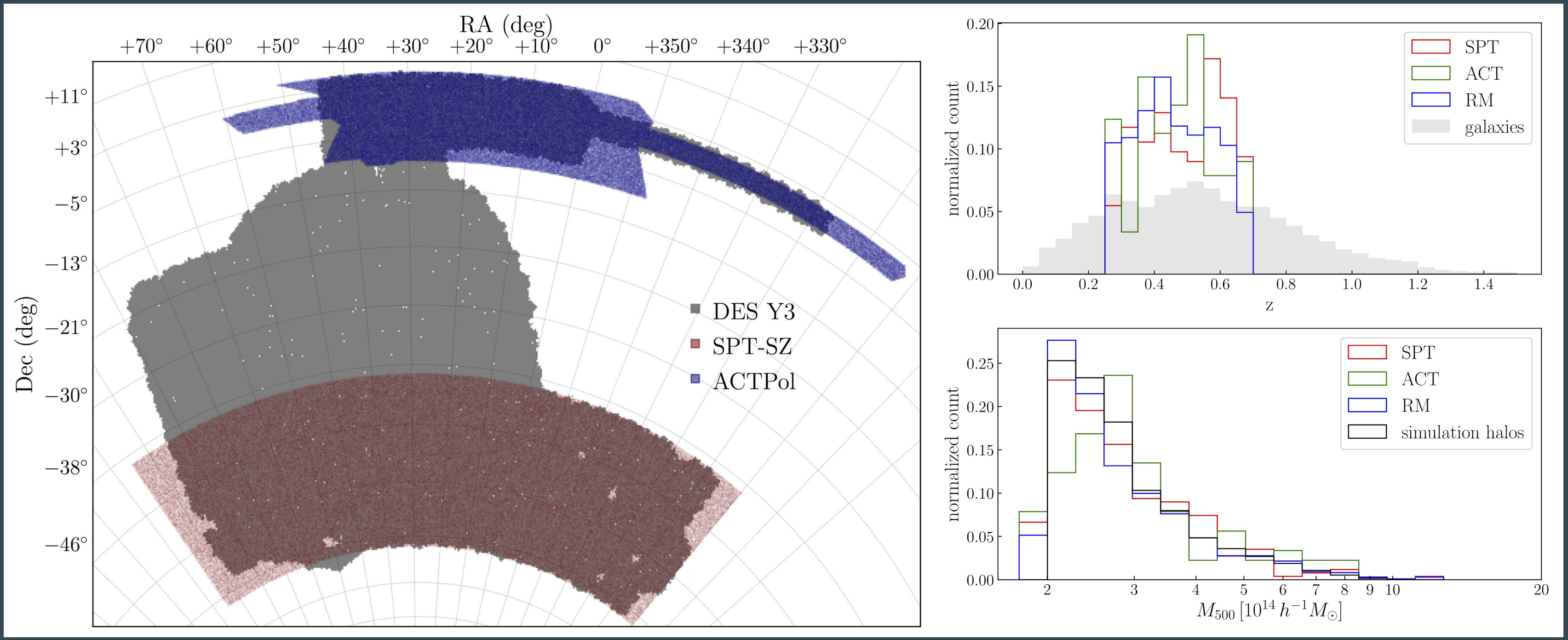
SZ clusters

- We perform a similar analysis with clusters selected by Sunyaev-Zel'dovich effect (SZ) which identifies clumps of hot gas in the clusters (integrated pressure)

  - The SZ observable is completely independent of all the observables in optical surveys used to measure the feature (in particular, the galaxy density)
  - The SZ signal is expected to correlate more tightly with cluster mass than optical richness, reducing the impact of scatter in the mass-observable relation (easier comparison w.r.t. the simulation)
  - SZ-selection is expected to be less affected by projection effects than optical cluster finders ($y \sim M^{5/3}$)
  - The SZ-selected cluster samples employed here allow us to extend splashback measurements to the high-mass, high-redshift regime

- These SZ clusters are cross-correlated to the DES galaxies

Data



Redshift Range: 0.25<z<0.7

Clusters:

~300 SPT clusters: SNR > 4.5, <M500c> = 3.0e14Msun/h, <z> = 0.49

~100 ACT clusters: SNR* > 4.0, <M500c> = 3.3e14Msun/h, <z> = 0.49

~1,000 Optical (redMaPPer) clusters: λ>58, <z>= 0.46; mass matched to SPT clusters

Galaxies: DES galaxies with absolute magnitude cut at M_i < -19.87

(apparent magnitude cut m_i = 22.5 at the maximum redshift 0.7)

Data

- Profiles of subhalos and dark matter particles are drawn from MultiDark Planck 2 (MDPL2) simulation

  - 1 $(\mathrm{Gpc}/h)^3$ box size
  - redshift snapshot at z=0.49
  - mean halo mass is matched to that of our SZ samples with a mininum mass cut
  - the scatter in SZ observable-mass relation does not change the splashback feature significantly

Halo Model

We model the mass profile following Diemer & Kravtsov (2014)
⇒ truncated Einasto profile (1-halo) in addition to the power-law infalling term (2-halo)
: good up to ~9R_{vir} (above it, infall regime breaks down)

$$\rho(r) = \rho^{\rm coll}(r) + \rho^{\rm infall}(r)$$

$$\rho^{\rm coll}(r) = \rho^{\rm Ein}(r) f_{\rm trans}(r)$$

$$\rho^{\rm Ein}(r) = \rho_s \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right)$$

$$f_{\rm trans}(r) = \left[1 + \left(\frac{r}{r_{\rm t}}\right)^{\beta}\right]^{-\gamma/\beta}$$

$$\rho^{\rm infall}(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-s_{\rm e}},$$

Truncation of the 1-halo Einasto profile

- Integrated along the line of sight into a 2D profile
- MCMC fitting with jackkinfe covariance
- Priors on α, β and γ from previous simulation studies
  (Gao+ 2008, Diemer&Kravtsov 2014)
- Priors on miscentering from Saro+2015 (SZ: SPT) and Rykoff+2014 (BCG: ACT/RM)

Correlation Function

The 2D two-point correlation function measures the excessive probability of finding two galaxies being separated by a distance of R

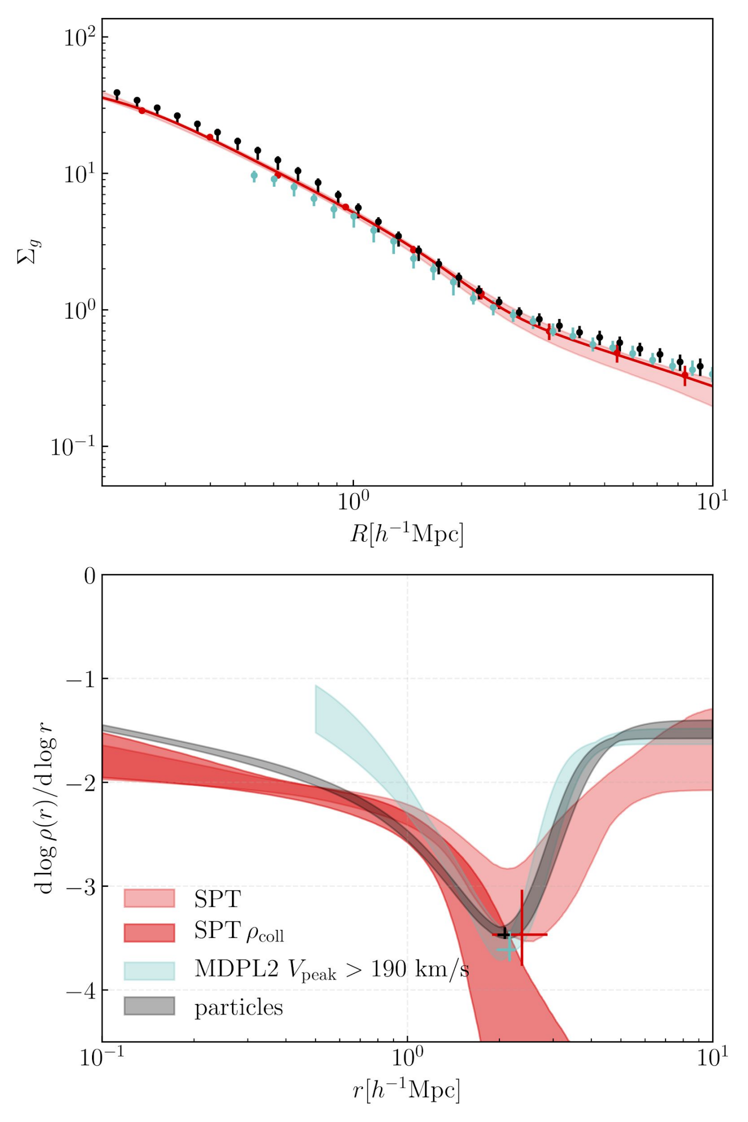
$$dP(R) = n_1 n_2 (1+\omega(R)) dA_1 dA_2$$

