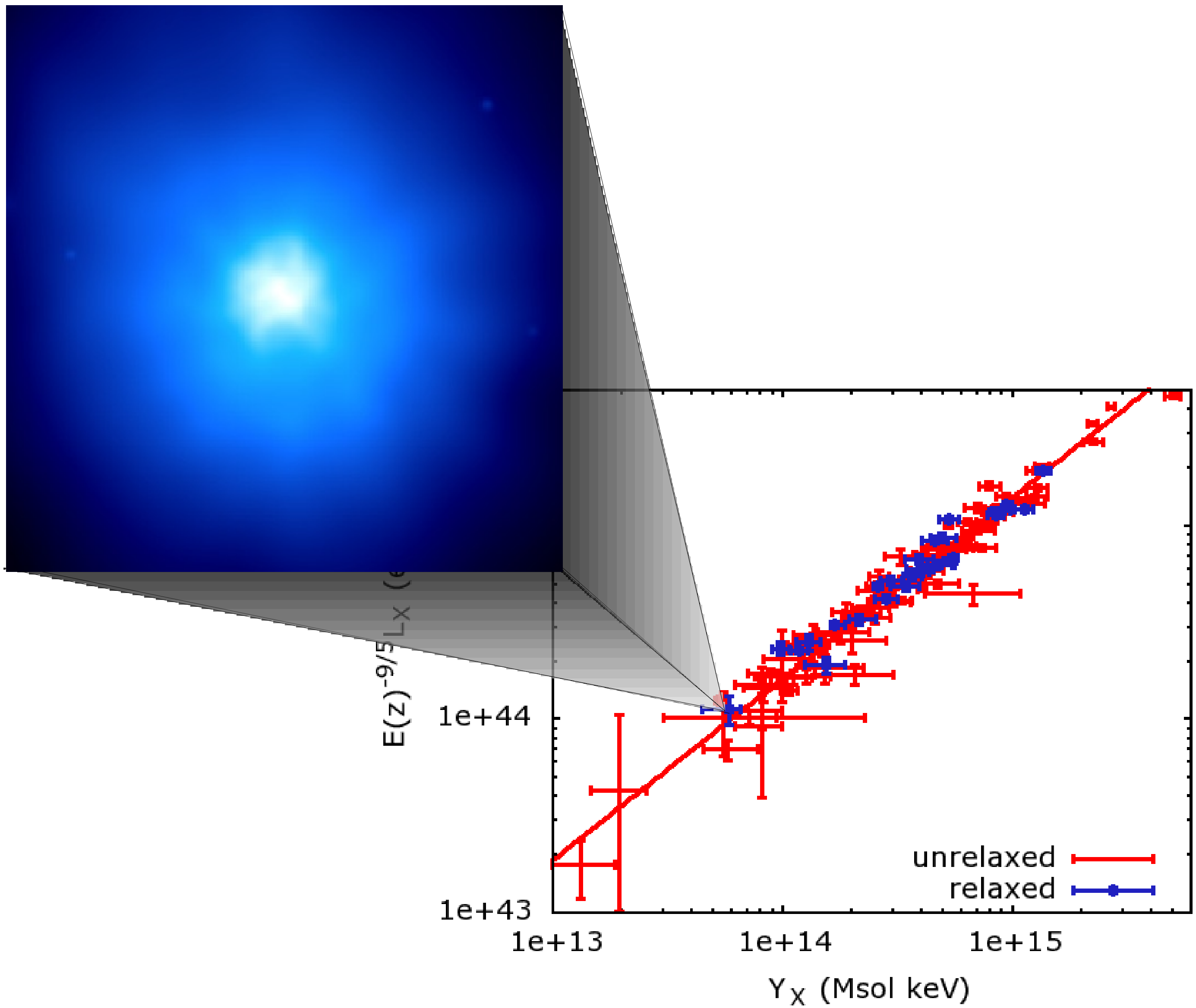
Galaxy Clusters and Self Similarity III



Course Outline

- Introduction to galaxy clusters and properties at different wavelengths
- Self similarity in galaxy clusters – theoretical background and comparison with observations
- Observational results on similarity breaking and causes

Summary I

Self-similar model assumes:

- Clusters form in single collapse at z_{obs}
- Gravity only source of energy

Self-similar model predicts:

- Clusters of different masses are scaled versions
- Clusters at different z identical if scaled for $\rho_c(z)$

Define cluster properties within overdensity radii

- Mean density enclosed is Δ times $\rho_c(z)$
- Fair comparison of clusters of different M and z

Summary II

Derive self-similar scaling relations

- Simple power laws relating cluster properties
- MT, LT, etc

Compare scaling relations with observation

- Differences from SS model reveal physical processes no included

Scaling relations have potential to allow estimation of cluster masses from easily measured properties

- Cosmological tests

Reading List & Exam

Read at least one of the following papers:

- Branchesi et al. (2007), A&A, 472, 739-748
- Kotov & Vikhlinin (2005), ApJ, 633, 781-790
- Lumb et al. (2004), A&A, 420, 853-872
- Magliocchetti & Bruggen (2007), MNRAS, 379, 260-274

Exam consists of short and long answer question on each topic

- answer all short and 2 long questions
- full marks on my long question requires correctly referencing one paper above e.g.

  "Maughan et al. (2007) showed that the scatter in the X-ray luminosity – mass relation is significantly lower than previously thought."

Today

Observational results on similarity breaking and causes

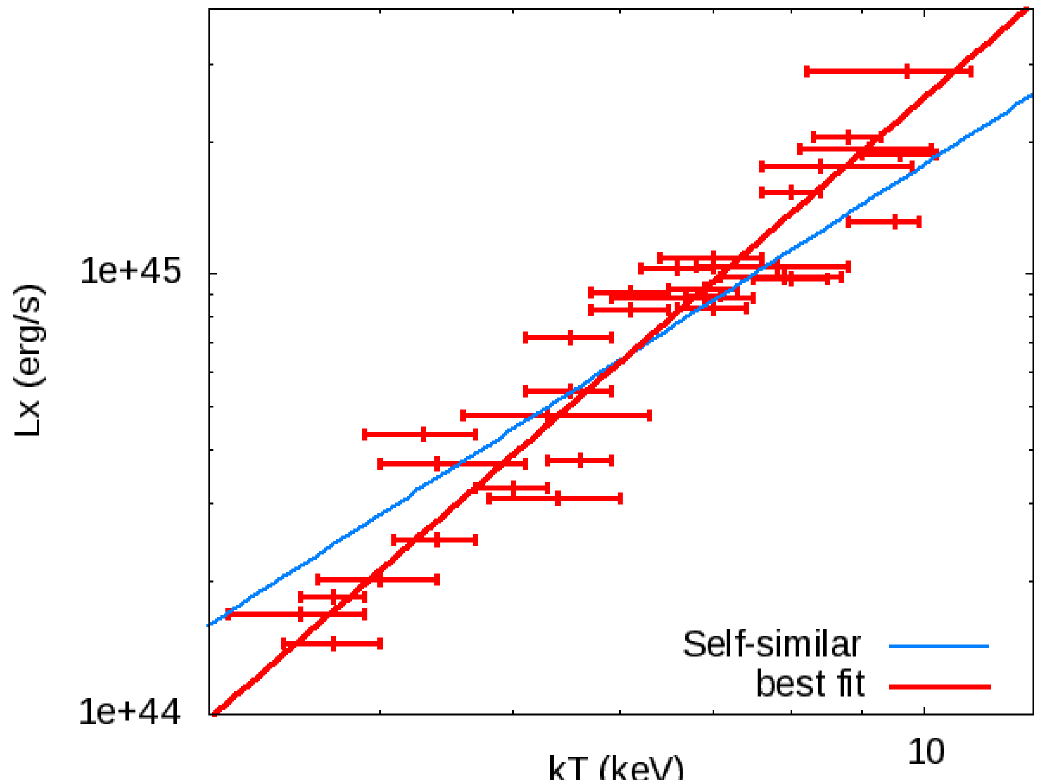
- Selection effects and evolution
- Effects of cooling cores, AGN, and mergers
- Scatter in the scaling relations
- Yx – a super scaler

Observational Results: Slopes

Self-similar model predicts $L \propto kT^2$ but **observations find slopes of 2.5-3**

Probably steepens further at lower kT or M - why?

- Non-gravitational processes not included in SS model are needed to
  - Raise kT
  - Lower ρ
- Effect is stronger compared to gravitational energy in lower mass systems
  - Steepens relation



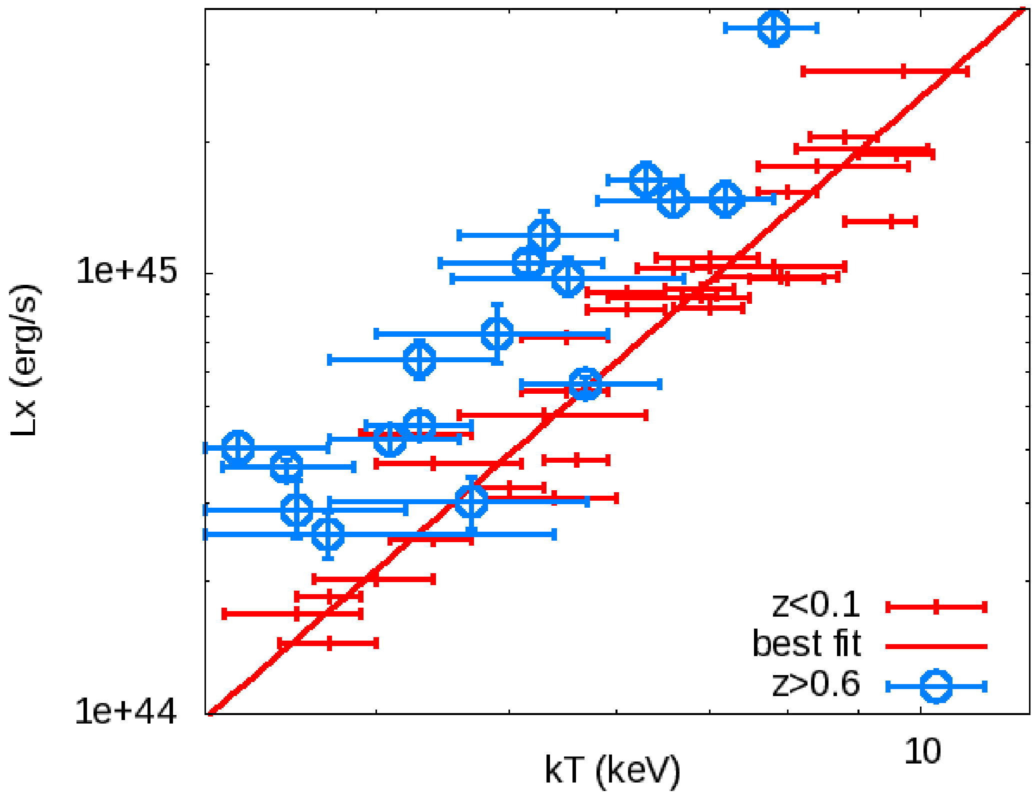
Observational Results: Evolution

Recall (2.4):

$$L_X \propto \Delta^{1/2} E(z)(kT)^2$$

Add high-z (z>0.6) clusters onto the previous low-z LT relation

- High-z clusters have higher Lx at a given kT than low-z clusters
- There is evolution, but is it self-similar?



