Probing physical boundaries of dark matter halos from cosmic density and velocity fields

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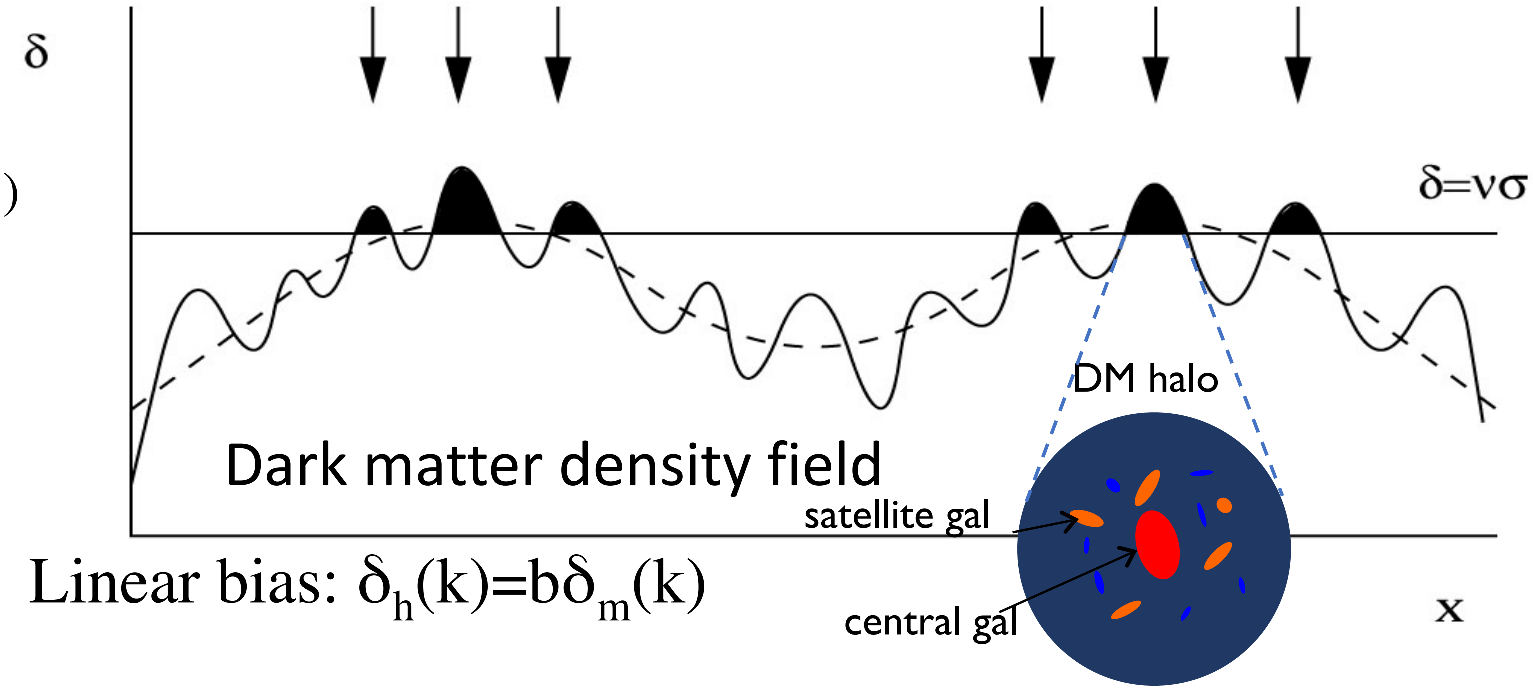
Concepts of dark matter halos and bias

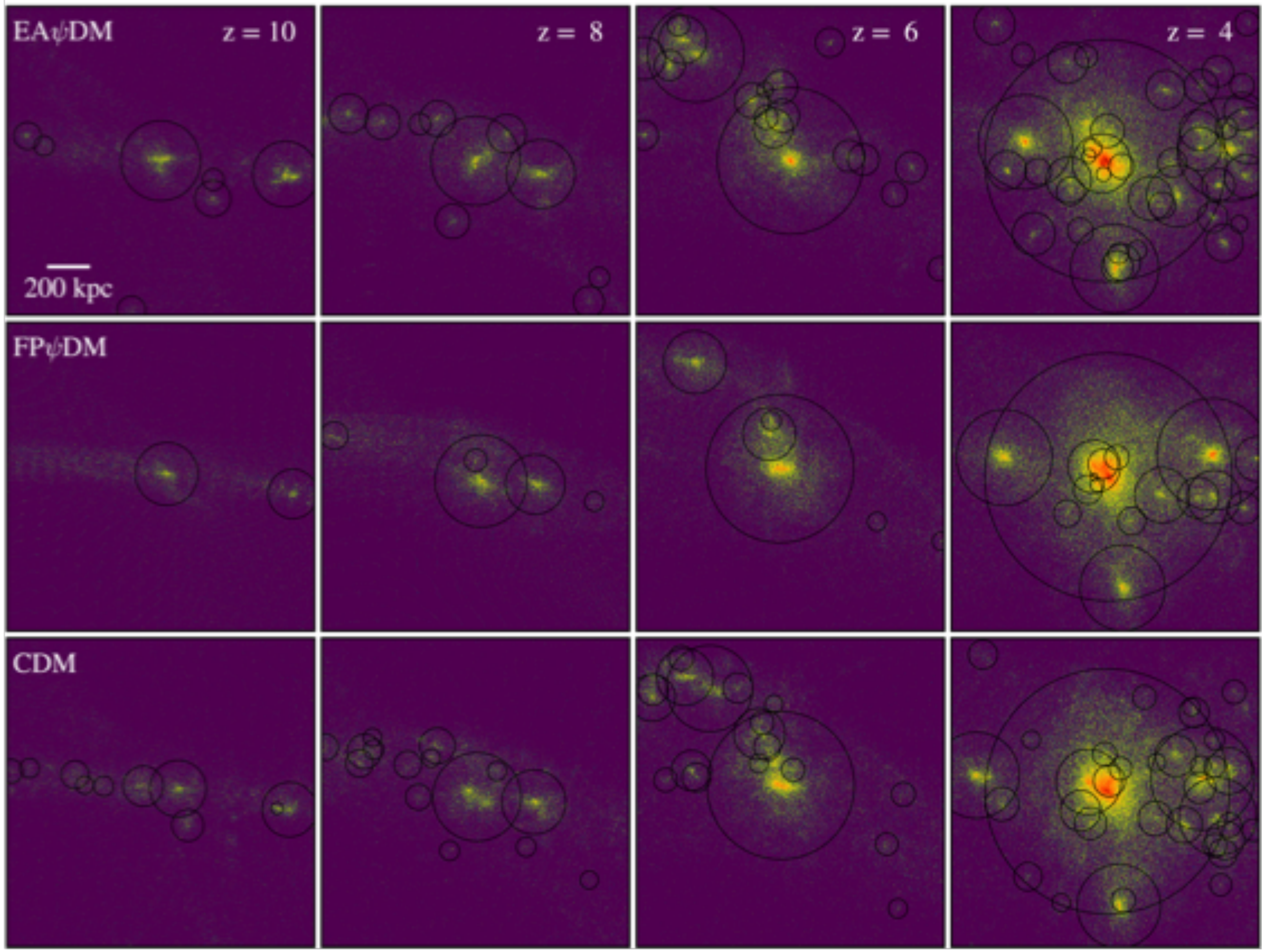
$$\rho(x) = \bar{\rho}(1 + \delta(x))$$

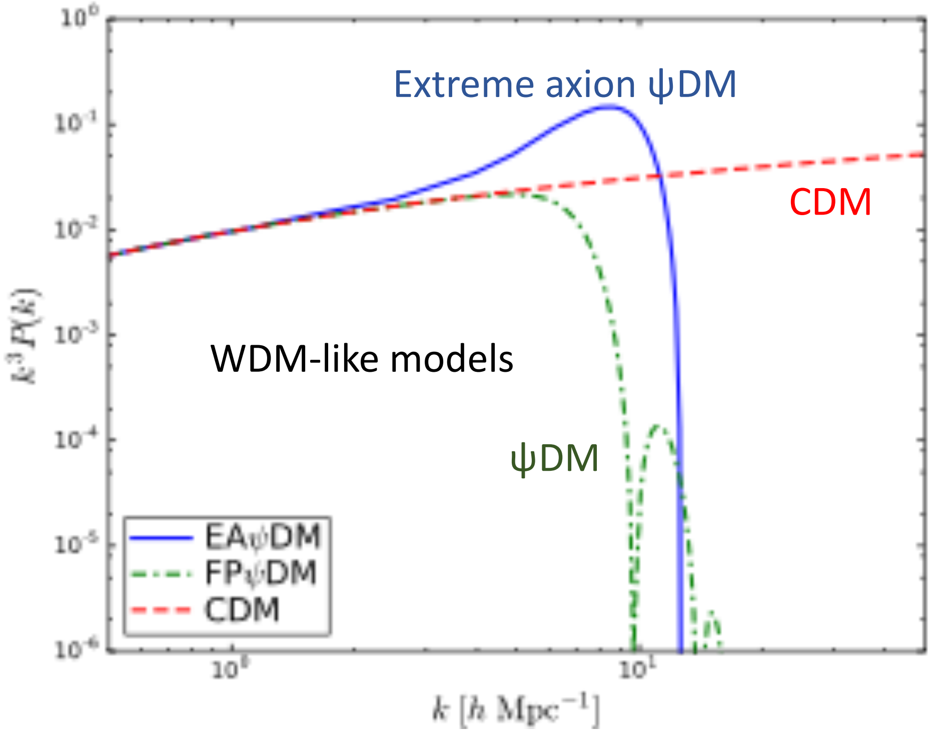


Linear bias: $\delta_h(k) = b\delta_m(k)$

- All the galaxies are considered to form within halos
- Modeling halo power spectrum is the first step to interpret the observed galaxy clustering. $\delta_D(k - k')\, P_{hh}(k) = \langle \delta_h(k)\delta_h^*(k') \rangle$
- Halo mass is the most fundamental quantity, related to observables.

