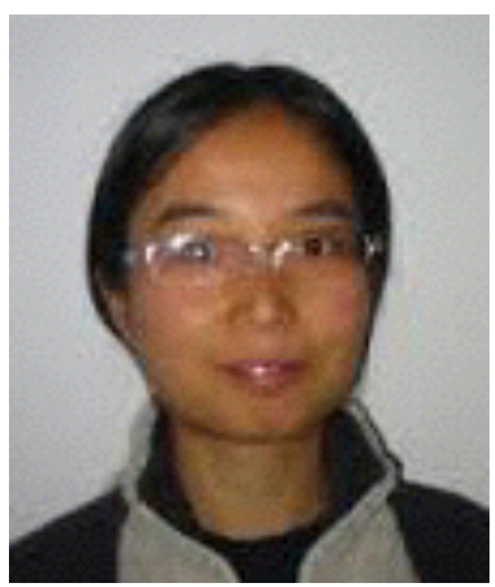
(Toward) A Solution to the Hydrostatic Mass Bias Problem in Galaxy Clusters

Eiichiro Komatsu (MPA)
UTAP Seminar, December 22, 2014

References

- Shi & EK, MNRAS, 442, 512 (2014)
- Shi, EK, Nelson & Nagai, arXiv:1408.3832



Xun Shi (MPA)

Kaylea Nelson (Yale)

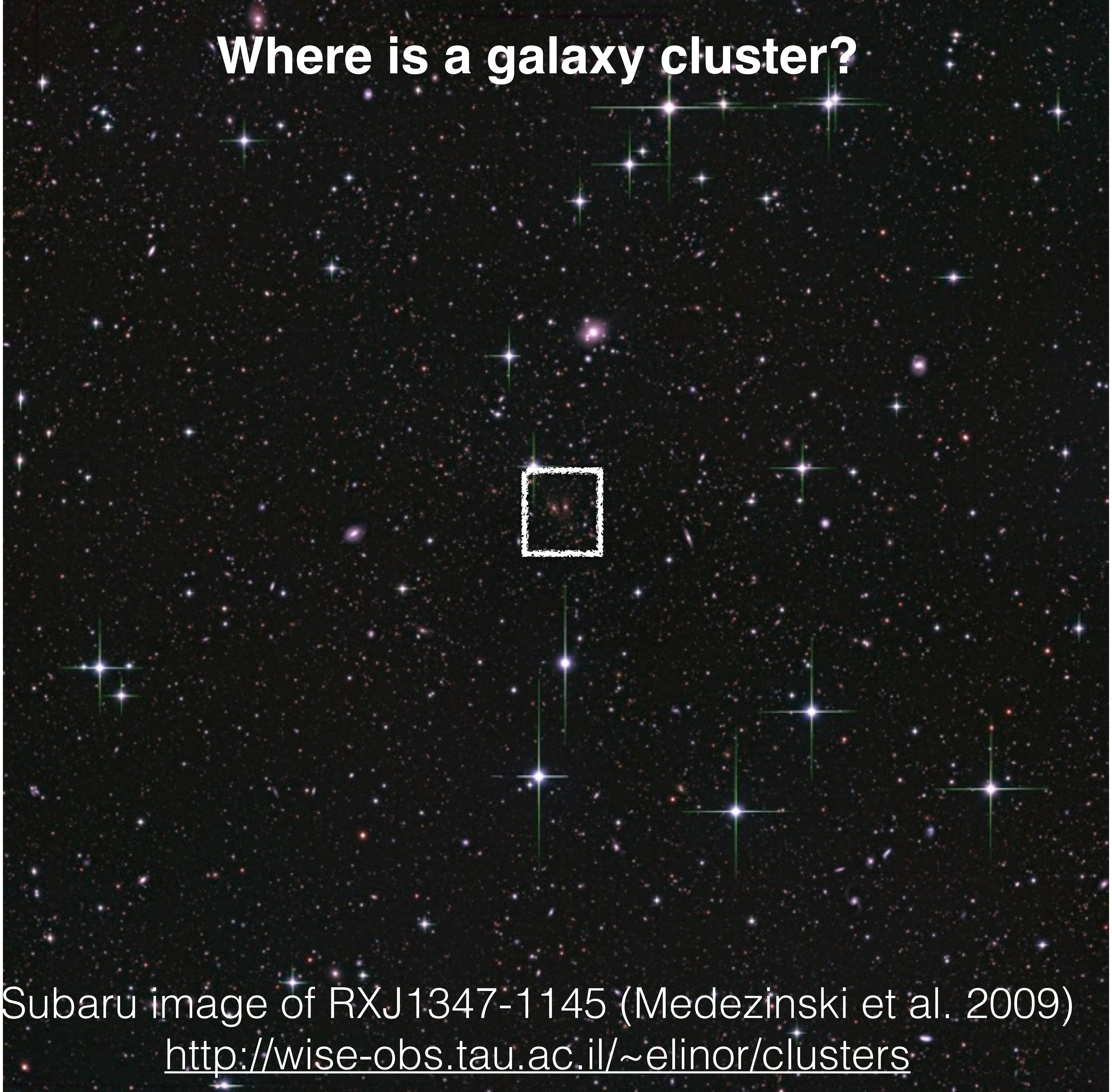
Motivation

- We wish to determine the mass of galaxy clusters accurately

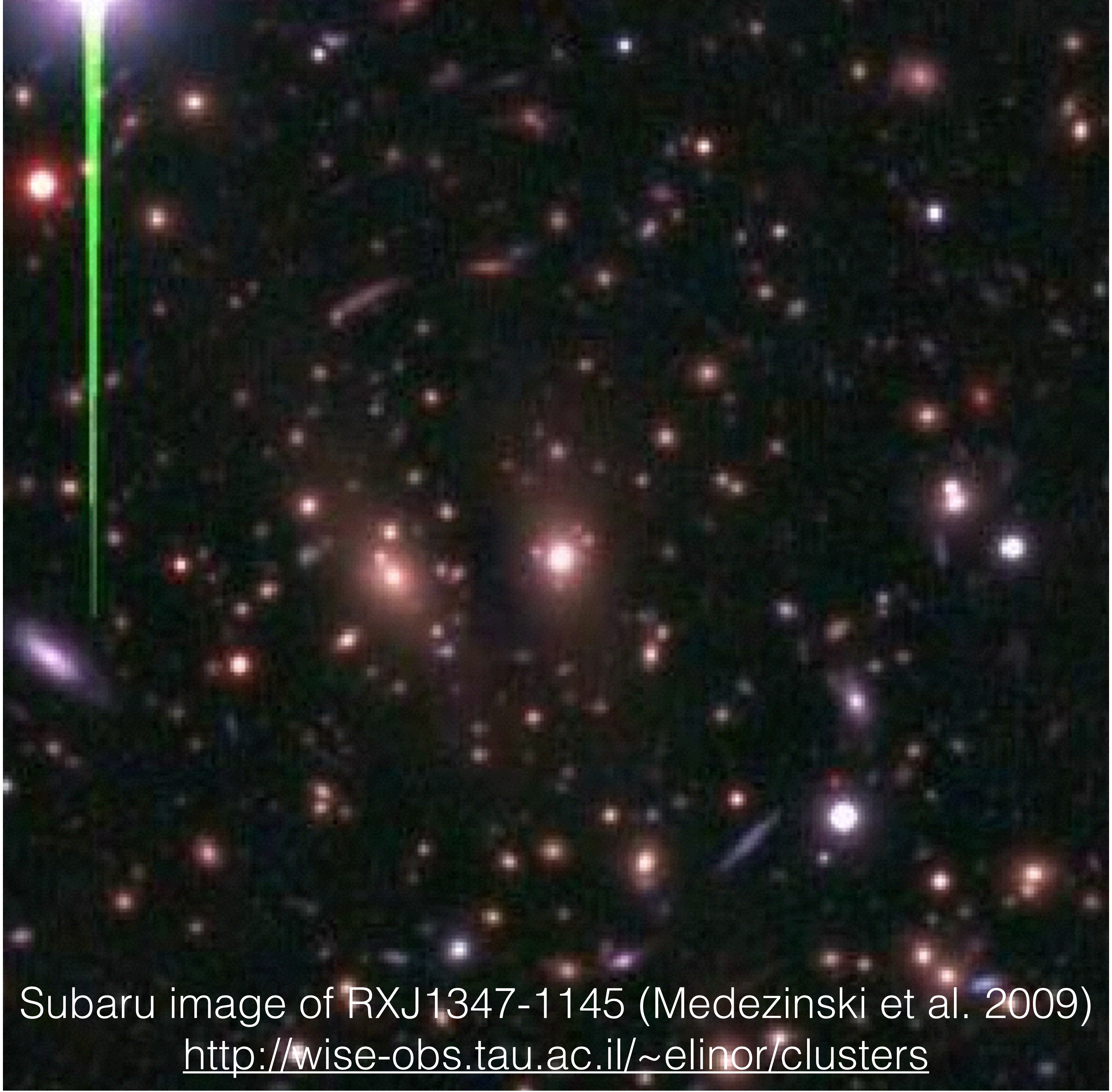
Where is a galaxy cluster?

Subaru image of RXJ1347-1145 (Medezinski et al. 2009)
http://wise-obs.tau.ac.il/~elinor/clusters

Where is a galaxy cluster?

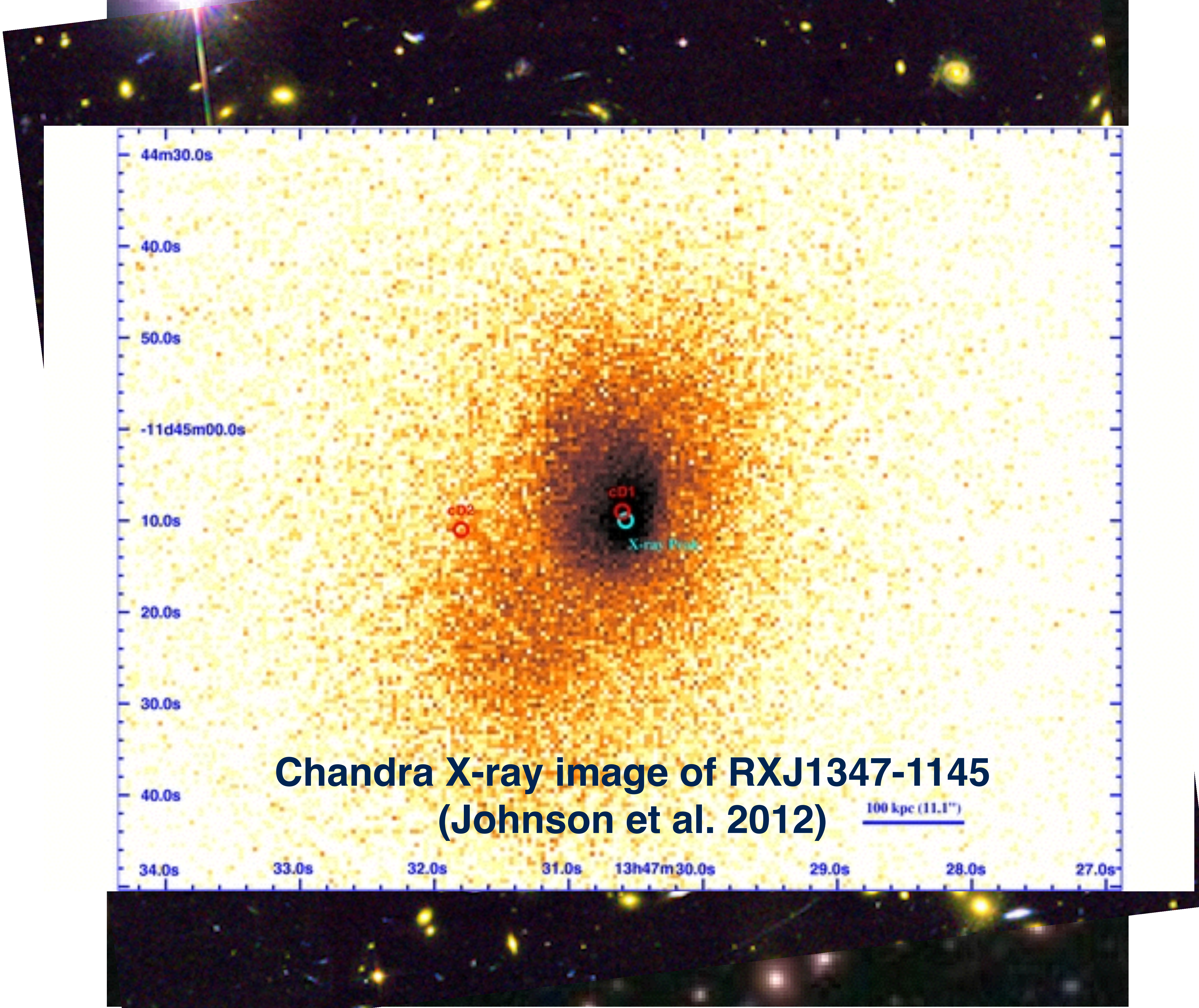


Subaru image of RXJ1347-1145 (Medezinski et al. 2009)
http://wise-obs.tau.ac.il/~elinor/clusters



Subaru image of RXJ1347-1145 (Medezinski et al. 2009)
http://wise-obs.tau.ac.il/~elinor/clusters

Hubble image of RXJ1347-1145 (Bradac et al. 2008)



Chandra X-ray image of RXJ1347-1145
(Johnson et al. 2012)

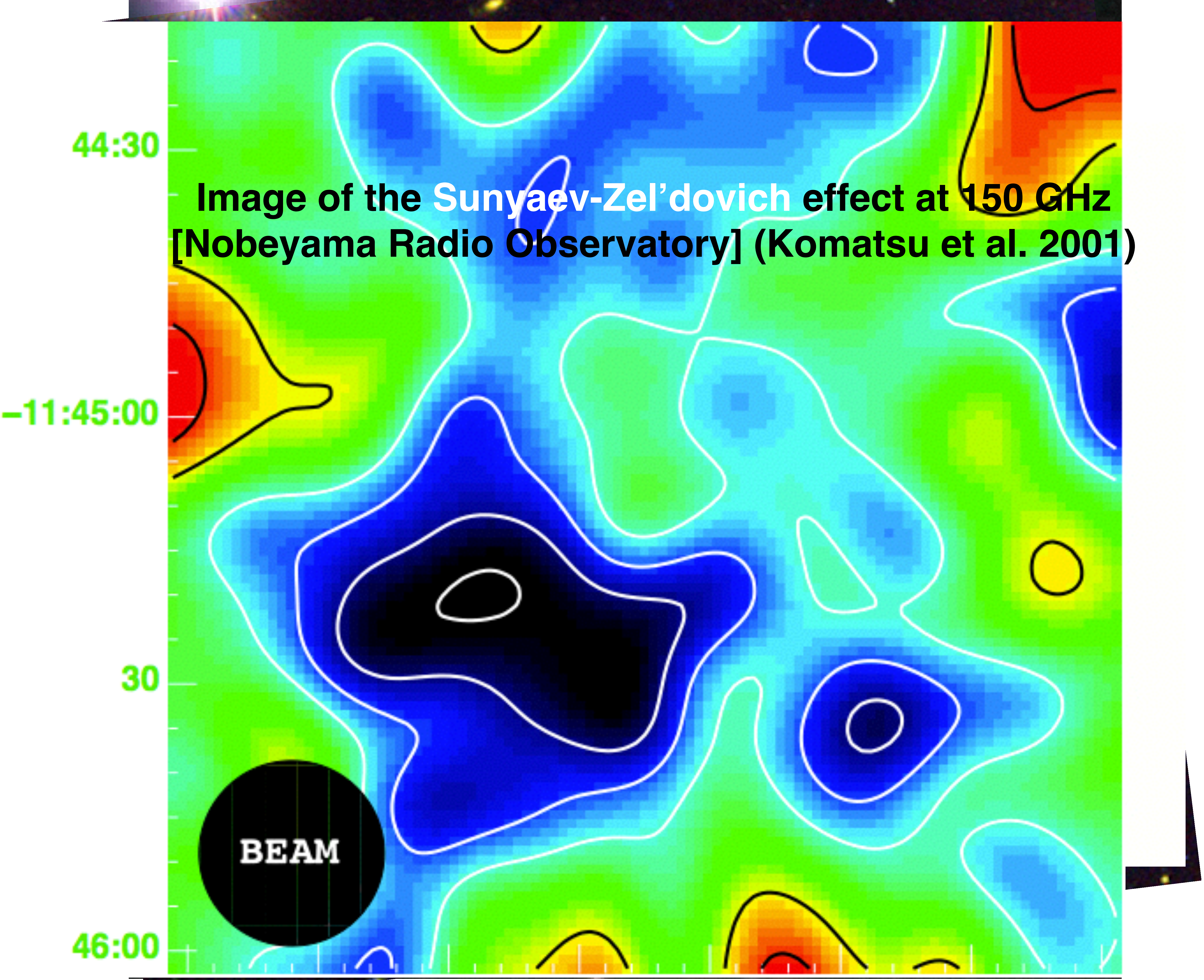
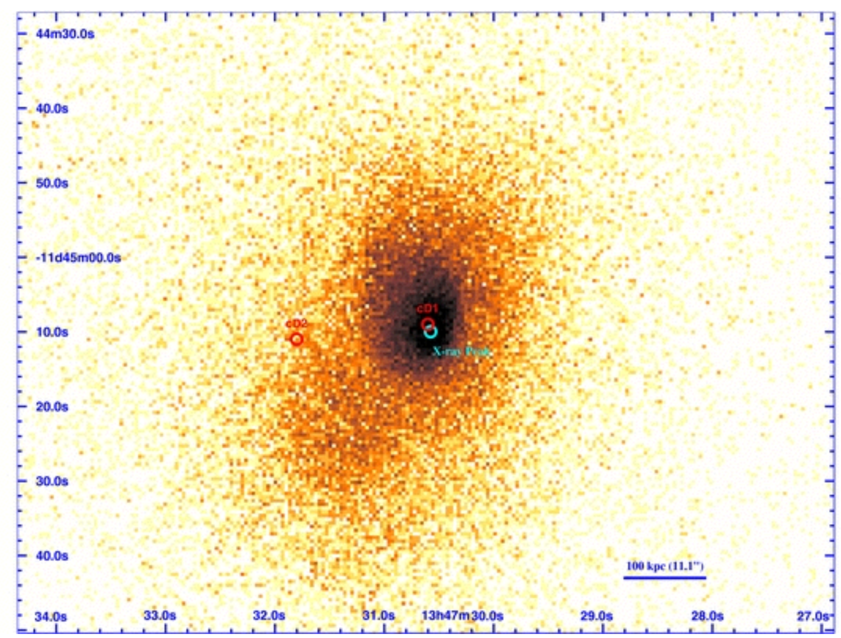
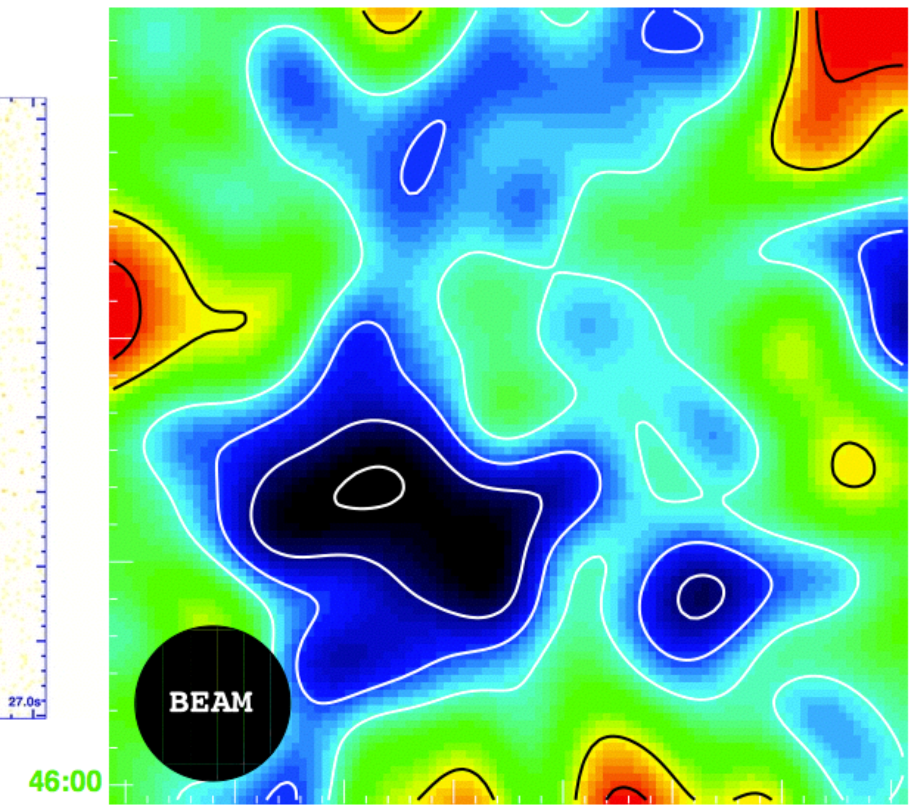


