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

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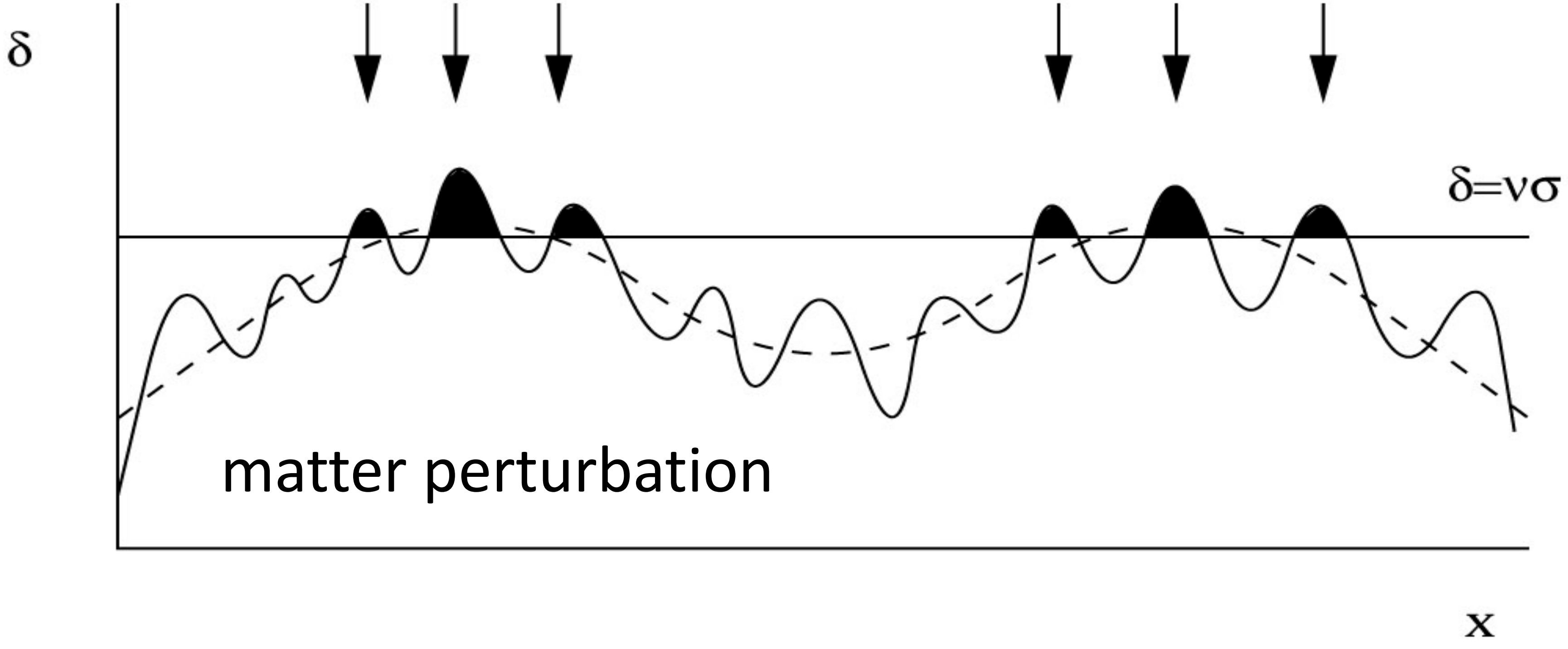
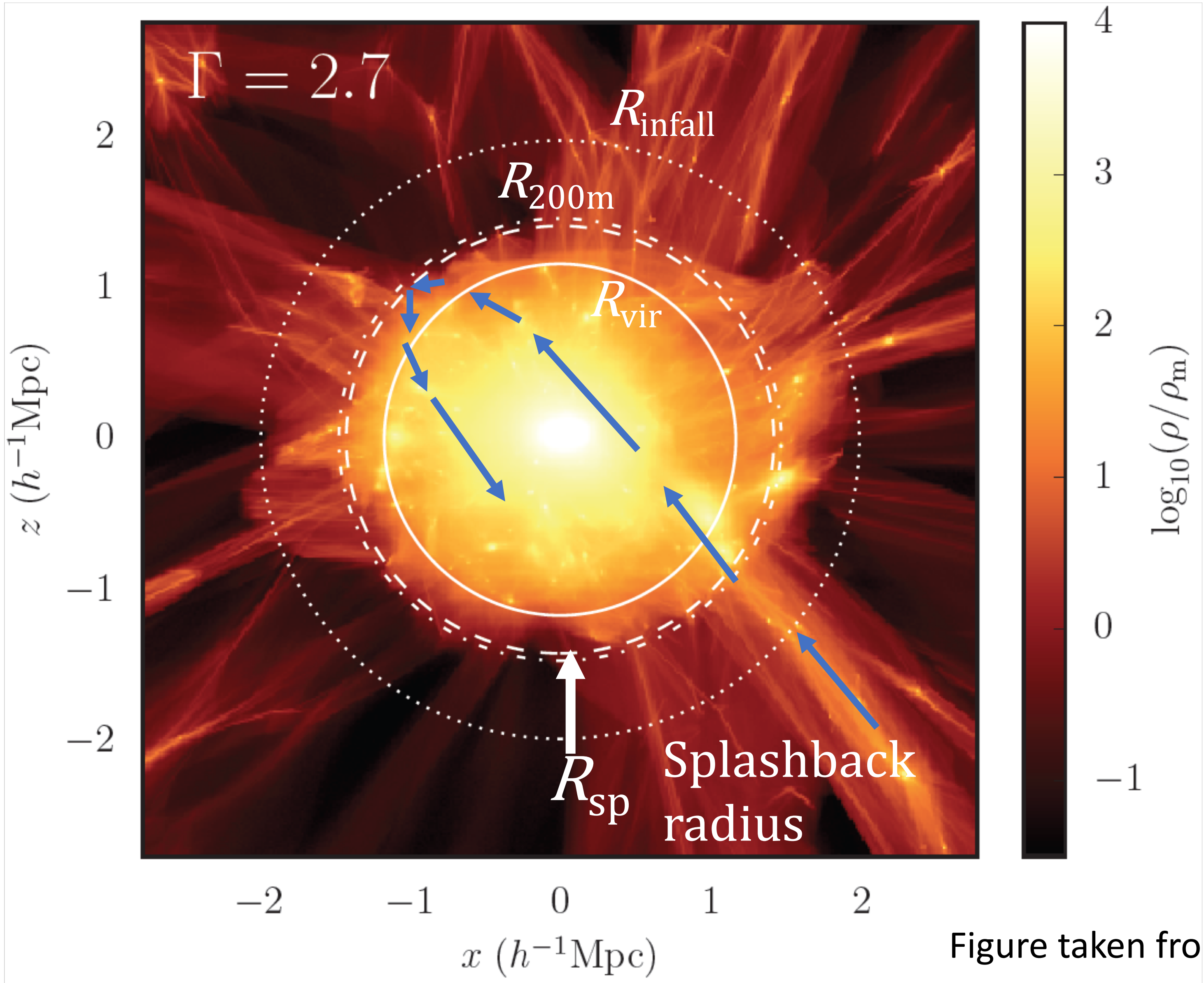
Concepts of dark matter halos

Matter density
$\rho(x) = \bar{\rho}[1 + \delta(x)]$



- All the galaxies are considered to form within halos
- Modeling halo power spectrum is the first step to interpret the observed galaxy clustering to study dark energy /modified gravity. $\delta_D(k - k')\, P_{hh}(k) = \langle \delta_h(k) \delta_h^*(k') \rangle$

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)

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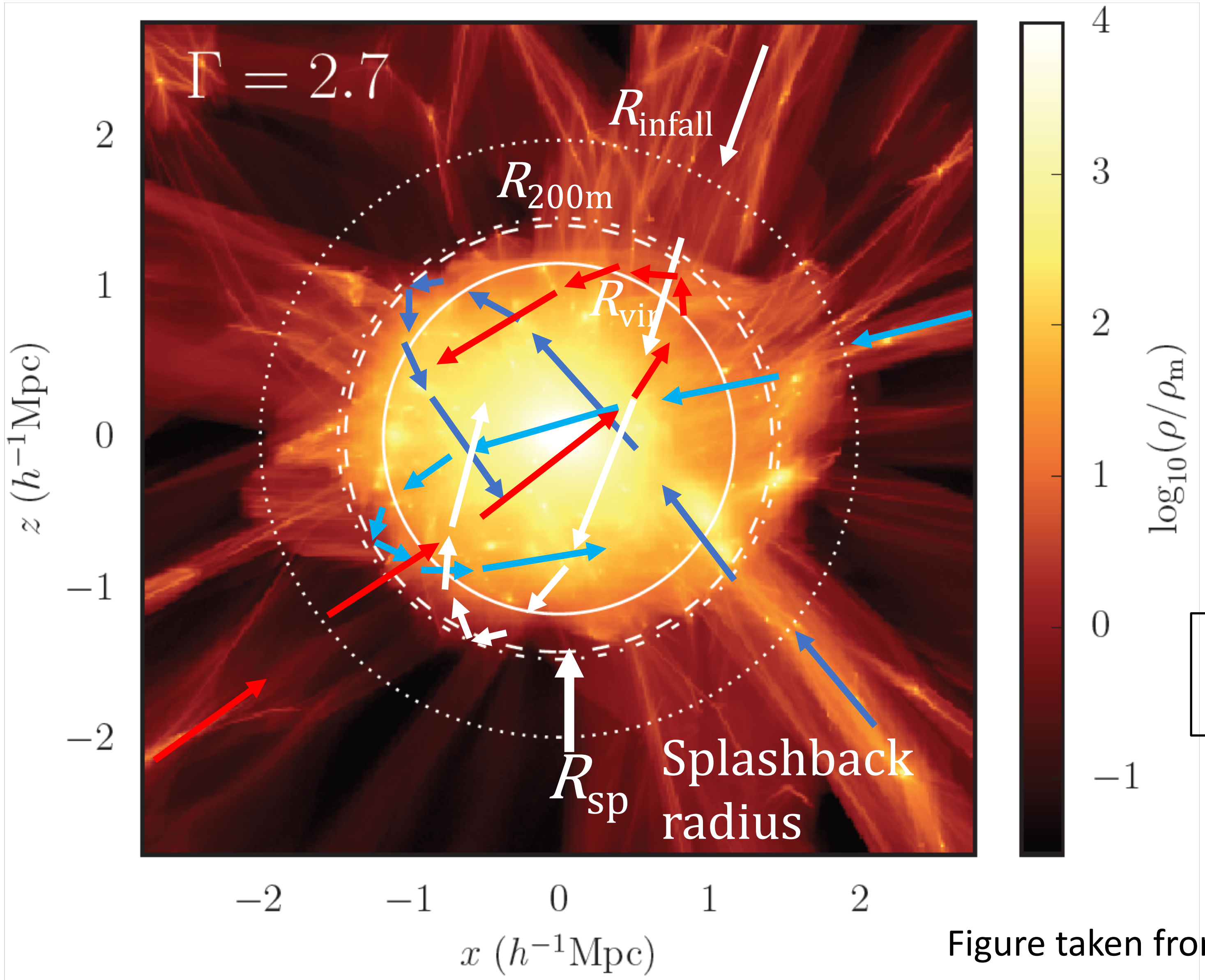


Sharp density enhancement associated with the orbital apocenter of the recently accreted matter in the growing halo potential.
(Diemer & Kravtsov 2014, Adhikari et al 2014)

$r > R_{sp}$: infall region
$r < R_{sp}$: multi-streaming region

Figure taken from S. More et al (2016)

