MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut
für Astrophysik

Analytical model for non-thermal pressure in galaxy clusters & its application to mass estimation

Xun Shi

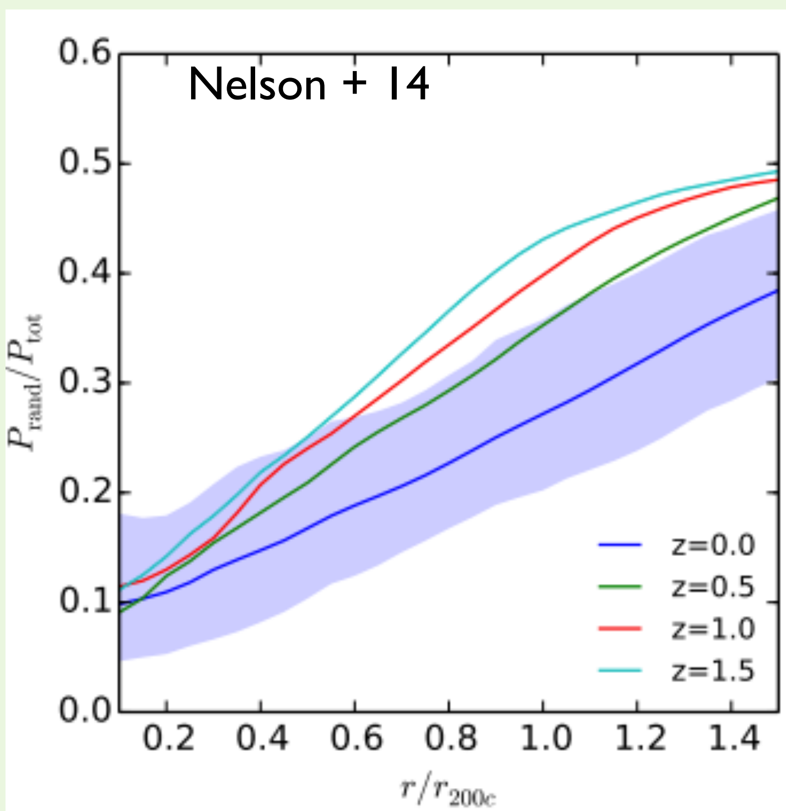
with Eiichiro Komatsu (MPA), Kaylea Nelson, Daisuke Nagai (Yale)

ICM physics and modeling, June 16th, 2015

Non-thermal pressure in galaxy clusters

Hydro simulations find kinetic pressure in the ICM

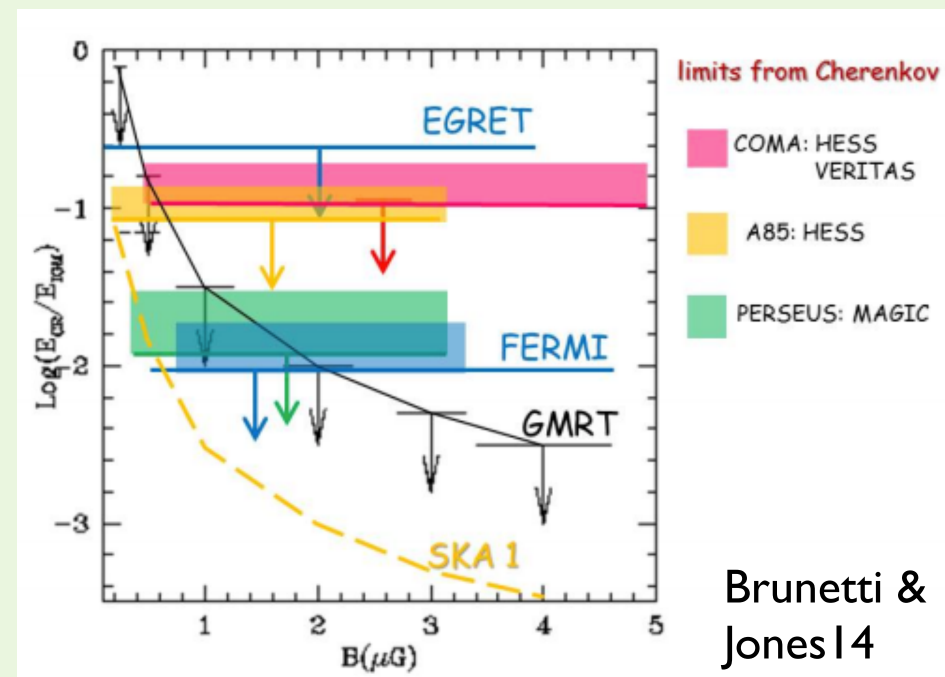
- increasing fraction with radius
- of order 20% at r_{500}



Evrard90, Rasia+04,12, Dolag+05, Nagai+07, Lau+09, Battaglia+12...

$P_{\rm rand}$: the major known physical contributor to the HSE mass bias

- B field contribution unclear but not dominating
- CR upper limits already tight



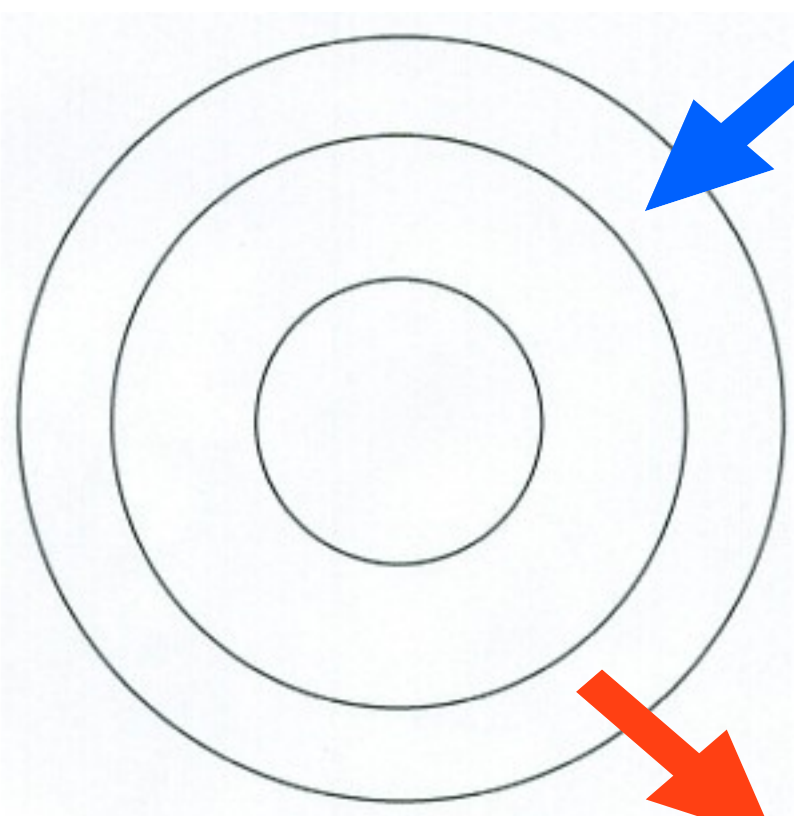
$P_{\rm rand}$ hard to observe (esp. at large radii where cluster masses are estimated)

