# Edge of darkness:
# The splashback radius as a physical halo boundary

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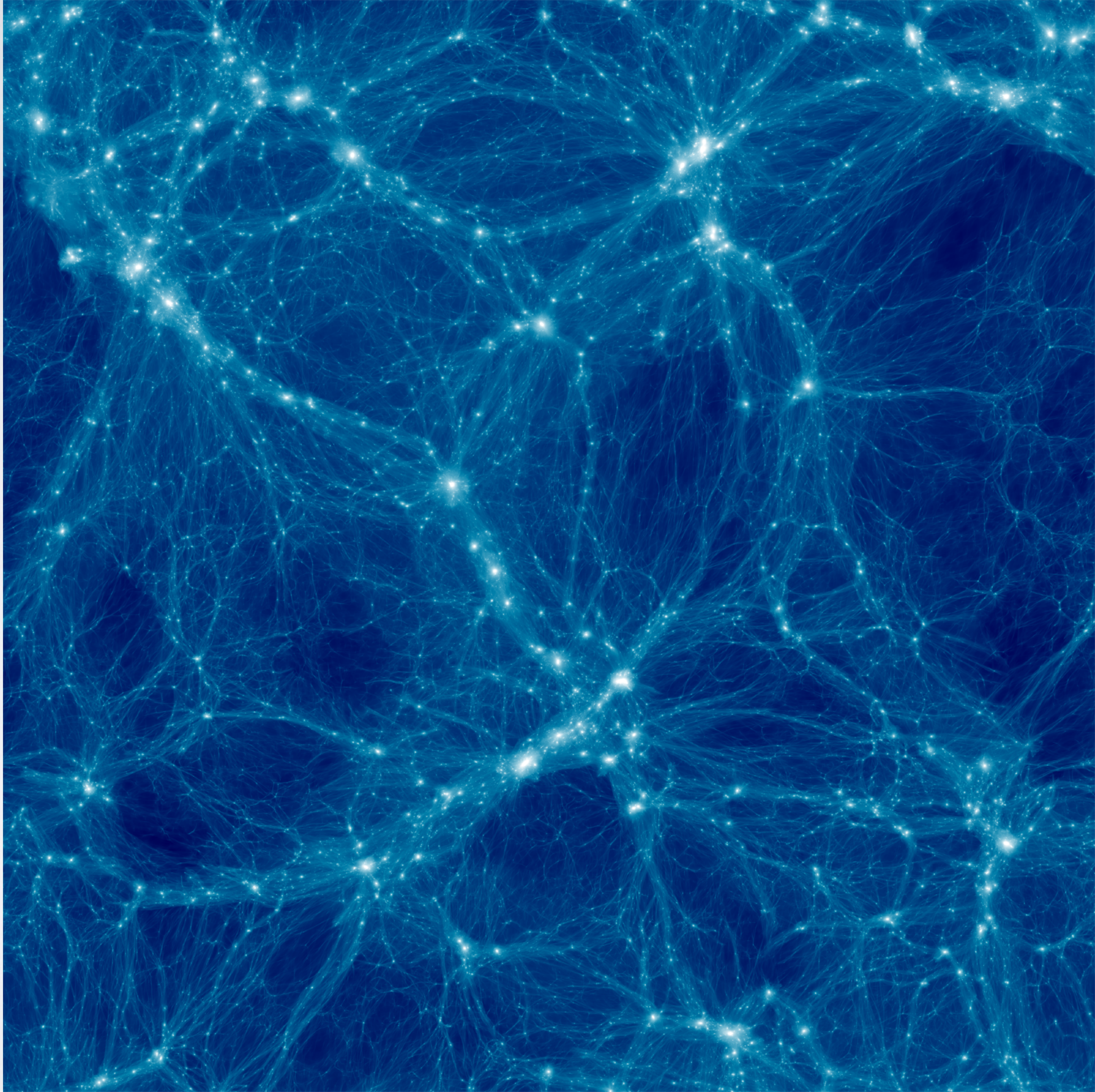
*In collaboration with:*
Andrey Kravtsov, Surhud More, and Philip Mansfield

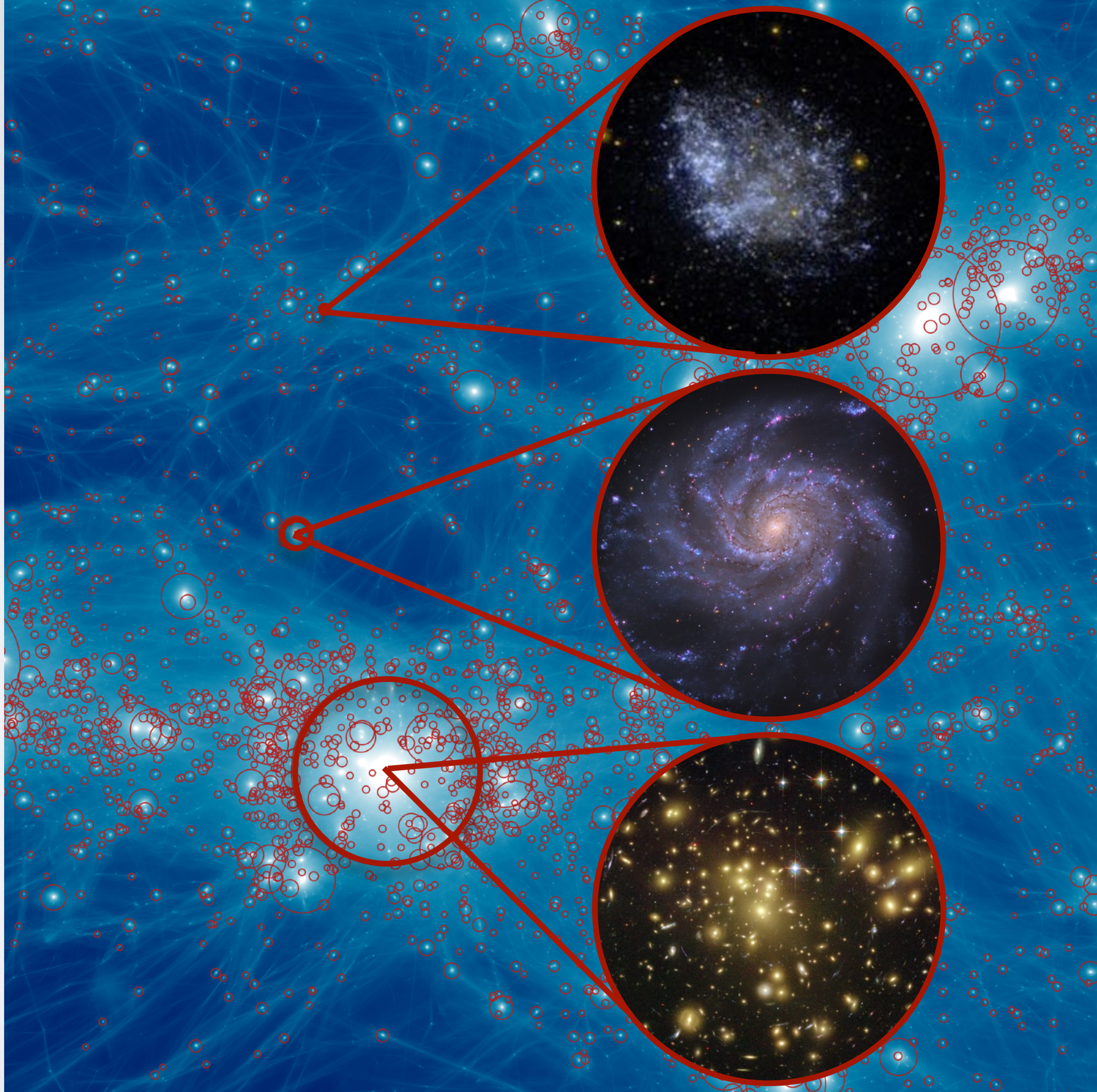
Cosmology Seminar • UC Berkeley • 04/17/2018

89 Mpc

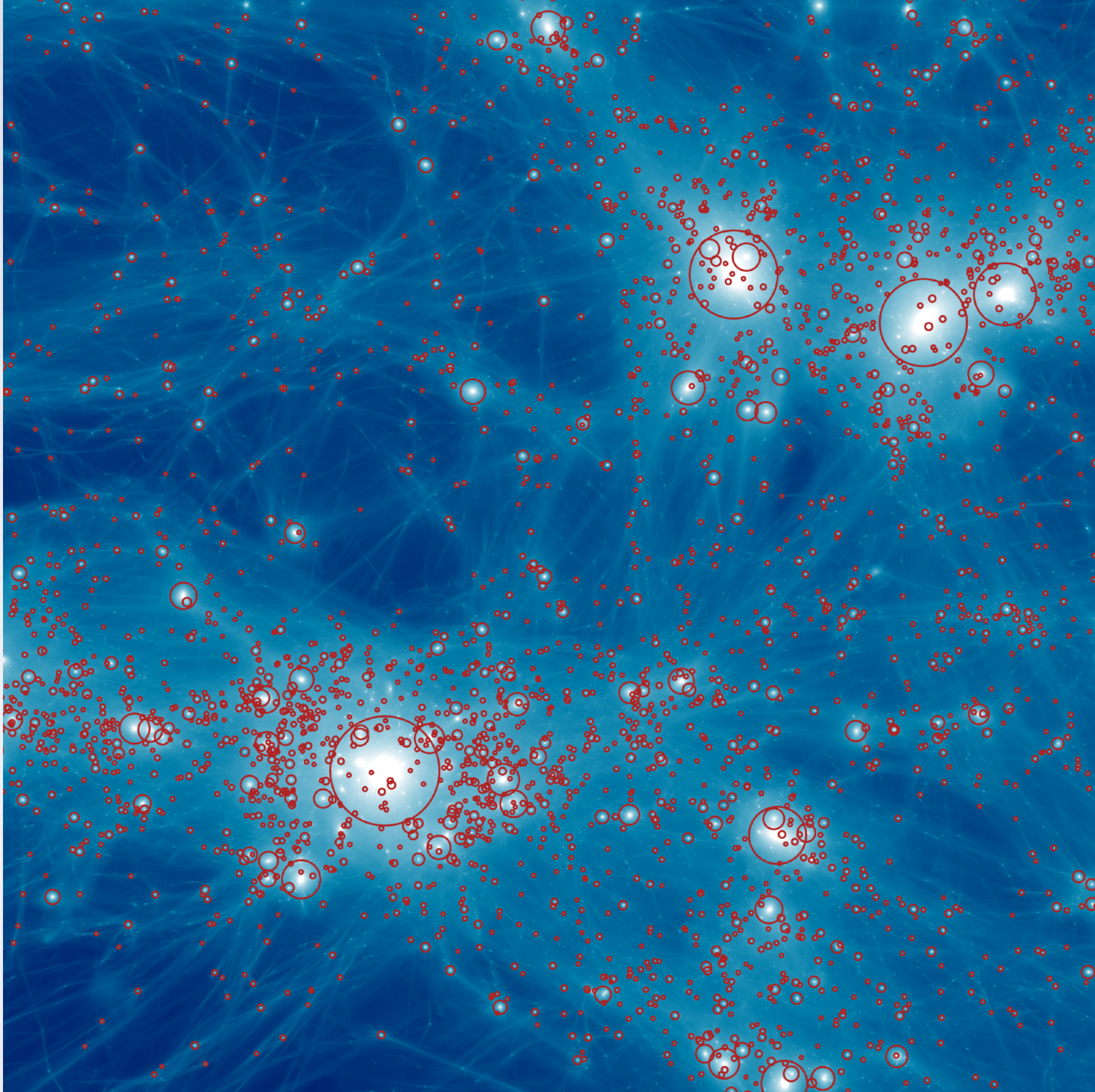


**Visualization code:**
Phil Mansfield
**Algorithm:**
Tom Abel, Oliver Hahn,
Ralf Kaehler

11 Mpc

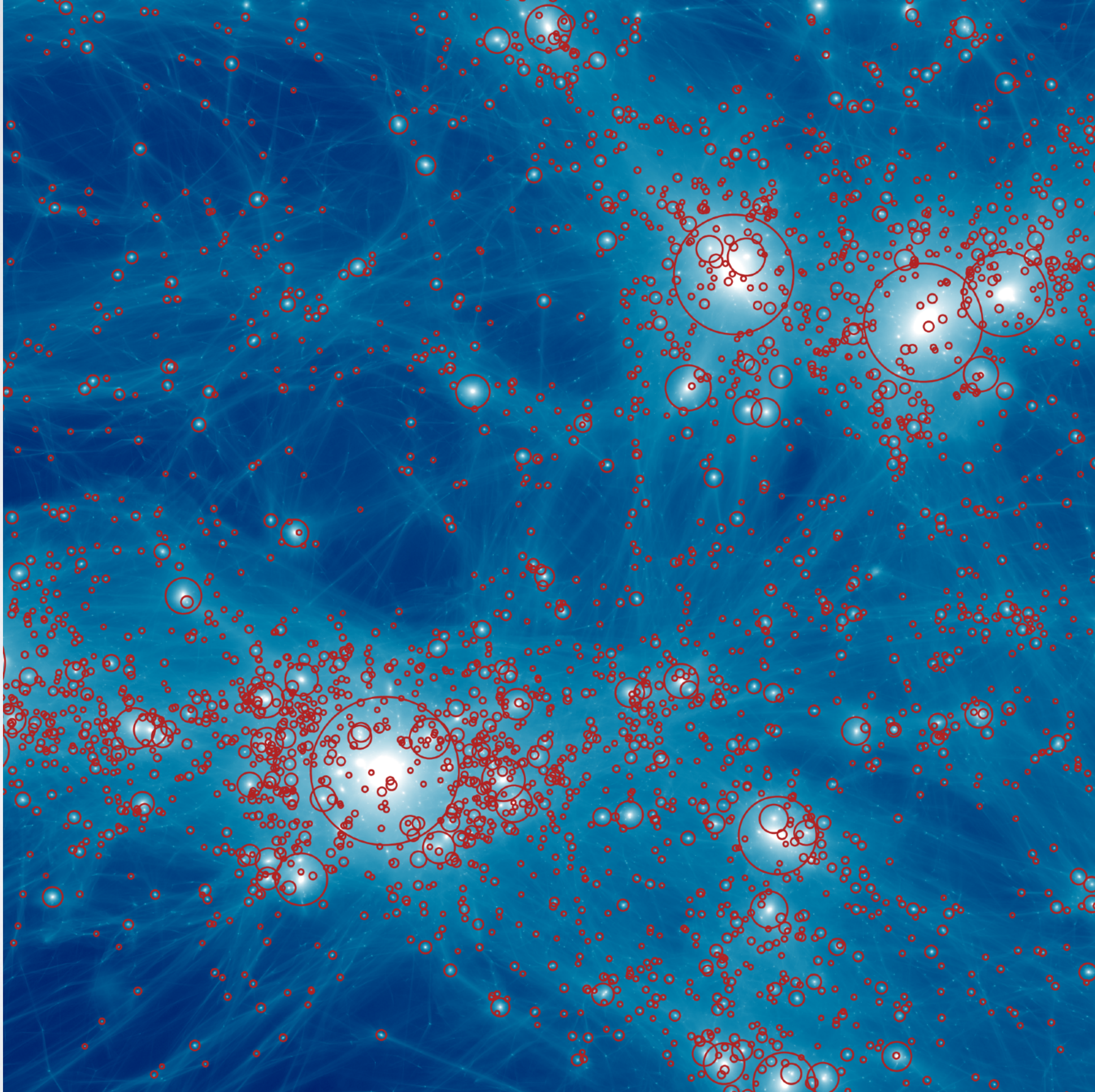


$R_{500c}$



Halo finder: Rockstar
(Behroozi et al. 2013)

$R_{200c}$

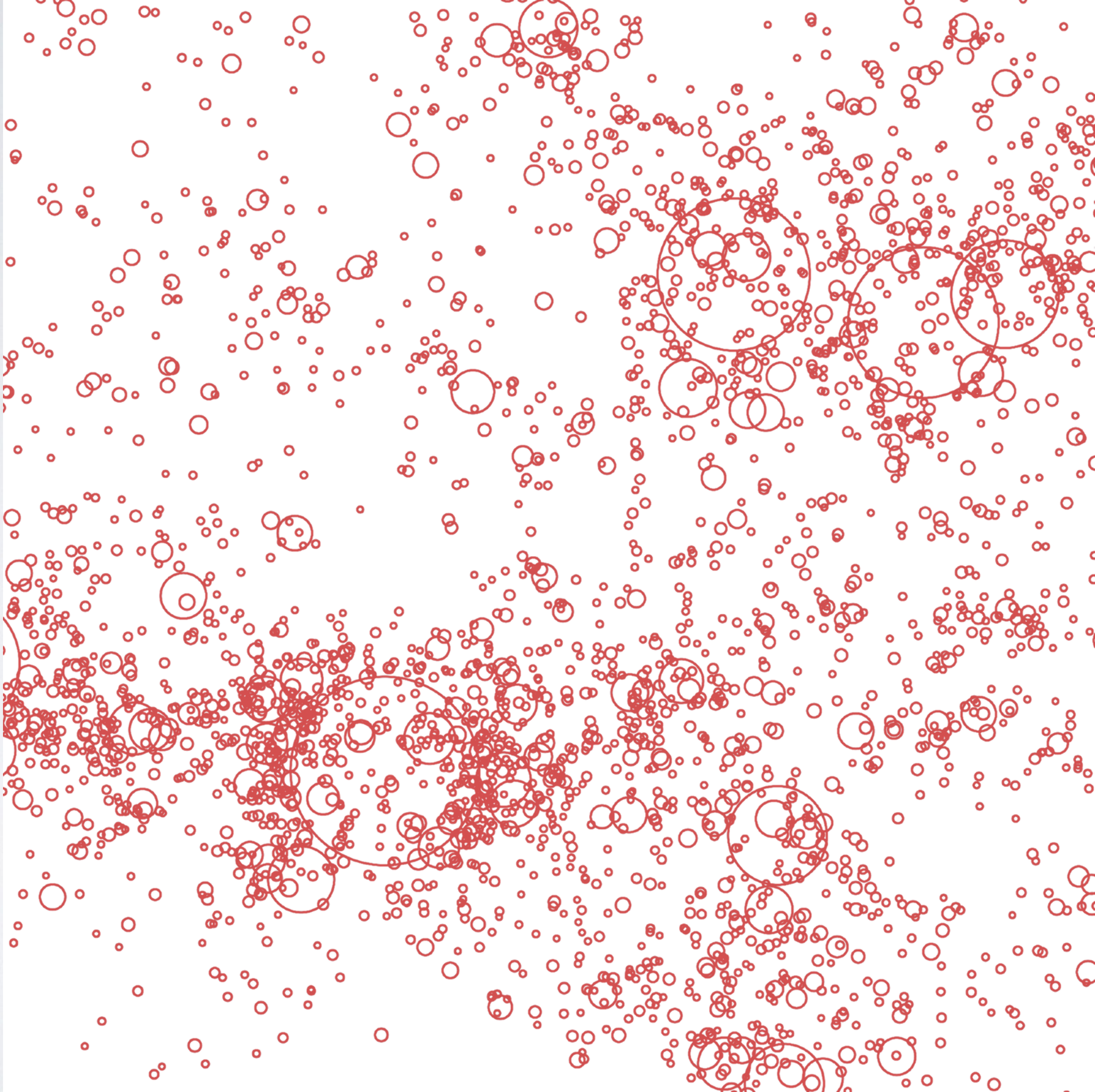


Halo finder: Rockstar
(Behroozi et al. 2013)

$R_{vir}$

Halo finder: Rockstar
(Behroozi et al. 2013)