Splashback feature in phase space

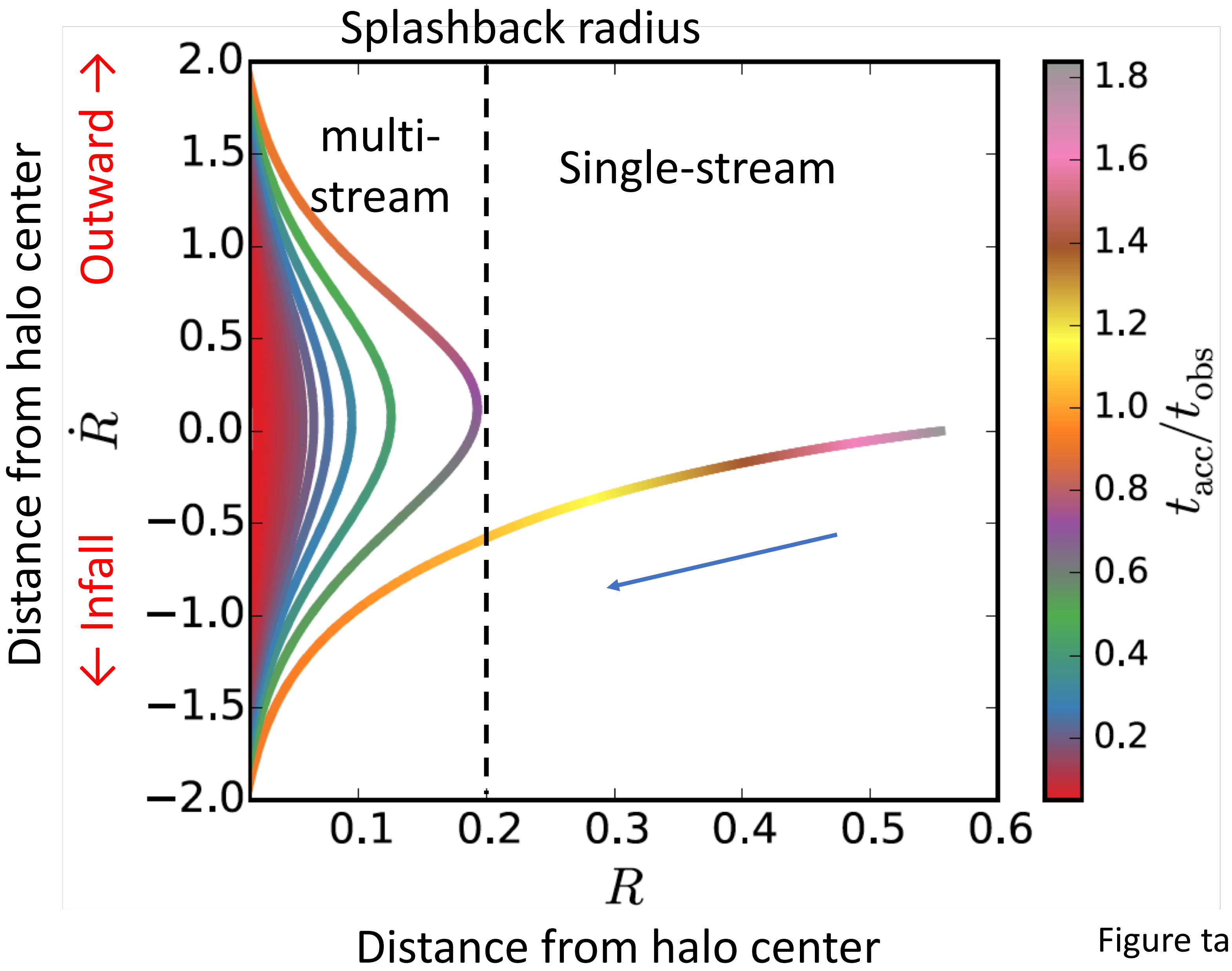
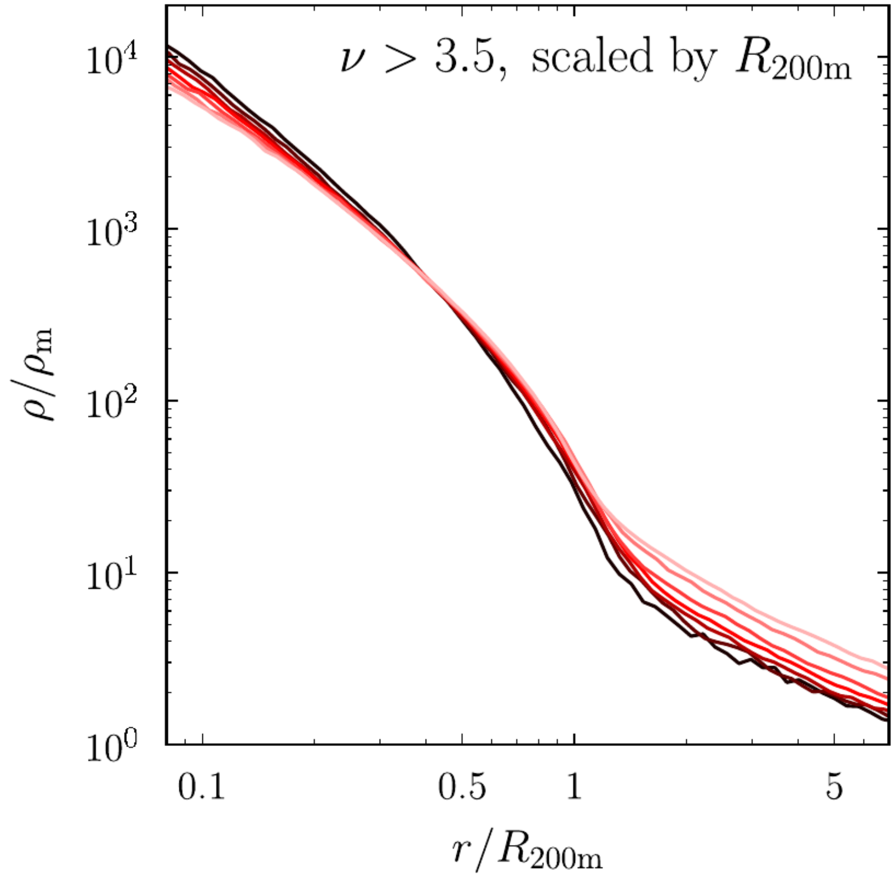


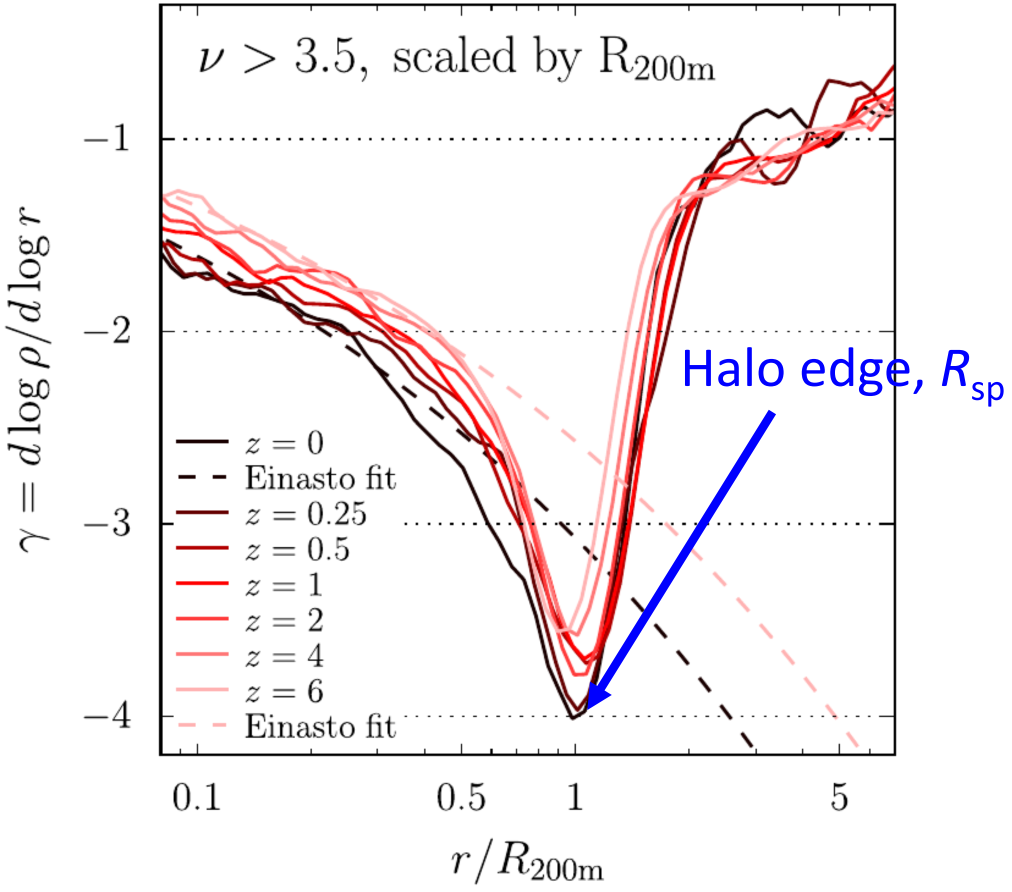
Figure taken from X. Shi (2016)

Splashback feature in density profile

DM density steepening relative to Einasto/NFW

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

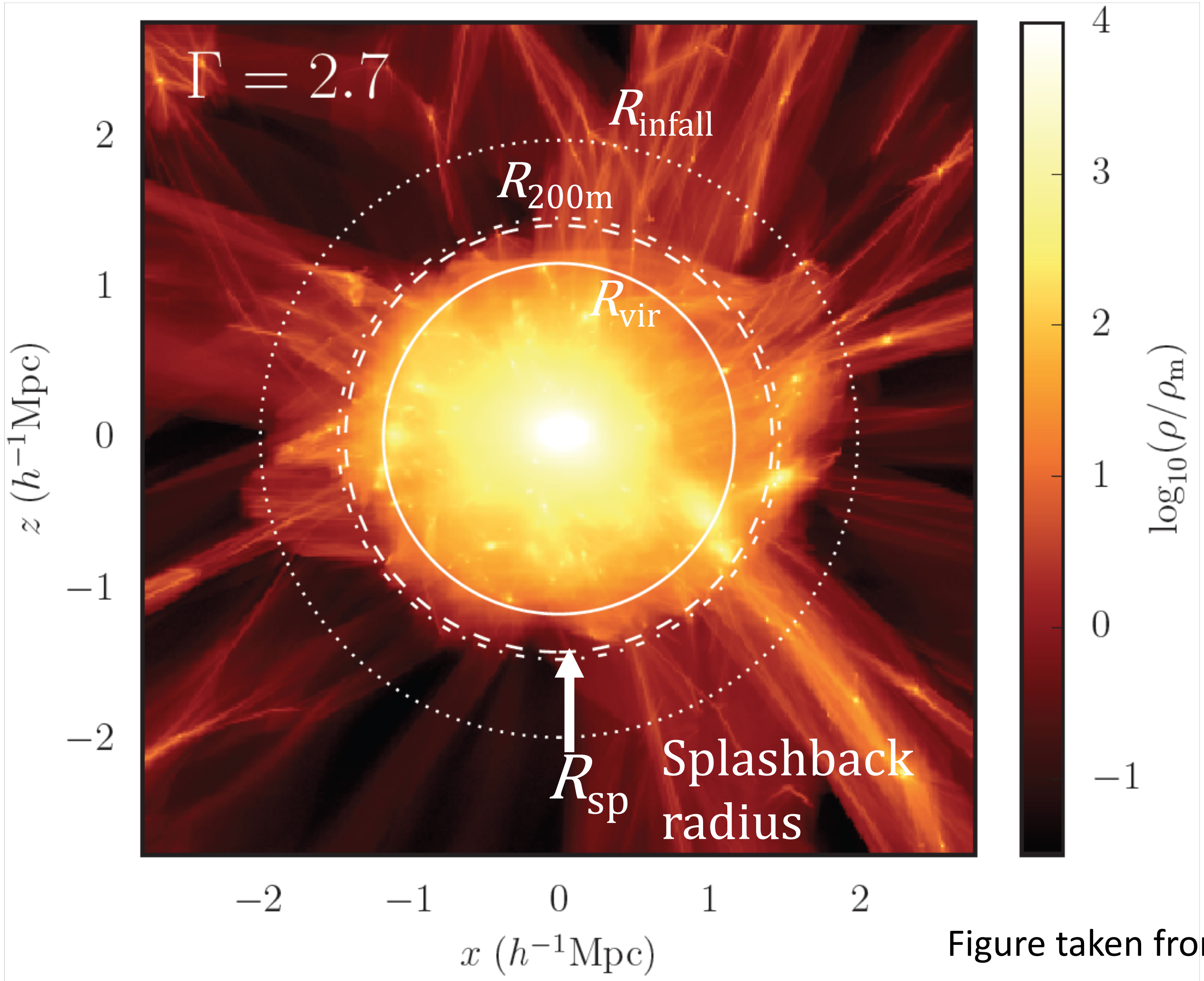




N-body simulations from Diemer & Kravtsov 2014

First measurement of splashback radius

- More, Miyatake, Takada et al. 2016



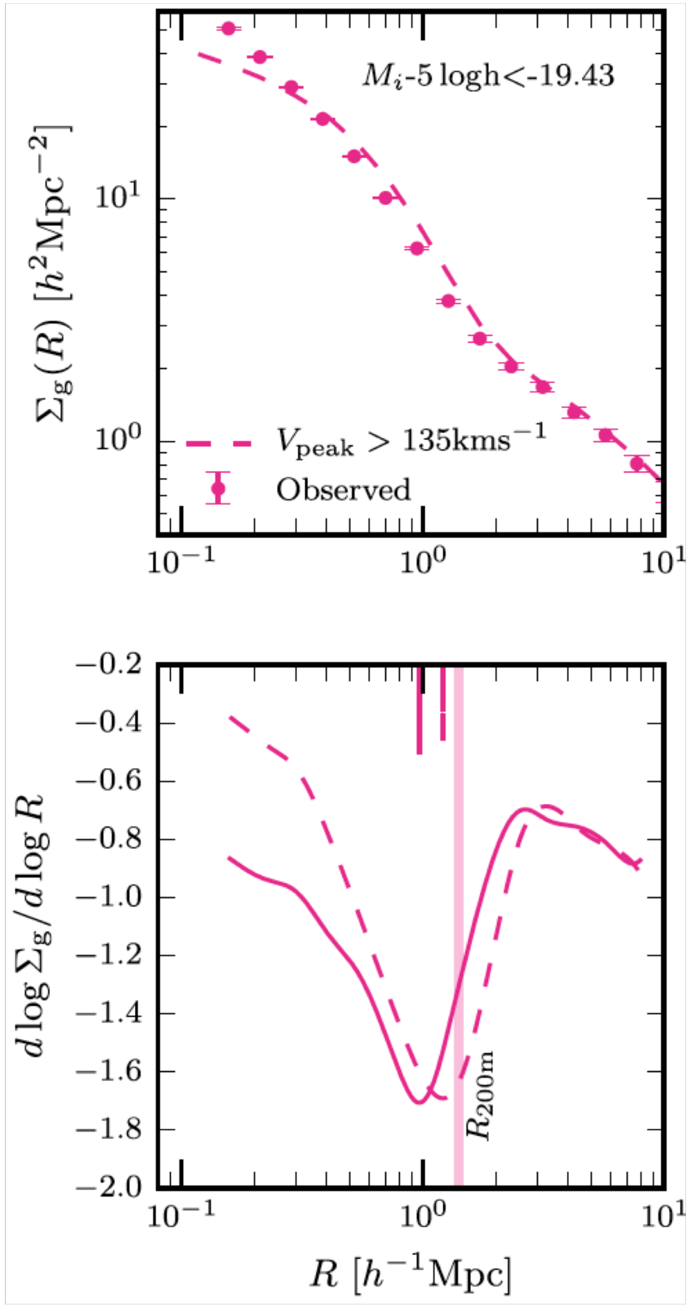


Figure taken from S.

