The edge of darkness, and other halo surprises

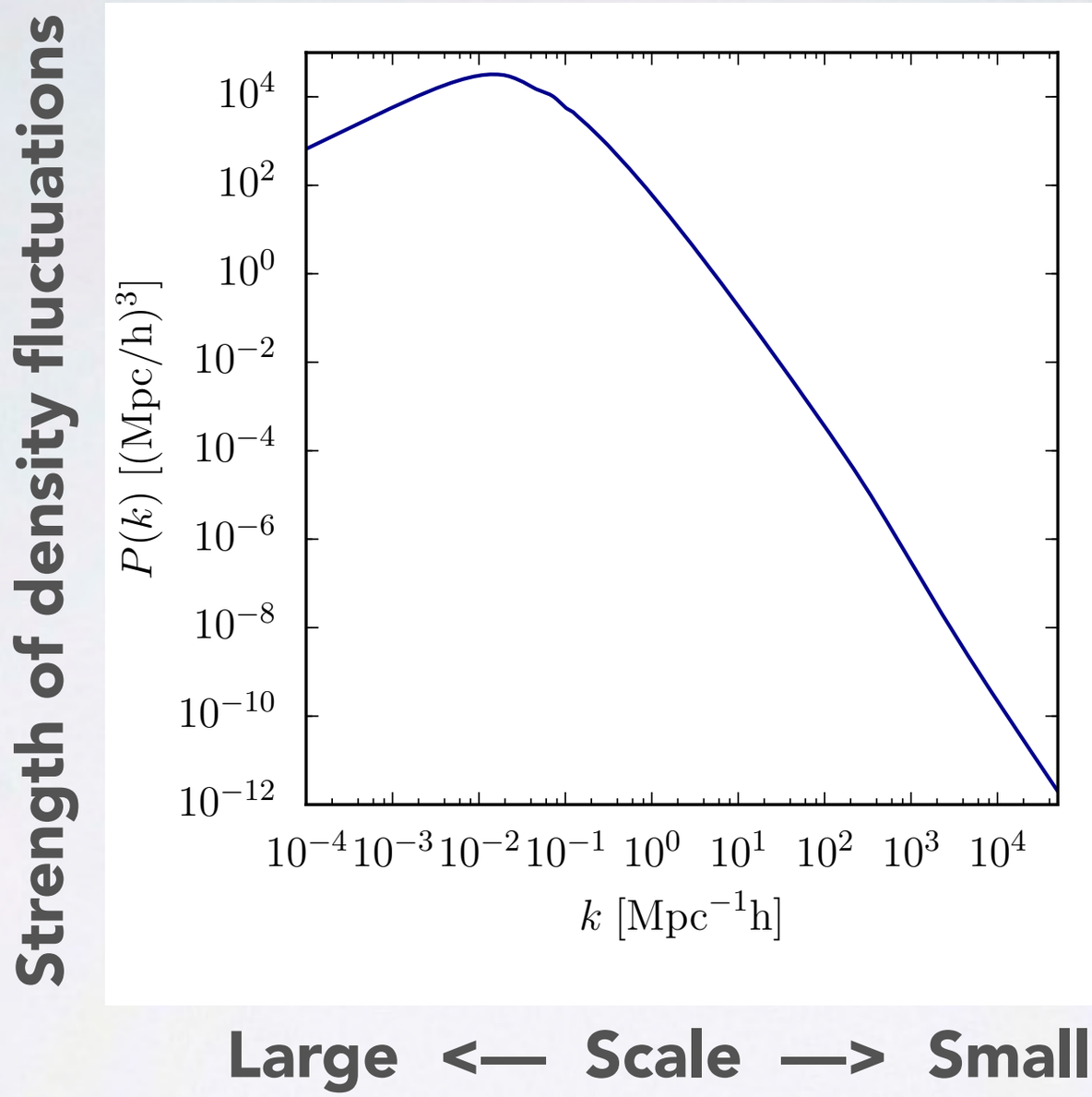
Benedikt Diemer

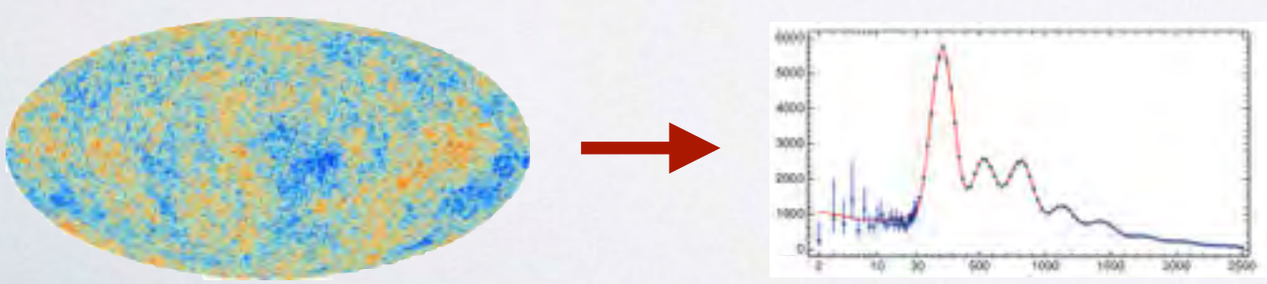
ITC Fellow, Harvard-Smithsonian Center for Astrophysics

(in collaboration with Andrey Kravtsov and Surhud More)

