Observations of Galaxy Cluster X-ray Scaling Relations

Effects of Cool Cores and Mergers on Cluster Cosmology

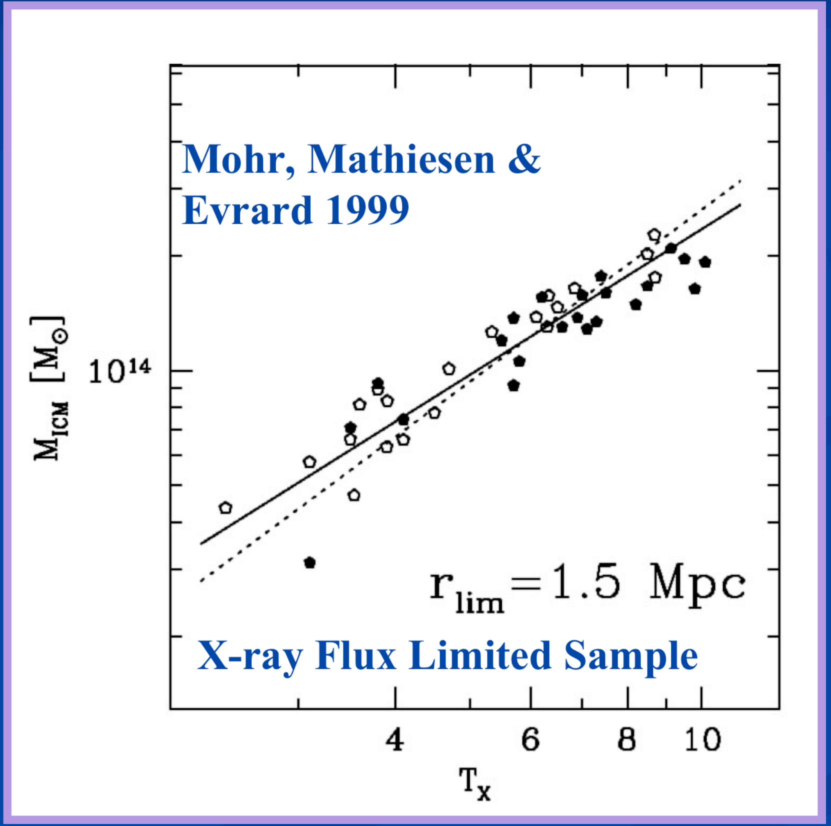
Joe Mohr and Tim O'Hara
Department of Astronomy
Department of Physics & NCSA
University of Illinois

Reporting on some of Tim O'Hara's thesis work…

- Scaling relations as tools
- Tale of scatter in scaling relations
- Cool core and merging effects

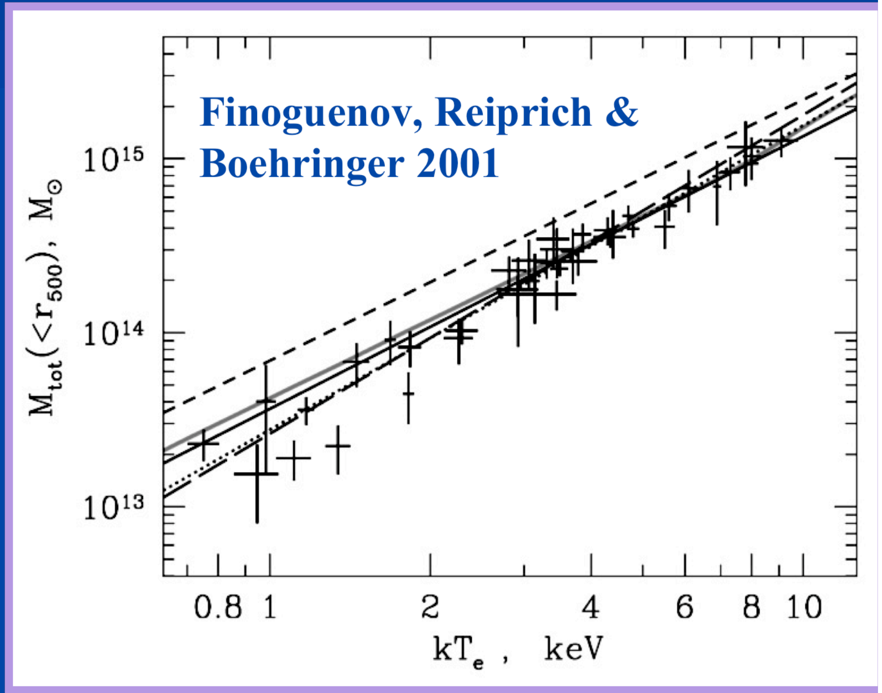
Cluster Scaling Relations

- Cluster scaling relations discovered in observations and reproduced in hydro simulations indicate a reasonably high degree of regularity
- Scaling relations have been observed using X-ray, NIR and Optical properties of galaxy clusters



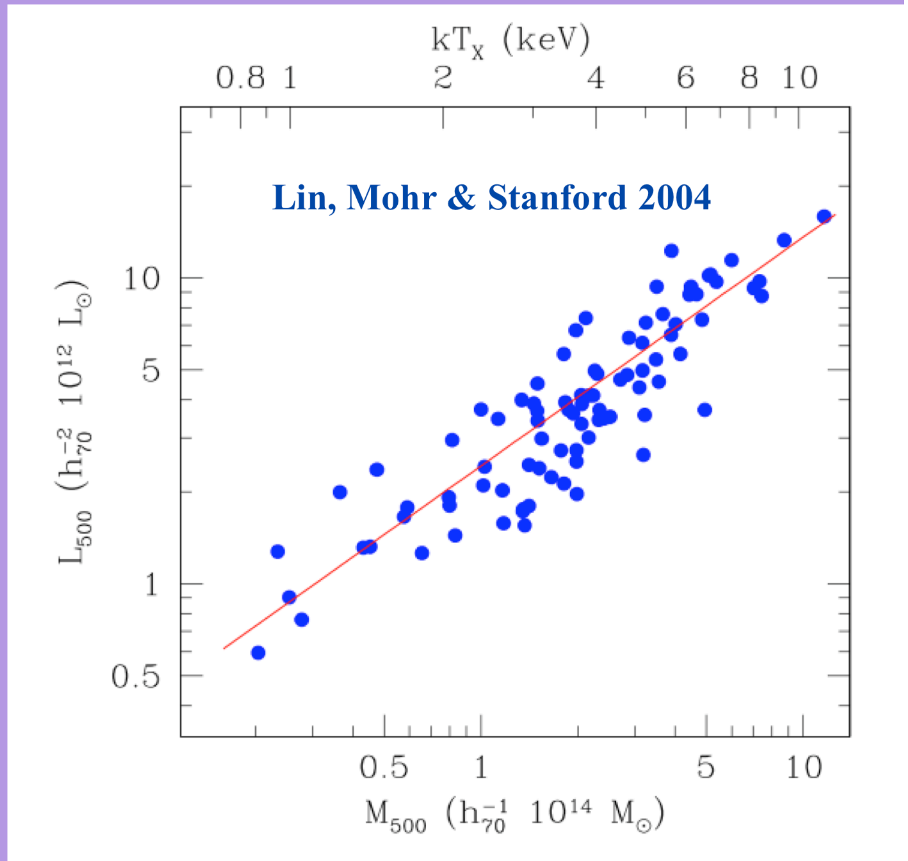
Cluster Scaling Relations

- Cluster scaling relations discovered in observations and reproduced in hydro simulations indicate a reasonably high degree of regularity
- Scaling relations have been observed using X-ray, NIR and Optical properties of galaxy clusters