Dark matter distributions for different DM models

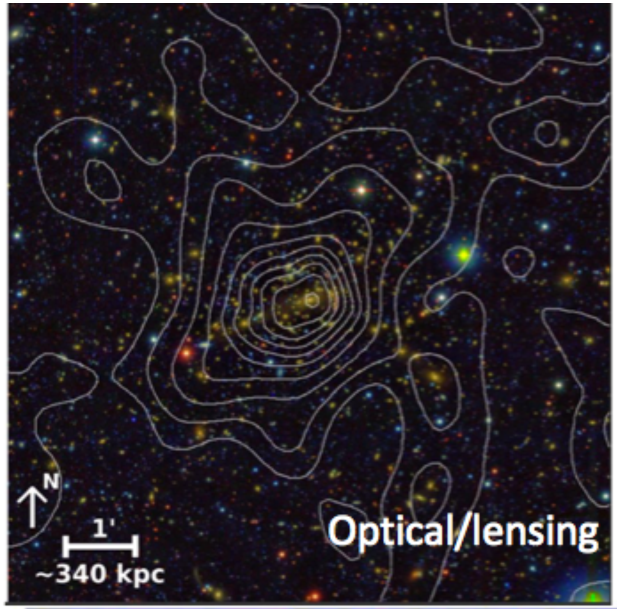


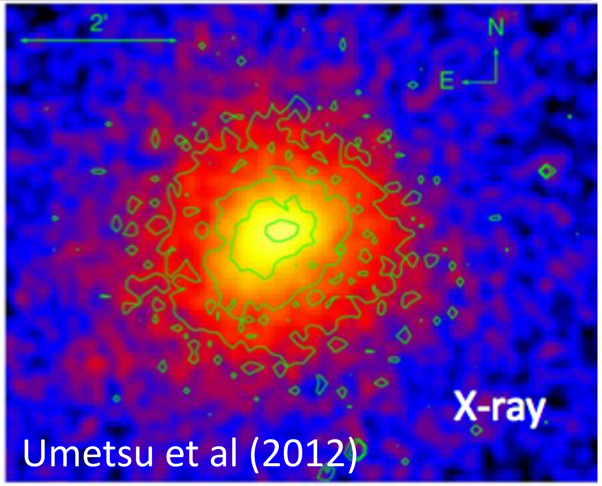


Schive & Chiueh (2018)

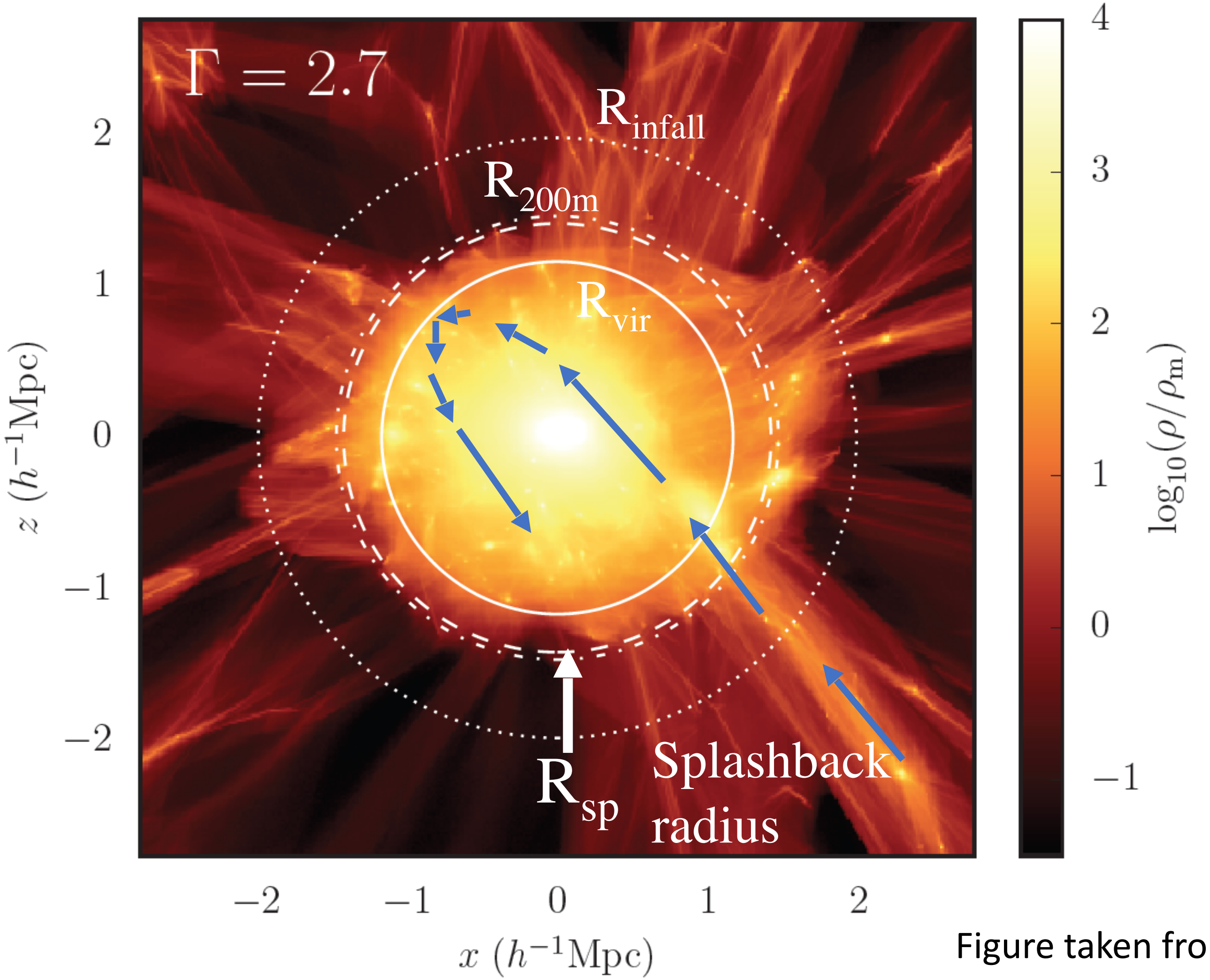
Galaxy clusters

- Largest self-gravitating objects formed in the universe
- Dominated by dark matter (DM)
- Can be observed with various ways:
  - Optical/NIR
  - X-ray
  - Radio (Sunyaev-Zel'dovich effects)
  - Gravitational lensing





What is physical boundary of a halo?



Sharp density enhancement associated with the orbital apocenter of the recently accreted matter in the growing halo potential. (Diemer & Kravtsov 2014, Adhikari et al 2014)

Figure taken from S. More et al (2016)

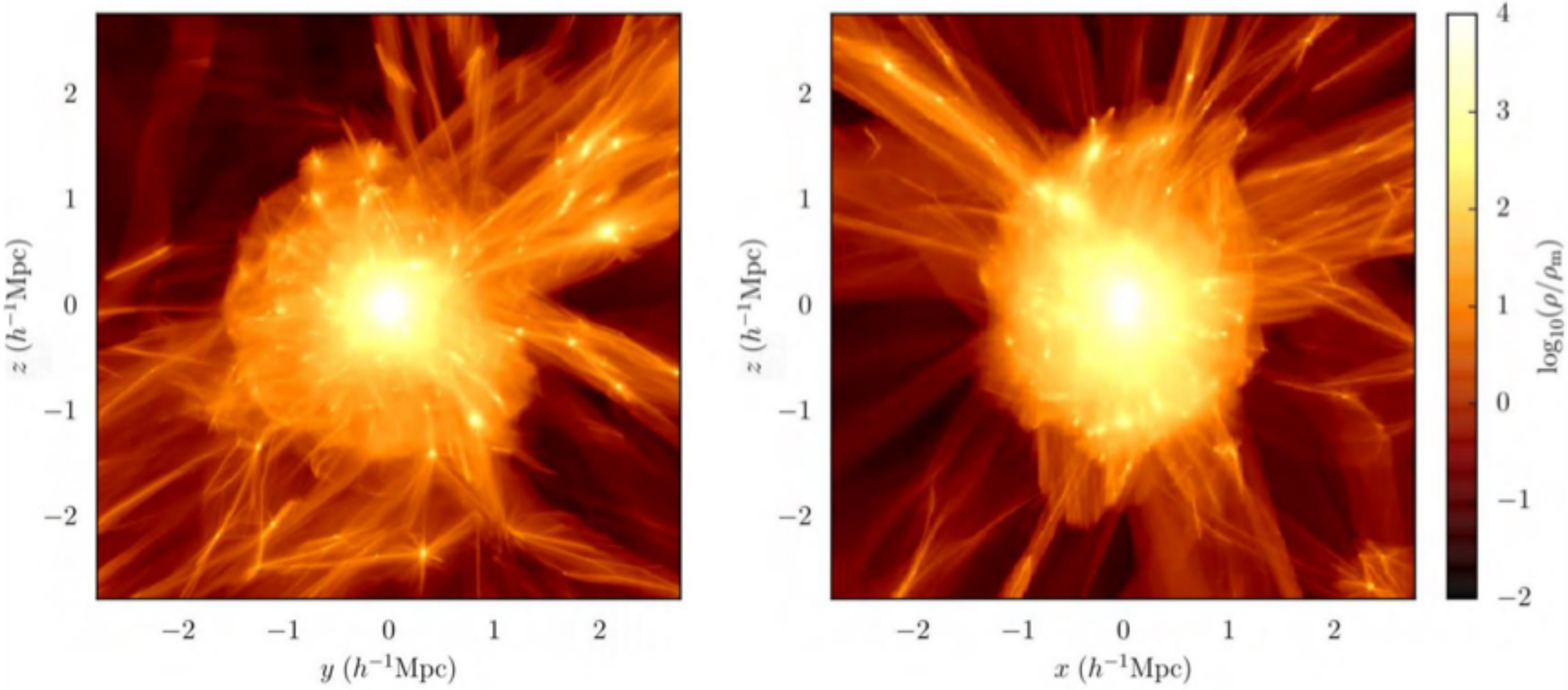
Splashback radius R_{sp}: Physical halo boundary

$r > R_{sp}$: infall region
$r < R_{sp}$: multi-stream intra-halo region

Splashback radius depends on MAR, halo peak height, cosmology (Ω_m)