APEC Seminar • IPMU • 4/7/2016

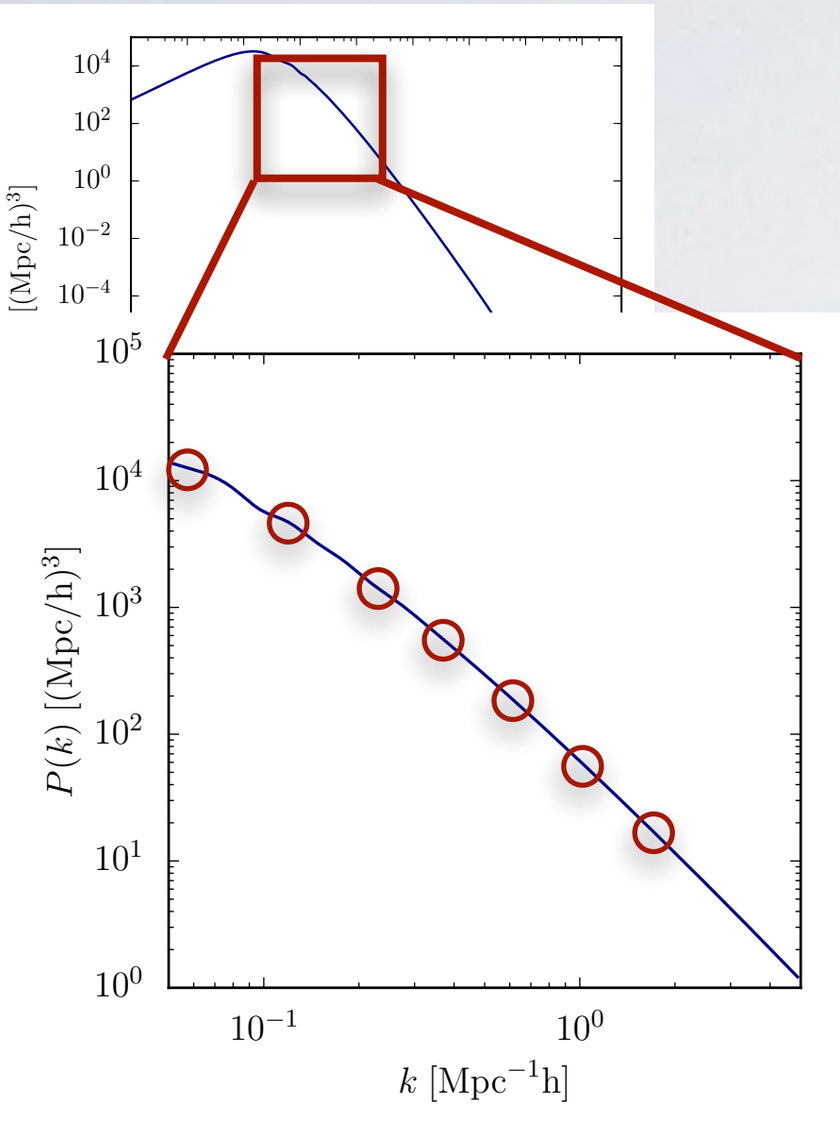
Dark matter power spectrum

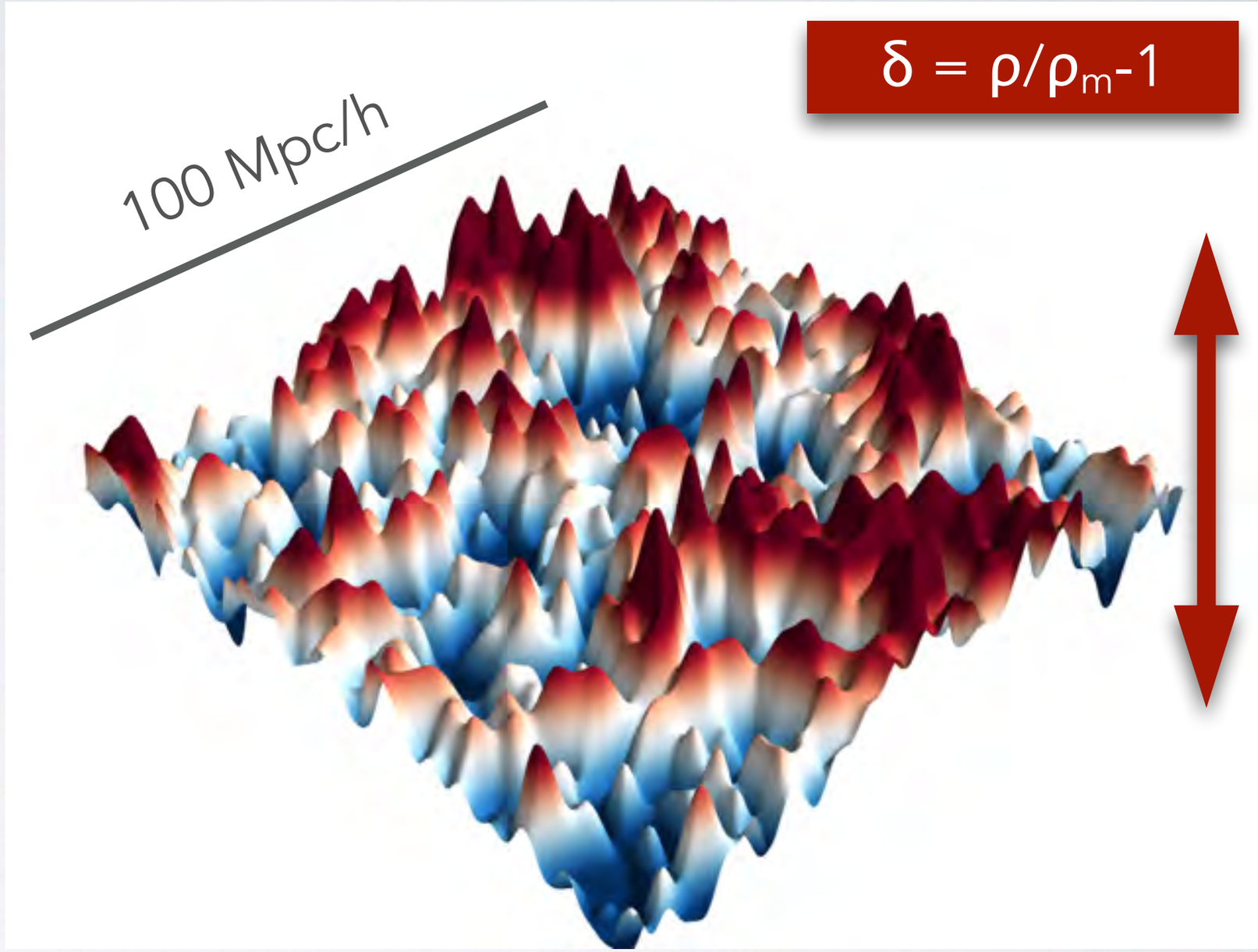


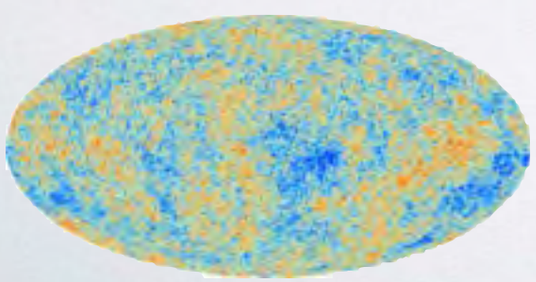


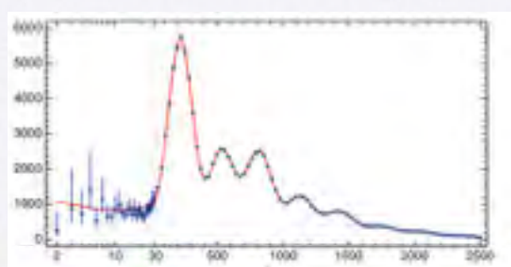
CAMB, Lewis et al. 2000

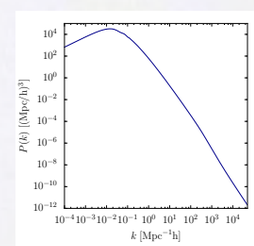
Dark matter power spectrum



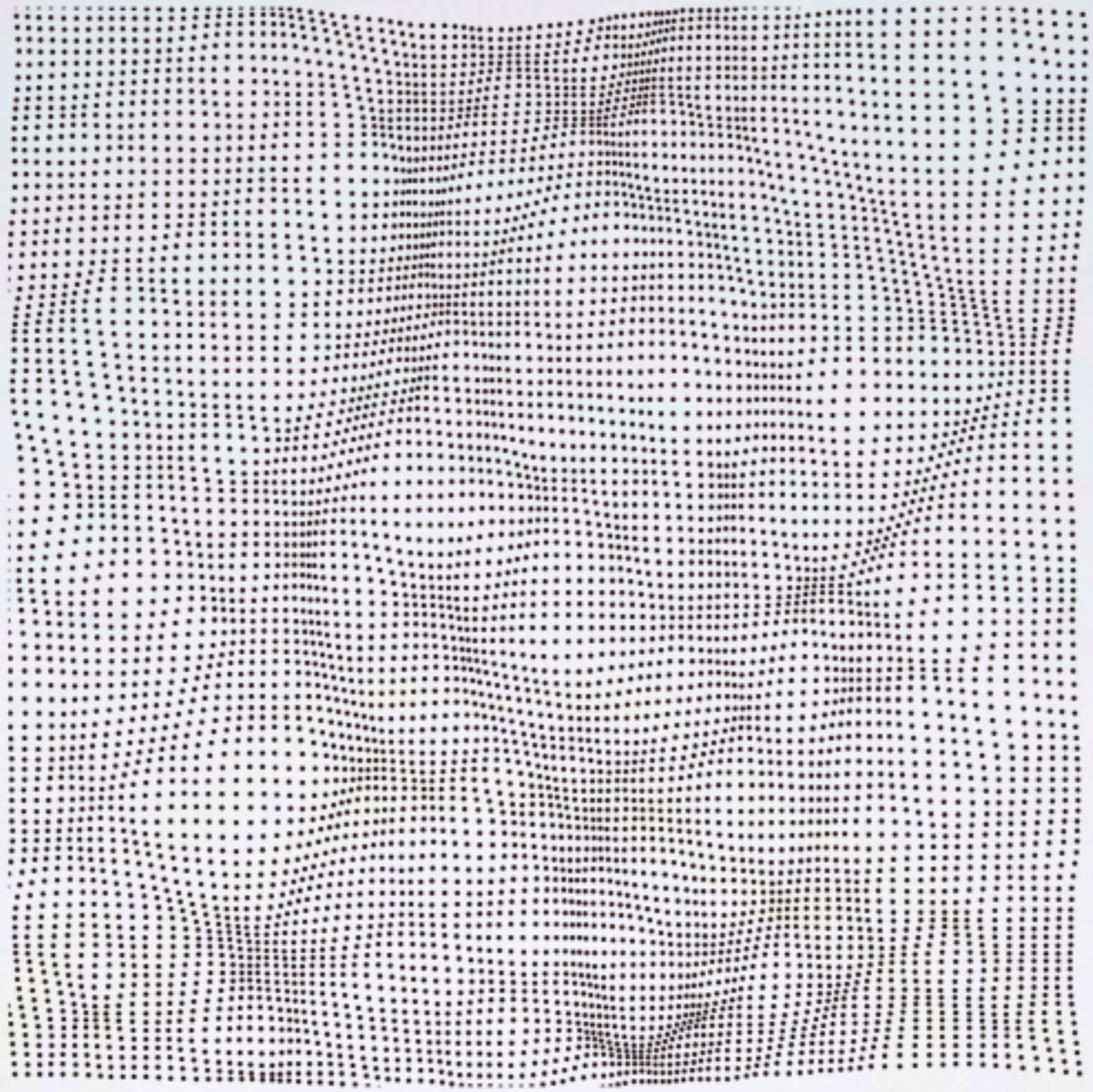


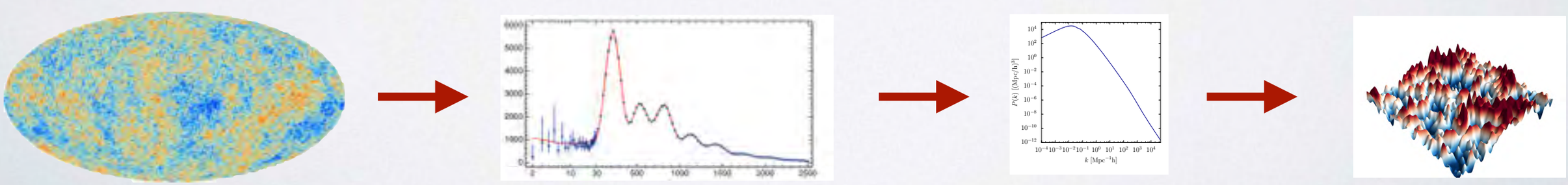






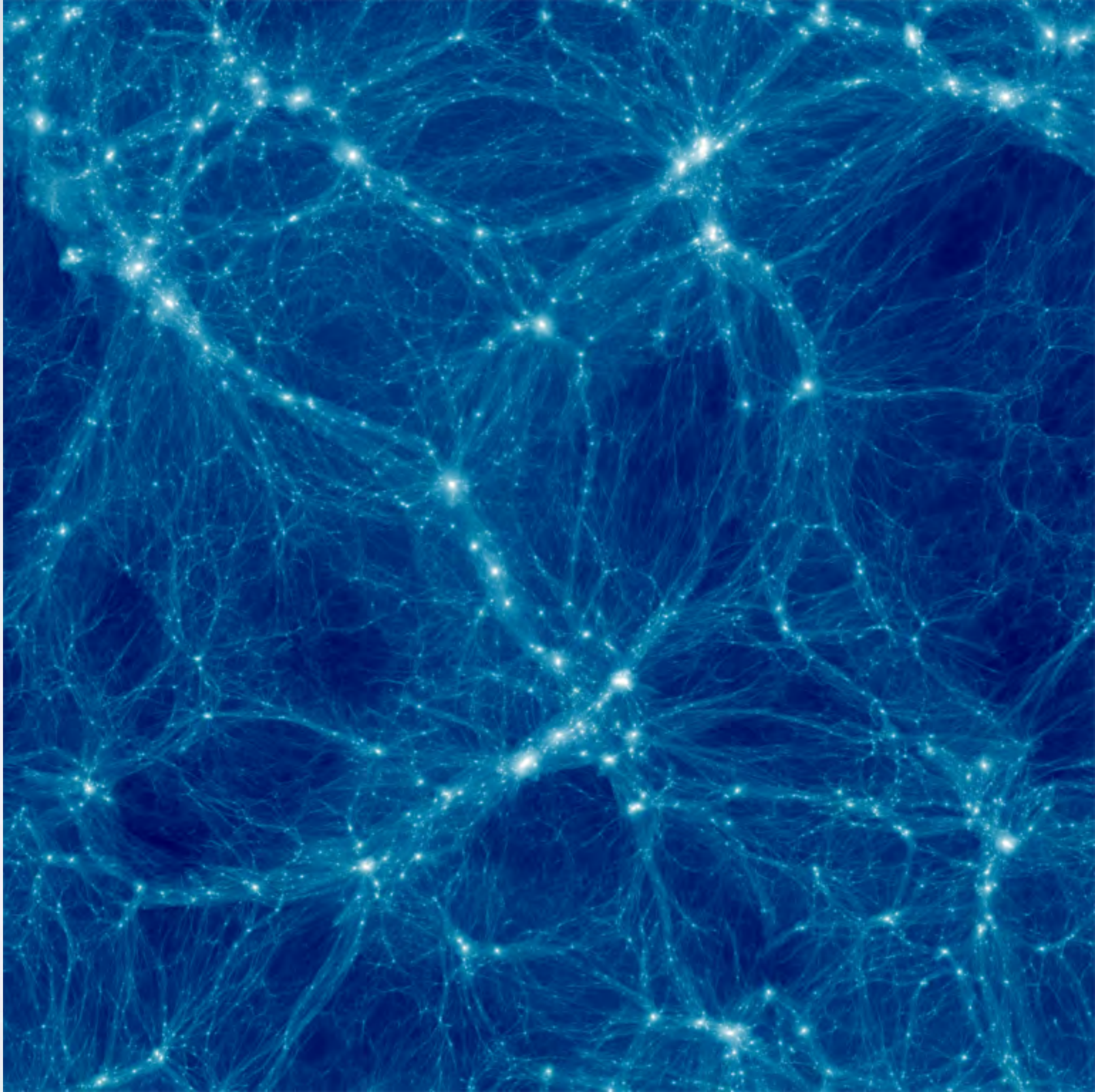
N-body simulations





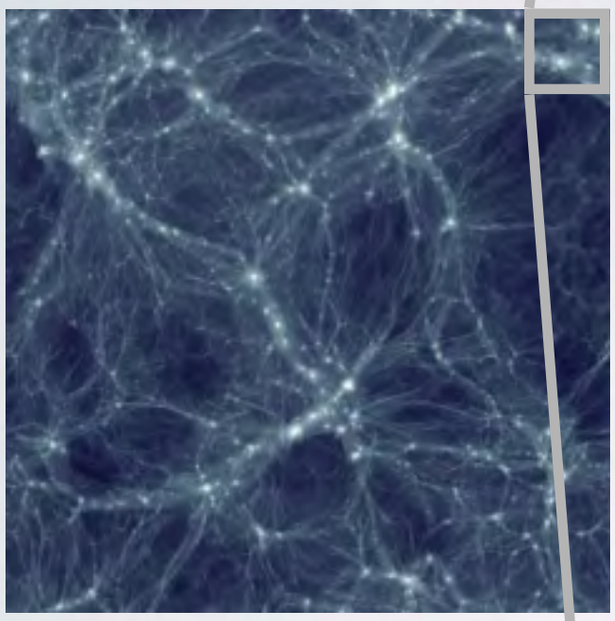
Crocce et al. 2006

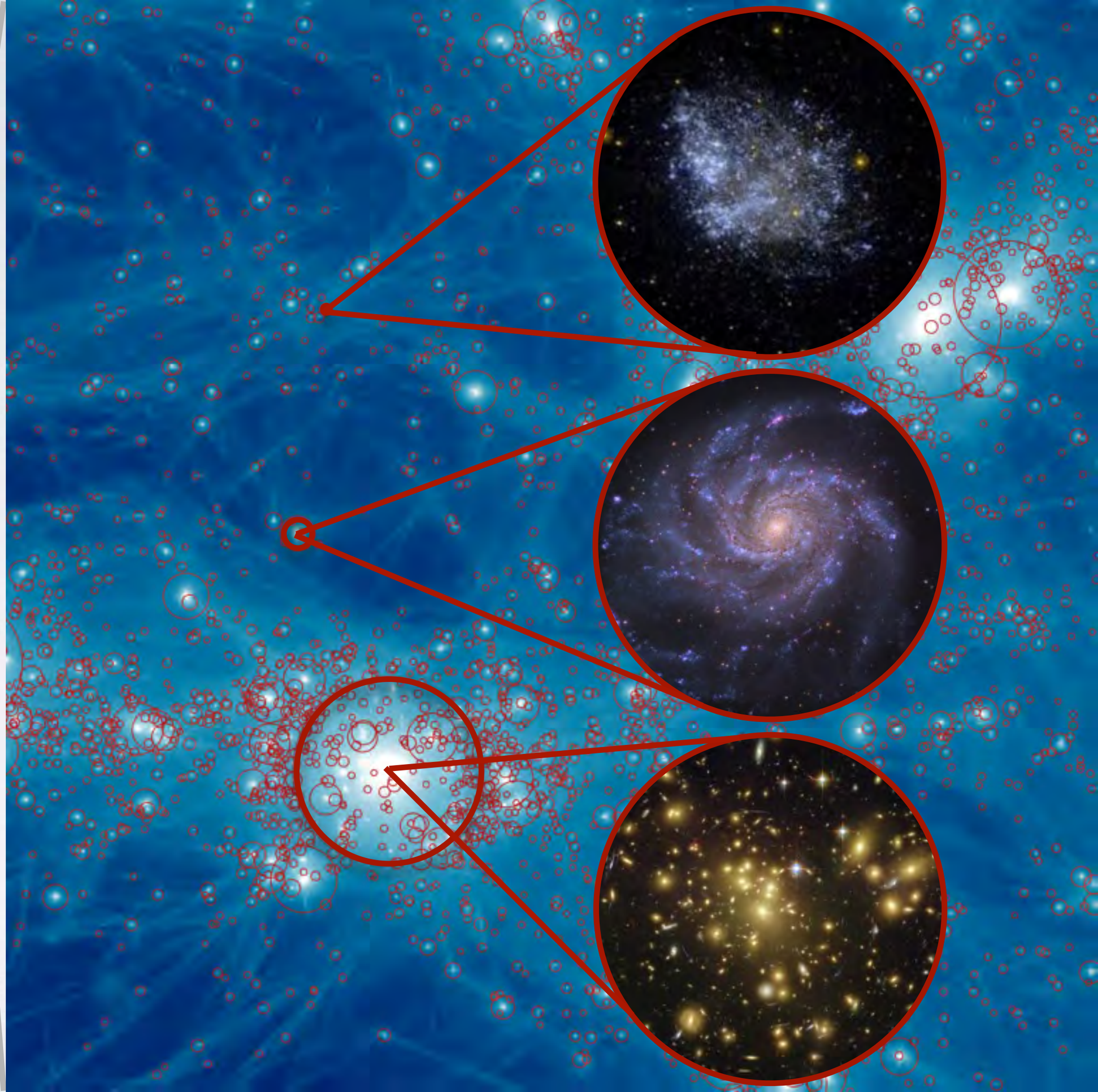
89 Mpc



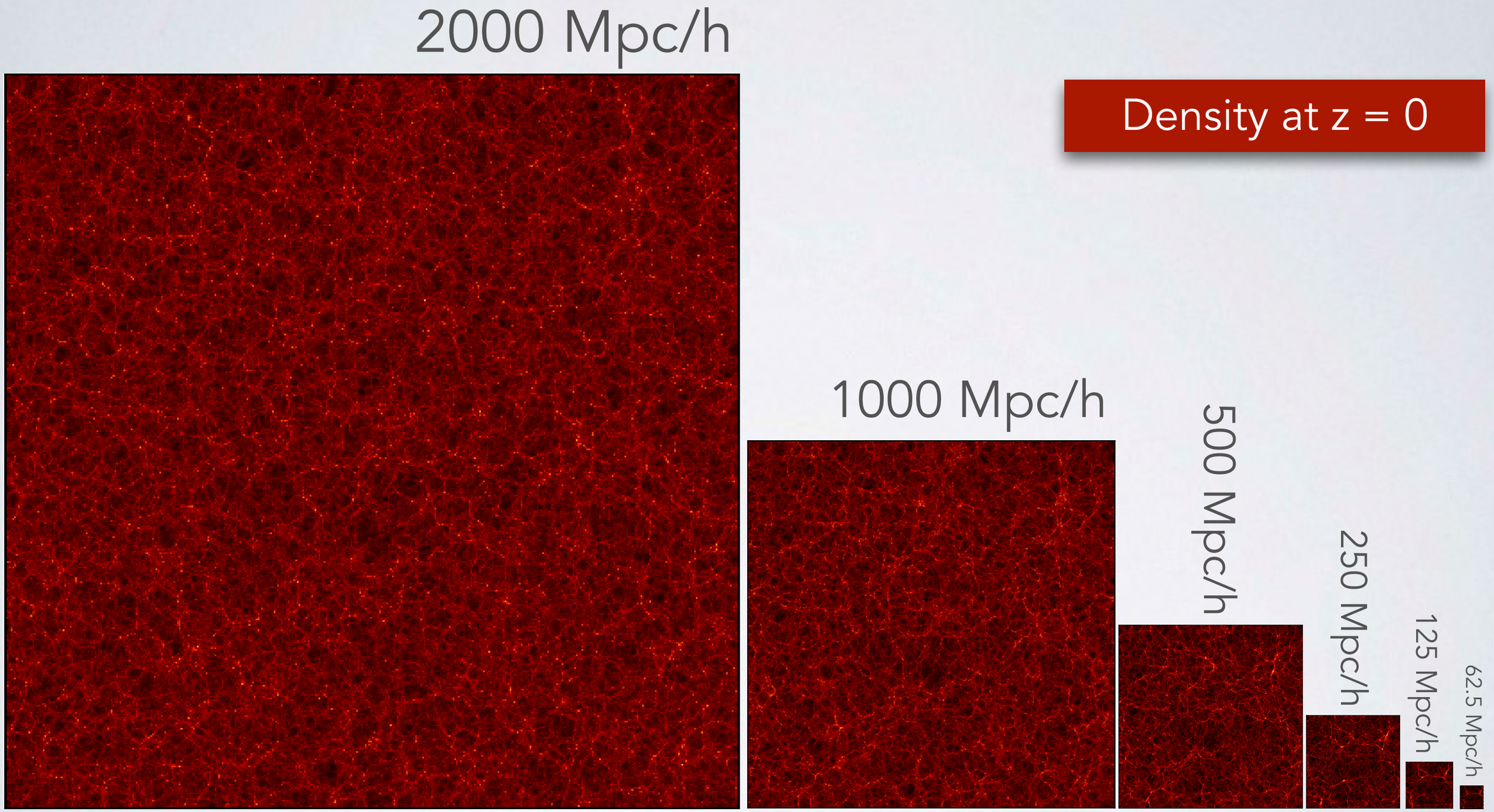
Visualization code:
Phil Mansfield

11 Mpc

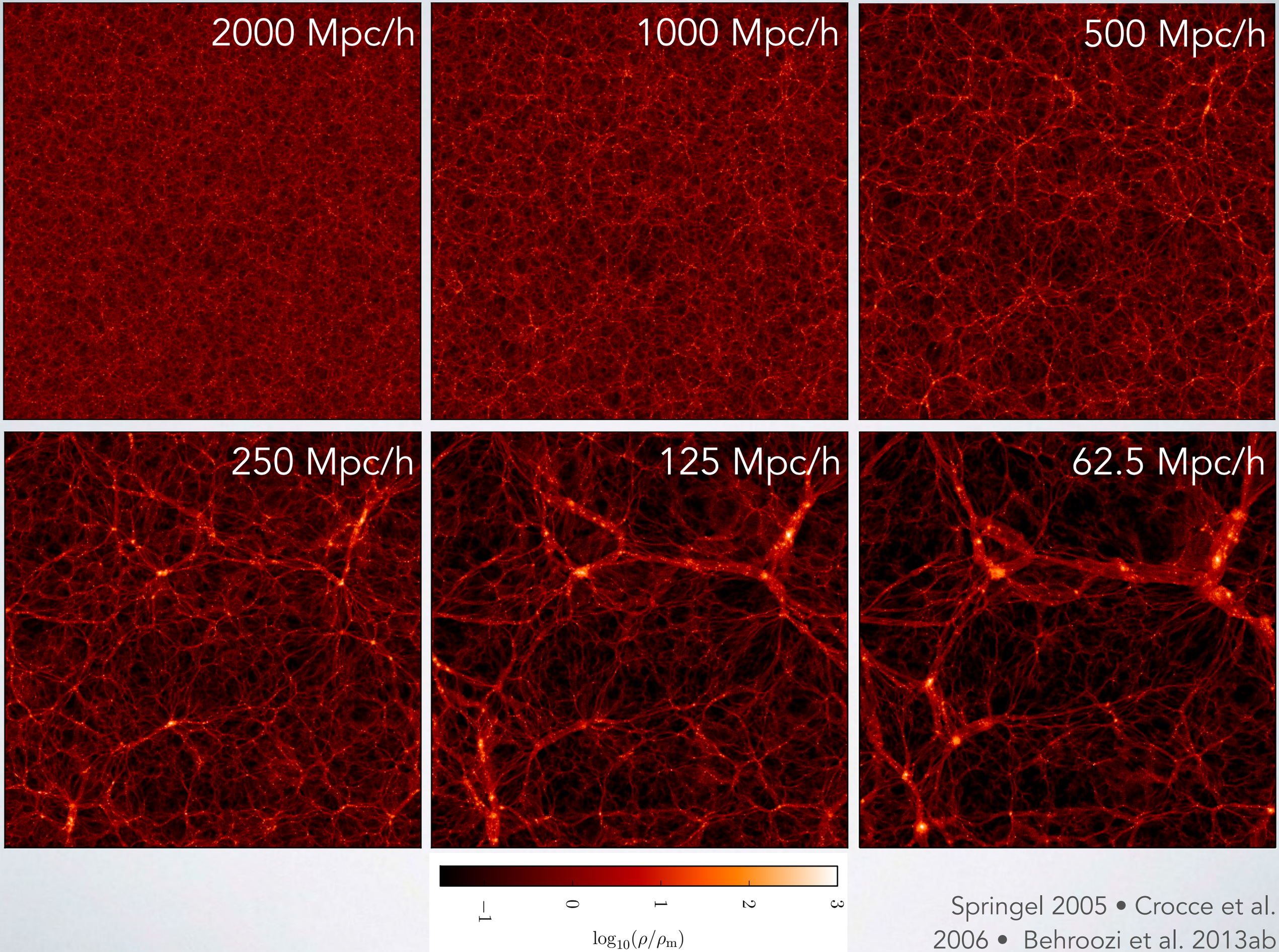




N-body simulations

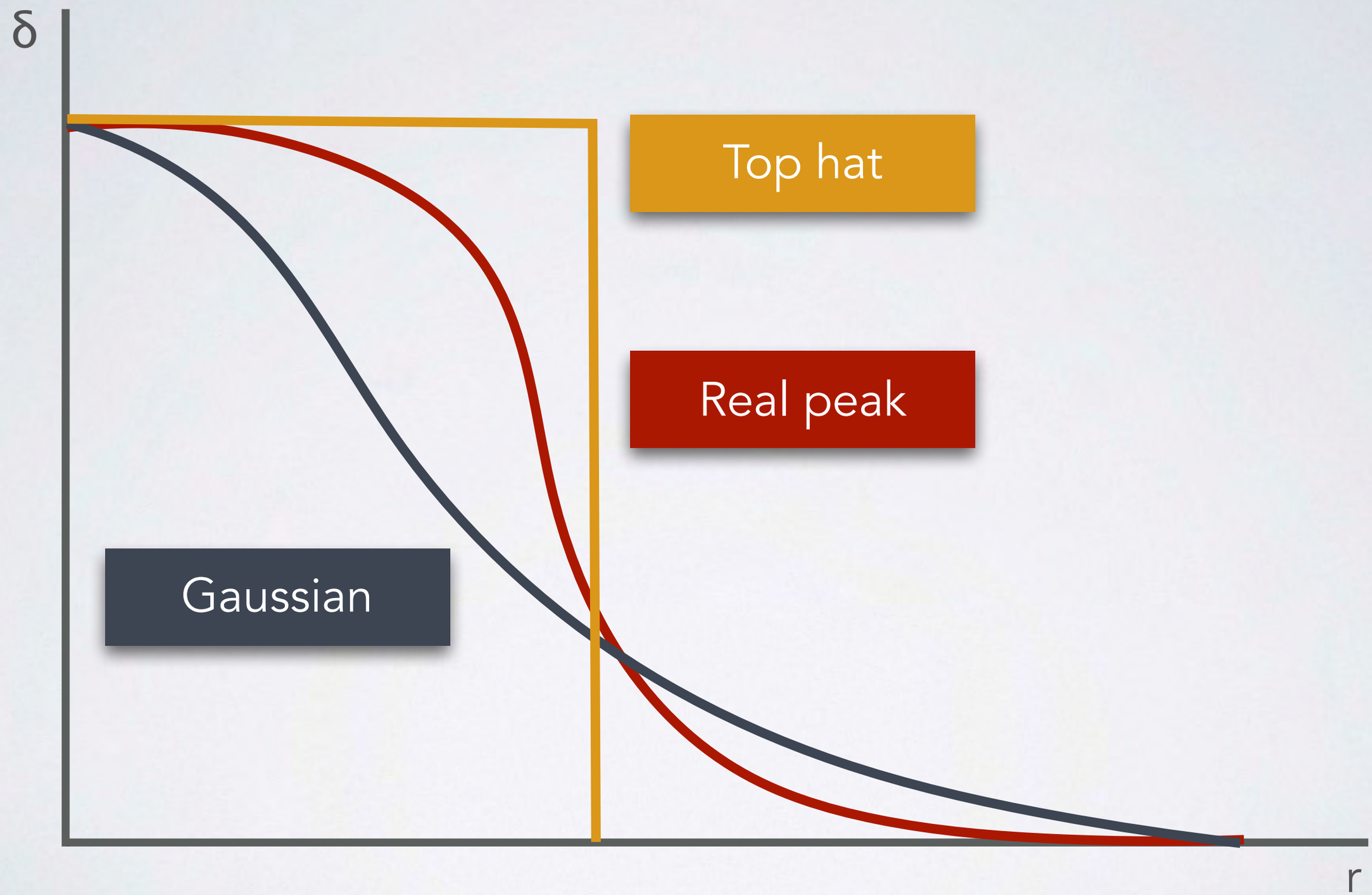


Diemer & Kravtsov 2014, 2015 • Springel 2005 • Crocce et al. 2006 • Behroozi et al. 2013ab



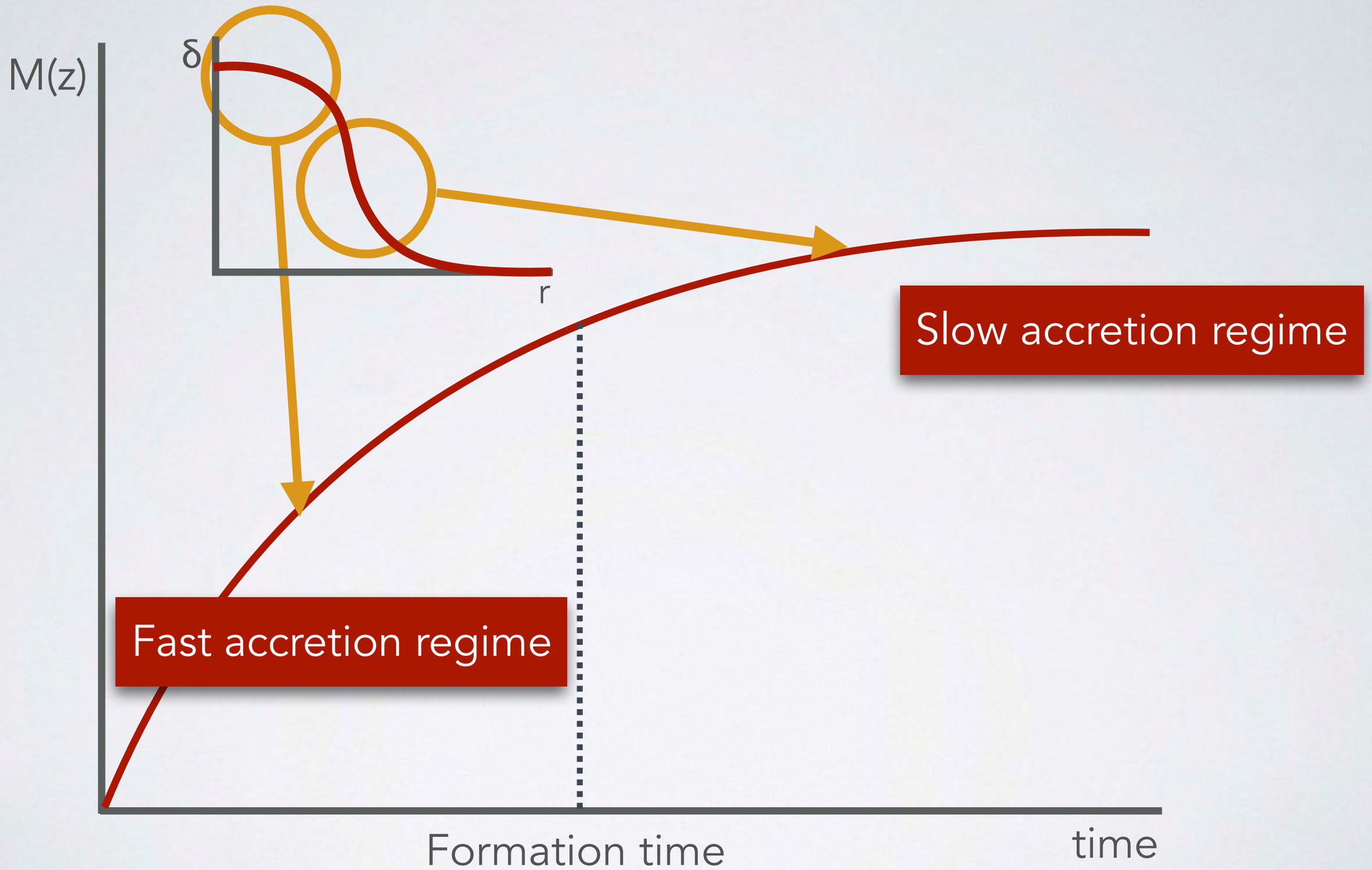
Springel 2005 • Crocce et al. 2006 • Behroozi et al. 2013ab

Initial peaks



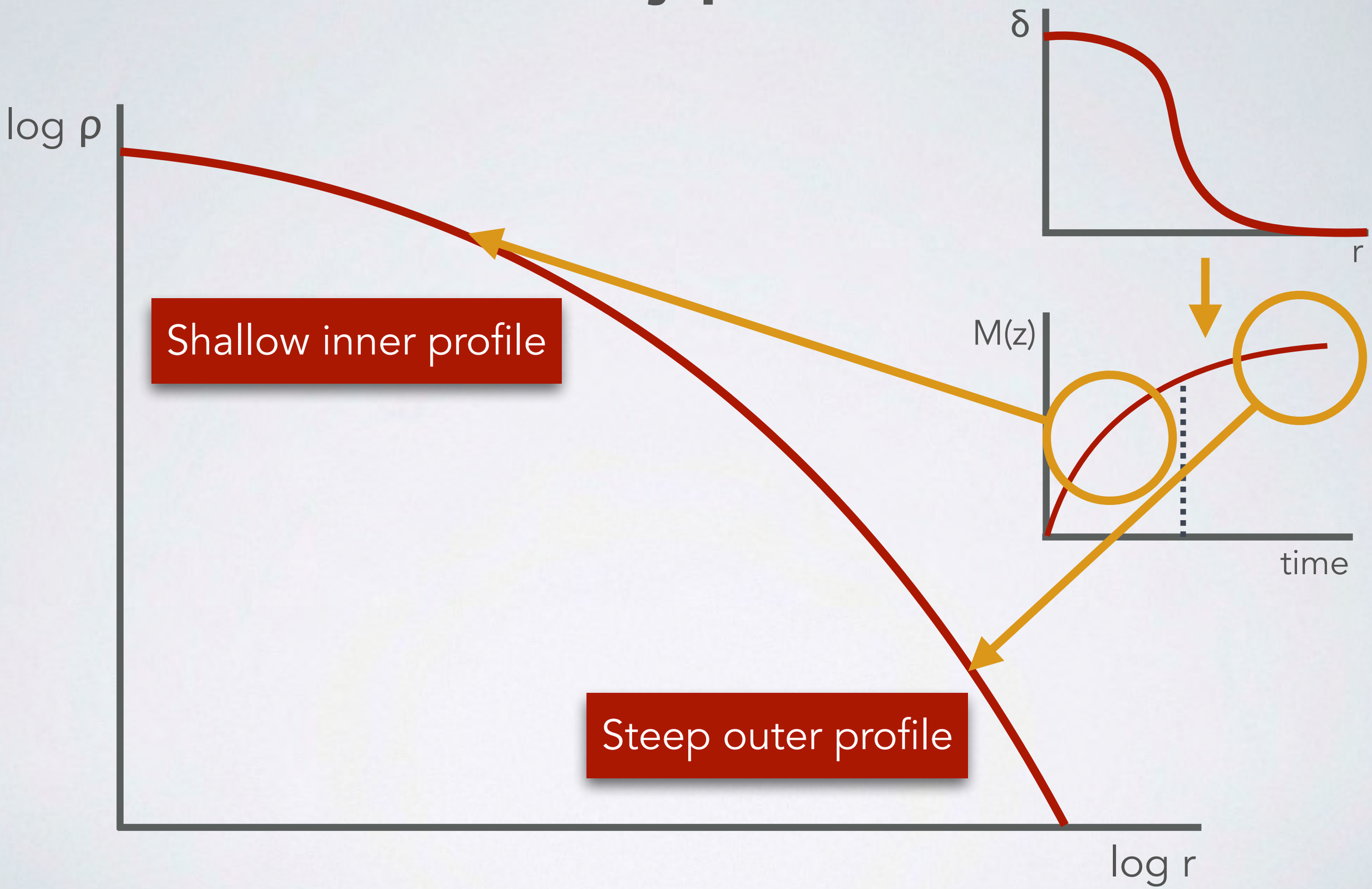
Bardeen et al. 1986 • Dalal et al. 2008

Mass accretion history



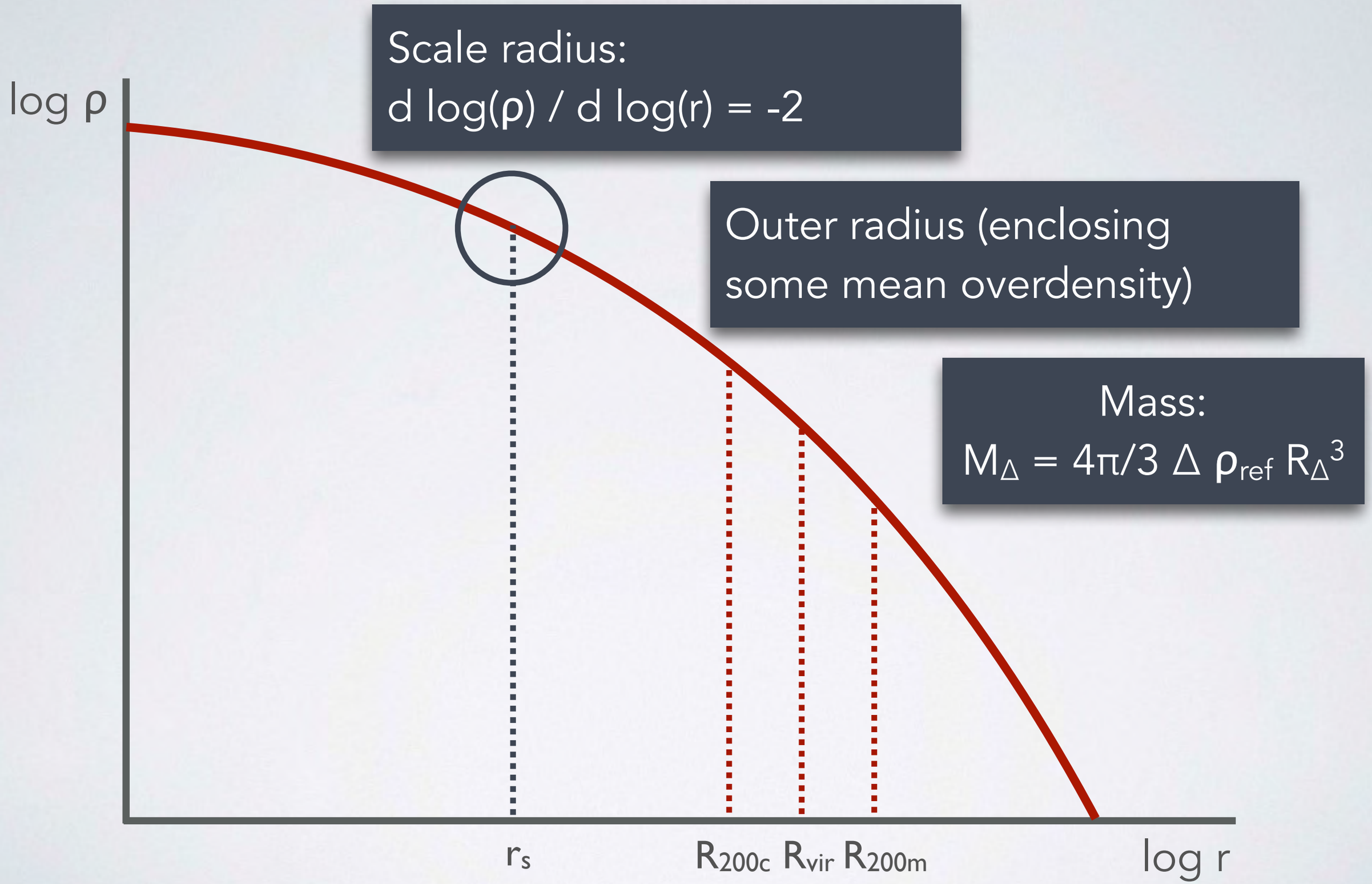
Wechsler et al. 2002 • van den Bosch 2002 • Zhao et al. 2003/2009 • Dalal et al. 2008

Density profile

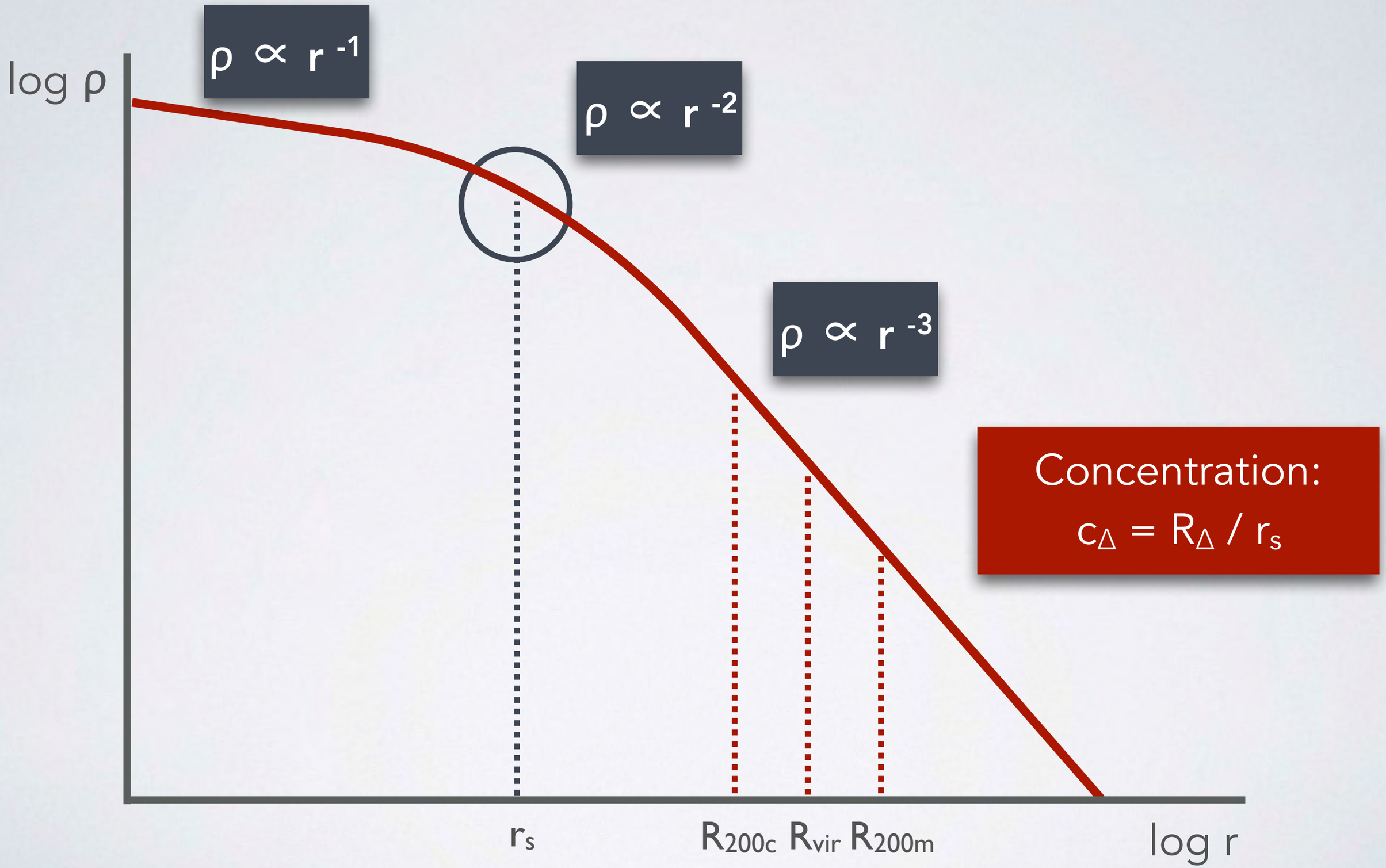


Dalal et al. 2008 • Ludlow et al. 2013

Density profile

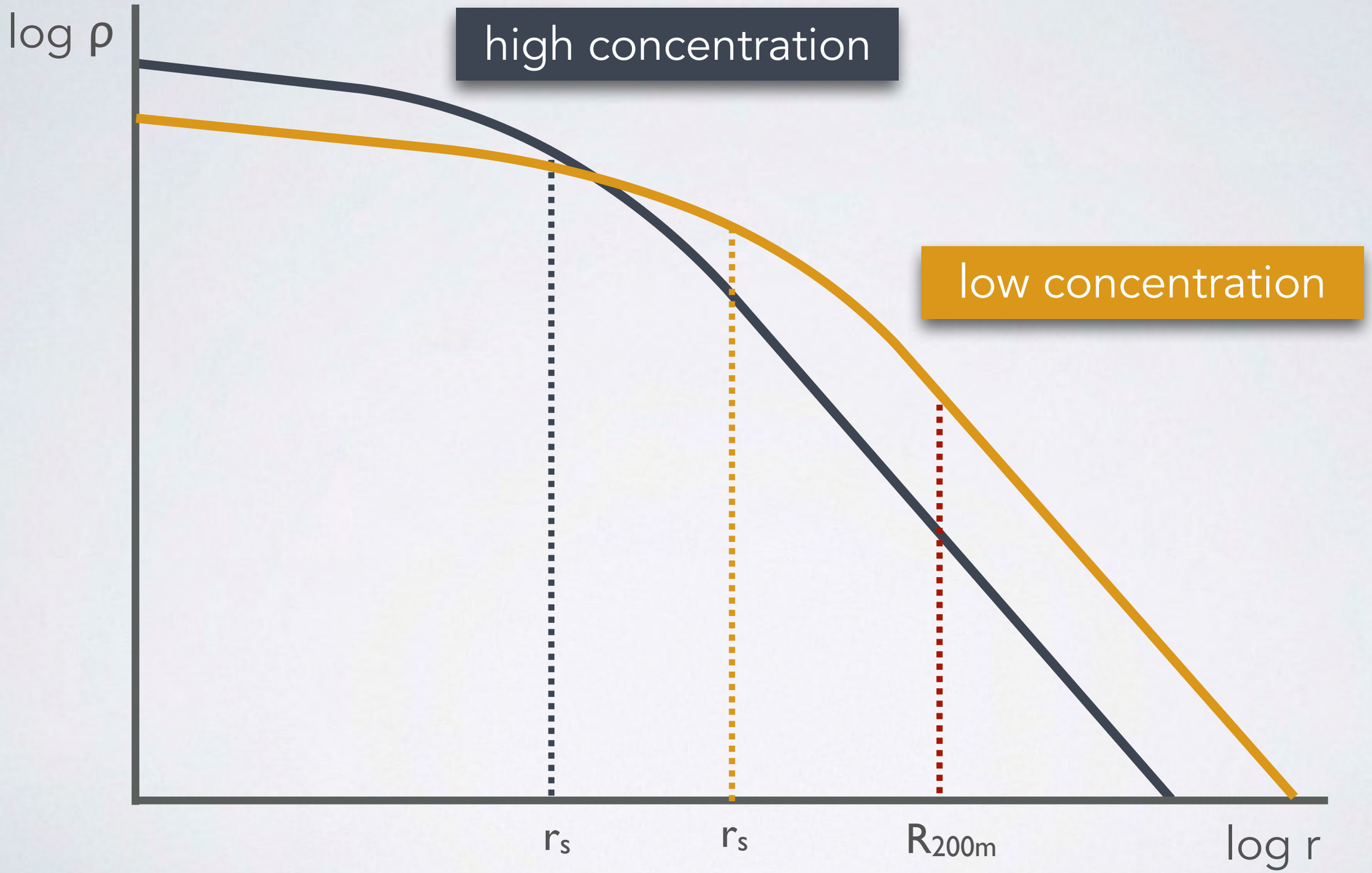


Navarro-Frenk-White profile



Navarro et al. 1995/1996/1997

Navarro-Frenk-White profile



Navarro et al. 1995/1996/1997

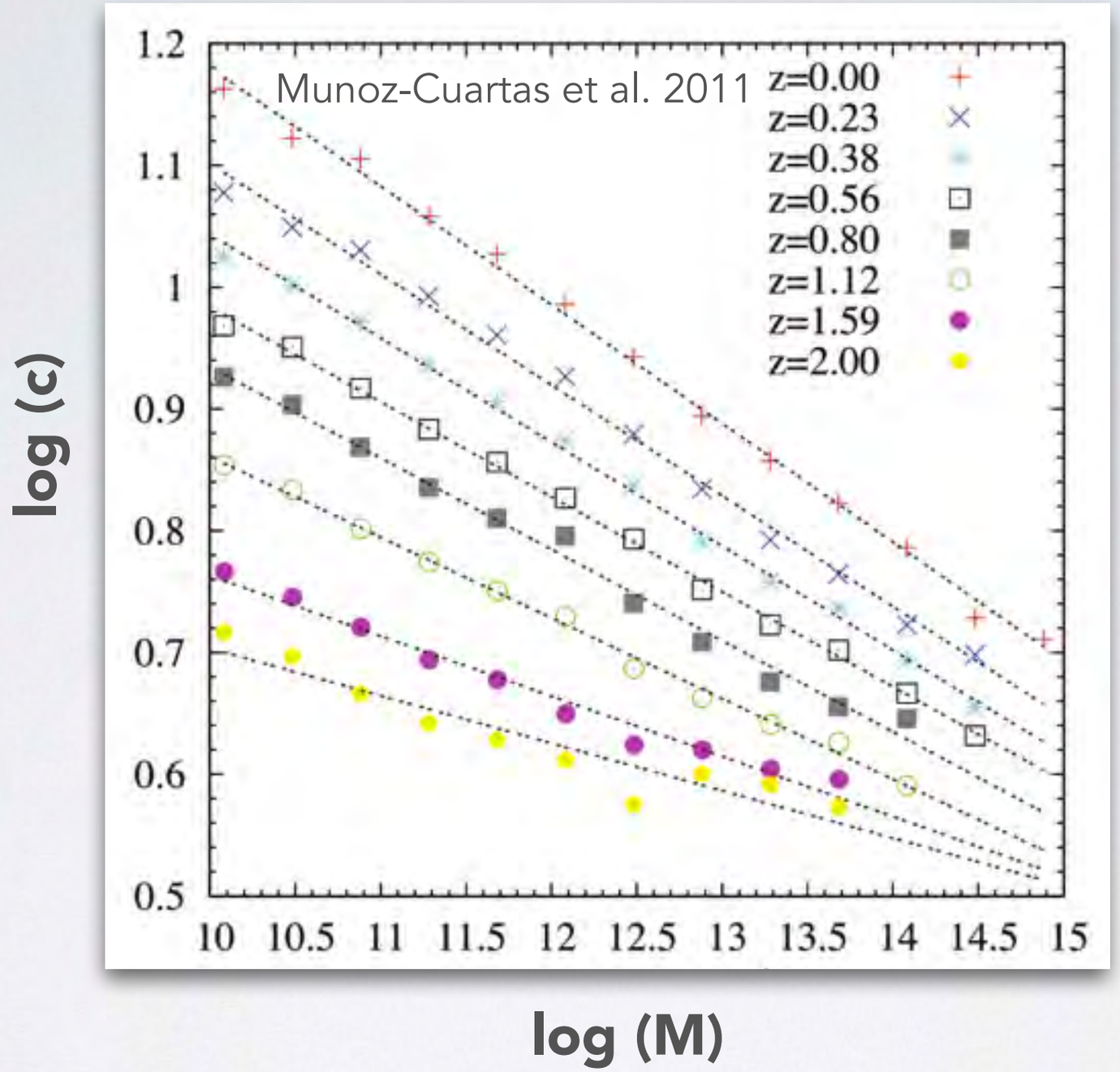
Questions

1. Can we find a universal **concentration-mass** relation?
2. Are the **outer** profiles universal?
3. Is there a well-defined **edge** to a halo?