Cluster Scaling Relations

- Cluster scaling relations discovered in observations and reproduced in hydro simulations indicate a reasonably high degree of regularity
- Scaling relations have been observed using X-ray, NIR and Optical properties of galaxy clusters



Crude Observables as Structure Tests

- Measurements of the X-ray luminosity, ICM mass, X-ray mean temperature, galaxy light, X-ray isophotal size, etc provide integral constraints on the structure of the cluster

- Taken together, this ensemble of observables allows us to examine structural variations in clusters at fixed T_x (a mass proxy)

$$L_X = \int_{V_{500}} d^3\vec{x}\, n_e^2 \tfrac{\mu_e}{\mu_H} \Lambda(T)$$

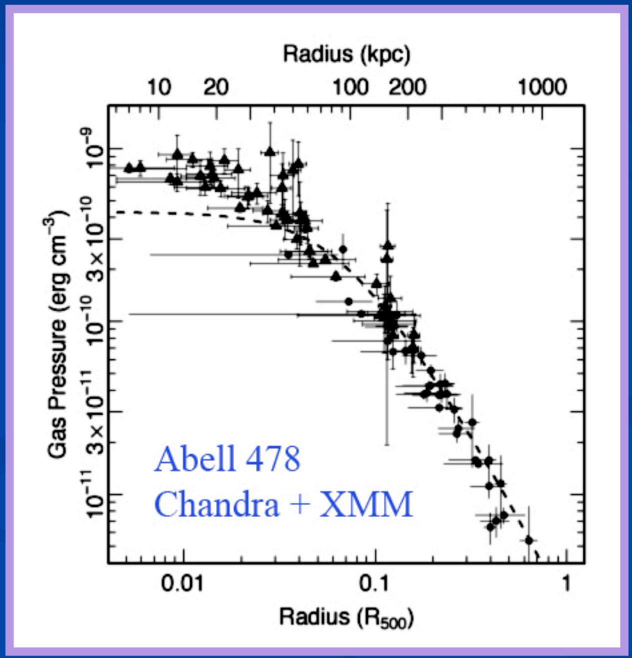
$$M_{ICM} = \int_{V_{500}} d^3\vec{x}\, \mu_e m_p n_e$$

$$\langle T_X \rangle = \int_{V_{500}} d^3\vec{x}\, n_e^2 \tfrac{\mu_e}{\mu_H} \Lambda(T) T \Big/ L_X$$

$$L_K = \sum_{V_{500}} L_i$$

Scaling Relation Studies are Complementary to Detailed Studies

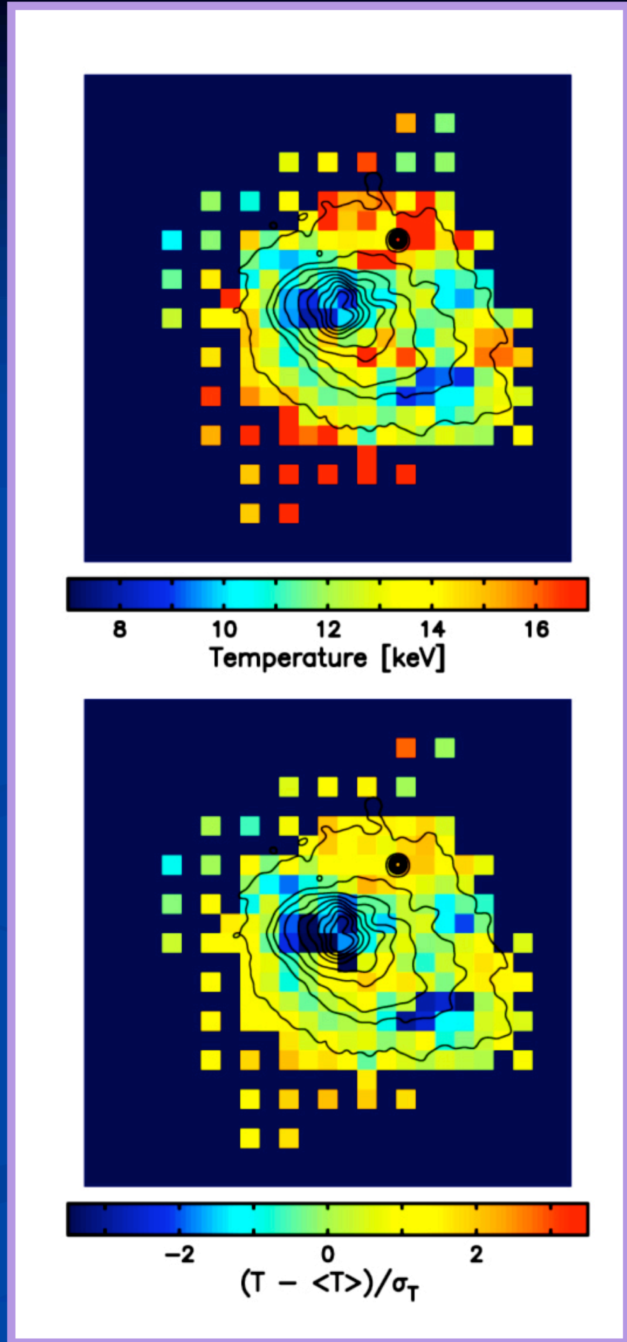
- Long exposures of bright clusters with Chandra and XMM produce ~10^5 photons, which enable non-parametric deprojection
- These highly detailed studies are critically important, but dependent upon assumptions of spherical symmetry and regularity
- Crude observables can be extracted on a much wider range of clusters



Sanderson, Finoguenov & Mohr 2005

Cluster Populations are Young

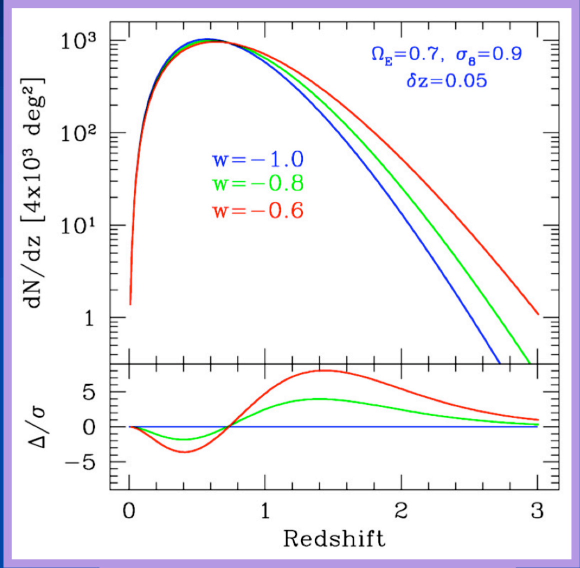
- Morphological merger indicators have been used to study flux limited samples of clusters. A large fraction of local clusters exhibit evidence for recent mergers (> 50%; e.g. Mohr et al 1995)
- Chandra observations of higher redshift clusters provide evidence that cluster substructure is even more common at higher redshift (e.g. Canizares et al 2004)
- If we restrict ourselves to the clusters that are roughly circular on the sky, then we study a rarer and rarer subclass of objects as we move to higher redshift