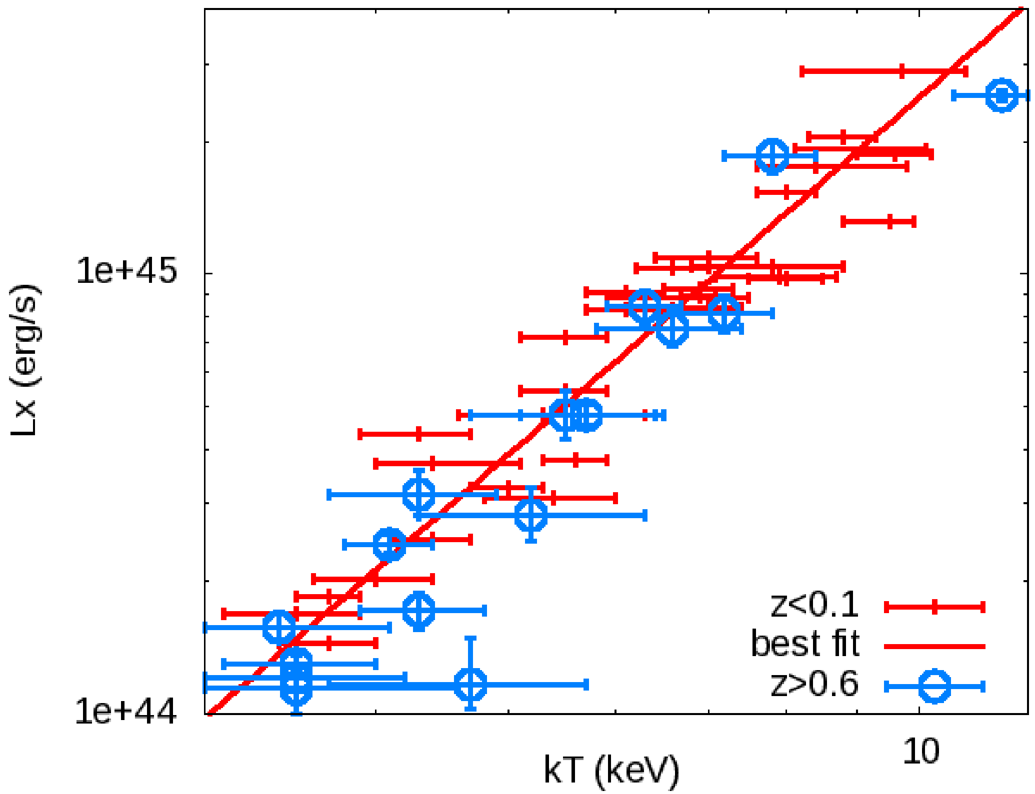
Observational Results: Evolution

$$L_X \propto \Delta^{1/2} E(z)(kT)^2$$

Divide measured Lx by E(z) to remove self-similar evolution

- High-z clusters now consistent with local relation
- Weak self-similarity is obeyed (to 1st order)

Detailed measurements of evolution difficult as sample selection effects mask/mimic true evolution



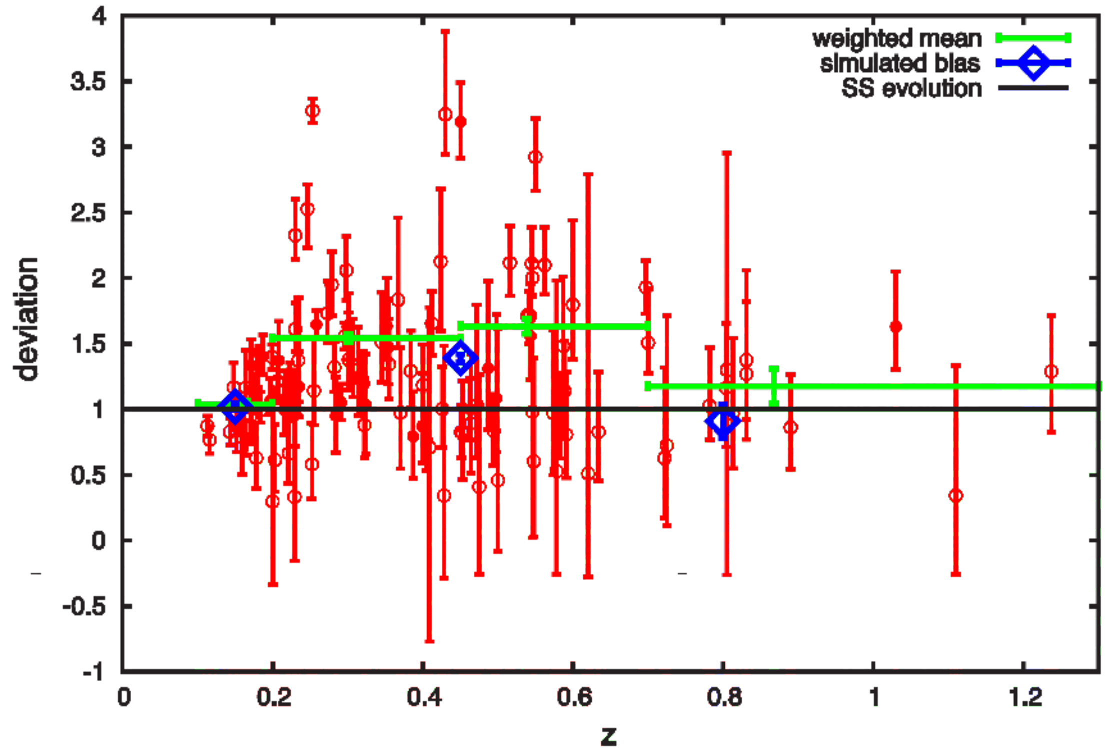
Observational Results: Evolution

Plot of observed Lx divided by Lx predicted by local LT relation – SS evolution included

- SS clusters should scatter about 1 – do they?
-
-

The way the moderate-z clusters are selected makes it more likely to find overluminous clusters

- Currently no reason to reject SS evolution



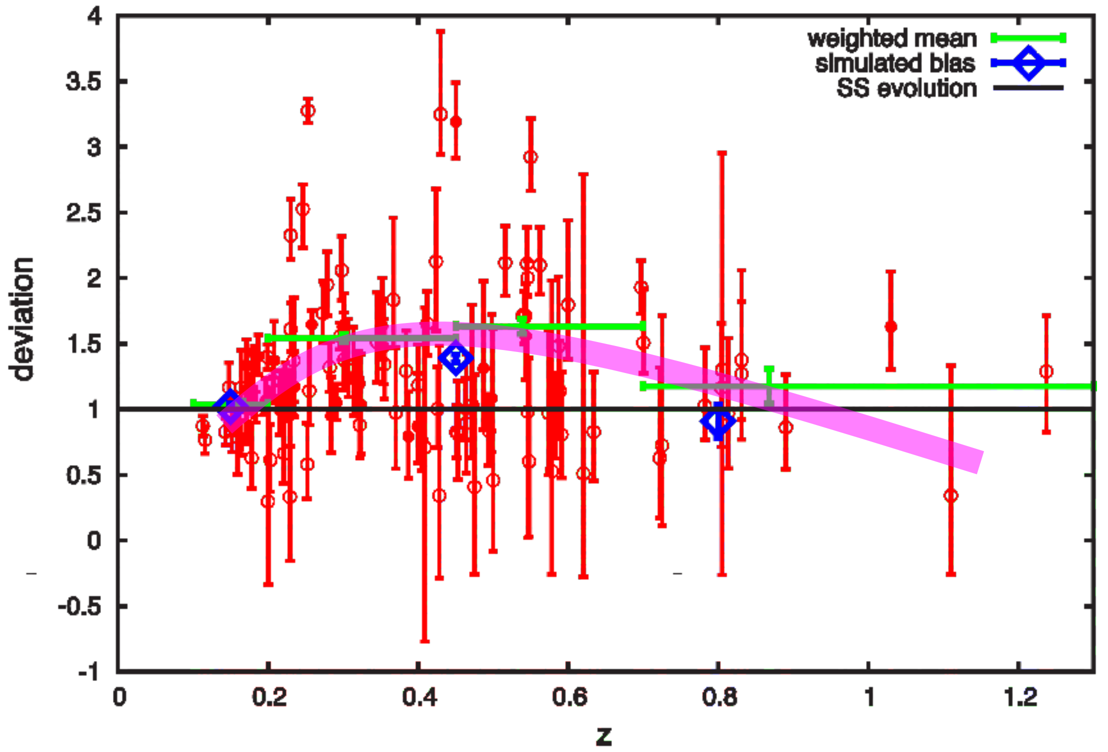
Observational Results: Evolution

Plot of observed Lx divided by Lx predicted by local LT relation – SS evolution included

- SS clusters should scatter about 1 – do they?
- Data suggest overluminous clusters at moderate z
- Non-SS evolution?

The way the moderate-z clusters are selected makes it more likely to find overluminous clusters

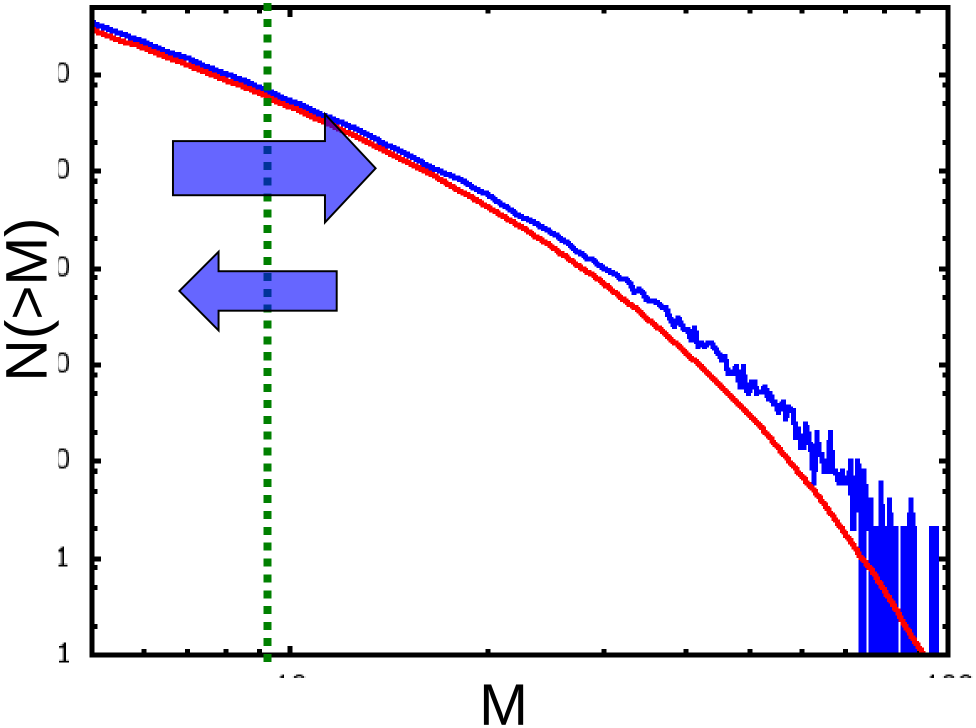
- Currently no reason to reject SS evolution