Concentration-mass models

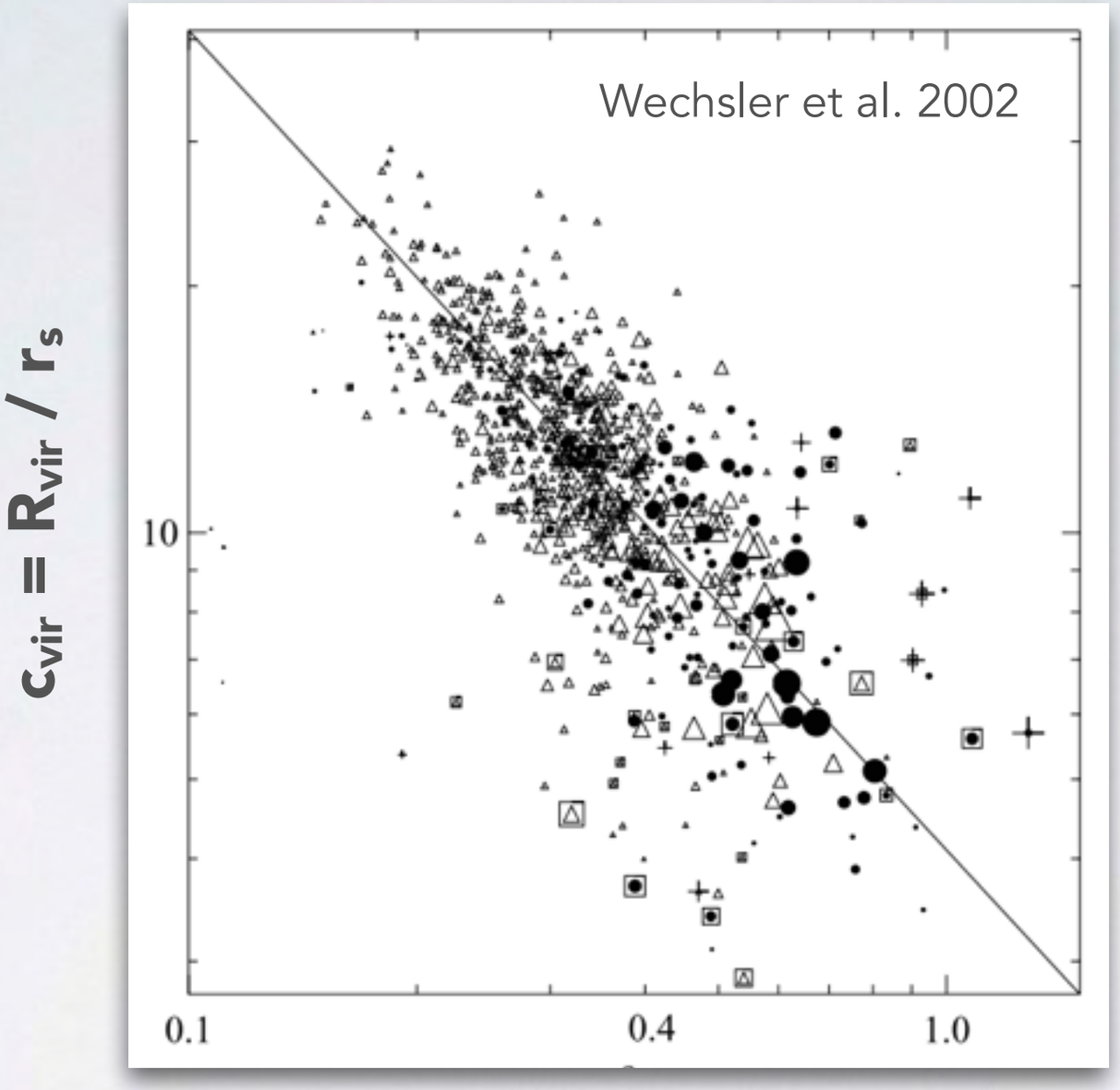
- Navarro et al. 1996
- Navarro et al. 1997
- Avila-Reese et al. 1999
- Jing 2000
- Bullock et al. 2001
- Eke et al. 2001
- Wechsler et al. 2002
- Zhao et al. 2003
- Colin et al. 2004
- Dolag et al. 2004
- Neto et al. 2007
- Duffy et al. 2008
- Maccio et al. 2008
- Gao et al. 2008
- Zhao et al. 2009
- Klypin et al. 2011
- Munoz-Cuartas et al. 2011
- Prada et al. 2012
- Giocoli et al. 2012
- Bhattacharya et al. 2013
- Ludlow et al. 2014
- Dutton & Maccio 2014
- Klypin et al. 2015

Power-law fits



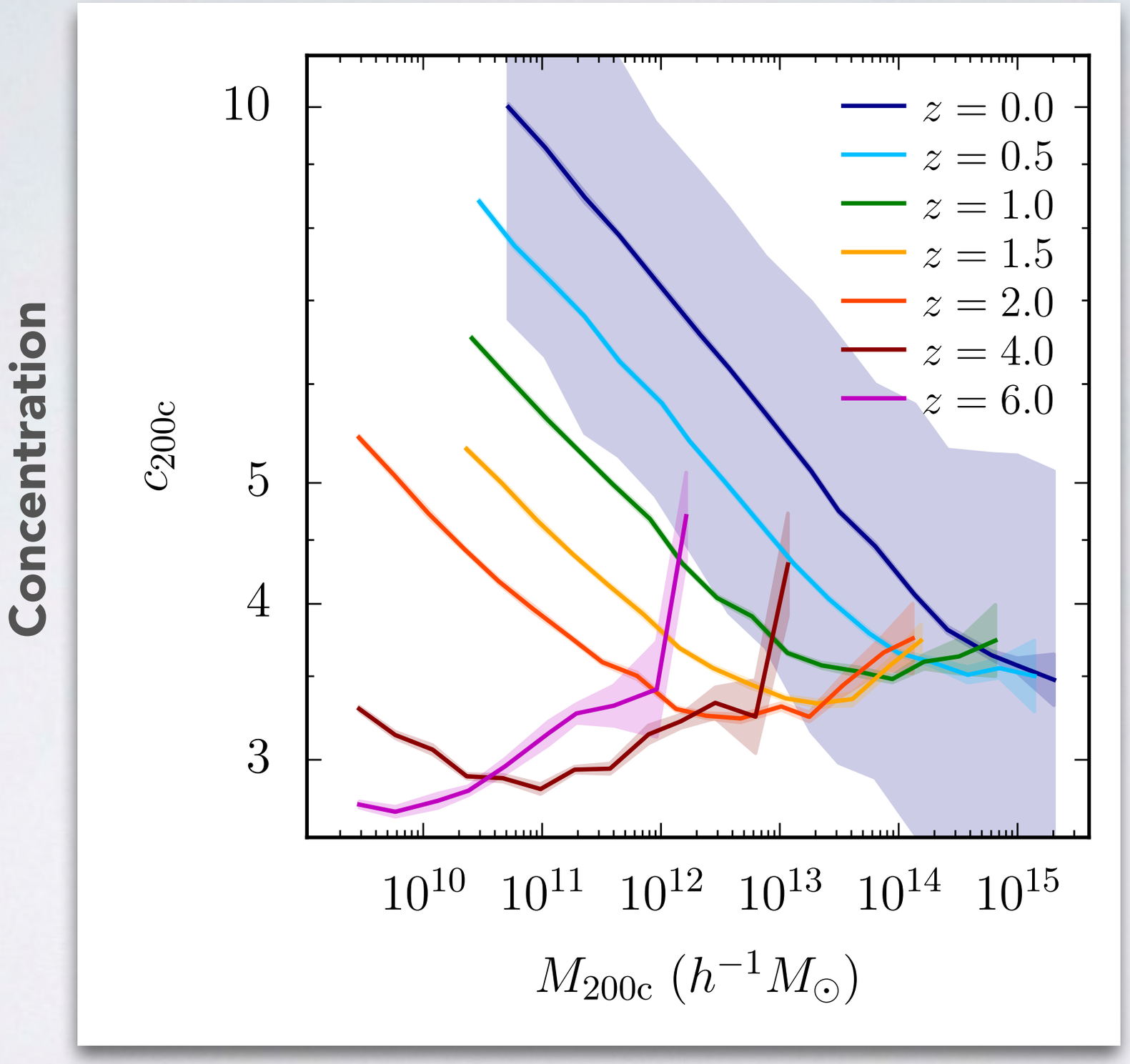
Avila-Reese et al. 1999 • Jing 2000 • Neto et al. 2007 • Duffy et al. 2008 • Maccio et al. 2008
Gao et al. 2008 • Klypin et al. 2011 • Munoz-Cuartas et al. 2011 • Dutton & Maccio 2014

History-based models



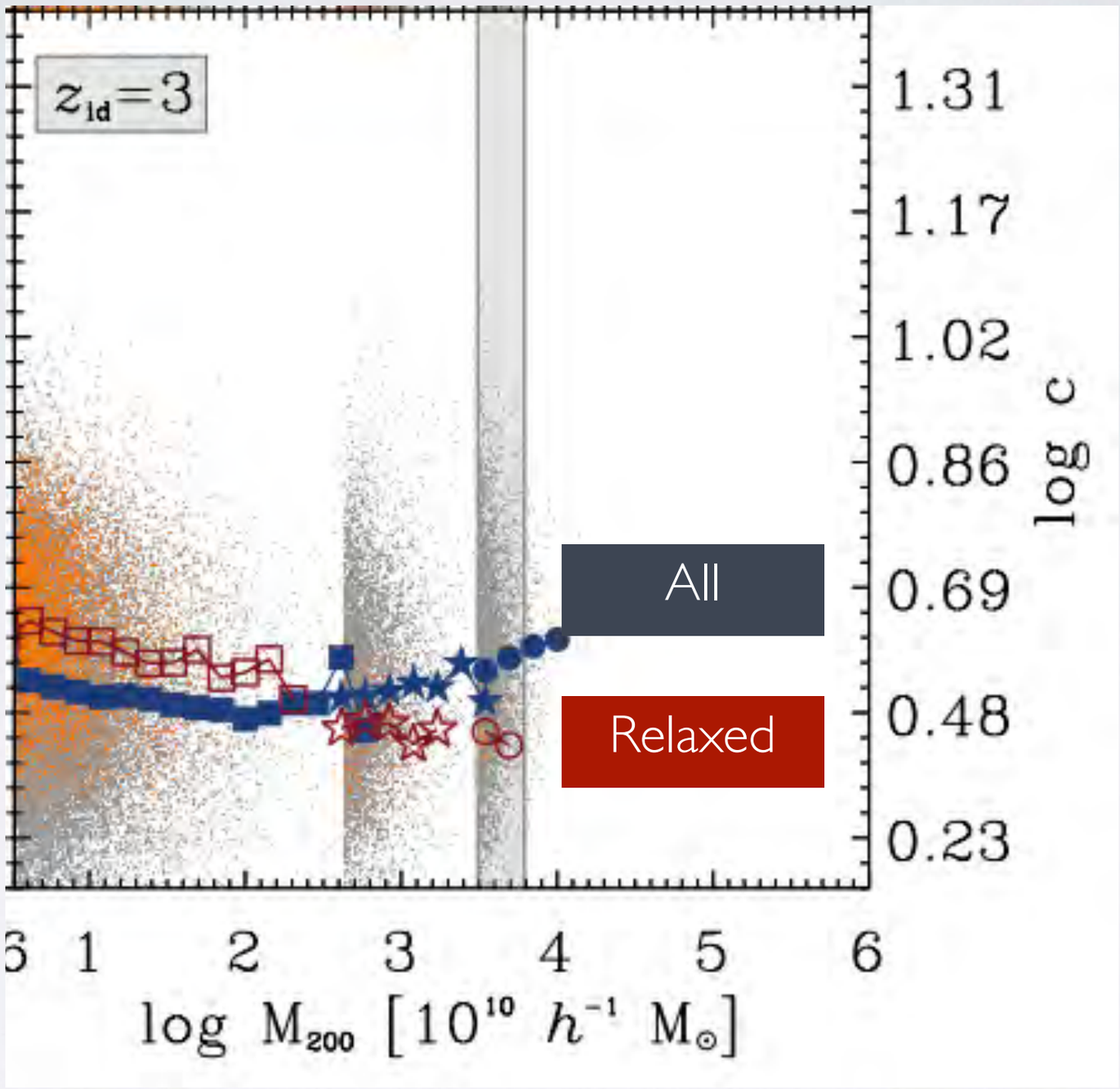
Navarro et al. 1997 • Bullock et al. 2001 • Eke et al. 2001 • Wechsler et al. 2002
Zhao et al. 2009 • Giocoli et al. 2012 • Ludlow et al. 2014

Concentration-mass relation



Diemer & Kravtsov 2015

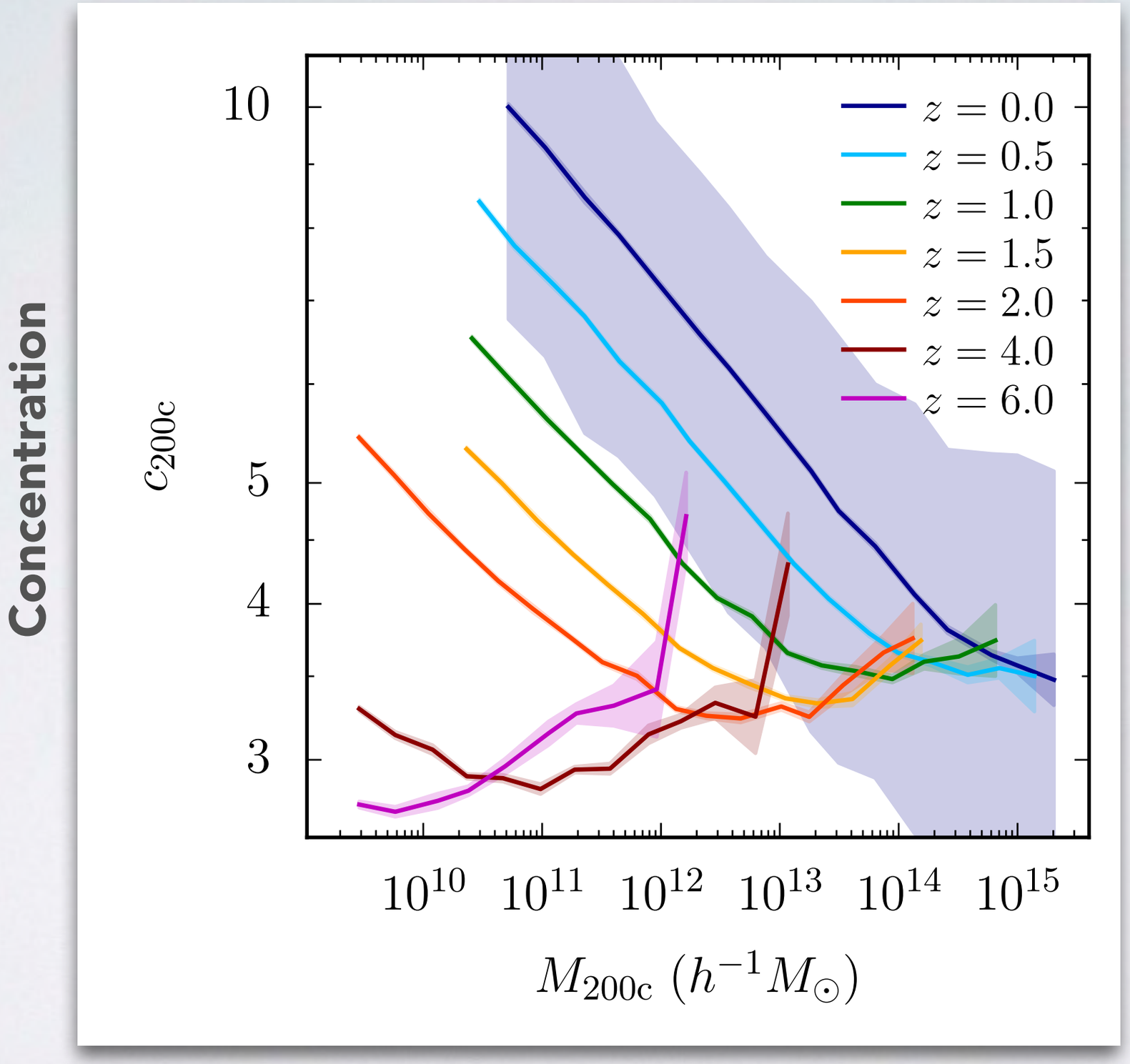
Is there an upturn?



