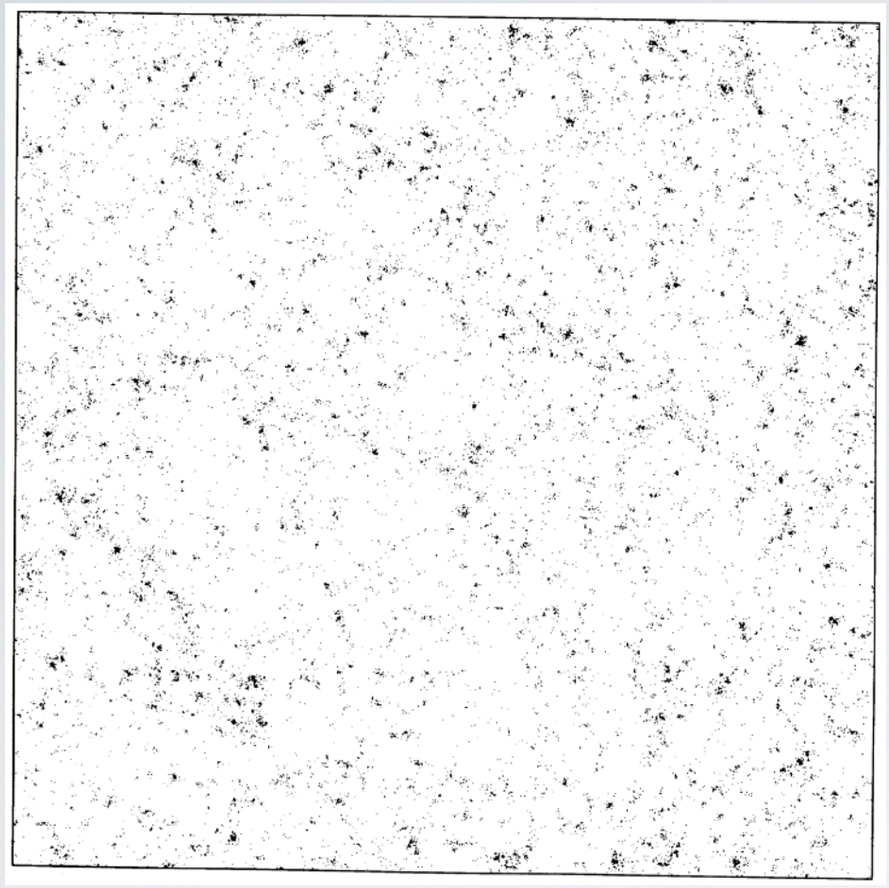
Universality, history, and circumstance: On the structure and boundary of CDM halos

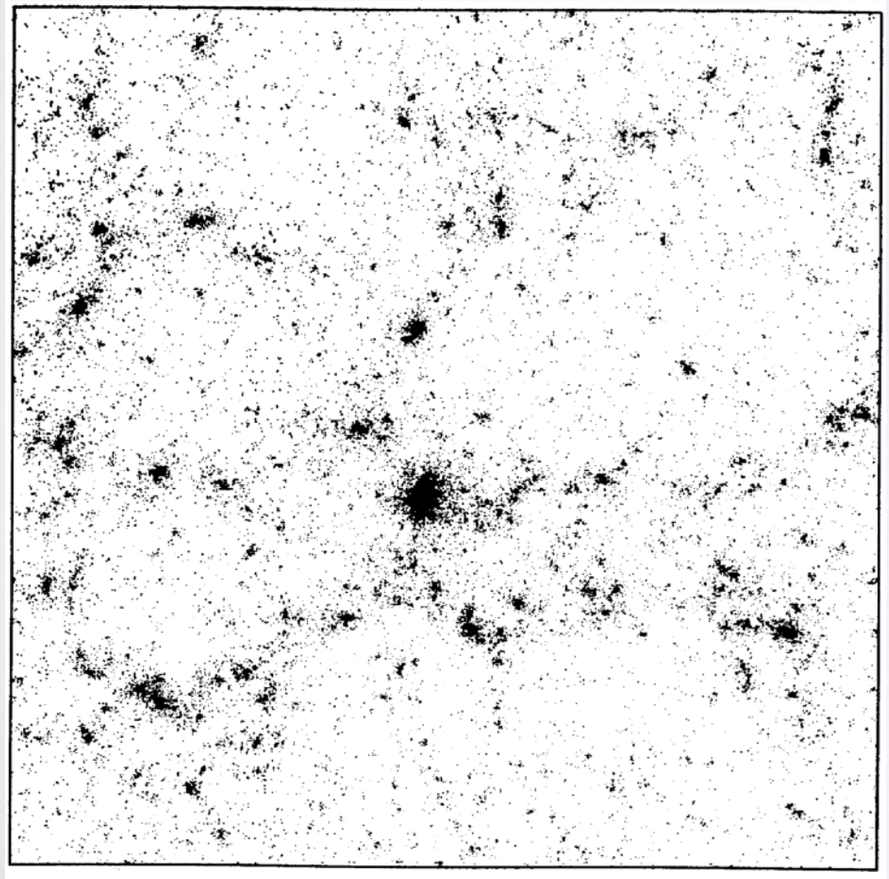
Benedikt Diemer
ITC Fellow, Harvard-Smithsonian Center for Astrophysics

Quantifying and understanding the galaxy-halo connection • KITP • 05/16/17

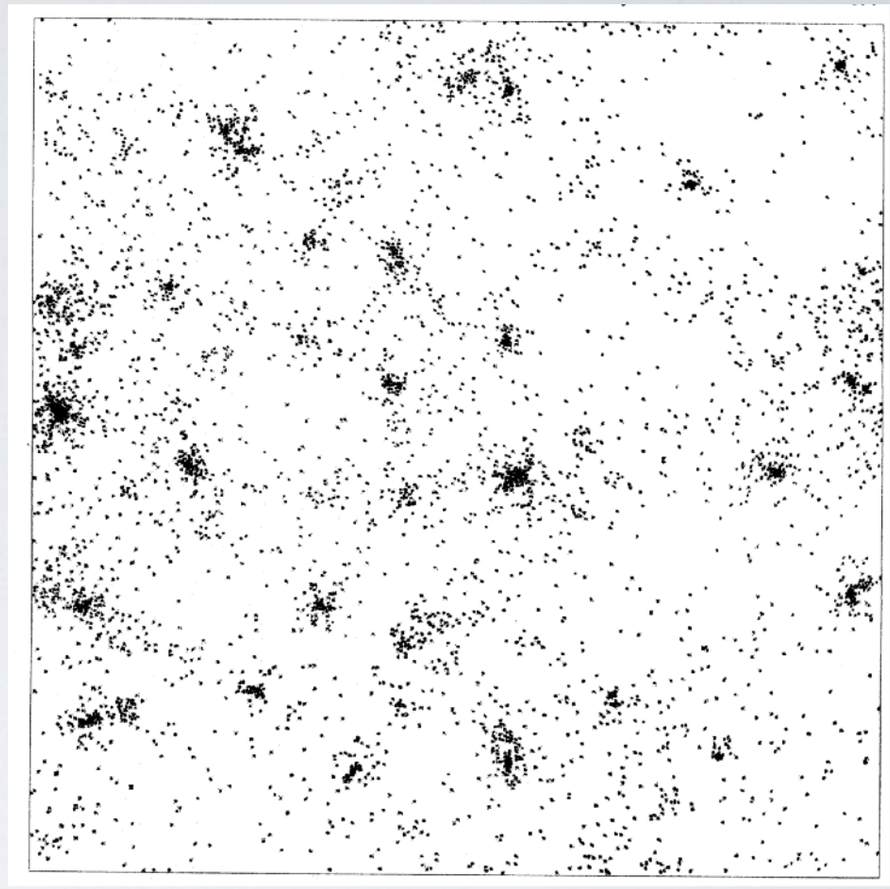
Efstathiou et al. 1981



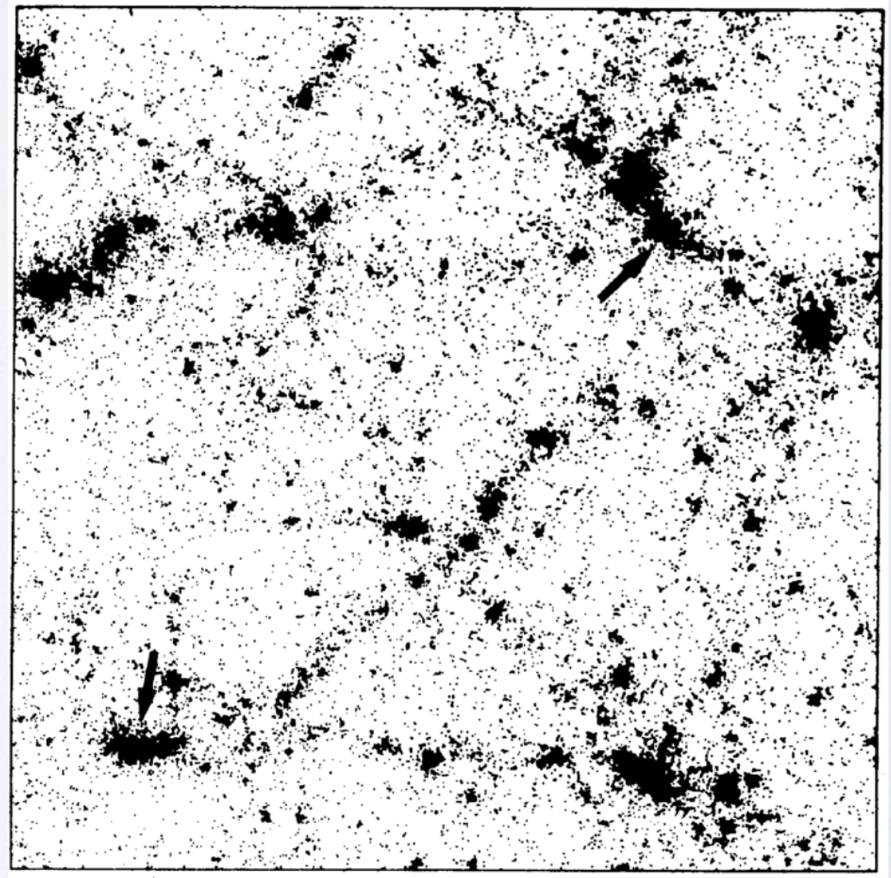
Davis et al. 1985



Klypin & Shandarin 1983

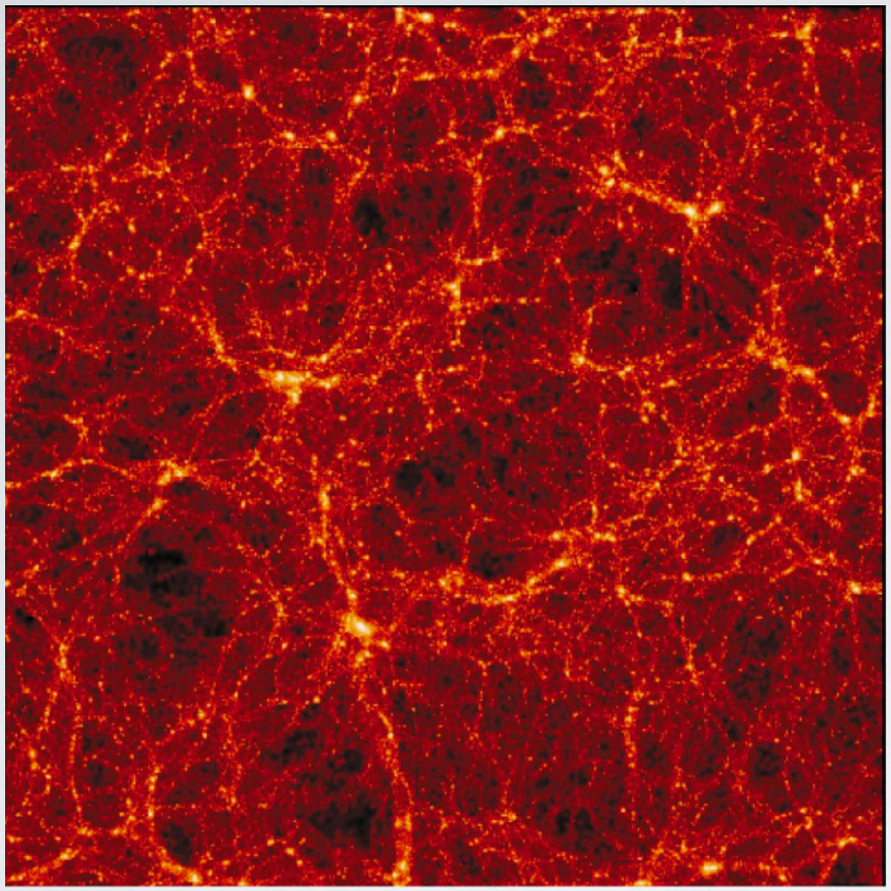


Frenk et al. 1988

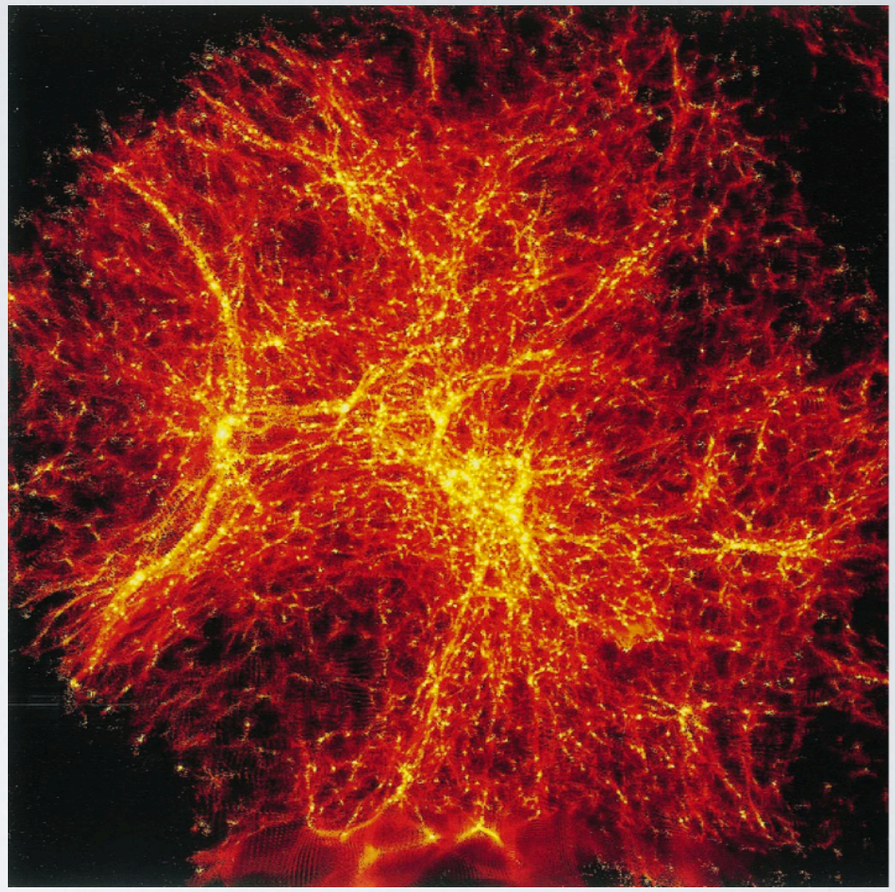


Efstathiou et al. 1981/1985/1988 • Klypin & Shandarin 1983 • Frenk et al. 1983/1985/1988 • Davis et al. 1985