<u>Slow accreting halos</u> $R_{sp} > r_{200m}$

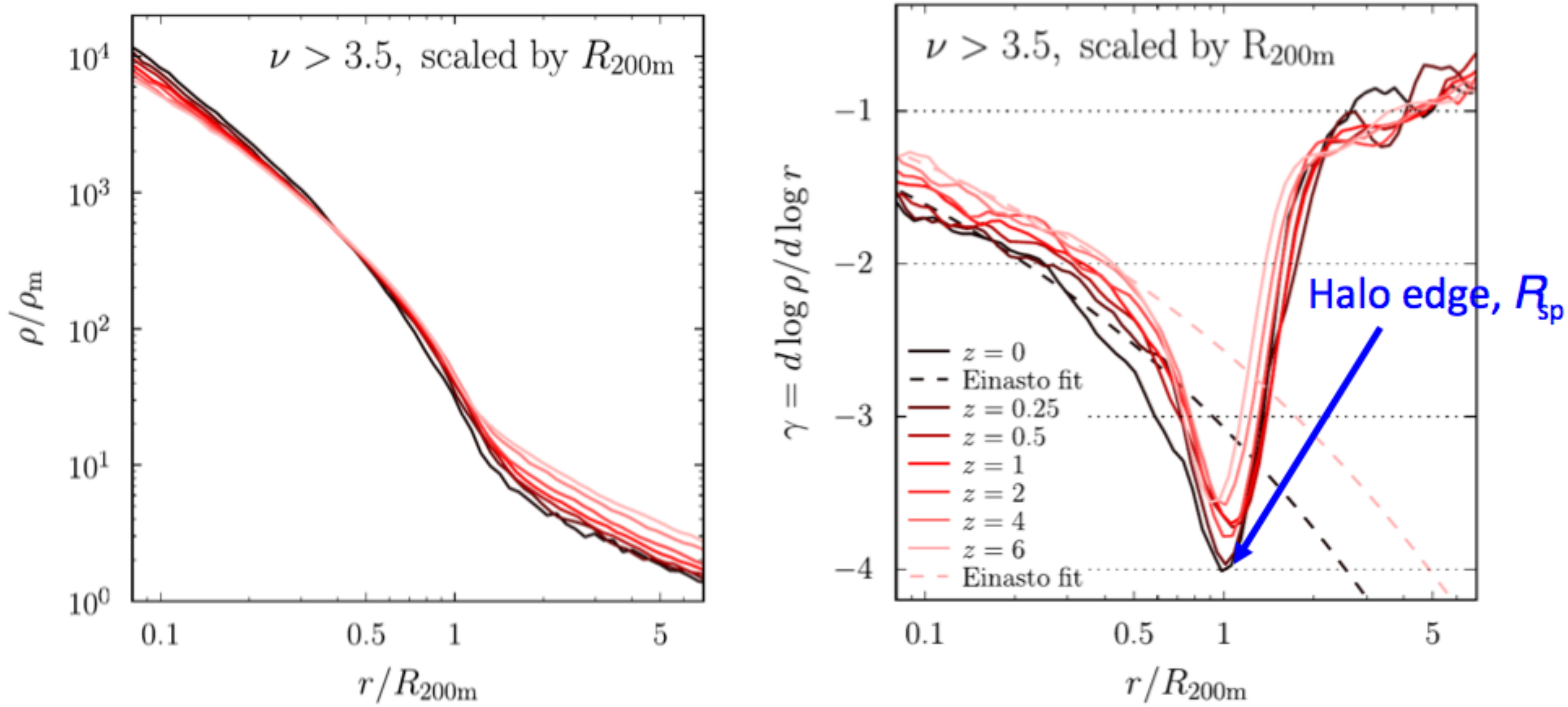
<u>Fast accreting halos</u> $R_{sp} \sim r_{200m}$



Splashback feature in density profile

DM density steepening relative to Einasto/NFW

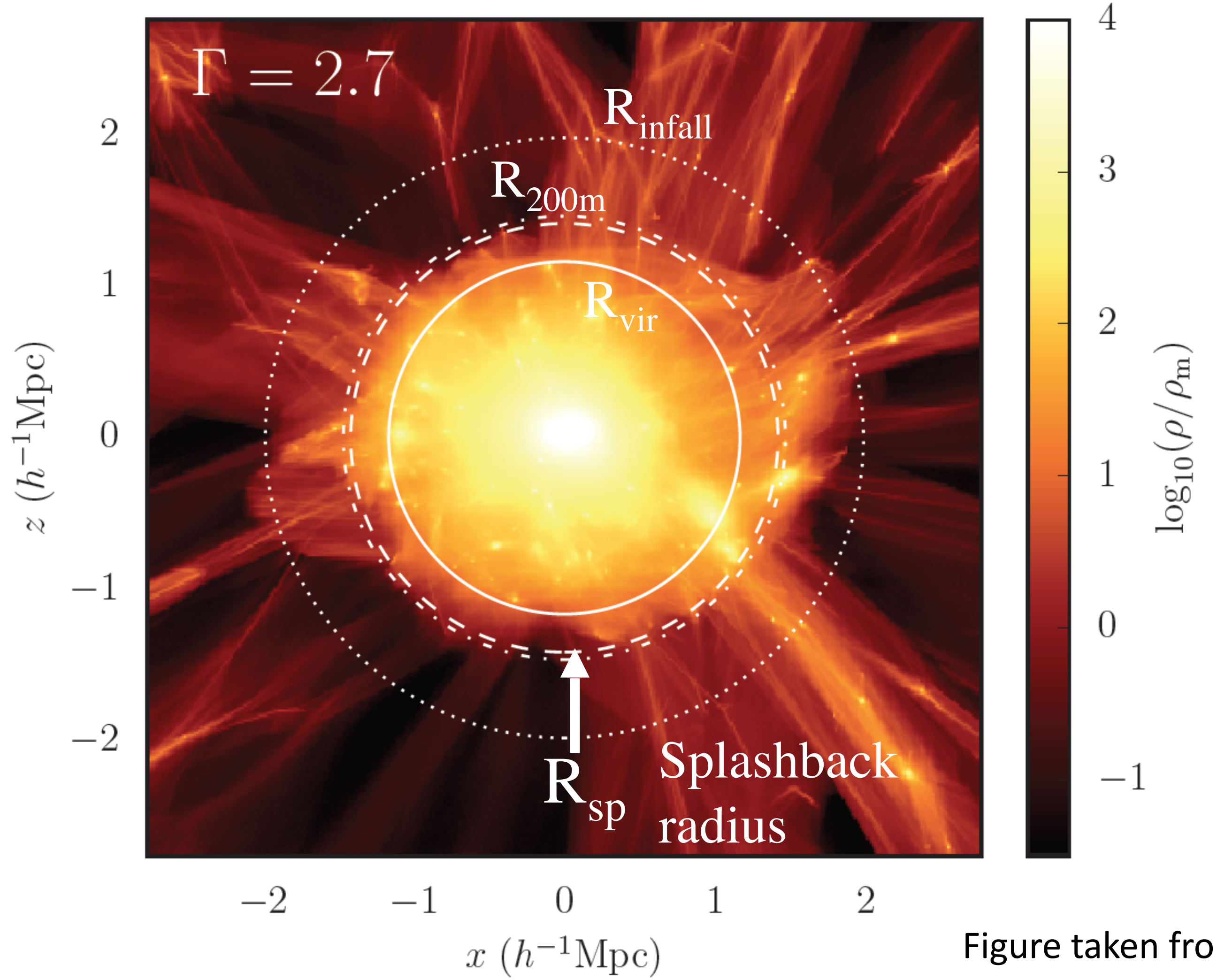
$R_{sp} \sim r_{200m}$ for high-mass forming halos



N-body simulations from Diemer & Kravtsov 2014 (DK14)

First detection (?) of splashback radius

- More, Miyatake, Takada et al. 2016



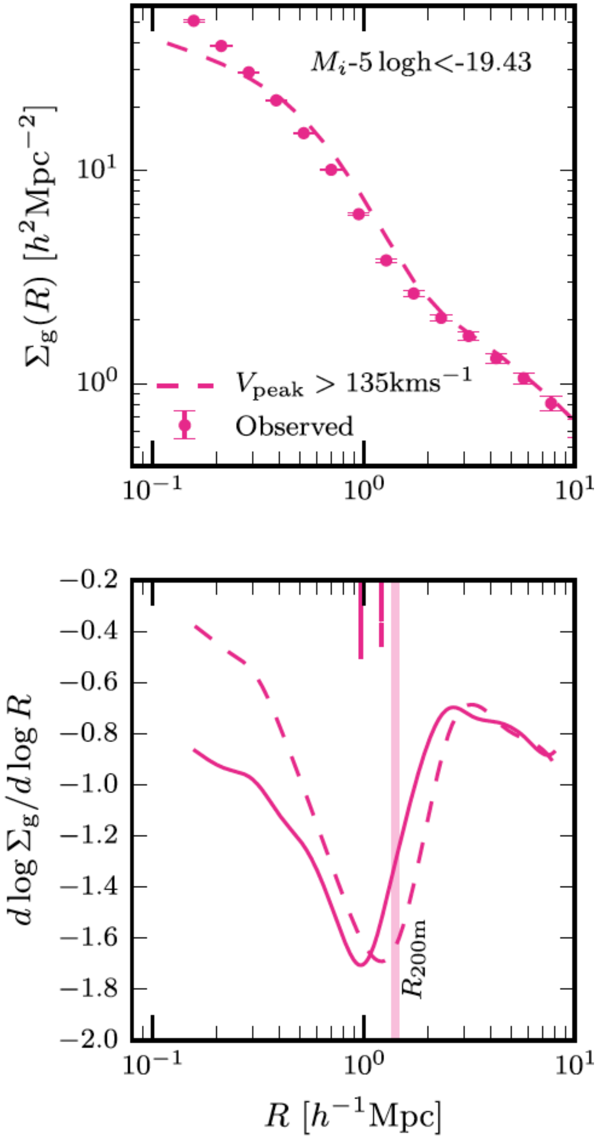


Figure taken from S.

Dark matter self-interactions have long been proposed to alleviate problems on small scales in the standard cosmological model (see e.g., Spergel & Steinhardt 2000). Under certain conditions, discussed below, the drag force due to interactions between dark matter particles of subhalos and cluster halos could lead to loss of orbital energy by subhalos even on the first crossing, thereby reducing the splashback radius.