Ludlow et al. 2012

Prada et al. 2012 • Ludlow et al. 2012 • Meneghetti & Rasia 2013

Concentration-mass relation

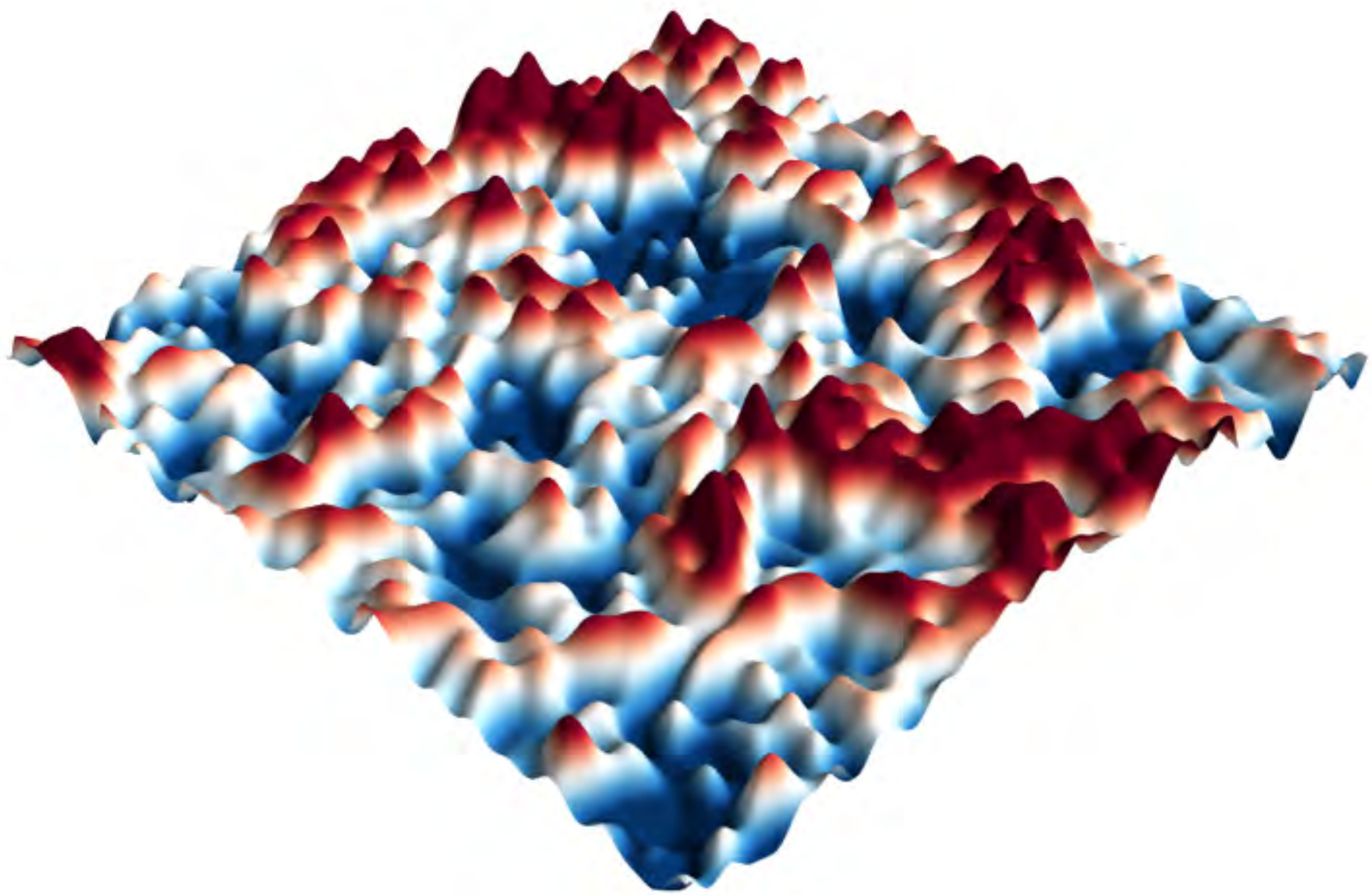


Halo mass

Diemer & Kravtsov 2015 • Dutton & Maccio 2015

Peak height

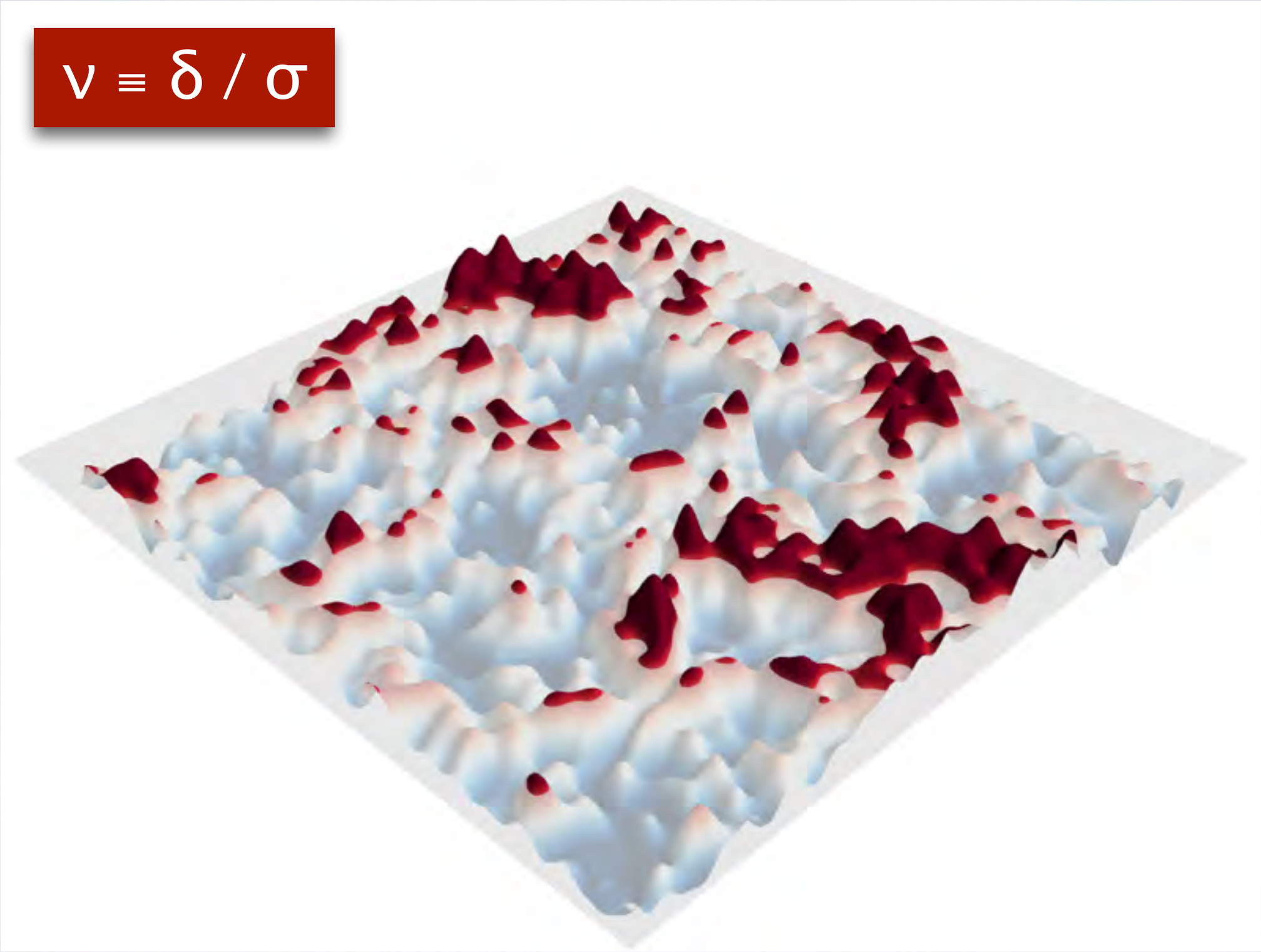
$\nu \equiv \delta / \sigma$



Bardeen et al. 1986

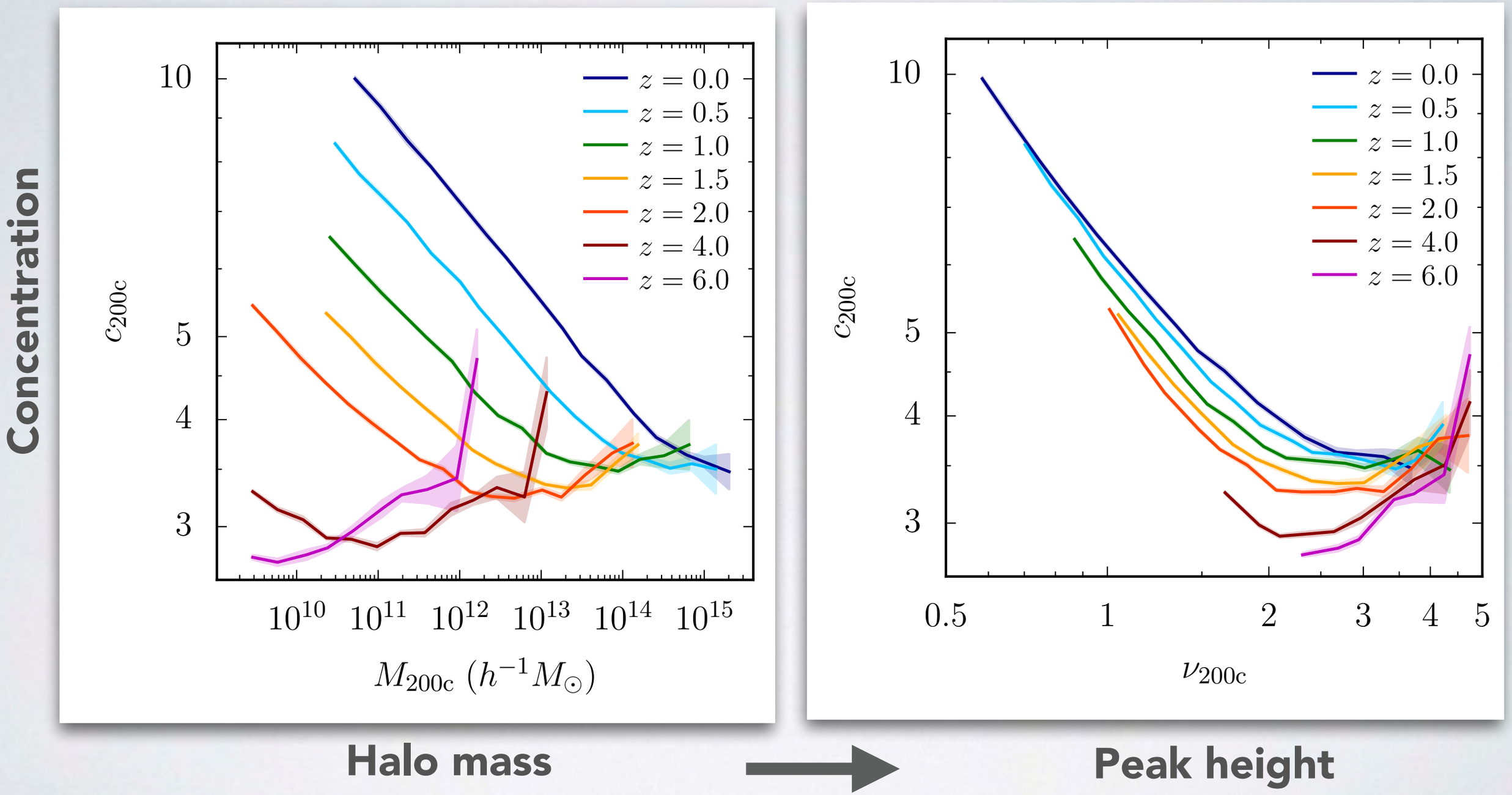
Peak height

$\nu \equiv \delta / \sigma$



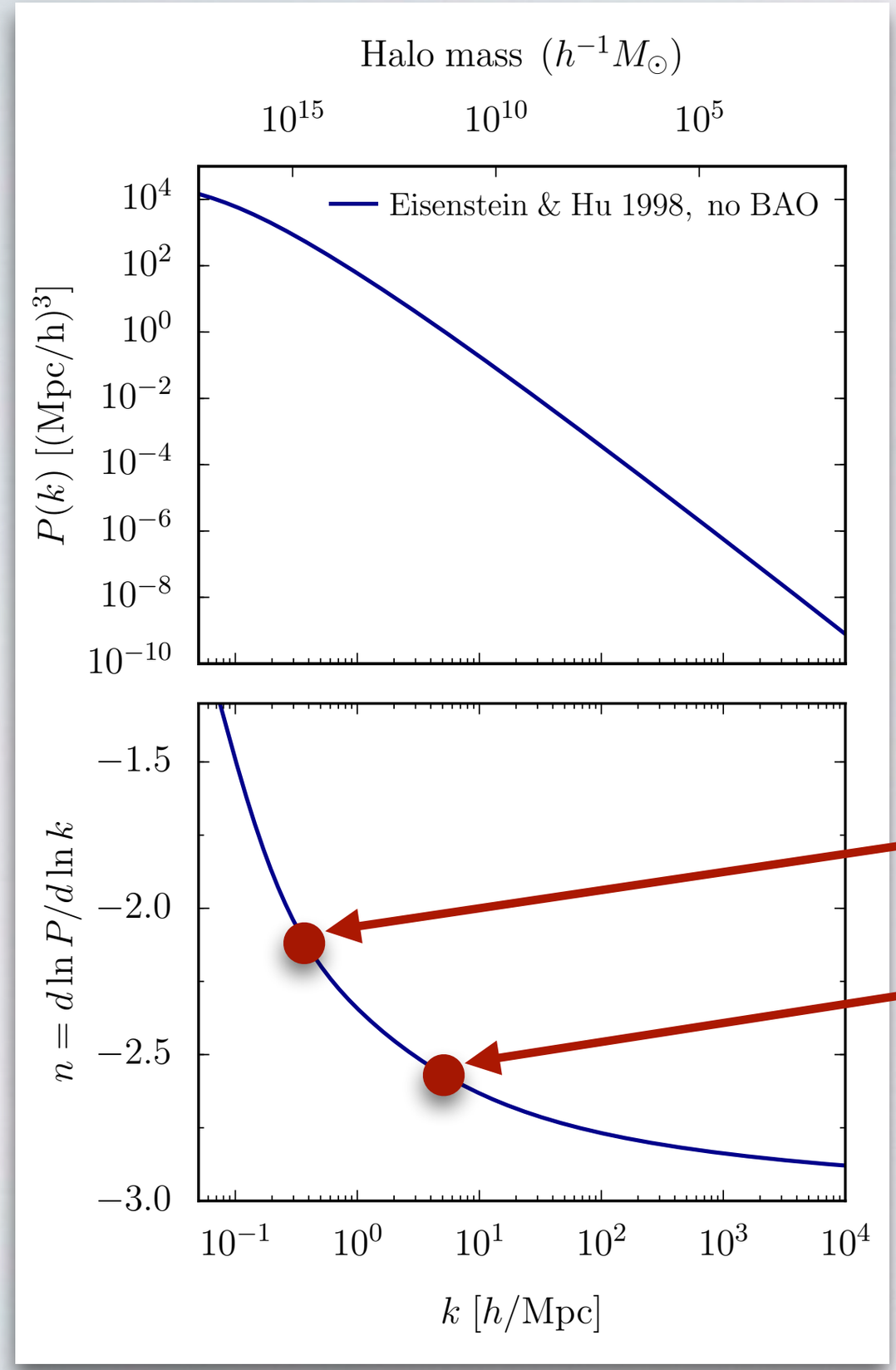
Bardeen et al. 1986

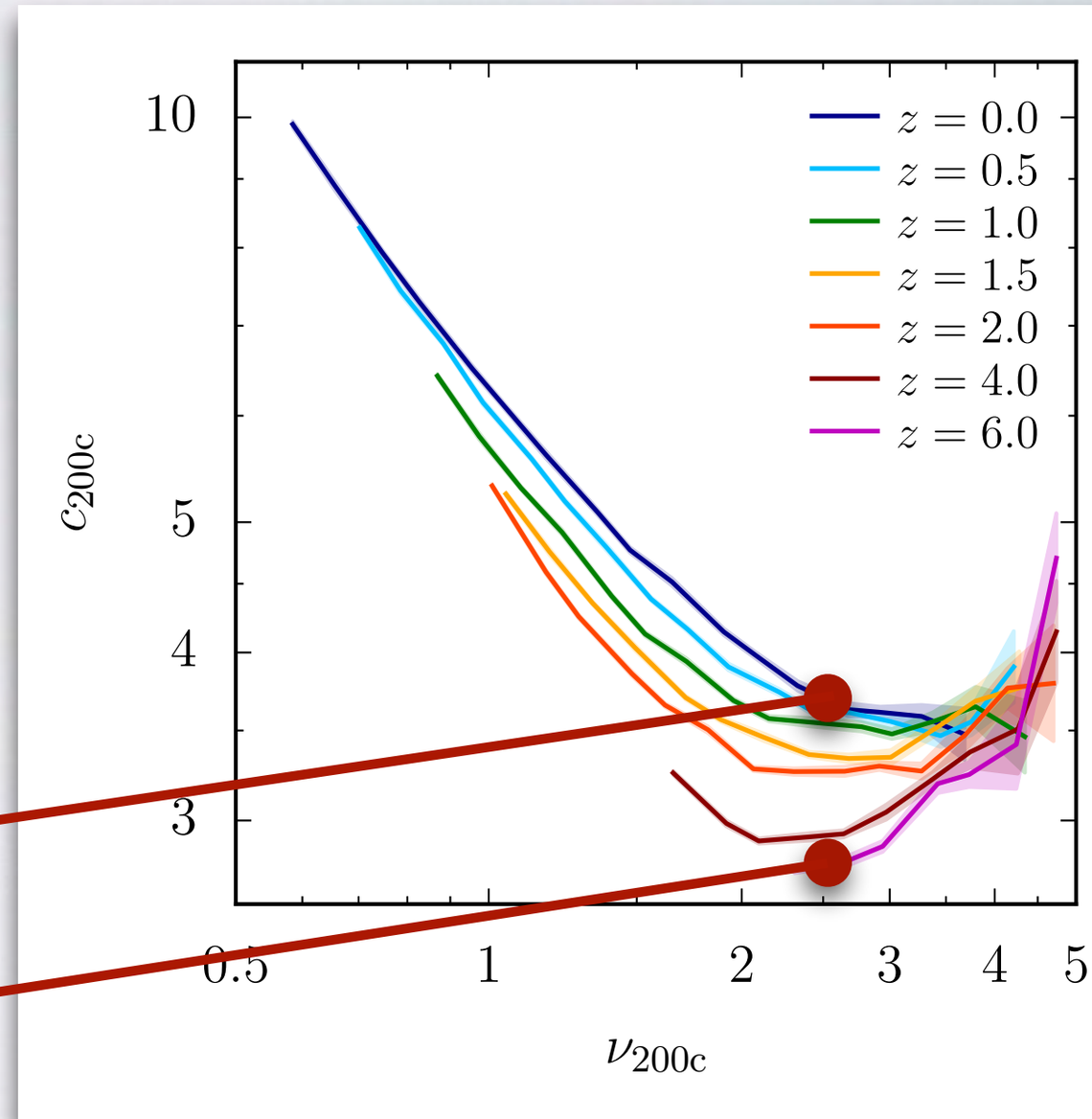
Concentration-peak height relation



Prada et al. 2012 • Ludlow et al. 2013 • Diemer & Kravtsov 2015

Power spectrum slope

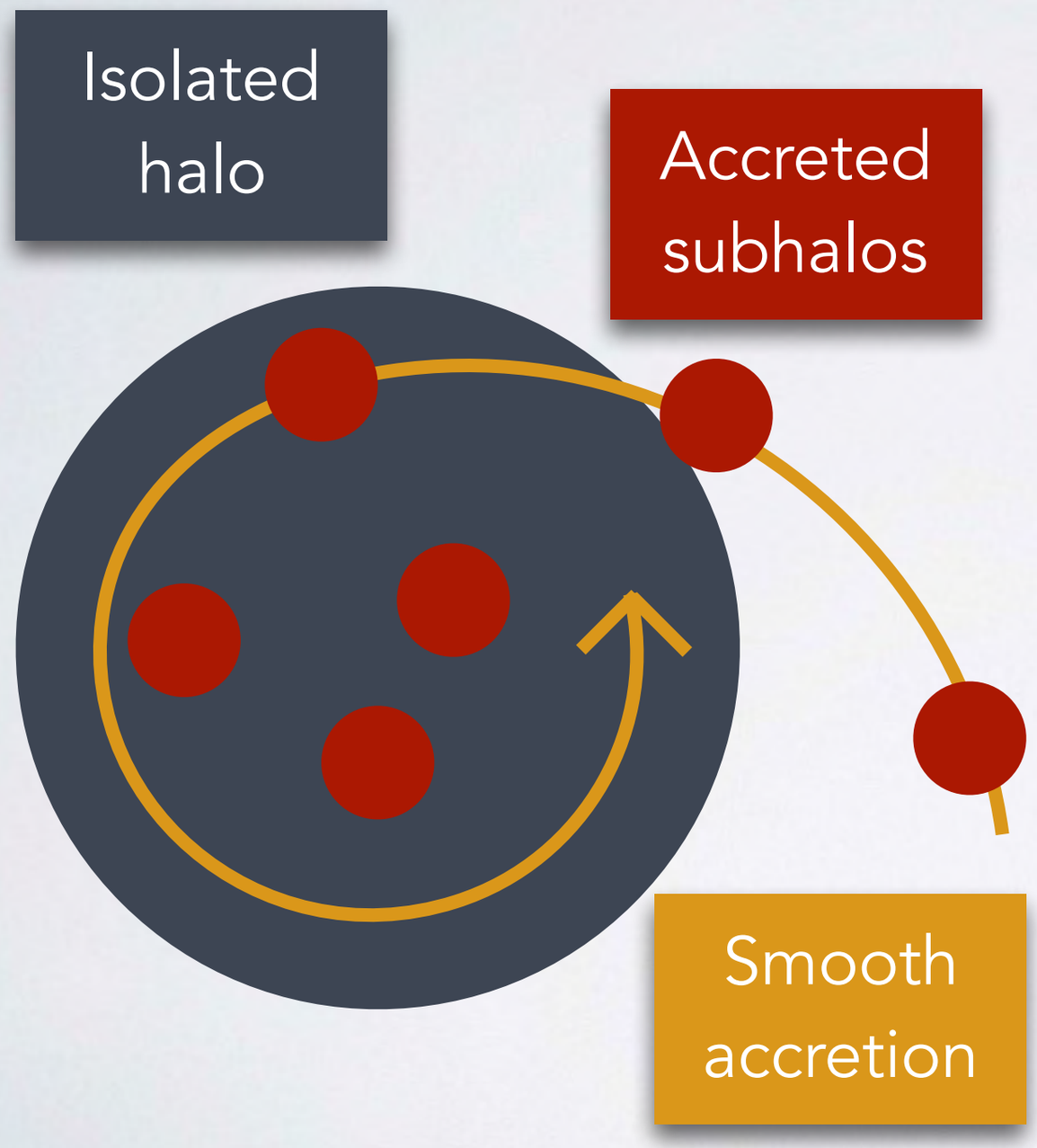




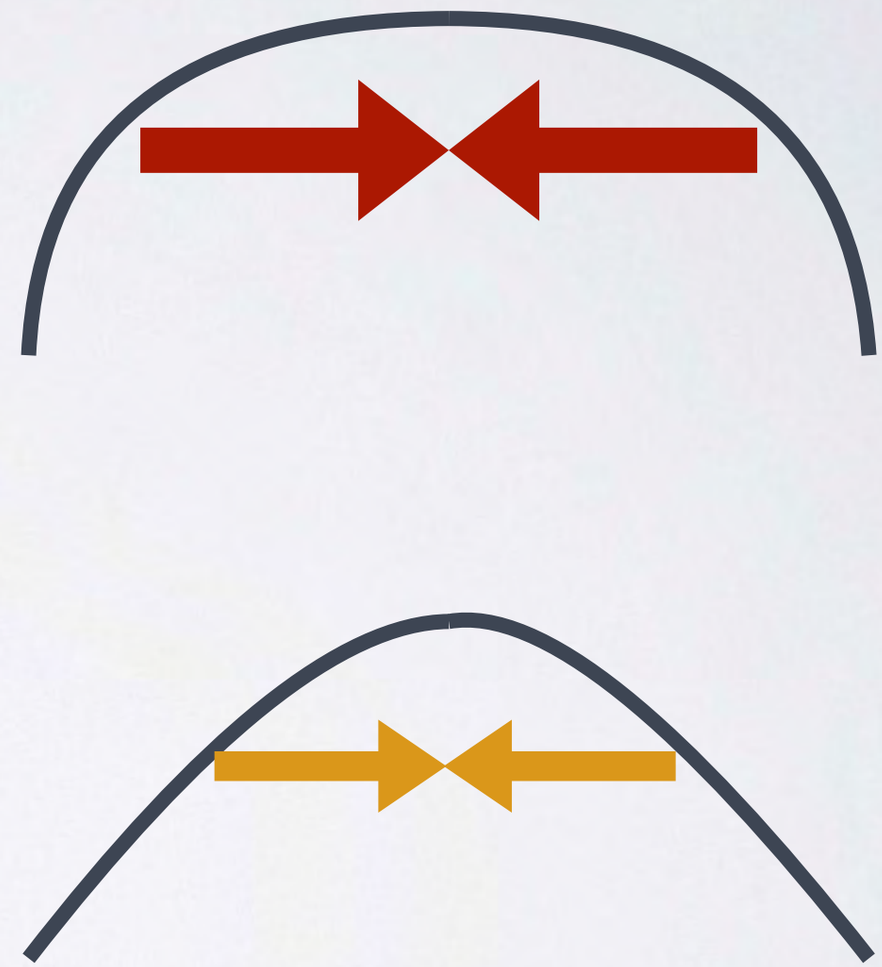
Eisenstein & Hu 1998 • Diemer & Kravtsov 2015

Effects of power spectrum slope

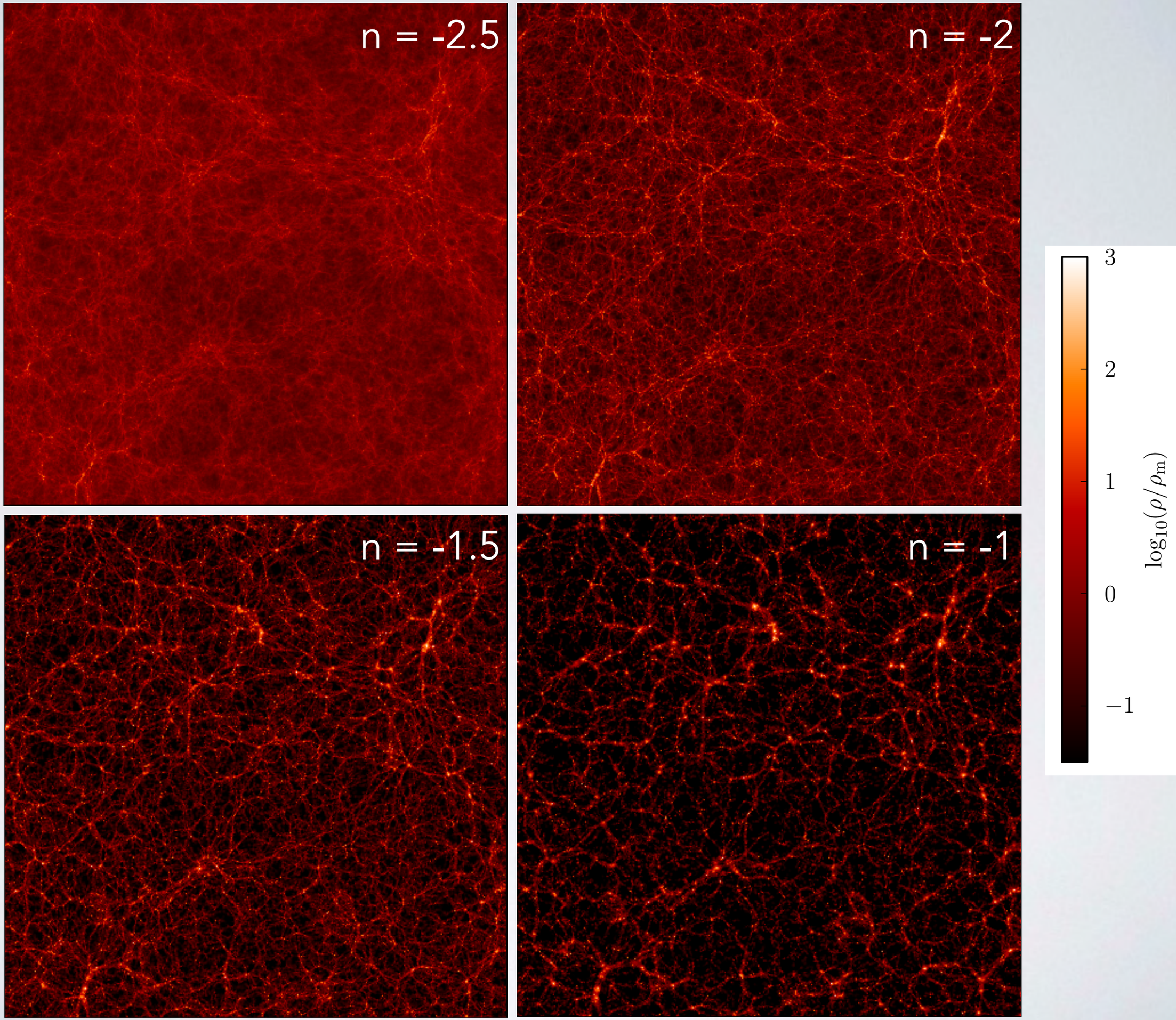
Substructure



Peak shape



Bardeen et al. 1986 • Moore et al. 1998 • Dalal et al. 2010

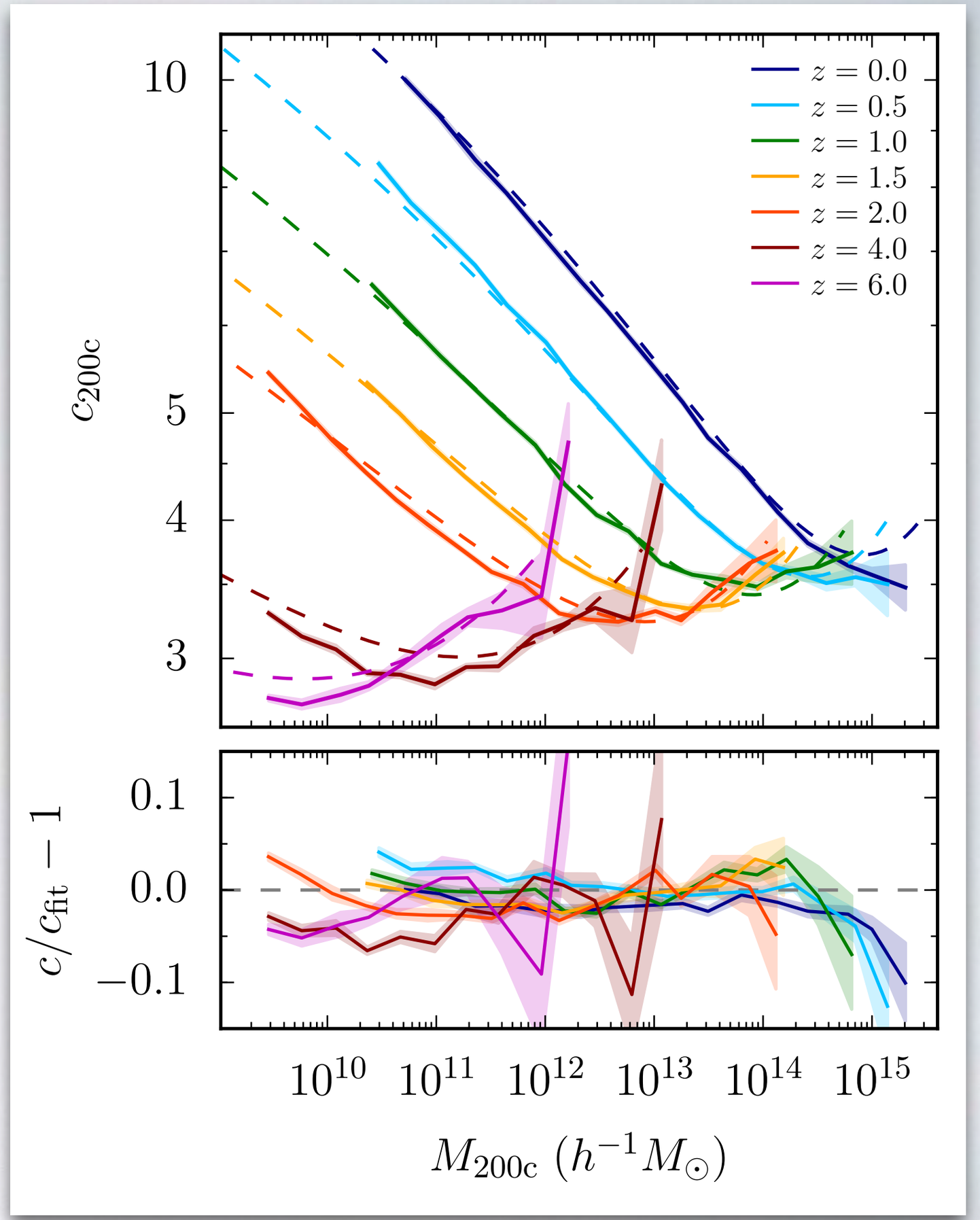

n = -2.5
n = -2
n = -1.5
n = -1
3
2
1
0
−1
$\log_{10}(\rho/\rho_{\rm m})$

Simulation

Model

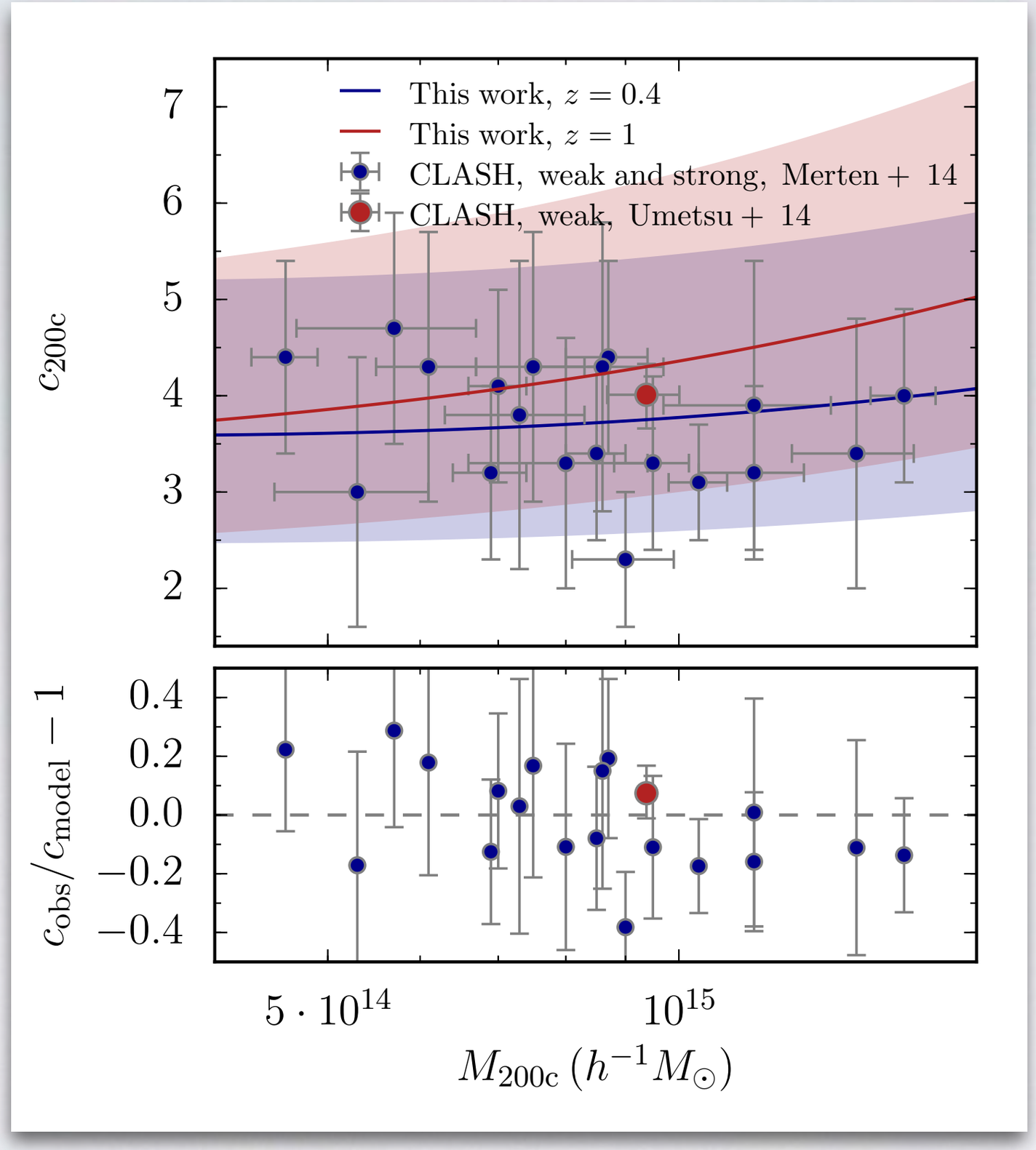
$c = c(M, z, \Omega_x, \ldots)$

$c_{200c} = c_{200c}(\nu, n)$



Diemer & Kravtsov 2015

Comparison to CLASH observations

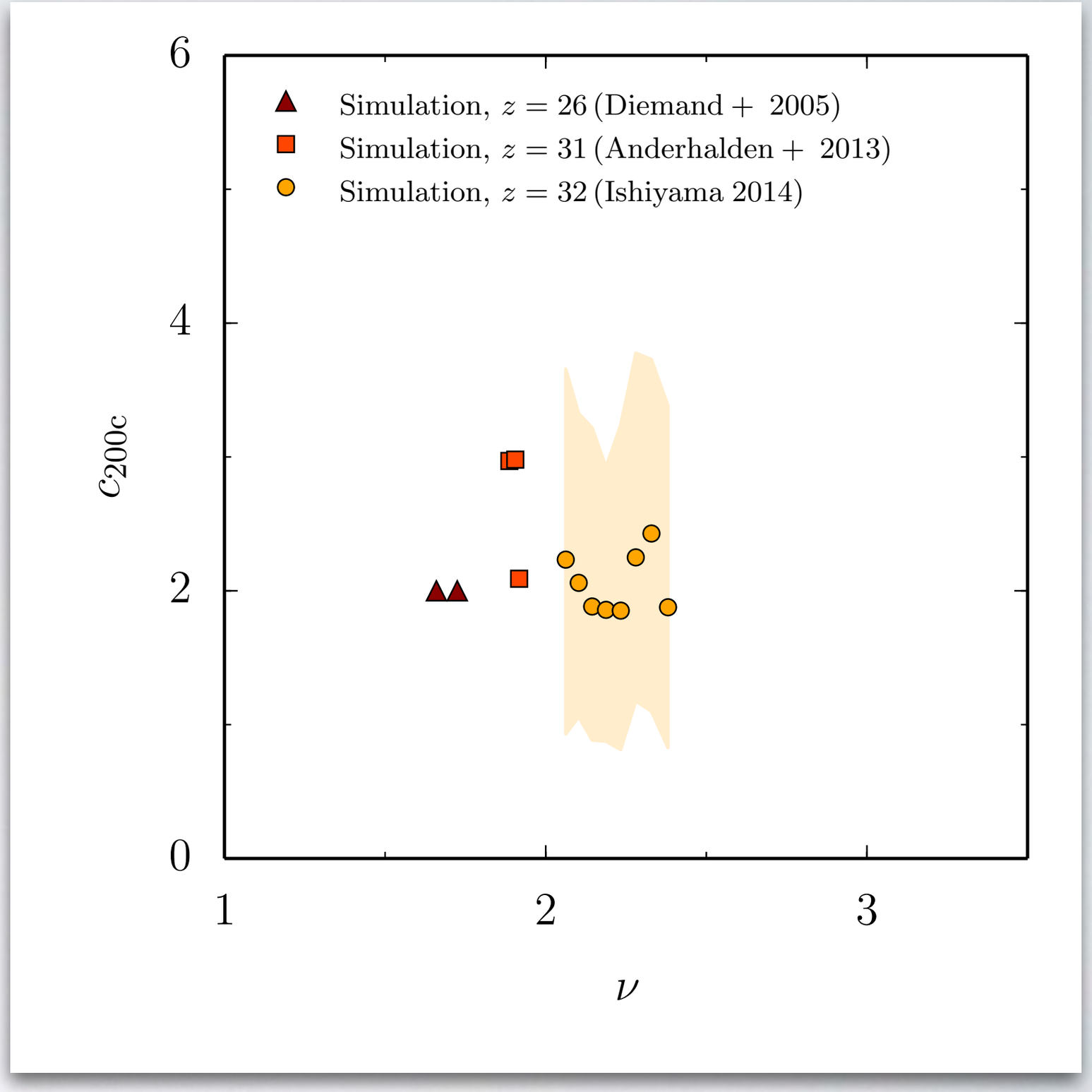


Umetsu et al. 2014 • Merten et al. 2014 • Meneghetti et al. 2014

Micro-halos at high redshift

$z \approx 30$

$M \approx M_{earth}\text{-}M_{\odot}$



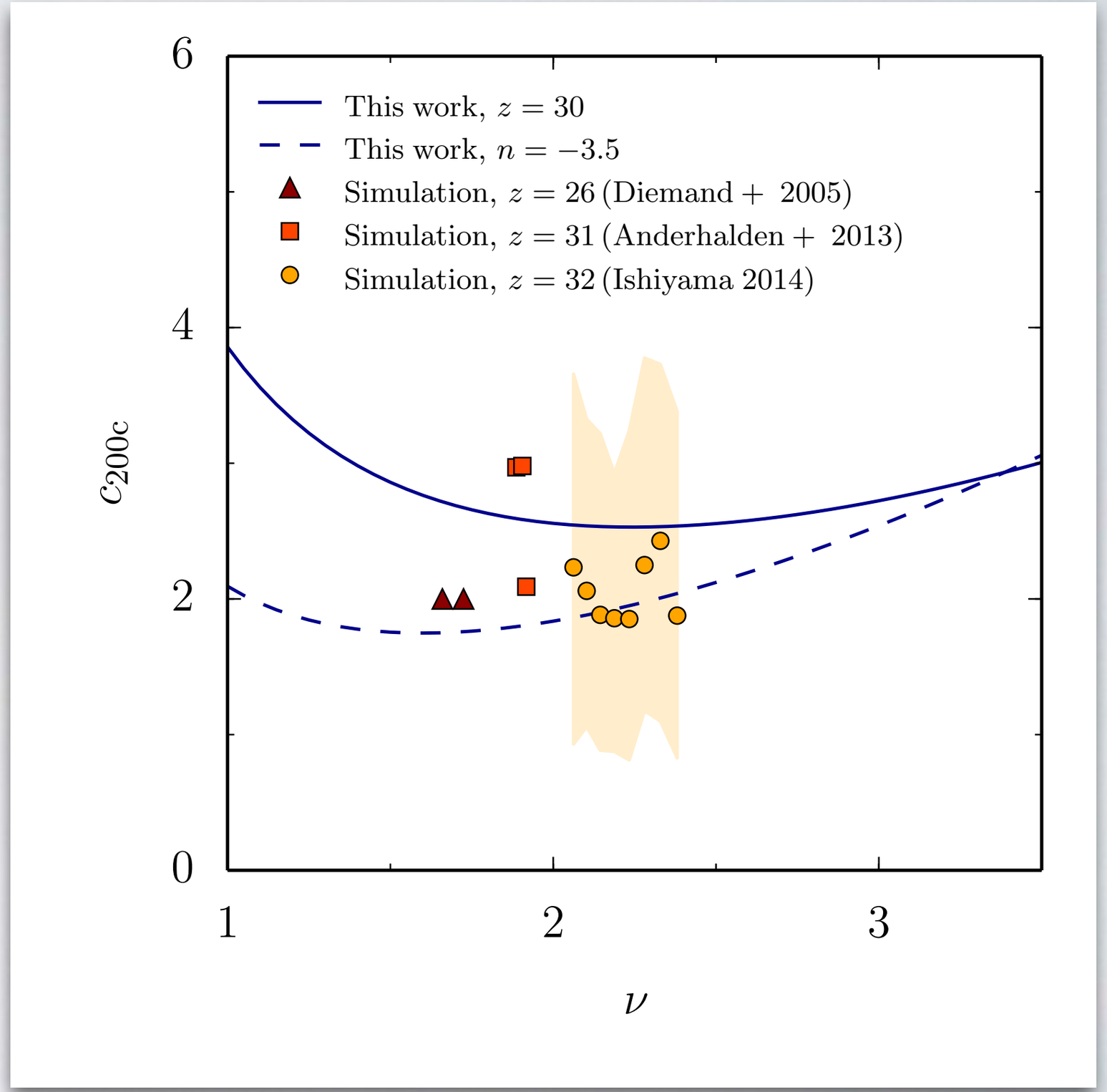
Diemand et al. 2005 • Anderhalden & Diemand 2013 • Ishiyama 2014

Micro-halos at high redshift

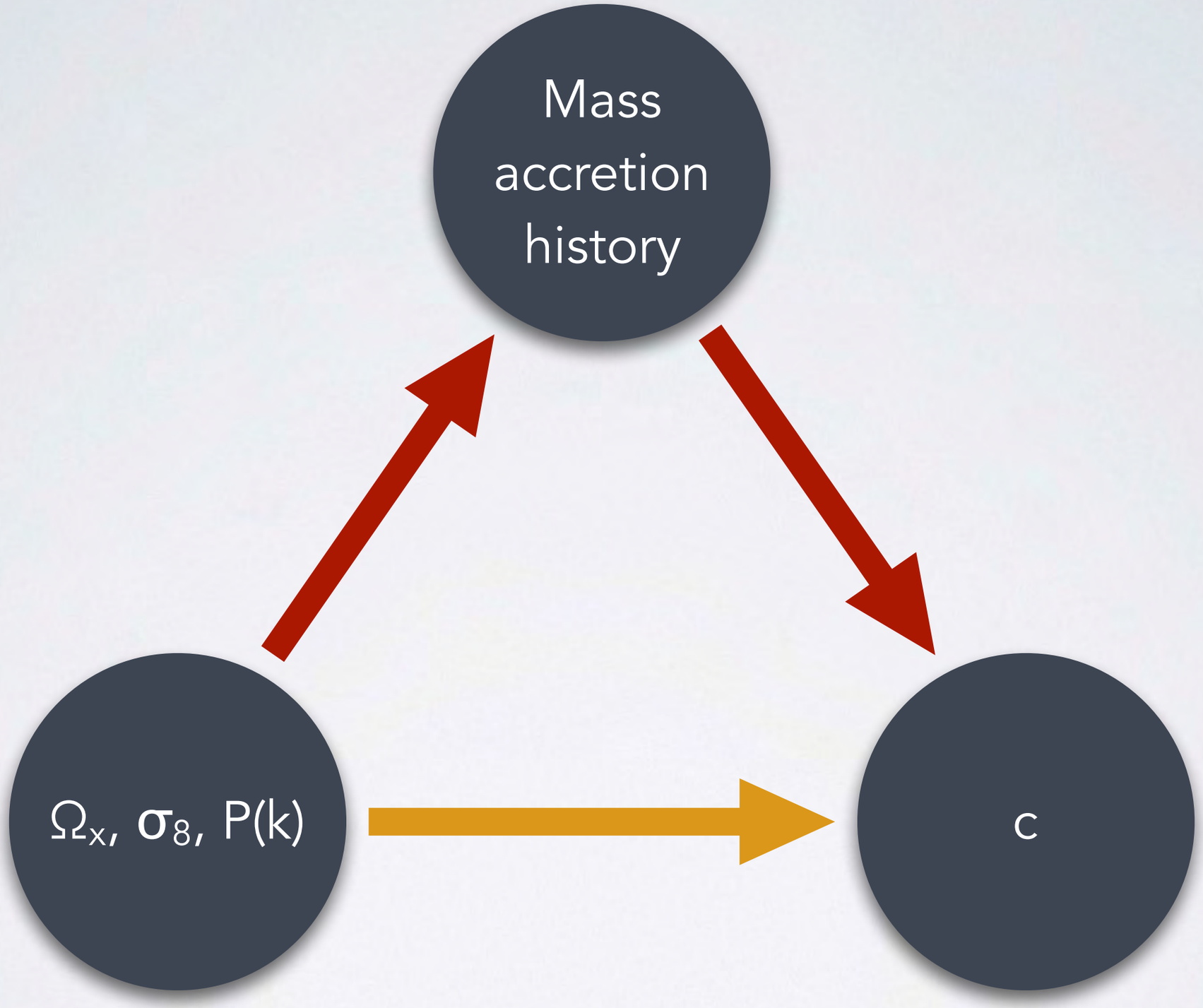
$z \approx 30$

$M \approx M_{earth}\text{-}M_{\odot}$

16 orders of mag. below calibrated masses!