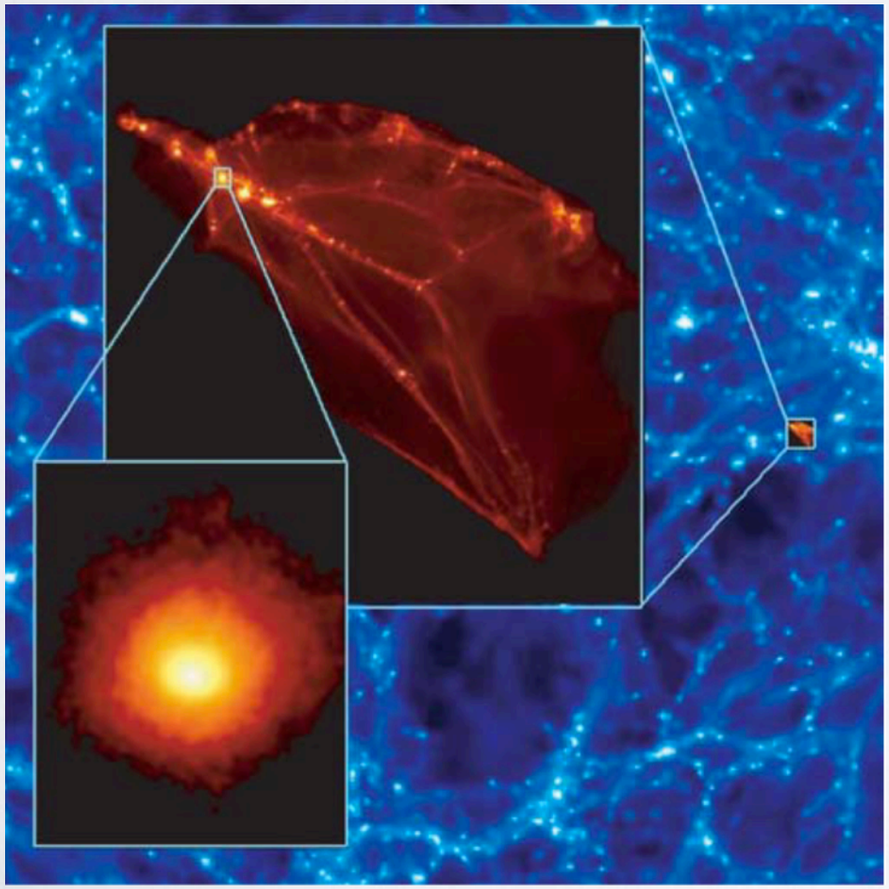
Jenkins et al. 1998



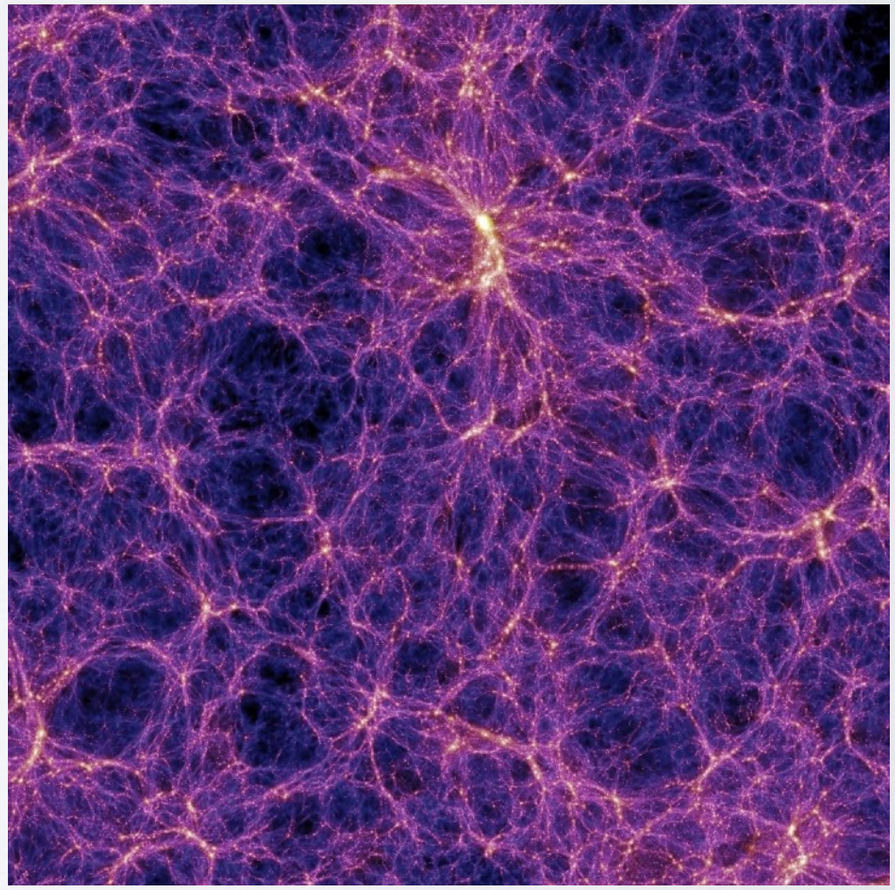
Moore et al. 1999



Diemand et al. 2005

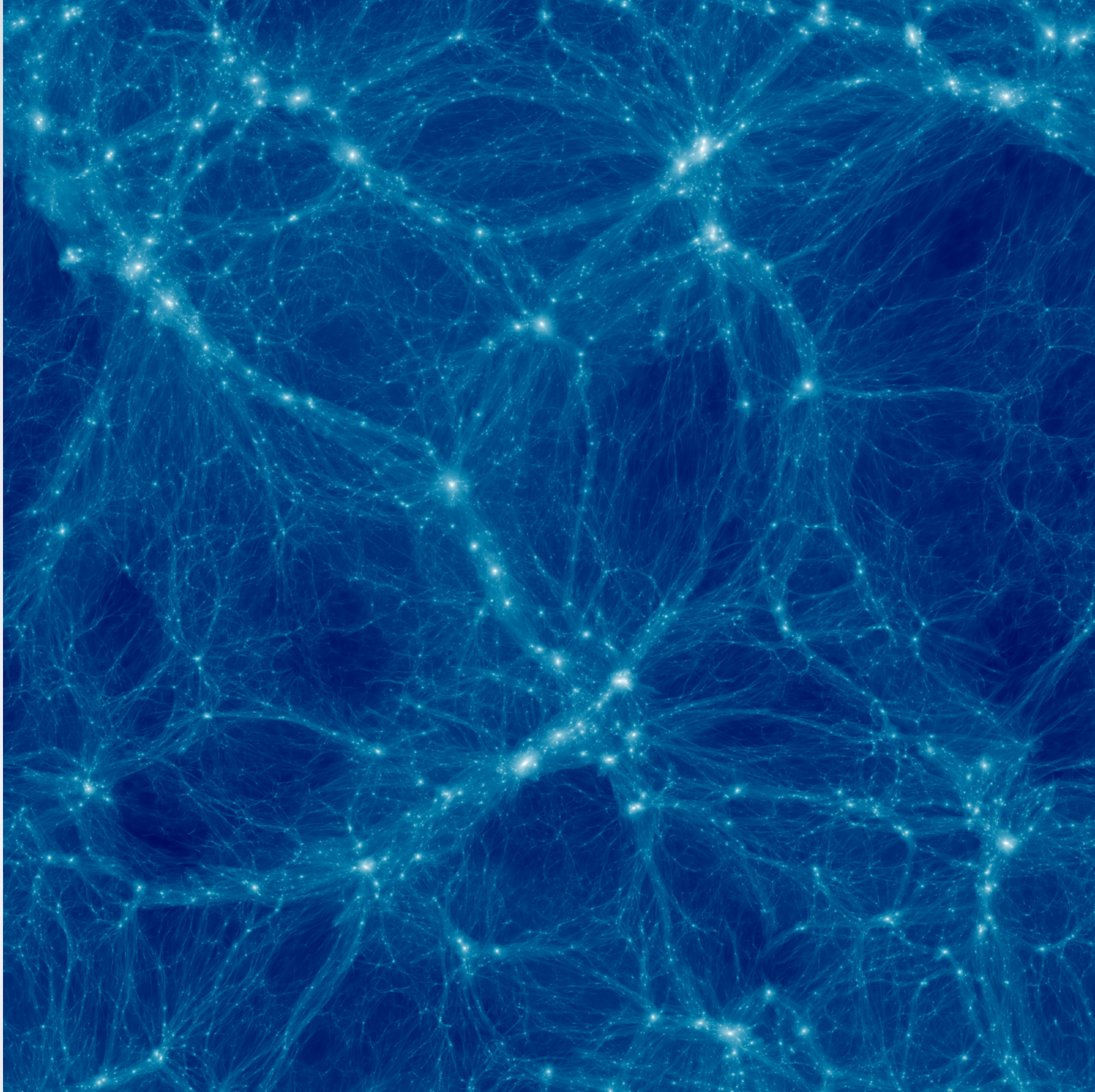


Springel et al. 2005



Jenkins et al. 1998 • Moore et al. 1999 • Diemand et al. 2005 • Springel et al. 2005/2008 • Klypin et al. 2011

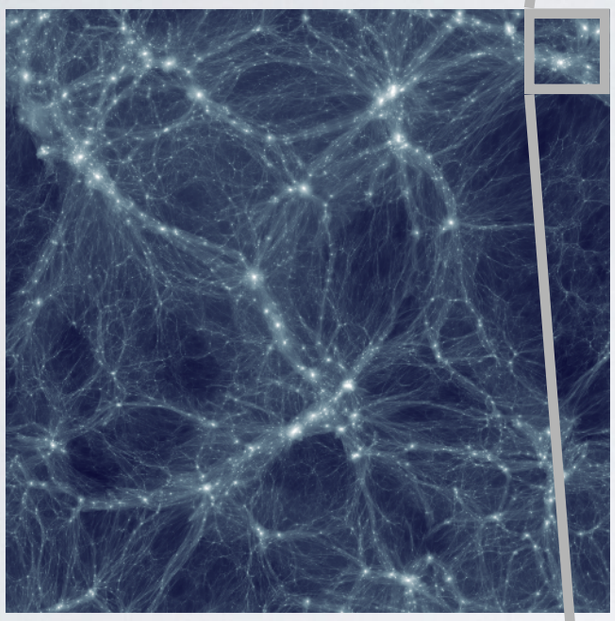
89 Mpc



Simulation:
Benedikt Diemer
(Gadget2)

Visualization code:
Philip Mansfield

11 Mpc



Halo finder: Rockstar
(Behroozi et al. 2013)

11 Mpc

Not talking about…

Halo finding, subhalos, and numerical issues

Number of halos (mass function)

Position of halos (correlation function, assembly bias…)

Baryonic effects & hydro sims

Talking about…

What do we mean by “halo”?

Which structural properties do we use for the galaxy-halo connection?

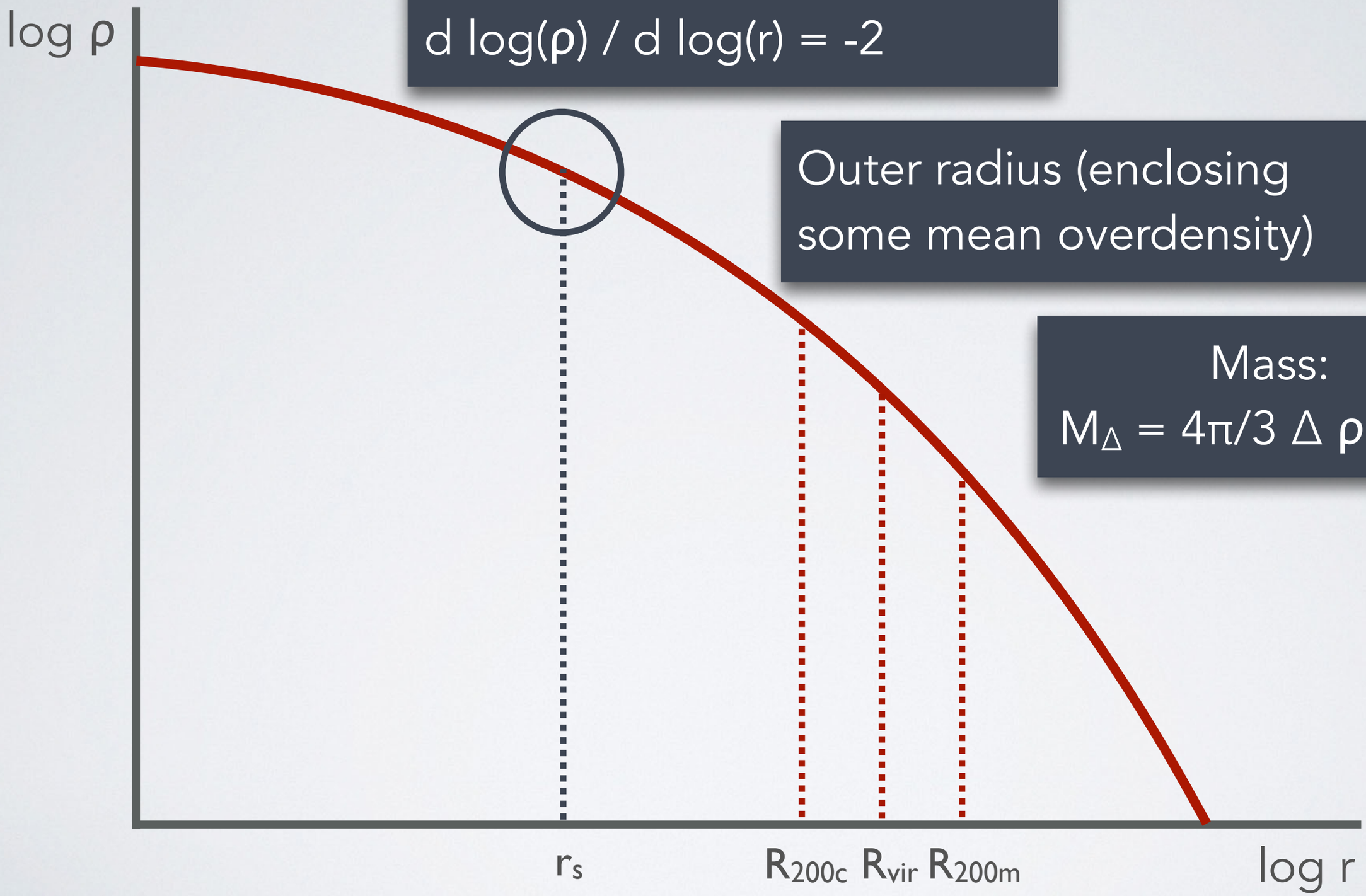
Halo finder: Rockstar
(Behroozi et al. 2013)

Density profile

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

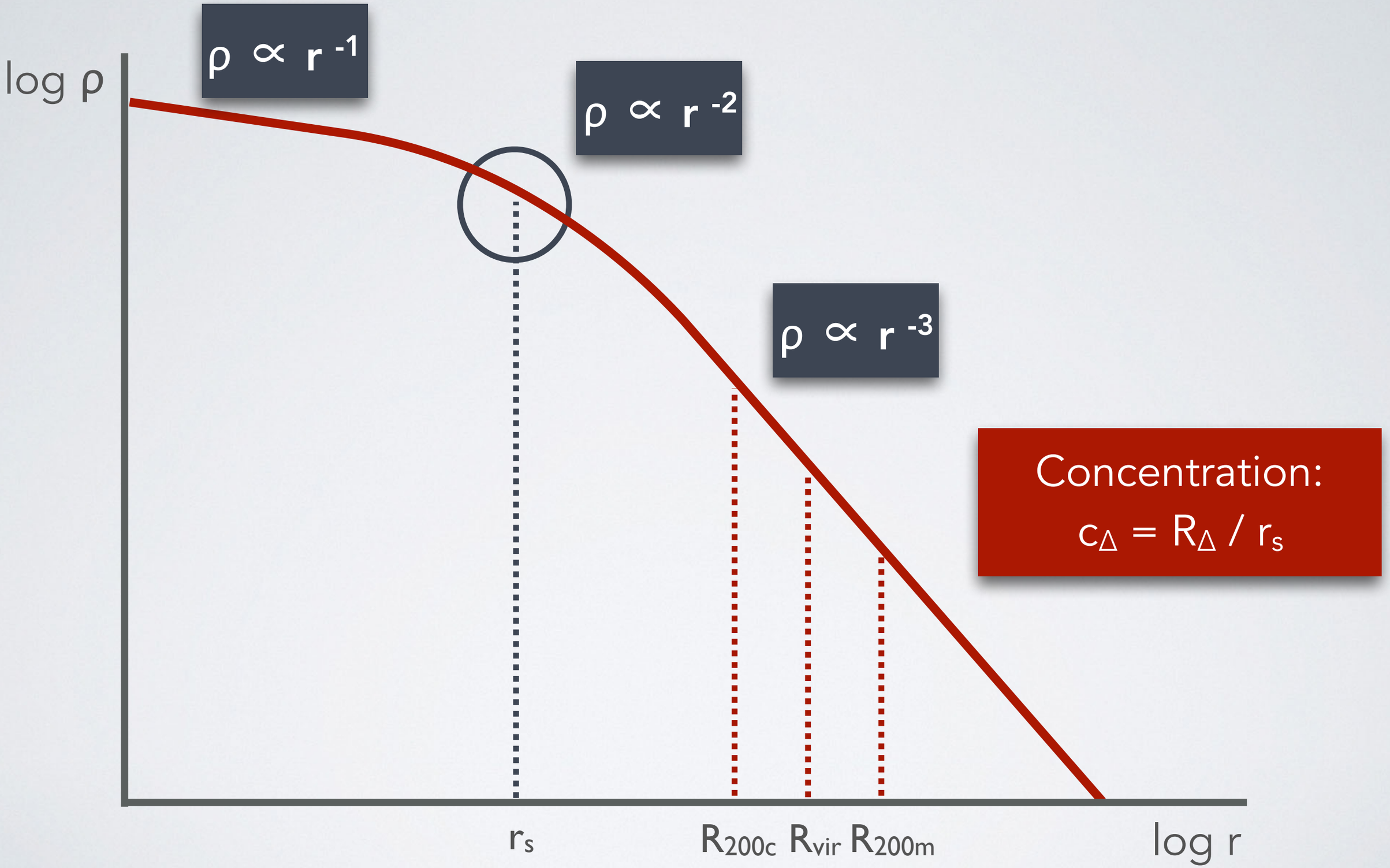
Outer radius (enclosing some mean overdensity)

