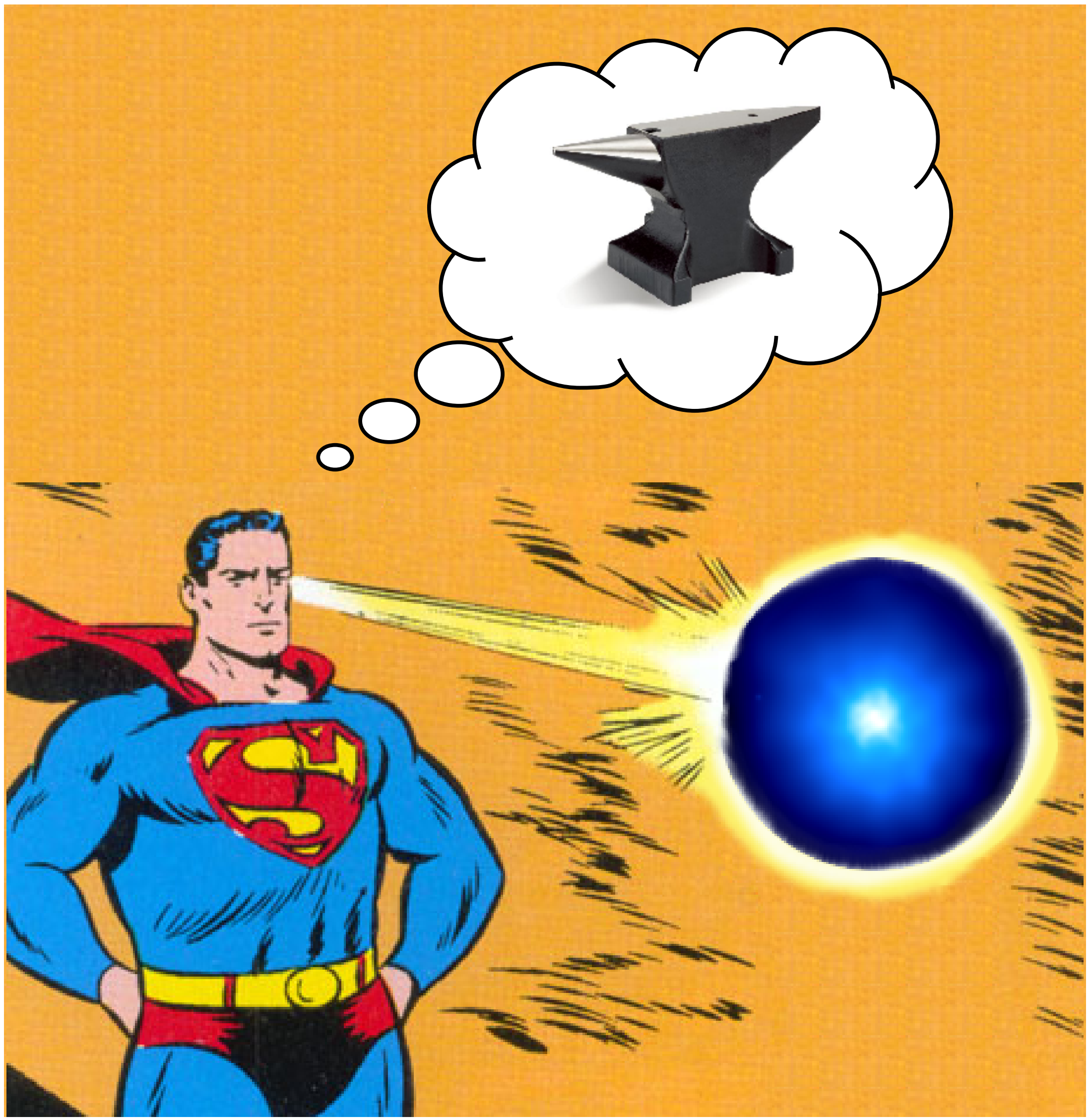
Using X-ray Vision to Weigh Clusters of Galaxies



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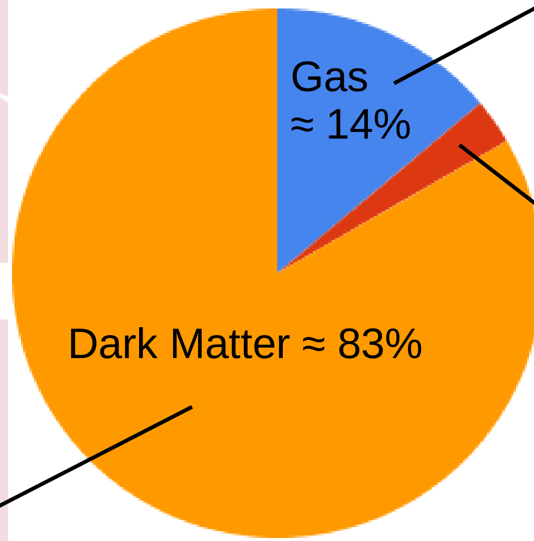
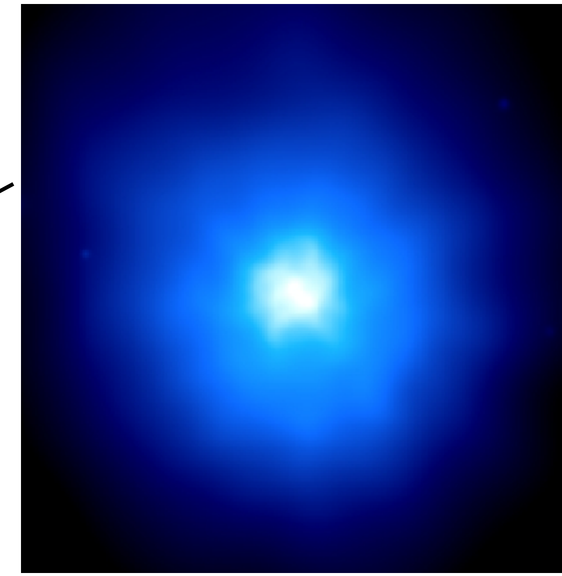
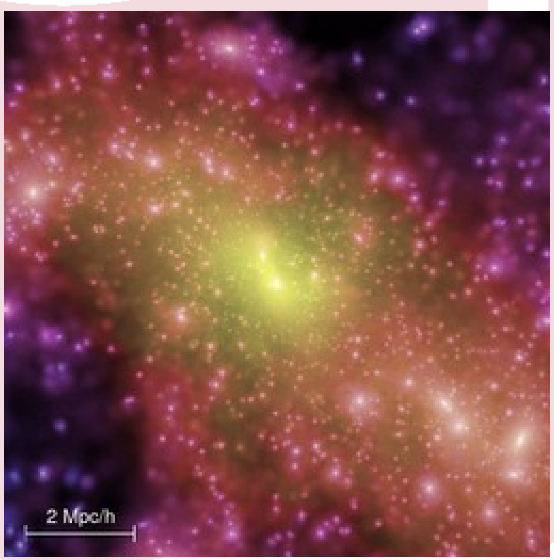
Overview

- ★ Introduction to galaxy clusters
  - Why should we weigh them?
- ★ X-ray self-similar scaling relations
  - Use for mass estimates
  - Use for probing physical processes in clusters
- ★ Using X-ray luminosity as simple mass indicator
- ★ Similarity breaking

Galaxy Cluster Recipe





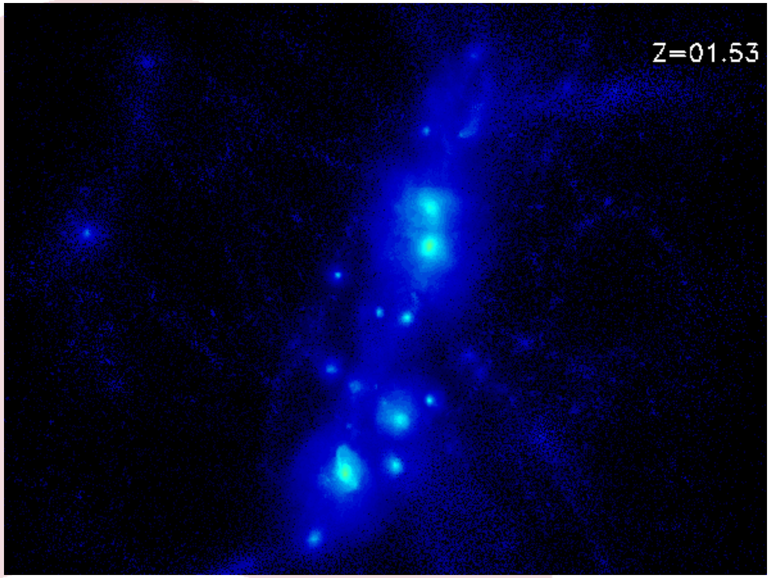


Galaxies ≈ 3%

Cluster Formation

Early Universe was smooth with tiny density perturbations

- ★ Density peaks amplified by gravity
- ★ Galaxy clusters form via series of mergers of smaller systems – **hierarchical formation**
- ★ Largest gravitationally bound objects in Universe



Yepes et al. (2002)

Clusters & Cosmology

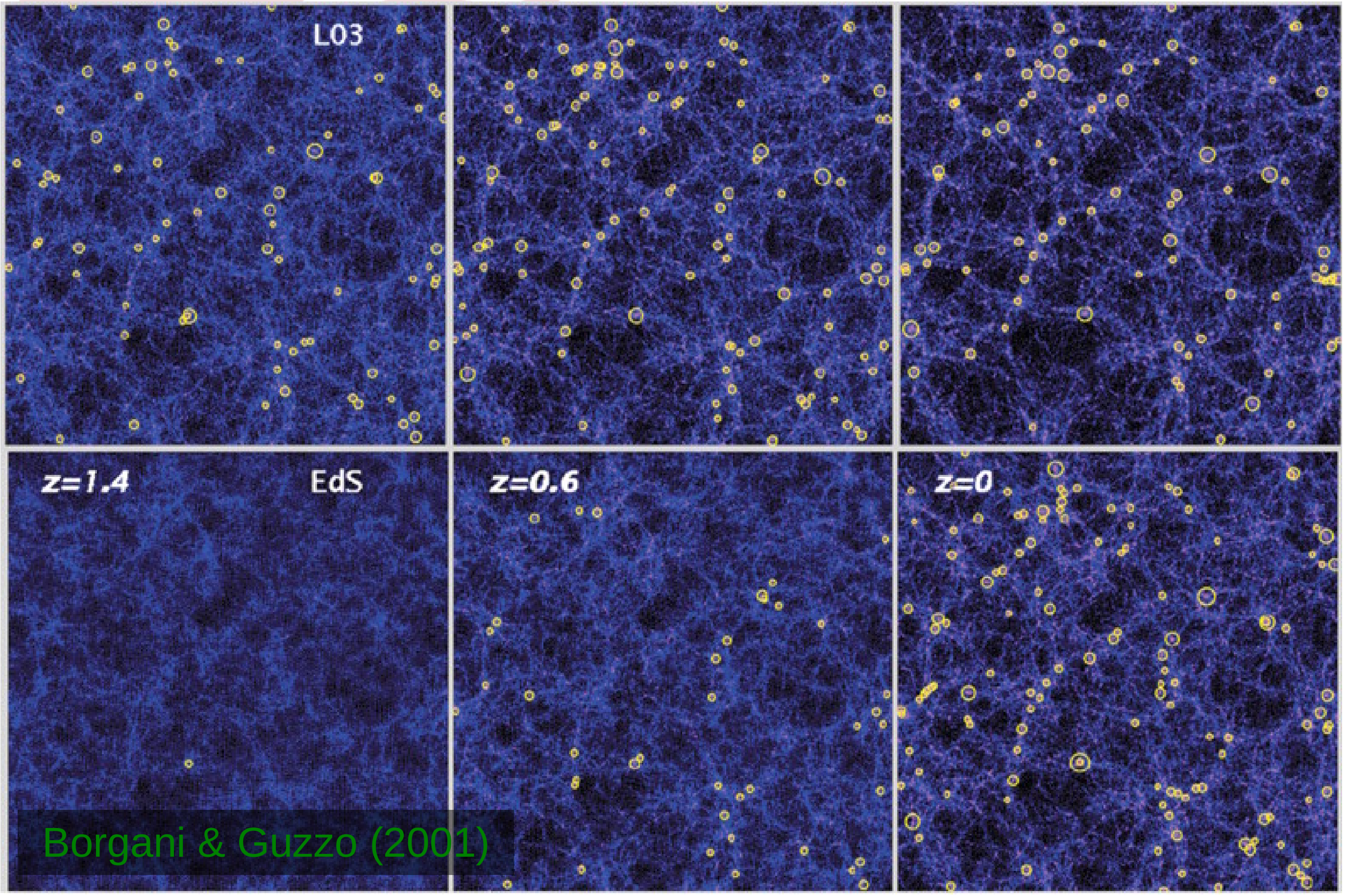
Growth of large scale structure traced by clusters