O'Hara, Mohr & Guerrero ApJ 2005

Galaxy Cluster Surveys are Powerful Structure Formation Based Cosmological Tests

- Cluster surveys measure the:
  - Cluster redshift distribution
  - Cluster observable distribution at each redshift (mass function)
  - Spatial clustering of the clusters
- Cosmology sensitivity through
  - Volume-redshift relation
  - Distance-redshift relation
  - Growth rate of cosmic structure
  - Power spectrum shape



$$\frac{dN(z)}{dz\,d\Omega} = \frac{dV}{dz\,d\Omega}\,n(z)$$

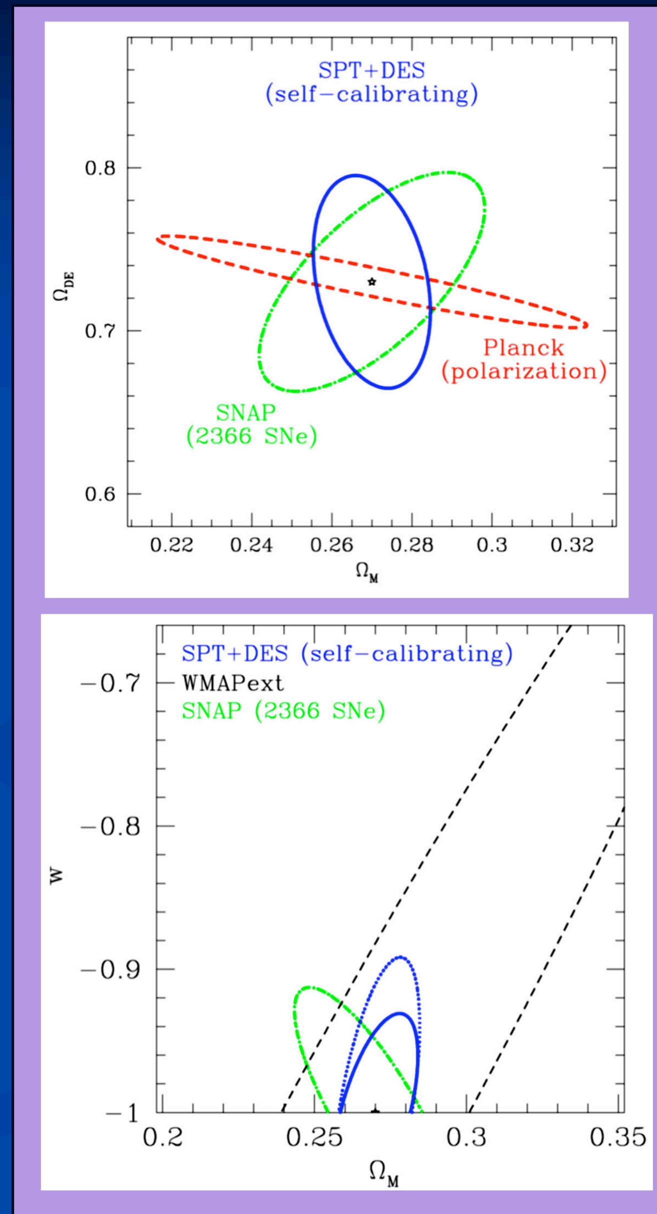
Some papers focused on the Cluster Survey Technique

Wang & Steinhardt 1999	Majumdar & Mohr 2003
Haiman, Mohr & Holder 2000	Hu 2003
Holder, Haiman & Mohr 2001	Weller & Battye 2003
Weller et al 2001	Majumdar & Mohr 2004
Levine et al 2002	Lima & Hu 2004
Benson et al 2002	Wang et al. 2004
Weller et al 2002	White & Majumdar 2004
Hu & Kravtsov 2003	Lima & Hu 2005

Technique does not require direct mass measurements. Rather, it relies on the use of mass-observable scaling relations and the technique of self-calibration.

Cluster Surveys Provide a Powerful Tool for Cosmology

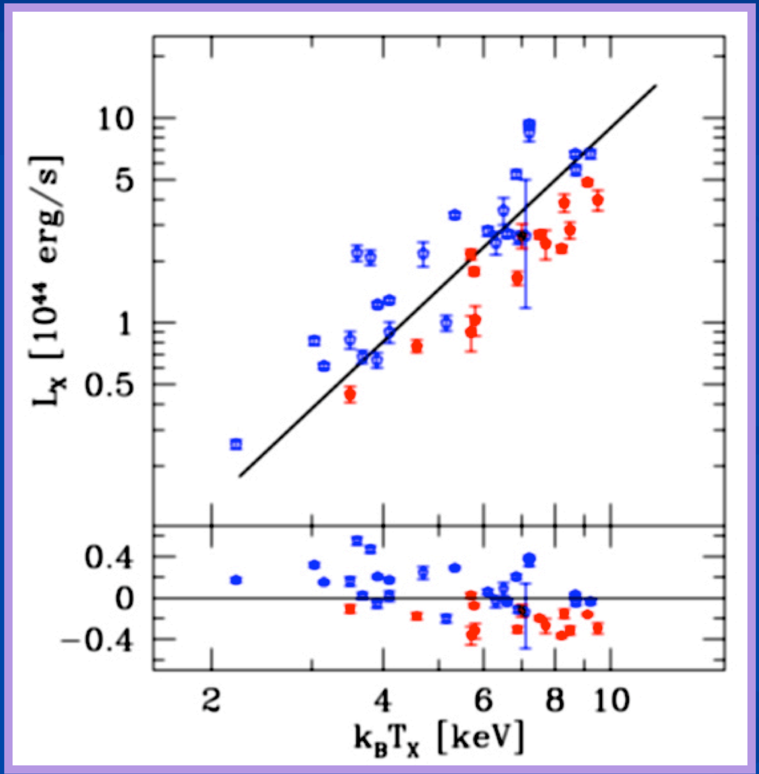
- Cluster constraints on dark energy:
  - The cluster redshift distribution, the cluster power spectrum and 30% accurate mass measurements for 100 clusters between z of 0.3-1.2
  - Fiducial cosmology (WMAP: σ_8=0.84, Ω_m=0.27); 29000 clusters in the 4000 deg^2 SPT survey.
- The joint constraints on w and Ω_m:
  - Curvature free to vary (dashed); fixed (solid)
  - Marginalized constant w 68% uncertainty is 0.046 (flat) or 0.071 (curvature varying)
- Parameter degeneracies are complementary
- Several large scale cluster surveys are in the build phase or almost underway



SPT: Majumdar & Mohr 2003 SNAP: Perlmutter & Schmidt 2003

So What About Scatter in Scaling Relations?