Diemand et al. 2005 • Anderhalden & Diemand 2013 • Ishiyama 2014

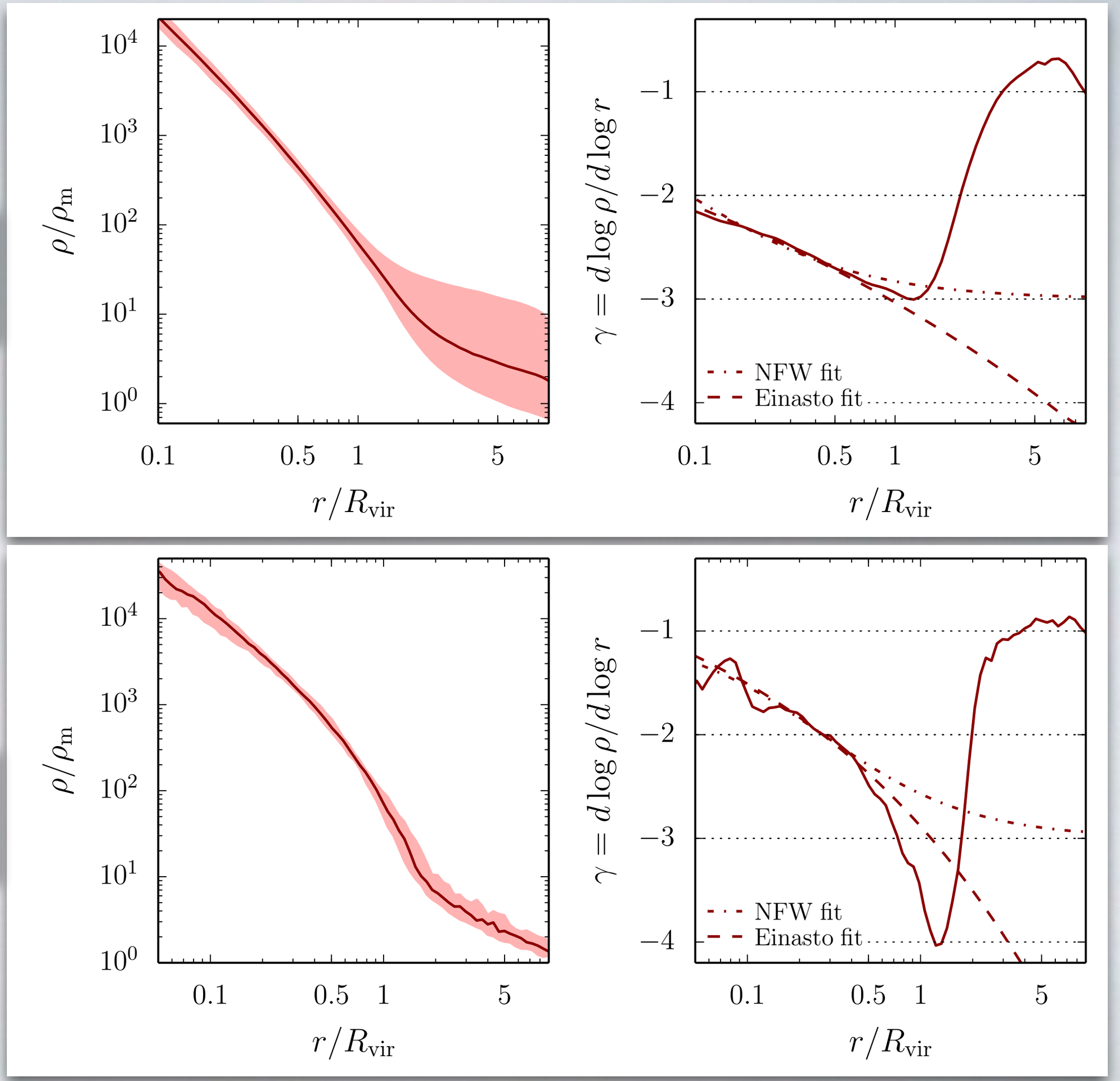

Mass accretion history
Ω_x, σ_8, P(k)
c

We found a universal c-M relation, and thus a universal **inner** profile.

But what about the **outer** profile?

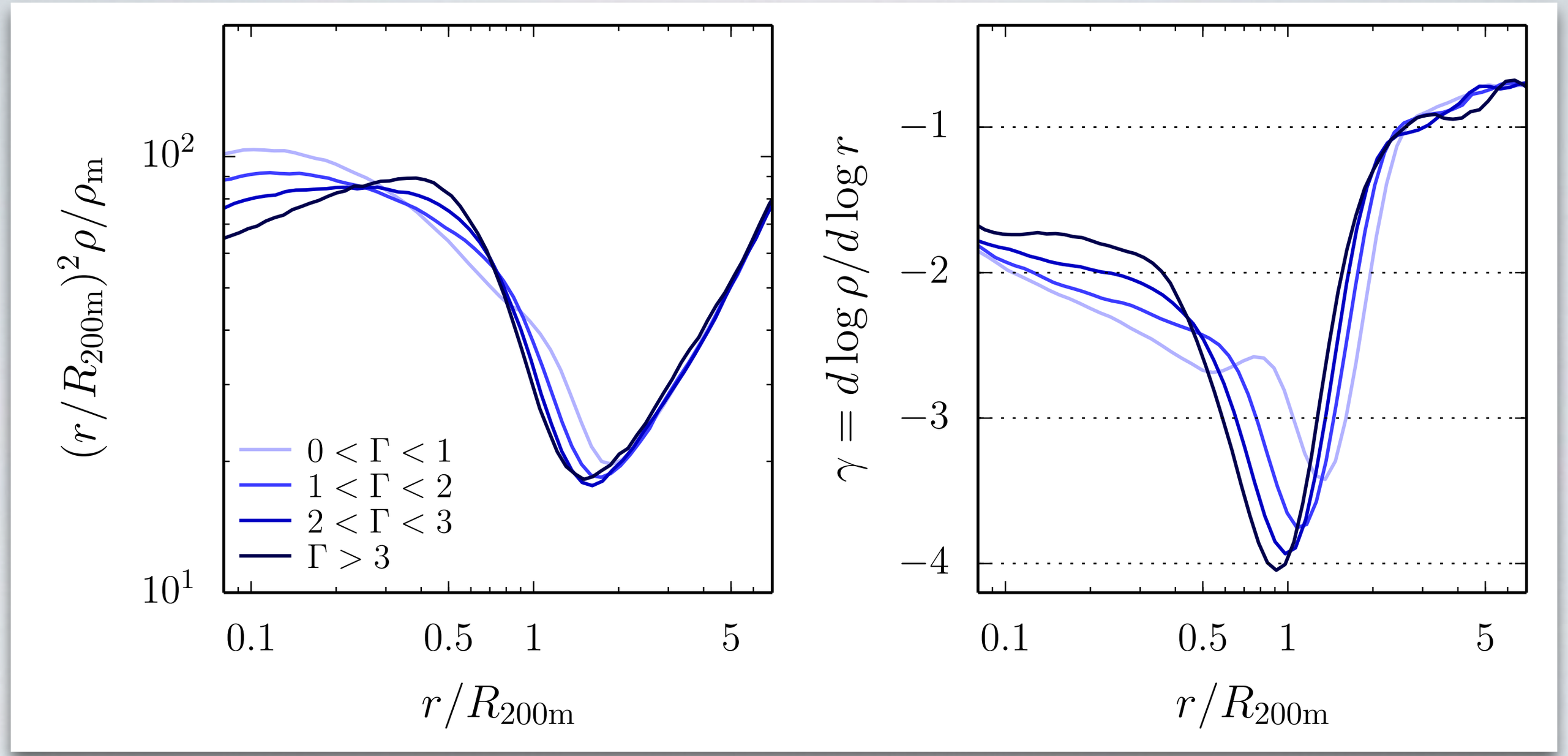
Small halos
(10^{10}<M<3×10^{11})

Large halos
(M>10^{15})



Diemer & Kravtsov 2014

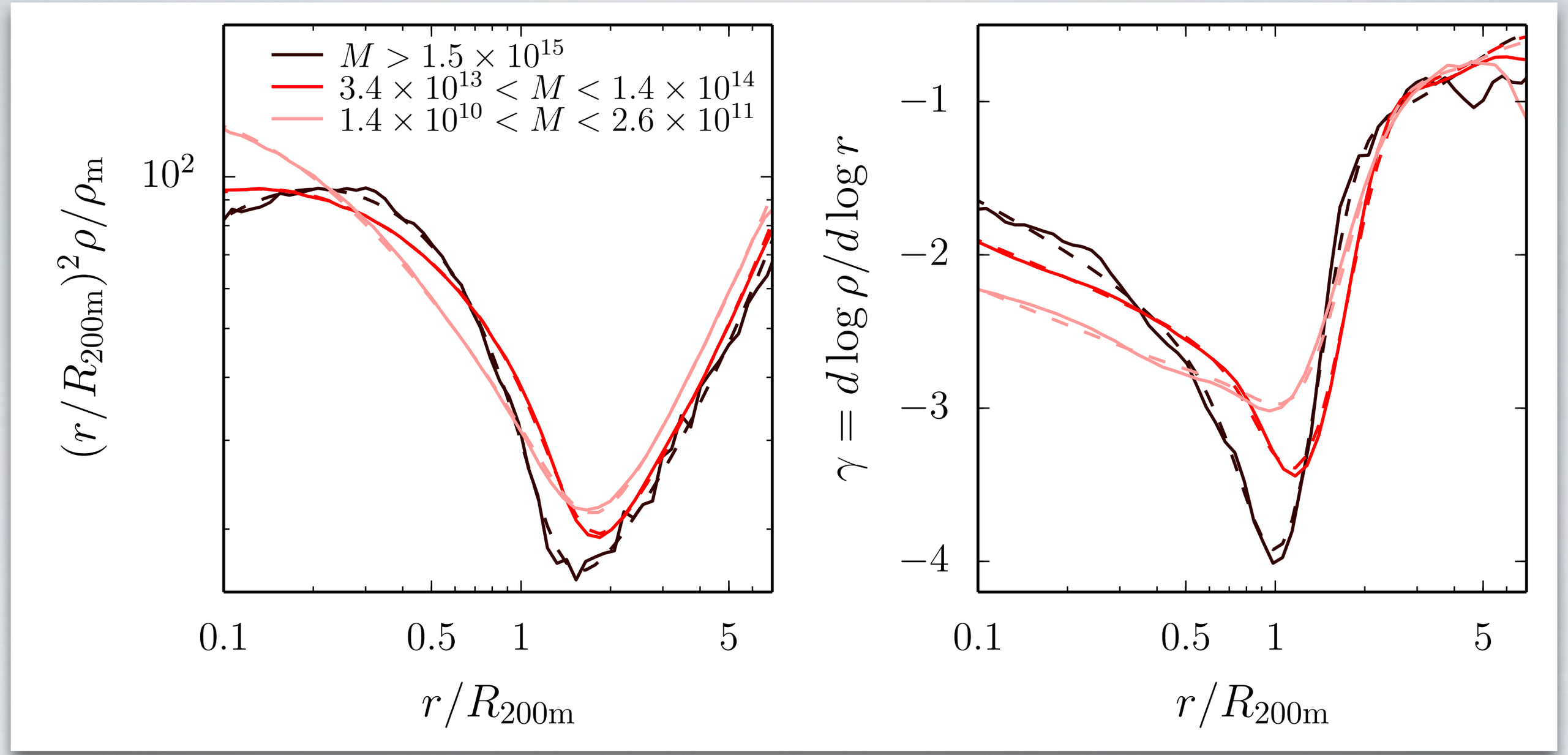
$3\times10^{13} < M < 10^{14}$



$\Gamma = \Delta \log(M_{vir}) / \Delta \log(a)$

Diemer & Kravtsov 2014

New fitting function

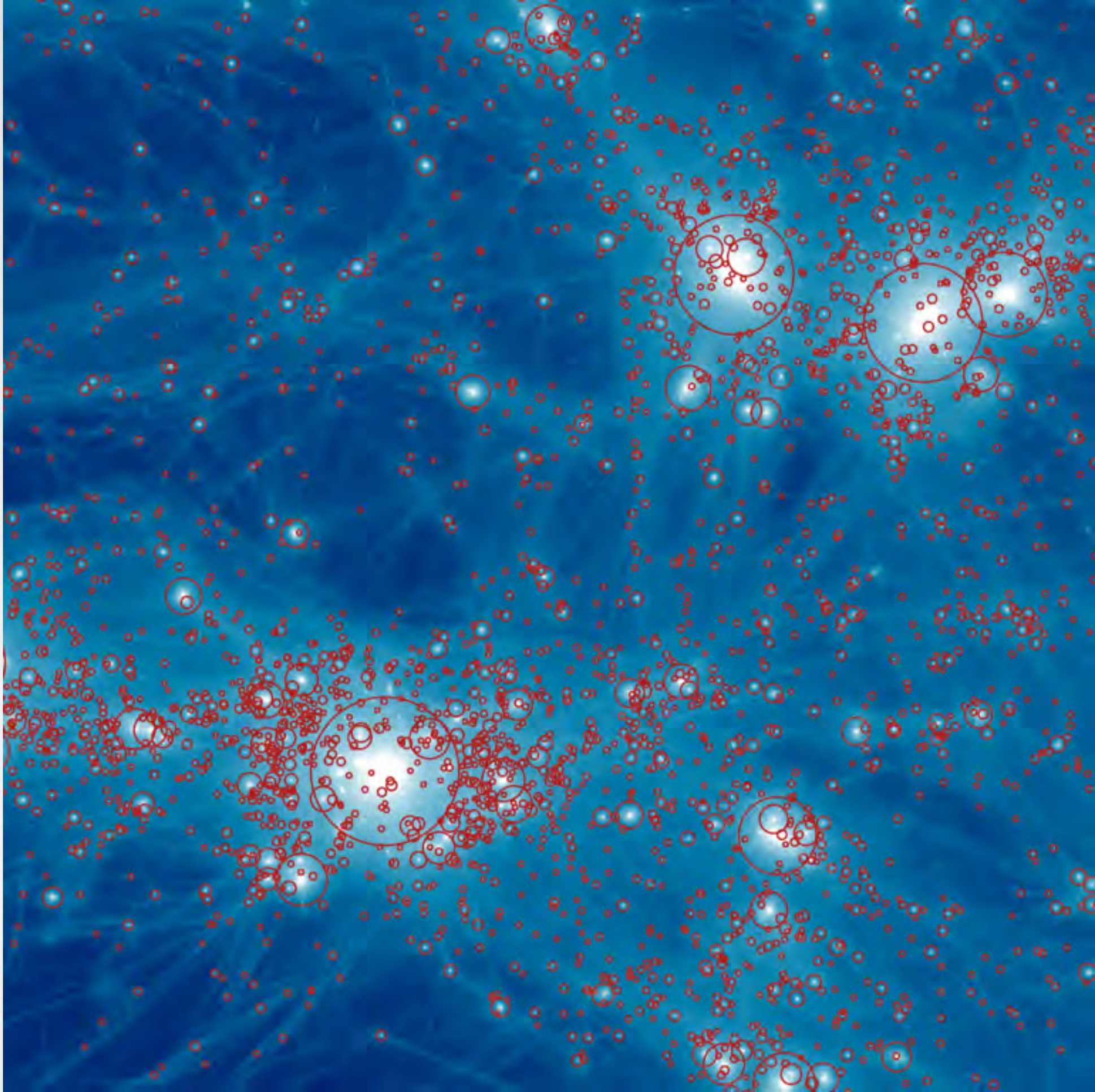


- 10% accuracy (selected by mass or accretion rate)
- Valid between 0.1 and 9 R_{vir}

The outer profiles **are not universal**, they exhibit a steepening that depends on the mass accretion rate

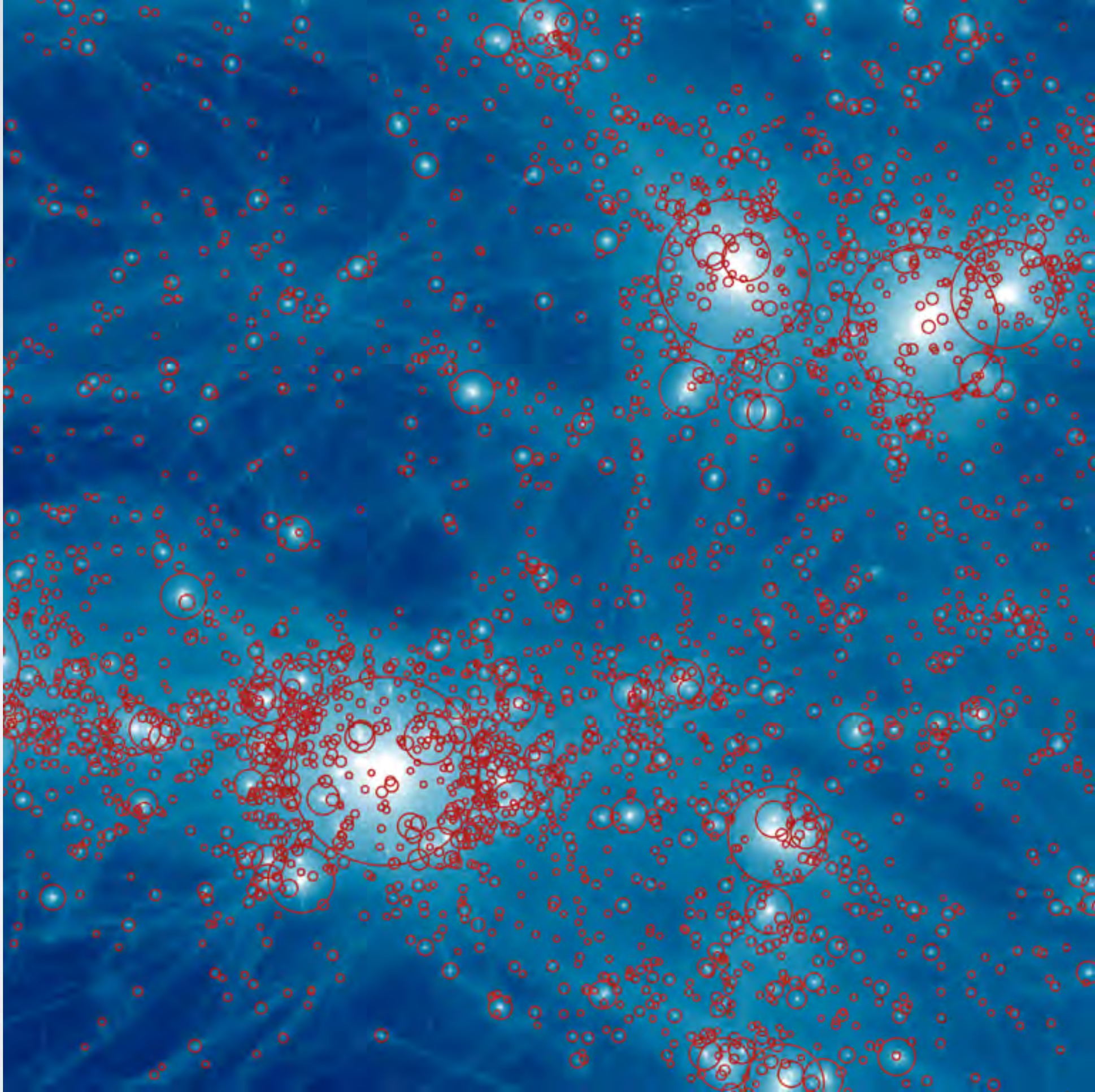
Is there an **edge** to a halo?

R_{200c}



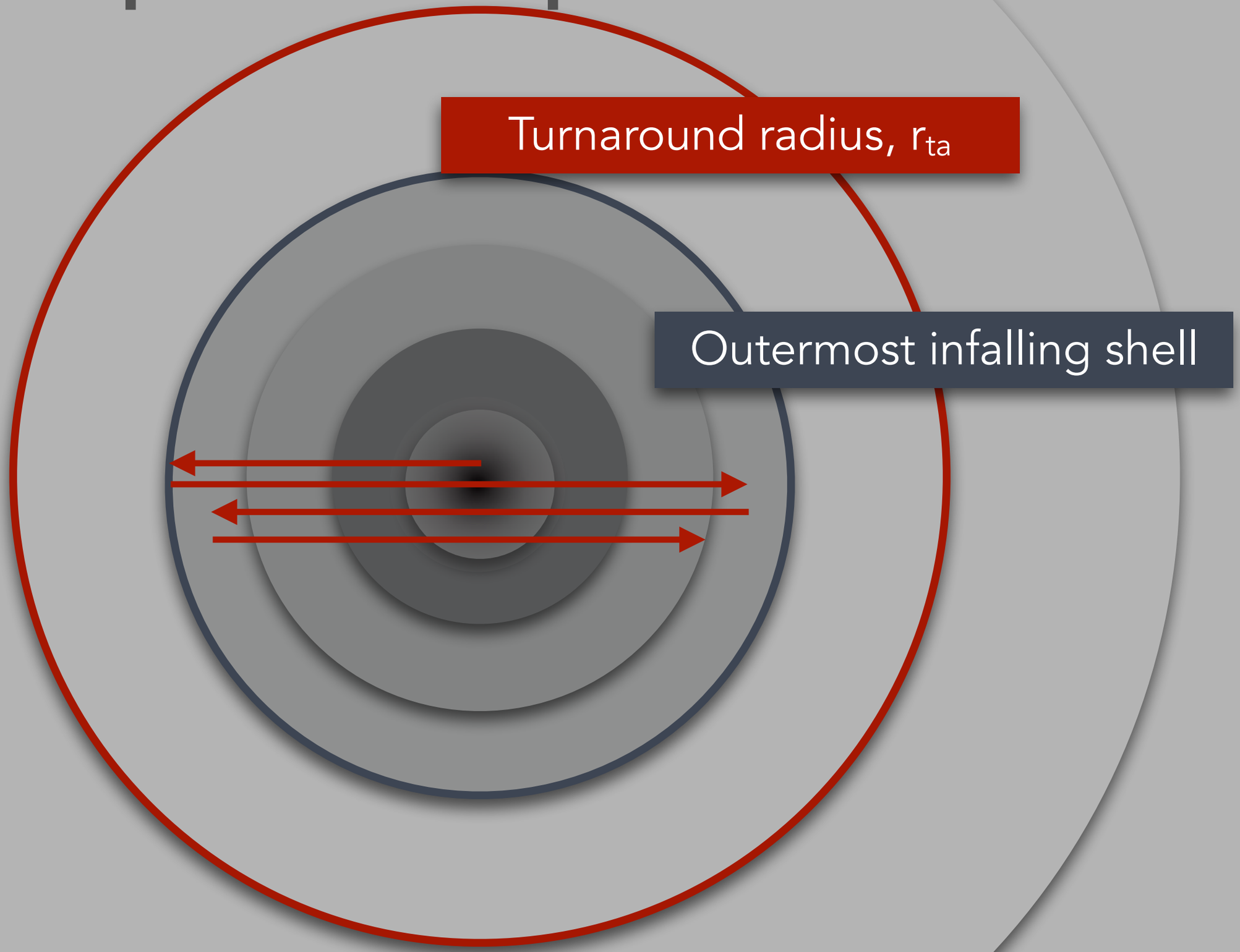
Halo finder: Rockstar
(Behroozi et al. 2013)

R_{vir}



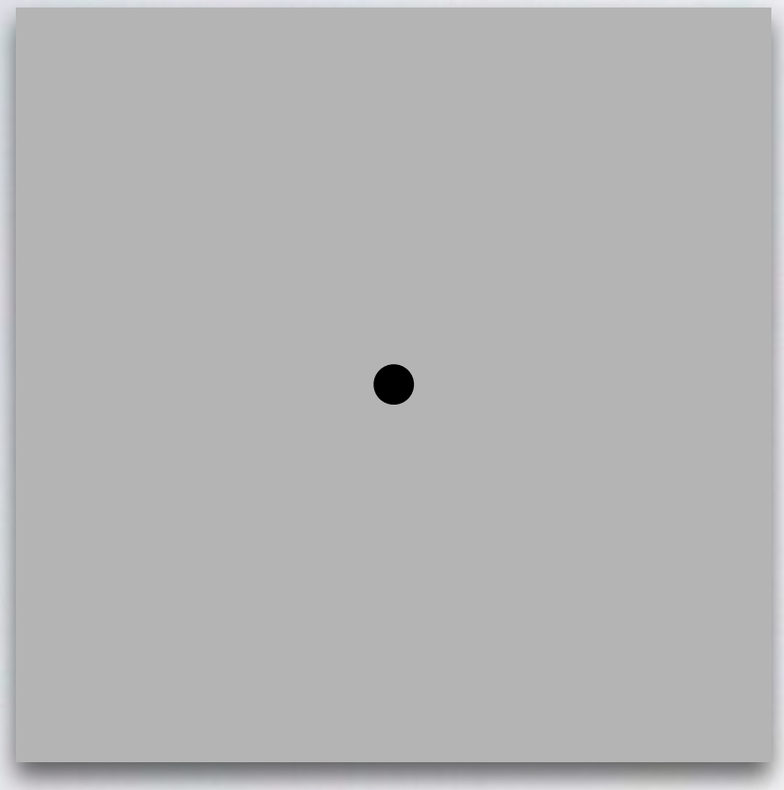
Halo finder: Rockstar
(Behroozi et al. 2013)

