The (non-)universality of halo density profiles

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in collaboration with Andrey Kravtsov (UChicago) and Surhud More (IPMU)

UC Berkeley • 10/07/2014

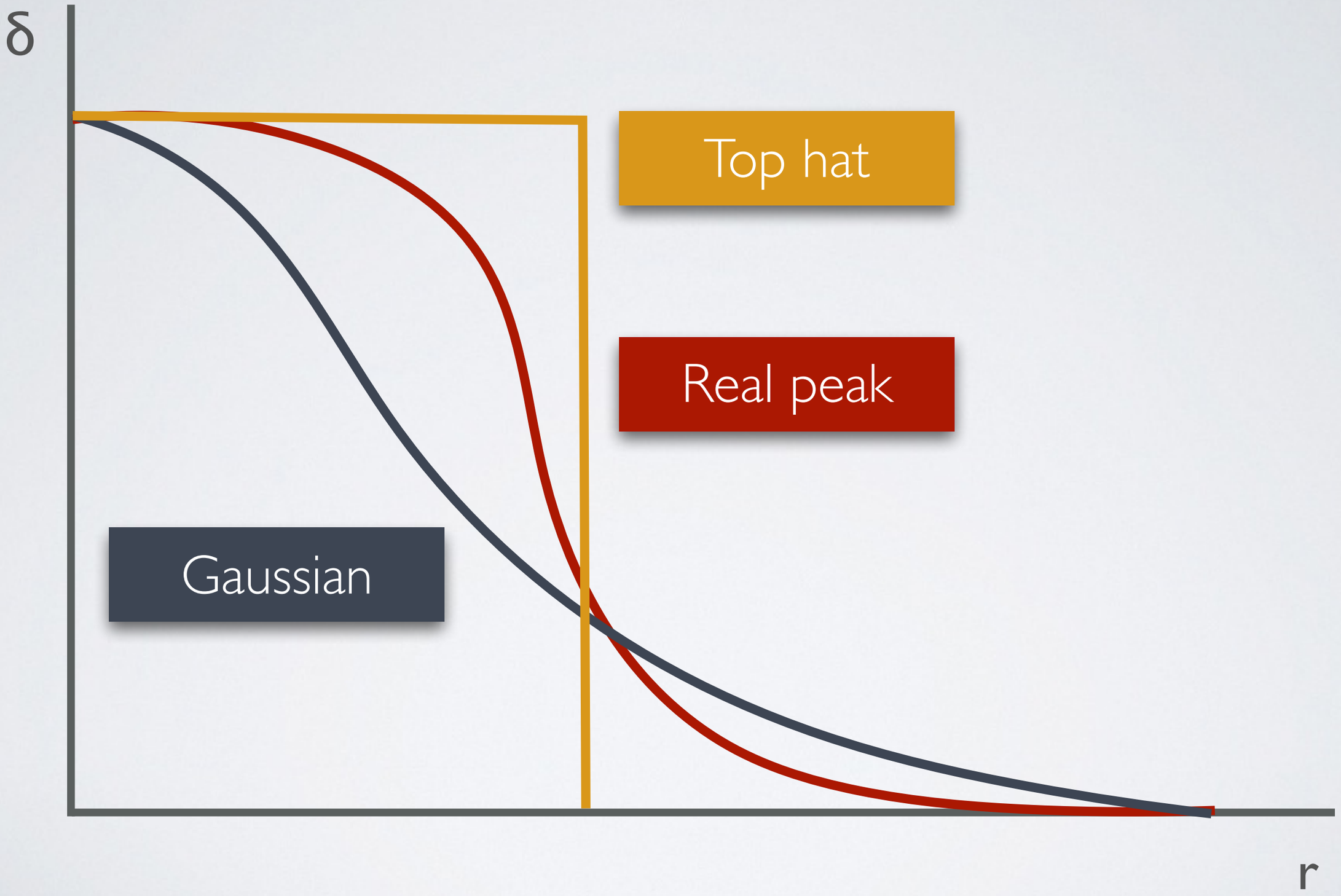
The topic

The **radial**, spherically averaged density profiles of **isolated** dark matter halos

Common wisdom

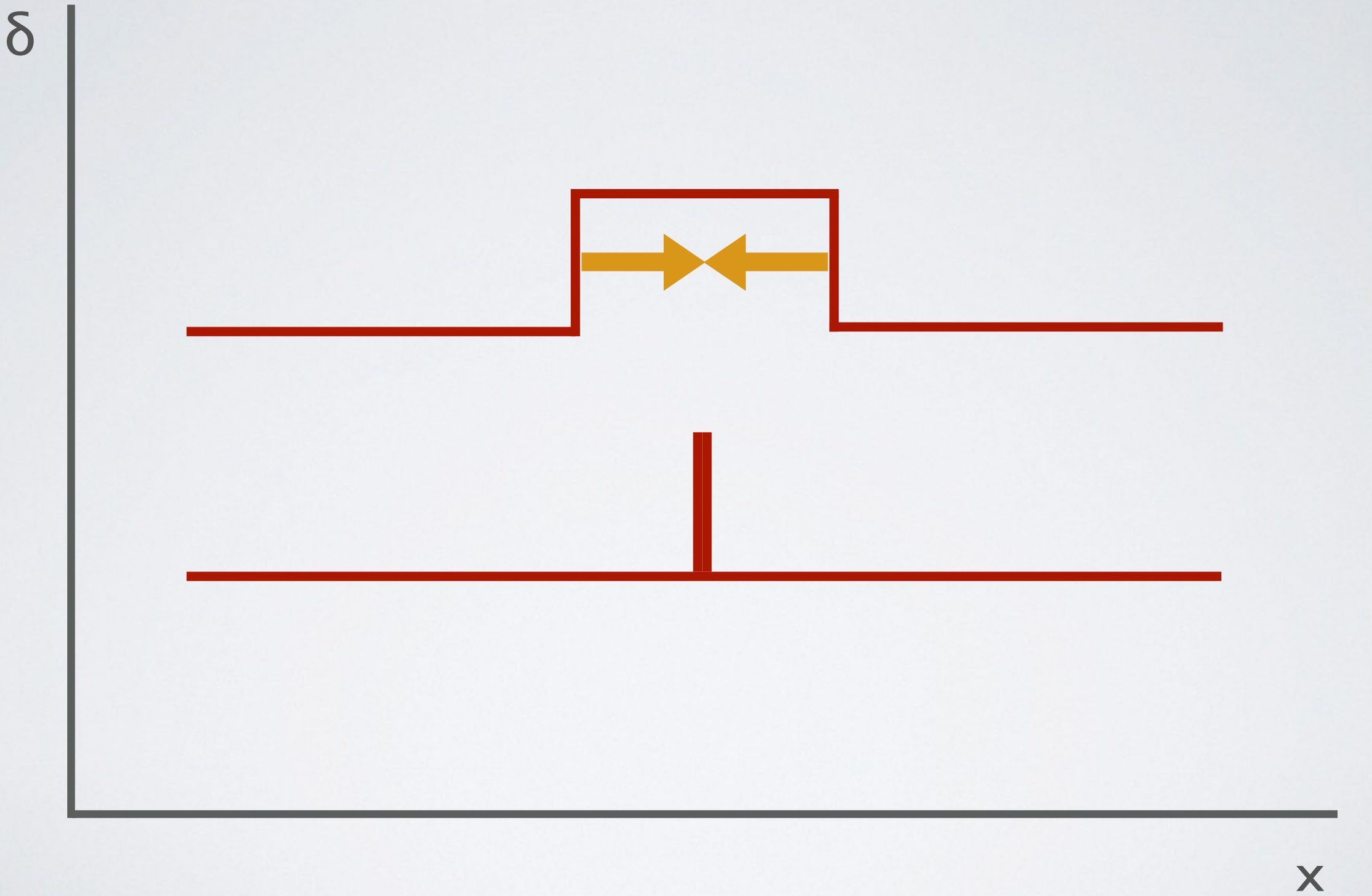
- Halo density profiles are **universal**
- They follow the NFW / Einasto form
- There is no preferred definition of the outer radius