see Zhuraveleva and Vacca's talks, though

Analytical model for P_{rand}

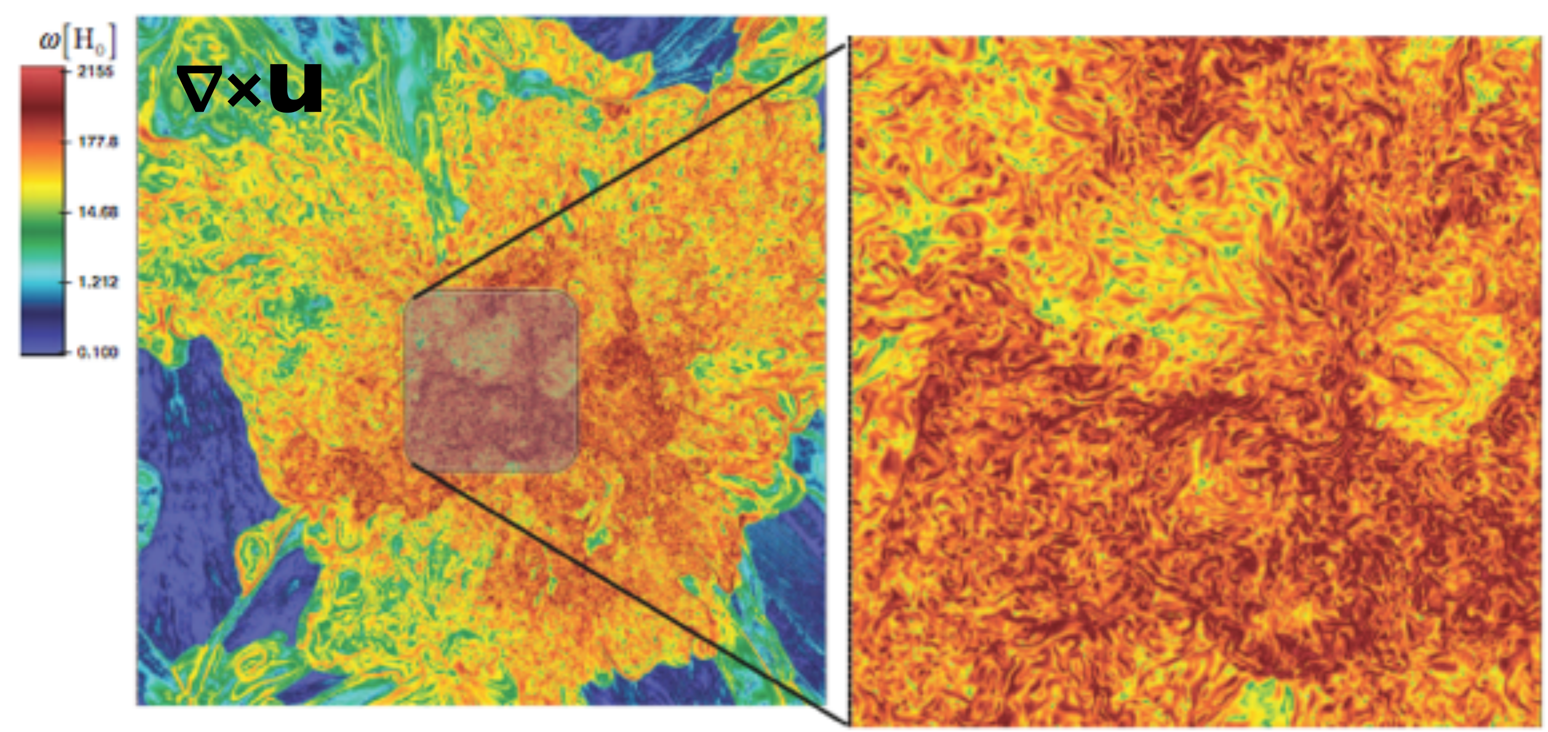
Is this possible ... ?

Injection



1d model of P_{rand} Dissipation

Miniati13, the Matryoshka run



turbulent ICM

Pressure ~ energy density

Our model

Injection & dissipation of random kinetic energy

at Eulerian positions

$$\frac{d\sigma^2_{\rm nth}}{dt} = \boxed{-\frac{\sigma^2_{\rm nth}}{t_{\rm d}}} + \boxed{\eta \frac{d\sigma^2_{\rm tot}}{dt}} \cancel{+ [\text{Diffusion}] + [\text{Advection}]}$$

