Splashback Radius as a Probe of Cosmology and Astrophysics

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Halo Boundary Workshop
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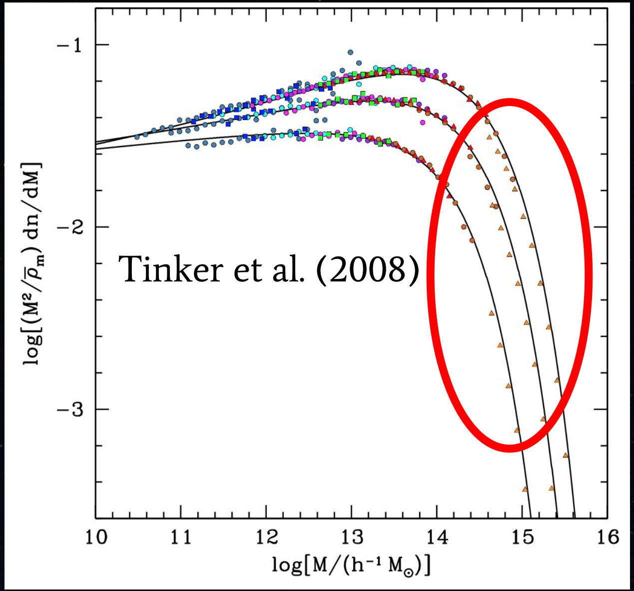
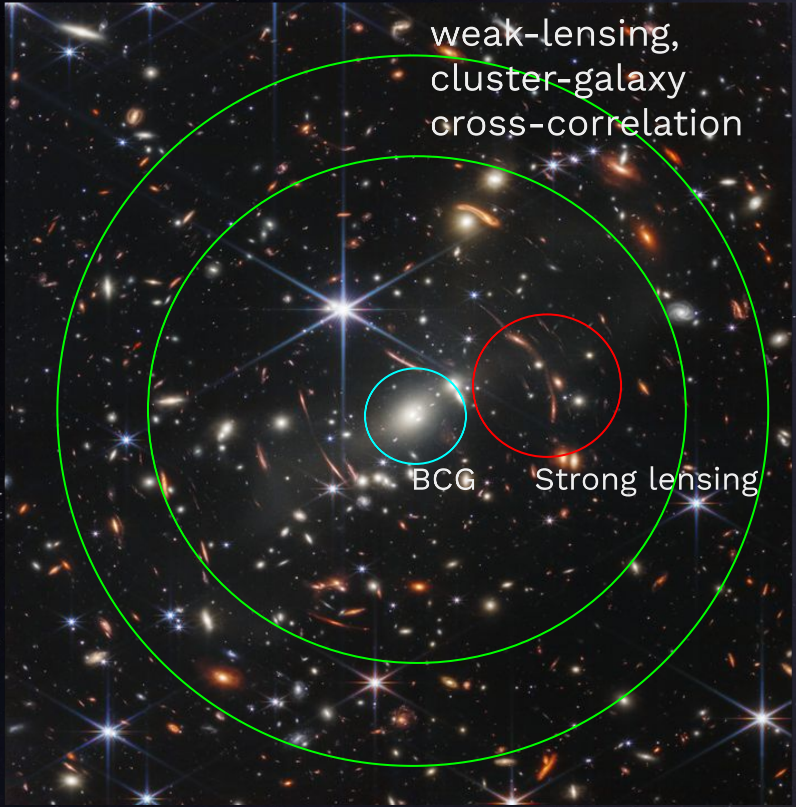
THE GALAXY CLUSTERS



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

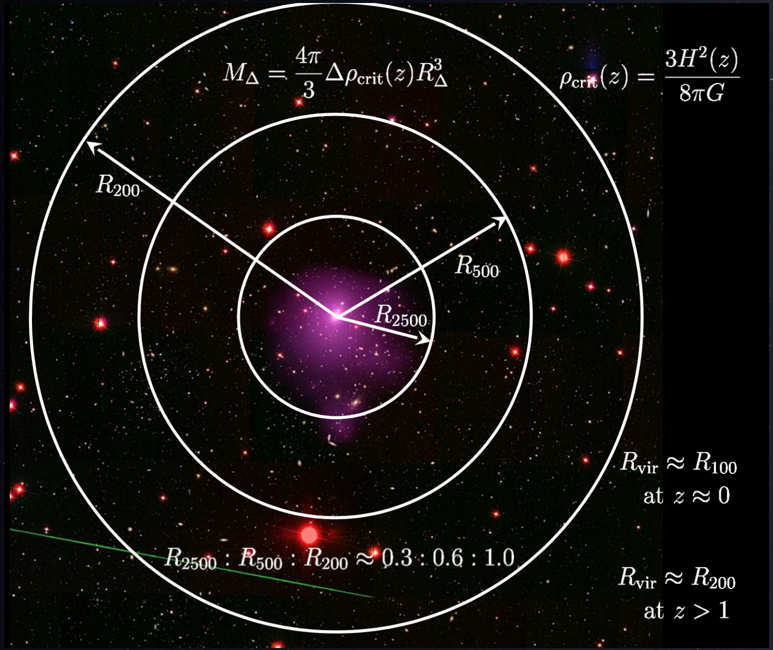


THE BOUNDARY OF HALOS

R_Δ: boundary based on the overdensity level

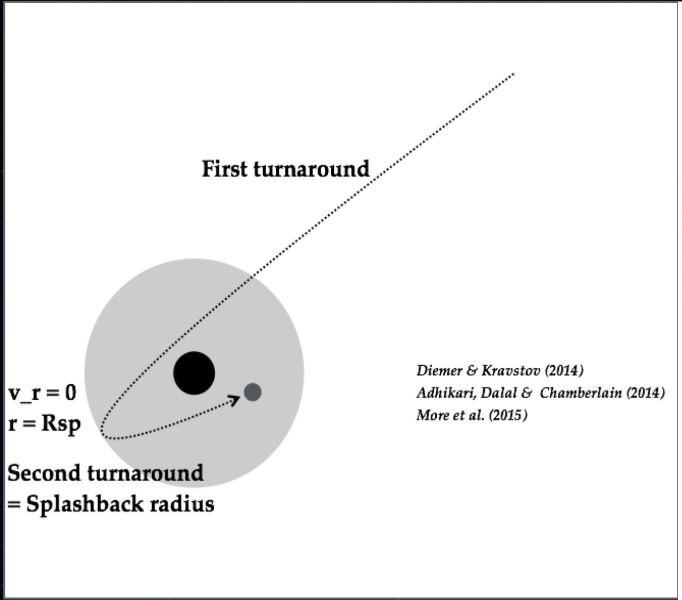
- **Pseudo-evolution** (Diemer+13): change in the background density
- Halos **continuously accrete** matter: no radius within which the particles are fully virialized

Then, how can we find a **physical boundary** of halos?