- Scatter is resolved in scaling relations
  - Scatter quantifies the variation in structural properties at a fixed mass in the cluster population
- We examine whether mergers or some other process are the primary driver of the scatter
  - Examine cluster deviation from scaling relation and whether that correlates with merger indicators



O'Hara et al, in preparation

Merger Indicators and Cluster Sample

- For each cluster we measure the centroid variation, axial ratio (Mohr et al 1993) and two power ratios P_1/P_0 and P_2/P_0 (Buote & Tsai 1995)
- No substructure indicator is 100% accurate… typically indicators are insensitive to mergers taking place along the line of sight

Local sample:

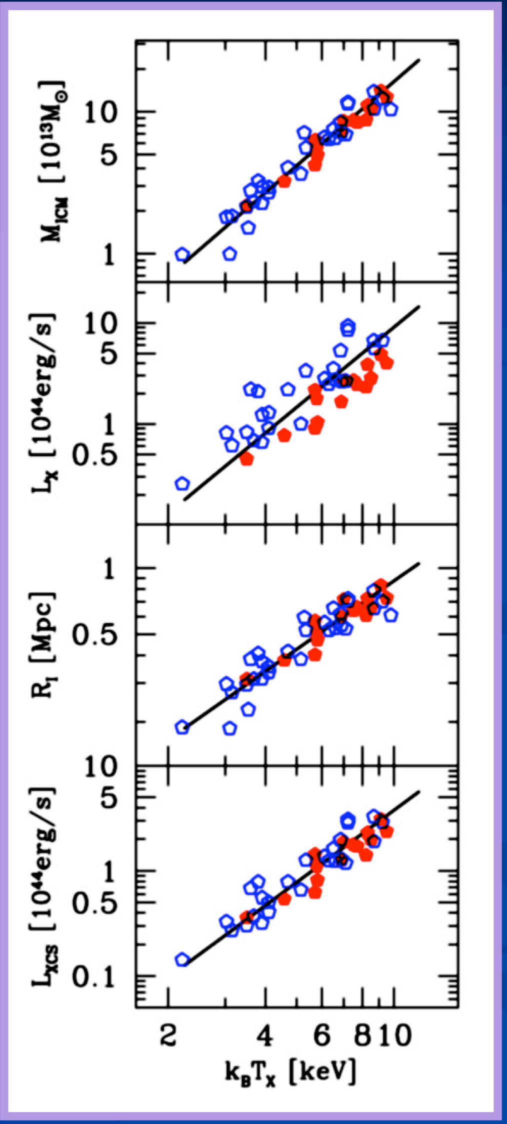
Use ROSAT observations of the Edge sample of brightest clusters (45 of 55 observed)

Intermediate redshift sample:

Use sample of clusters from the Chandra archive

Scaling Relations

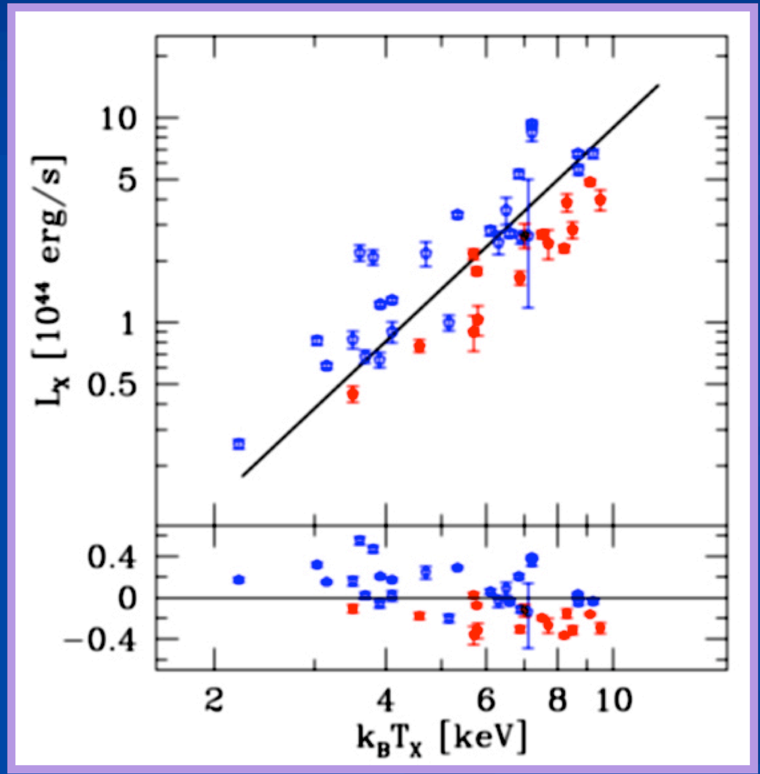
- Correlated excursions in two observables may lead to minimal merger related effects, so we look at a wide range of observables
  - T_x
  - L_x(r500), L_x(no core), R_I(3e-14cgs), M_{icm}(r500), L_K(r500)
  - L_x(r2500), R_I(1.5e-14cgs), M_{icm}(r2500)
- We are effectively examining the cluster morphology in a 9 dimensional space of crude cluster observables
  - To aid in visualization, we examine the population using individual pairs of observables



O'Hara et al, in preparation

Effects of Cool Cores

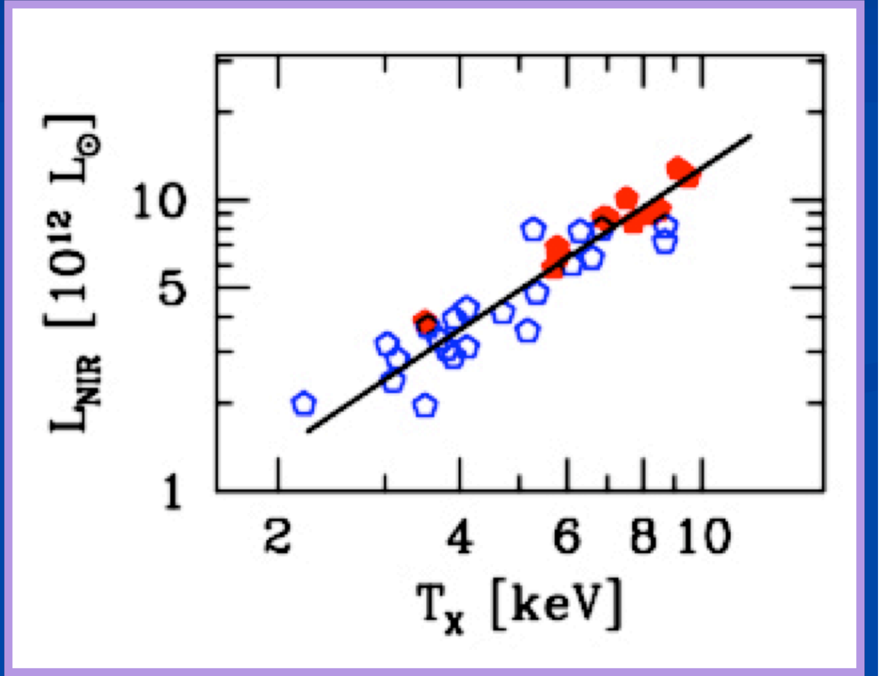
- The first thing one notices is that CC and NCC clusters (as measured by estimates of central cooling times) behave differently
- Consider the Lx-T relation (and see Fabian et al 1994)
- This effect is huge in the Lx-T relation, but it is present at a measureable level in other relations