average over large regions

$\sigma_{nth}^2 = P_{rand} / \rho_{gas} \propto E_{rand}$ per unit mass

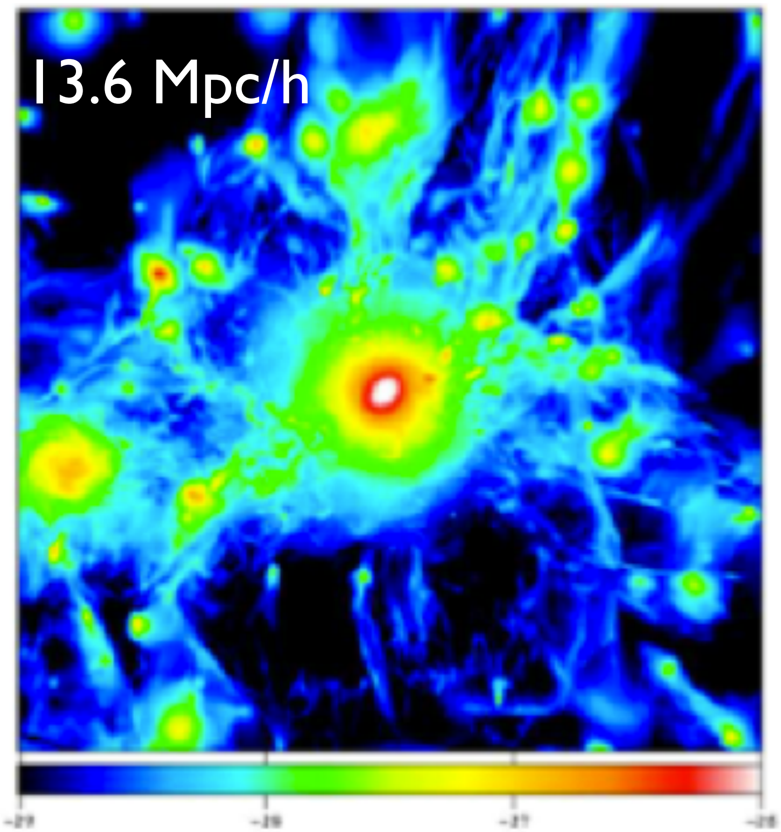
dissipation injection

Shi & Komatsu 2014

Injection

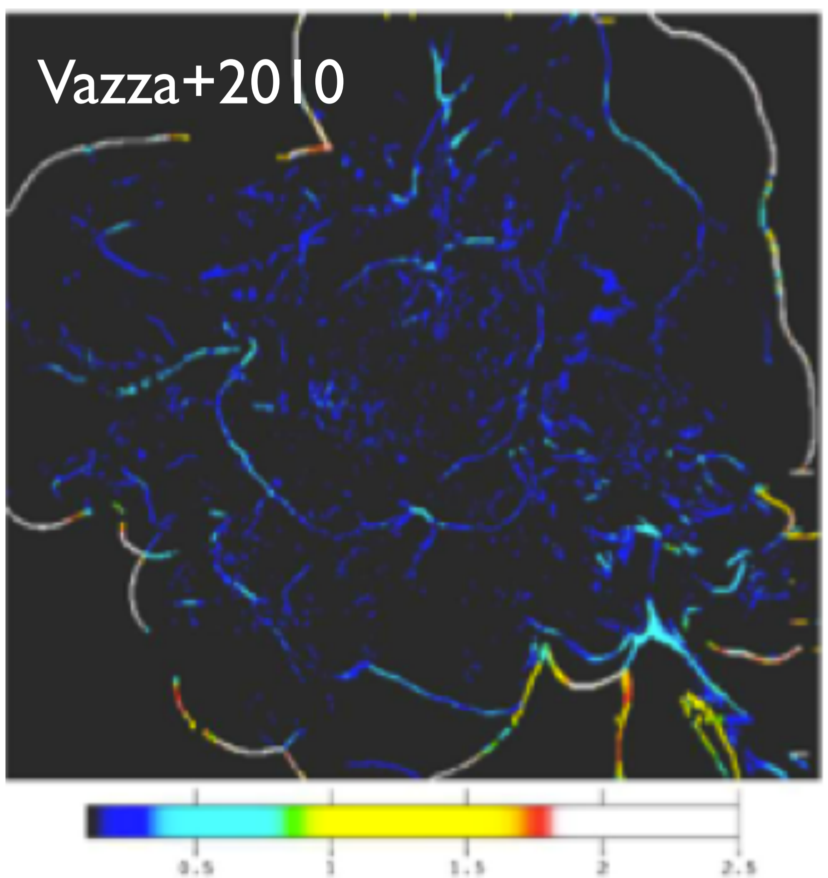
But *WHERE* and *HOW* ?

Original source of energy: <u>gravitational energy of infalling material</u>



1e-29 1e-26

Gas density



M=3 M=100

Mach number of shocked cells

A previous idea: Cavaliere +11: $E_{kin} \rightarrow E_{th} + E_{rand}$ at accretion shock

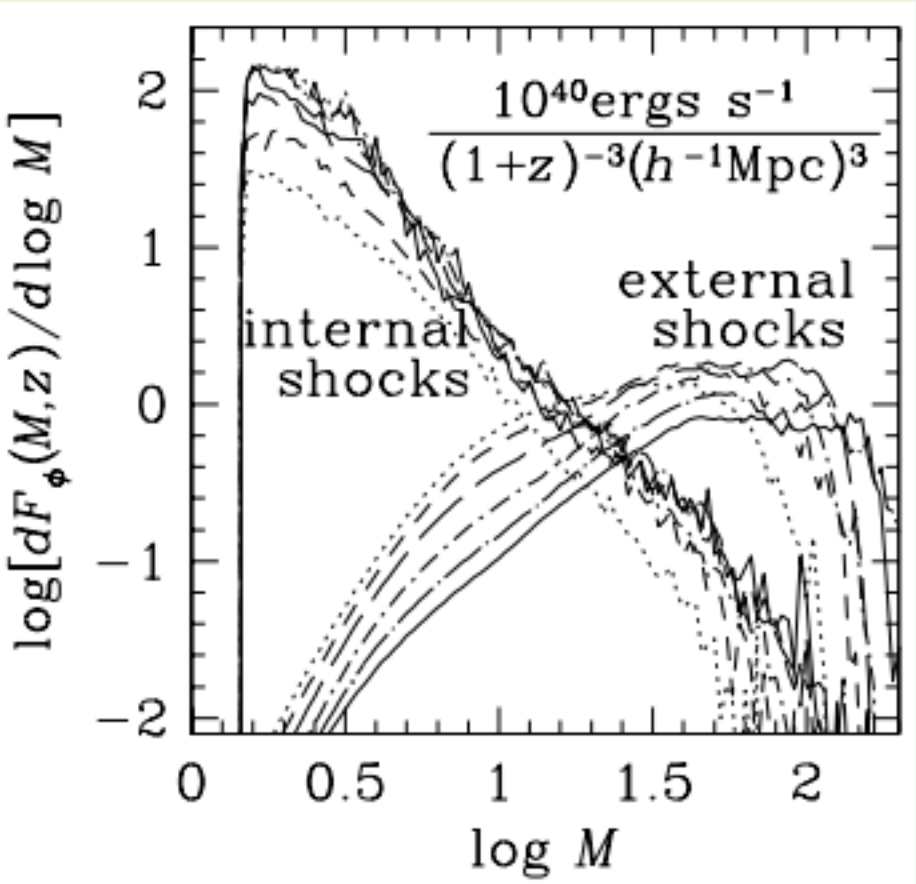
Injection

WHERE and *HOW* ?