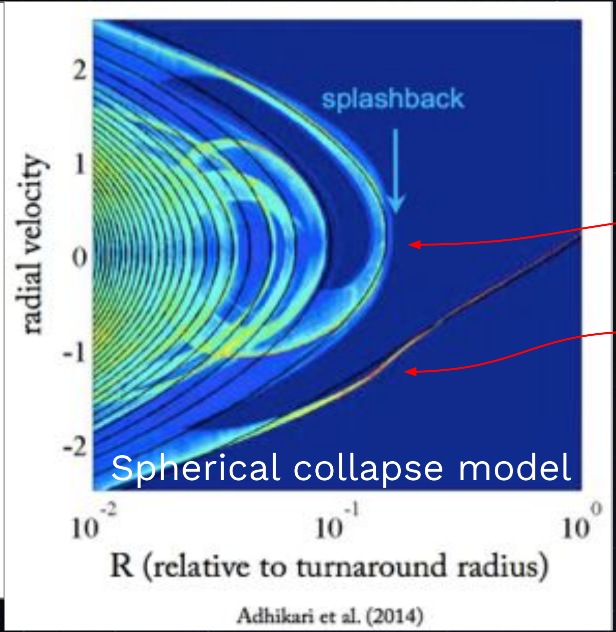


Credit: Andrey Kravtsov

THE BOUNDARY OF HALOS



Credit: Chihway Chang



+Gunn & Gott 1972
Fillmore & Goldreich 1984
Bertschinger 1985

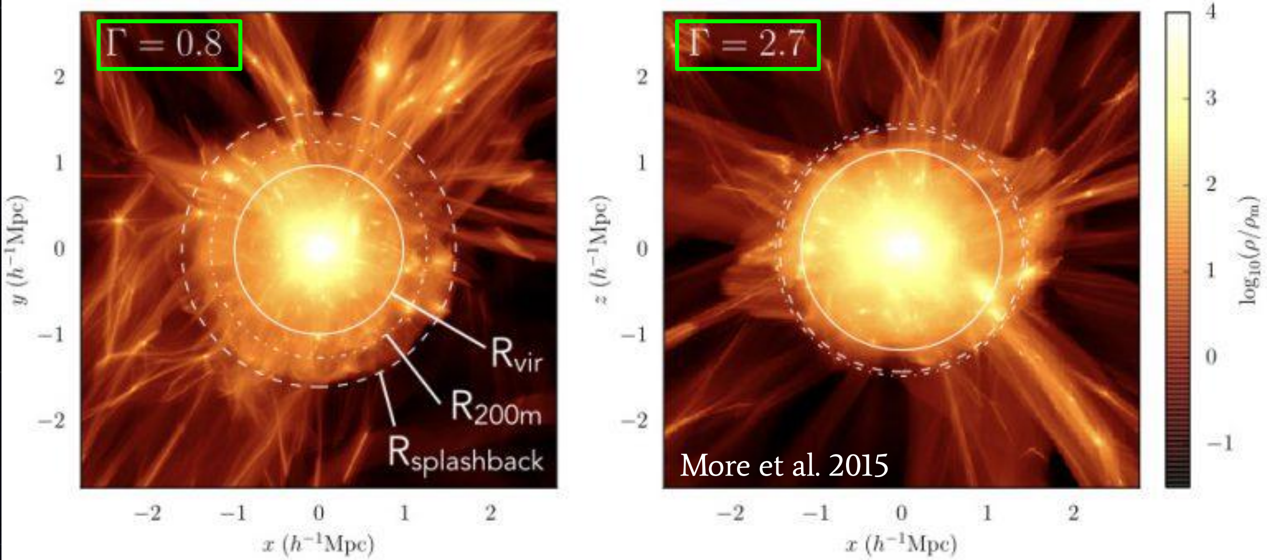
Splashback radius demarcates the **boundary** between the **multistreaming** region (1-halo) and the **infall** stream (2-halo)

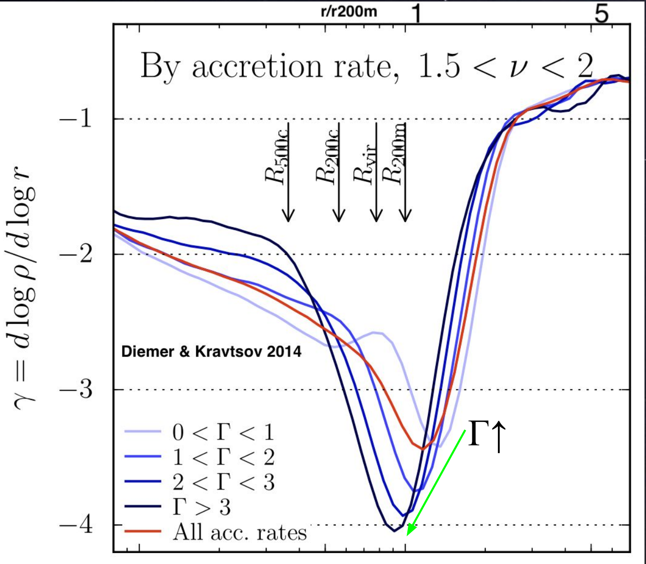
Infalling particles form a sharp **physical** boundary around the **first apocenters**
⇒ splashback radius

SPLASHBACK & MASS ACCRETION

- Halos 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 majorly depends on the **recent mass accretion rates** of halos, given the mass

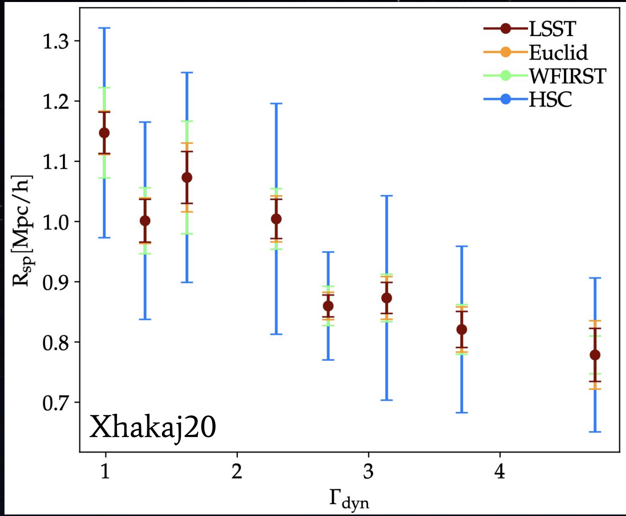
+Shi16a,b
Sugiura20, 23

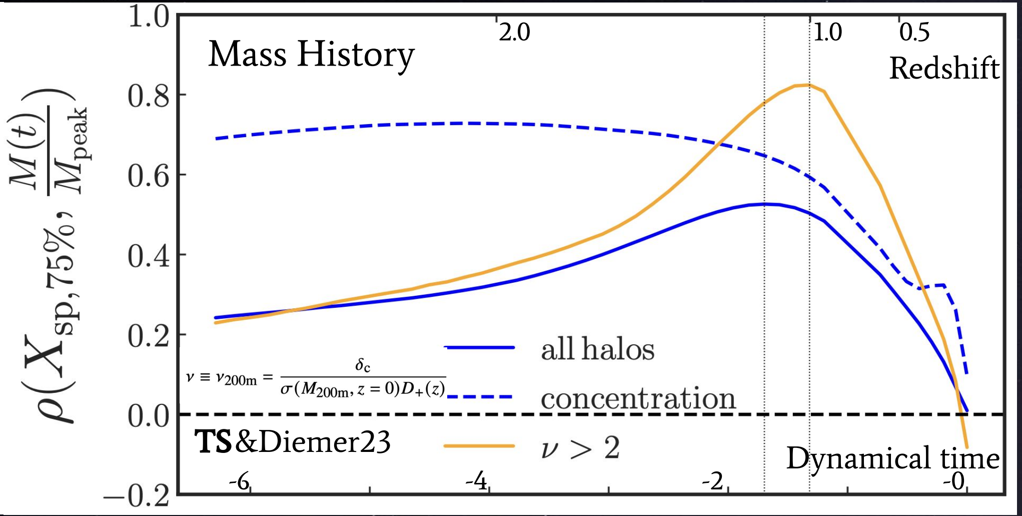




SPLASHBACK & MASS ACCRETION

- Splashback radius is the most sensitive to the mass accretion over the recent **1 dynamical time** ($2R_{200m}/V_{200m}$), Γ_{200m}, while concentration retains information of **earlier** times (**TS**&Diemer 2023)
- With the statistical power of **LSST** and **Euclid**, we can **directly constrain the mass accretion rate** of halos using splashback radius (Xhakaj+2020), therefore infer **cosmology**