For isotropic elastic scattering, we do not expect dark matter self-interactions to significantly affect the splashback feature, because the upper limits on such an interaction cross-section are sufficiently stringent to ensure that most dark matter particles do not experience any scattering events during a single orbit (Gnedin & Ostriker 2001; Randall et al. 2008). Of the few subhalo particles that do scatter, most are ejected from their subhalos, since the orbital velocities of subhalos within massive hosts are typically larger than the internal escape velocities of those subhalos. Therefore we would expect evaporation of subhalo masses, without a significant drag for isotropic scattering.

On the other hand, if dark matter self-interactions are anisotropic, with large cross-sections for small angle scattering and low cross-sections otherwise, then the momentum transfer during dark matter interactions may not necessarily be large enough to ensure ejection. The small angle scattering cross-sections could then be large enough for dark matter particles to experience frequent interactions and yet obey the bounds on subhalo evaporation. The subhalos would experience a net deceleration give

where $v(t)$ is the time-dependent mass of the dar transfer cross-sec

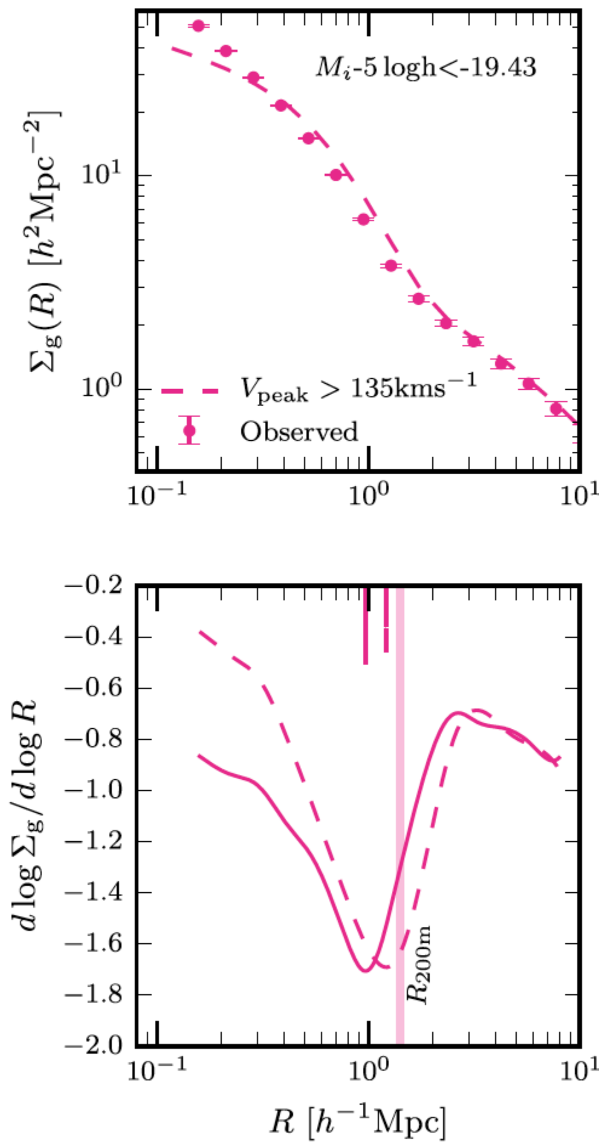
We have carried out simple analytical calculations based on a spherical collapse model similar to Adhikari et al. (2014; see also Adhikari & Dalal 2016), but including a velocity-dependent drag term of the above form. We find that the momentum transfer cross-section required to reduce the splashback radius by ≈20% can range from 1 to 10 $\mathrm{cm}^2\,\mathrm{g}^{-1}$ depending upon the pericenter of accreting halos on their first passage through the halo (S. More 2016, in preparation). The ambient dark matter density, and the relative velocity, hence the resultant drag, reach a maximum at the pericenter. Therefore, a proper treatment of the orbital parameters of subhalos expected in the standard structure formation model is required to determine the effects of dark matter self-interactions on the splashback radius (Jiang et al. 2014). We defer such investigations to a future paper.

Although the existing constraints on such scenarios are pretty weak, the recent discovery of galaxy displacement with respect to its subhalo in one of the clusters (Harvey et al. 2015) could be a signature of self-interaction (with a cross-section consistent with that required to explain $R_{\rm sp}$ discrepancy, see Kahlhoefer et al. 2015). Numerical simulations of this type of dark matter self-interaction, similar to the simulations performed for hard-sphere interactions (Elbert et al. 2015), would be required to refine the estimate of the cross-sections stated above further.

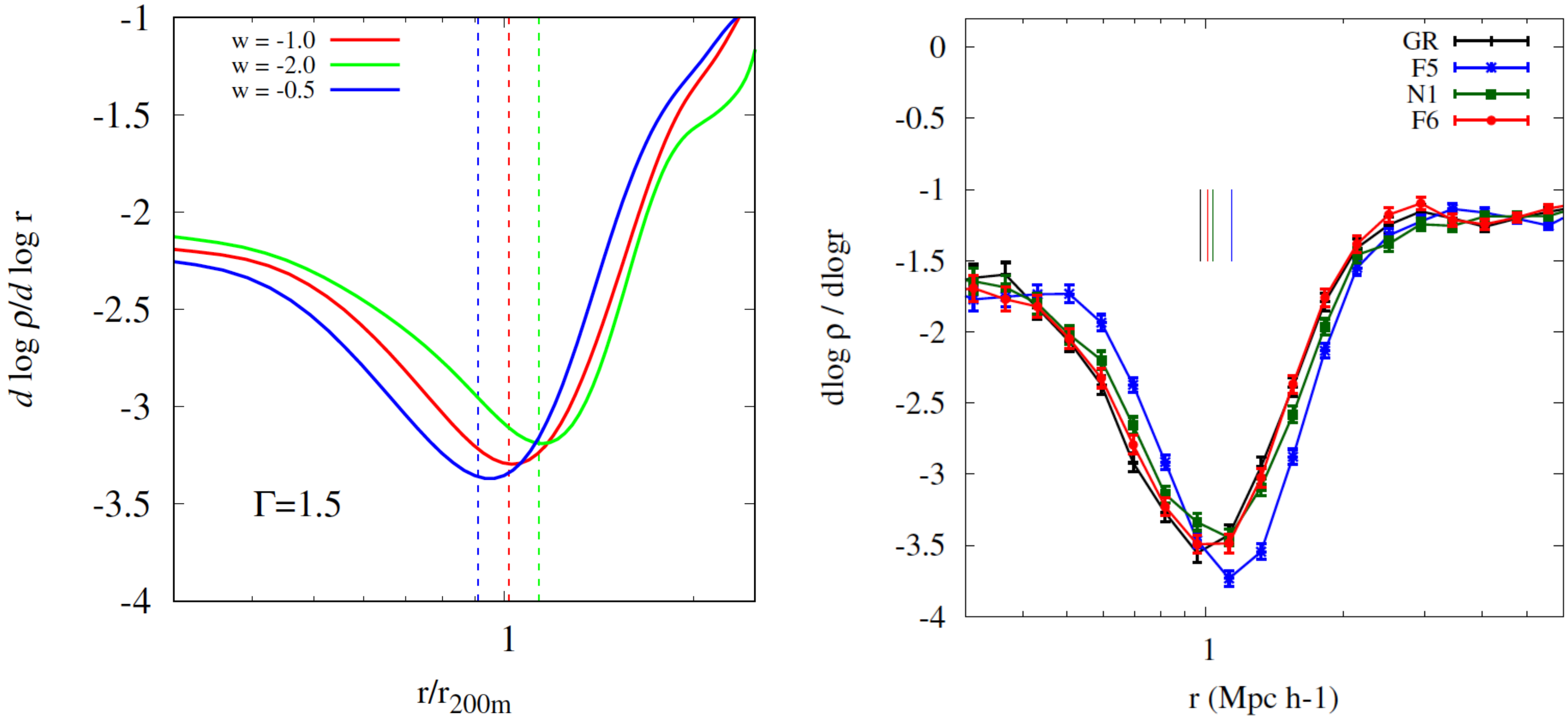
Note that even if the self-interactions will ultimately not turn out to be the explanation for the splashback radius discrepancy, our analysis shows that precise measurements of galaxy distributions in clusters could provide valuable and competitive constraints on the cross-section of dark matter self-interaction.

If we assume that the differences in the splashback radius we find are not due to the above possibilities and we trust the simple dynamics within the gravitational potential of halos, then our measurements of the smaller splashback radius would either require a different phase space structure in the outskirts ... luster ... es of ... r. For ... uires ... of Γ ... ndard ... could ... from ... ation (Adhikari et al. 2016).

- Finally, it finally turned out that the discrepancy was very likely due to the observational projection effect (Busch & White 2017).



Effects of dark energy/modified gravity on splashback



Adhikari et al. [arXiv:1806.04302]

Two issues I will address in this talk

- Asphericity of dark matter halos
  - If we really want to constrain SIDM, WDM, ψDM, etc. with the splashback radius, anisotropies of halo shapes should be properly taken into account.
- Full 6-d phase-space information of the splashback
  - Only 3-d position space can be probed through the density profile and weak lensing.

