AGN Feedback and Scatter in Galaxy Cluster Mass-Observable Relations

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Outline

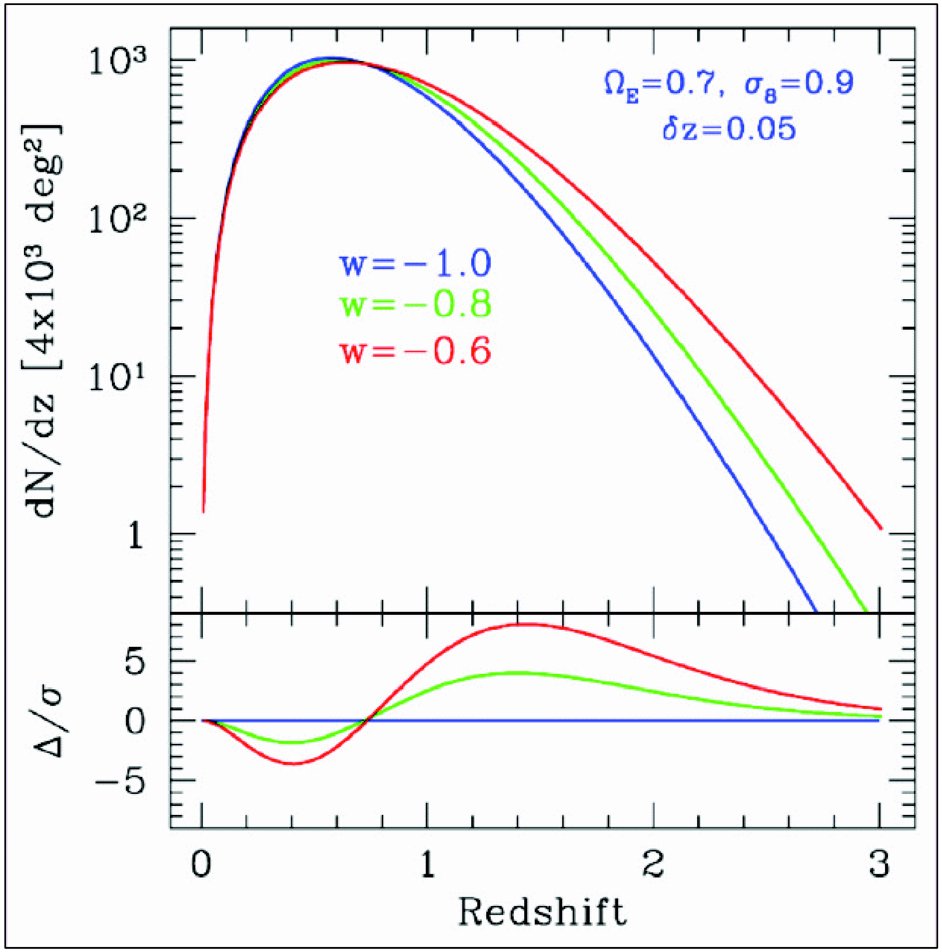
- Cluster scaling relations and cosmology
- Effects of cluster dynamics
- Modeling AGN feedback
- Effects of AGN feedback
- Conclusions

Galaxy clusters as cosmological probes

Cluster abundance as a function of mass and redshift

$$\frac{d^2 N}{dM\,dz} = \frac{dV}{dz} n(M,z)$$

$$n(M,z) \propto \frac{\rho_b}{\sigma M} \int_{\delta_c}^{\infty} d\delta\, \exp\left(-\frac{\delta^2}{2\sigma^2}\right)$$



Mohr (2005)

Depends on:

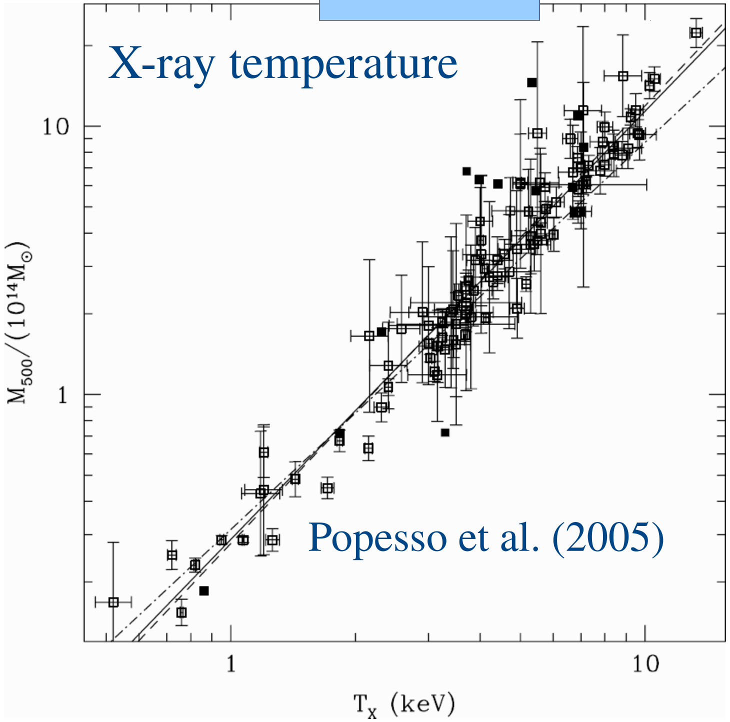
- Volume-redshift relation *dV*/*dz*
- Linear growth factor (→ δ(*z*))
- Power spectrum (→ σ(*M*,*z*))

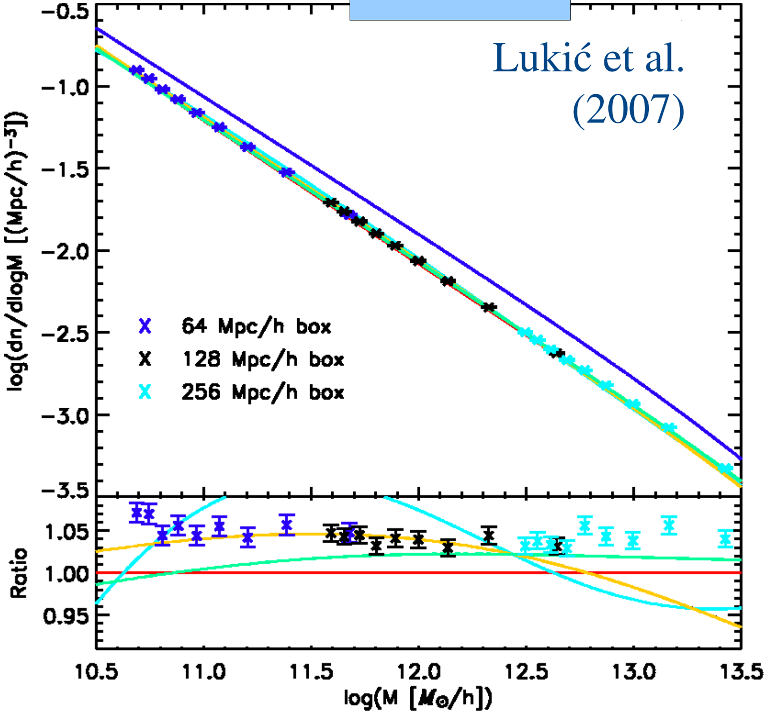
Cluster masses must be measured using proxies

$$P(X|\text{cosmology}) \approx \underbrace{P(X|M,\eta_1,\eta_2,\ldots)}_{\text{Mass-observable relation}}\ \underbrace{P(M,\eta_1,\eta_2,\ldots|\text{cosmology})}_{\text{Mass function}}$$