Simplified model

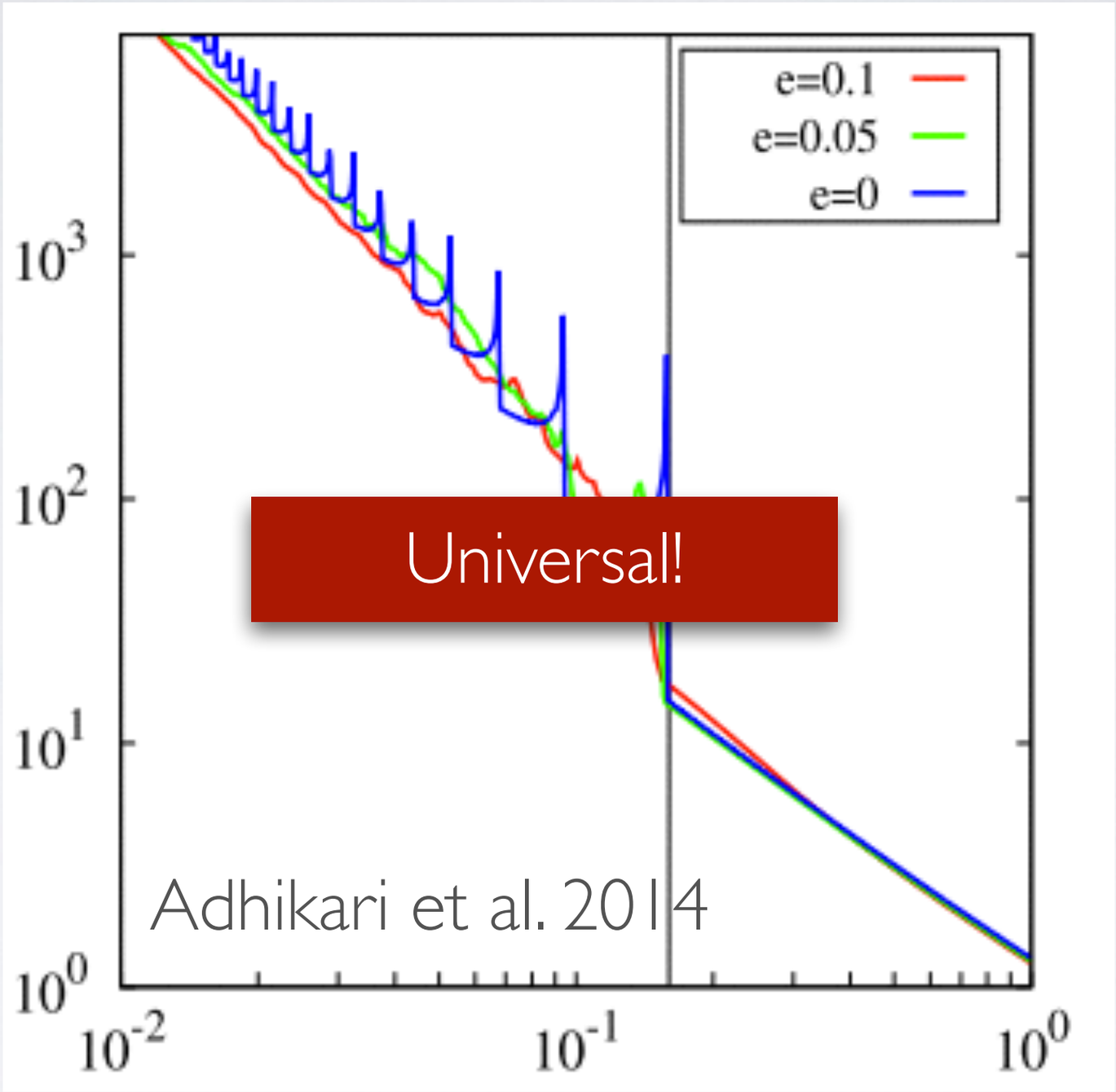


Bardeen et al. 1986 • Dalal et al. 2008

Top-hat collapse

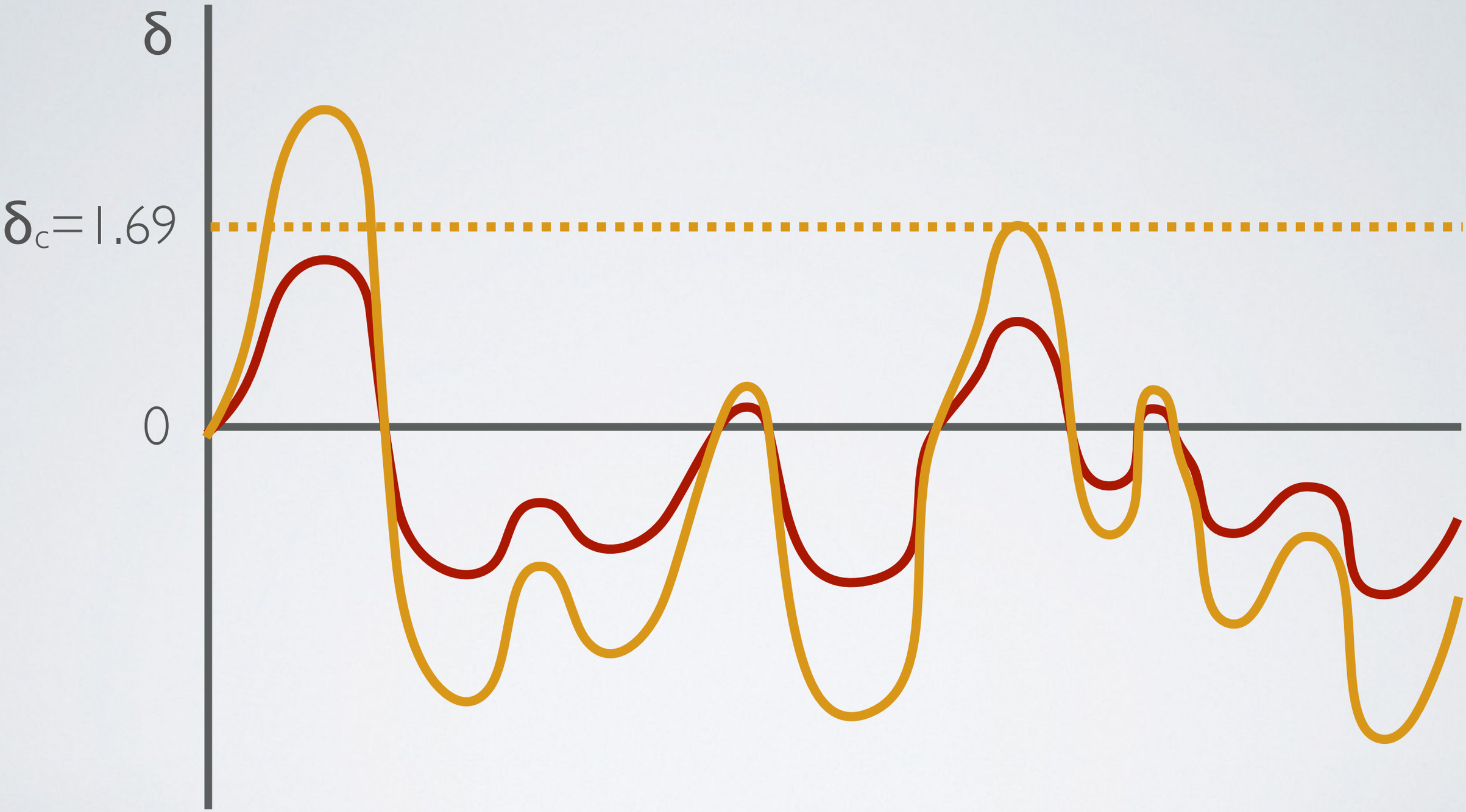


Simplified model



Fillmore & Goldreich 1984 • Bertschinger 1985 • Lithwick & Dalal 2011

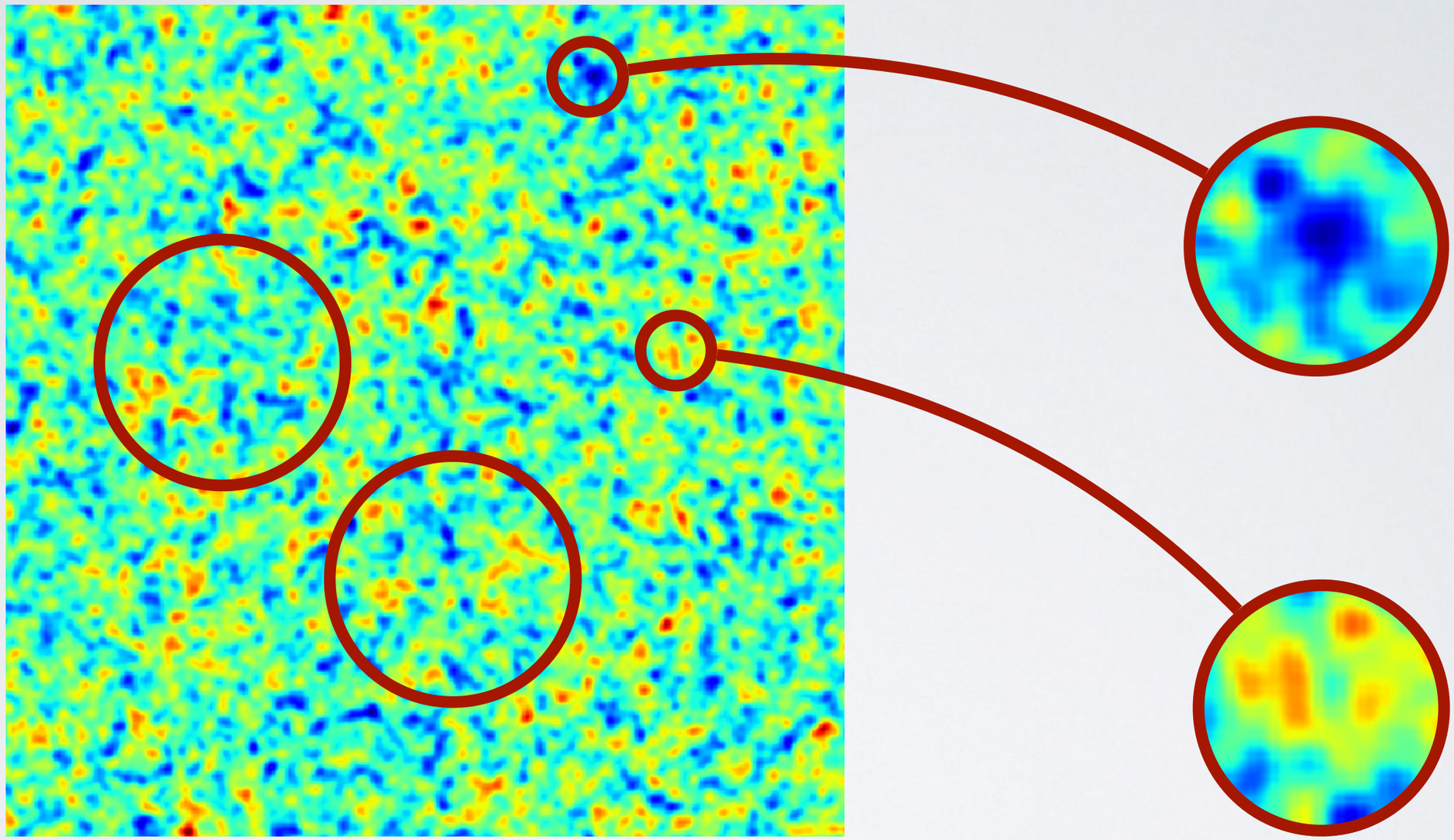
Peak height



$$\nu \equiv \delta / \sigma$$

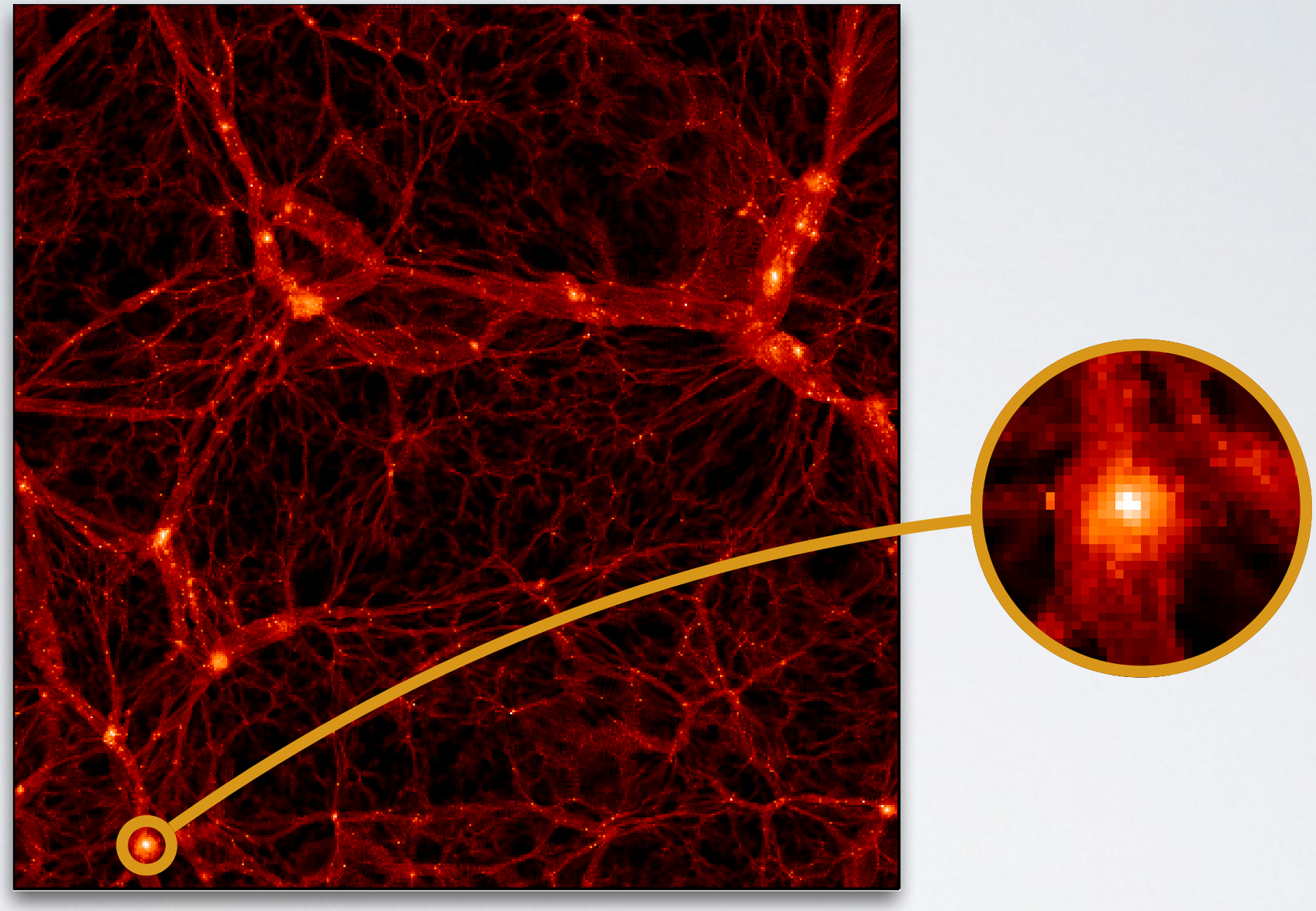
Bardeen et al. 1986

Peak height



$\sigma(R, z)$

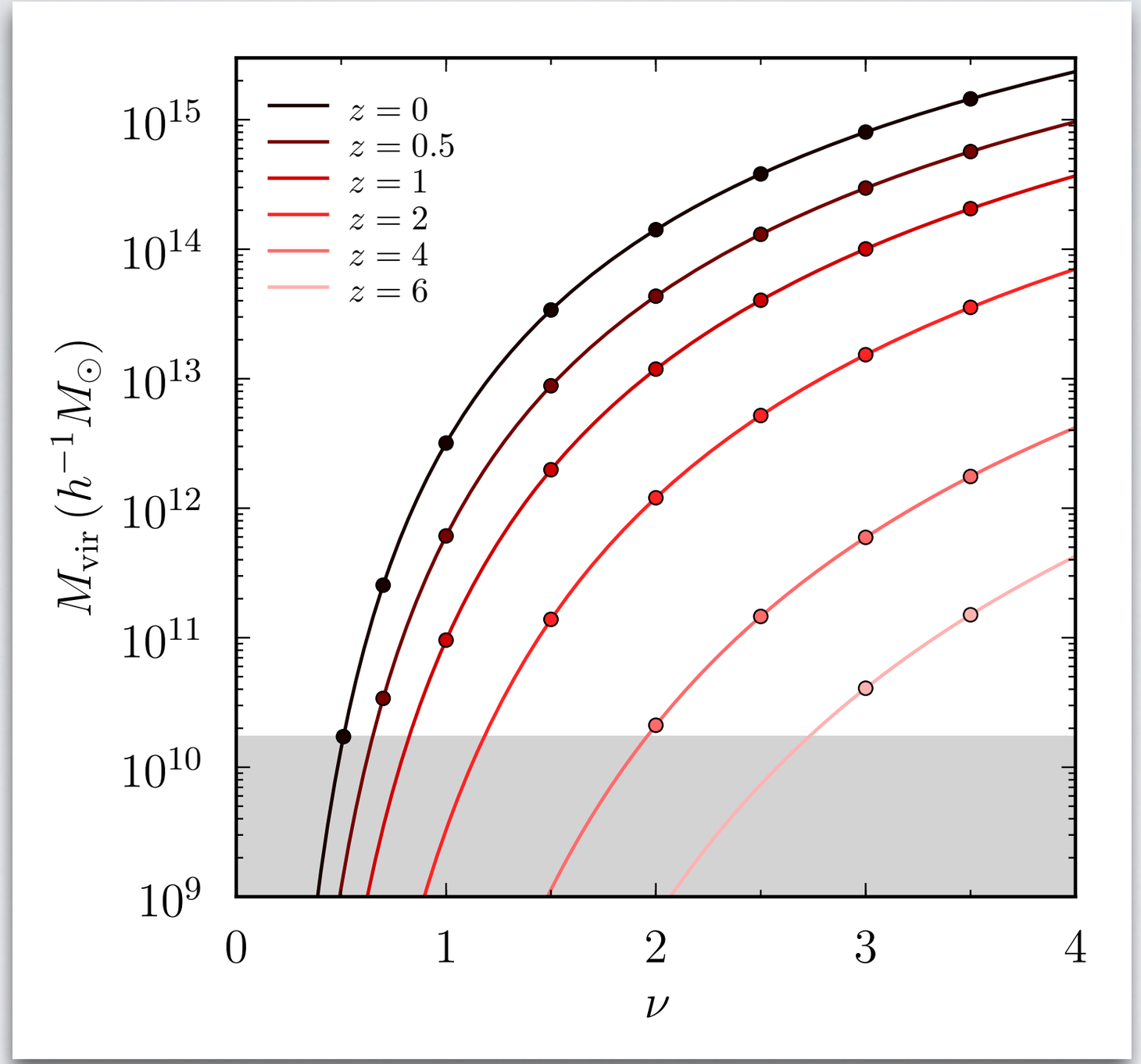
Peak height



$$M_{vir} = 4\pi/3\ \rho_m(z=0)\ R^3_{Lagrangian}$$

$$\nu = \delta_c\ /\ \sigma(R_{Lagrangian}, z)$$

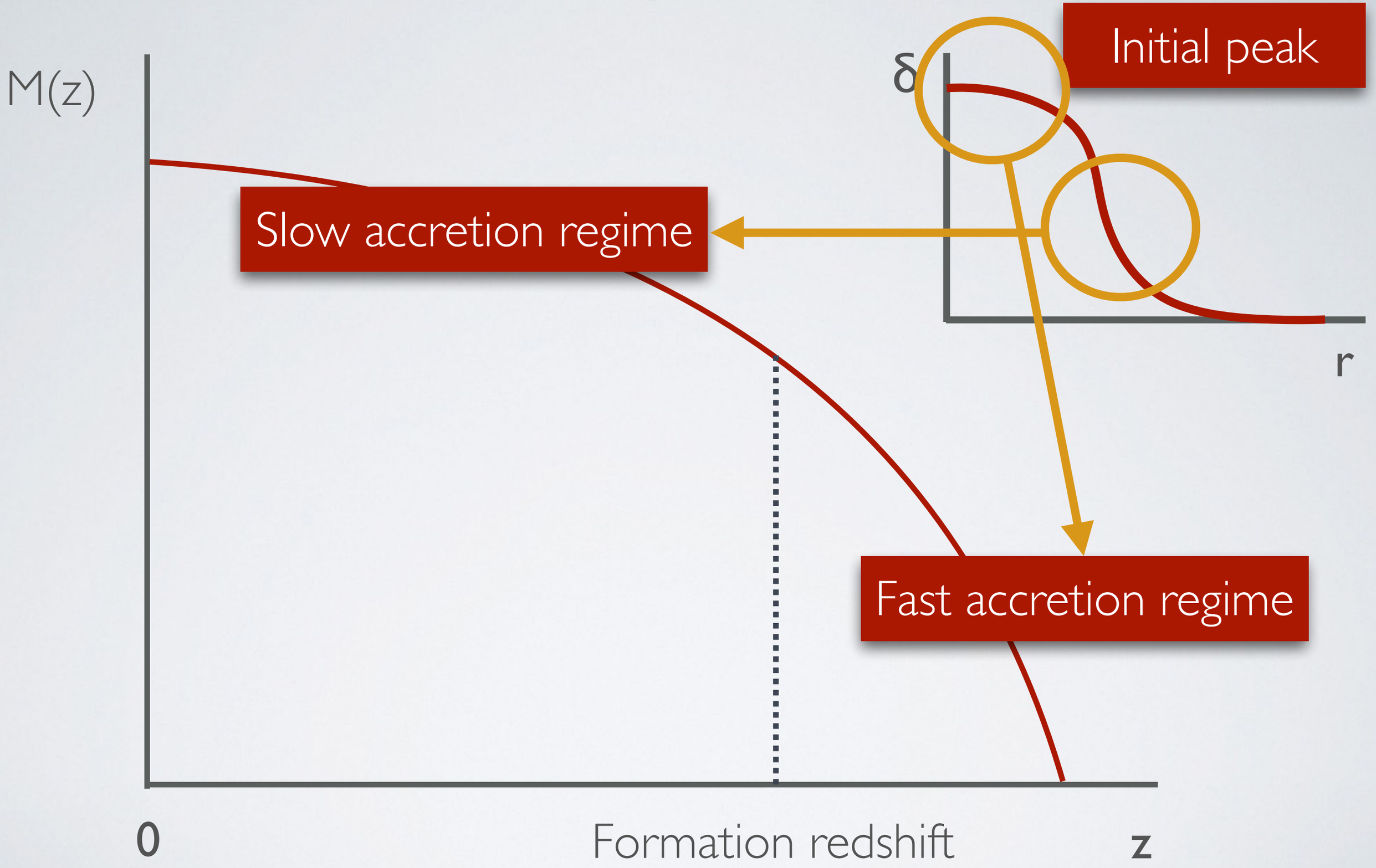
Peak height



mass

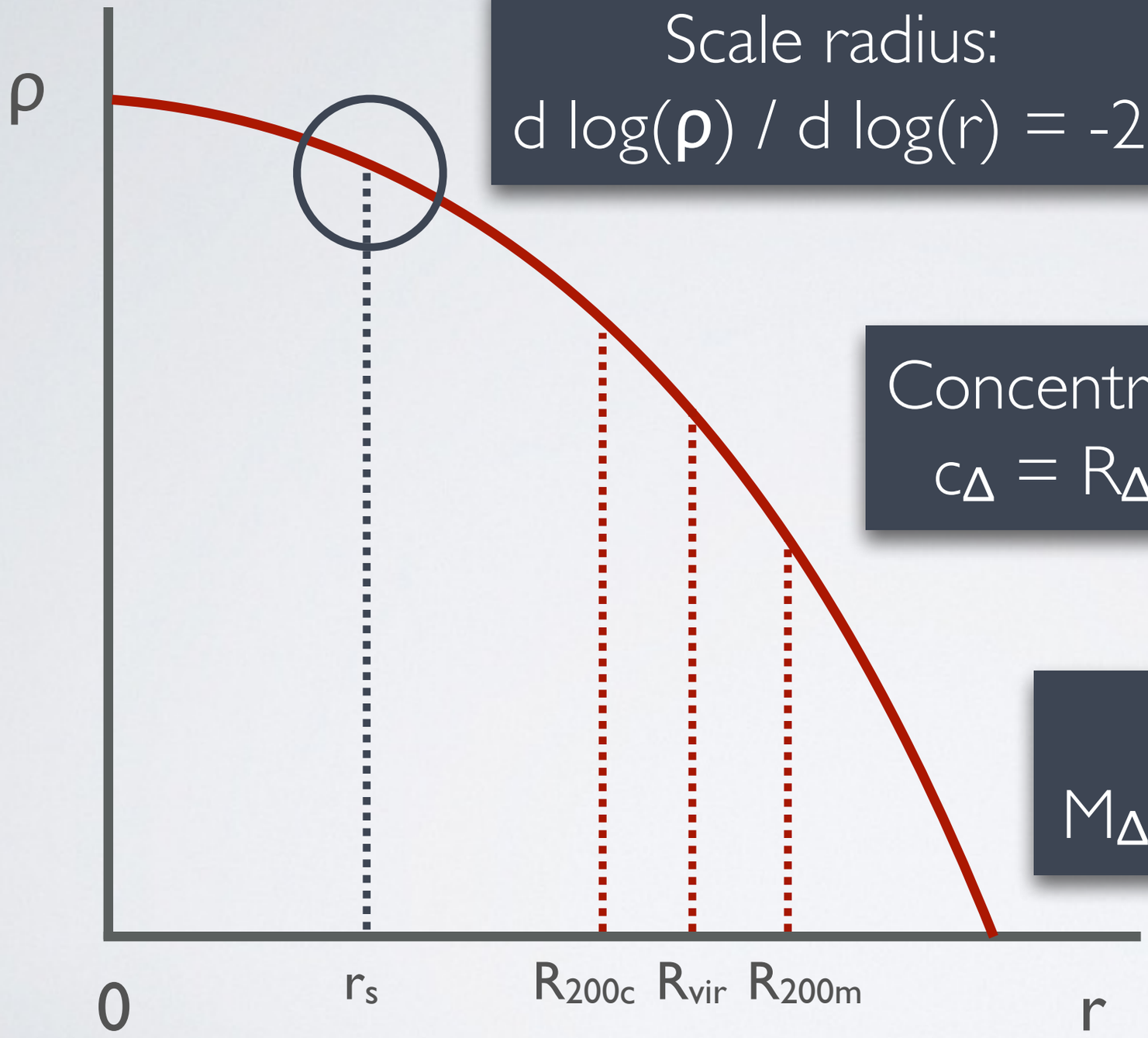
peak height

Mass accretion history



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

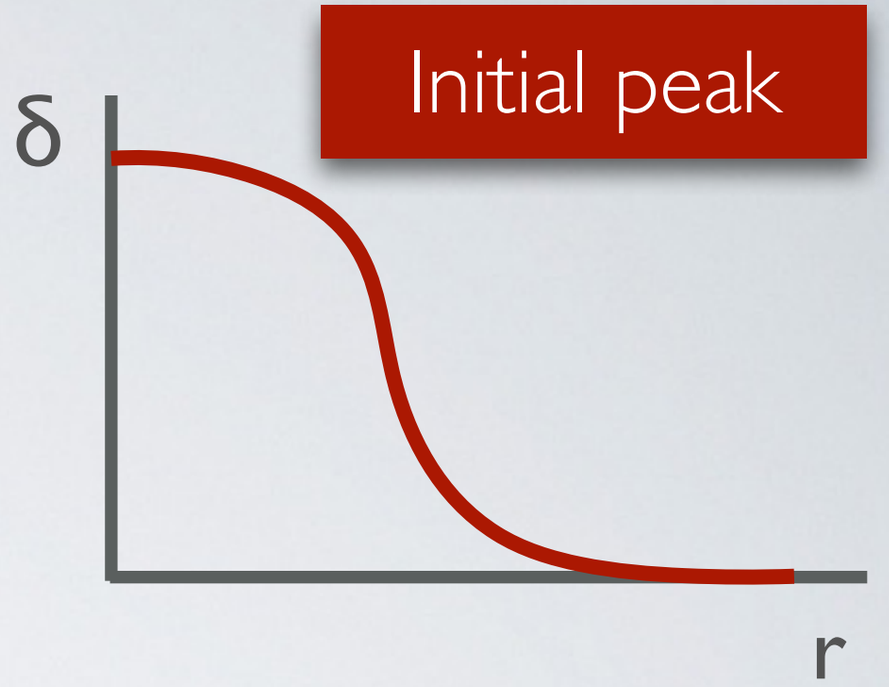
Density profile



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

Concentration:
$c_\Delta = R_\Delta / r_s$

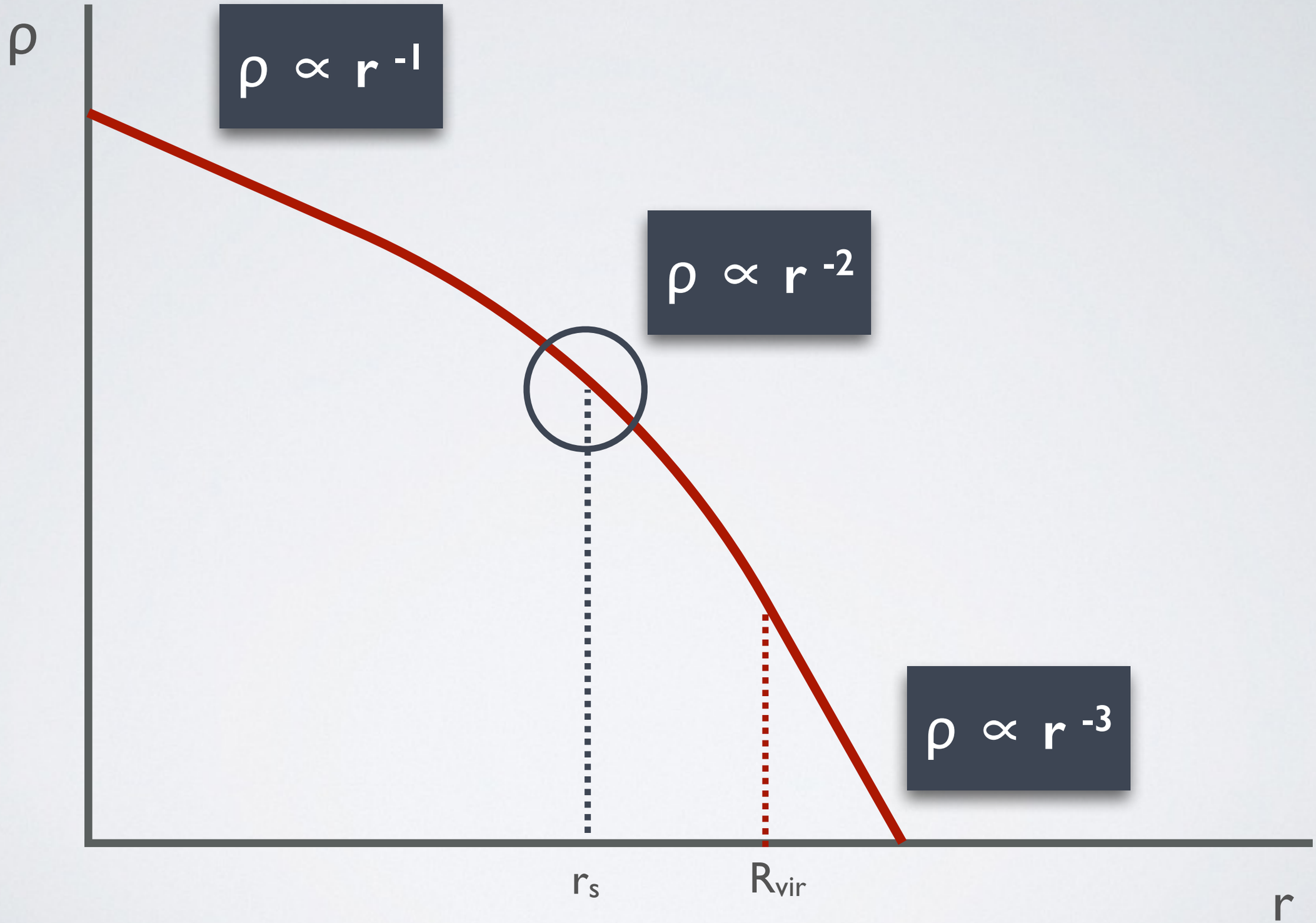
Mass:
$M_\Delta = 4\pi/3\ \Delta\ \rho_{ref}\ R_\Delta^3$