★ Sensitive to cosmological parameters

★ **Clusters provide powerful tests of cosmological models**

Flat Universe
Λ=0.7

Flat Universe
Λ=0

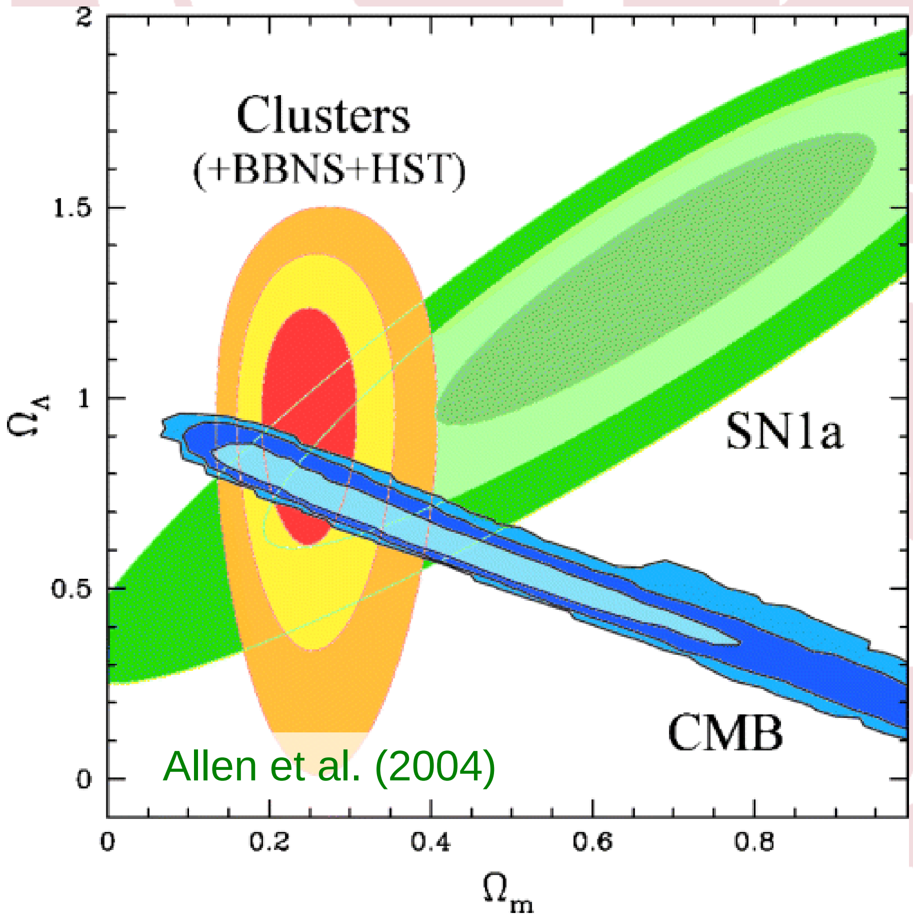


Borgani & Guzzo (2001)

Clusters & Cosmology

Cluster constraints competitive, independent and different degeneracies to other methods

★ **Cosmological tests require cluster masses**



Precise measurements of e.g. w require masses for

★ Large samples (100's-1000's)

★ Samples at high redshift (z~1)

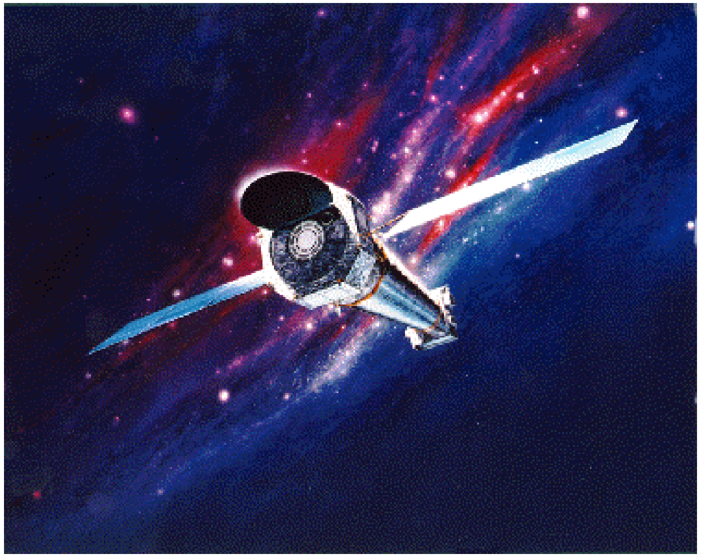
An observational challenge!

★ **X-ray observations are powerful way to study clusters**

X-ray Observatories

Superman (1932 -)

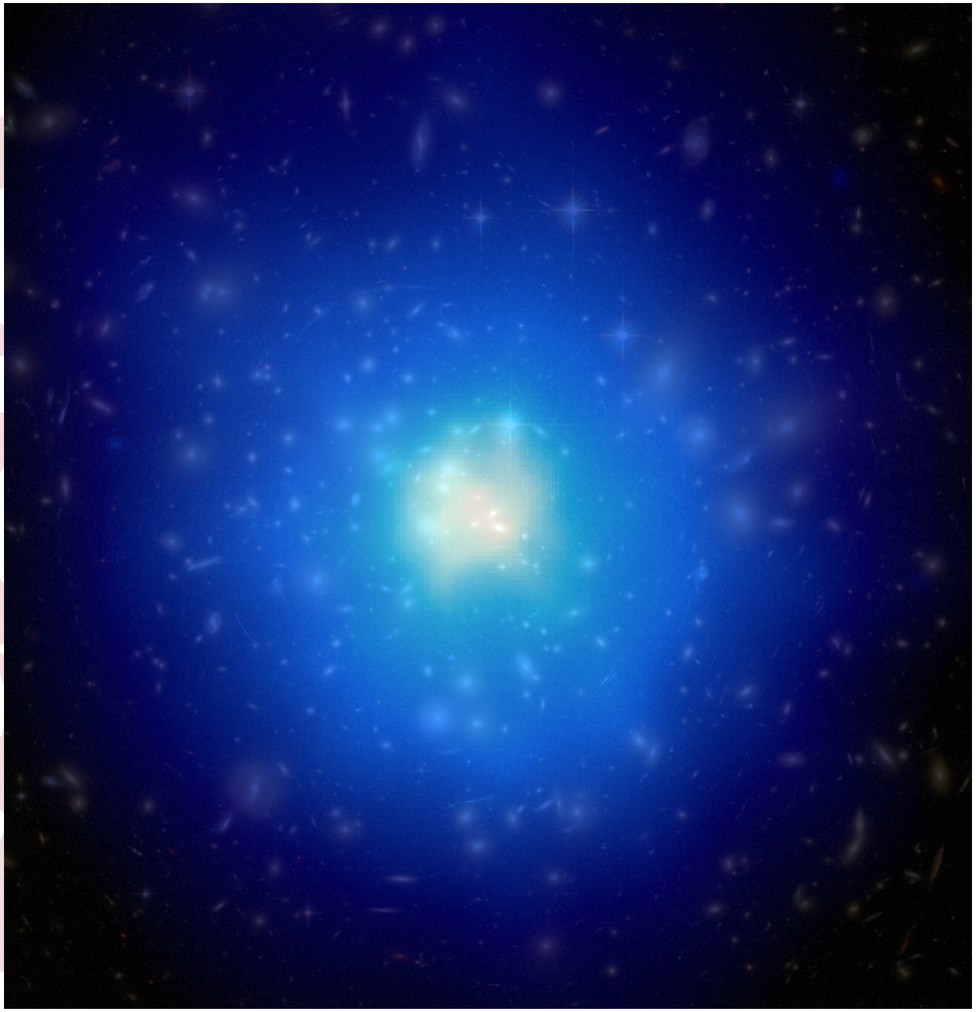
Chandra (1999 -)



XMM-Newton (1999 -)

Weighing Clusters: X-ray

- ★ Cluster filled with hot (~10^7K) ionised gas (ICM)
  - Extremely X-ray luminous
  - Detect & study to high-z
- ★ Measure X-ray properties:
  - Luminosity (Lx), Temperature (kT), Gas density (hence mass)
- ★ Radial kT and density profiles give total mass (inc. dark matter) assuming hydrostatic equilibrium
  - High quality data



Weighing Clusters: Scaling Relations

If we assume:

★ Clusters form in single gravitational collapse at z_{obs}

★ Gravitation is only energy input into ICM

Clusters will be "self-similar" - simple scaled up and down versions of one another

★ Predict simple power law relations between cluster observables and mass

$$\text{e.g. } L_X \propto M^{4/3}$$

★ Simply measure Lx and get mass of cluster – Bob's your uncle!

X-ray Scaling Relations

However, things not quite that simple!

★ Observationally, slopes of relations differ from SS models

  – e.g. Lx-M slope is ~5/3 not 4/3

★ Relations found to have significant intrinsic scatter

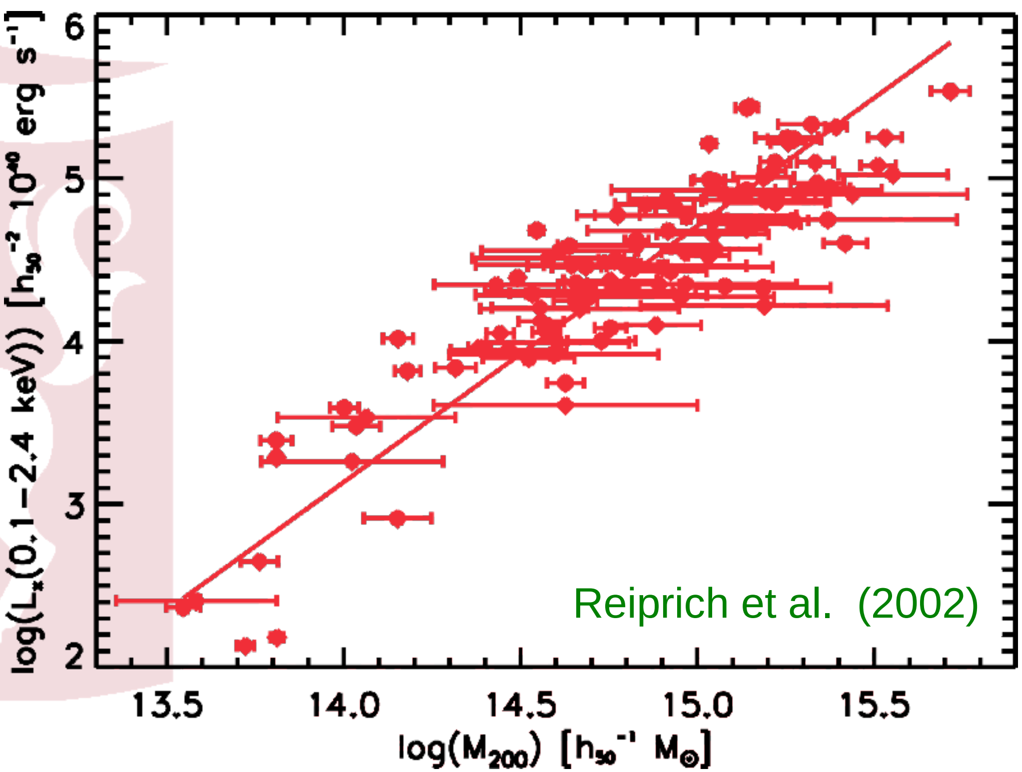
  – Luminosity found to have ~60% scatter with mass

★ Points to physical processes not in SS model

★ Use scaling relations to:

  – Probe these processes

  – Provide easy masses



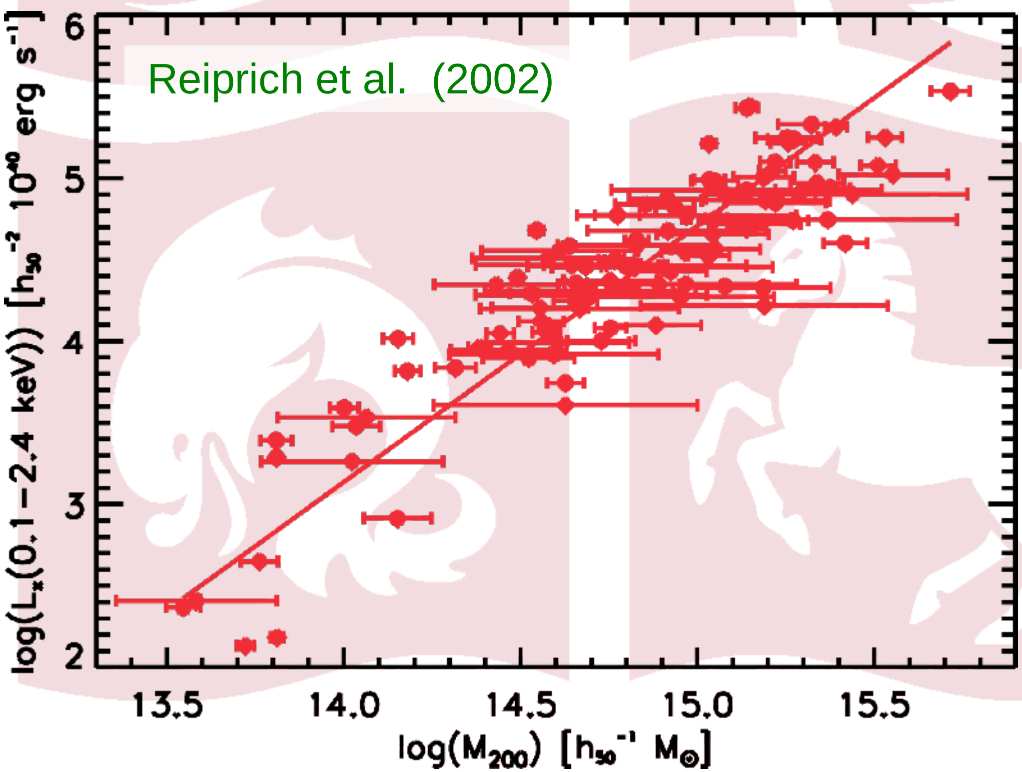
X-ray Mass Proxies

What do we want from an X-ray mass proxy?