$R_{vir}$



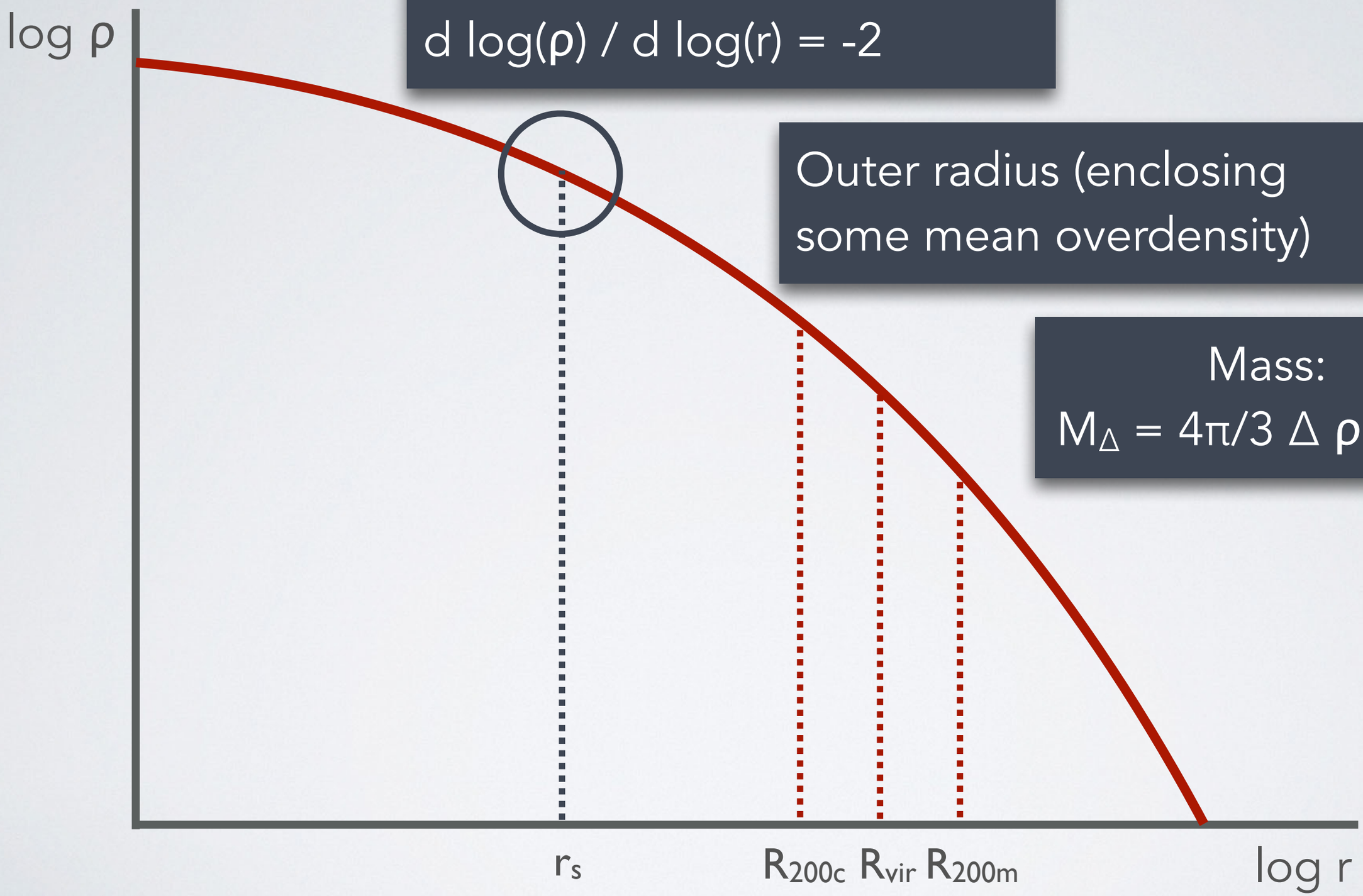
Halo finder: Rockstar
(Behroozi et al. 2013)

# Density profile

Scale radius:
d log(ρ) / d log(r) = -2

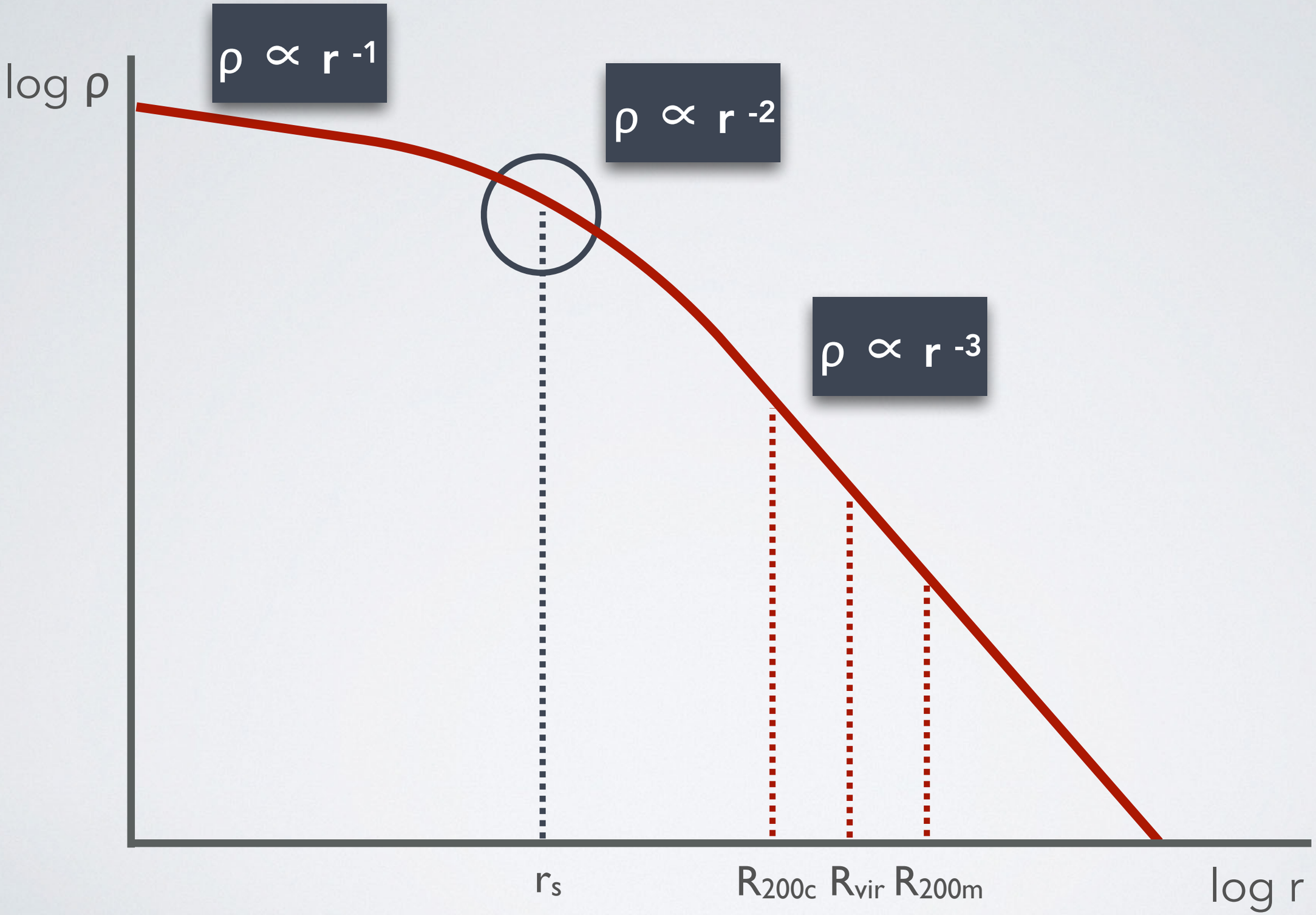
Outer radius (enclosing some mean overdensity)

Mass:
$M_\Delta = 4\pi/3\ \Delta\ \rho_{ref}\ R_\Delta^3$




Einasto 1965 • Frenk et al. 1988 • Hernquist 1990 • Dubinski & Carlberg 1991
Navarro et al.1995/1996/1997/2004

# Navarro-Frenk-White profile




Navarro et al. 1995/1996/1997

# The “virial” radius

Peebles 1980 • Lacey & Cole 1993

# The “virial” radius

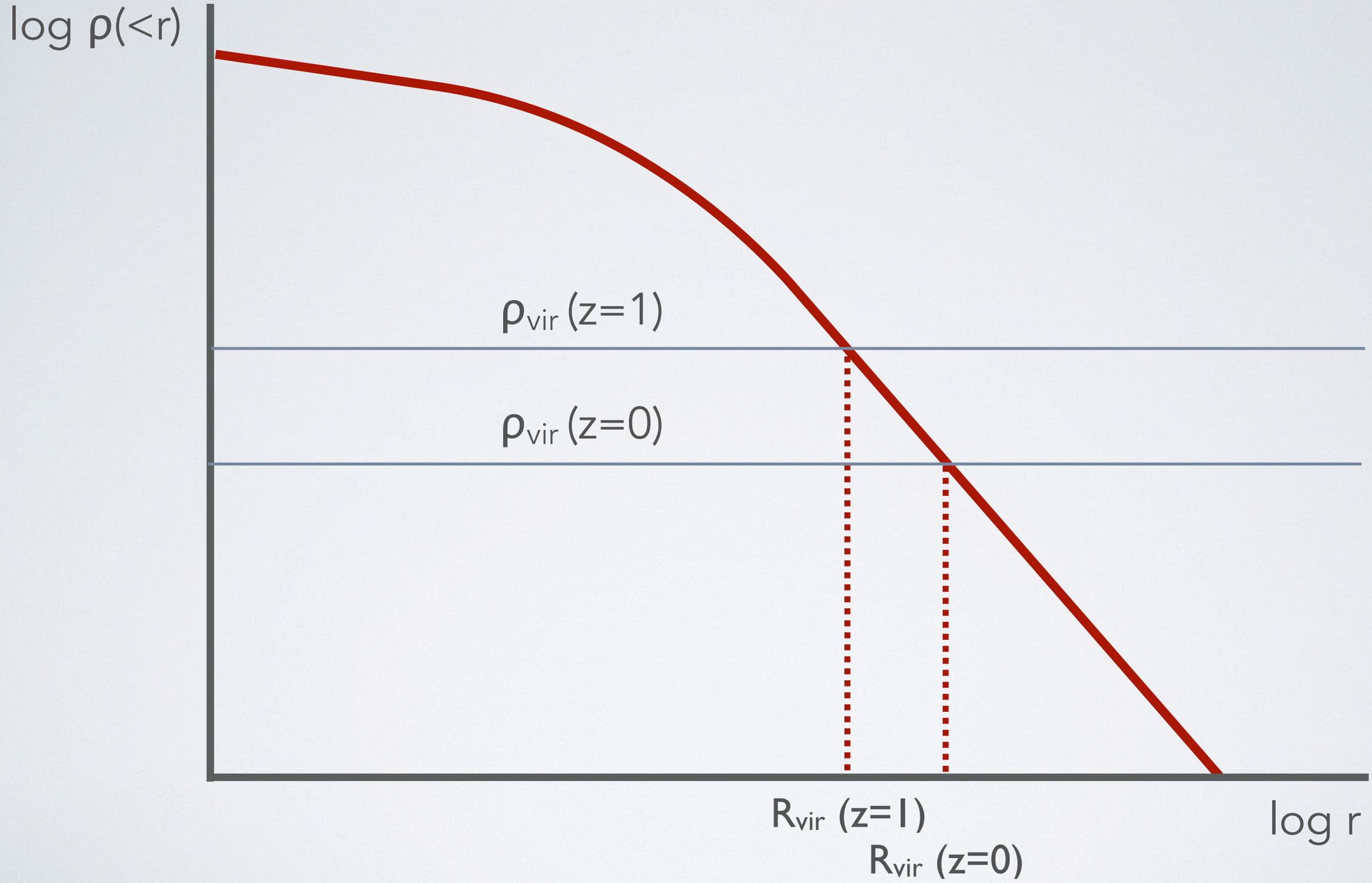

$W = -2K$

$\rightarrow R_{vir} = 1/2\ R_{max}$

$\rightarrow \Delta_{vir} = 18\ \pi^2 = 178$

Peebles 1980 • Lacey & Cole 1993

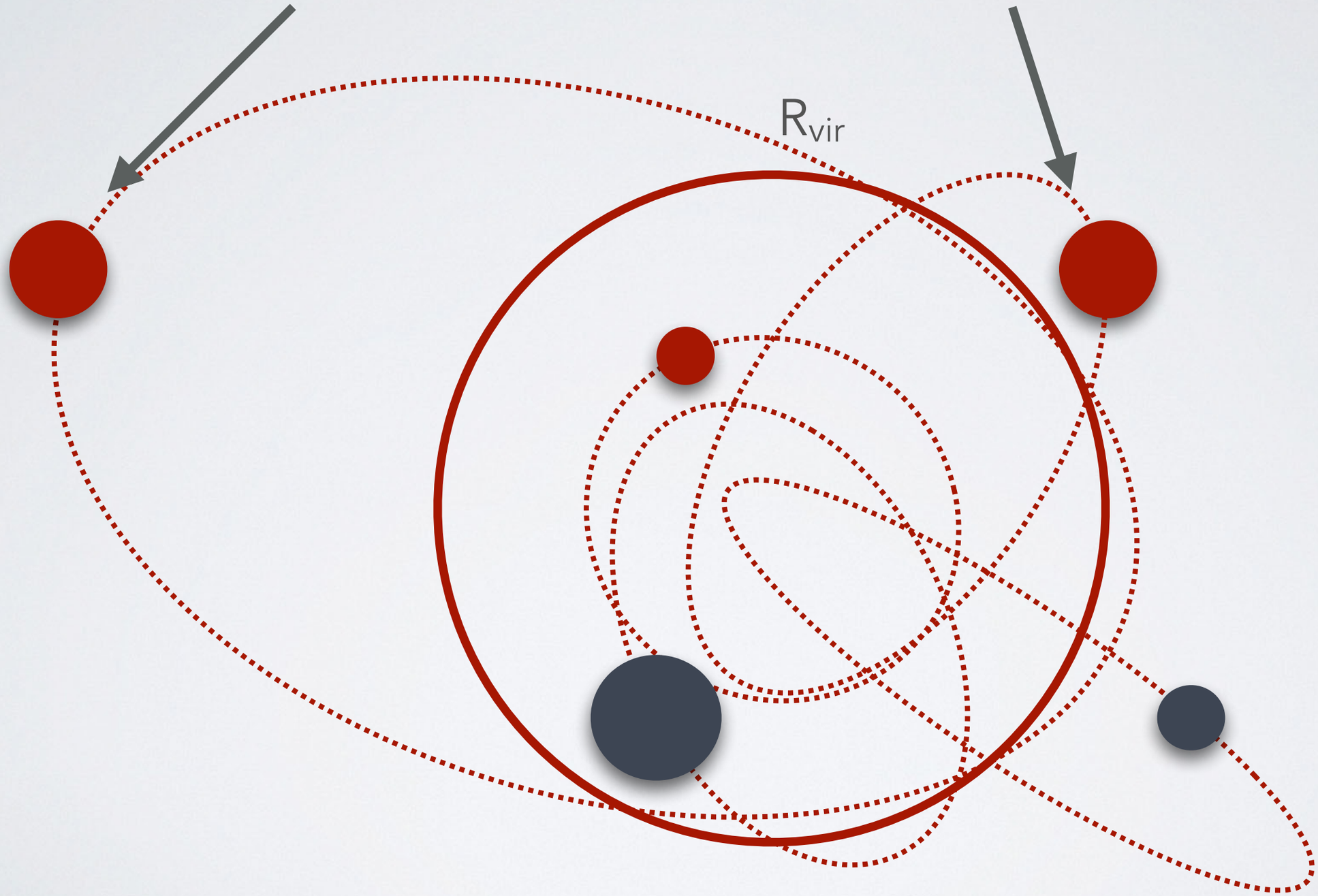
# Pseudo-evolution




Diemer et al. 2013 • More et al. 2015 • Cuesta et al. 2008 • Zemp 2014

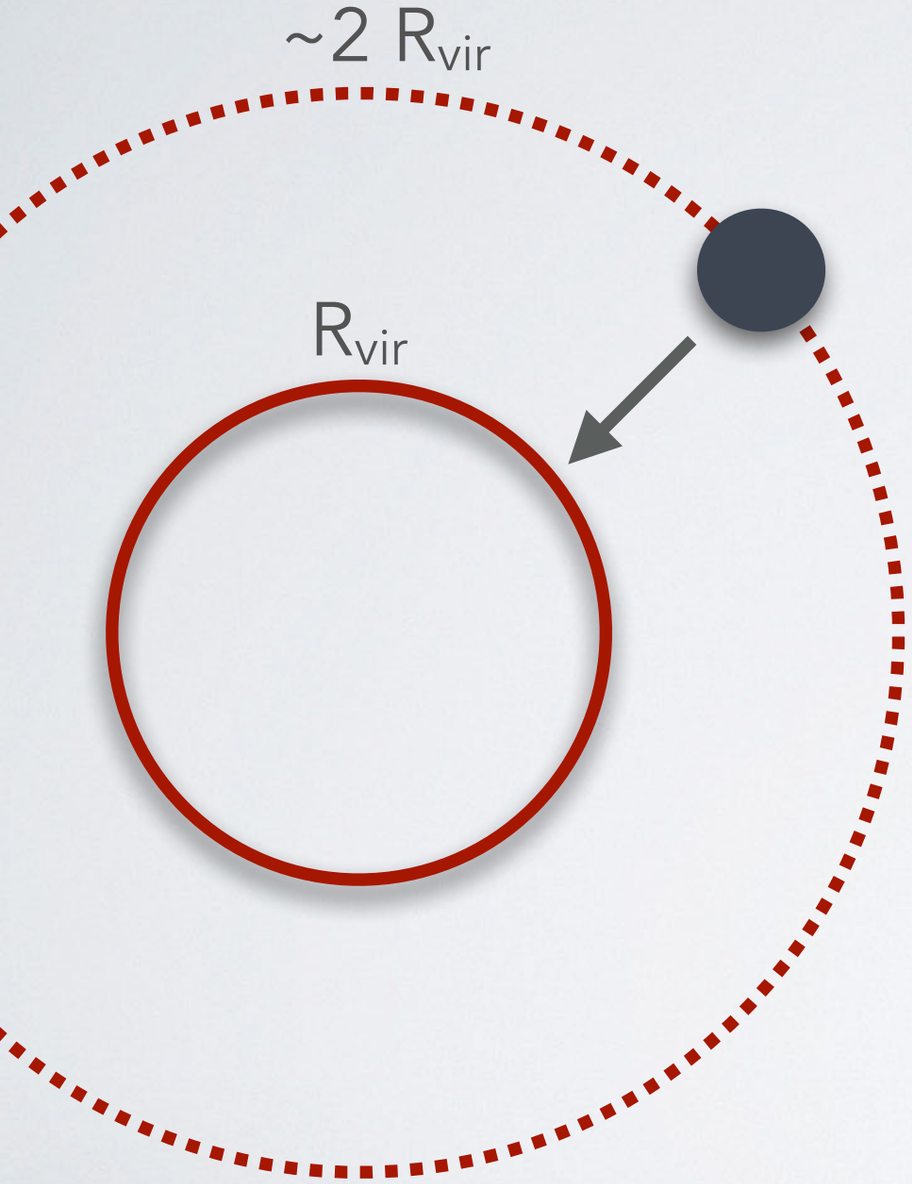
# “Ejected” satellites

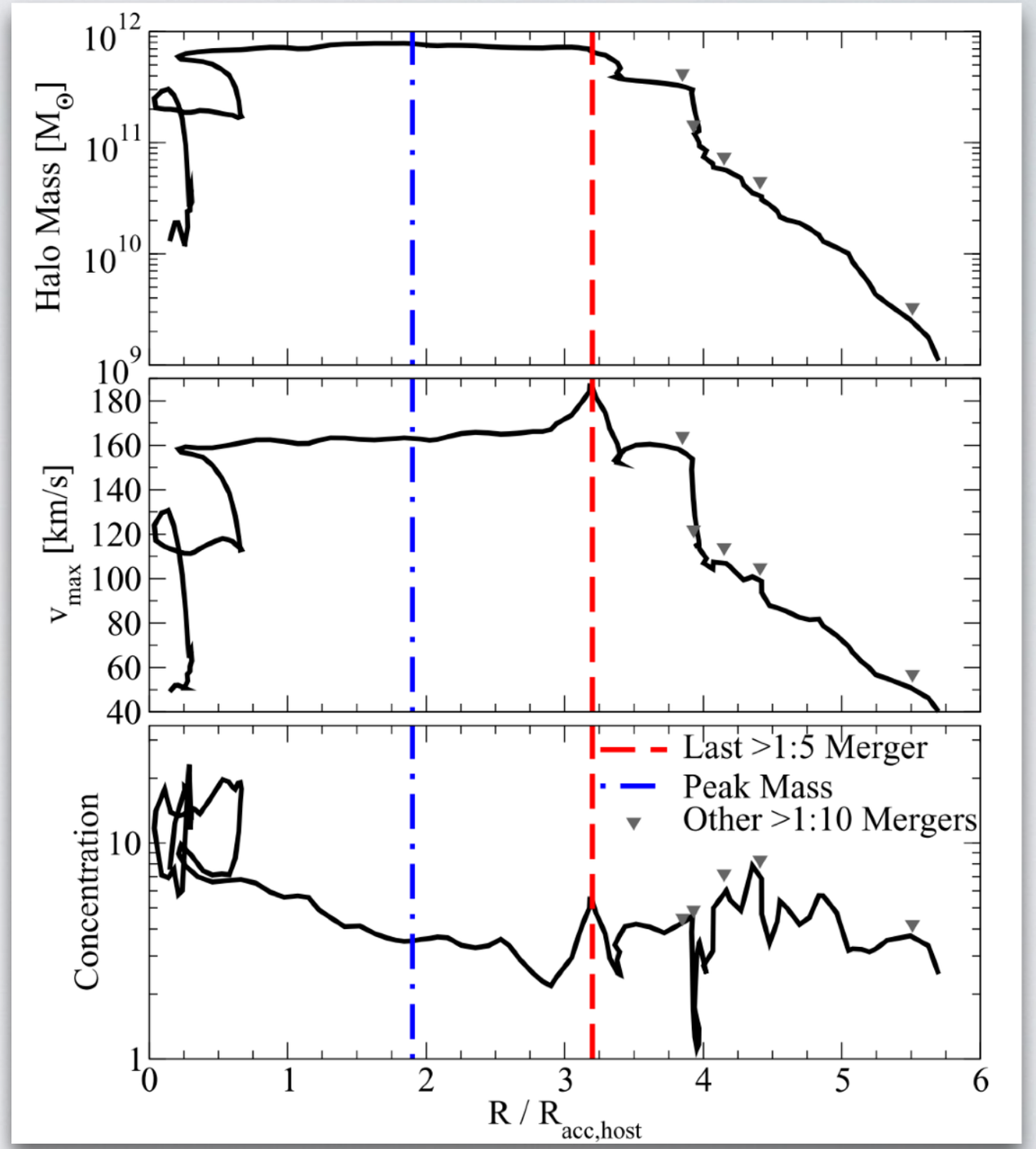
Quenched satellites out to ~2.5 $R_{vir}$