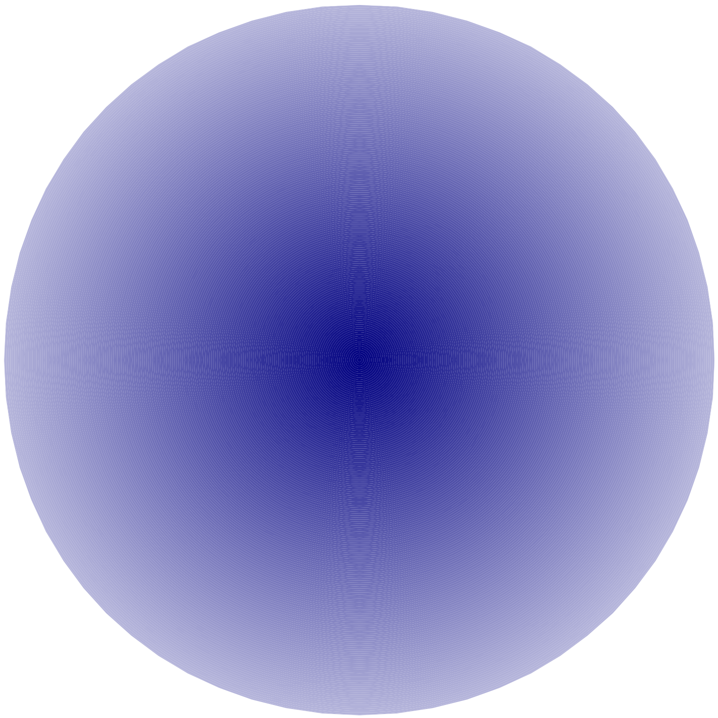
Scaling relations

N-body

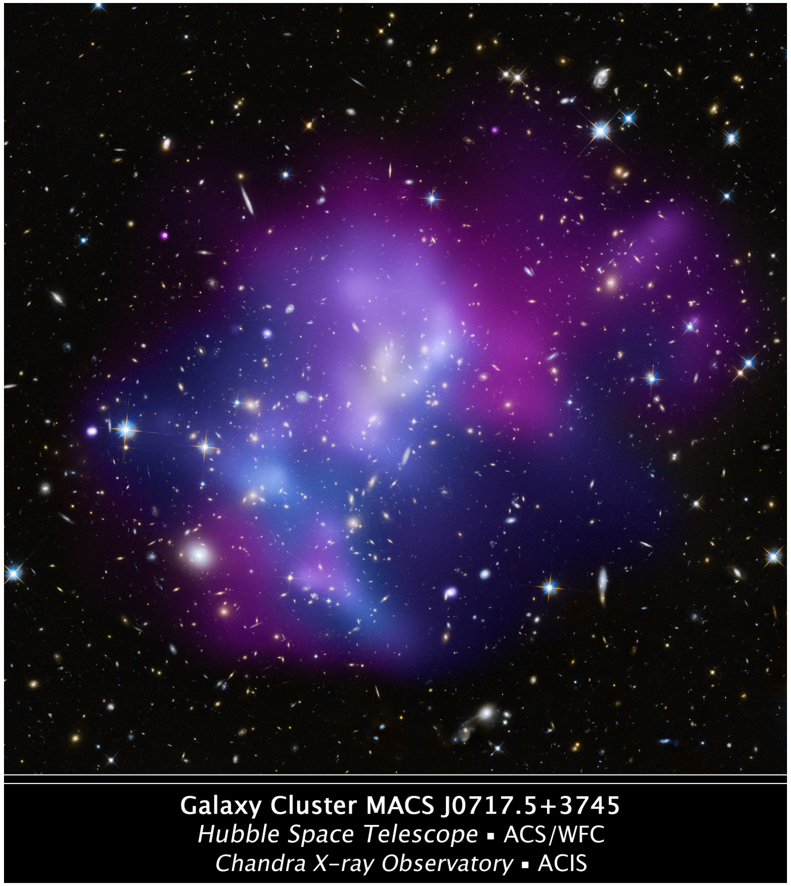




Galaxy clusters



Theory view



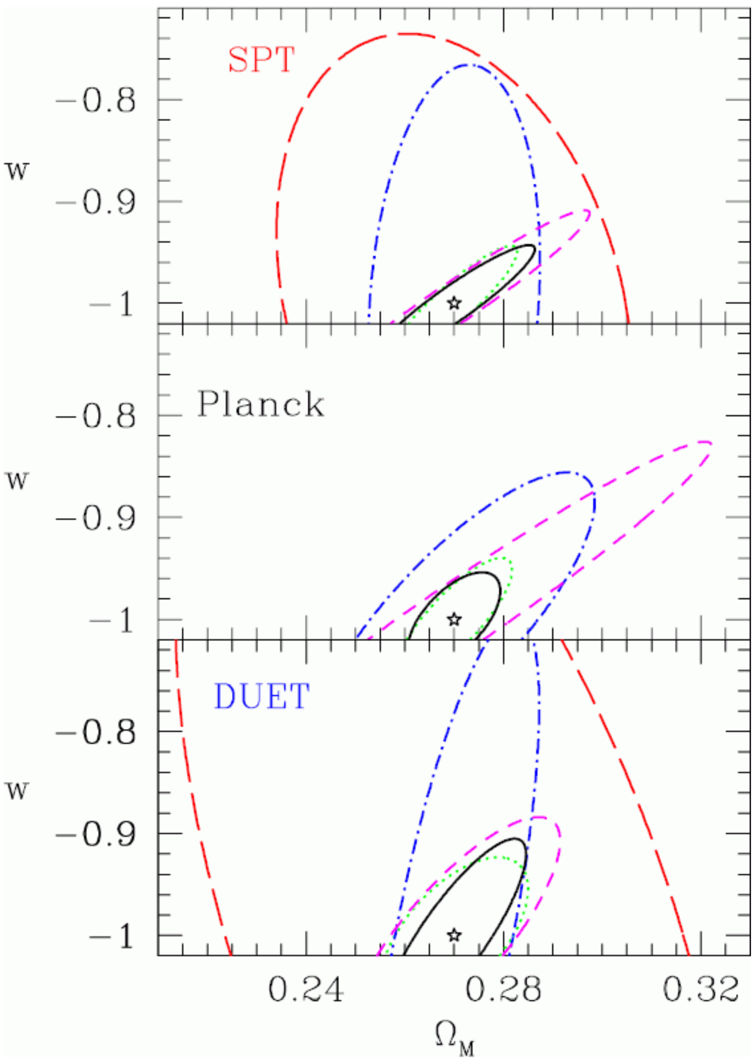
Observational view

Reasons we might worry

- Cluster mergers
- Feedback from active galactic nuclei
- Additional sources of pressure support (magnetic fields, cosmic ray pressure, turbulence)
- Clumpy accretion and lack of electron-ion equilibrium

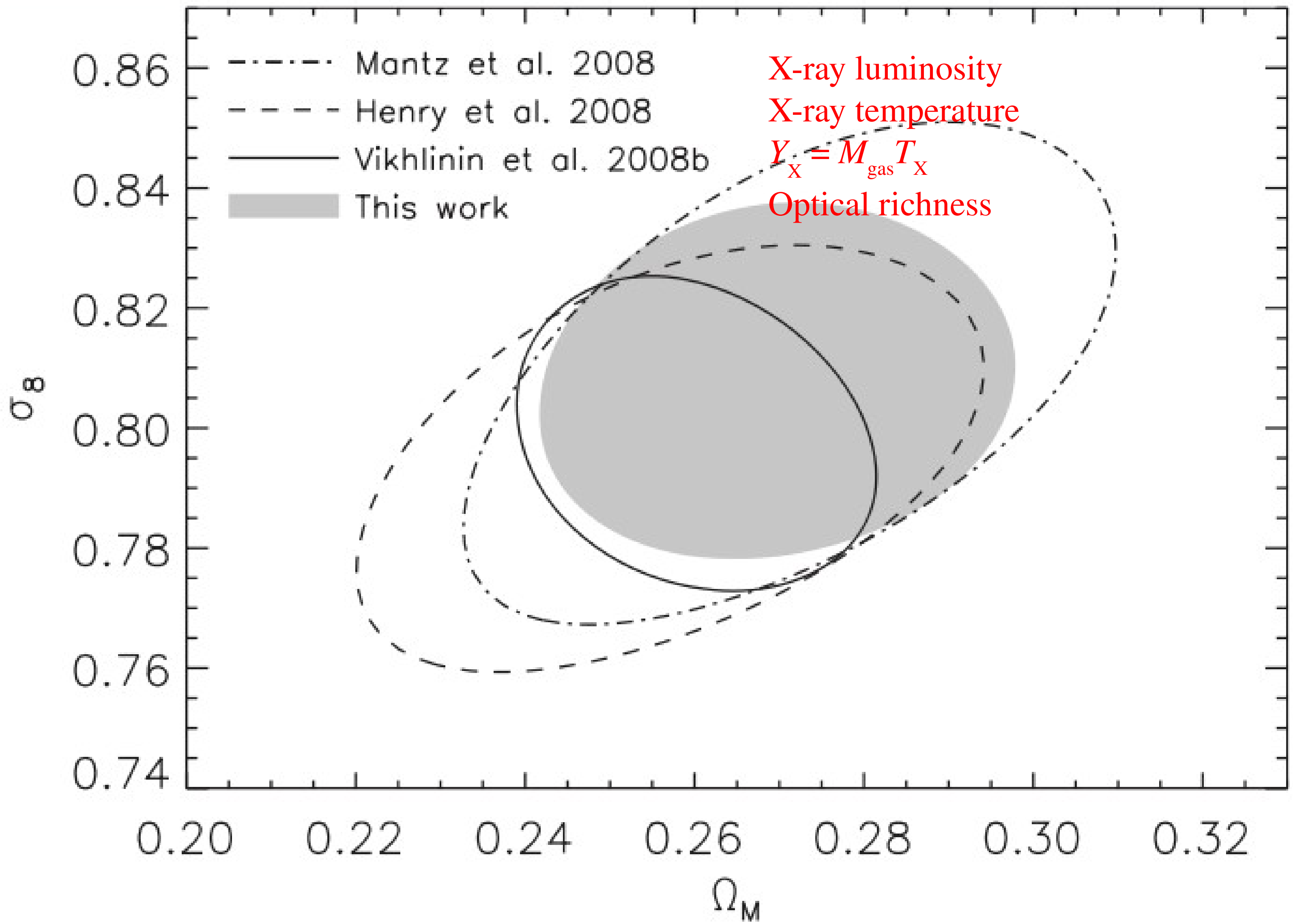
Self-calibration (Levine et al.; Hu; Majumdar & Mohr; Lima & Hu)