Image of the Sunyaev-Zel'dovich effect at 150 GHz
[Nobeyama Radio Observatory] (Komatsu et al. 2001)
44:30
−11:45:00
30
46:00
BEAM

Multi-wavelength Data

$$I_X = \int dl\ n_e^2 \Lambda(T_X) \qquad I_{SZ} = g_\nu \frac{\sigma_T k_B}{m_e c^2} \int dl\ n_e T_e$$





<u>Optical</u>:
- $10^{2\text{–}3}$ galaxies
- velocity dispersion
- gravitational lensing

<u>X-ray</u>:
- hot gas ($10^{7\text{–}8}$ K)
- spectroscopic T_X
- Intensity ~ $n_e^2 L$

<u>SZ</u> [microwave]:
- hot gas ($10^{7\text{-}8}$ K)
- electron pressure
- Intensity ~ $n_e T_e L$

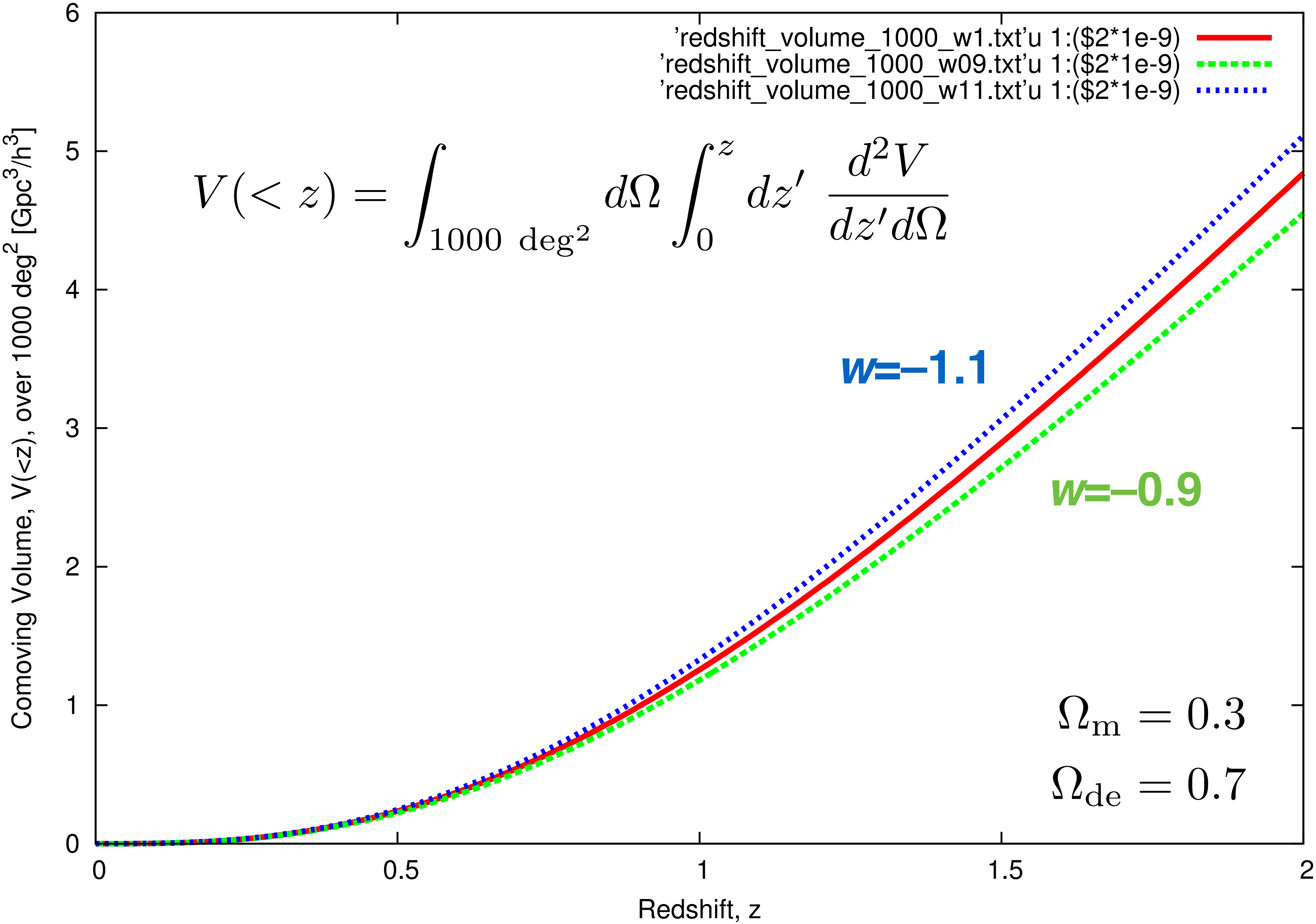
Galaxy Cluster Counts

- We count galaxy clusters over a certain region in the sky [with the solid angle Ω_{obs}]
- Our ability to detect clusters is limited by noise [limiting flux, F_{lim}]
- For a comoving number density of clusters per unit mass, dn/dM, the observed number count is

$$N = \Omega_{\rm obs} \int_0^\infty dz \, \frac{d^2V}{dz d\Omega} \int_{F_{\rm lim}(z)}^\infty dF \, \frac{dn}{dM} \frac{dM}{dF}$$

DE vs Galaxy Clusters

- **Counting** galaxy clusters provides information on dark energy by
  - Providing the comoving volume element which depends on $d_A(z)$ and $H(z)$
  - Providing the amplitude of matter fluctuations as a function of redshifts, $\sigma_8(z)$


'redshift_volume_1000_w1.txt'u 1:($2*1e-9)
'redshift_volume_1000_w09.txt'u 1:($2*1e-9)
'redshift_volume_1000_w11.txt'u 1:($2*1e-9)
$V(< z) = \int_{1000\ \mathrm{deg}^2} d\Omega \int_0^z dz' \ \frac{d^2V}{dz'd\Omega}$
w=−1.1
w=−0.9
$\Omega_\mathrm{m} = 0.3$
$\Omega_\mathrm{de} = 0.7$
Comoving Volume, V(<z), over 1000 deg^2 [Gpc^3/h^3]
Redshift, z
0
1
2
3
4
5
6
0.5
1
1.5
2

Mass Function, dn/dM

- The comoving number density per unit mass range, dn/dM, is **exponentially** sensitive to the amplitude of matter fluctuations, σ_8, for high-mass, rare objects
  - By “high-mass objects”, we mean “high peaks,” satisfying $1.68/\sigma(M) > 1$

δ is a Random Gaussian field:

$$\boxed{\underbrace{P(\delta)}_{\text{probability}} = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\delta^2/2\sigma^2}}$$

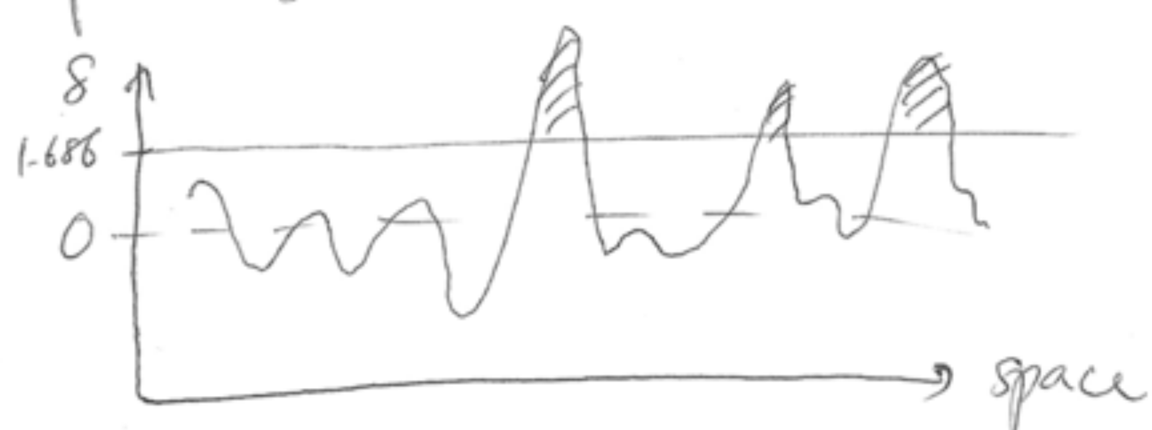
$\int_{-\infty}^{\infty} d\delta\, P(\delta) = 1$

σ^2: variance of δ

Mass Function, dn/dM

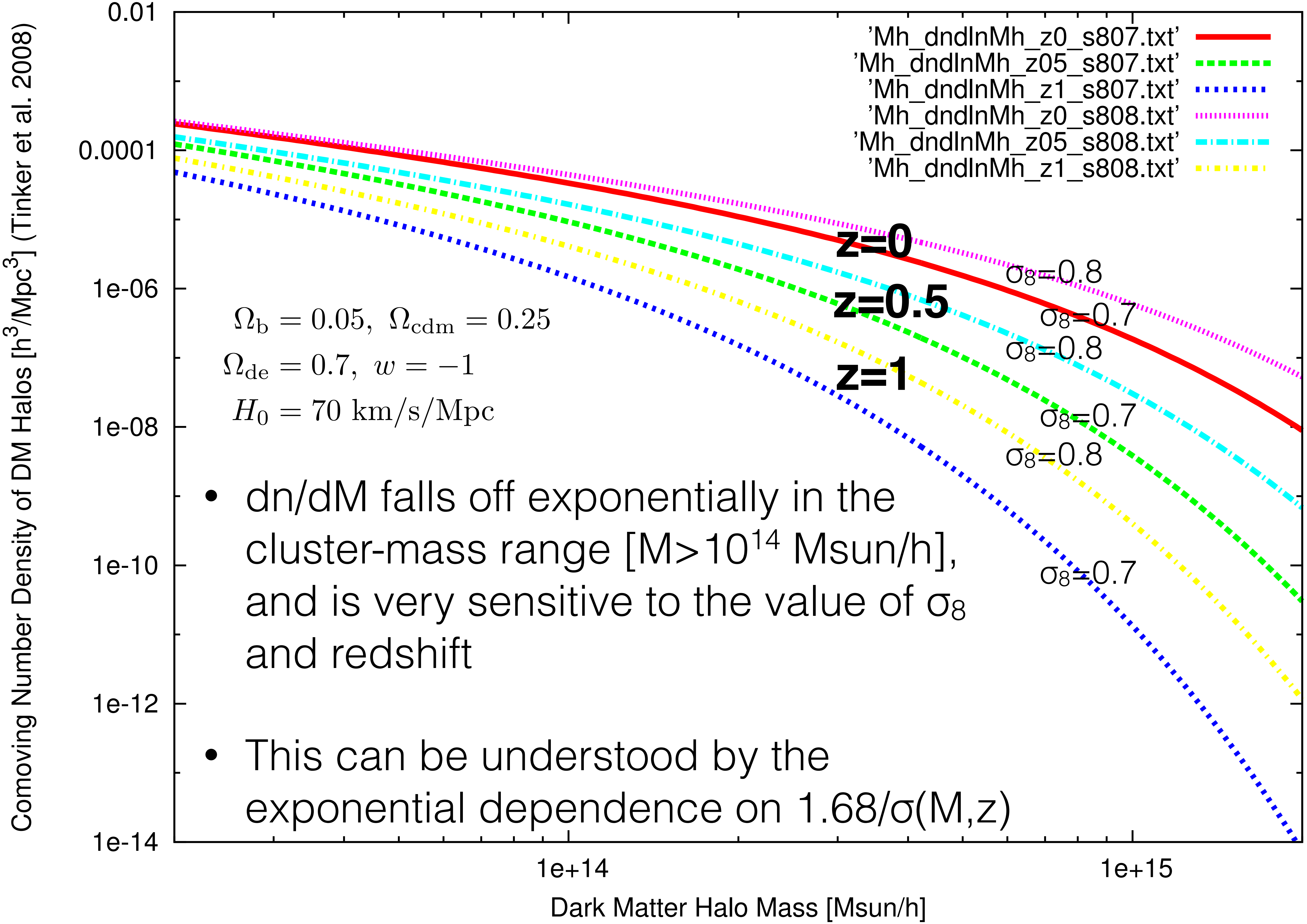
- The comoving number density per unit mass range, dn/dM, is **exponentially** sensitive to the amplitude of matter fluctuations, σ_8, for high-mass, rare objects
  - By "high-mass objects", we mean "high peaks," satisfying $1.68/\sigma(M) > 1$