Initial peak

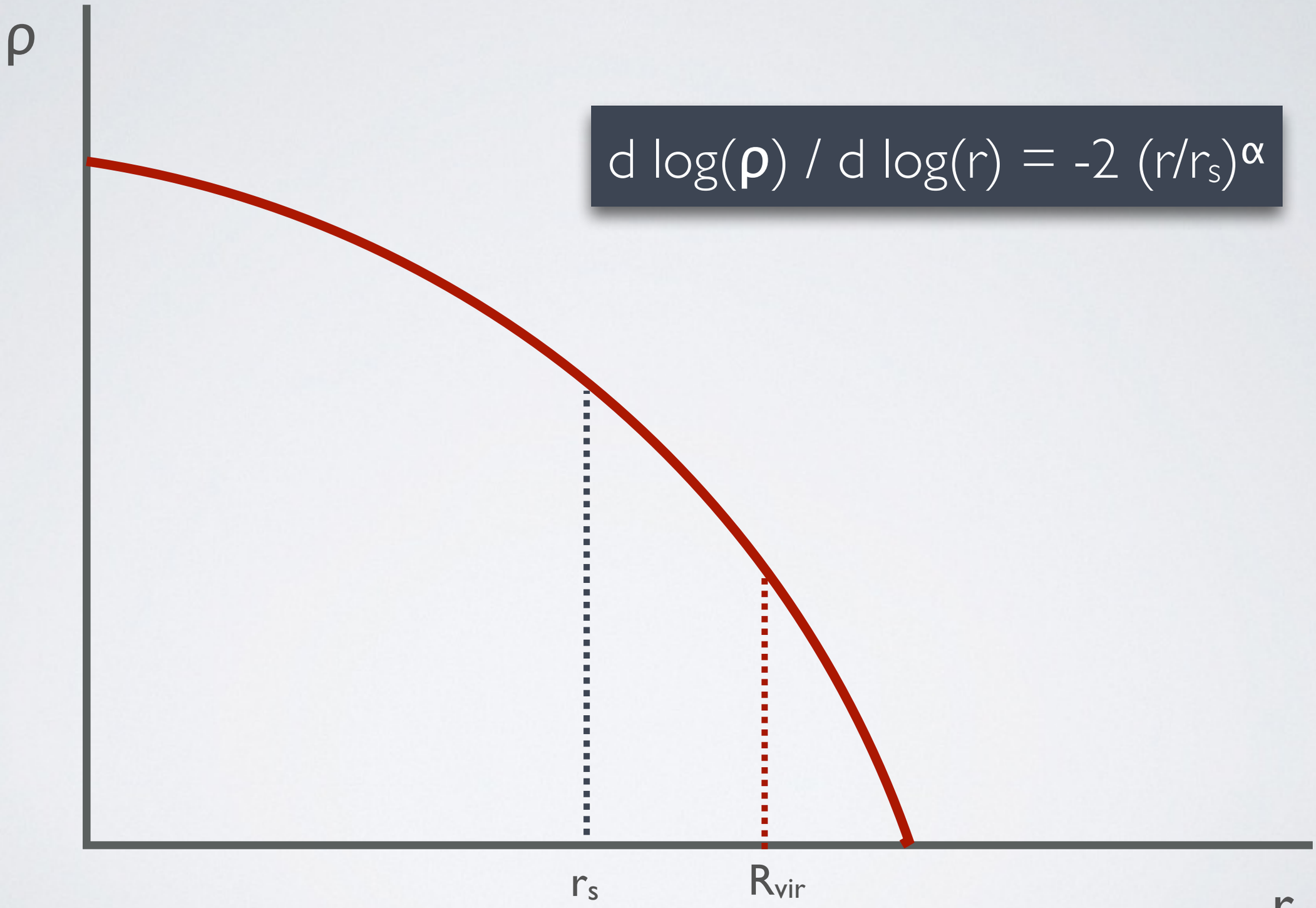
Dalal et al. 2010 • Ludlow et al. 2013

Navarro-Frenk-White profile



Navarro et al. 1995/1996/1997

Einasto profile



Einasto 1965

2000 Mpc/h

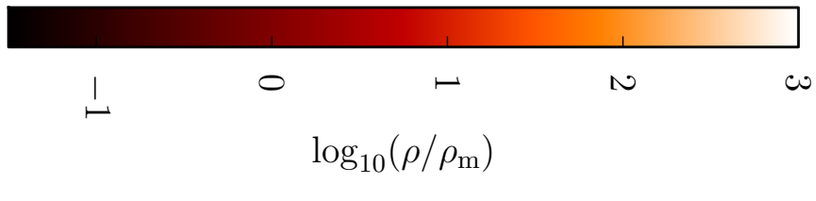
1000 Mpc/h

500 Mpc/h

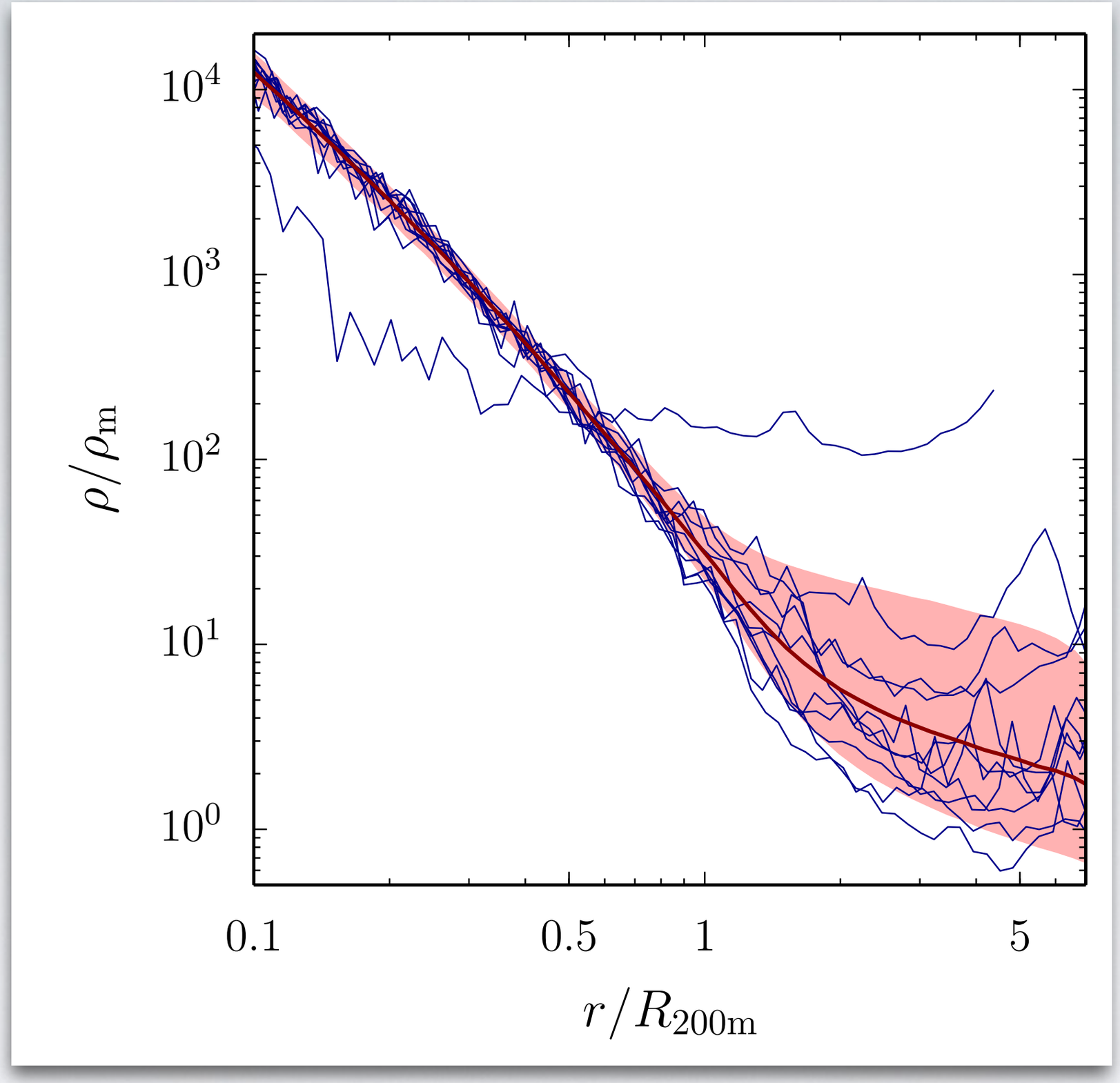
250 Mpc/h

125 Mpc/h

62.5 Mpc/h

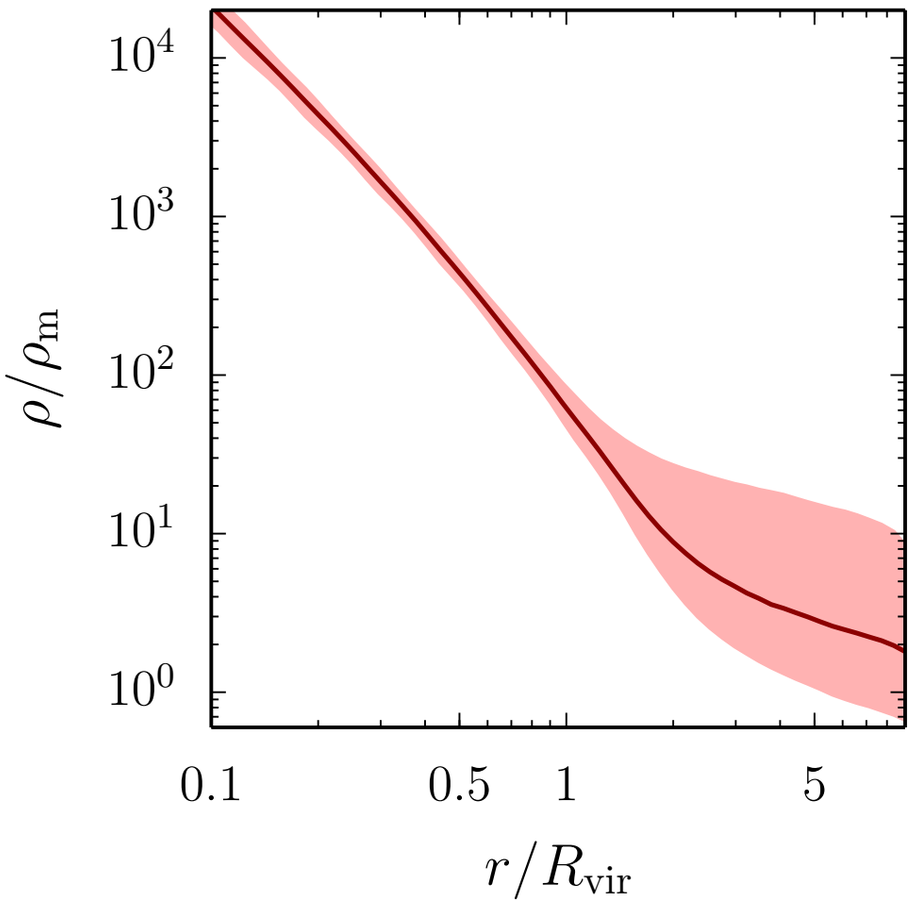


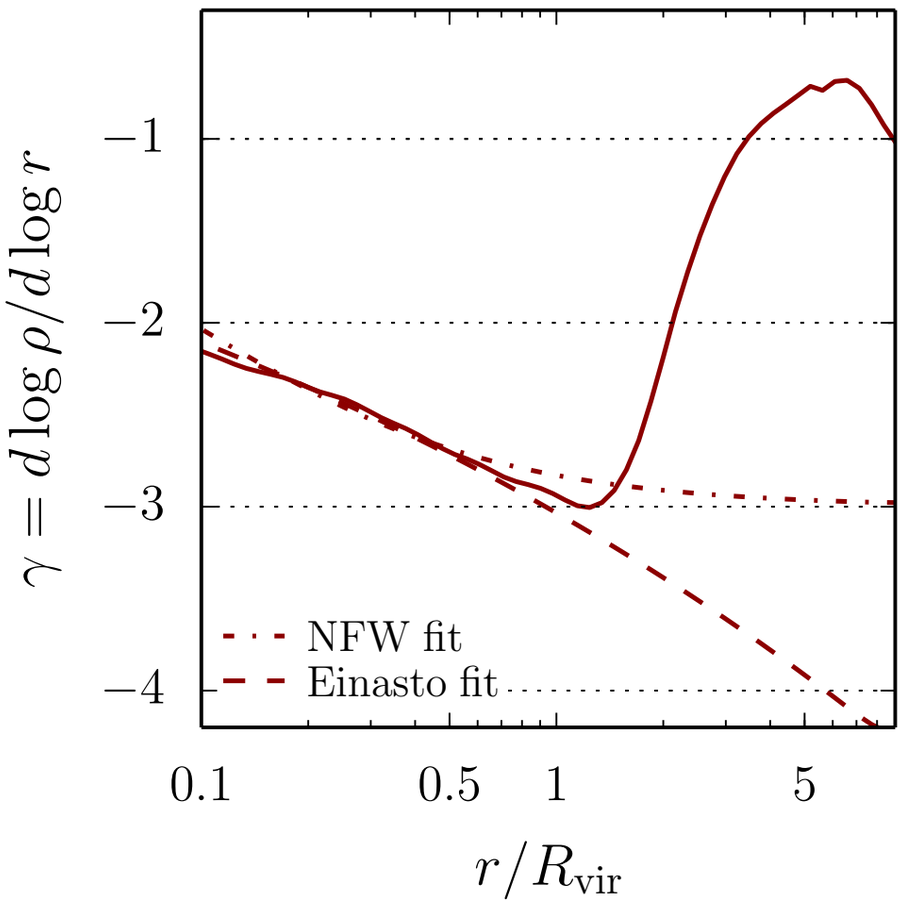
Springel 2005 • Crocce et al. 2006 • Behroozi et al. 2013ab