SPLASHBACK & MA HISTORY

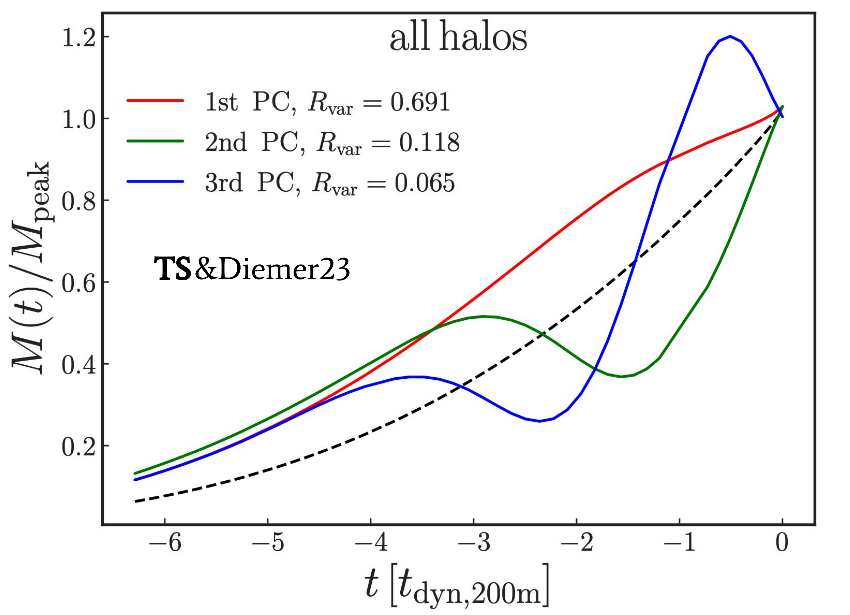
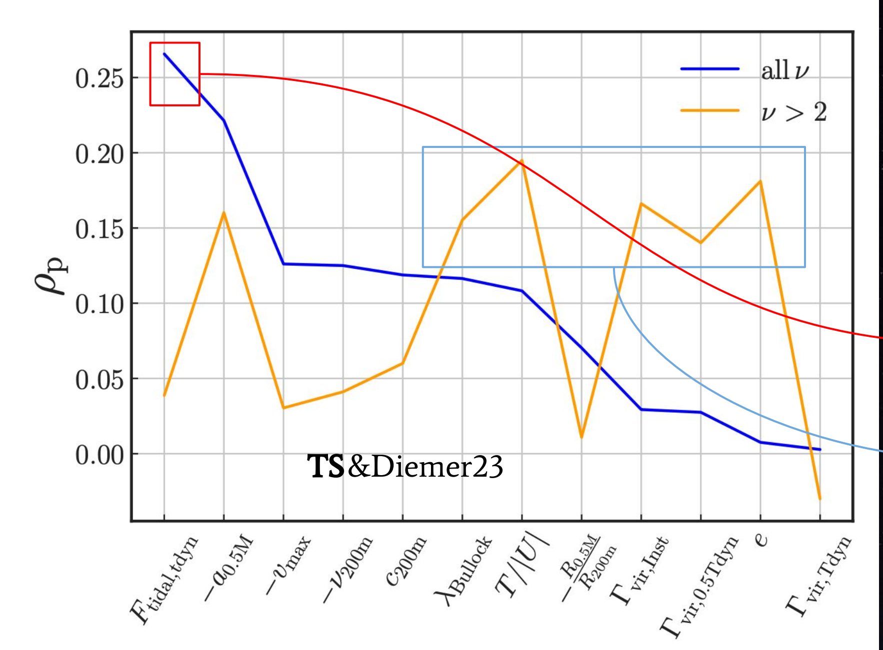


Figure B1. The first three principal components (red, green, blue) of the fractional mass history $M(t)/M_{\rm peak}$ (black dashed). $R_{\rm var}$ represents the explained variance ratio of each component.

- ~70% of the variation in the individual mass accretion history can be summarized with **one** principal function, which shows a high correlation (~0.76) to splashback radius for cluster-sized halos
  ⇒ splashback for MAH

- It is driven by the high correlation (-0.89) between the principal function and Γ_{200m}.

SPLASHBACK & OTHER PROPERTIES



Partial correlation between R_{sp} and other halo properties, w.r.t. $\mathbf{\Gamma_{200m}}$

- Compared with the recent mass accretion rate (Γ_{200m}), other halo properties show subordinate levels of correlation to R_{sp}
- For low-mass halos (blue, typically galaxy-sized) the effect of tidal force is not negligible, while for group- and cluster-sized halos there are hints that recent mergers may perturb the splashback radius

CONSTRAINING R_{SP} FROM DATA

WL, cluster-galaxy correlation

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

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

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

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

Truncation of the Einasto profile

$$\rho^{\text{infall}}(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-s_e}$$

OR

$$\rho(r) = \rho_m \left(\delta_1 \left[\frac{\delta_1}{\delta_{max}} + \left(\frac{r}{R}\right)^{s}\right]^{-1} + 1\right)$$

Diemer&Kravtsov14

Limiting central amplitude

The model used so far

$$\rho_{orb} = \rho_s e^{S(r)} \quad \gamma \equiv \frac{d\ln\rho}{d\ln r} = r\frac{dS}{dr} \quad S(r) = \int \frac{\gamma(r)}{r} dr$$

Orbiting (1-halo) term

$$\gamma(r) = -2\left(\frac{r}{r_s}\right)^{\alpha} - \left(\frac{r}{r_t}\right)^{\beta}$$

Halos have two different characteristic radii (c.f. NFW profile has only 1)

Scale radius — Truncation radius

$$S(r) = -\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right] - \frac{1}{\beta}\left[\left(\frac{r}{r_t}\right)^{\beta} - \left(\frac{r_s}{r_t}\right)^{\beta}\right]$$

Einasto — Truncation

NEW MODEL (Diemer22)

$$\rho(r) = \rho_m \left(\delta_1 \left[\left(\frac{\delta_1}{\delta_{max}}\right)^{\frac{1}{\zeta}} + \left(\frac{r}{R}\right)^{\frac{s}{\zeta}}\right]^{-\zeta} + 1\right)$$

transition smoothness parameter (set to 0.5)

Setting the maximum amplitude at the center

$$\rho(r) = \rho_m \left(\frac{\delta_1}{\sqrt{(\delta_1/\delta_{max})^2 + (r/R)^{2s}}} + 1\right)$$

Infalling (2-halo) term

CLUSTER-GALAXY CROSS-CORRELATION

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

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

$$\omega(r) = \frac{[DD(r) - DR(r) - RD(r) + RR(r)]}{[RR(r)]}$$

(Landy-Szalay estimator)