- With enough clusters ...
  - Parametrize cluster physics
  - Fit it along with cosmology
- Requirements
  - Mass function known
  - Assumed mass-observable functional form
  - Well-understood scatter
  - Redshift information (e.g., from optical surveys)



Majumdar & Mohr (2004)

Exploiting multiple observables



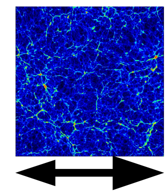
Rozo et al. (2010)

Cluster cosmology simulations at Illinois

- Program to parametrize contributions to cluster mass-observable scatter due to different cluster physical processes
- Improve self-calibrated cluster-based estimates of cosmological parameters

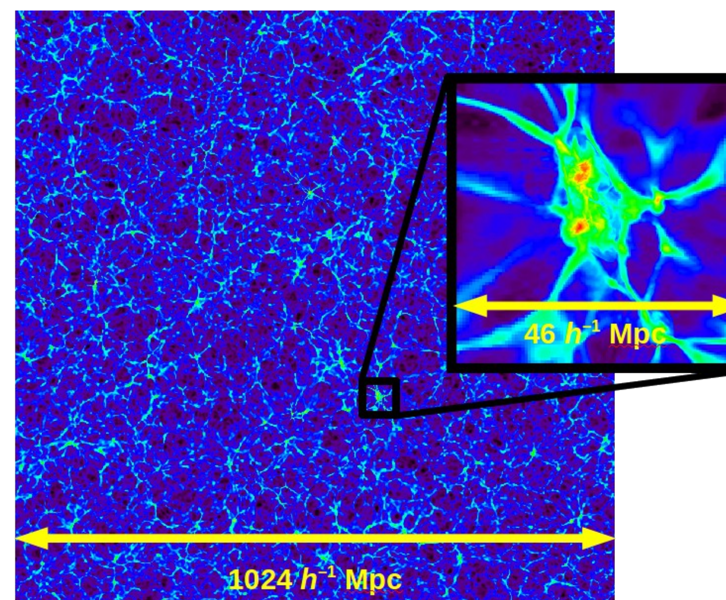
- Simulations: AMR code FLASH

Observable	Physics	Reference
T_X	dynamics	Yang+ 09
SZ	dynamics	Yang+ 10
T_X, SZ	cooling + AGN	Yang+ 12
T_X, SZ	dynamics cooling + AGN	in prep.

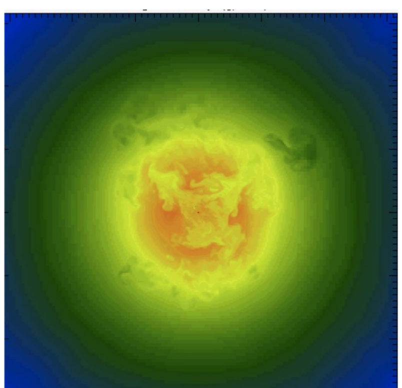


256 h^{-1} Mpc

FLASH 2.4
1024^3 particles
$\Delta x = 250\ h^{-1}$ kpc
$m_p = 5\text{x}10^8\ h^{-1}\ M_\odot$
600 clusters



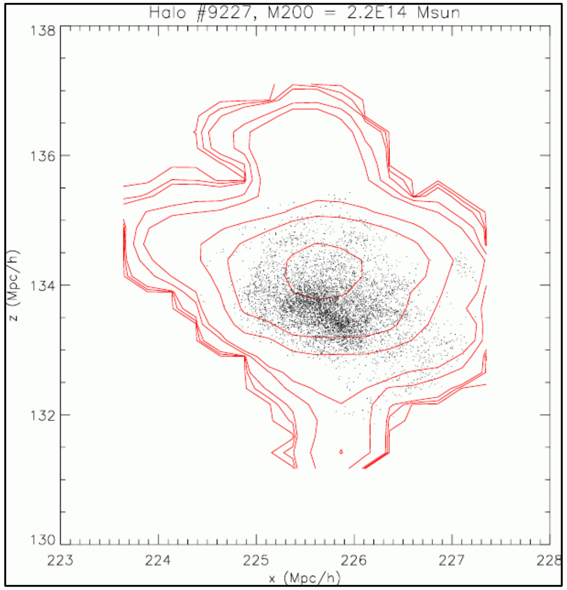
FLASH 3.2
1024^3 particles
$\Delta x = 31\ h^{-1}$ kpc
$m_p = 3\text{x}10^{10}\ h^{-1}\ M_\odot$
130 refined clusters

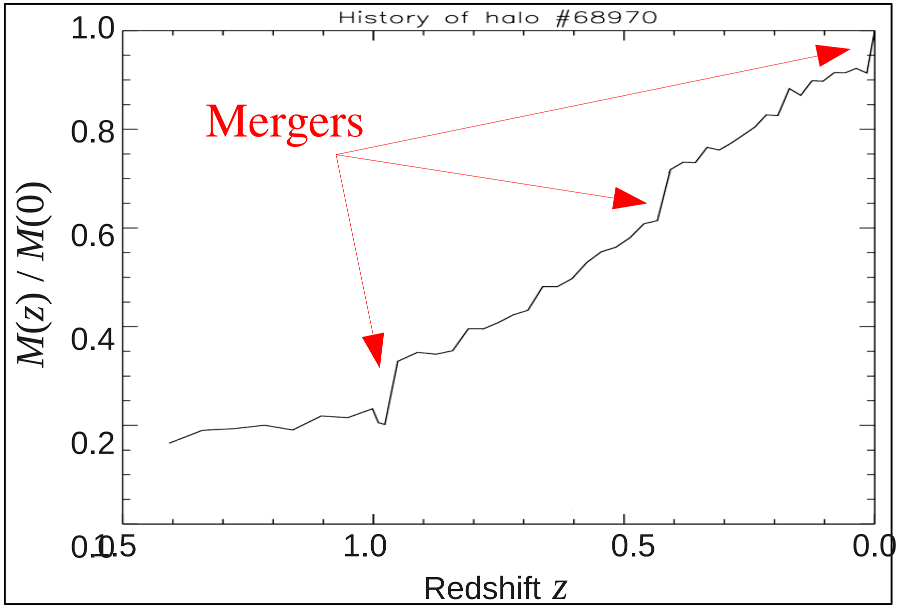


FLASH 3.2
Static DM halo
$L = 2\ h^{-1}$ Mpc
$\Delta x = 1\ h^{-1}$ kpc
1 cluster