10^4
10^3
10^2
10^1
10^0
$\rho/\rho_{\rm m}$
0.1
0.5
1
5
$r/R_{\rm 200m}$

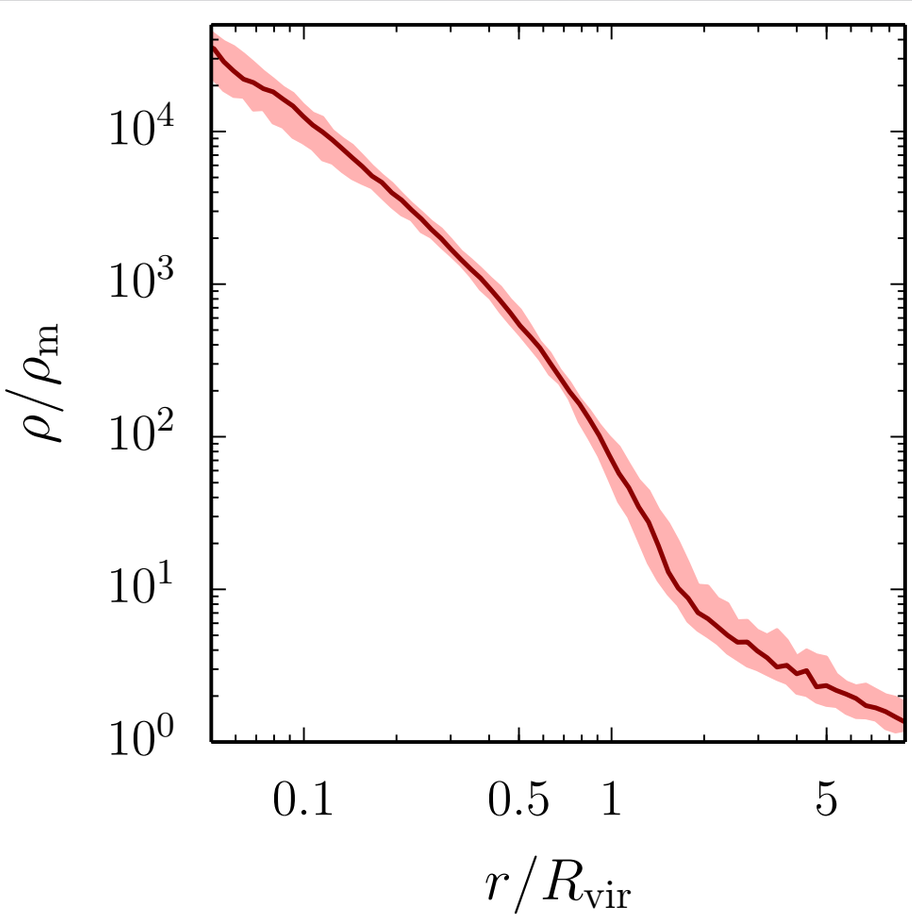
Part I: The outer profile

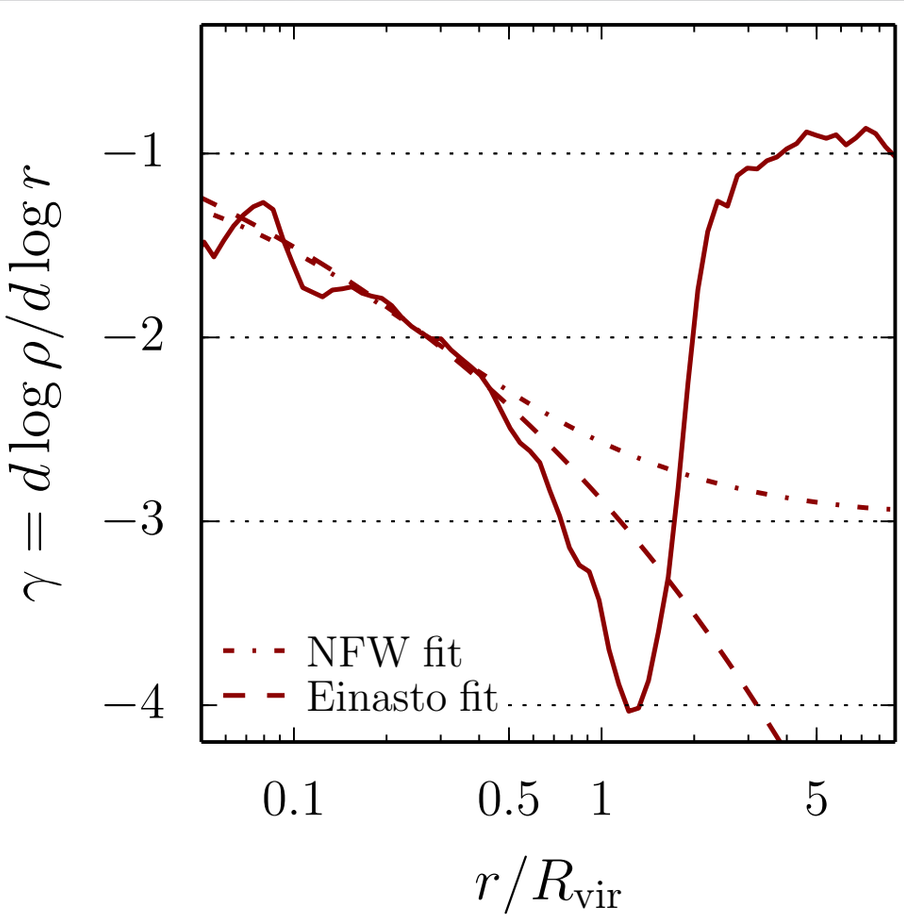
Small halos



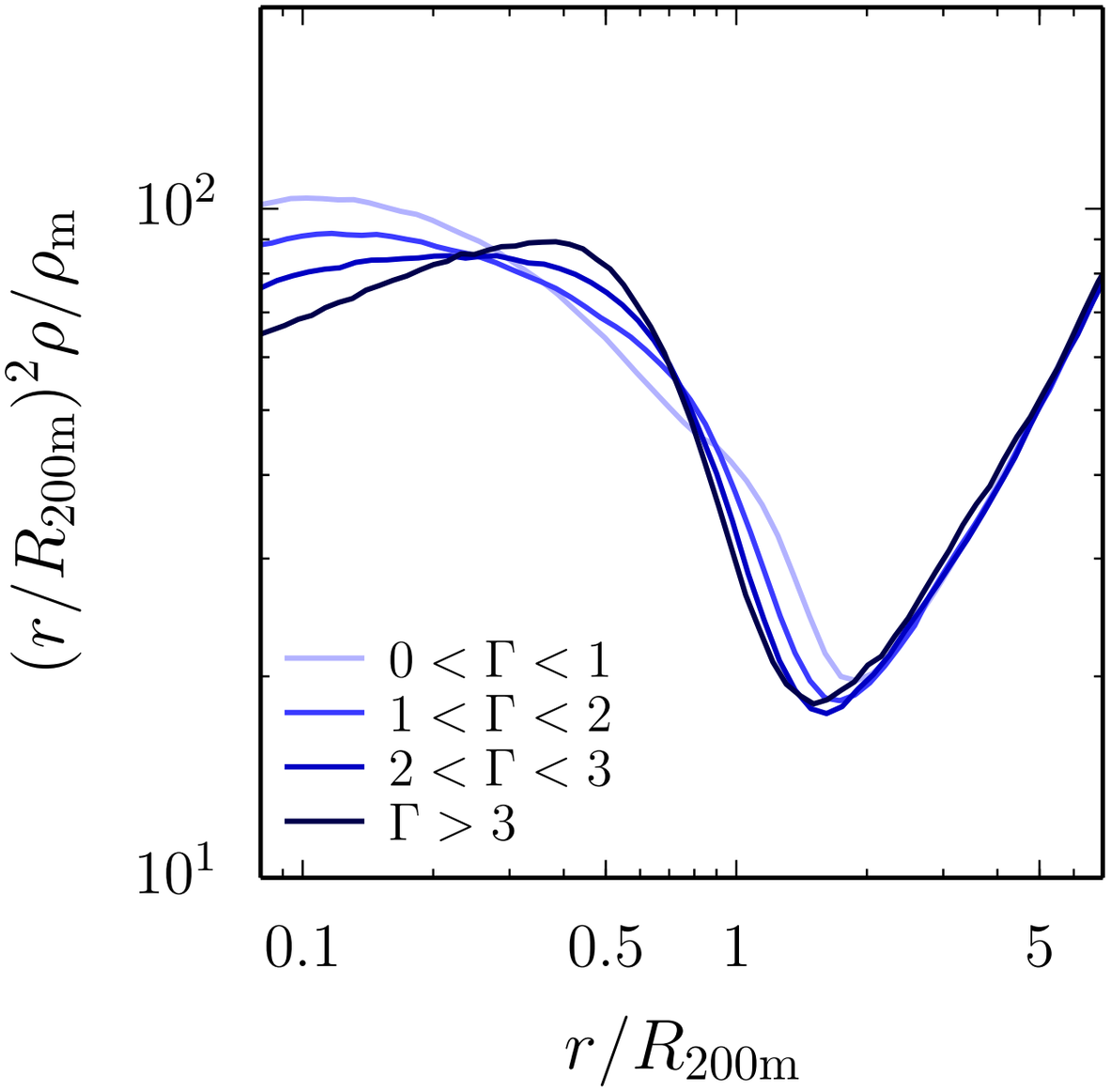


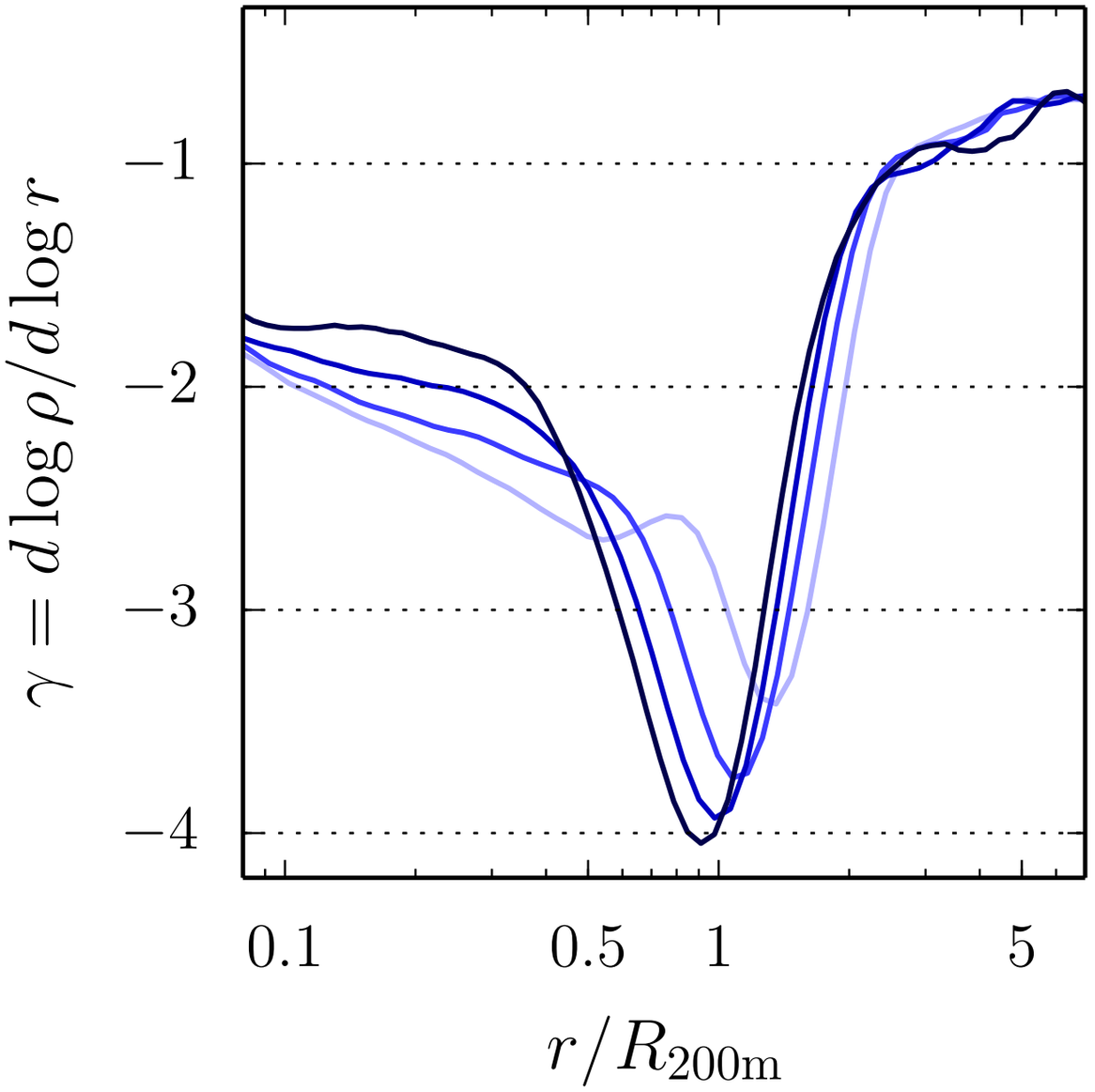
Large halos



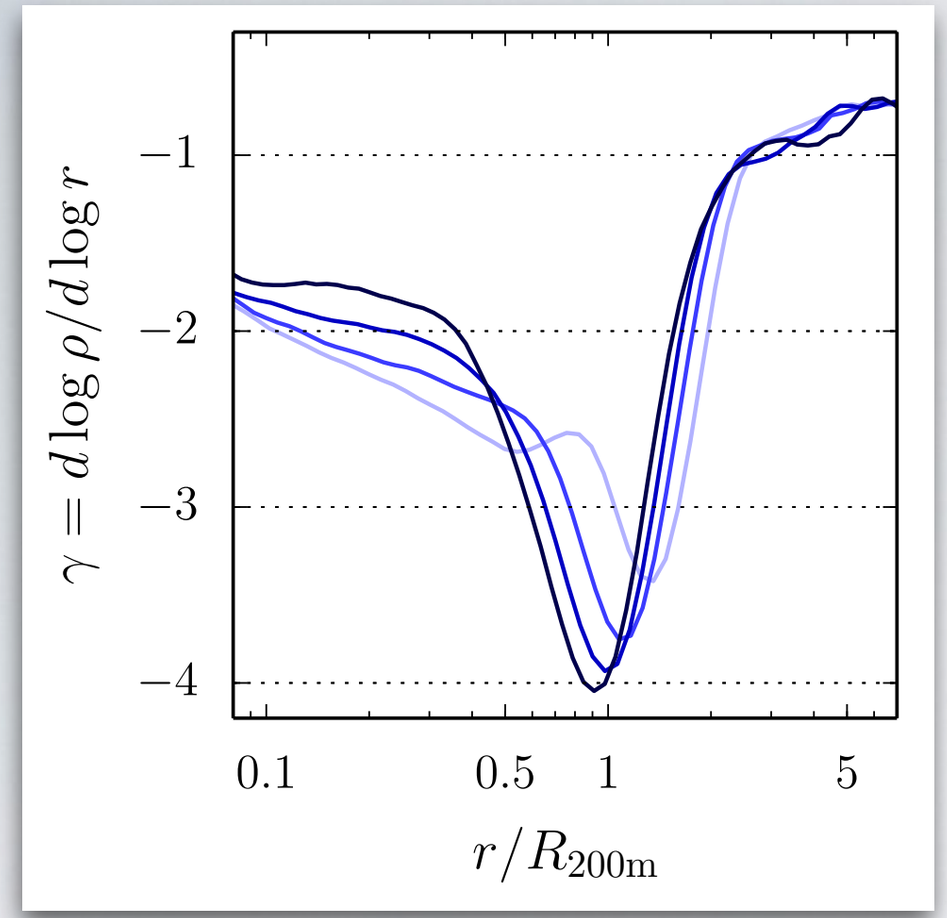


$3 \times 10^{13} < M < 10^{14}$

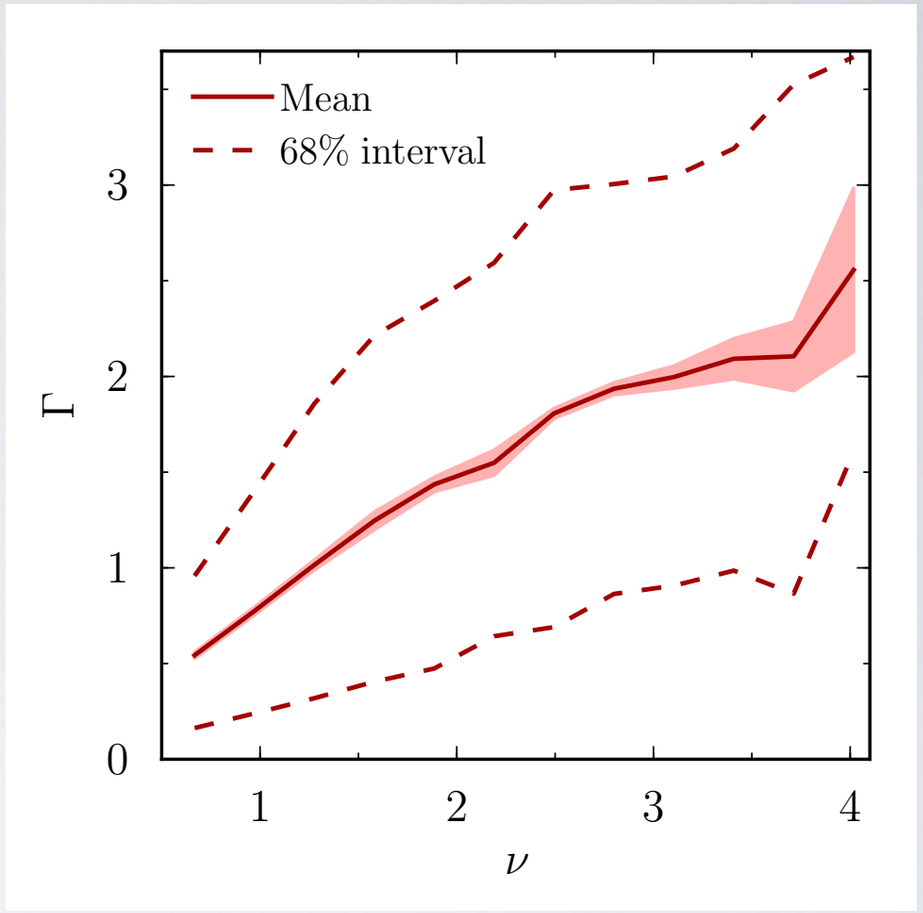




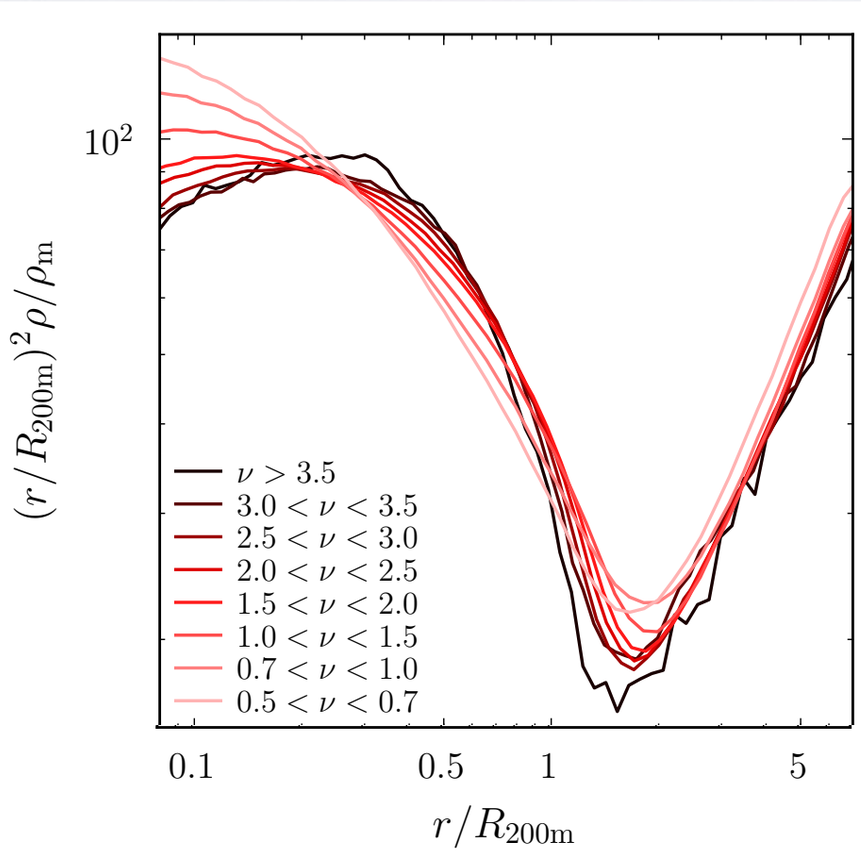
$\Gamma = \Delta \log(M_{vir}) / \Delta \log(a)$

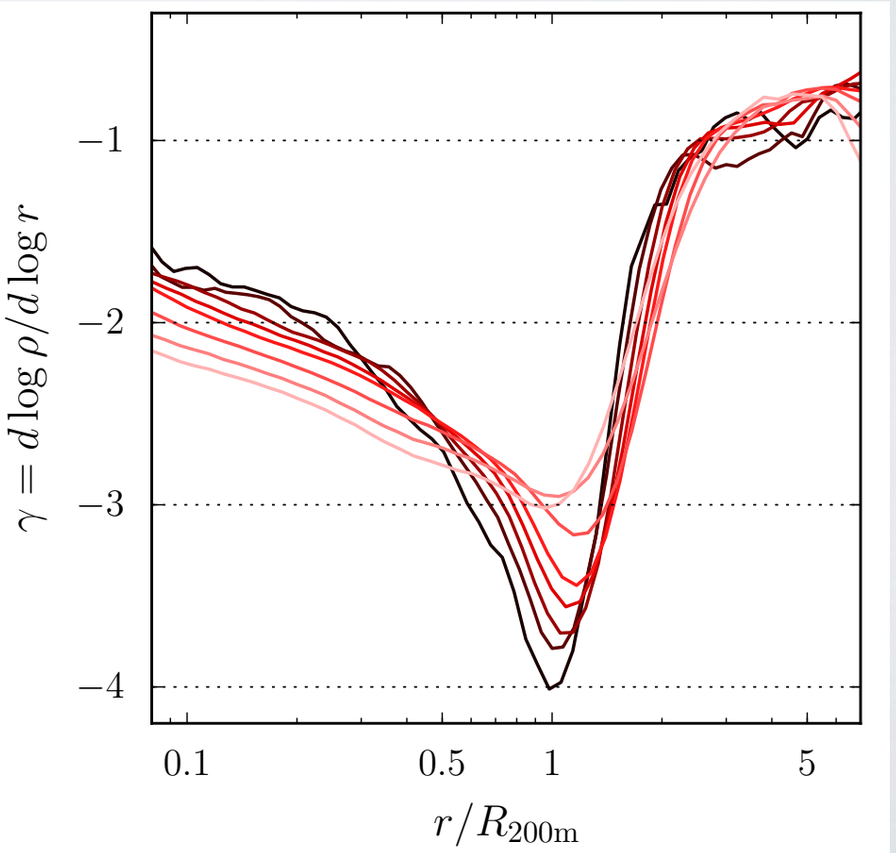

$\gamma = d\log\rho/d\log r$
−1
−2
−3
−4
0.1
0.5
1
5
$r/R_{200\mathrm{m}}$

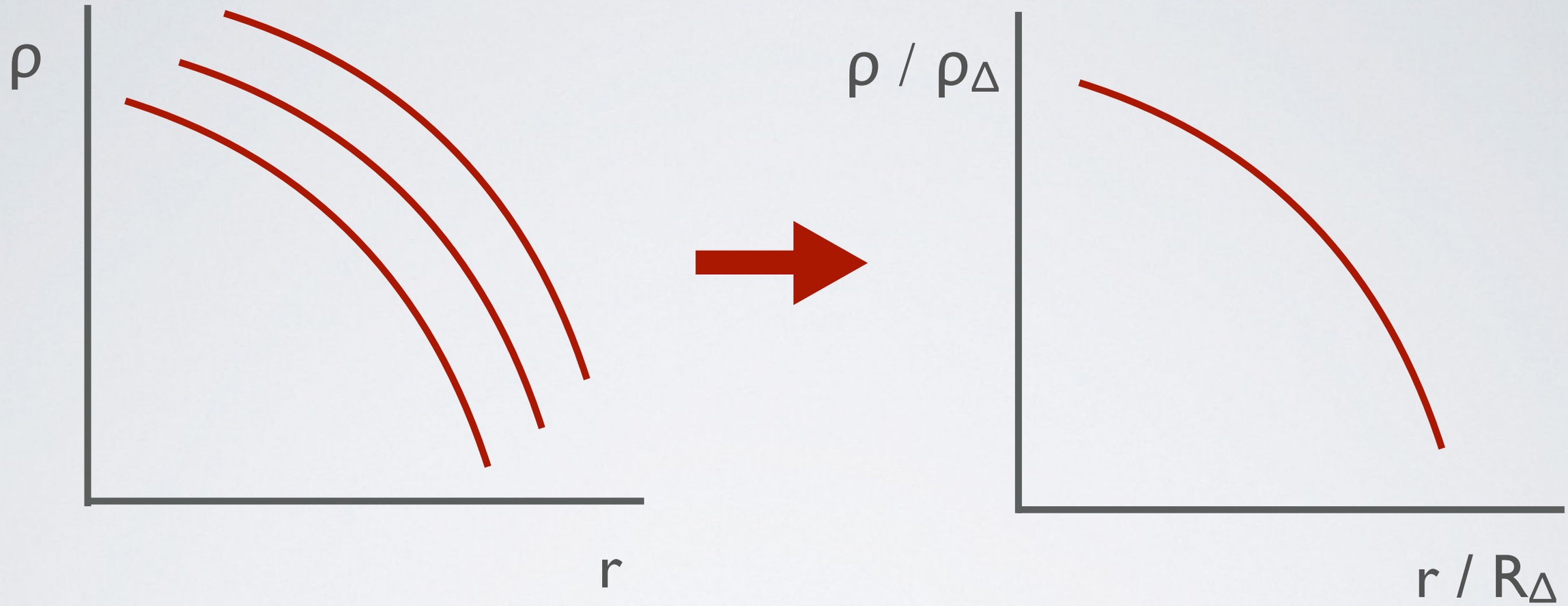
+


Mean
68% interval
Γ
0
1
2
3
1
2
3
4
ν

=


10^2
$(r/R_{200\mathrm{m}})^2\rho/\rho_{\mathrm{m}}$
$\nu > 3.5$
$3.0 < \nu < 3.5$
$2.5 < \nu < 3.0$
$2.0 < \nu < 2.5$
$1.5 < \nu < 2.0$
$1.0 < \nu < 1.5$
$0.7 < \nu < 1.0$
$0.5 < \nu < 0.7$
0.1
0.5
1
5
$r/R_{200\mathrm{m}}$

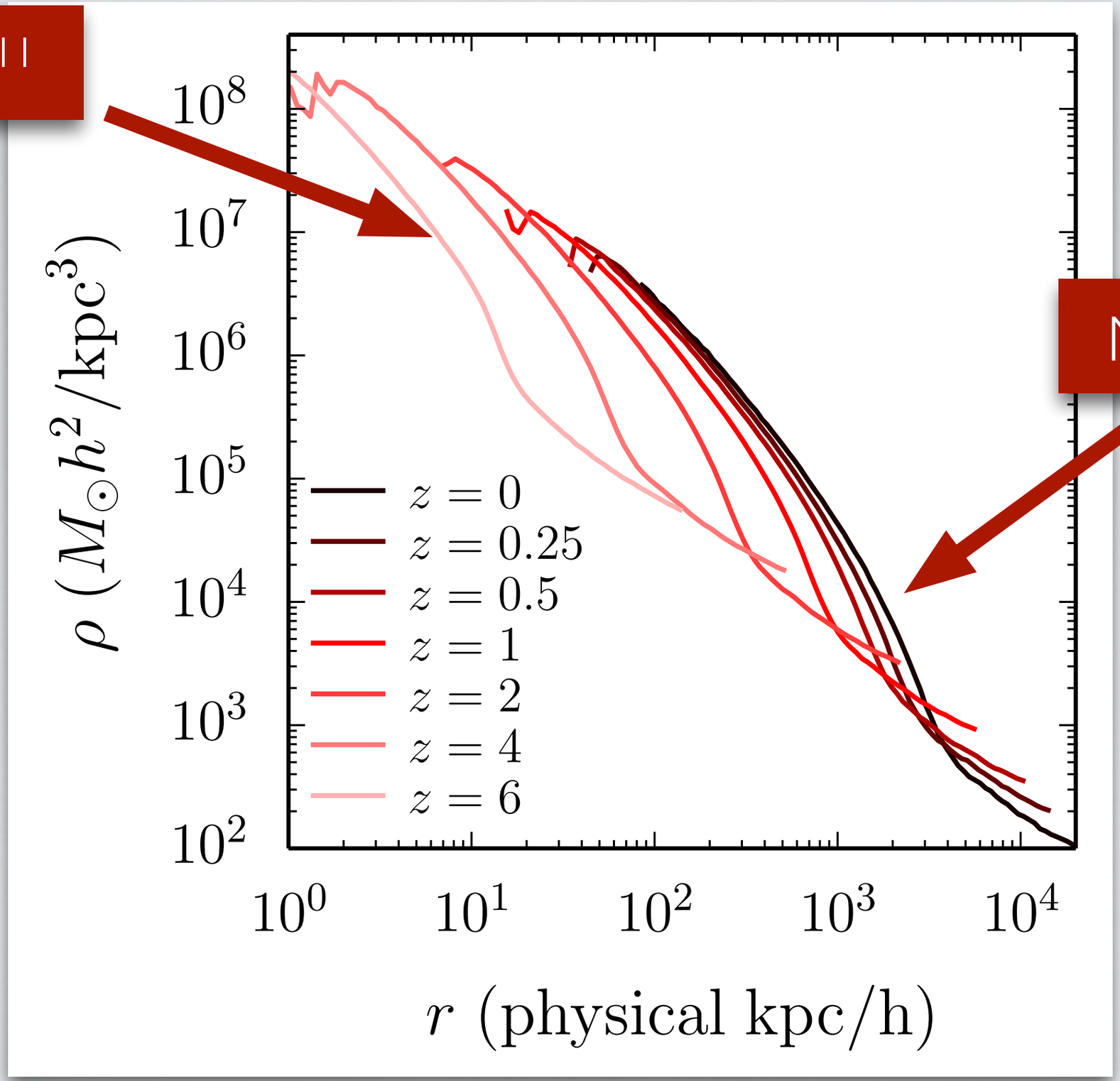

$\gamma = d\log\rho/d\log r$
−1
−2
−3
−4
0.1
0.5
1
5
$r/R_{200\mathrm{m}}$



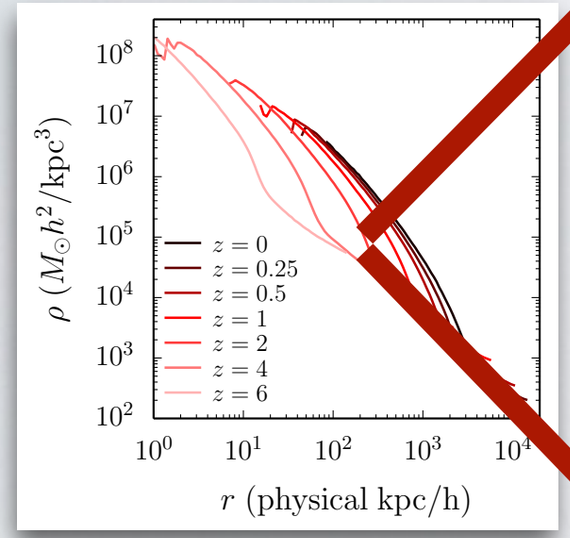
At fixed z, this works for (almost) any R_Δ!