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 given by

$$d = \frac{\rho(r, t) v(t)^2 \sigma_{\rm tr}}{2 m_{\rm dm}} \tag{3}$$

where $v(t)$ is the relative velocity of the subhalo, $\rho(r, t)$ is the time-dependent density profile of the cluster halo, $m_{\rm dm}$ is the mass of t

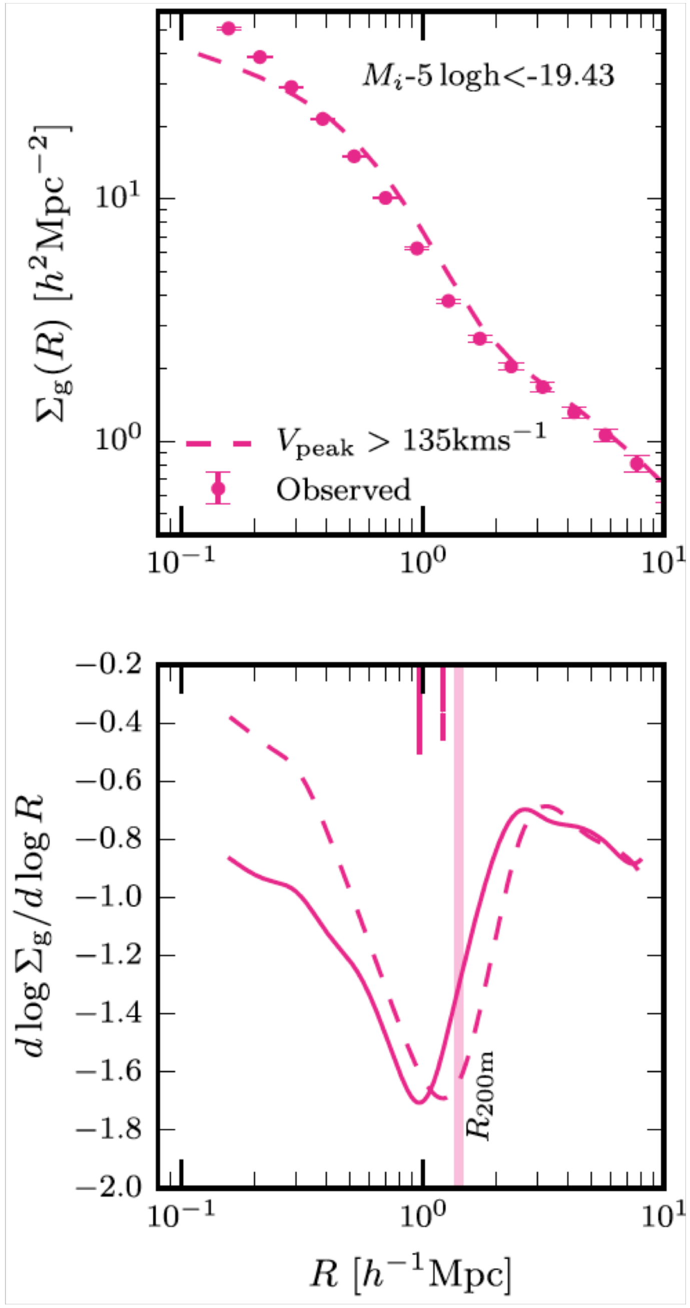
transfer cr

We hav

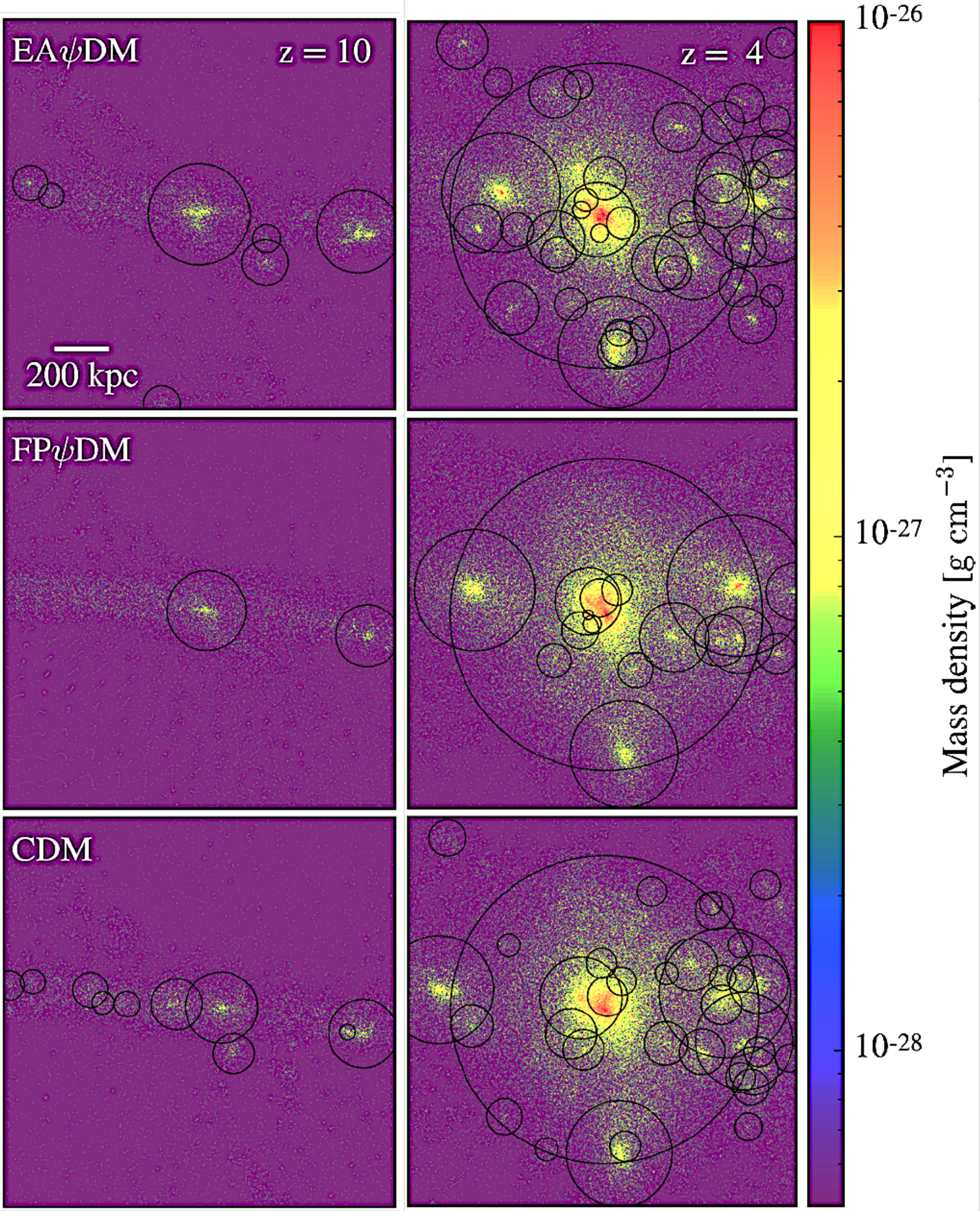
a spherical

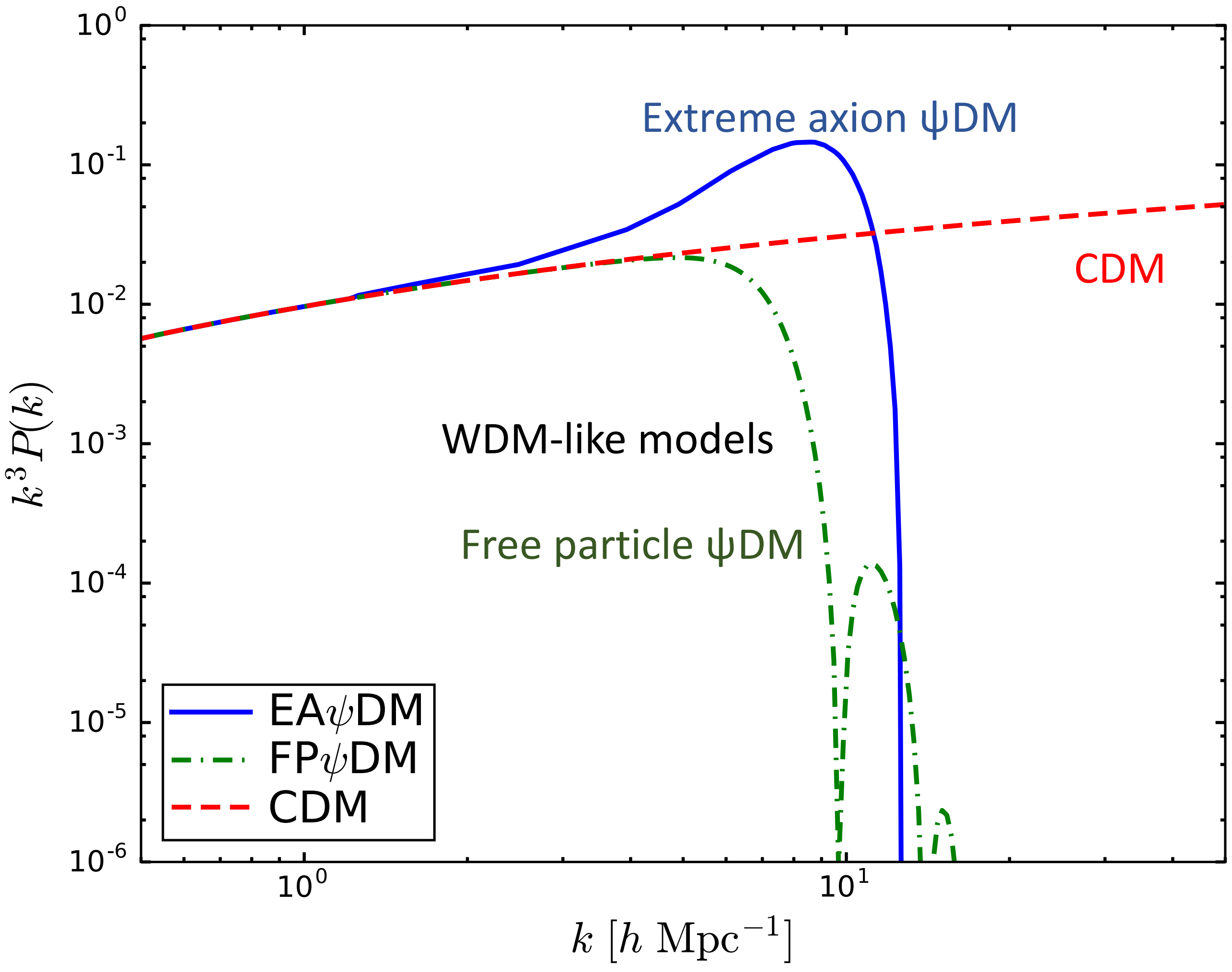
- Finally, it turned out that the discrepancy was likely due to the observational projection effect (Busch & White 2017).

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 cm^2 g^{-1} depending upon the pericenter of accreting halos on their first passage through the halo (S. More 2016, in



Dark matter distributions for different DM models





Schive & Chiueh (2018)

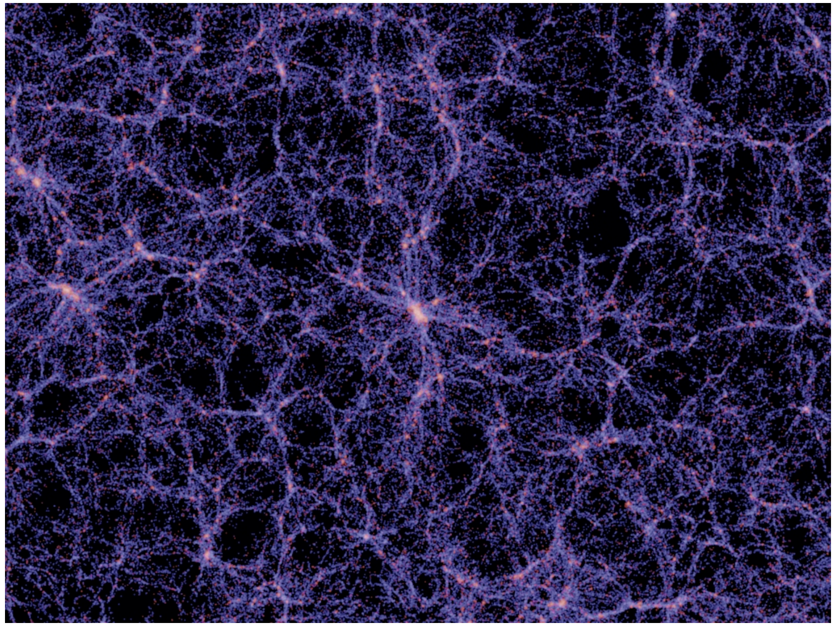
Two ways to determine the halo density profiles

- Galaxy-cluster clustering
  - Through galaxy distribution

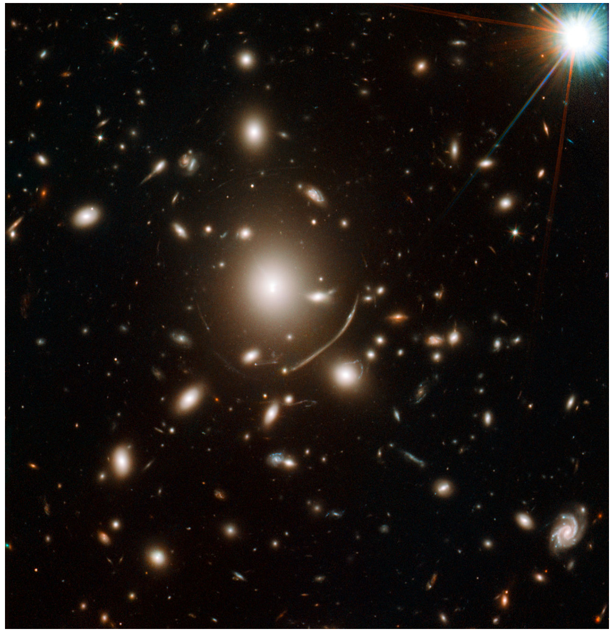
$$\xi_{gc}(r) = \langle \delta_g(\mathbf{x}_1)\delta_c(\mathbf{x}_2)\rangle$$