Thus, the mean-subtracted galaxy surface density around the clusters can be expressed as,

$$\Sigma_g(R) = \langle\Sigma_g\rangle\, \omega(R)$$

When applying the absolute magnitude cut & calculating correlation function, we assume all the galaxies are located at the cluster redshift
⇒ the correlation function picks up the galaxies that are correlated with the clusters: avoiding the photo-z uncertainties of the galaxies

Result: SPT clusters



$r_{sp} = 2.37^{+0.51}_{-0.48}$ Mpc/h

slope at $r_{sp} = -3.47^{+0.43}_{-0.30}$

slope of ρ_{coll} at $r_{sp} = -5.17^{+1.06}_{-0.60}$

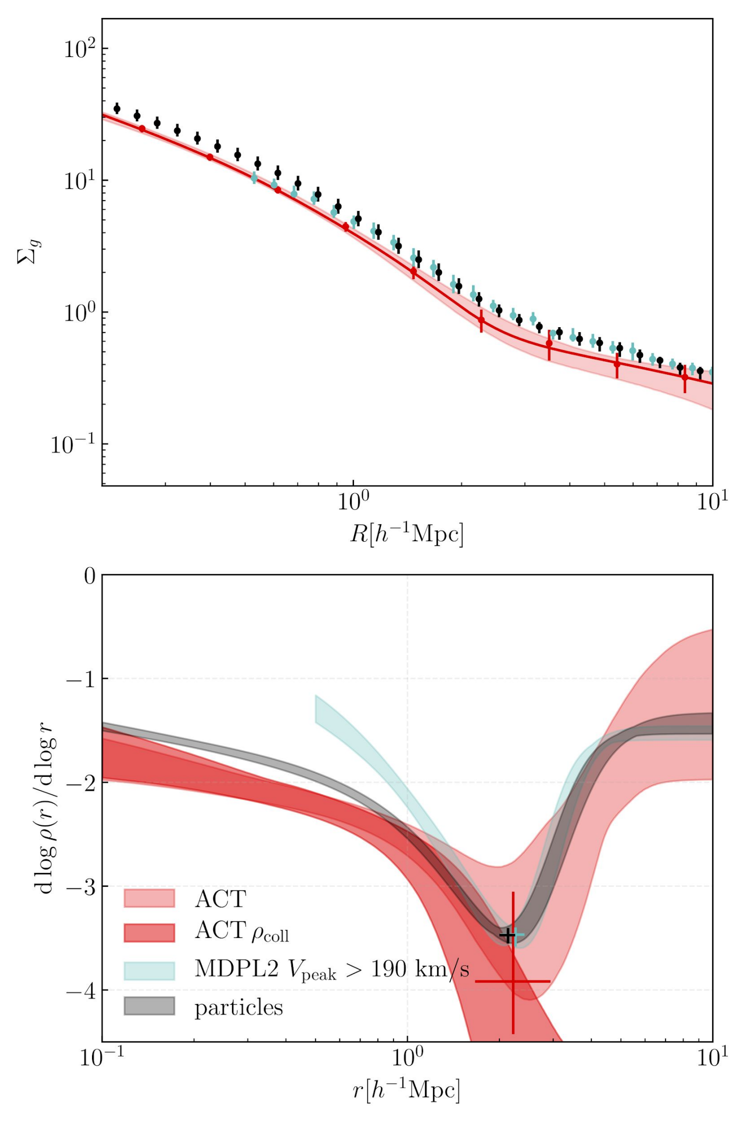
For simulation halos,

$r_{sp} = 2.16^{+0.10}_{-0.20}$ Mpc/h (subhalos, cyan)
$2.08^{+0.08}_{-0.11}$ Mpc/h (particles, black)

⇒ The observed feature agrees with that of simulation within 1σ

* The subhalos lose mass due to tidal interactions and pass below the resolution limit in the central regions, resulting in a flattening of the inferred slope

Result: ACT clusters



$r_{sp} = 2.22^{+0.72}_{-0.56}$ Mpc/h

slope at $r_{sp} = -3.92^{+0.86}_{-0.51}$

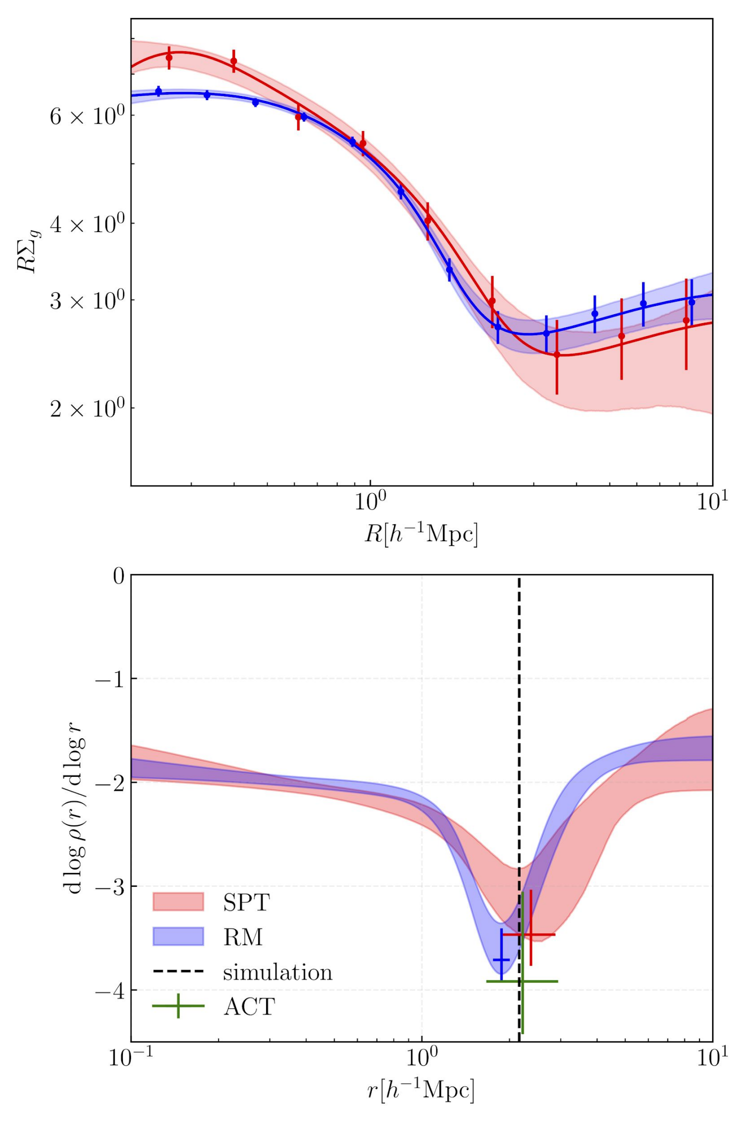
slope of ρ_{coll} at $r_{sp} = -5.40^{+1.27}_{-0.58}$

For simulation halos,

$r_{sp} = 2.26^{+0.15}_{-0.25}$ Mpc/h (subhalos, cyan)
$2.13^{+0.12}_{-0.14}$ Mpc/h (particles, black)

⇒ The observed feature agrees with that of simulation within 1σ

Result: RM (vs simulation)