Collapsed Regions have linearly-extrapolated $\delta \geq 1.686$



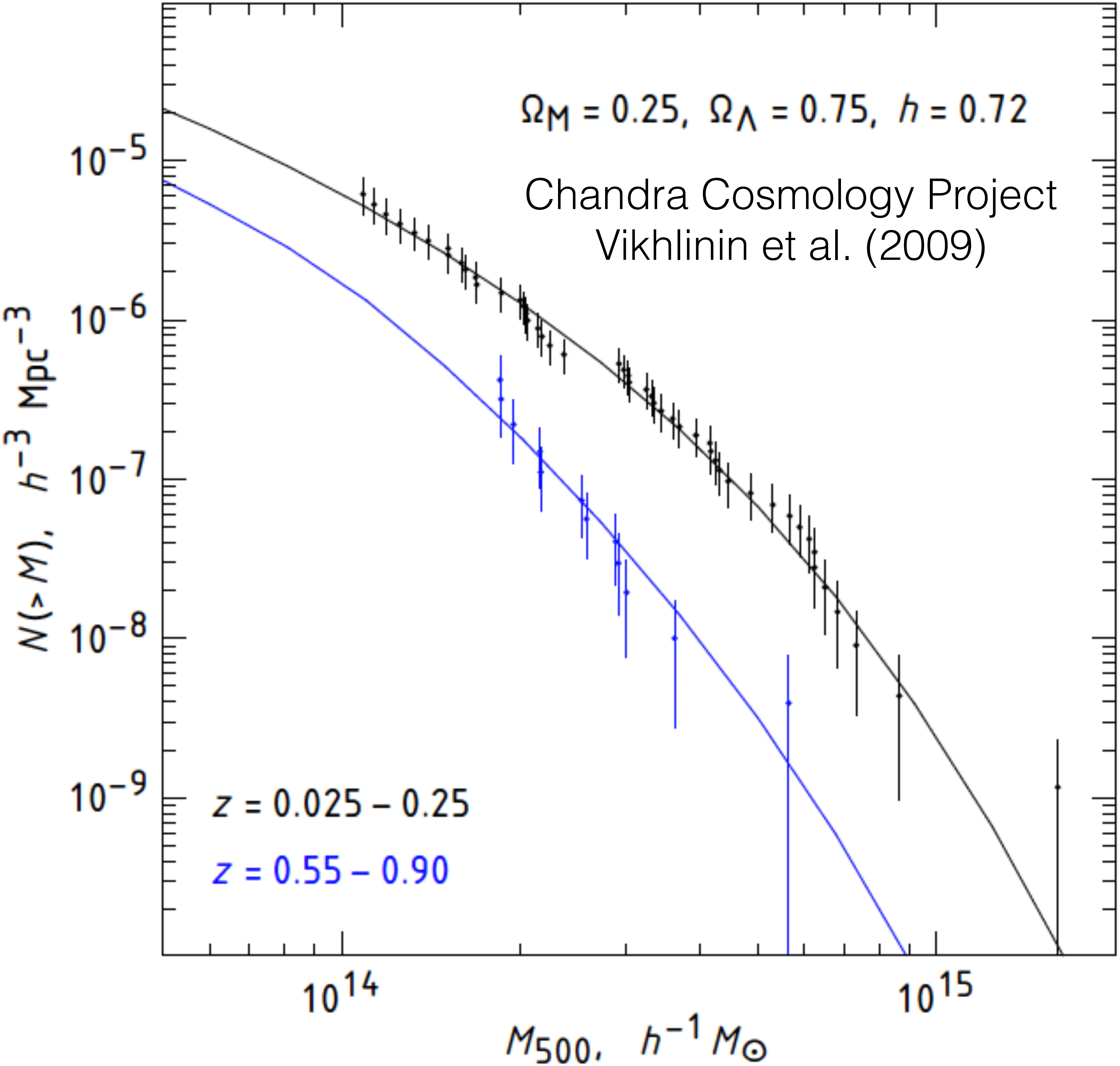
Areas of those collapsed regions

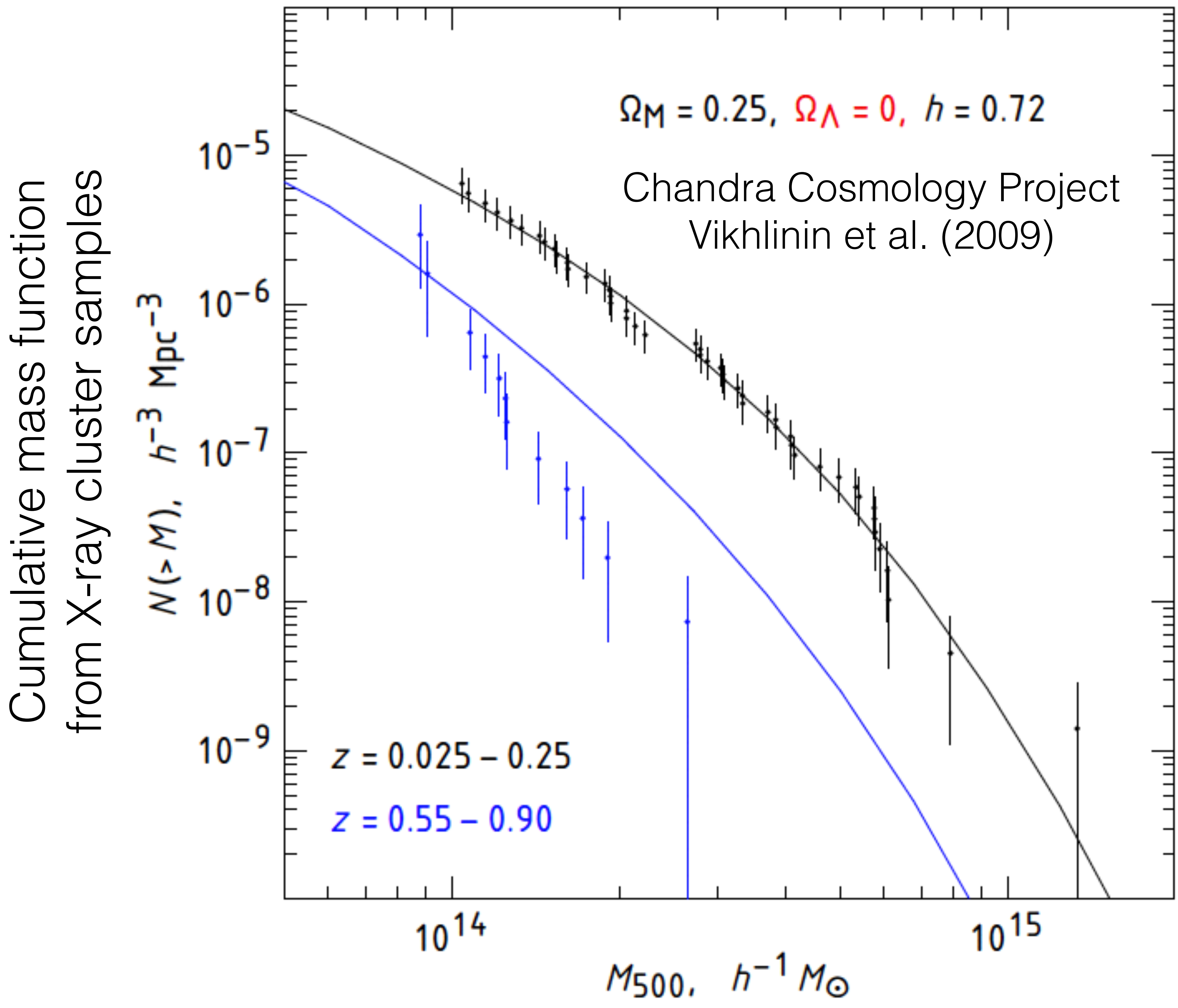
$$= \int_{\delta_c = 1.686}^{\infty} P(\delta)\, d\delta$$



- dn/dM falls off exponentially in the cluster-mass range [M>10^{14} Msun/h], and is very sensitive to the value of σ_8 and redshift
- This can be understood by the exponential dependence on 1.68/σ(M,z)

Cumulative mass function
from X-ray cluster samples





Cumulative mass function
from X-ray cluster samples
$\Omega_M = 0.25$, $\Omega_\Lambda = 0$, $h = 0.72$
Chandra Cosmology Project
Vikhlinin et al. (2009)
$N(>M)$, h^{-3} Mpc^{-3}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$z = 0.025 - 0.25$
$z = 0.55 - 0.90$
10^{14}
10^{15}
M_{500}, $h^{-1} M_\odot$

The Challenge

$$N = \Omega_{\rm obs} \int_0^\infty dz \, \frac{d^2V}{dz d\Omega} \int_{F_{\rm lim}(z)}^\infty dF \, \frac{dn}{dM} \boxed{\frac{dM}{dF}}$$

- **Cluster masses are not directly observable**
- The observables "F" include
  - Number of cluster member galaxies [optical]
  - Velocity dispersion [optical]
  - Strong- and weak-lensing masses [optical]
  - X-ray intensity [X-ray]
  - X-ray spectroscopic temperature [X-ray]
  - SZ intensity [microwave]

Mis-estimation of the masses from the observables severely compromises the statistical power of galaxy clusters as a DE probe

HSE: the leading method

- Currently, most of the mass cluster estimations rely on the X-ray data and the assumption of hydrostatic equilibrium [HSE]

    - The measured X-ray intensity is proportional to $\int n_e^2\, dl$, which can be converted into a radial profile of electron density, $\mathbf{n_e(r)}$, assuming spherical symmetry

    - The spectroscopic data give a radial electron temperature profile, $\mathbf{T_e(r)}$

These measurements give an estimate of the **electron pressure profile**, $P_e(r)=n_e(r)k_BT_e(r)$

HSE: the leading method

- Recently, more SZ measurements, which are proportional to $\int n_e k_B T_e \, dl$, are used to directly obtain an estimate of the **electron pressure profile**

HSE: the leading method

- In the usual HSE assumption, the total gas pressure [including contributions from ions and electrons] gradient balances against gravity

[X=0.75 is the hydrogen mass abundance]

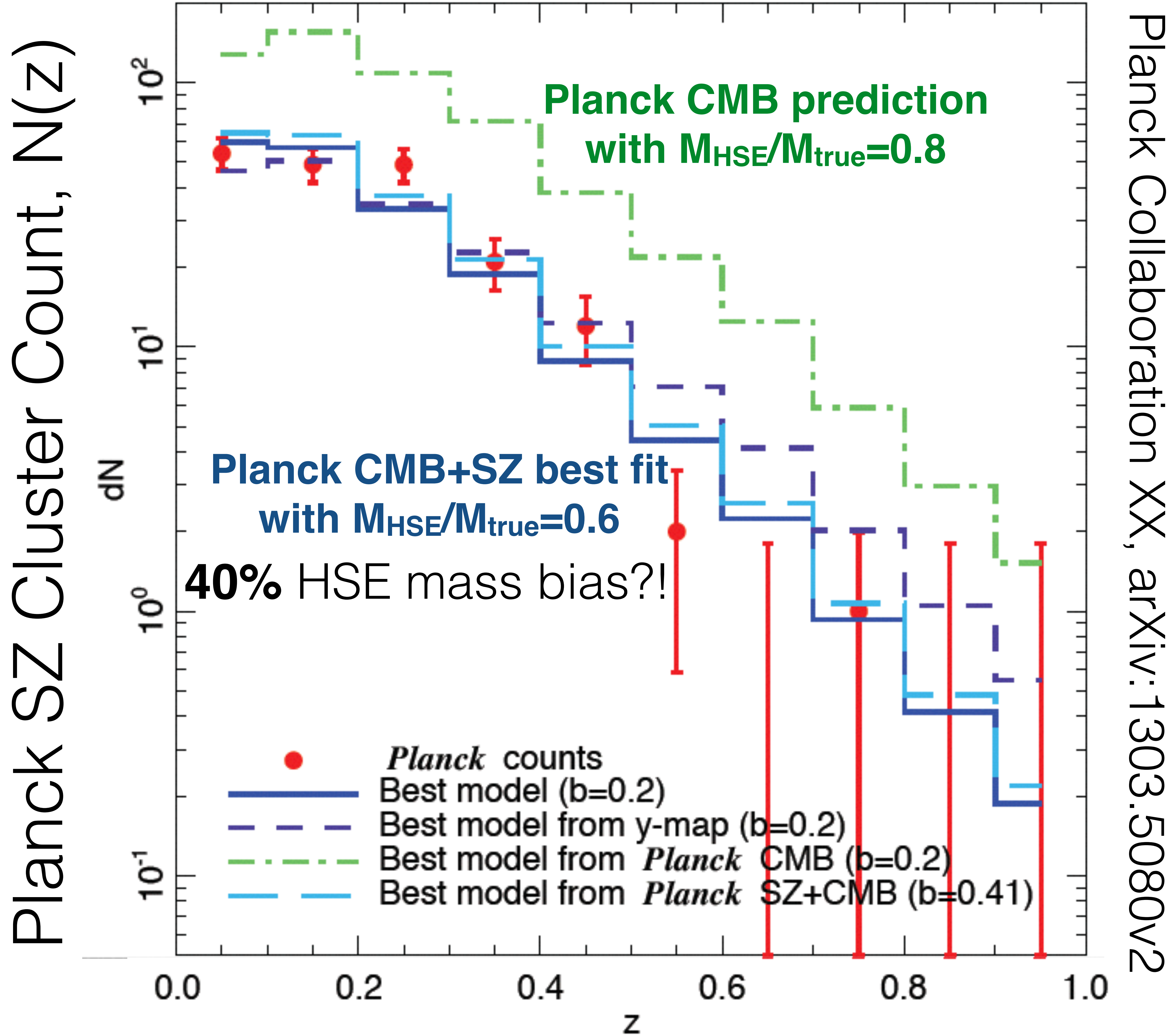
- $n_{gas} = n_{ion}+n_e = [(3+5X)/(2+2X)]n_e = 1.93n_e$
- Assuming $T_{ion}=T_e$ [which is not always satisfied!]
    - $P_{gas}(r) = 1.93P_e(r)$
- Then, HSE $$\frac{1}{\rho_{\rm gas}(r)}\frac{\partial P_{\rm gas}(r)}{\partial r} = -\frac{GM(<r)}{r^2}$$
    - gives an estimate of the total mass of a cluster, M

Limitation of HSE

- The HSE equation $$\frac{1}{\rho_{\rm gas}(r)}\frac{\partial P_{\rm gas}(r)}{\partial r} = -\frac{GM(<r)}{r^2}$$
  - only includes **thermal** pressure; however, not all kinetic energy of in-falling gas is thermalised
  - There is evidence that there is significant **non-thermal pressure support** coming from bulk motion of gas (e.g., turbulence)
- Therefore, the correct equation to use would be

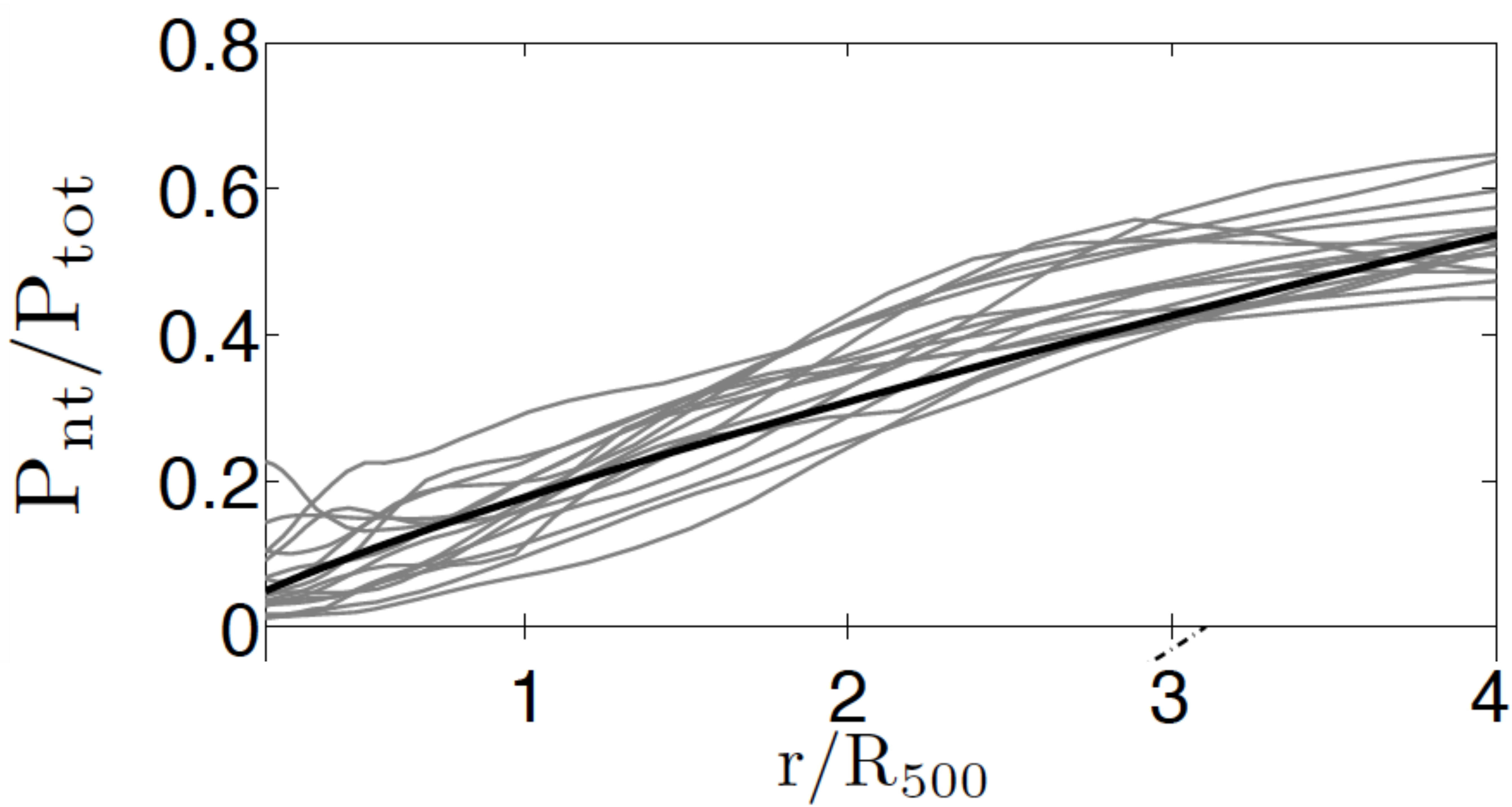
$$\frac{1}{\rho_{\rm gas}(r)}\frac{\partial[P_{\rm th}(r) + P_{\rm non-th}(r)]}{\partial r} = -\frac{GM(<r)}{r^2}$$

Not including $P_{\rm non\text{-}th}$ leads to underestimation of the cluster mass!