Our idea: trace the bulk of energy flow

Low Mach number internal (merger) shocks process more kinetic energy

kinetic energy flux



Ryu+03, see also Pfrommer+06

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

injection

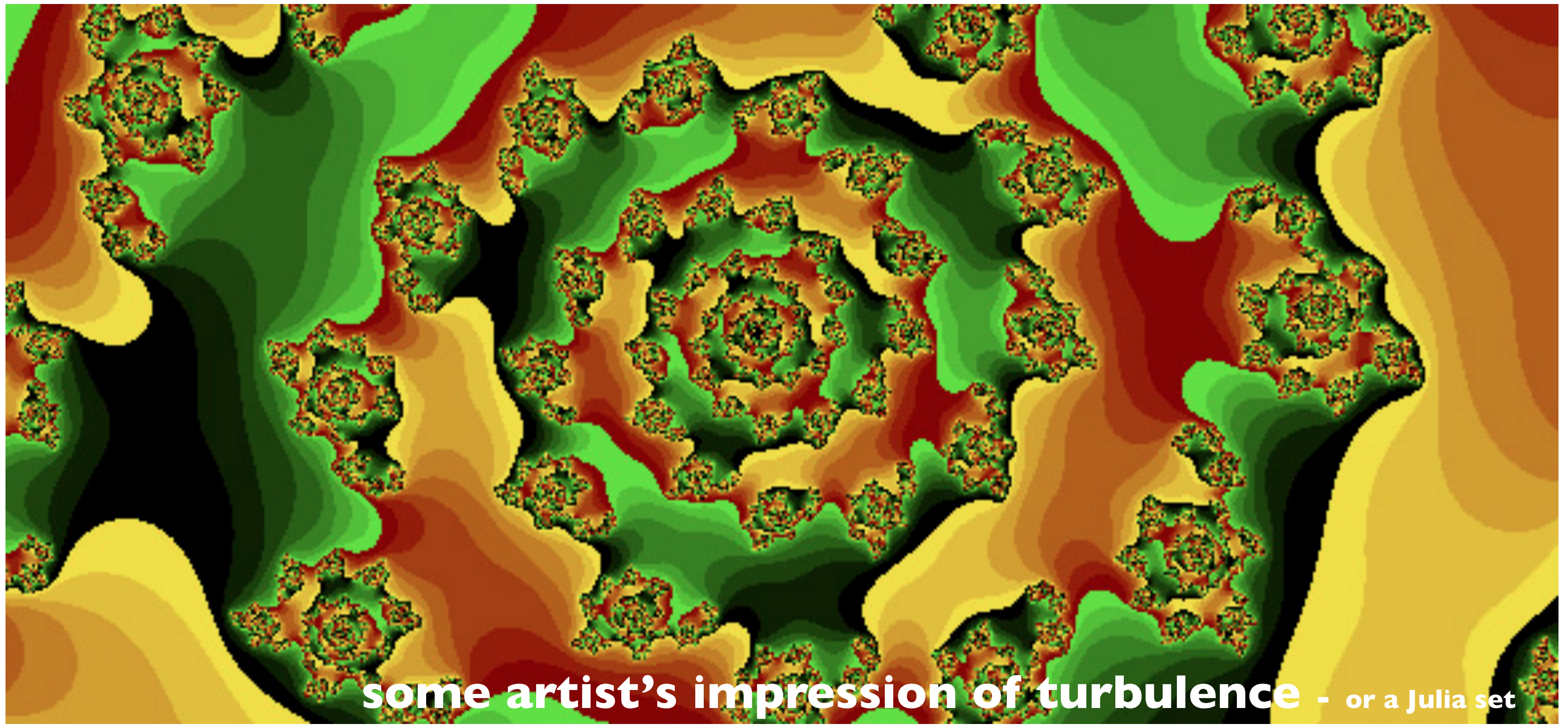
same source responsible for the heating of ICM, and synchronized with growth of gravitational potential

$\sigma_{tot}^2 = \sigma_{th}^2 + \sigma_{nth}^2 \quad \sim T \sim \phi$

efficiency $\eta \lesssim 1$ (characteristic of weak shocks)

Dissipation

Time scale determined by the turnover time of the largest eddies
- doesn't depend on how viscosity works on small scales



"Big whorls have little whorls
That feed on their velocity;
And little whorls have lesser whorls
And so on to viscosity"

-- Lewis F. Richardson
Weather prediction by numerical processes (1922)

$$t_d = \beta\, t_{dyn} / 2$$

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

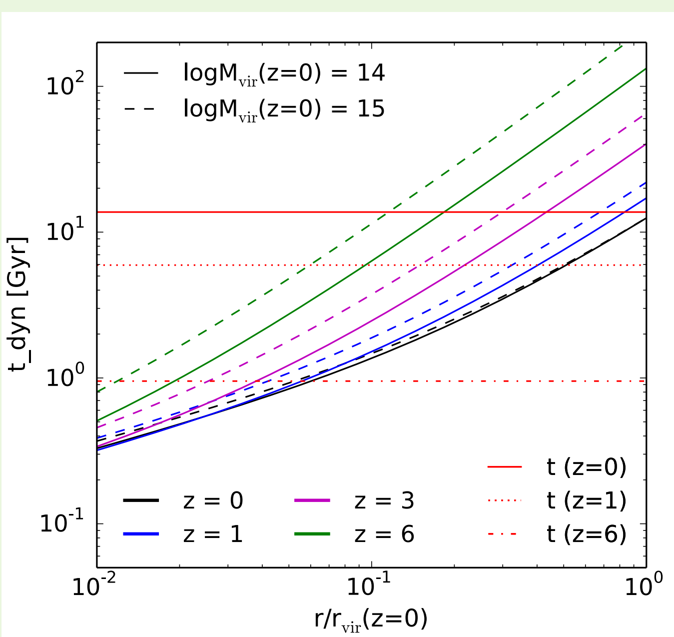
Properties of non-thermal fraction f_{nth}

$$t_{growth} = \frac{\sigma_{tot}^2}{d\sigma_{tot}^2/dt} \approx \frac{M}{Mdot}$$

