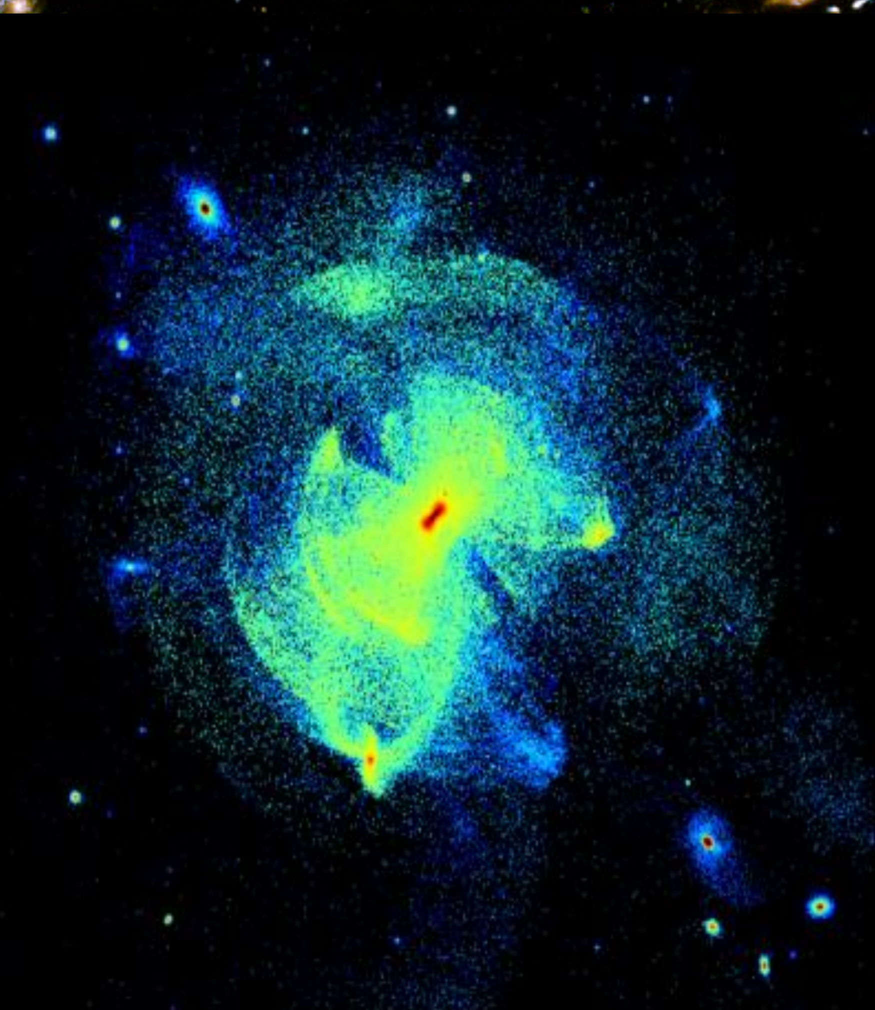


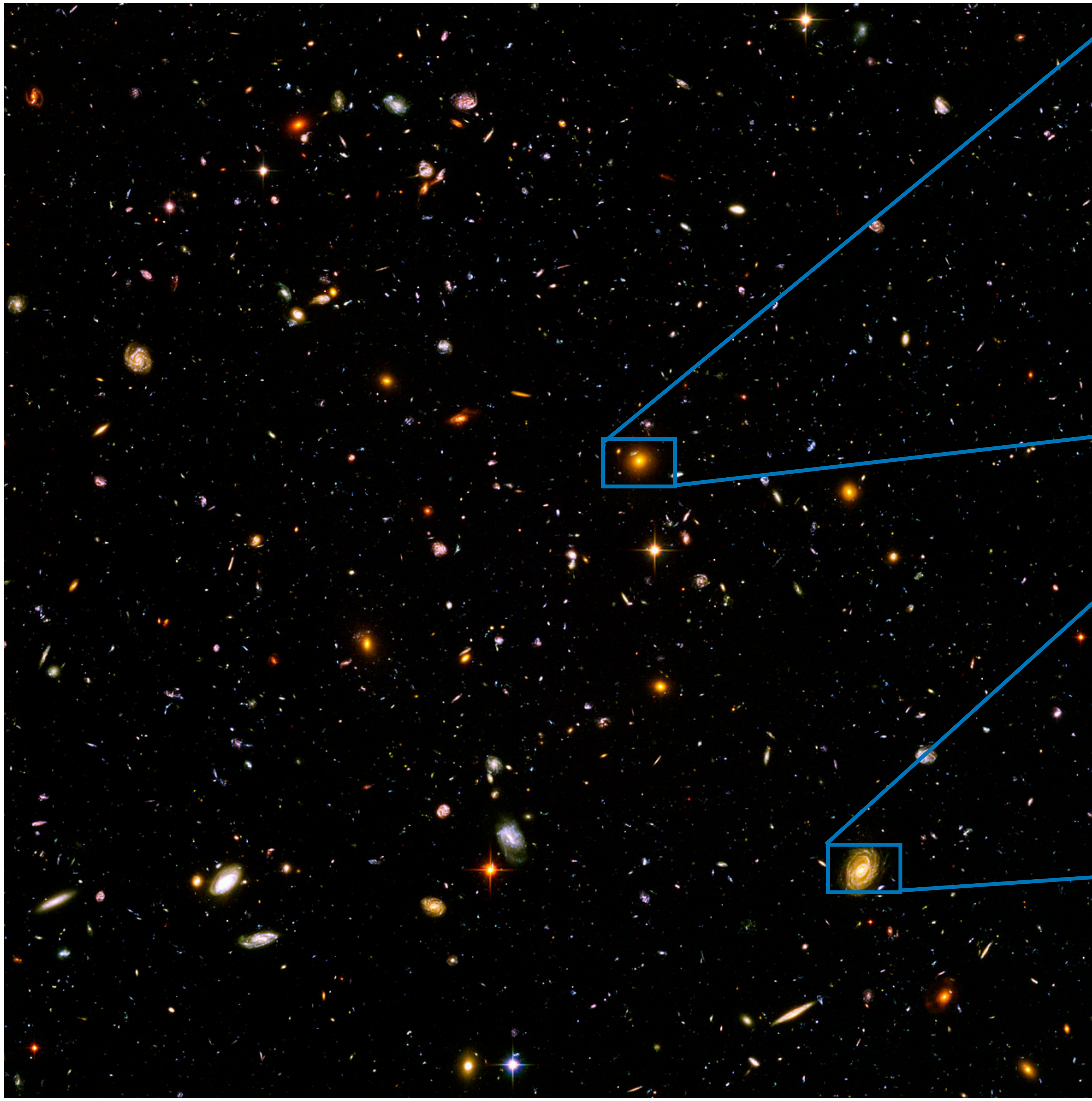
Splashback radius as probes of cosmology, dark matter and galaxy evolution

Susmita Adhikari
KIPAC Postdoctoral Fellow, Stanford University

IIT Hyderabad (15th July 2020)

Collaborators- Tae-hyeon Shin, Ethan Nadler, Arka Banerjee, Eric Baxter, Chihway Chang, Neal Dalal, Bhuvnesh Jain, Andrey Kravtsov, Jeremy Sakstein, Risa Wechsler

Image of the night sky taken with the Hubble Space telescope



clusters of bound galaxies

Galaxies are formed by baryonic matter and are held together by gravity and hydrodynamic forces

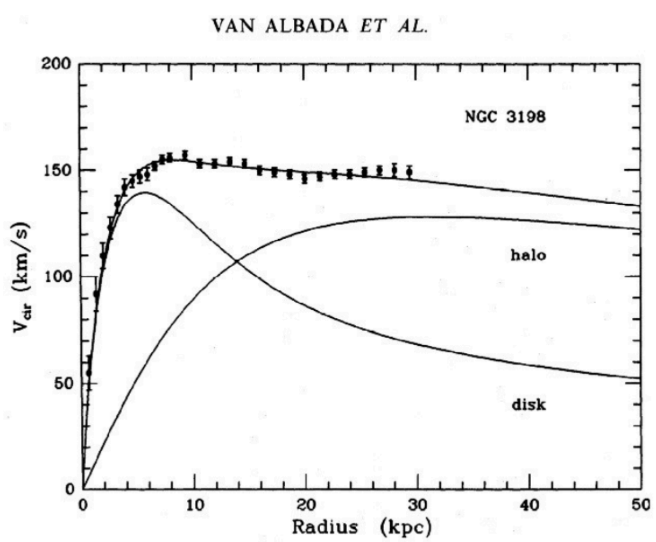
Evidence for a dark component to gravity

Galaxy rotation curves

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡

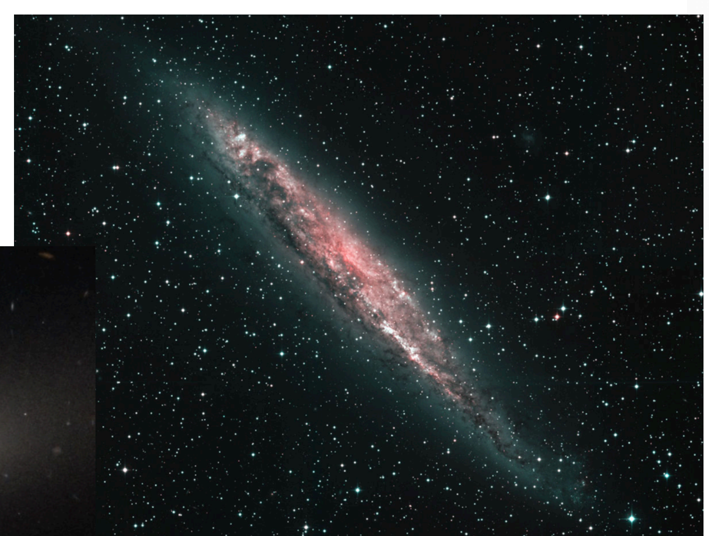
Received 1969 July 7; revised 1969 August 21



Velocity dispersion of Coma cluster -

Fritz Zwicky - 1933
Velocity dispersion was not consistent with viral theorem.

Existence of thin disks



A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

J. P. OSTRIKER
Princeton University Observatory
AND
P. J. E. PEEBLES
Joseph Henry Laboratories, Princeton University

Received 1973 May 29

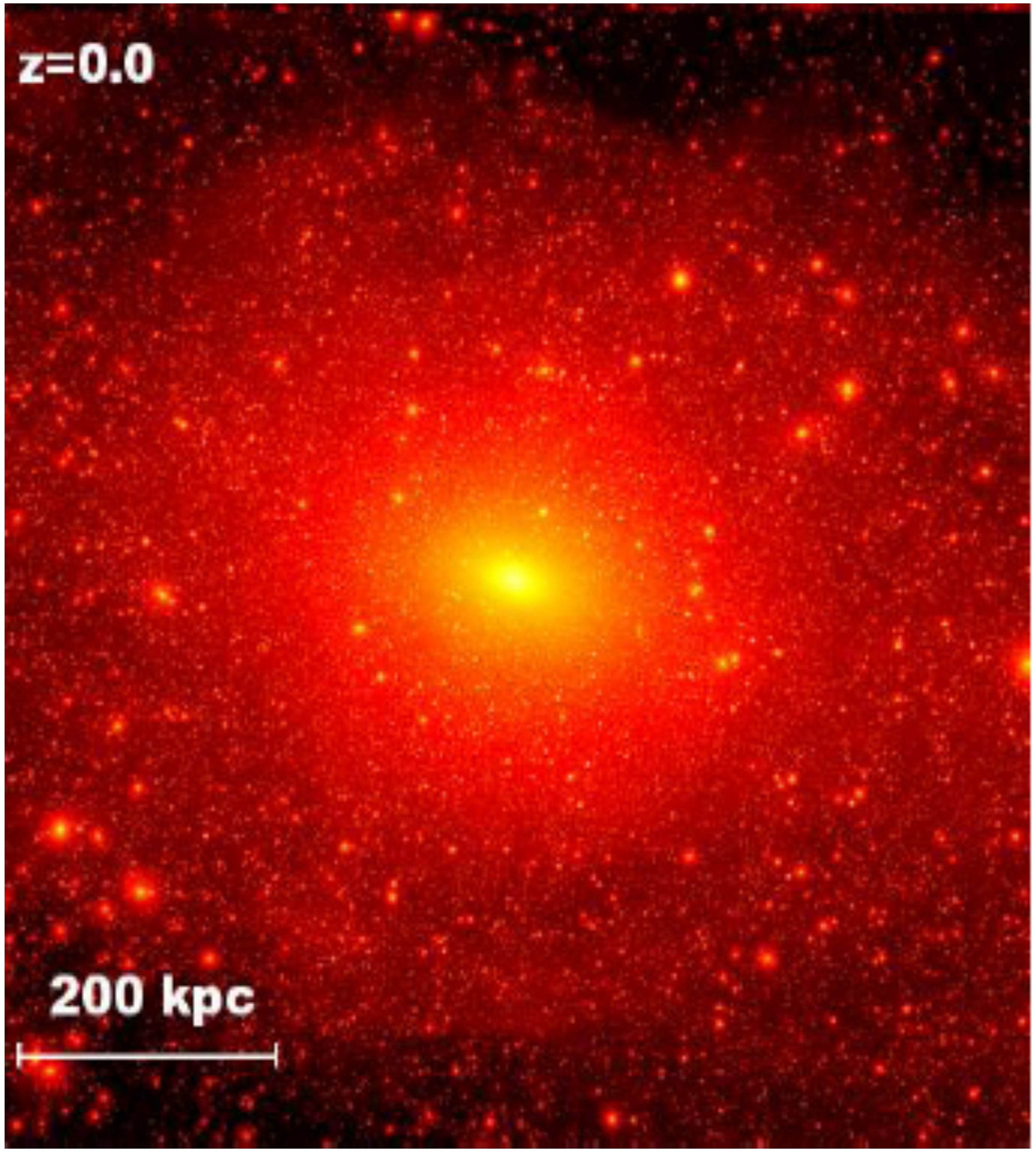
$$Q \equiv \frac{\sigma\kappa}{3.36 G \Sigma_0} \geqslant 1.$$

Direct evidence for the existence of dark matter

Image composite credit: X-ray: NASA / CXC / CfA / M.Markevitch et al.; Optical: NASA / STScI; Magellan / U.Arizona / D.Clowe et al.; Lensing Map: NASA / STScI; ESO WFI; Magellan / U.Arizona / D.Clowe et al.

Merging clusters -The bullet cluster system

What are Dark Matter Halos ?

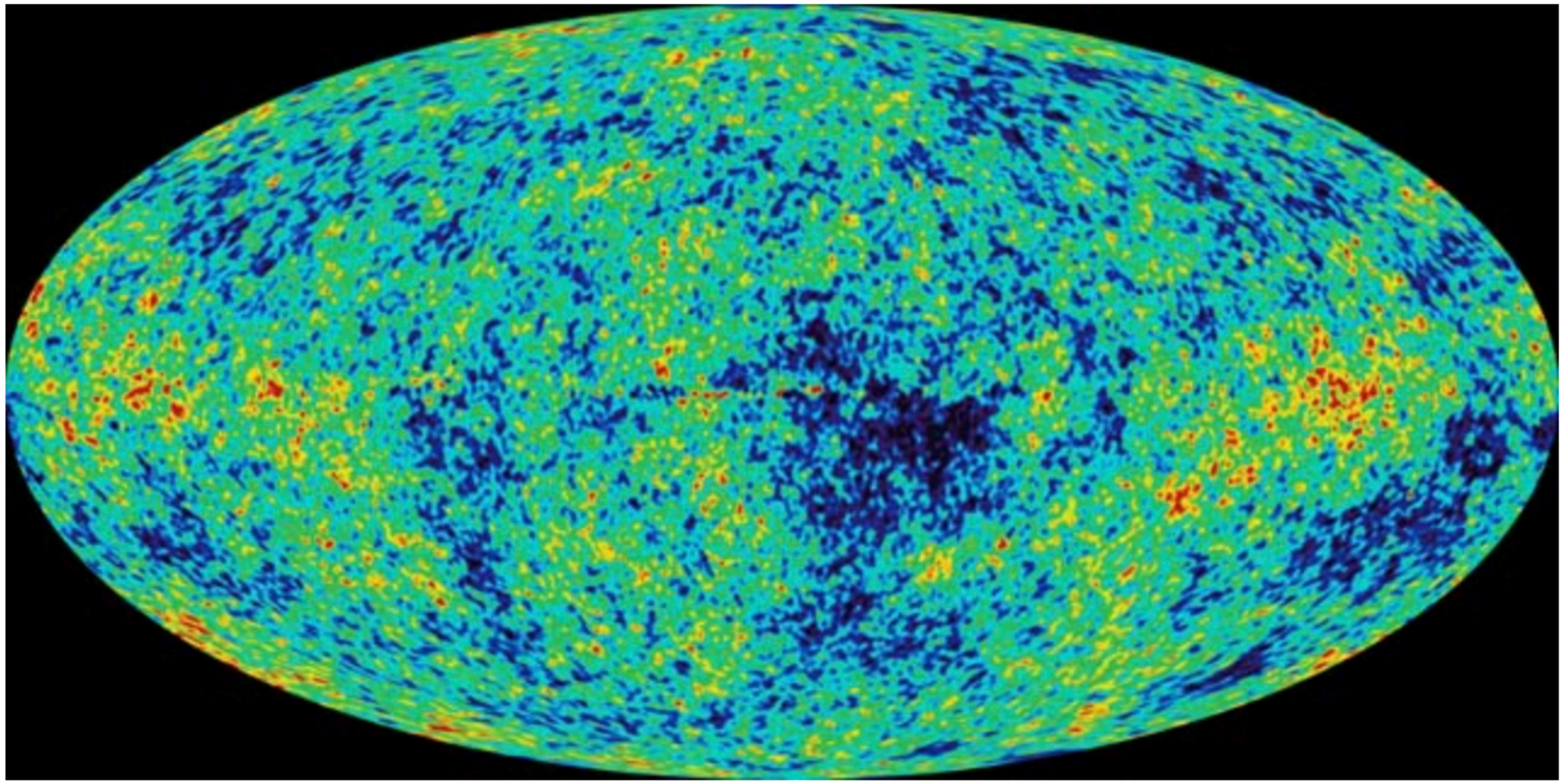


Via Lactea simulation

- Dark matter halos are endpoints of all cosmological structure formation
- Self-bound, virialized structures
- Harbor all stars, galaxies, quasars

Structure formation in the universe

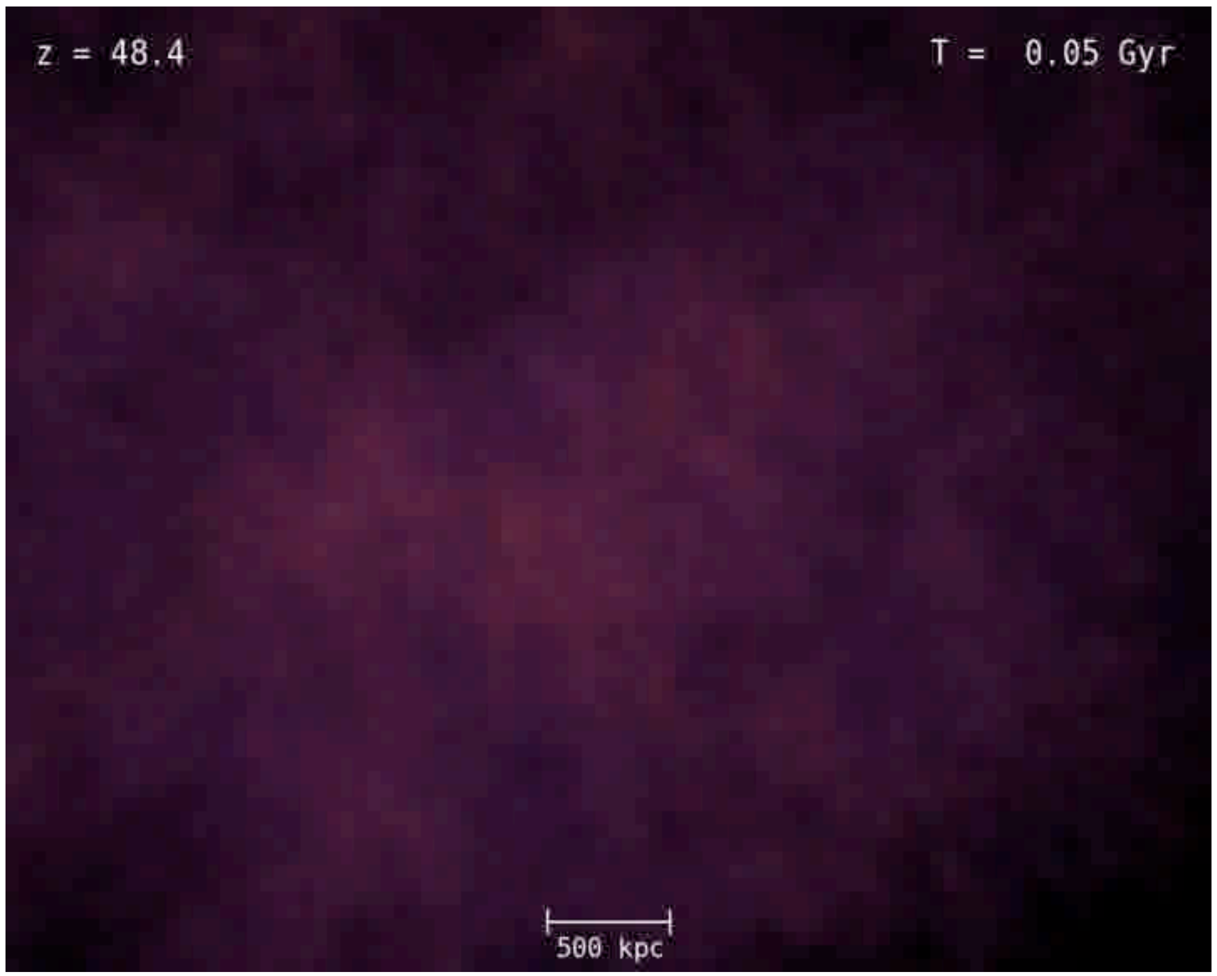
Initial quantum fluctuations in the density of matter magnified by inflation