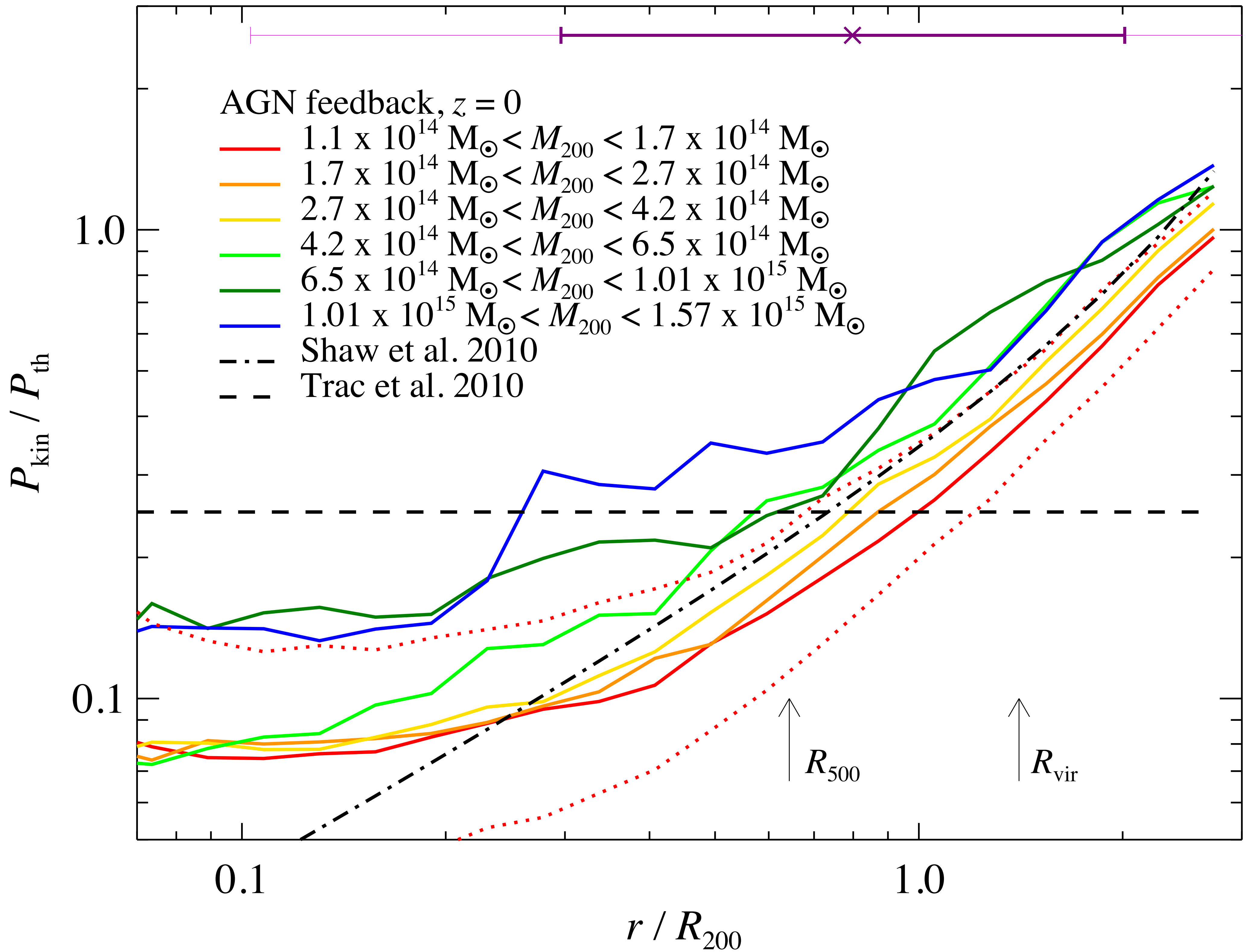
Planck SZ Cluster Count, N(z)
Planck CMB prediction
with M_{HSE}/M_{true}=0.8
Planck CMB+SZ best fit
with M_{HSE}/M_{true}=0.6
40% HSE mass bias?!
Planck counts
Best model (b=0.2)
Best model from y-map (b=0.2)
Best model from Planck CMB (b=0.2)
Best model from Planck SZ+CMB (b=0.41)
dN
10^2
10^1
10^0
10^{-1}
0.0
0.2
0.4
0.6
0.8
1.0
z
Planck Collaboration XX, arXiv:1303.5080v2

Shaw, Nagai, Bhattacharya & Lau (2010)



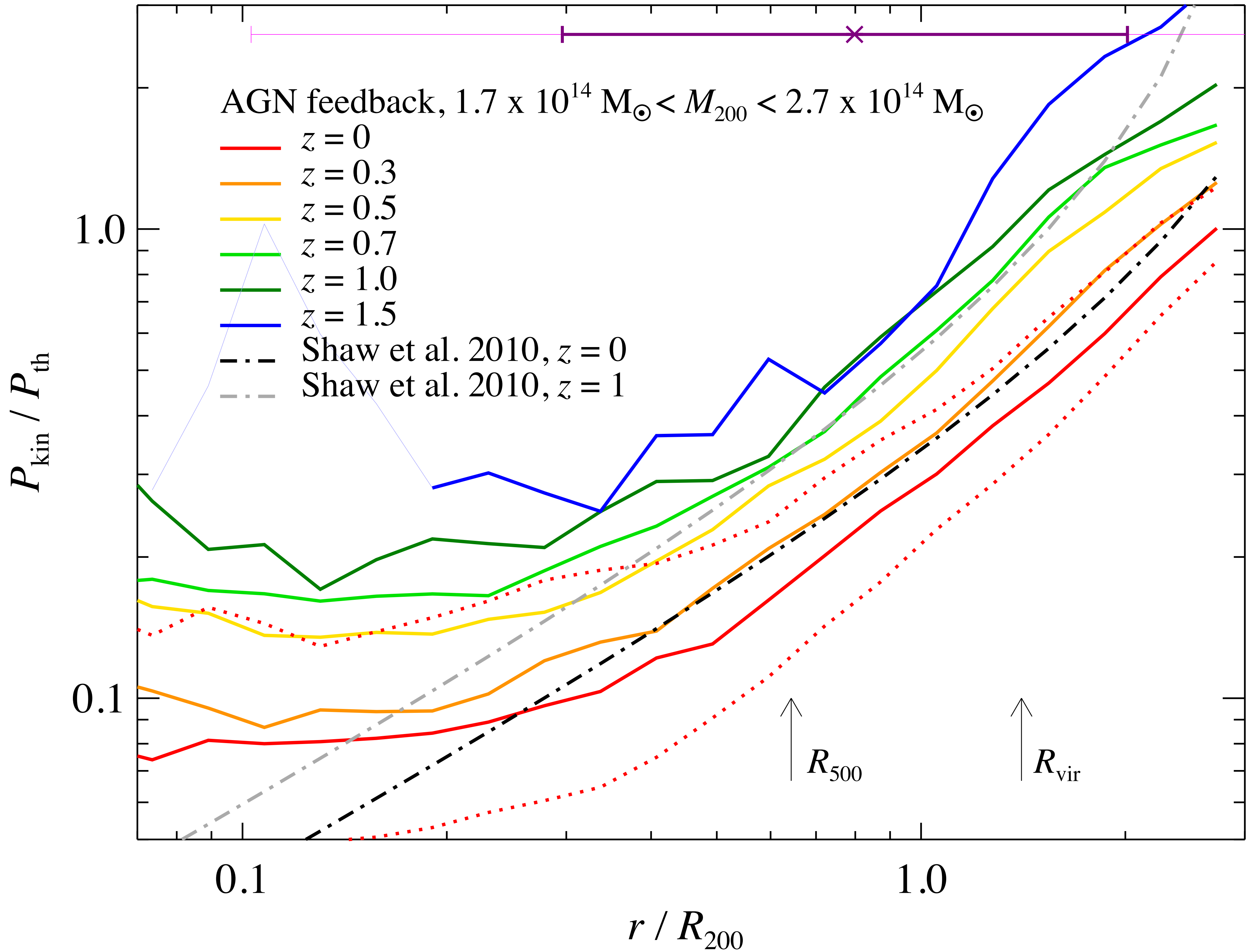
- Simulations by Shaw et al. show that the non-thermal pressure [by bulk motion of gas] divided by the total pressure increases toward large radii. But why?

Battaglia, Bond, Pfrommer & Sievers (2012)



- Battaglia et al.'s simulations show that the ratio increases for larger masses, and…

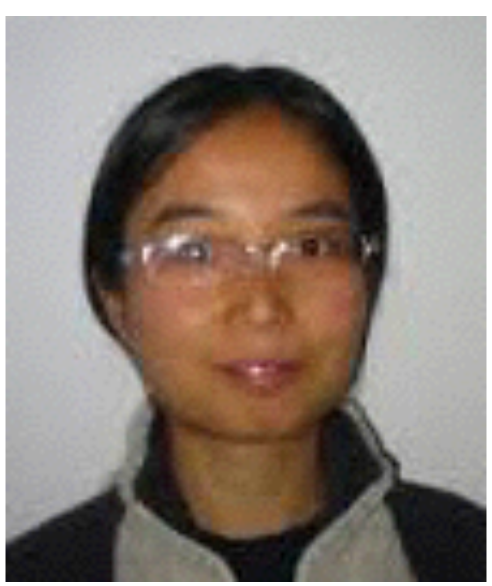
Battaglia, Bond, Pfrommer & Sievers (2012)



- …increases for larger redshifts. But why?

Part I:
Analytical Model

Shi & Komatsu (2014)



Xun Shi (MPA)

Analytical Model for Non-Thermal Pressure

- **Basic idea 1**: non-thermal motion of gas in clusters is sourced by the mass growth of clusters [via mergers and mass accretion] with efficiency η

- **Basic idea 2**: induced non-thermal motion decays and thermalises in a dynamical time scale

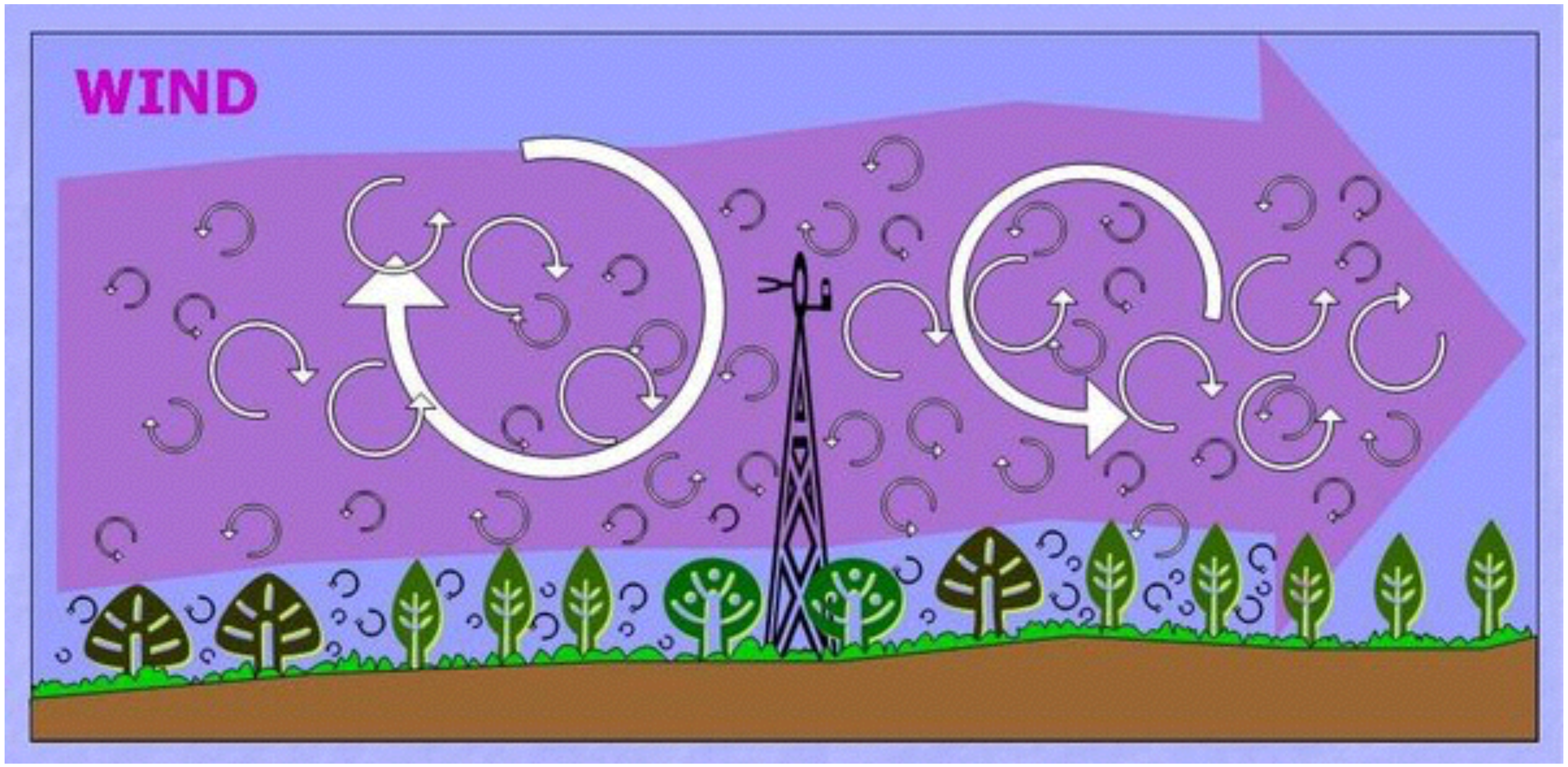
- Putting these ideas into a differential equation:

$$\frac{d\sigma^2_{\rm nth}}{dt} = -\frac{\sigma^2_{\rm nth}}{t_{\rm d}} + \eta \frac{d\sigma^2_{\rm tot}}{dt}$$

Shi & Komatsu (2014)

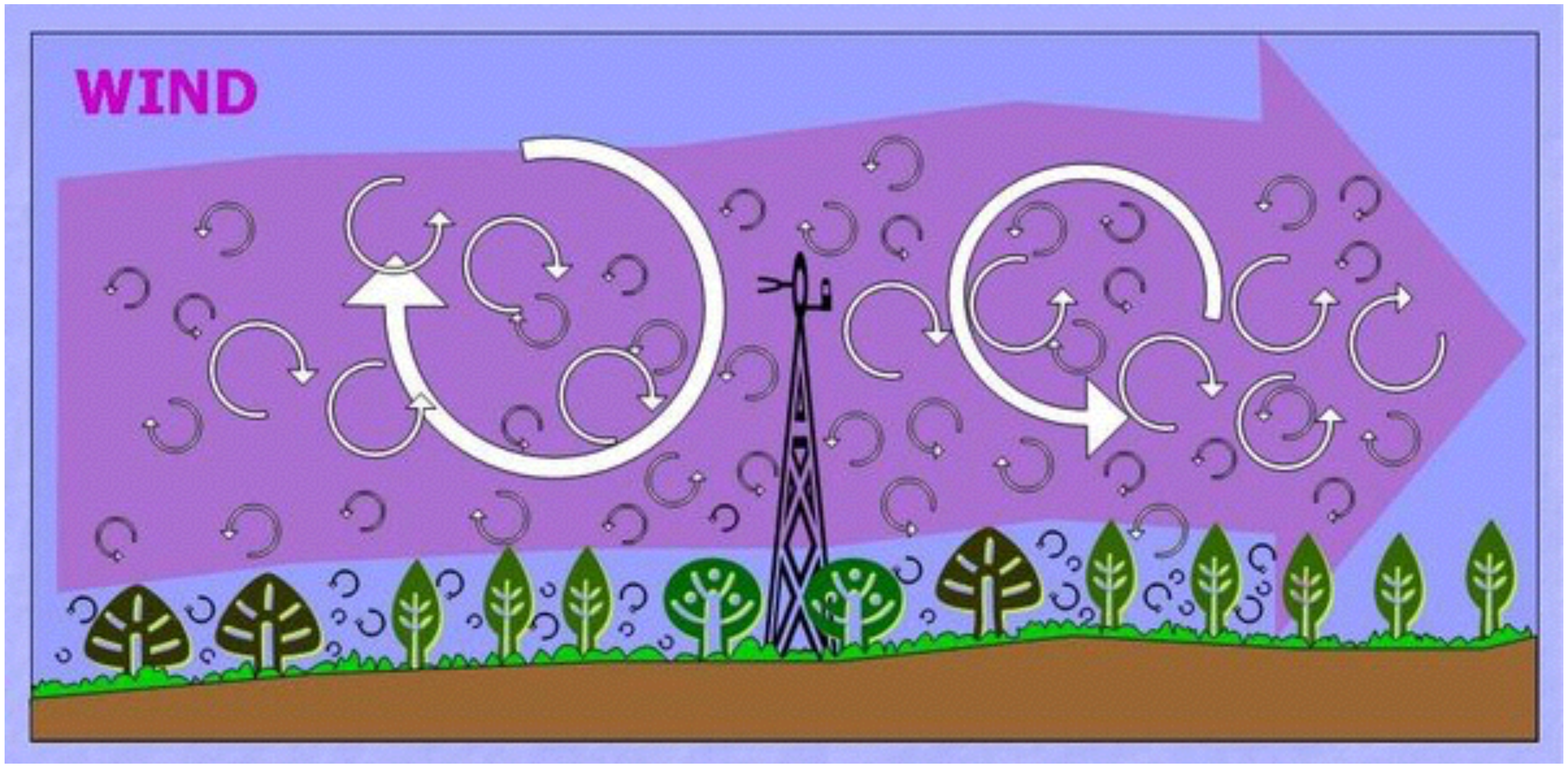
$[\sigma^2 = P/\rho_{\rm gas}]$

Finding the decay time, t_d



- Think of non-thermal motion as turbulence
- Turbulence consists of “eddies” with different sizes

Finding the decay time, t_d



- Largest eddies carry the largest energy
- Large eddies are unstable. They break up into smaller eddies, and transfer energy from large-scales to small-scales

Finding the decay time, t_d

- Assumption: the size of the largest eddies at a radius r from the centre of a cluster is proportional to r