- Weak gravitational lensing
  - Through dark matter distribution

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

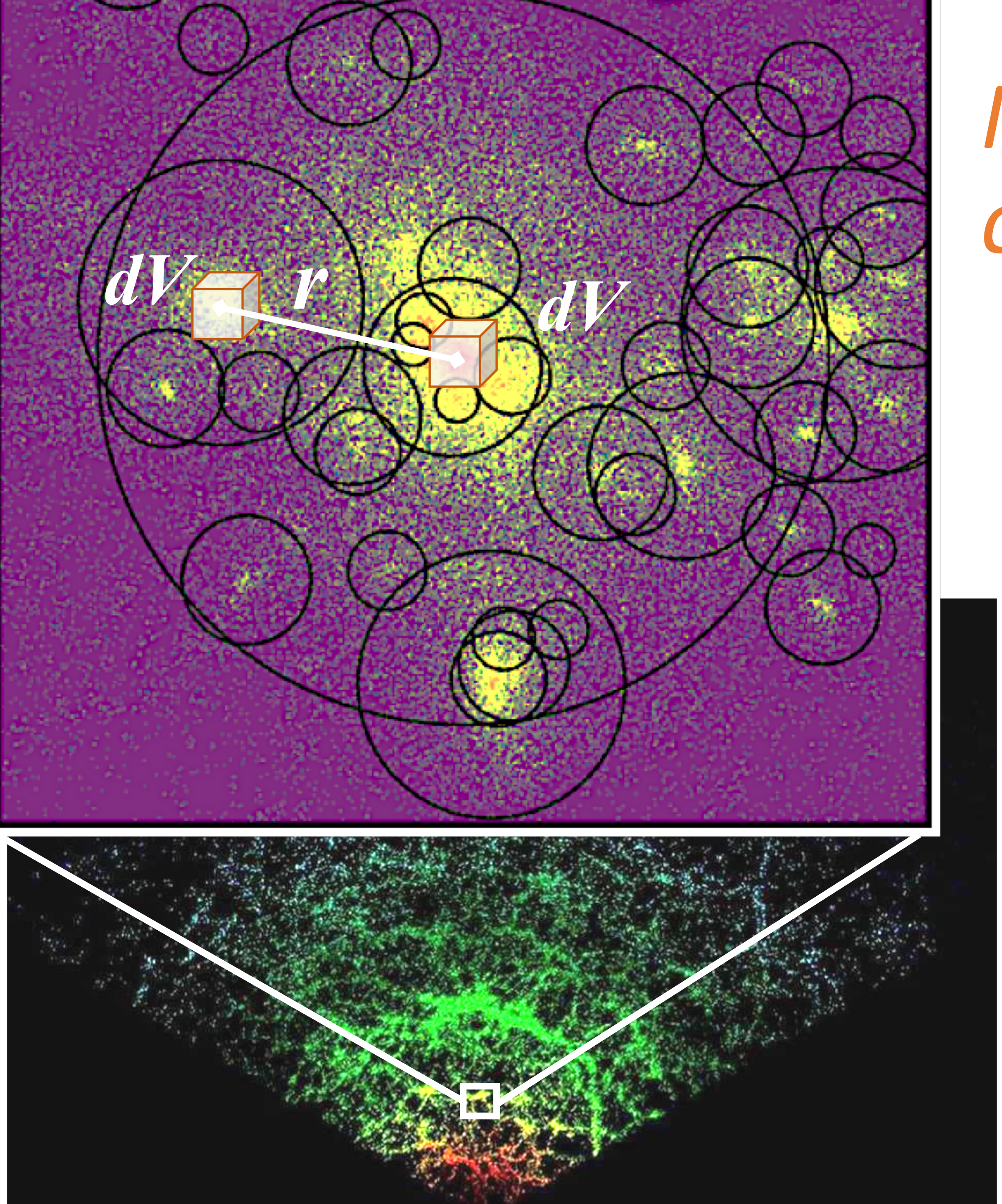


$$\langle \rho(r)\rangle = (1 + \xi(r))\bar{\rho}$$



On linear scales $\xi_{gc}(r,\theta) = b_g \xi_{mc}(r,\theta)$

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



Measuring cluster-galaxy correlation function

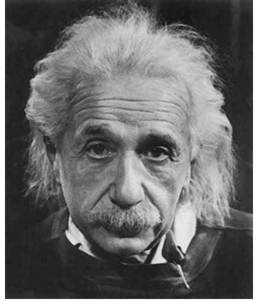
$$dP = \bar{n}_g \bar{n}_c dV^2 \left(1 + \xi_{gc}(r)\right)$$

- r : separation between galaxies and clusters

  = distance from cluster centers
- Density profile of halos/clusters traced by galaxy distribution

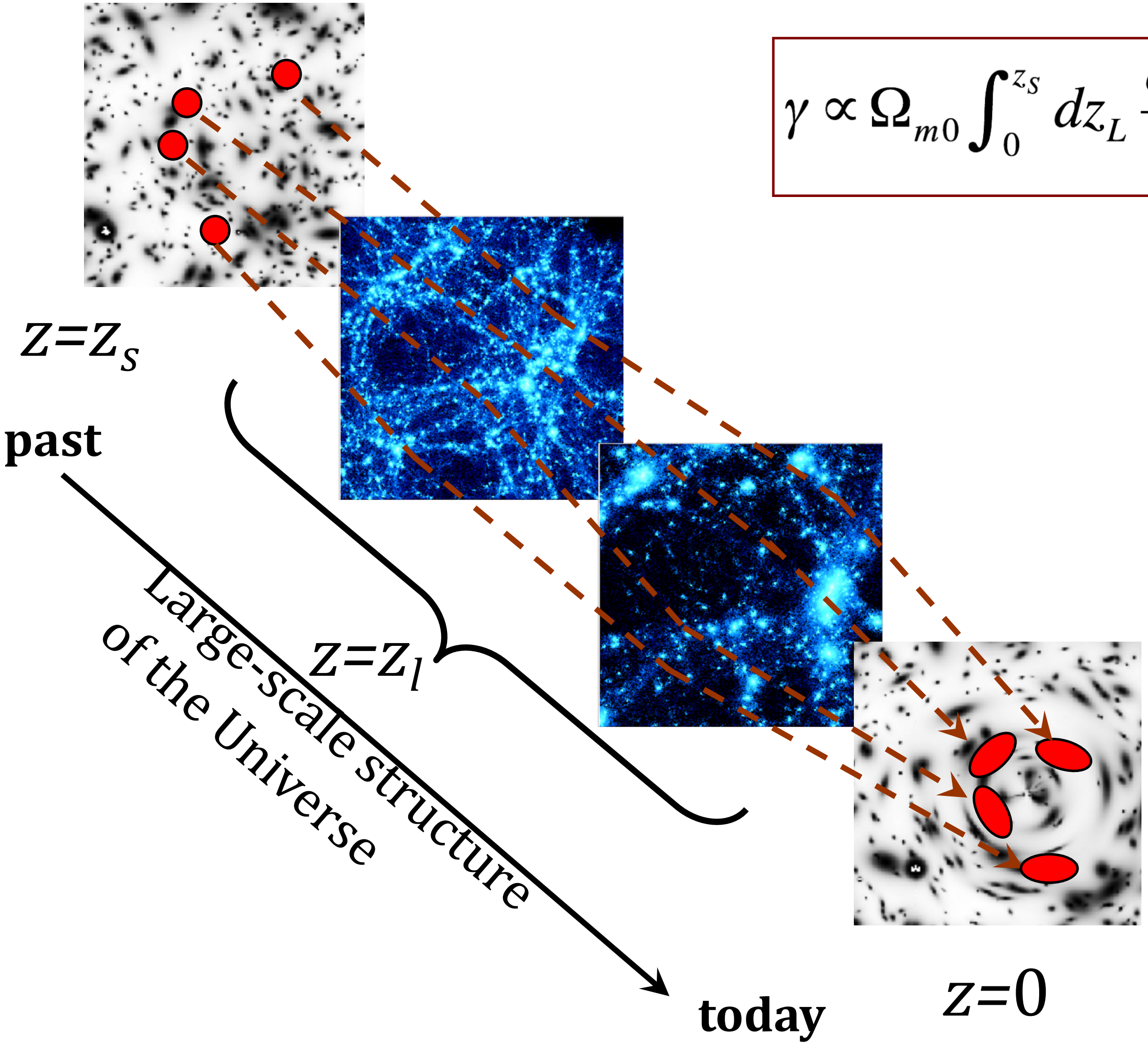
$$\langle \rho(r) \rangle = \bar{\rho}\left(1 + \xi_{gc}(r)\right)$$

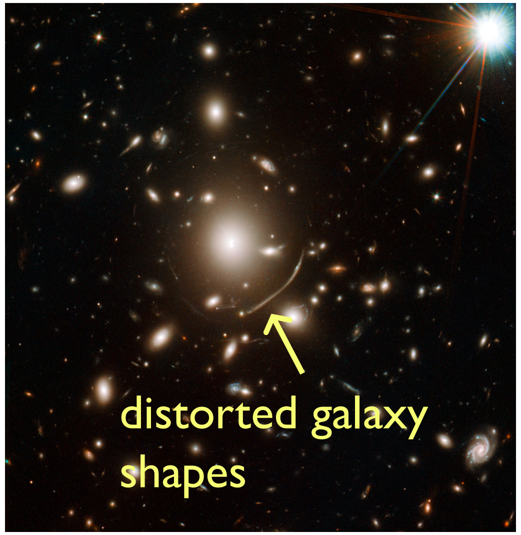
Weak Gravitational Lensing



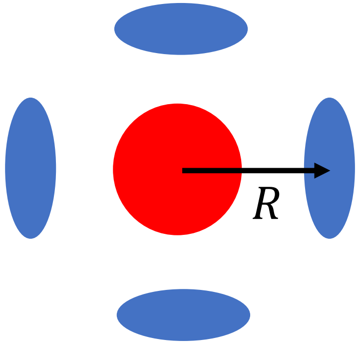
- Directly predicted by Einstein's general theory of relativity

$$\gamma \propto \Omega_{m0} \int_0^{z_S} dz_L \frac{d(z_L, z_S) d(z_L)}{d(z_S)} \delta(z_L, \vec{\theta})$$





Measuring cluster-matter correlation: Halo-shear (weak) lensing



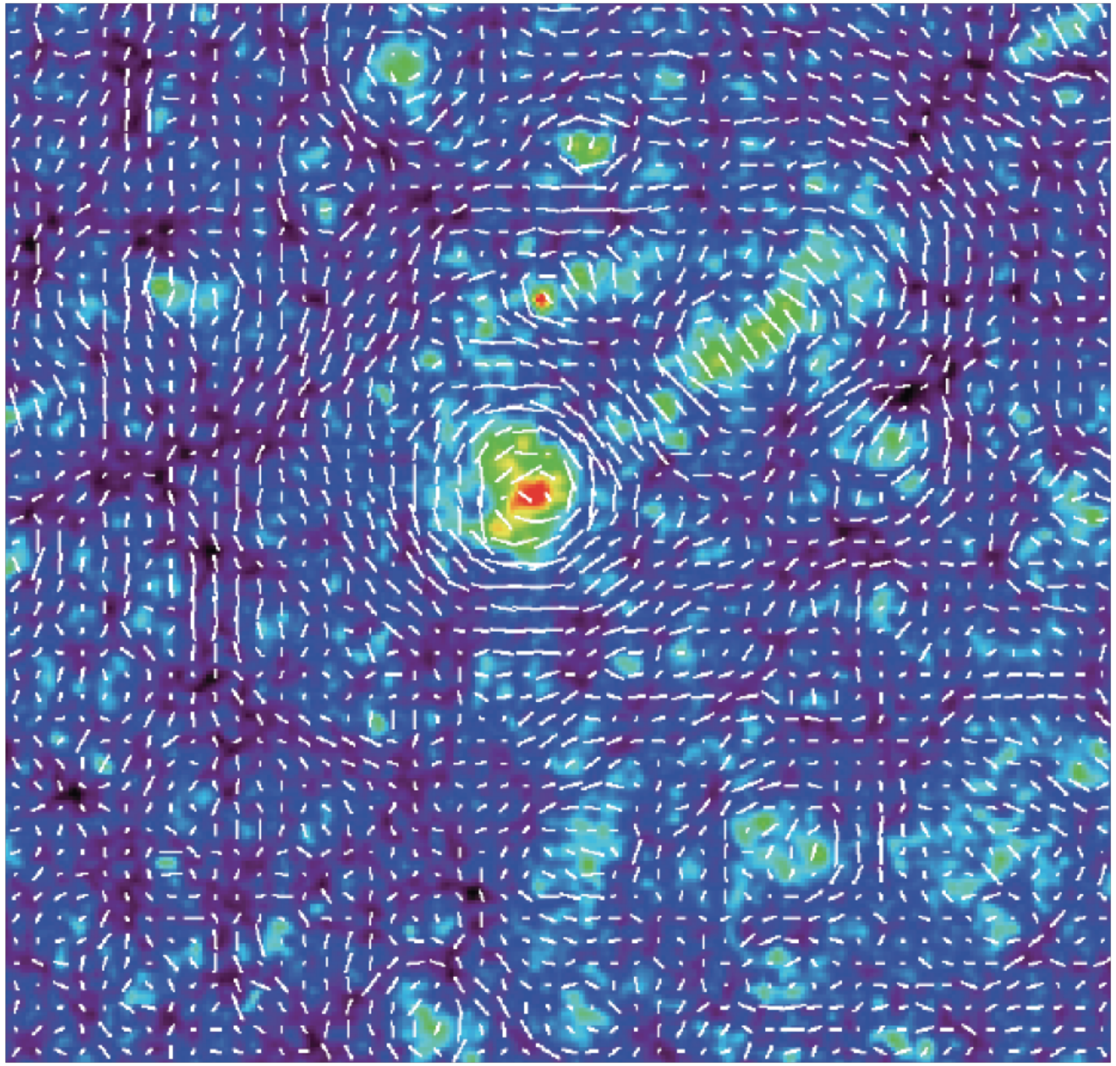
$\gamma_t(R)$

- Dark matter around clusters induces tangential distortions of background galaxies.