Balogh et al. 2000 • Mamon et al. 2004 • Wetzel et al. 2014

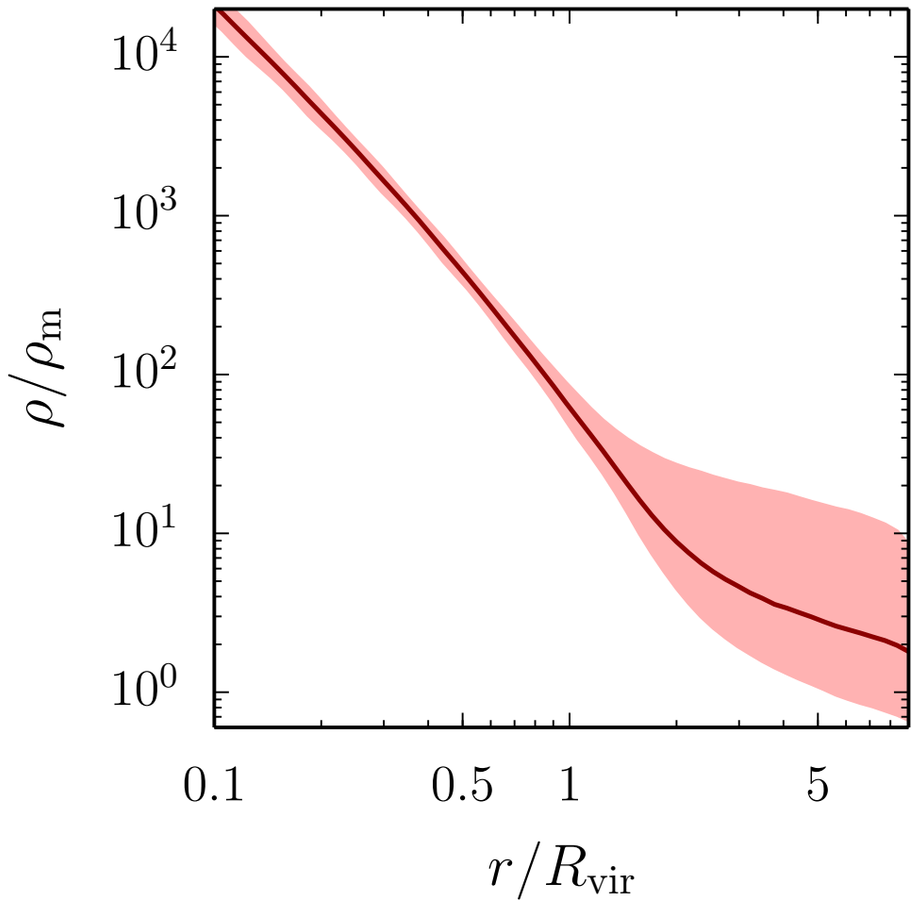
# Sphere of influence

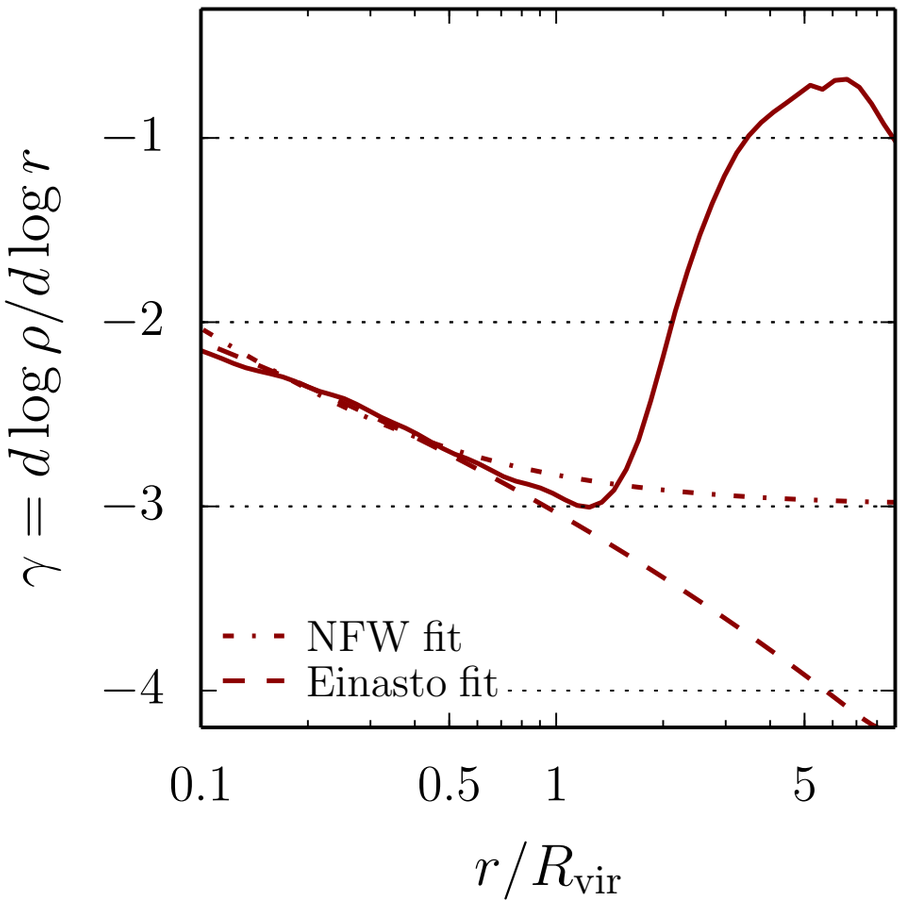


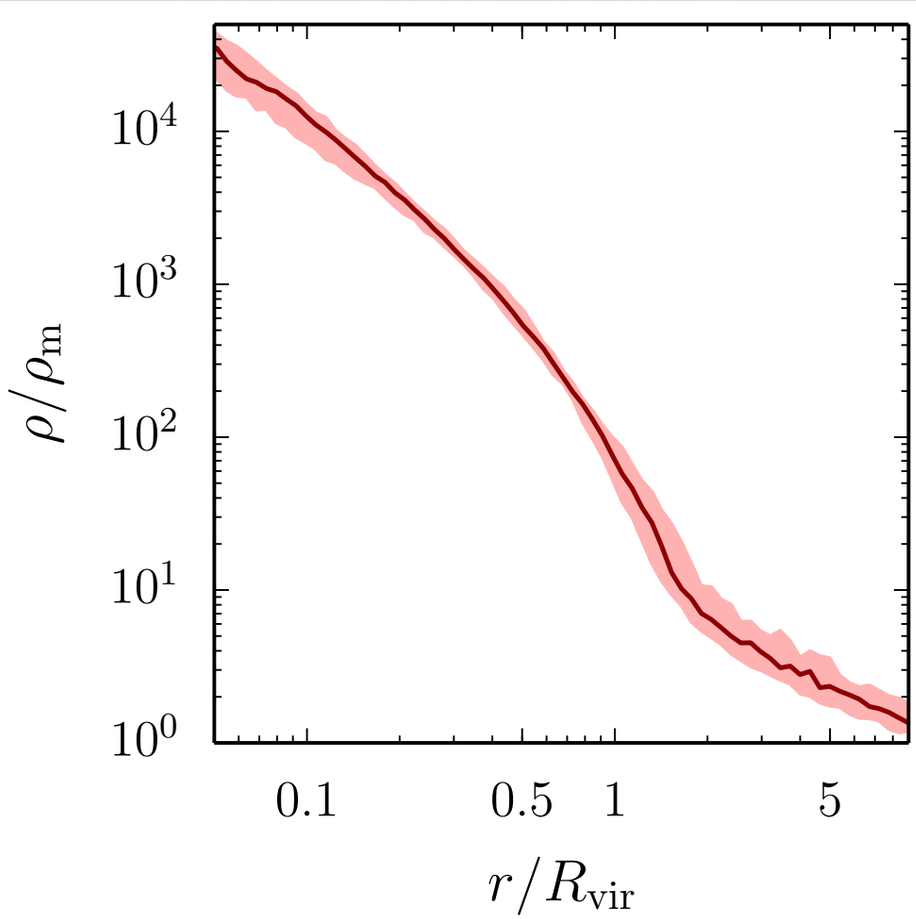

Behroozi et al. 2014

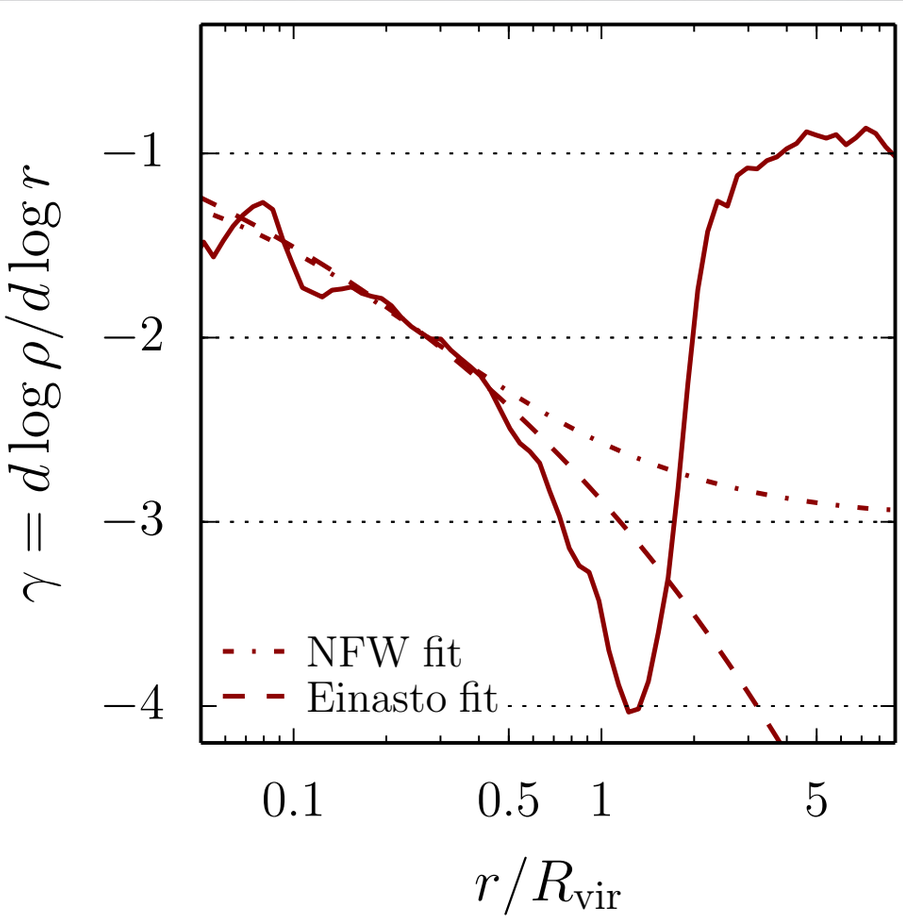
Small halos
($10^{10}$<M<$3\times10^{11}$)



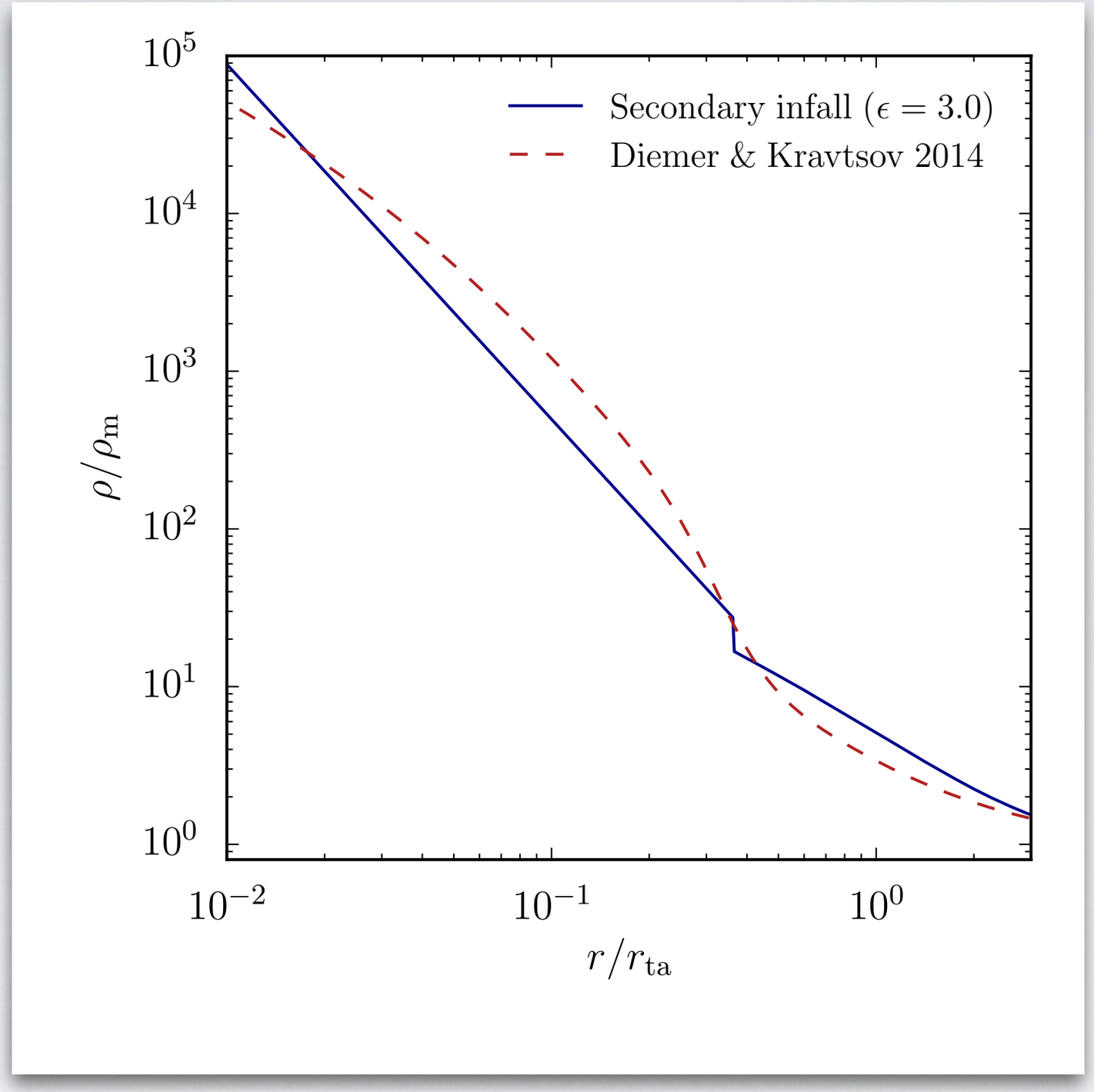

Large halos
(M>$10^{15}$)



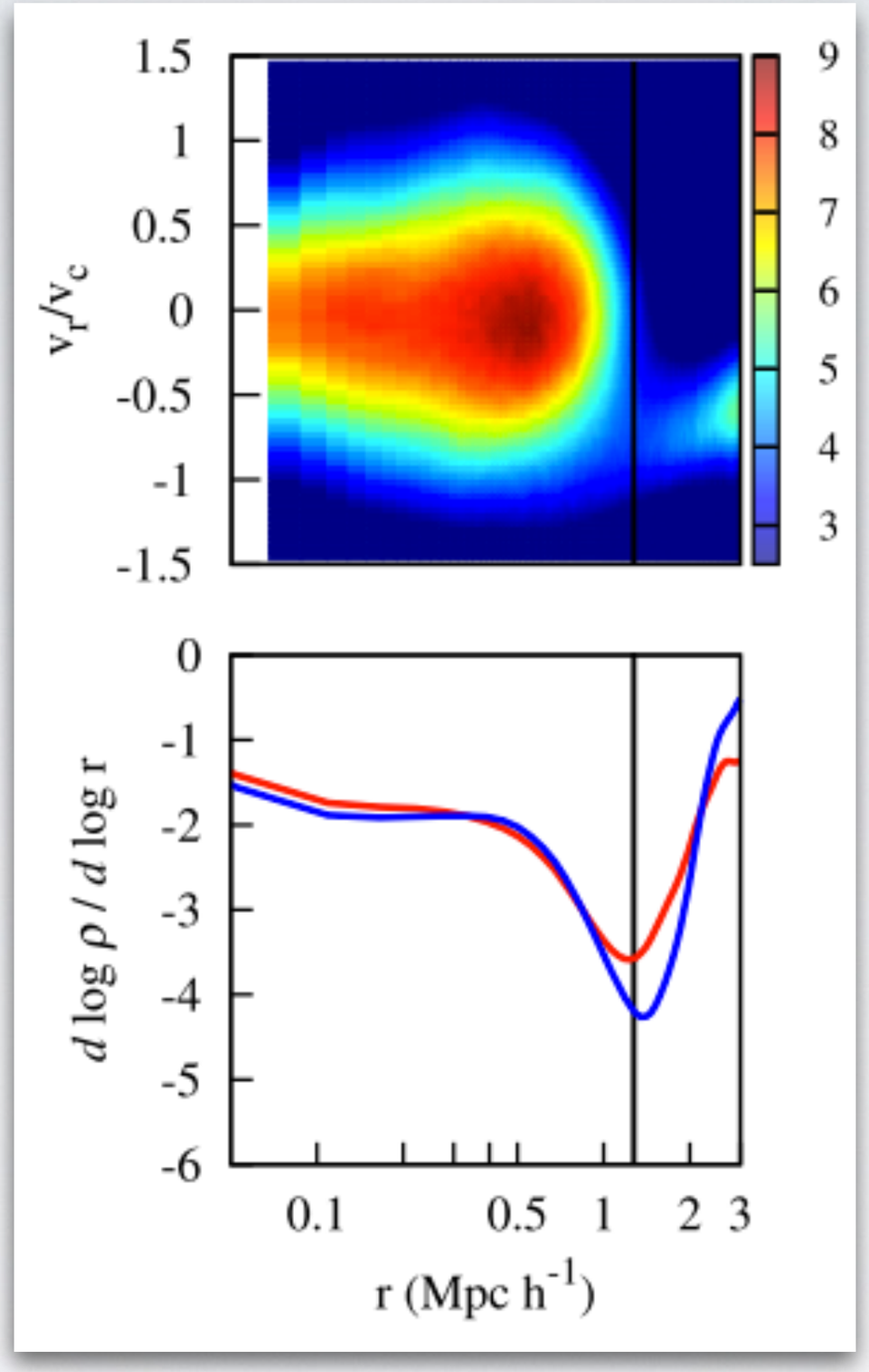

Diemer & Kravtsov 2014

# The Splashback Radius



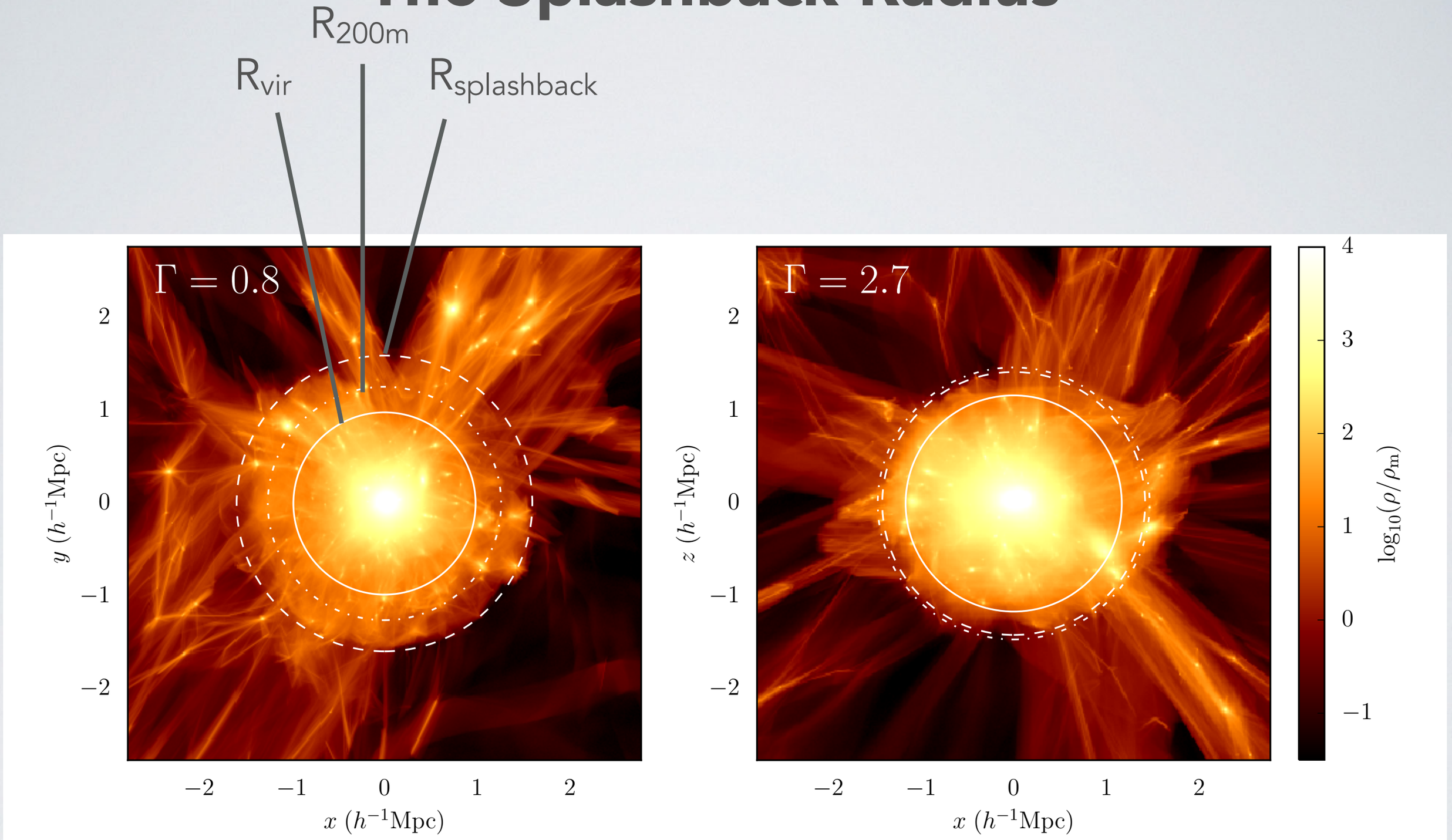

Fillmore & Goldreich 1984 • Bertschinger 1985 • Diemand & Kuhlen 2008
Vogelsberger et al. 2011 • Lithwick & Dalal 2011 • Adhikari et al. 2014 • Diemer & Kravtsov 2014