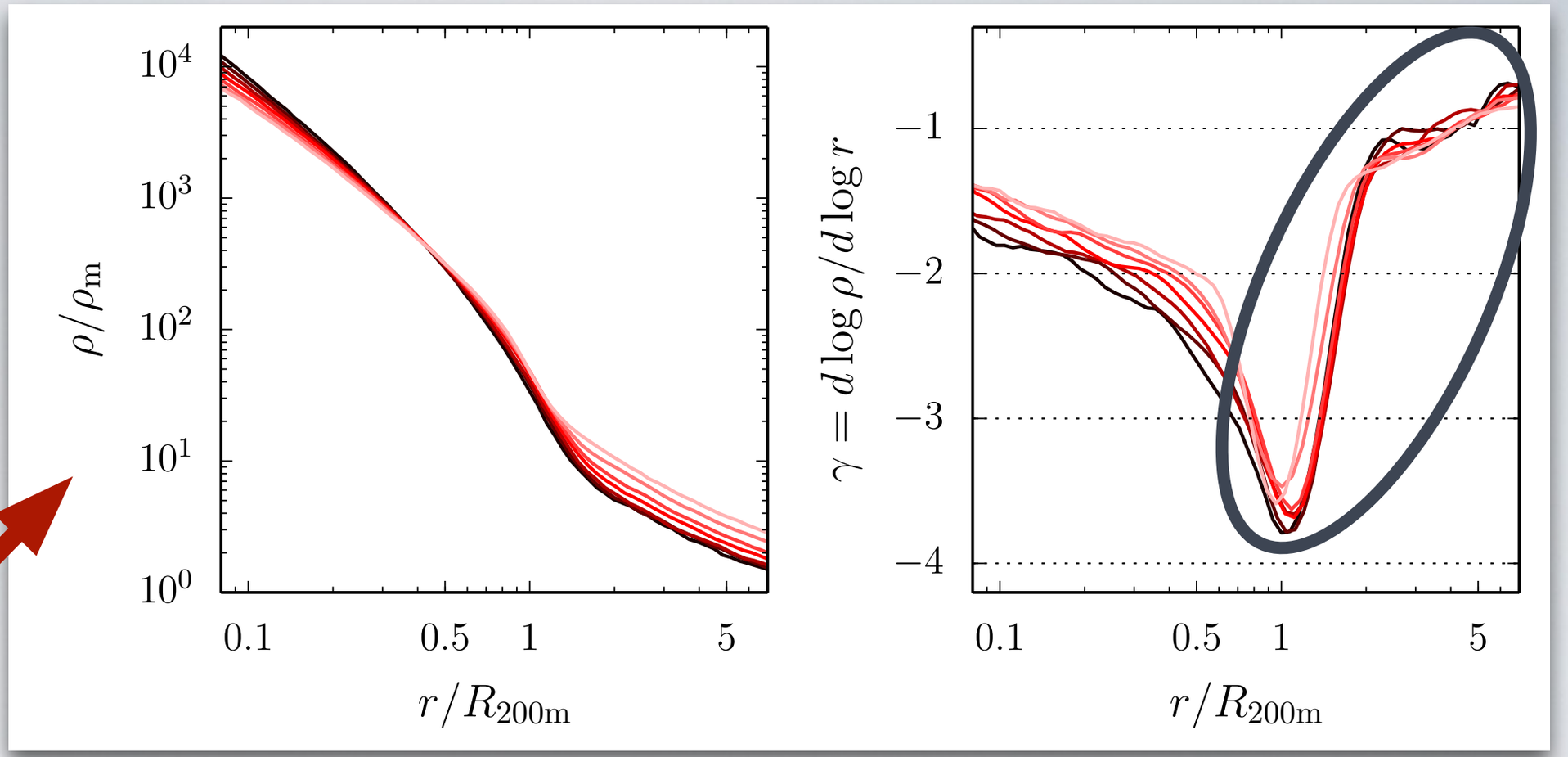
3 - 3.5 σ fluctuations at different z

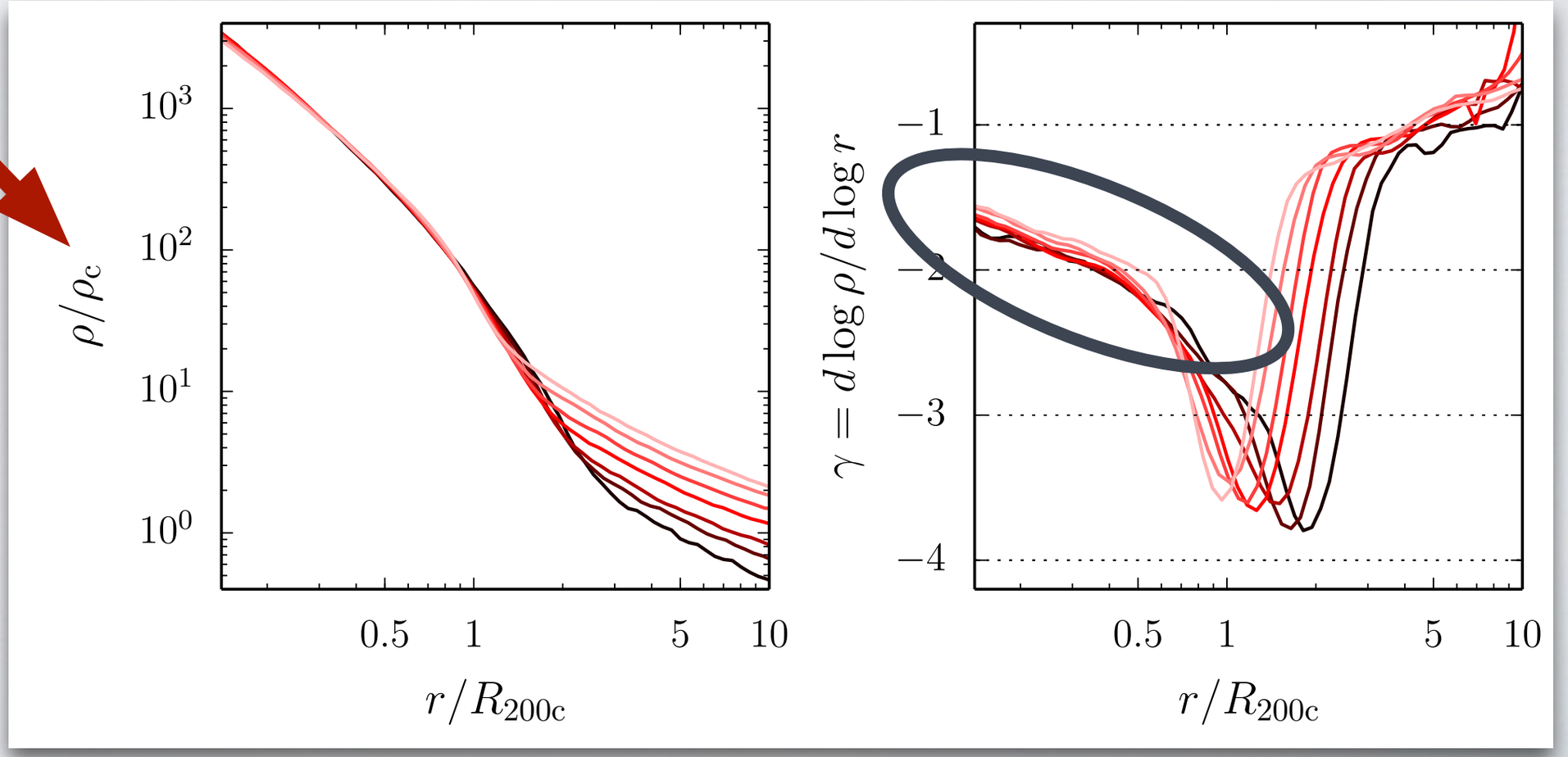
$M \approx 10^{11}$



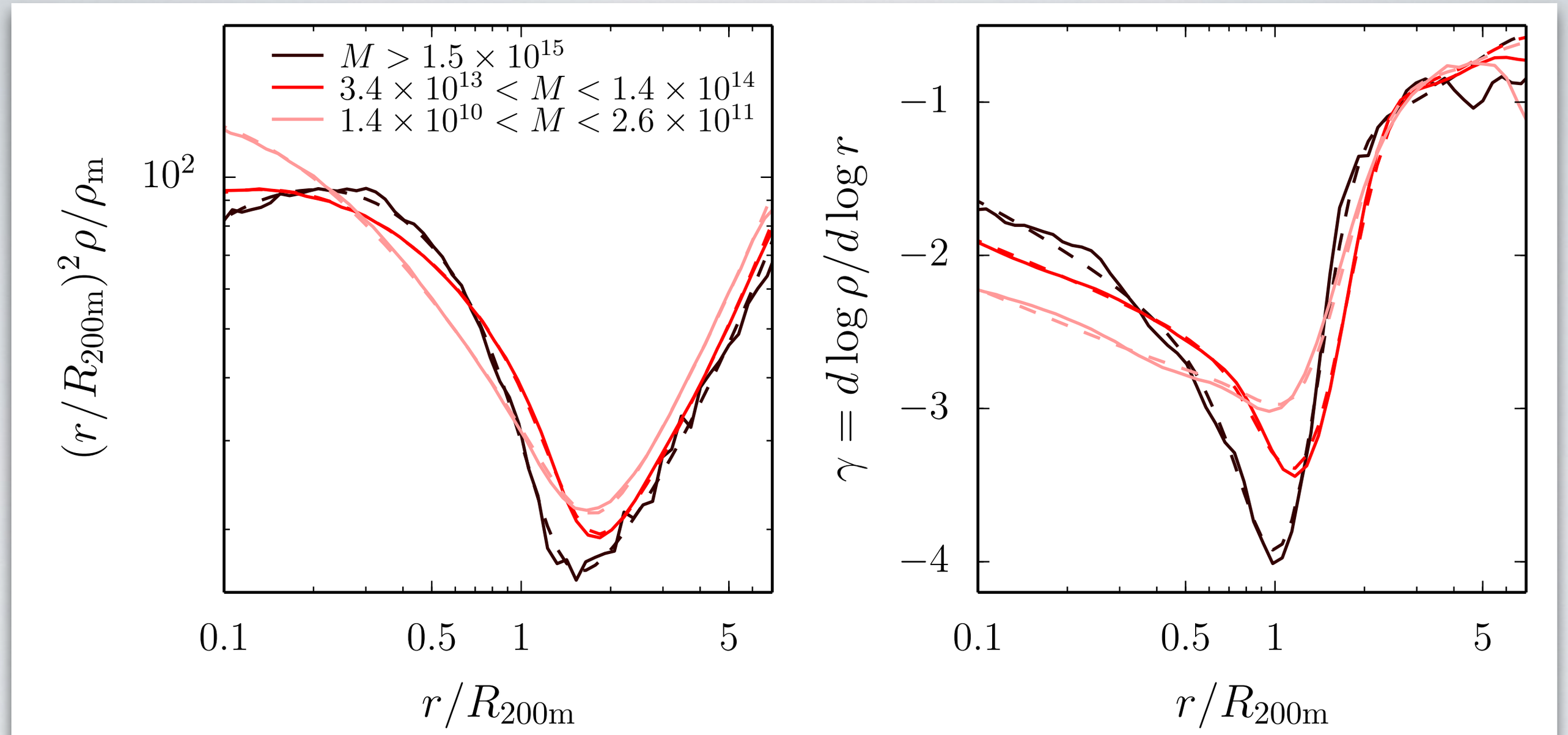
$M \approx 10^{15}$


ρ ($M_\odot h^2$/kpc^3)
r (physical kpc/h)
$z = 0$
$z = 0.25$
$z = 0.5$
$z = 1$
$z = 2$
$z = 4$
$z = 6$


$\rho/\rho_{\rm m}$
$r/R_{\rm 200m}$
$\gamma = d\log\rho/d\log r$
$r/R_{\rm 200m}$

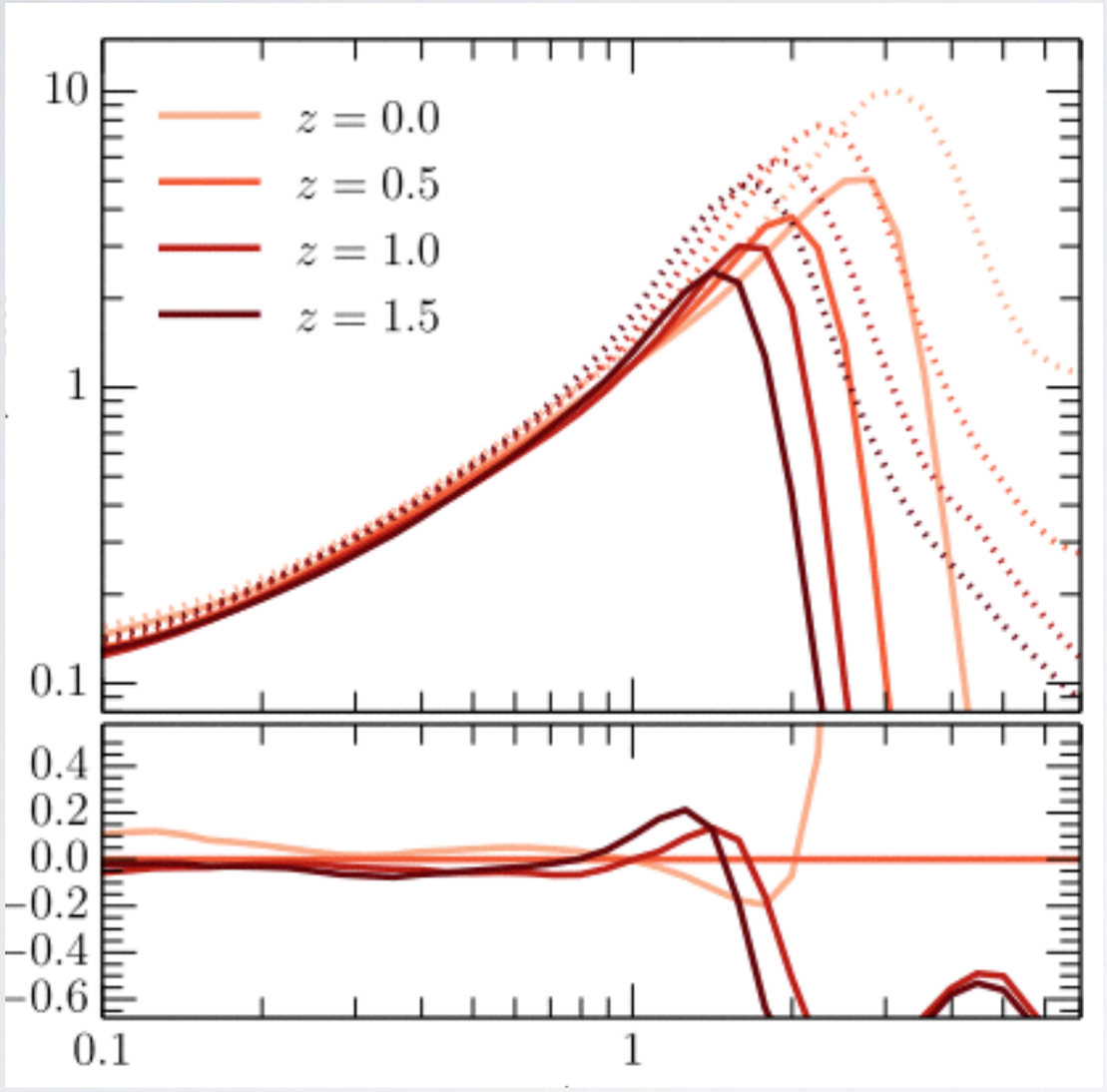

$\rho/\rho_{\rm c}$
$r/R_{\rm 200c}$
$\gamma = d\log\rho/d\log r$
$r/R_{\rm 200c}$

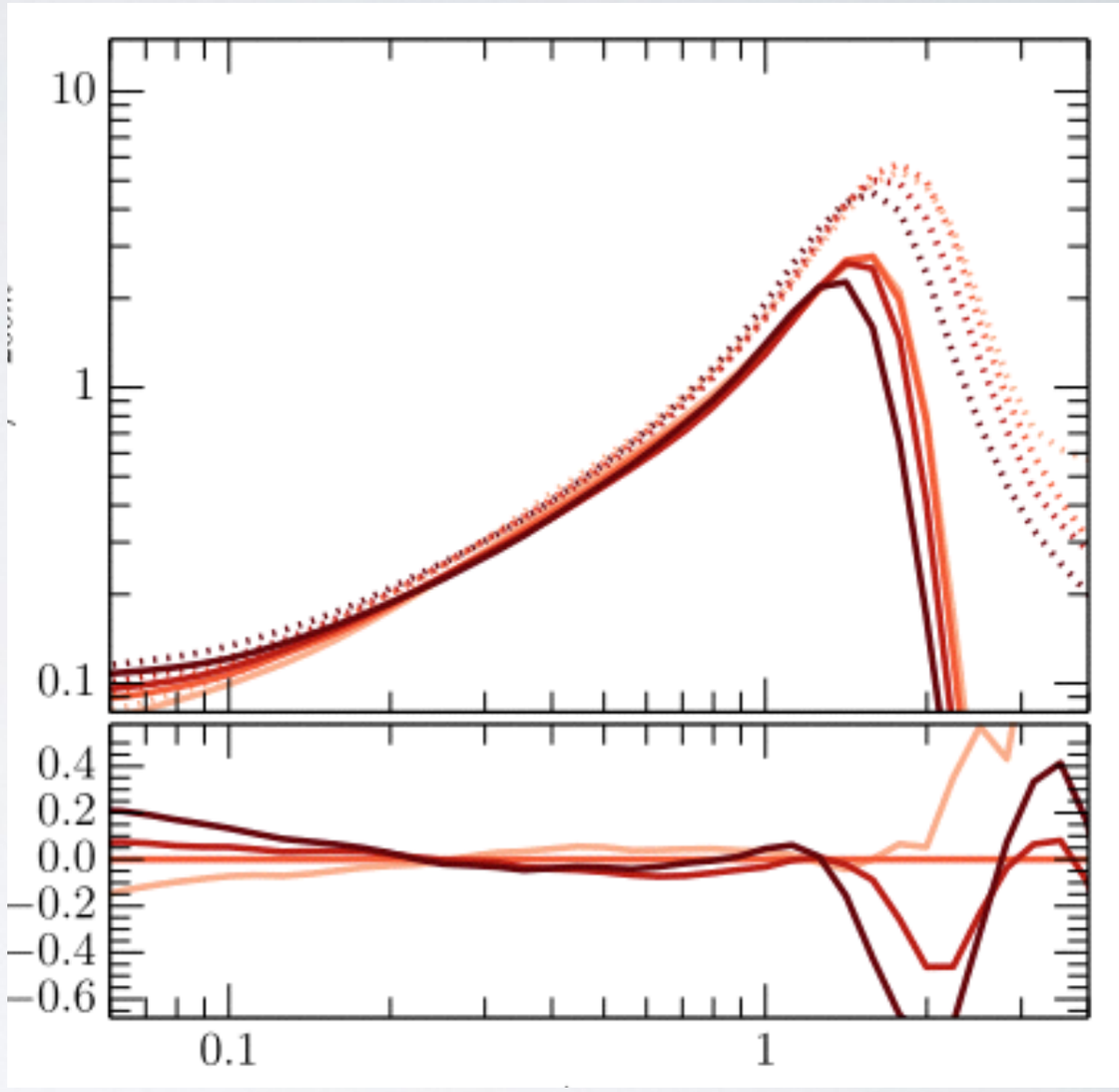
New fitting function



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

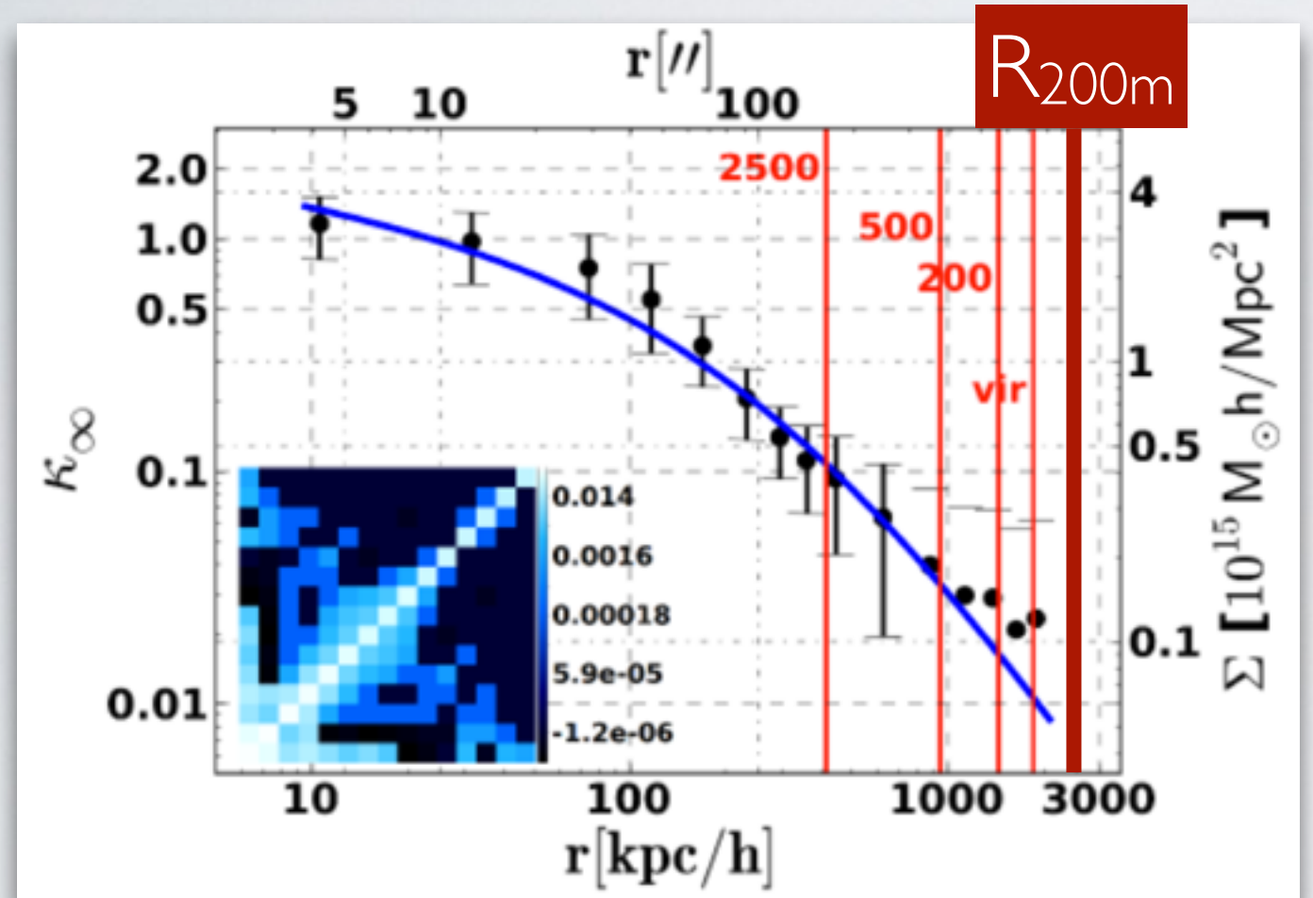
Gas profiles (entropy)

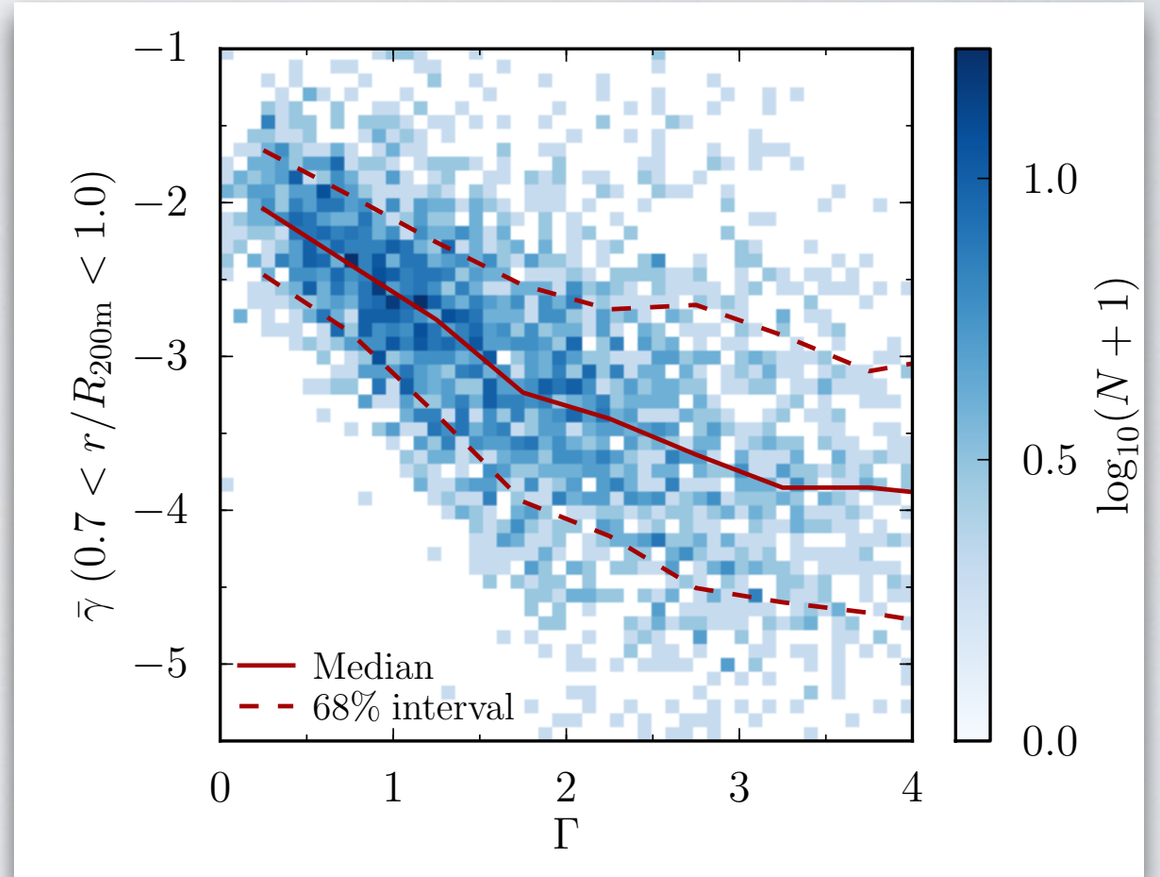




Lau et al. 2014

Is the steepening observable?





CLASH (Merten et al. 2014)

Conclusions (outer profiles)

- The dark matter density profiles of halos are not universal, they depend on the mass accretion rate.

- At large radii, the NFW and Einasto profiles are not good descriptions of the profiles.

- Radii defined wrt. the mean density of the universe are preferred for describing the outer density profiles.