O'Hara et al, in preparation

Effects of Cool Cores

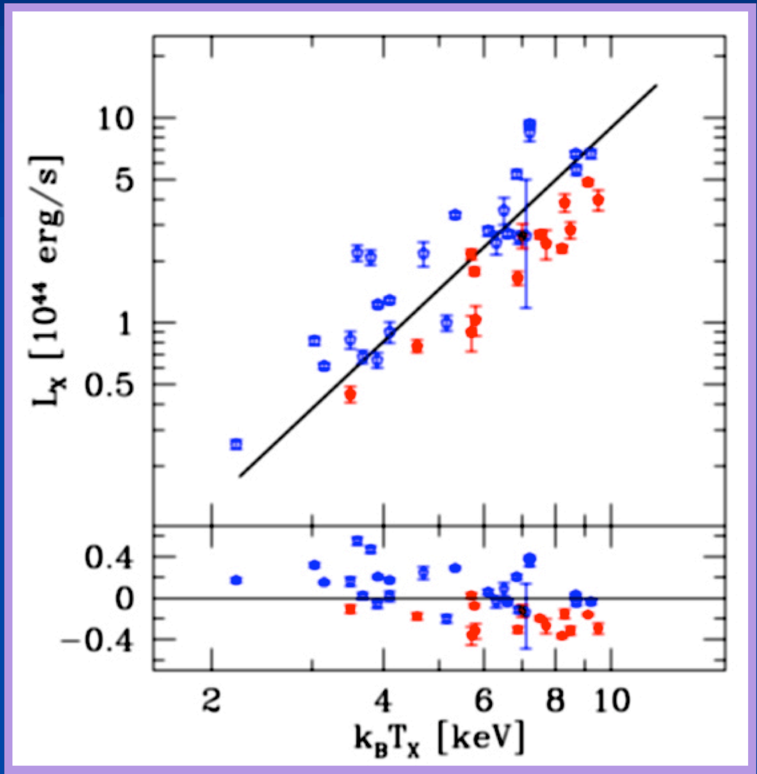
- The first thing one notices is that CC and NCC clusters (as measured by estimates of central cooling times) behave differently
- Consider the Lx-T relation (and see Fabian et al 1994)
- This effect is huge in the Lx-T relation, but it is present at a measureable level in other relations



Estimating Offsets Between CC and NCC Relations

- To go beyond this dominant CC effect, we attempt to remove it by introducing a temperature scale factor to "heat" the CC clusters (or equivalently "cool" the NCC clusters)

- We examine the χ^2 around the relations as a function of this scale factor-- taking the minimum in the scatter as the preferred temperature scale factor



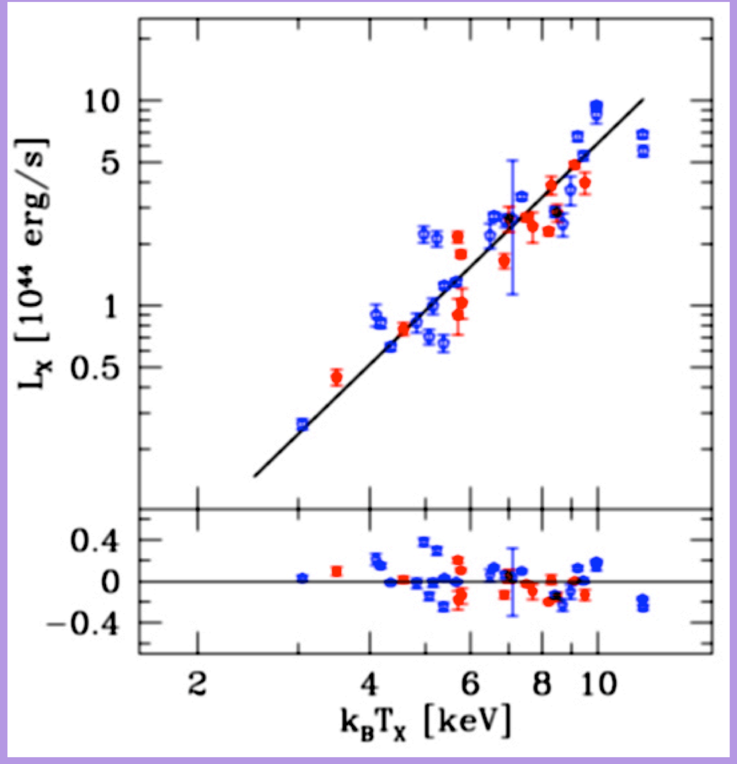
O'Hara et al., in preparation

$$\langle T_x \rangle_{CC} \Rightarrow \langle T_x \rangle_{CC} (1+\beta)$$

Estimating Offsets Between CC and NCC Relations

- To go beyond this dominant CC effect, we attempt to remove it by introducing a temperature scale factor to "heat" the CC clusters (or equivalently "cool" the NCC clusters)

- We examine the χ^2 around the relations as a function of this scale factor-- taking the minimum in the scatter as the preferred temperature scale factor



O'Hara et al, in preparation

$$\langle T_x \rangle_{CC} \Rightarrow \langle T_x \rangle_{CC} (1+\beta)$$

Estimating Offsets Between CC and NCC Relations

- To go beyond this dominant CC effect, we attempt to remove it by introducing a temperature scale factor to "heat" the CC clusters (or equivalently "cool" the NCC clusters)
- We examine the χ^2 around the relations as a function of this scale factor-- taking the minimum in the scatter as the preferred temperature scale factor

$$\langle T_x \rangle_{CC} \Rightarrow \langle T_x \rangle_{CC} (1+\beta)$$

Estimating Offsets Between CC and NCC Relations

- For L_x(r2500) the temperature scale factor is huge! (50%), but for M_{icm}(r500) it is rather small (5%).
- The more "core sensitive" an observable the larger the CC effect
  - Can use non-core sensitive measures to estimate how much the emission weighted mean temperature T_x is really biased! (~10%)
- Even with this "binary" CC/NCC correction, our dominant source of scatter is still residual CC effects
  - Scatter in CC sample larger than NCC sample in every case, e.g.
    - L_x-T (CC-0.16, NCC-0.12)
    - M_{icm}-T (CC-0.09, NCC-0.04)
    - R_I-T (CC- 0.07, NCC-0.04)