$r_{sp} = 1.88^{+0.13}_{-0.12}$ Mpc/h (blue)

slope at $r_{sp} = -3.71^{+0.30}_{-0.20}$

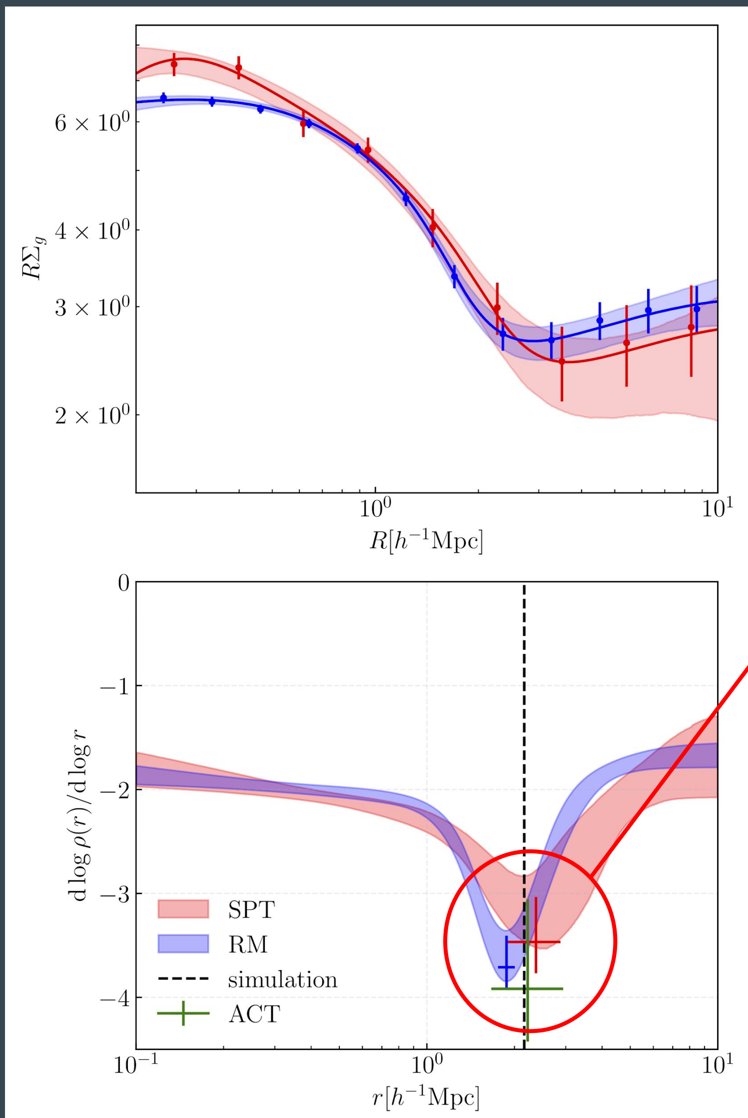
slope of ρ_{coll} at $r_{sp} = -5.52^{+0.88}_{-0.61}$

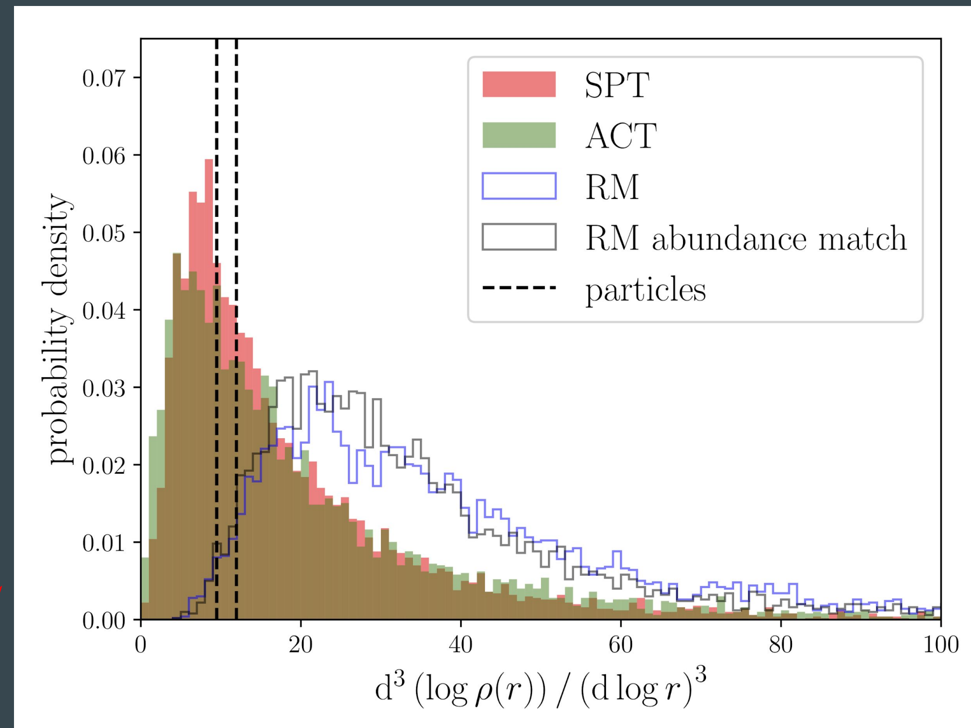
For simulation halos,

$r_{sp} = 2.16^{+0.10}_{-0.20}$ Mpc/h (dashed line)

$\Rightarrow$ The observed r_{sp} in optically selected RM clusters are ~2σ lower than that of simulation (subhalo profile)

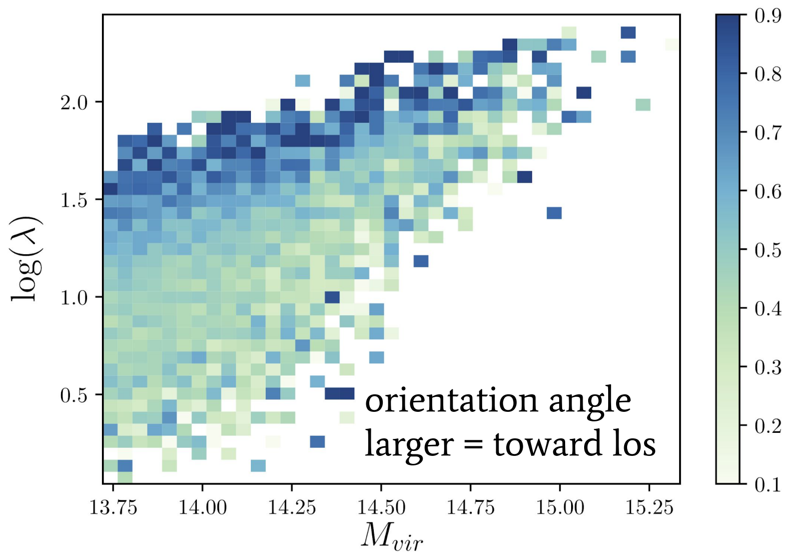
Result: shape of the feature (SZ vs RM vs Sim)

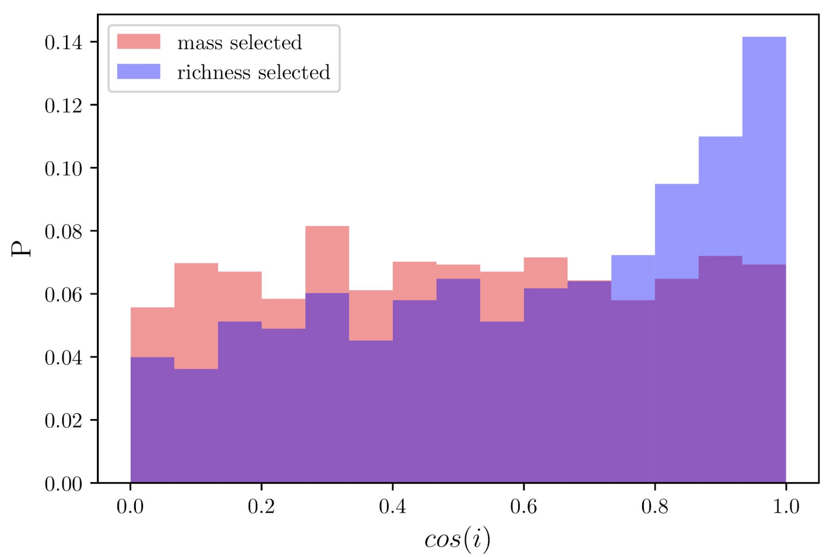




The RM clusters exhibit a sharper splashback feature (larger 3rd deriv at r_{sp}) than that of SZ clusters and simulation halos