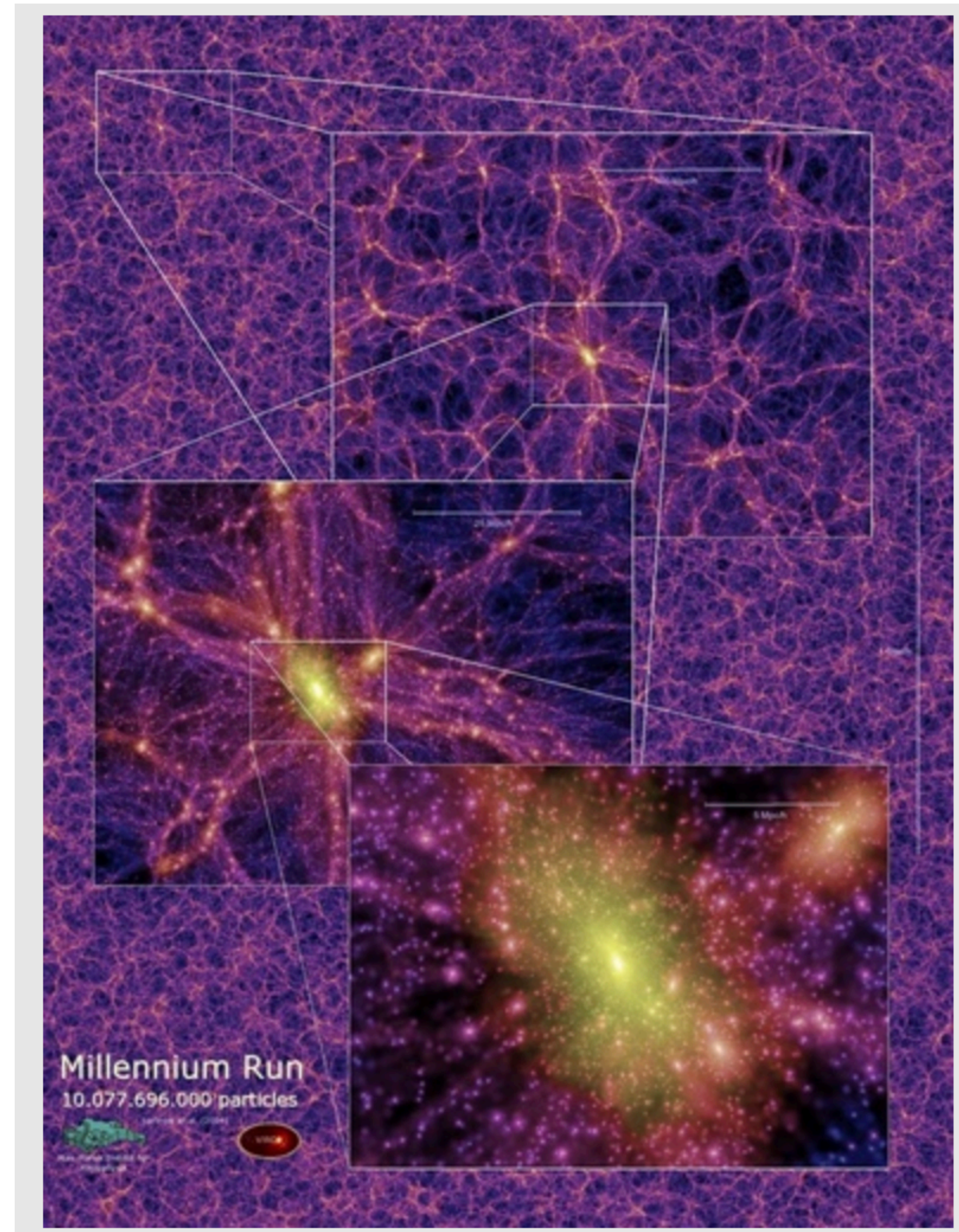


The cosmic microwave background

Density perturbations collapse gravitationally to form dark matter halos

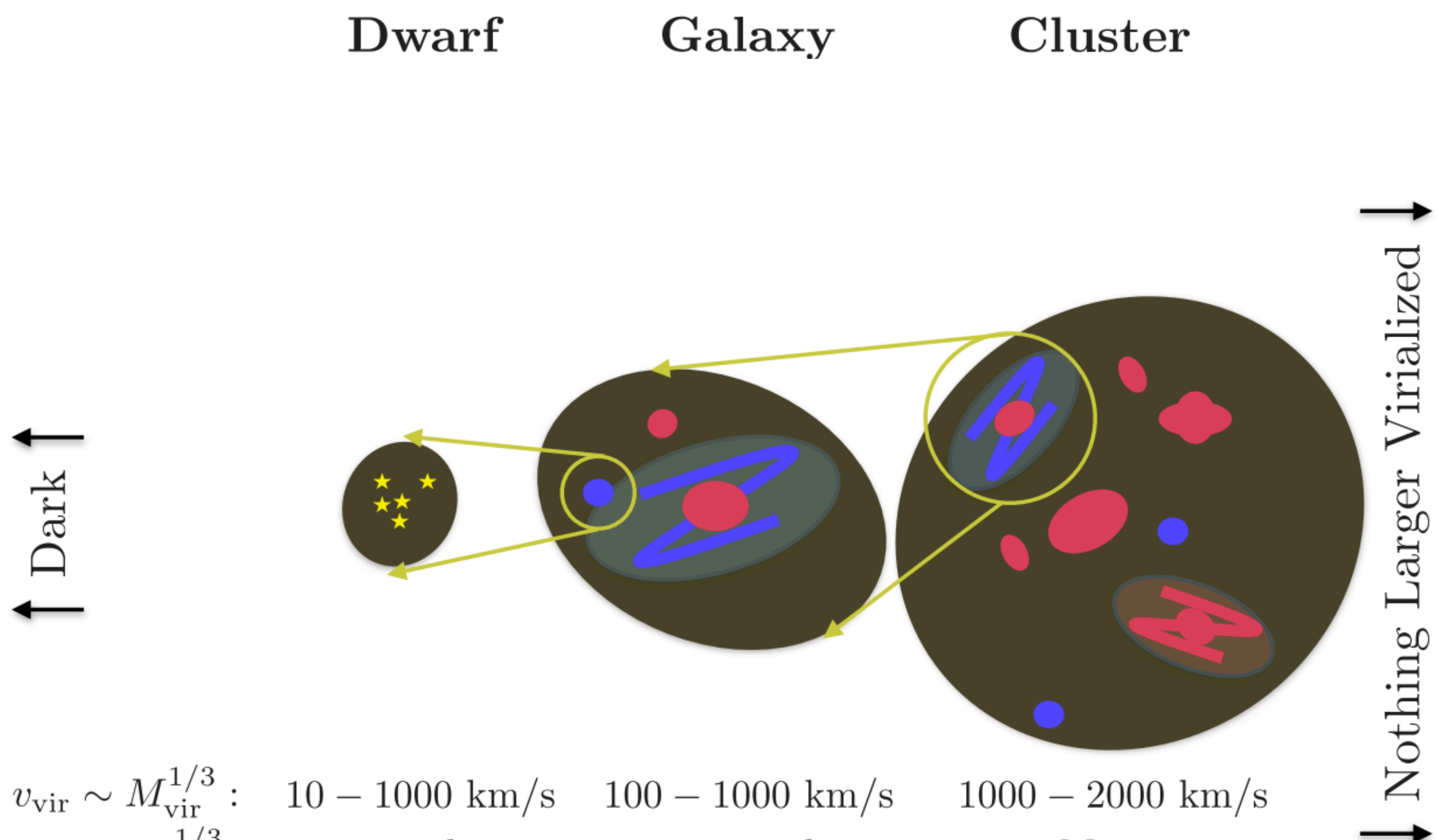
Structure formation in the universe





Density perturbations collapse gravitationally to form halos

Small halos form first and merge to form more massive halos



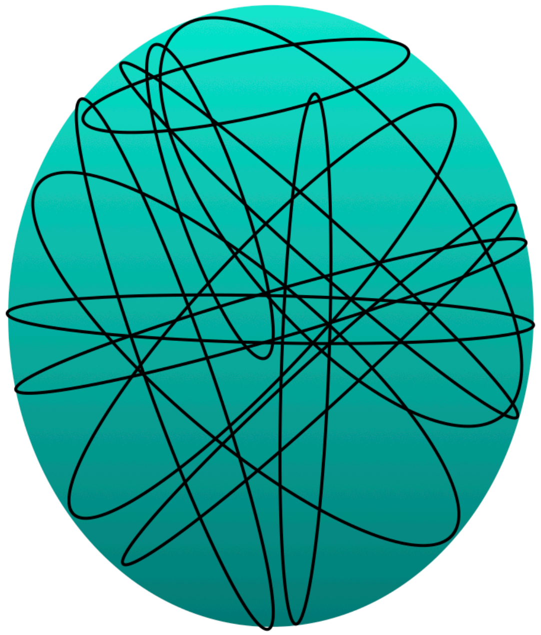
$v_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 1000$ km/s	$100 - 1000$ km/s	$1000 - 2000$ km/s
$R_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 100$ kpc	$100 - 1000$ kpc	$1 - 2$ Mpc
$R_* \sim 0.02 R_{\rm vir}$:	$\sim 0.1 - 1$ kpc	$\sim 1 - 10$ kpc	~ 20 kpc
$k_{\rm hm} \sim M_{\rm vir}^{-1/3}$:	$\sim 4 - 40$ Mpc^{-1}	$\sim 0.4 - 4$ Mpc^{-1}	$\sim 0.2 - 0.4$ Mpc^{-1}

credit: Buckley and Peter 2017

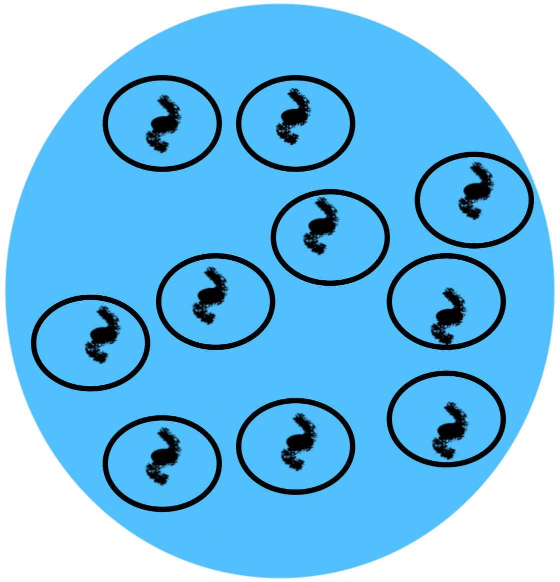
Hierarchical structure formation

Hierarchical structure formation

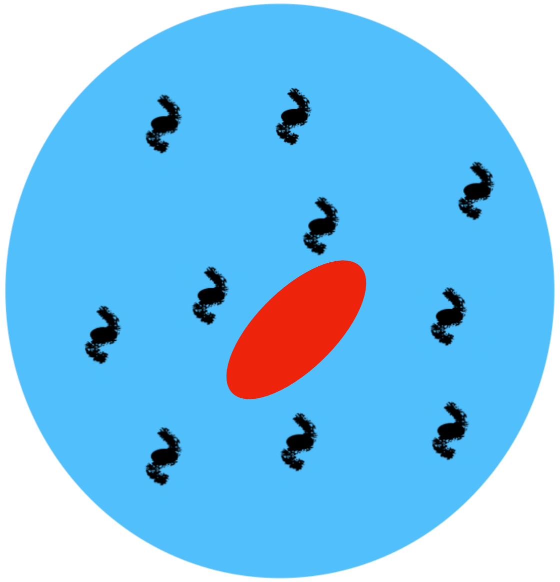
Main components of a halo



Dark matter particles that are orbiting in a central potential

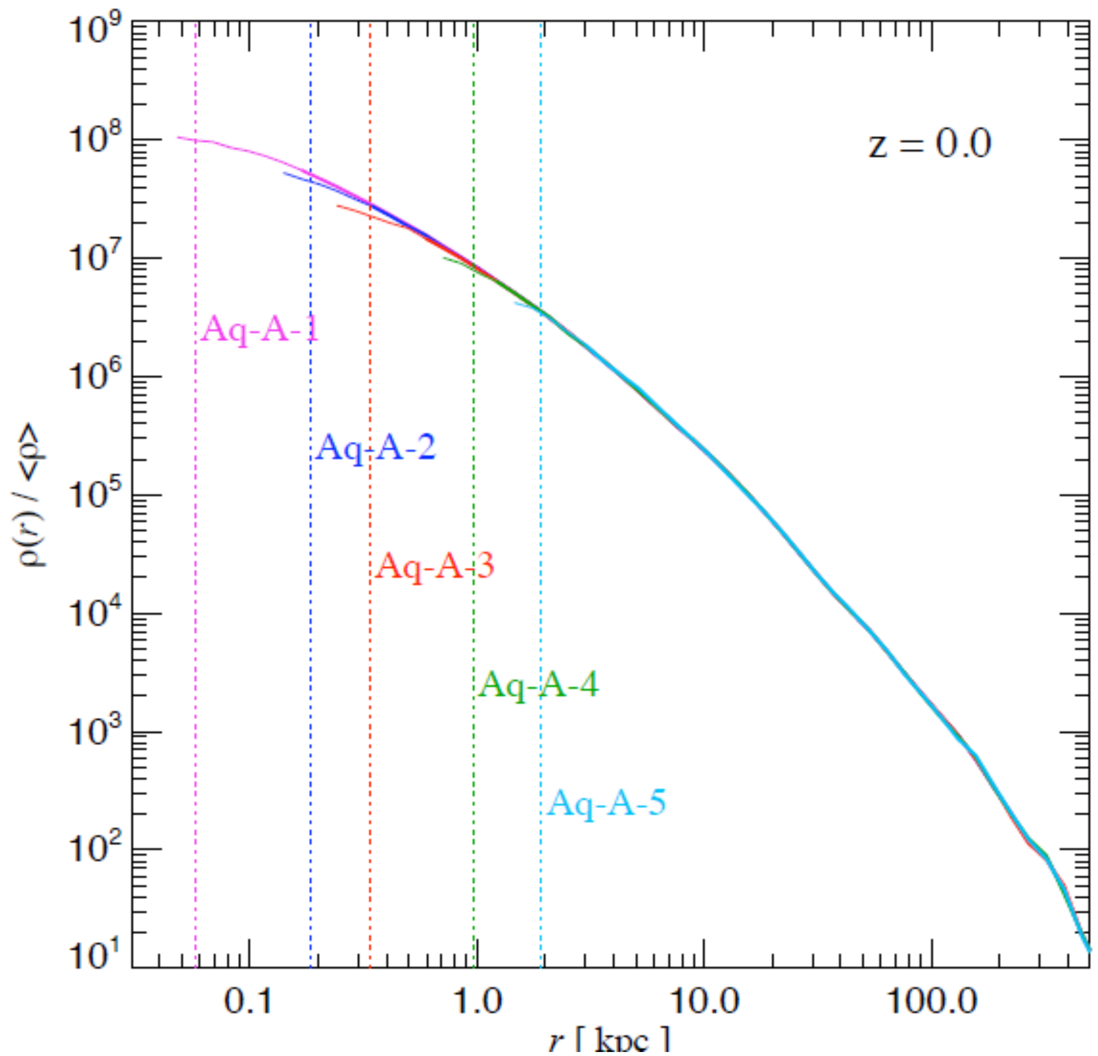


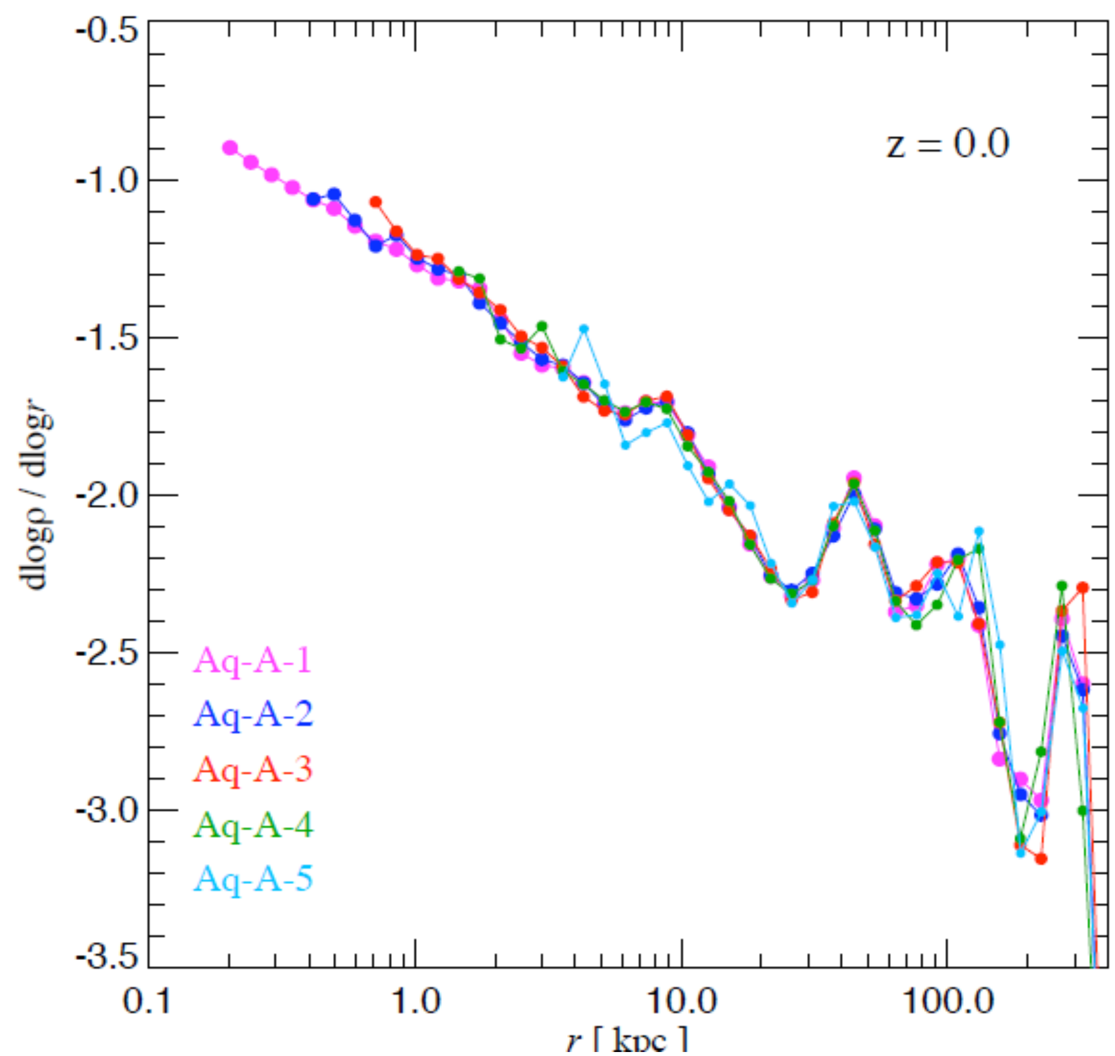
Halos grow hierarchically -
small objects form first and fall into massive halos
So halos contain subhalos that also harbor galaxies



Baryonic matter in the form of diffuse stars, gas and galaxies

The density profiles of dark matter halos





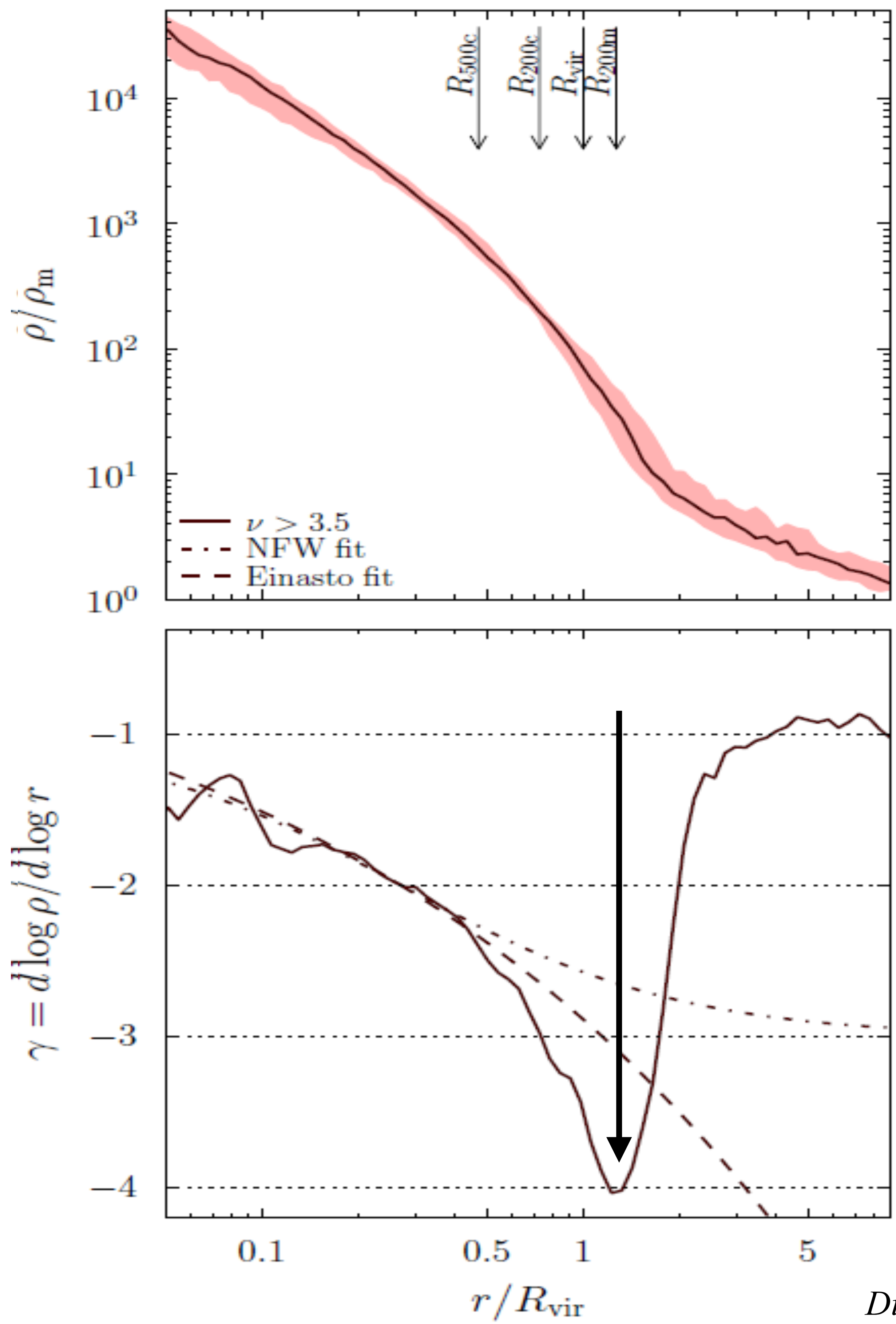
"Aquarius" Springel et. al 2008

- The density of halos is well described by the NFW profiles

$$\frac{\rho_0}{\frac{R}{R_S}\left(1+\frac{R}{R_s}\right)^2}$$

- Slope is -1 in the inner regions and rolls over to -3 in the outskirts of the halo.