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



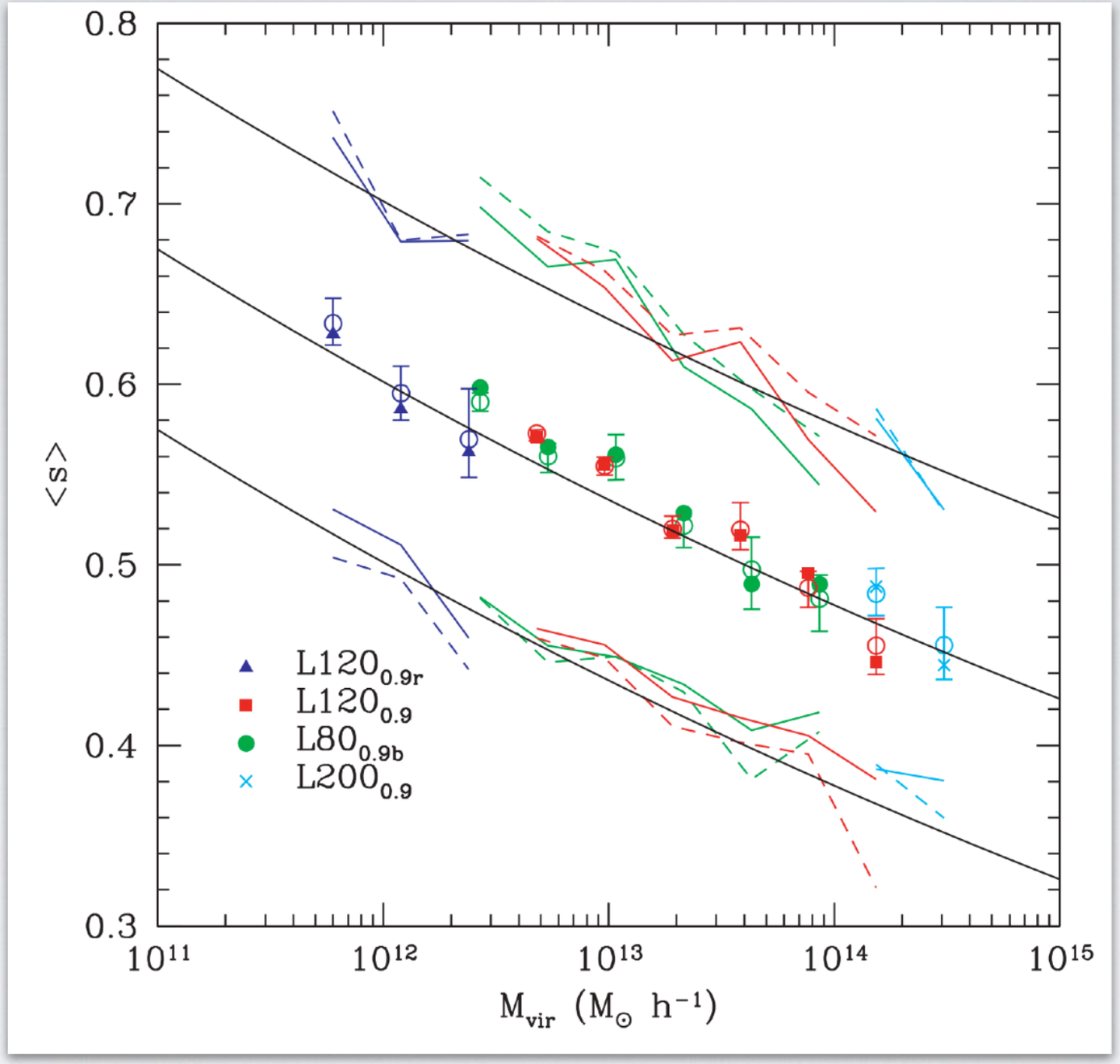
Einasto 1965 • Frenk et al. 1988 • Hernquist 1990 • Dubinski & Carlberg 1991
Navarro et al.1995/1996/1997/2004

Navarro-Frenk-White profile



Navarro et al. 1995/1996/1997

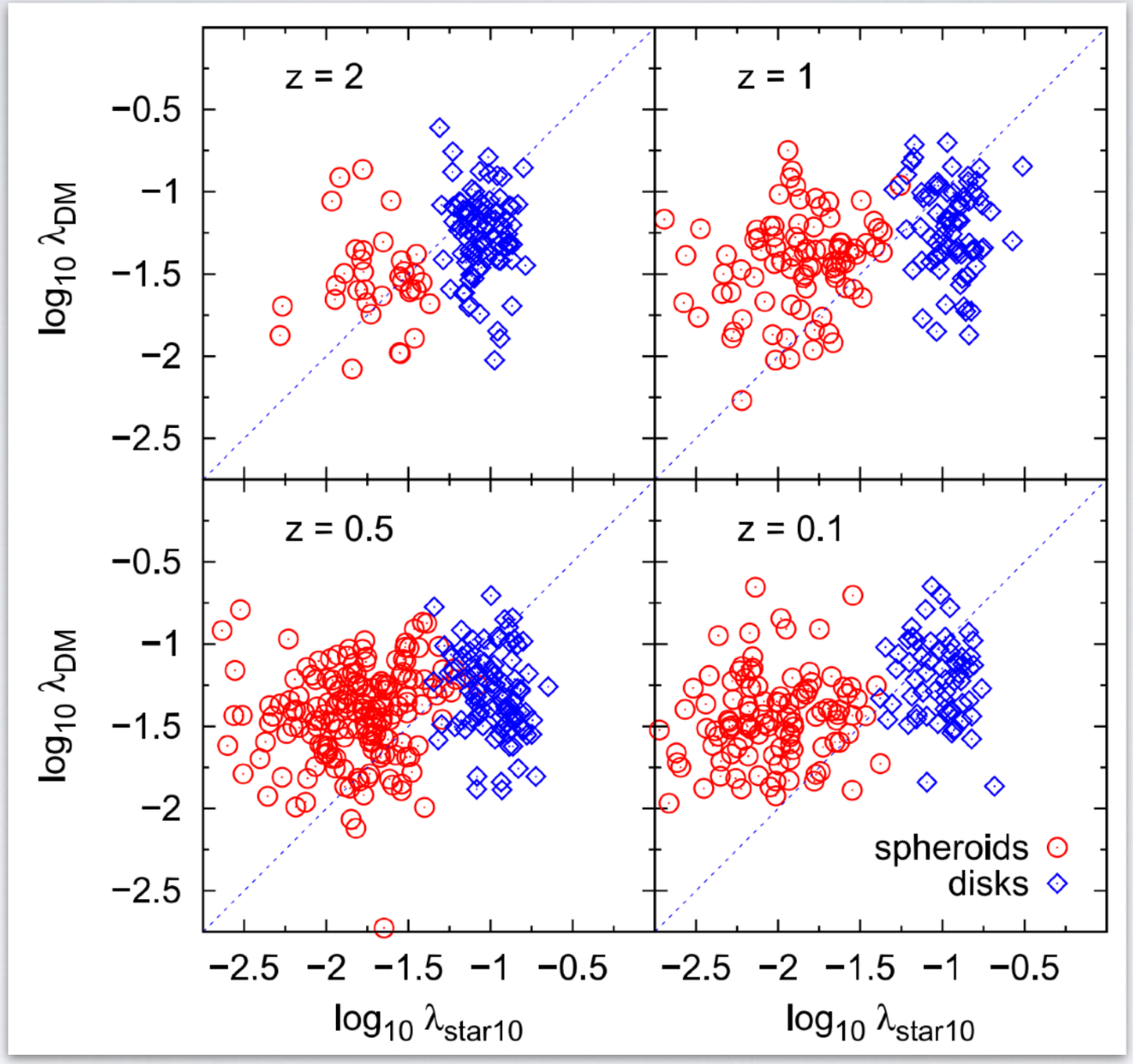
Shape



Halo mass

Cole & Lacey 1996 • Jing & Suto 2002 • Allgood et al. 2006 • Despali et al. 2014

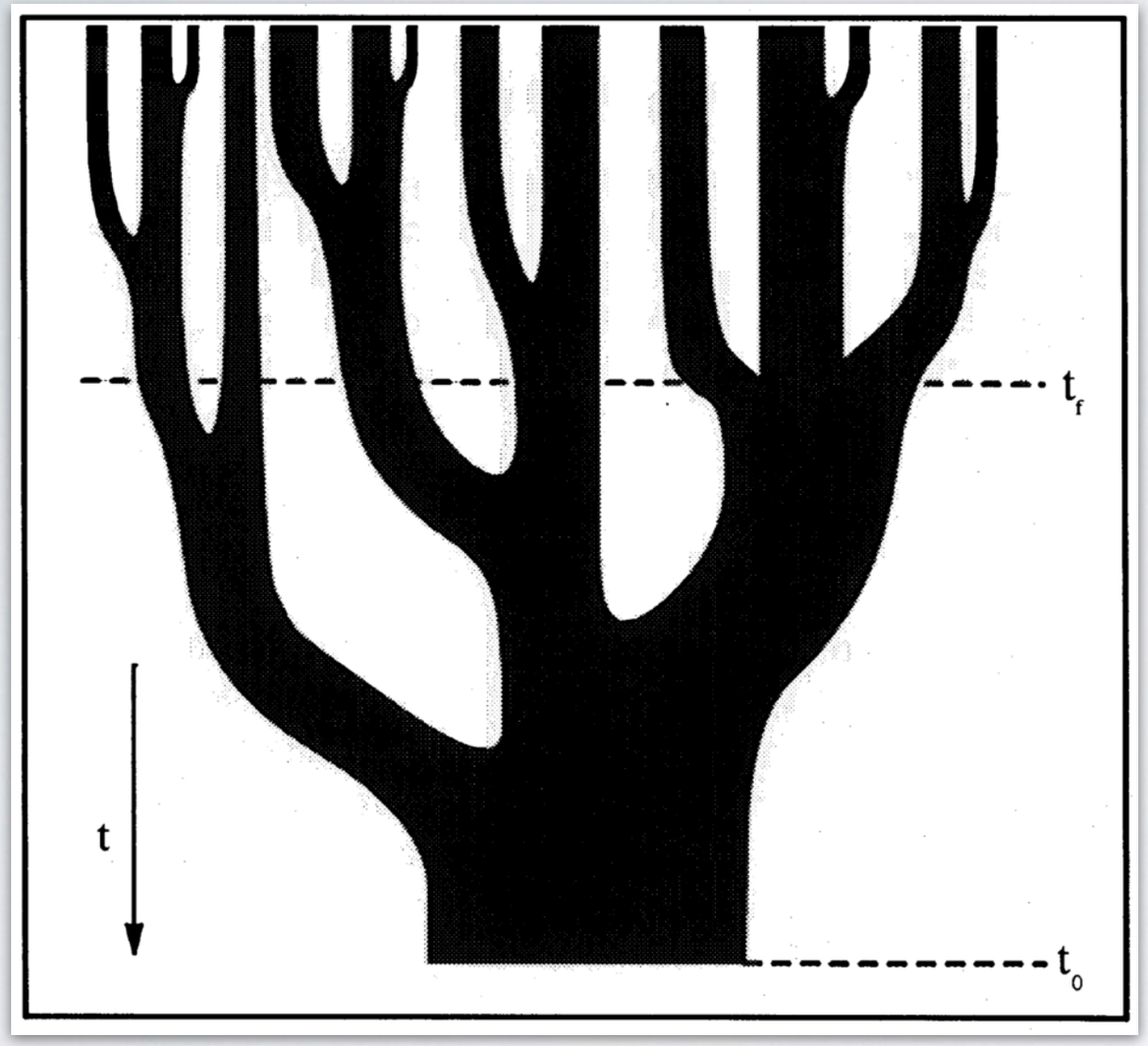
Spin



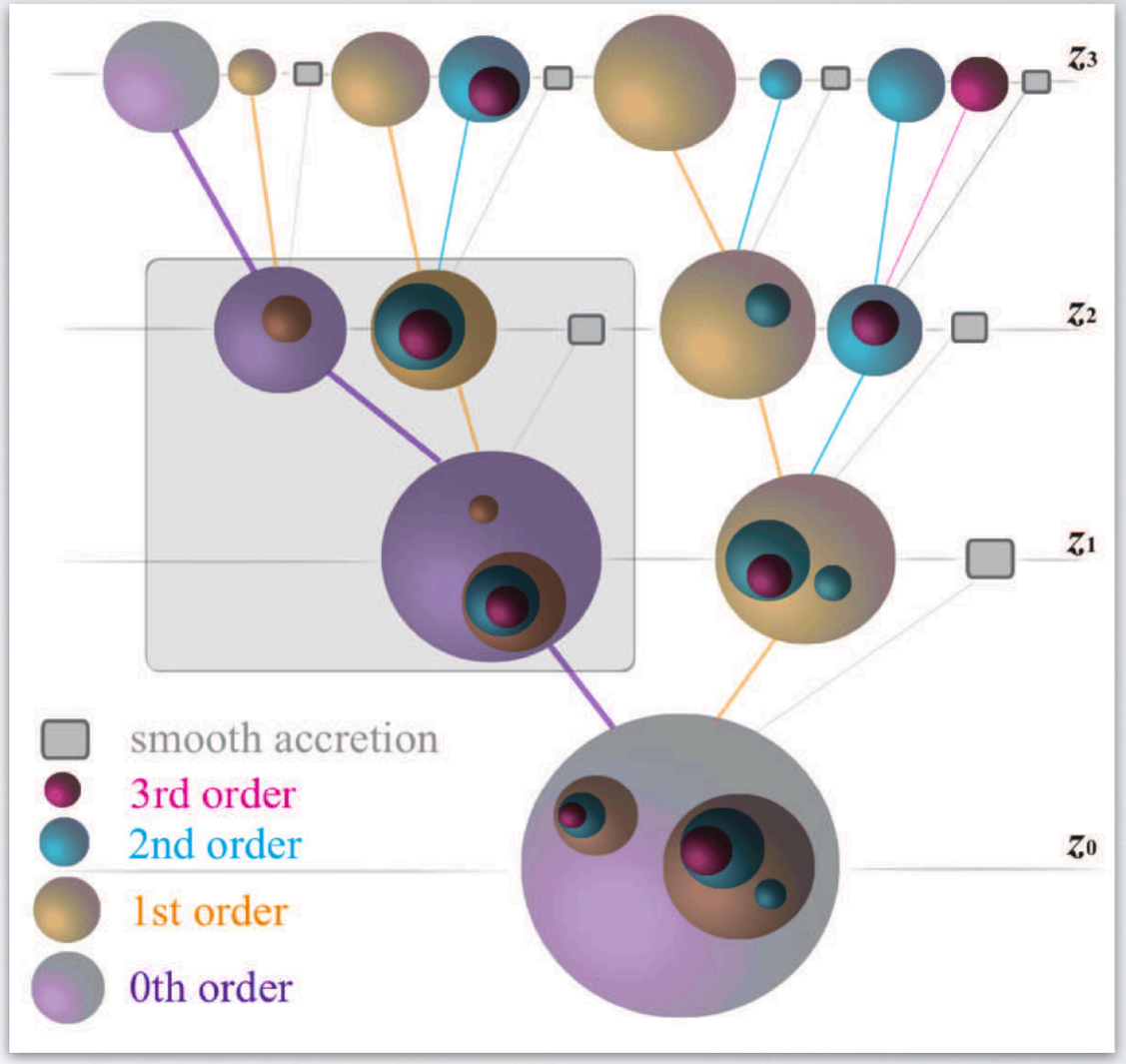
Teklu et al. 2015

Peebles 1969 • Warren et al. 1992 • Bullock et al. 2001 • van den Bosch et al. 2002 • Mo et al. 1998
Teklu et al. 2015 • Genel et al. 2015 • Zavala et al. 2016 • Somerville et al. 2017 • Benson 2017