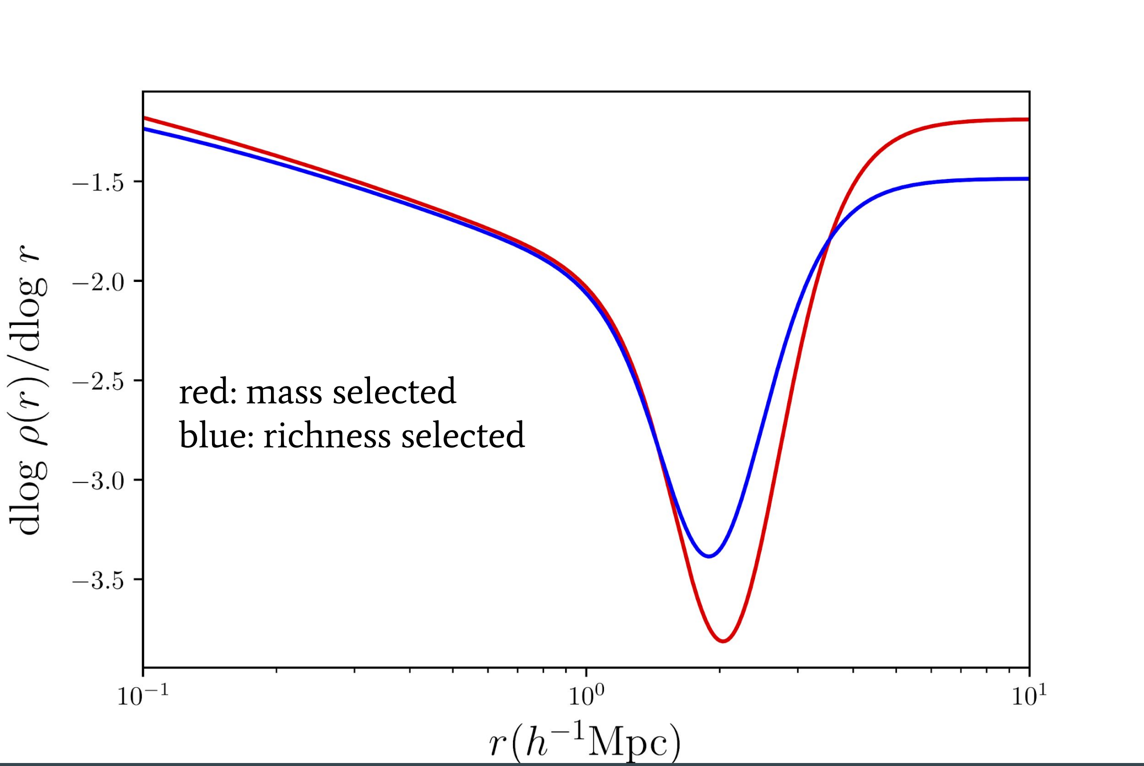
Systematic test: comparison between mass- and richness-selected sample





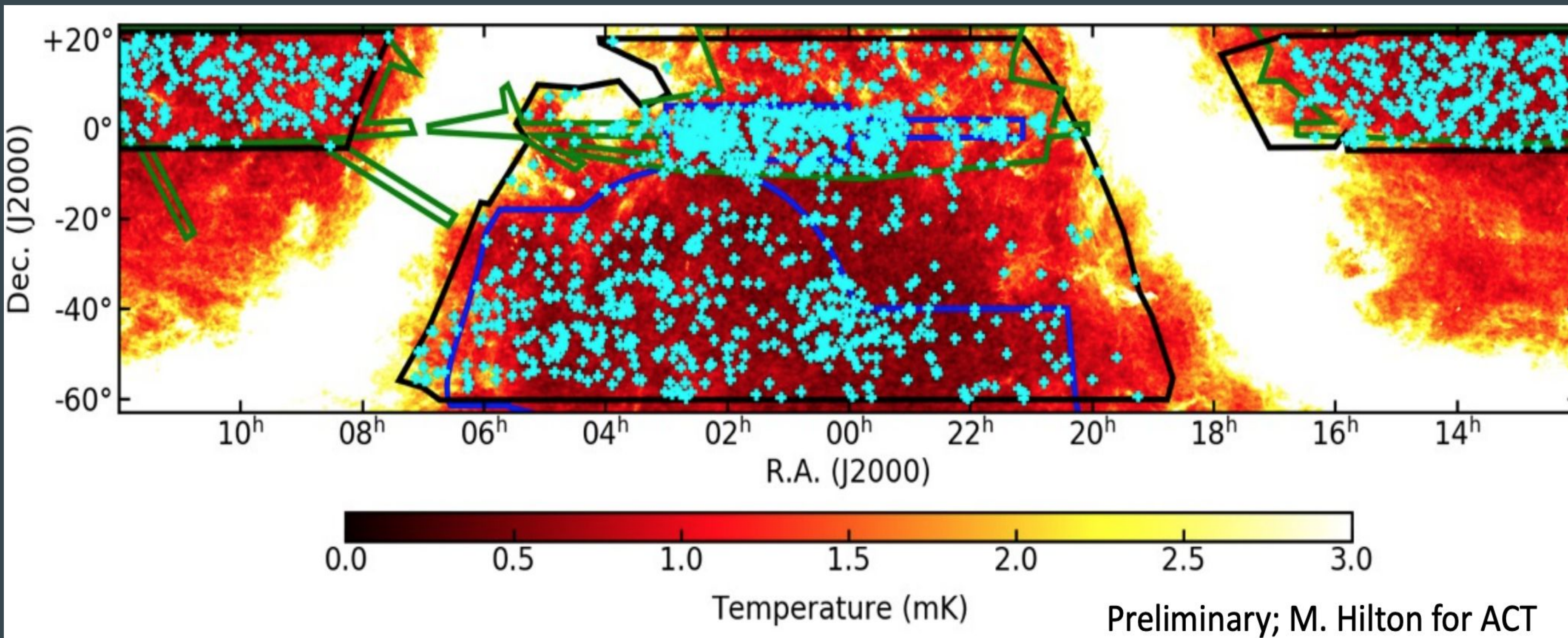
- For a given mass, optical clusters with high richness tend to be more aligned w.r.t. the l.o.s. than those with low richness
- Thus, richness selection (>20) results in a biased selection of clusters in terms of their orientation

Systematic test: comparison between mass- and richness-selected sample



- The difference is ~6% in the location of the r_{sp}, but it is not enough to explain the observed discrepancy between RM and SZ/simulation