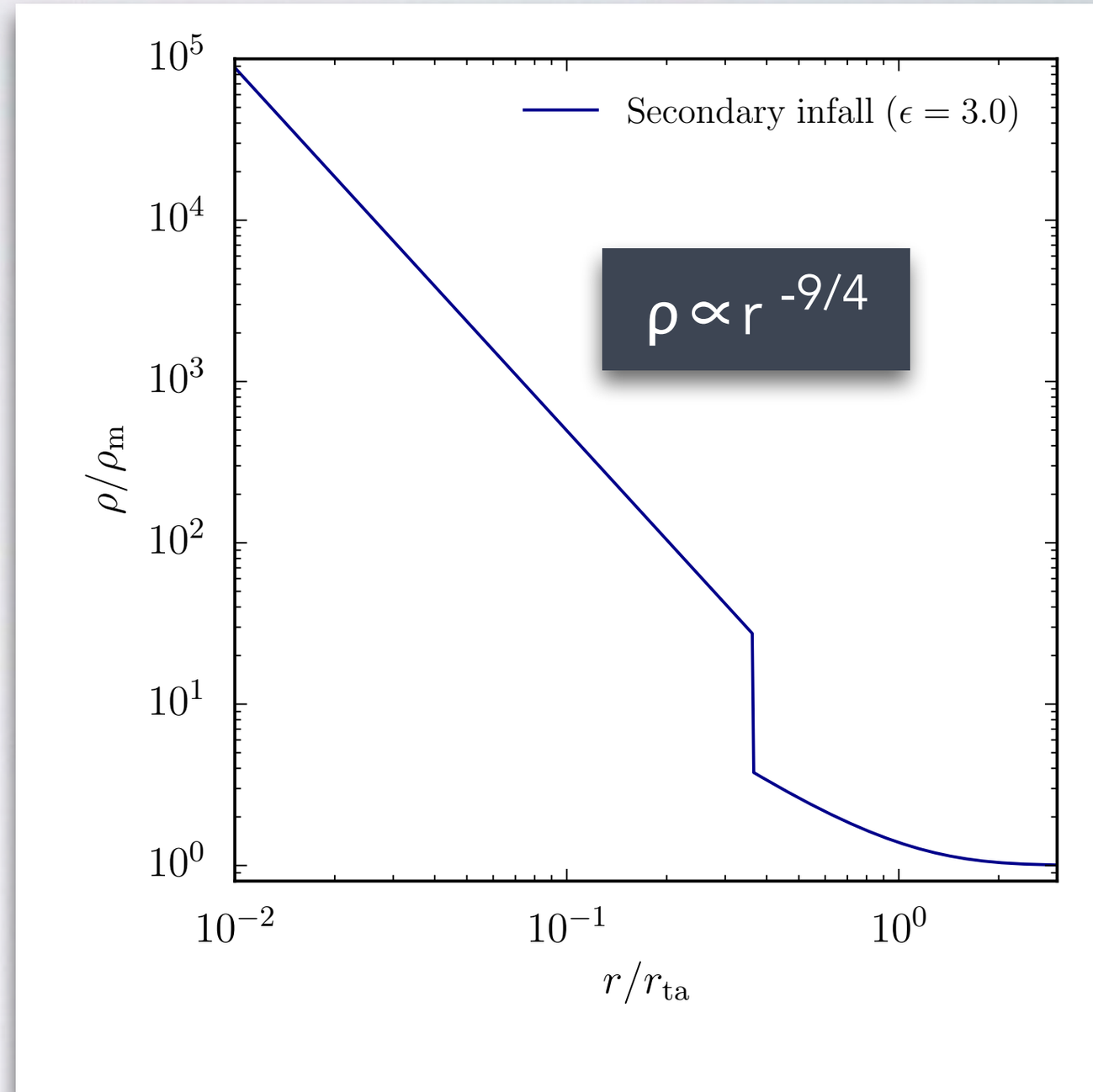
Spherical collapse model



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

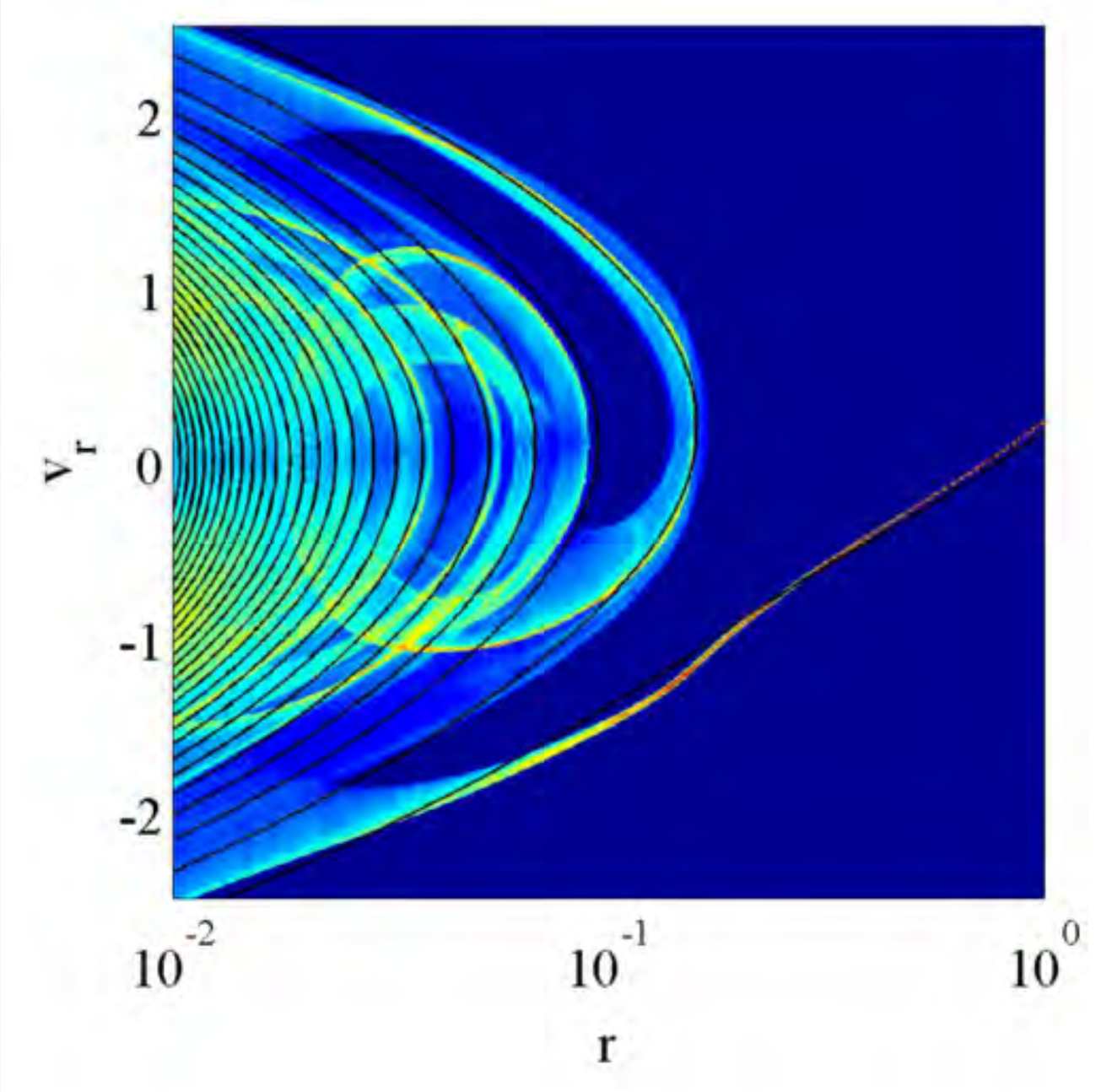
Spherical collapse model





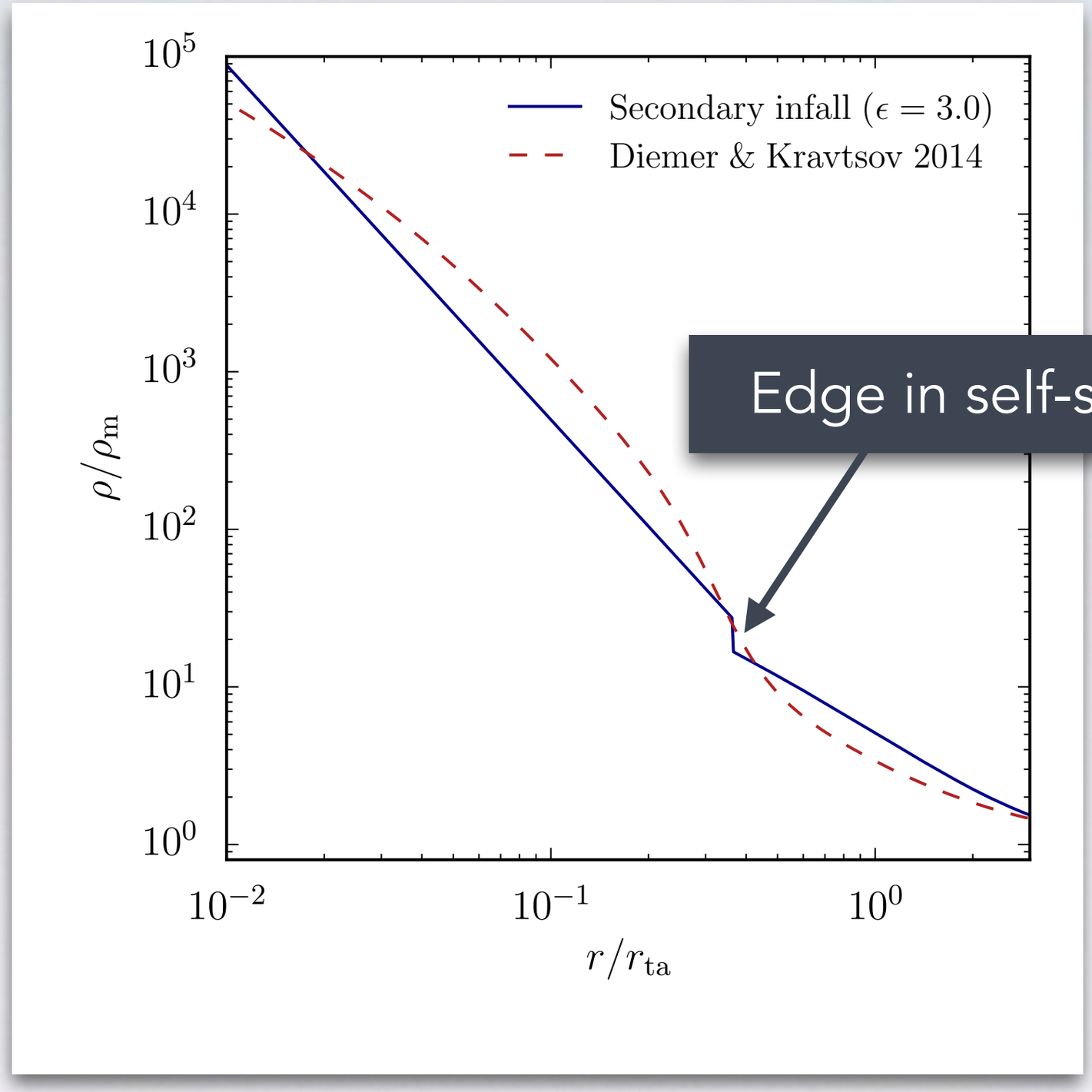
Fillmore & Goldreich 1984 • Bertschinger 1985 • Diemand & Kuhlen 2008
Vogelsberger et al. 2011 • Lithwick & Dalal 2011 • Adhikari et al. 2014

Spherical collapse model



Adhikari et al. 2014 • cf. Diemand & Kuhlen 2008

The Splashback Radius



Edge in self-similar model

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

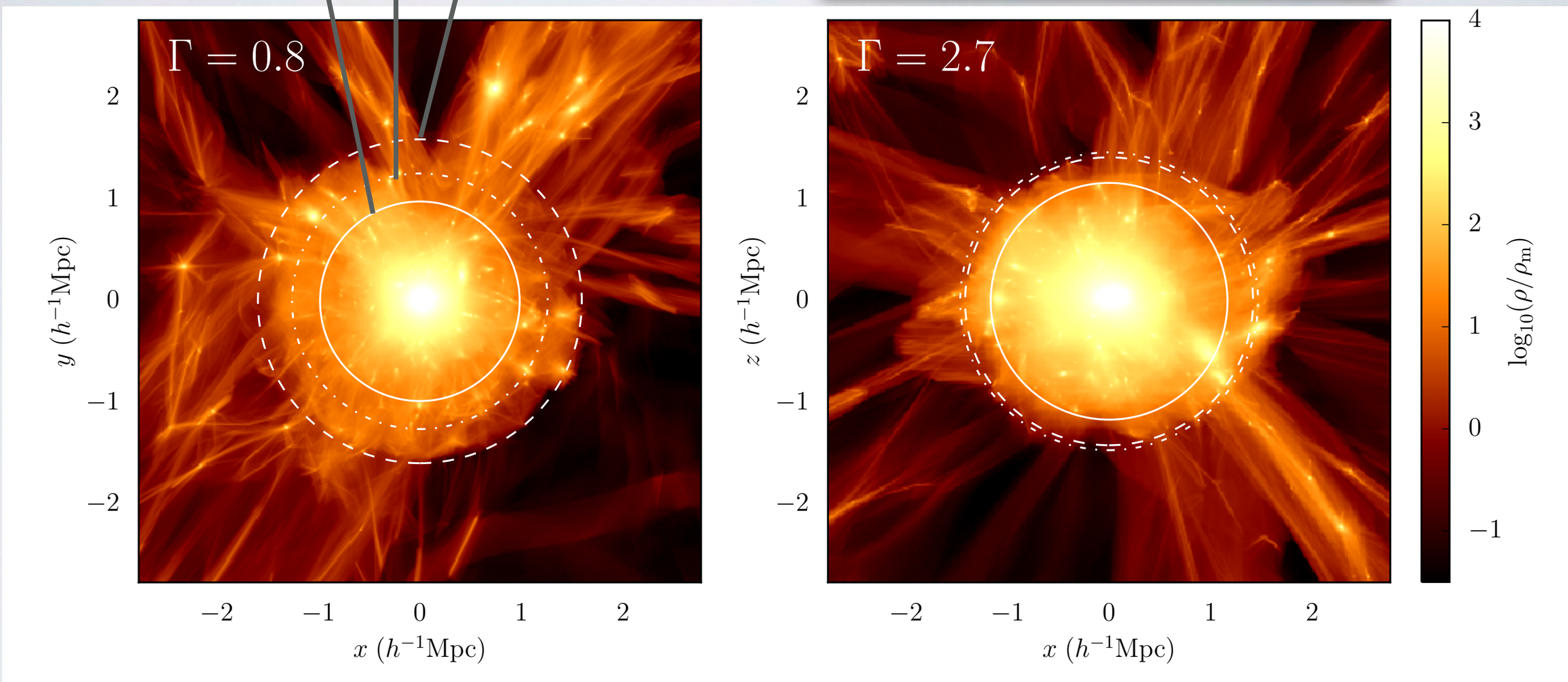
The Splashback Radius

R_{200m}

R_{vir} $R_{splashback}$

$R_{splashback} = f(\Gamma, z) \times R_{200m}$

$0.8 \lesssim f \lesssim 1.6$

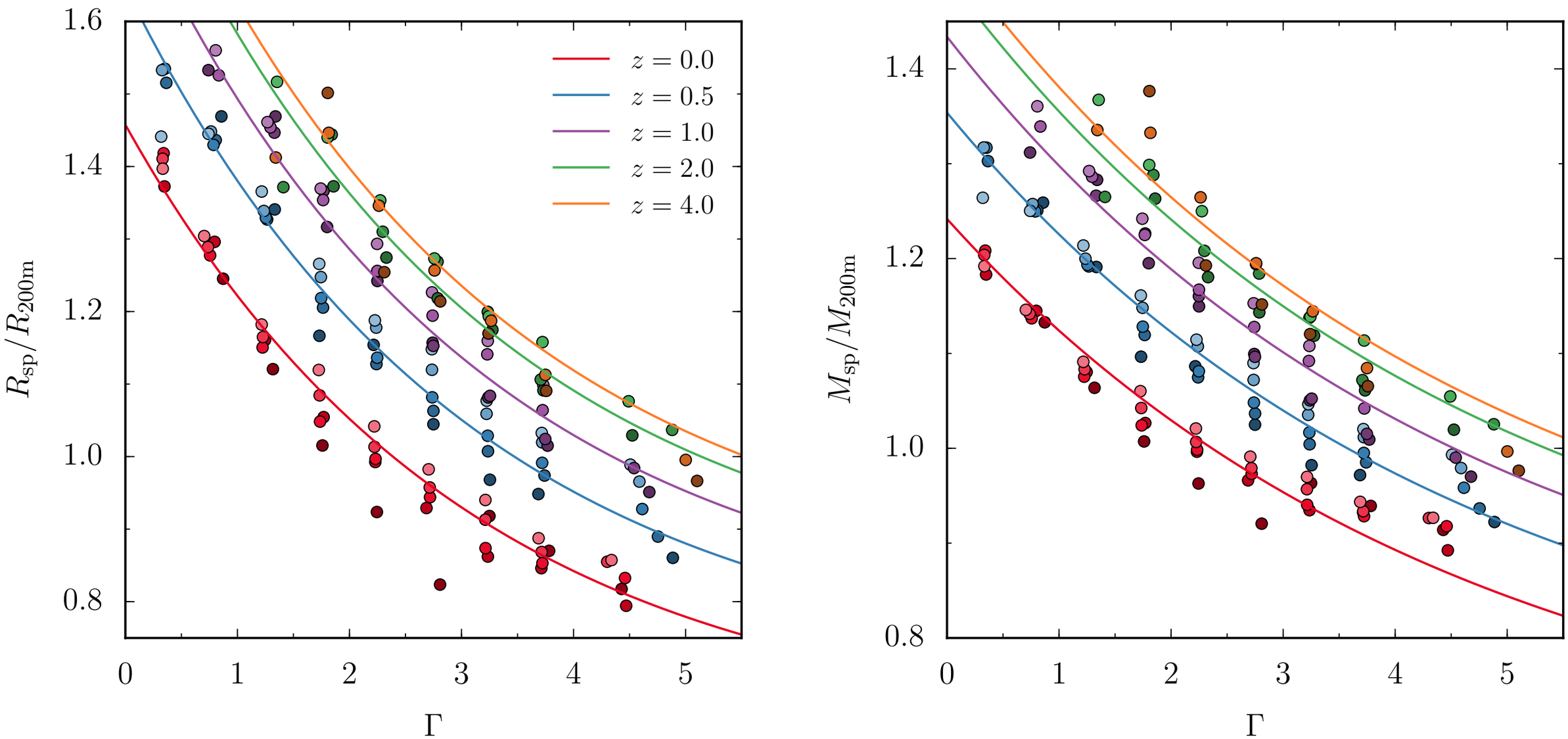


Low accretion rate

High accretion rate

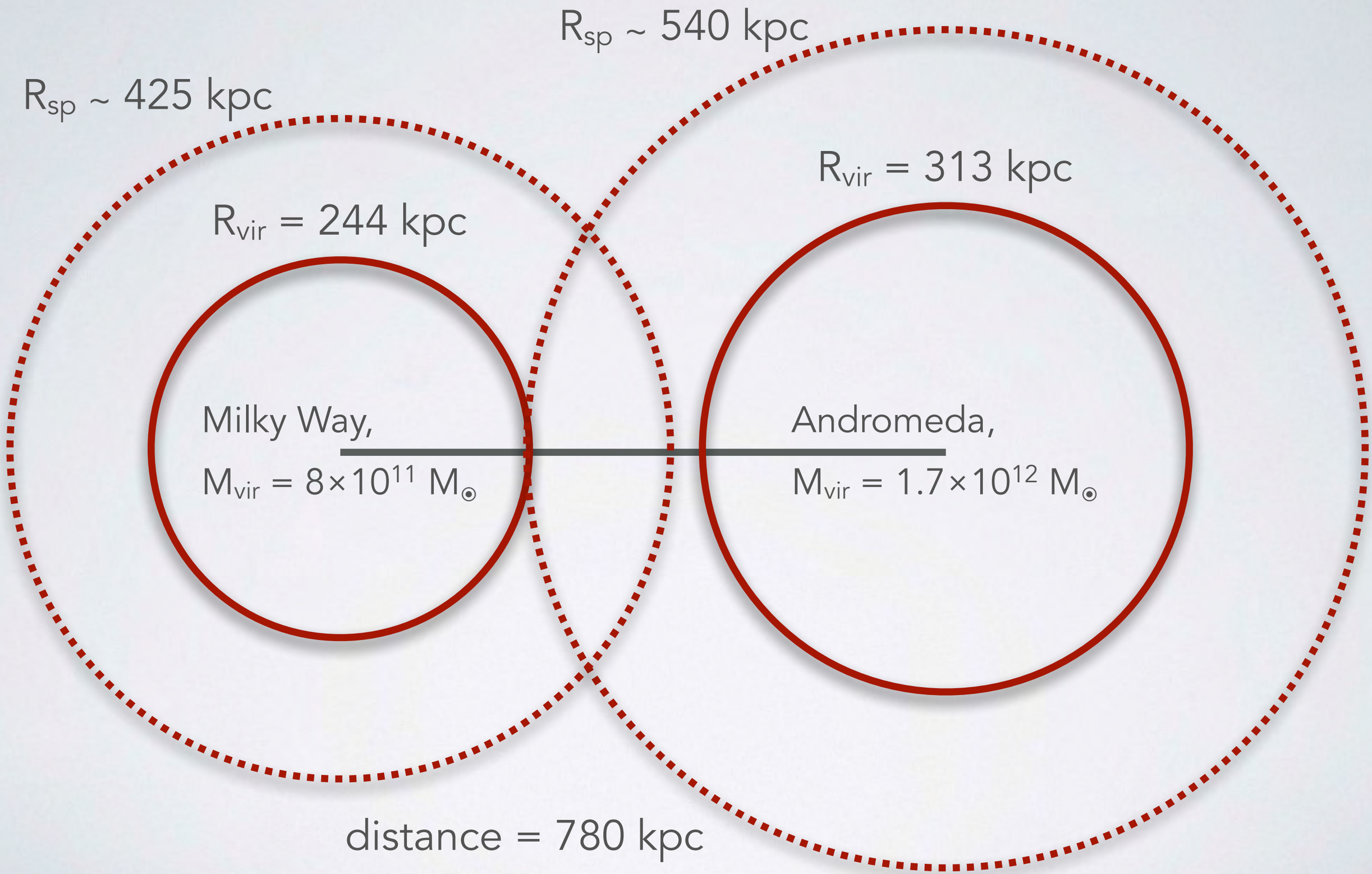
Diemer & Kravtsov 2014 • More, Diemer & Kravtsov 2015

R_{sp}/M_{sp} as a function of MAR



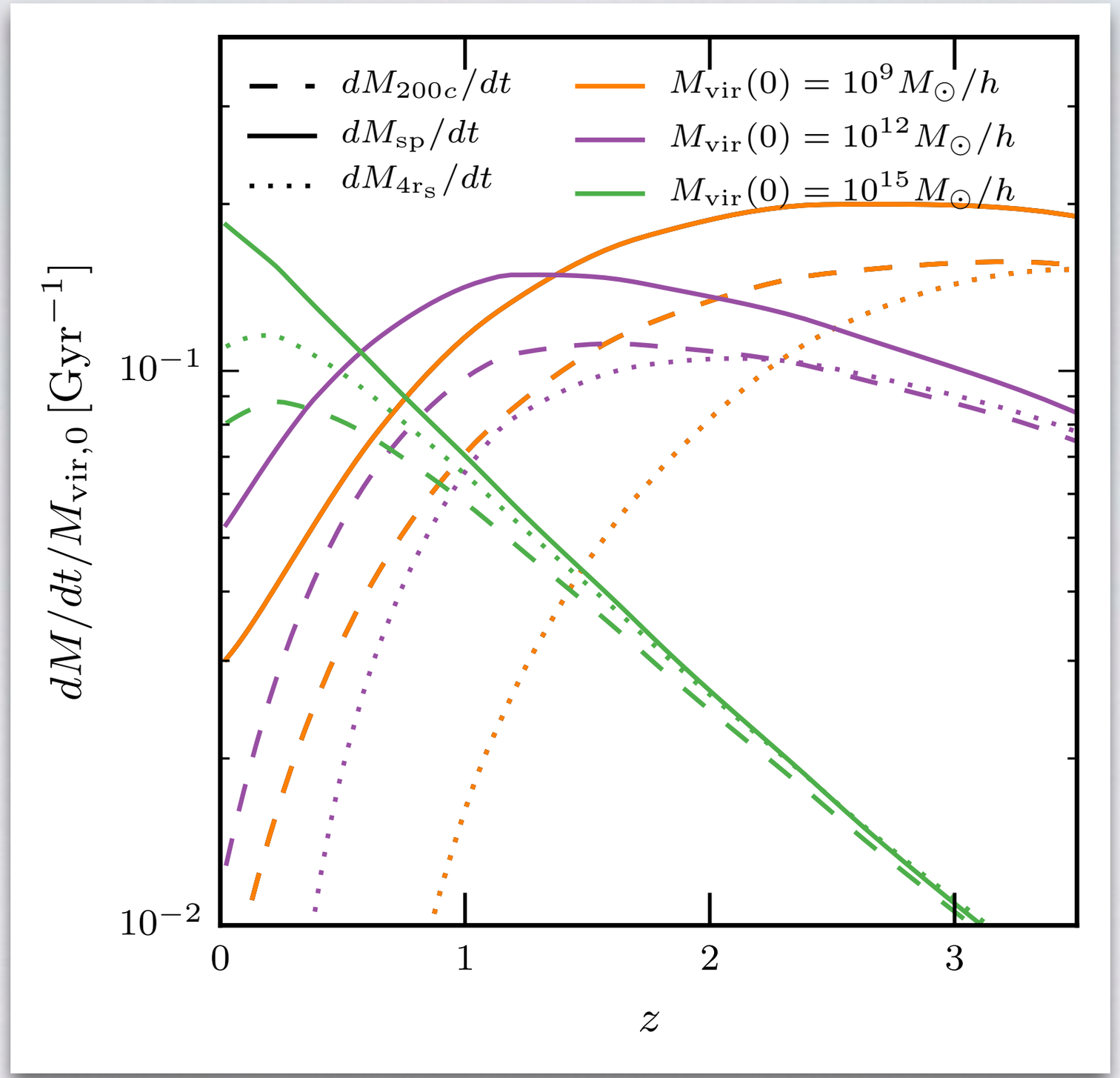
More, Diemer & Kravtsov 2015 • cf. Vogelsberger et al. 2011 • cf. Adhikari et al. 2014

Do the Milky Way and Andromeda halos overlap?



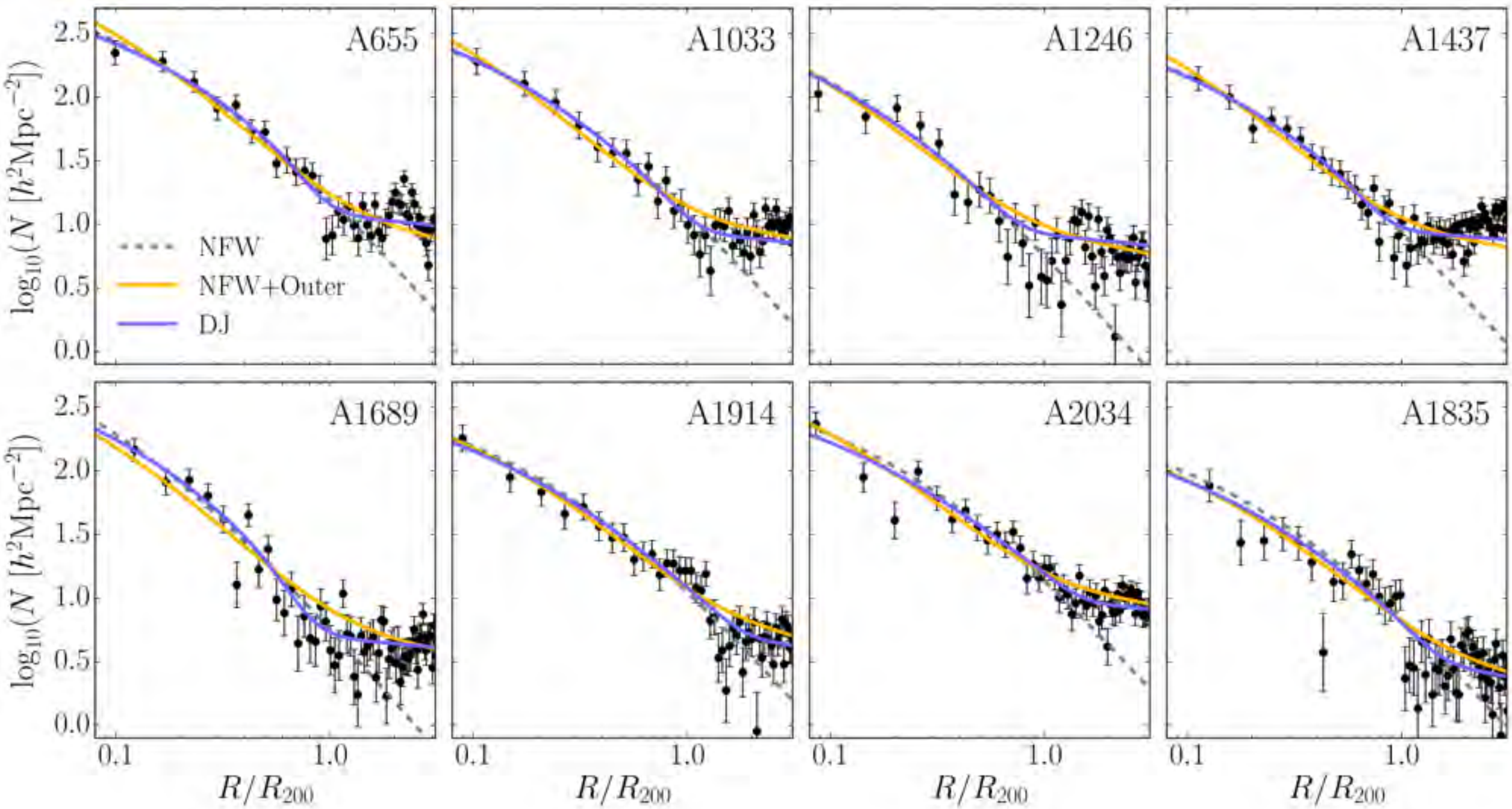
More, Diemer & Kravtsov 2015 • Diaz et al. 2014