Mass accretion history



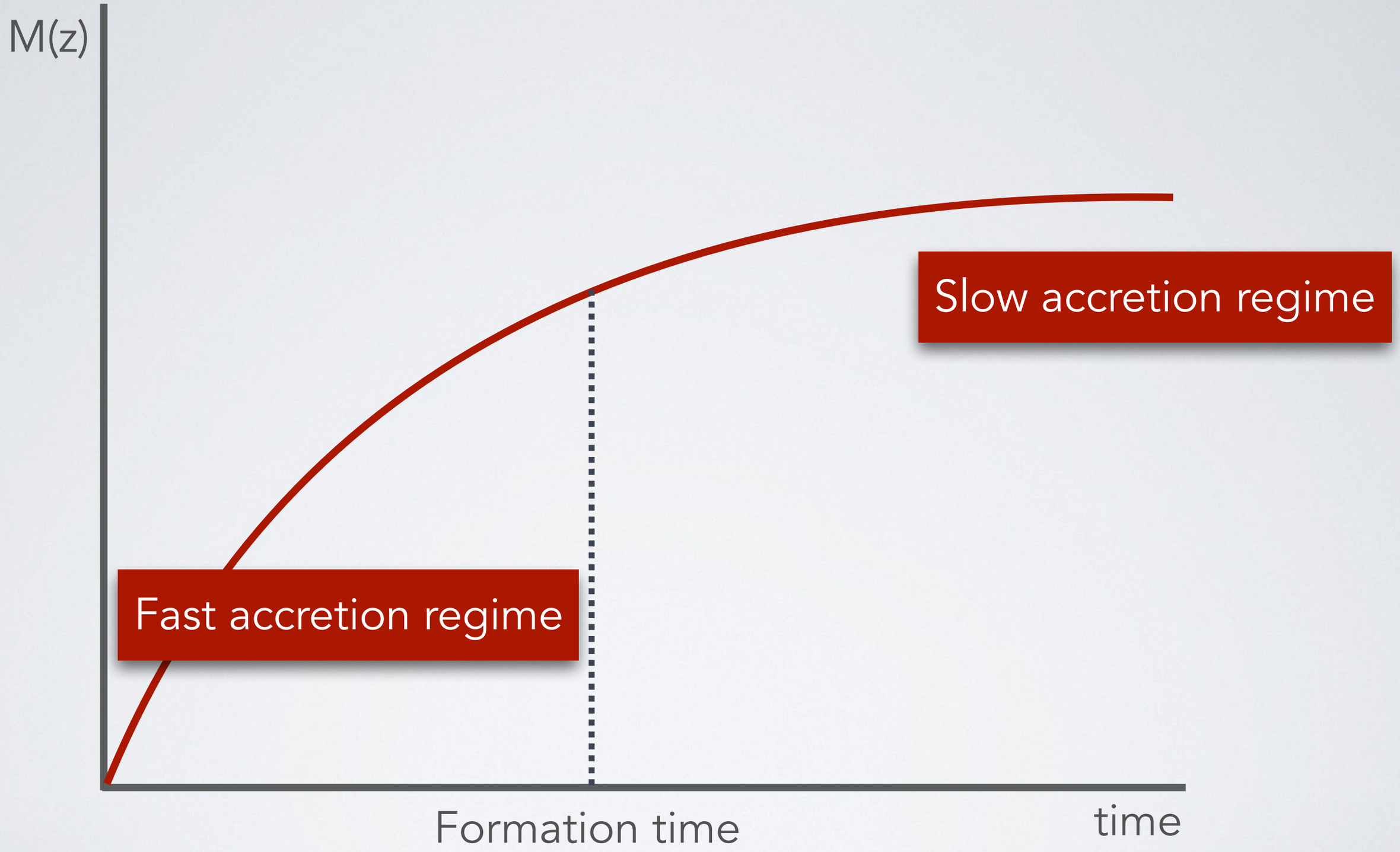
Lacey & Cole 1993



Jiang & van den Bosch 2016

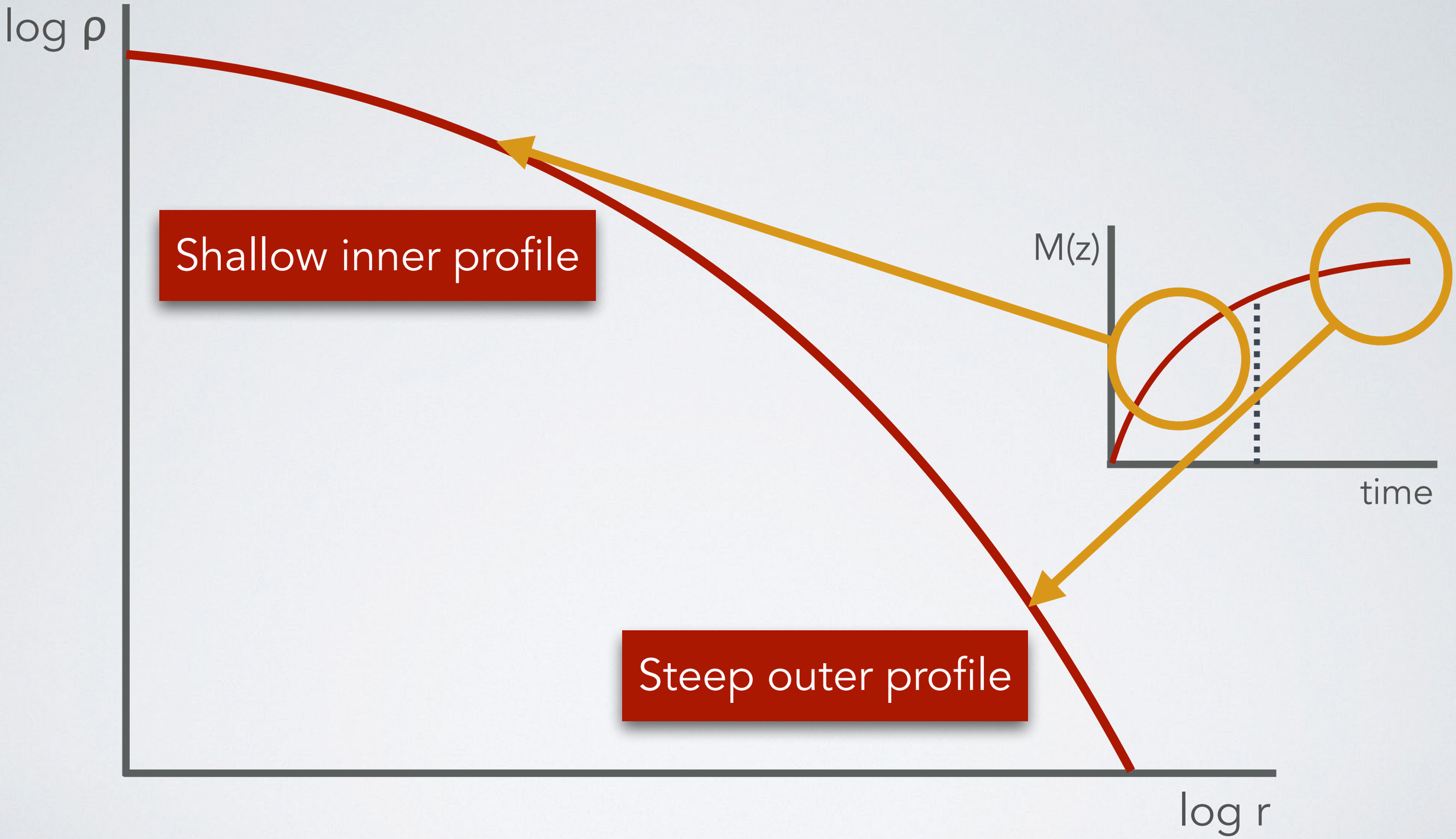
Press & Schechter 1974 • Davis et al. 1985 • Lacey & Cole 1993 • Behroozi et al. 2013

Mass accretion history



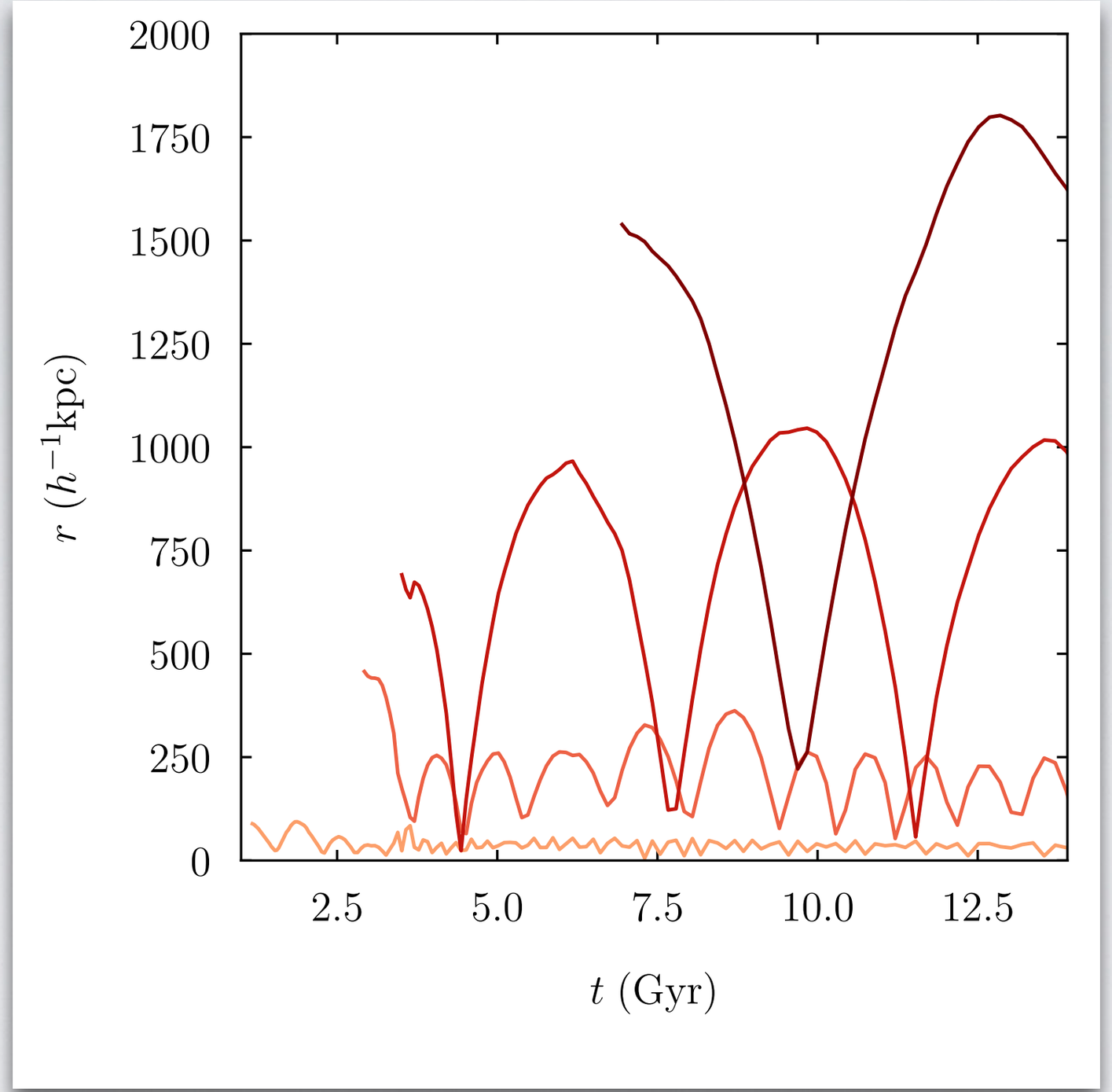
Wechsler et al. 2002 • van den Bosch 2002 • Zhao et al. 2003/2009 • Tasitsiomi et al. 2004
Dalal et al. 2008 • Mc Bride et al. 2009

Mass accretion history



e.g., Bullock et al. 2001 • Wechsler et al. 2002 • Lu et al. 2006 • Dalal et al. 2008 • Ludlow et al. 2013

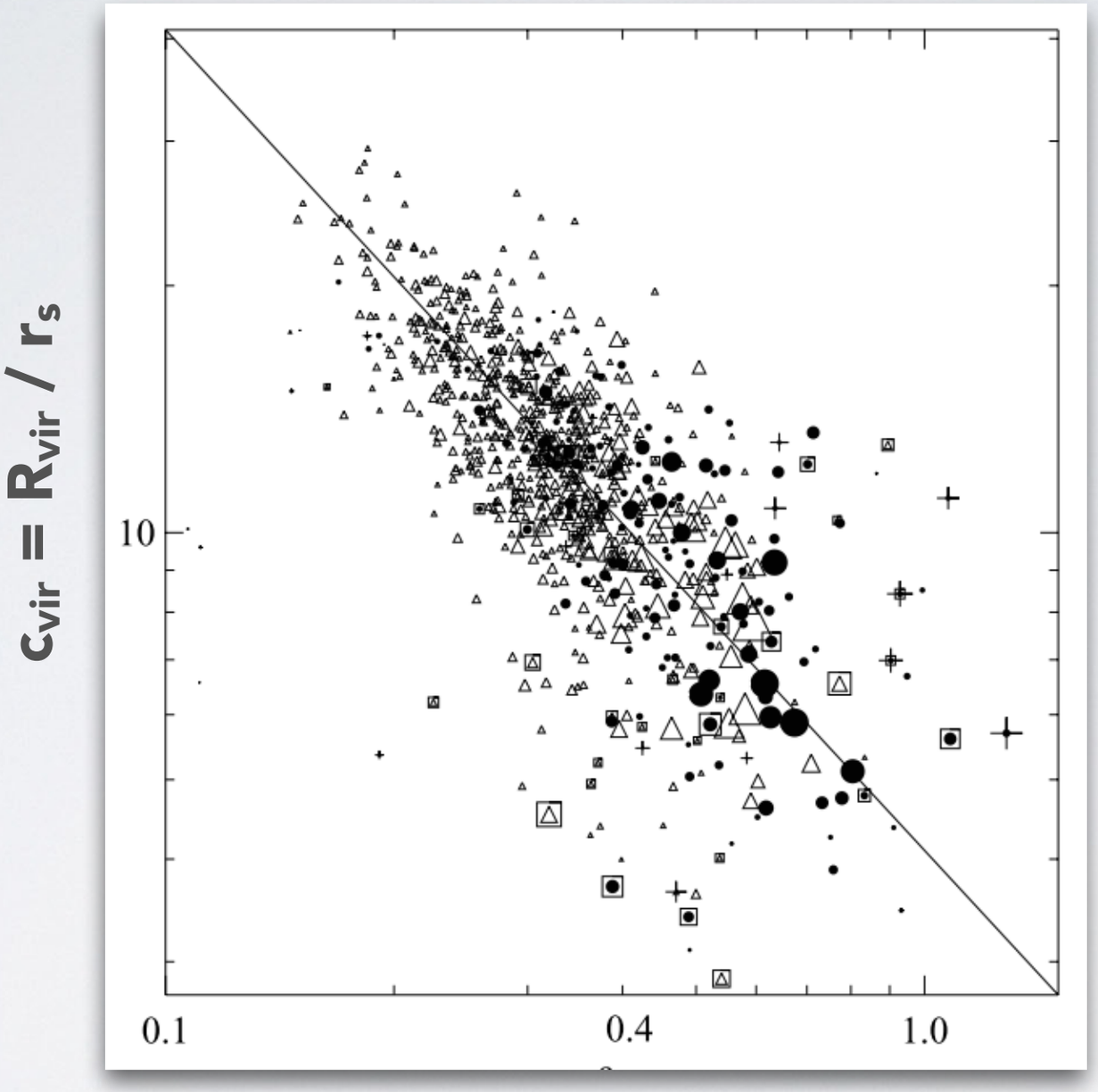
Particle orbits



Diemer 2017

Mass accretion history

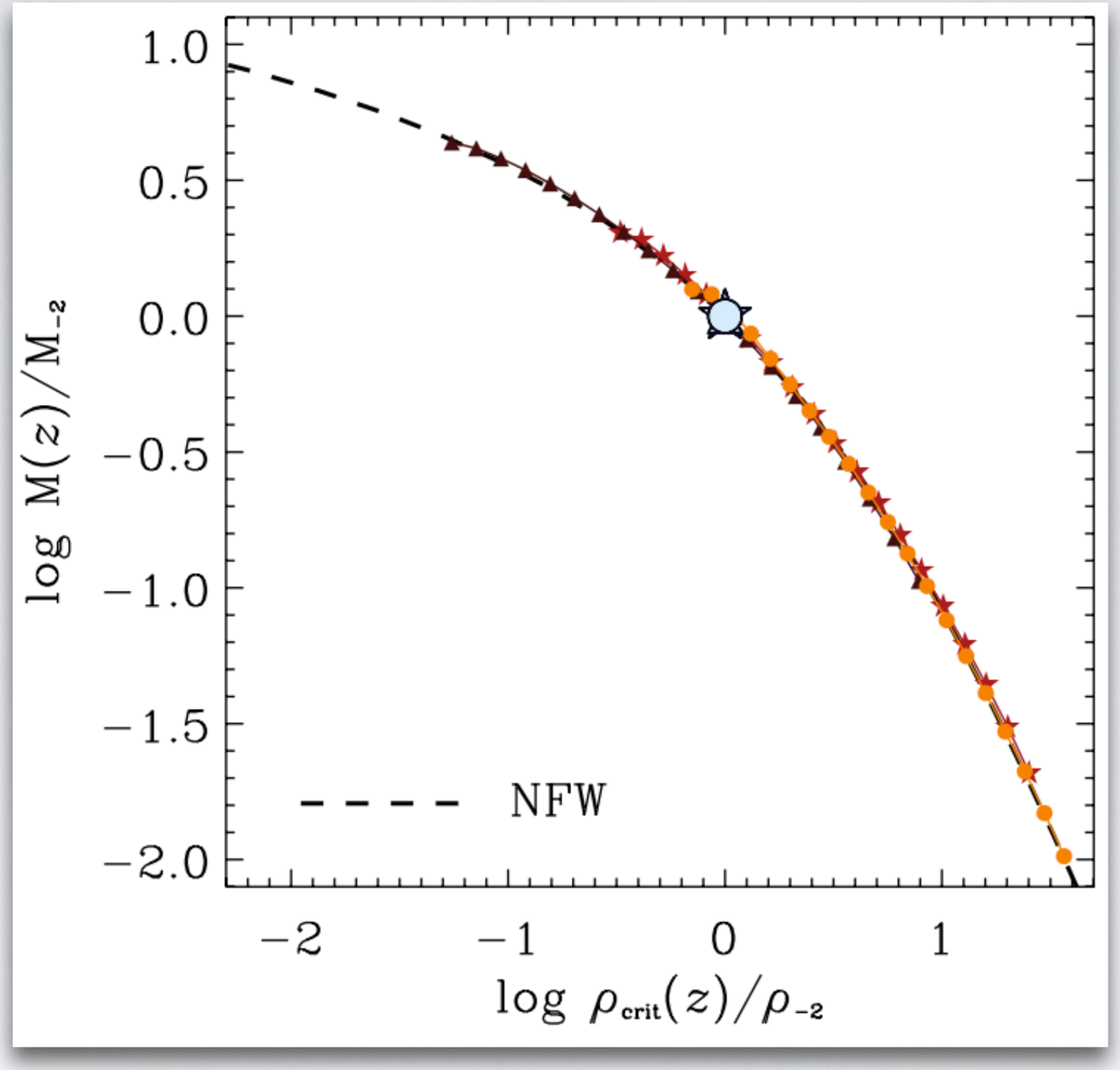
Wechsler et al. 2002



Formation scale

Navarro et al. 1997 • Bullock et al. 2001 • Eke et al. 2001 • Wechsler et al. 2002
Zhao et al. 2009 • Giocoli et al. 2012 • Ludlow et al. 2013