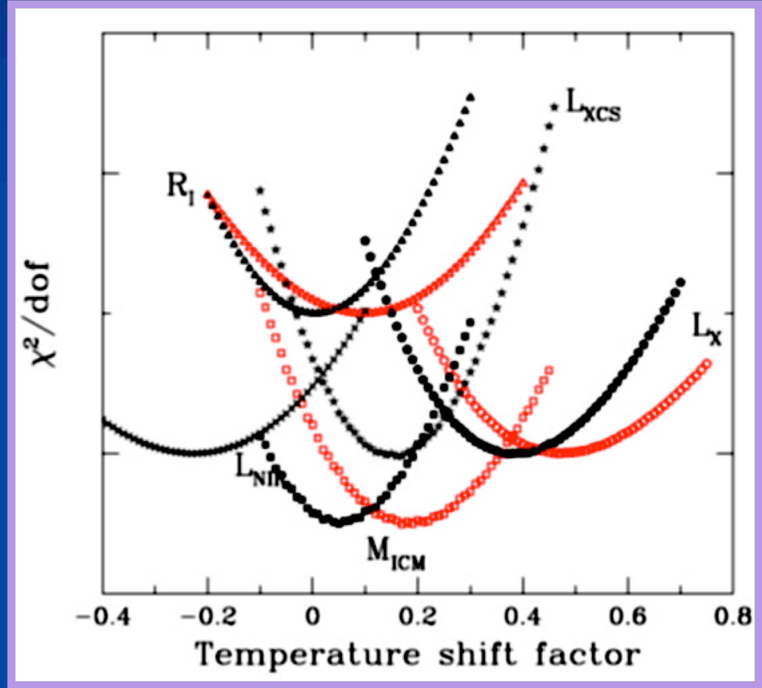
$$\langle T_x \rangle_{CC} \Rightarrow \langle T_x \rangle_{CC} (1+\beta)$$

Estimating Offsets Between CC and NCC Relations

- For L_x(r2500) the temperature scale factor is huge! (50%), but for M_{icm}(r500) it is rather small (5%).

- The more "core sensitive" an observable the larger the CC effect
  - Can use non-core sensitive measures to estimate how much the emission weighted mean temperature T_x is really biased! (~10%)

- Even with this "binary" CC/NCC correction, our dominant source of scatter is still residual CC effects
  - Scatter in CC sample larger than NCC sample in every case, e.g.
    - L_x-T (CC-0.16, NCC-0.12)
    - M_{icm}-T (CC-0.09, NCC-0.04)
    - R_I-T (CC- 0.07, NCC-0.04)

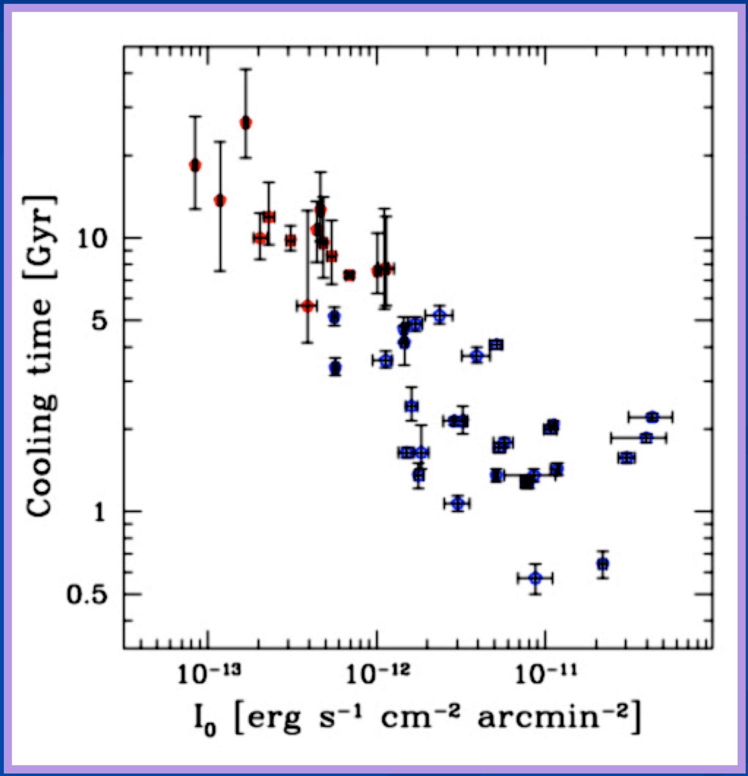


$$\langle T_x \rangle_{CC} \Rightarrow \langle T_x \rangle_{CC}(1+\beta)$$

O'Hara et al. in preparation

Correcting for Cool Cores Using Central Surface Brightness

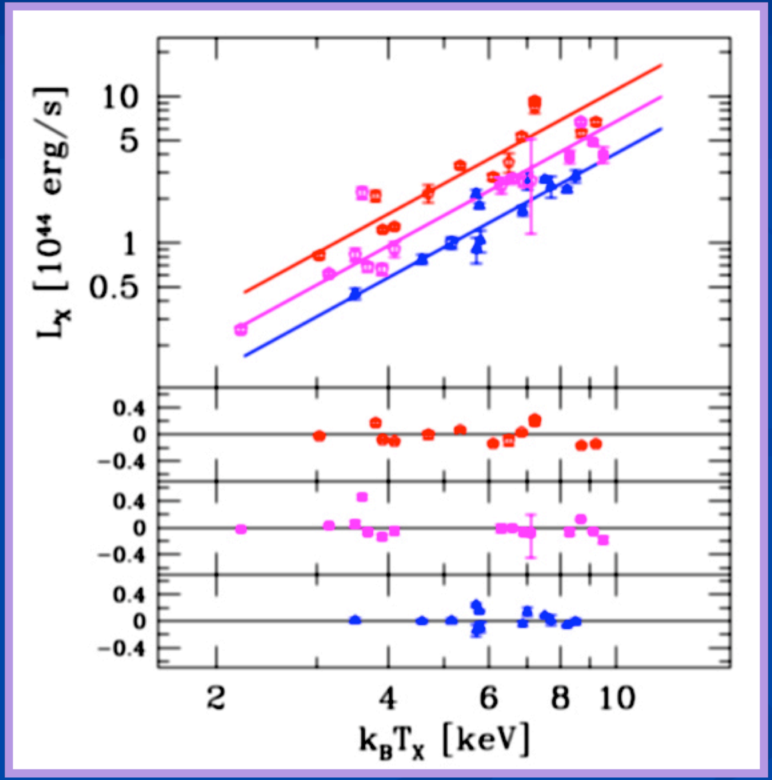
- Binary CC/NCC sample division (by central cooling time) is still unsatisfactory-- there is a continuum of clusters lying between NCC to strong CC
- With a tracer of the CC strength, one could further remove the CC related effects-- and then probe the residual scatter for merger effects
- Notice that central surface brightness traces central cooling time reasonably well, and that it also correlates with scatter in the scaling relations



O'Hara et al, in preparation

Correcting for Cool Cores Using Central Surface Brightness

- Binary CC/NCC sample division (by central cooling time) is still unsatisfactory-- there is a continuum of clusters lying between NCC to strong CC
- With a tracer of the CC strength, one could further remove the CC related effects-- and then probe the residual scatter for merger effects
- Notice that central surface brightness traces central cooling time reasonably well, and that it also correlates with scatter in the scaling relations