★ Easy to measure & low-scatter relationship with mass

Historically, kT & Mgas were preferred (scatter ~20%)

★ Luminosity found to have ~60% scatter with mass



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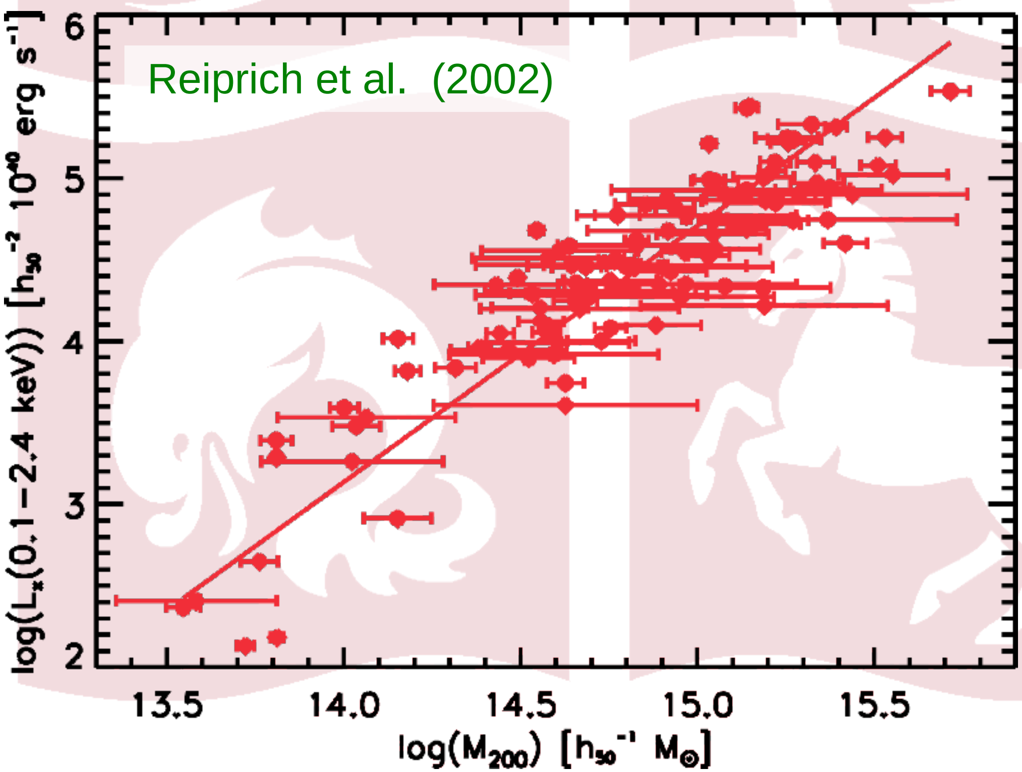


Lx-M relation required for

★ **Low quality data**

★ **Understanding survey selection functions**

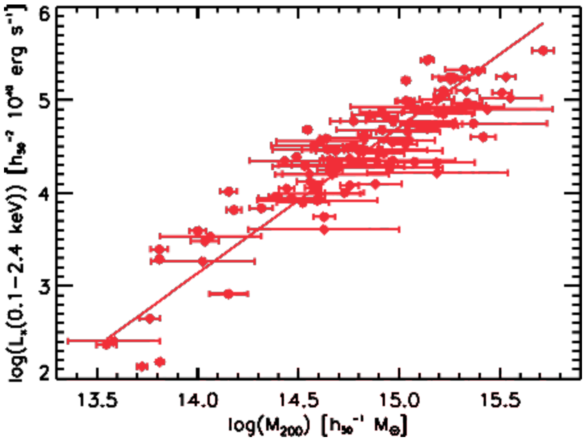
<u>Key stages:</u>

★ Calibrate mass proxies

★ Measure/minimise scatter

Calibration

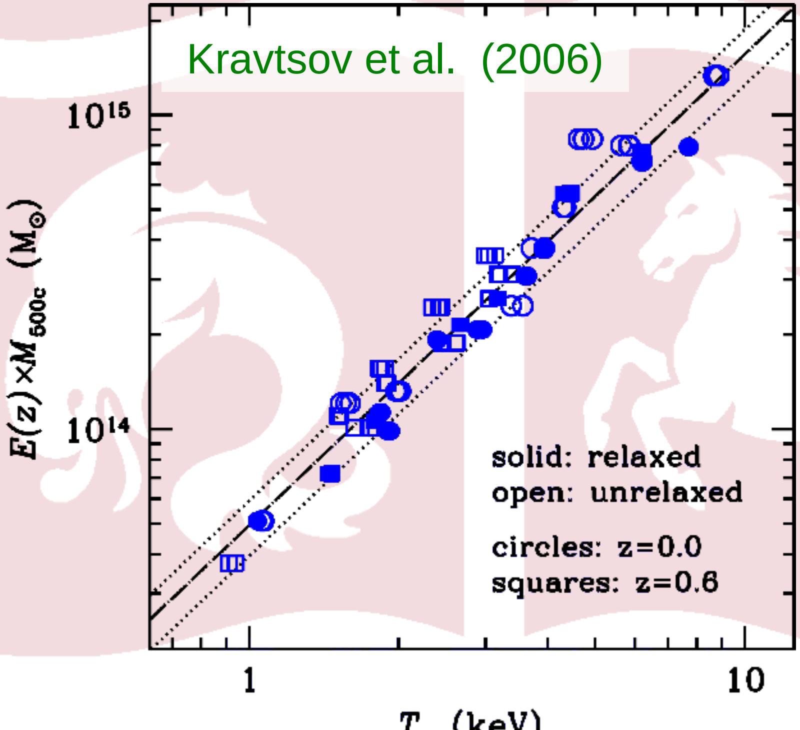
In order to calibrate mass – observable scaling relations, need to know masses of clusters!

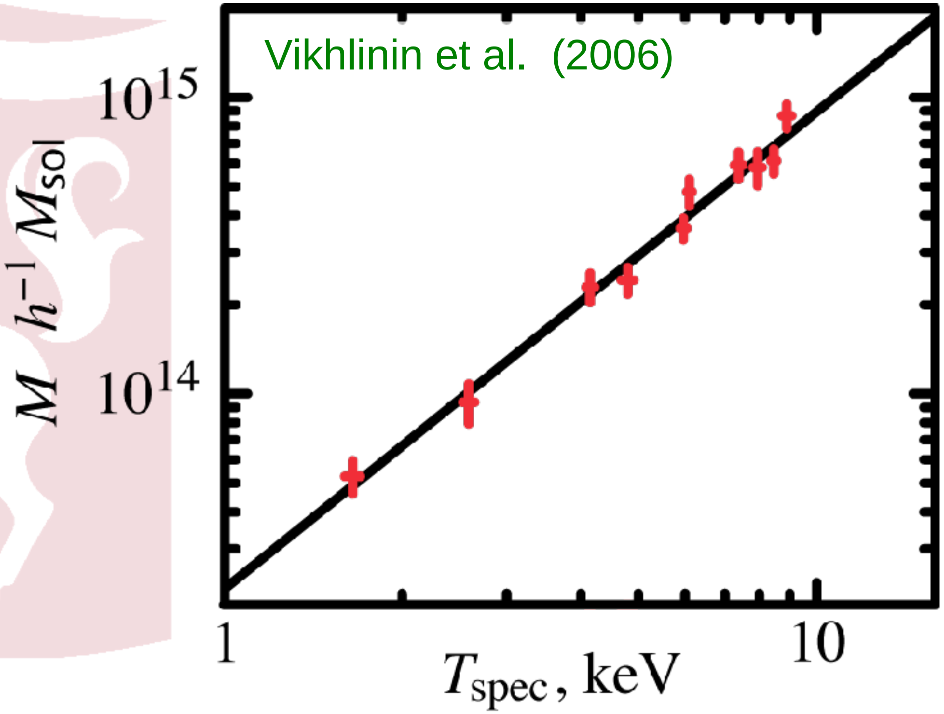


★ Simulations

★ Full hydrostatic masses

★ Use kT and assume isothermal

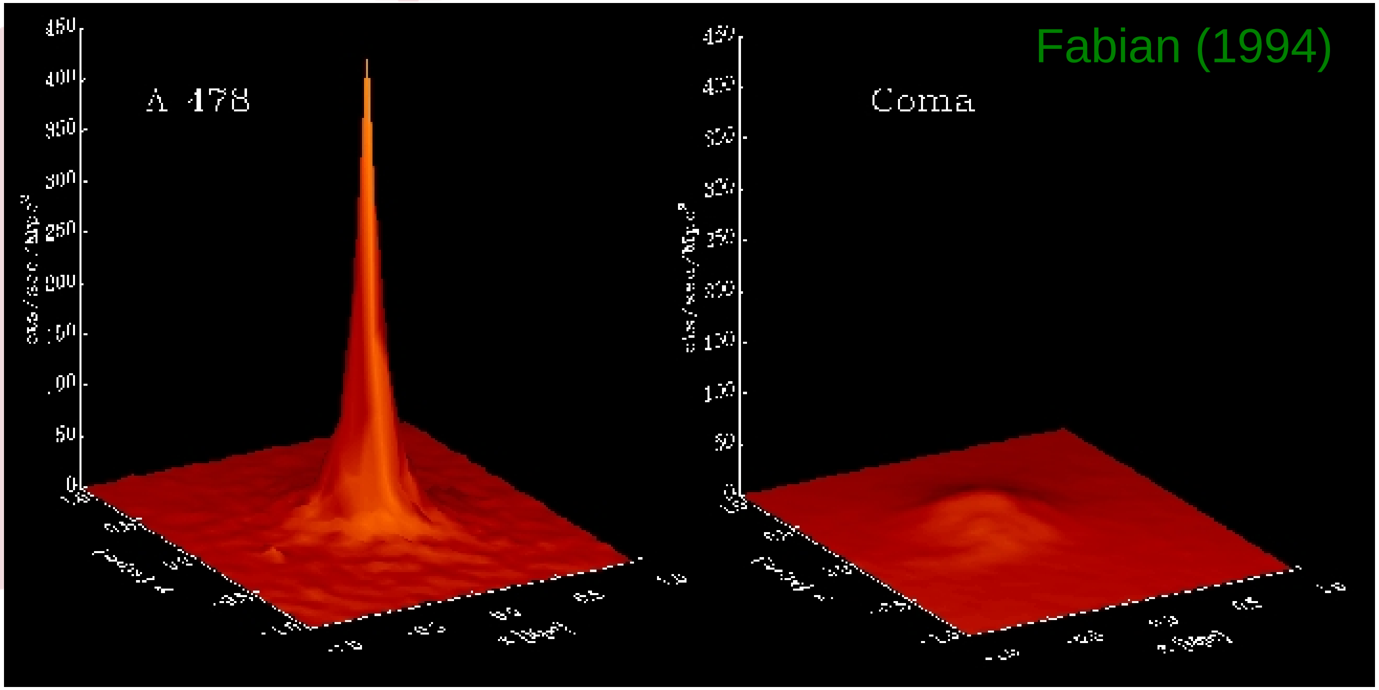




Scatter Sources: Cooling

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

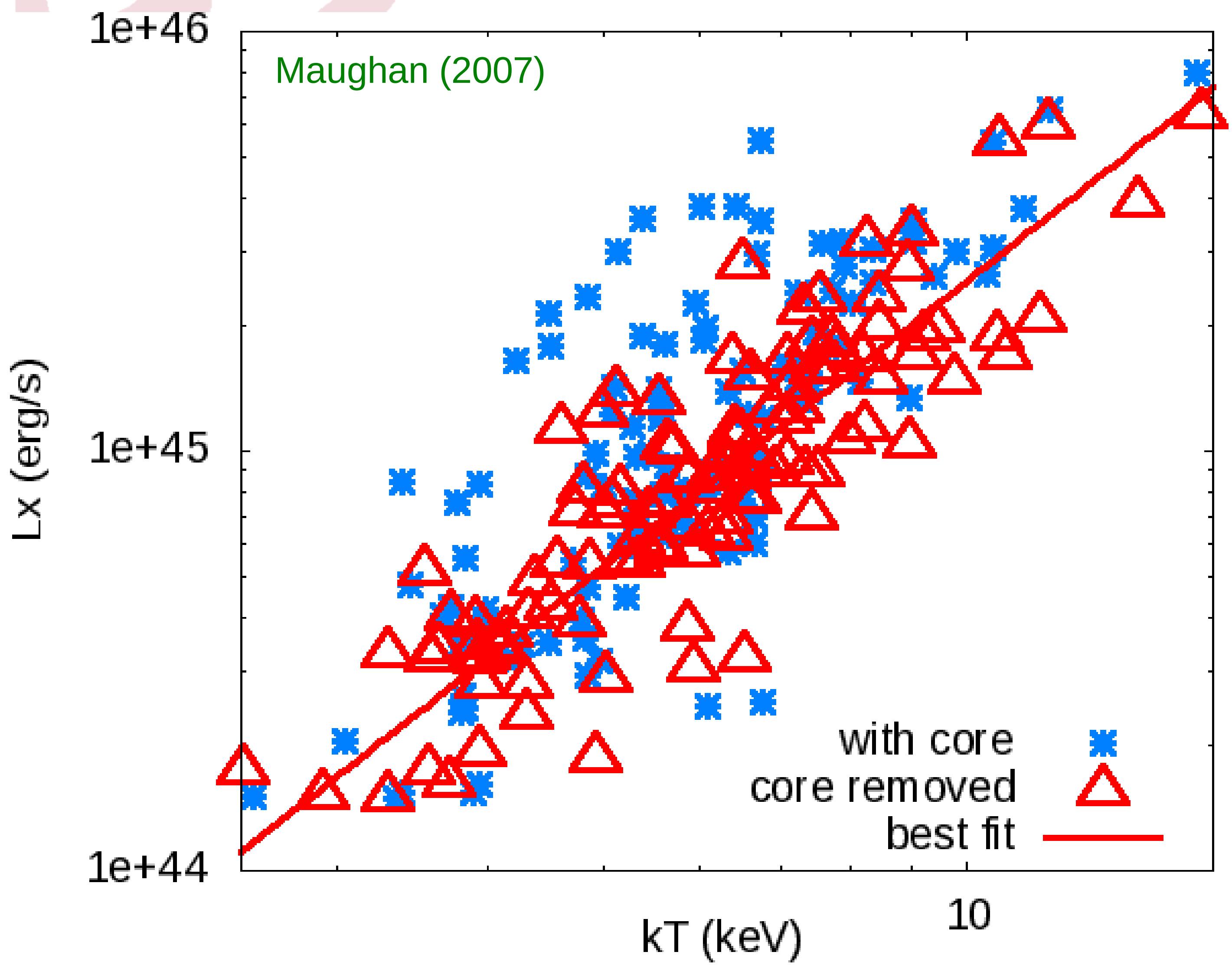
- ★ Gas cools efficiently and condenses, replaced by gas cooling in from larger radii
- ★ Runaway process, known as a **cooling core**
- ★ Cores disrupted by mergers
- ★ Cooling balanced by AGN energy input