- Typical peculiar velocity of turbulence is

$$v(r) = r\Omega(r) = \sqrt{\frac{GM(<r)}{r}}$$

- Breaking up of eddies occurs at the time scale of

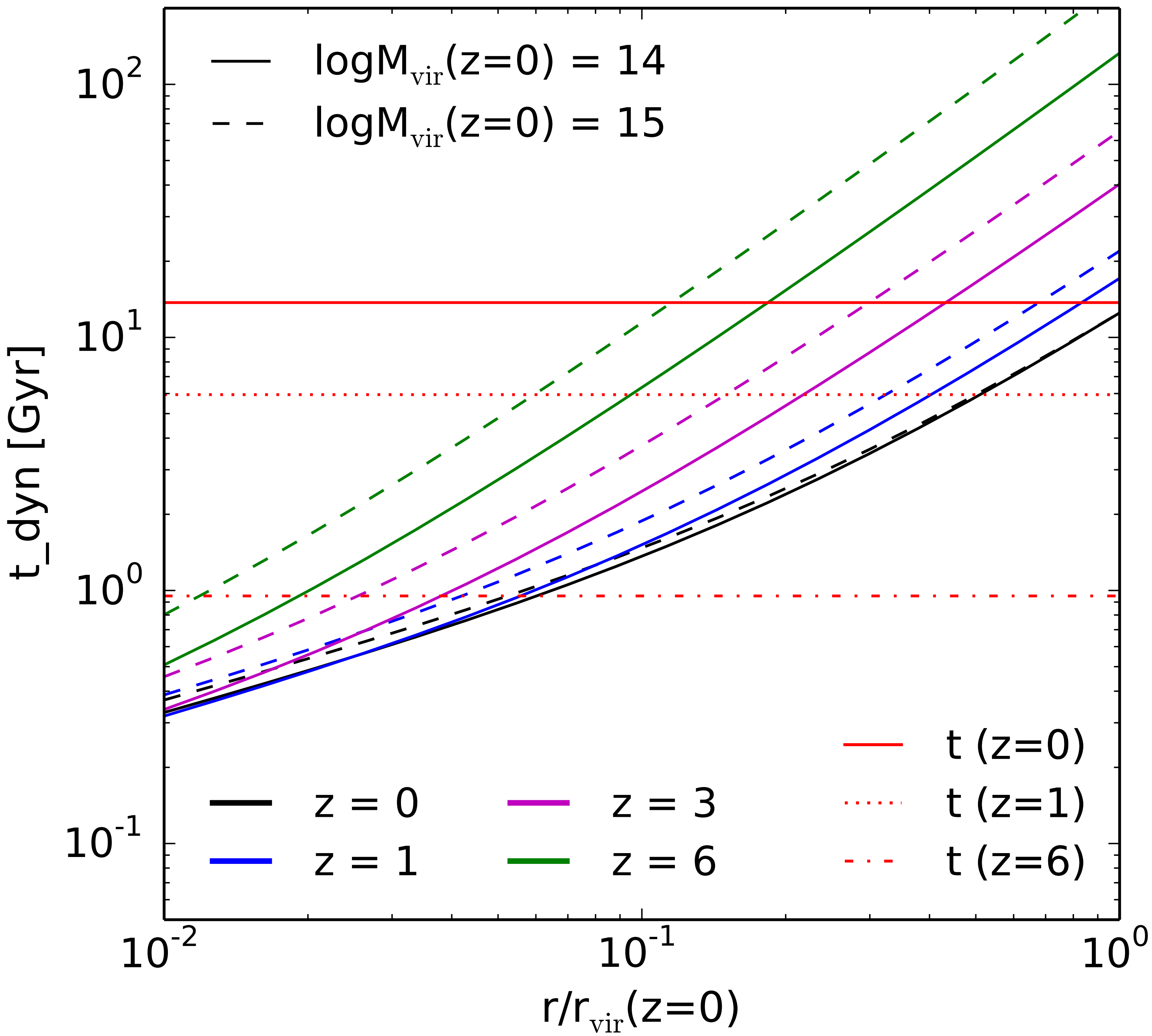
$$t_d \approx \frac{2\pi}{\Omega(r)} \equiv t_{dynamical}$$

- We thus write:

$$t_d \equiv \frac{\beta}{2} t_{dynamical}$$

Shi & Komatsu (2014)

Dynamical Time



- Dynamical time increases toward large radii. **Non-thermal motion decays into heat faster in the inner region**

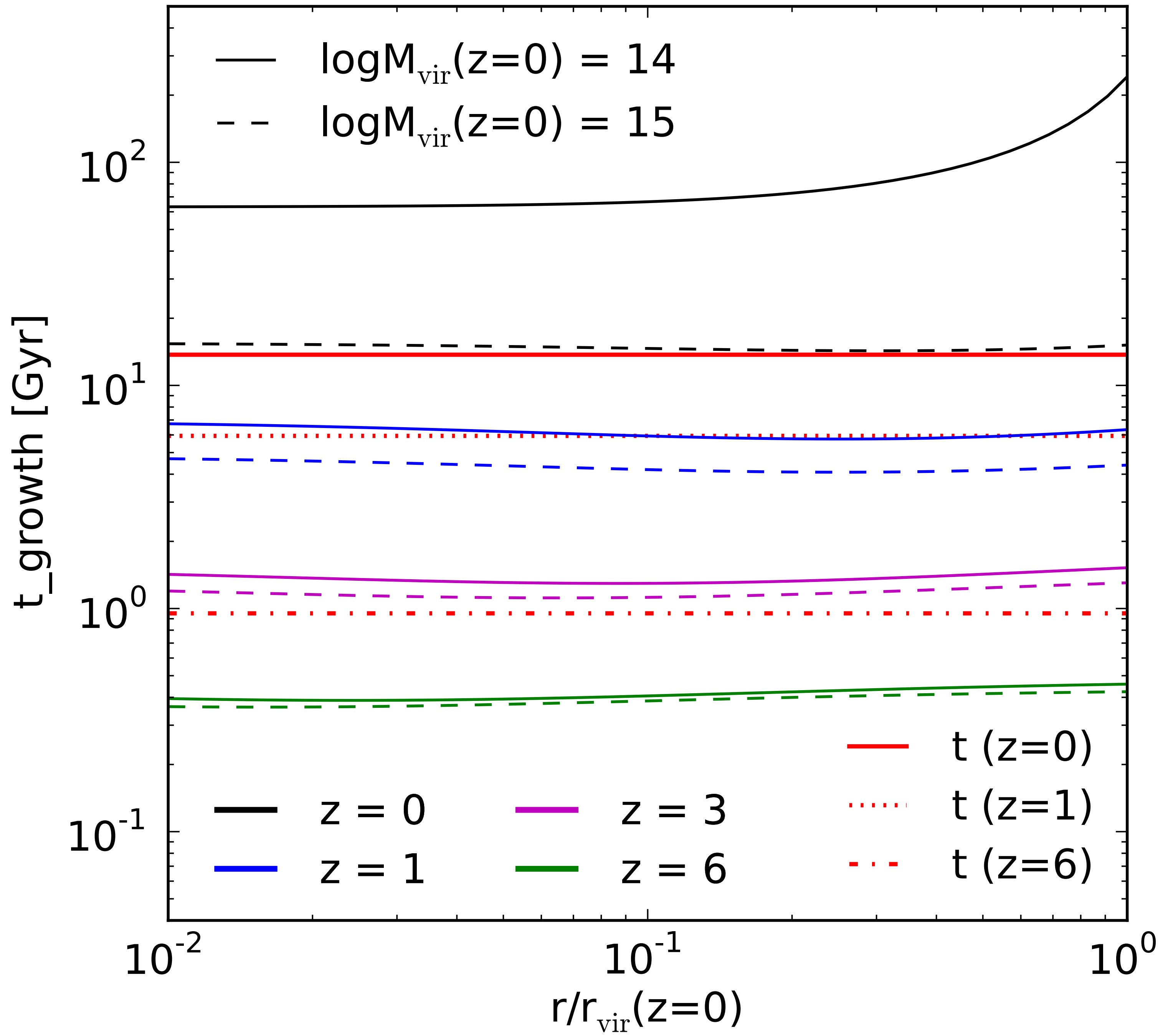
Source term

$$\frac{\mathrm{d}\sigma^2_{\mathrm{nth}}}{\mathrm{d}t} = -\frac{\sigma^2_{\mathrm{nth}}}{t_{\mathrm{d}}} + \eta\,\frac{\mathrm{d}\sigma^2_{\mathrm{tot}}}{\mathrm{d}t}$$

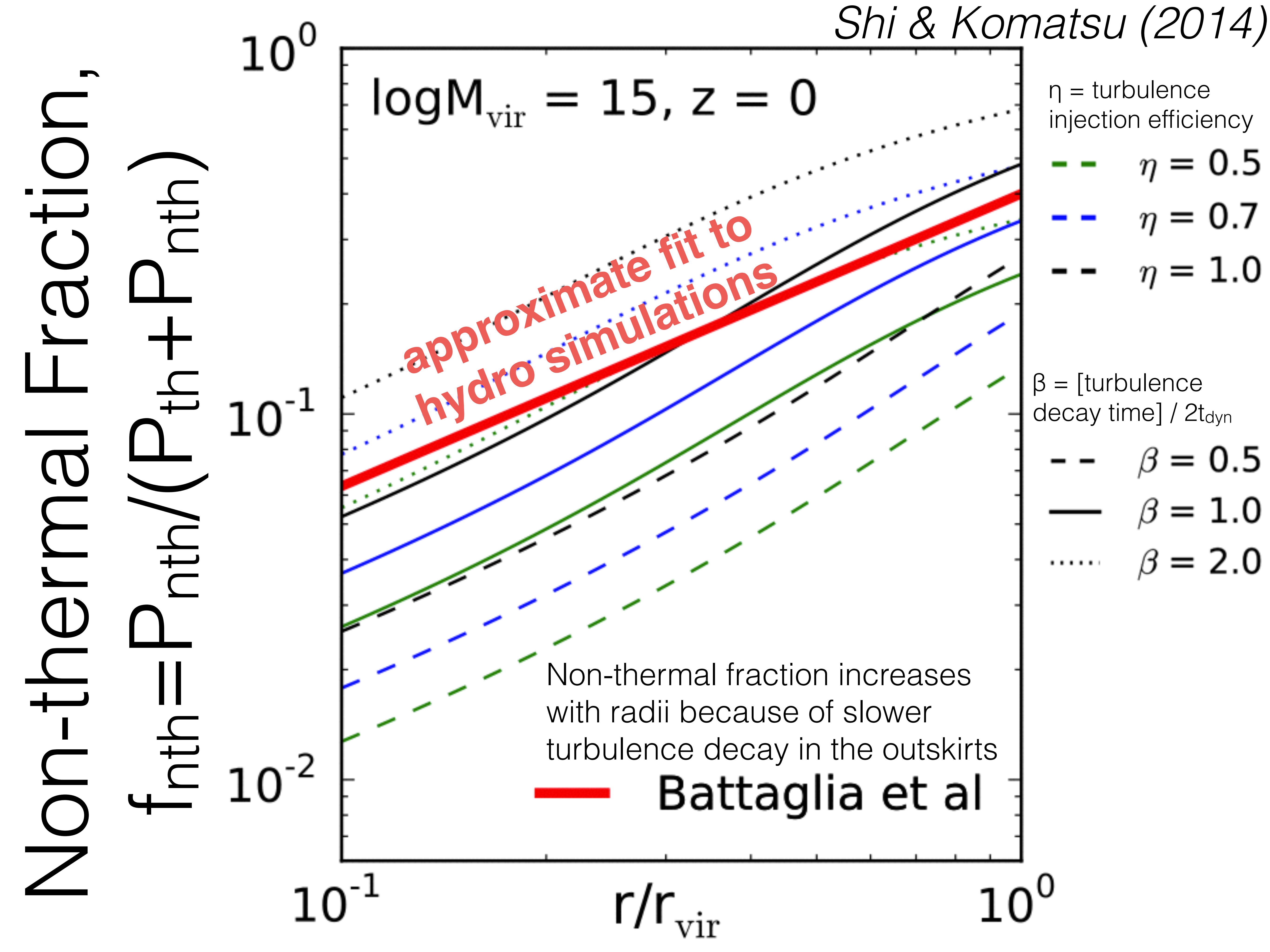
- Define $t_{growth} \equiv \sigma^2_{tot}\left(\frac{d\sigma^2_{tot}}{dt}\right)^{-1}$

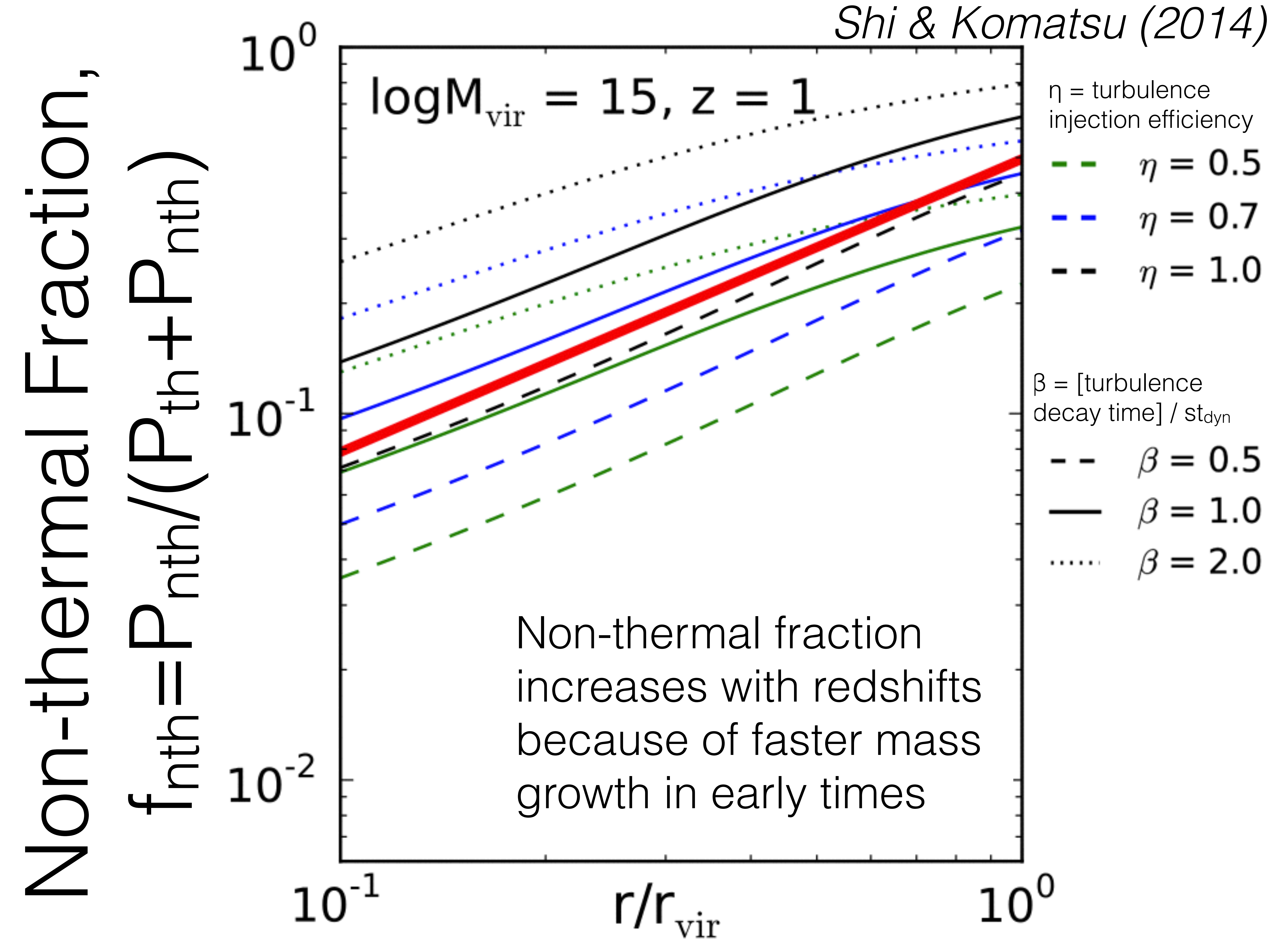
Shi & Komatsu (2014)

Growth Time



- Growth time increases toward lower redshifts and smaller masses. **Non-thermal motion is injected more efficiently at high redshifts and for large-mass halos**

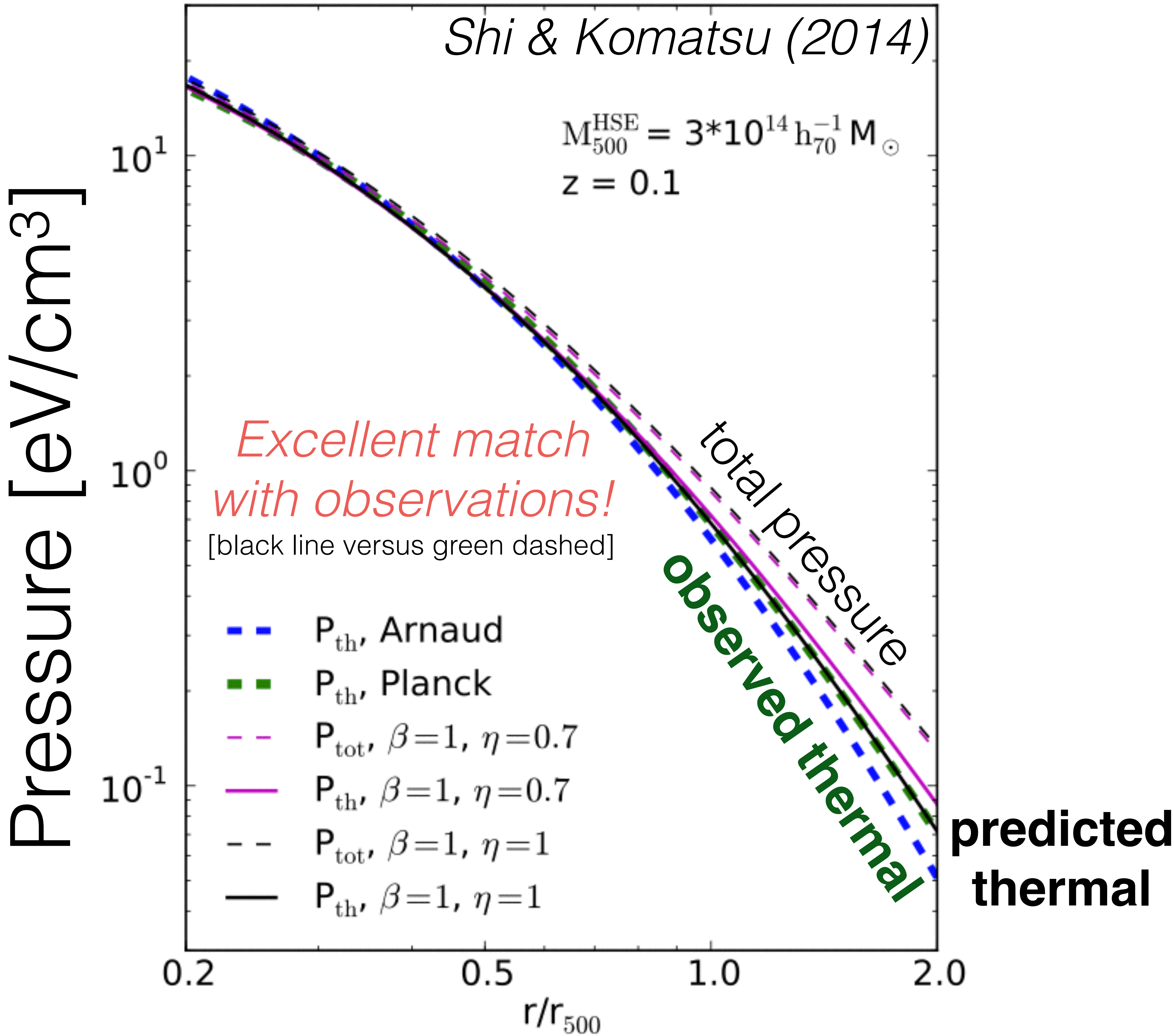

Shi & Komatsu (2014)
logM$_{vir}$ = 15, z = 0
Non-thermal Fraction,
$f_{nth}=P_{nth}/(P_{th}+P_{nth})$
approximate fit to hydro simulations
η = turbulence injection efficiency
$\eta = 0.5$
$\eta = 0.7$
$\eta = 1.0$
β = [turbulence decay time] / 2t$_{dyn}$
$\beta = 0.5$
$\beta = 1.0$
$\beta = 2.0$
Non-thermal fraction increases with radii because of slower turbulence decay in the outskirts
Battaglia et al
10^{0}
10^{-1}
10^{-2}
10^{-1}
r/r_{vir}
10^{0}