$$\gamma_t(R) = \frac{\Delta\Sigma\,(R)}{\Sigma_{\mathrm{crit}}} = \frac{\bar{\Sigma}(R) - \Sigma(R)}{\Sigma_{\mathrm{crit}}}$$

$$\Sigma(R) = \bar{\rho} \int [1 + \xi_{mc}\left(\sqrt{R^2 + z^2}\right) dz$$

$$\langle \rho(r) \rangle = \bar{\rho}(1 + \xi_{mc}(r)) \quad r = \sqrt{R^2 + z^2}$$



Two ways to determine the halo density profiles

- Galaxy-cluster clustering
  - Through galaxy distribution

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

  - Affected by galaxy bias
  - Affected by dynamical friction
  - Less affected by substructures
  - Higher precision

- Weak gravitational lensing
  - Through dark matter distribution

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

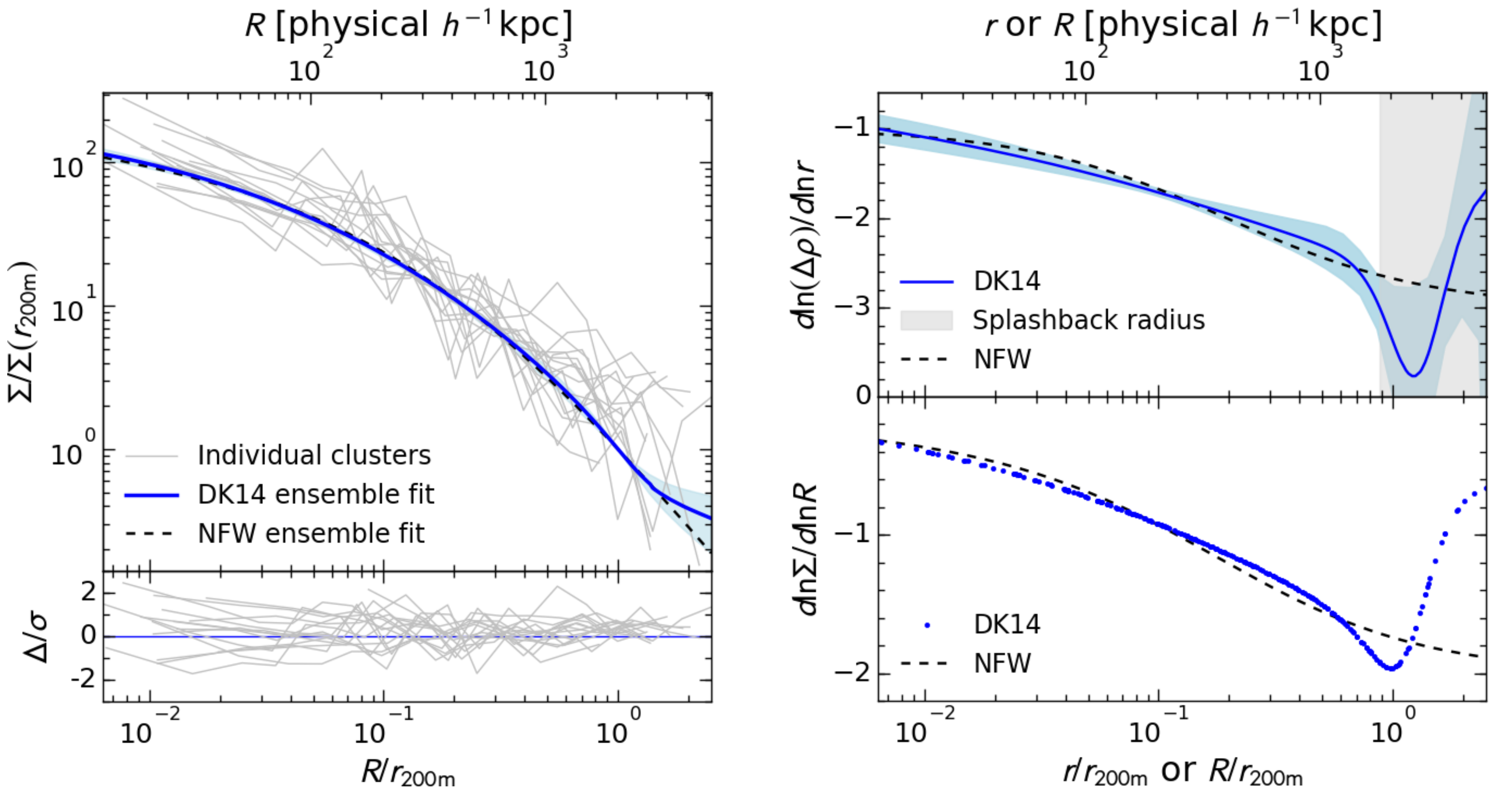
  - Directly probe dark matter
  - Not affected by dynamical friction
  - Affected by substructures
  - Noisier

On linear scales $\xi_{gc}(r,\theta) = b_g \xi_{mc}(r,\theta)$

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

Cluster lensing constraints on R_{sp}

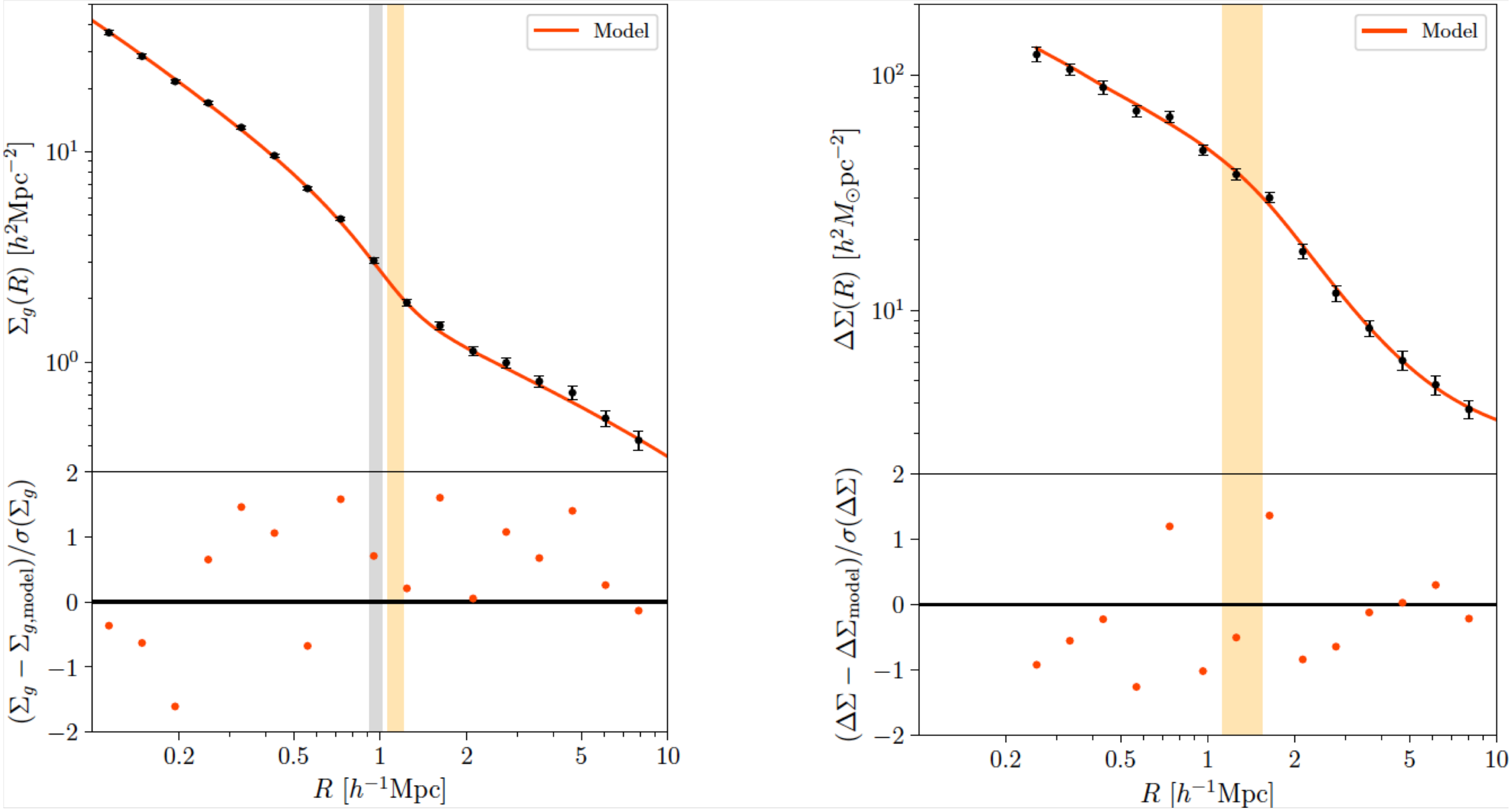
Simultaneous model fit to “scaled” Σ profiles of 16 X-ray-selected CLASH clusters



$$\boxed{R_{sp}/r_{200m} > 0.89\ (1\sigma)\ \text{at}\ M_{200m} = 1.3\times10^{15} M_{sun}/h \quad (z=0.34)}$$