Measuring dynamical state

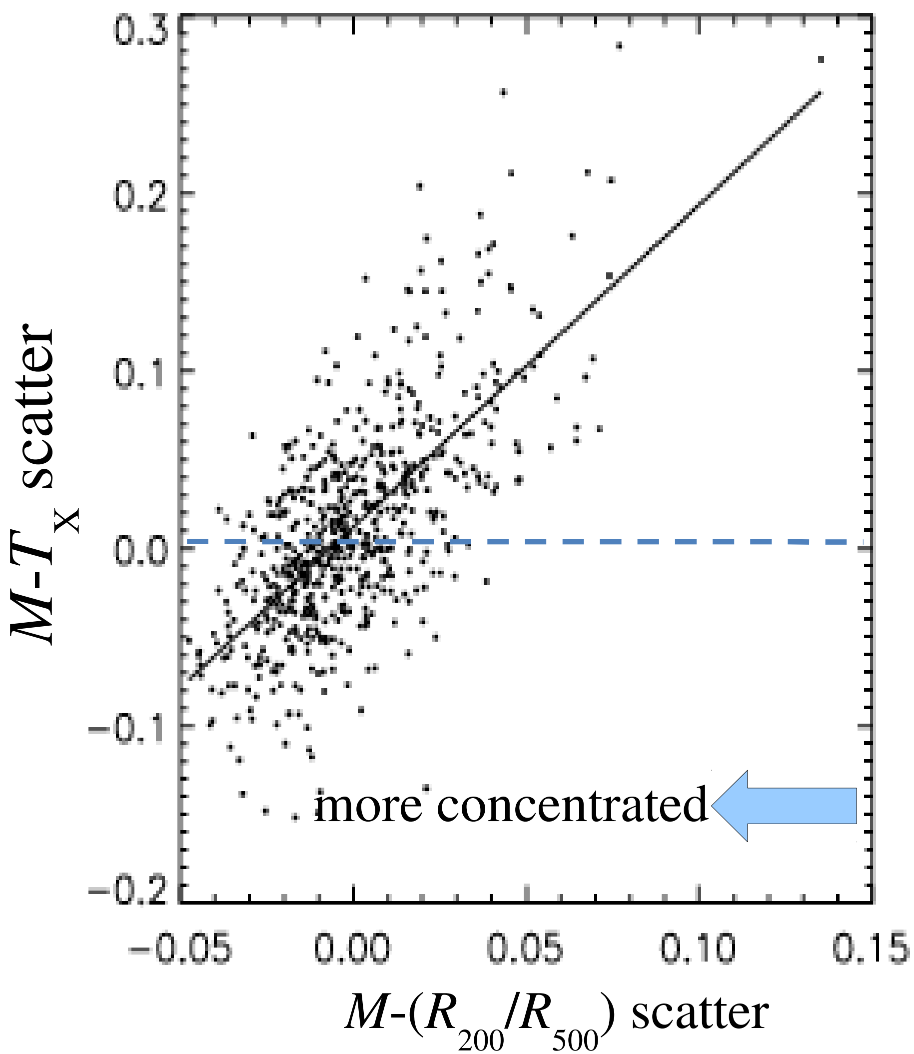
- Centroid offset (Mohr et al. 1995)
- Multipole power (Buote & Tsai 1995, 6)
- Merger history (Cohn & White 2005)
  - Use particle tags to trace halo progenitors
  - Identify merging events using
    - *Mass jump* – ratio of halo mass to mass of largest progenitor
    - *Mass ratio* – ratio of masses of two largest progenitors

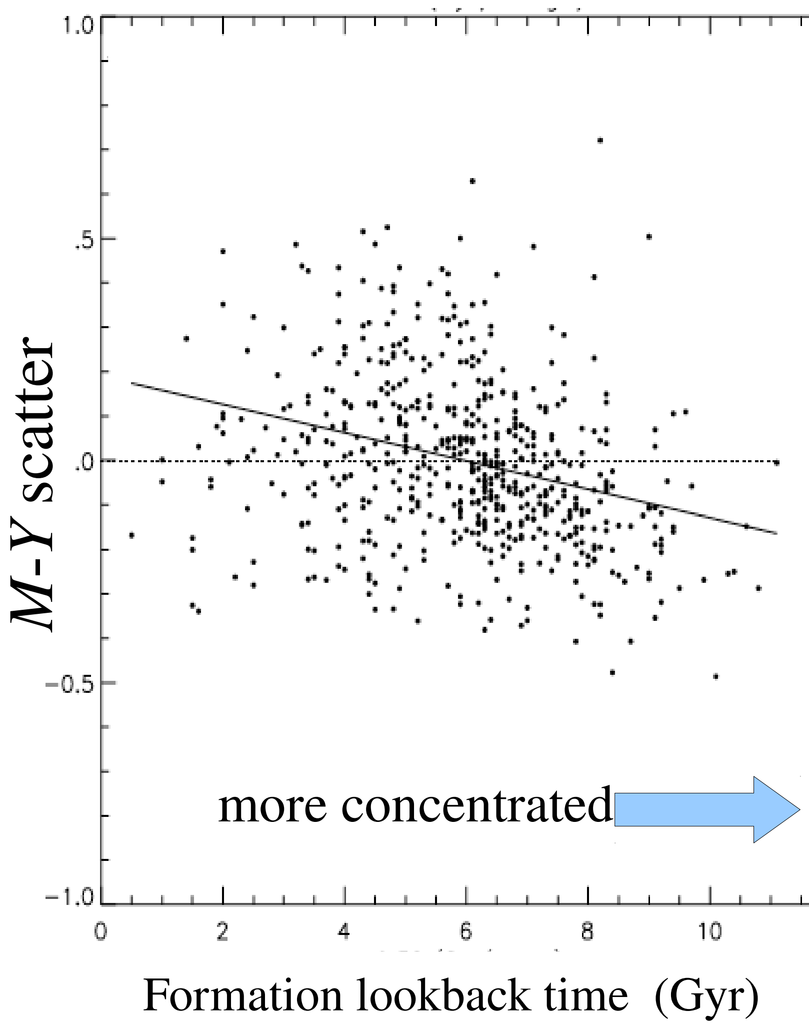




Influence of dynamics on M-T_X and M-Y (Yang et al. 2009, 10)

- Scatter within R_{500} shows strong negative correlation with concentration
- Weak/no sensitivity to mergers and merger-driven distortions