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

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

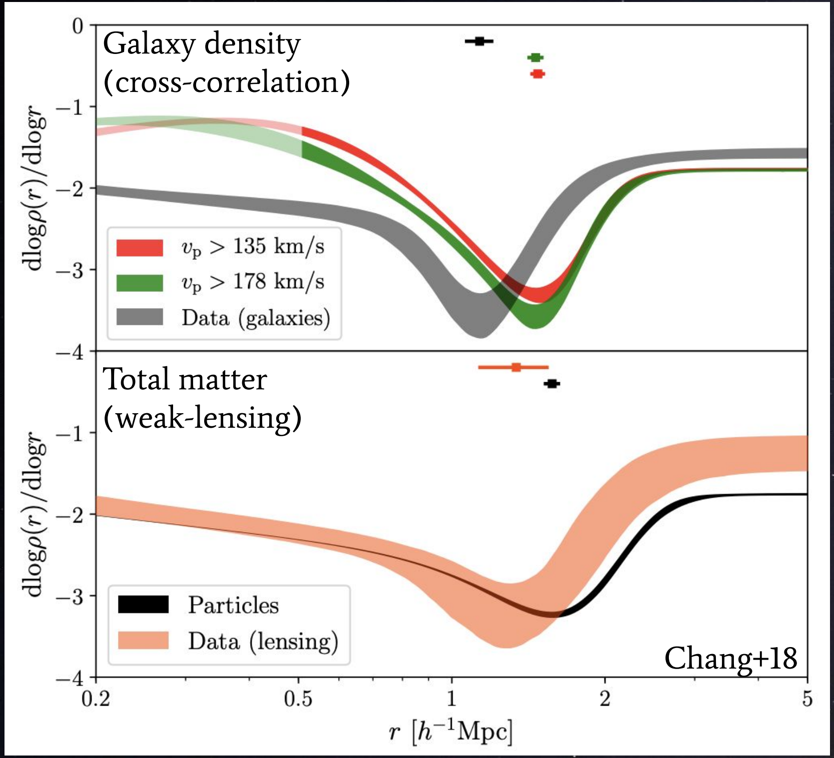
Correlation function picks up the galaxies that are correlated with the clusters: **avoiding the photo-z uncertainties of the galaxies**

R_{SP} FROM OPTICAL CLUSTERS

Optically selected clusters from the Sloan Digital Sky Survey (SDSS) and the Dark Energy Survey (DES) shows **~20% smaller** splashback radius in galaxy density profile than those from simulations (More+16, Baxter+17, Chang+18)

A large fraction of this discrepancy is attributed to the **projection effect** in the optical cluster **selection** (Busch&White17, Zu+17) and cluster LOS orientation (**TS**+19)

Optical clusters from the Hyper Suprime-Cam (HSC) survey showed splashback feature that is more consistent to theory (different algorithm)

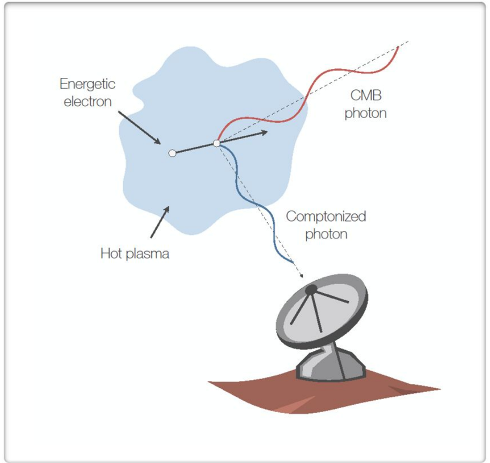


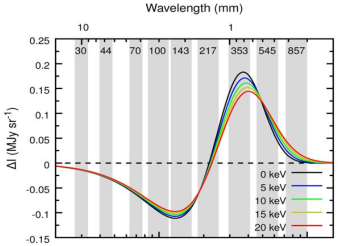
R_{SP} FROM SZ CLUSTERS

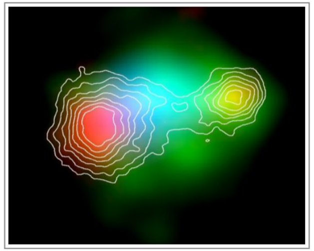
Sunyaev-Zel'dovich effect: CMB photons scattered off the hot gas within the clusters
⇒ energy transferred to higher frequencies

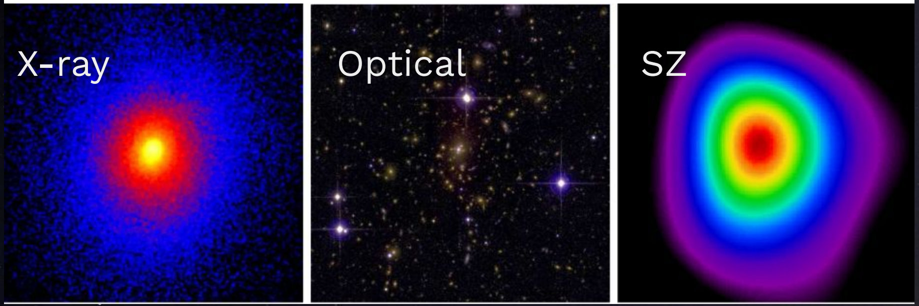
SZ-selected clusters

- Selection is nearly **independent** of the observables in the optical survey
- The SZ signal is expected to correlate **more tightly with cluster mass** than optical richness
- **Less affected** by projection effects
- **More massive** & **higher redshift** clusters