Scatter Sources: Cooling

Cooling core clusters are **cooler** and **brighter** than those without

- ★ Significant source of scatter
- ★ Improve by excluding core regions
  - – Requires good spatial resolution

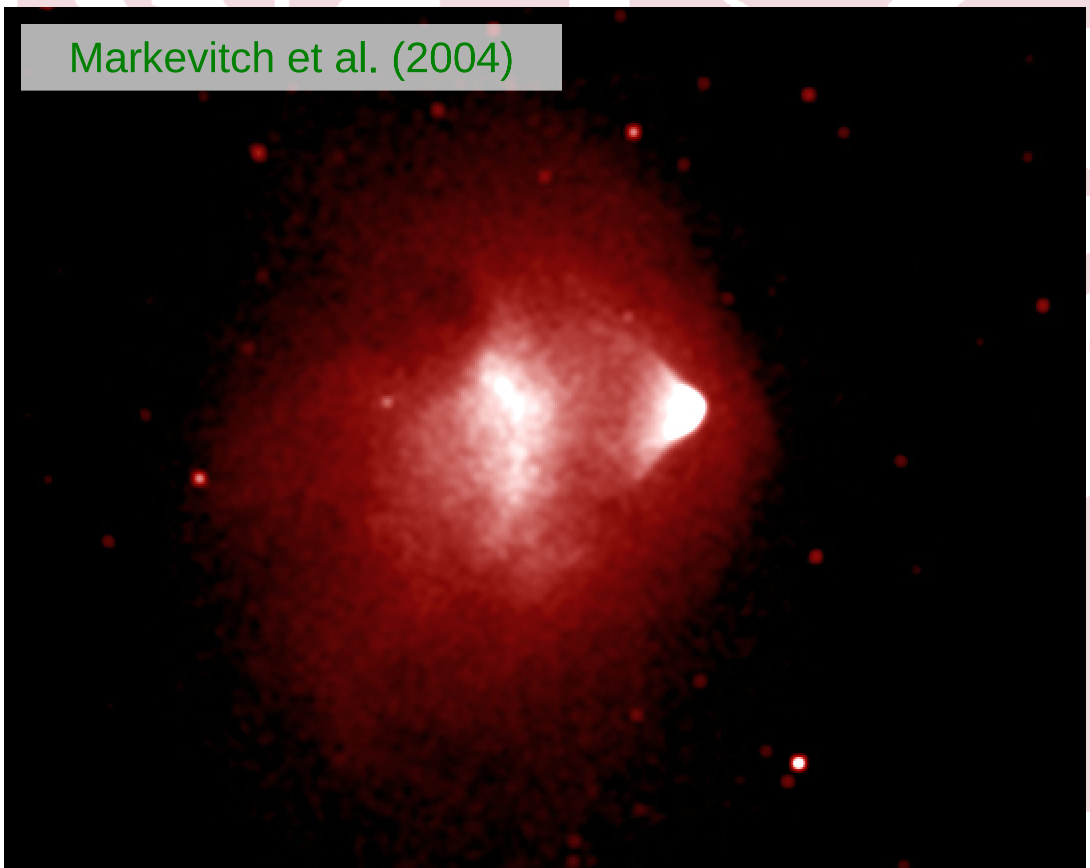


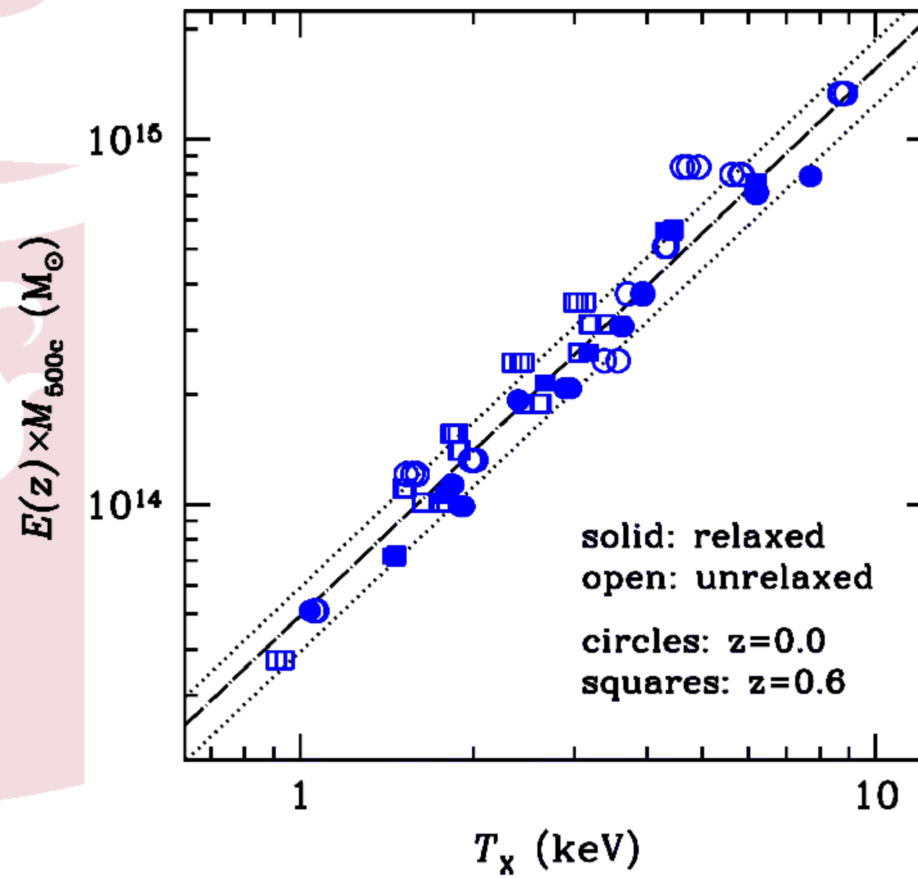
Scatter Sources: Mergers

Clusters form via hierarchical series of mergers of smaller systems

★ Mergers extremely energetic, disrupt ICM properties

★ Adds scatter to e.g. M-kT relation





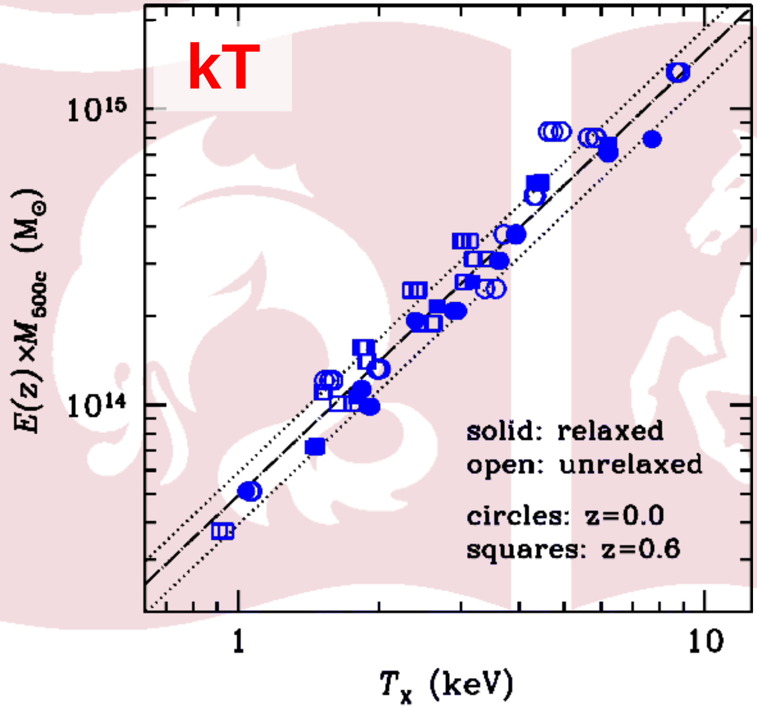
Yx: A Super Scaler

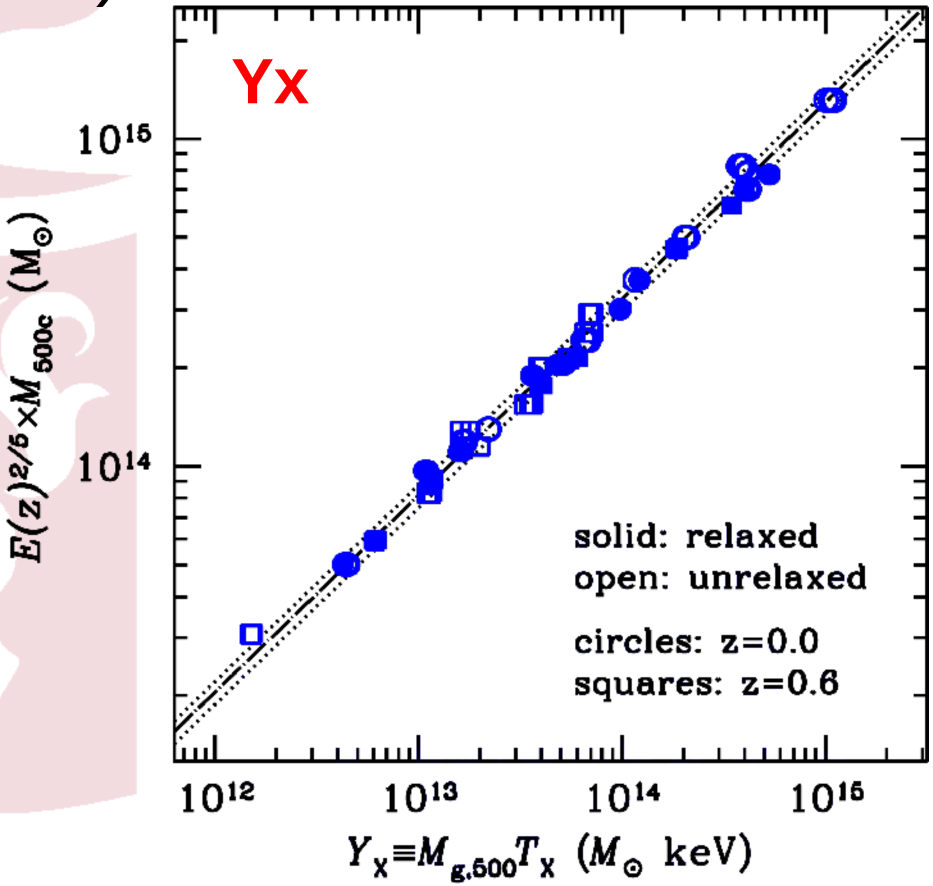
Recent work (Kravtsov et al. 2006) shown that Yx is superior mass proxy

★ Product of kT & Mgas (cores excluded)

★ Very low scatter with mass (~8%)

★ Insensitive to mergers

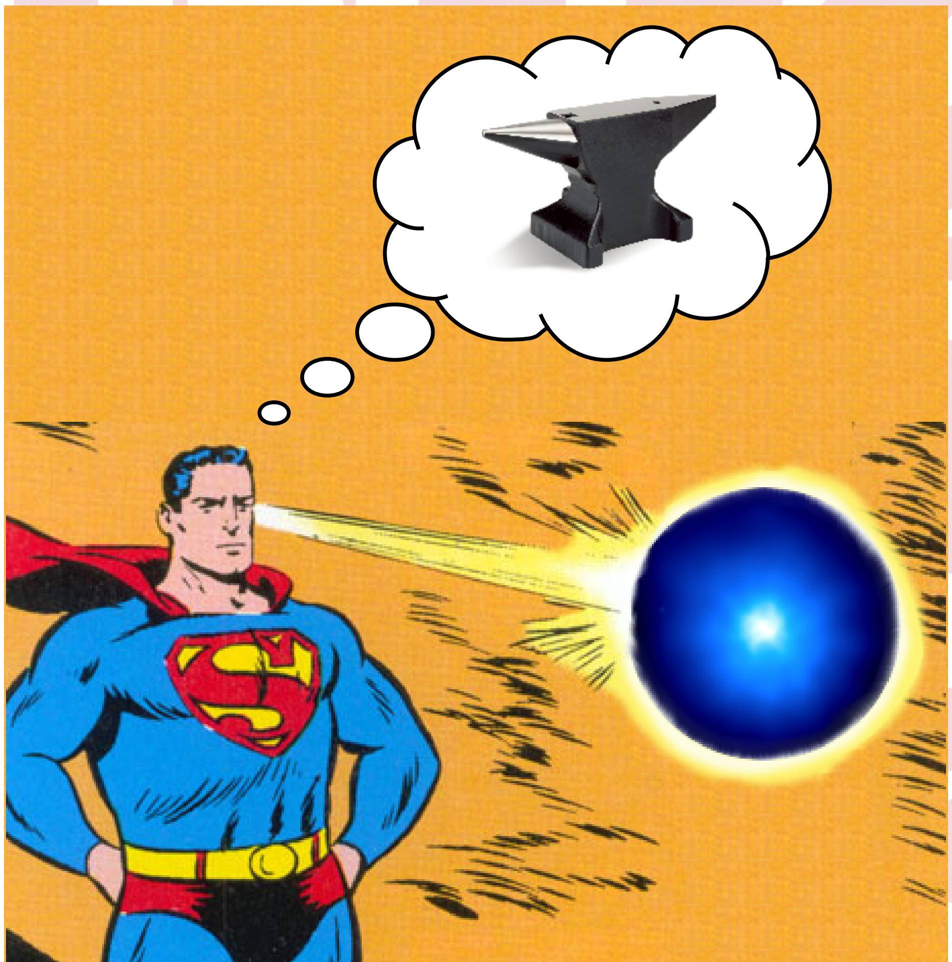




Recap

Clusters important cosmological probes, but need masses

- ★ Self-similar model predicts simple relations between X-ray properties and mass