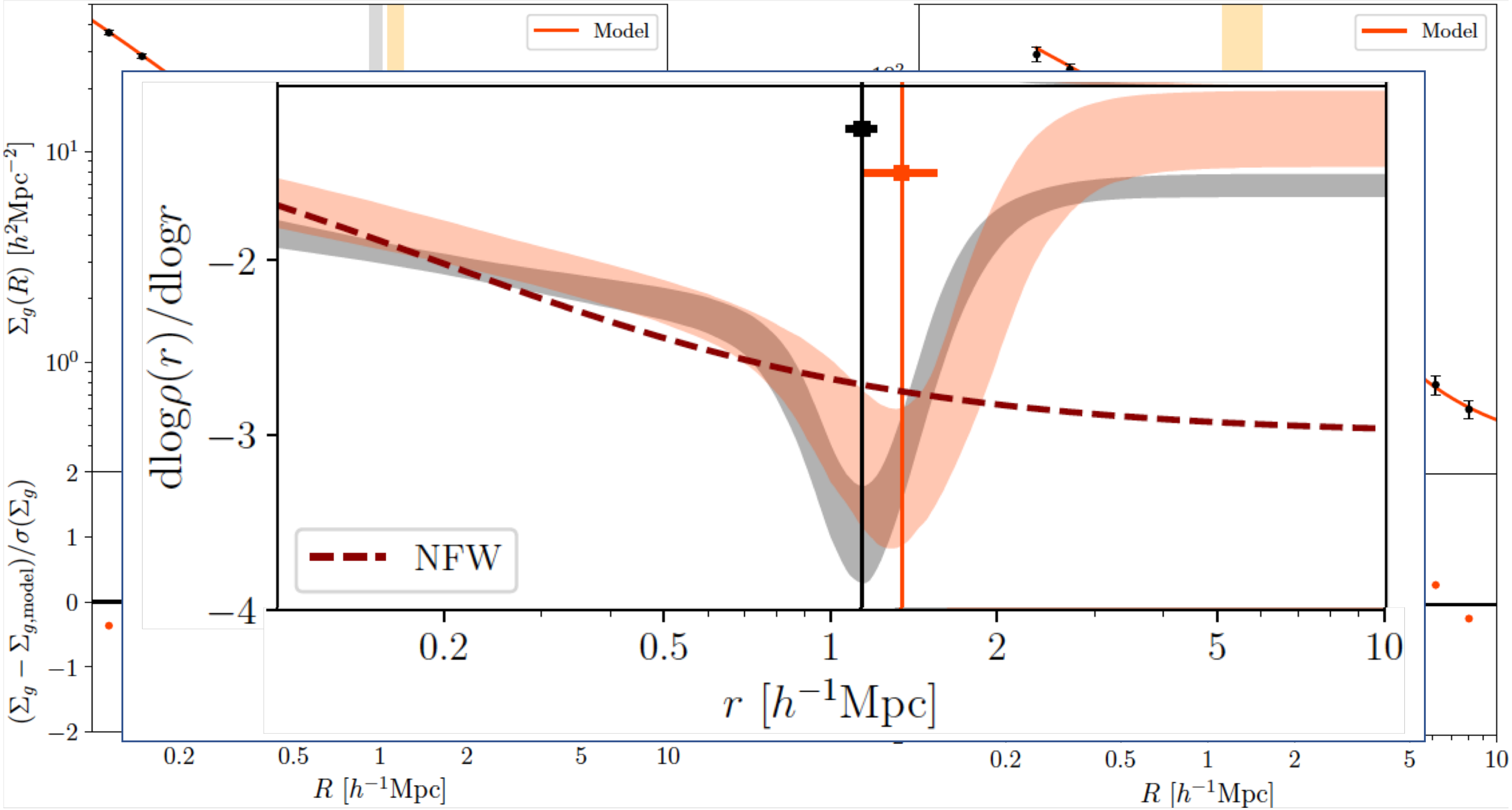
Umetsu & Diemer 17, *ApJ*, 836, 231

Measurements of R_{sp} with both clustering and lensing



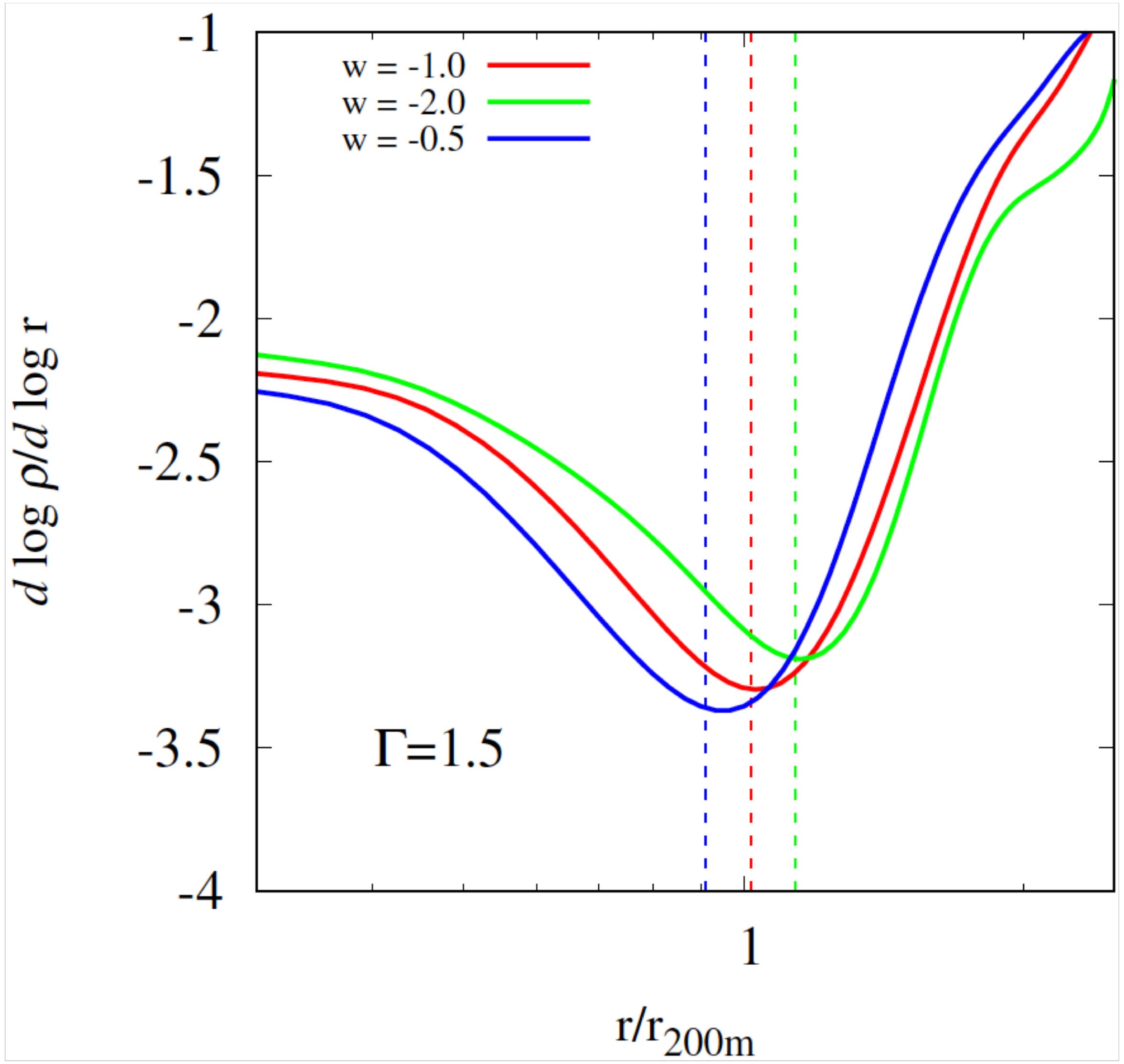
From Dark Energy Survey (DES) Chang et al. [arXiv:1710.06808]

Measurements of R_{sp} with both clustering and lensing



From Dark Energy Survey (DES)   Chang et al. [arXiv:1710.06808]

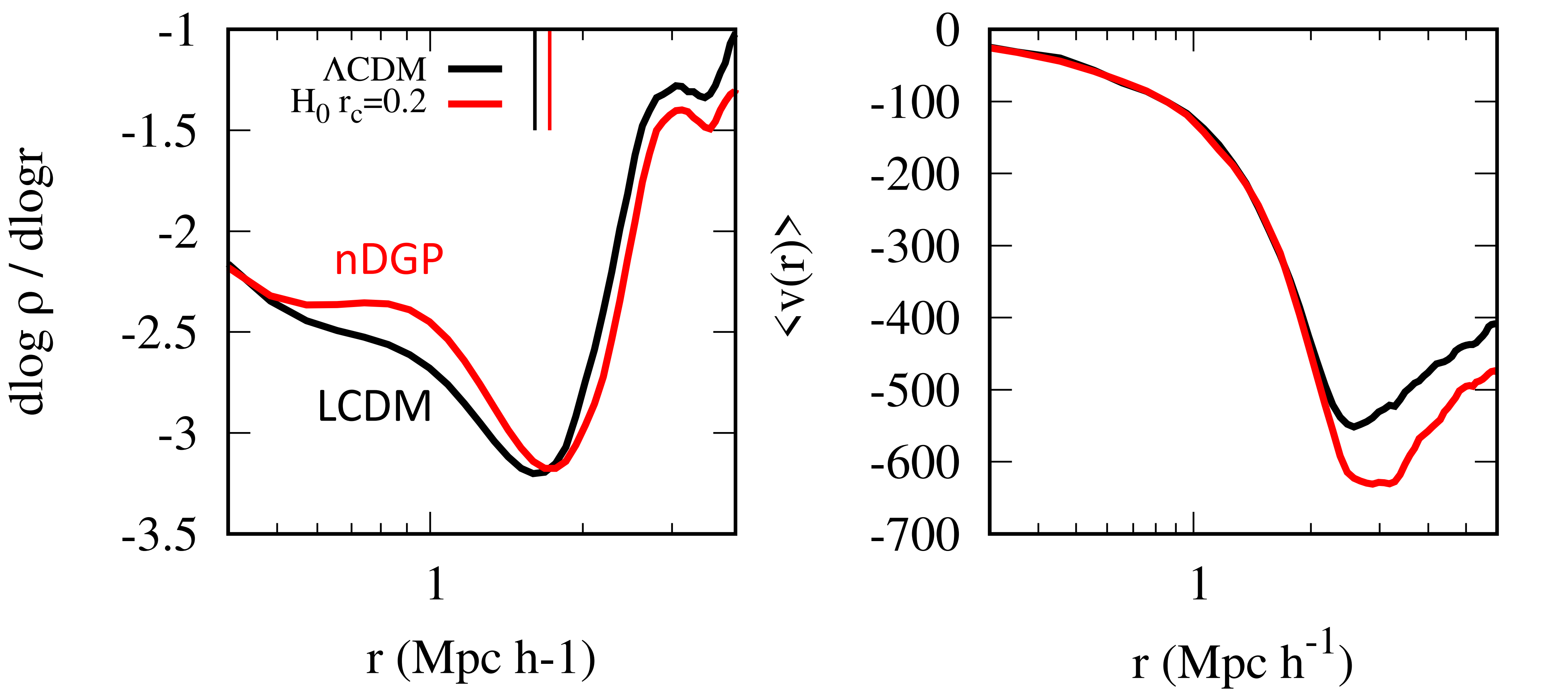
Effects of dark energy on splashback



- R_{sp} is sensitive to *w*.
- But 10 % difference of R_{sp} corresponds to 50% difference of *w* that are already ruled out.
- We need to wait for larger galaxy surveys such as LSST, Euclid and WFIRST.

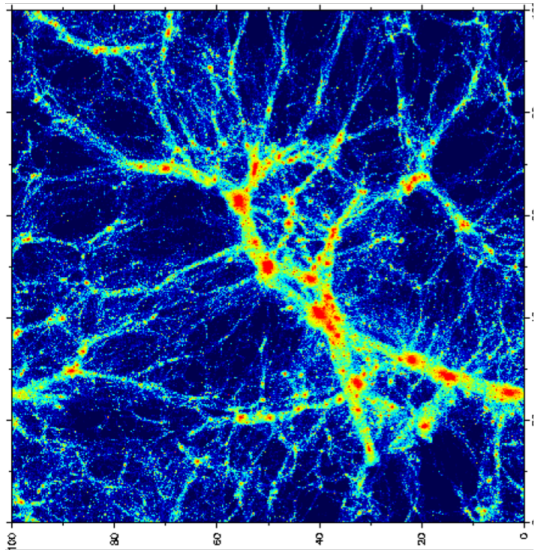
Adhikari, Sakstein, Jain, Dalal, Li [arXiv:1806.04302]

Effects of modified gravity on splashback



Adhikari, Sakstein, Jain, Dalal, Li [arXiv:1806.04302]

Two issues considered 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.

Splashback radius of nonspherical dark matter halos from cosmic density and velocity fields

PRD, 98, 023523 [arXiv 1807.02669]

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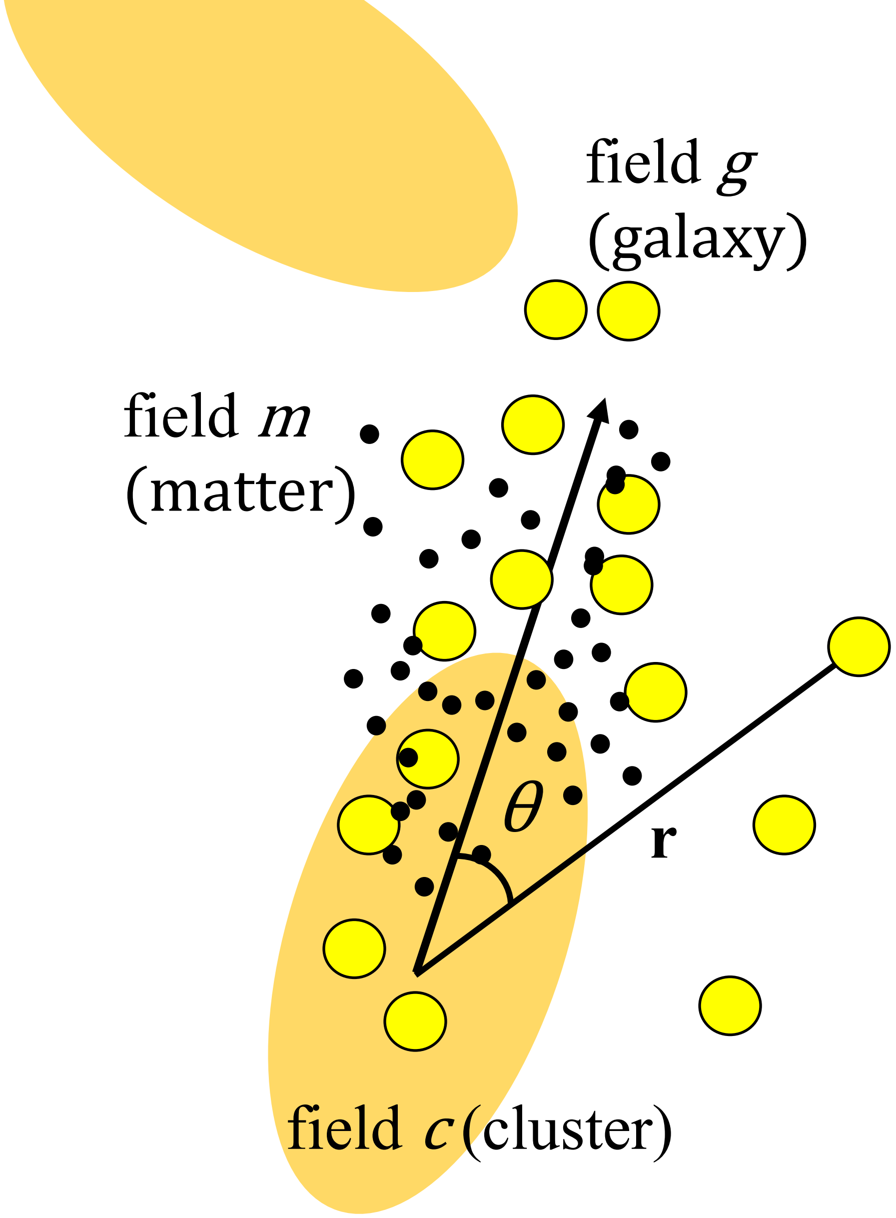
Angle-dependent density profile



Paz et al 2008
Faltenbacher et al 2009

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

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

$$\xi_{gc}(r,\theta) = \langle \delta_c(\mathbf{x}_1,\theta)\delta_g(\mathbf{x}_2)\rangle = b_g \xi_{mc}(r,\theta)$$

on linear scales

- **Conventional correlation function** (A={mc})

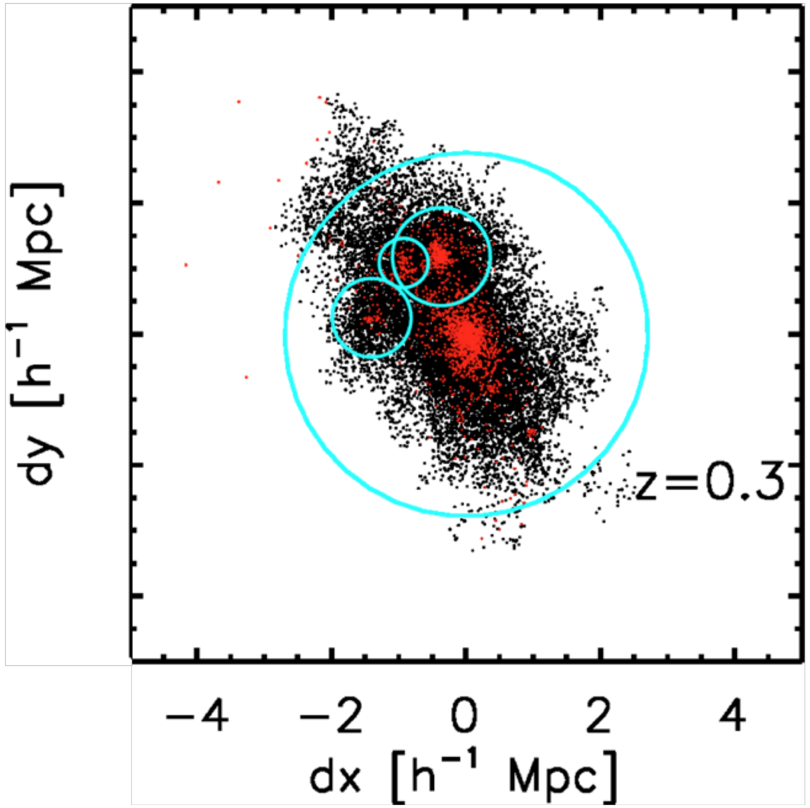
$$\xi_{Ac}(r) = \int_0^1 d\cos\theta\, \xi_{Ac}(r,\theta)$$