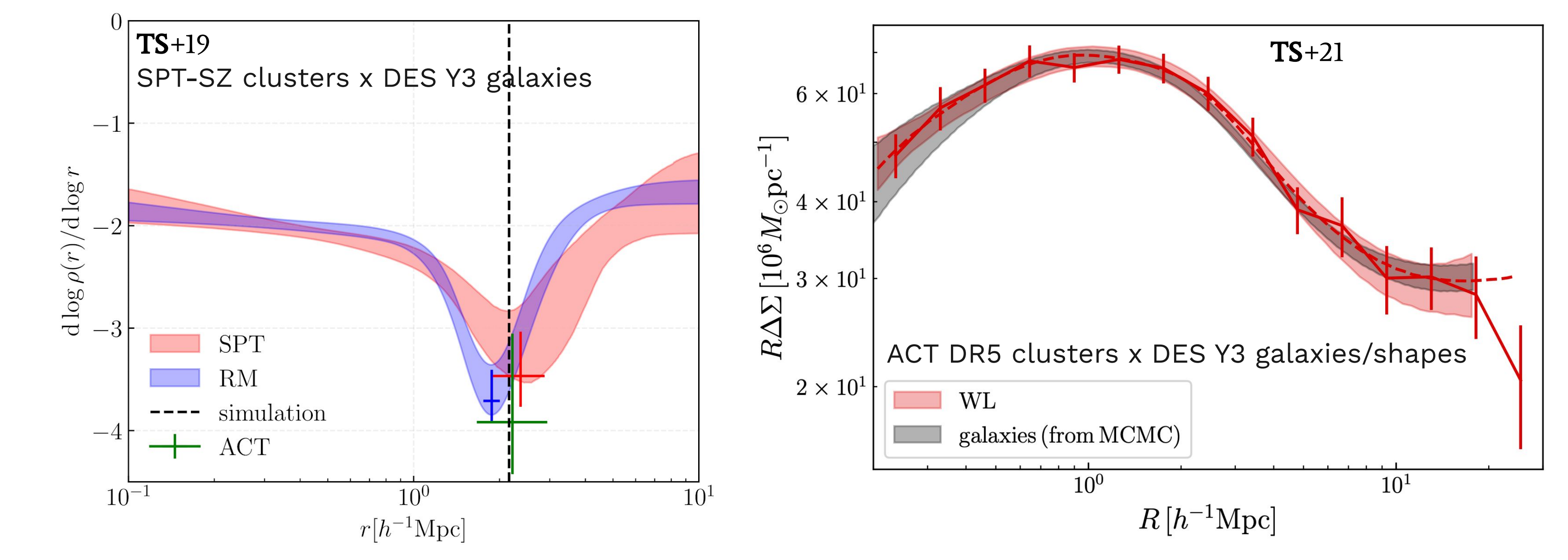






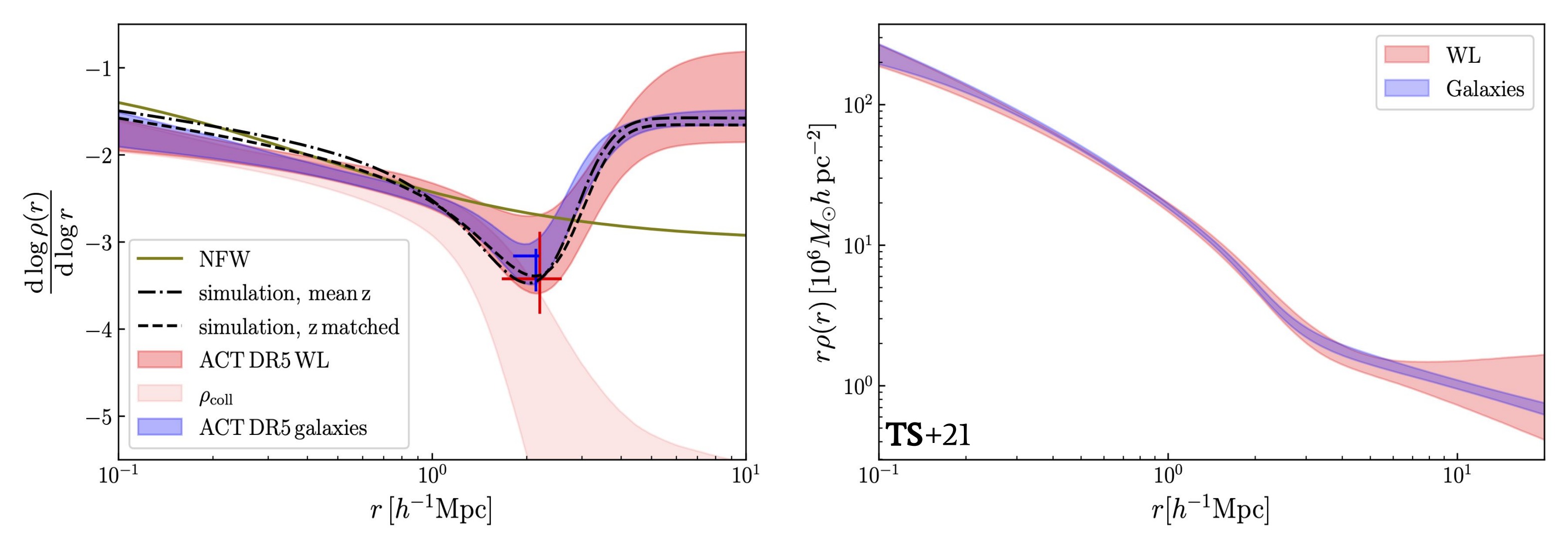


R_{SP} FROM SZ CLUSTERS



The location of splashback radius for the SZ clusters agrees with that from the theory (N-body simulation)

R_{SP} FROM SZ CLUSTERS



Furthermore, in massive SZ clusters (M_{500c}~3e14M_{sun}/h), the galaxy density profile and the total matter profile are surprisingly similar in shape
⇒ Gravity being the dominant factor in shaping massive halos

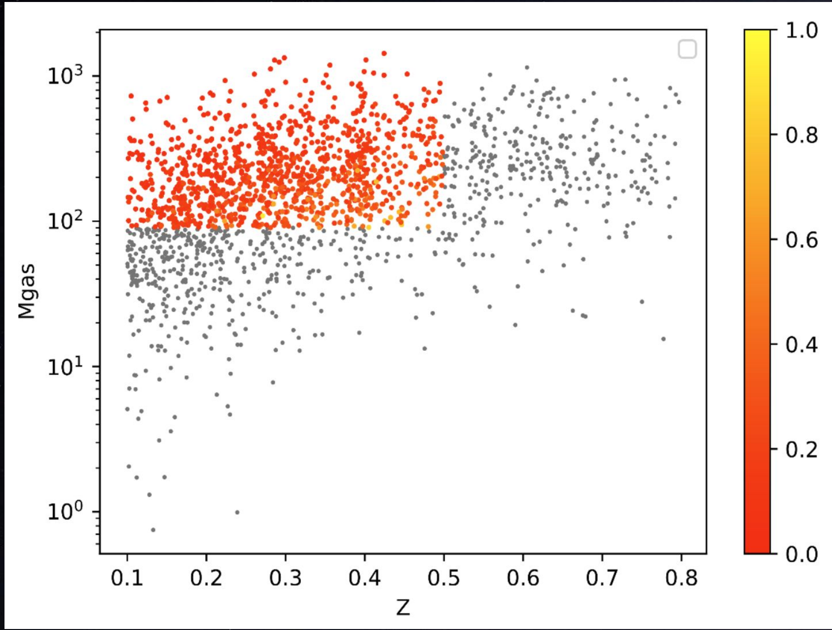
Assembly bias with R_{SP} of X-ray clusters

<Cluster sample>
X-ray clusters from eROSITA survey (eRASS1)
Z = [0.1, 0.5]
$M_{gas,500c}$ > 9e12 M_{sun}

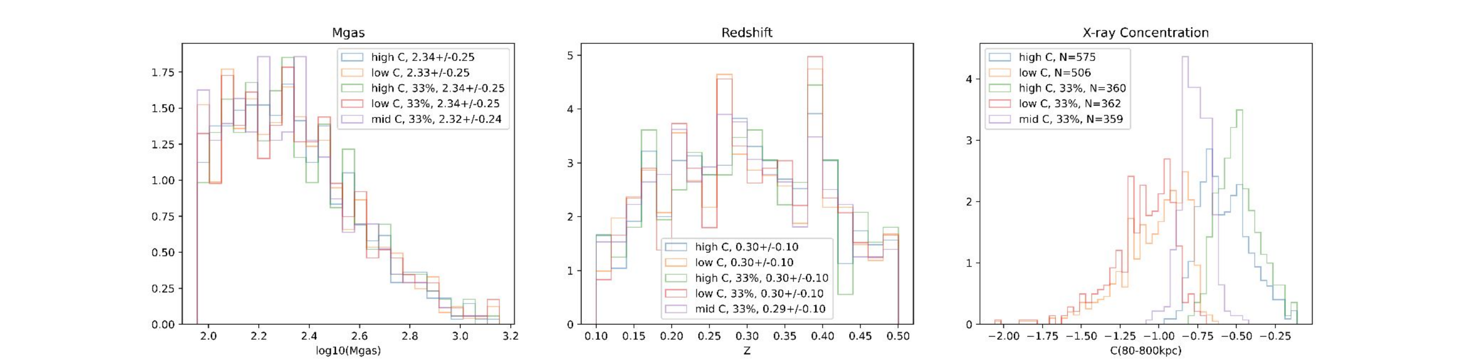
<Galaxy sample>
Dark Energy Survey Year-3