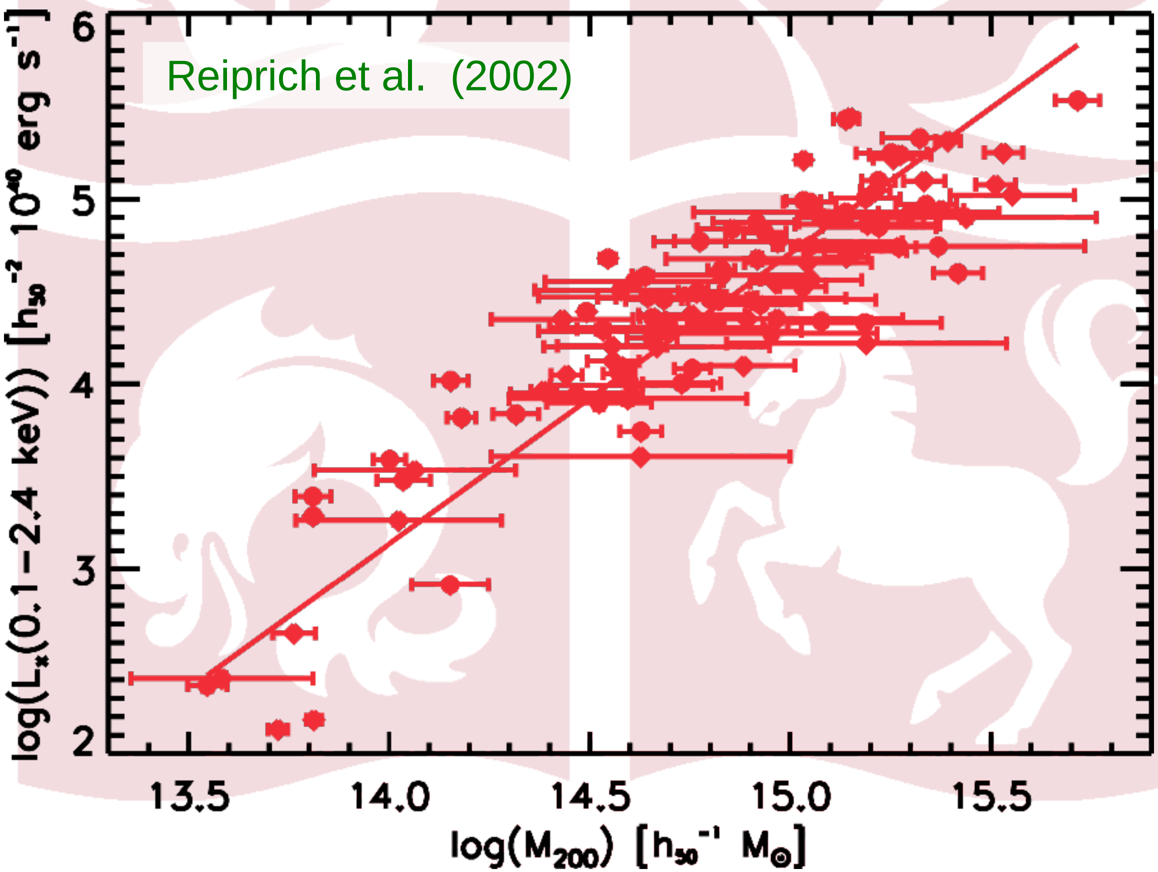
- ★ Want easily measured property
  - Calibrate relation with mass
  - Minimise scatter
- ★ Scatter caused by cool cores and mergers
- ★ Yx-M relation seems perfect
- ★ Lx-M relation has high scatter but still important

Lx-M Relation Revisited

Now in position to improve on earlier studies of Lx-M

★ Use Yx instead of kT to investigate Lx-M for **first time**

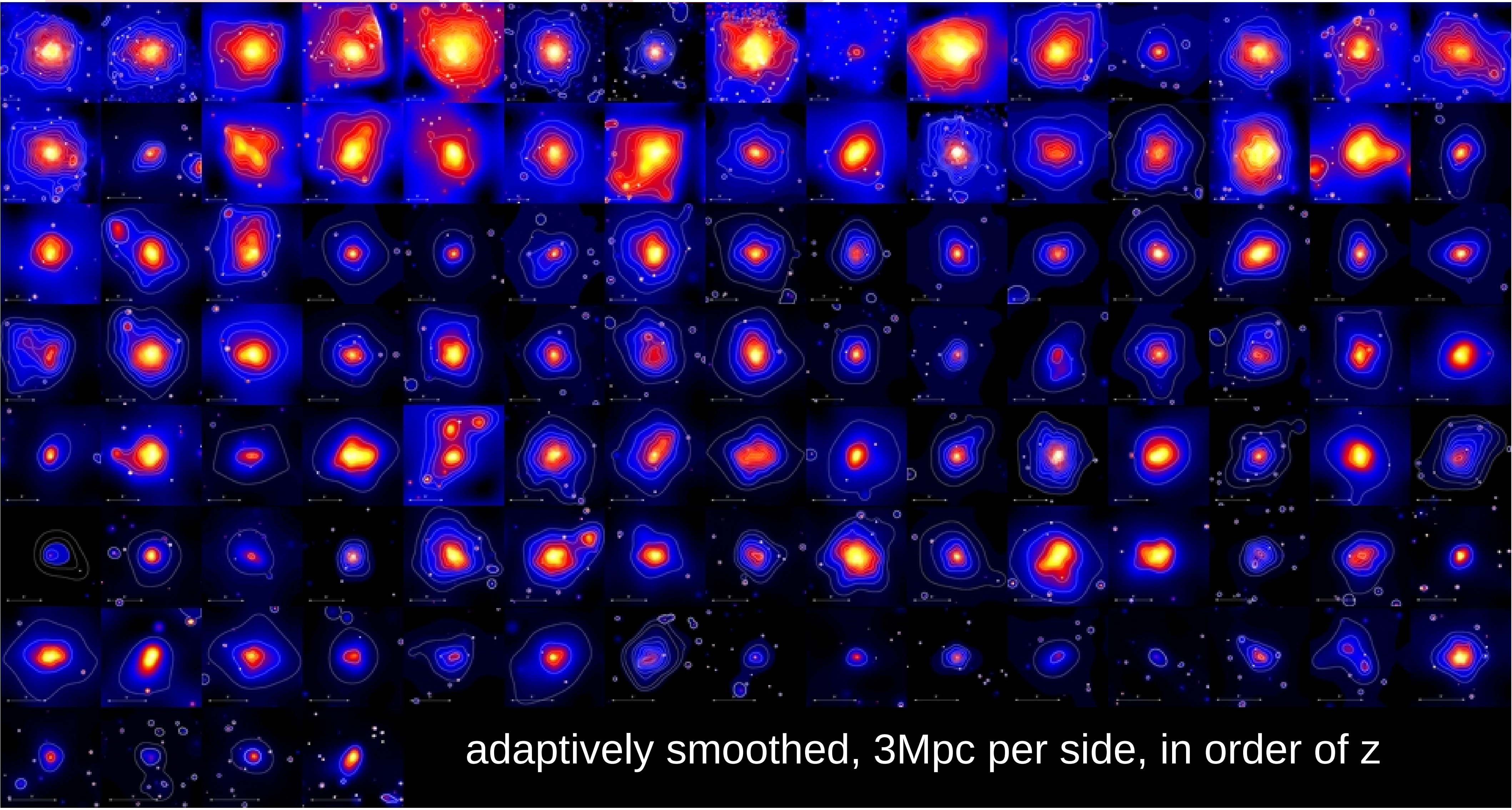
★ Investigate removing cores to reduce scatter



★ Does the 60% scatter found in earlier work hold up?

The Sample

115 clusters observed with Chandra (0.1<z<1.3)



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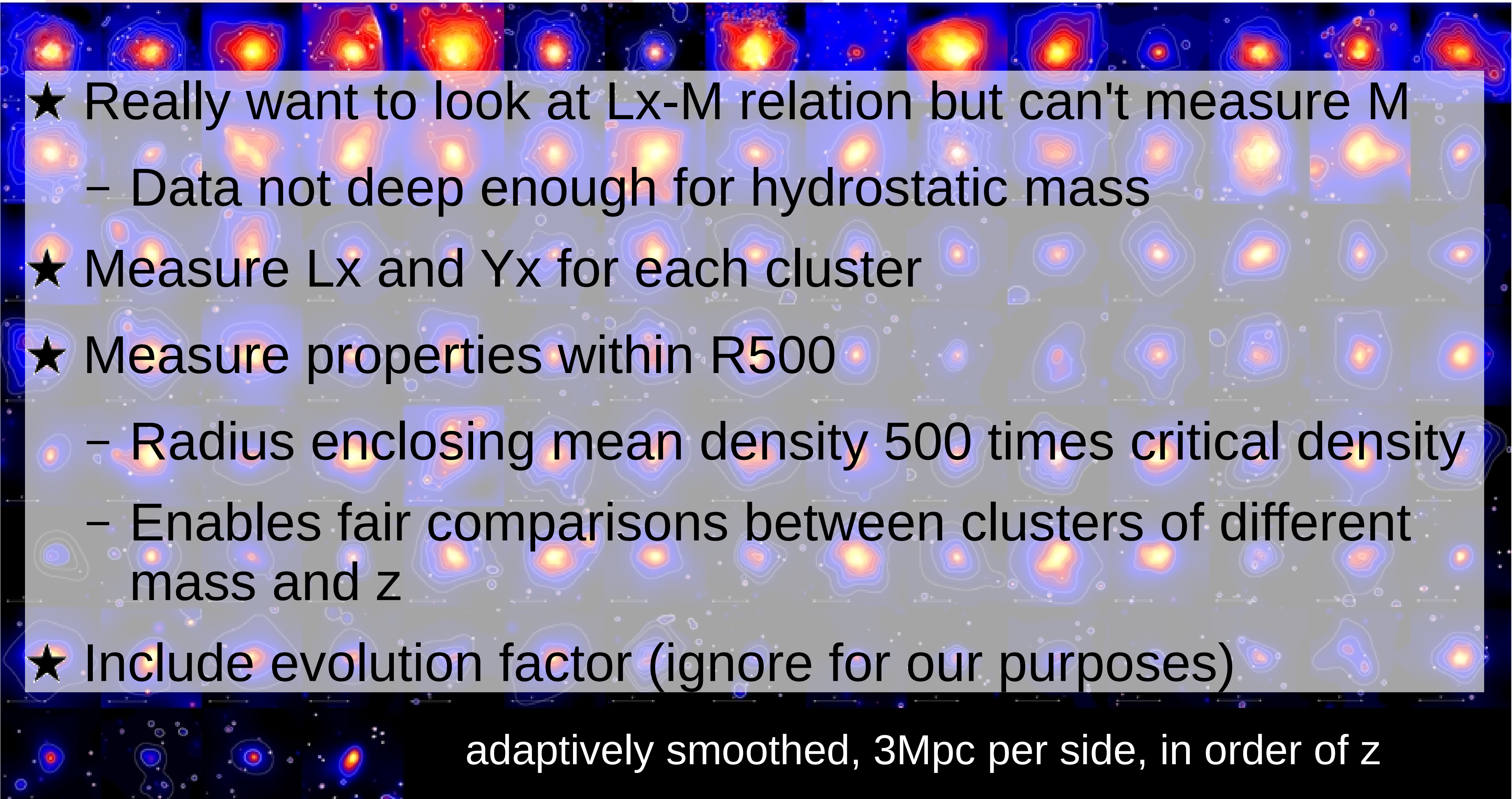


- ★ Really want to look at Lx-M relation but can't measure M
  - – Data not deep enough for hydrostatic mass
- ★ Measure Lx and Yx for each cluster
- ★ Measure properties within R500
  - – Radius enclosing mean density 500 times critical density
  - – Enables fair comparisons between clusters of different mass and z
- ★ Include evolution factor (ignore for our purposes)

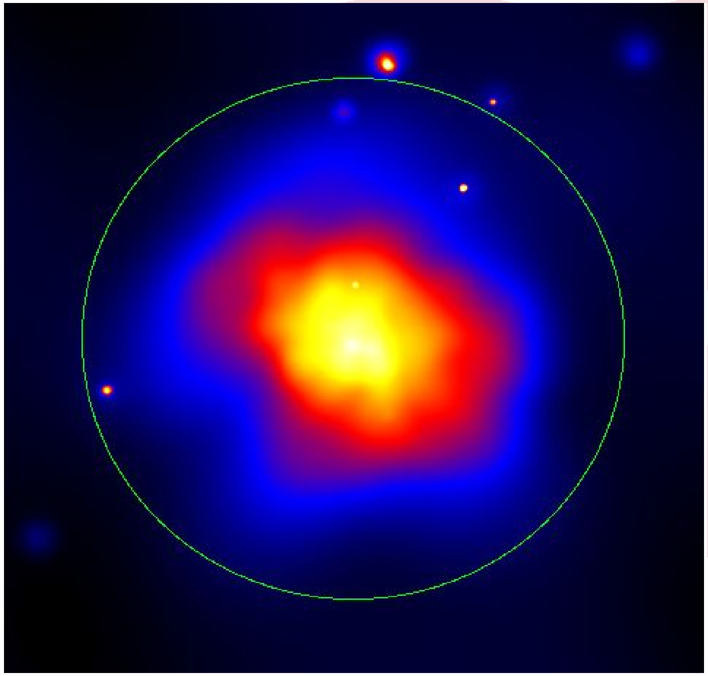
adaptively smoothed, 3Mpc per side, in order of z