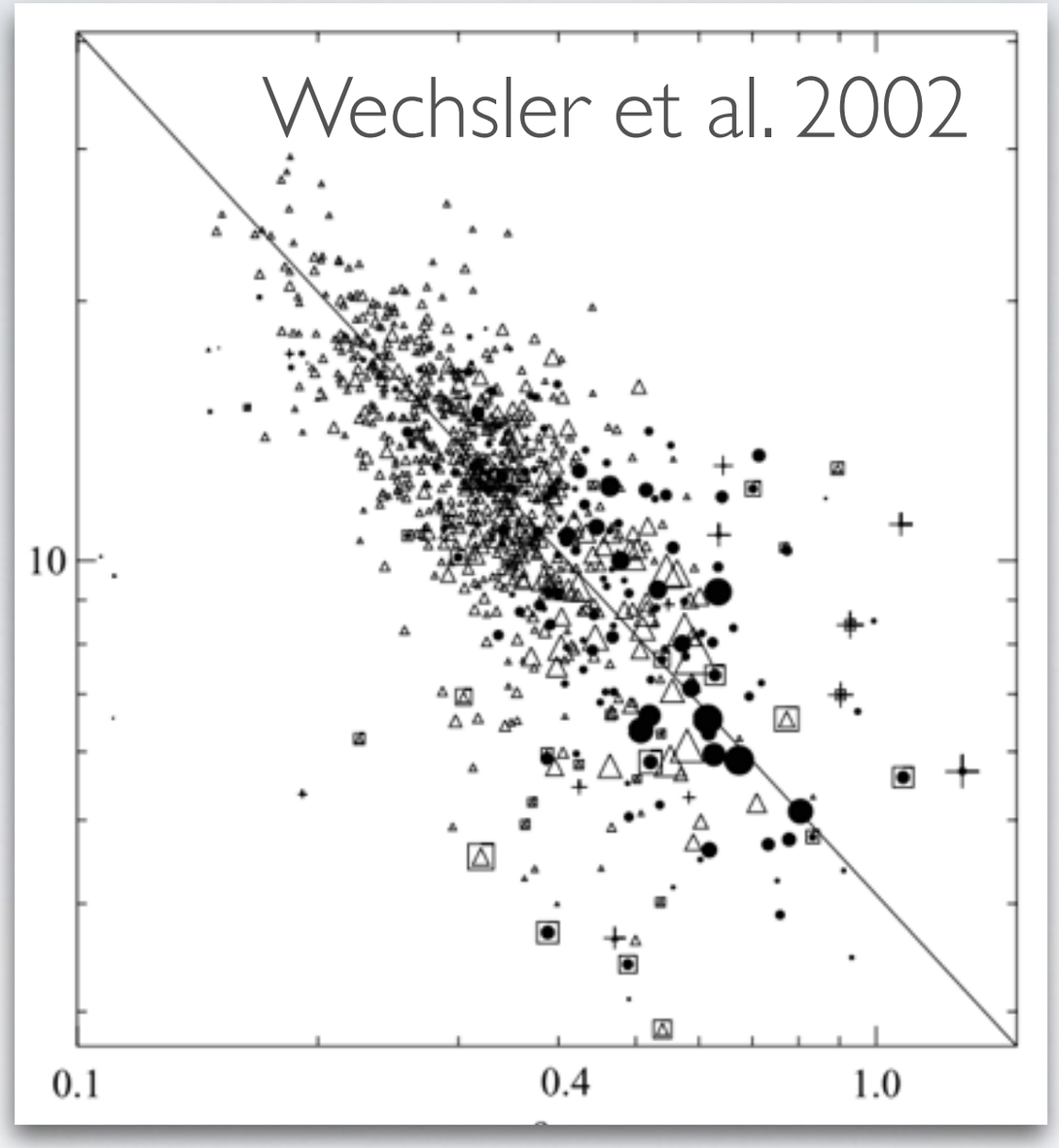
Diemer & Kravtsov 2014 • ApJ 789, 1 • arXiv 1401.1216

Part II: The inner profile & concentration

c-M models

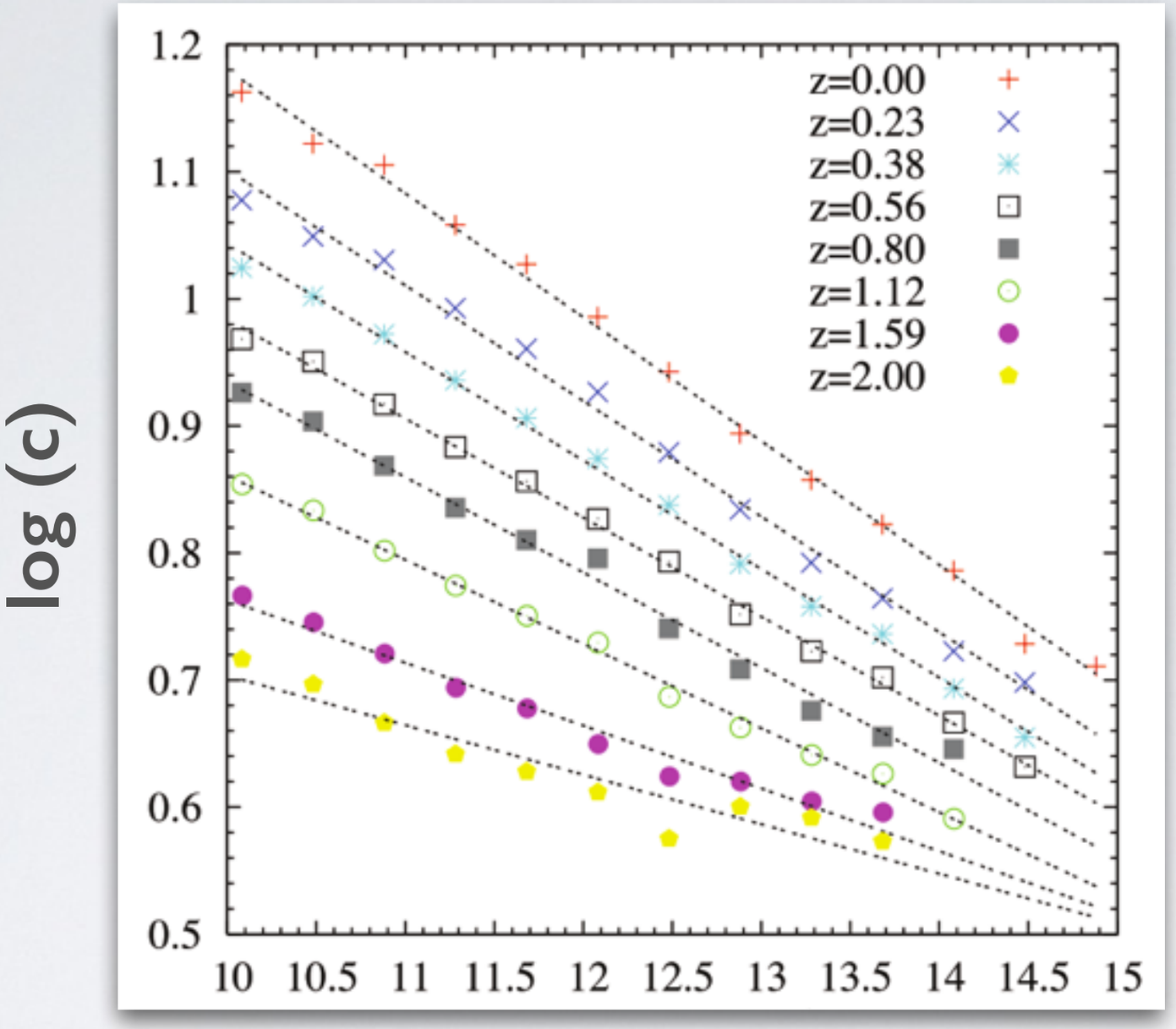
Navarro et al. 1996
Navarro et al. 1997
Avila-Reese et al. 1999
Jing 2000
Bullock et al. 2001
Eke et al. 2001
Wechsler et al. 2002
Zhao et al. 2003
Colin et al. 2004
Dolag et al. 2004
Neto et al. 2007
Duffy et al. 2008
Maccio et al. 2008
Gao et al. 2008
Zhao et al. 2009
Klypin et al. 2011
Munoz-Cuartas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

MAH-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. 2013

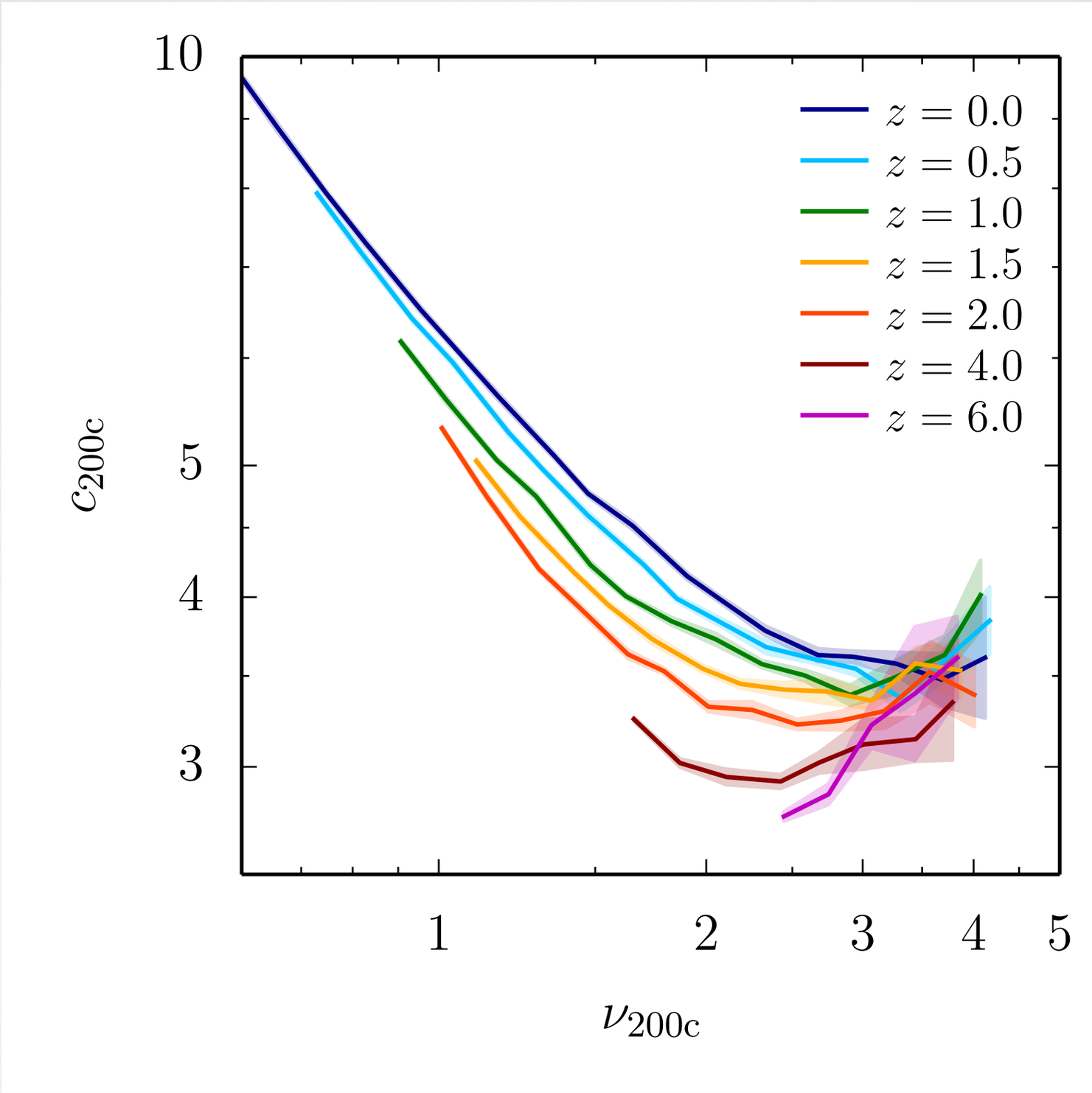
Power-law fits

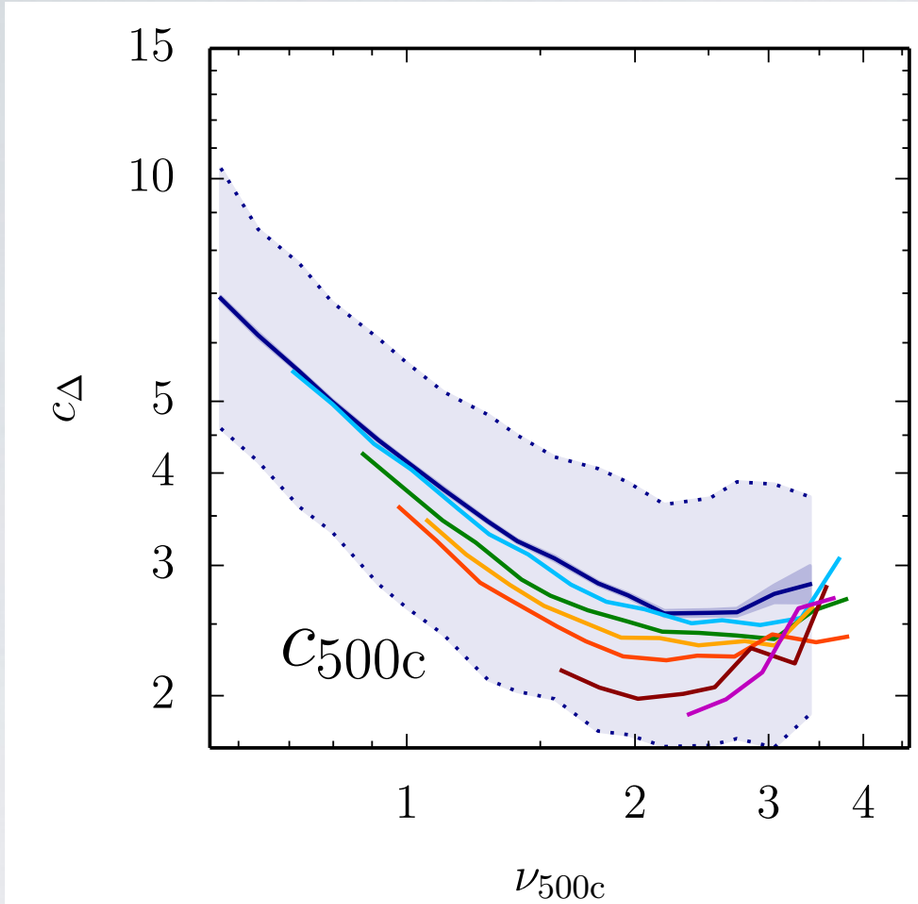


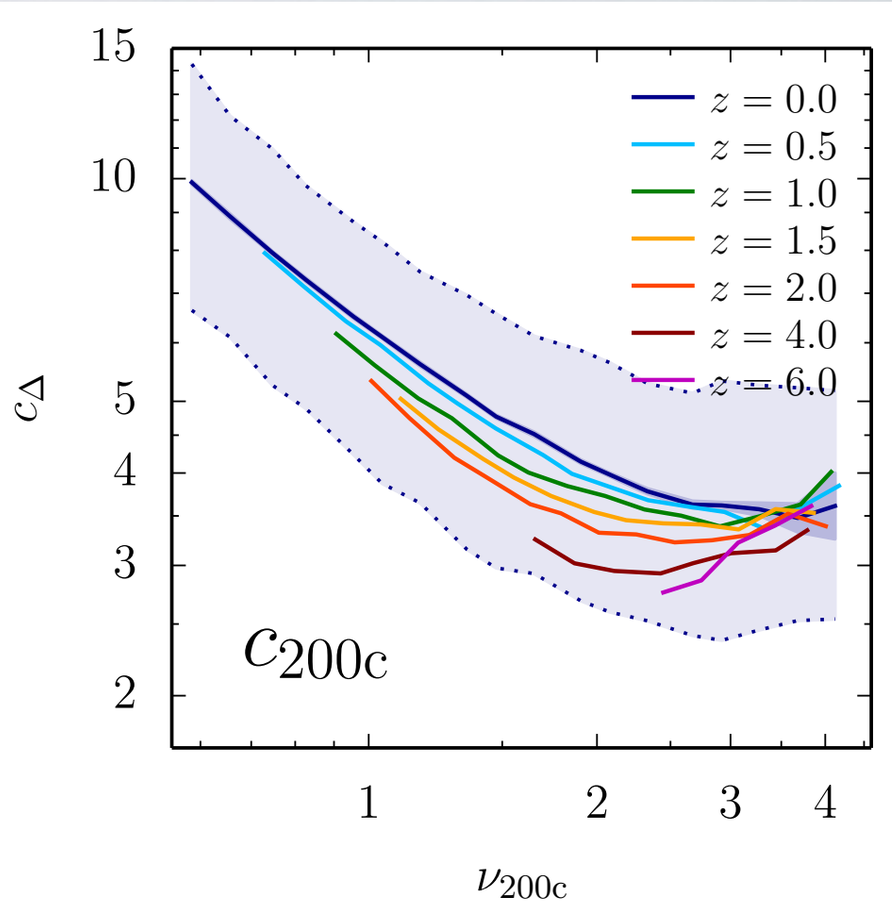
Munoz-Cuartas et al. 2011

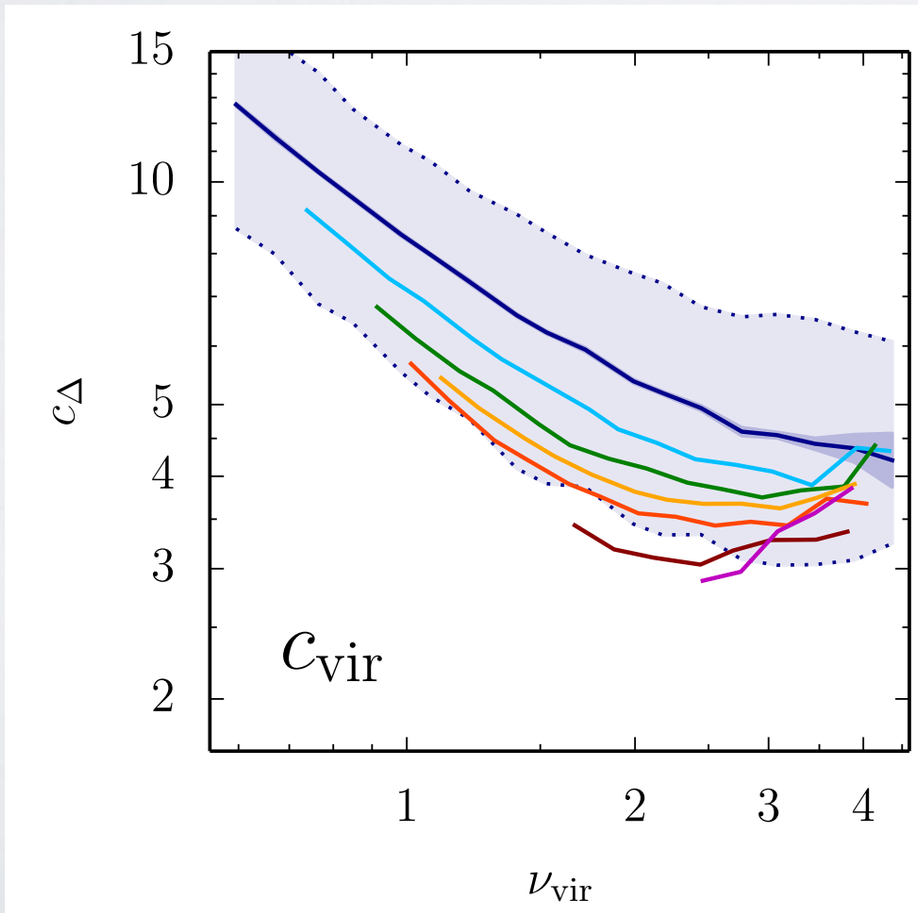
Avila-Reese et al. 1999 • Jing 2000 • Neto et al. 2007 • Duffy et al. 2008 • Maccio et al. 2008
Gao et al. 2008 • Klypin et al. 2011 • Munoz-Cuartas et al. 2011 • Dutton et al. 2014

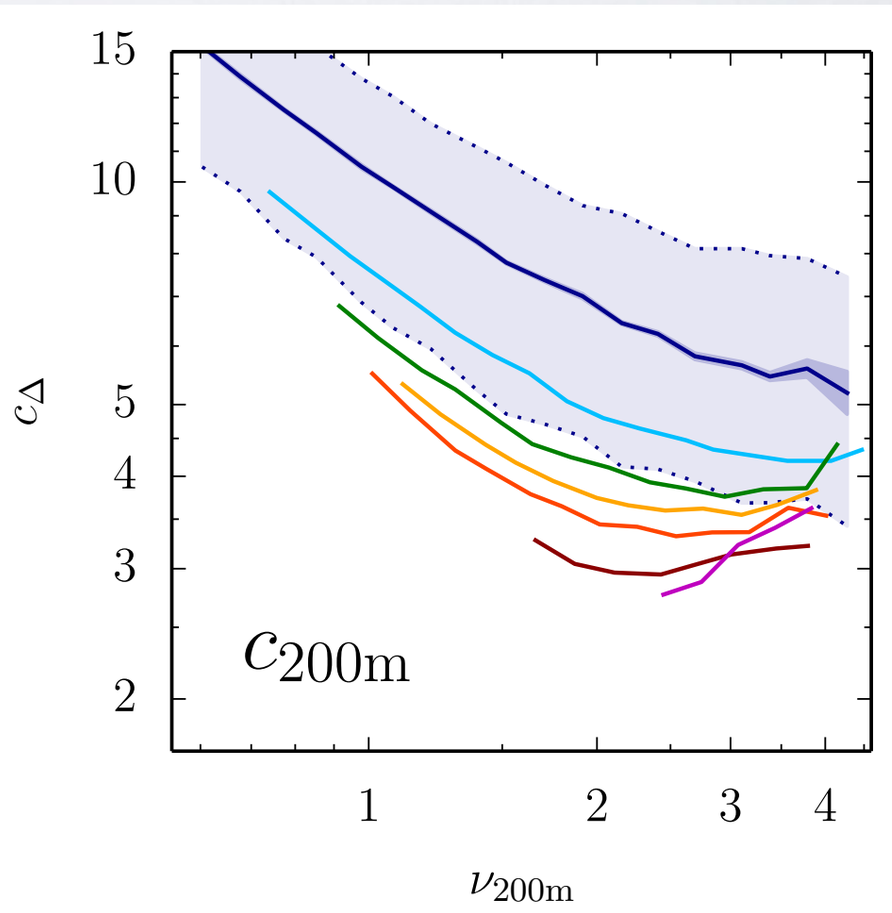
Concentration-peak height relation




15
10
5
4
3
2
c_Δ
1
2
3
4
ν_{500c}
c_{500c}

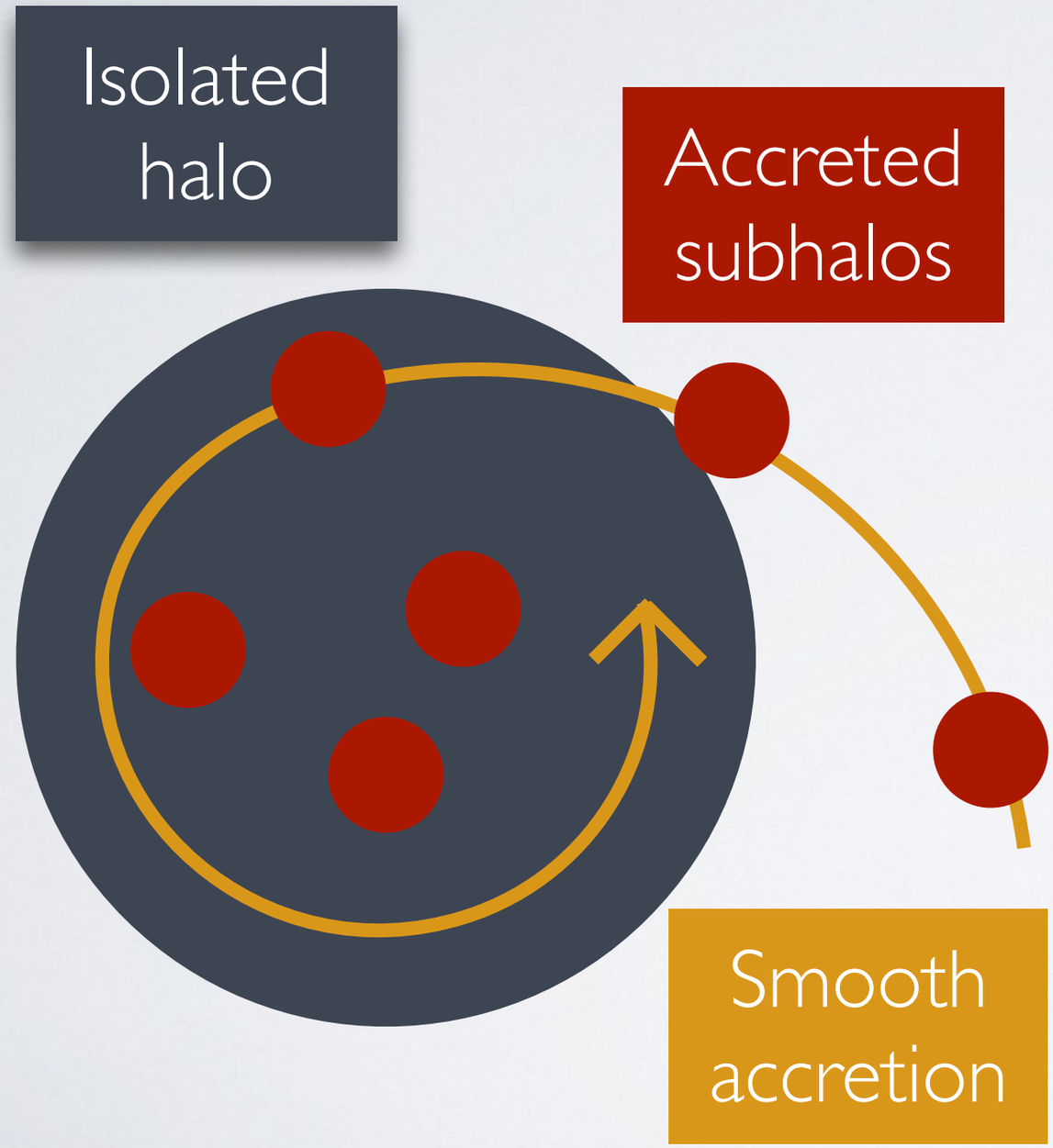

15
10
5
4
3
2
c_Δ
1
2
3
4
ν_{200c}
c_{200c}
$z = 0.0$
$z = 0.5$
$z = 1.0$
$z = 1.5$
$z = 2.0$
$z = 4.0$
$z = 6.0$