# Phase space (stacked halos)




Adhikari, Dalal & Chamberlain 2014

# The Splashback Radius

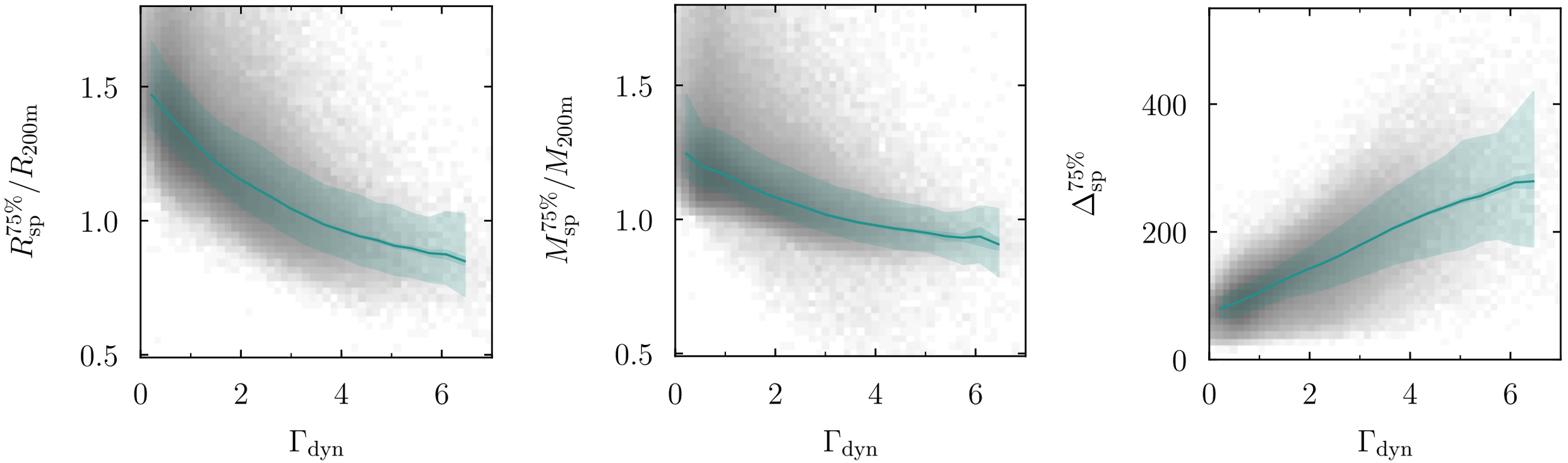



Low accretion rate

High accretion rate

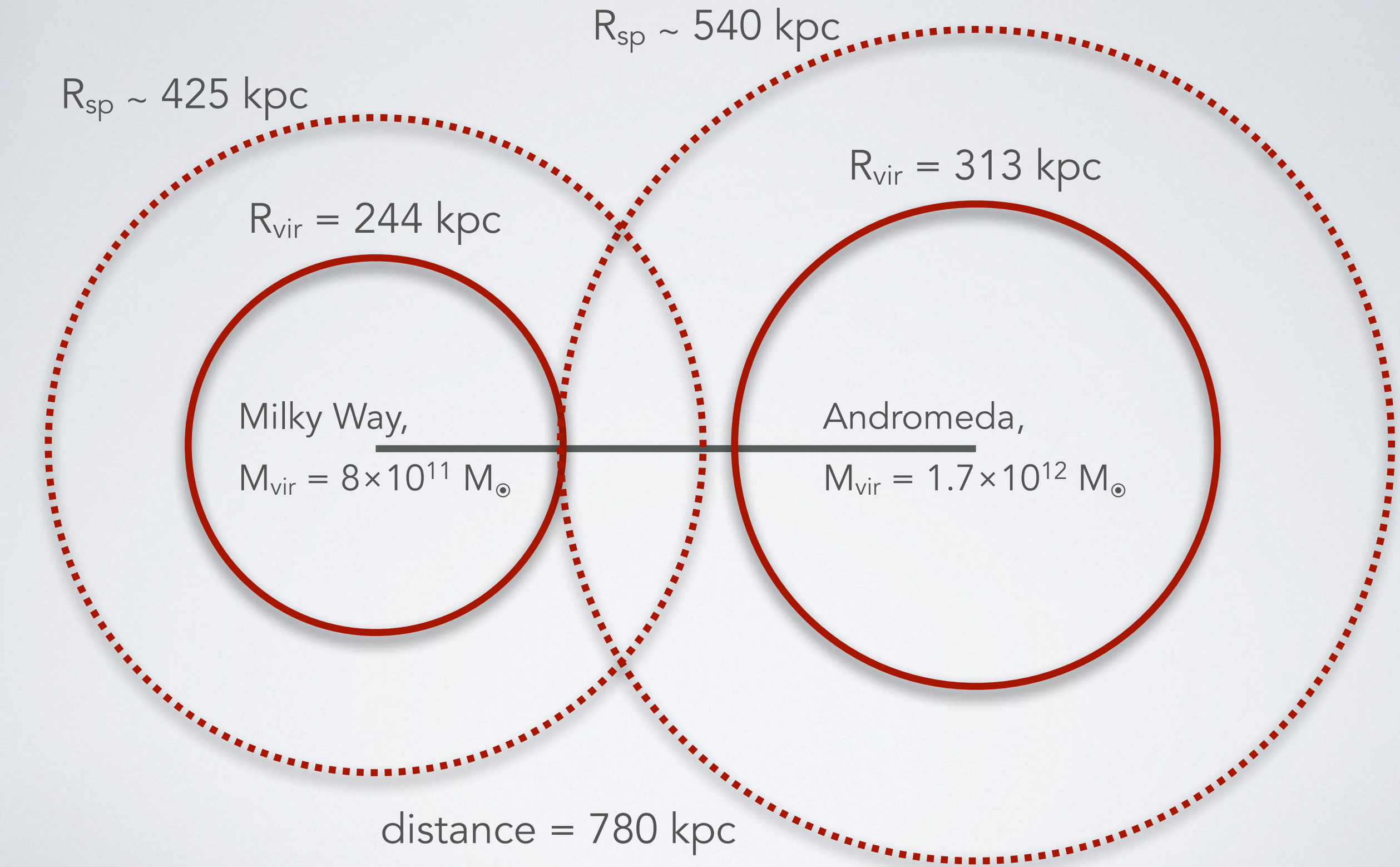
Diemer & Kravtsov 2014 • More, Diemer & Kravtsov 2015 • Adhikari et al. 2014

# The Γ-$R_{sp}$relation

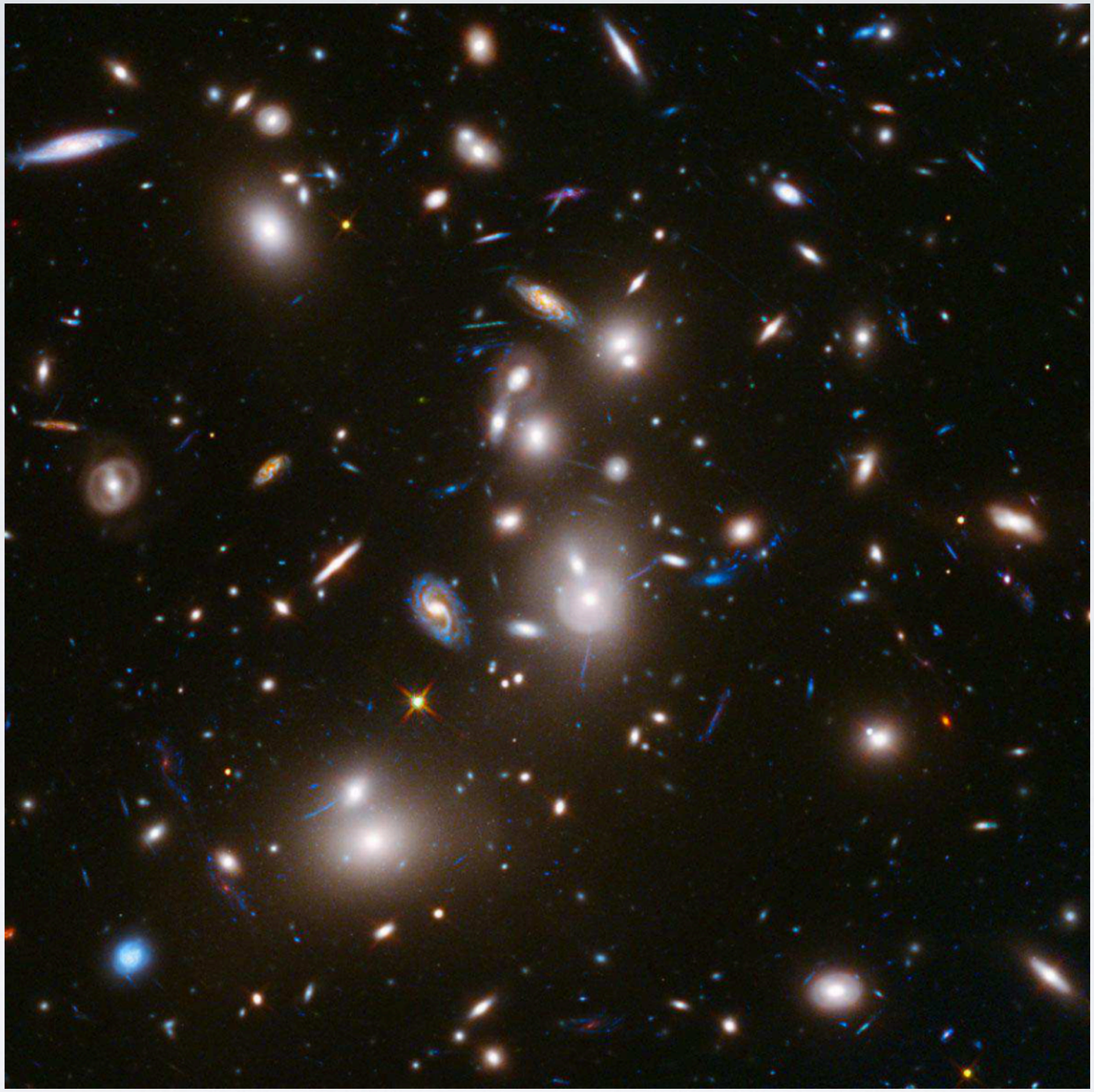



Diemer et al. 2017

# Do the Milky Way and Andromeda halos overlap?

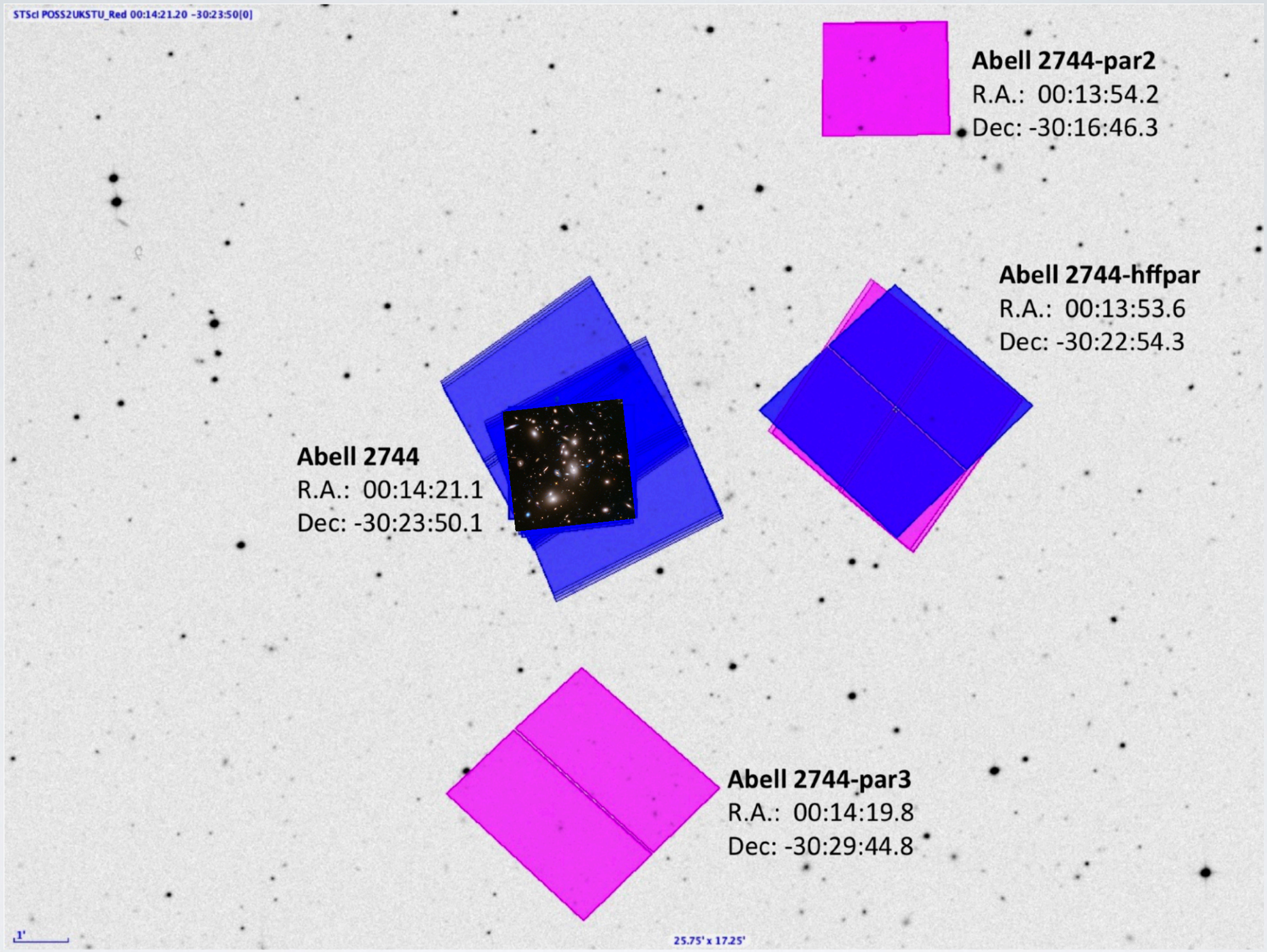



More, Diemer & Kravtsov 2015 • Diaz et al. 2014



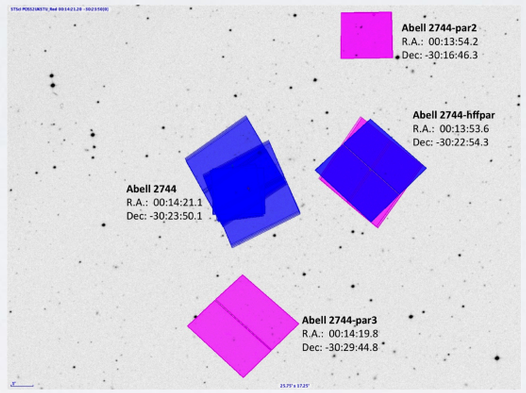
55 kpc

Abell 2744 / HST Frontier Fields • Koekemoer et al. 2017 • Lotz et al. 2017




950 kpc

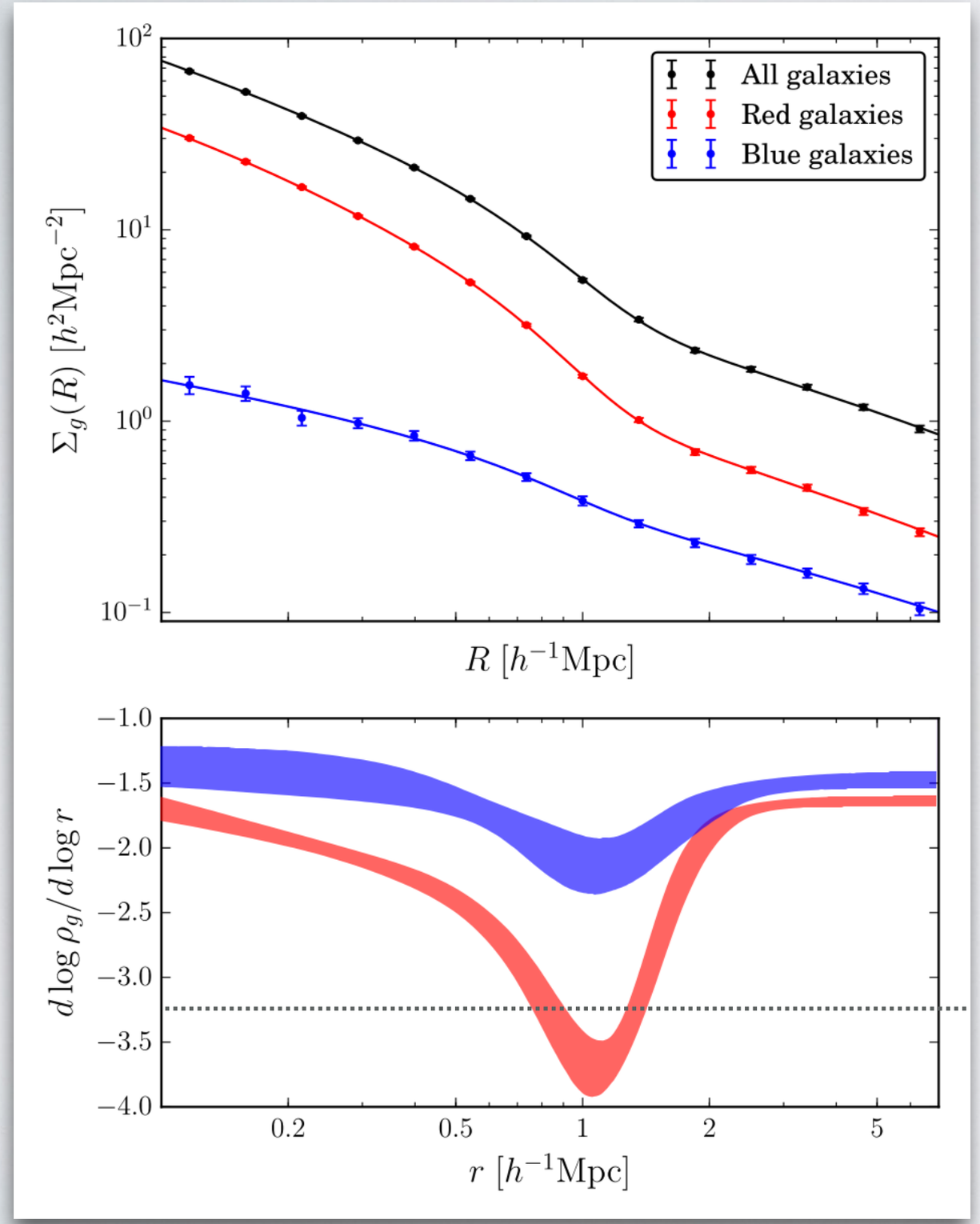
Abell 2744 / HST Frontier Fields • Koekemoer et al. 2017 • Lotz et al. 2017