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

growth rate dependence

dissipation injection



radial dependence

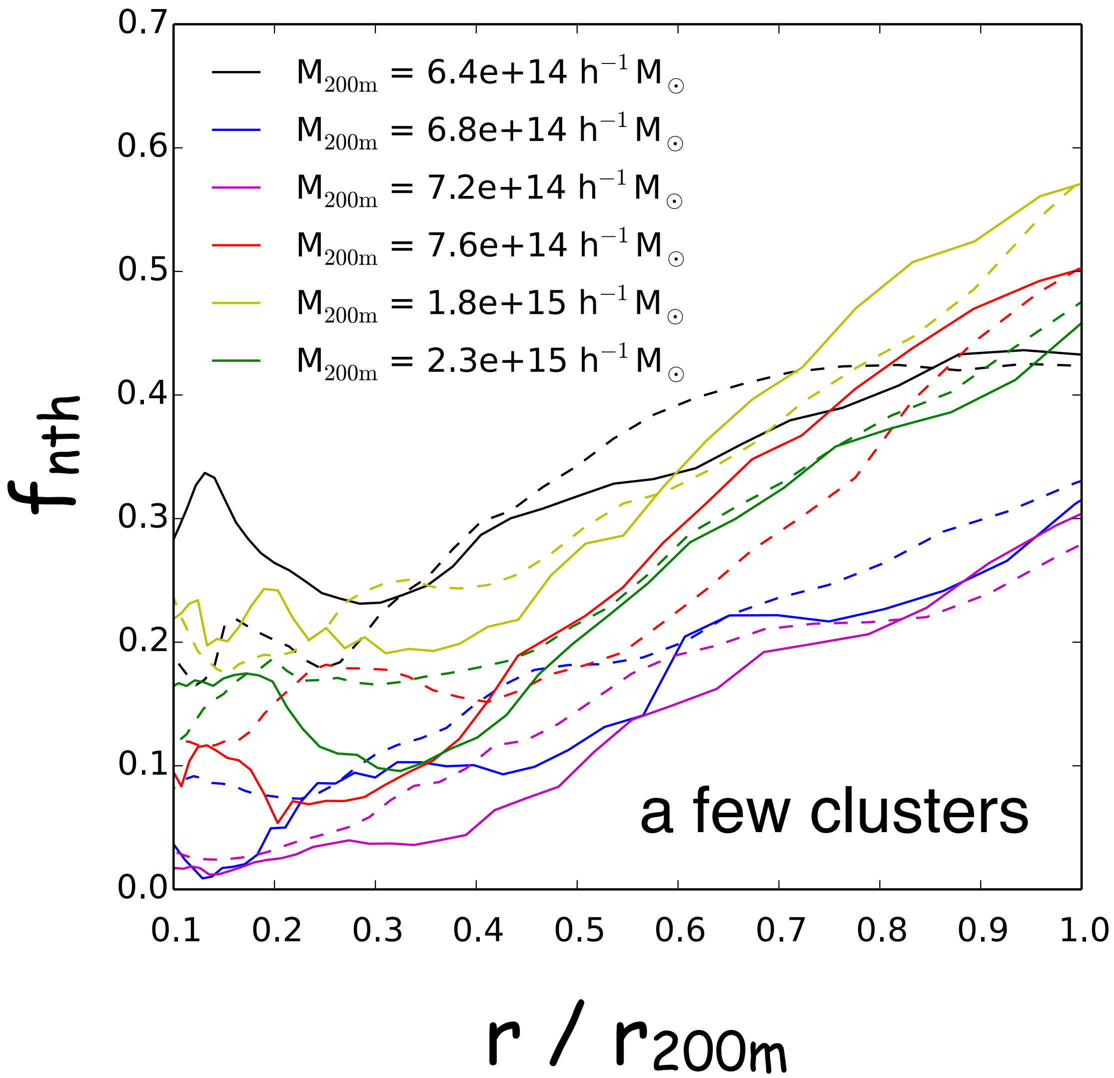
attractor of f_{nth} at : $f^{lim}_{nth} = \eta \frac{t_d}{t_d + t_{growth}}$

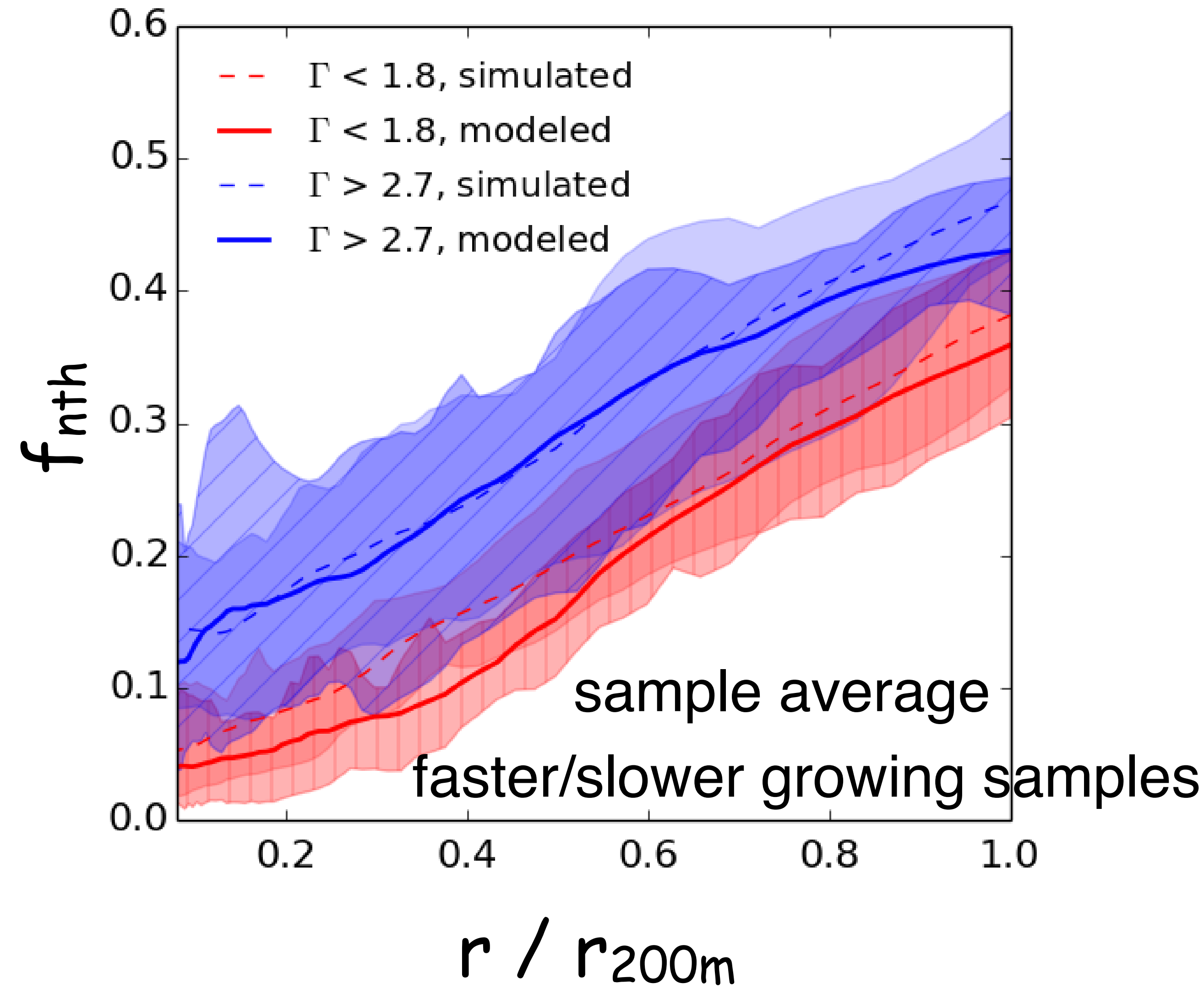
Predicted non-thermal fraction vs simulations

A mass-limited sample of 65 simulated clusters at z=0

Omega500 simulation (Nelson+14)

use $\sigma_{tot}(r,t)$ from simulation as input





reproduce the variation among clusters

both mean & scatter match;
confirms the relation between f_{nth} & growth rate

note: not all relaxed

Shi, Komatsu, Nelson, Nagai, 2015

From non-thermal pressure to mass bias

- How well can we correct for HSE mass bias using predicted P_{rand} ?
- If we know the accretion histories, can we correct for individual clusters ?