Observational Results: Evolution

Consider the mass function of clusters

- Many samples defined by luminosity limit
  - corresponds to some mass from Lx-M relation
- Scatter in Lx-M means some clusters with masses too low will be in sample and vice-versa
- Slope of mass func means more clusters scattered **into** sample
  - Biases sample to clusters with Lx high for their M



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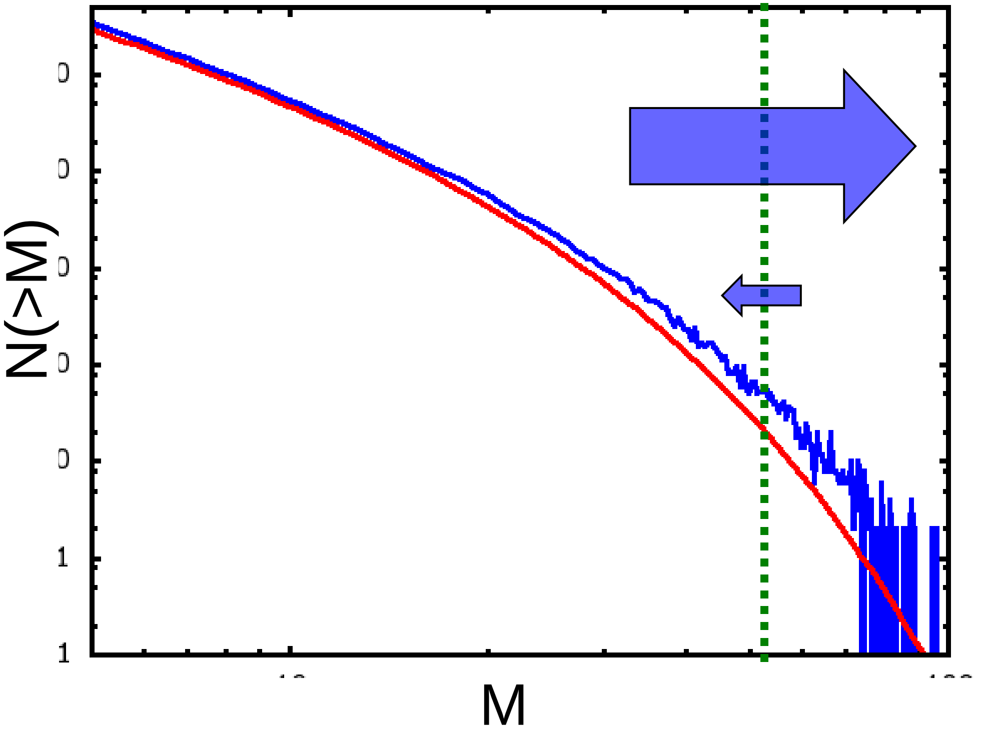
- Slope of mass func means more clusters scattered **into** sample
  - Biases sample to clusters with Lx high for their M
  - Amount of bias depends on Lx limit



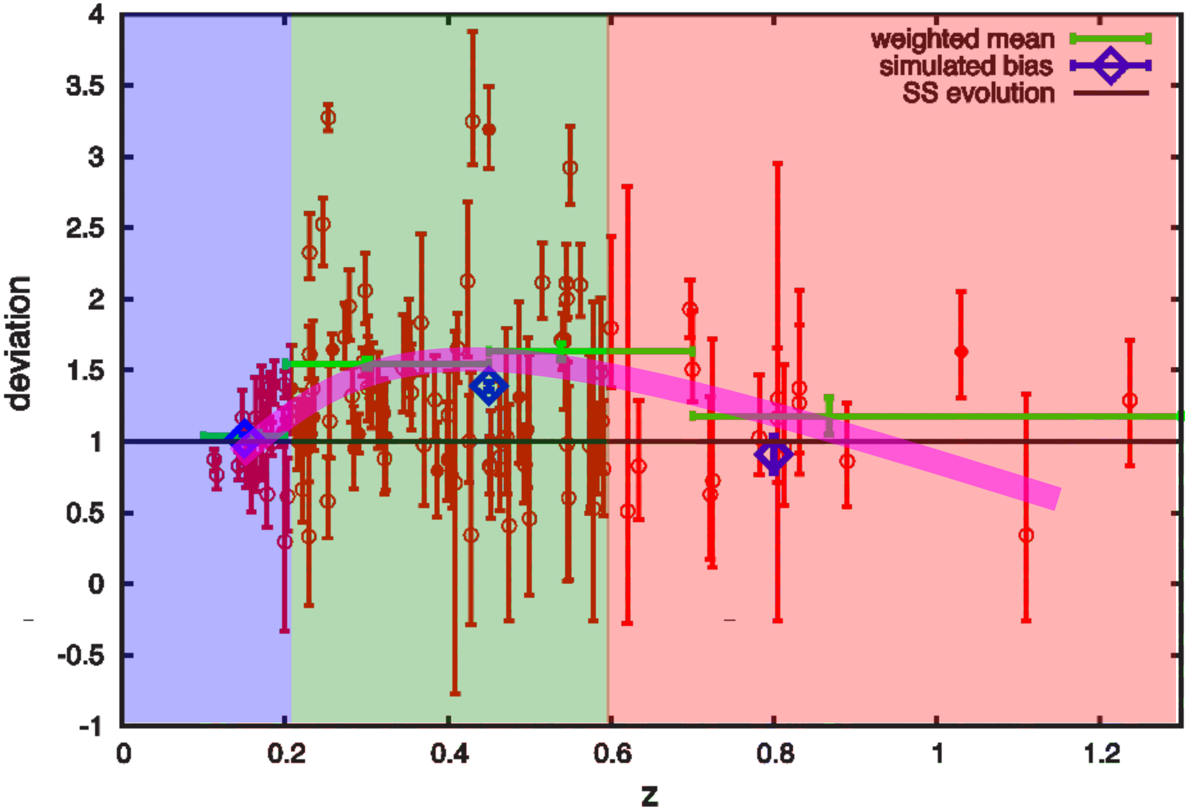
Observational Results: Evolution

The way cluster surveys are designed split into 3 rough categories with redshift

At low-z, flux limit corresponds to low Lx limit (bias low)

Medium z, same Fx limit gives higher Lx limit (large bias)

High-z, deeper surveys so Fx limit lower, gives lower Lx limit (bias low)



Observational Picture

Slopes of the various scaling relations generally do not agree with self-similar predictions

- Strong self-similarity not obeyed

Evolution of scaling relations generally found to be consistent with self-similar predictions

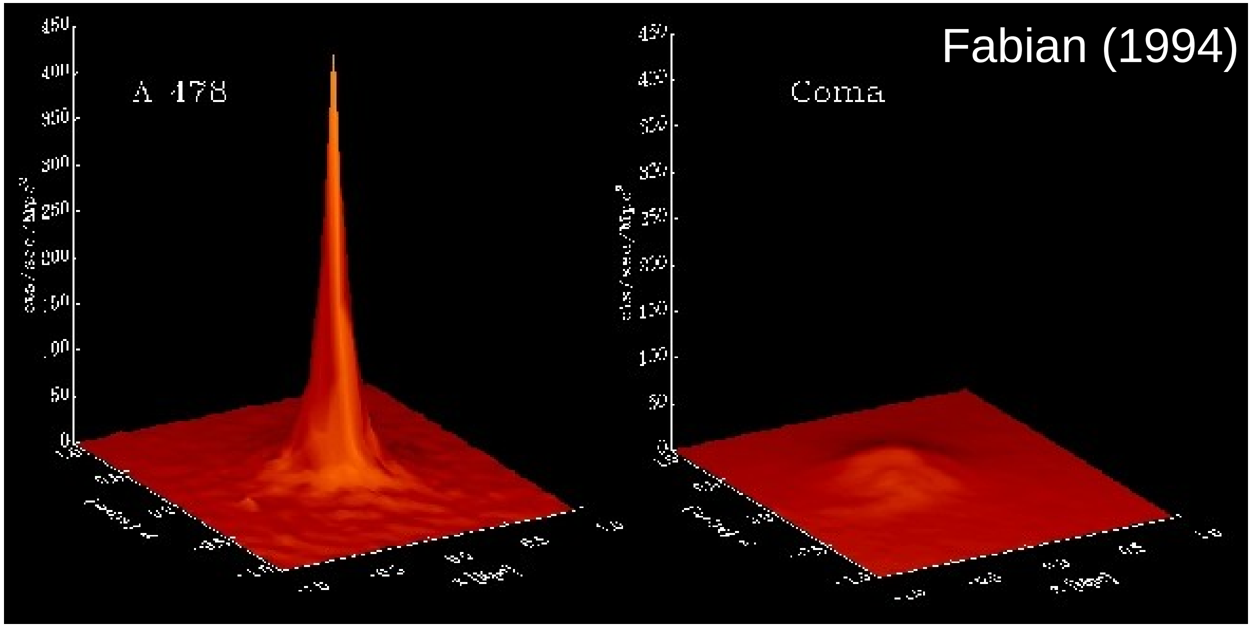
- Weak self-similarity is obeyed to 1st order
- Sample selection effects make more detailed tests of evolution difficult

Similarity Breaking: Cooling

We know $Lx \propto \rho^2$ - gas in dense cluster cores radiates thermal energy away as X-ray emission

- Cooling time significantly shorter than age of cluster
- Gas cools efficiently and condenses, replaced by gas cooling in from larger radii
- Runaway process, known as a **cooling core**

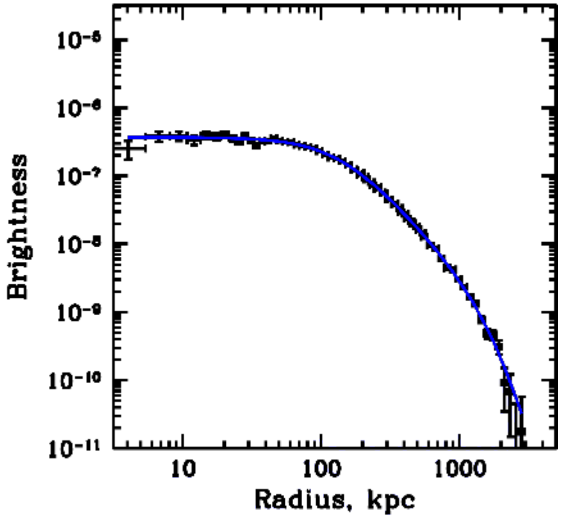
Which of these clusters has a cooling core?