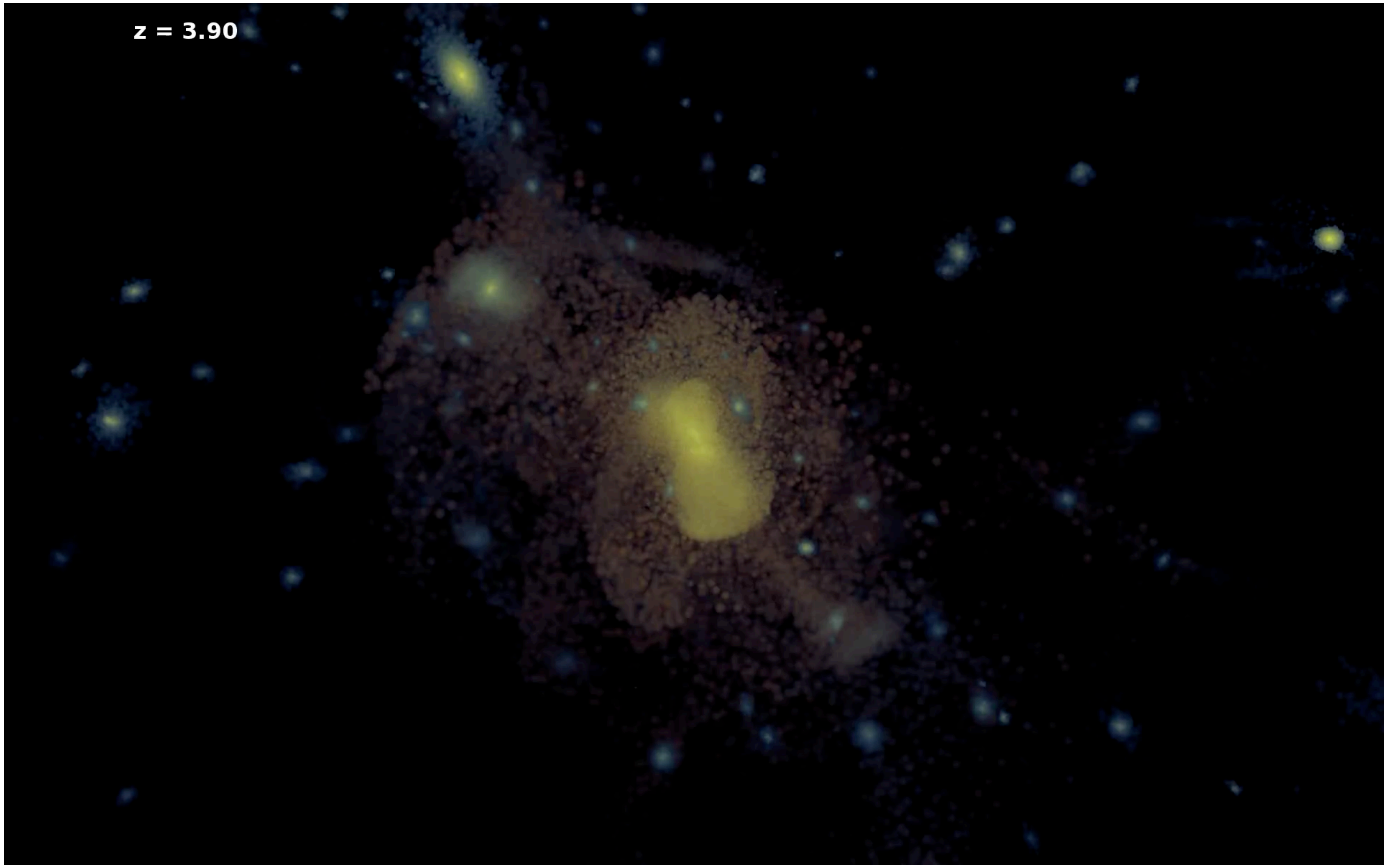
Outer density profiles of Dark Matter Halos



Diemer & Kravtsov 2014

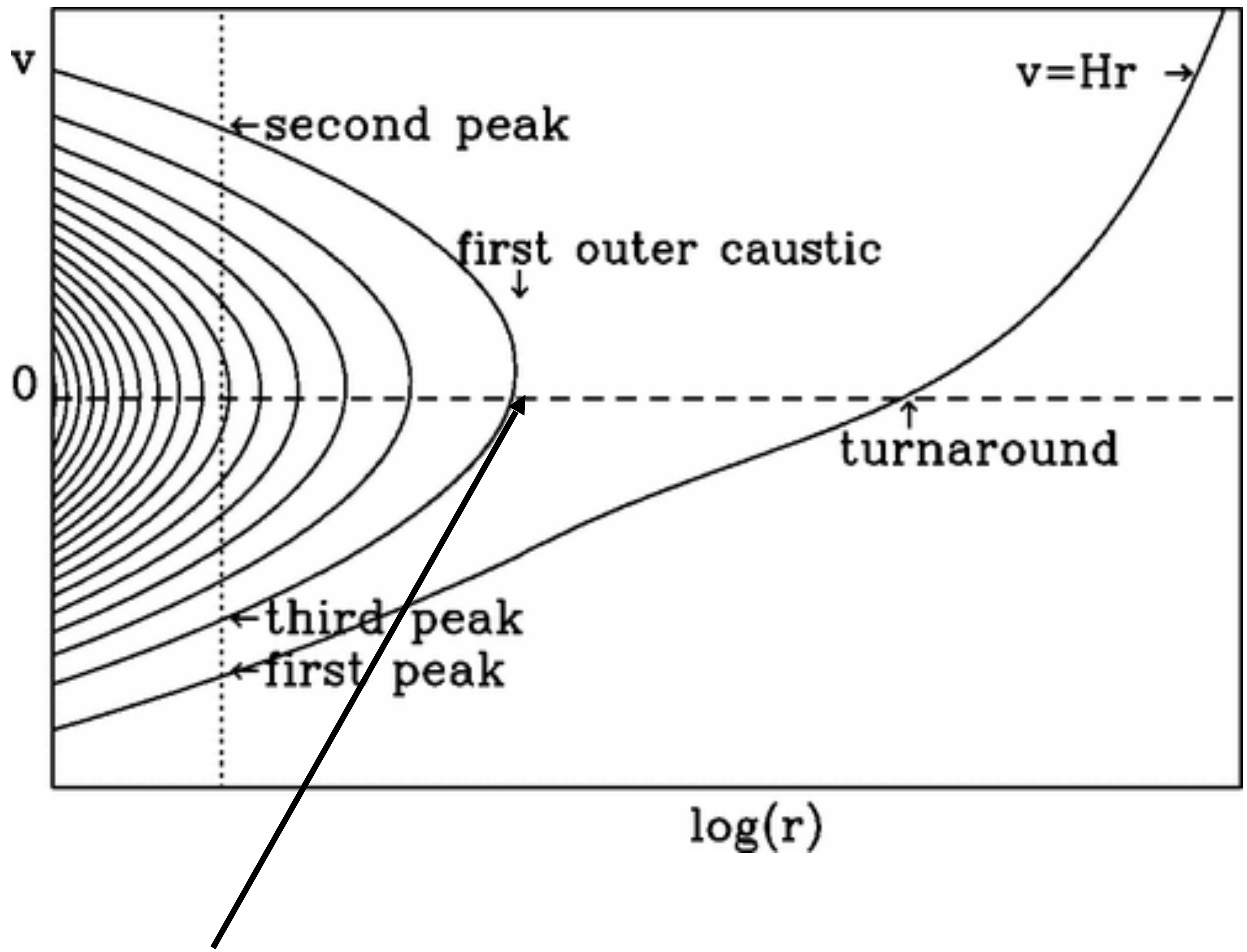
- Deviation from NFW and Einasto profile in the outer regions of the halo
- Slope of the local density deviates in a narrow confined region

The evolution of dark matter halos



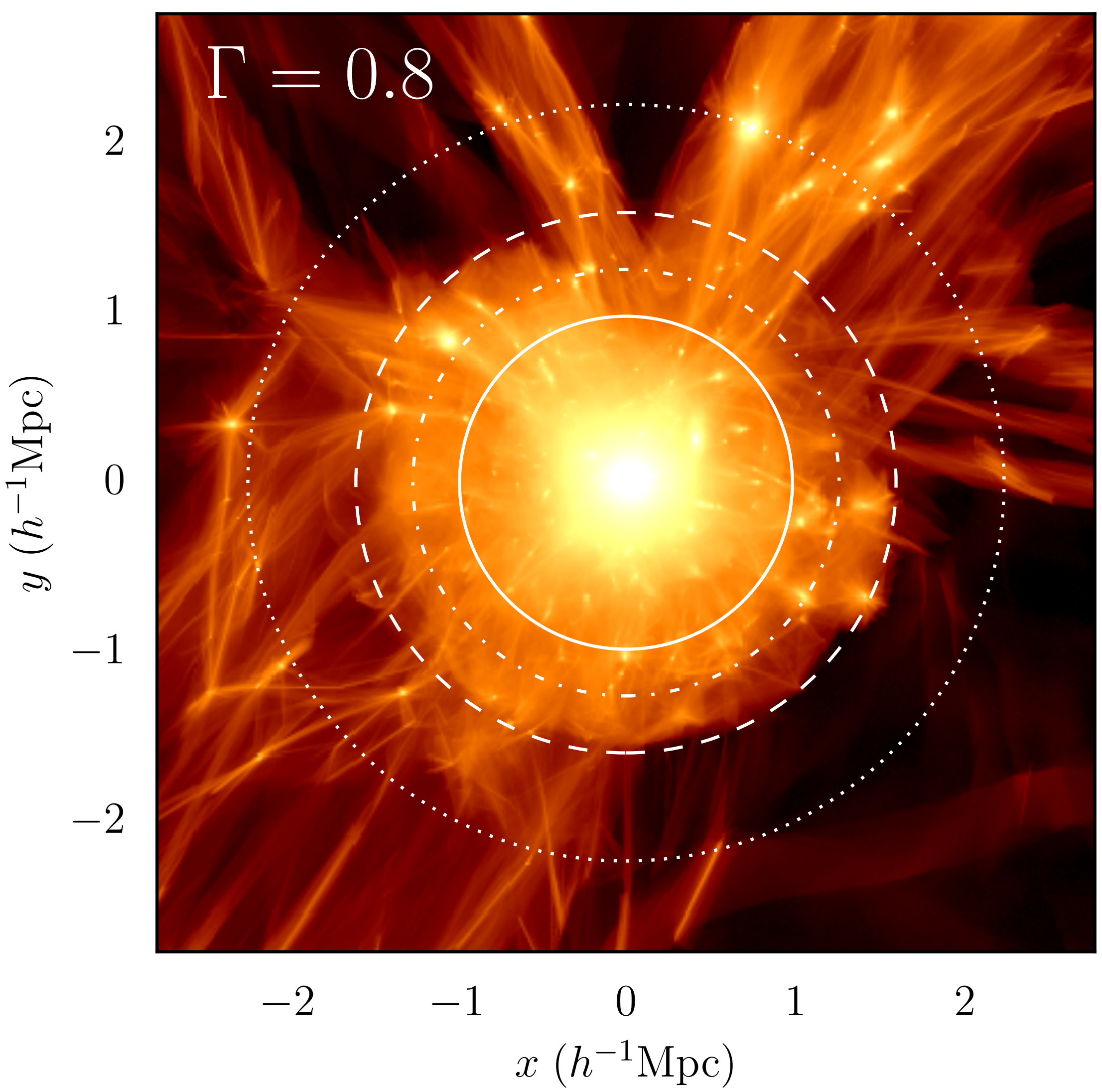
Phase space Diagram of Halo evolution

For spherical potential and smooth accretion

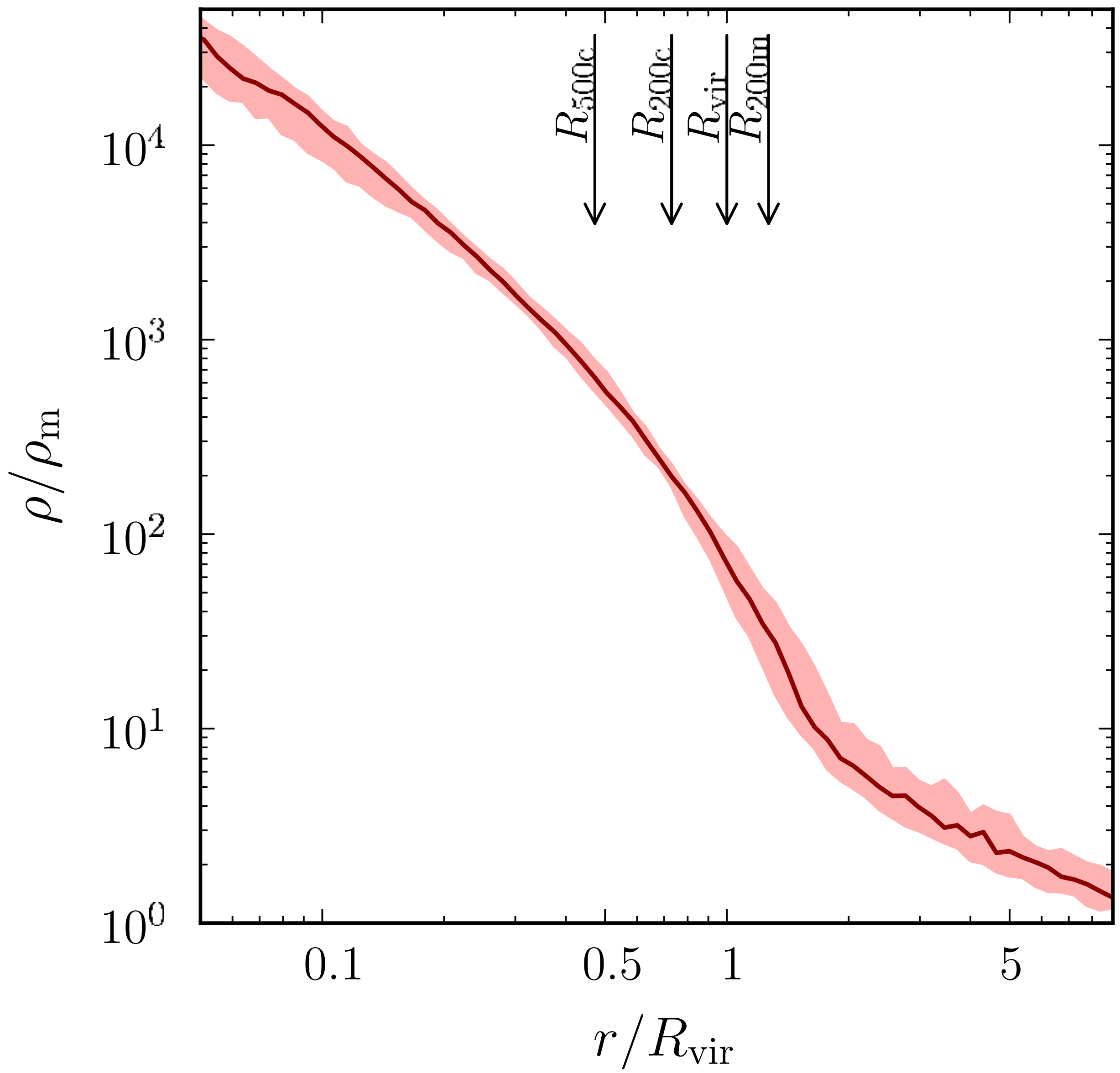


Splashback - corresponds to first apoapses passage after collapse

Where is the boundary of a halo?

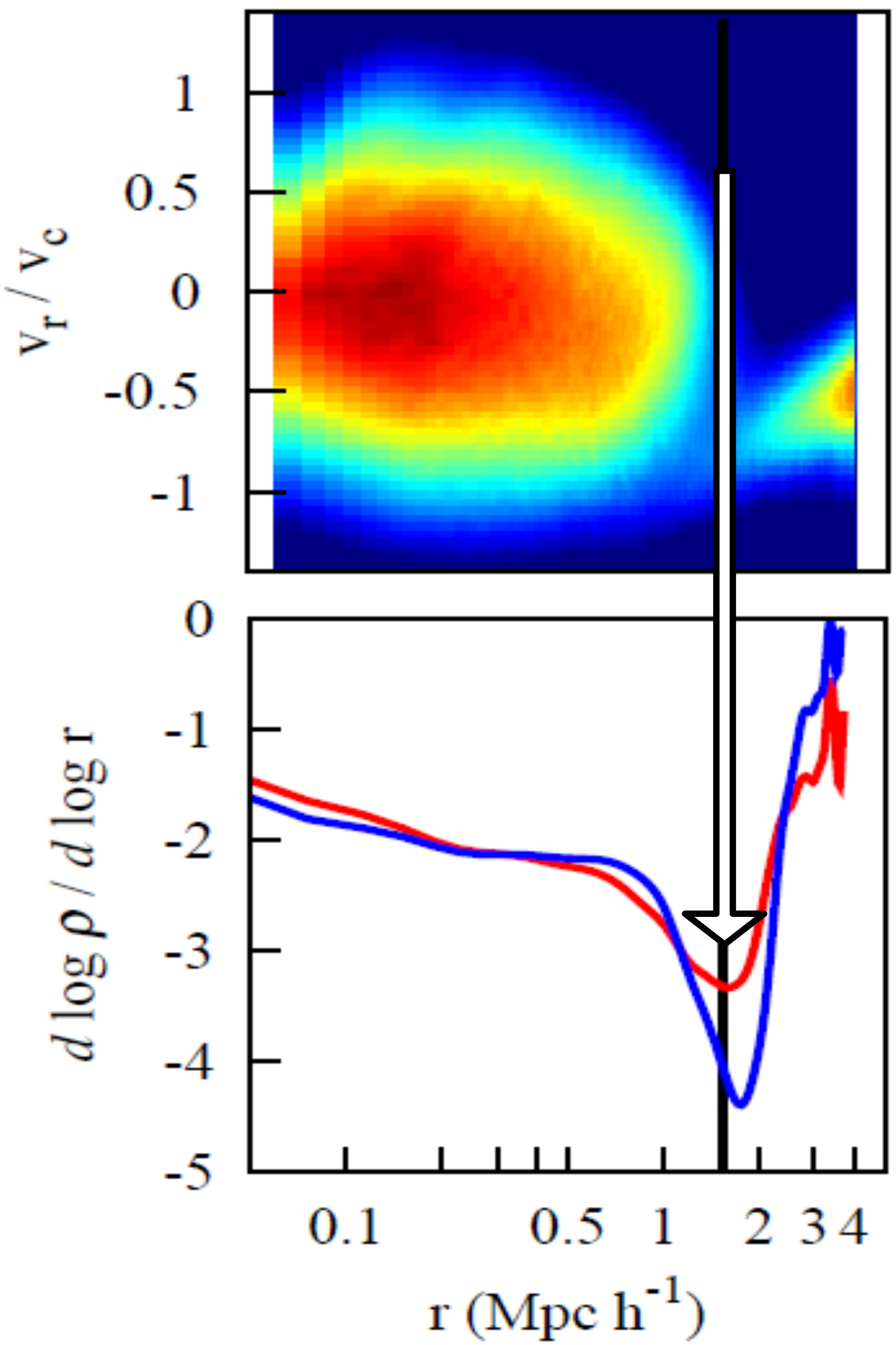


More et al. 2015



Diemer & Kravtsov 2014

$$M_\Delta = \frac{4}{3}\pi R_\Delta^3 \Delta\rho_{\rm ref}$$

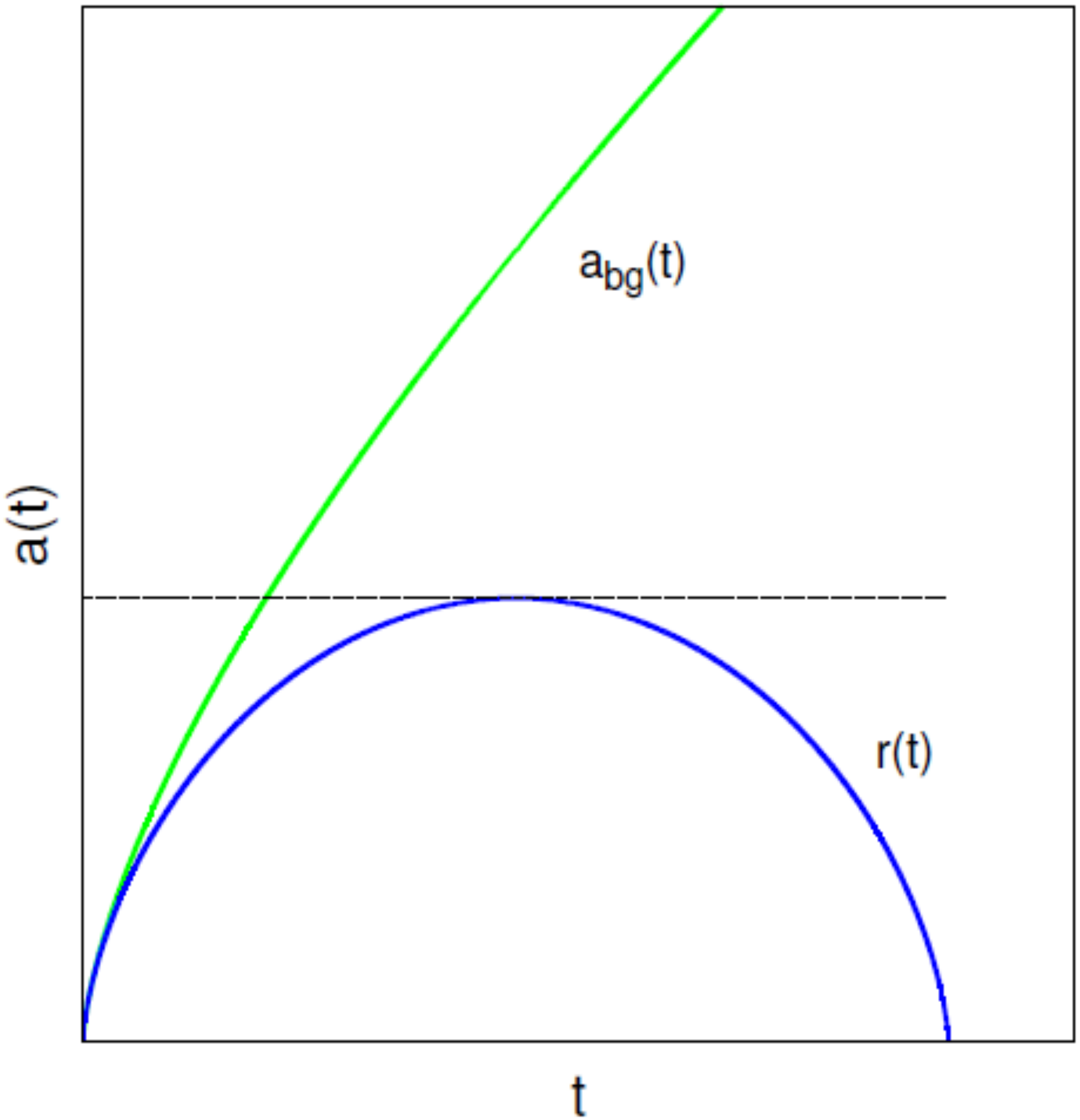


Adhikari et al. 2014

- Phase space diagram of N-body halos from the Multidark simulation
- Halos stacked in the mass range of 1-4e14 Msun
- Position of splashback coincides exactly with feature