P_{rand}

depends (~10% for relaxed clusters) on the particular pipeline used for estimating the mass (since ICM has structures)

mass bias

$$M_{\rm HSE}(<r) \equiv -\frac{r^2}{G\rho_{\rm gas}(r)}\frac{\partial P_{\rm th}}{\partial r}$$

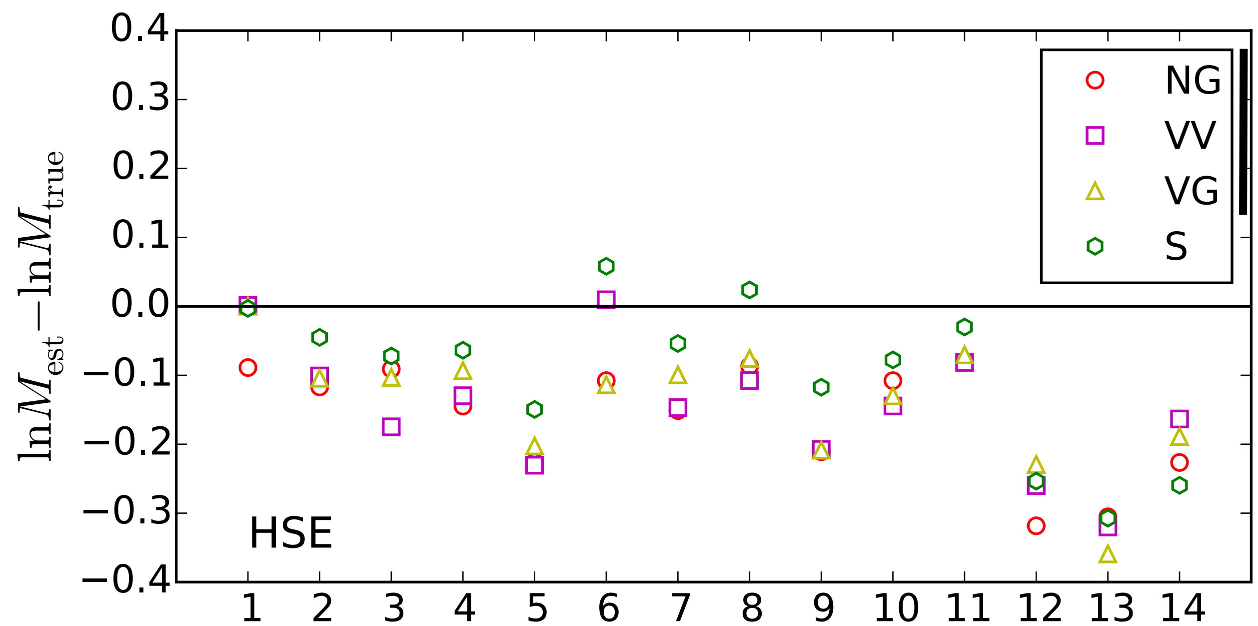
$$M_{\rm corr}(<r) \equiv -\frac{r^2}{G\rho_{\rm gas}(r)}\frac{\partial P_{\rm tot}}{\partial r}$$

the curse of derivative and division
- fitting / smoothing necessary

HSE mass of rather relaxed clusters:

5-10% scatter among different methods

M500

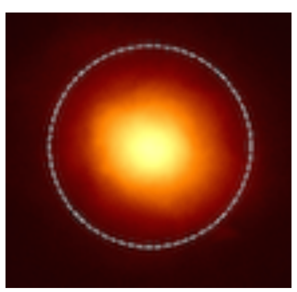


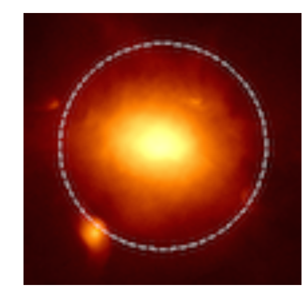
different fitting methods

spline smoothing

most relaxed

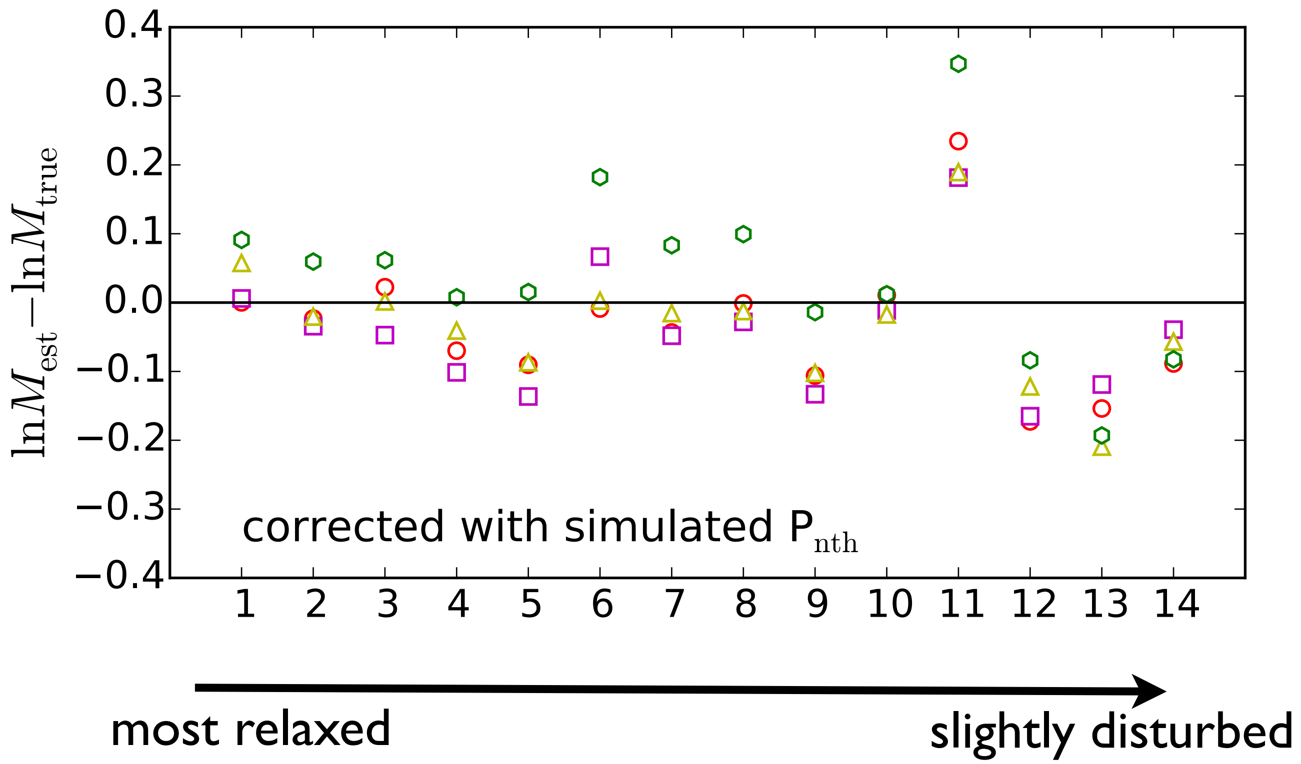
slightly disturbed





top relaxed 14/65 from X-ray mock of Omega500 clusters

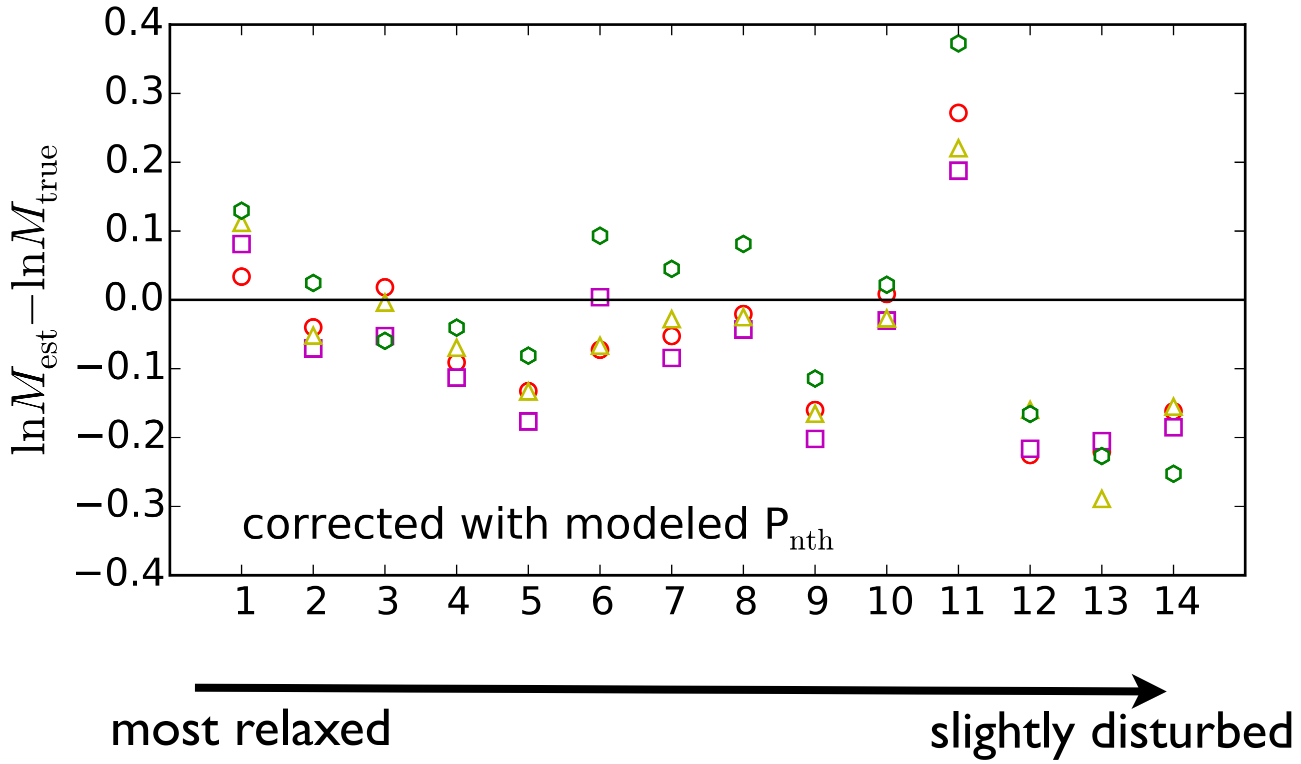
Corrected mass using <u>simulated</u> P_{rand}: much less biased on average



top relaxed 14/65 from X-ray mock of Omega500 clusters

What causes the residues? probably density structure and accelerations

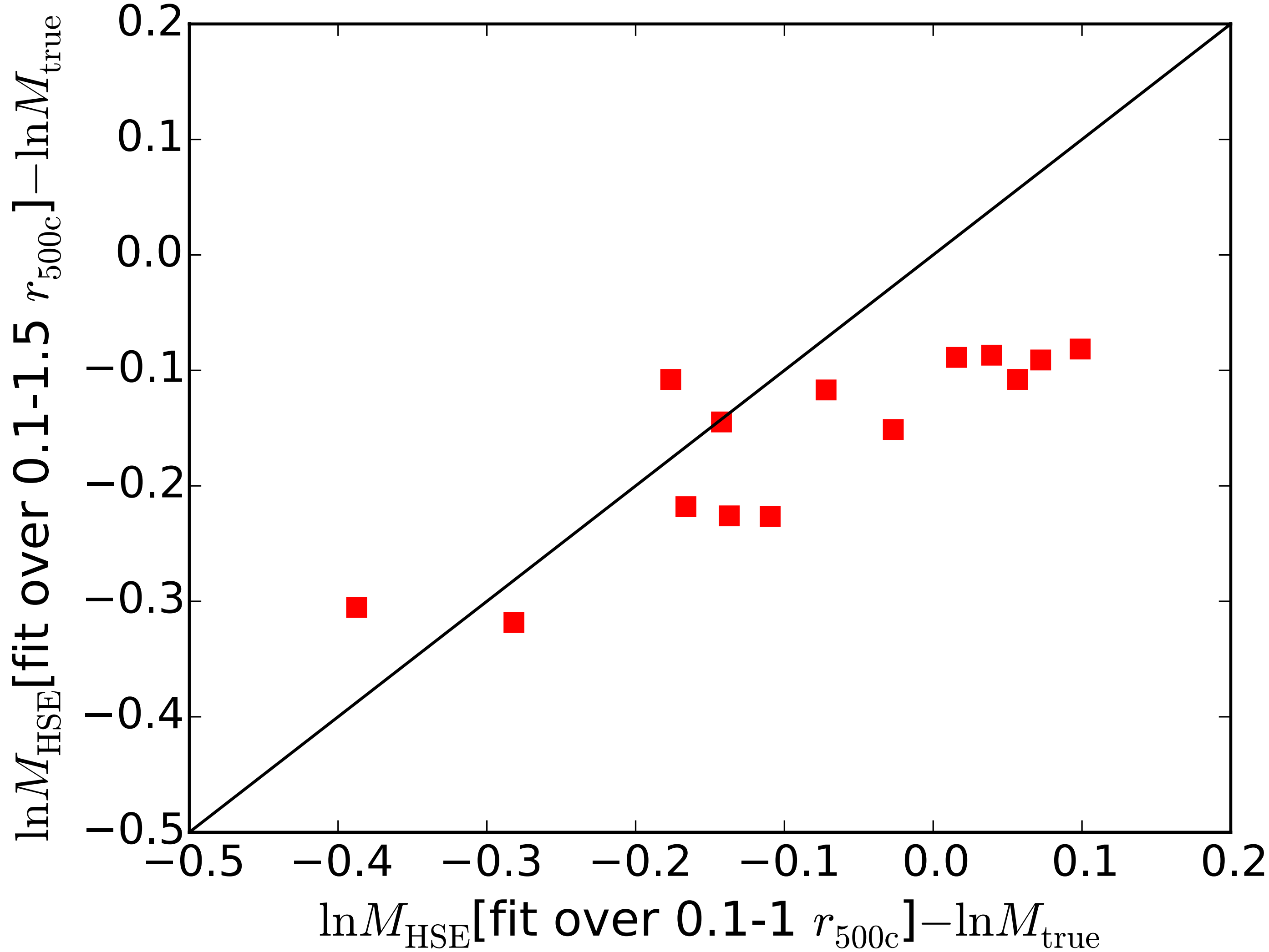
Corrected mass using <u>predicted</u> P_{rand}: much less biased on average, a bit more scatter