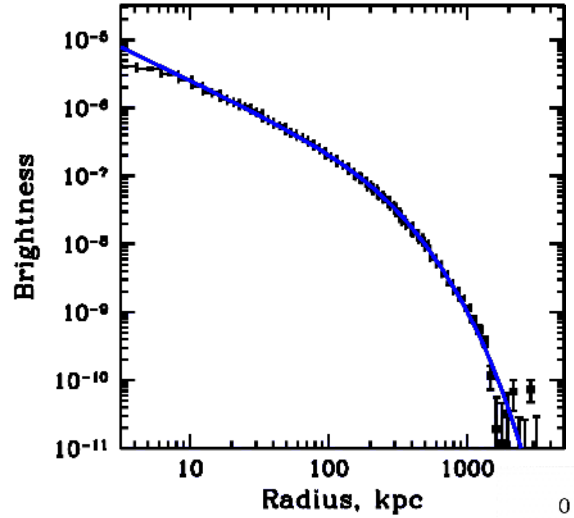


Fabian (1994)

Similarity Breaking: Cooling

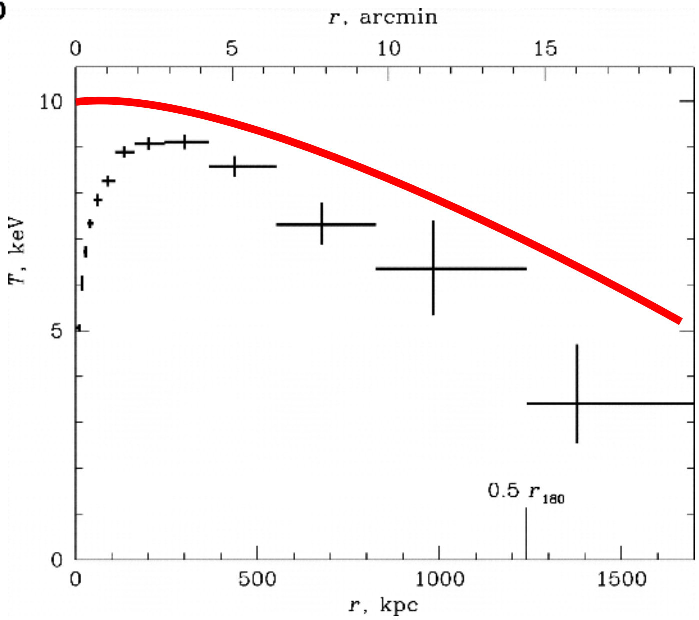
Cooling core diagnosis:





Sharp peak in **gas** density profile

Declining kT profile in core
Otherwise, profile may be flat or increasing in core

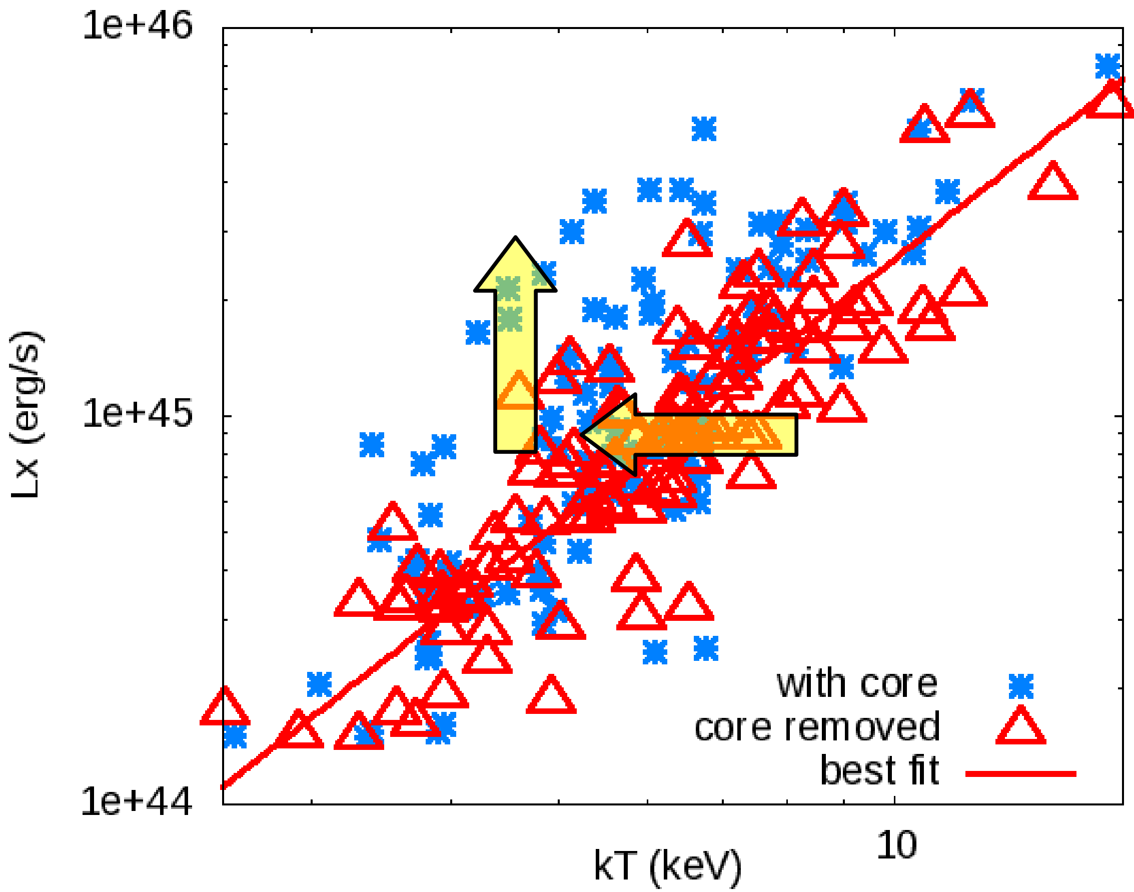


Similarity Breaking: Cooling

Radiative cooling is not included in self-similar model

- Cool core clusters are **cooler** and **brighter** than self-similar predictions

- Eliminate the effect by removing the core regions from measurements of Lx and kT
- Must exclude central $\mathbf{0.15R_{500}}$ (~150kpc)



Similarity Breaking: Cooling

Early work suggested 1,000s $M_\odot$/yr condensing in cores of CC clusters

- Problem: Fate of gas unknown

More recently found cooling rates much lower

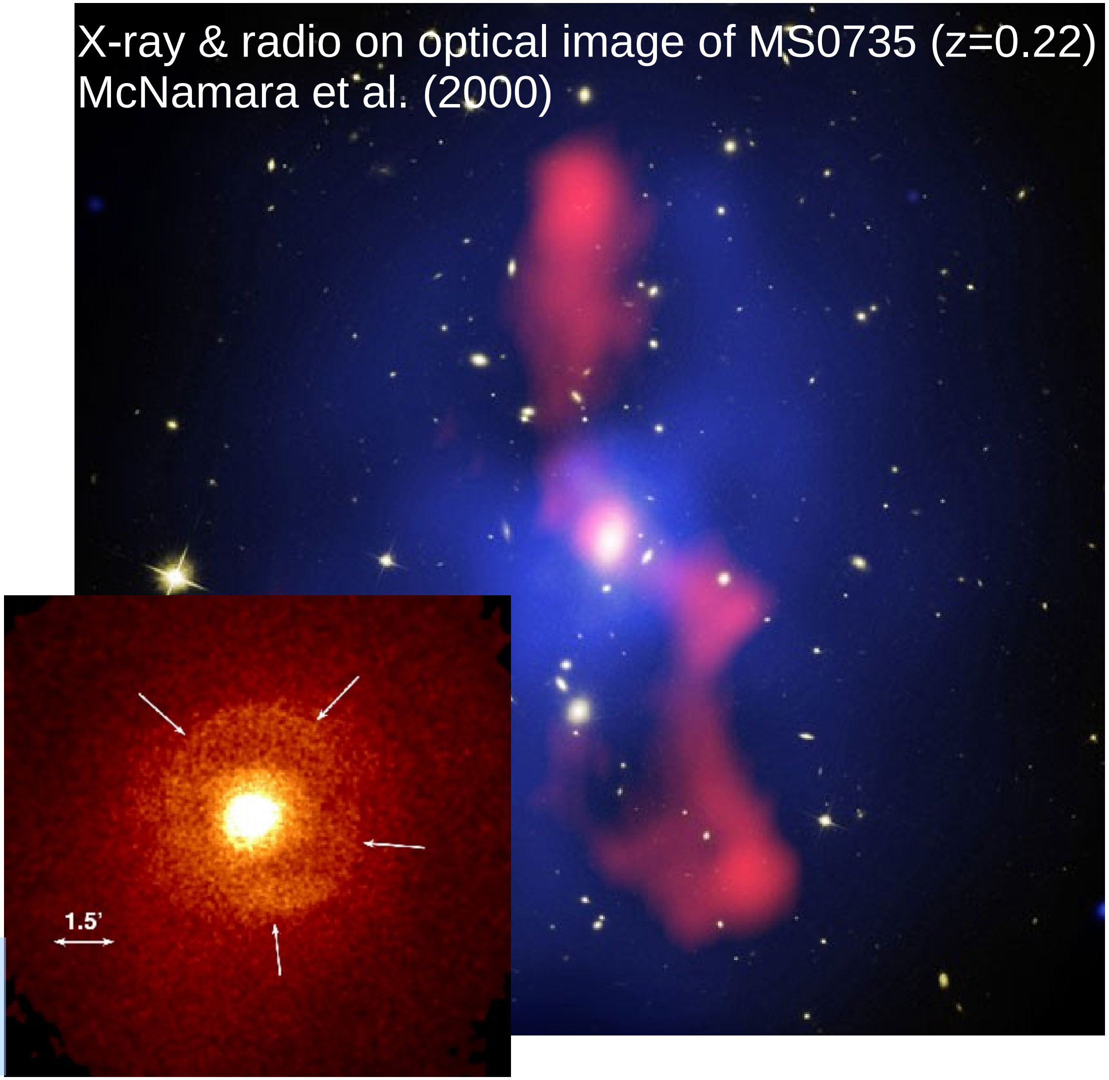
- Problem: What balances cooling?

Similarity Breaking: AGN

CC clusters tend to host active galactic nuclei (AGN) in central galaxy

- AGN fuel jets of relativistic material
- Observed interacting with X-ray plasma

Mechanisms not understood fully (rising cavities and weak shocks), but energy from intermittent AGN can balance cooling



X-ray & radio on optical image of MS0735 (z=0.22)
McNamara et al. (2000)

X-ray image of weak shock in core of M87 (Virgo cluster)