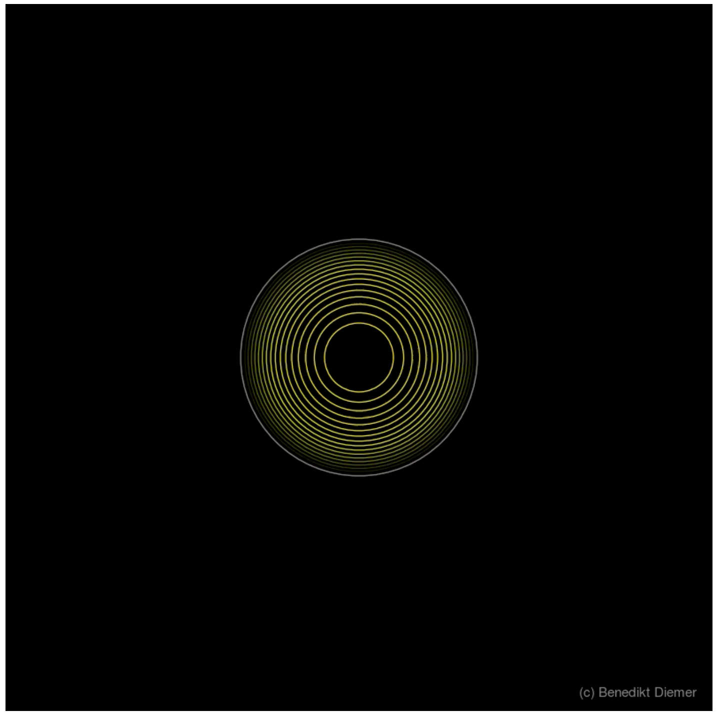
Phase space boundary at the location of turnaround of the most recently accreted material

Collapsing shells of matter around a dark matter over density

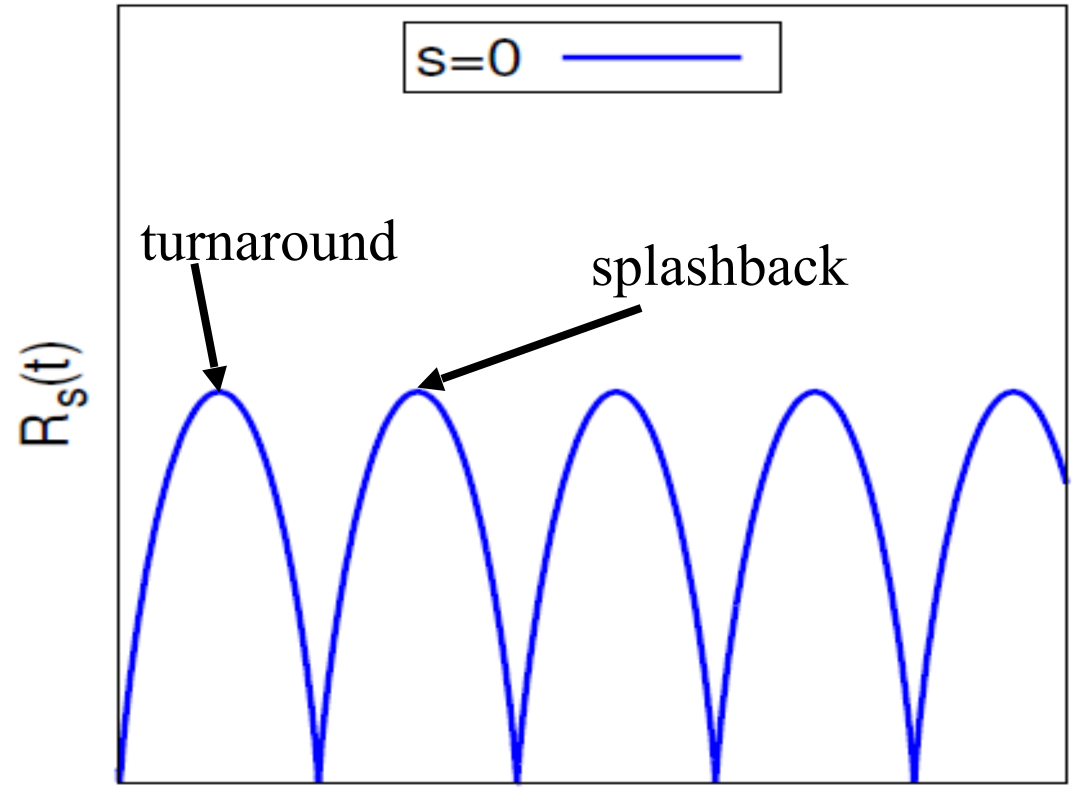


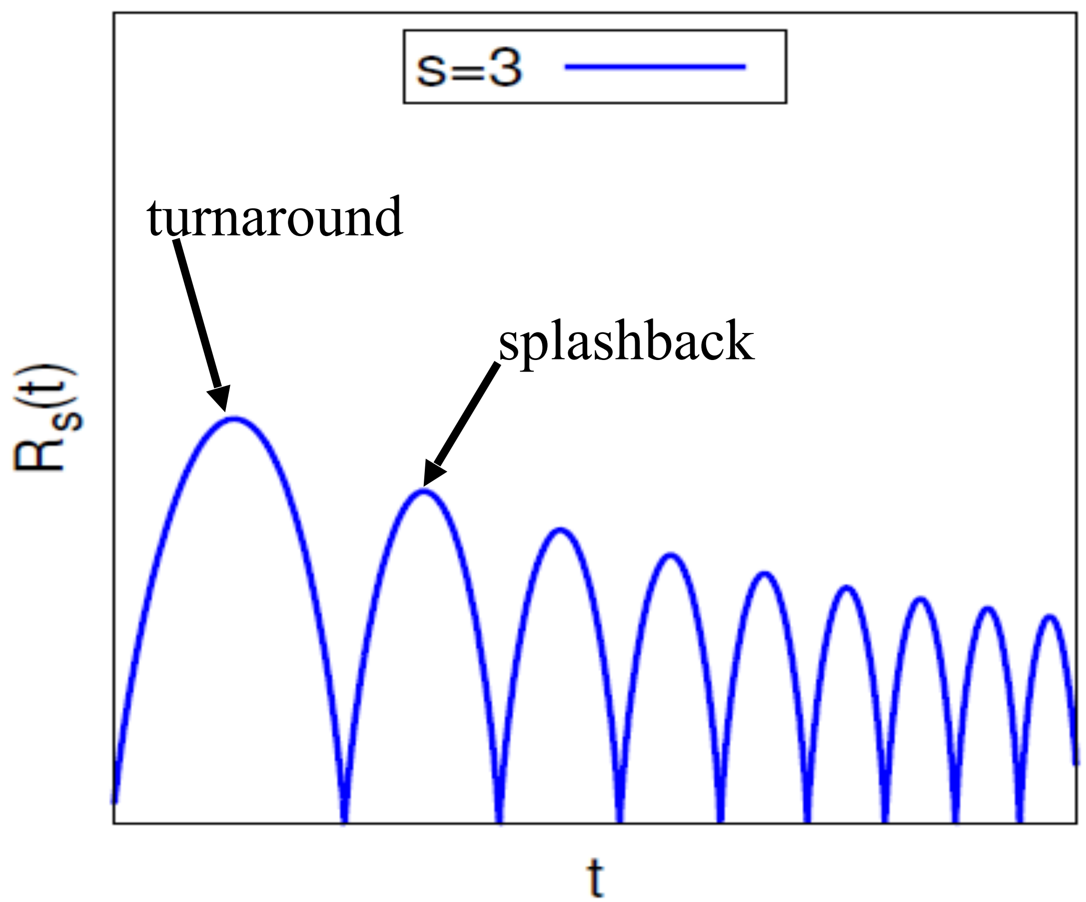
$$\frac{d^2r}{dt^2} = -\frac{GM(<r)}{r^2}$$

$$\frac{d^2r}{dt^2} = -\frac{GM(<r)}{r^2} + \frac{\Lambda c^2}{3}r$$



Particle Orbits



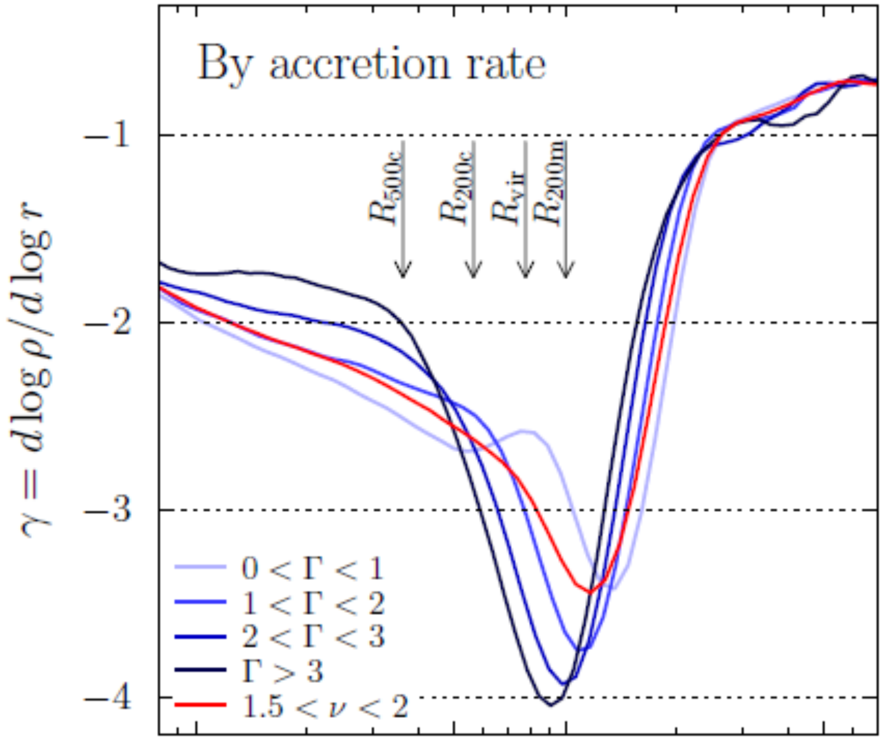


$$\frac{d^2r}{dt^2} = -\frac{GM(<r,t)}{r^2} + \frac{\Lambda c^2}{3} r$$

- For a constant potential the subequent orbits are exactly the same

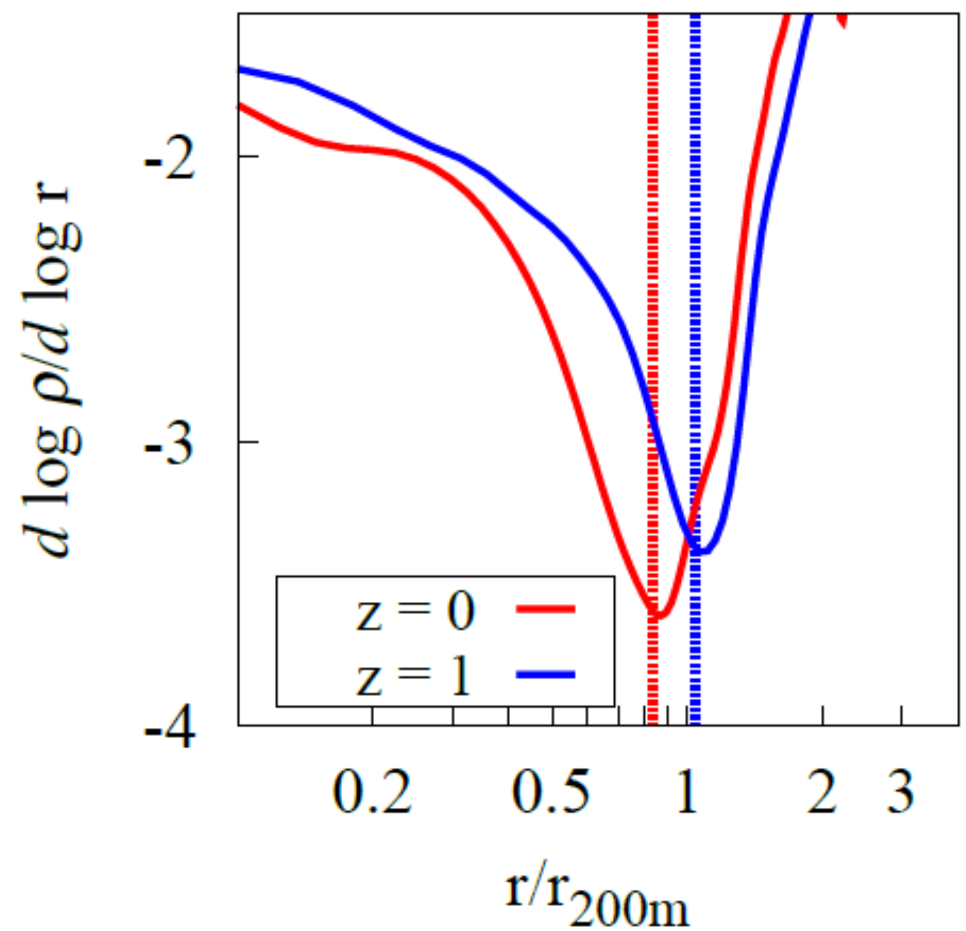
- Mass accretion - potential becomes deeper with time - Subsequent orbits shrink and become faster

Function of Accretion Rate and halo redshift

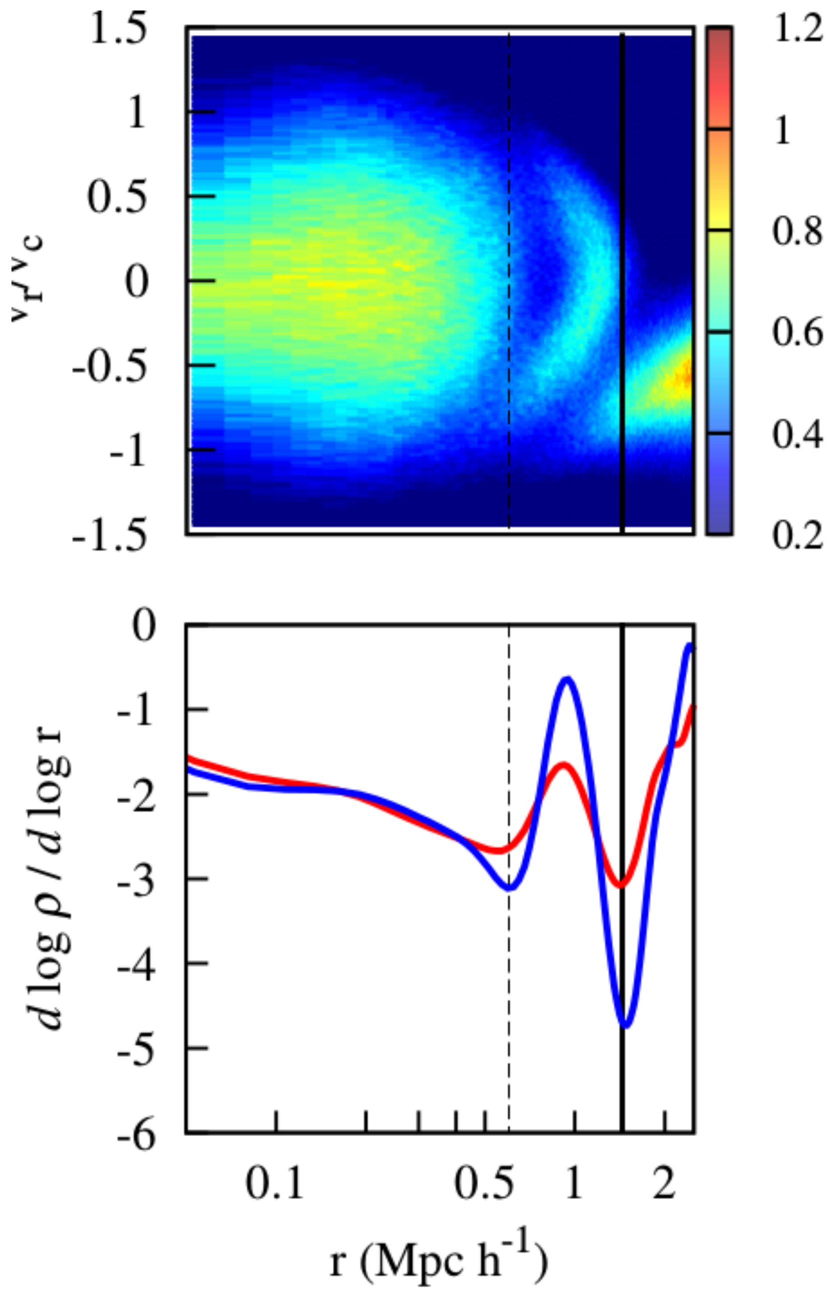


Faster a halo grows, the smaller is its splashback radius in units of R200.

At a given accretion rate it is a function of redshift

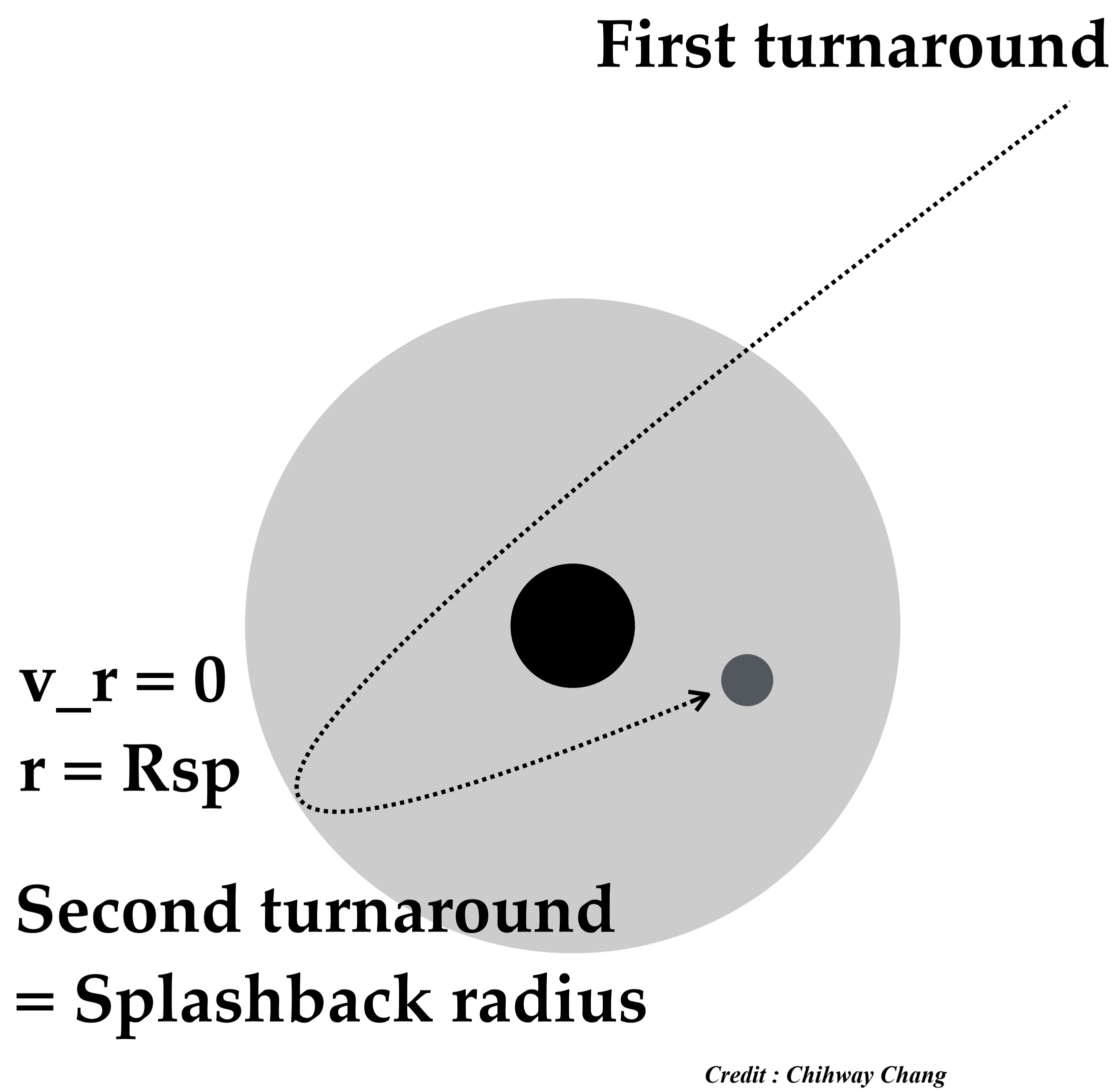


Why is this feature interesting?



- It forms the boundary of the halo
- Physical definition of halo mass
- The splashback radius probes growth history of the halo.
- It forms at the boundary that separates the virialized region of a halo from the infalling region.
- Fundamental length scale in the halo structure, should be present if there is a dark matter halo.
- Simple to understand formed by the most recently accreted material - that is not yet phase mixed.
- Inner regions of halos are often dominated by baryons

The location of the splashback radius is set by **simple physical principles** - Gravitational collapse of cold dark matter in an expanding universe.



Gravitational collapse of collisionless dark matter in an expanding universe

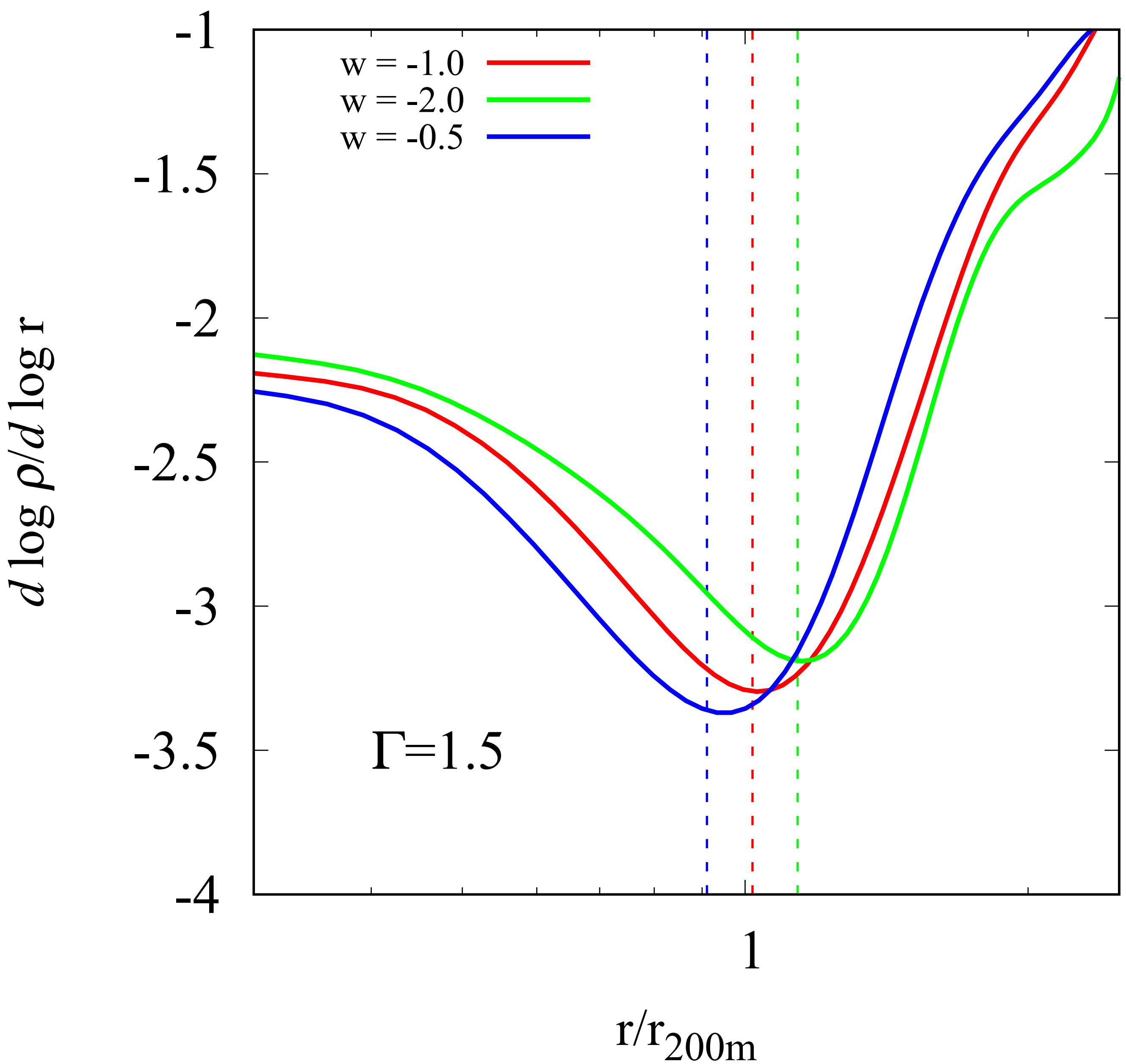
Gravitational collapse of collisionless dark matter in an expanding universe

What happens if we change gravity?