15
10
5
4
3
2
c_Δ
1
2
3
4
$\nu_{\rm vir}$
$c_{\rm vir}$

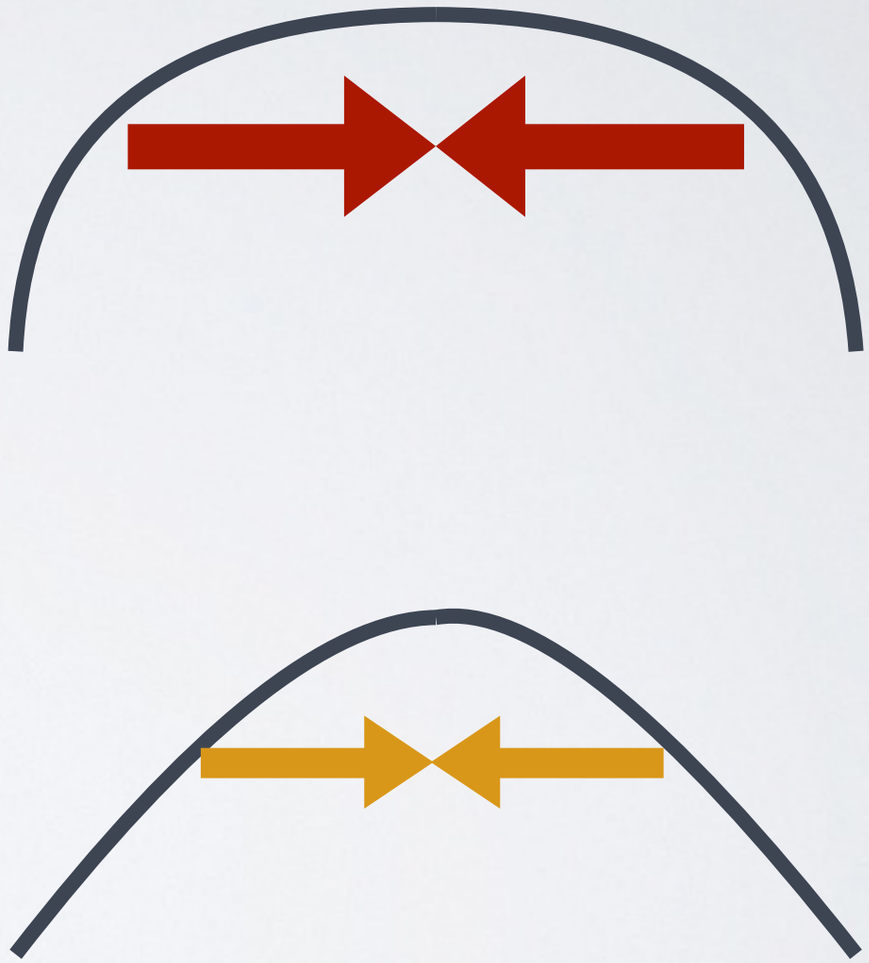

15
10
5
4
3
2
c_Δ
1
2
3
4
ν_{200m}
c_{200m}

Effects of power spectrum slope

Substructure



Peak shape



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

n = -2.5

n = -2

n = -1.5

n = -1

3

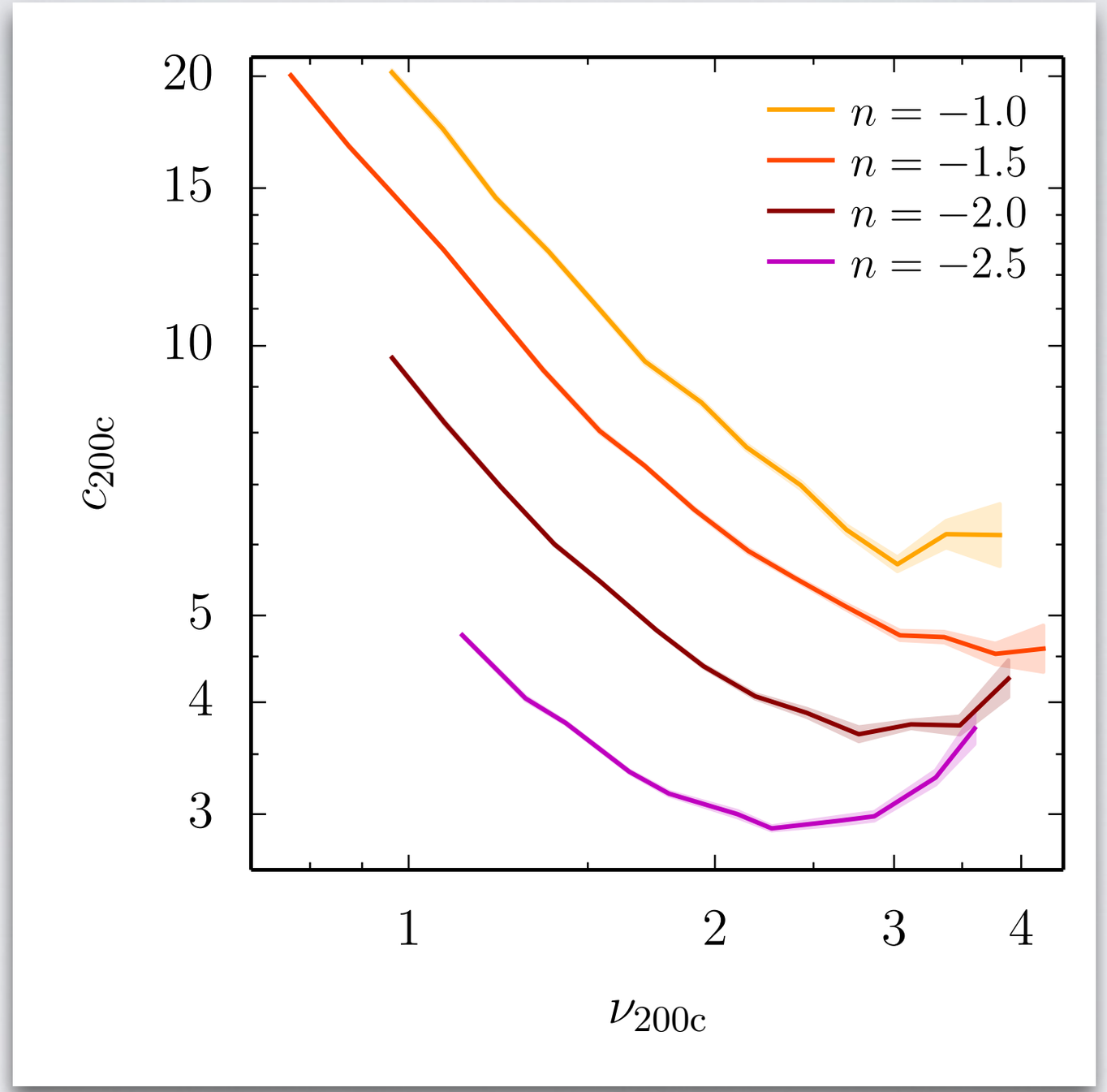
2

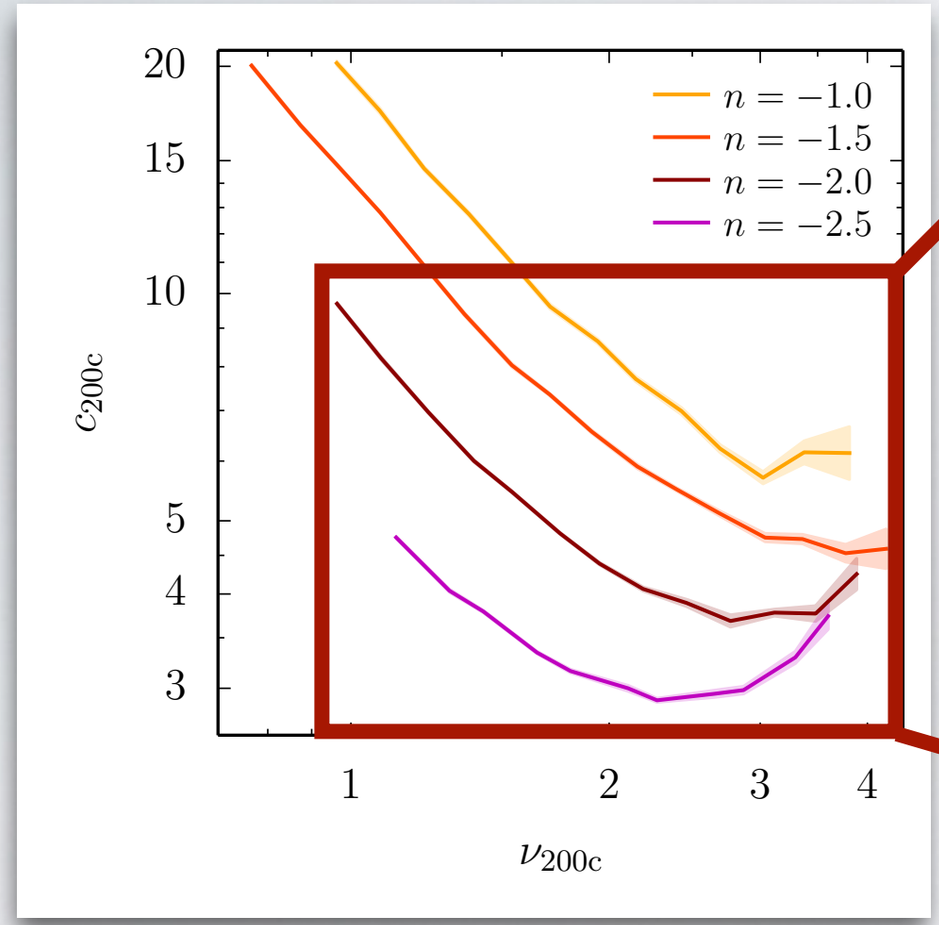
1

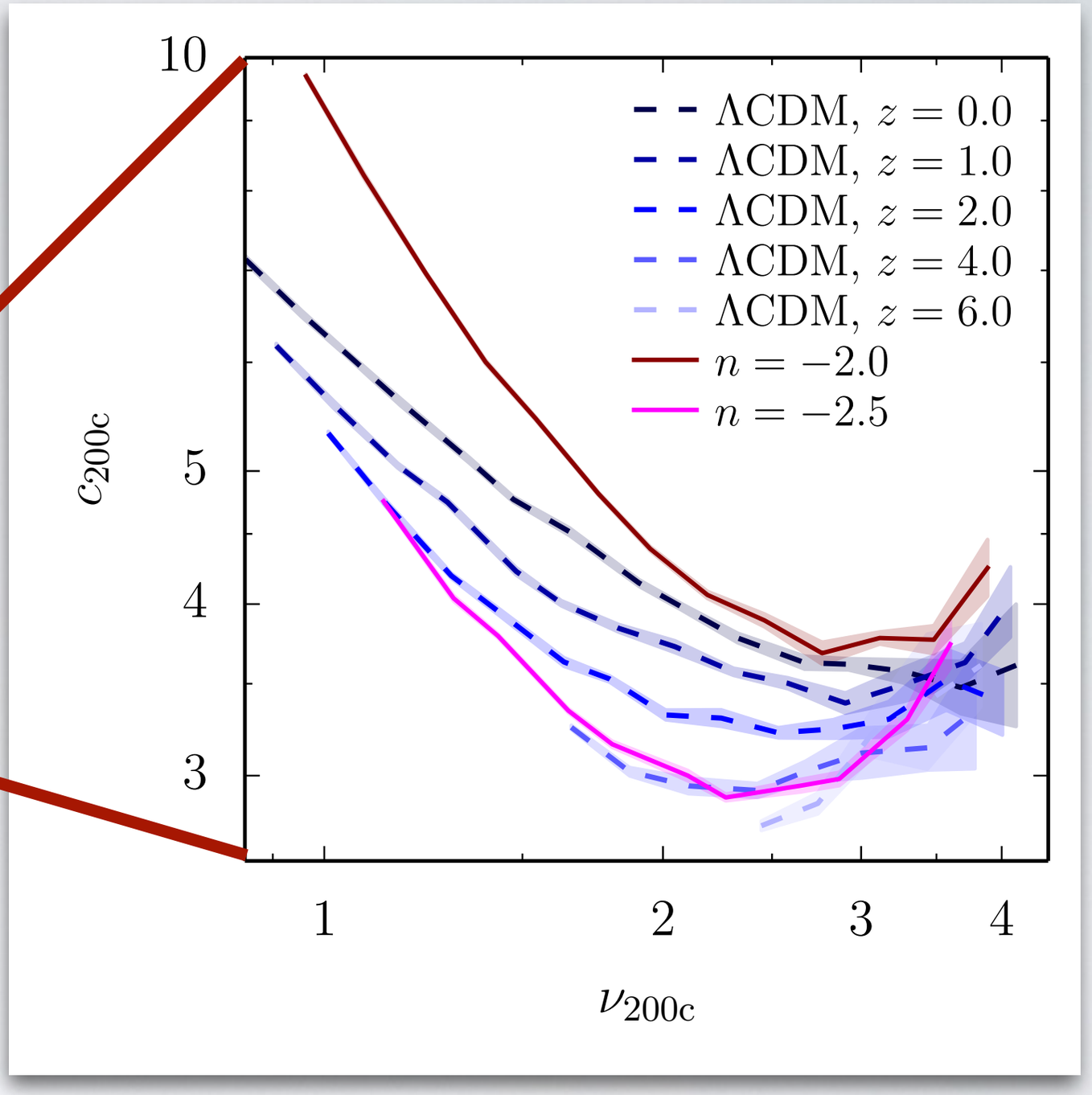
0

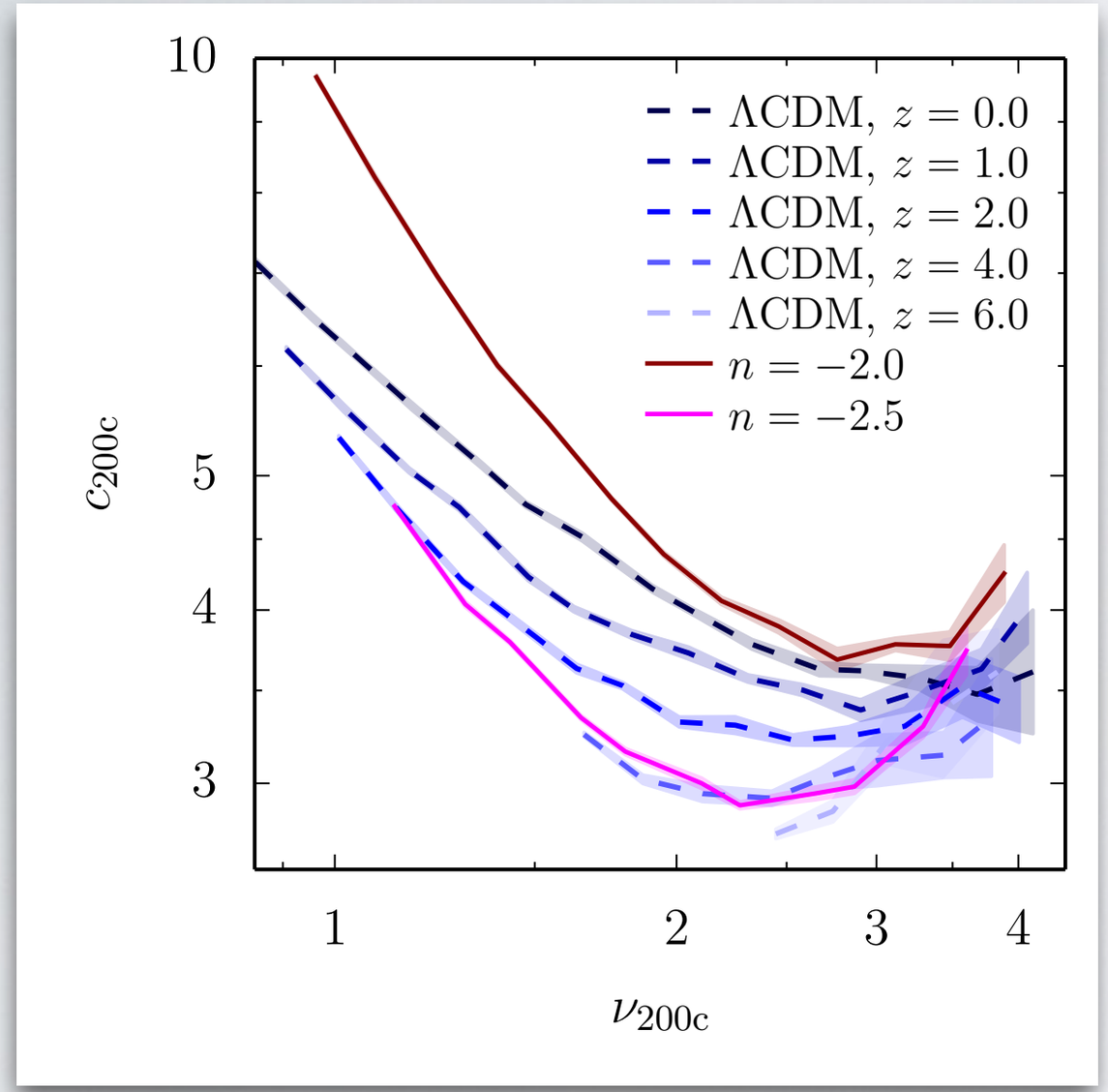
−1

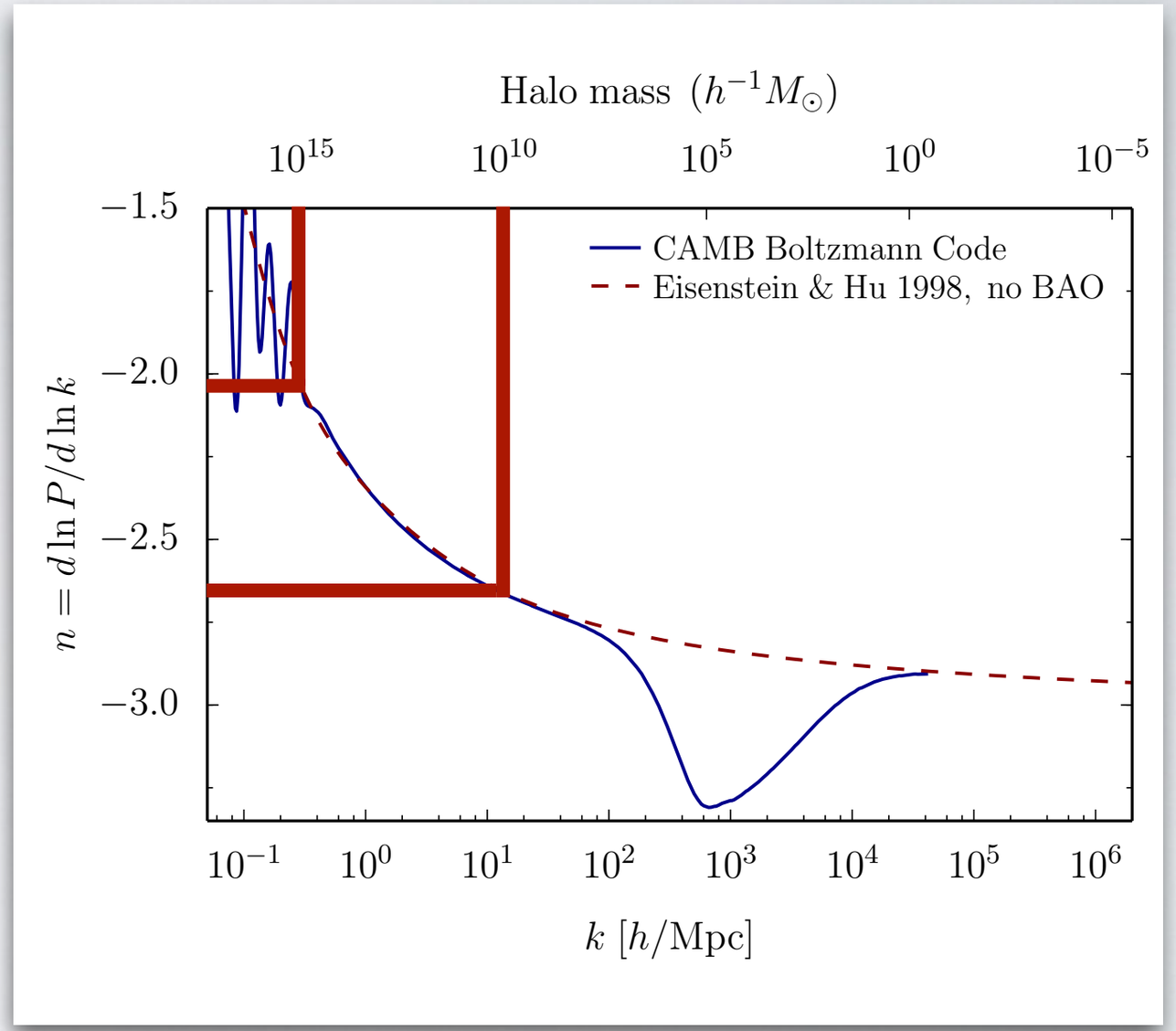
$\log_{10}(\rho/\rho_{\rm m})$


20
15
10
5
4
3
1
2
3
4
c_{200c}
ν_{200c}
$n = -1.0$
$n = -1.5$
$n = -2.0$
$n = -2.5$