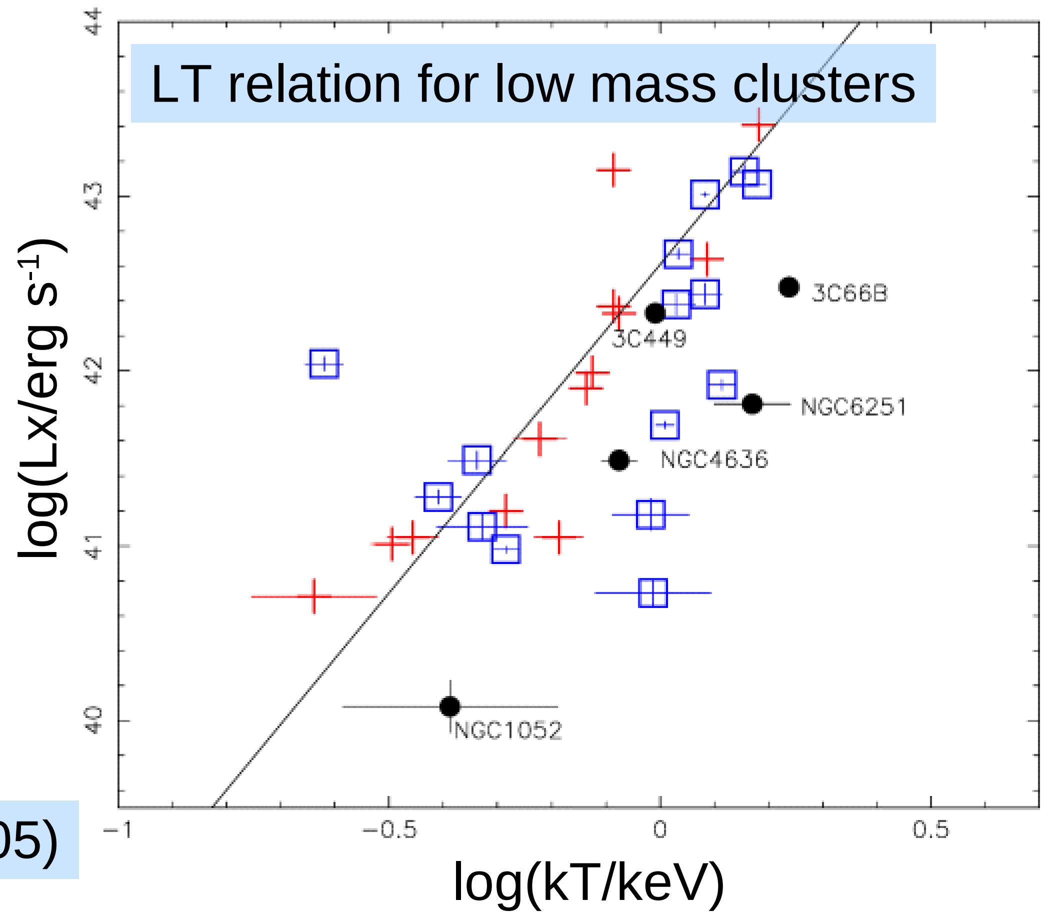
Similarity Breaking: AGN

AGN energy input not included in SS model

- Evidence in low mass clusters that active AGN clusters (□, ●) are **hotter** than inactive (+)

Effect likely smaller compared to gravitational energy in higher mass clusters

- Steepening of LT relation?



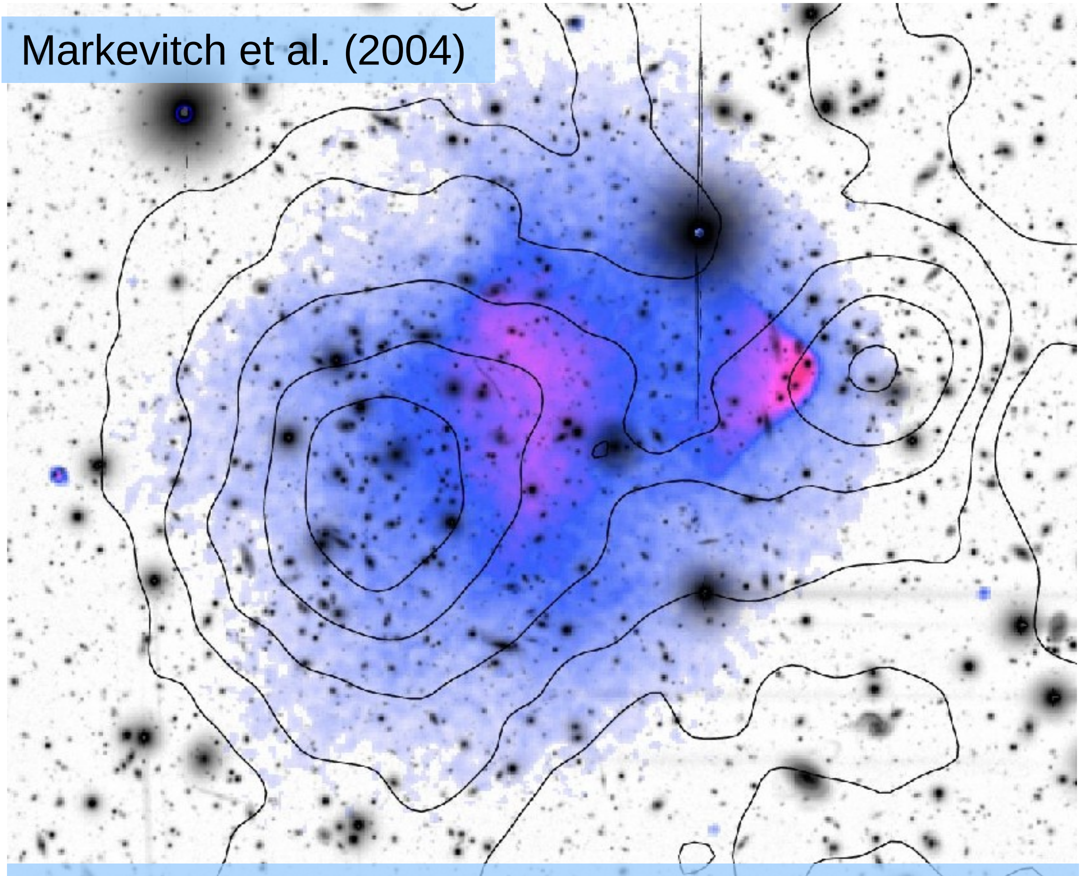
Croston et al. (2005)

Similarity Breaking: Mergers

In SS model, clusters form in single collapse at z_{obs}

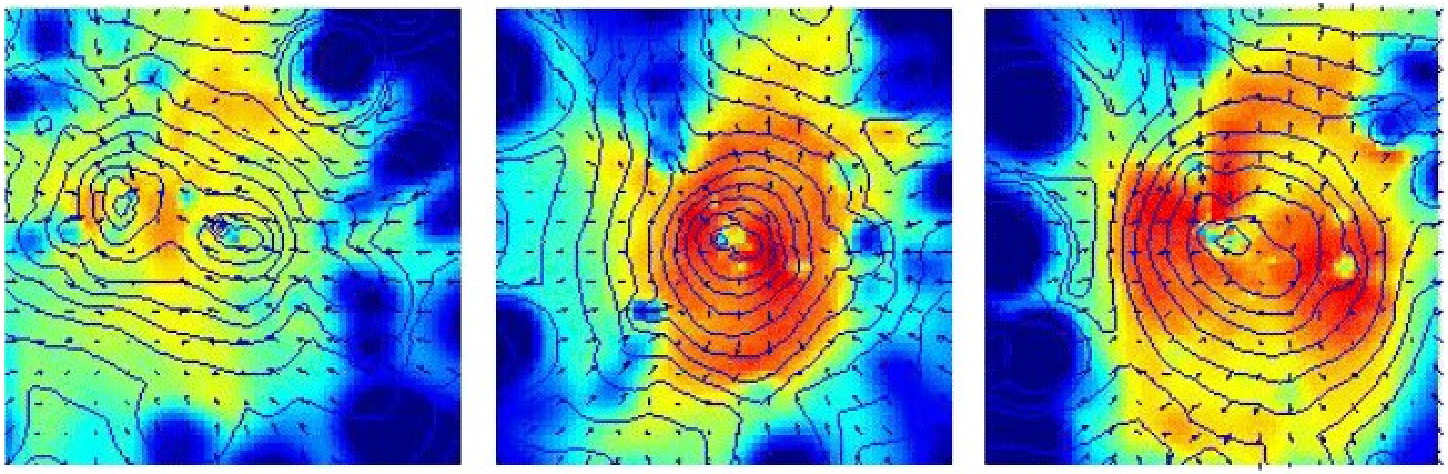
- Real clusters form via hierarchical series of mergers of smaller systems

Mergers extremely energetic and cause **transient spikes** in Lx and kT of ICM

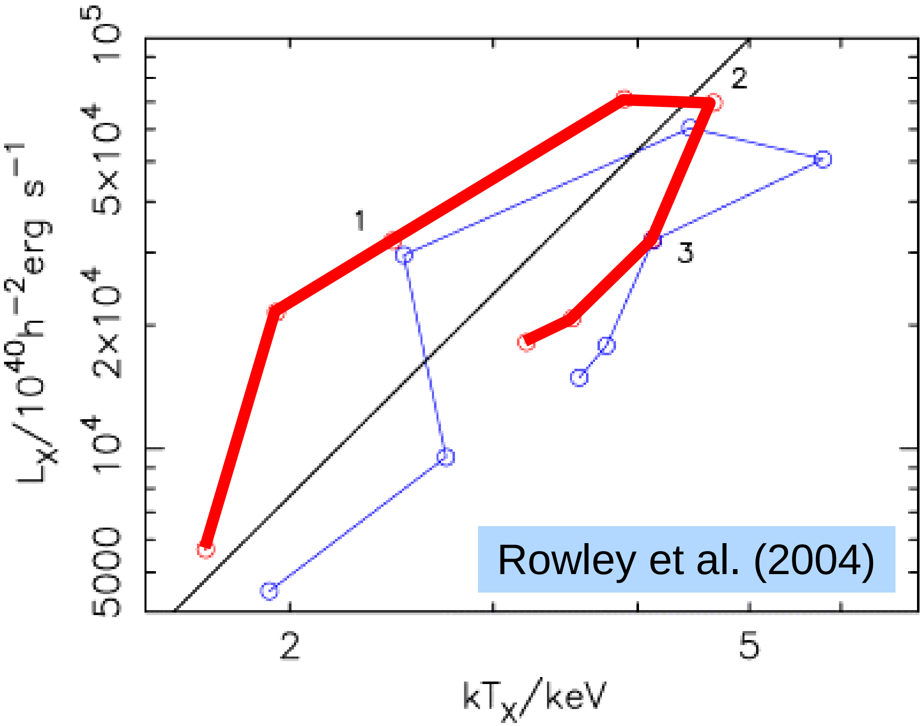


X-ray & weak lensing on optical image of bullet cluster

Similarity Breaking: Mergers



Simulations show clusters tend to move **along** the LT relation during a merger



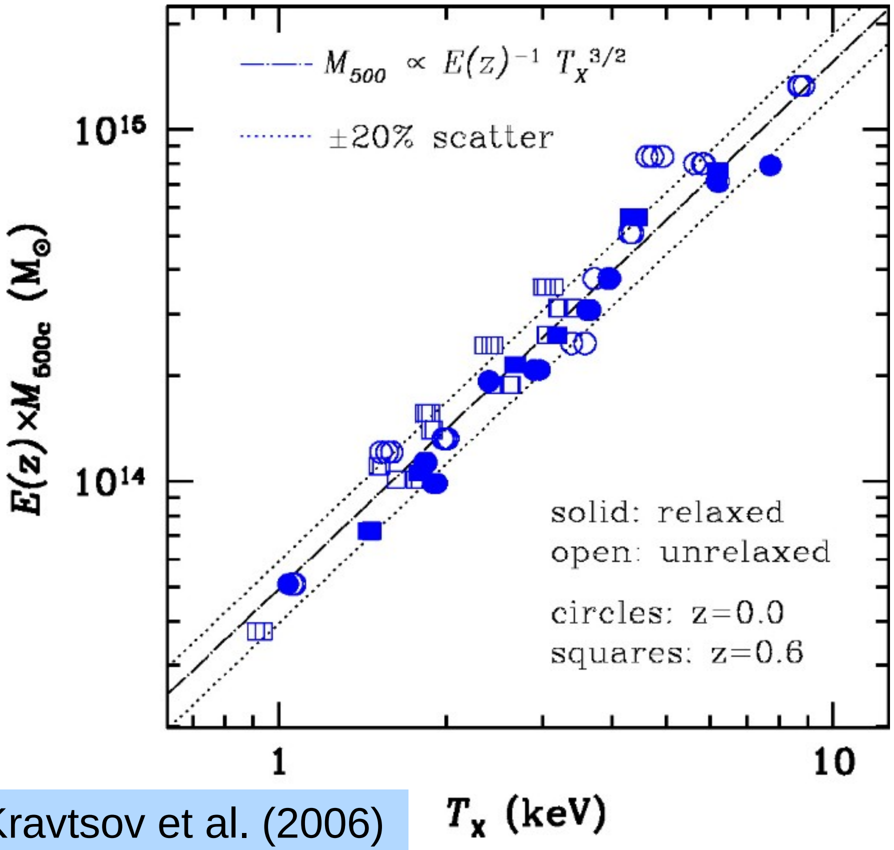
Similarity Breaking: Mergers

However, while kT has short lived spikes, it is **low** compared to the final cluster mass for most of merger