top relaxed 14/65 from X-ray mock of Omega500 clusters

5-10% scatter between different fitting limits (r500 or 1.5 r500)

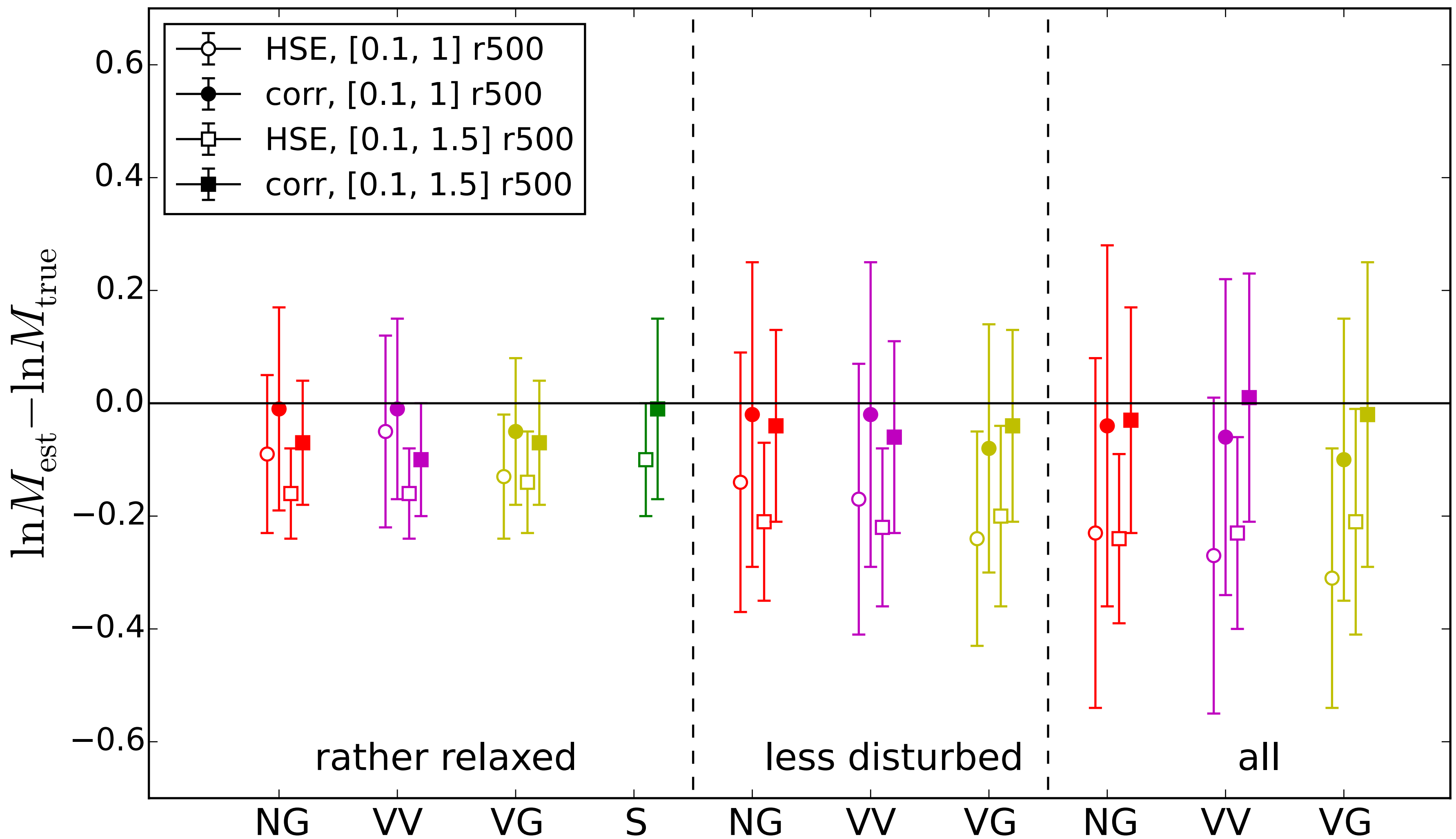
M500



M500

On average: larger bias when *fitting to larger radii*
(non-thermal pressure more prominent)

Correction works well for the sample mean, irrespective of methods, fitting range, or even dynamical state of the sample



top 20% ‘relaxed’ top 50% ‘relaxed’ 100% of the mass-limited sample

Using predicted $P_{\rm rand}$

Conclusions

A physical motivated 1d model for non-thermal pressure without free parameters,

Key elements:
- Infall kinetic energy converts to turbulence (η) + thermal energy (1- η), mostly by weak internal shocks
- Injected turbulence dissipates with a time scale $t_d \propto$ eddy turnover time $\propto$ dynamical time

Captures behaviors in hydro simulations,

Improves cluster mass estimation

- correcting for individual cluster seems hard due to real life complications
- good for the sample mean in all cases