If dark matter self-interacts?

If universe is not Lambda CDM?

What happens to splashback if you change the equation of state parameter?



Adhikari et al. 2018

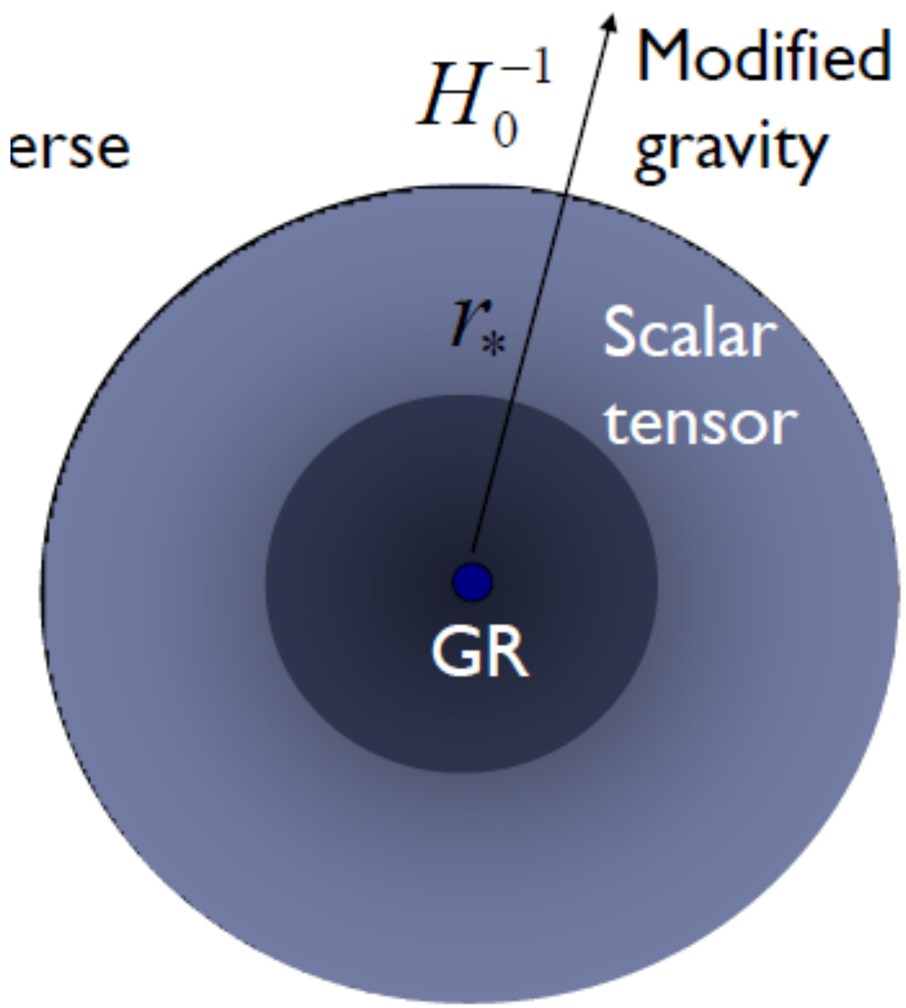
$$P_{\mathrm{DE}} = w\rho \qquad w \neq -1$$

$$\frac{\ddot{a}}{a} = H_0 \sqrt{\Omega_m a^{-3} + \Omega_{DE} a^{-3(1+w)}}$$

$$\ddot{r} = -\frac{GM}{r^2} - \frac{H_0^2}{2} \Omega_{DE} (1+3w) r^{-2-3w}$$

Splashback is a weak function of the w

What happens if we change gravity?



Large scales - Gravity is modified so that the universe accelerates

Intermediate scales - Gravity is still modified by a fifth force

Small scales - Solar system tests constrain gravity to normal GR

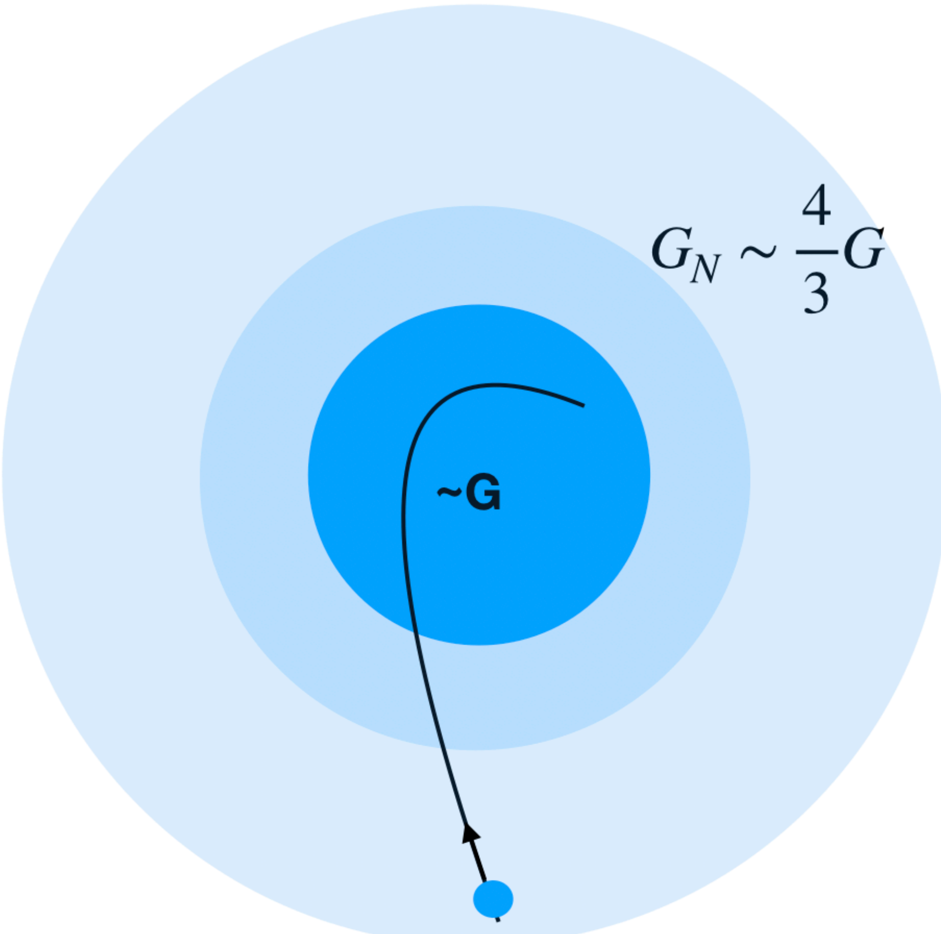
Screening mechanism :

Chameleon screening. - Mass of scalar mode becomes large in dense regions (f(R))

Vainshtein screening - non-linear derivative of fifth force becomes large in dense regions (DGP)

What happens if we change gravity?

Does the location of splashback radius change in modified gravity?



$$\ddot{r} = -\frac{GM}{r^2} + \frac{\Lambda r}{3} + F_\pi$$

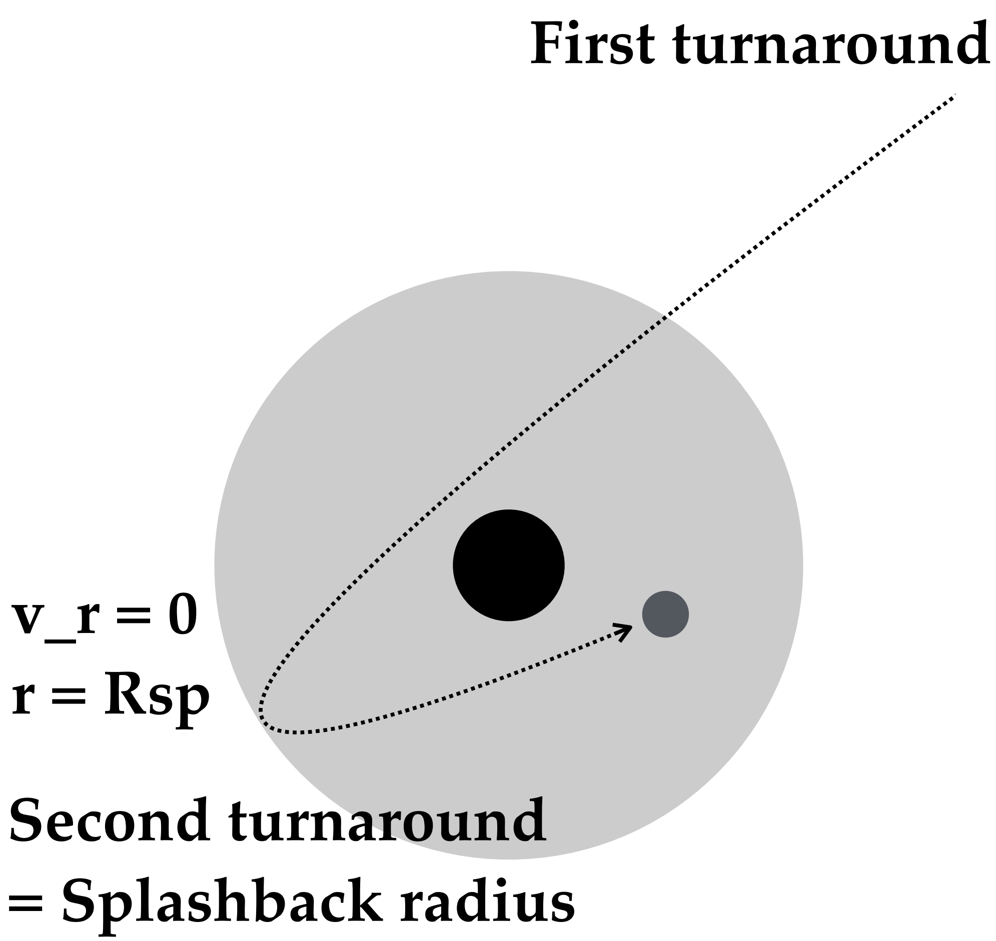
$$F_\pi = -\alpha\pi' = -4\alpha^2 \frac{GM}{r^2} g\left(\frac{r}{r_*}\right)$$

$$g(\zeta) = \zeta^3\left(\sqrt{1+\zeta^{-3}} - 1\right)$$

i) **Extra force mediated by the scalar field**

ii) **The enhanced gravity in the outskirts makes infall velocity higher.**

Splashback of Substructure in modified gravity

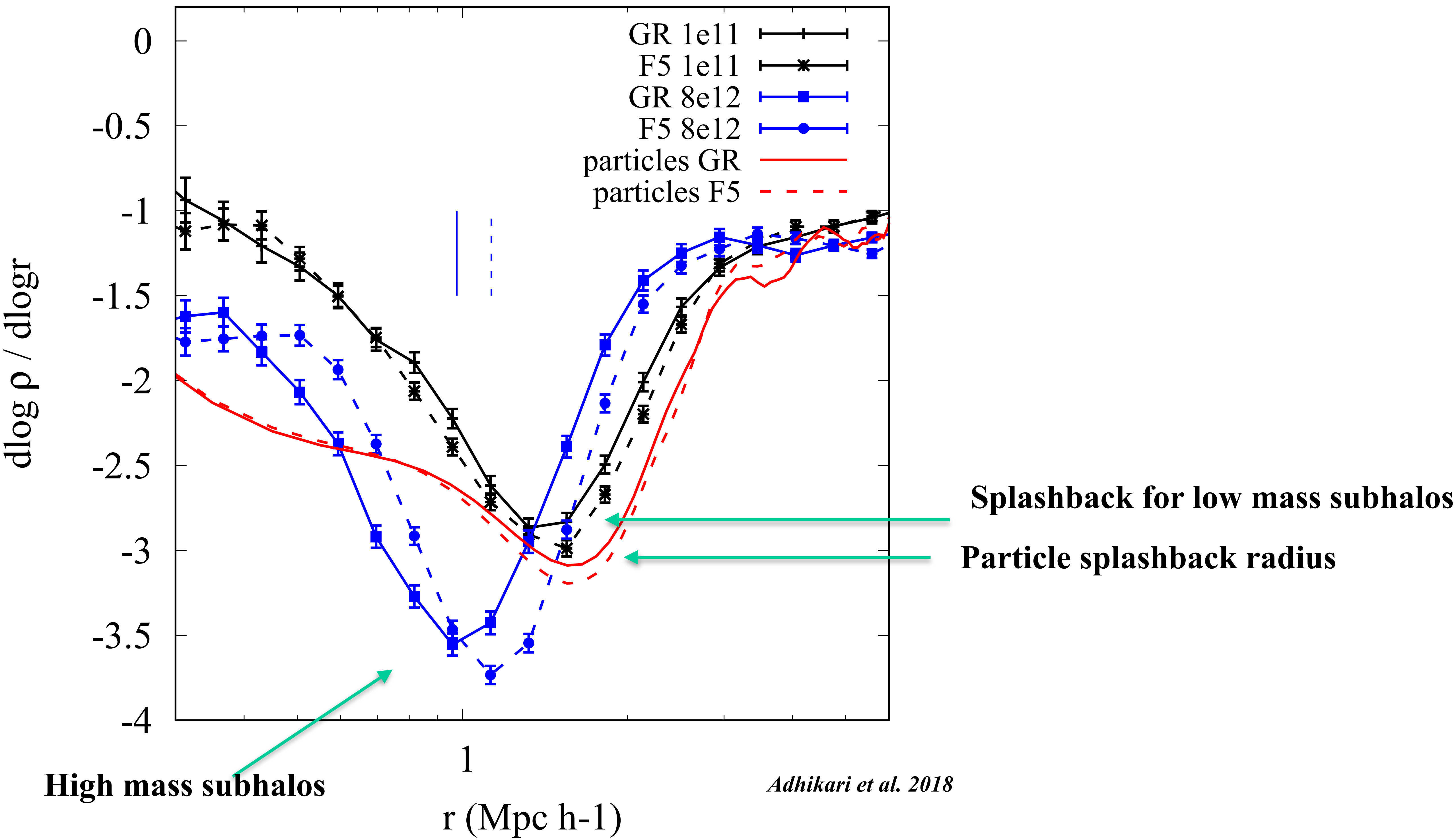


What happens to the subhalos?

Dynamical friction in subhalos

$$\frac{dv}{dt} \propto -\frac{G^2 M \rho}{v^3} v f(v, \sigma)$$

Faster a massive object moves, lower is the force of friction



High mass subhalos in feel lesser amount of dynamical friction in modified gravity - splashback at larger radius than their counterparts in GR

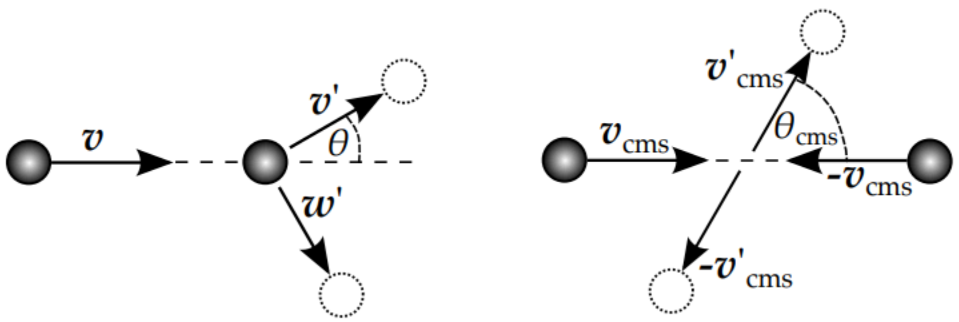
Gravitational collapse of collisionless dark matter in an expanding universe

What happens if we change gravity?

If dark matter self-interacts?

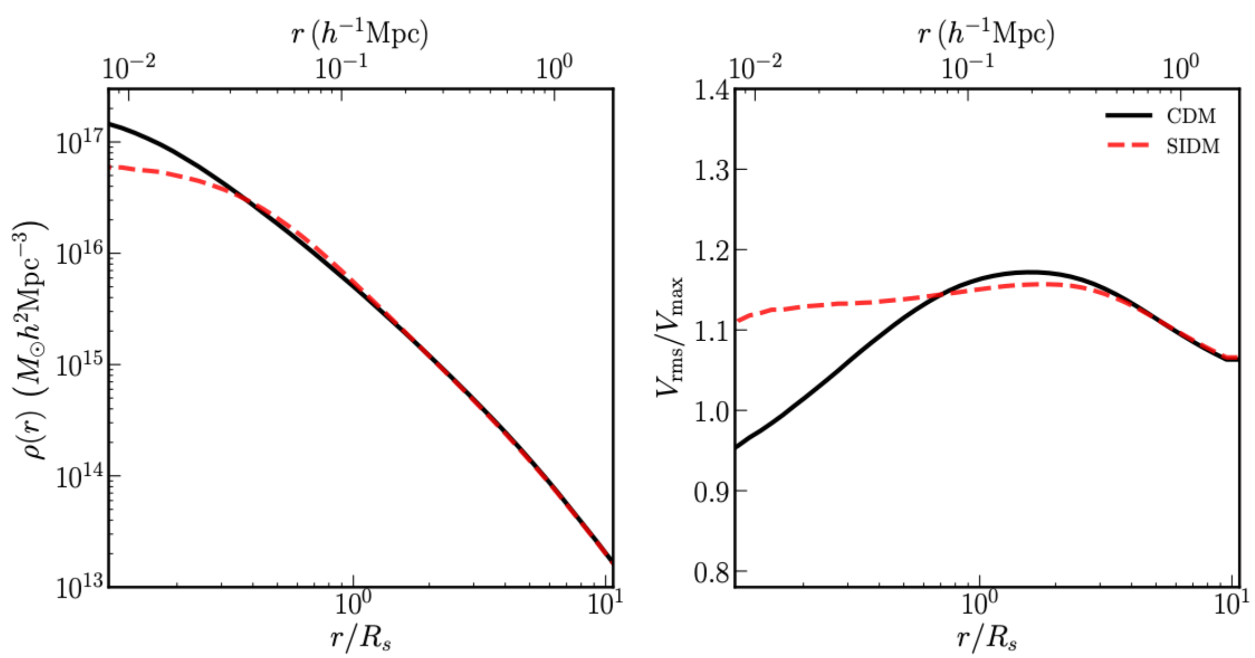
If universe is not Lambda CDM?

Self interacting dark matter and halo profiles



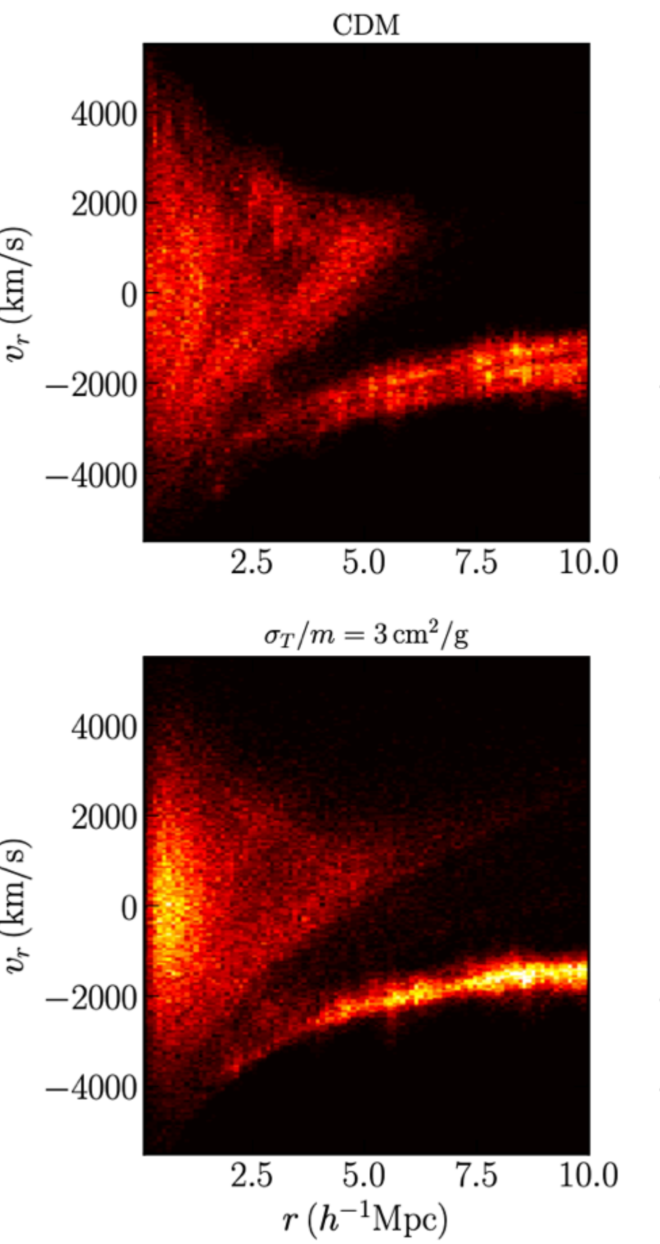
- **Particles lose energy their orbits are altered**
- **Velocity dependent - subhalos and host are at different interaction cross-sections**

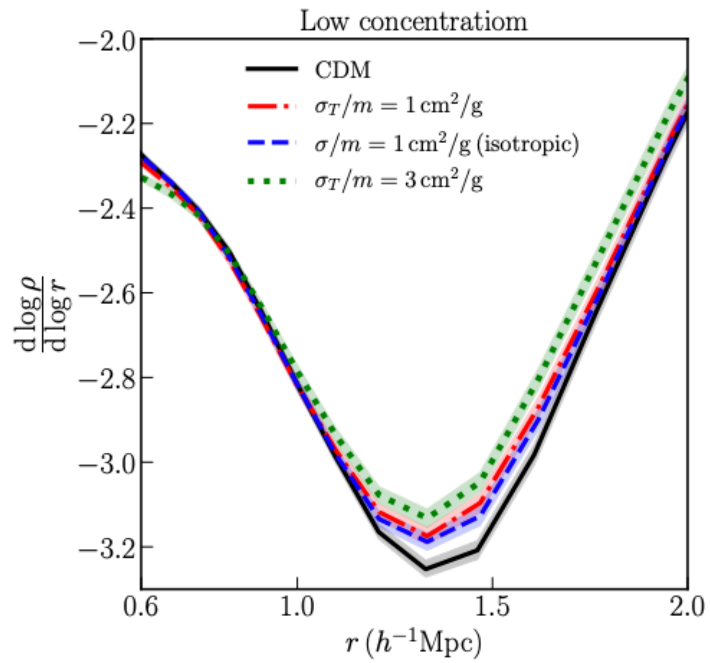
$$\frac{d\sigma}{d\Omega} = \frac{\sigma_0}{2\left[1 + \frac{v^2}{w^2}\sin^2\left(\frac{\theta}{2}\right)\right]^2}.$$