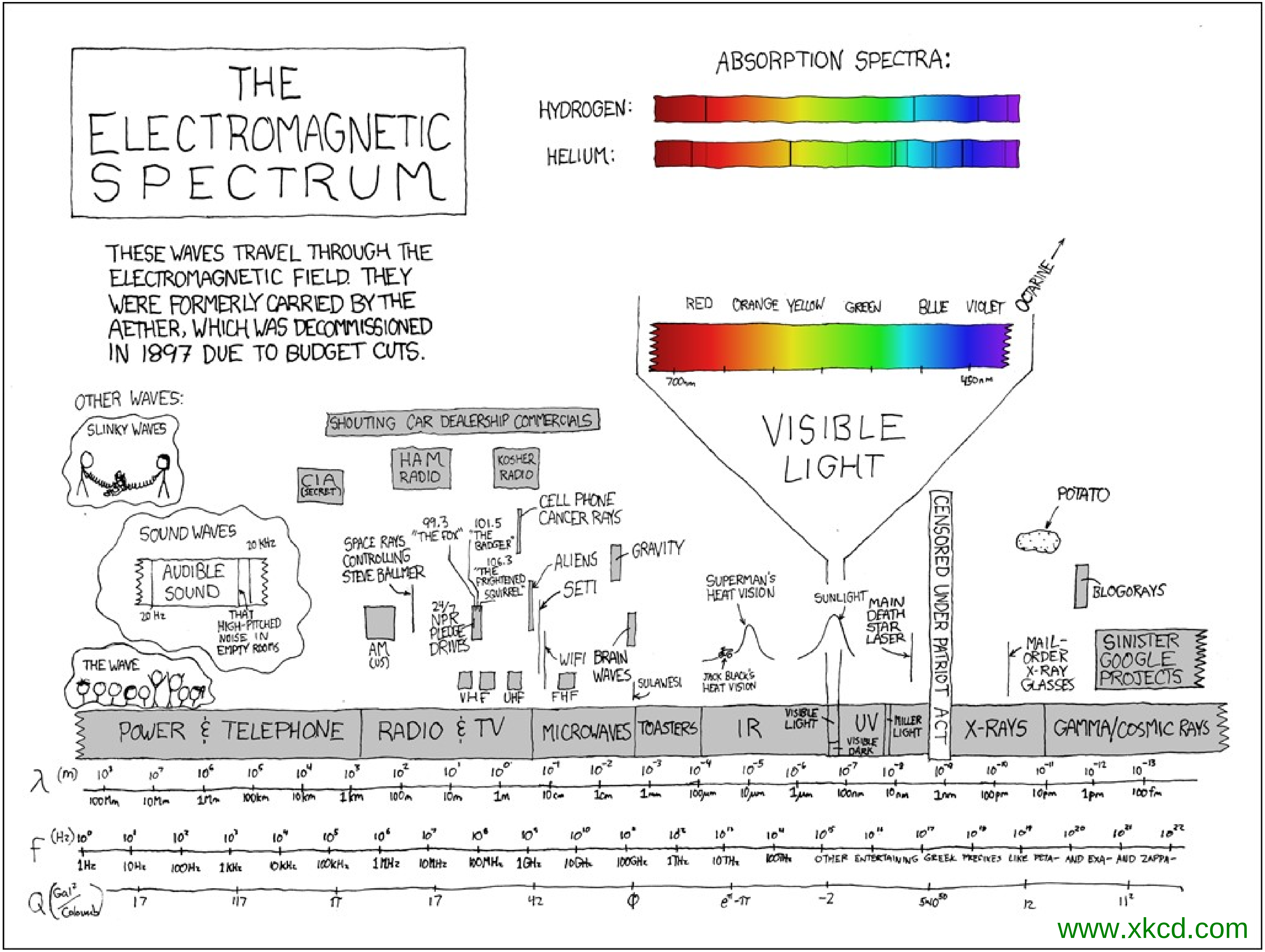
- Gas doesn't feel effect of larger gravitational potential until relaxes

Simulations show merging clusters ☐ offset from relaxed clusters ■ in the MT relation

- Hard to test observationally as merging clusters not in hydrostatic eqm (mass???)
- Could ignore merging clusters from studies but risk biasing samples



Kravtsov et al. (2006)


THE ELECTROMAGNETIC SPECTRUM
THESE WAVES TRAVEL THROUGH THE ELECTROMAGNETIC FIELD. THEY WERE FORMERLY CARRIED BY THE AETHER, WHICH WAS DECOMMISSIONED IN 1897 DUE TO BUDGET CUTS.
ABSORPTION SPECTRA:
HYDROGEN:
HELIUM:
RED
ORANGE
YELLOW
GREEN
BLUE
VIOLET
OCTARINE
700nm
450nm
VISIBLE LIGHT
OTHER WAVES:
SLINKY WAVES
SOUND WAVES
20 kHz
AUDIBLE SOUND
20 Hz
THAT HIGH-PITCHED NOISE IN EMPTY ROOMS
THE WAVE
SHOUTING CAR DEALERSHIP COMMERCIALS
CIA (SECRET)
HAM RADIO
KOSHER RADIO
CELL PHONE CANCER RAYS
SPACE RAYS CONTROLLING STEVE BALLMER
99.3 "THE FOX"
101.5 "THE BADGER"
106.3 "THE FRIGHTENED SQUIRREL"
ALIENS
GRAVITY
SETI
AM (US)
24/7 NPR PLEDGE DRIVES
VHF
UHF
FHF
WIFI
BRAIN WAVES
SULAWESI
SUPERMAN'S HEAT VISION
JACK BLACK'S HEAT VISION
SUNLIGHT
MAIN DEATH STAR LASER
CENSORED UNDER PATRIOT ACT
POTATO
BLOGORAYS
MAIL-ORDER X-RAY GLASSES
SINISTER GOOGLE PROJECTS
POWER & TELEPHONE
RADIO & TV
MICROWAVES
TOASTERS
IR
VISIBLE LIGHT
UV
VISIBLE DARK
MILLER LIGHT
X-RAYS
GAMMA/COSMIC RAYS
λ (m)
10^8 10^7 10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}
100Mm 10Mm 1Mm 100km 10km 1km 100m 10m 1m 10cm 1cm 1mm 100μm 10μm 1μm 100nm 10nm 1nm 100pm 10pm 1pm 100fm
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10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20} 10^{21} 10^{22}
1Hz 10Hz 100Hz 1kHz 10kHz 100kHz 1MHz 10MHz 100MHz 1GHz 10GHz 100GHz 1THz 10THz 100THz
OTHER ENTERTAINING GREEK PREFIXES LIKE PETA- AND EXA- AND ZAPPA-
Q (Gal²/Coloumb)
17 117 1T 17 42 Φ $e^\pi - \pi$ -2 5×10^{50} 12 11^2
www.xkcd.com

Similarity Breaking: Summary

Radiative cooling in cluster cores is unstable

- Cooling cores boost Lx and lower kT
- Remove central $0.15R_{500}$ from measurements
- Energy input needed to balance cooling

AGN activity is strong candidate to balance cooling

- Cavities and weak shocks deposit energy into ICM
- Low mass clusters with AGN hotter than those without
- Smaller effect at high mass? Steepening LT relation?

All clusters form and grow via mergers

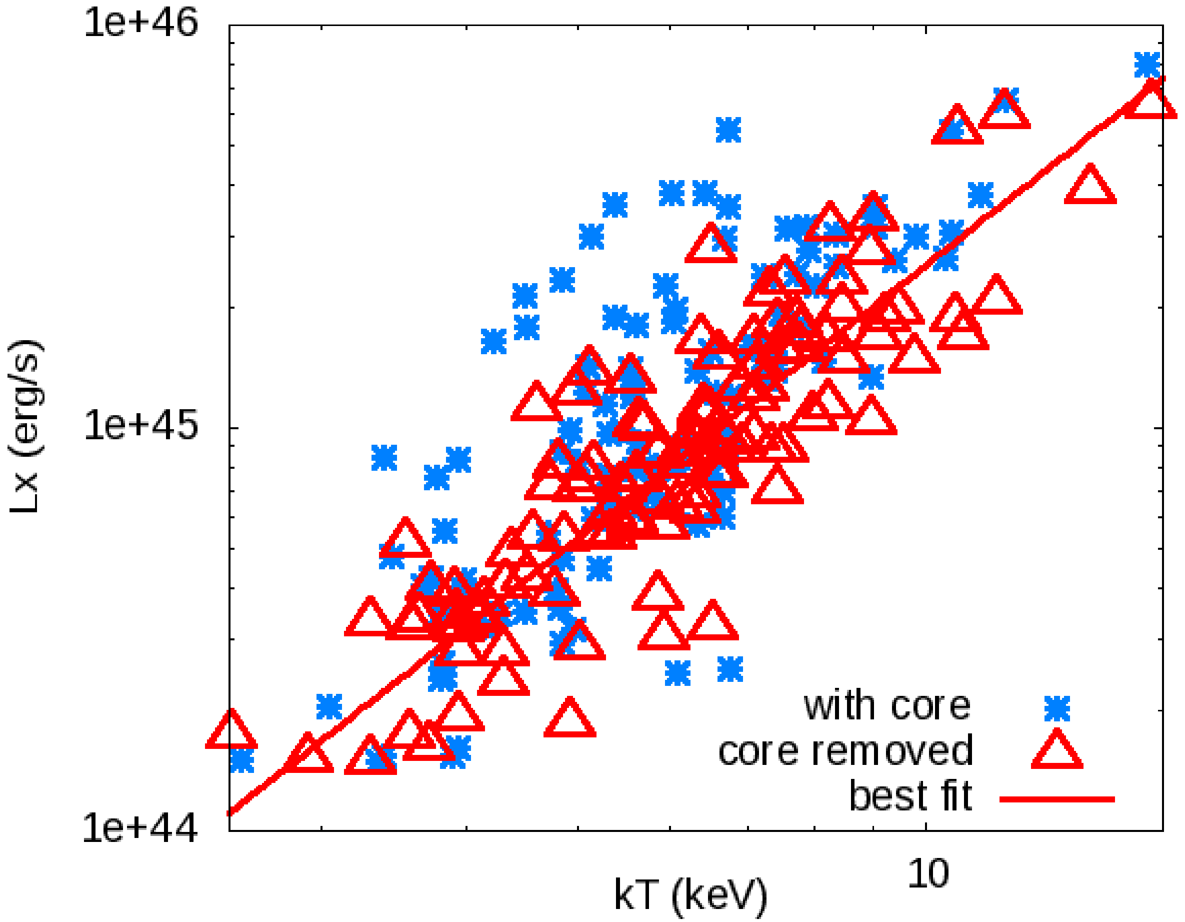
- Temporary spikes in Lx and kT during merger
- Clusters tend to move along LT, but offset from MT
- Can exclude merging clusters, but bias samples