Old version available at arXiv (1706.08860v2)

Splashback Radius of Non-spherical Dark Matter Halos from Cosmic Density and Velocity Fields

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N-body simulations: mock galaxies and clusters

- Run as a part of *dark emulator* project (Nishimichi et al. in prep.)
  - 2048^3 particles, L_{box}=1000Mpc/h → $m_p=1.0\times10^{10}M_{sun}/h$

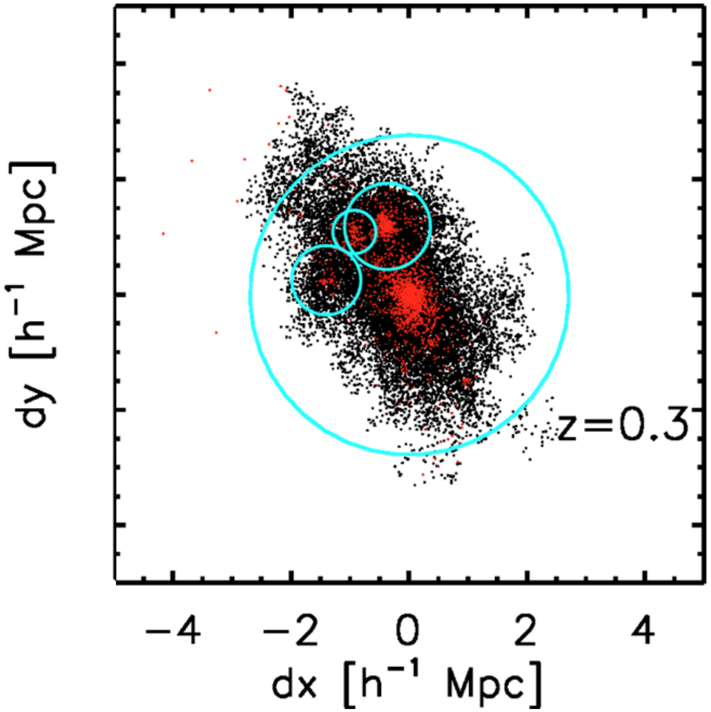


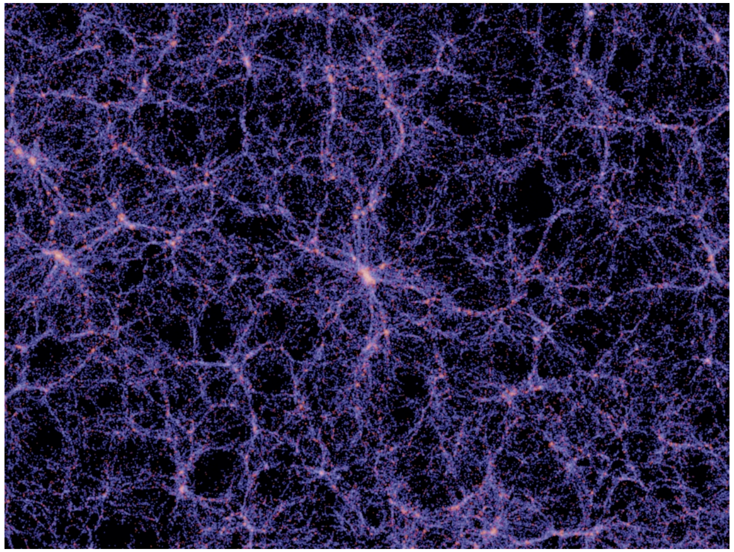
Figure from Masaki et al 2013

- subhalos are identified using phase-space friends-of-friends (*Rockstar*)
- "clusters" are chosen from halos with the threshold $M_h>10^{14}M_{sun}/h$
- Halos are assumed to have triaxial shapes and the major axes are determined on the projected celestial plane.
- "galaxies" are selected from subhalos based on HOD for BOSS LOWZ sample

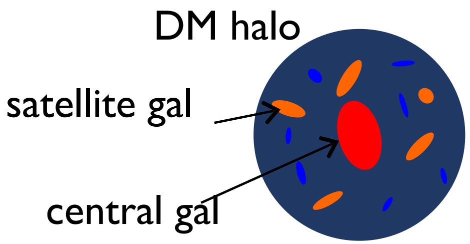
$$N_{\rm LOWZ}(M_h)=N_{\rm cen}(M_h)+N_{\rm sat}(M_h)$$

Two ways to determine the halo density profiles

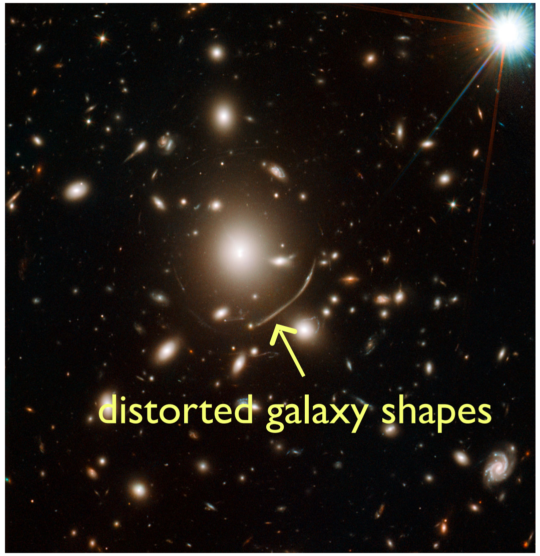
- Galaxy clustering
  - Through galaxy distribution



$$\xi_{cg}(x) = \left\langle \delta_c(\mathbf{r}_1)\delta_g(\mathbf{r}_2) \right\rangle$$



- Weak gravitational lensing
  - Through dark matter distribution



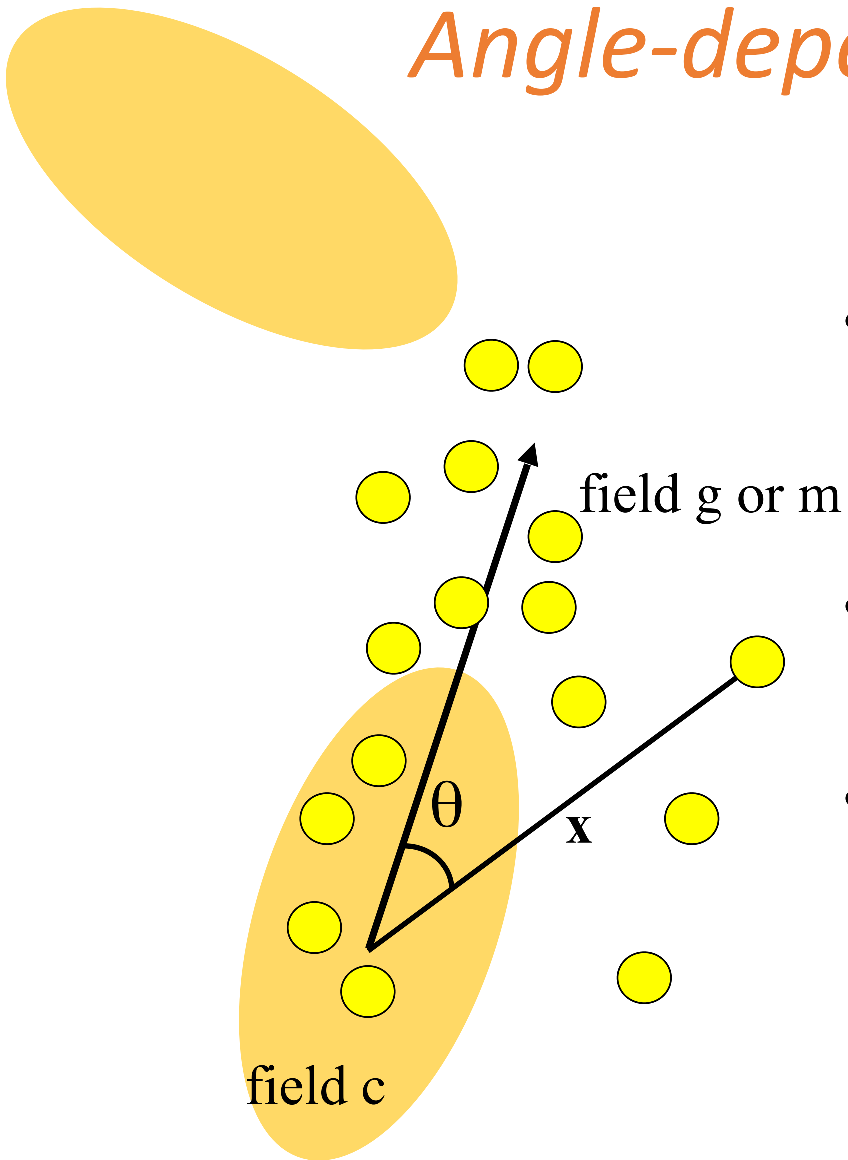
$$\xi_{cm}(x) = \left\langle \delta_c(\mathbf{r}_1)\delta_m(\mathbf{r}_2) \right\rangle$$

On linear scales $\xi_{cg}(x, \theta) = b_g \xi_{cm}(x, \theta)$

(c: cluster, g: galaxy, m: mass)

Angle-dependent density profile

Paz et al 2008
Faltenbacher et al 2009



- Definition (c: cluster, g: galaxy, m: mass)

$$\xi_{cm}(x,\theta) = \left\langle \delta_c(\mathbf{r}_1)\delta_m(\mathbf{r}_2,\theta) \right\rangle$$

$$\xi_{cg}(x,\theta) = \left\langle \delta_c(\mathbf{r}_1)\delta_g(\mathbf{r}_2,\theta) \right\rangle = b_g \xi_{cm}(x,\theta)$$