Shi & Komatsu (2014)
Non-thermal Fraction,
$f_{nth}=P_{nth}/(P_{th}+P_{nth})$
$\log M_{vir} = 15, z = 1$
η = turbulence injection efficiency
$\eta = 0.5$
$\eta = 0.7$
$\eta = 1.0$
β = [turbulence decay time] / st_{dyn}
$\beta = 0.5$
$\beta = 1.0$
$\beta = 2.0$
Non-thermal fraction increases with redshifts because of faster mass growth in early times
r/r_{vir}
10^{0}
10^{-1}
10^{-2}

With $P_{non\text{-}thermal}$ computed

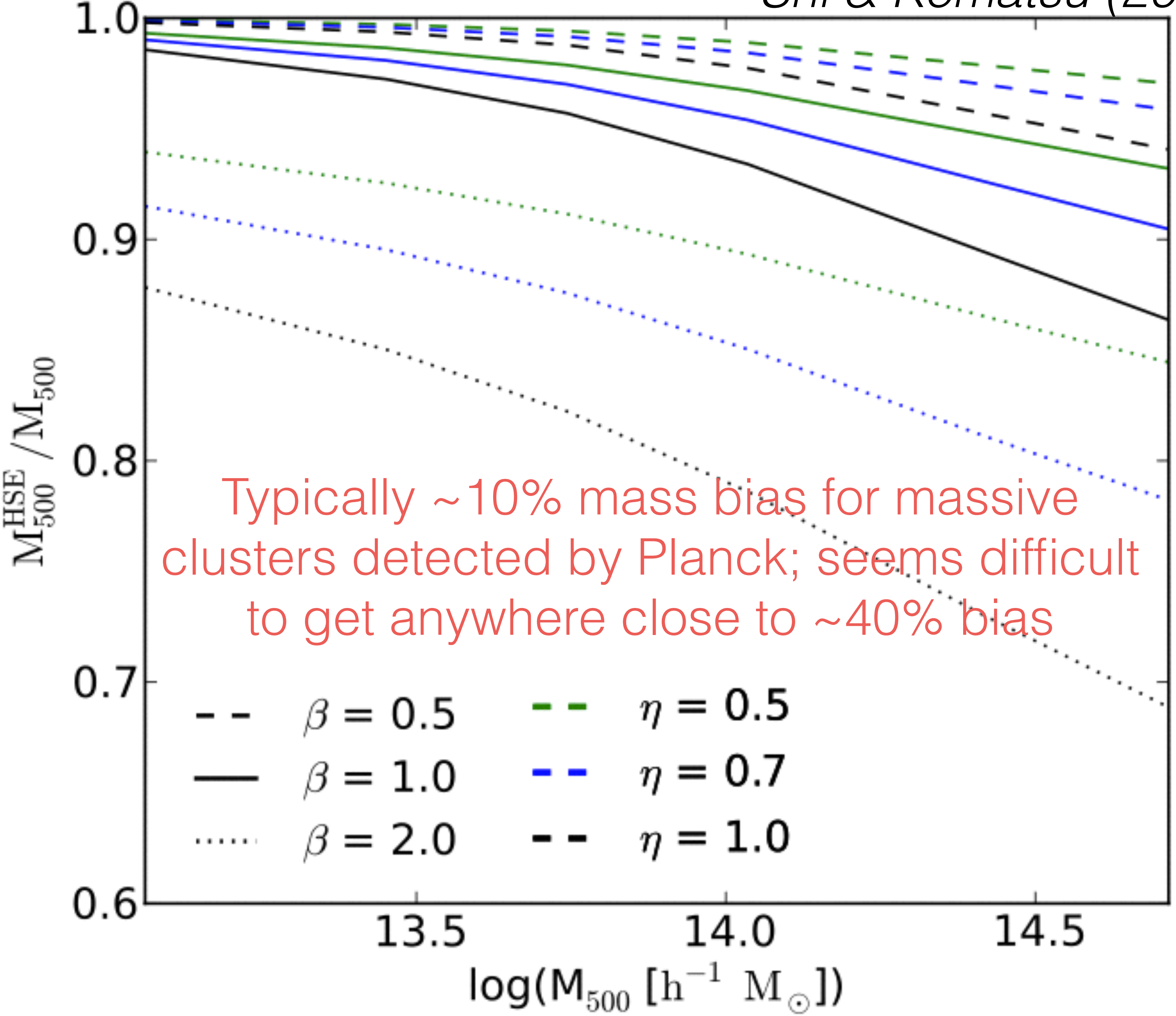
- We can now predict the X-ray and SZ observables, by subtracting $P_{non\text{-}thermal}$ from P_{total}, which is fixed by the total mass

- We can then predict what the bias in the mass estimation if hydrostatic equilibrium with thermal pressure is used


Shi & Komatsu (2014)
$M_{500}^{HSE} = 3*10^{14} h_{70}^{-1} M_{\odot}$
z = 0.1
Excellent match
with observations!
[black line versus green dashed]
total pressure
observed thermal
predicted
thermal
P_{th}, Arnaud
P_{th}, Planck
P_{tot}, $\beta=1$, $\eta=0.7$
P_{th}, $\beta=1$, $\eta=0.7$
P_{tot}, $\beta=1$, $\eta=1$
P_{th}, $\beta=1$, $\eta=1$
Pressure [eV/cm^3]
10^1
10^0
10^{-1}
0.2
0.5
1.0
2.0
r/r_{500}

Shi & Komatsu (2014)

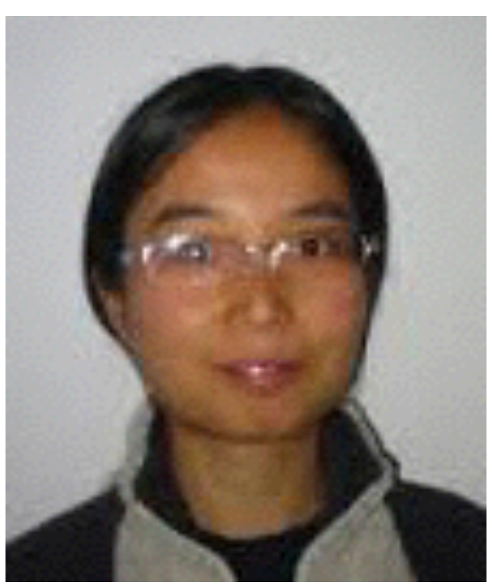
[Hydrostatic Mass] / [True Mass]



Part II:
Comparison to Simulation

Shi, Komatsu, Nelson & Nagai (2014)

Kaylea Nelson (Yale)



Xun Shi (MPA)

Cluster-by-cluster Comparison

- So far, the results look promising
- We have shown that the simple analytical model can reproduce simulations and observations on average
- But, can we reproduce them on a cluster-by-cluster basis?

Approach

- We solve

$$\frac{\mathrm{d}\sigma^2_{\mathrm{nth}}}{\mathrm{d}t} = -\frac{\sigma^2_{\mathrm{nth}}}{t_{\mathrm{d}}} + \eta\,\frac{\mathrm{d}\sigma^2_{\mathrm{tot}}}{\mathrm{d}t}$$

- Using the measured $\sigma_{tot}^2(t)$ from a simulation on a particular cluster, and predict the non-thermal pressure. We them compare the prediction with the measured non-thermal pressure from the same cluster

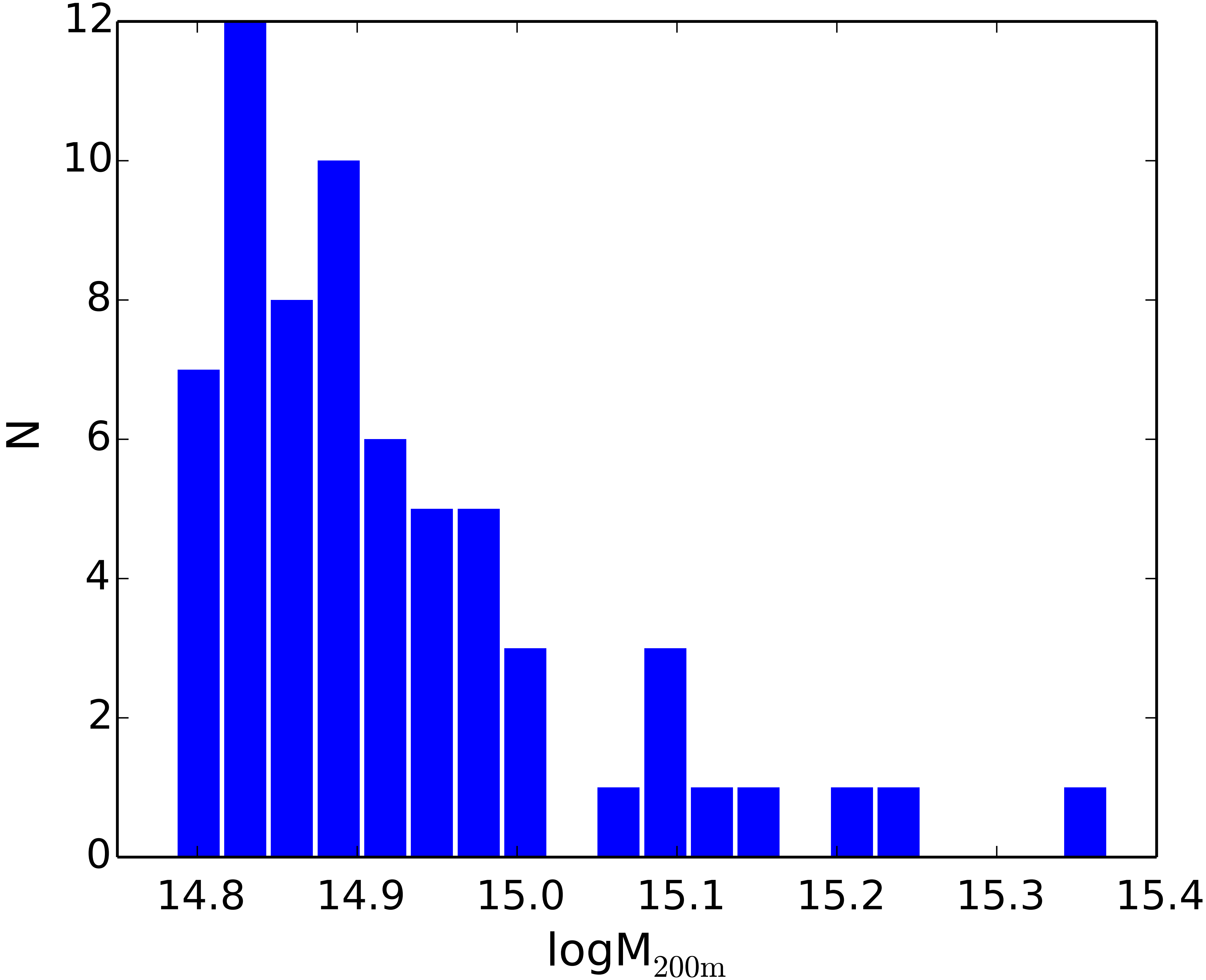
Nelson et al. (2014)

Omega500 Simulation

- A sample of 62 clusters simulated in a cosmological N-body+hydrodynamics simulation
  - Using the ART code of Kravtsov and Nagai
- 500/h Mpc volume
- 512^3 grids with refinements up to the factor of 2^8
  - Maximum spatial resolution of 3.8/h kpc

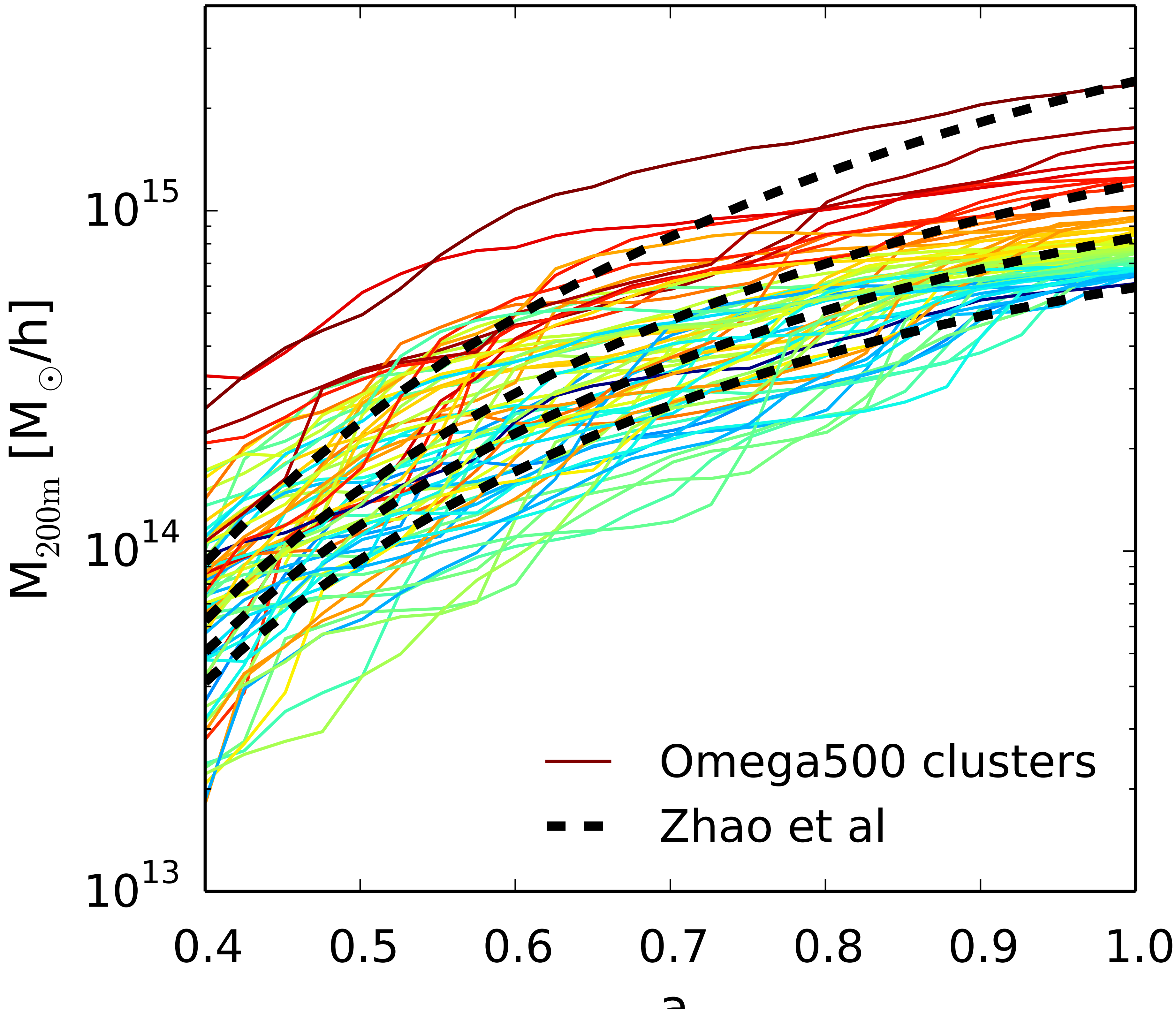
Nelson et al. (2014)

Omega500 Simulation



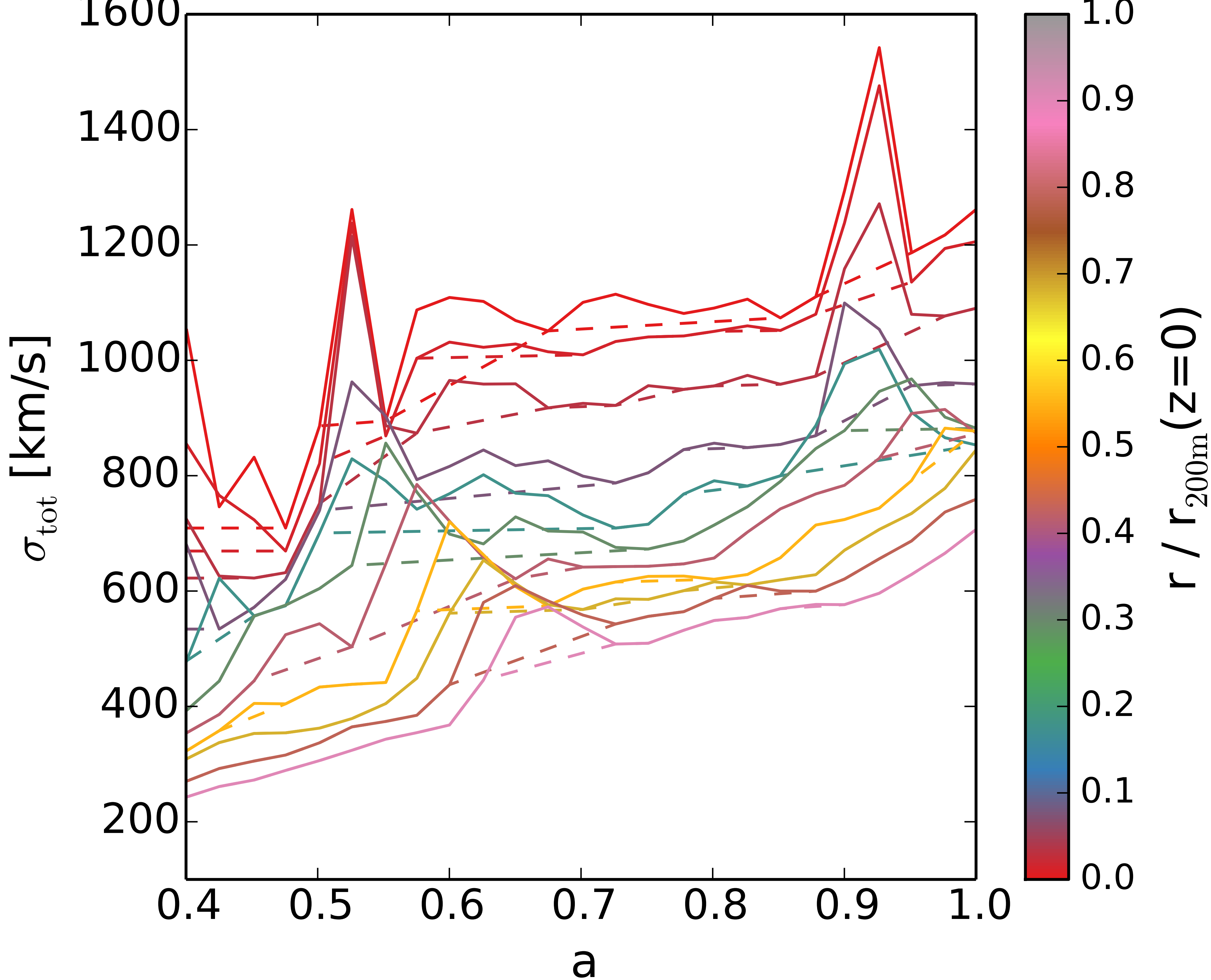
Shi, Komatsu, Nelson & Nagai (2014)