Scatter in Scaling Relations

These non-gravitational processes in clusters contribute to observed non-statistical scatter in scaling relations

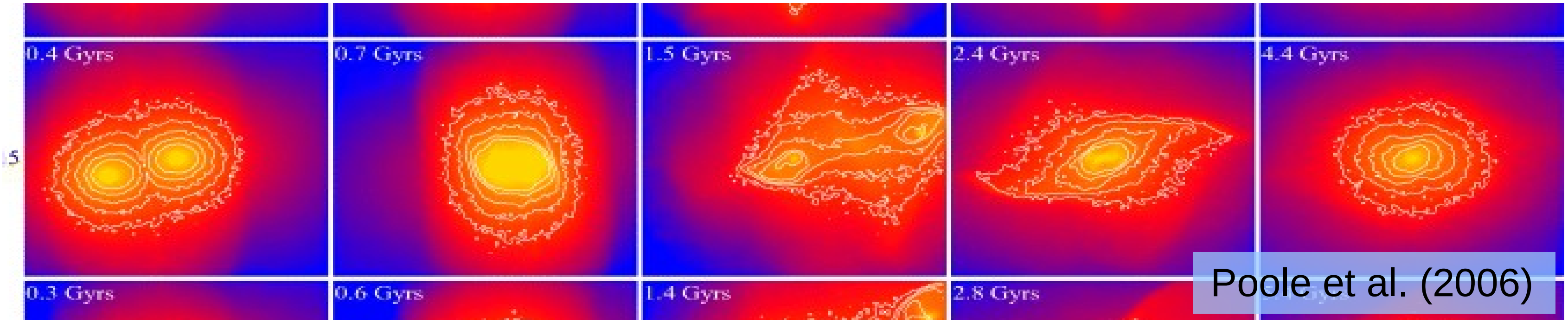
- Scatter is **dominated by core regions** of clusters

e.g. Scatter in LT relation is greatly reduced by excluding central $0.15R_{500}$



Scatter in Scaling Relations

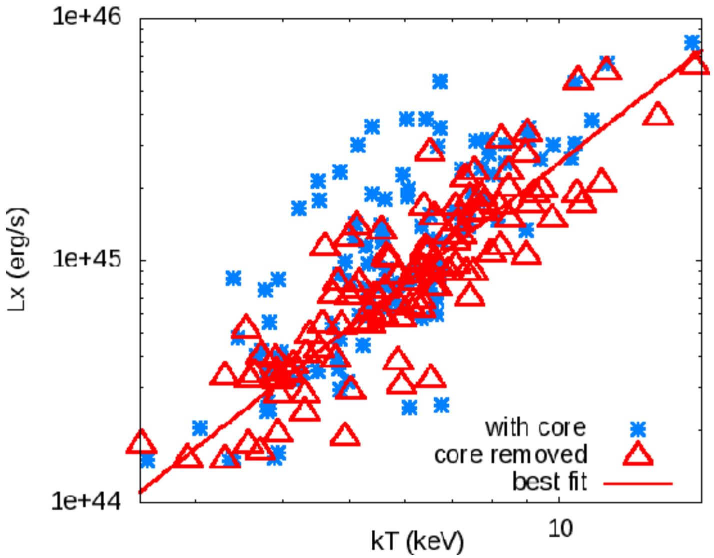
Excluding core regions eliminates effects of cooling cores – dominant contribution to scatter



Also strongest effects of mergers occur at core passage

- Eliminate some of merger effects
- AGN effects also likely to be reduced by excluding cores

Removing cores effective way to reduce scatter



Yx – A Super Scaler

We've looked at physical processes that we can learn about from scaling relations

Other important application is **estimating masses** for large samples of distant clusters for cosmology

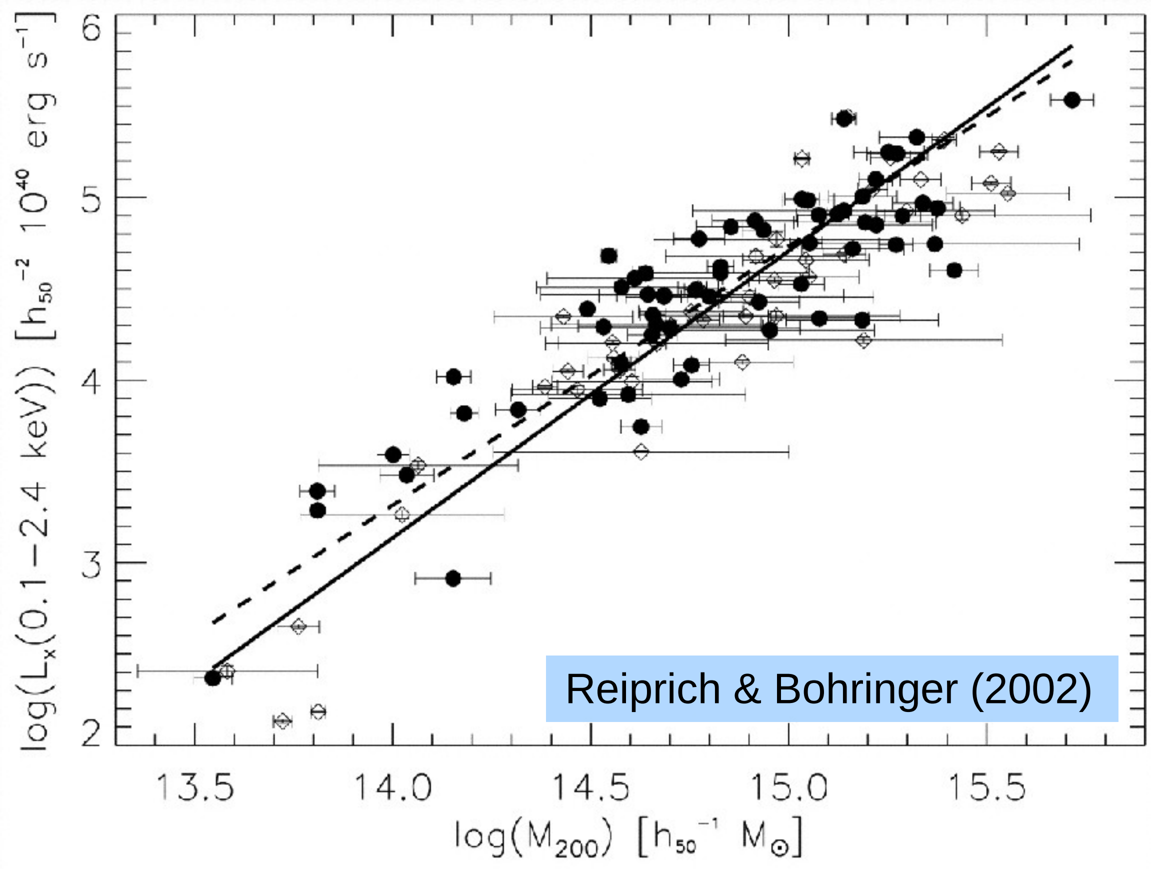
We need:

- Easy to measure property
- Low scatter relation to mass
- Insensitive to non-gravitational effects

Yx – A Super Scaler

Lx is **easiest** property to measure

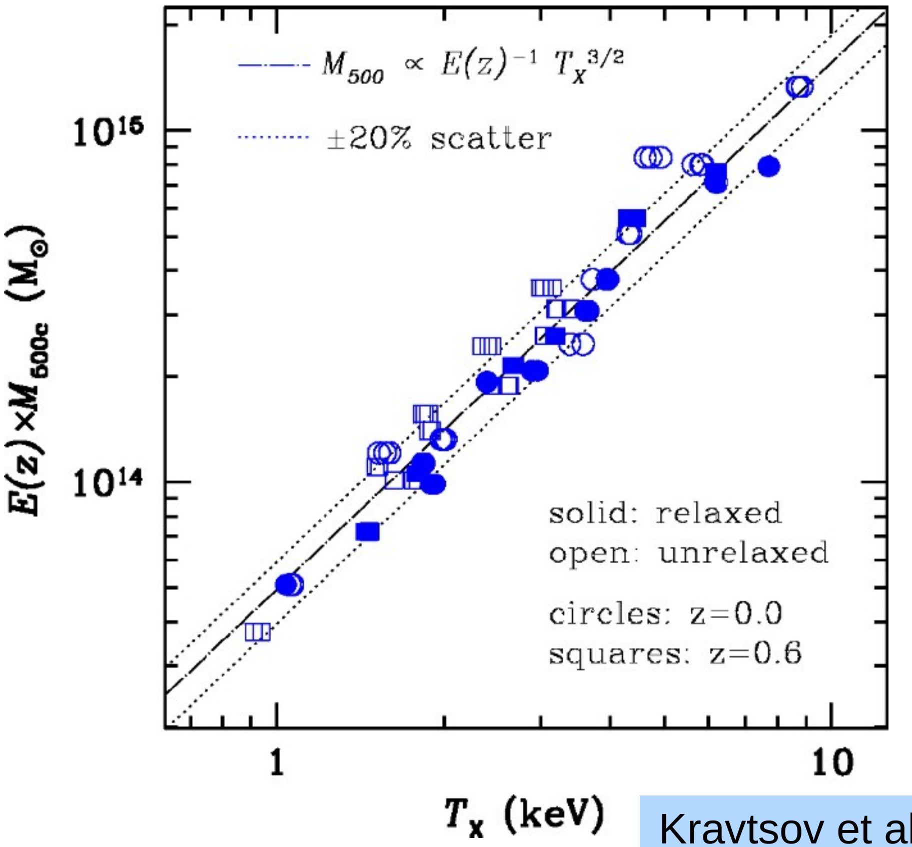
- Early work showed large scatter with mass (~60%)
- This can be improved on...