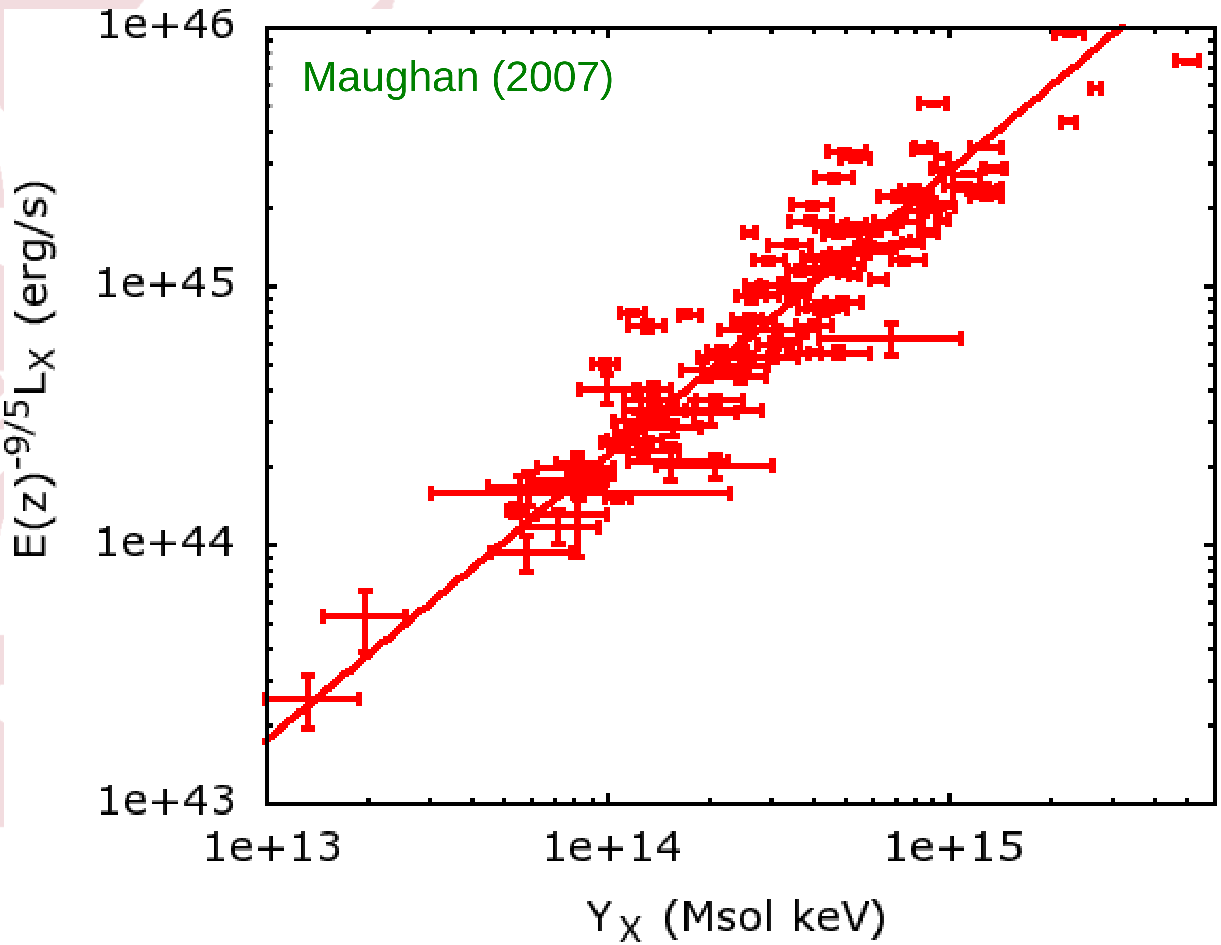
The Lx-Yx Relation

Start with Lx-Yx relation:

★ Use Lx measured within R500 including core

★ Scatter in Lx: σ_L = 36%



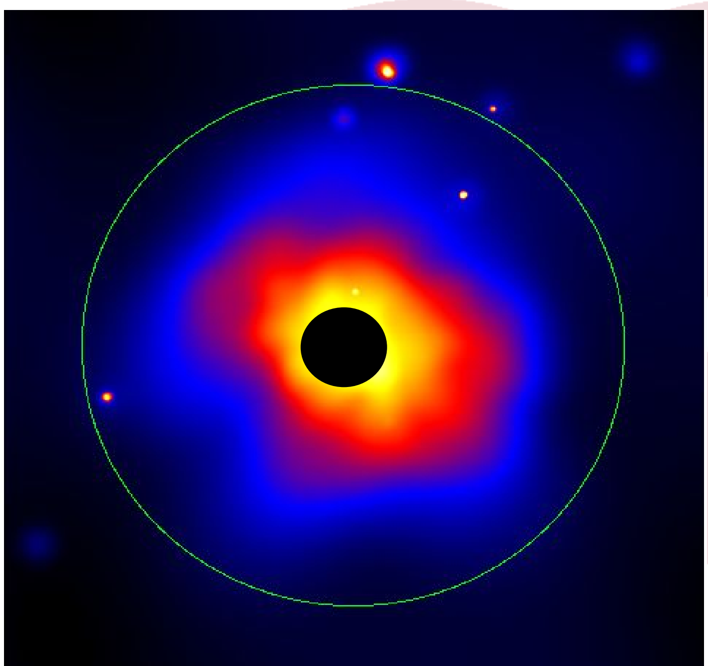


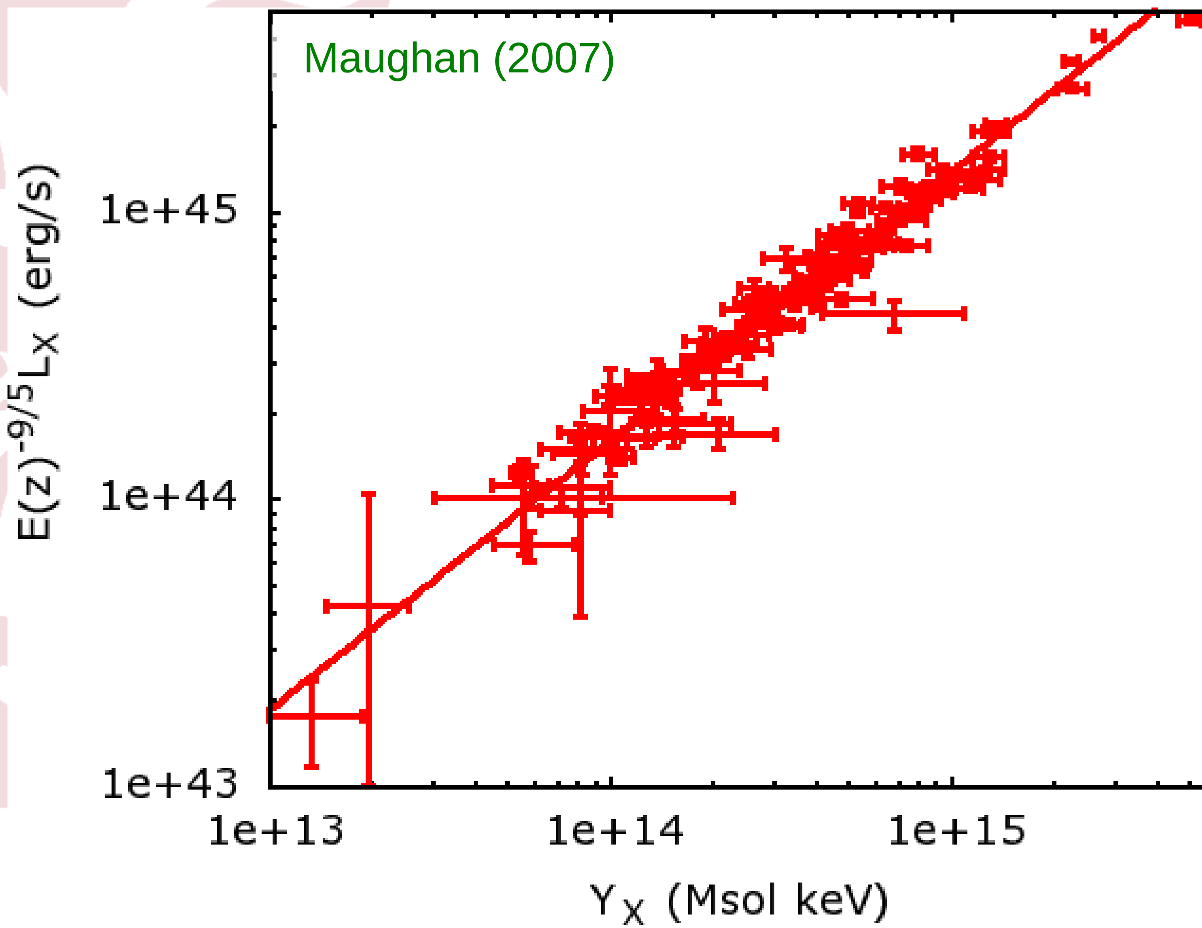
The Lx-Yx Relation: Cool Cores

Exclude central 0.15R500 from measurements

★ Scatter in Lx including core: σ_L = 36%

★ Scatter in Lx excluding core: σ_L = 11%





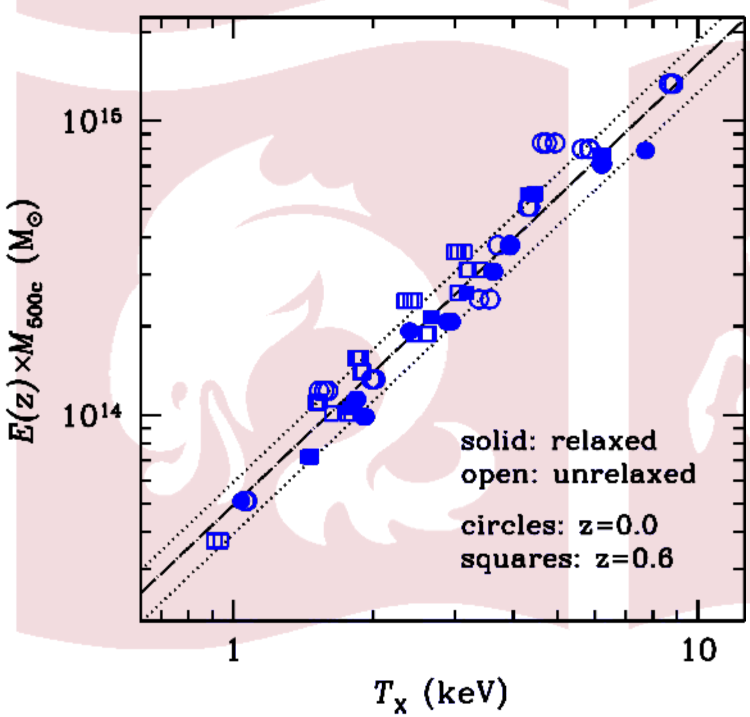
The Lx-Yx Relation: Mergers

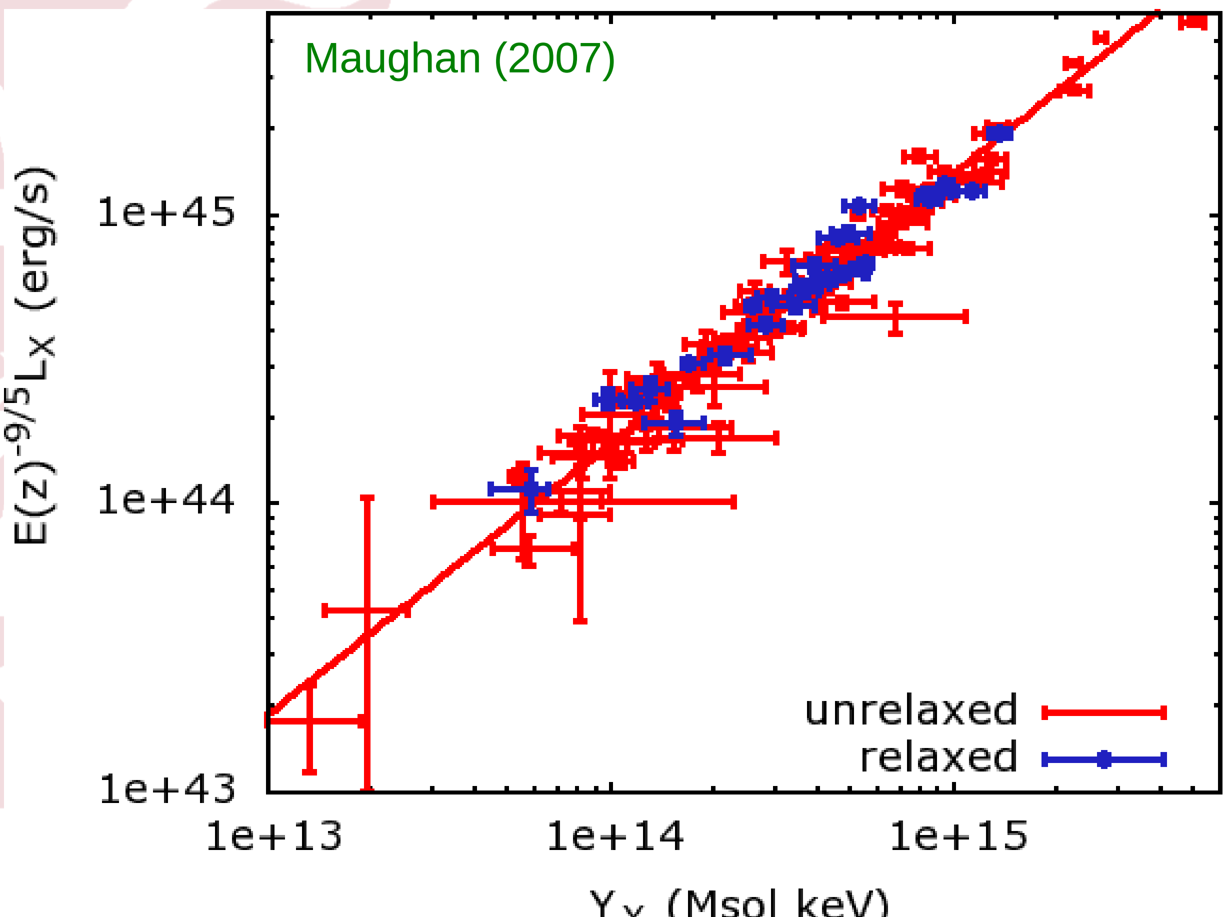
How do mergers effect the relation?