on linear scales

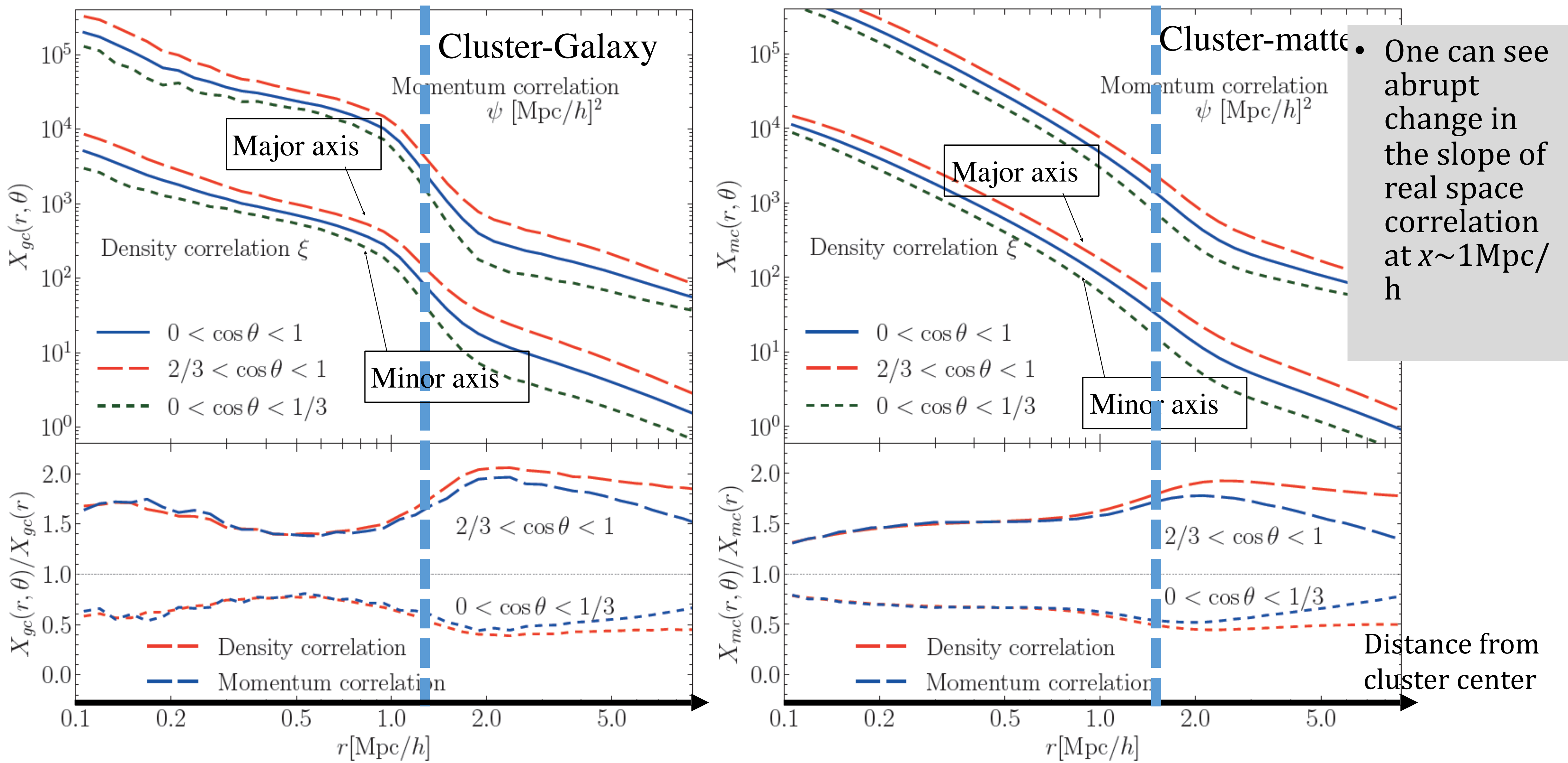
- Relation to conventional correlation

$$\xi_{AB}(\mathbf{x}) = (2/\pi)\int_0^{\pi/2} d\theta \xi_{AB}(\mathbf{x},\theta)$$

- Relation to intrinsic alignment (GI correlation)

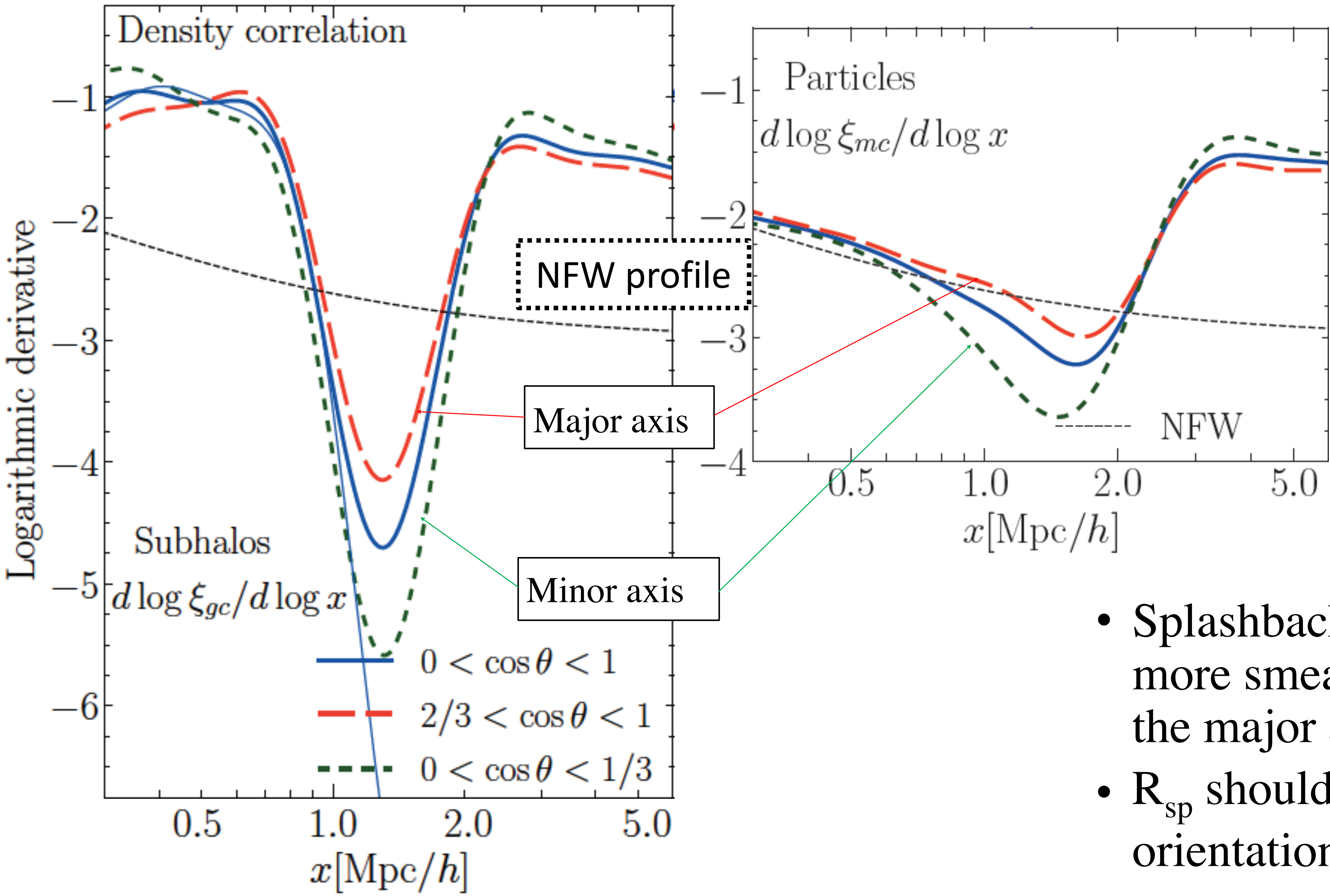
$$\tilde{\xi}_{A+}(\mathbf{x}) = (2/\pi)\int_0^{\pi/2} d\theta \cos(2\theta)\xi_{AB}(\mathbf{x},\theta)$$

Angle-dependent density profile



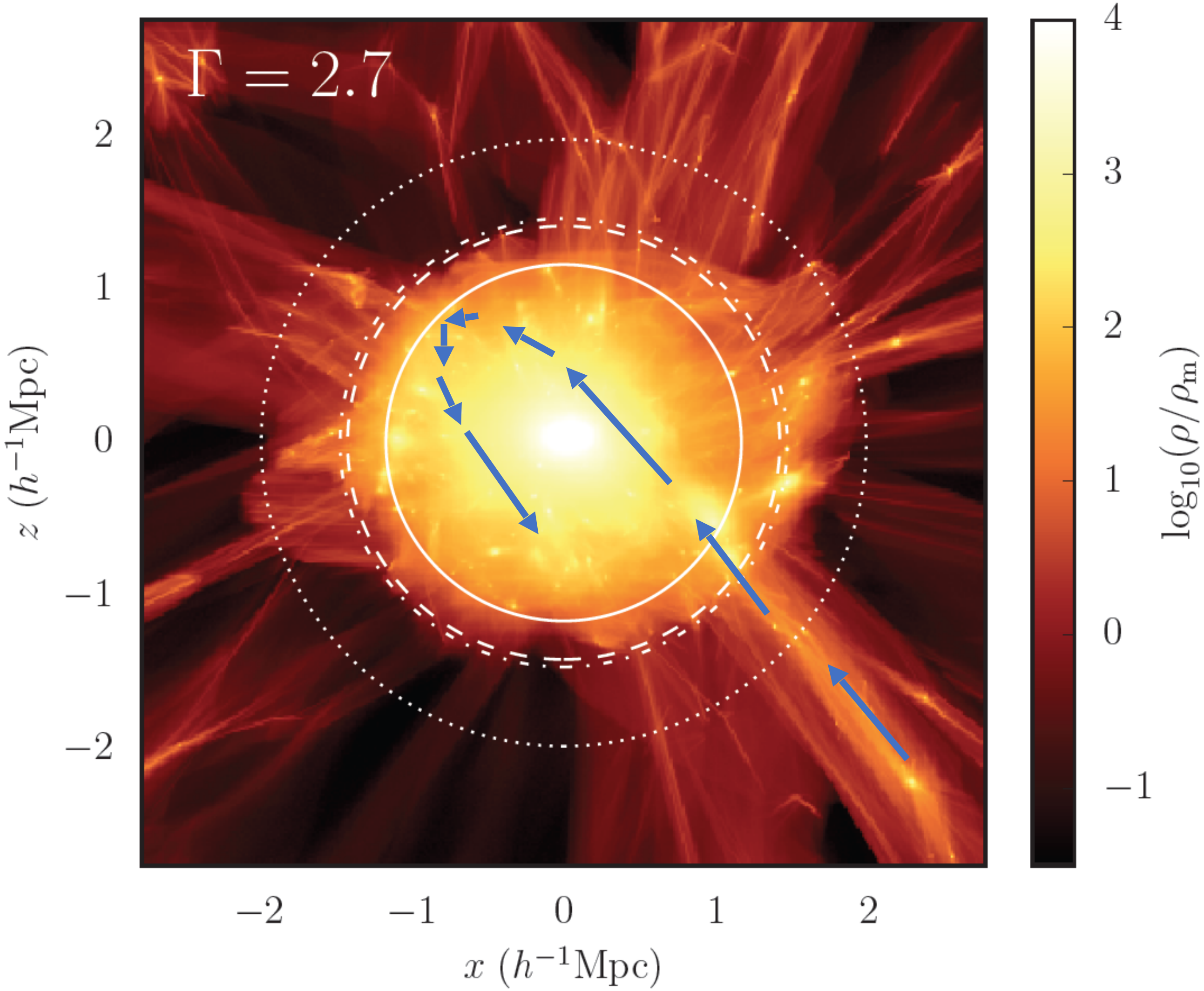
- One can see abrupt change in the slope of real space correlation at x~1Mpc/h