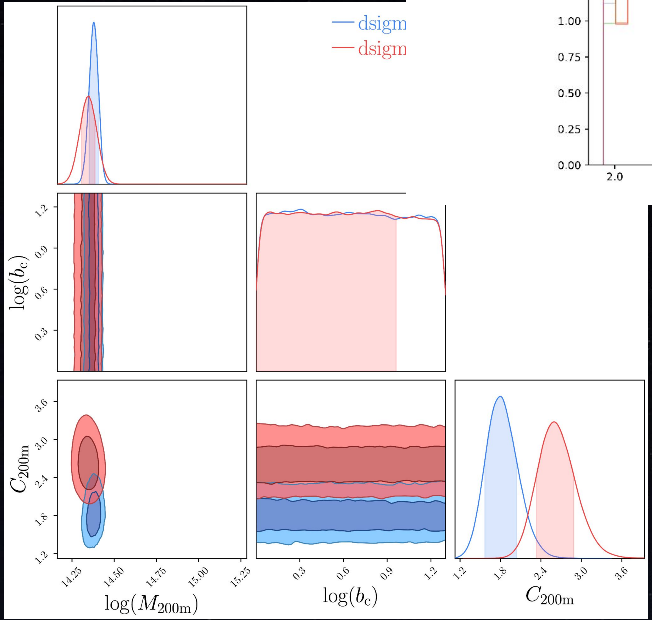
⇒ To detect dependence of the splashback feature on secondary halo properties other than the halo mass (assembly bias)

We split the clusters into the low and high **X-ray concentration** sample



Assembly bias with R_{SP} of X-ray clusters



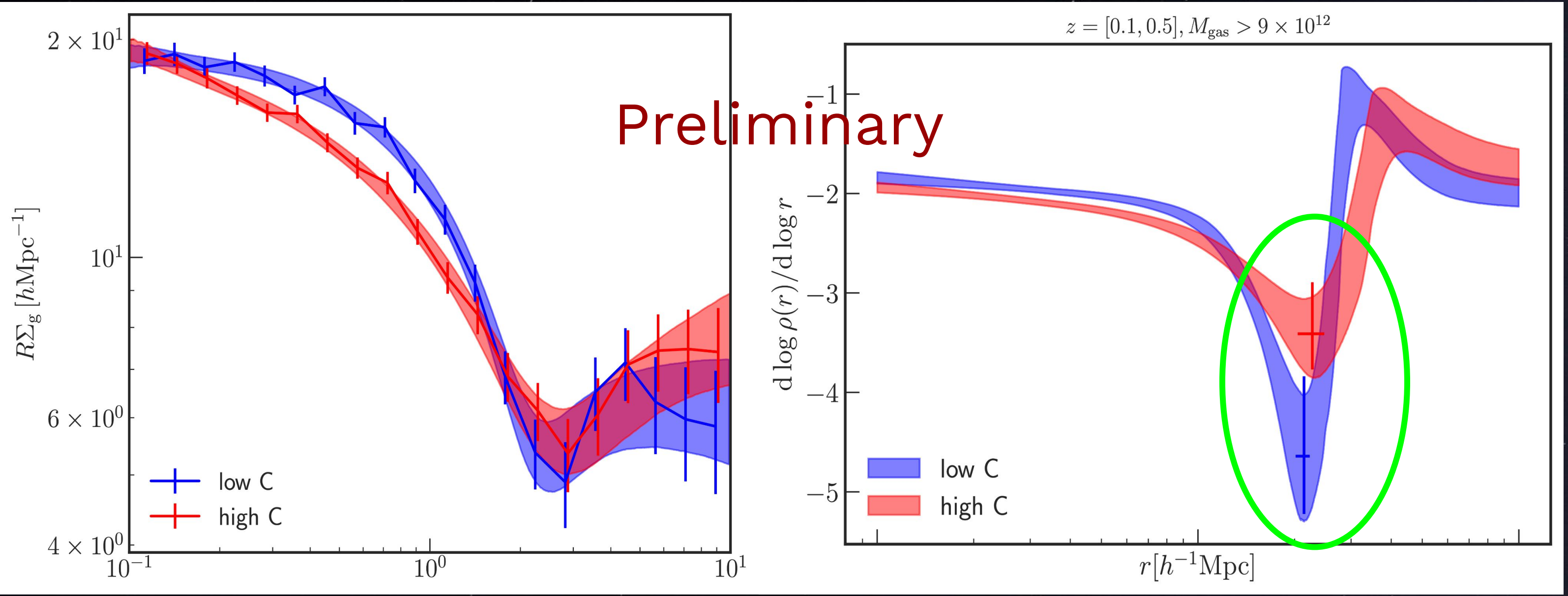


(Upper) The split of X-ray cluster – consistent M_{gas} and z distribution, but different X-ray concentration

(Left) WL NFW constraints of the high and the low X-ray concentration sample ⇒ consistent mass, different concentration (total matter)

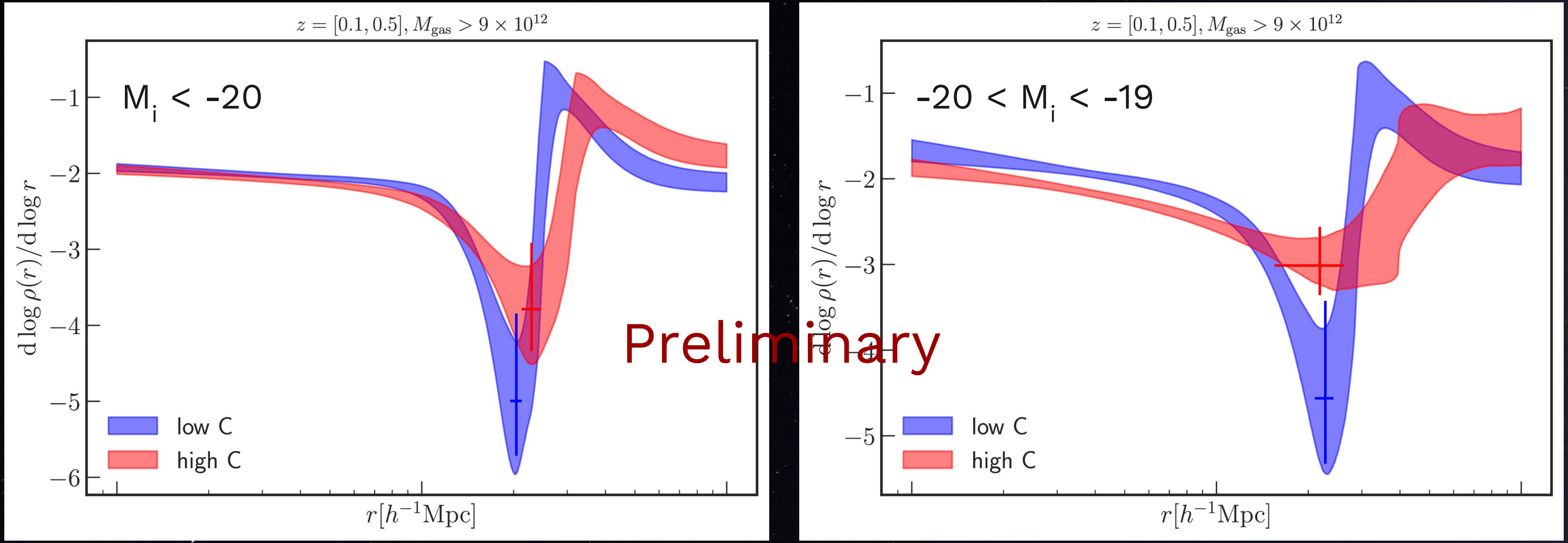
⇒ we measure splashback feature using galaxy density profiles