Mass accretion history



Ludlow et al. 2013

Navarro et al. 1997 • Bullock et al. 2001 • Eke et al. 2001 • Wechsler et al. 2002
Zhao et al. 2009 • Giocoli et al. 2012 • Ludlow et al. 2013

Halo properties used in the G-H connection

Halo property	SHAM	SHAM+	HOD	SAM
Density profile	✗	✗	✓	~
Shape / ellipticity	✗	✗	✗	✗
Spin	✗	~	✗	✓
Concentration	✗	~	✓	~
Mass accretion history	✗	✓	✗	✓
V_{max}	✓	✓	✗	✓
Mass / radius	✓	✓	✓	✓

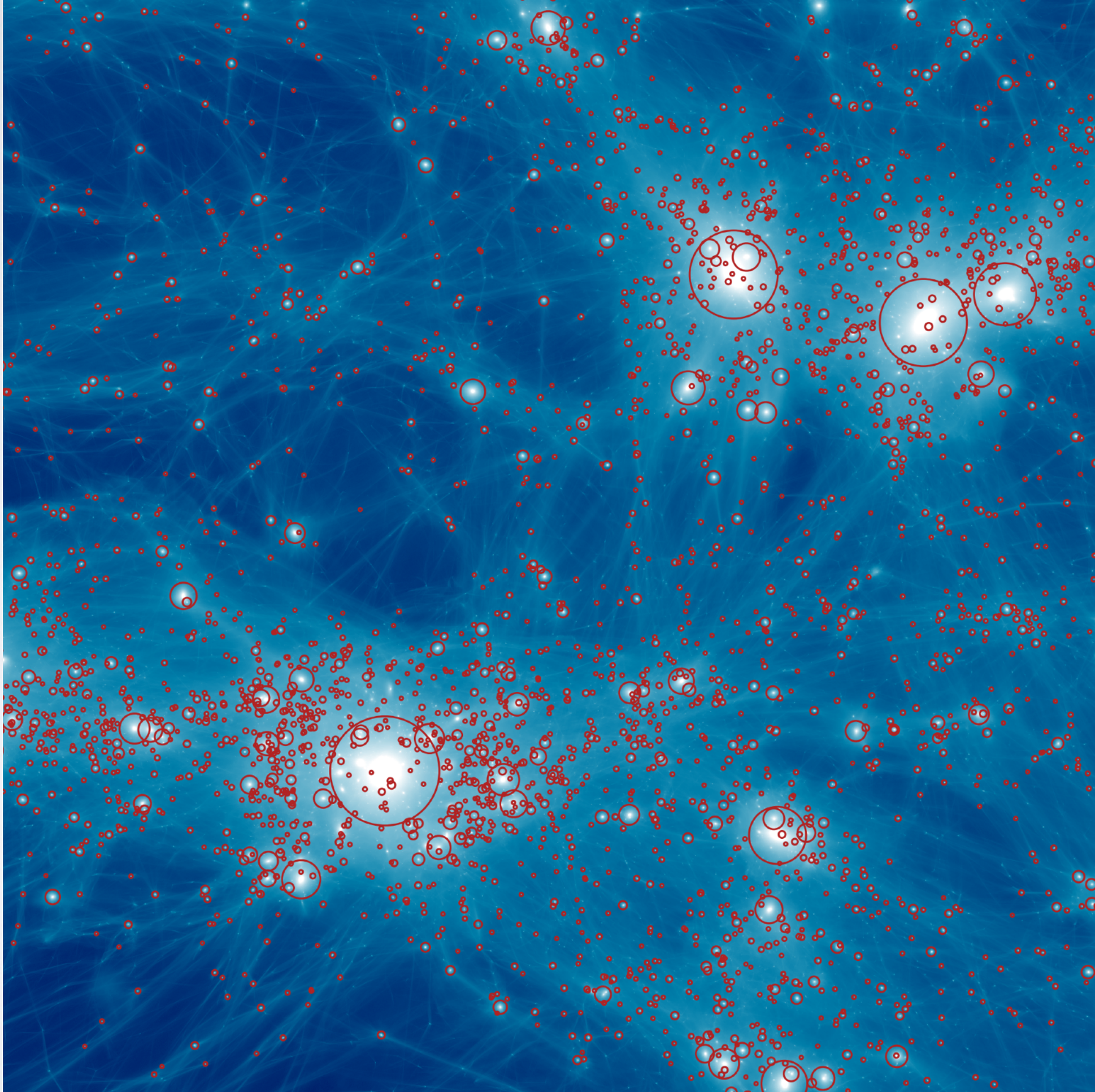
SHAM: e.g. Kravtsov et al. 2004 • Tasitsiomi et al. 2004 • Vale & Ostriker 2004 • Conroy et al. 2006 Conroy & Wechsler 2009 • Moster et al. 2010 • Behroozi et al. 2013 • Reddick et al. 2013

SHAM+: e.g. Hearin & Watson 2013 • Lehmann et al. 2016

HOD: e.g. Peacock & Smith 2000 • Seljak 2000 • Berlind & Weinberg 2002 • Zehavi et al. 05

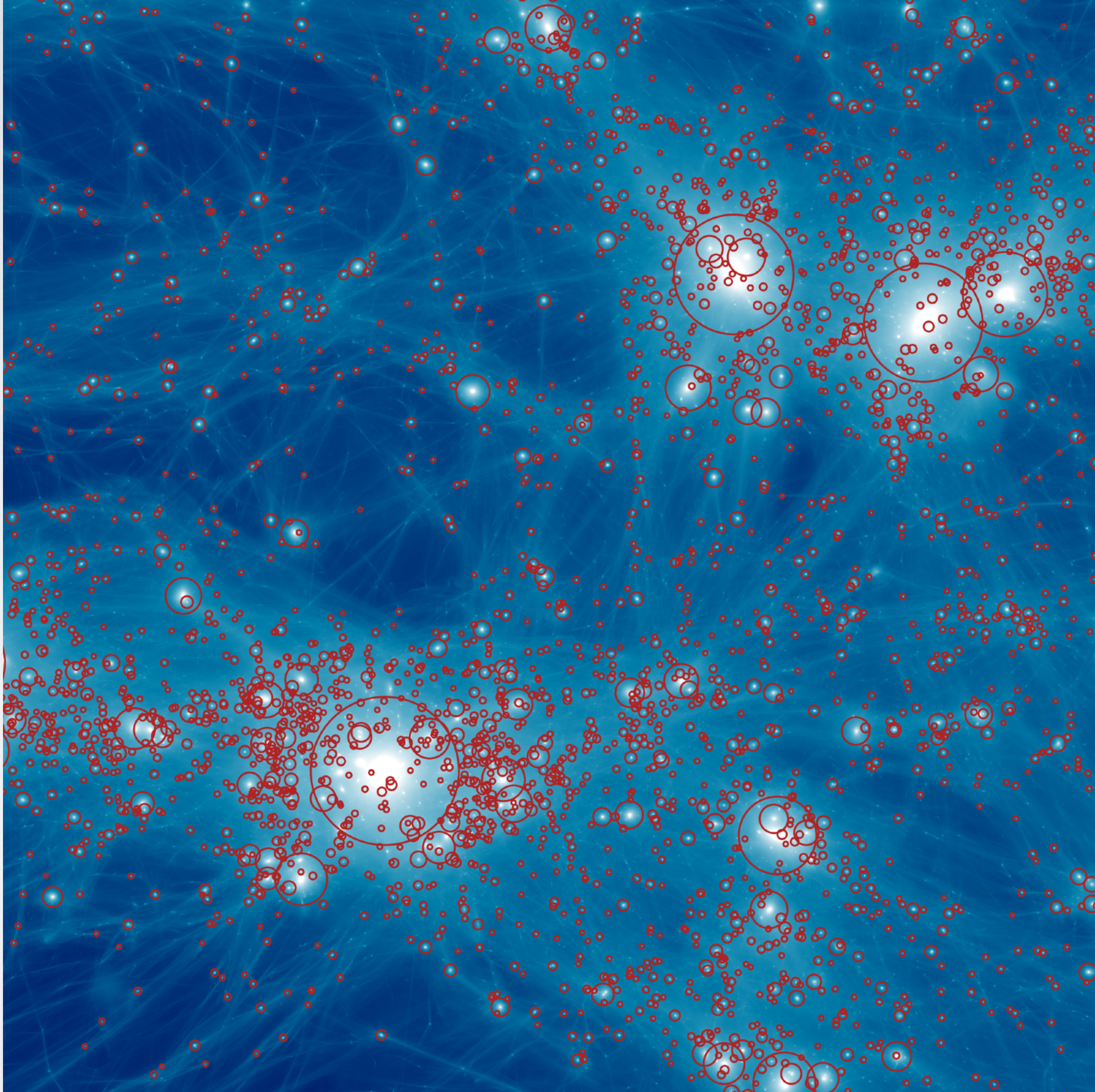
SAM: Leauthaud et al. 2011
e.g. Kauffmann et al. 1993 • Somerville et al. 2001 • Bower et al. 2006 • Guo et al. 2010 Benson 2012 • Henriques et al. 2015 • Croton et al. 2016

R_{500c}



Halo finder: Rockstar
(Behroozi et al. 2013)

R_{200c}

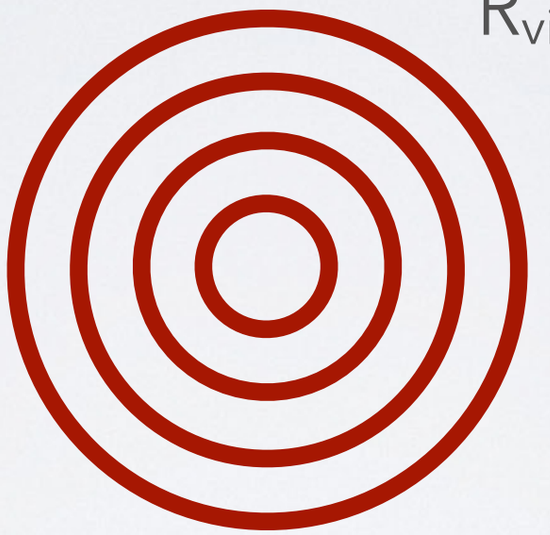


Halo finder: Rockstar
(Behroozi et al. 2013)

R_{vir}

Halo finder: Rockstar
(Behroozi et al. 2013)

The “virial” radius



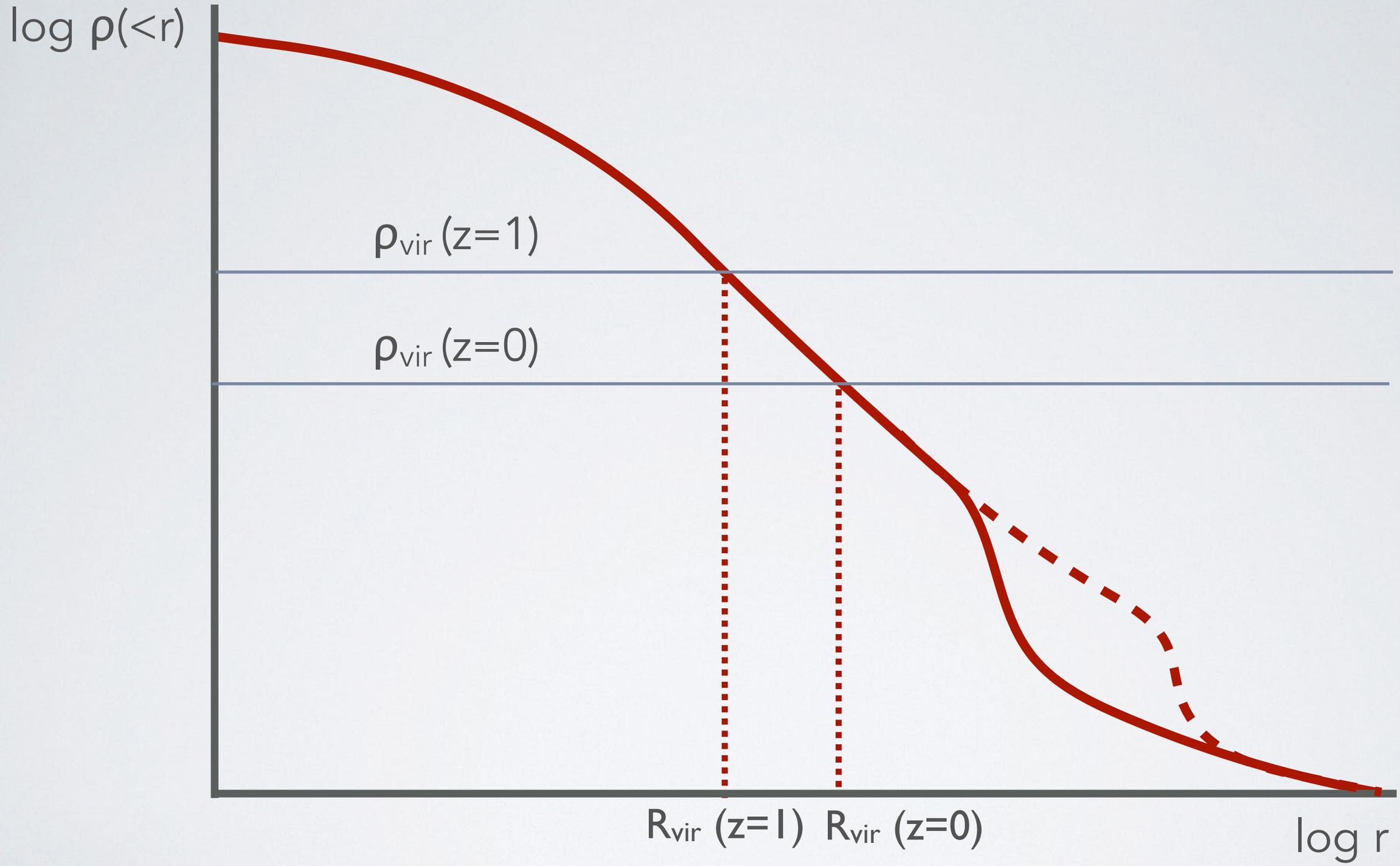
$W = -2K$

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

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

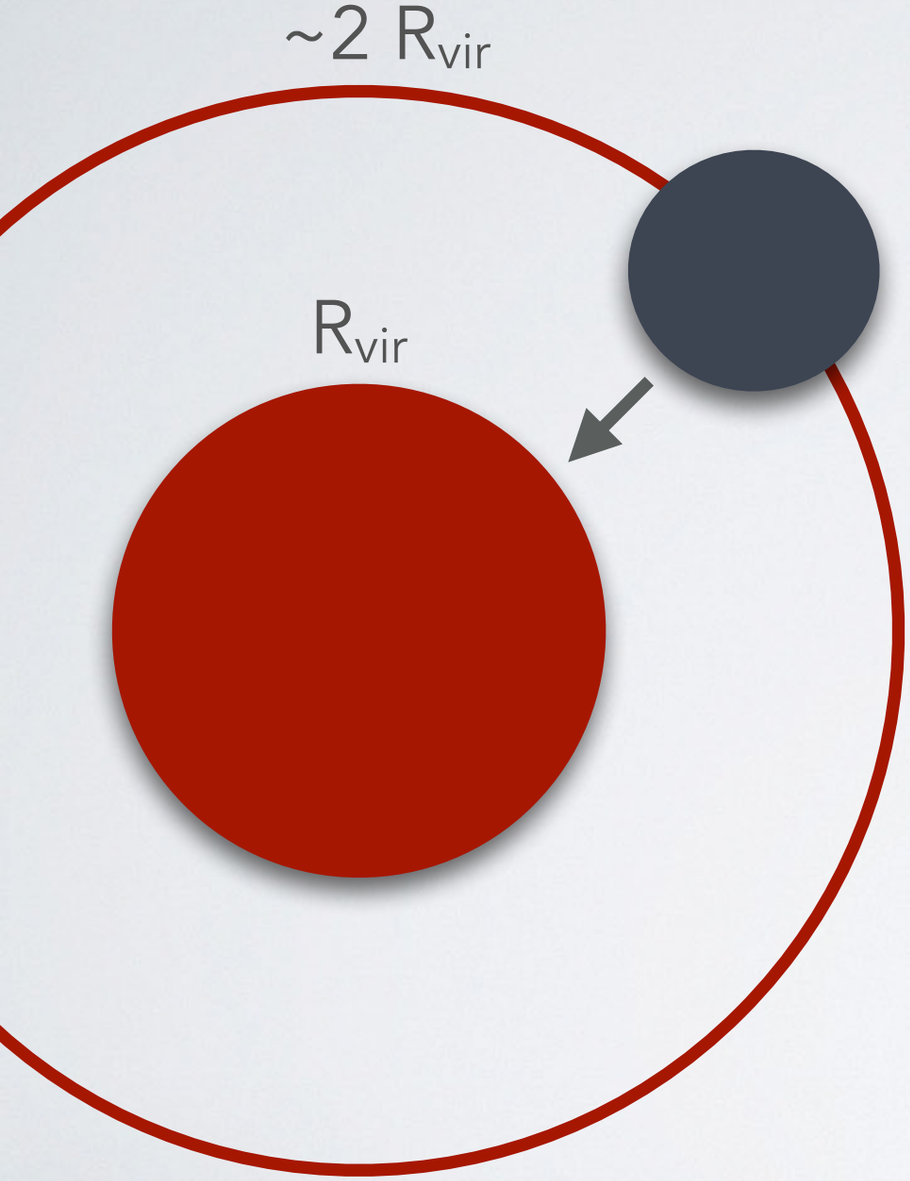
Gunn & Gott 1972 • Peebles 1980 • Lacey & Cole 1993 • Cole & Lacey 1996