★ Split sample into **relaxed** and **disturbed** clusters

★ No offset between populations

★ Unlike M-kT relation

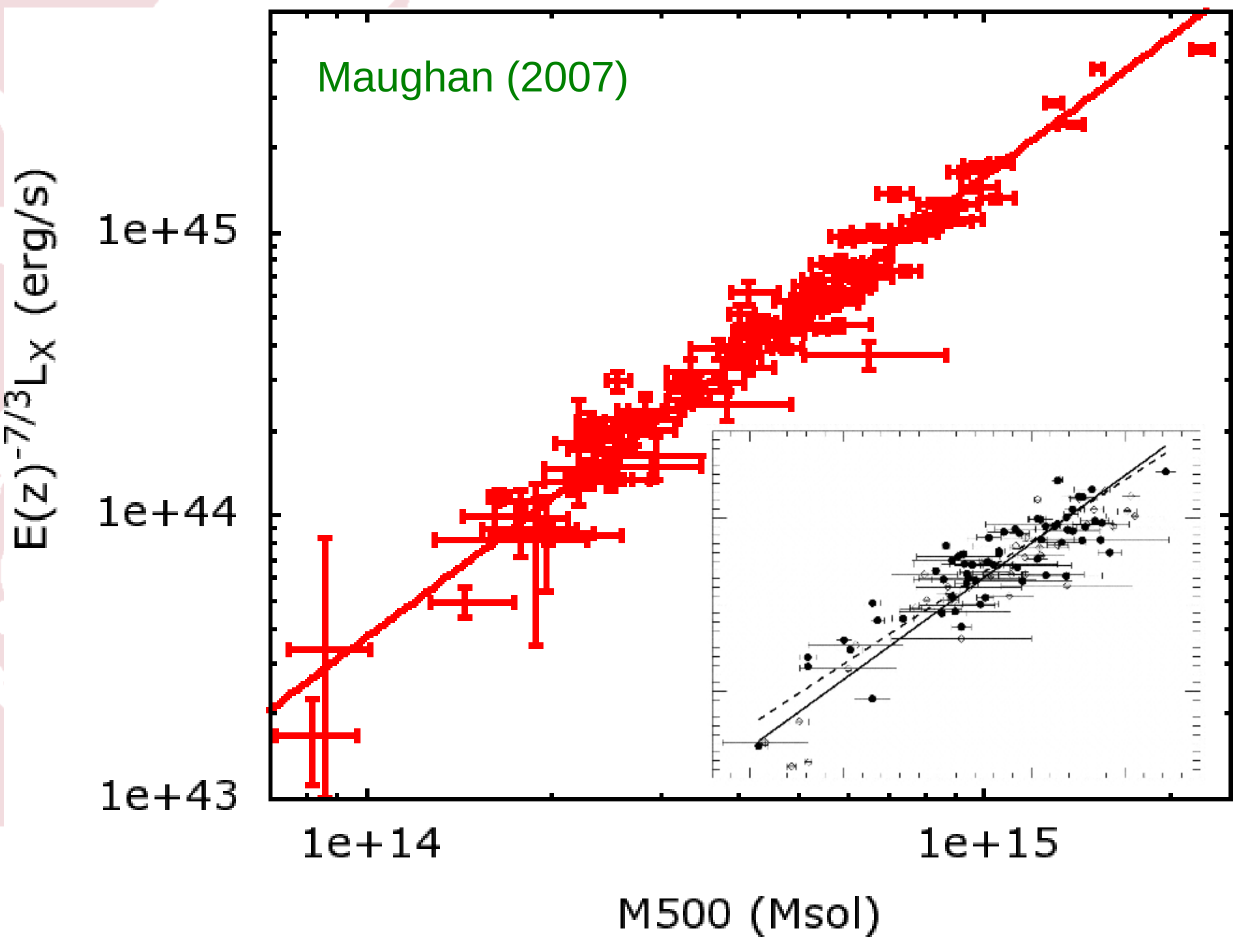




The Lx-M Relation

Lx-Yx relation implies Lx-M better than previously thought

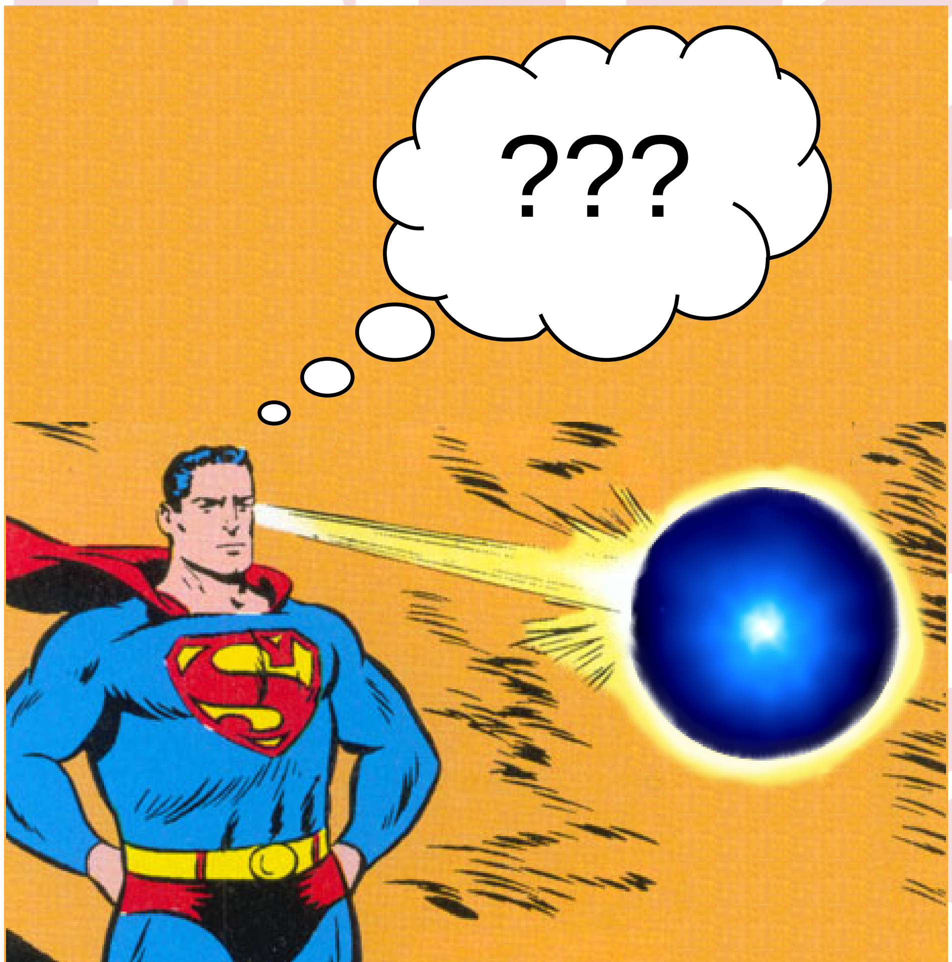
- ★ Convert Yx to M using Kravtsov et al. (2006) Yx-M relation
- ★ Include 8% scatter and errors on slope and norm (small)
- ★ σ_L=17%
- ★ Much lower than previous ~60%
  - Improved mass estimates from Yx
  - Conservative exclusion of cores



Hang on a Minute!

Yx has lower scatter than Lx with mass, so why bother?

★ If data are good enough to measure Yx then use that

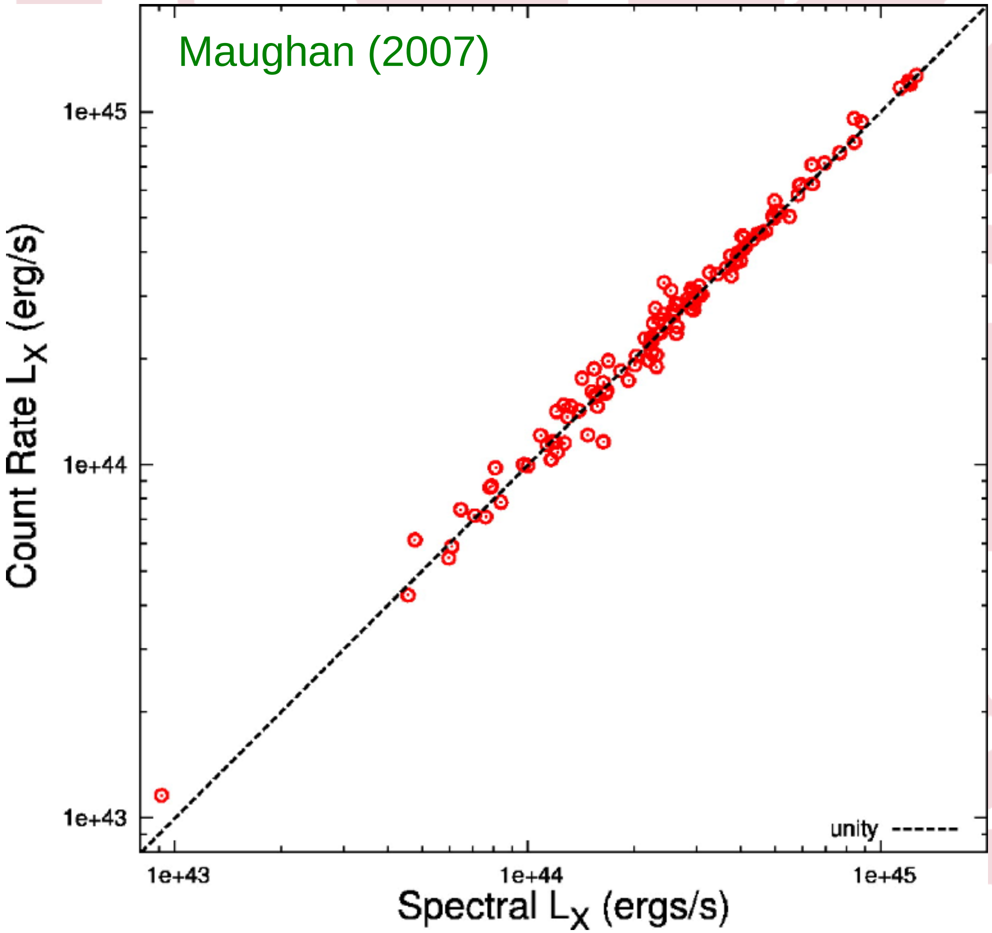


★ Clusters detected in X-ray surveys need follow up to measure Yx
  - Can measure count rate (Lx) from survey data
  - Need Lx-M relation for survey selection functions

Application to Survey Data

Typically measure soft X-ray count rate (no Yx, kT, R500)

★ Measure count rate in $(0.15\text{-}1)E(z)^{-1}$ Mpc aperture for sample



★ Use count rate and z to estimate Lx

★ Compare with Yx and M

Application to Survey Data

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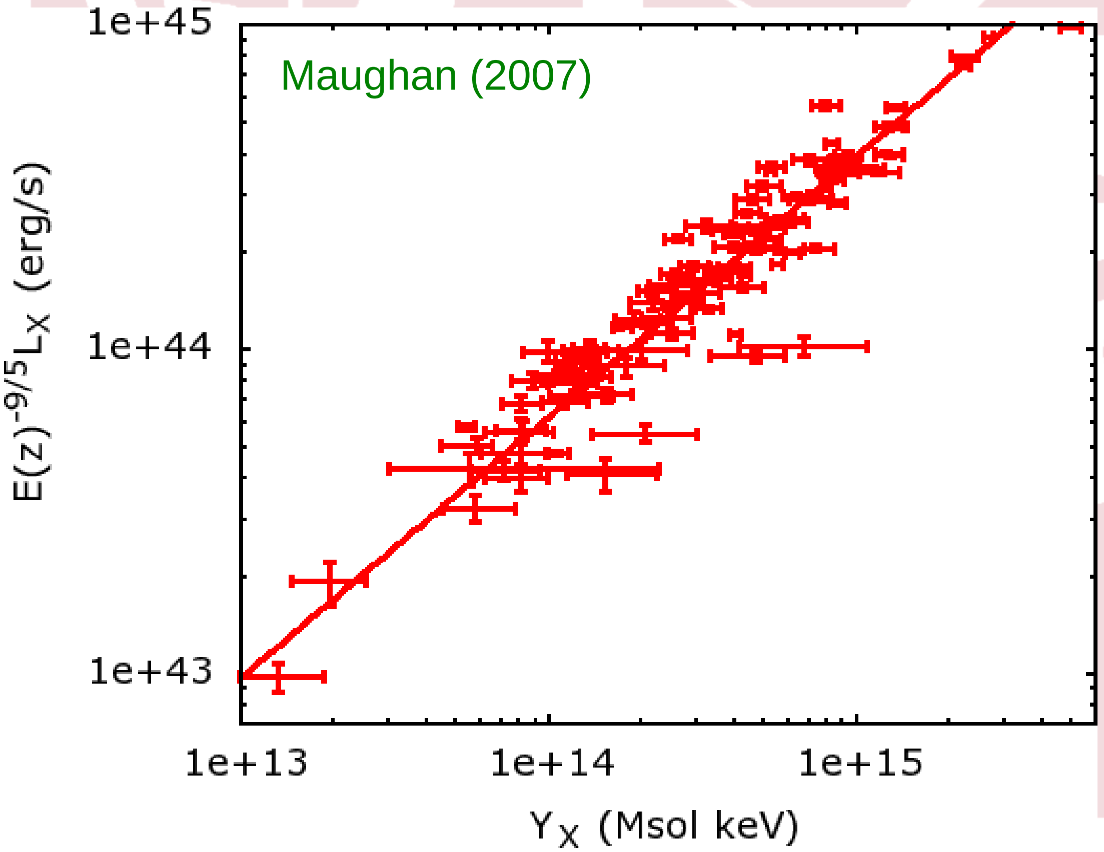