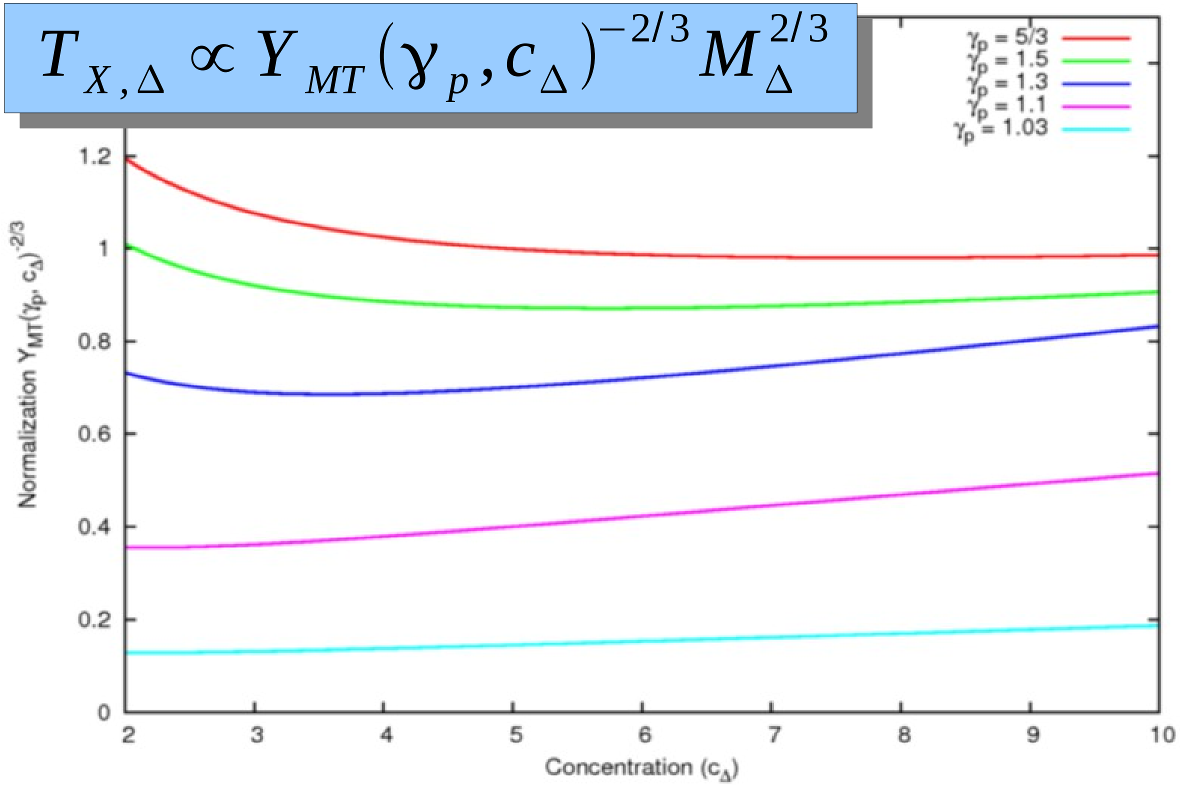




Slope of the concentration dependence

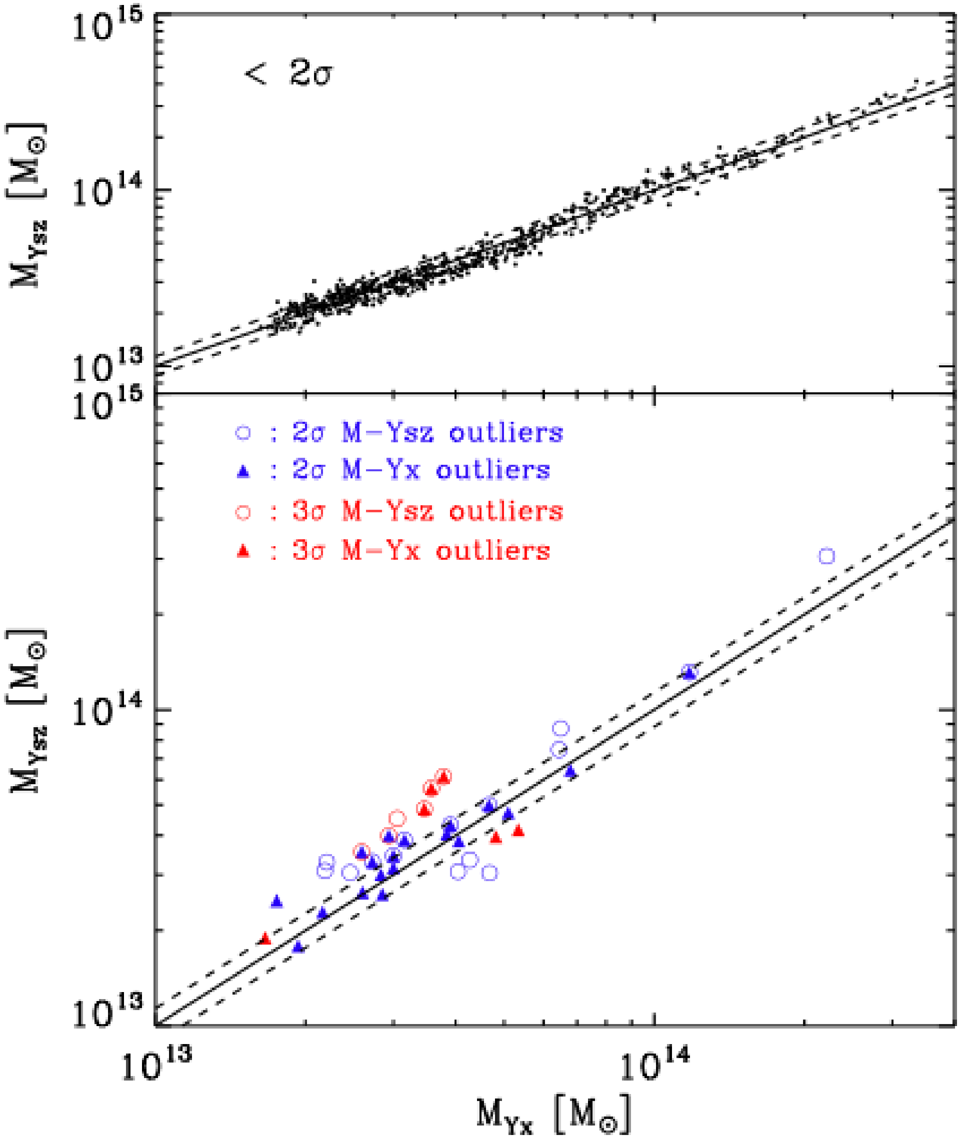
- Sense of correlation disagrees with Shaw et al. 08
- Difference lies in equation of state (Ascasibar et al. 06)
  - Polytropes $P \propto \rho^{\gamma_p}$
  - Extra physics reduces γ_p from 5/3 → 1
  - Slope flattens and then changes sign as γ_p decreases

$$T_{X,\Delta} \propto Y_{MT}(\gamma_p, c_\Delta)^{-2/3} M_\Delta^{2/3}$$



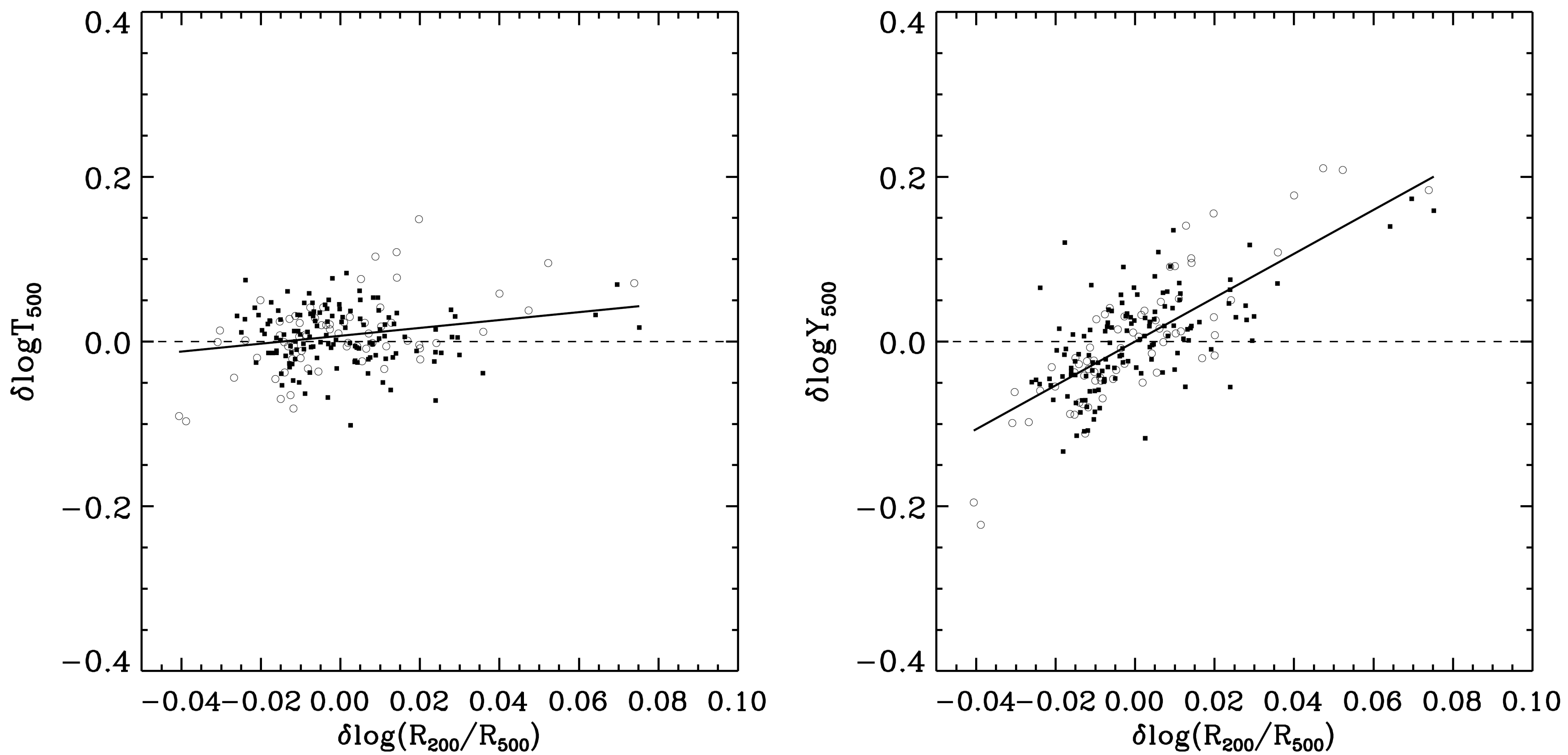
Influence of dynamics on *M-Y* (Yang, Bhattacharya, & Ricker 2010)

- Clusters that are outliers in both $M - Y_X$ and $M - Y_{SZ}$ have inconsistent mass estimates
- By excluding such cases we can reduce systematic errors in mass calibration by as much as a third