~3 Mpc

Abell 2744 / HST Frontier Fields • Koekemoer et al. 2017 • Lotz et al. 2017

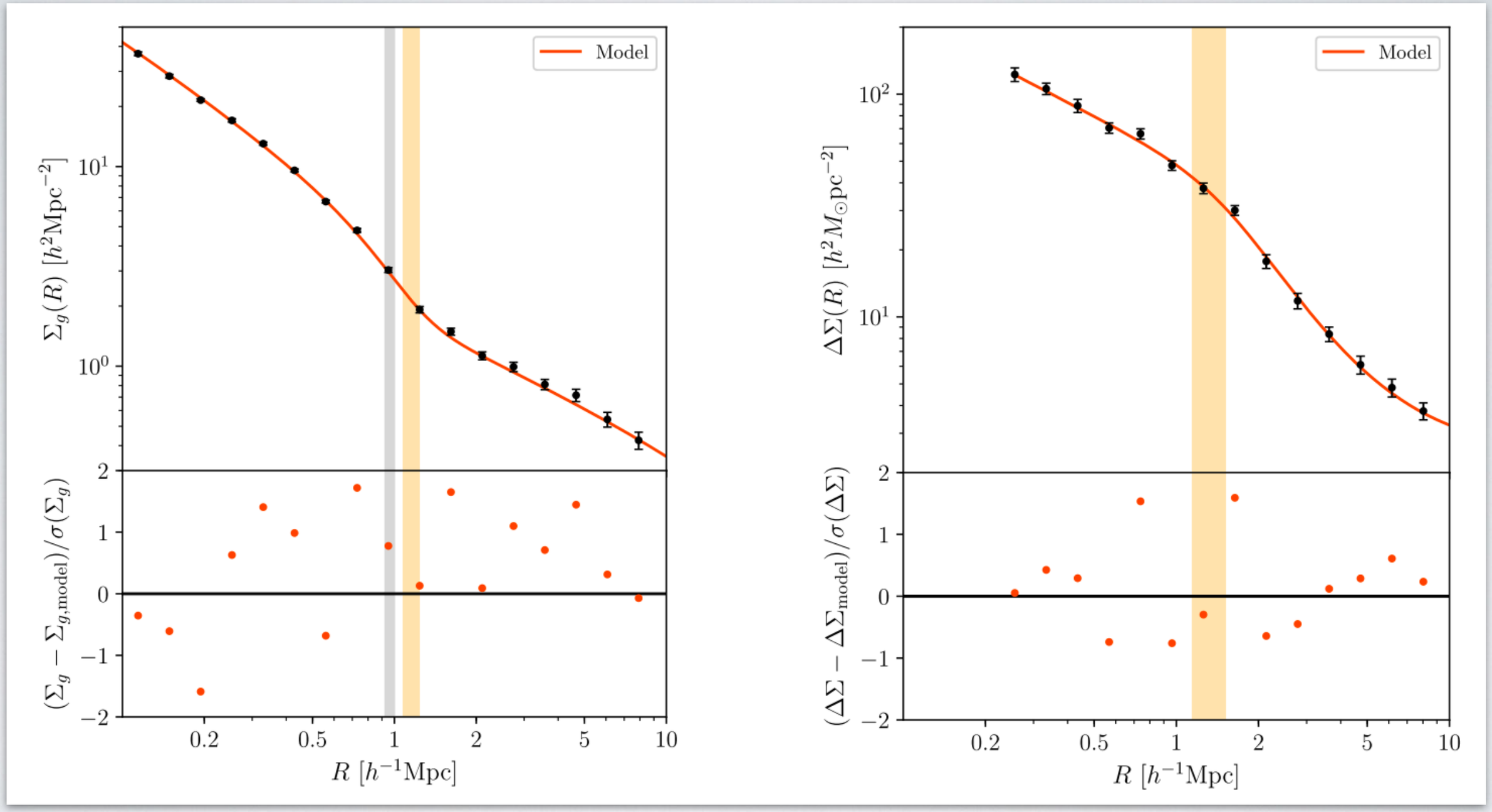
# $R_{sp}$ in cluster member profiles (SDSS)




Assume $\Sigma_{galaxies} \sim \Sigma_{subhalos} \sim \Sigma_{DM}$

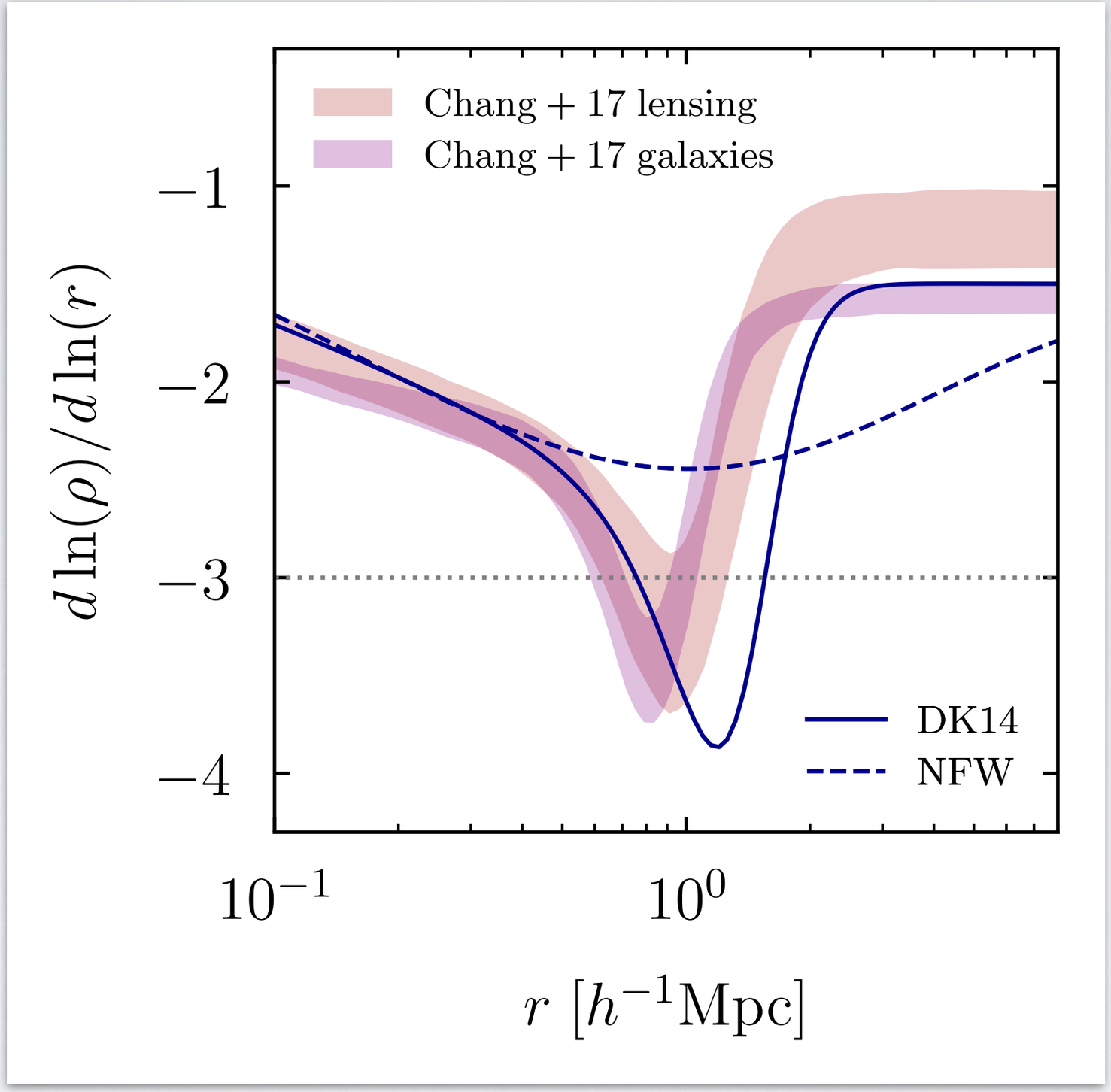
Baxter et al. 2017 • Rykoff et al. 2014 • More et al. 2016 • see, however, Zu et al. 2016 • Busch & White 2017

# $R_{sp}$ in cluster member profiles (DES)



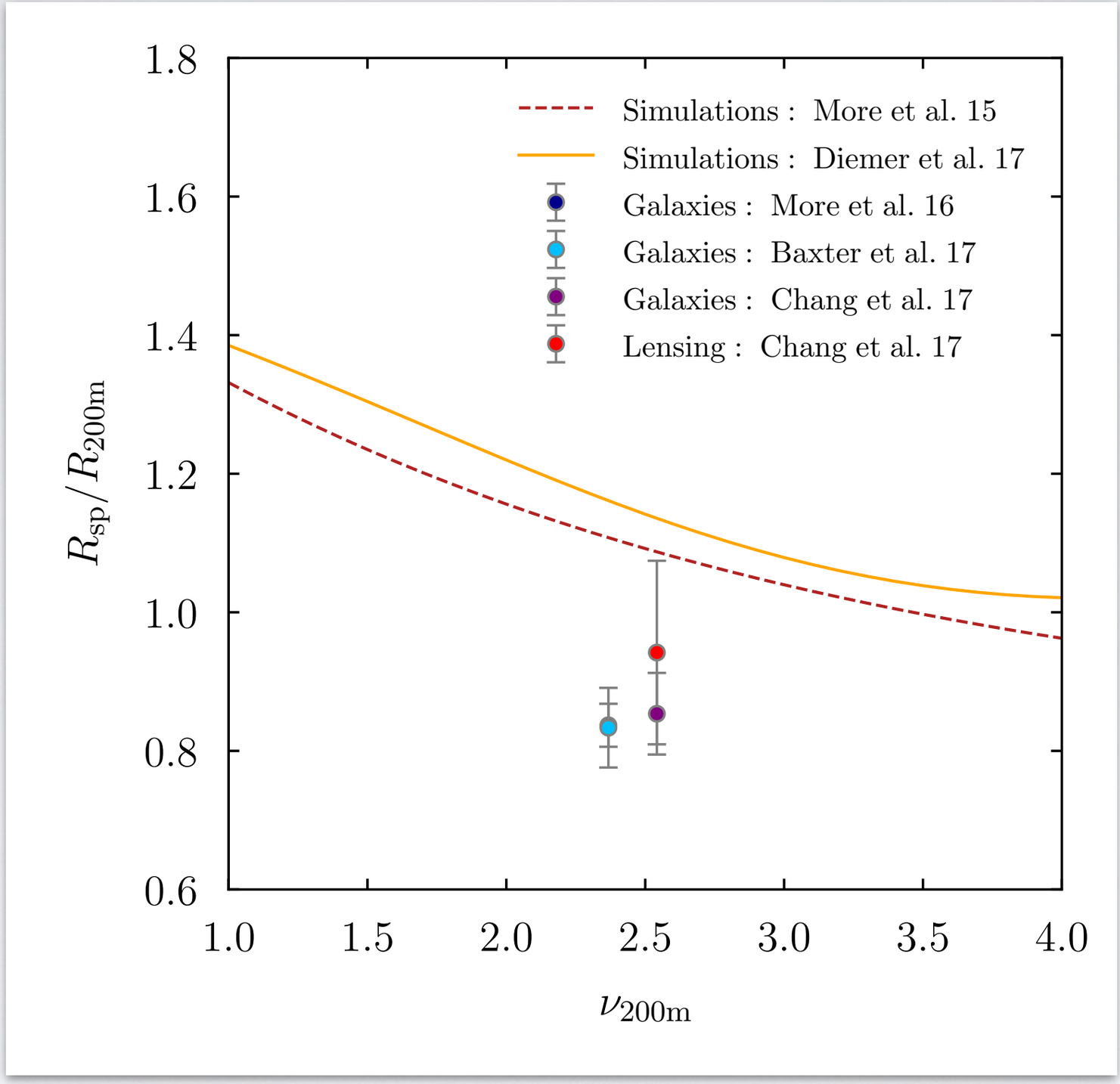

DES / RedMapper • Chang et al. 2017 • Rykoff et al. 2014

# $R_{sp}$ in cluster member profiles (DES)




Diemer & Kravtsov 2014 • Chang et al. 2017

# Summary of $R_{sp}$ observations




More et al. 2015 • Diemer et al. 2017 • More et al. 2016 • Baxter et al. 2017 • Chang et al. 2017
Zu et al. 2017 • Busch & White 2017

# $R_{sp}$ of individual halos in simulations

**1) Find drop in spherical density profiles**

Too much sub-structure and noise

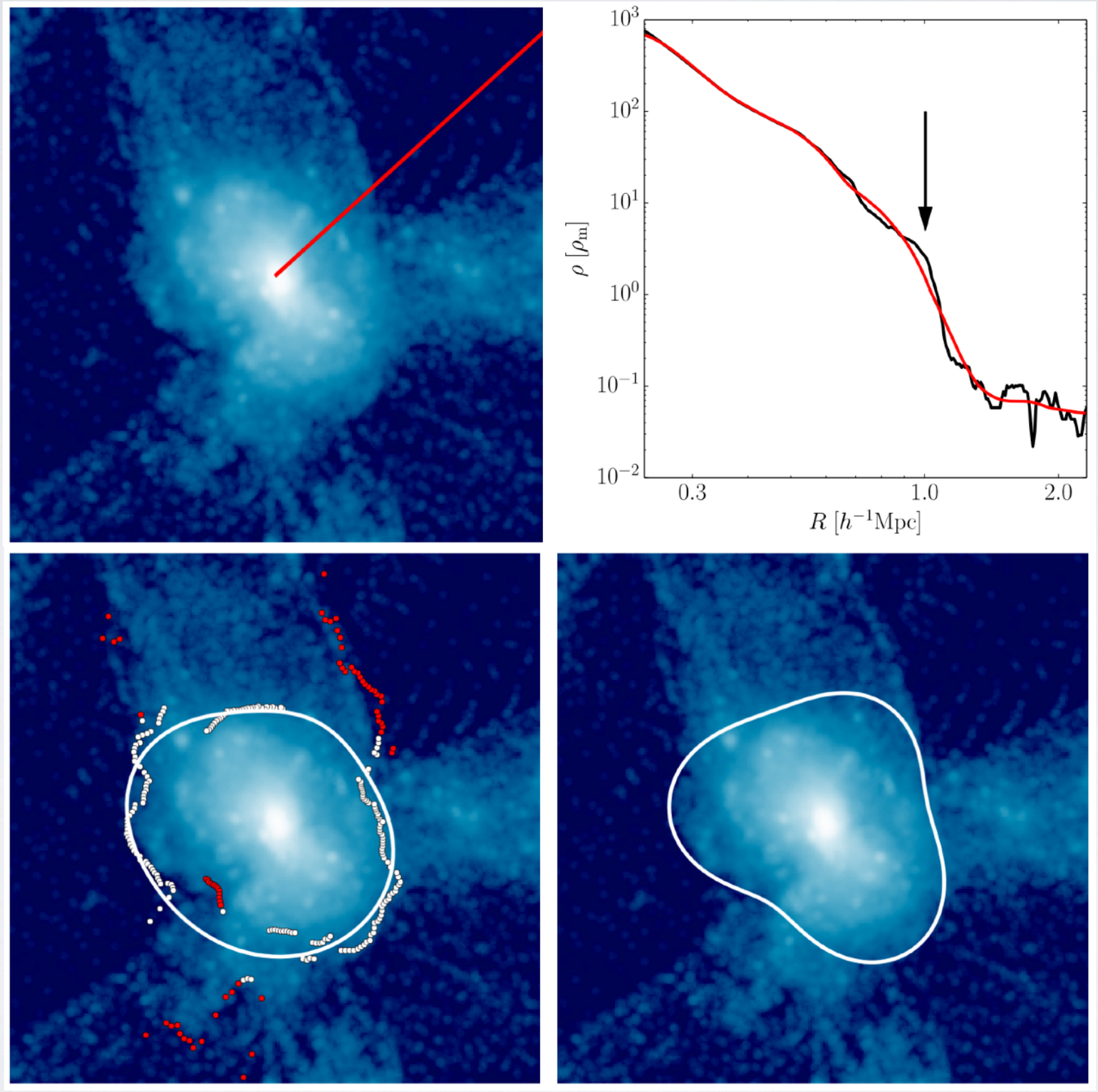
**2) Consider the full 3D density information**

Non-trivial, but can explore non-spherical effects

**3) Measure the splashback in particle orbits**

Sounds like a lot of work?

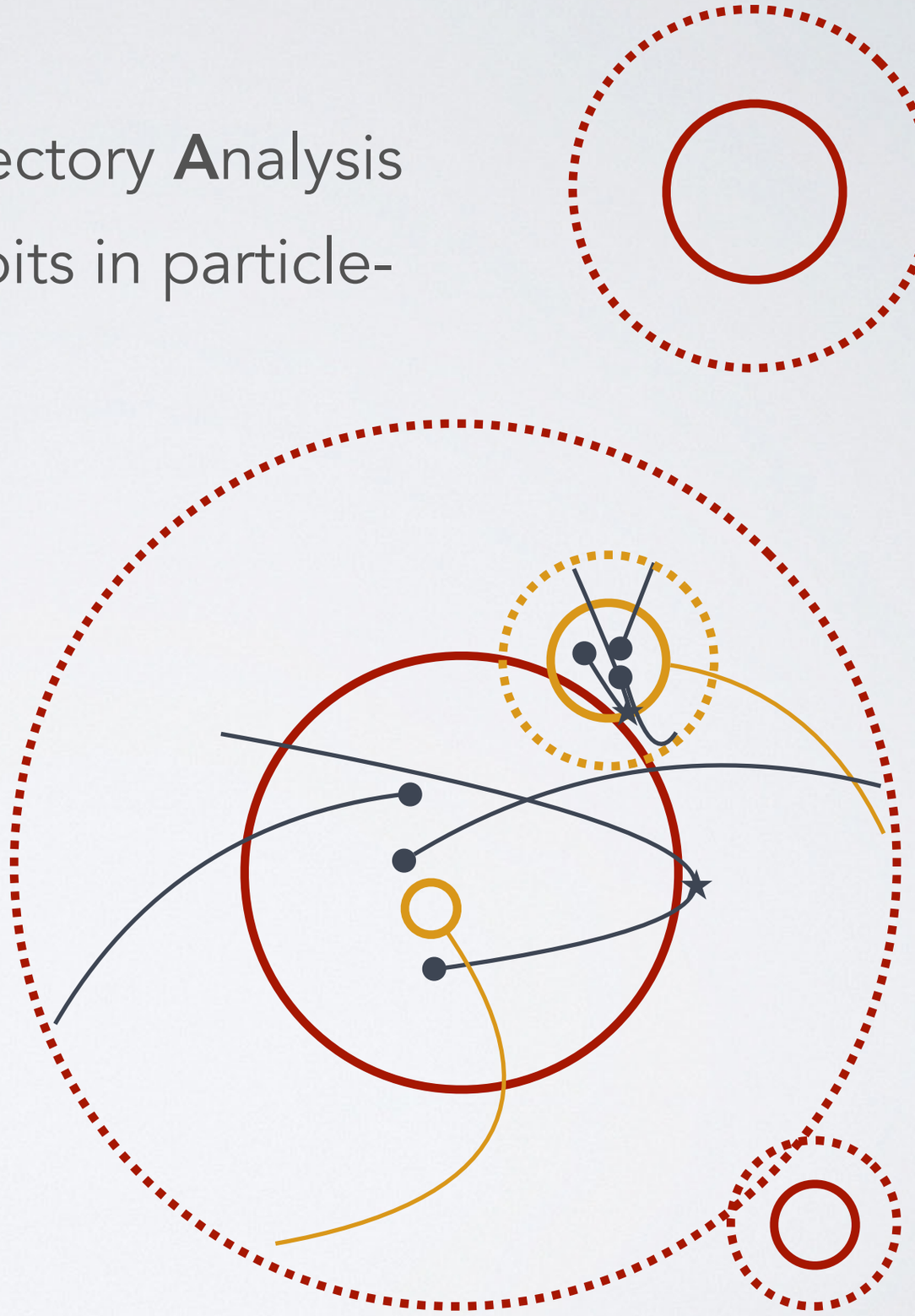
# Option 2): Shell finding with SHELLFISH




Mansfield, Kravtsov & Diemer 2017

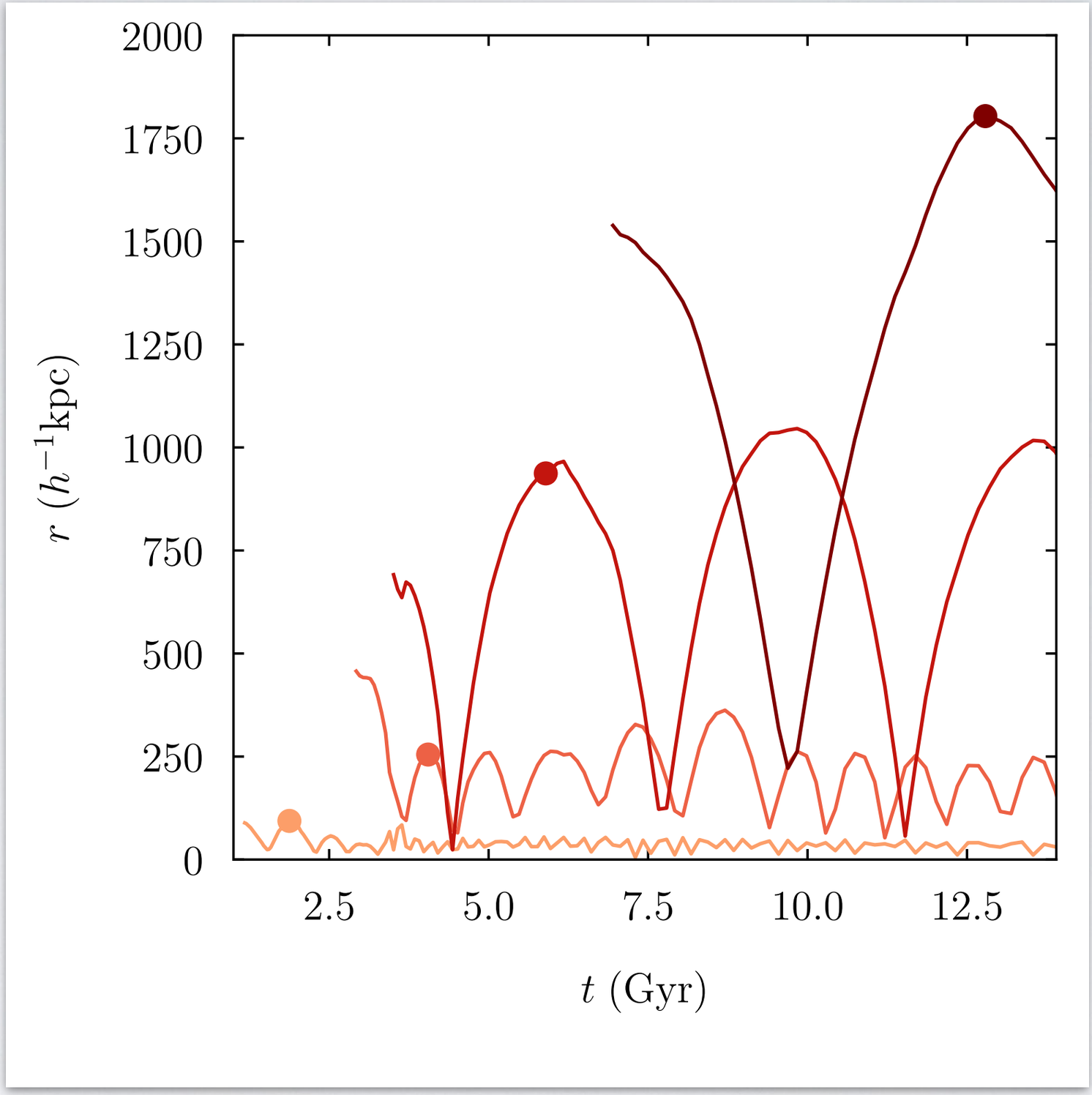
# SPARTA

- **S**ubhalo and **PAR**ticle **T**rajectory **A**nalysis
- Framework for tracking orbits in particle-based simulations
- MPI-parallelized, pure C