AdvACT clusters

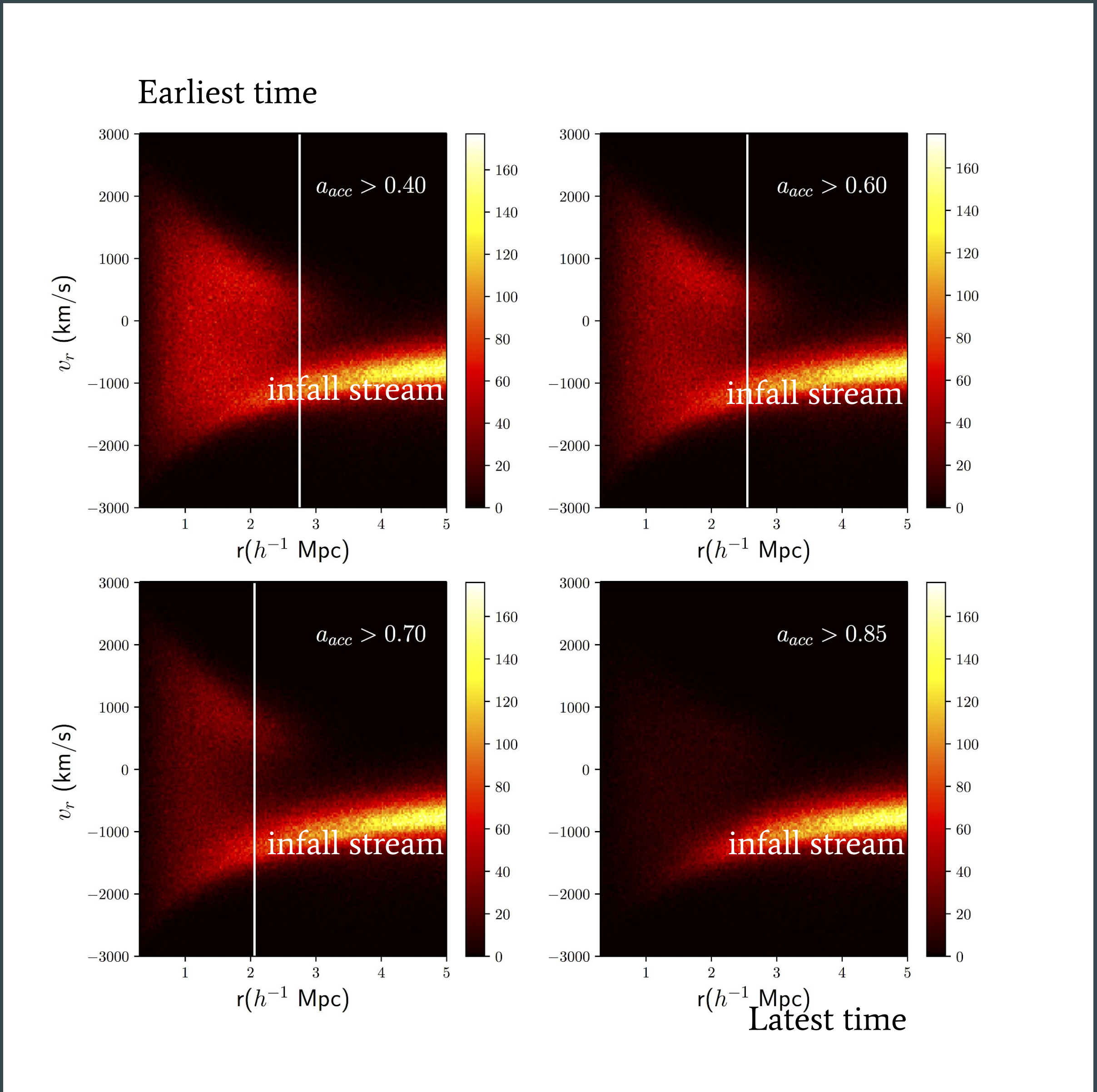


863 clusters (subject to change) in the DES footprint having SNR>4, w/
$0.15 < z < 0.7$
<M500c> = 3.0e14 Msun/h
<z> = 0.44
ANALYSIS UNDERWAY!

w.r.t. the previous SPT measurements, the error bars in the galaxy density profile and lensing profile are expected to reduce by a factor of ~2 as we will have 3-4x more clusters

Galaxy Quenching and Splashback

Infalling particles in phase space

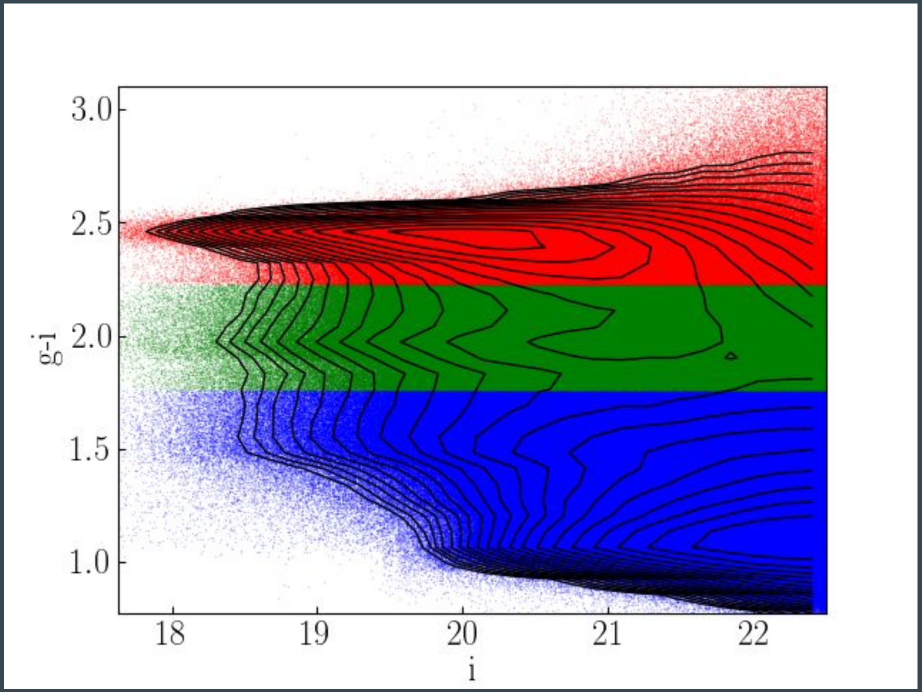


⇐ Subhalos accreted to a cluster at different times in simulation

Galaxies in the infall stream do not show any splahsback feature, while those that have completed at least one crossing show a distinctive splashback feature

⇒ Can we separate the infall population from the observational data?