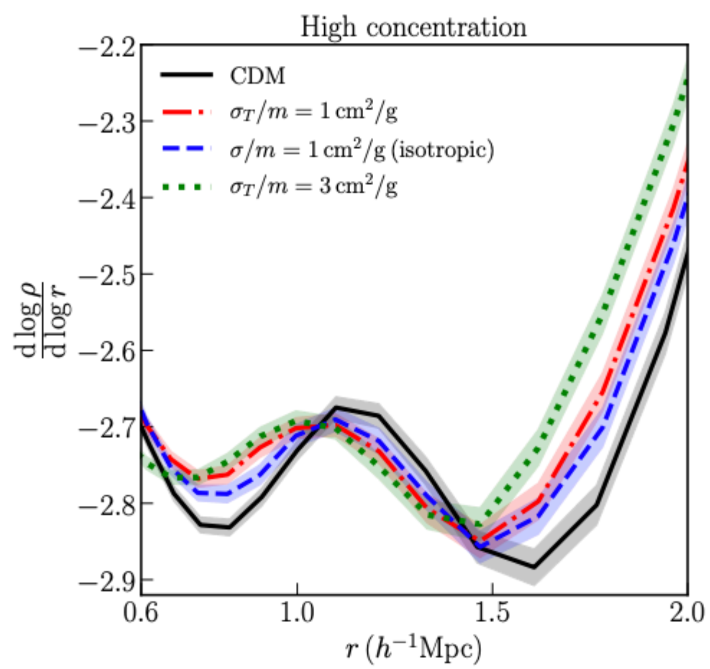
*Banerjee, **Adhikari** et al. 2019*

In the case of self-interacting dark matter we see effects on splashback radius in older halos





Young halos



Old halos

*Banerjee, **Adhikari** et al. 2019*

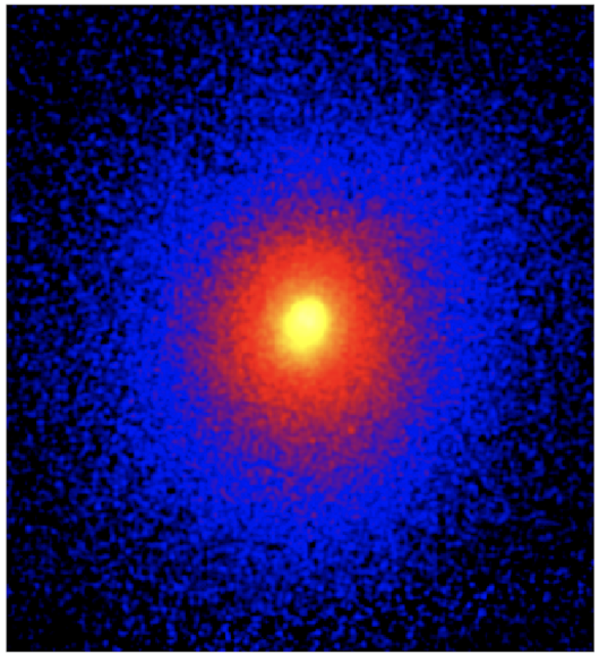
The movement in splashback becomes more prominent when halos are split on accretion history

Observations of the splashback radius

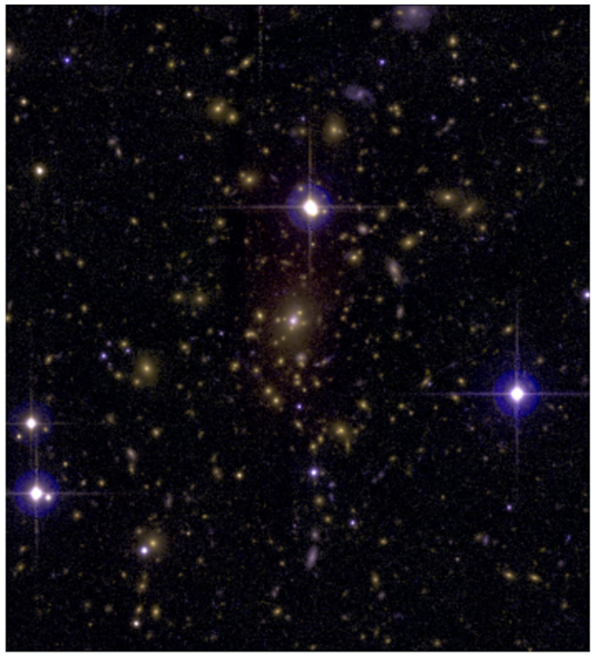
How do we observe dark matter halos?

We study the most massive bound structures in the universe
Cluster mass halos

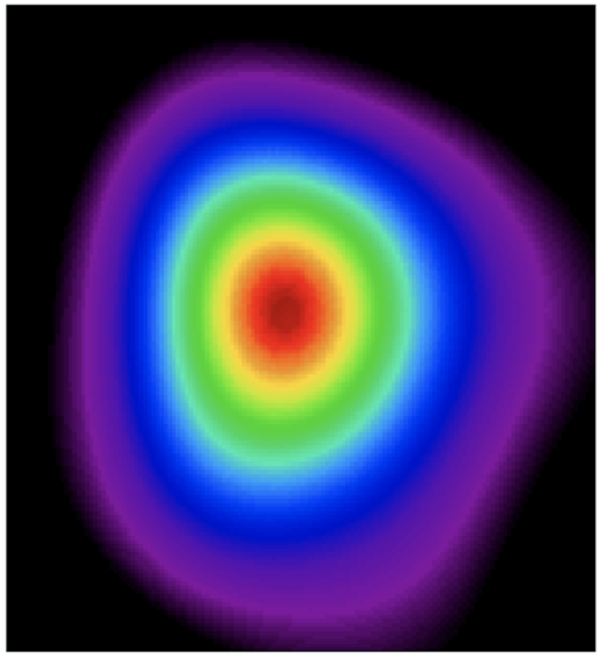
$$10^{14} - 10^{15}\ M_{sun}$$



X-ray



Optical



tSZ

They can be identified as “clusters” of galaxies in the sky

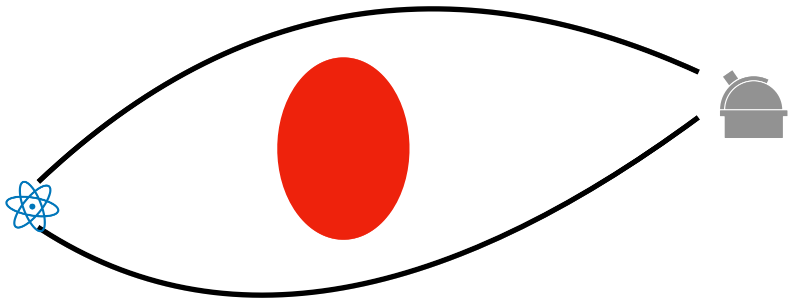
Galaxy clusters

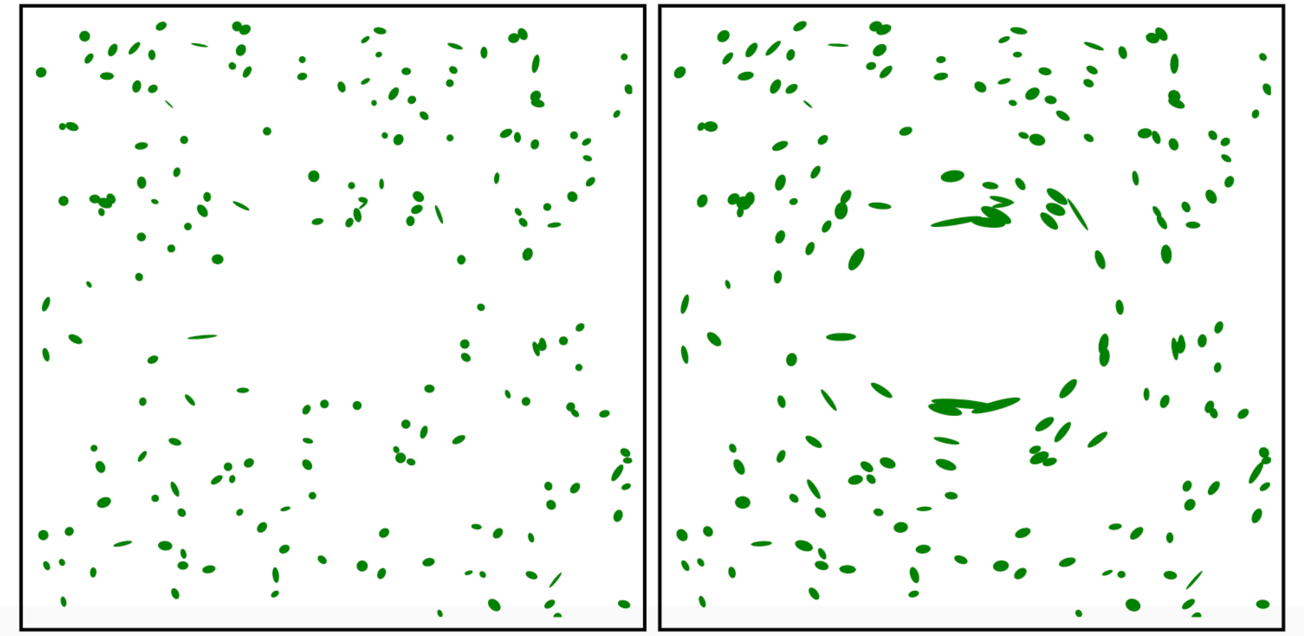
Distribution of Galaxies

Abell 2218

Study the distribution of galaxies that trace the potential of the parent dark matter halos

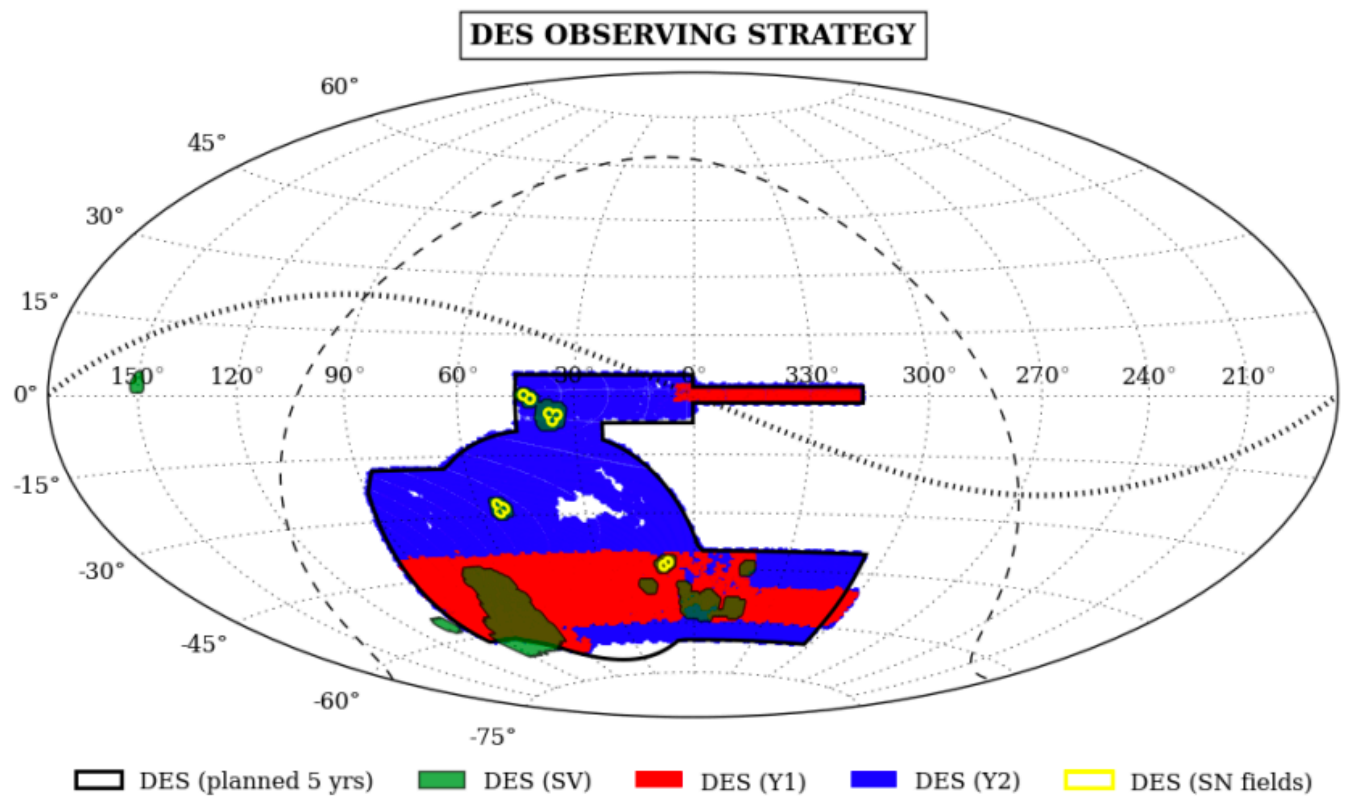
Lensing of background galaxies





Study the distortion of background galaxies due to massive halo in the line of sight

Dark Energy Survey (DES)



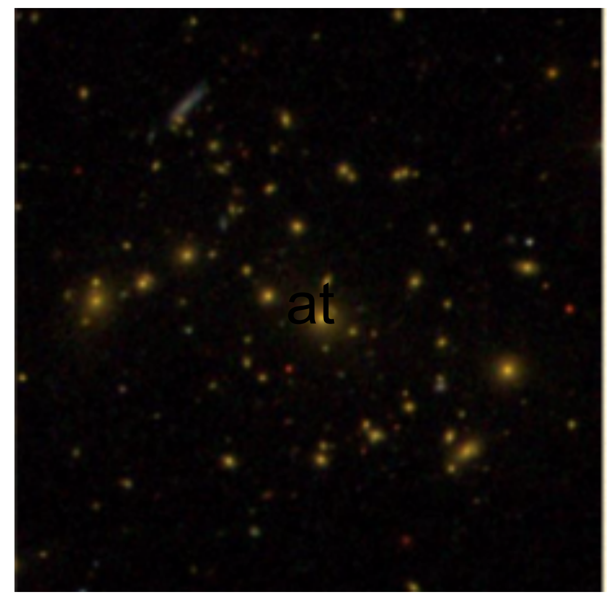
5000 sq. deg

Observes millions of galaxies

https://www.darkenergysurvey.org/

Blanco 4m telescope in Chile

Galaxy Clusters in SDSS data selected with the RedMaPPer algorithm



Clusters with richness $20 < \Lambda < 100$ corresponds to $M > 10^{14} M_{\odot} h^{-1}$

8648 RedMaPPer clusters

0.1 < z < 0.33

Observations of Splashback radius

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

SURHUD MORE[1], HIRONAO MIYATAKE[1,2,3], MASAHIRO TAKADA[1], BENEDIKT DIEMER[4], ANDREY V. KRAVTSOV[5,6,7], NEAL K. DALAL[1,8], ANUPREETA MORE[1], RYOMA MURATA[1,9], RACHEL MANDELBAUM[10], EDUARDO ROZO[11], ELI S. RYKOFF[12], MASAMUNE OGURI[1,9,13], AND DAVID N. SPERGEL[1,3]

The Halo Boundary of Galaxy Clusters in the SDSS

Eric Baxter[1⋆], Chihway Chang[2], Bhuvnesh Jain[1], Susmita Adhikari[3], Neal Dalal[3,4], Andrey Kravtsov[2,5,6], Surhud More[7], Eduardo Rozo[8], Eli Rykoff[9,10], Ravi K. Sheth[1,11]

THE SPLASHBACK FEATURE AROUND DES GALAXY CLUSTERS:
GALAXY DENSITY AND WEAK LENSING PROFILES

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(DES COLLABORATION)

Cluster - galaxy cross correlation

Measurement - Number density of galaxy in projection as a function of radius

$$\boxed{\Sigma(R) = \int_{-h_{\max}}^{h_{\max}} dh\, \rho(\sqrt{R^2 + h^2})}$$

$$\begin{aligned}
\rho(r) &= \rho^{\mathrm{coll}}(r) + \rho^{\mathrm{infall}}(r), \\
\rho^{\mathrm{coll}}(r) &= \rho^{\mathrm{Ein}}(r) f_{\mathrm{trans}}(r) \\
\rho^{\mathrm{Ein}}(r) &= \rho_s \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right) \\
f_{\mathrm{trans}}(r) &= \left[1 + \left(\frac{r}{r_t}\right)^{\beta}\right]^{-\gamma/\beta}, \\
\rho^{\mathrm{infall}}(r) &= \rho_0 \left(\frac{r}{r_0}\right)^{-s_e},
\end{aligned}$$