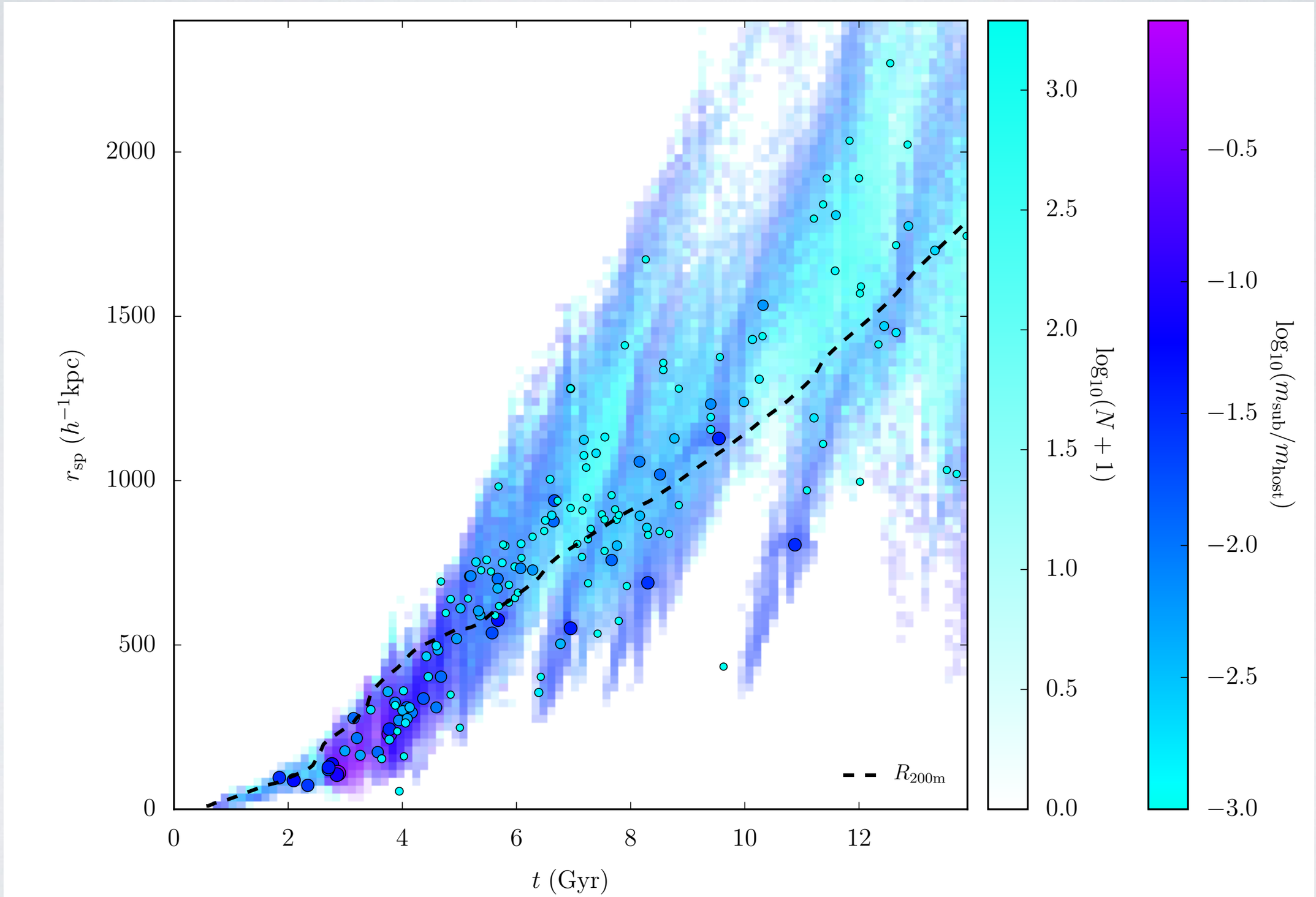
Diemer 2017

# What do the orbits look like?



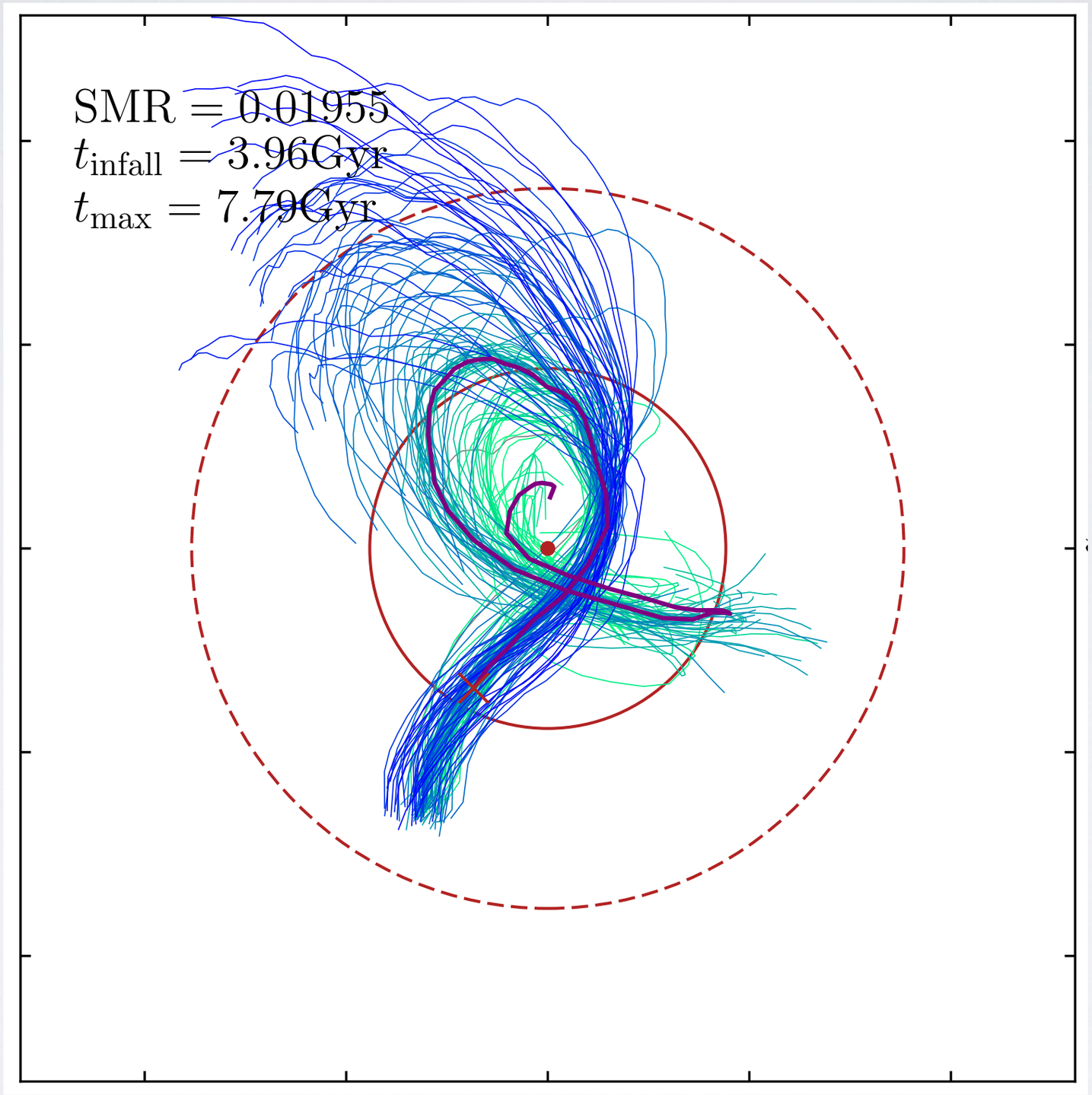

Diemer 2017

# Splashback in an individual halo

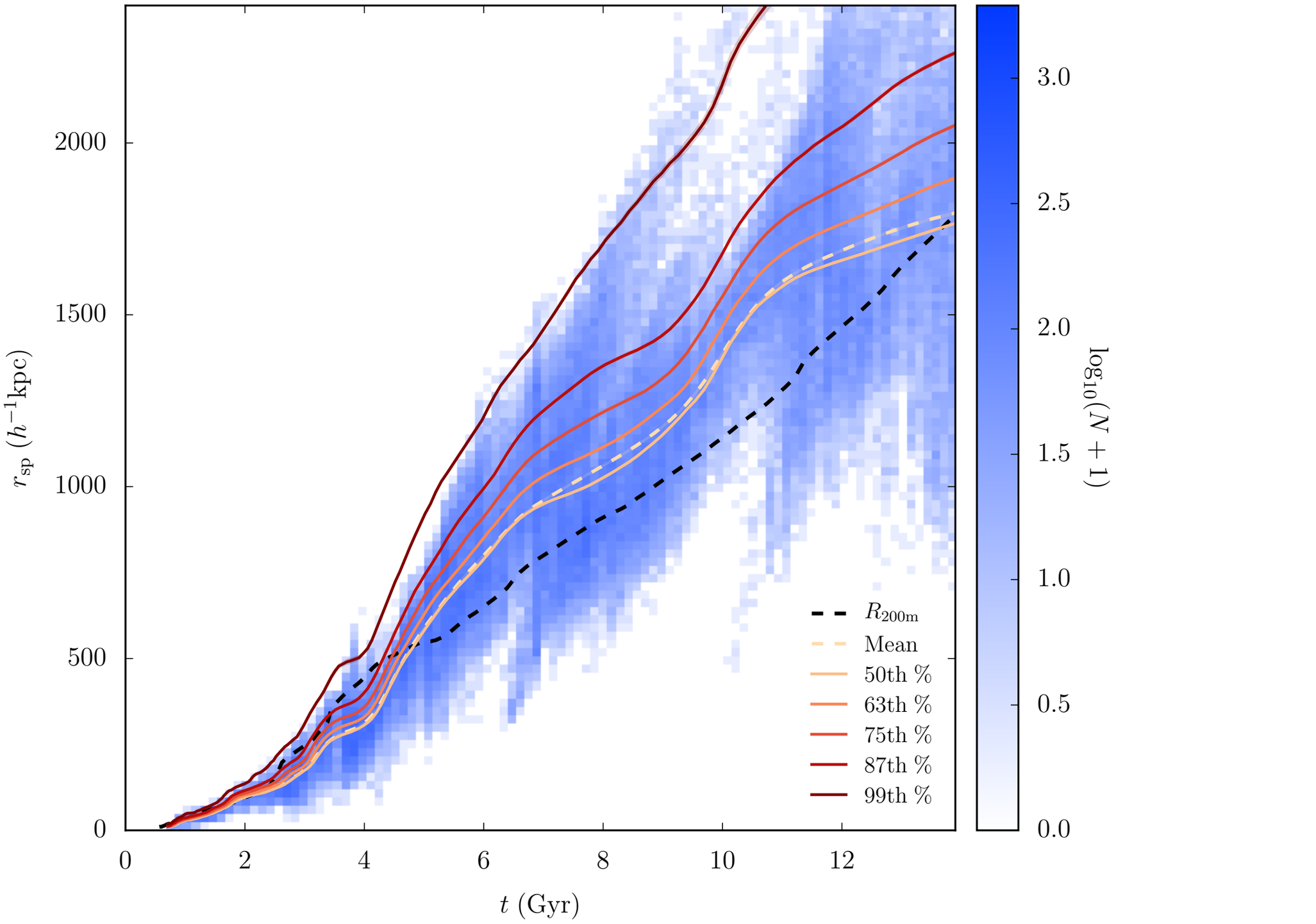



Diemer 2017

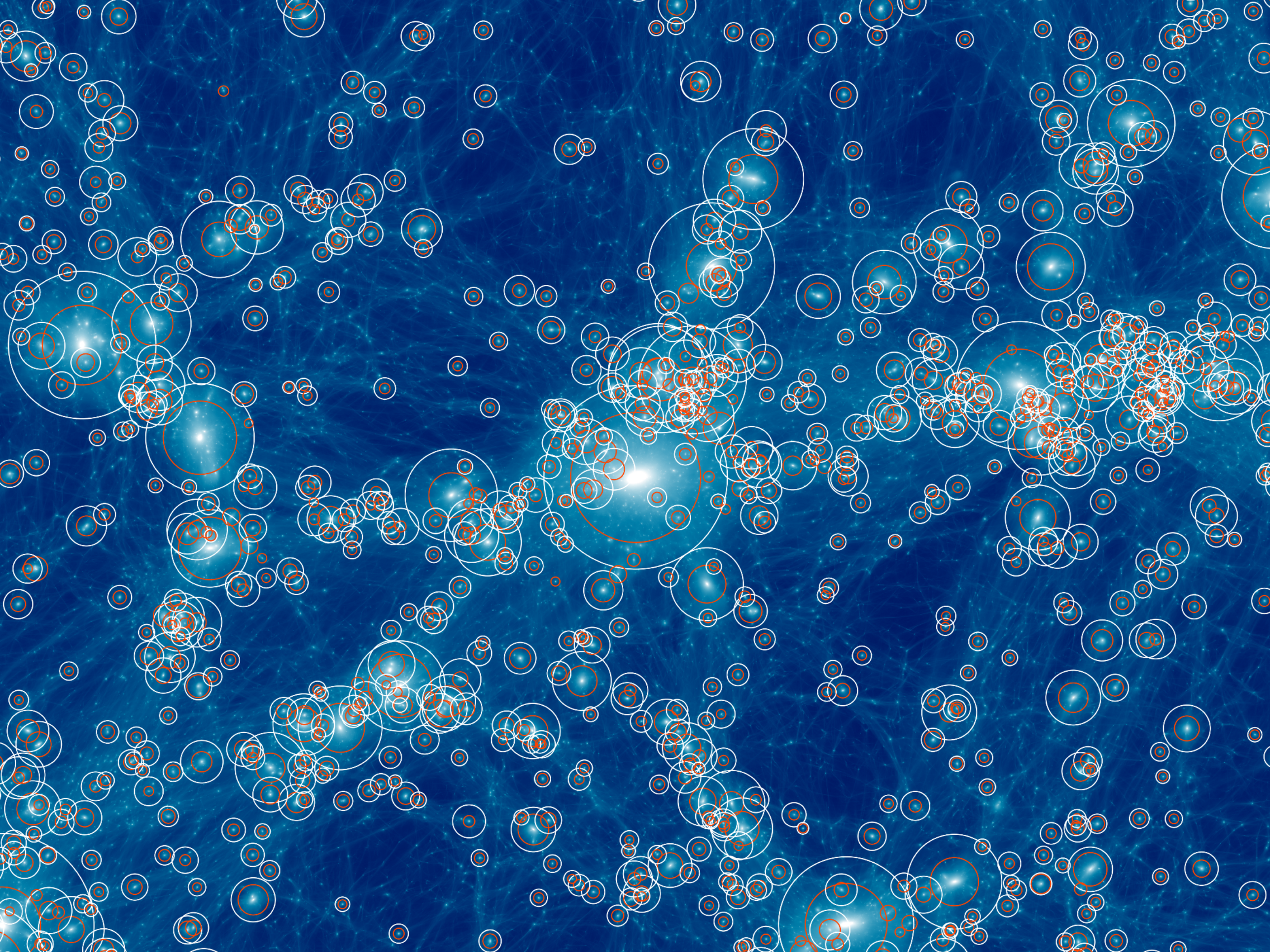
# Subhalo disruption



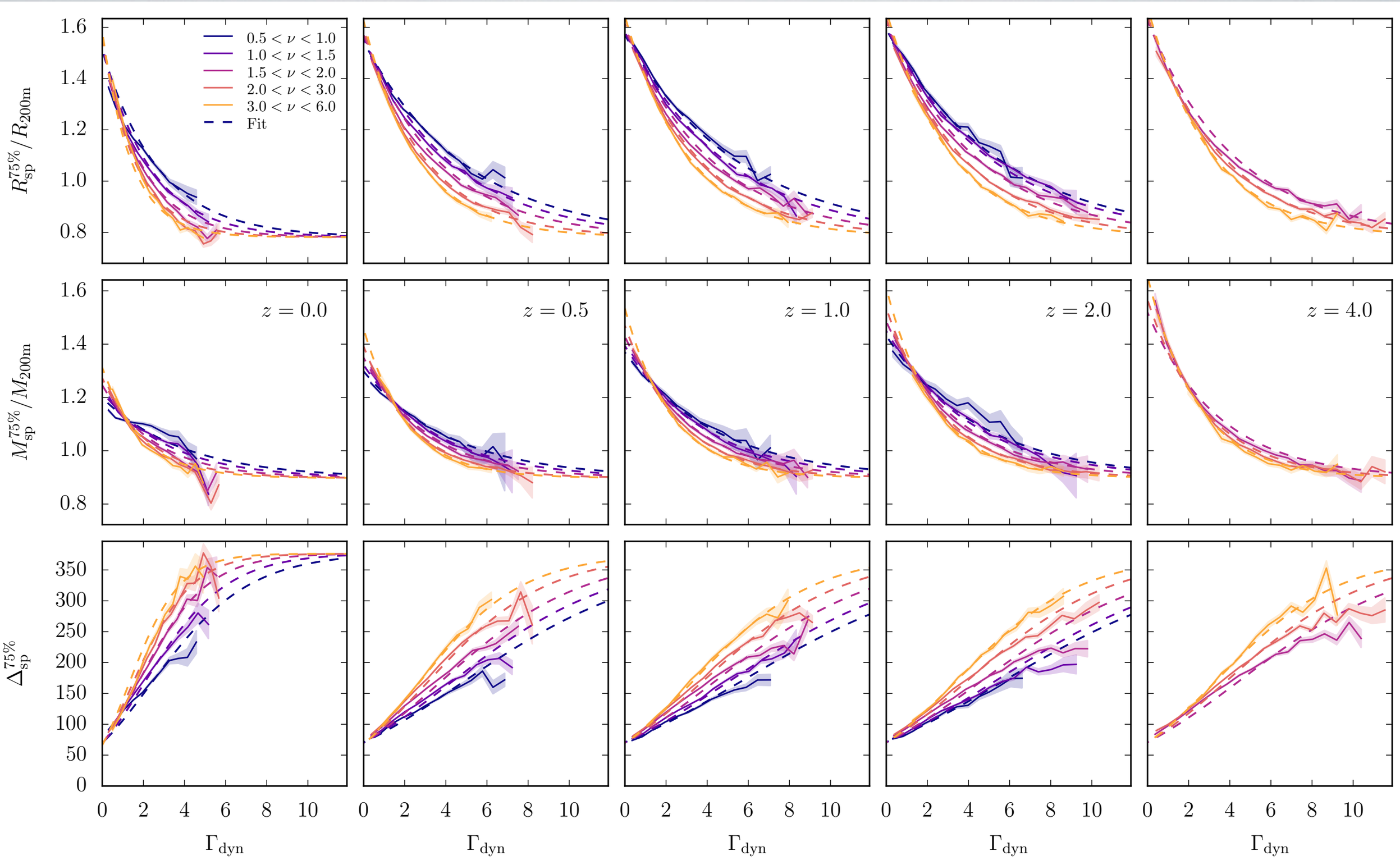
# Splashback in an individual halo




Diemer 2017



# The Γ-$R_{sp}$relation




Diemer et al. 2017

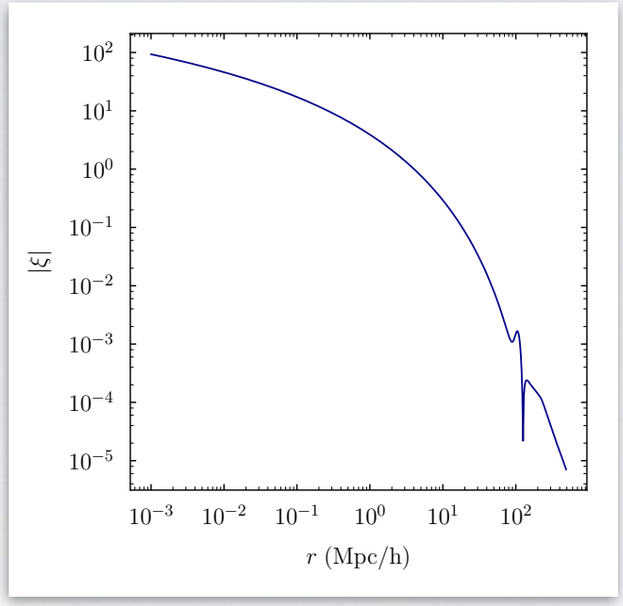
# COLOSSUS

## Cosmology, halos, and large-scale structure

## benediktdiemer.com/code/colossus

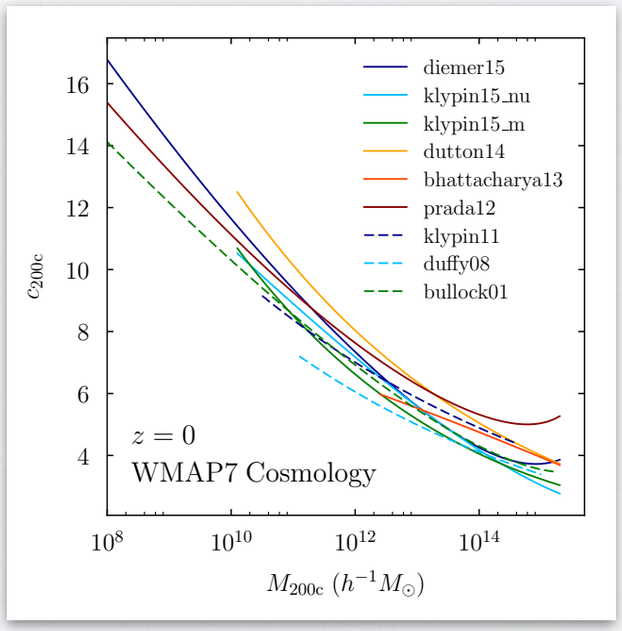

```
from colossus.cosmology import cosmology

cosmo = cosmology.setCosmology('WMAP9')
xi = cosmo.correlationFunction(10.0)
```




```
from colossus.halo import concentration as hc

cosmology.setCosmology('bolshoi')
c = hc.concentration(1E12, 'vir', 0.0,
      model = 'bullock01')
```