Split of galaxies in color space

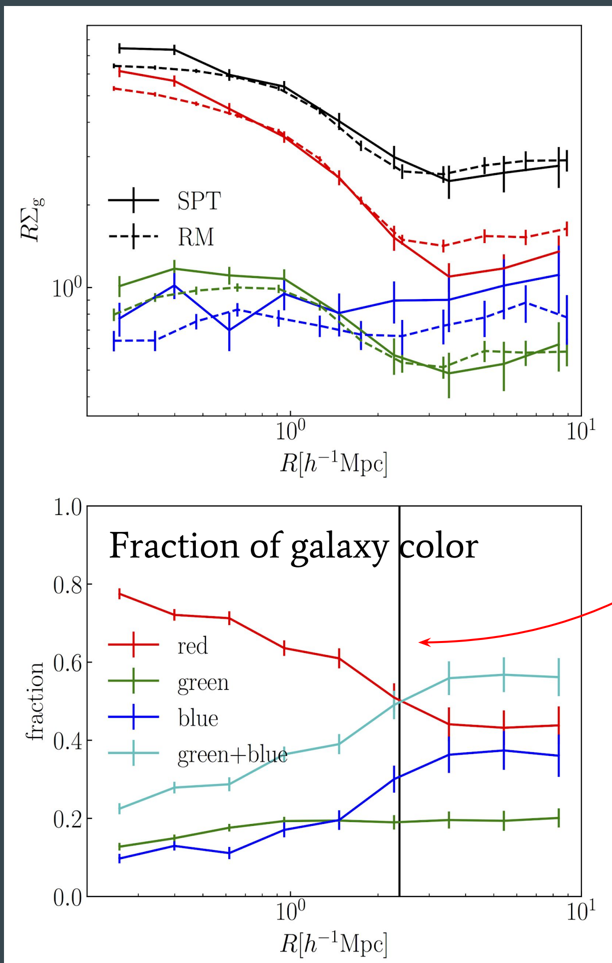


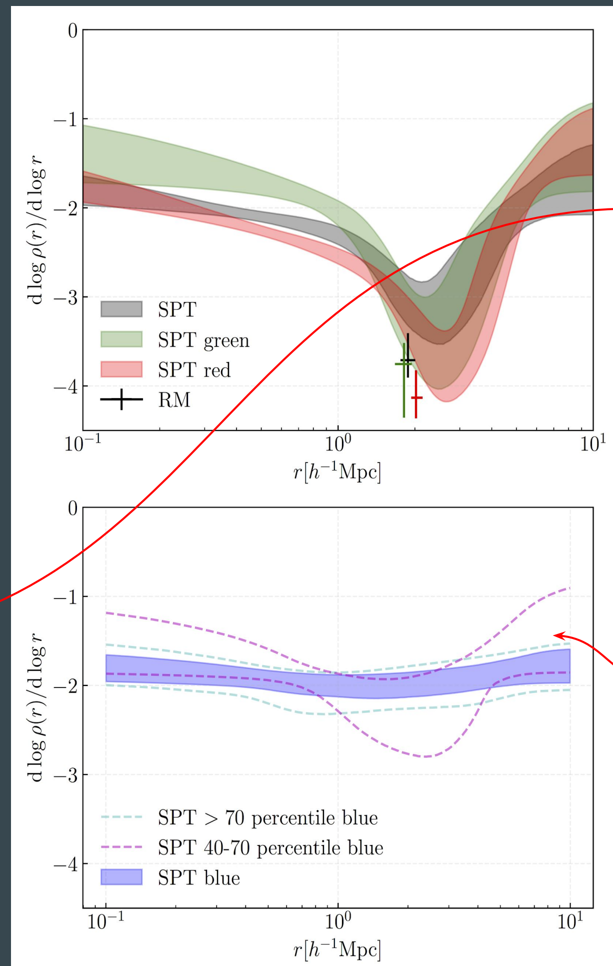
⇐ Galaxies are split in *g-i* color in each redshift bin of Δz=0.025
: 20% red, 20% green, 60% blue

- The variation in the fraction with the redshift is not significant given our noise level

- Blue star-forming galaxies are quenched within clusters, becoming red quiescent galaxies, by various possible processes (Gunn&Gott 1972, Abadi+1999, Larson+1980, Wetzel+2013, von der Linden+2010, Brodwin+2013, Ehlert+2014, Wagner+2015)
- With these color-split galaxies samples, the same analysis has been done with the same SPT cluster as before

Result: profiles of galaxies with different colors





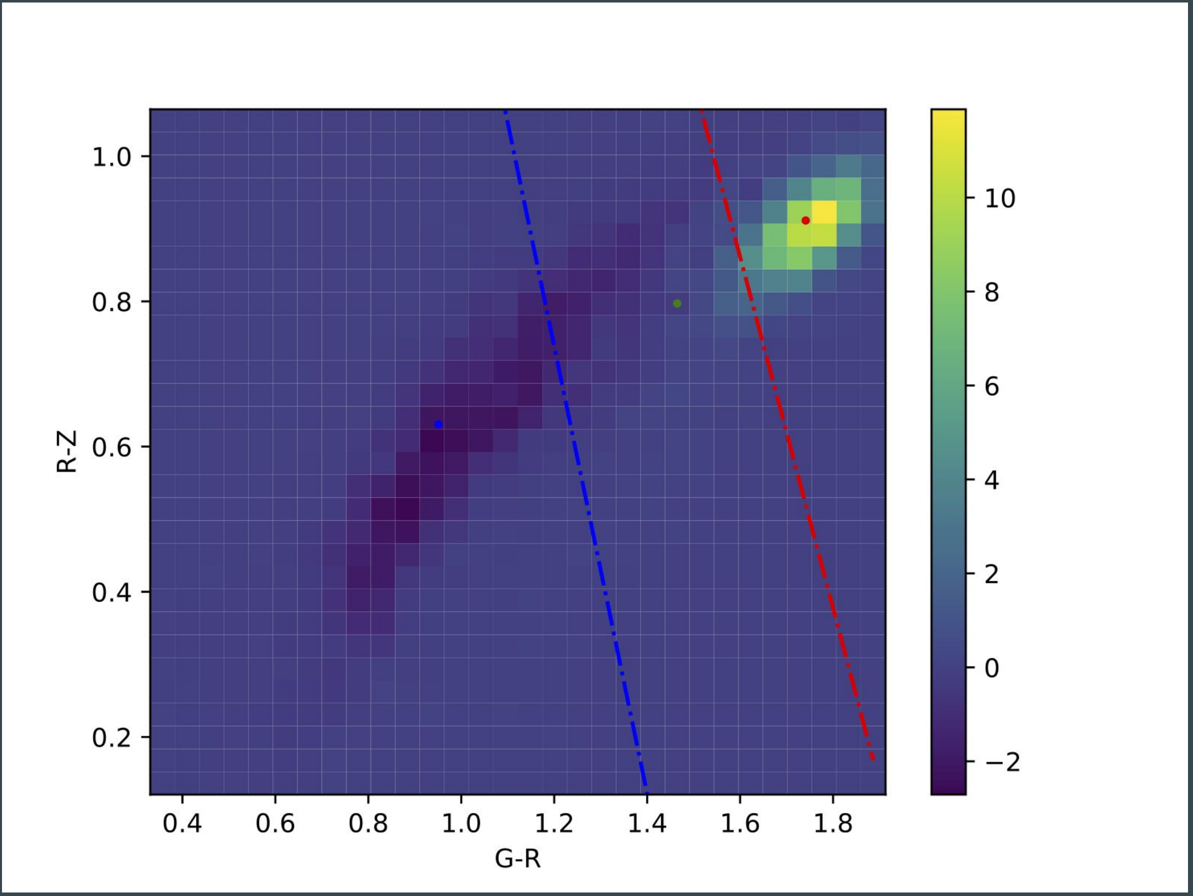
We measure profiles of galaxies split on color.

The upturn of the red fraction around r_{sp} = evidence of quenching of galaxy star formation inside clusters

Blue galaxies are consistent to a pure power-law profile; indicating that they are still on their first infall passage

(with S. Adhikari)

New color split scheme (w/ AdvACT SZ clusters)

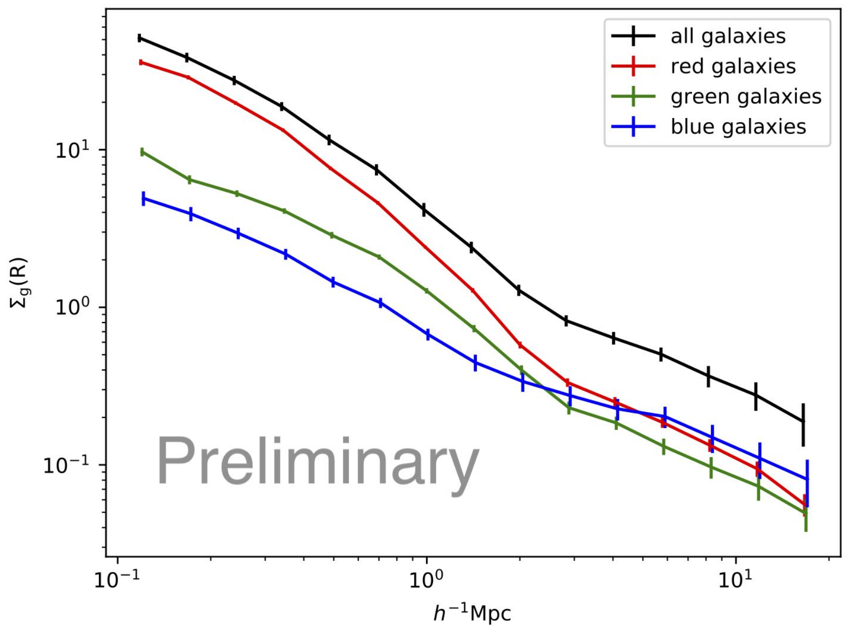


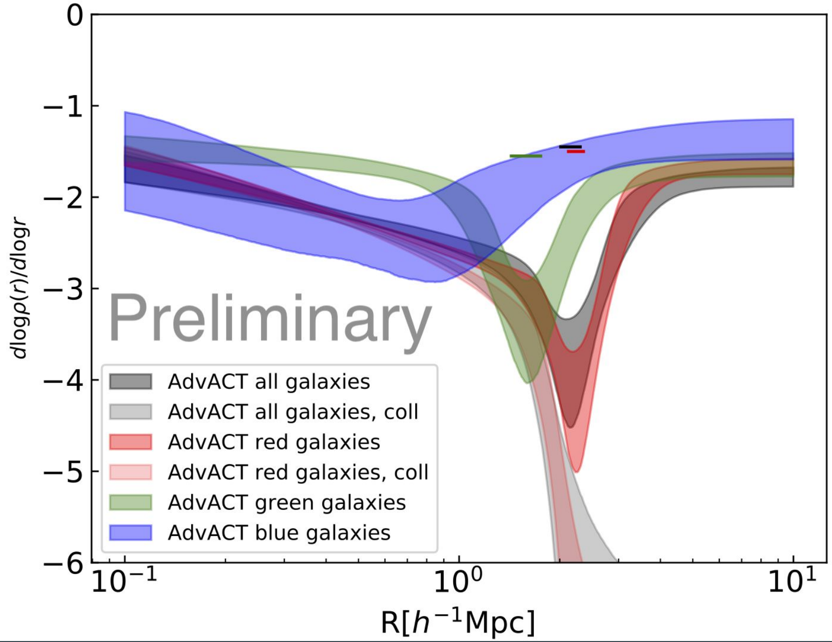
In G-R vs R-Z color-color space:

Subtract the density of all galaxies from that <2.5Mpc/h from the AdvACT clusters, in each redshift bin of dz=0.075

⇒ excess of red galaxies, deficit of blue galaxies as well as the green valley

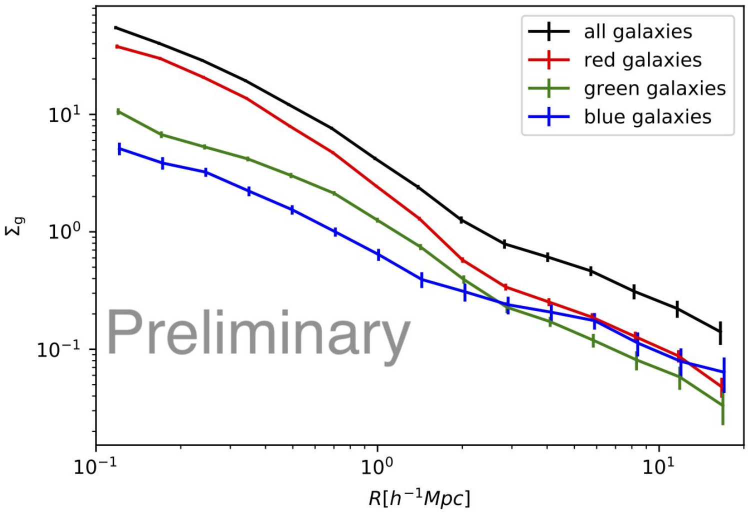
(Preliminary) result with AdvACT clusters

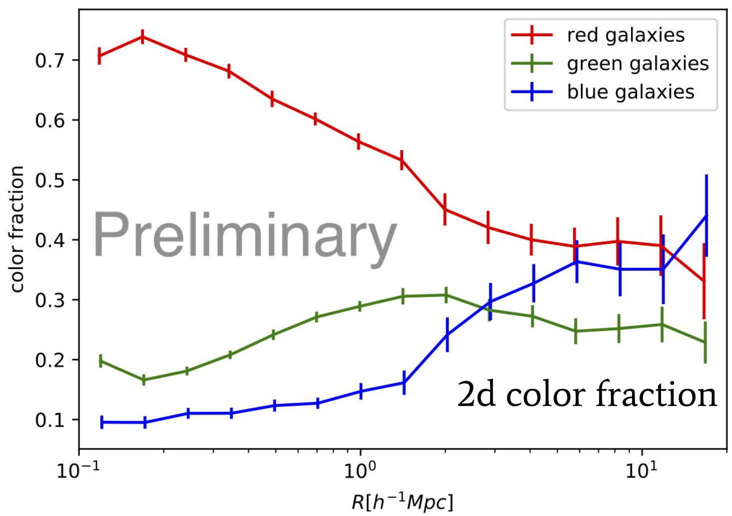


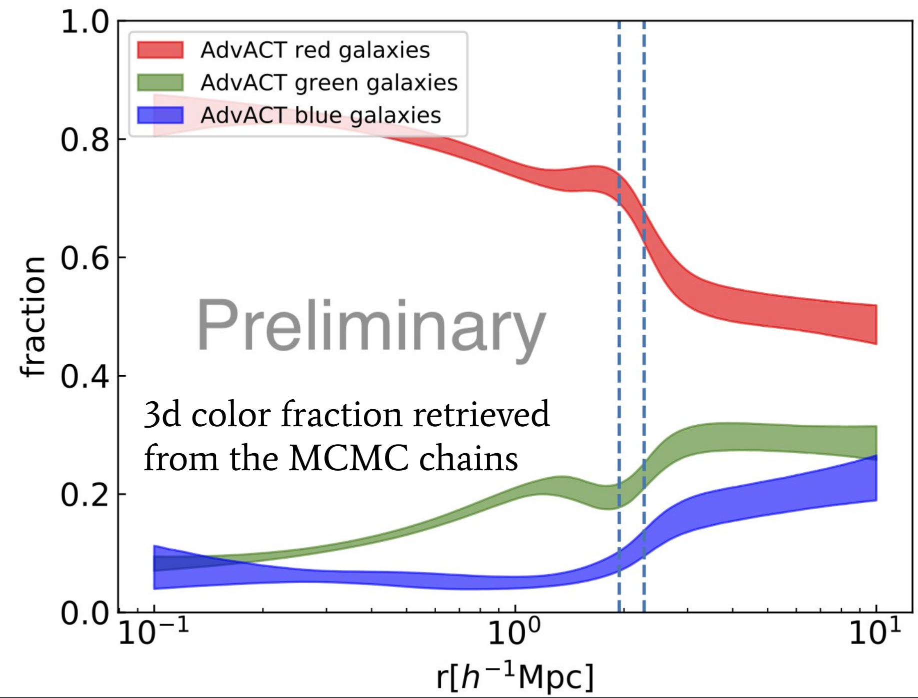


Blue galaxy profile is again largely consistent with a power law profile: majority of them are still in their first infall passage

(Preliminary) result with AdvACT clusters







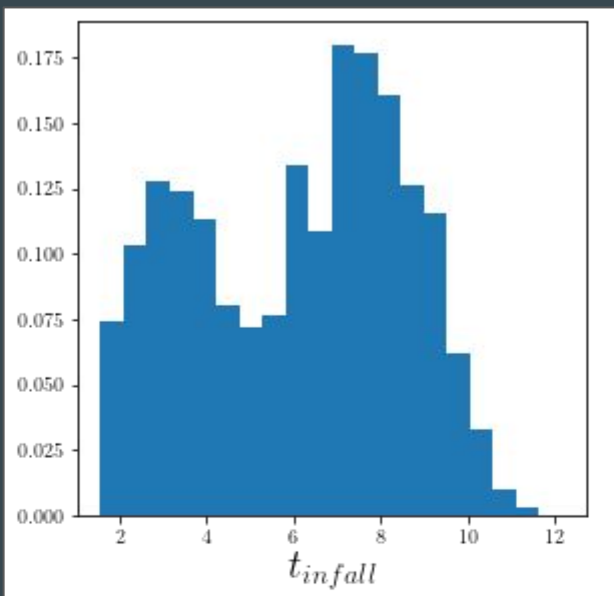
Around the splashback radius, red fraction starts to increase inward, while blue fraction decreases

⇒ we can use this fraction to constrain the quenching timescale quantitatively, per quenching model