- **Relation to intrinsic alignment in gravitational lensing**

$$\tilde{\xi}_{g+}(\mathbf{r}) = (2/\pi)\int_0^{\pi/2} d\theta \cos(2\theta_p)\xi_{gc}(\mathbf{r},\theta_p)$$

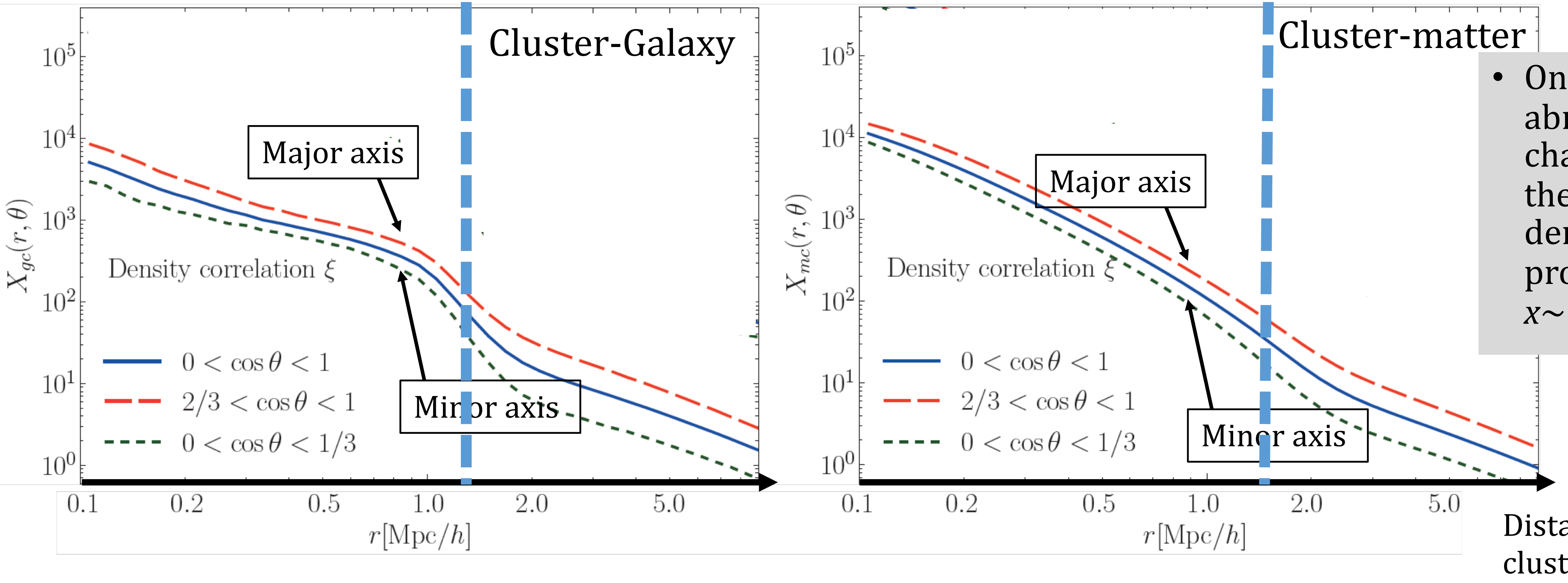
N-body simulations: mock galaxies and clusters

- 24 realizations in total. $24 \times \{2048^3$ particles in 1 [Gpc/h]^3 box$\}$



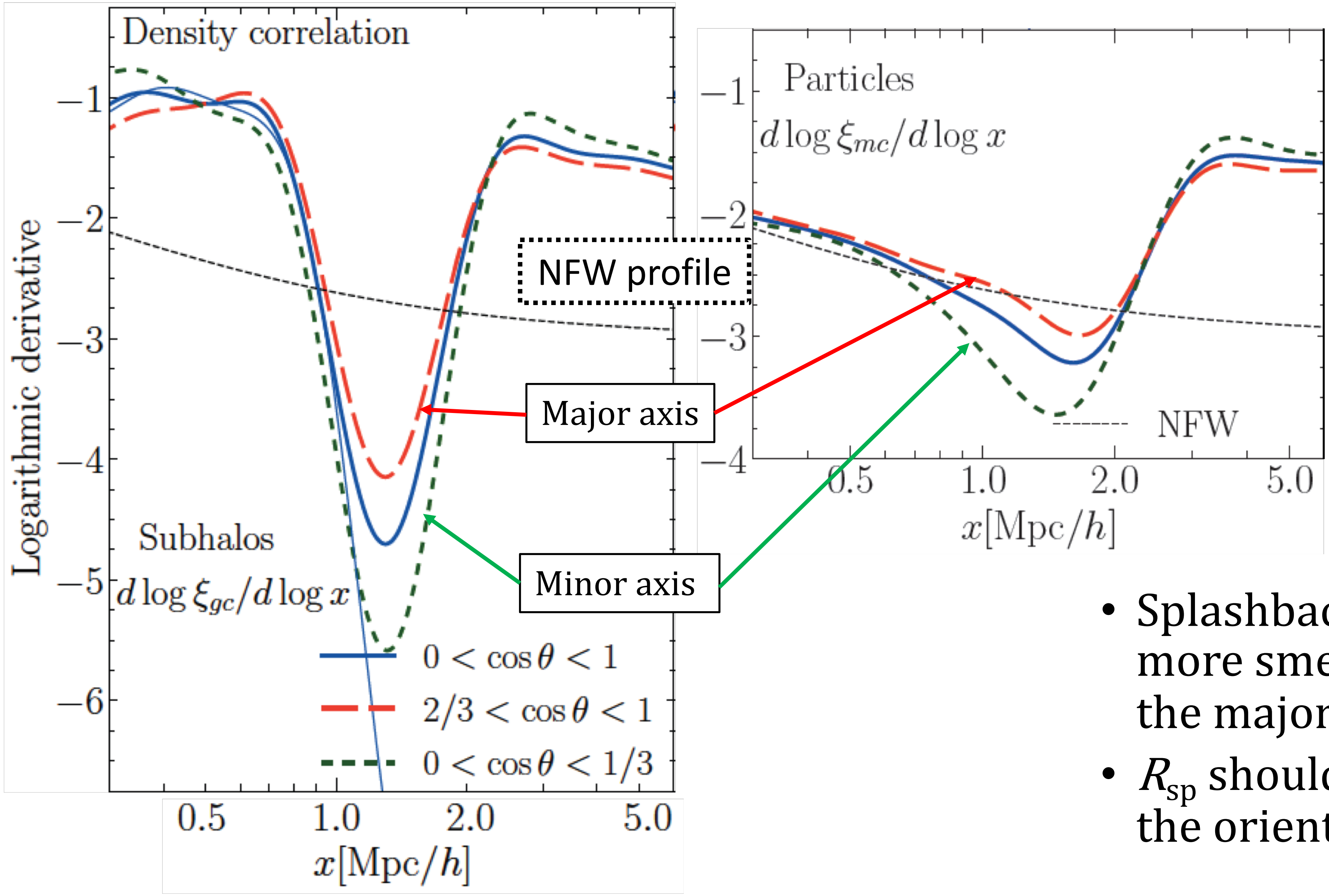
- Halos/subhalos are identified
- ~20,000 "clusters" are chosen from halos with the threshold $M_{\mathrm{h}} > 10^{14} M_{\mathrm{sun}}/\mathrm{h}$
- Halos are assumed to have triaxial shapes and the major axes are determined on the projected celestial plane.
- Galaxies are assumed to form within subhalos, and ~560,000 "galaxies" are selected from subhalos to match observed number density (SDSS)

Angle-dependent density profile



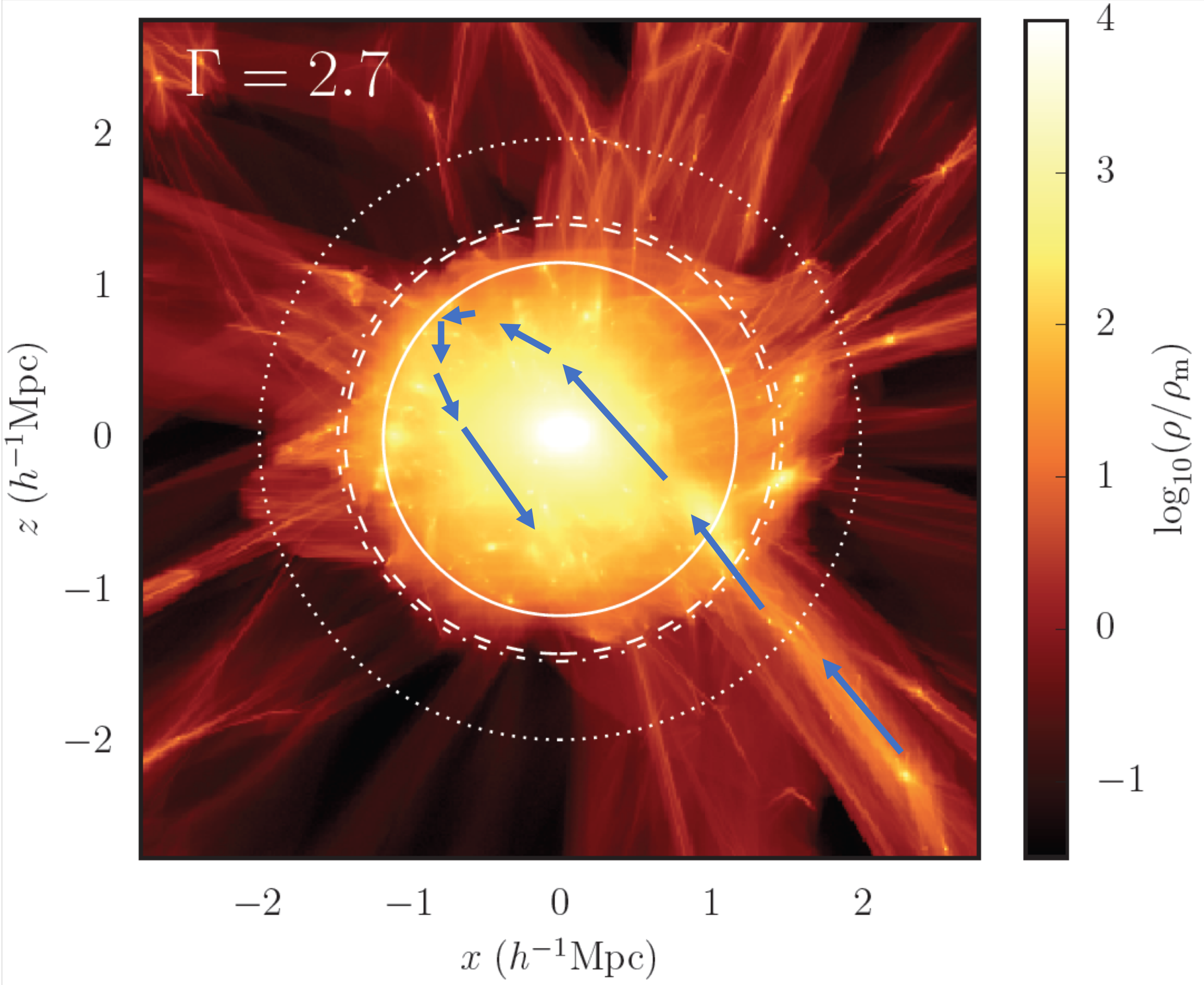
- One can see abrupt change in the slope of density profile at x~1Mpc/h

Splashback radius of non-spherical halos



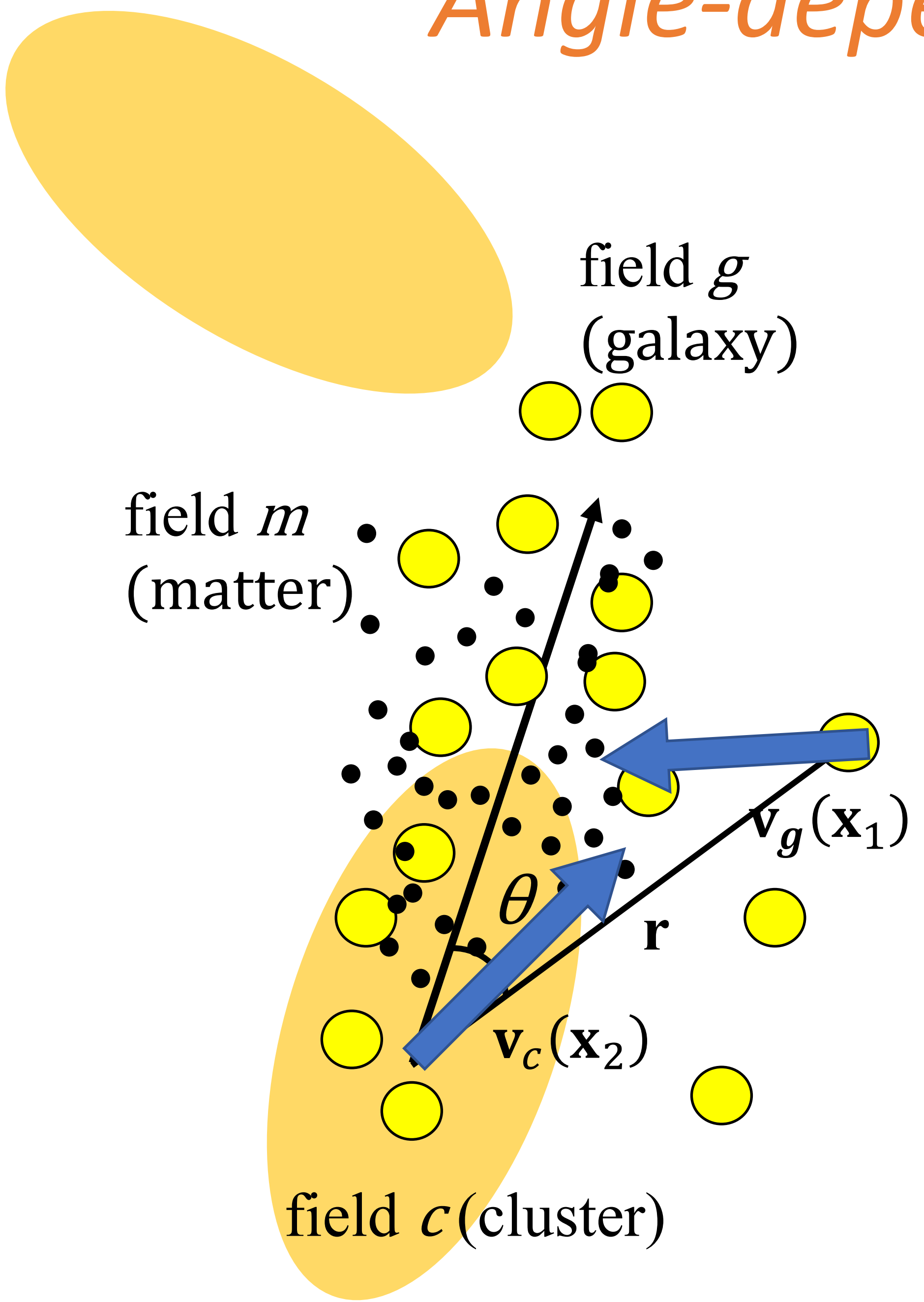
- Splashback feature is more smeared out along the major axis.
- R_{sp} should depend on the orientation of halos