Mass growth history



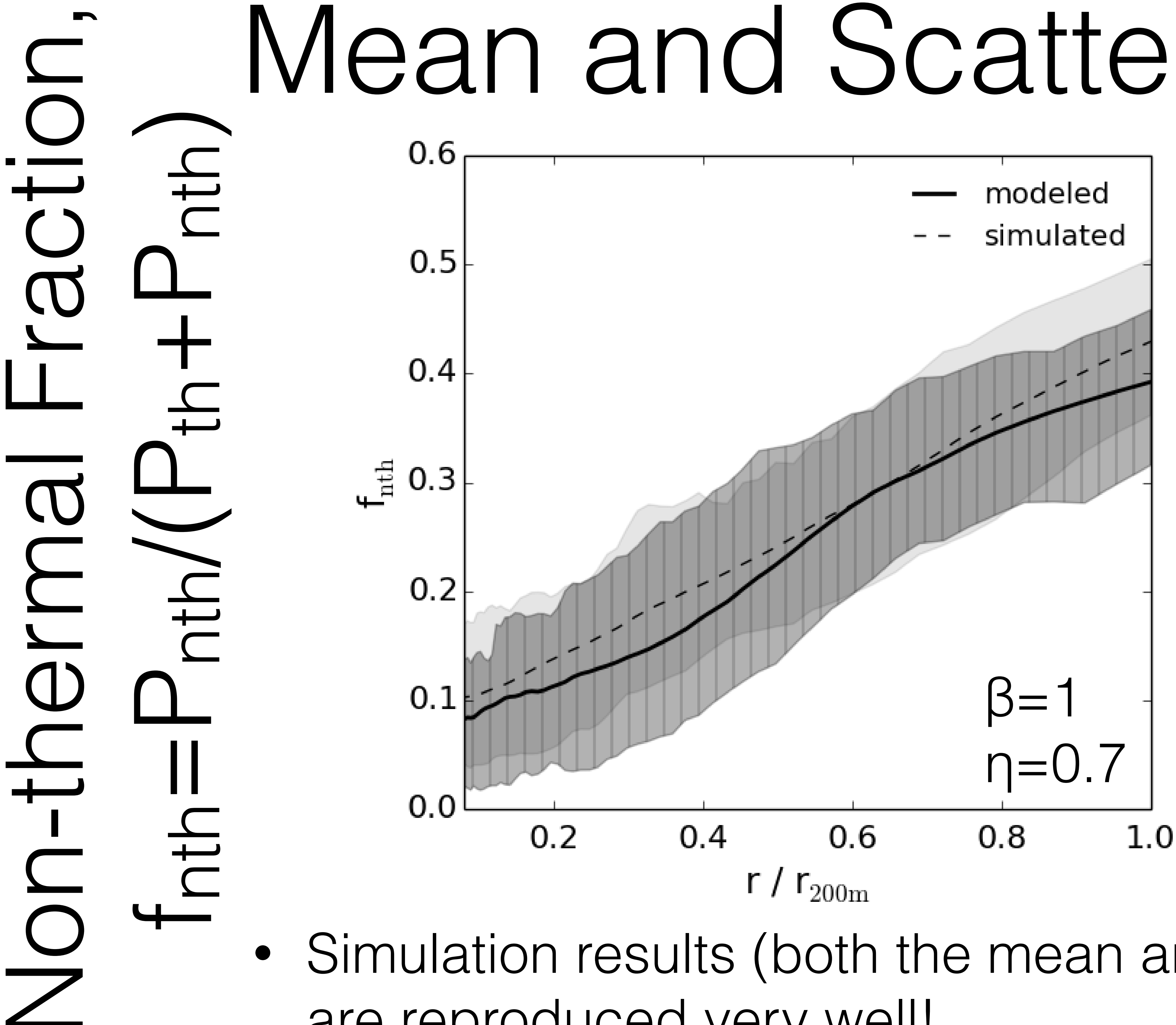
Shi, Komatsu, Nelson & Nagai (2014)

$\sigma_{tot}{}^2$ growth history



Shi, Komatsu, Nelson & Nagai (2014)

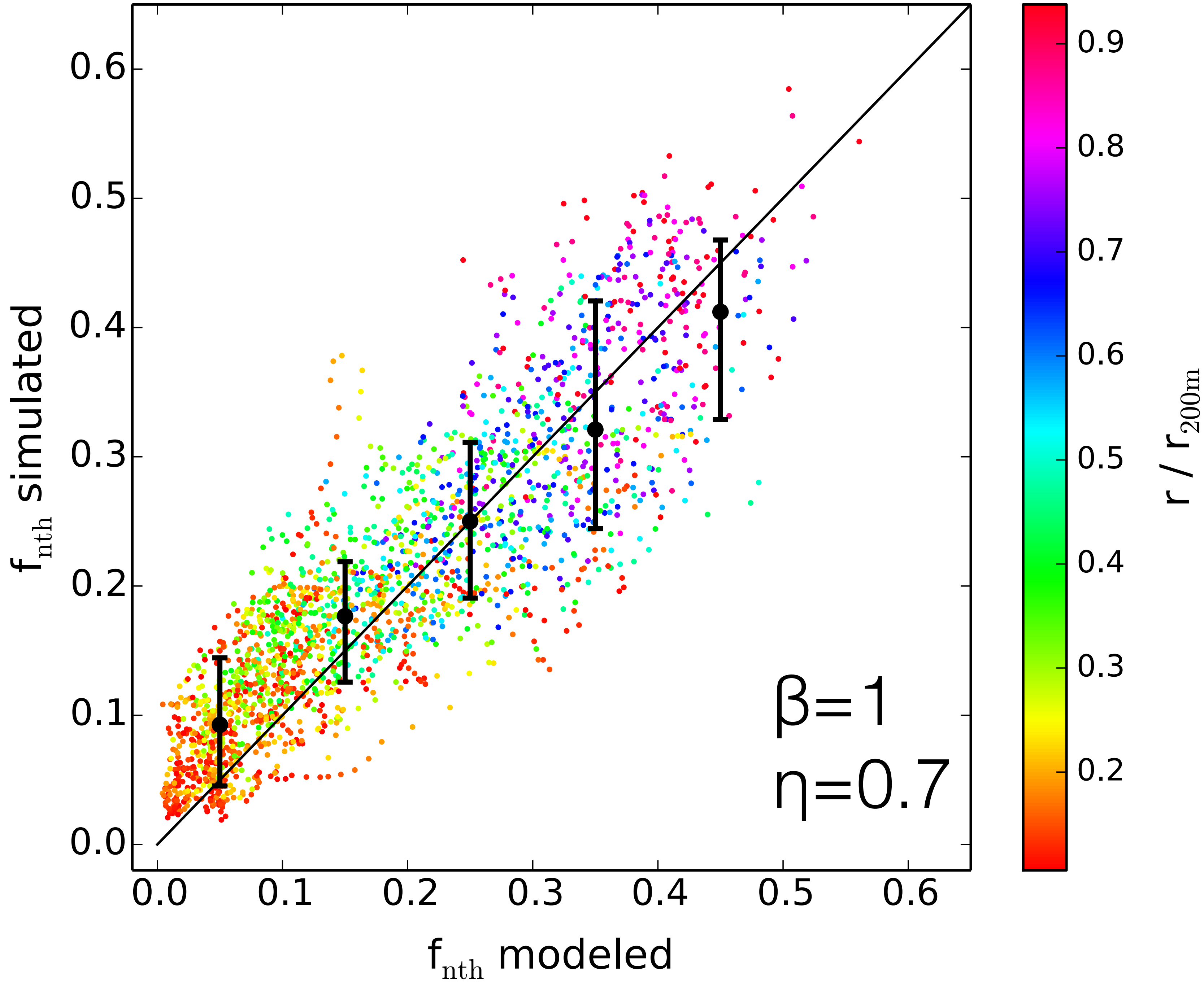
Mean and Scatter



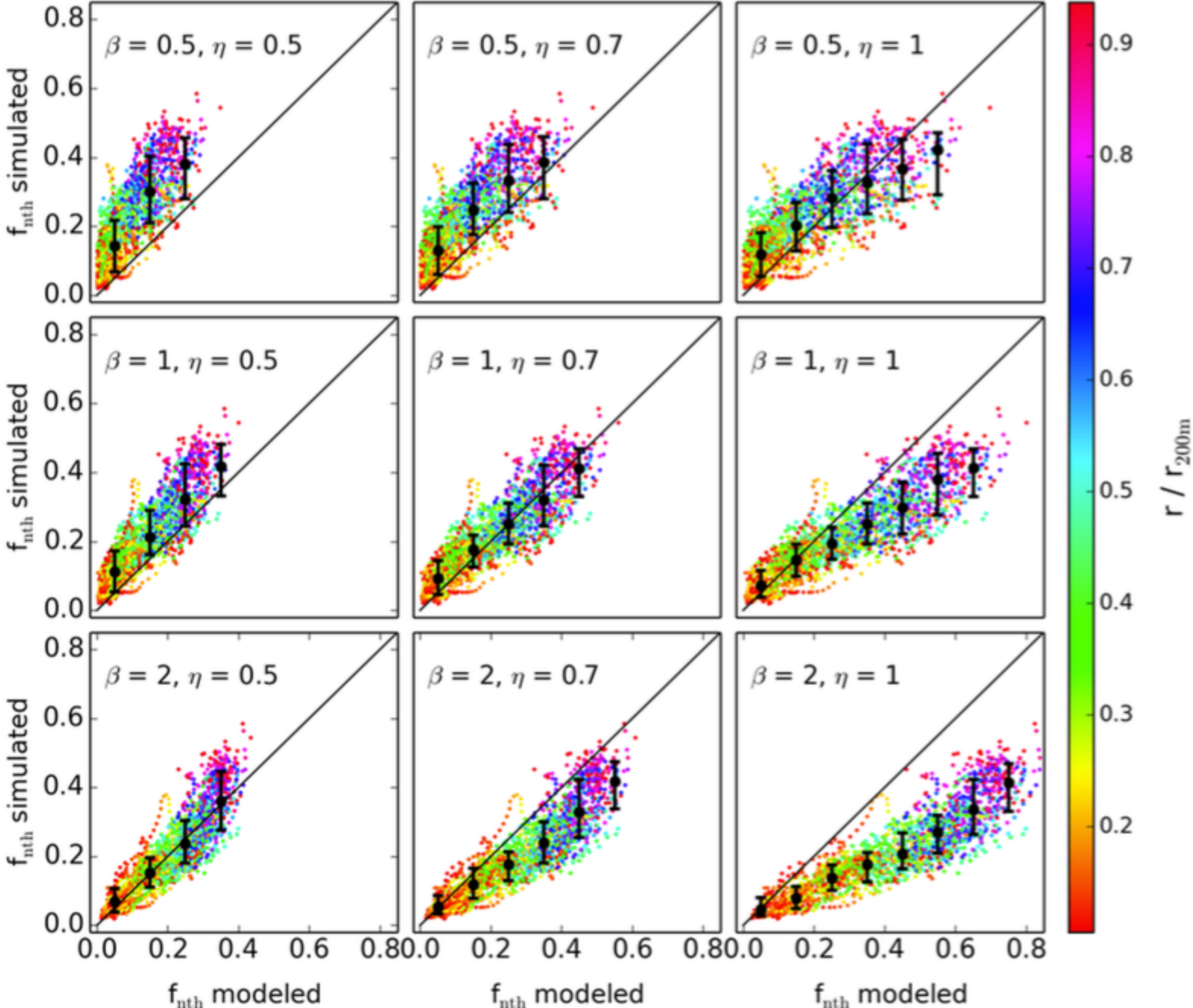
- Simulation results (both the mean and scatter) are reproduced very well!

Shi, Komatsu, Nelson & Nagai (2014)

Cluster-by-cluster



- The analytical model can predict the non-thermal fraction in **each cluster**



$\beta = 0.5$, $\eta = 0.5$
$\beta = 0.5$, $\eta = 0.7$
$\beta = 0.5$, $\eta = 1$
$\beta = 1$, $\eta = 0.5$
$\beta = 1$, $\eta = 0.7$
$\beta = 1$, $\eta = 1$
$\beta = 2$, $\eta = 0.5$
$\beta = 2$, $\eta = 0.7$
$\beta = 2$, $\eta = 1$
f_{nth} simulated
f_{nth} modeled
r / r_{200m}
0.0
0.2
0.4
0.6
0.8
0.9
0.7
0.5
0.3

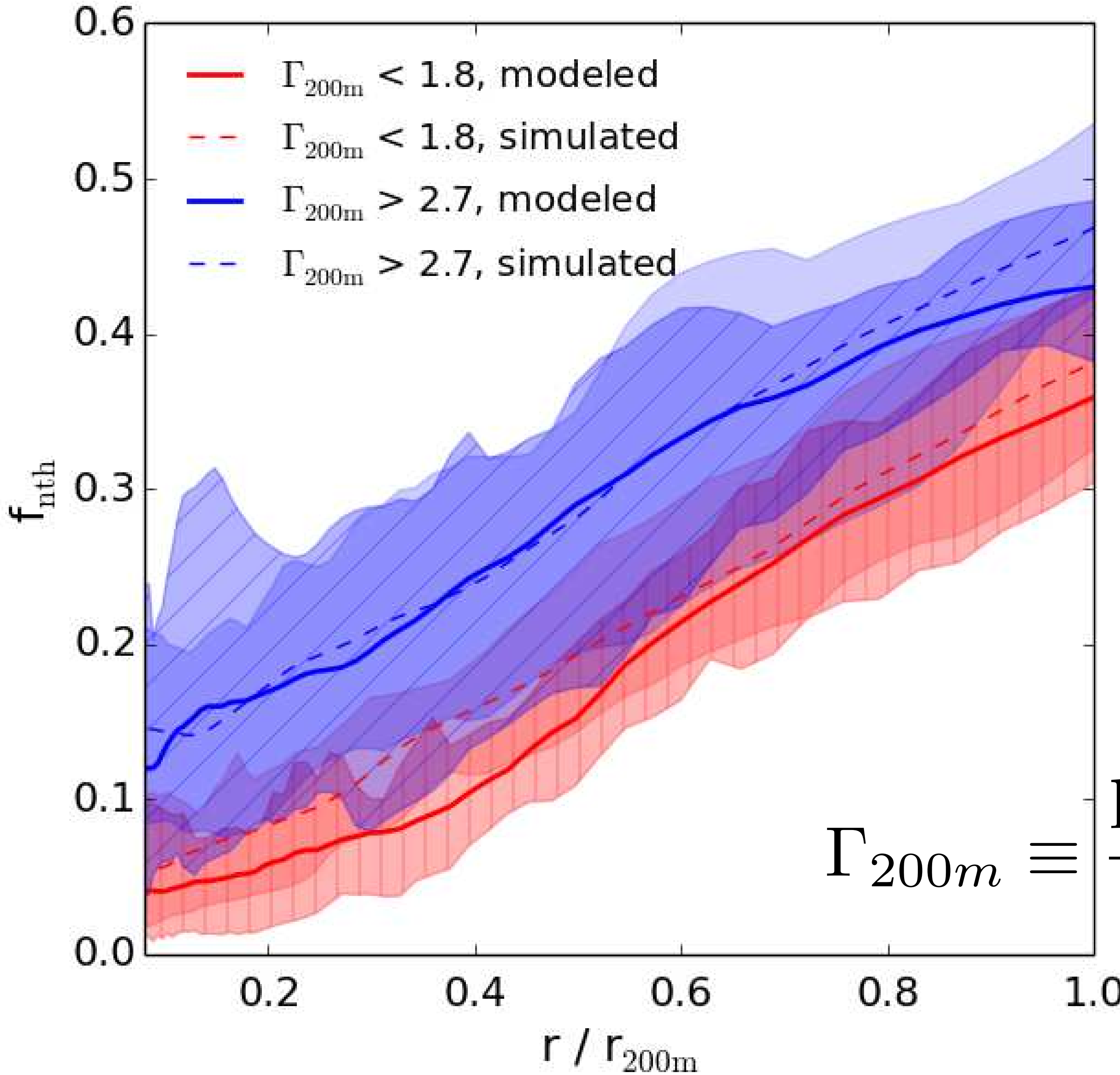
Dependence on the mass accretion history

- Separate the samples into “fast accretors” and “slow accretors” by using a mass accretion proxy:

$$\Gamma_{200m} \equiv \frac{\log[M(z=0)/M(z=0.5)]}{\log[a(z=0)/a(z=0.5)]}$$

Shi, Komatsu, Nelson & Nagai (2014)