Splashback radius of non-spherical halos



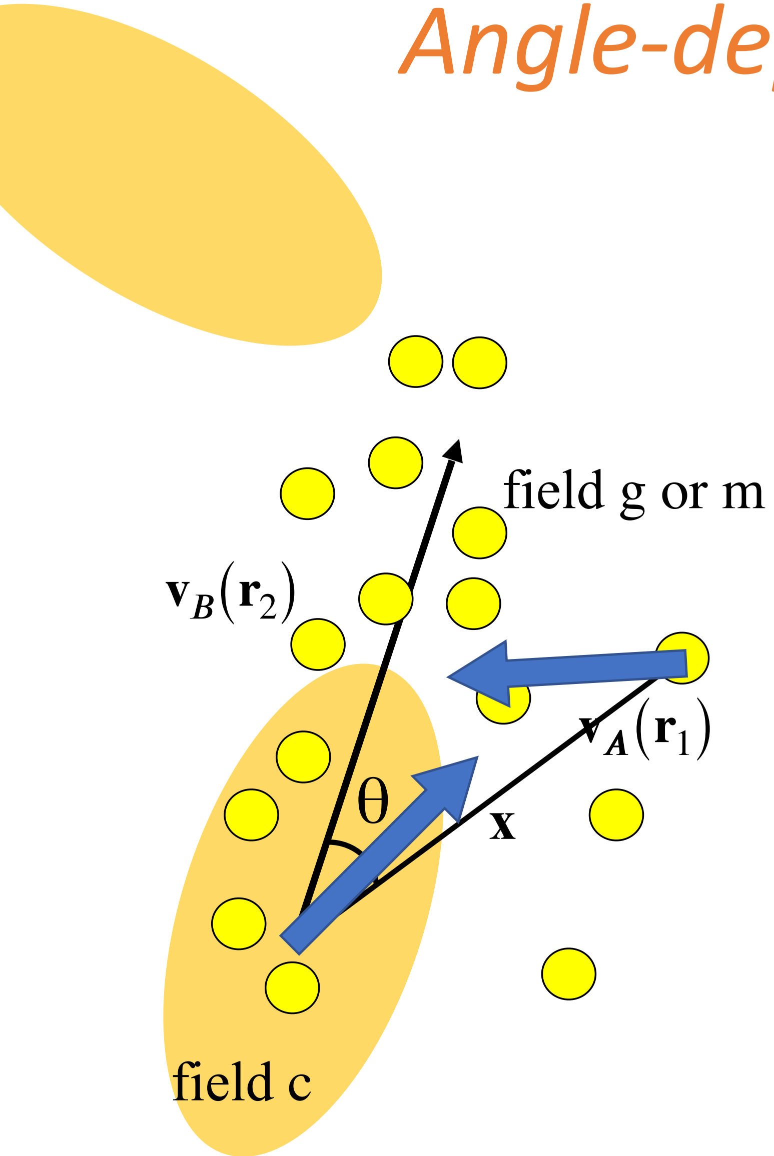
- Splashback feature is more smeared out along the major axis.
- R_{sp} should depend on the orientation of halos

Splashback features are fully characterized in 6-d phase space



- Density profile uses only 3-d position-space information.

Angle-dependent velocity statistics

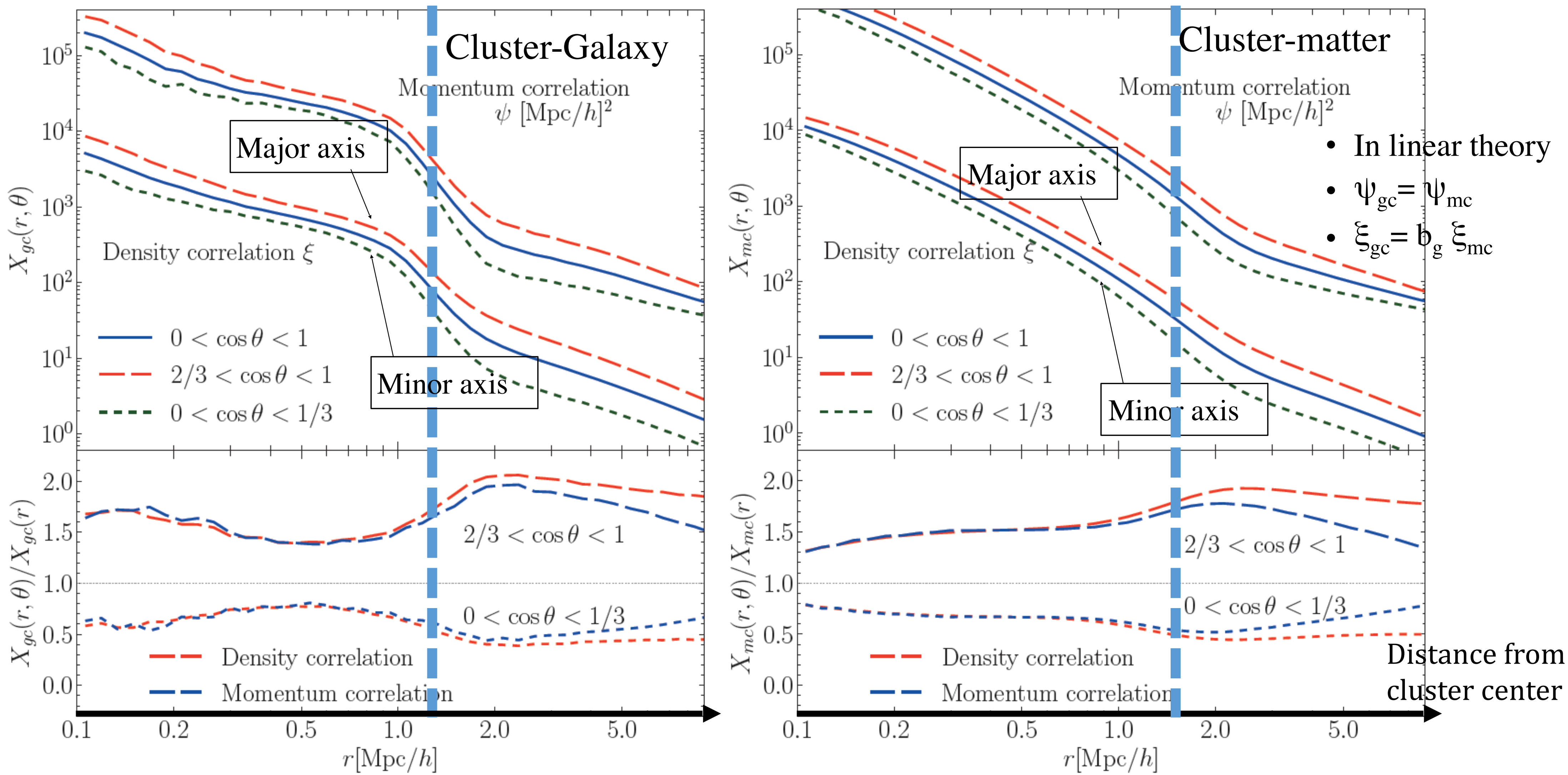


- Velocities inside/outside halo boundaries
  - $r > R_{sp}$: infall
  - $r < R_{sp}$: multi-stream intra-halo region
- Angle-binned momentum correlation

$$\psi_{cm}(x,\theta) = \left\langle \left[1 + \delta_c(\mathbf{r}_1)\right]\left[1 + \delta_m(\mathbf{r}_2,\theta)\right]\mathbf{v}_c(\mathbf{r}_1) \bullet \mathbf{v}_m(\mathbf{r}_2) \right\rangle$$