Assembly bias with R_{SP} of X-ray clusters



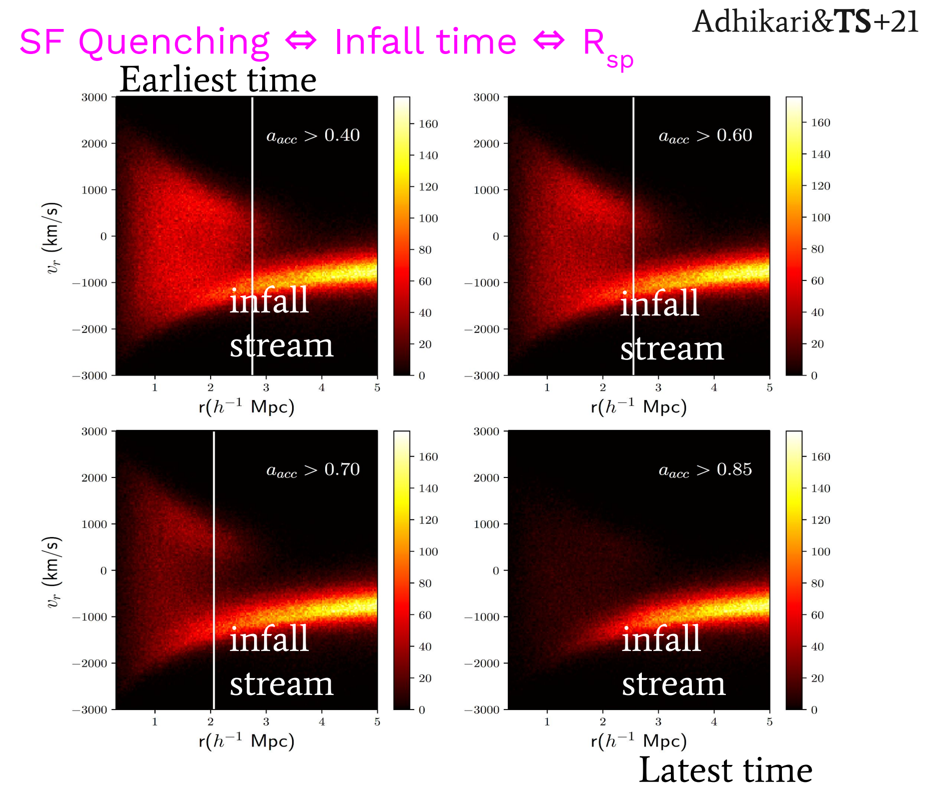
Absolute magnitude $M_i < -19$
Higher concentration ⇔ lower mass accretion (older) ⇔ larger/shallower splashback radius
⇒ consistent with the theoretical expectation (Diemer14, Adhikari14, More15 etc.)

Assembly bias with R_{SP} of X-ray clusters



The low and the high magnitude galaxy profiles have qualitatively similar trend in halo concentration with each other, but show a visible trend especially for the high concentration halos ⇒ analysis ongoing to characterize this assembly bias signal as a function of halo and galaxy properties

R_{SP} AS A QUENCHING CLOCK

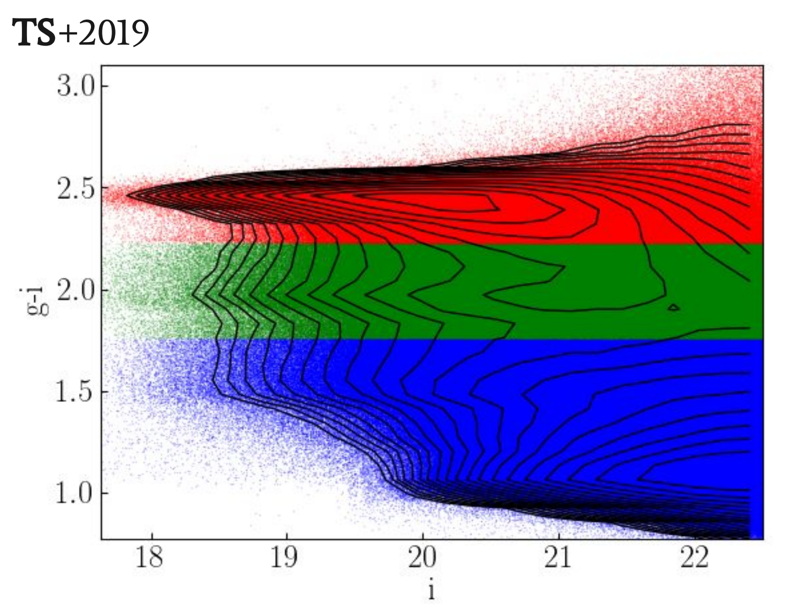


⇐ Subhalos accreted to a cluster at different times in simulation

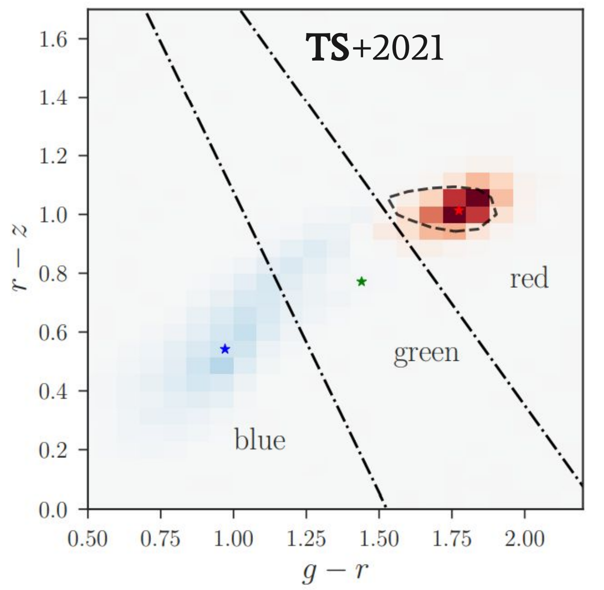
Galaxies in **the infall stream** do **not** show any splahsback feature, while those that have completed at least one crossing show a distinctive splashback feature