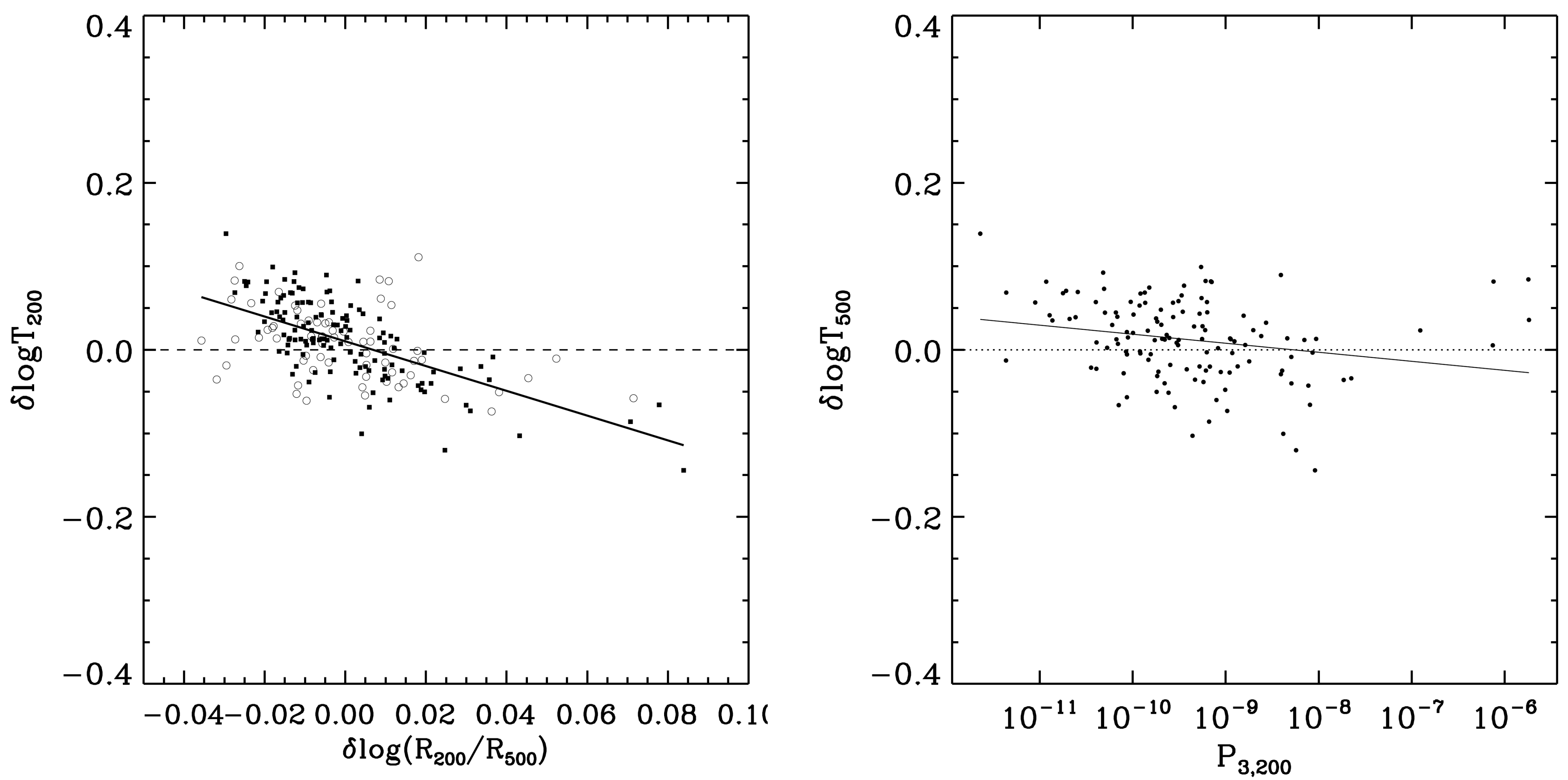
Updated dynamics results (1024 h^{-1} Mpc volume)

- Sense of concentration correlation is maintained with much better resolution



Updated dynamics results (1024 h^{-1} Mpc volume)

- Sense of correlation flips when we consider quantities within R_{200}
- Scatter dependence on power ratios starts to become important within R_{200}



AGN feedback in clusters

AGN modeling in simulations

Seeding and merging of AGN within cosmological context

- Constant seed mass
- Seeding on M-σ relation
- Instant merging
- Merging based on proximity
- Merging based on velocity
- Frequency of tests

Accretion onto AGN

- α-Bondi (Sijacki et al. 07)
- β-Bondi (Booth & Schaye 09)
- Stochastic (Pope 07)

Feedback onto surroundings

- Bubble (Sijacki et al. 07)
- Jet (Cattaneo & Teyssier 07)

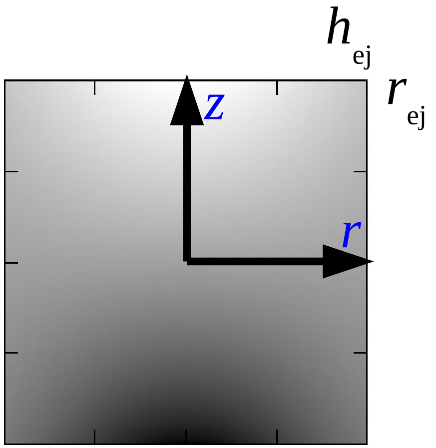
AGN modeling (Yang, Sutter, & Ricker 2012)

- Accretion model

$$\dot{M}_{\rm bh} = \min\left[\alpha\,\dot{M}_{\rm Bondi}\left(M_{\rm bh},\rho_{\rm grid},c_{\rm s,grid}\right),\dot{M}_{\rm Edd}\left(M_{\rm bh}\right)\right]$$

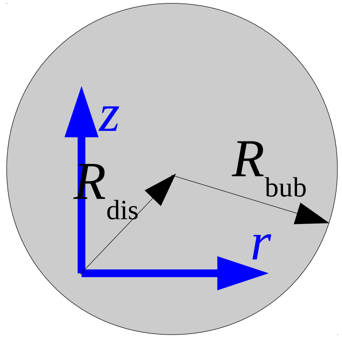
- Feedback model
  - Jets (Cattaneo & Teyssier 07)

$$\dot{M}_{\rm gas} = \eta\,\dot{M}_{\rm bh}\left|\Psi\left(\boldsymbol{x}\right)\right|$$
$$\dot{\boldsymbol{P}}_{\rm gas} = \sqrt{2\epsilon_{\rm F}}\,\dot{M}_{\rm bh}\,c\,\Psi\left(\boldsymbol{x}\right)$$
$$\dot{E}_{\rm gas} = \epsilon_{\rm F}\,\dot{M}_{\rm bh}\,c^2\left(1-\eta\right)\left|\Psi\left(\boldsymbol{x}\right)\right|$$



  - Bubbles (Sijacki et al. 07)

$$\dot{E}_{\rm gas} = \epsilon_{\rm m}\,\epsilon_{\rm F}\,\Delta\,M_{\rm bh}\,c^2$$
$$R_{\rm bub} = R_0\left(\frac{\dot{E}\,\Delta t}{E_0}\,\frac{\rho_0}{\rho}\right)^{1/5}$$



AGN model parameter sensitivity

Vary:

- Resolution (Δx)
- Accretion strength (α)
- Mechanical heating efficiency ($\epsilon_f \epsilon_m$)
- Bubble injection frequency (δ_{bh})
- Size and offset of injection region (R_0, R_{dis}, r_{ej}, h_{ej})
- Thermal-to-kinetic ratio ($\epsilon_m/(1-\epsilon_m)$)