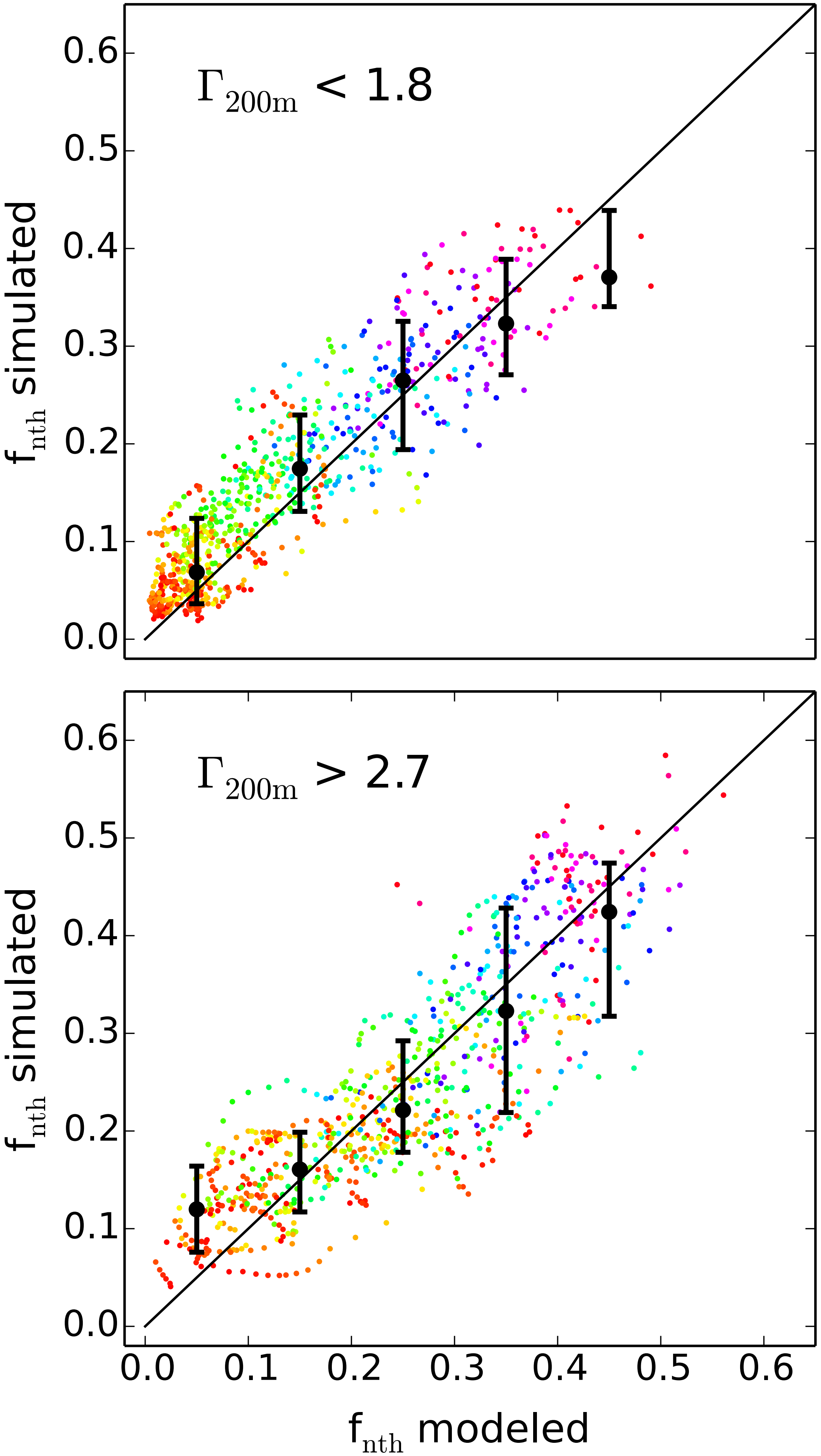
Dependence on the mass accretion history



- It is clear that fast accretors have larger non-thermal pressure, because the injection of non-thermal motion is more efficient while the dissipation time is the same

$$\Gamma_{200m} \equiv \frac{\log[M(z=0)/M(z=0.5)]}{\log[a(z=0)/a(z=0.5)]}$$

Shi, Komatsu, Nelson & Nagai (2014)



The model still works for fast accretors

- The model is able to reproduce the non-thermal fraction on a cluster-by-cluster basis for fast accretors
- The scatter is somewhat larger

Toward A Solution to the Hydrostatic Mass Bias Problem

– A Proposal –

All we need is the mass accretion history of a halo

$$\frac{d\sigma^2_{\rm nth}}{dt} = -\frac{\sigma^2_{\rm nth}}{t_{\rm d}} + \eta \frac{d\sigma^2_{\rm tot}}{dt}$$

- How do we estimate the source term (i.e., the second term on the right hand side)?
- The answer may be in the density profile in itself!

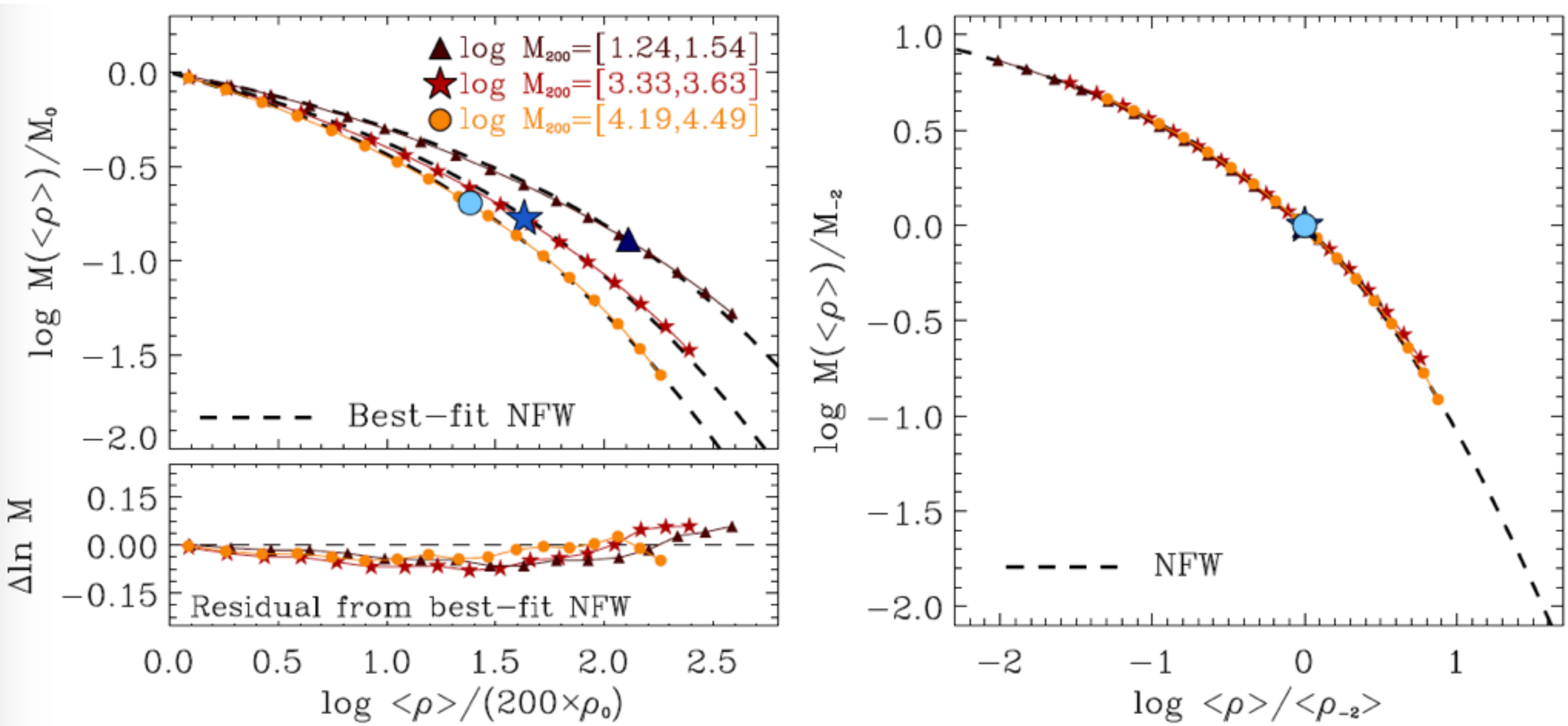
Ludlow et al. (2013)

NFW fits both

- Consider the density profile of a halo, ρ(r)
  - You can convert this into the mass, M, as a function of the mean density within a certain radius, <ρ>
- Consider the mass accretion history, M(z)
  - You can convert this into the mass, M, as a function of the critical density of the universe at the same redshift, $\rho_{crit}(z)$
- **Remarkably, they agree!**

Ludlow et al. (2013)

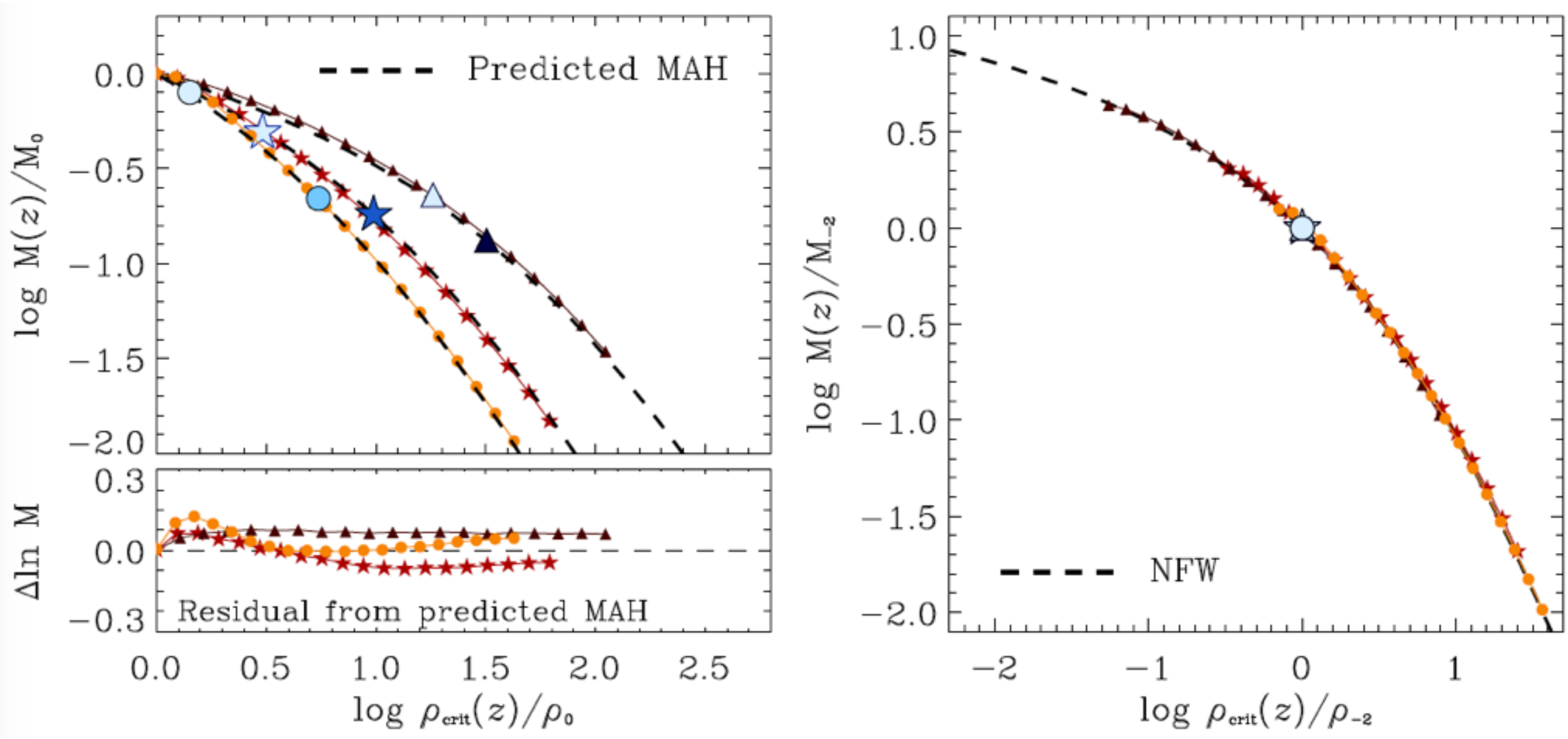
NFW fits both



- You can convert ρ(r) into the mass, M, as a function of the mean density within a certain radius, <ρ>

Ludlow et al. (2013)

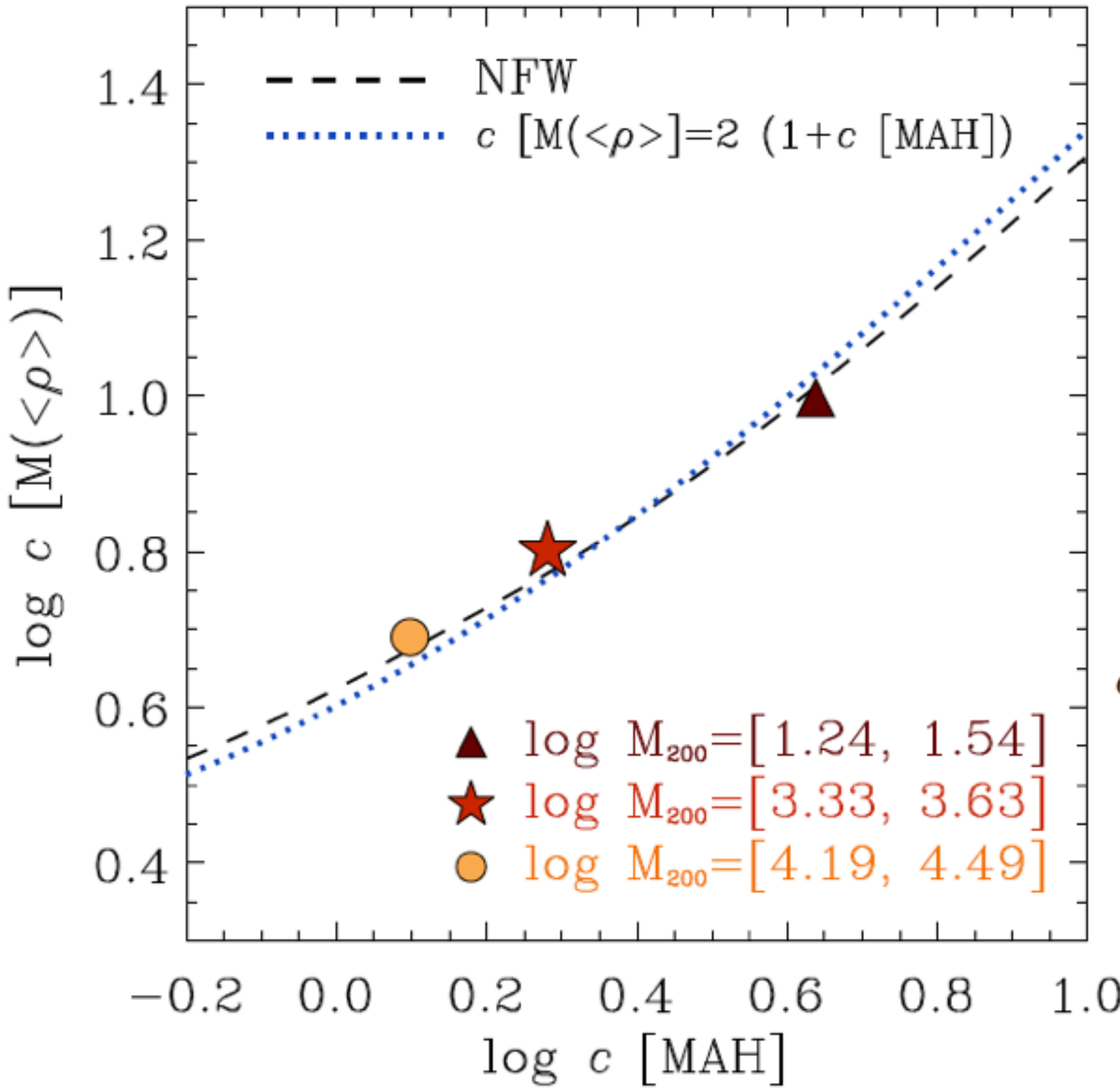
NFW fits both



- You can show M(z) as a function of the critical density of the universe at the same redshift, $\rho_{crit}(z)$

Ludlow et al. (2013)

Concentration Parameter Relation



- While the NFW profile fits both, their respective concentration parameters are different
- There is a [cosmology-dependent] relationship between them

$$c\,[\mathrm{M}\langle\rho\rangle] = a_1\,(1 + a_2 \times c\,[\mathrm{MAH}])^{a_3}$$

a_1	a_2	a_3
2.521	0.729	0.988

A Proposal

- Take the X-ray or SZ data
- Compute the mass density profile using the hydrostatic equilibrium $$\frac{1}{\rho_{\rm gas}(r)}\frac{\partial P_{\rm gas}(r)}{\partial r} = -\frac{GM(<r)}{r^2}$$
- Compute the mass accretion history from the inferred density profile
- Compute the non-thermal pressure profile from the mass accretion history

A Proposal

- Compute the non-thermal pressure profile from the mass accretion history

- Re-compute the mass density profile using the observed thermal pressure and the inferred non-thermal pressure $$\frac{1}{\rho_{\rm gas}(r)}\frac{\partial[P_{\rm th}(r)+P_{\rm non-th}(r)]}{\partial r} = -\frac{GM(<r)}{r^2}$$

- Re-compute the mass accretion history

- Re-compute the non-thermal pressure, and repeat

Summary

- A simple analytical model works!
  - In agreement with simulations and the Planck data on average
  - In agreement with simulations on a cluster-by-cluster basis
- We have a physically-motivated approach to correcting for the hydrostatic mass bias
  - It seems that the only missing piece at the moment is the cosmology dependence of the concentration parameter relationship