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

R_{SP} AS A QUENCHING CLOCK

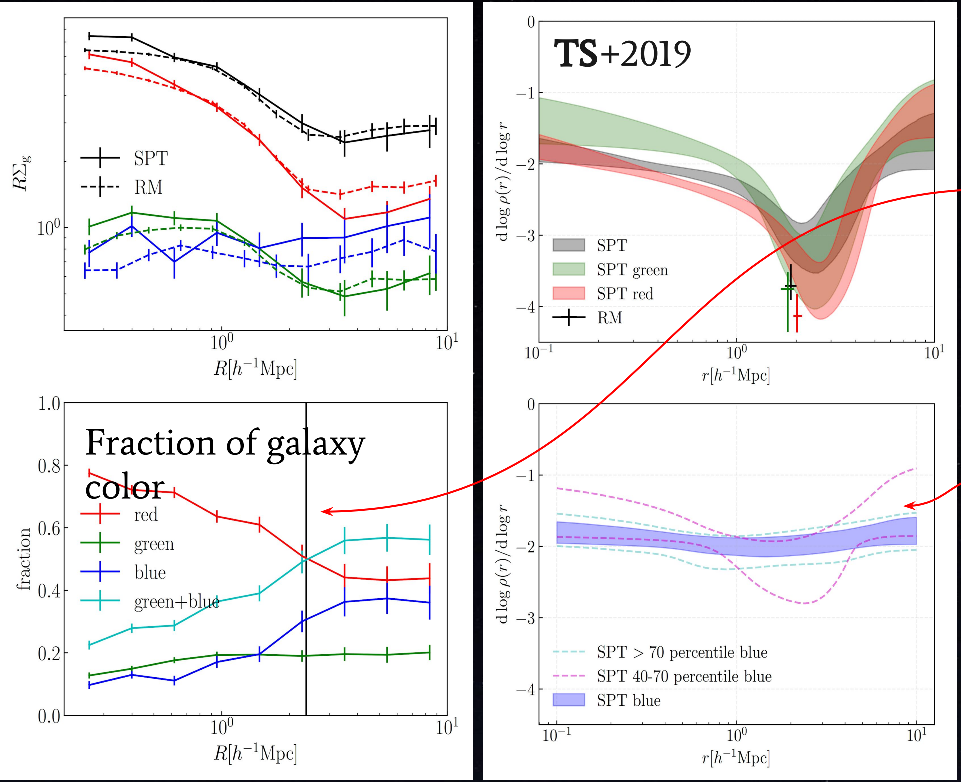


Splitting galaxies simply by color



Splitting galaxies on the color-color space (subtracting random directions from the cluster field)

R_{SP} AS A QUENCHING CLOCK

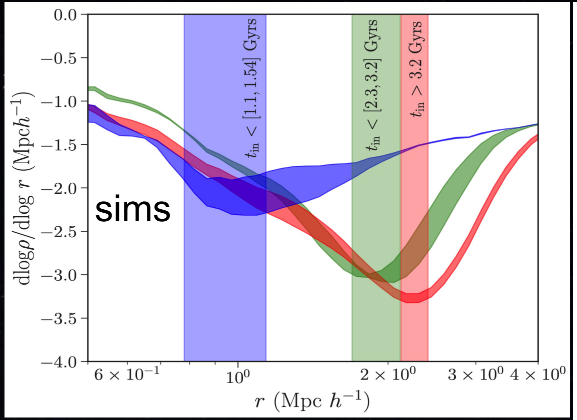


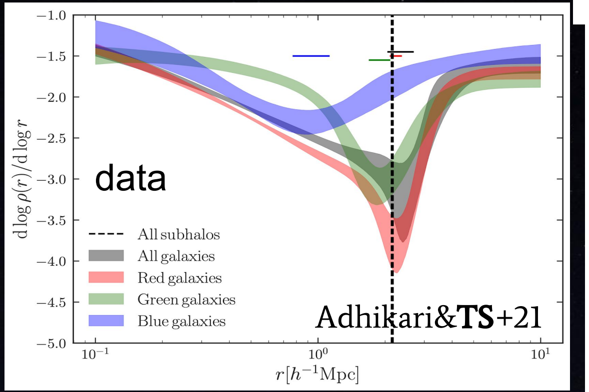
We measure profiles of galaxies split on color.

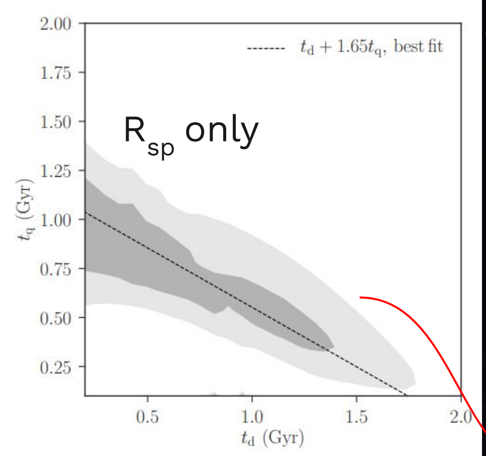
The upturn of the red fraction around r_{sp} = evidence of **quenching of galaxy star formation** inside clusters

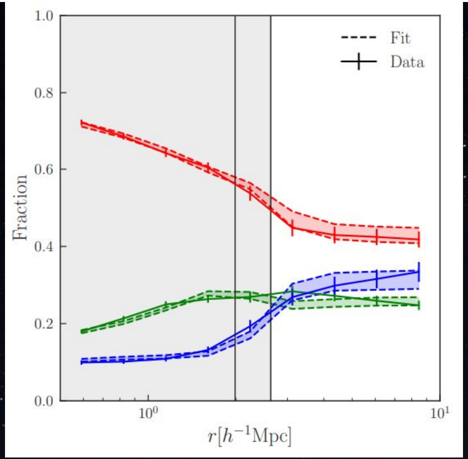
Blue galaxies are consistent to **a pure power-law** profile; indicating that they are still on their **first infall passage ⇒ qualitatively constrains maximum quenching timescale**

R_{sp} AS A QUENCHING CLOCK



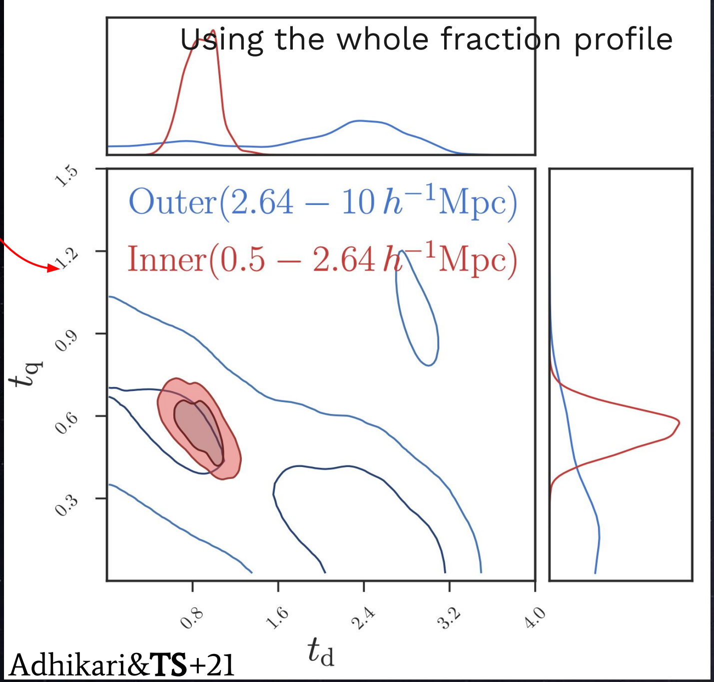






Wetzel+13

$$SFR_{sat}(t) = \begin{cases} SFR_{iso}(t), & \text{if } t < t_d \\ SFR_{iso}(t)\exp\left(-\frac{t-t_d}{t_q}\right) & \text{if } t > t_d \end{cases}$$



Constraints of Mass Accretion Rate from R_{sp}

Using splashback radius calibrated against simulations to directly constrain the mass accretion rates of halos

R_{sp} as a Cosmological Probe

Using splashback radius to constrain cosmology (especially, Ω_m)
⇒ supplementary to the number-count cluster cosmology

Further Applications to Constrain Physics

Nature of dark matter, modified gravity, galaxy star-formation quenching and etc.