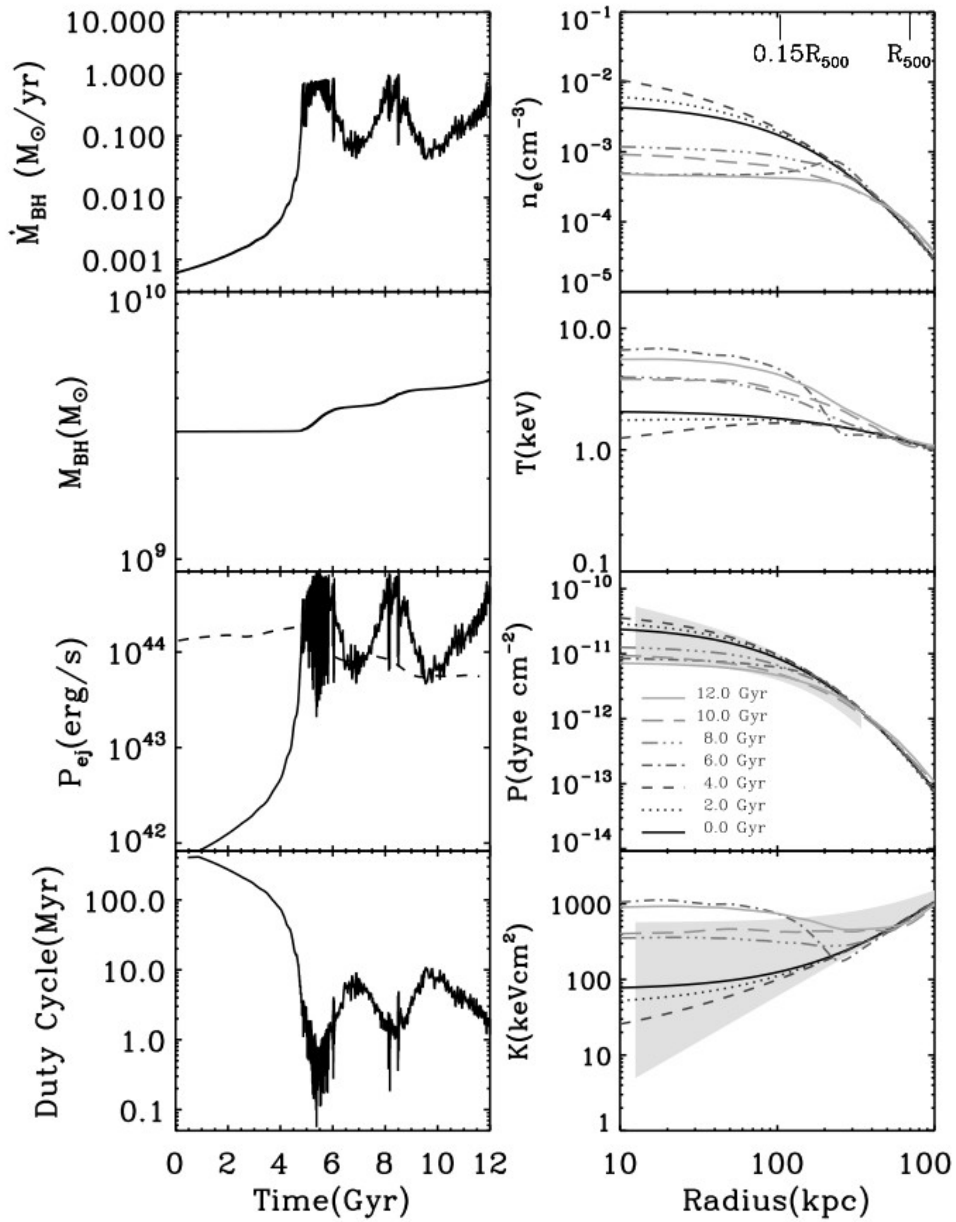
Most important

AGN in a single cluster

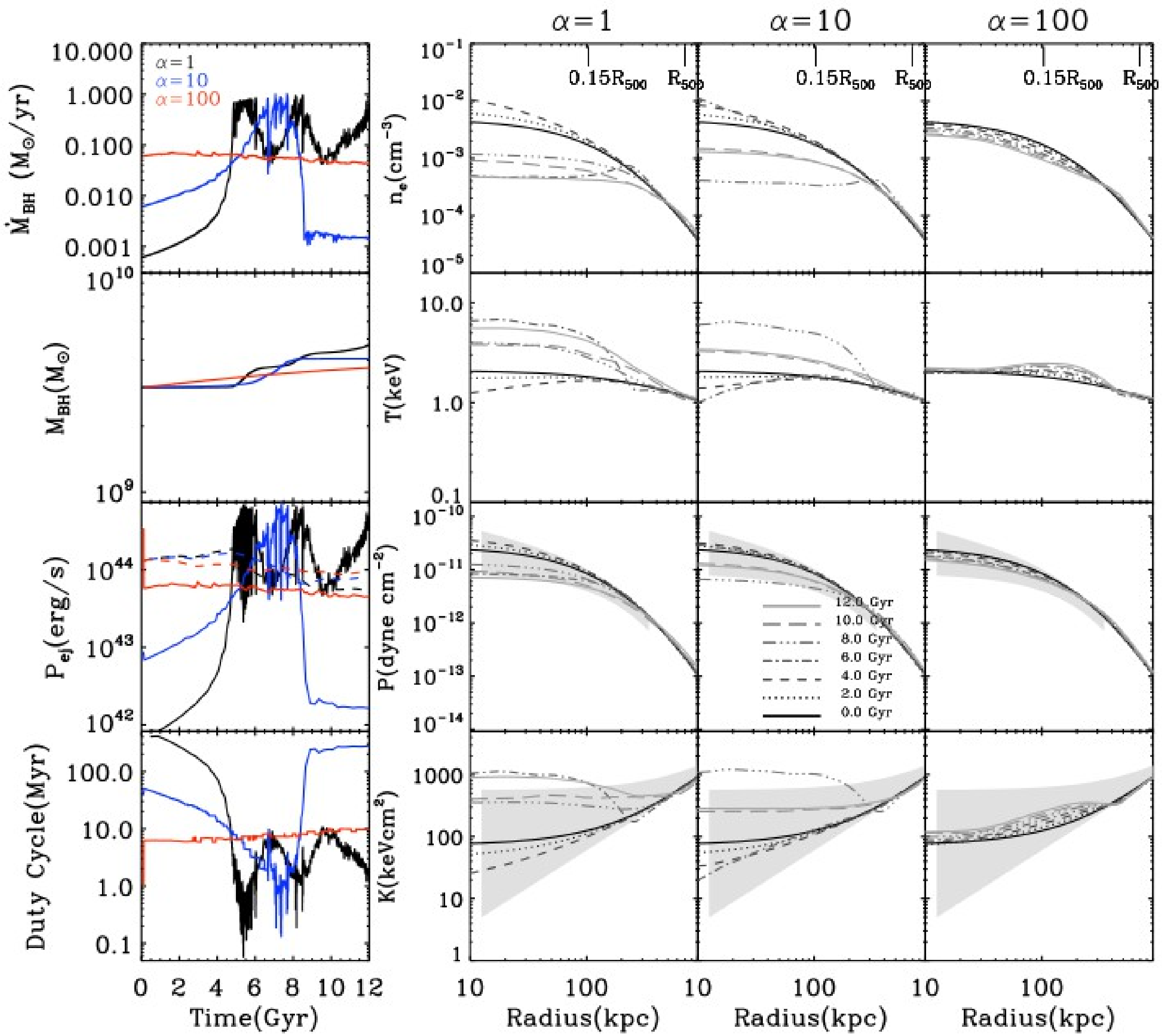
- With dynamical AGN it is possible to achieve feedback cycles that look like observations
- Significant variation in results due to variation in AGN modeling and parameter choices

Fiducial run

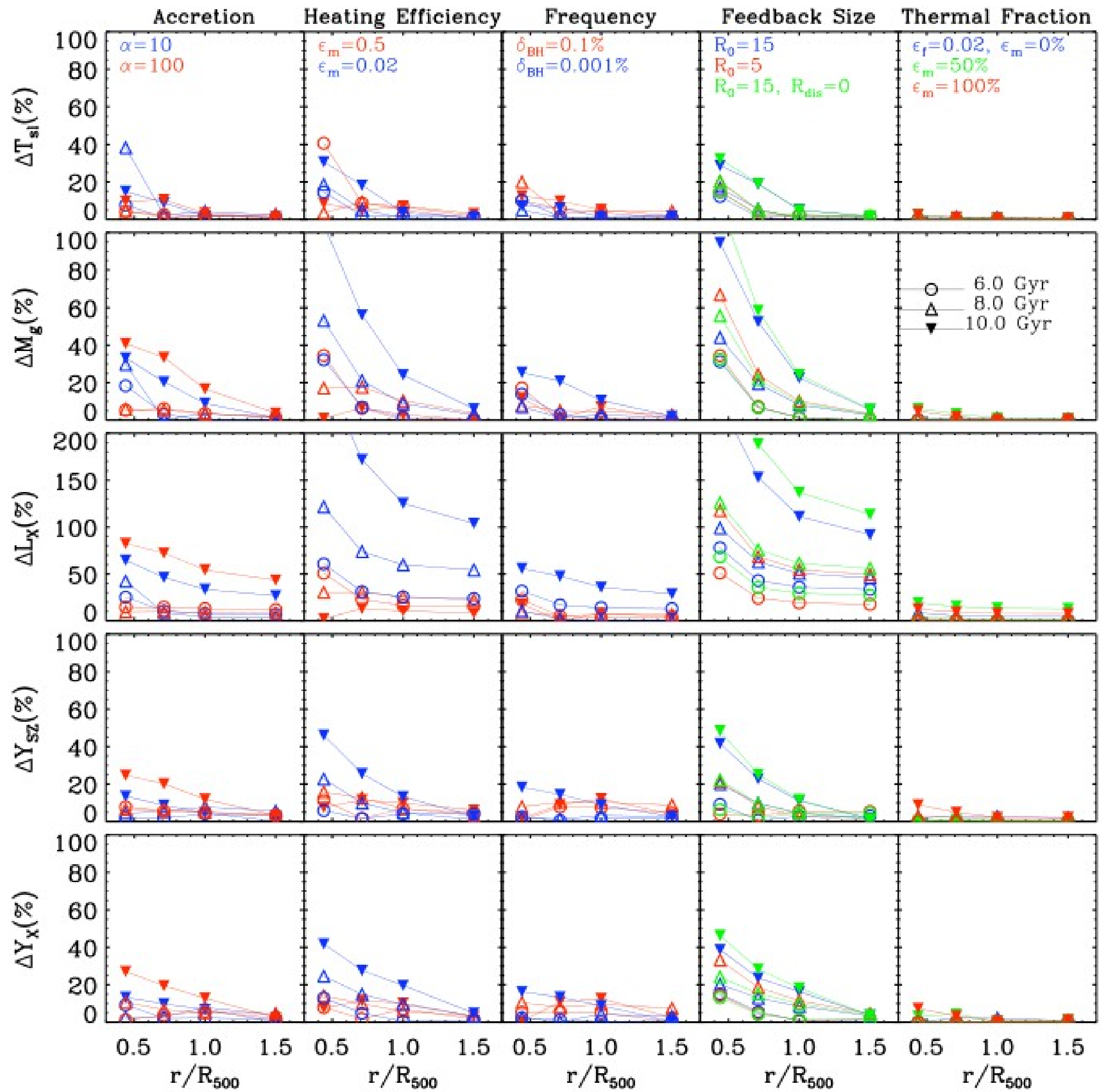
Bubbles
$\alpha = 1$
$R_0 = 30\ h^{-1}$ kpc
$R_{dis} = R_{bub}$
$\epsilon_f = 0.1$
$\epsilon_m = 0.2$
$\delta_{bh} = 0.01\%$