## Modules:

- Cosmology
- Power spectrum
- Gaussian random peaks
- Halo mass function
- Bias
- Density profiles
- Halo mass definitions
- Concentration
- Splashback
- …

**Code contributions:** Andrey Kravtsov, Matt Becker

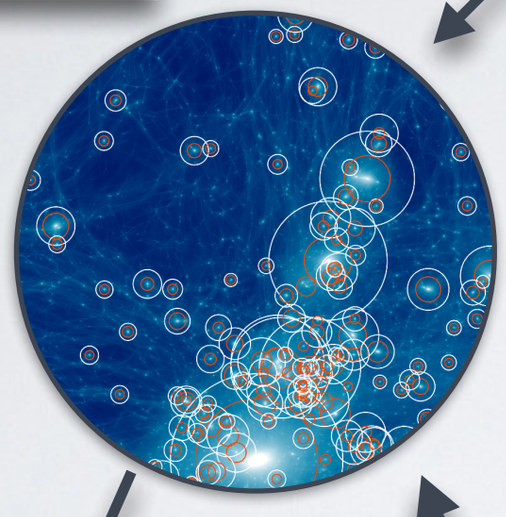
Diemer 2017

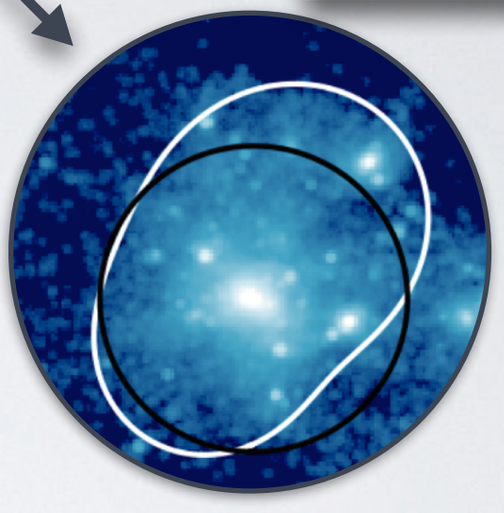
???

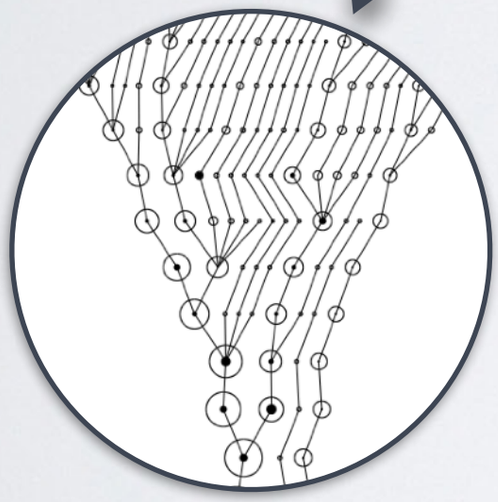
SPARTA

Splashback radii

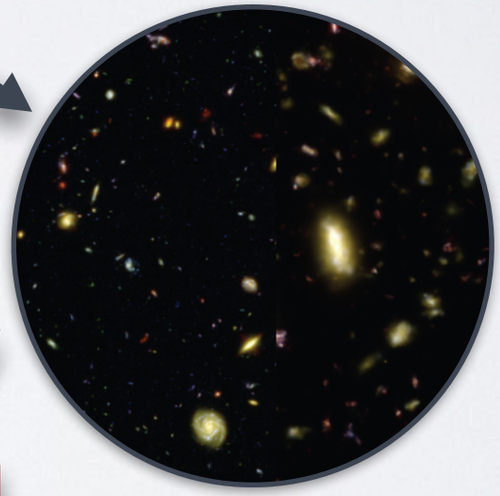
3D shells







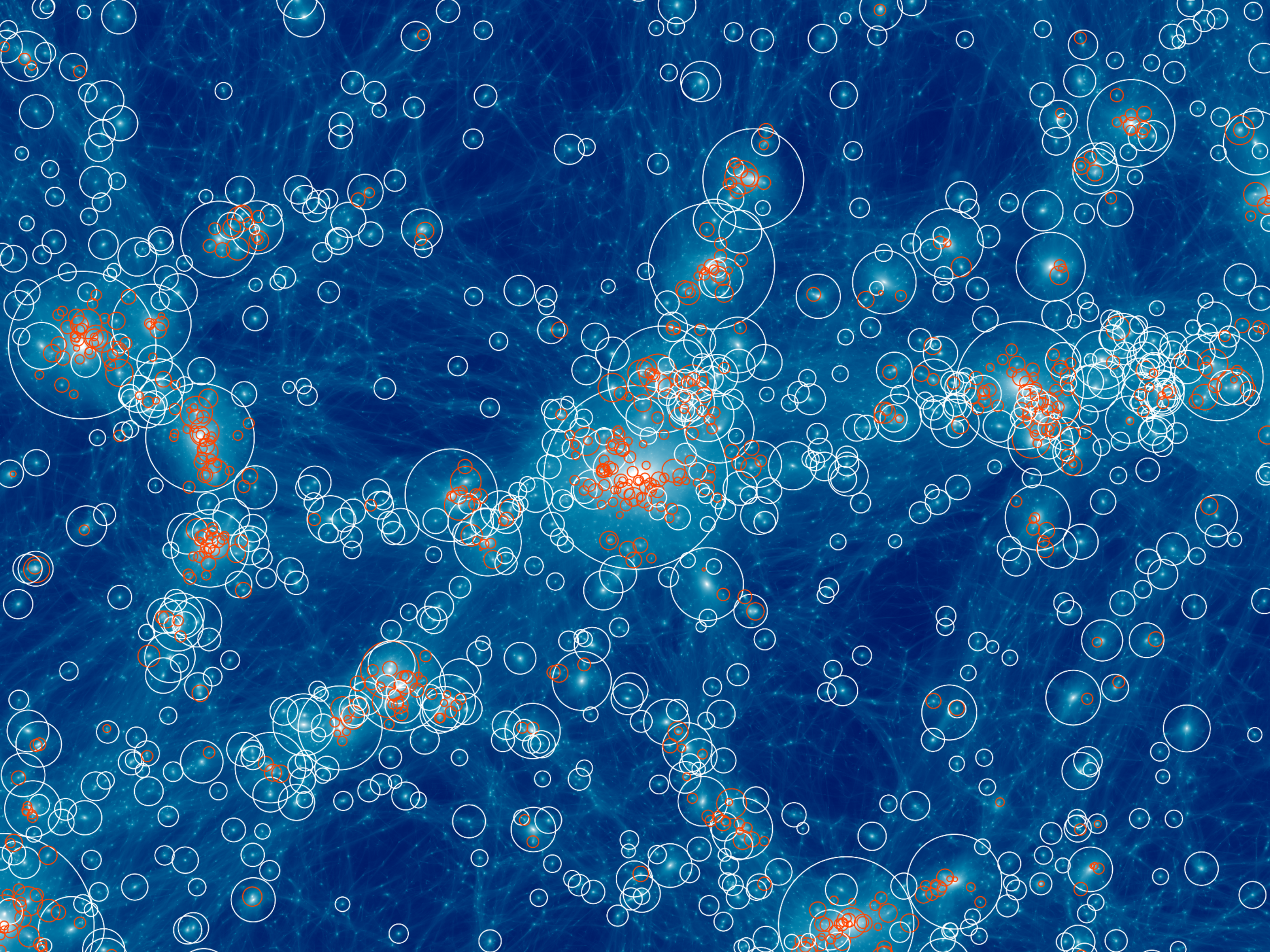
Illustris TNG



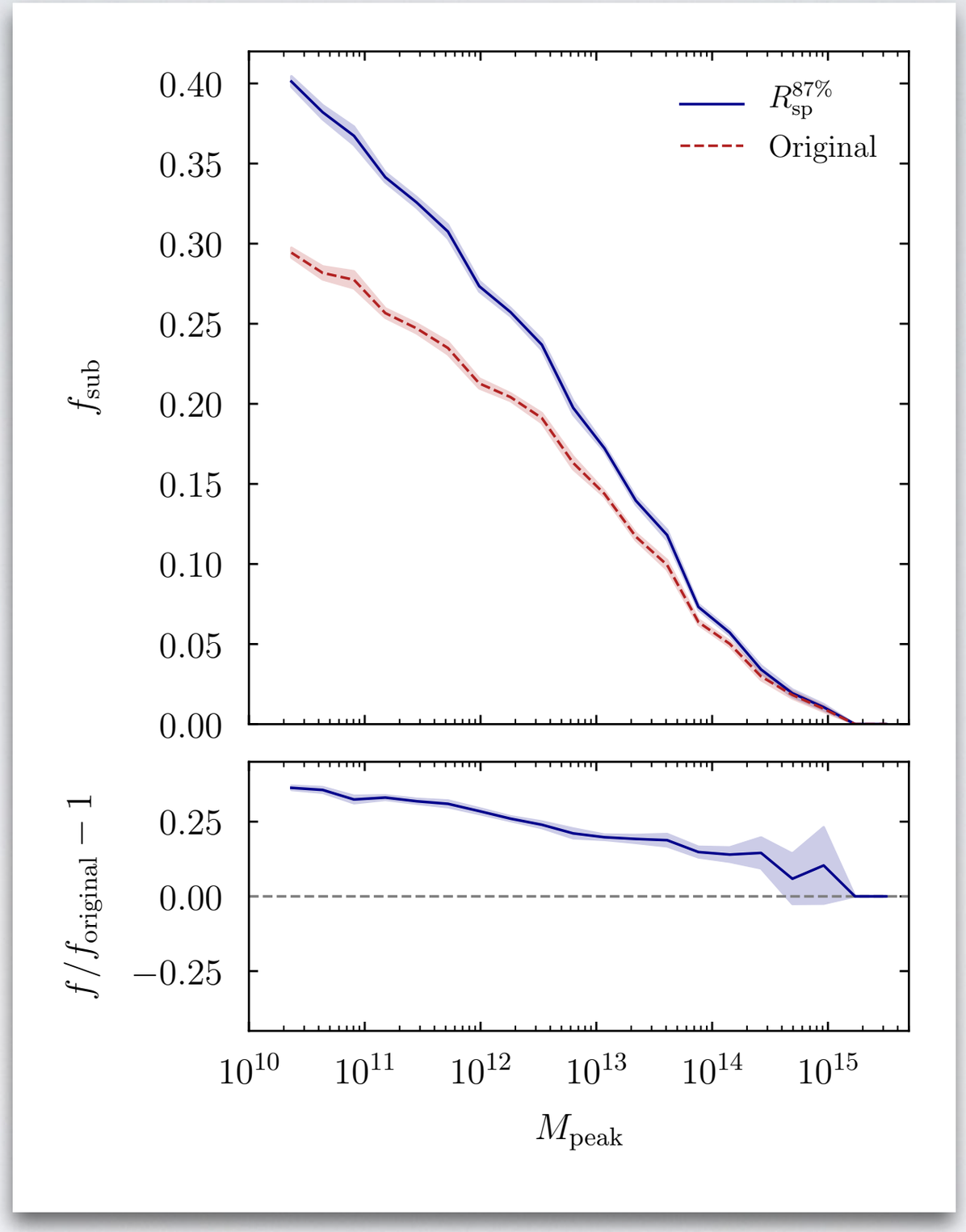
Merger trees, mass functions, accretion rates…