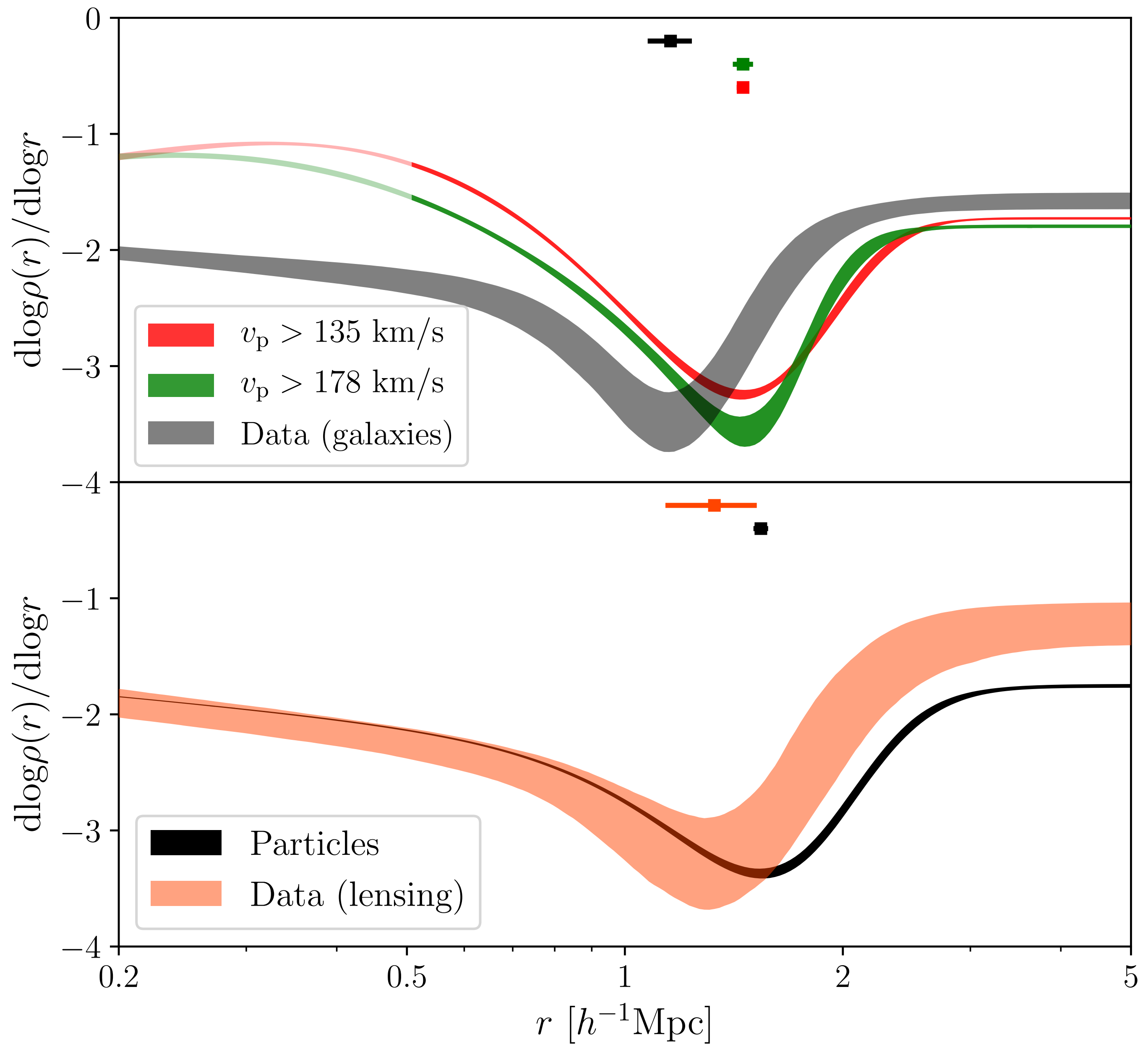
Stack clusters based on richness

richness > 20
M > 1e14 M_{sun} h^{-1}

Diemer & Kravtsov 2014

Splashback radius in DES Y1 results

First measurement in weak lensing around halos



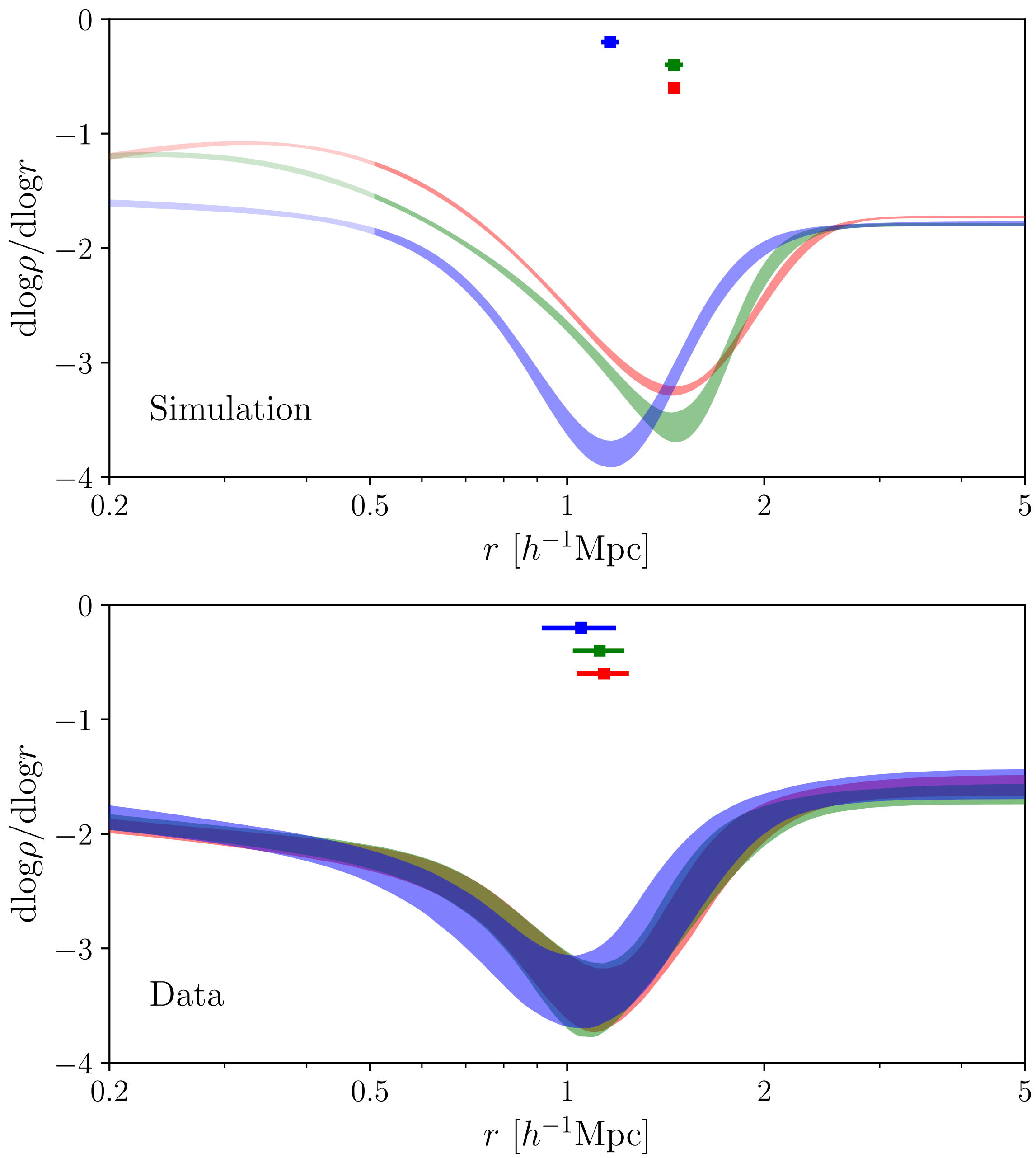
Galaxy number density

Weak lensing around clusters

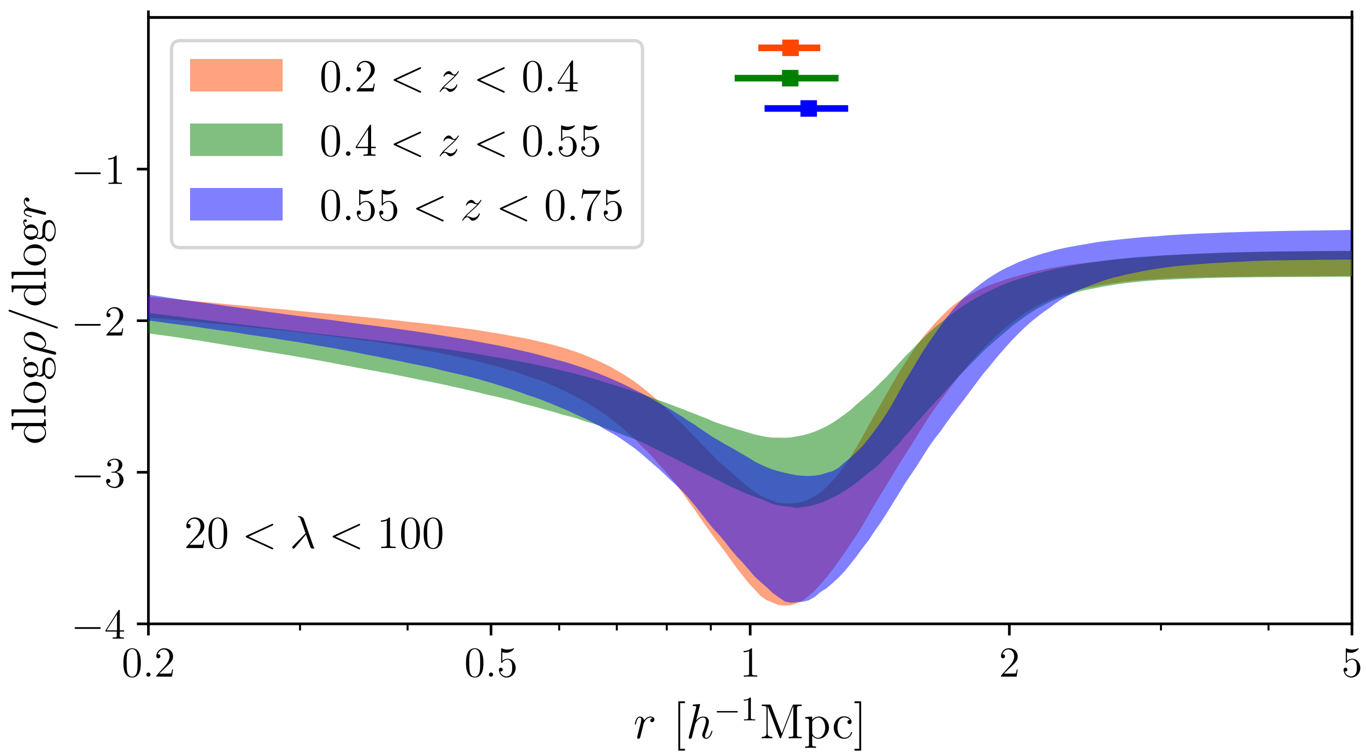
*Chang,+, **Adhikari** et al.2017*

Discrepancy persists in the lensing splashback radius as well

Outstanding issues



No movement with galaxy magnitude



Chang, Baxter, Jain, Sanchez, ***Adhikari*** *et al.2017*

No movement with redshift of host cluster

Why is splashback discrepant with simulations?

a) Dynamical Friction?

b) New Physics?

c) Observational bias?

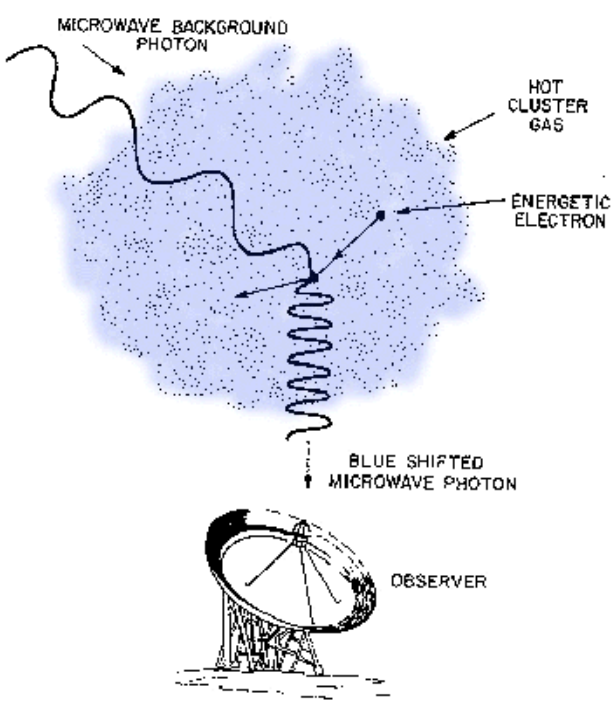
Cluster selection?

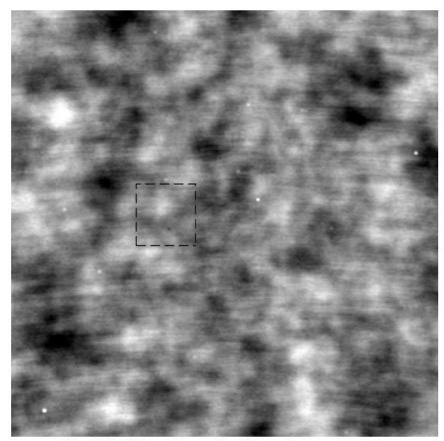
Projection effects? (*Busch & White 2017*)
Orientation bias?
Aperture selection? (*Busch & White 2017*)

Different cluster selection method - SZ selected clusters

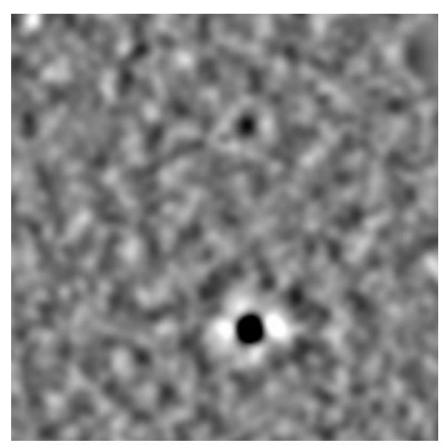
Splashback radius in SZ clusters from the South Pole telescope (SPT) and Atacama Cosmology telescope (ACT)

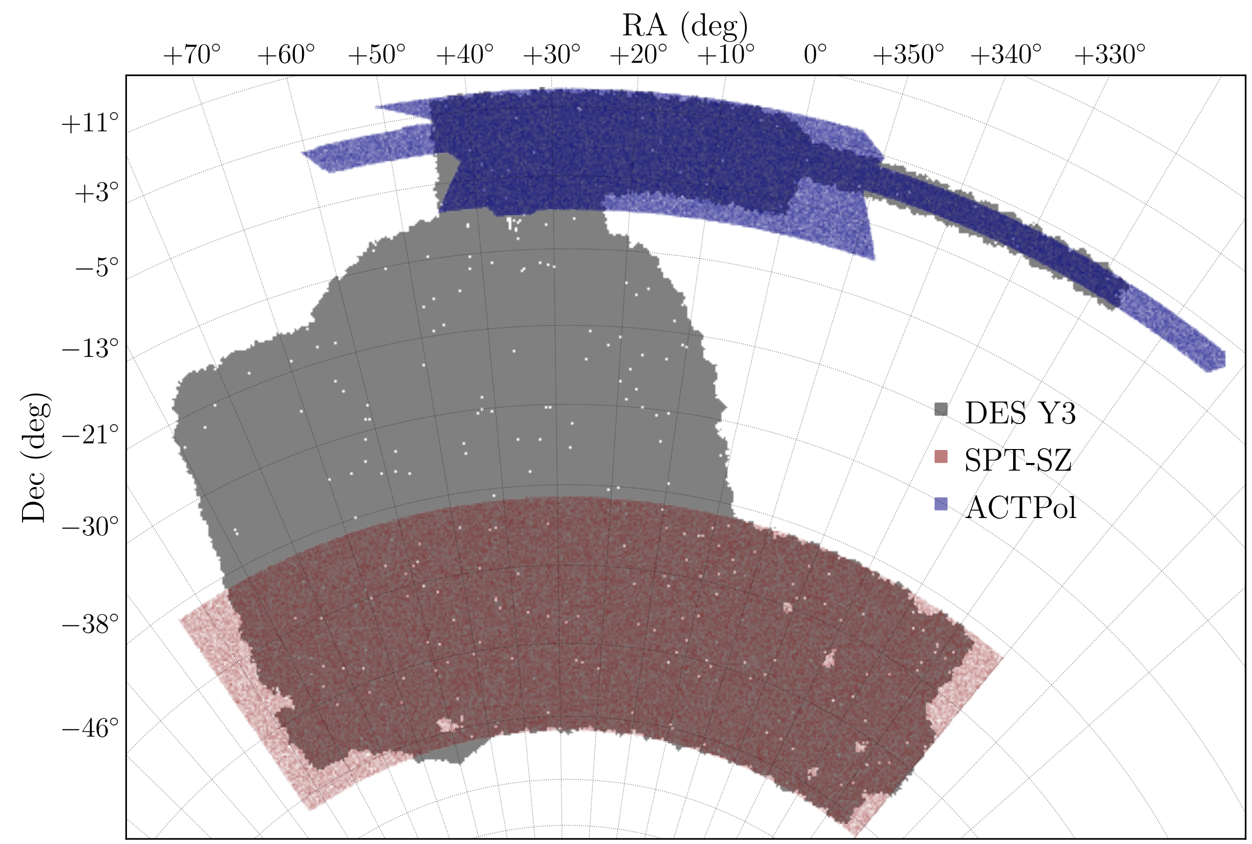
Clusters seen as a temperature decrement in CMB



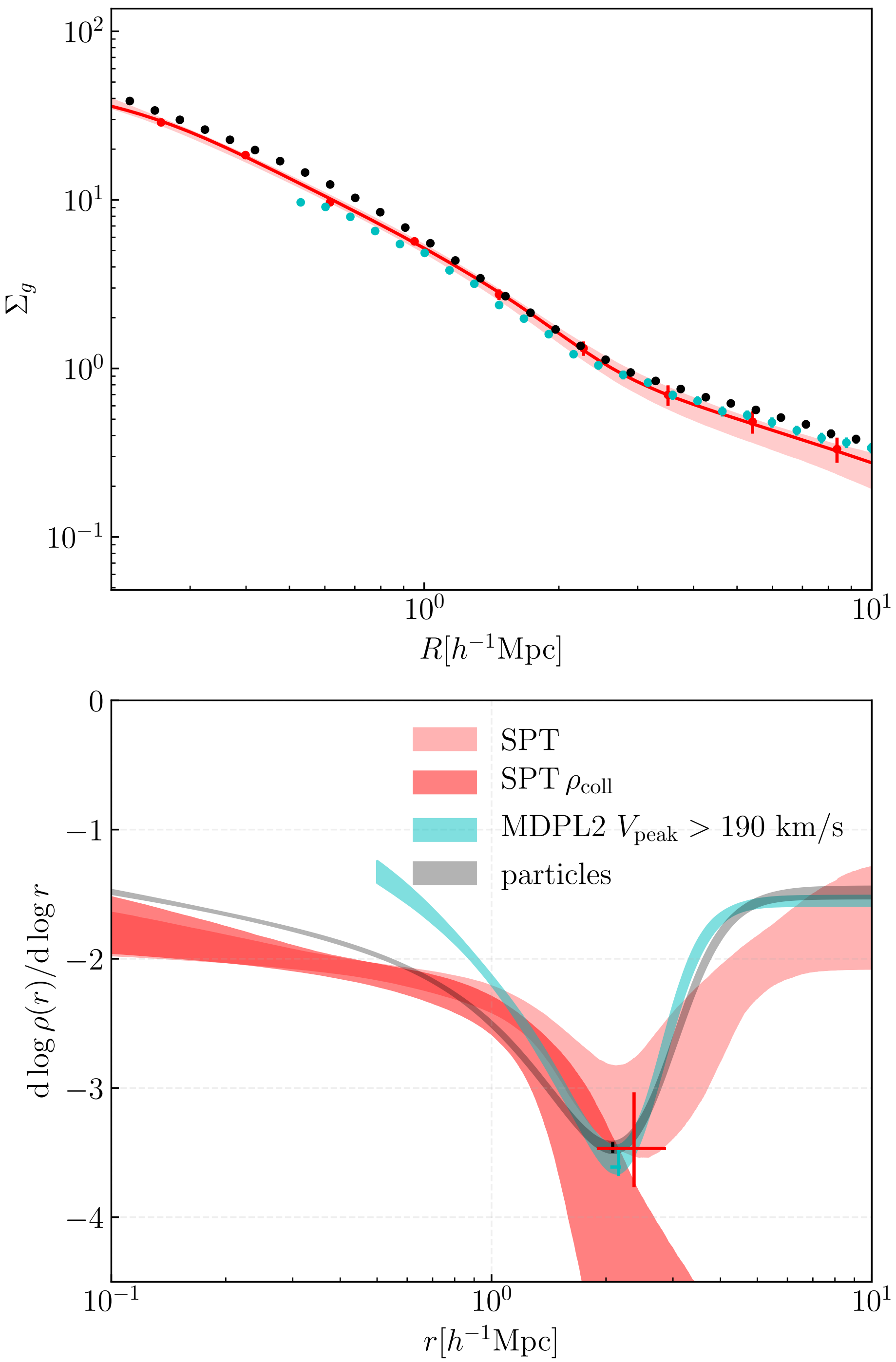


(b) 150 GHz minimally filtered map cutout





Splashback radius in SPT SZ clusters, DES galaxies



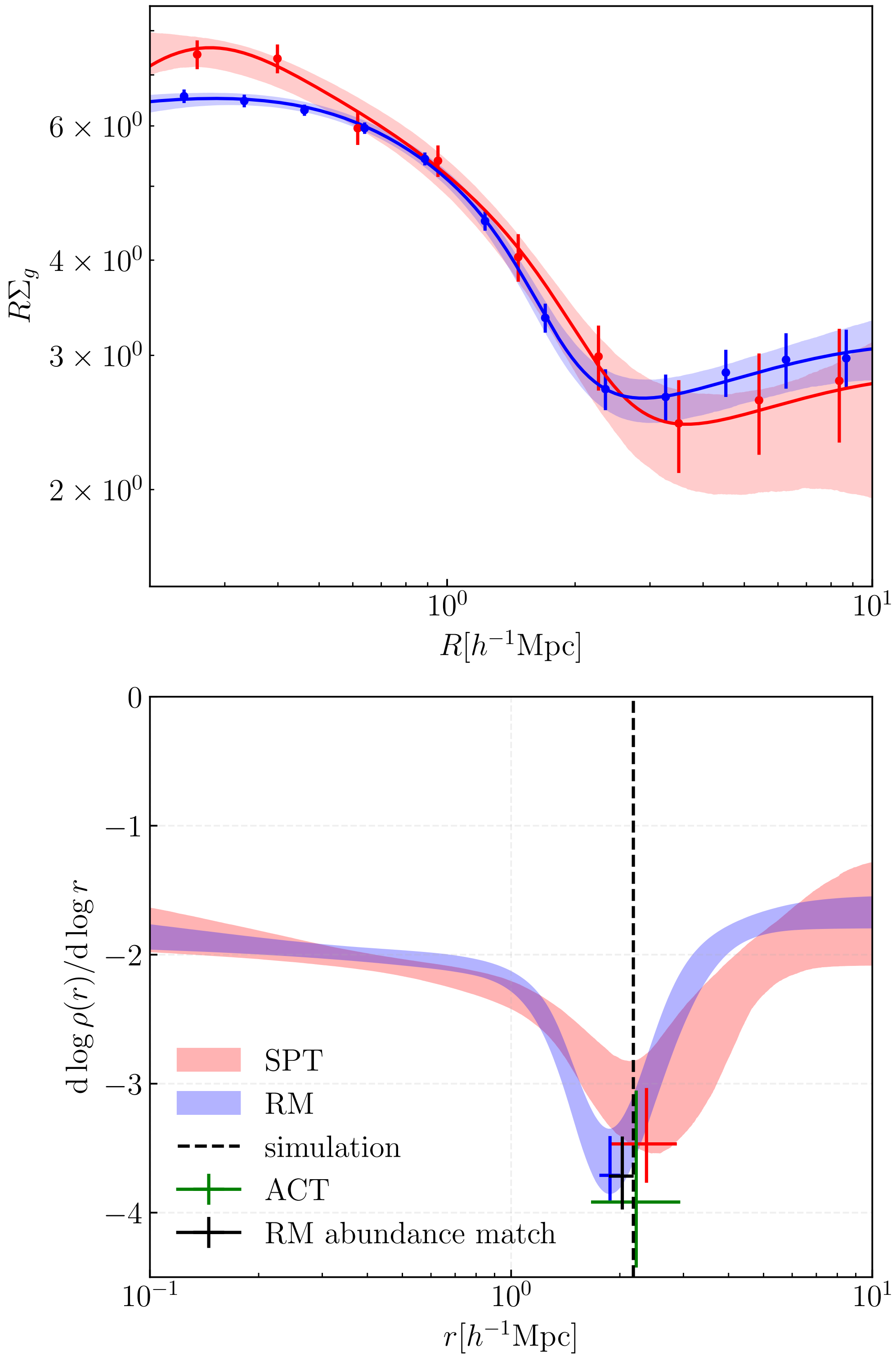
Hyeon-Shin, Adhikari et al. 2019

Splashback radius SZ clusters are statistically consistent with simulations

Pink - Slope of the fitted density profile
Black- Particles from MDPL2
Blue - Subhalos abundance matched

Consistent with Zuercher & More 2019 who did a similar analysis with Planck clusters

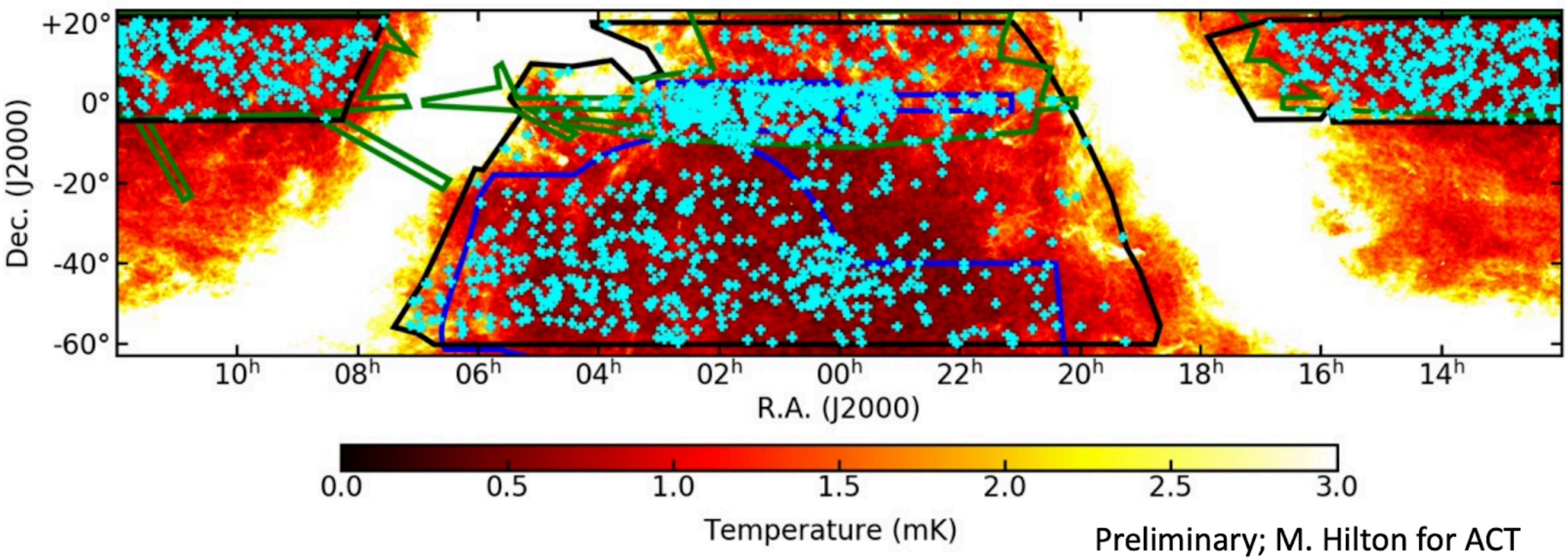
Comparison with RedMaPPer



Hyeon-Shin, Adhikari et al. 2019

RM and SPT are consistent within 1 sigma, but RM is inconsistent with sims.