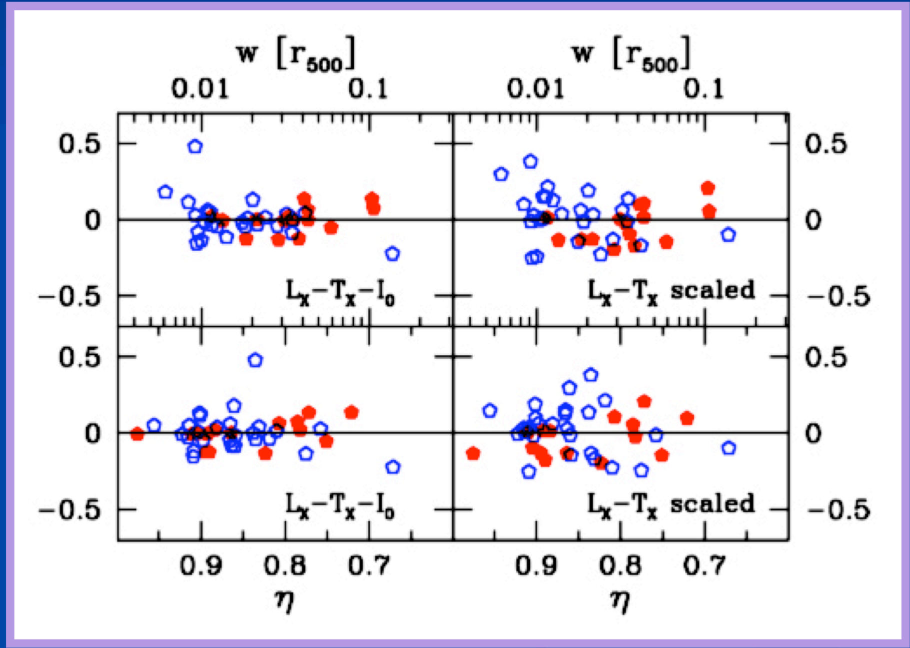


O'Hara et al. in preparation

So What About Residual Scatter After Removing CC/NCC Effects?

- After using the surface brightness to remove the dominant source of scatter-- the CC/NCC variation in the population-- we examine scatter about the Lx-T versus substructure indicators

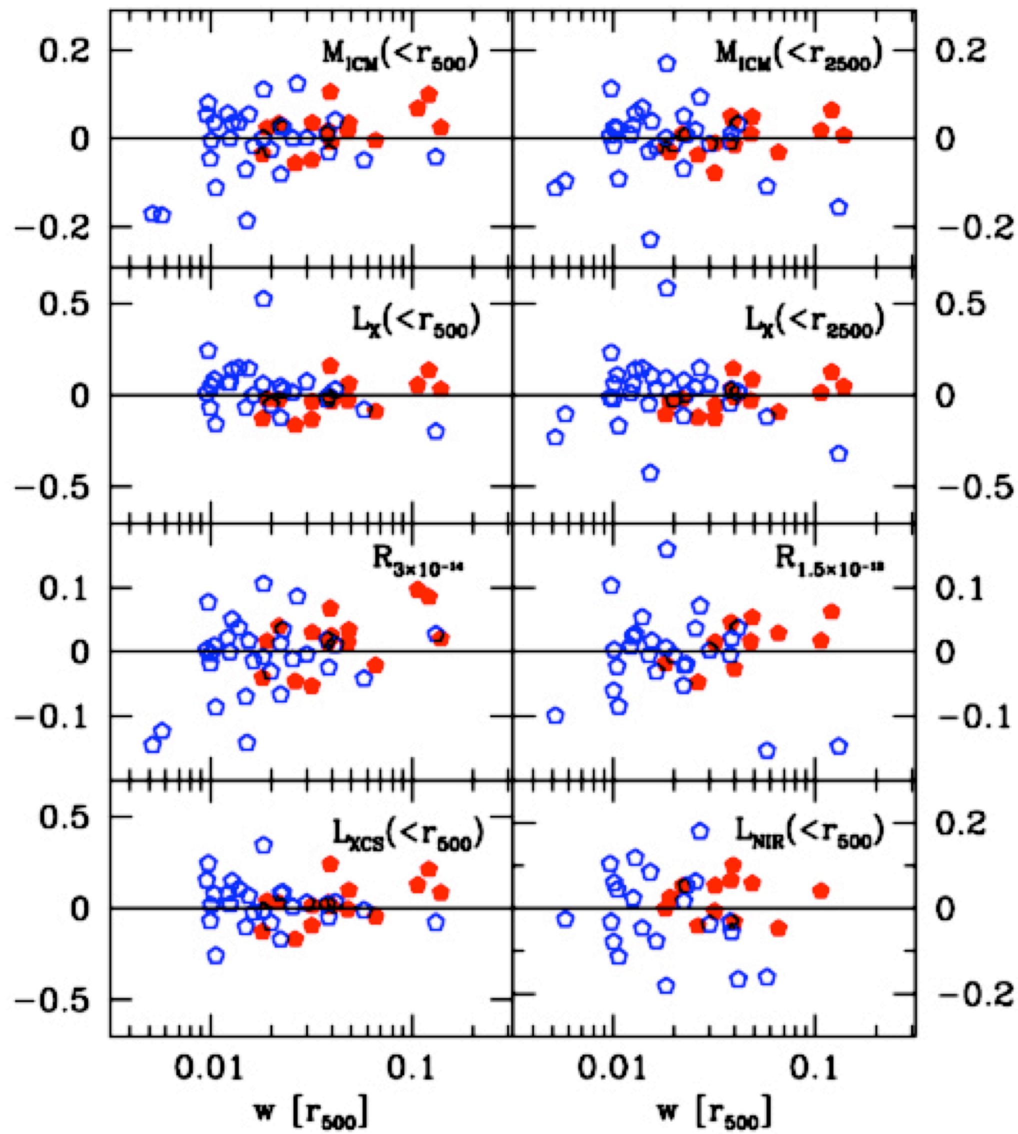
- Surprisingly, there are no clear indications that the clusters with higher substructure exhibit larger scatter about the scaling relations



O'Hara et al. in preparation

Scatter vs Substructure in All the Observables

- We find no clear trend for increasing scatter with level of substructure!
  - True for centroid variation, ellipticity, P_1/P_0, P_2/P_0
- This is true with the scaling relations treated using temperature boost factors or using the more elegant central surface brightness correction