**Observations (weak lensing, cluster profiles)**

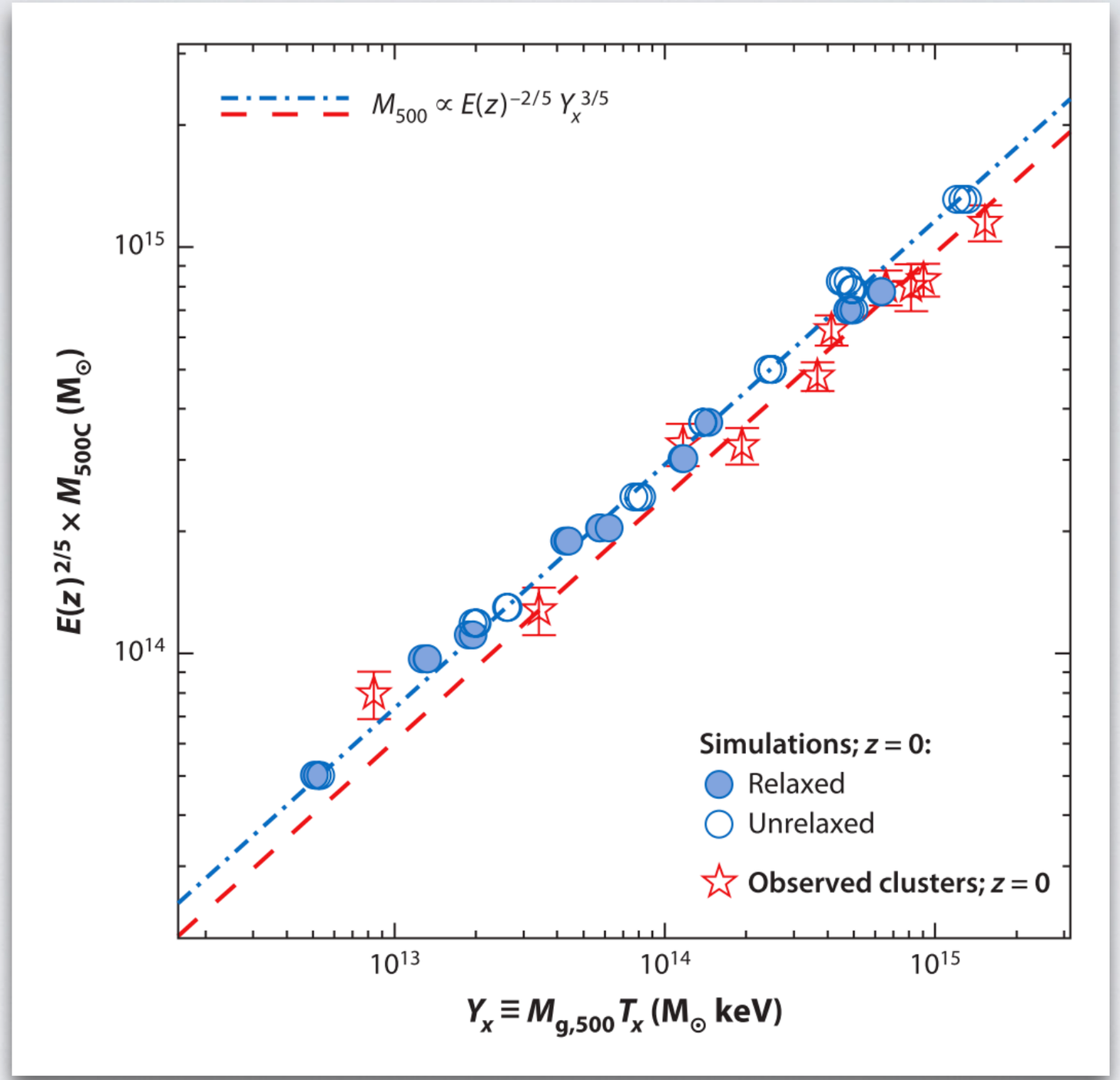
Predictions for obs. clusters



# Subhalo fraction

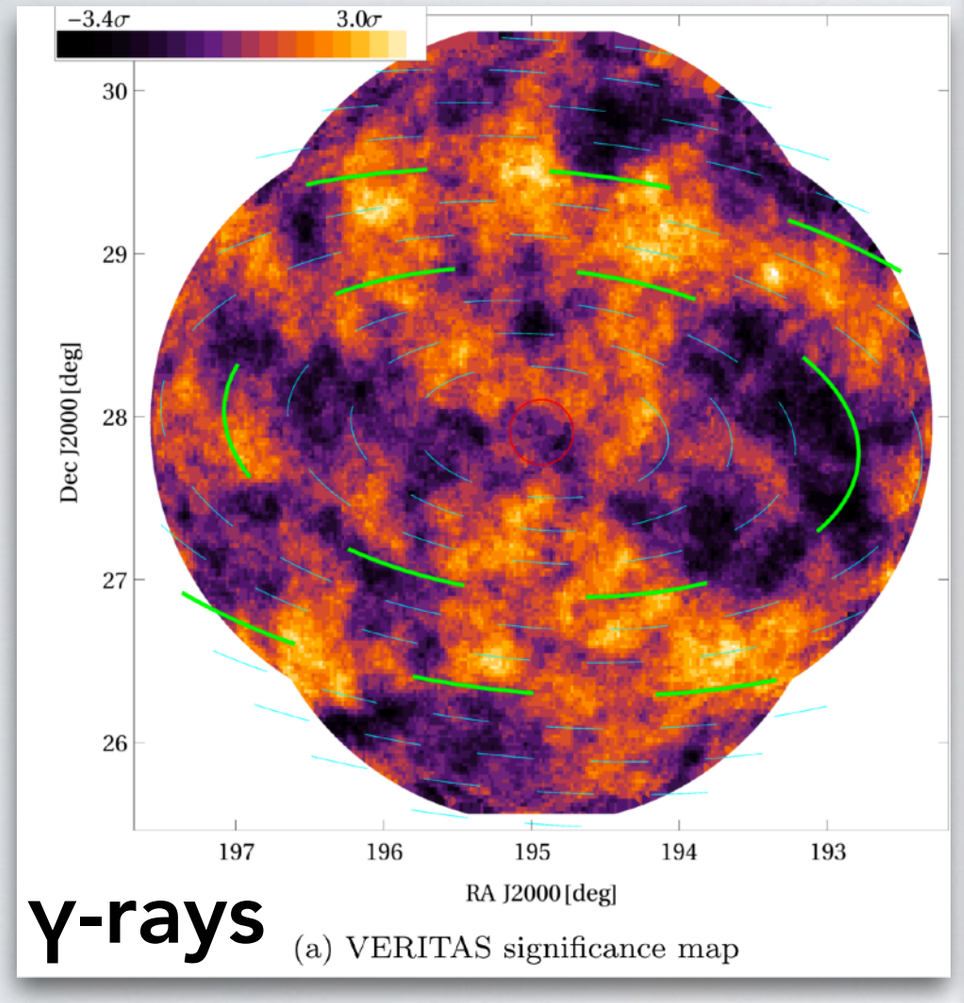


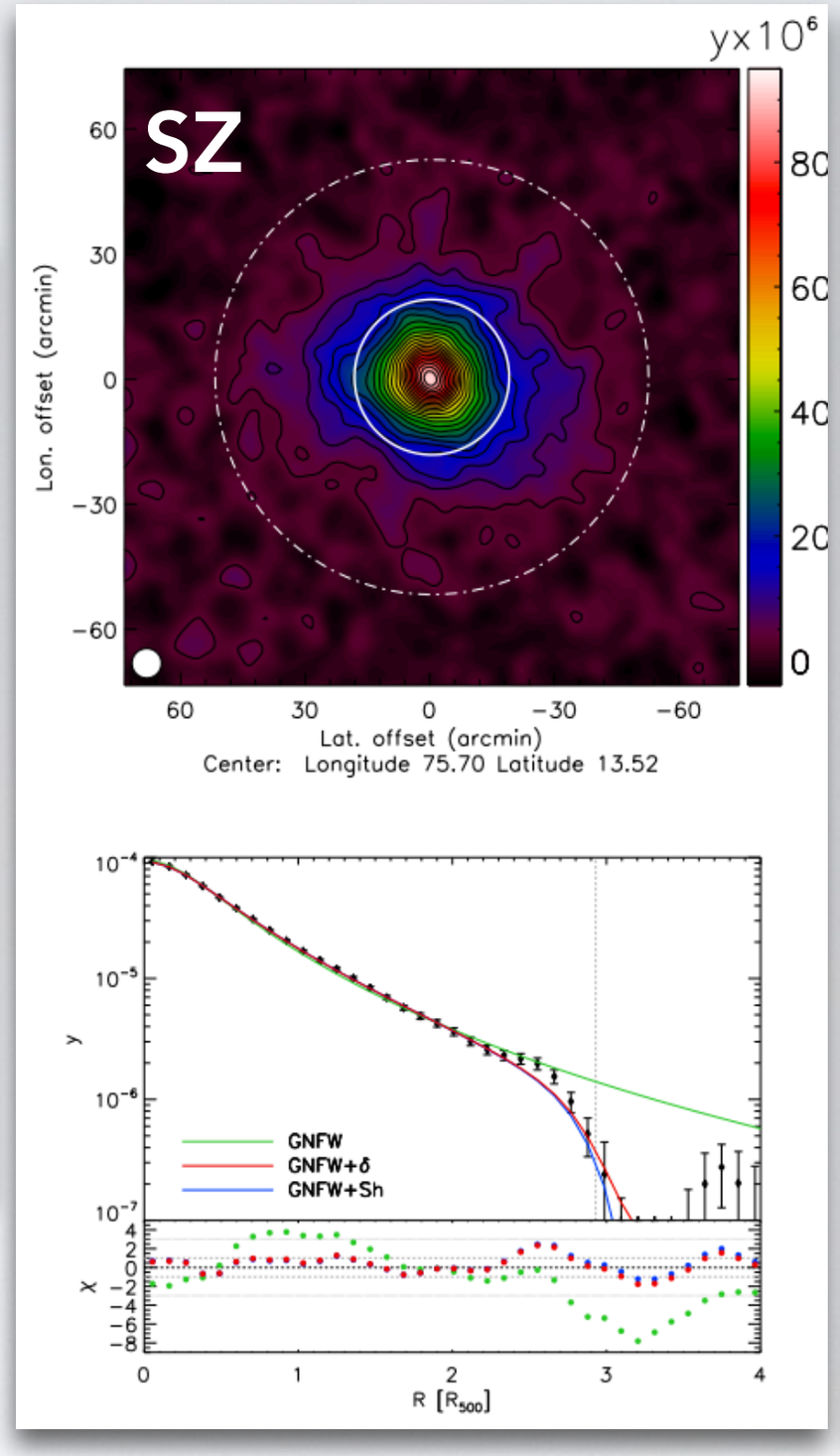
# Scaling relations

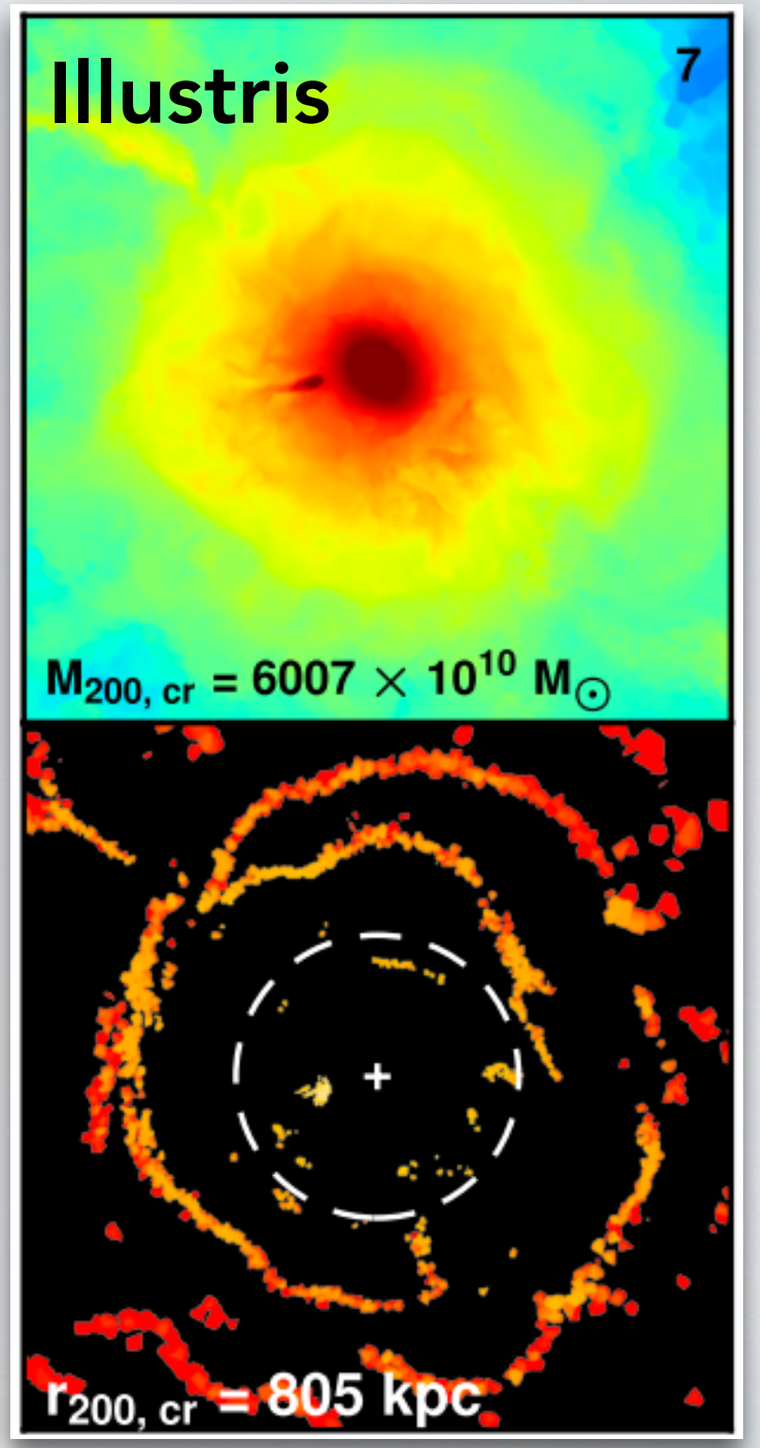



Kaiser 1986 • Kravtsov & Borgani 2012

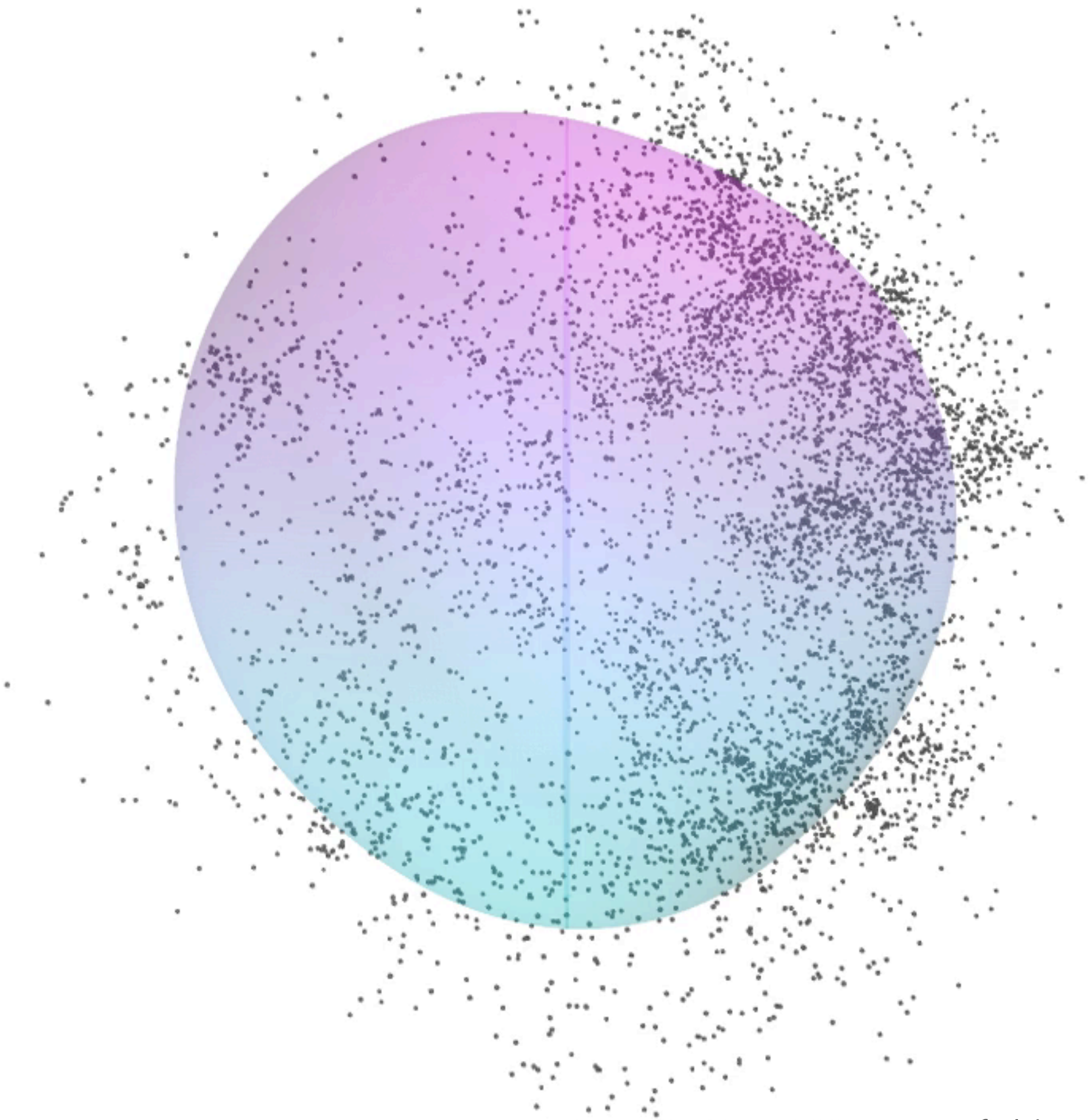
# A splashback-accretion shock relation?




Keshet et al. 2017ab • Hurier et al. 2017 • Schaal & Springel 2015 • Shi 2016

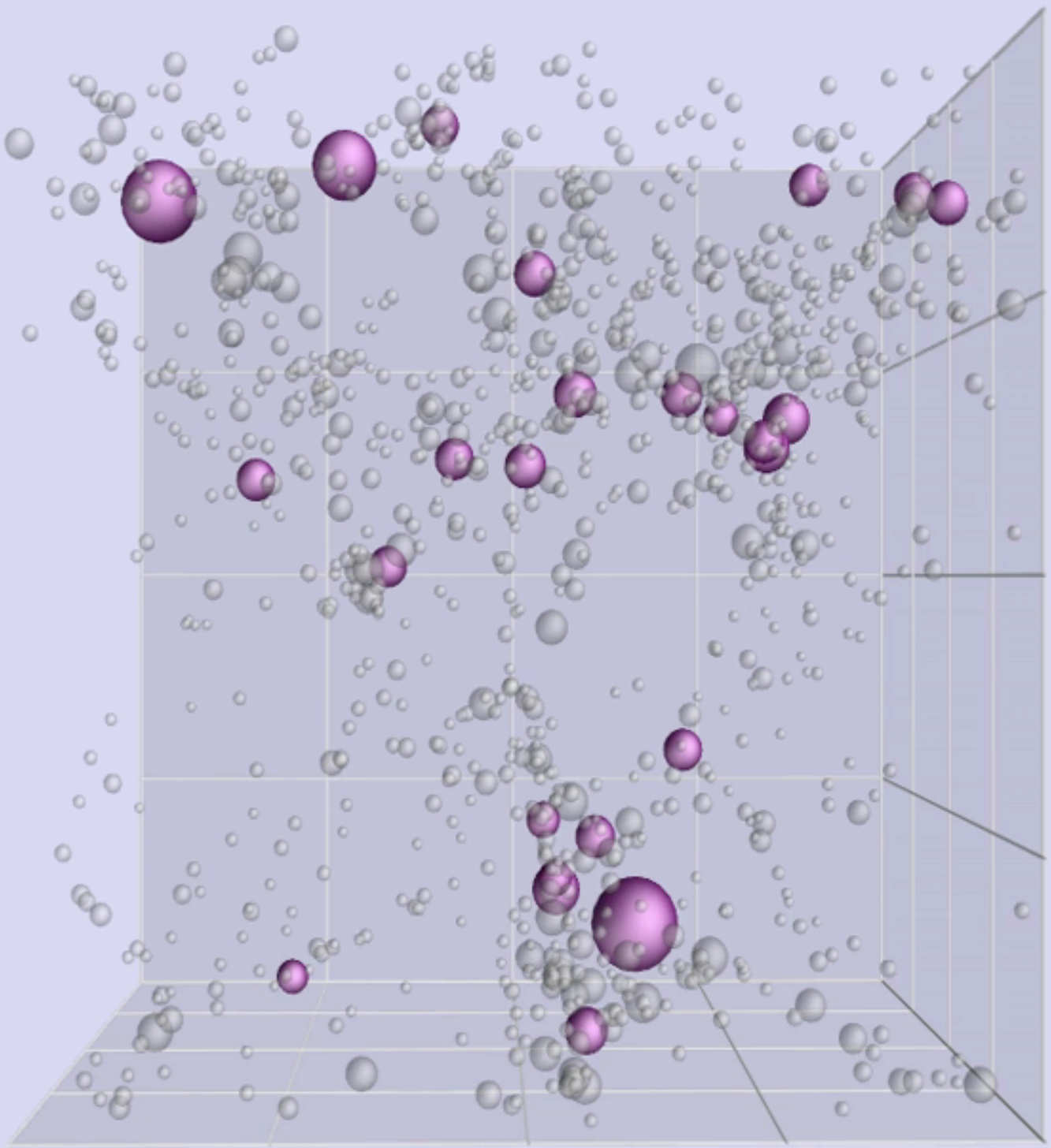


Penna & Dines 2007 • Mansfield, Kravtsov & Diemer 2017

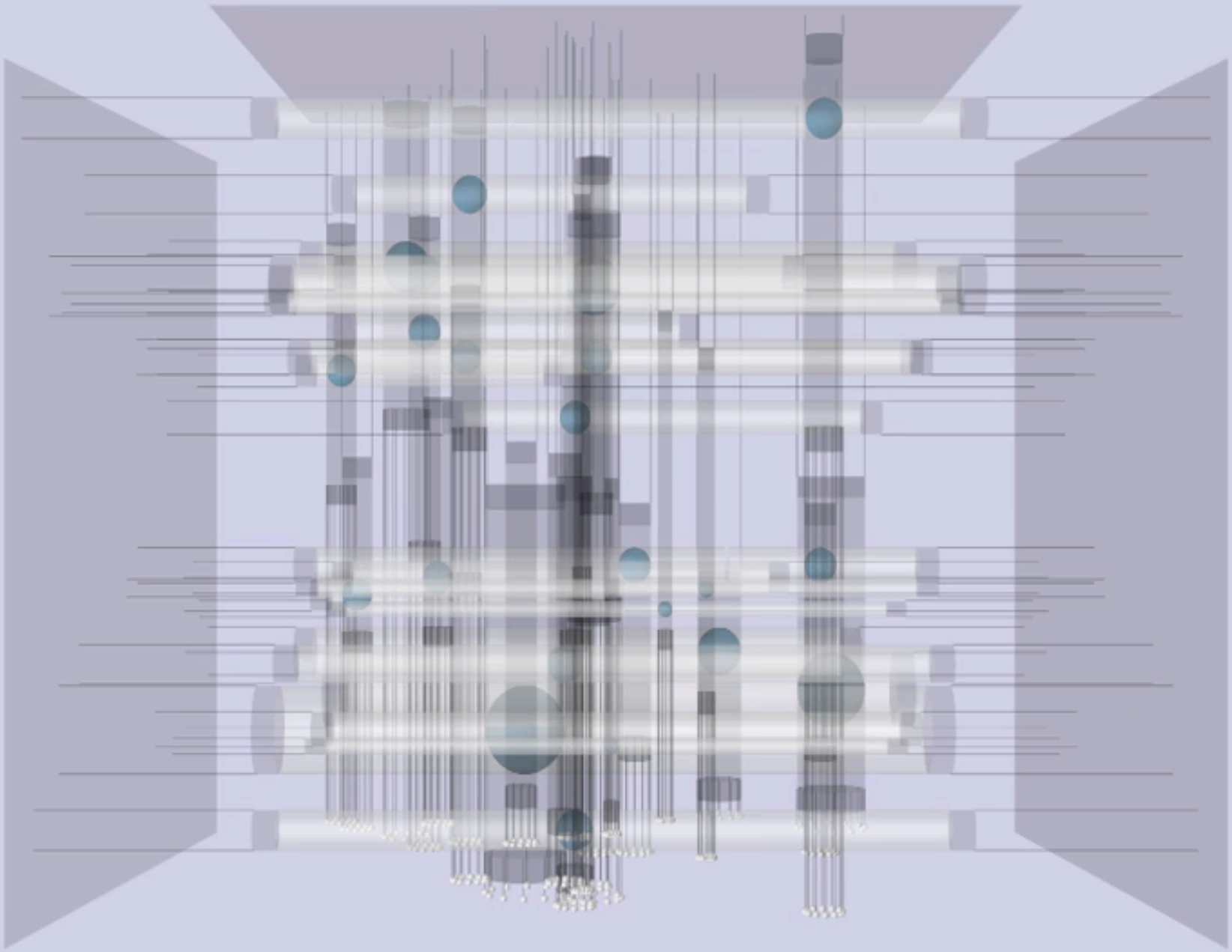
Diemer & Facio 2017 • The Fabric of the Universe

Diemer & Facio 2017 • The Fabric of the Universe

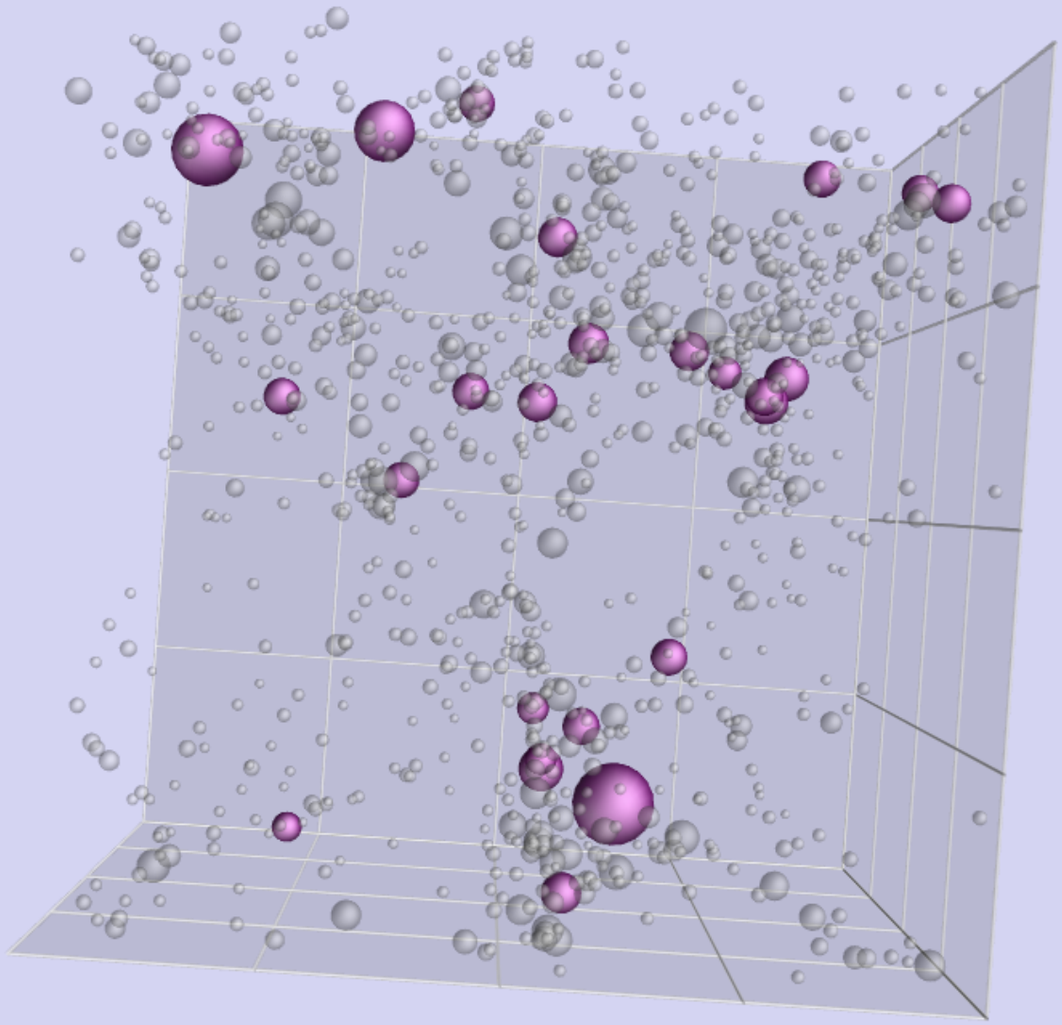
The Fabric of the Universe



The Fabric of the Universe



The Fabric of the Universe



# Conclusions

- The **structure of CDM halos** is not a solved problem

- The **splashback radius** provides a physical halo boundary

- **SPARTA** and **SHELLFISH** provide entirely new ways of analyzing N-body simulations


Diemer & Kravtsov 2014 • ApJ 789, 1 • arXiv 1401.01216
More, Diemer & Kravtsov 2015 • ApJ 810, 36 • arXiv 1504.05591
Mansfield, Kravtsov & Diemer 2017 • arXiv 1612.01531
Diemer 2017 • arXiv 1703.09712
Diemer et al. 2017 • arXiv 1703.09716