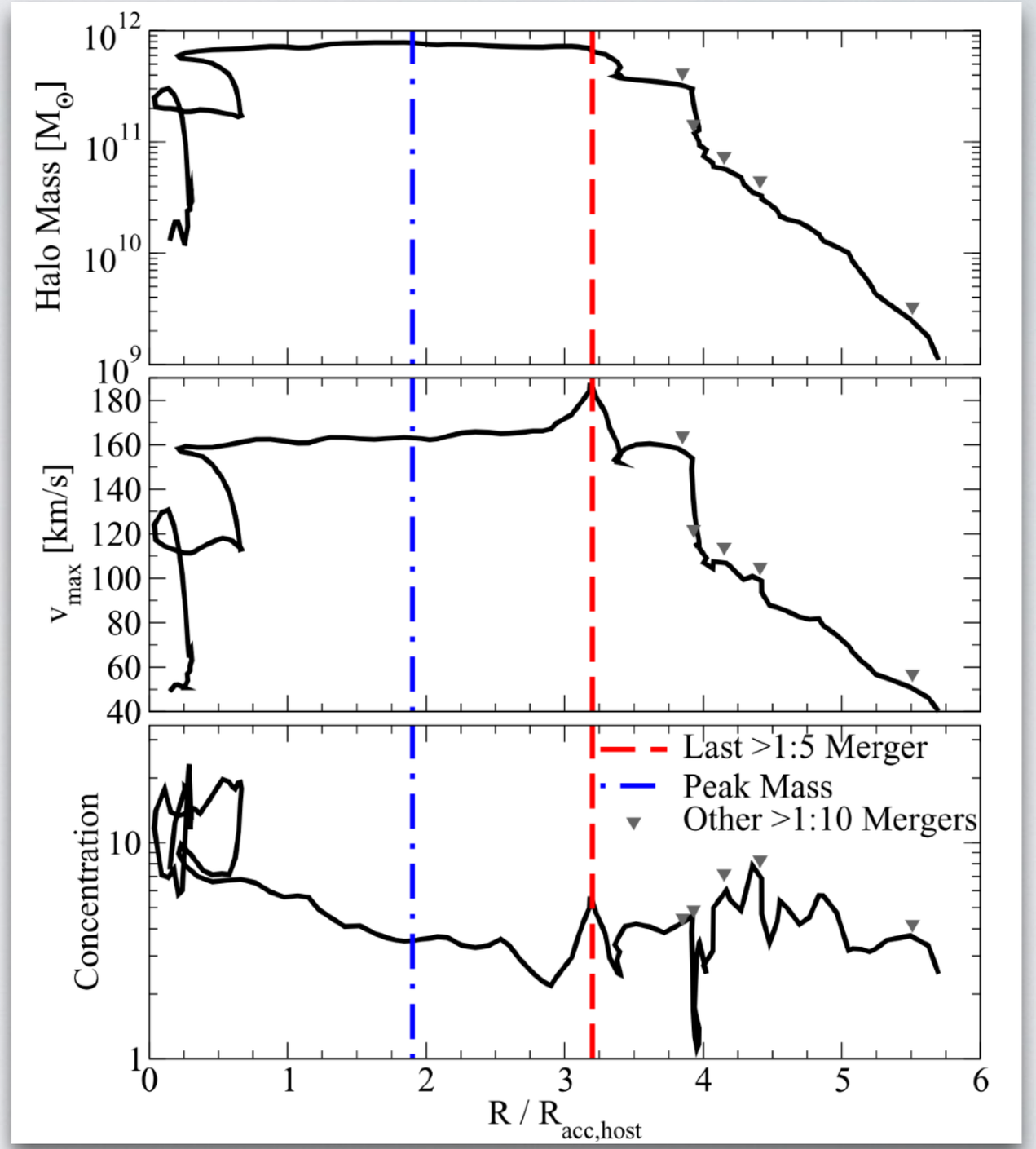
Pseudo-evolution vs. accretion



Diemand et al. 2007 • Cuesta et al. 2008 • Diemer et al. 2013 • Zemp 2014
More et al. 2015 • Wetzel & Nagai 2015

Influence on other halos





Behroozi et al. 2014

Alternative radius / mass definitions

Friends-of-friends mass

- Arbitrarily chosen linking length, results depend on resolution and concentration
- Can erroneously include neighboring halos

Radius where $v_r = 0$ (turn-around radius)

- Hard to measure observationally
- Why should all infalling matter be part of the halo?

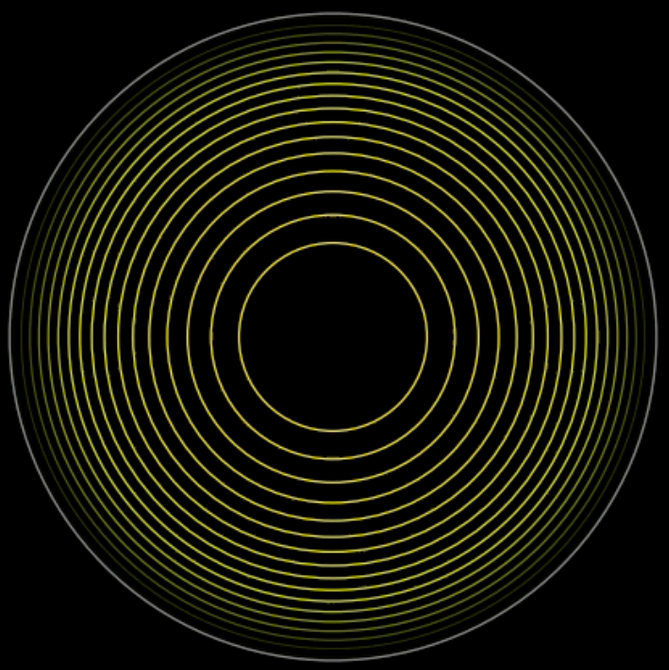
All mass that has ever been in the halo

- Impossible to measure observationally
- Can particles not truly leave a halo? What about backsplash halos?

ORIGAMI

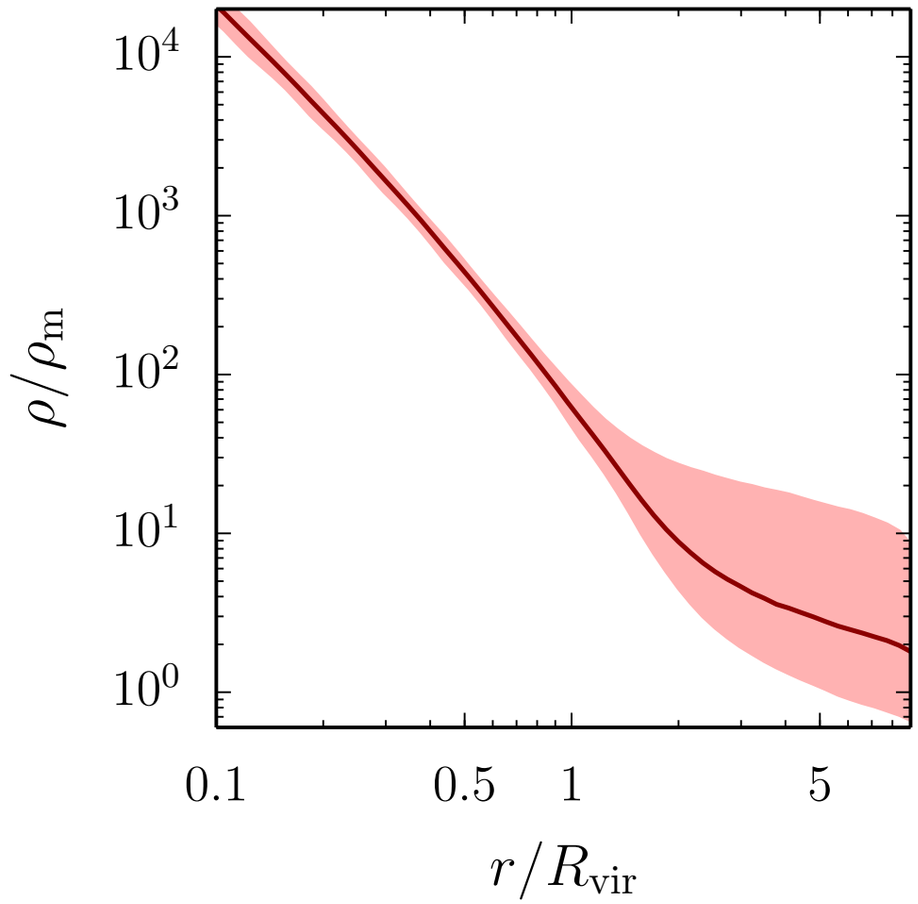
- Impossible to measure observationally
- Theoretically quite complicated

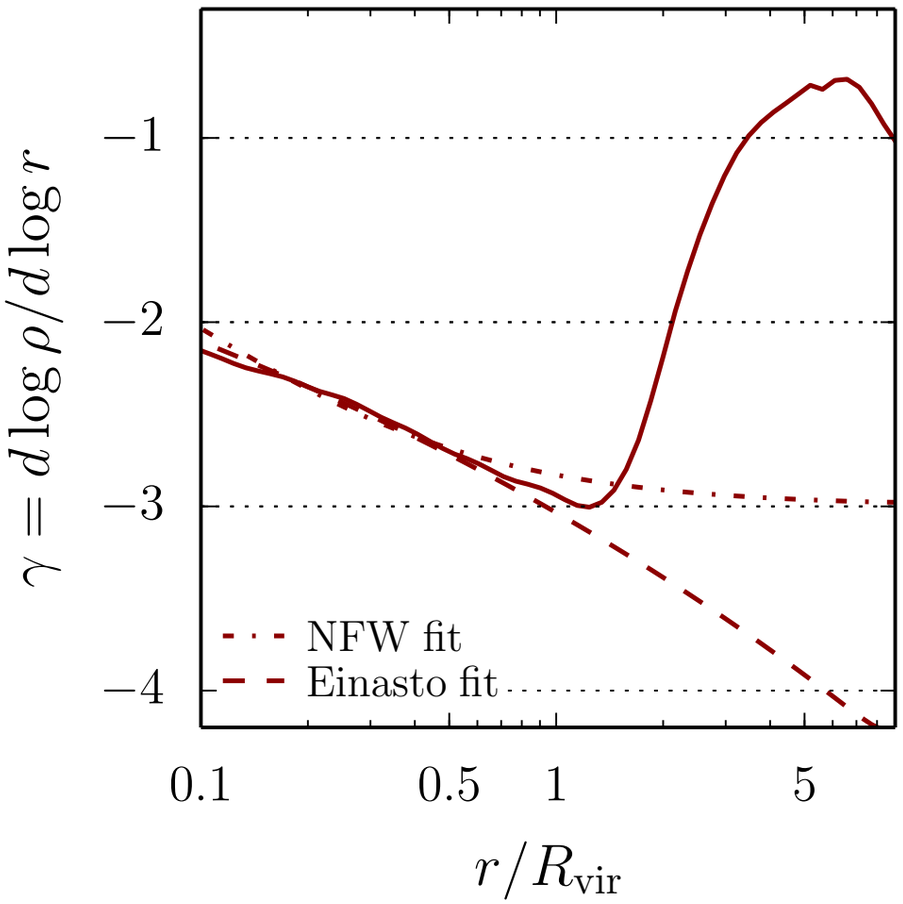
Davis et al. 1985 • White 2001 • Cuesta et al. 2008 • More et al. 2011
Anderhalden & Diemand 2011 • Falck et al. 2012



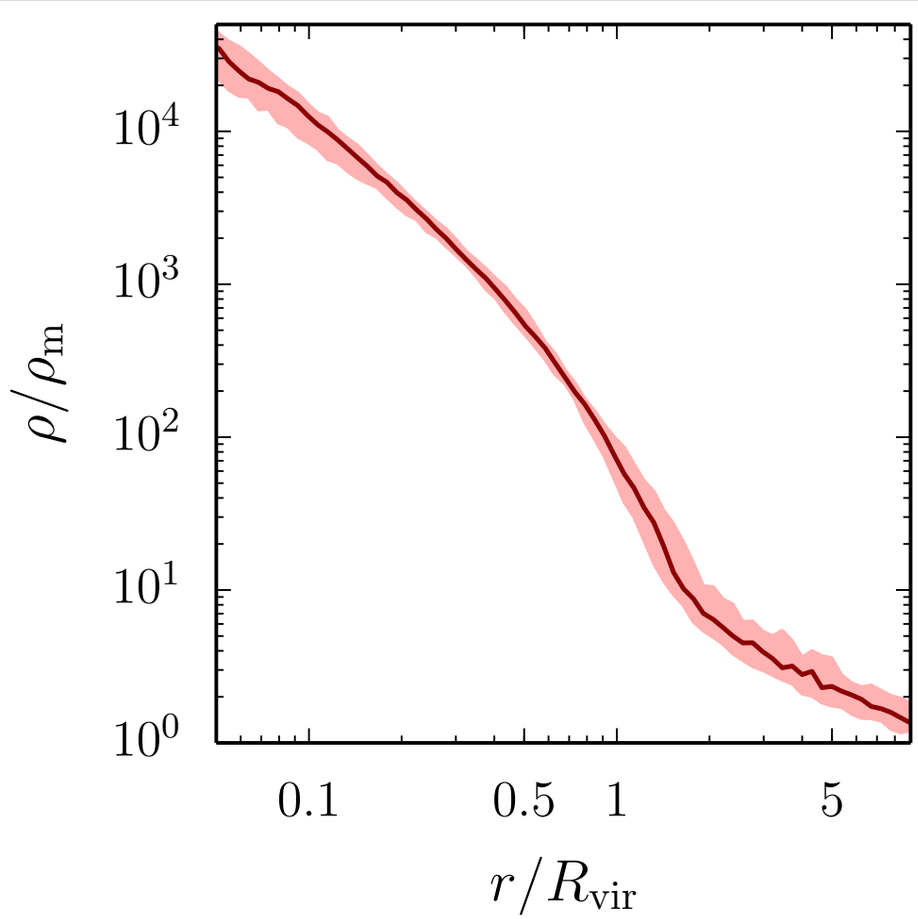
Fillmore & Goldreich 1984 • Bertschinger 1985 • Lu et al. 2006 • Diemand & Kuhlen 2008
Vogelsberger et al. 2011 • Lithwick & Dalal 2011 • Adhikari et al. 2014

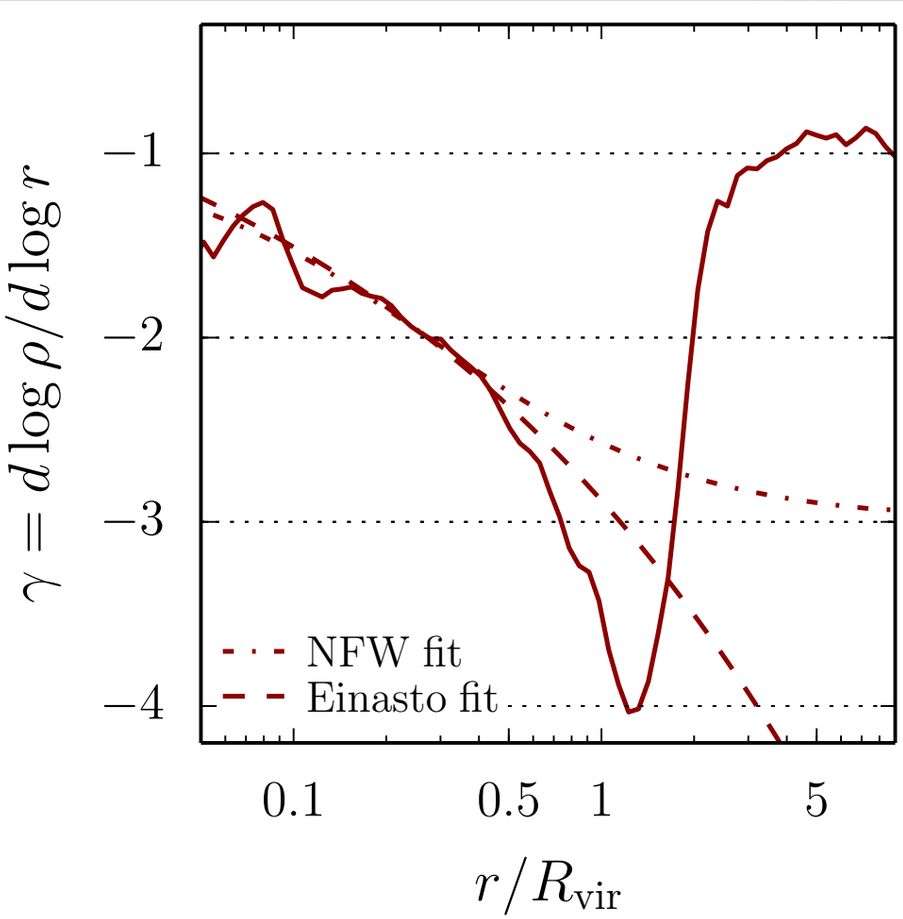
Small halos
(10^{10}<M<3×10^{11})