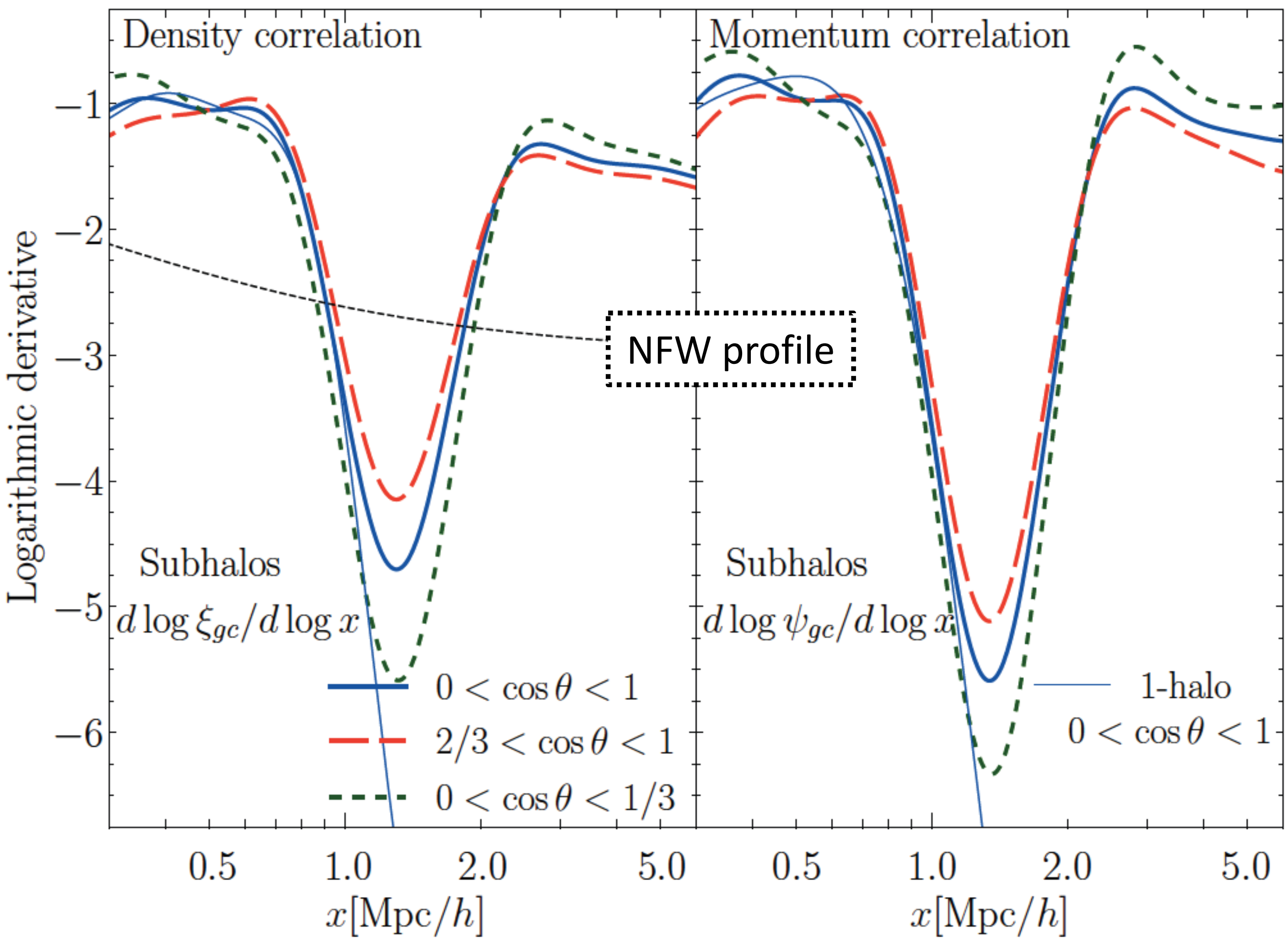
on linear scales

Angle-dependent momentum correlation

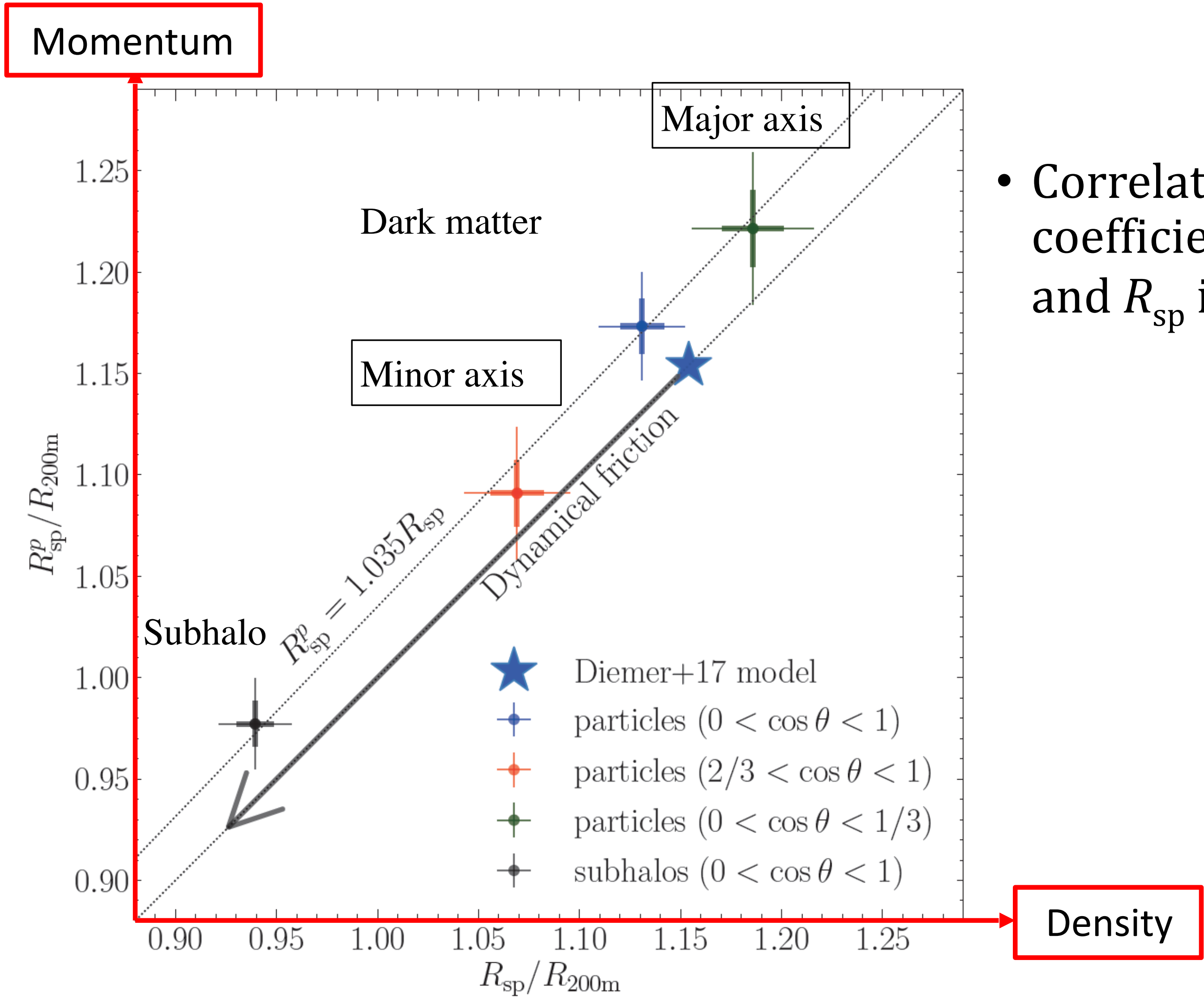


- In linear theory
- $\psi_{gc} = \psi_{mc}$
- $\xi_{gc} = b_g\ \xi_{mc}$

Splashback features in momentum correlation

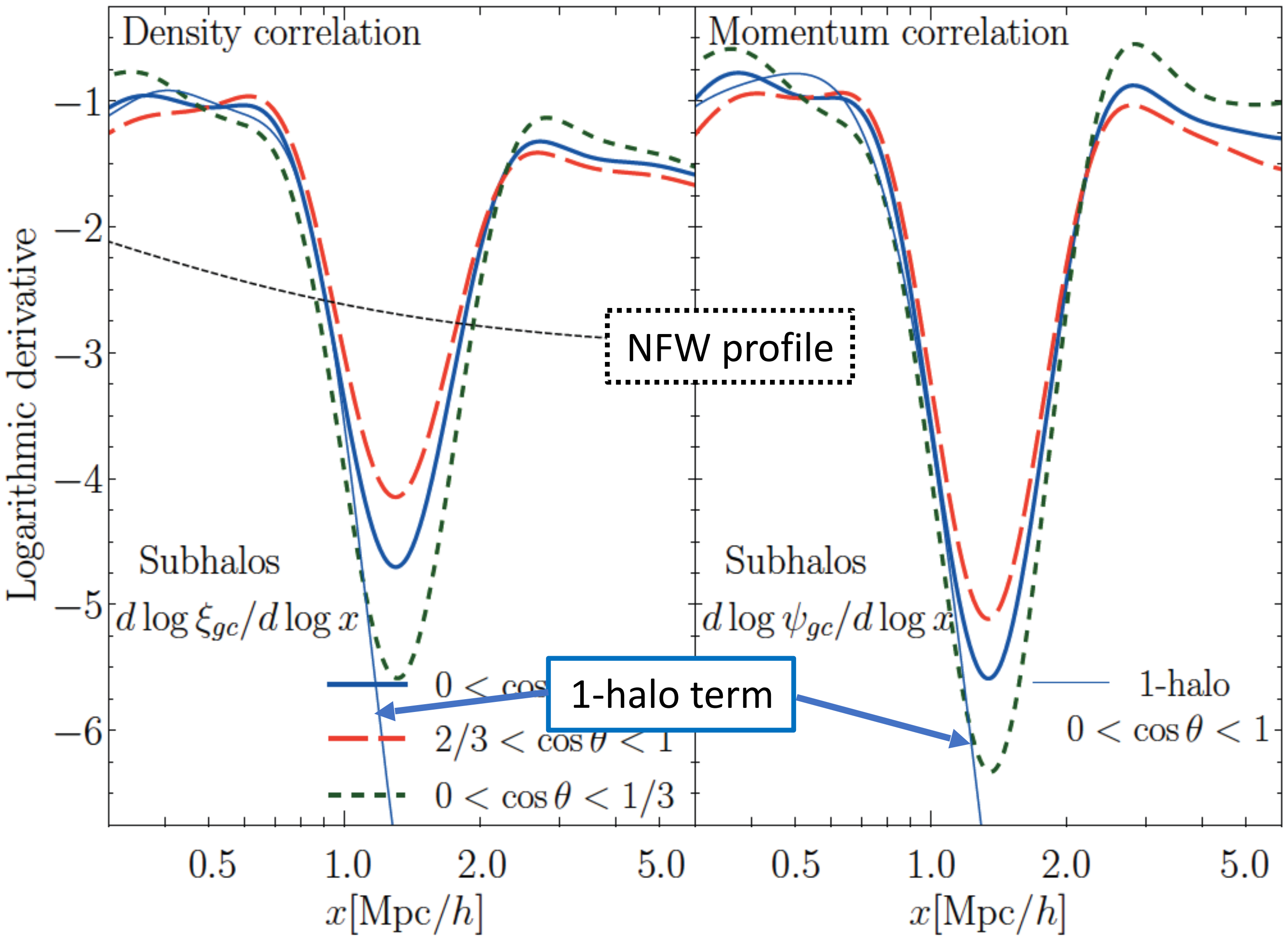


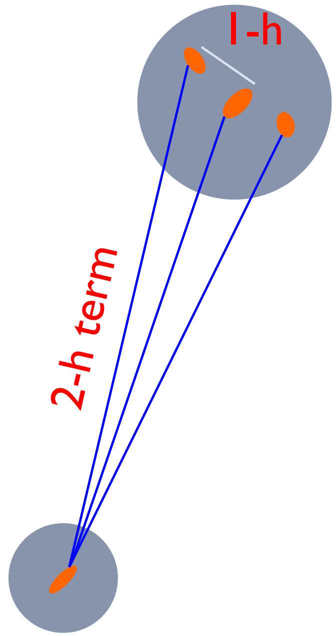
Constraints on splashback radius



- Correlation coefficient of $R_{sp}{}^{p}$ and R_{sp} is ~0.6.

Splashback features in momentum correlation





Conclusions and outlook

- We proposed angle-dependent density velocity statistics to study asphericity of splashback features.
- Splashback features are well determined with the velocity field
- One can use the splashback probed by the velocity field to calibrate the standard one (by density field).
- It is still not very clear if the splashback features can be properly measured from the density field in observations.
- In principle it is possible to determine the splashback from the velocity field in observations, using the pairwise velocity dispersion.
- There is a potential for the splashback radius to be a useful probe for testing non-LCDM models, but careful tests need to be done.

Old version of the paper available at arXiv (1706.08860v2)