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
  - $r > R_{\rm sp}$: infall
  - $r < R_{\rm sp}$: multi-stream intra-halo region
- Angle-binned momentum correlation

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

$$\psi_{gc}(r,\theta) = \left\langle \left[1+\delta_g(\mathbf{x}_1,\theta)\right]\left[1+\delta_g(\mathbf{x}_2)\right]\mathbf{v}_g(\mathbf{x}_1)\cdot\mathbf{v}_c(\mathbf{x}_2)\right\rangle$$

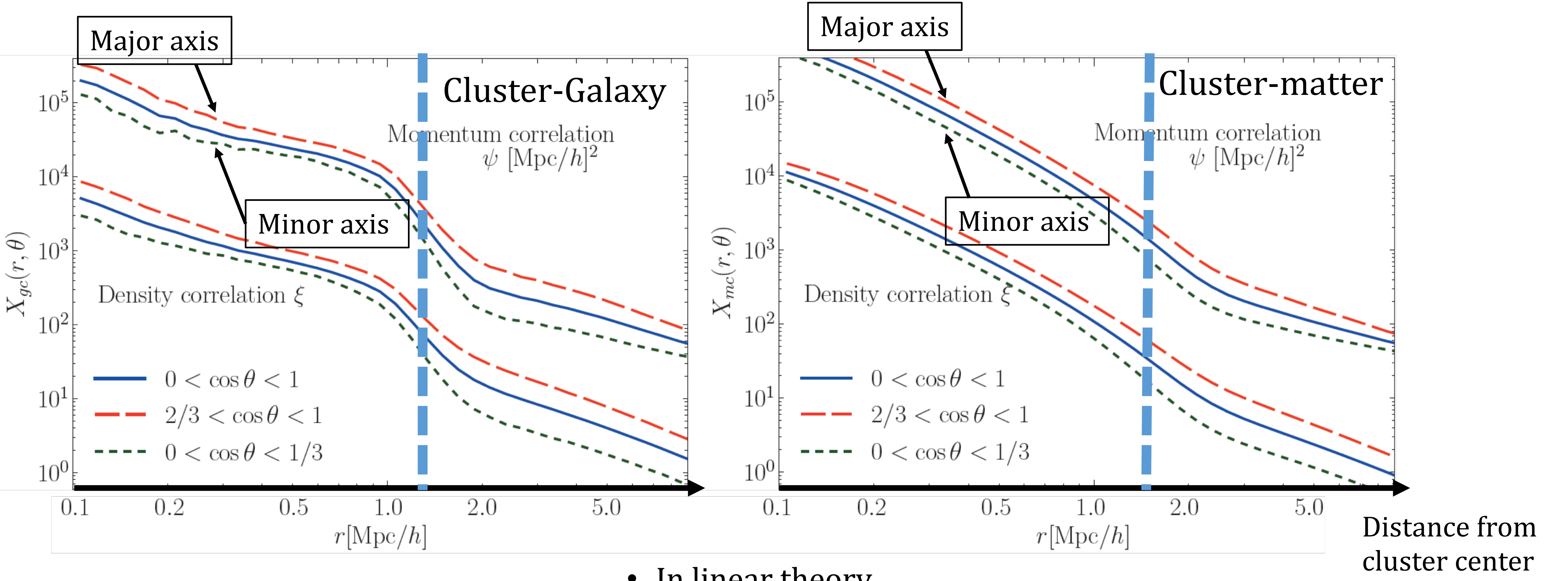
$$= \psi_{mc}(r,\theta)$$

on linear scales

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

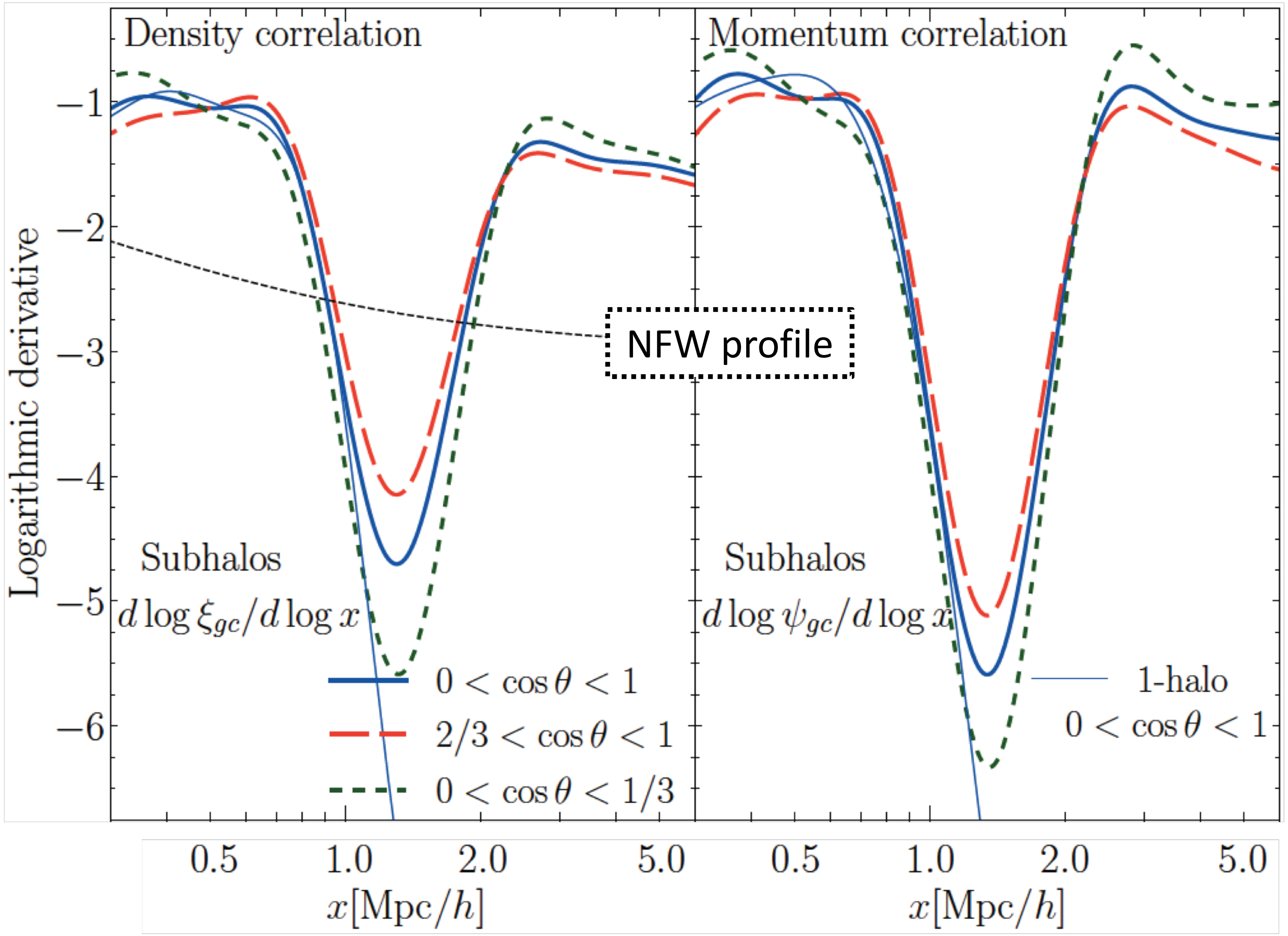
$$\xi_{gc}(r,\theta) = \left\langle \delta_c(\mathbf{x}_1,\theta)\delta_g(\mathbf{x}_2)\right\rangle = b_g\xi_{mc}(r,\theta)$$

Angle-dependent density profile

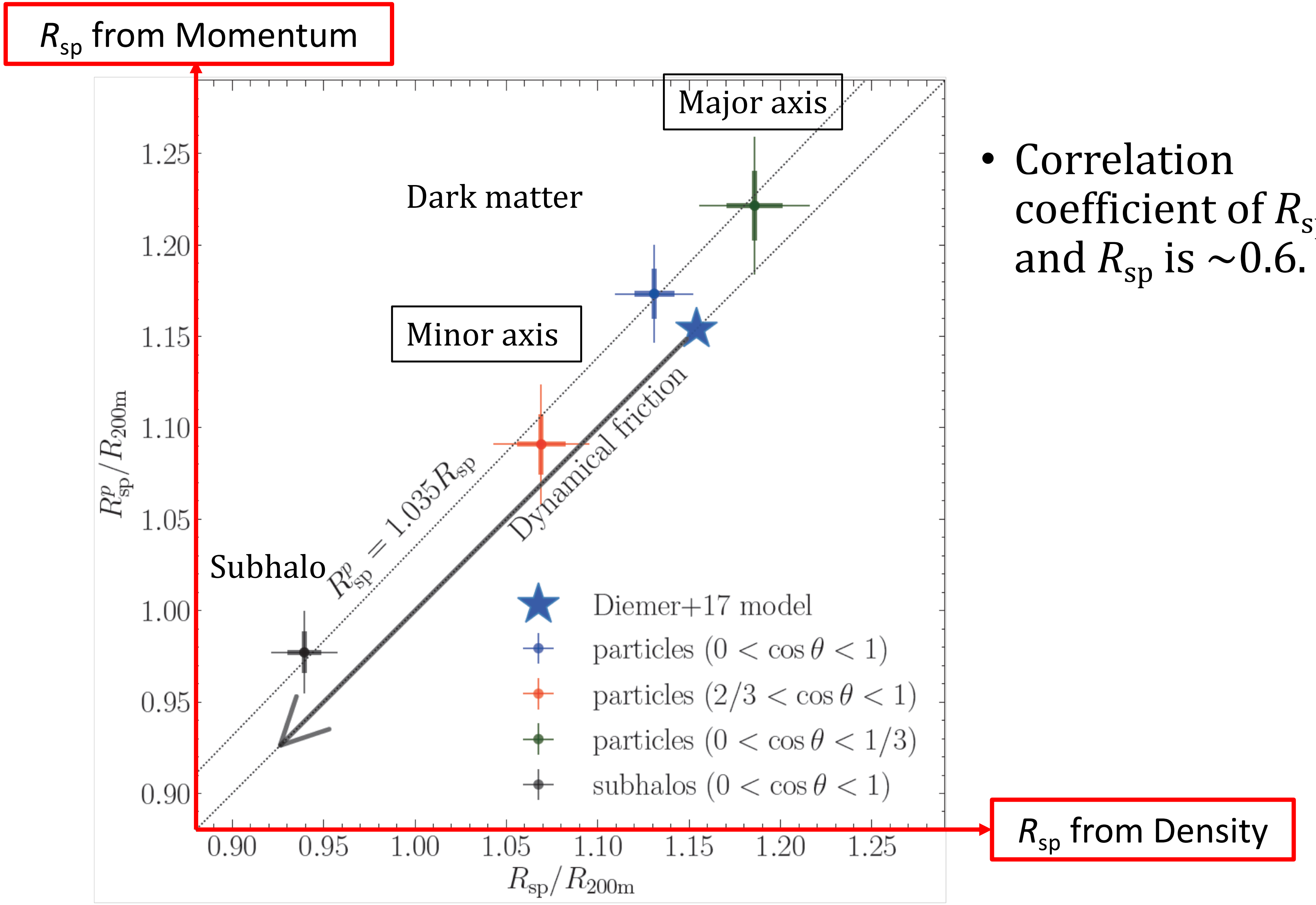


- In linear theory
- $\psi_{gc} = \psi_{mc}$
- $\xi_{gc} = b_g\, \xi_{mc}$

Splashback features in momentum correlation



Constraints on splashback radius



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

Conclusions and outlook

- The splashback radius provides physical boundaries of dark matter halos.
- The accurate measurement of the splashback feature in observation is challenging and its theoretical interpretation is not trivial.
- The splashback is a feature fully described in phase space, so the density profile of halos does not utilize the entire information.
- Angle-dependent density and velocity statistics have been proposed to study asphericity of splashback features.
- One can use the splashback probed by the velocity field to calibrate the standard one (by density field).
- 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 (S.-C. Lin, Okumura et al in progress).