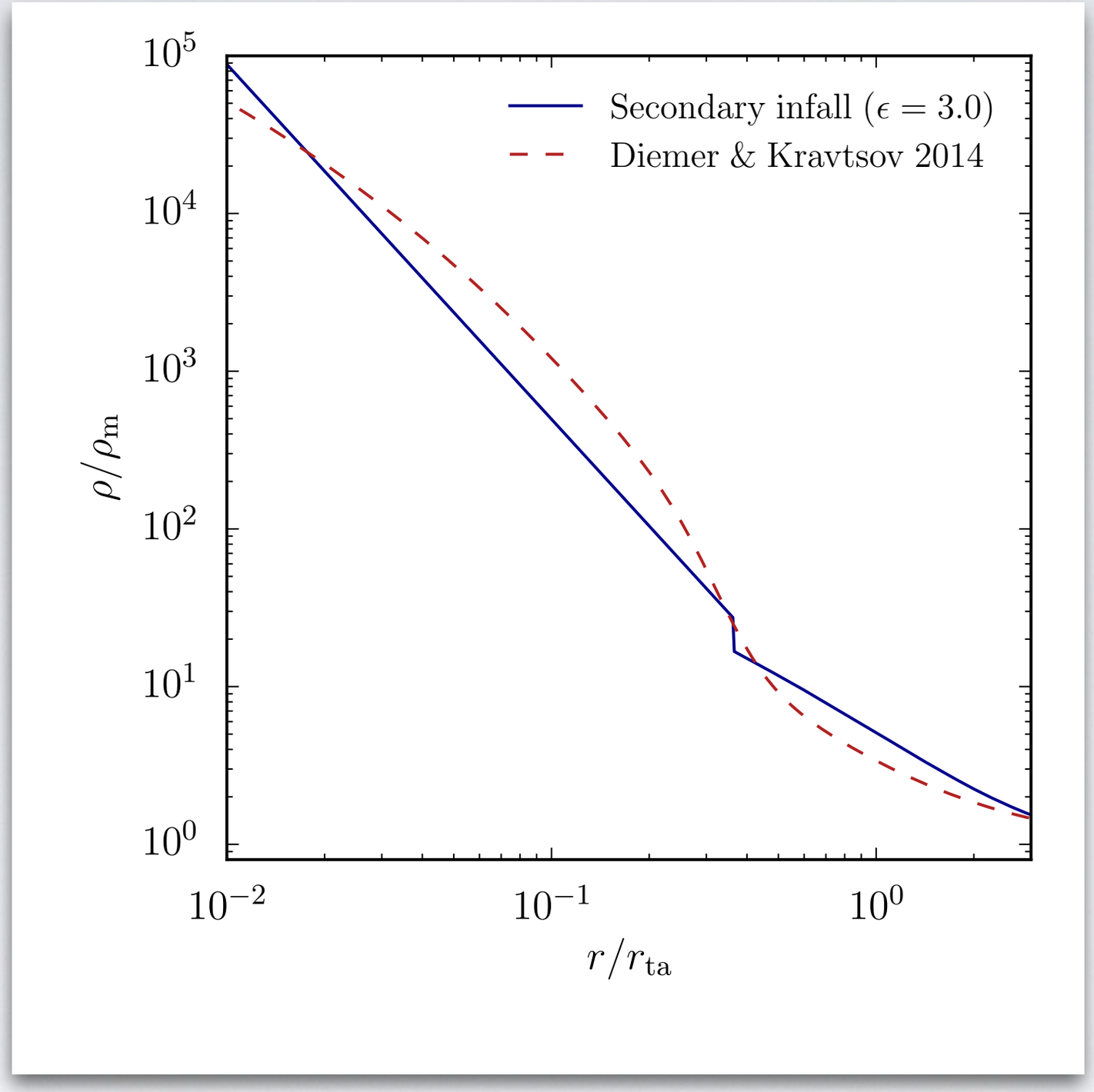
Large halos
(M>10^{15})





Diemer & Kravtsov 2014

The Splashback Radius



Fillmore & Goldreich 1984 • Bertschinger 1985 • Diemand & Kuhlen 2008
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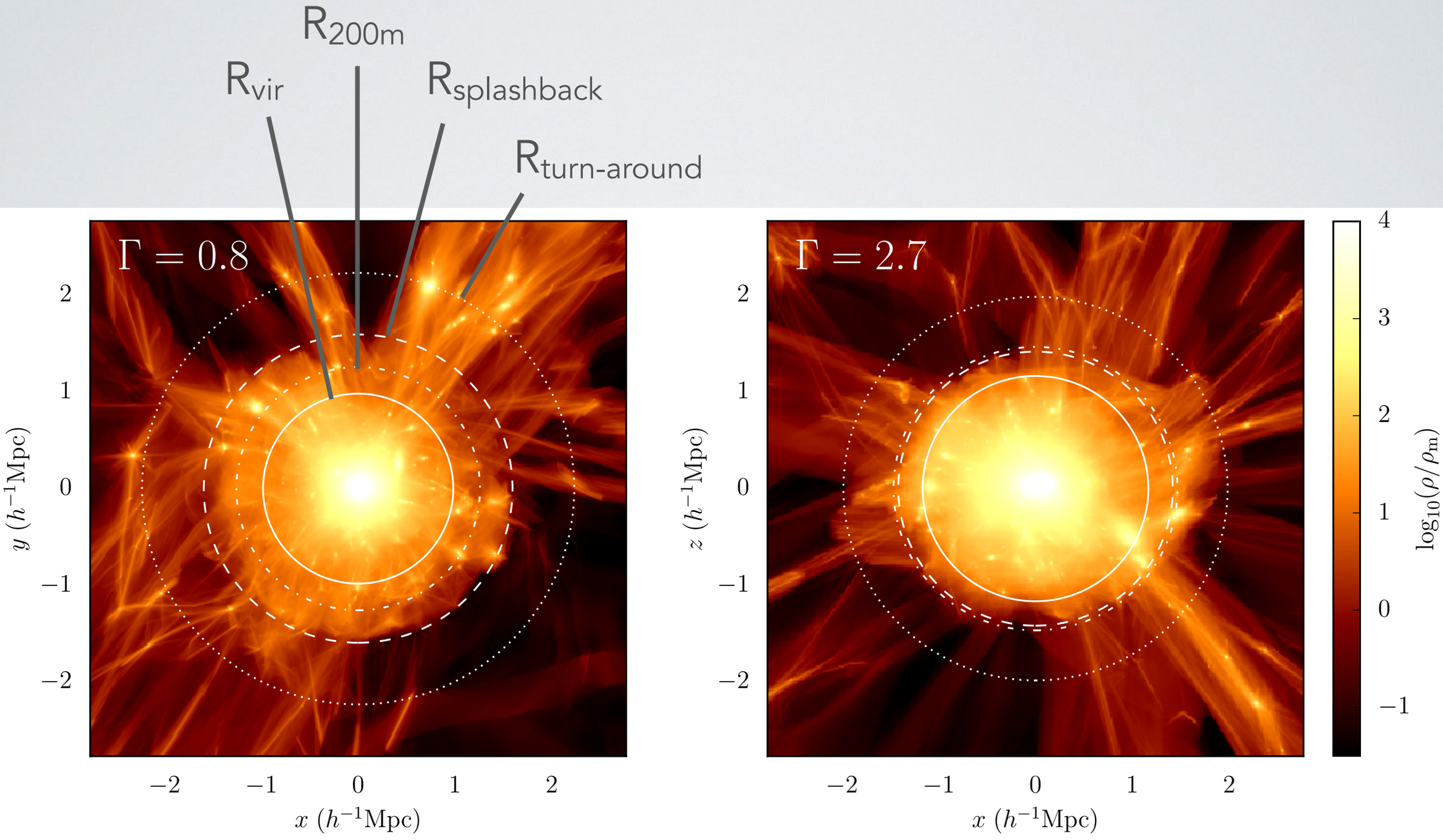
The Splashback Radius

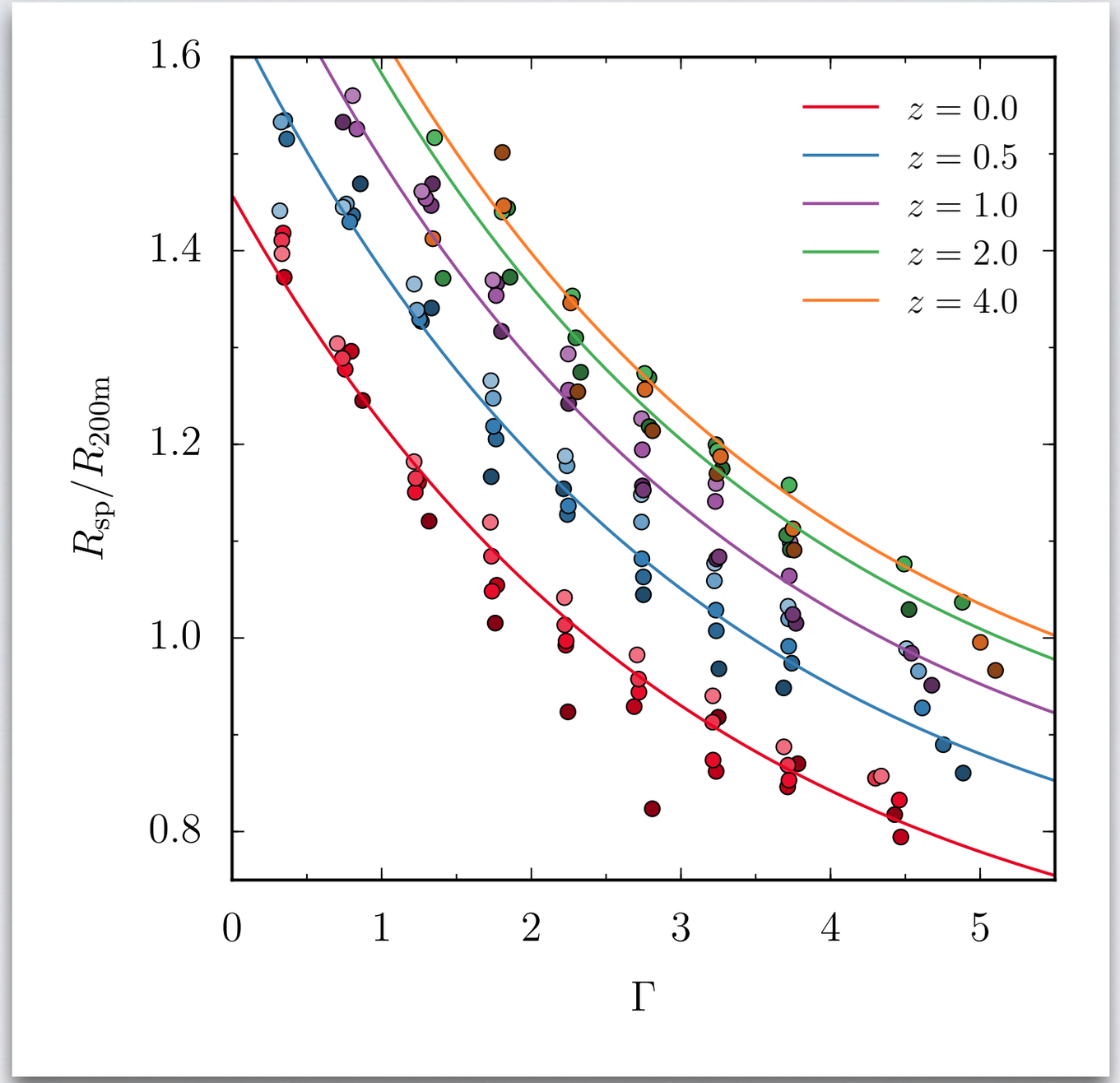


Low accretion rate

High accretion rate

Diemer & Kravtsov 2014 • More, Diemer & Kravtsov 2015

The Splashback Radius

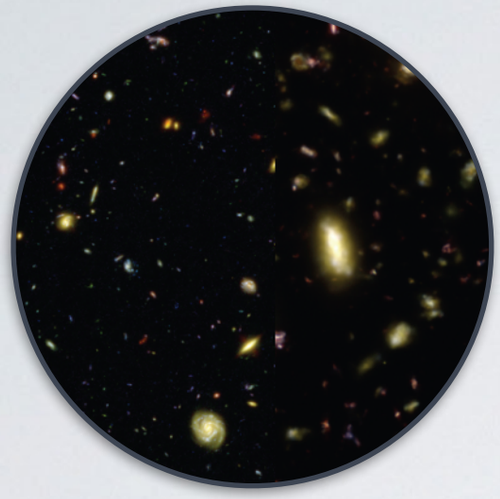


Mass accretion rate

More, Diemer & Kravtsov 2015

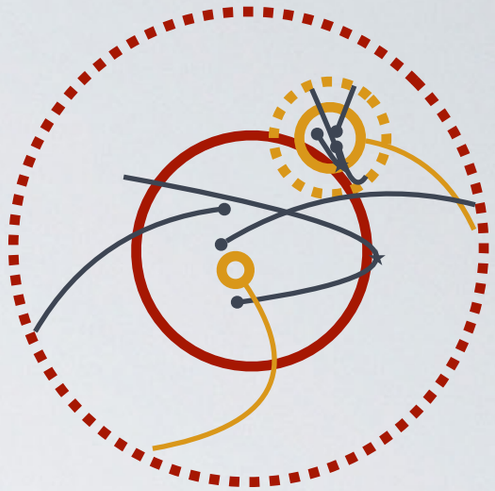
R_{sp} and the galaxy-halo connection

Effect of using R_{sp}	SHAM	SHAM+	HOD	SAM
Environment-dependent change in halo mass	✓	✓	✓	✗
Different subhalo statistics	~	~	✗	✓
Different mass accretion histories	✗	~	✗	✓

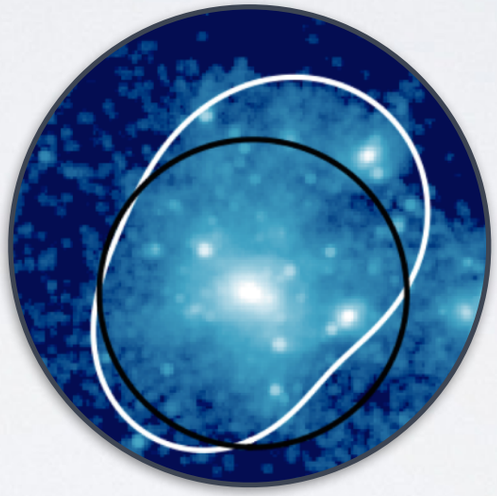


Observations
Surhud's talk (Monday)

R_{sp}



Particle orbit tracking

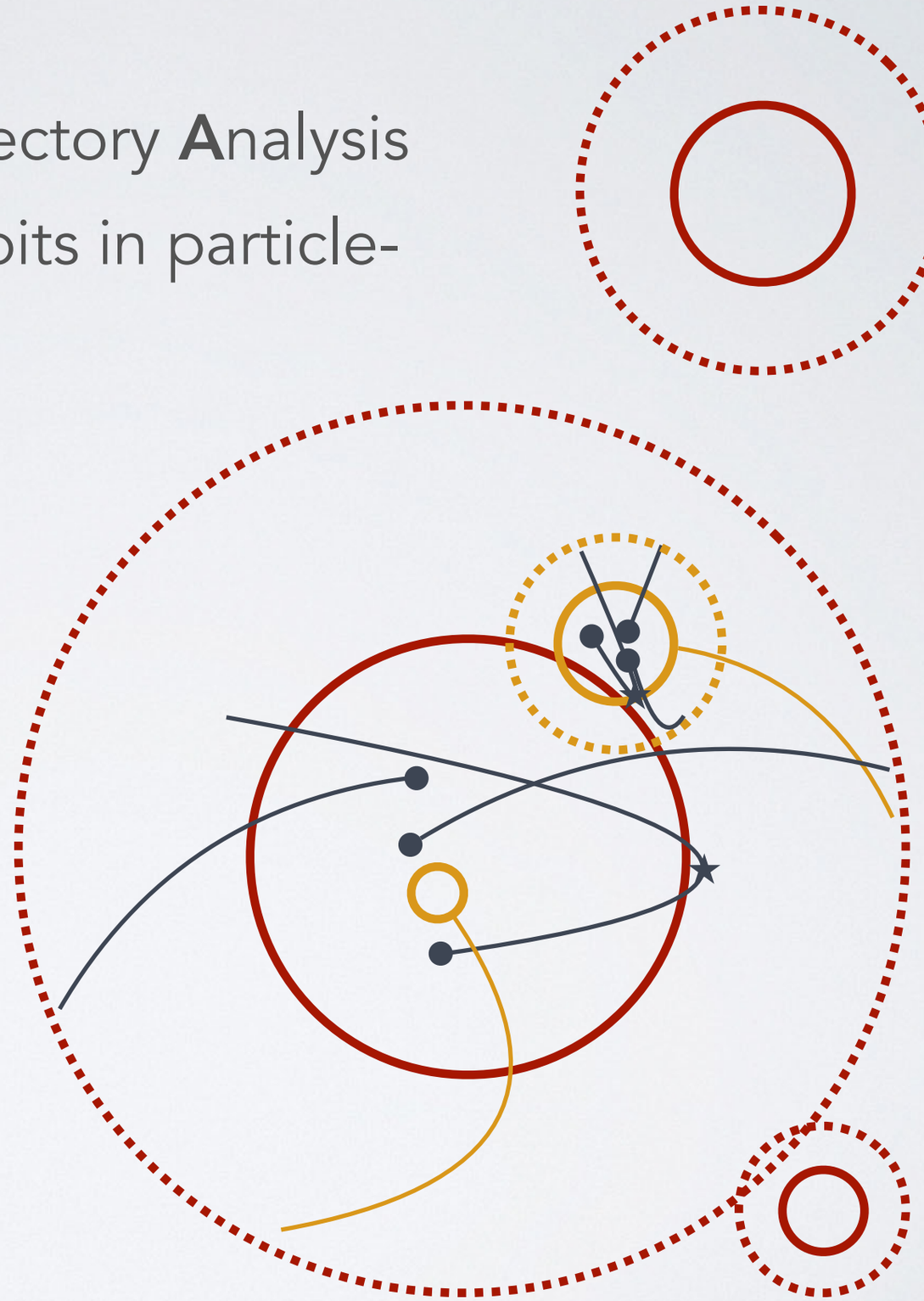


Shell finding
Phil's talk (Friday)