Varying bubble accretion strength (α)

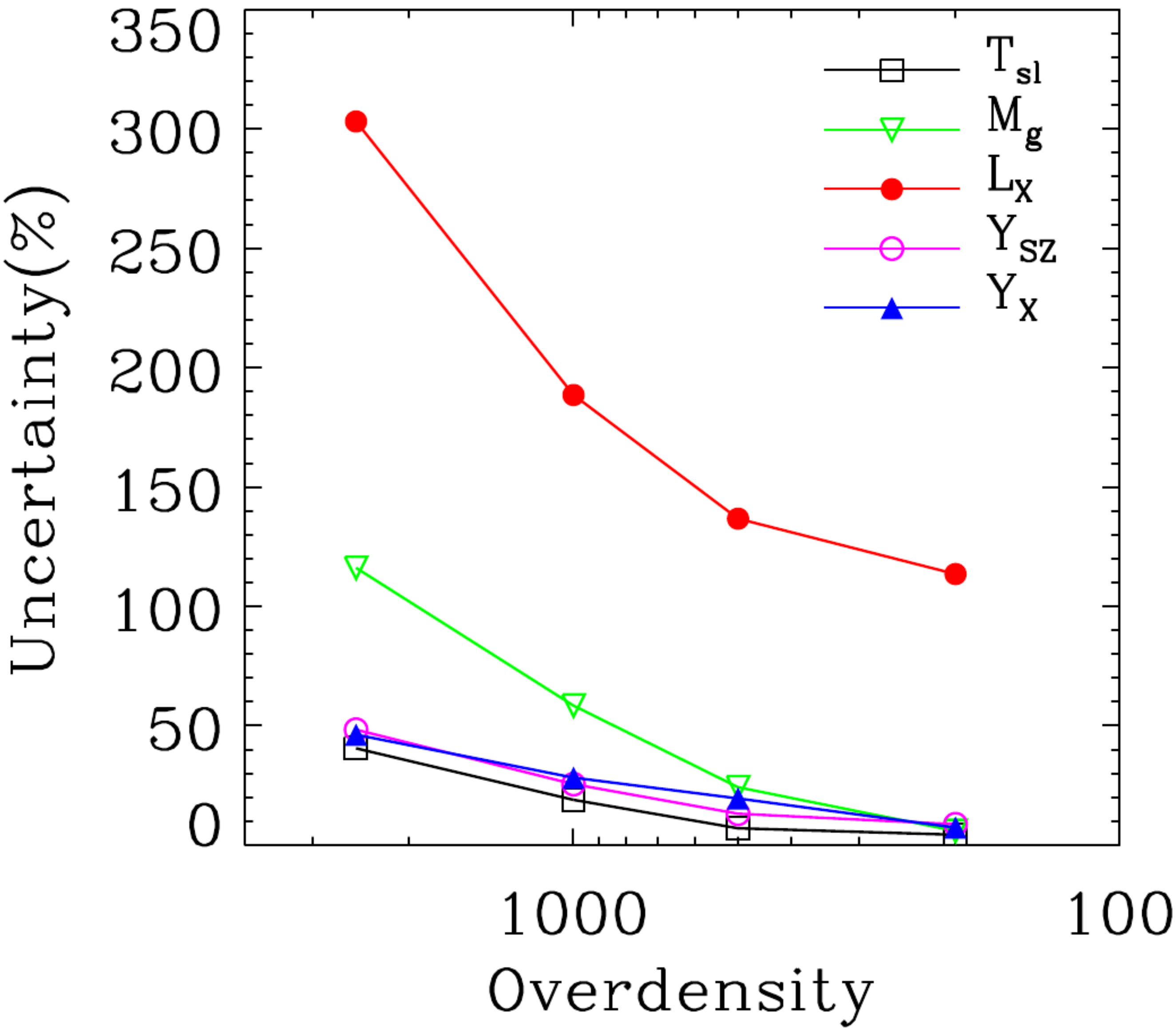


Different parameter choices lead to different histories



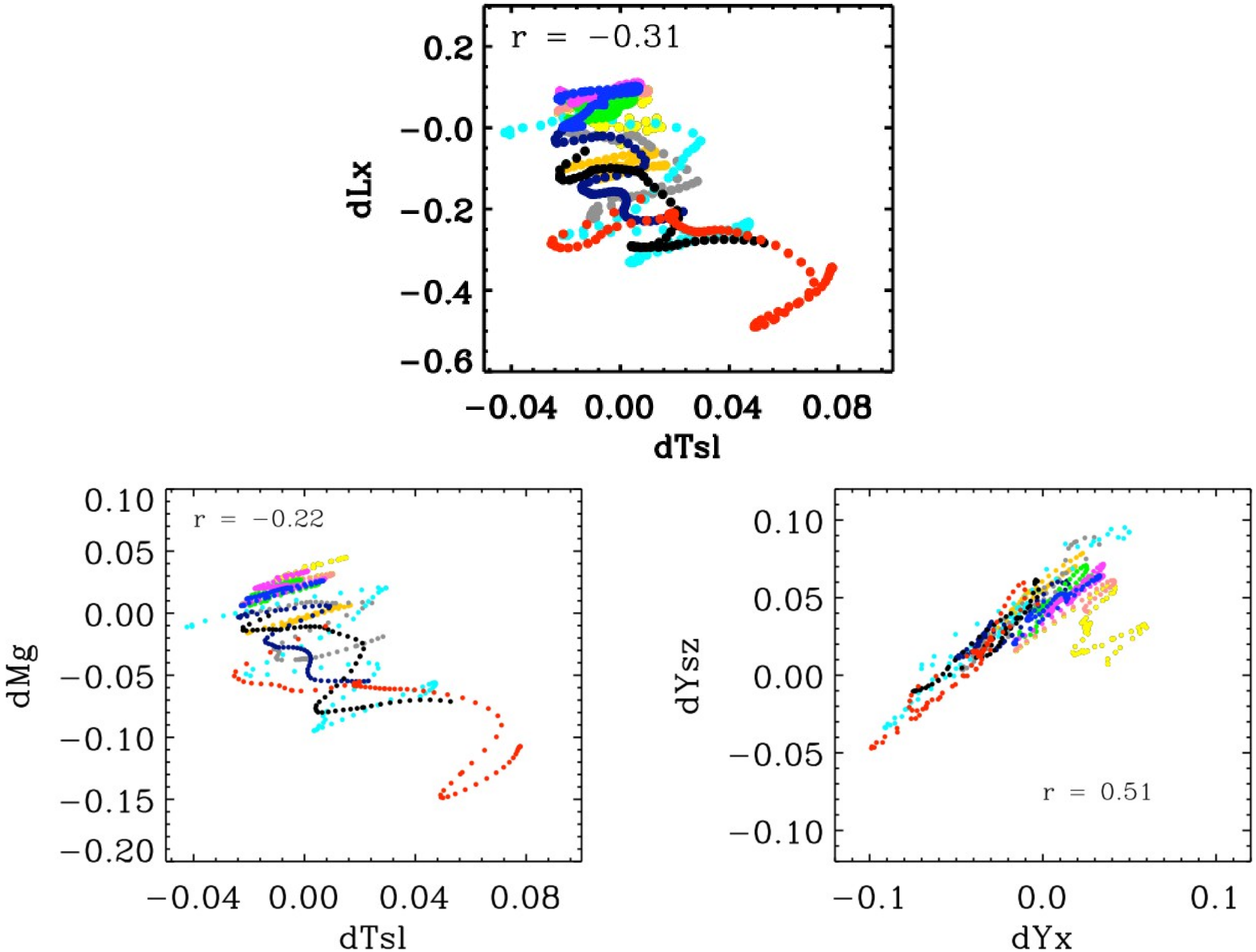
Max influence of parameter uncertainty on observable properties

- Y_{SZ} and T_X model uncertainty within R_{500} is ~ 10%



Trajectories of scaling relations

- AGN feedback contributes significantly to *L*-*T* and *M*-*T* scatter regardless of model; Y_{SZ}-Y_X continues to be tight



Conclusions

- Dynamics
  - When considering effects of dynamics only, observable scatter of *M*-*T* and *M*-*Y* within R_{500} is insensitive to merger effects
  - Correlation with halo concentration can be used to reduce scatter
  - Outliers are outliers in multiple observables ⇒ can improve scatter by throwing out clusters with inconsistent mass estimates
- AGN + cooling
  - AGN effects are likely to be dominant driver of scatter in cluster mass-observable relations
  - Nevertheless AGN may still be manageable for *M*-*T* and *M*-*Y*
- Future/ongoing
  - AGN in cosmological runs