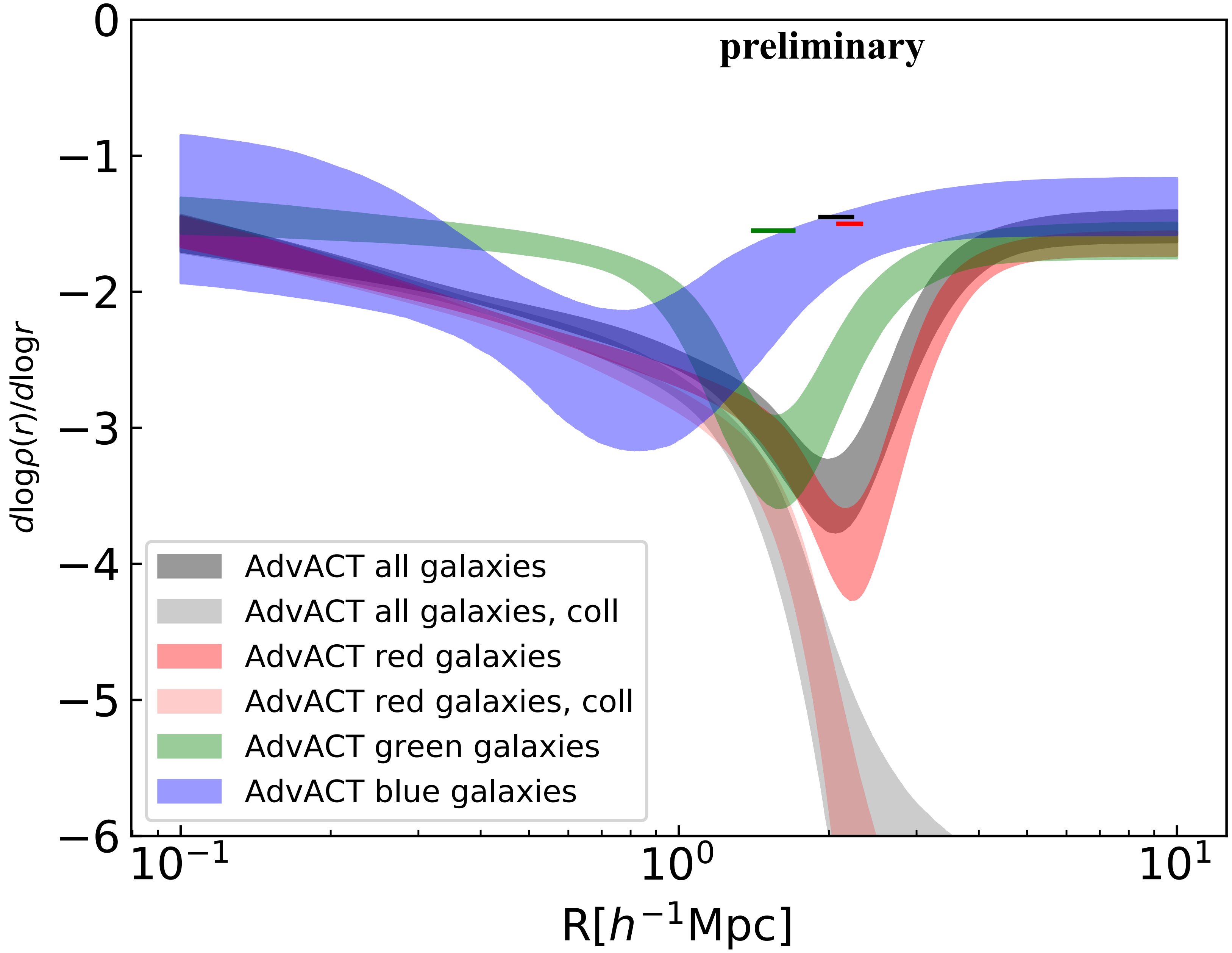
New AdvACT cluster sample



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

Galaxy quenching in Dark Matter halos

New AdvACT sample



(in prep)

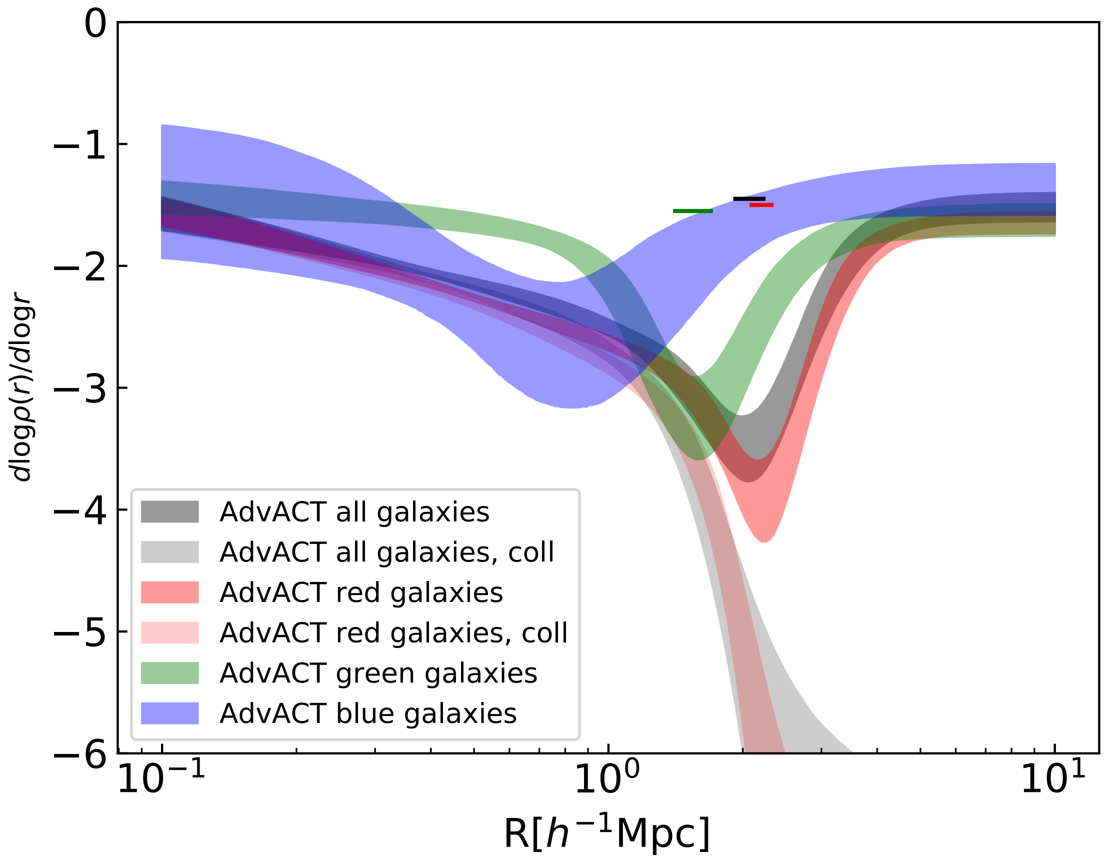
~700 cluste

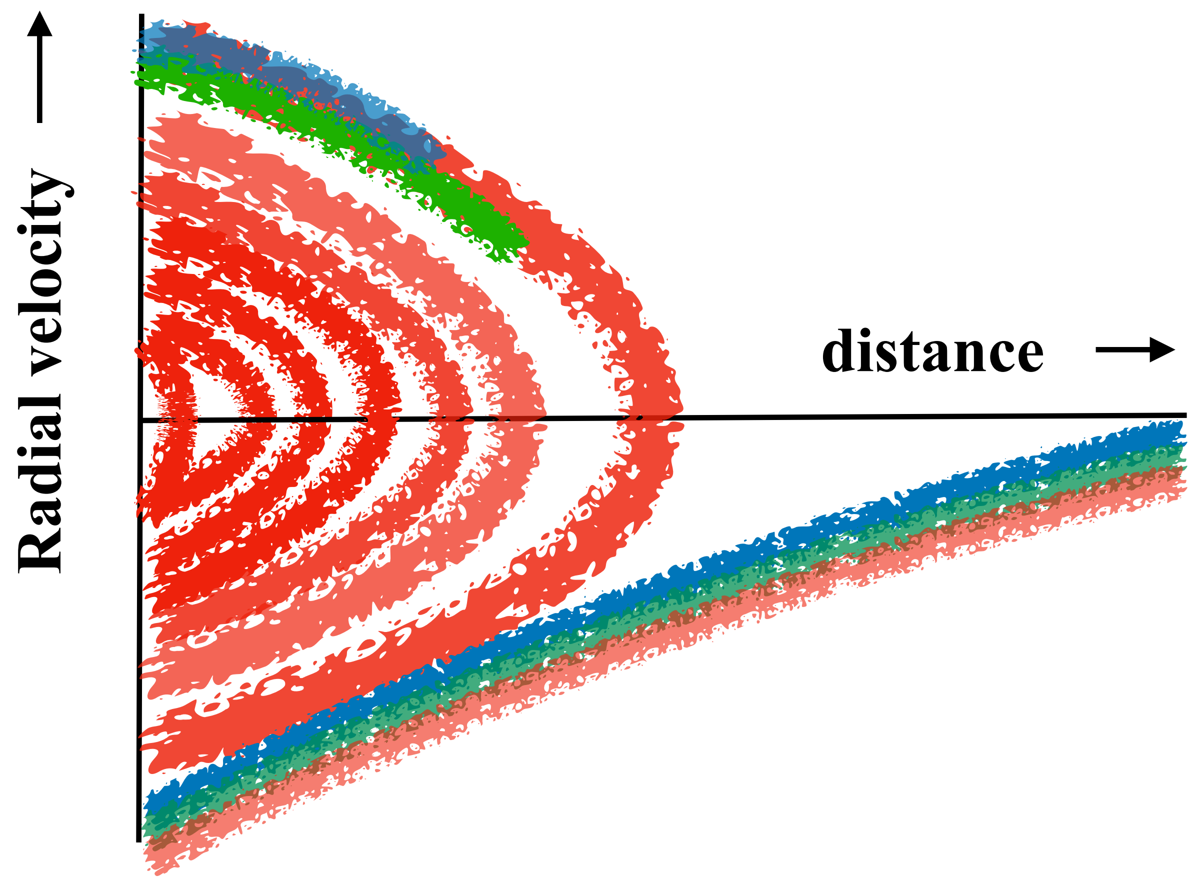
$$\mathrm{SFR_{sat}}(t) = \begin{cases} \mathrm{SFR_{cen}}(t) & t < t_{Q,\,\mathrm{start}} \\ \mathrm{SFR_{cen}}(t_{Q,\,\mathrm{start}})\, e^{\left\{-\frac{(t - t_{Q,\,\mathrm{start}})}{\tau_{Q,\,\mathrm{fade}}}\right\}} & t > t_{Q,\,\mathrm{start}} \end{cases}$$

The splashback radius as a clock in the halo

Galaxies stop forming stars with time as they fall into a halo

Blue star-forming galaxies turn into red and dead galaxies





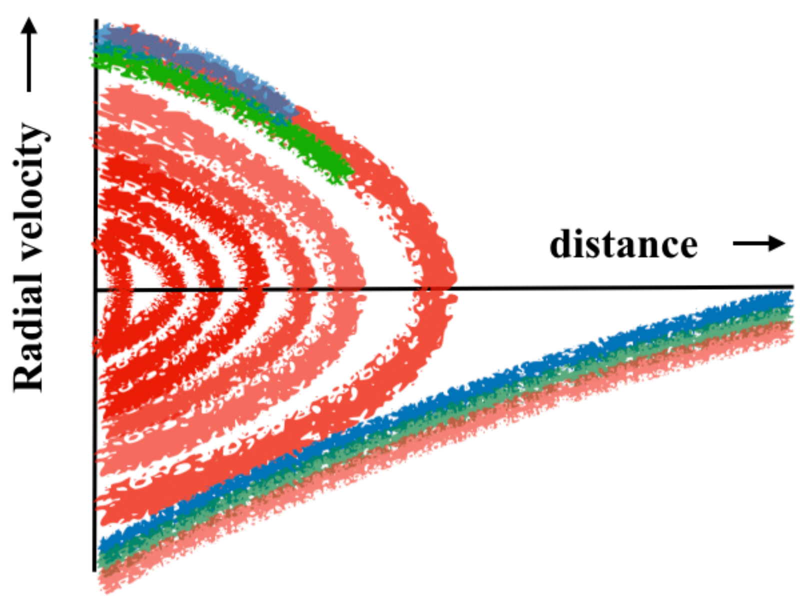
Longer delay , shorter quenching

Minimum traces the time spent in the cluster by a population of galaxies

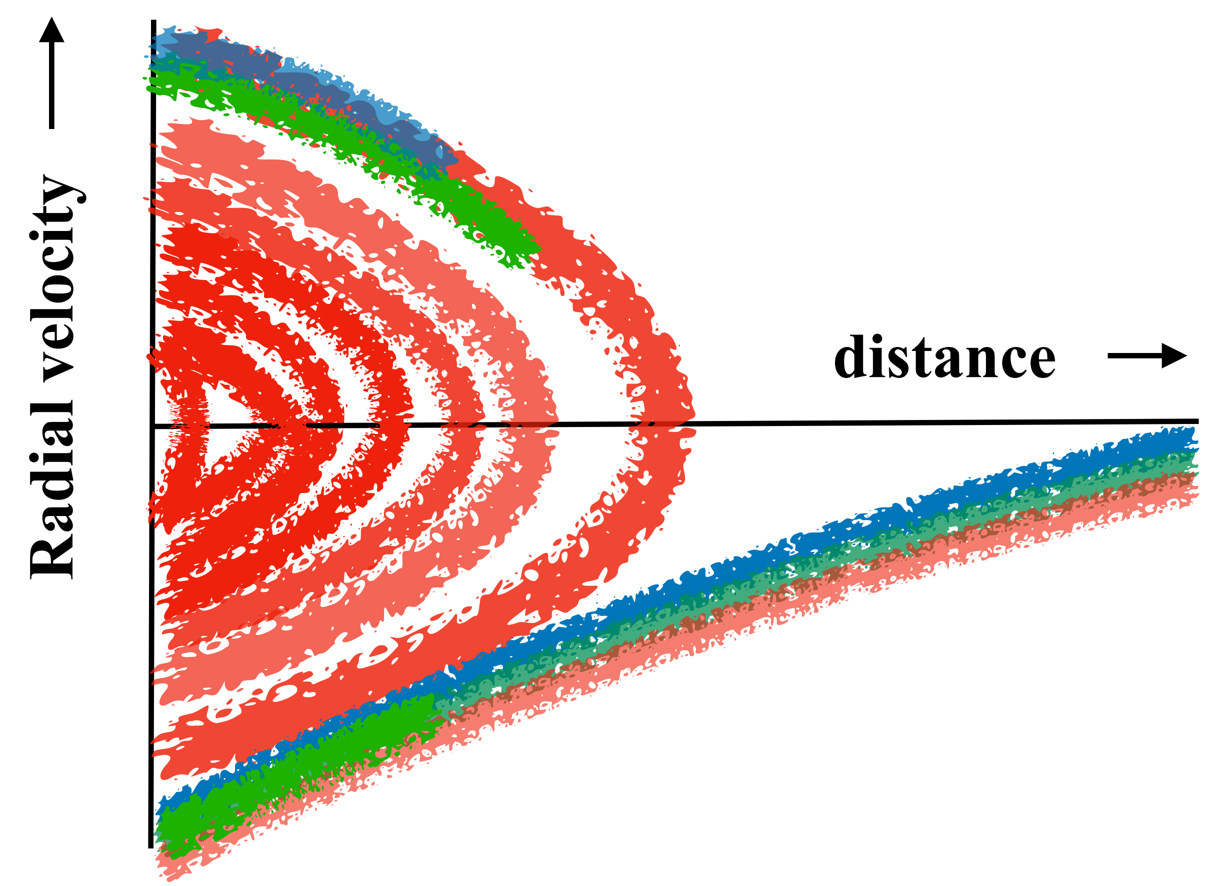
The splashback radius as a clock in the halo

Galaxies stop forming stars with time as they fall into a halo

Blue star-forming galaxies turn into red and dead galaxies

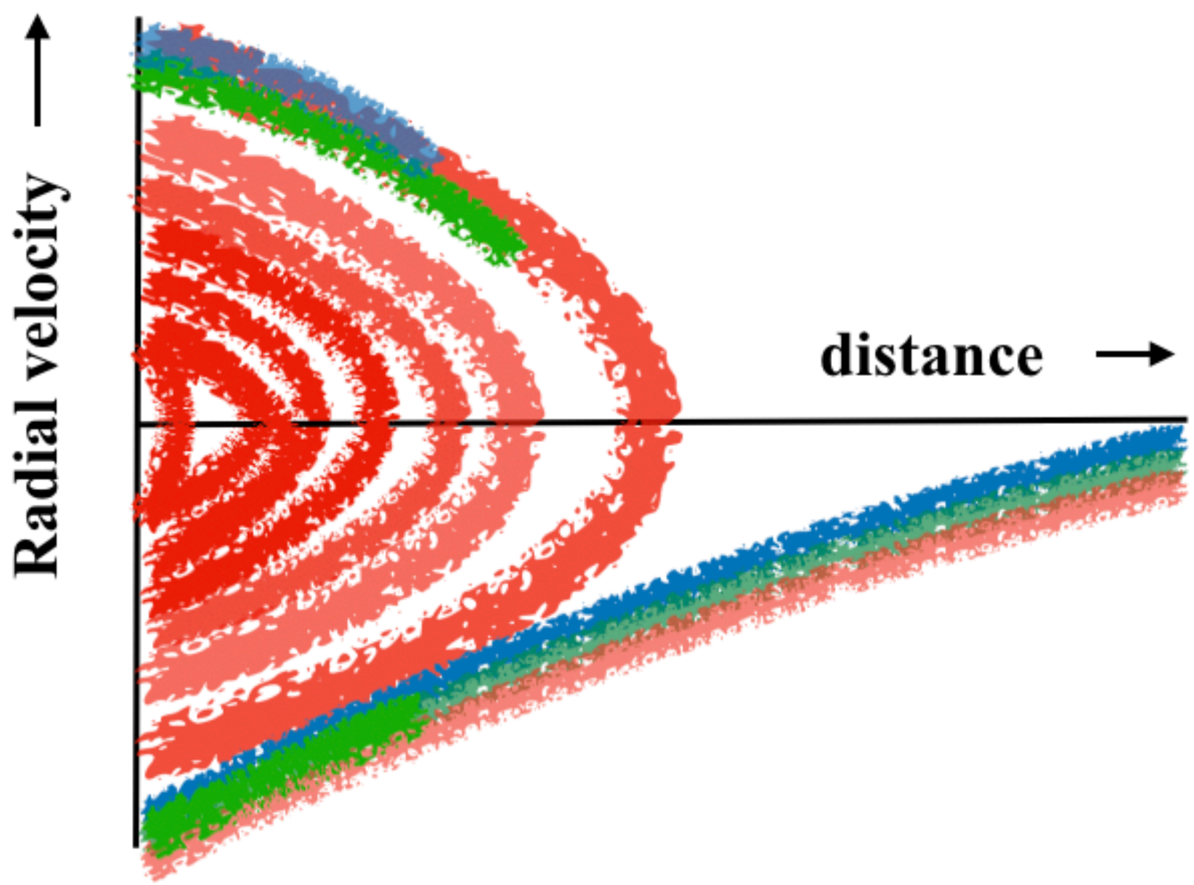


Longer delay , shorter quenching

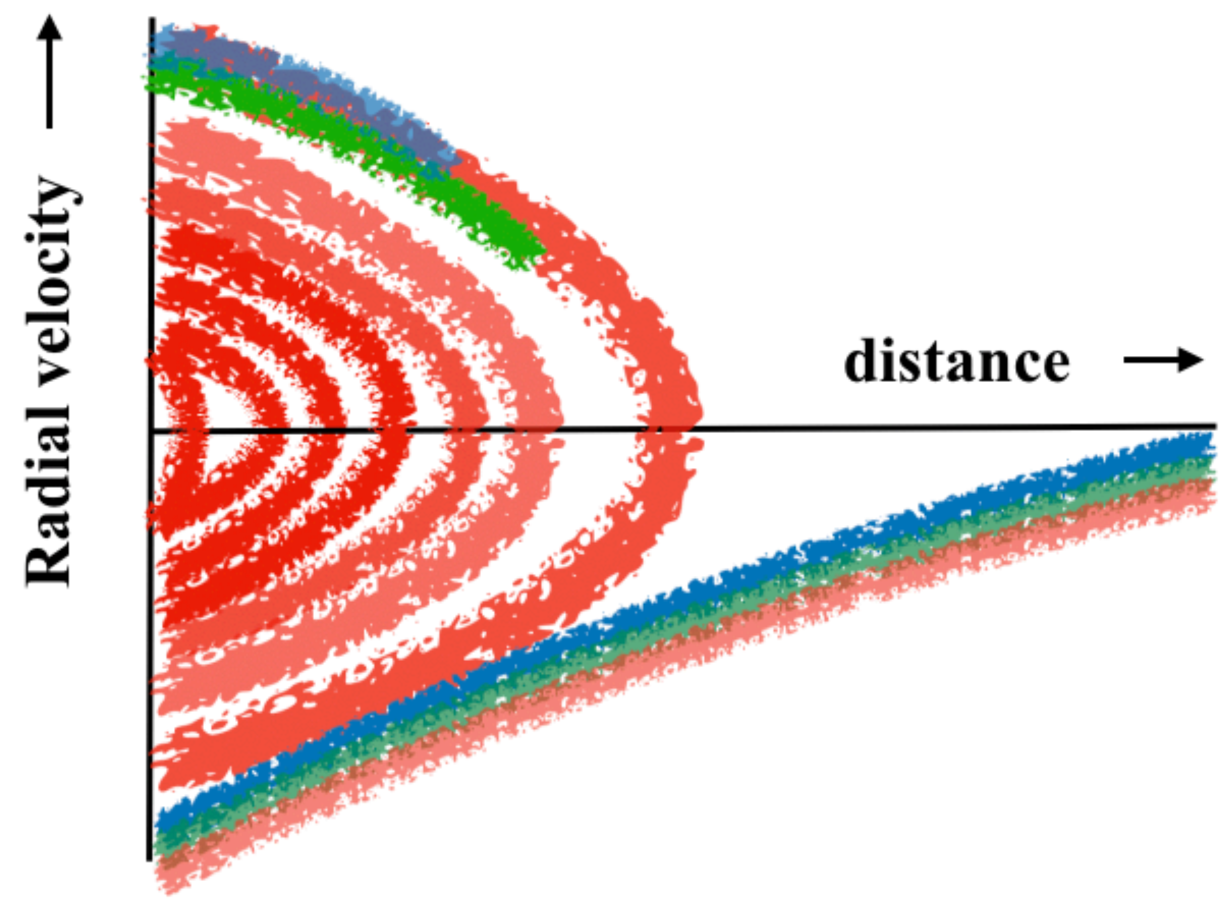


Short delay , long quenching

Minimum traces the time spent in the cluster by a population of galaxies



Short delay , long quenching



Longer delay , shorter quenching

Summary

- **The structure of dark matter halos contain information about the history of the universe**
- **The edges of halos can be understood through simple physical model**
- **The location of the edge is traced by the splashback radius that can be measured observationally**
- **Sensitive to modified gravity models**
- **Sensitive to models of self interacting dark matter, potentially any model that can change the energetics of dark matter particles**
- **A distinct scale in a halo that can tell us about galaxy evolution**