Initial splashback papers: Diemer & Kravtsov 2014 • Adhikari et al. 2014 • More, Diemer & Kravtsov 2015
Observational papers: More et al. 2016 • Tully 2015 • Patej & Loeb 2016 • Adhikari et al. 2016
Umetsu & Diemer 2017 • Zu et al. 2017 • Busch & White 2017 • Baxter et al. 2017
Splashback shell finding: Mansfield, Kravtsov & Diemer 2017
Particle orbit tracking: Diemer 2017 • Diemer et al. 2017

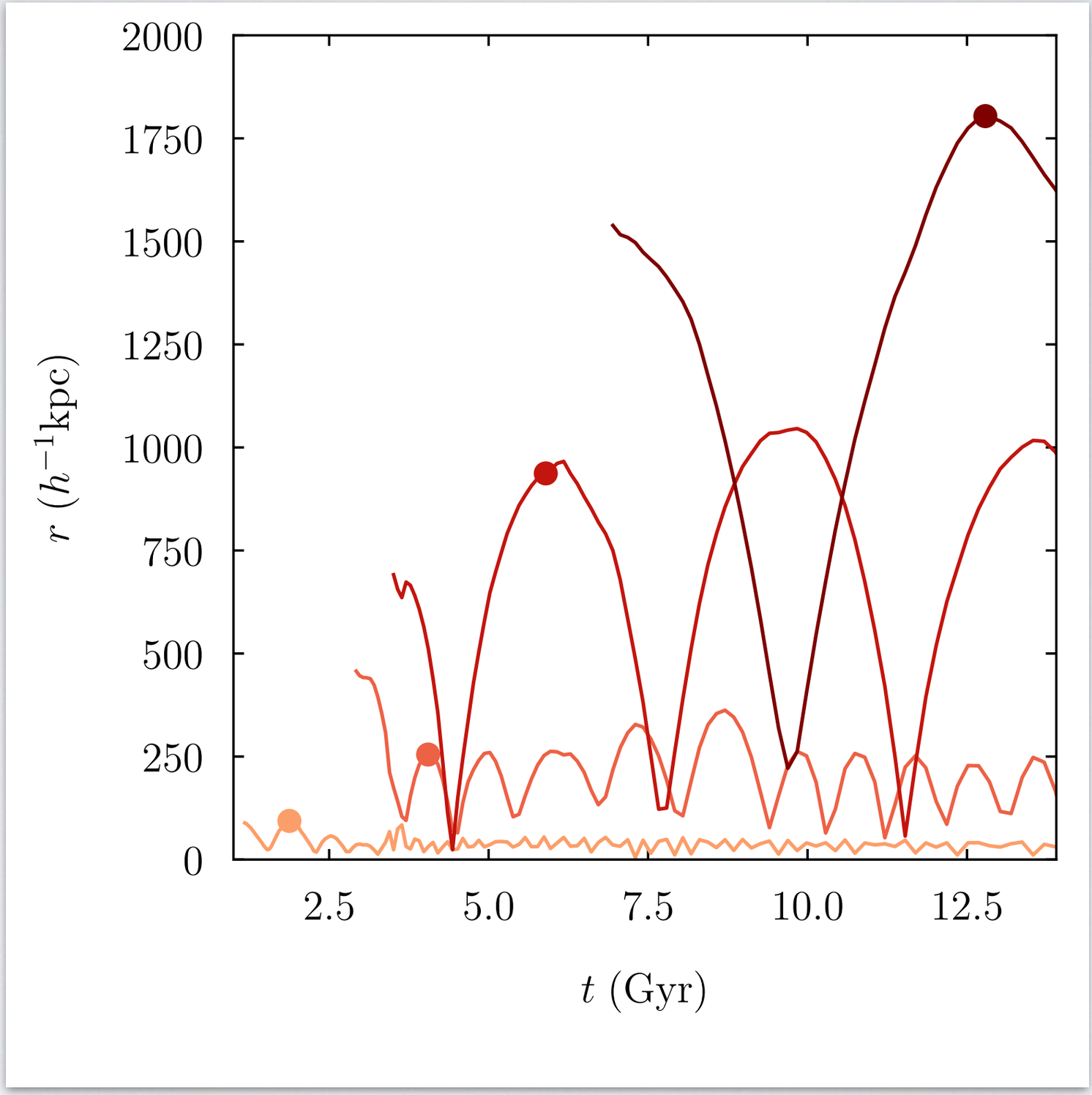
SPARTA

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

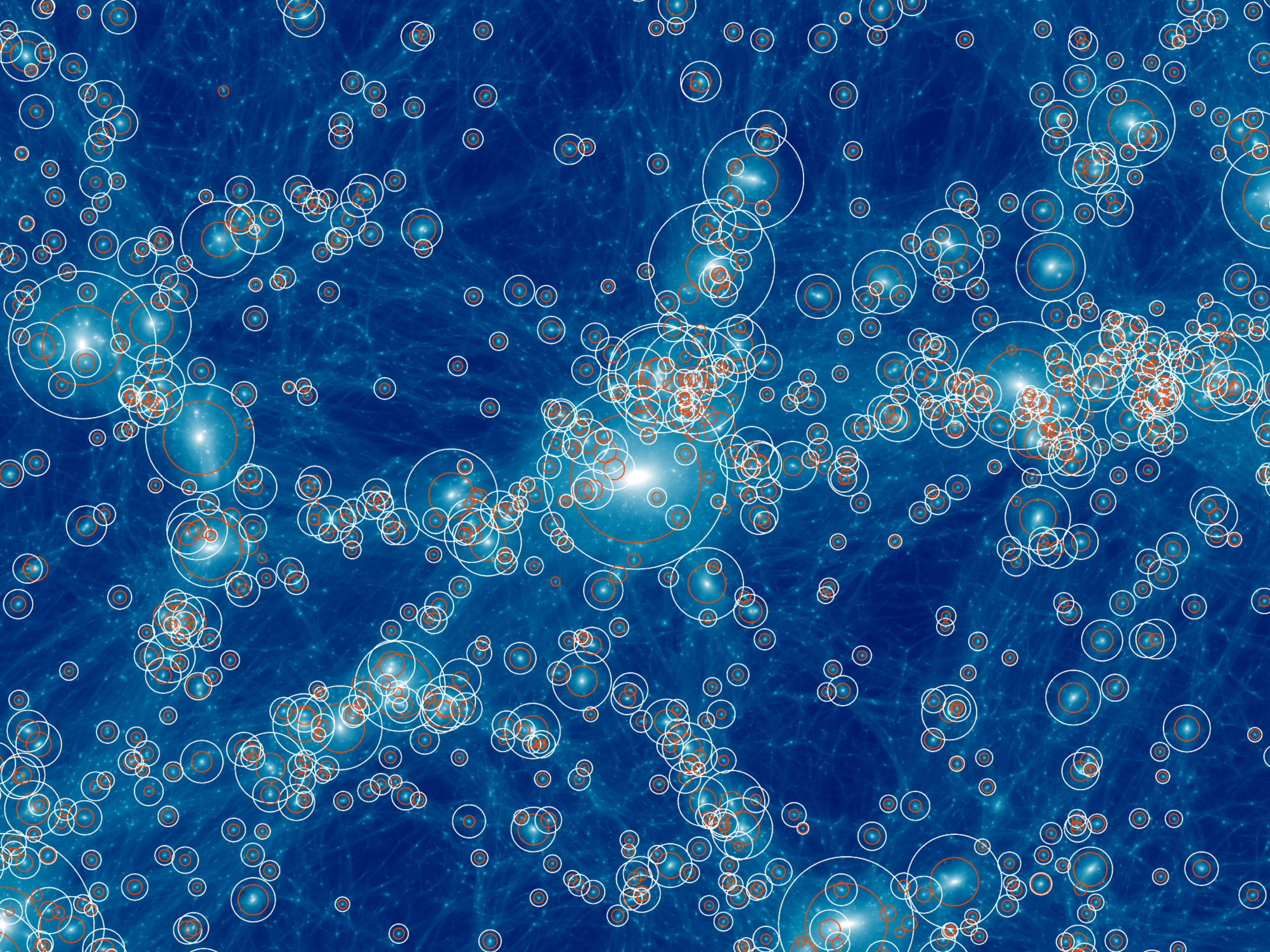


Diemer 2017 • Diemer et al. 2017

What do the orbits look like?



Diemer 2017

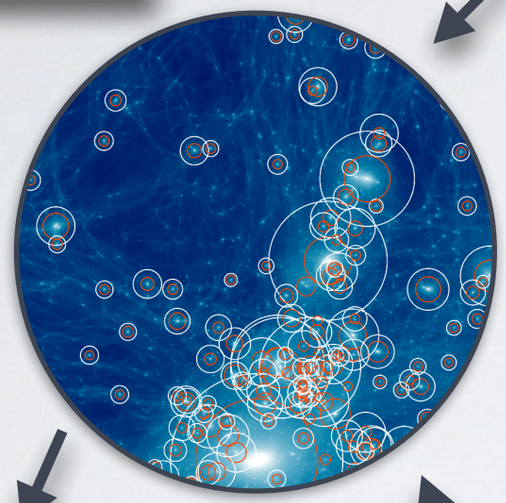


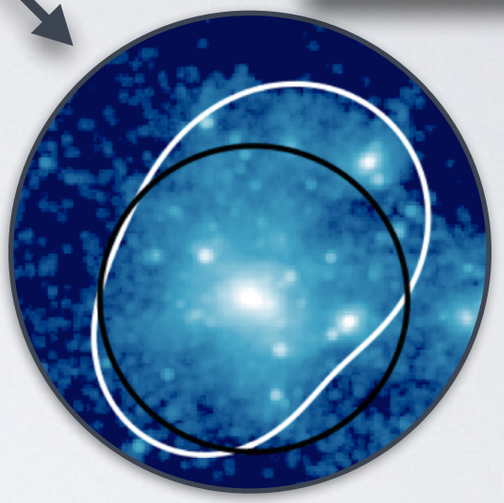
???

SPARTA

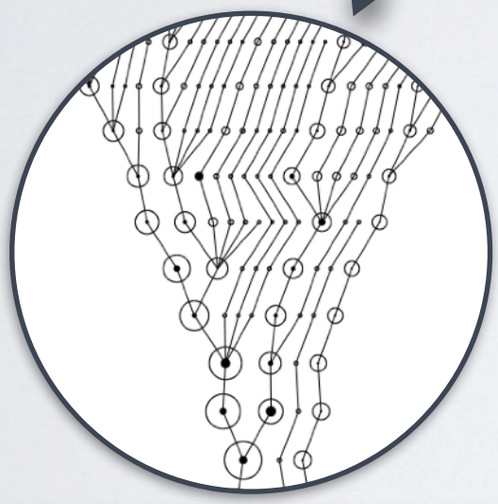
Splashback radii

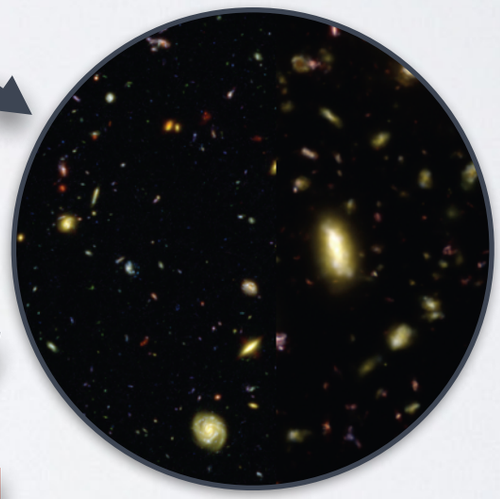
3D shells





Illustris TNG



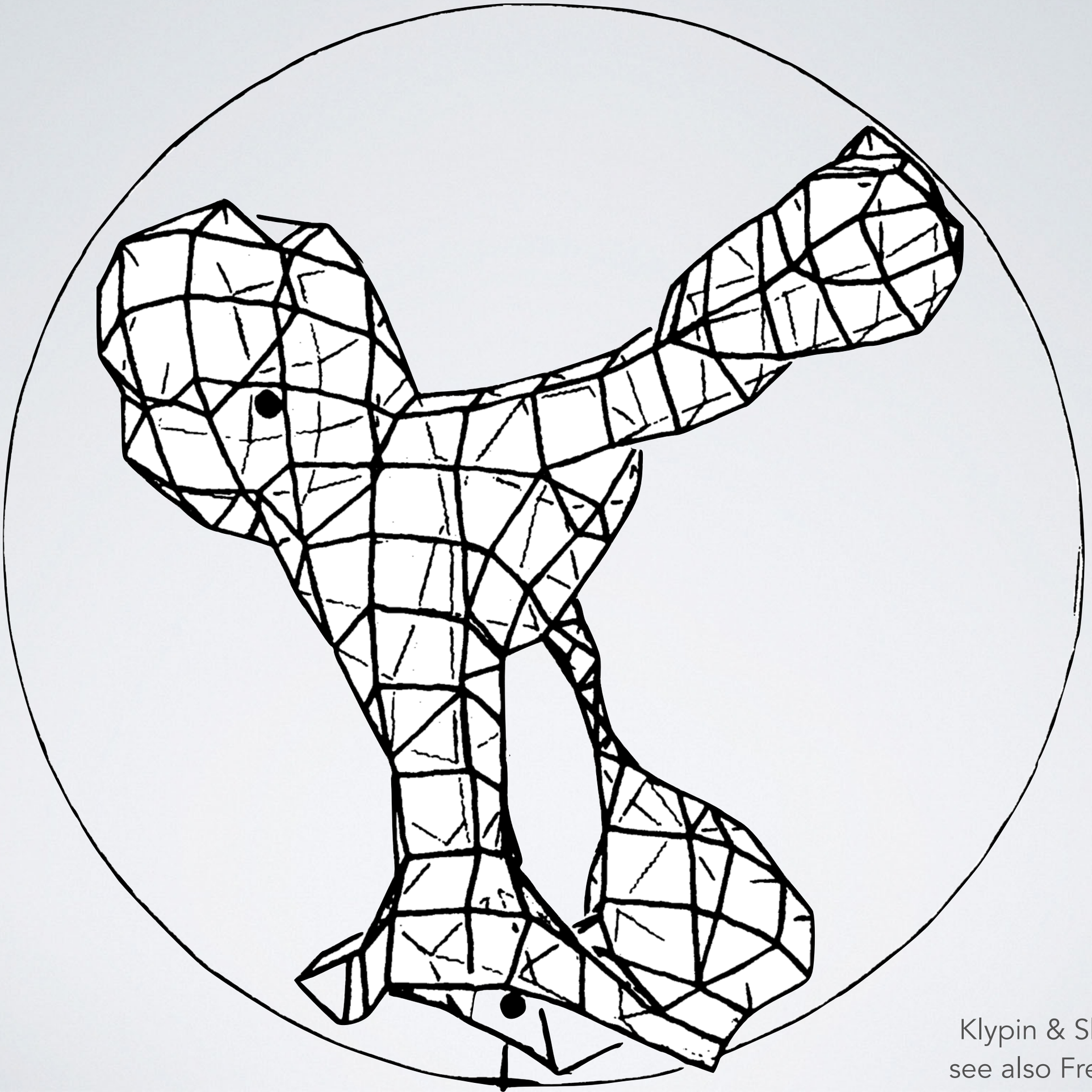


Merger trees: galaxy-halo connection,

mass functions…

Observations (weak lensing, cluster profiles)

Predictions for obs. clusters



Klypin & Shandarin 1983
see also Frenk et al. 1983

Diemer & Facio 2017 • The Fabric of the Universe

Conclusions

- The **structure of CDM halos** is not a solved problem
- The most important quantities for the galaxy-halo connection, **radius and mass, depend on definition**
- The **splashback radius** represents a physically motivated halo boundary