Yx – A Super Scaler

kT has a fairly tight scaling relation with M for **relaxed** clusters

- **Merging** clusters add scatter and systematic uncertainty



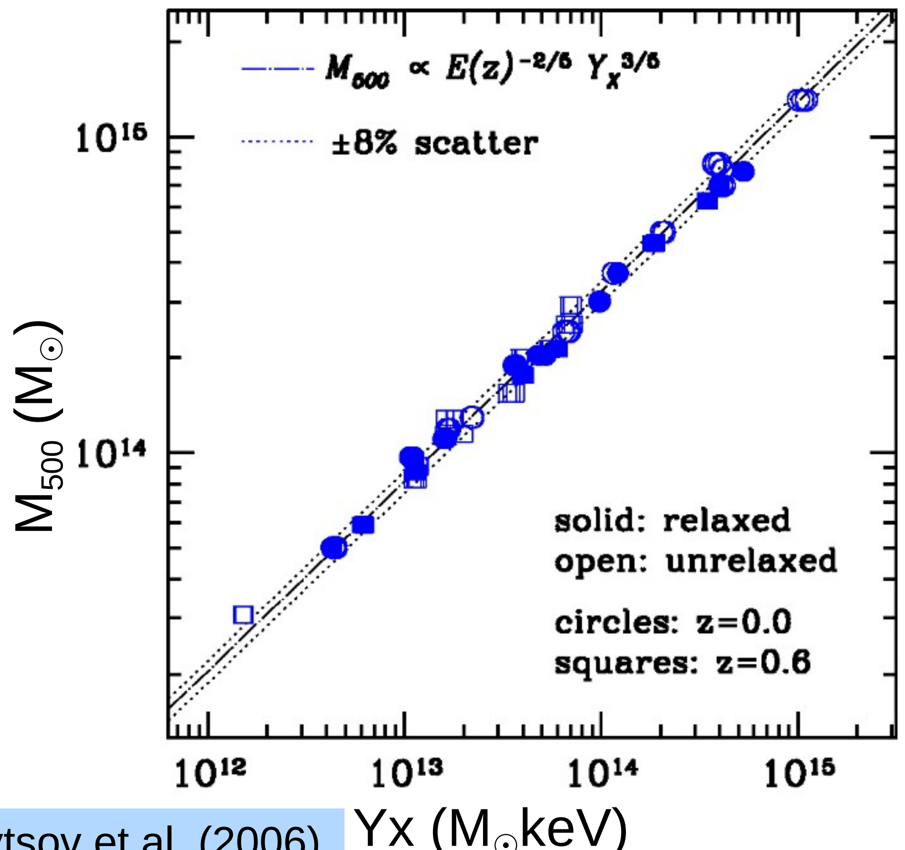
Kravtsov et al. (2006)

- Simulations show ~20% scatter in MT relation
- N.B. Simulations extremely helpful as we know true mass of clusters

Yx – A Super Scaler

Recent work has shown **Yx is superior mass indicator**

- **Product of kT and M_{gas}** (both easily measured) within R500 with central $0.15R_{500}$ excluded
- Just **8%** scatter with mass
- **Insensitive to mergers** (no offset between relaxed □ and merging ■ clusters)

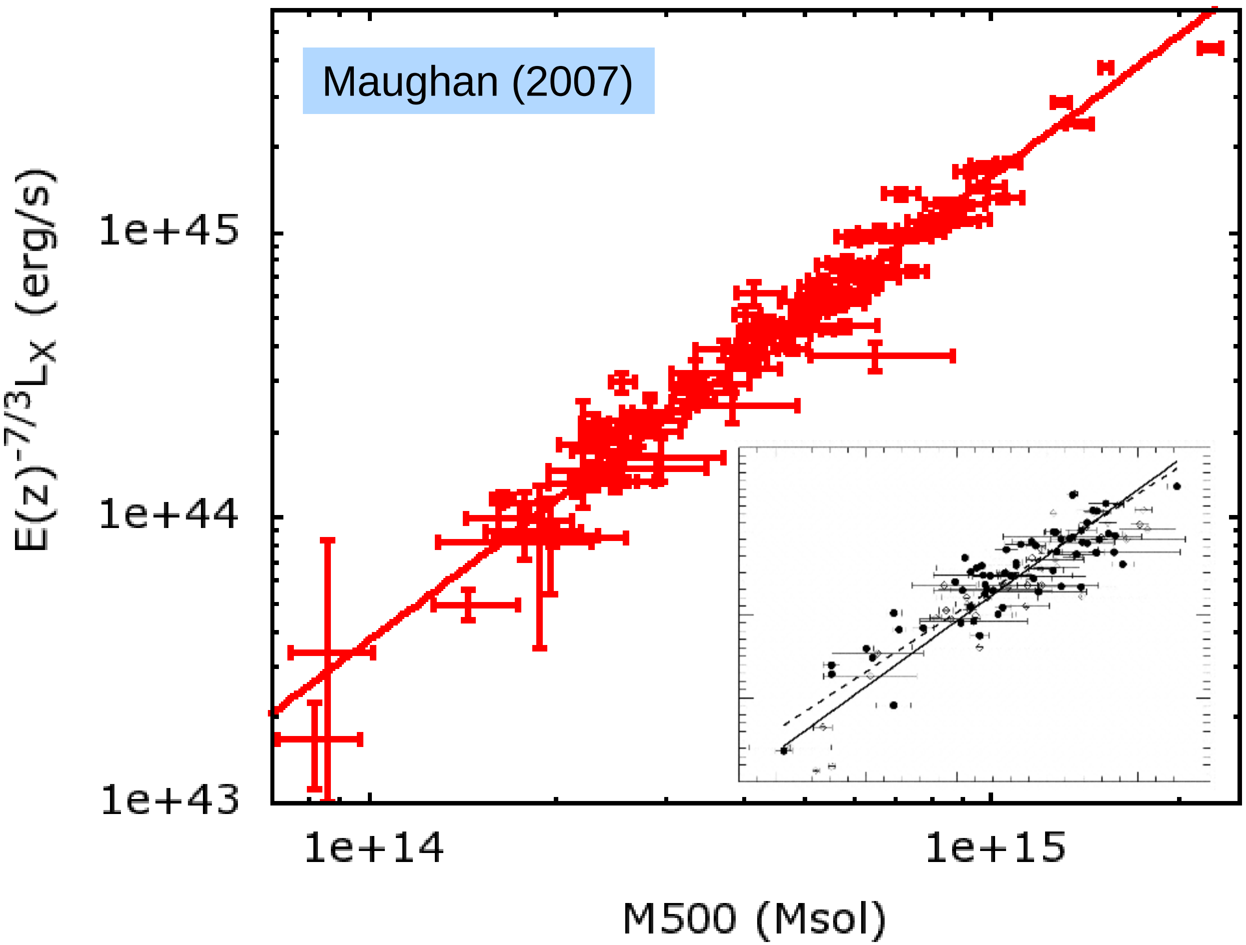


Kravtsov et al. (2006)

Lx – Also Super?

Earlier studies of LM relation used kT to estimate M, and did not exclude core regions

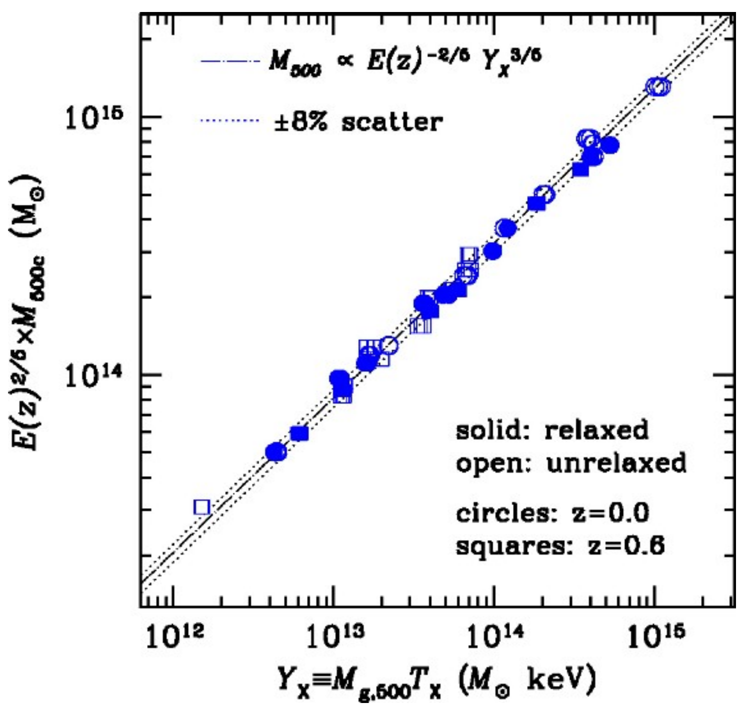
- Now know Yx gives better mass estimates
- Use **Yx** to estimate M
- **Exclude** central $0.15R_{500}$
- Scatter reduces from 63% to **17%**

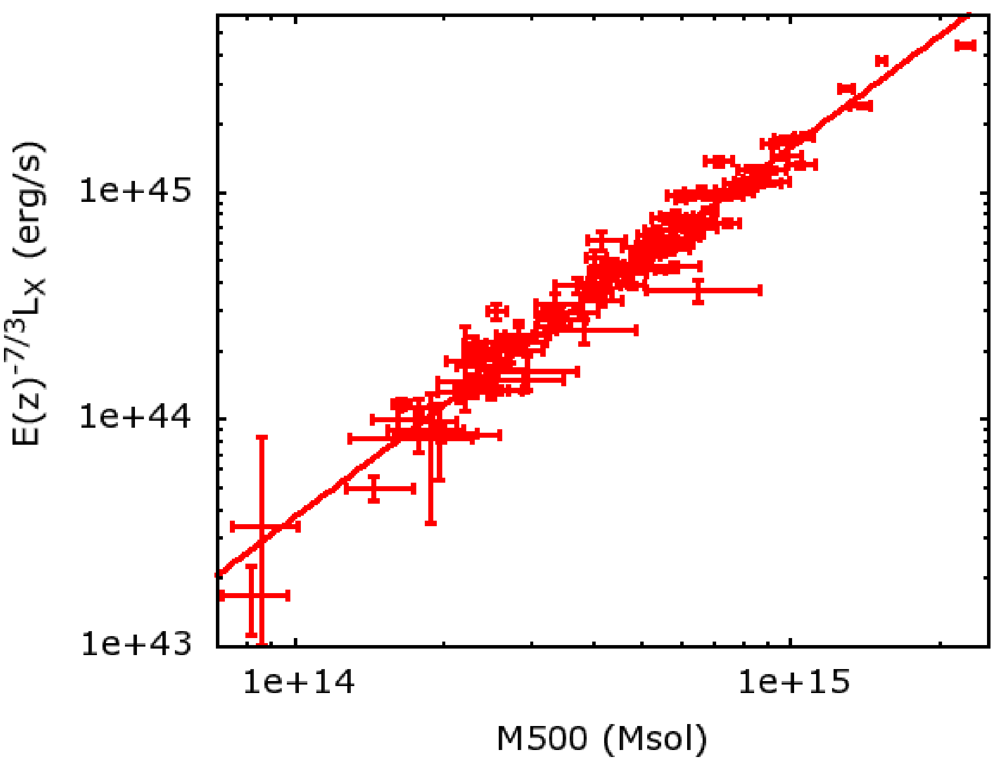


Lx – Also Super?

N.B. Lx not as good as Yx

- For distant/faint clusters can **only** measure Lx
- Can be applied to large samples of distant clusters to estimate masses and constrain cosmological parameters





Summary I

Observational results

- Scaling relation slopes generally not self-similar
- Evolution appears consistent with SS (selection effects)

Similarity breaking due to non-gravitational processes not included in SS model

- Cooling cores boost Lx and lower kT (ignore cores)
- AGN raise kT in low mass systems (steepen LT?)
- Mergers move clusters along LT but offset from MT

Summary II

Scatter in scaling relations dominated by cores

- Exclude cores to reduce effects of cool cores (and mergers and AGN)

Yx (product of kT and M_{gas}) superior mass estimator

- Low scatter scaling with mass and insensitive to mergers
- Lx (with core removed) is better mass estimator than previously thought