Mass accretion rate



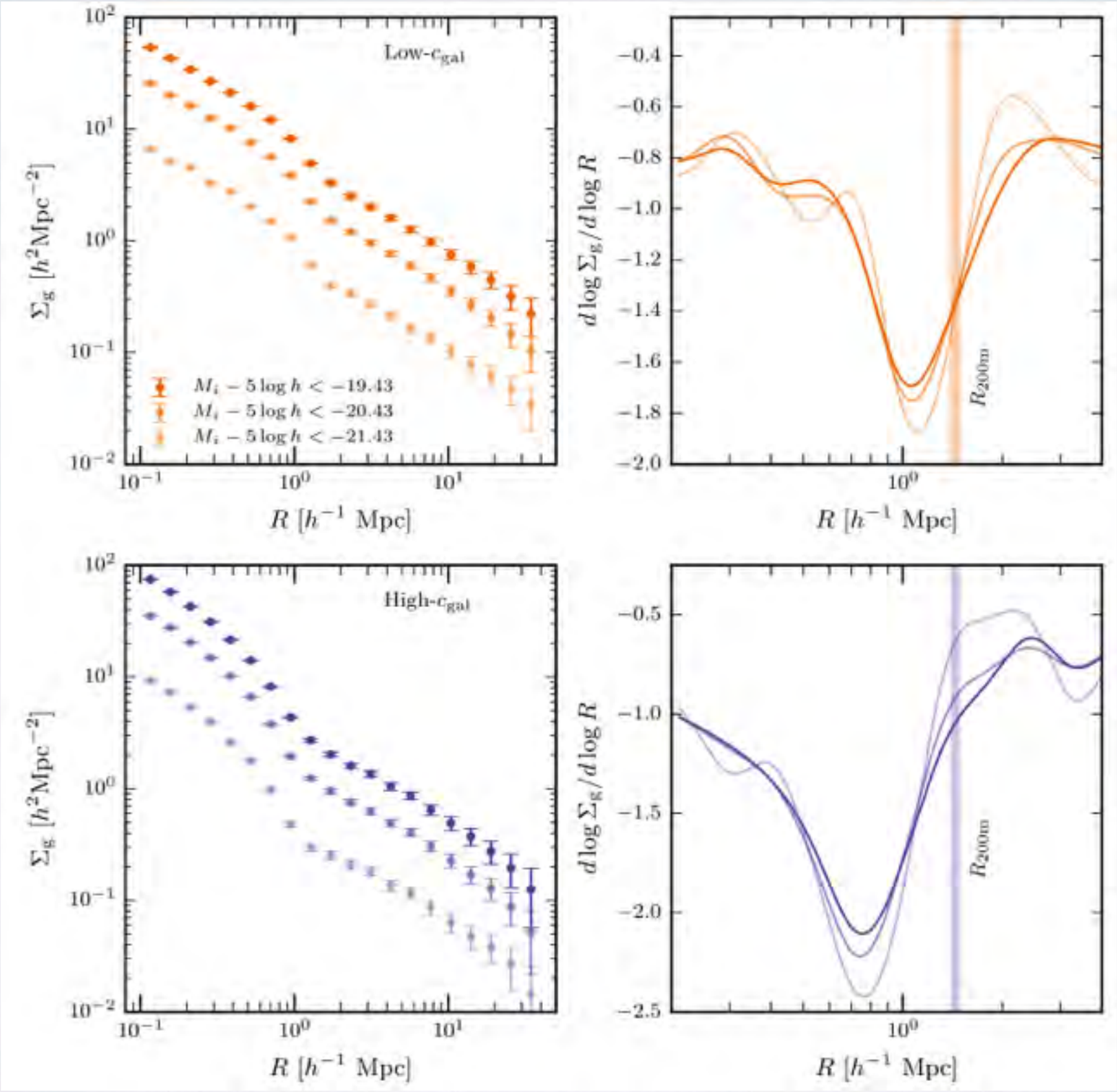
More, Diemer & Kravtsov 2015

R_{sp} in cluster member profiles



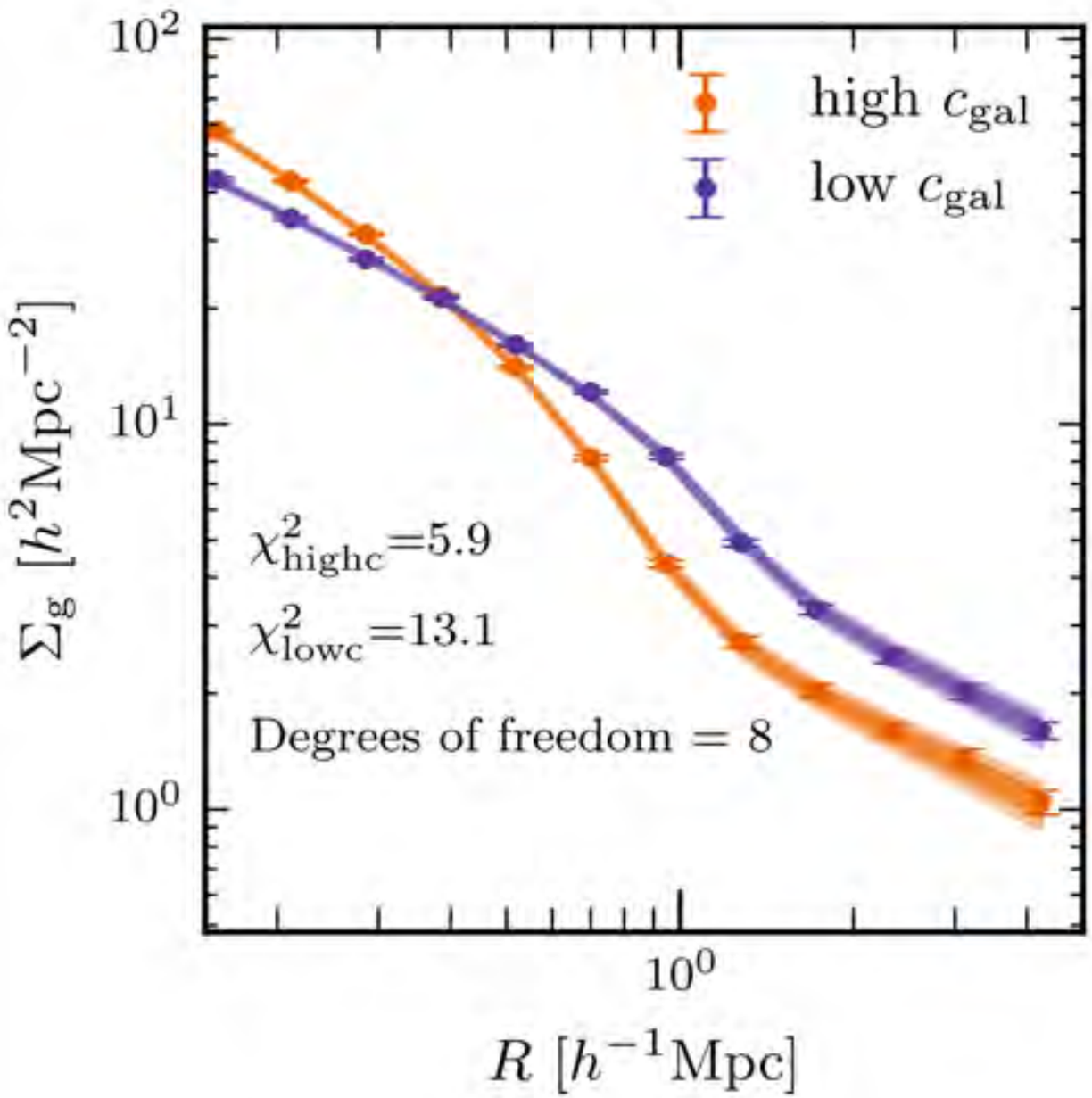
Patej & Loeb 2015 • cf. Tully 2015

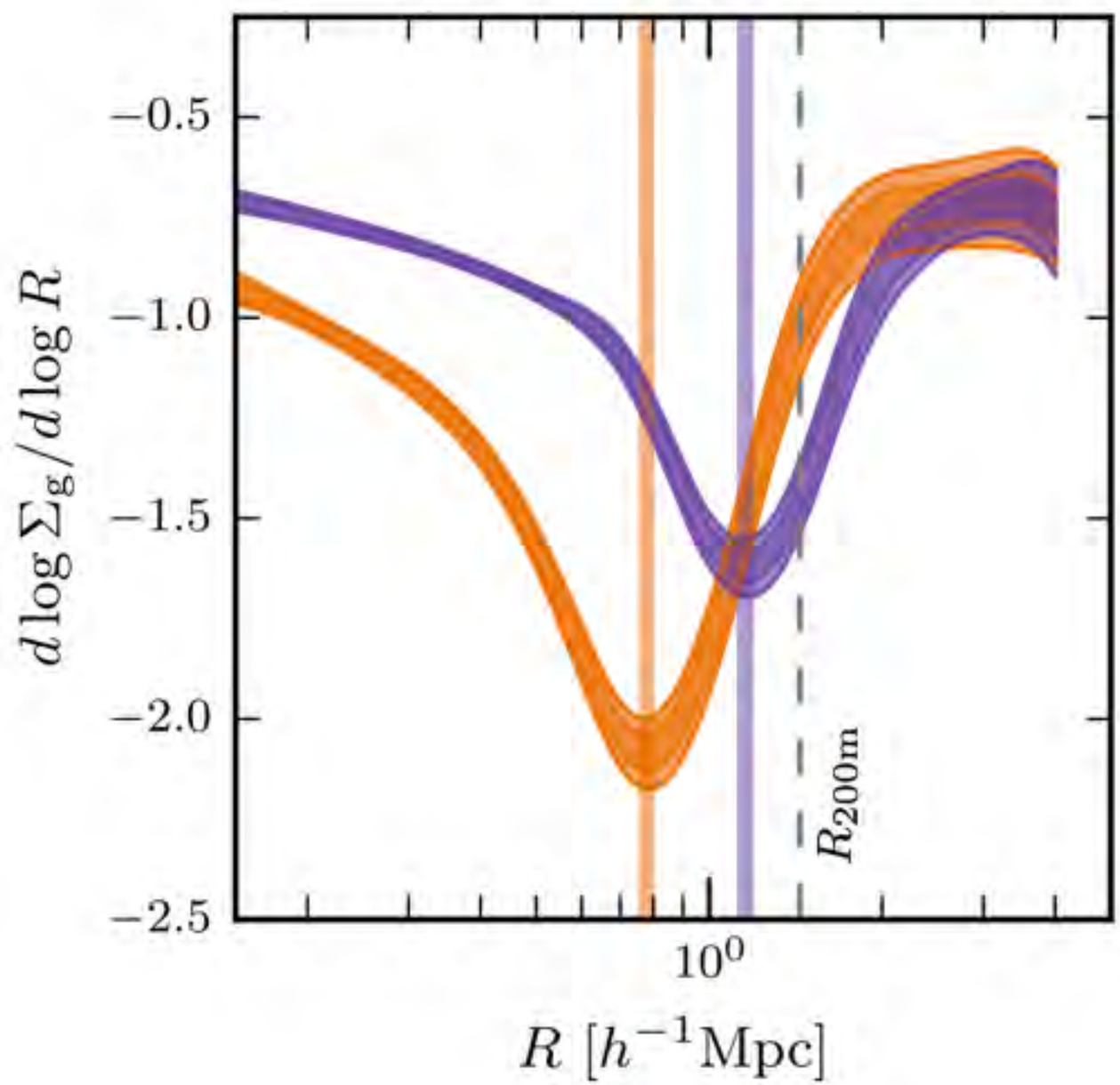
R_{sp} in cluster member profiles



More et al. 2015 • Miyatake et al. 2015

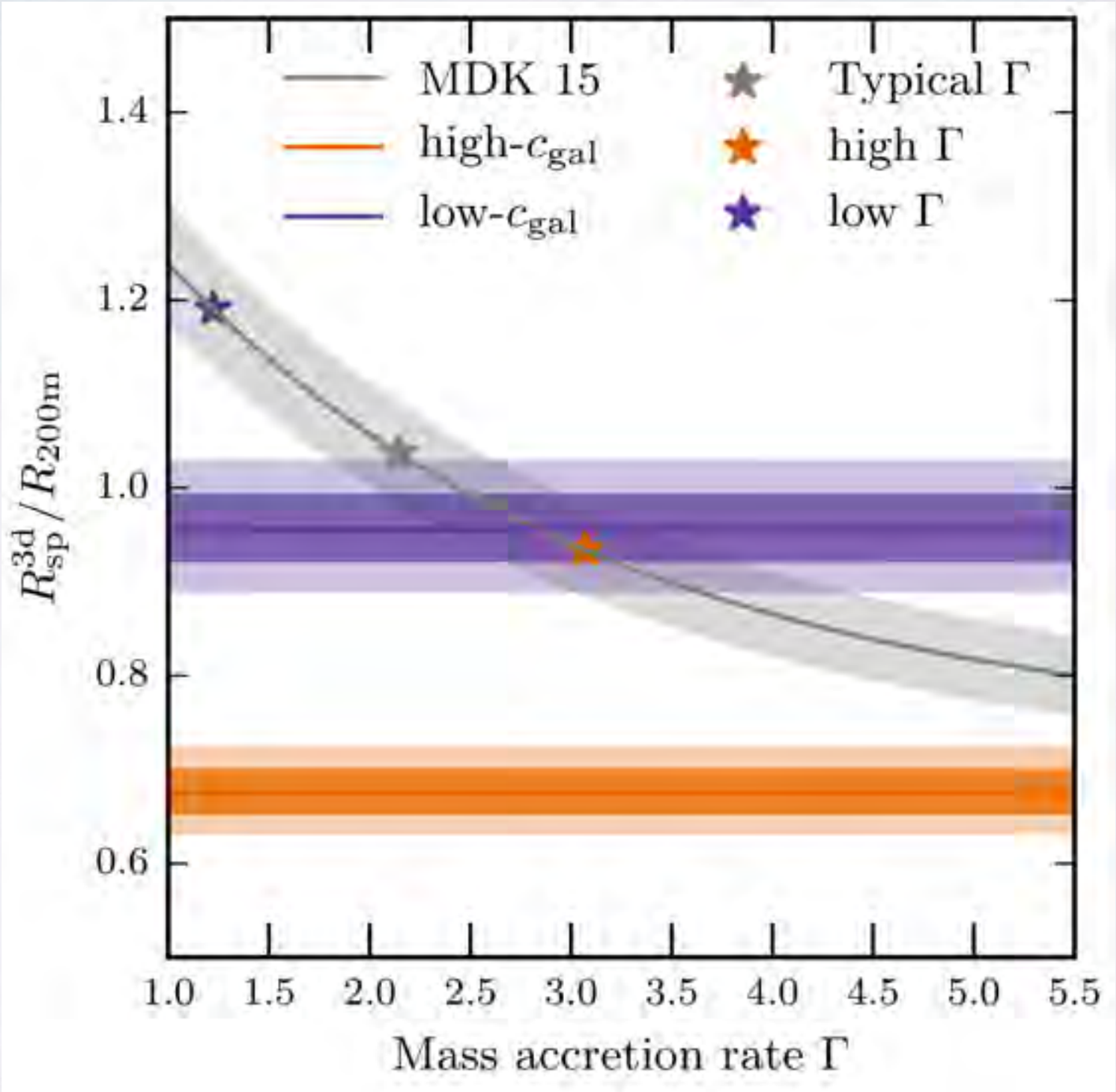
R_{sp} in cluster member profiles





More et al. 2015 • Miyatake et al. 2015

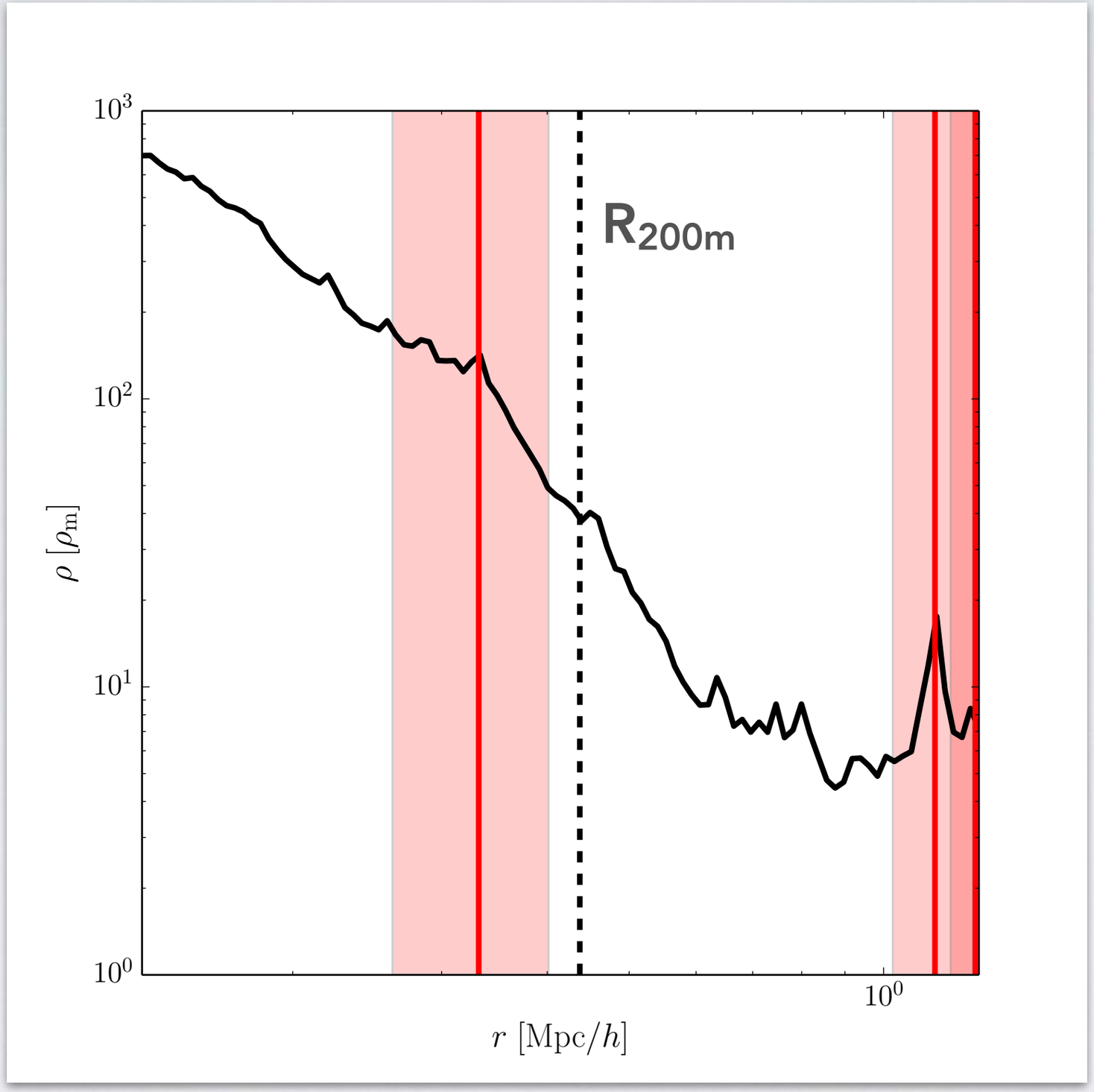
R_{sp} in cluster member profiles



More et al. 2015

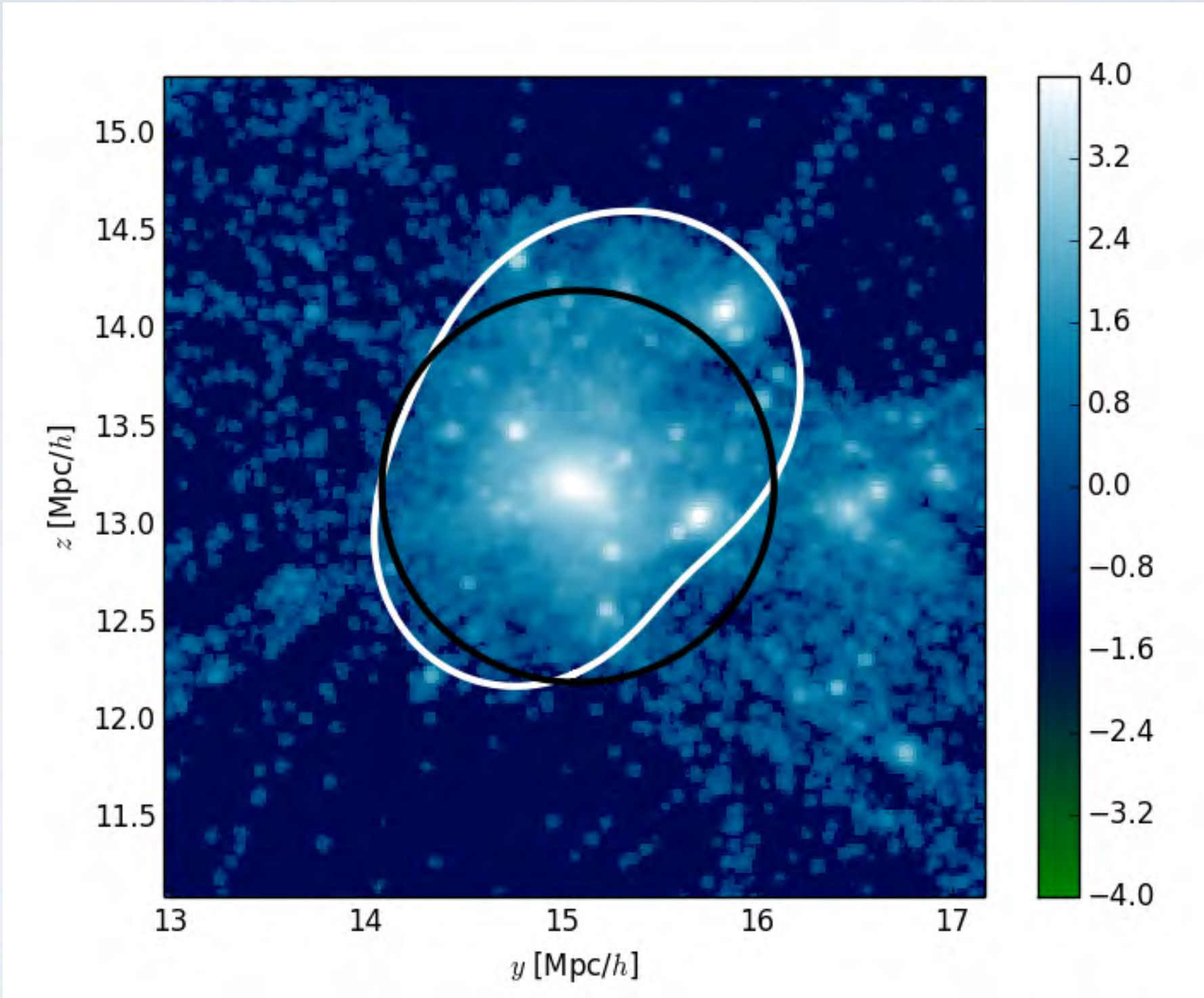
Can we measure R_{sp} in **individual** simulated halos?

R_{sp} in individual halos



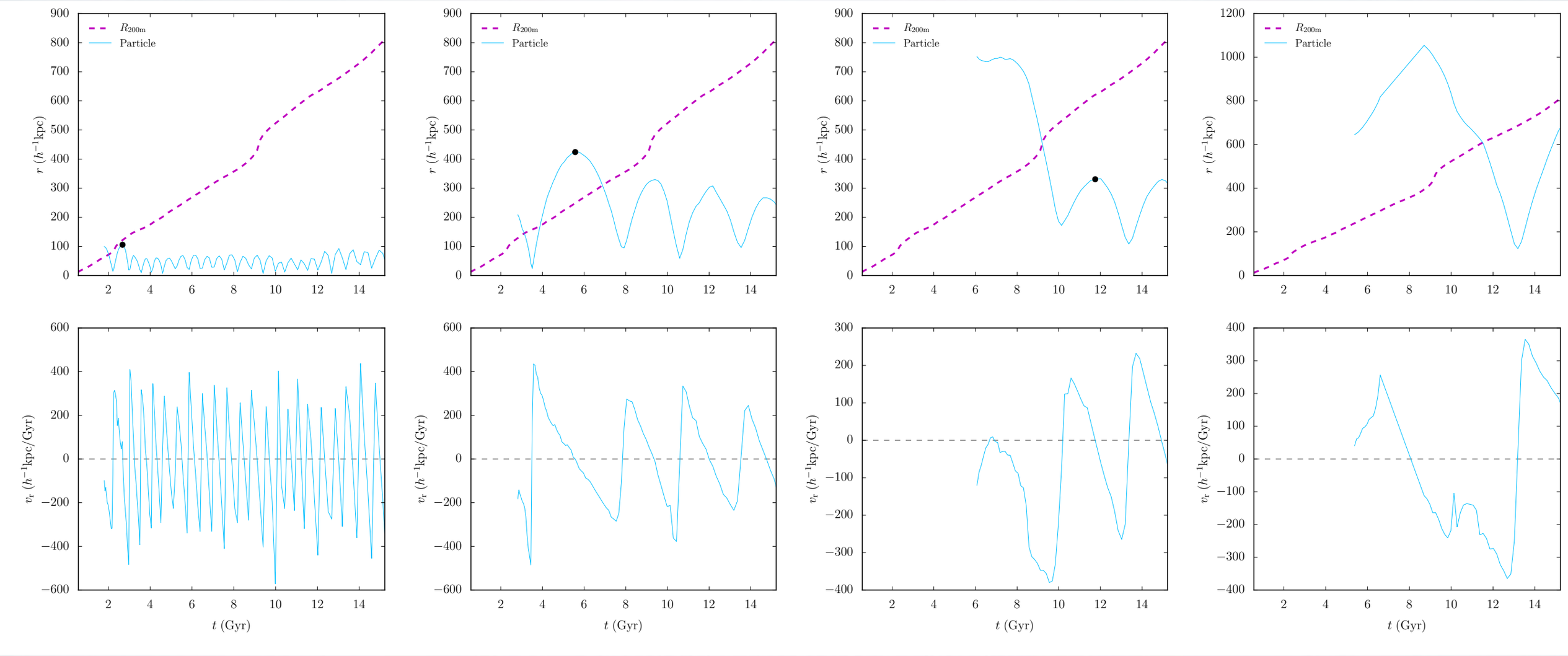
Mansfield et al. 2016 (in prep.)

SHELLFISH

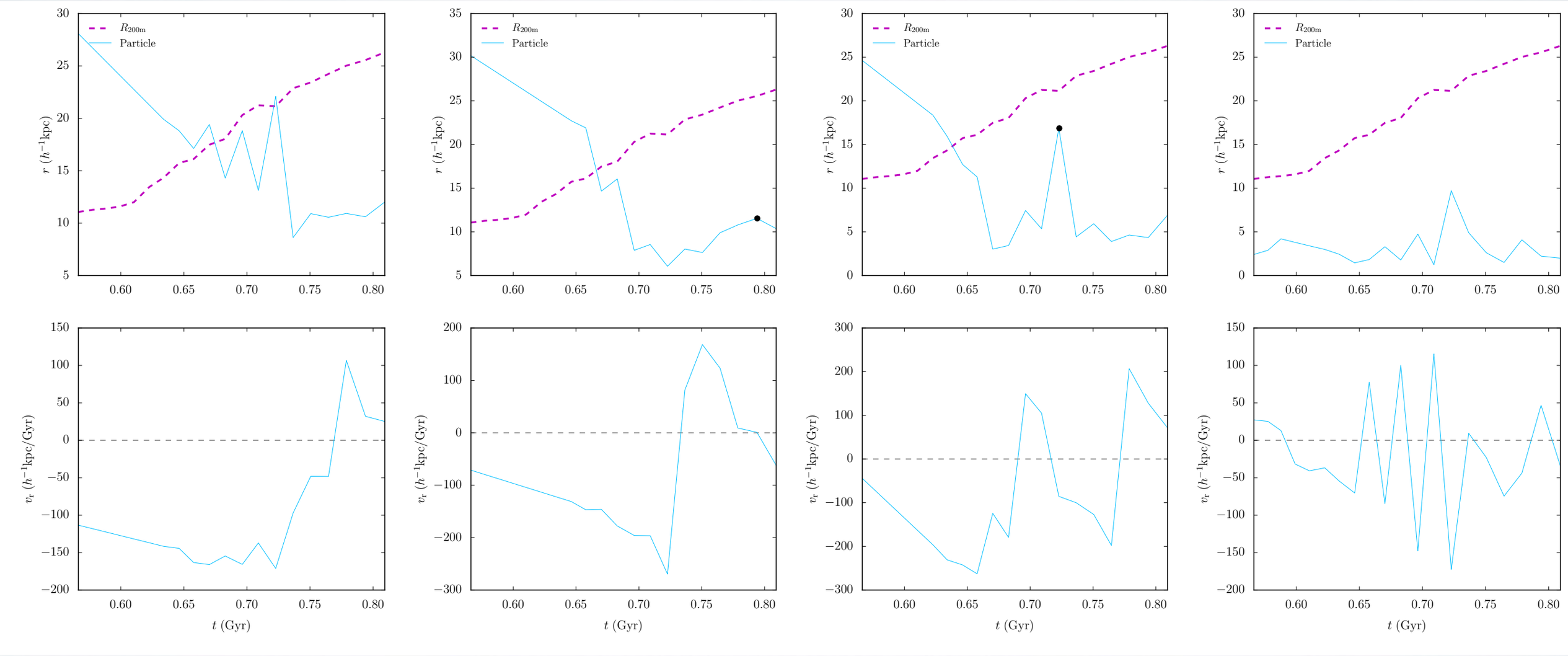


Mansfield et al. 2016 (in prep.)