20
15
10
5
4
3
c_{200c}
1
2
3
4
ν_{200c}
$n = -1.0$
$n = -1.5$
$n = -2.0$
$n = -2.5$


10
5
4
3
c_{200c}
1
2
3
4
ν_{200c}
ΛCDM, $z = 0.0$
ΛCDM, $z = 1.0$
ΛCDM, $z = 2.0$
ΛCDM, $z = 4.0$
ΛCDM, $z = 6.0$
$n = -2.0$
$n = -2.5$


10
5
4
3
c_{200c}
1
2
3
4
ν_{200c}
ΛCDM, $z = 0.0$
ΛCDM, $z = 1.0$
ΛCDM, $z = 2.0$
ΛCDM, $z = 4.0$
ΛCDM, $z = 6.0$
$n = -2.0$
$n = -2.5$


Halo mass $(h^{-1}M_\odot)$
10^{15}
10^{10}
10^5
10^0
10^{-5}
-1.5
-2.0
-2.5
-3.0
$n = d\ln P/d\ln k$
CAMB Boltzmann Code
Eisenstein & Hu 1998, no BAO
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
k $[h/\mathrm{Mpc}]$

The model

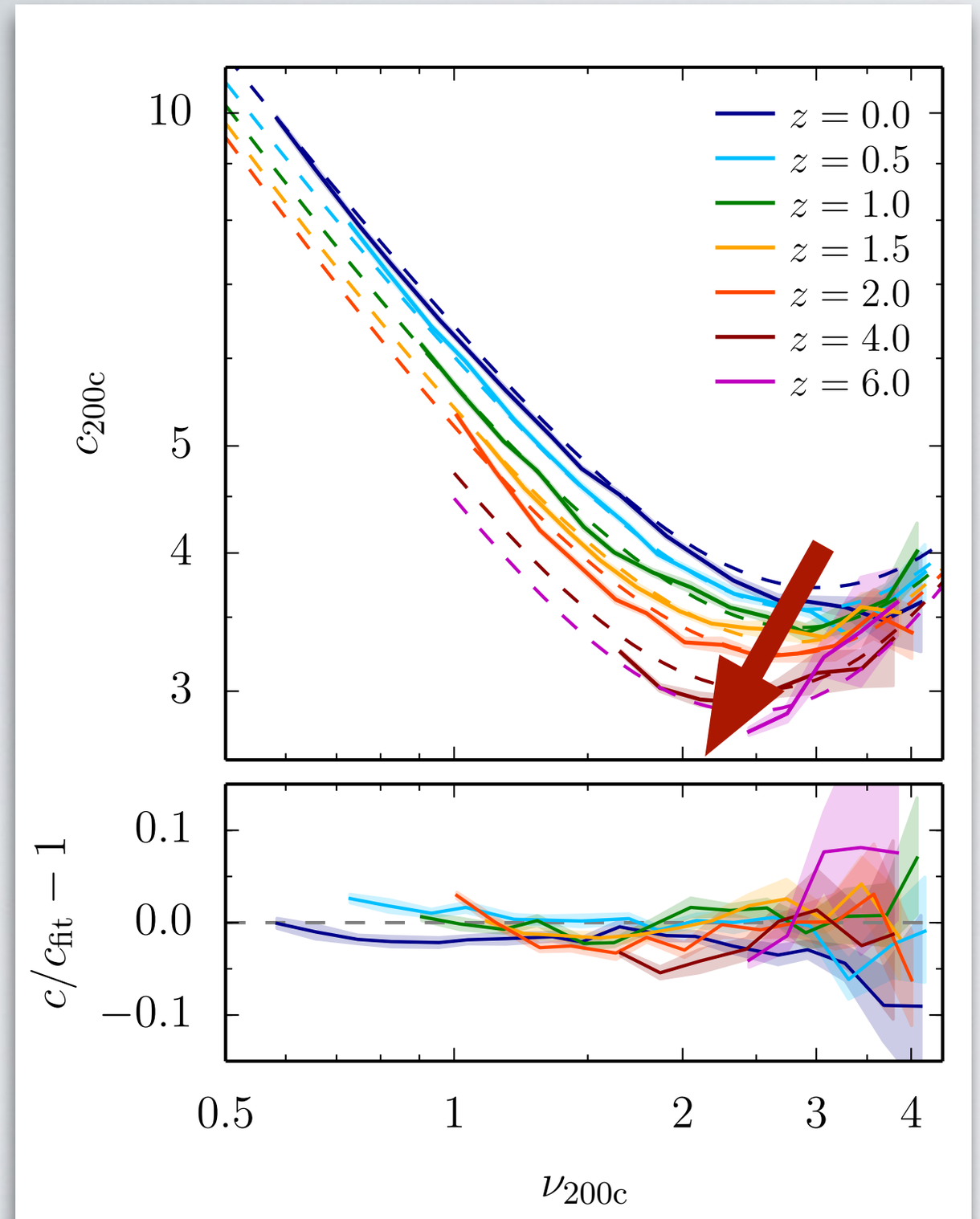
$$c_{200c} = \frac{c_{min}}{2}\left[\left(\frac{\nu}{\nu_{min}}\right)^{-\alpha} + \left(\frac{\nu}{\nu_{min}}\right)^{\beta}\right]$$

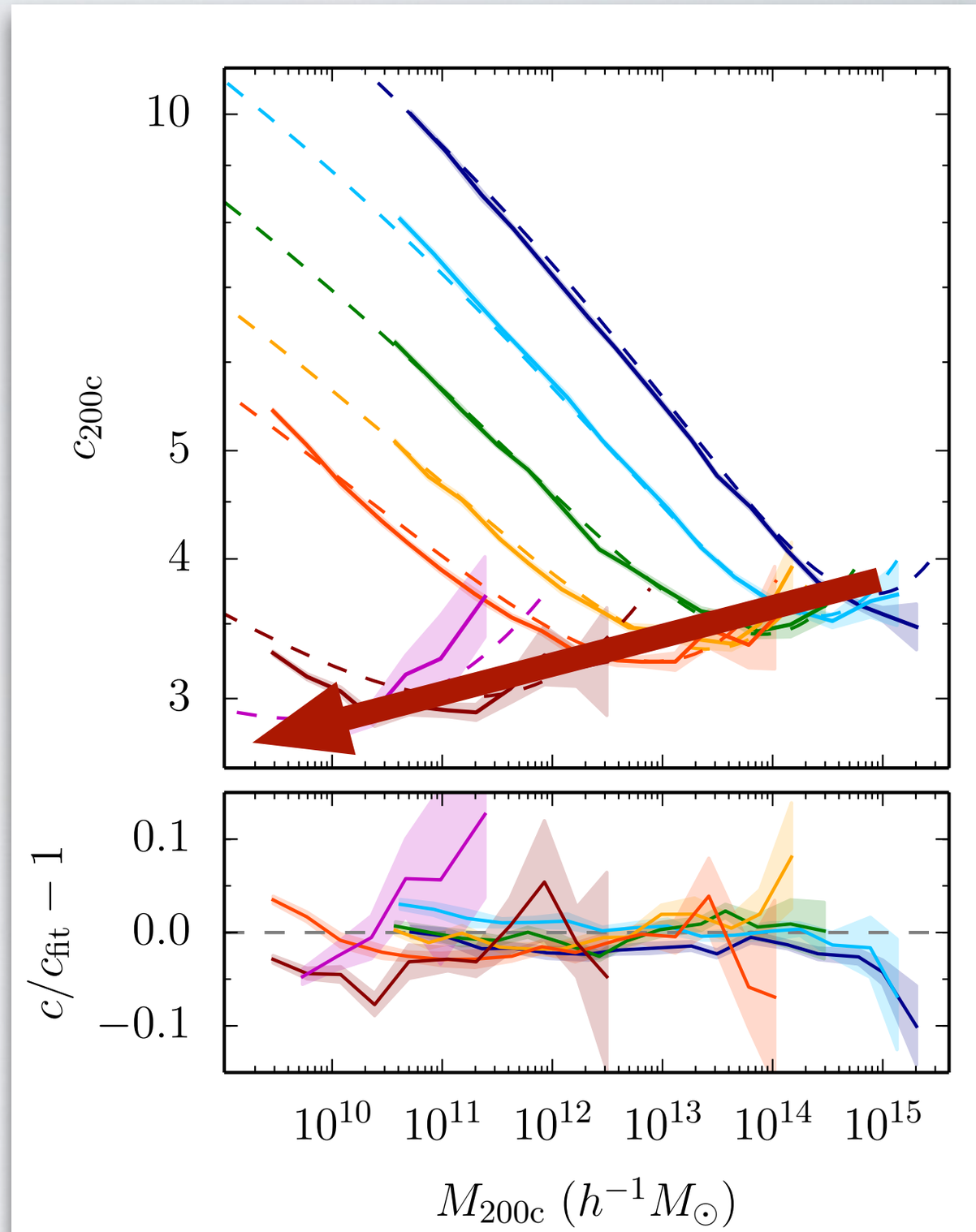
where

$$c_{min} = \phi_0 + \phi_1 n$$
$$\nu_{min} = \eta_0 + \eta_1 n$$

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

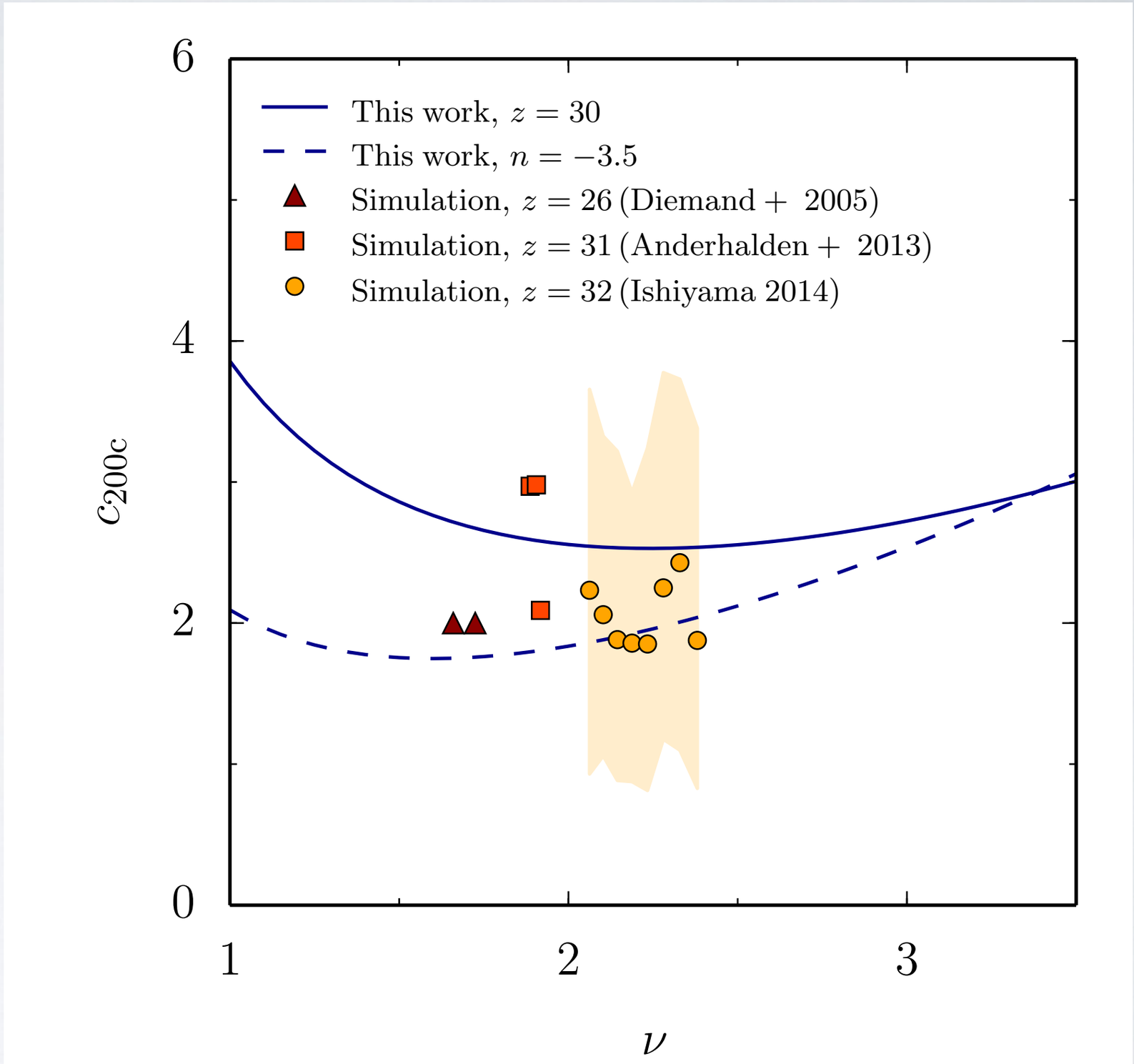
$$c_{200c} = c_{200c}(\nu, n)$$


10
5
4
3
c_{200c}
$z = 0.0$
$z = 0.5$
$z = 1.0$
$z = 1.5$
$z = 2.0$
$z = 4.0$
$z = 6.0$
0.1
0.0
−0.1
$c/c_{\rm fit} - 1$
0.5
1
2
3
4
ν_{200c}

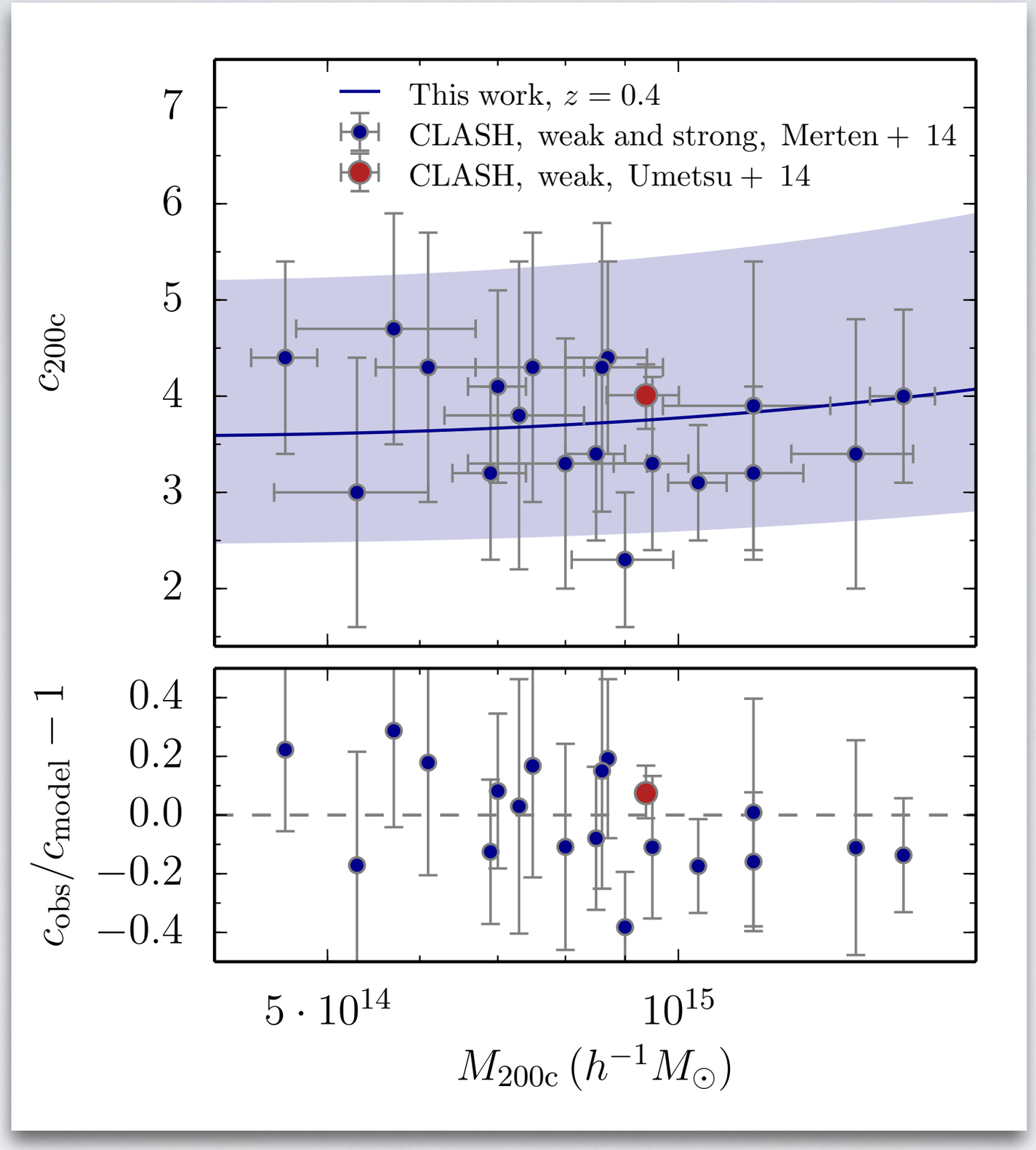

10
5
4
3
c_{200c}
0.1
0.0
−0.1
$c/c_{\rm fit} - 1$
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
$M_{200c}\ (h^{-1}M_\odot)$

z ≈ 30
M ≈ M_{earth}-$M_{\odot}$

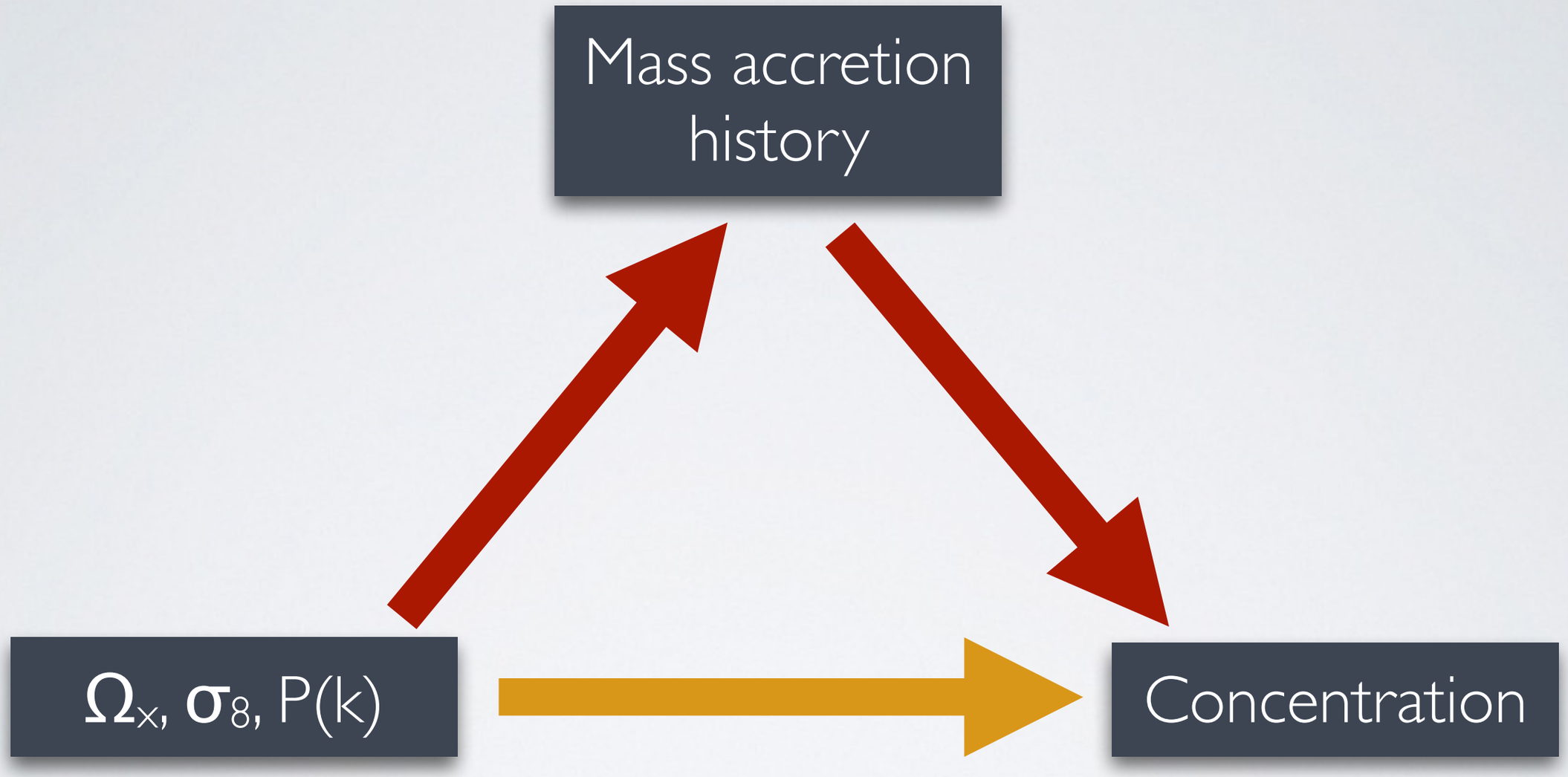
16 orders of mag. below calibrated masses!



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



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


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

Python Code

```
from Cosmology import *
from Concentration import *

setCosmology('WMAP9')
c = concentration(1E12, 0.0, statistic = 'median', mdef = 'vir')
```

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

Conclusions

- The outer profiles **are not universal** with mass, they depend on the mass accretion rate as well

- The outer profiles **are mostly universal** with redshift, but only if the correct rescaling is used

- Concentrations **are universal** when expressed as a function of peak properties

Diemer & Kravtsov 2014 • ApJ 789, 1 • arXiv 1401.1216
Diemer & Kravtsov 2014 • ApJ submitted • arXiv 1407.4730