Constraining SFR quenching timescale

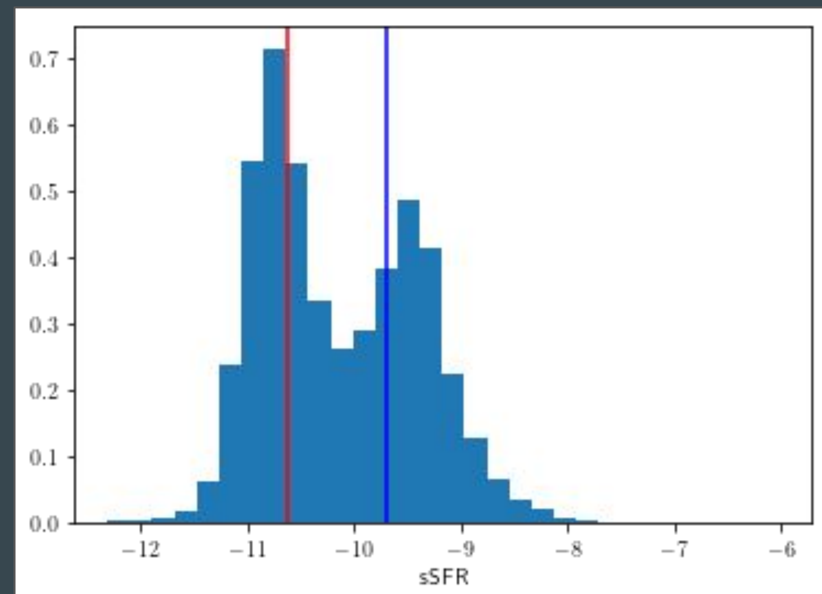
$$\mathrm{SFR_{sat}}(t) = \begin{cases} \mathrm{SFR_{cen}}(t) & t < t_{Q,\,\mathrm{start}} \\ \mathrm{SFR_{cen}}(t_{Q,\,\mathrm{start}})\, e^{\left\{-\frac{(t - t_{Q,\,\mathrm{start}})}{\tau_{Q,\,\mathrm{fade}}}\right\}} & t > t_{Q,\,\mathrm{start}} \end{cases}$$

quenching starts after $t_{Q,start}$ after infall, followed by quenching w/ with timescale of $\tau_{Q,\ fade}$



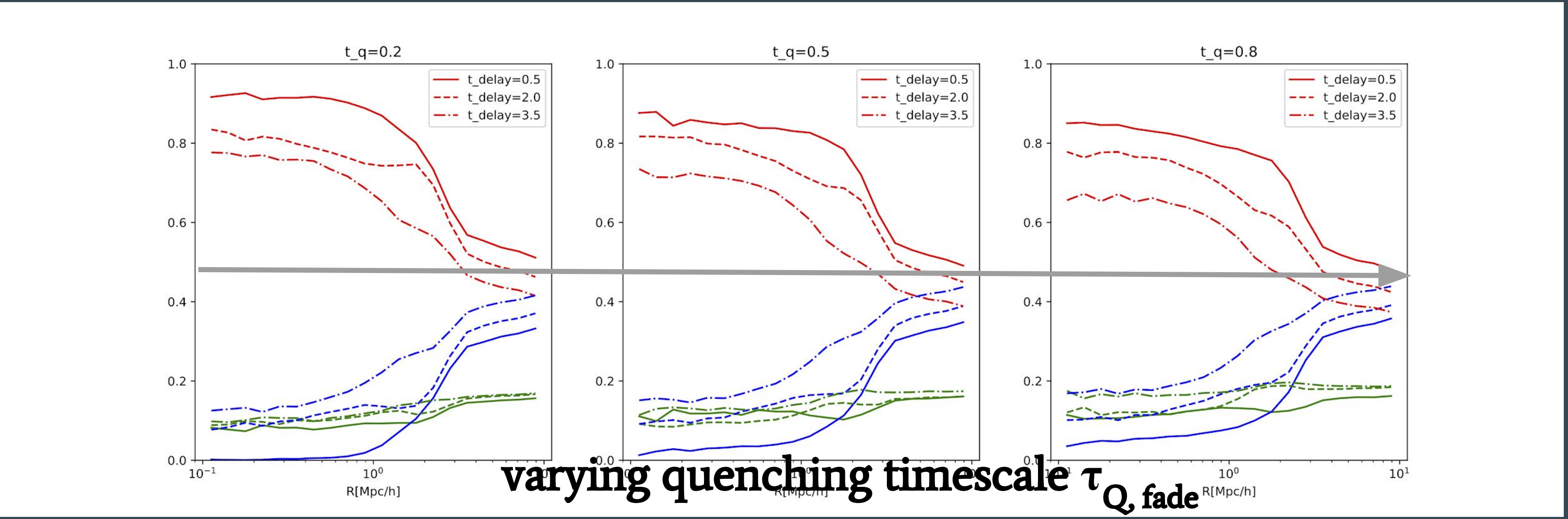
⇐ dist. of infall time in MDPL2 simumation

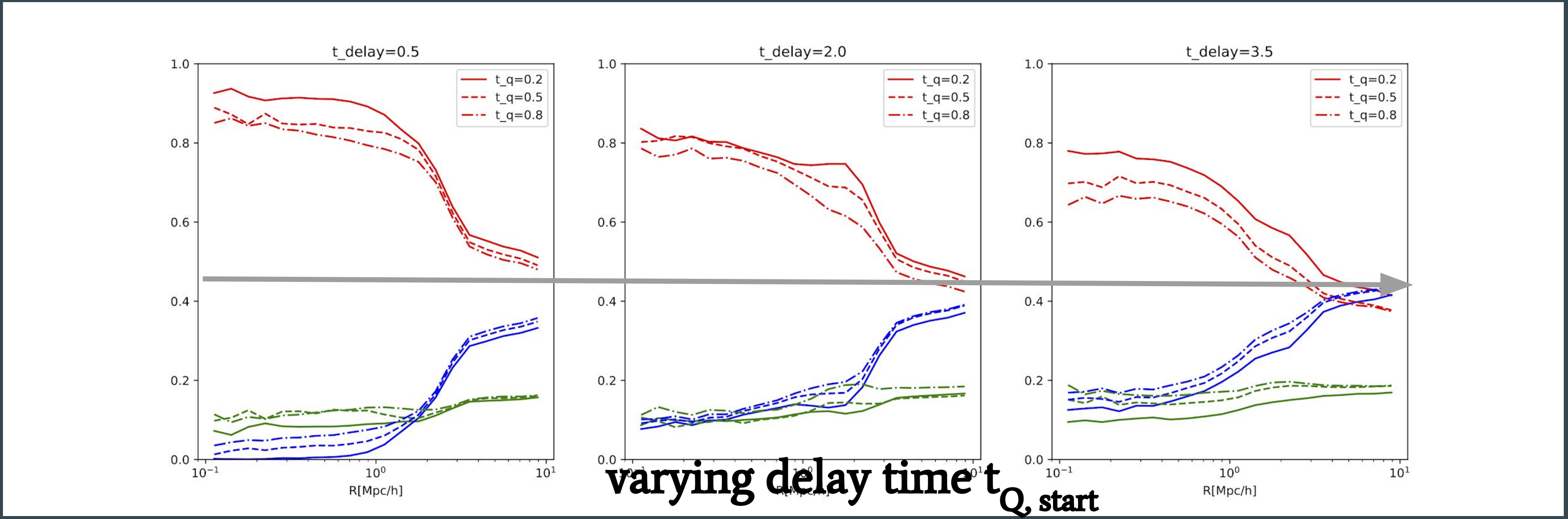
dist. of sSFR in SDSS spec-z sample ⇒



- Using the sSFR dist. of the field (in the data) and the quenching model, assign each subhalo (in the simulation) a sSFR value ⇒ compare the fraction of color (r/g/b) as a function of radial distance, to the observed value to constrain the quenching params

Ex) Color fraction in simulation w/ different params





Summary

- Splashback feature is a plausible physical boundary of the halo
: it is sensitive to e.g. accretion rate of the halo, cosmology (w), and gravity
- While the observed features in the optical cluster samples are located at ~20% smaller radii than in simulation halos, the SZ cluster samples used in this study show consistent splashback features as in the simulation
- Orientation bias and mass calibration does not fully explain the discrepancy in optical clusters (ongoing work)
- The profiles split in galaxy colors suggests that 1) galaxies start to be quenched at/around r_{sp} and 2) blue galaxies are mostly still in their first infall passage
- With a larger SZ cluster sample w/ AdvACT, we can constrain the parameters in quenching models using the fraction of galaxy colors as a function of radius
- Ongoing and future SZ / X-ray cluster survey (AdvACT, SPT3G, SPTPol, SO, CMB-S4, e-Rosita etc.) will provide additional understandings of physics of galaxy clusters