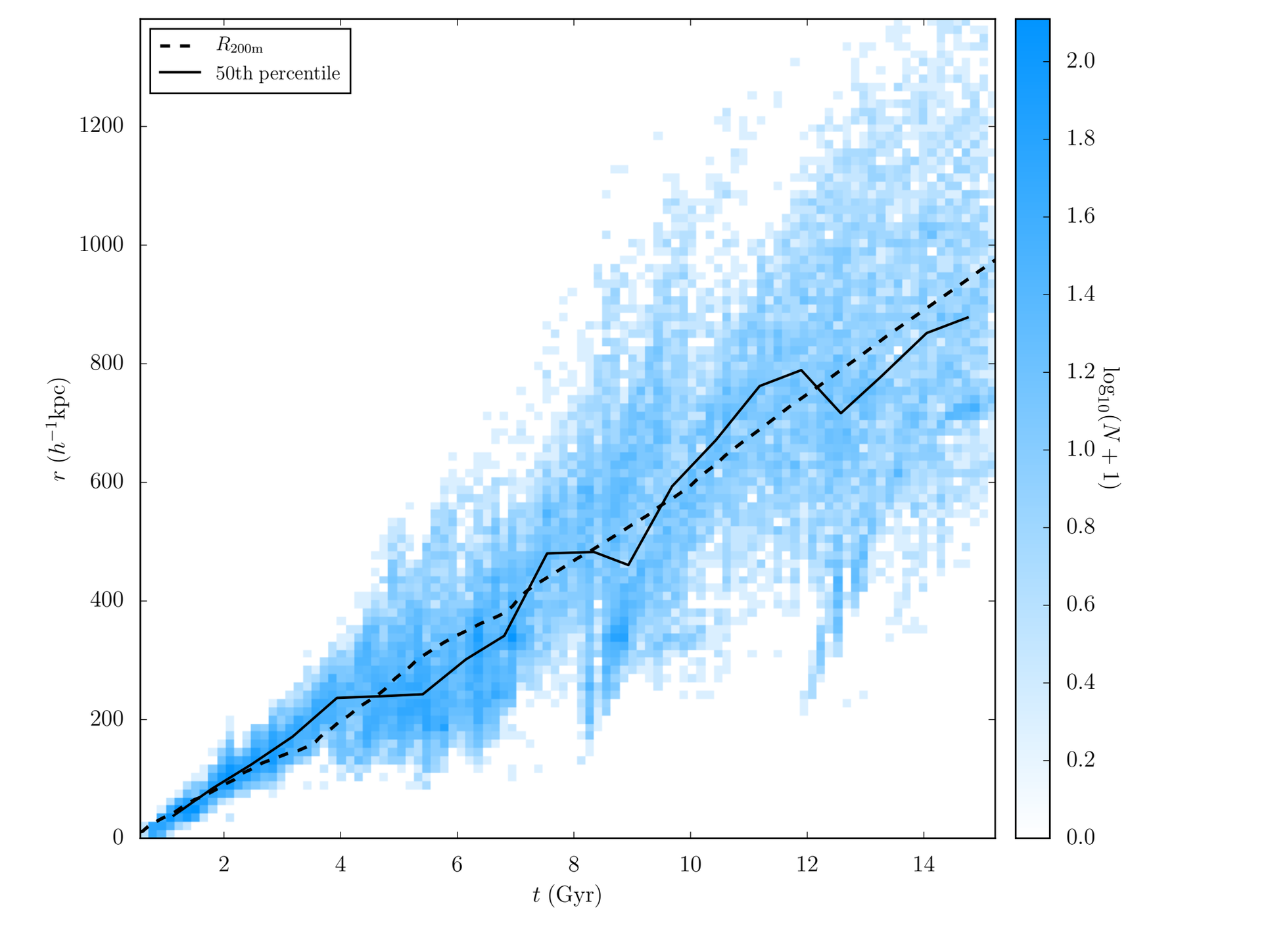
Finding R_{sp} in trajectories



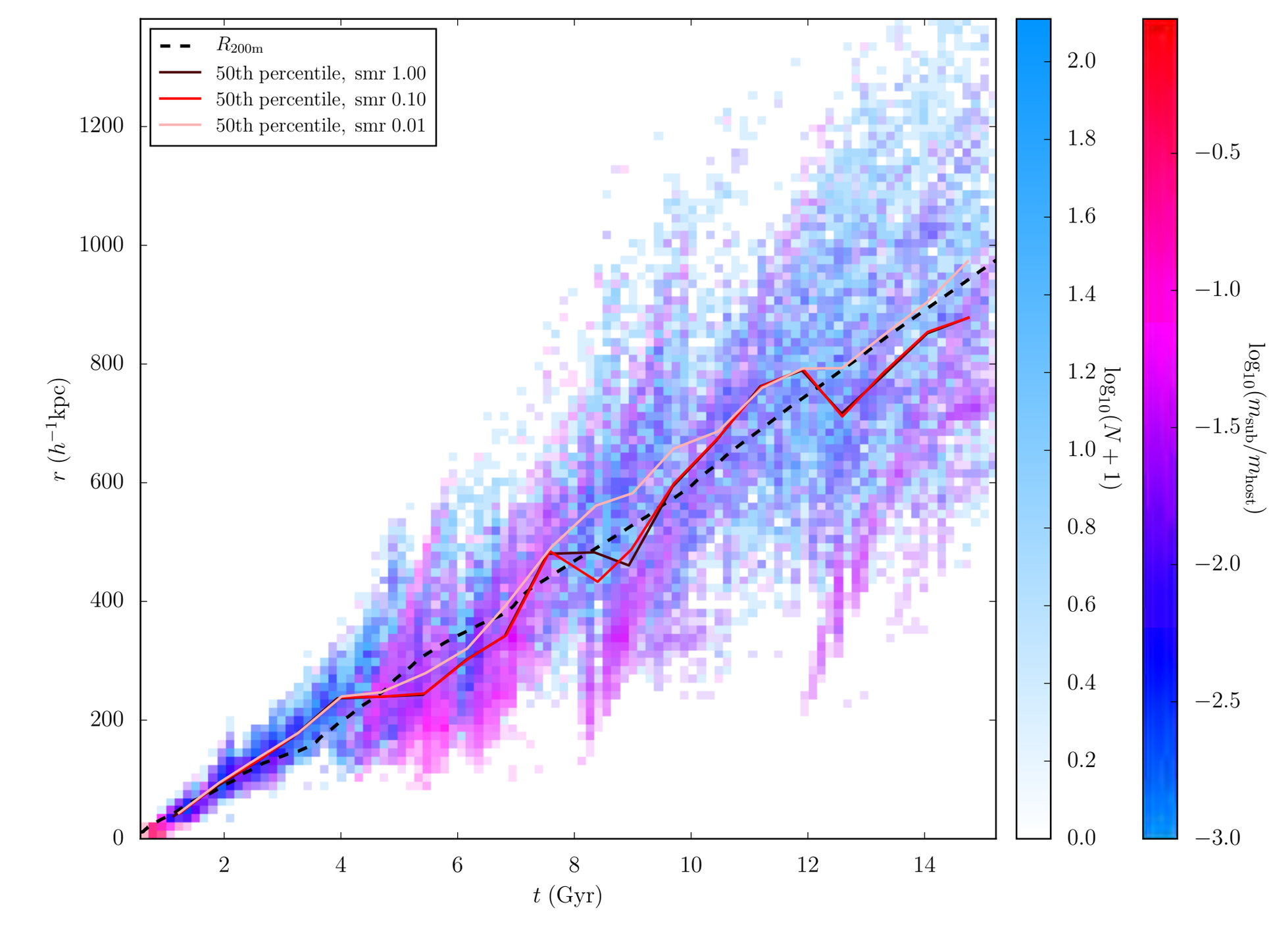
Finding R_{sp} in trajectories



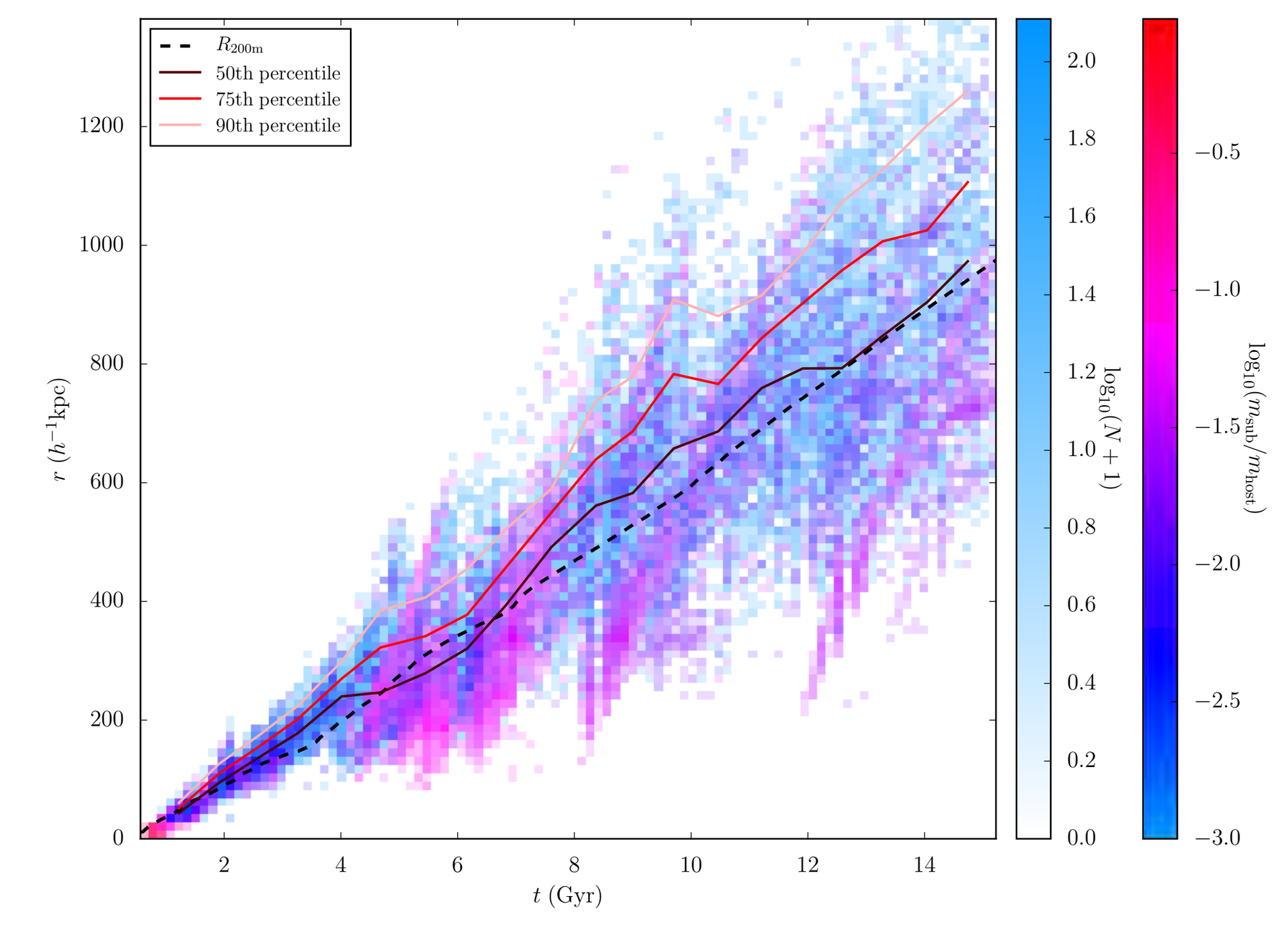
Finding R_{sp} in trajectories



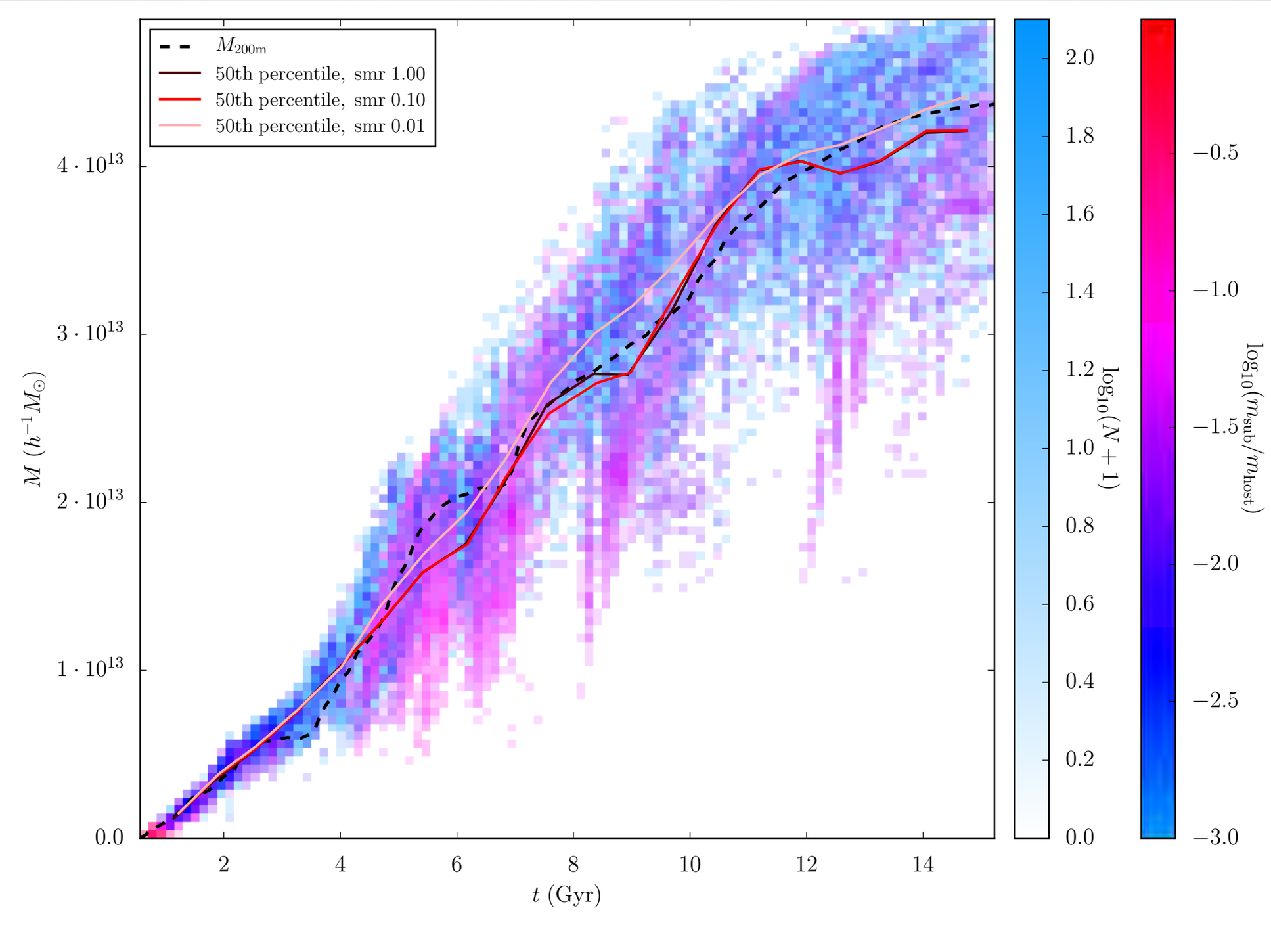
Finding R_{sp} in trajectories



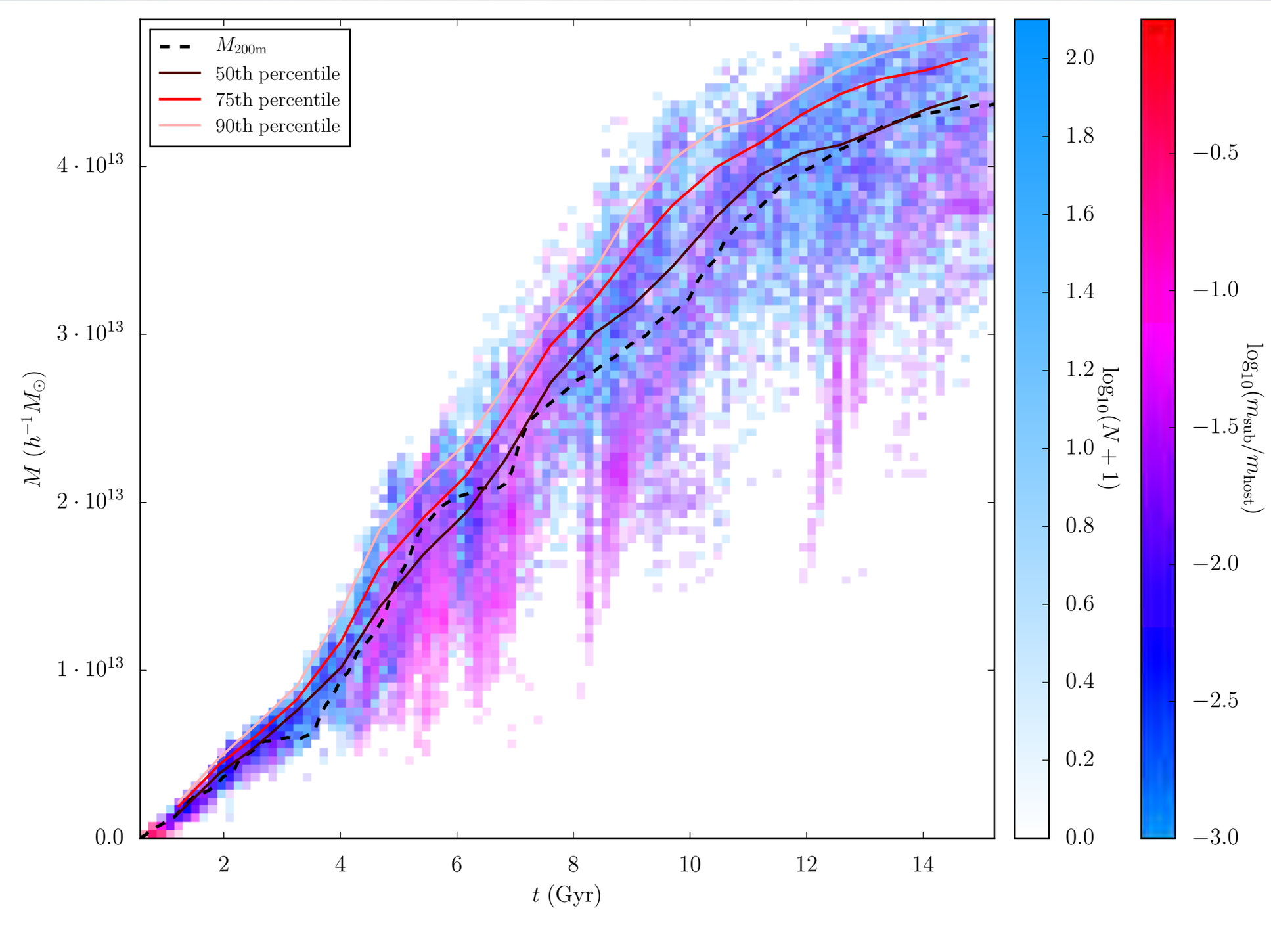
Finding R_{sp} in trajectories



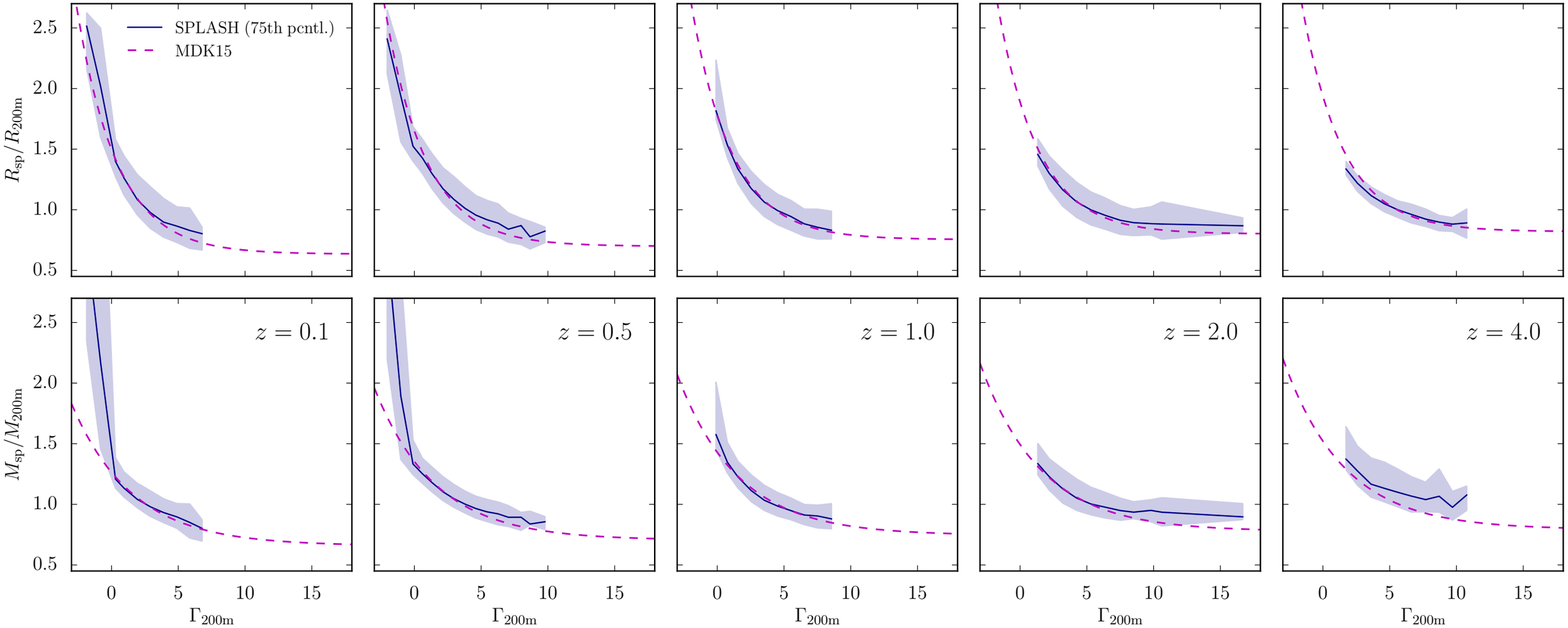
Finding M_{sp} in trajectories



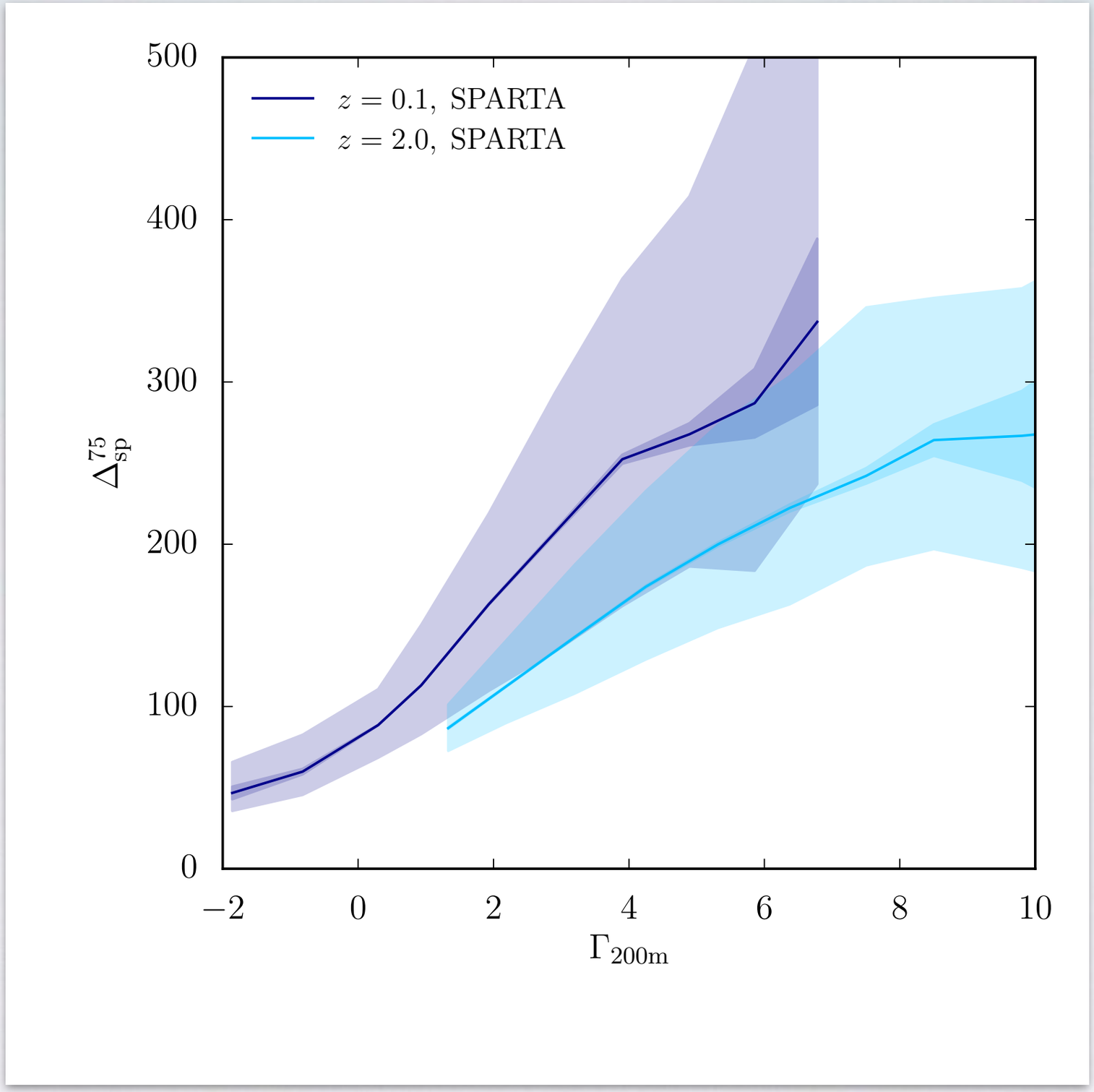
Finding M_{sp} in trajectories



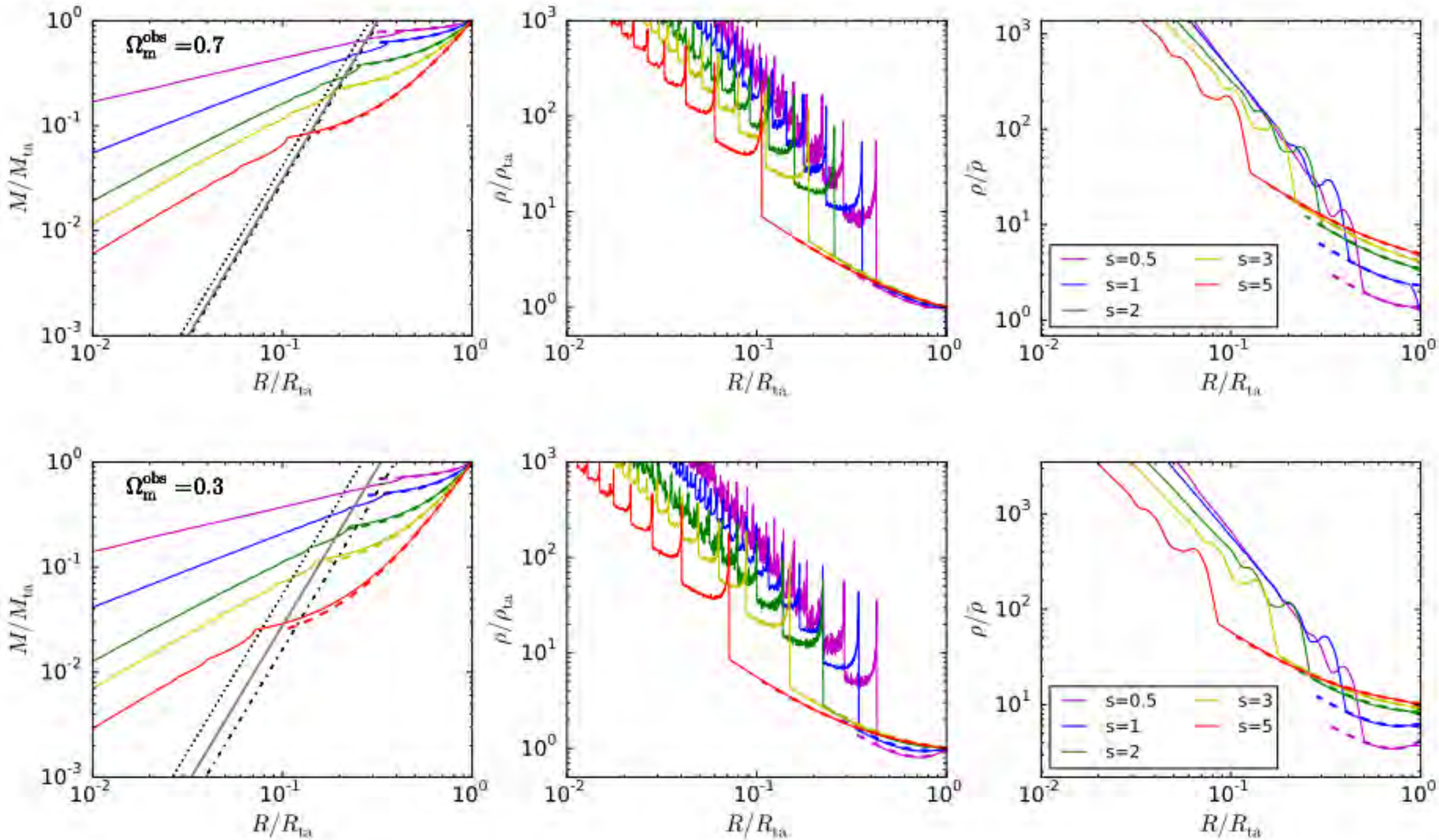
Results: R_{sp}-Γ relation



Results: Δ_{sp}

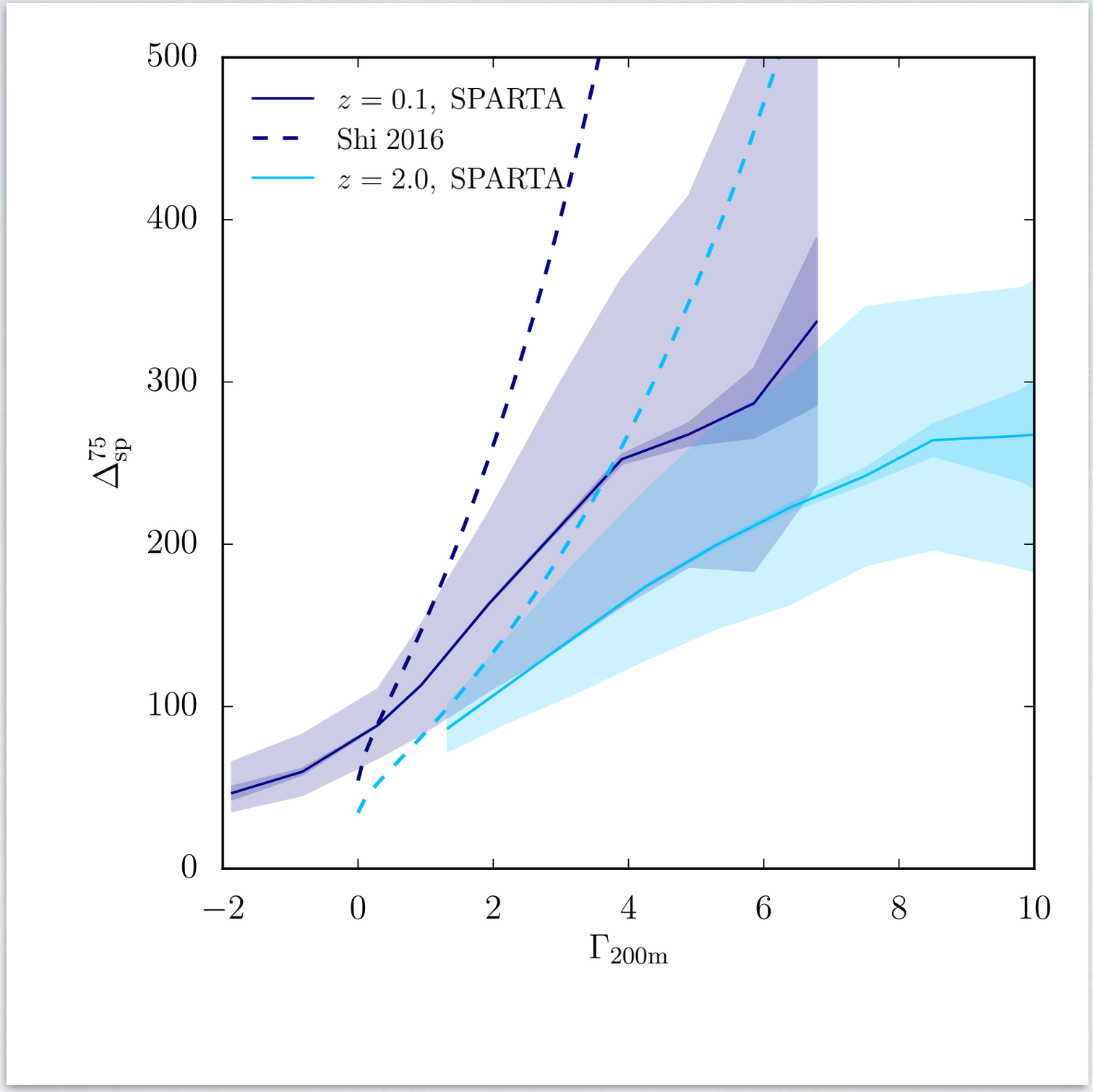


Spherical collapse model



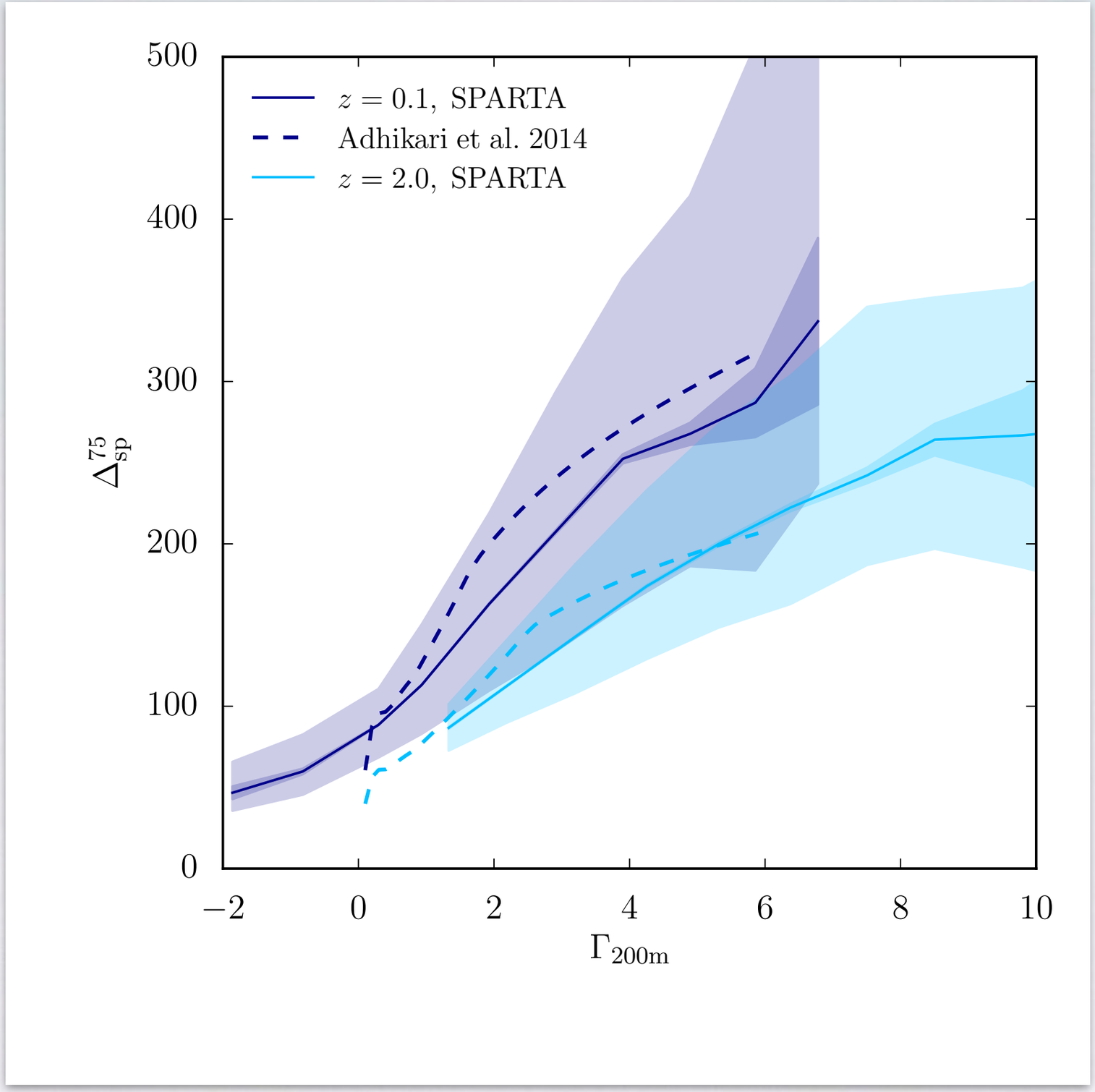
Shi 2016

Results: Δ_{sp}



Shi 2016

Results: Δ_{sp}



Adhikari et al. 2014

Future directions

- Measure R_{sp} in individual halos
- Quantify the mass function and accretion rates of M_{sp}
- Create halo catalogs and merger trees based on R_{sp}
- Find more observational signatures of R_{sp}

The Colossus Code

Cosmology

```
from colossus.cosmology import cosmology

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

Concentration

```
from colossus.halo import concentration as hc

c = hc.concentration(1E12, 'vir', 0.0, model = ‘diemer15')
```

Density profiles

```
from colossus.halo import profile_nfw as nfw
from colossus.halo import profile_dk14 as dk14

p1 = nfw.NFWProfile(M = 1E14, mdef = 'vir', c = 4.0, z = 0.0)
Sigma = p1.surfaceDensity(5.0)

p2 = dk14.DK14Profile(M = 1E14, mdef = 'vir', c = 4.0, z = 0.0)
splashback_radius = p2.Rsp()
```

http://www.benediktdiemer.com/code/

Conclusions

- Concentrations **are universal** when expressed as a function of peak properties
- The outer profiles **are not universal**, they depend on the mass accretion rate and are not well described by the NFW form
- The **splashback radius** provides a physical halo boundary

Diemer & Kravtsov 2014 • ApJ 789, 1 • arXiv 1401.1216
Diemer & Kravtsov 2015 • ApJ 799, 108 • arXiv 1407.4730
More, Diemer & Kravtsov 2015 • arXiv 1504.5591