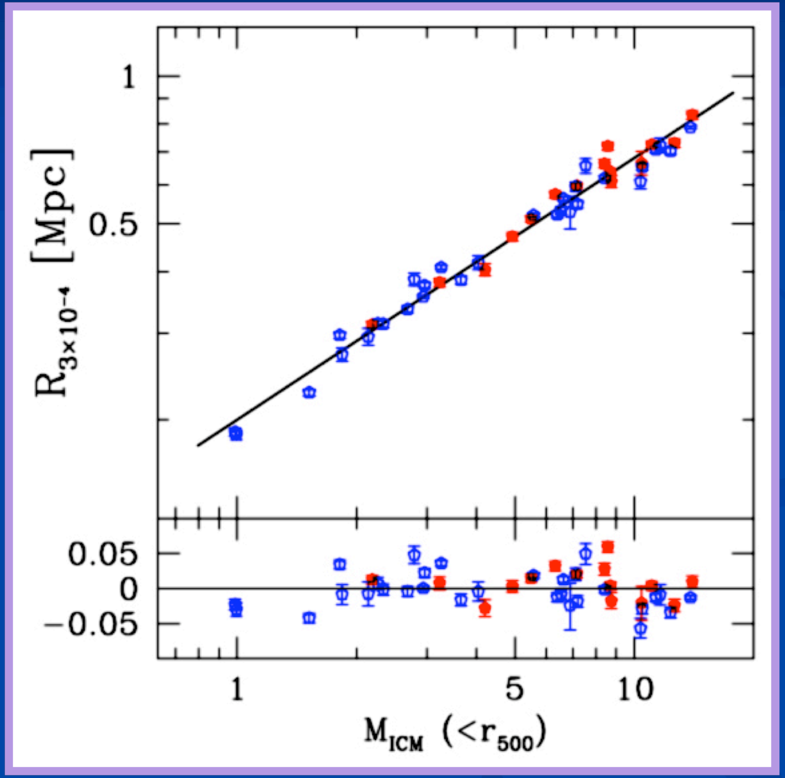
O'Hara et al, in preparation

What Could Be Going On?

- Merger related scatter could be masked by some additional source of scatter
  - Residual CC related scatter?
  - T_x measurement systematics? (could look at non-Tx relations)
  - Variations in AGN feedback from cluster to cluster?
- Morphological merger indicators may be poor tracers
  - Perhaps only trace major mergers well
  - Look at simulated clusters…
- Clusters are young objects and merger effects are long lived
  - Whether or not clusters appear to be regular they exhibit similar amounts of structural variation

Scaling Relations without T_x

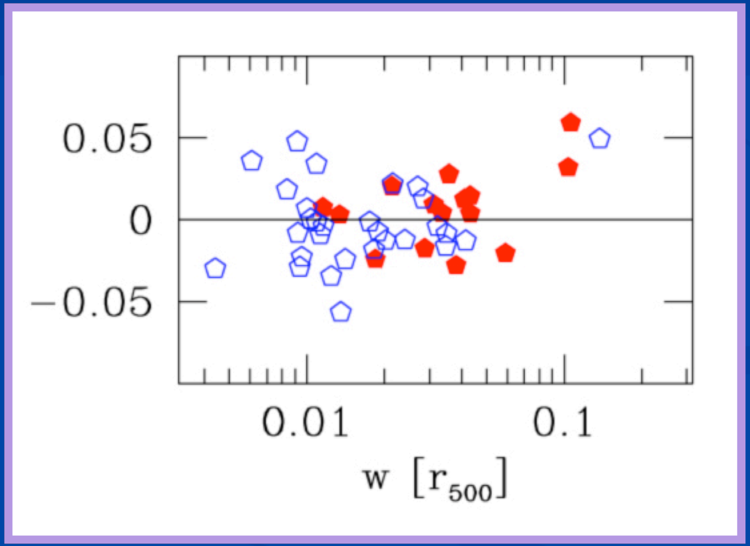
- We examine a scaling relation made without Tx and with quantities that are relatively insensitive to the core structure of the cluster: $M_{icm}(r500)$-R_I
- This scaling relation has strikingly small scatter, providing another indication that it is the core that is driving the scatter
- No clear indication that clusters with higher substructure scatter more in this relation



O'Hara et al, in preparation

Scaling Relations without T_x

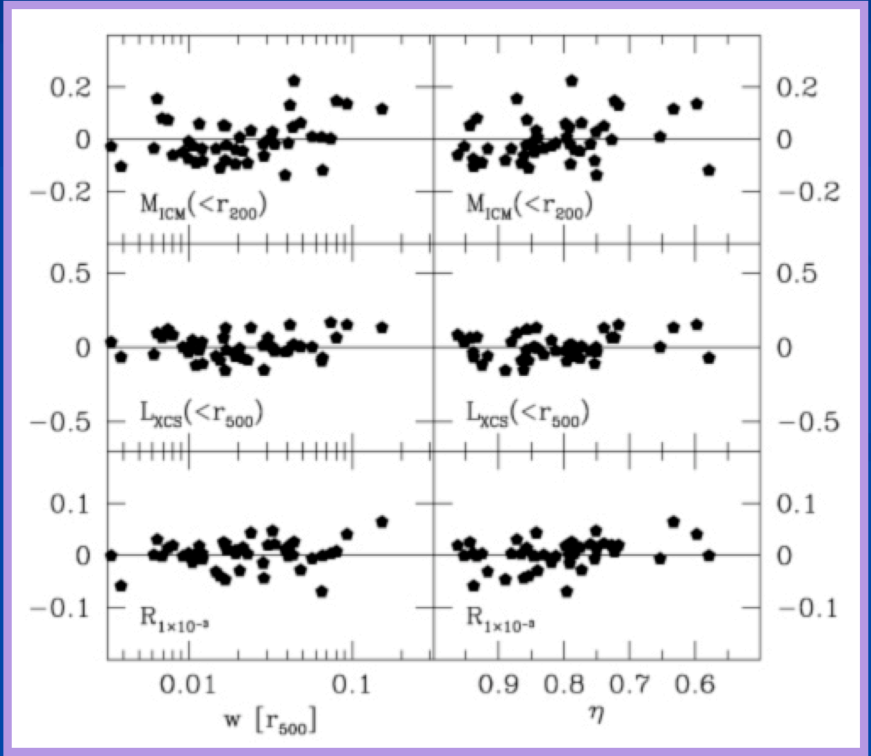
- We examine a scaling relation made without Tx and with quantities that are relatively insensitive to the core structure of the cluster: $M_{icm}(r500)$-R_I
- This scaling relation has strikingly small scatter, providing another indication that it is the core that is driving the scatter
- No clear indication that clusters with higher substructure scatter more in this relation



O'Hara et al, in preparation

Scaling Relations with Simulated Clusters

- We examine the scaling relations in 68 hydro simulations in collaboration with Gus Evrard and John Bialek
  - These sims do not include cooling, so there can be no CC effects
- Clusters with the highest substructure do, perhaps, provide some indication of higher scatter, but it is a subtle effect!



O'Hara et al, in preparation

Conclusions

Cluster scaling relations contain a wealth of information on *entire* cluster population

- Critically important for cosmology
- Slopes provide tests of self-similarity
- Scatter provides measure of structural variation

CC/NCC differences are the dominant structural variation in clusters

- Scatter in scaling relations completely dominated by CC effects

Merger related signatures weak or absent after removal of CC effects

- No correlations between scatter and substructure measures

- Implications
  - Cautionary tale for those who would use the low ellipticity or presence of a CC as evidence that the cluster is "highly relaxed"
  - Suggests that concern for cluster surveys will be the changing fraction of CC/NCC clusters with redshift rather than the increased number of mergers… this is good news for the SZE surveys