★ Use count rate and z to estimate Lx

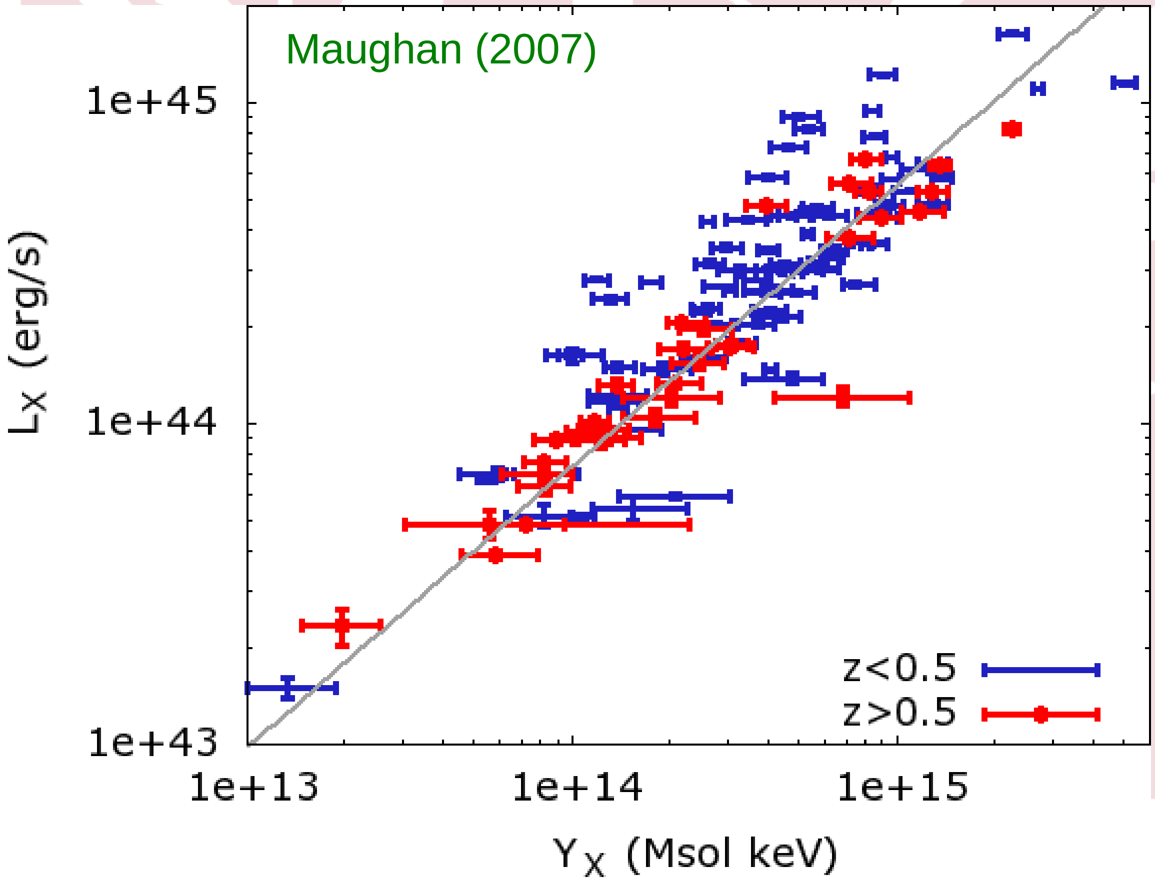
★ Compare with Yx and M

★ σ_L=19% (Lx-Yx)

★ σ_L=21% (Lx-M)

High-z Clusters in Surveys

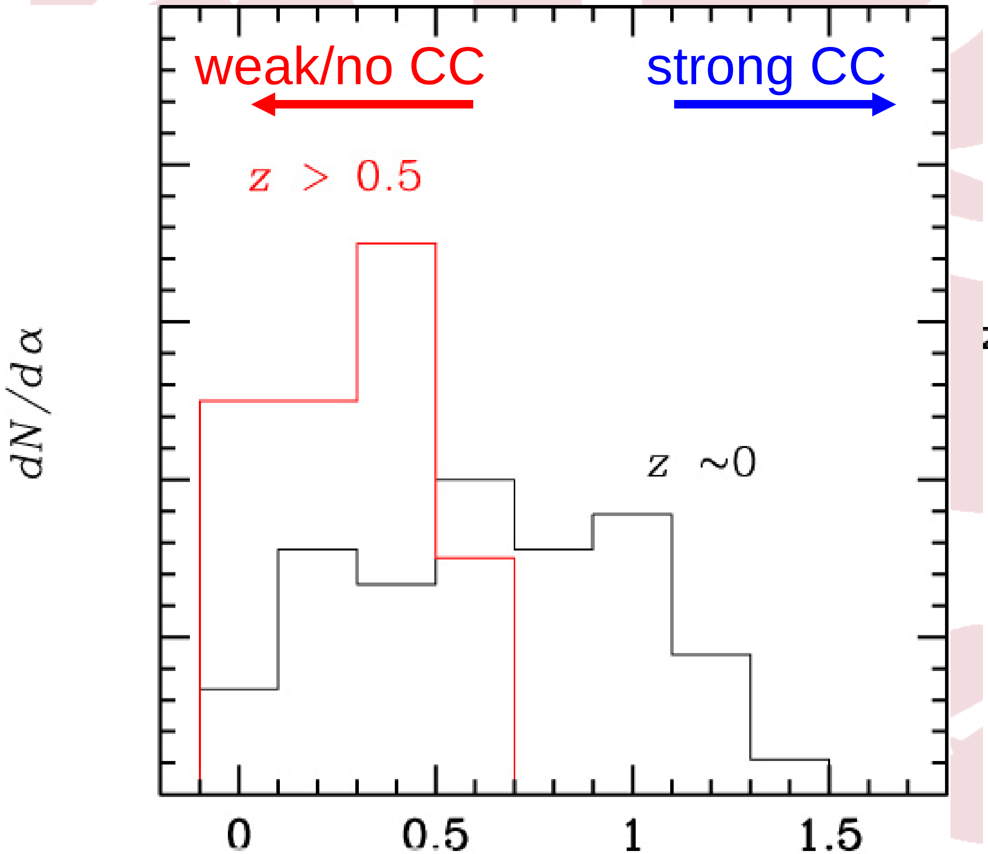
- ★ Lose ~30% of cluster emission when exclude cores
- ★ Large PSF (ROSAT & XMM) - can't exclude cores at high-z
- ★ Measure scatter in Lx-Yx with cores **included**



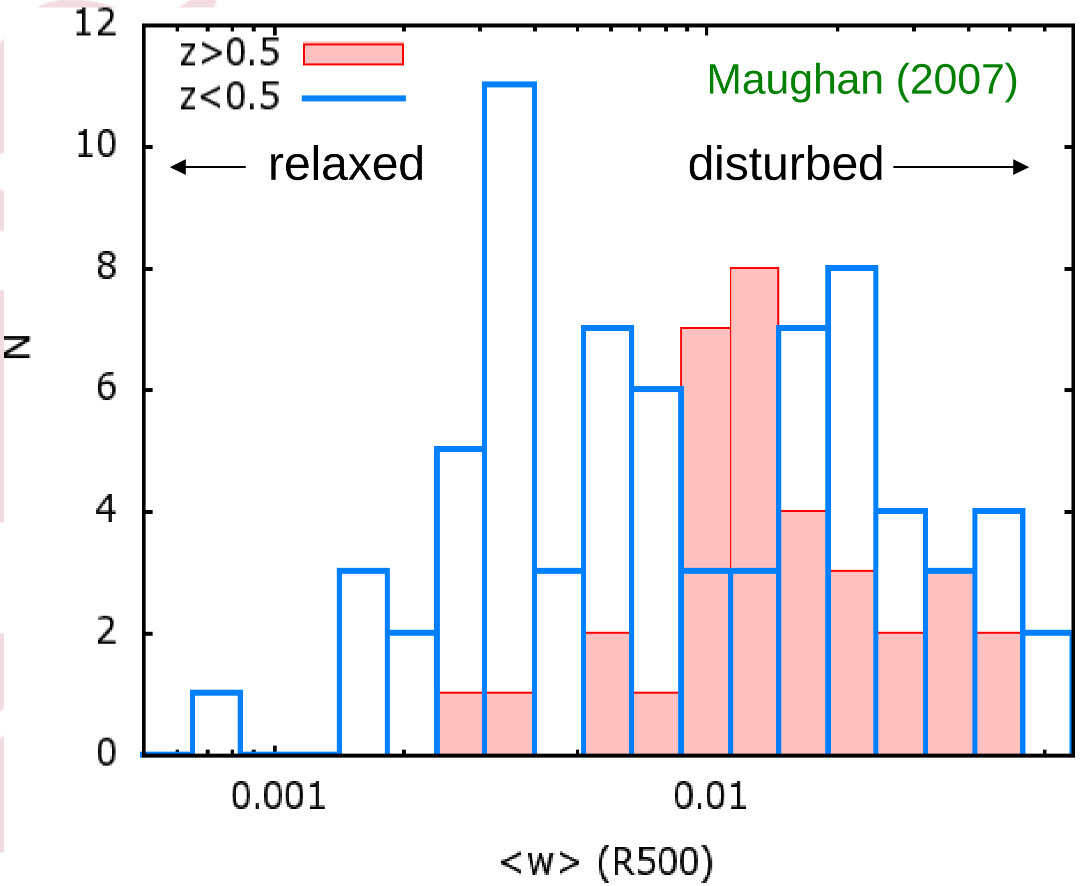
- ★ **z<0.5 → σ_L=44%**
- ★ **z>0.5 → σ_L=22%**
- ★ Not critical to exclude core regions for high-z clusters
  - – why?

High-z Clusters in Surveys

- ★ Significant absence of cool core clusters at z>0.5
- ★ Likely related to morphological evolution
  - – Fraction of mergers higher at z>0.5 in our sample

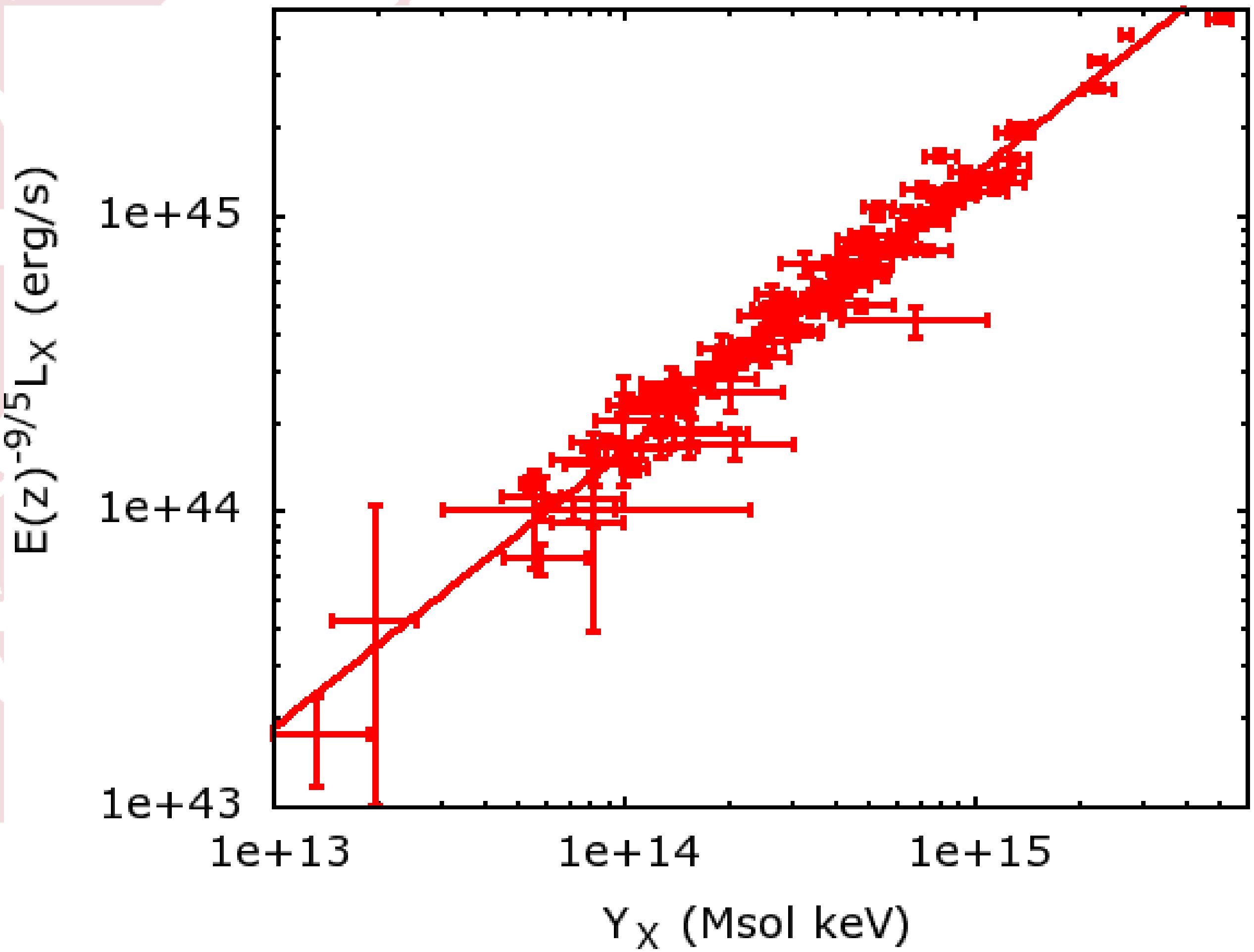


Vikhlinin et al. (2007)



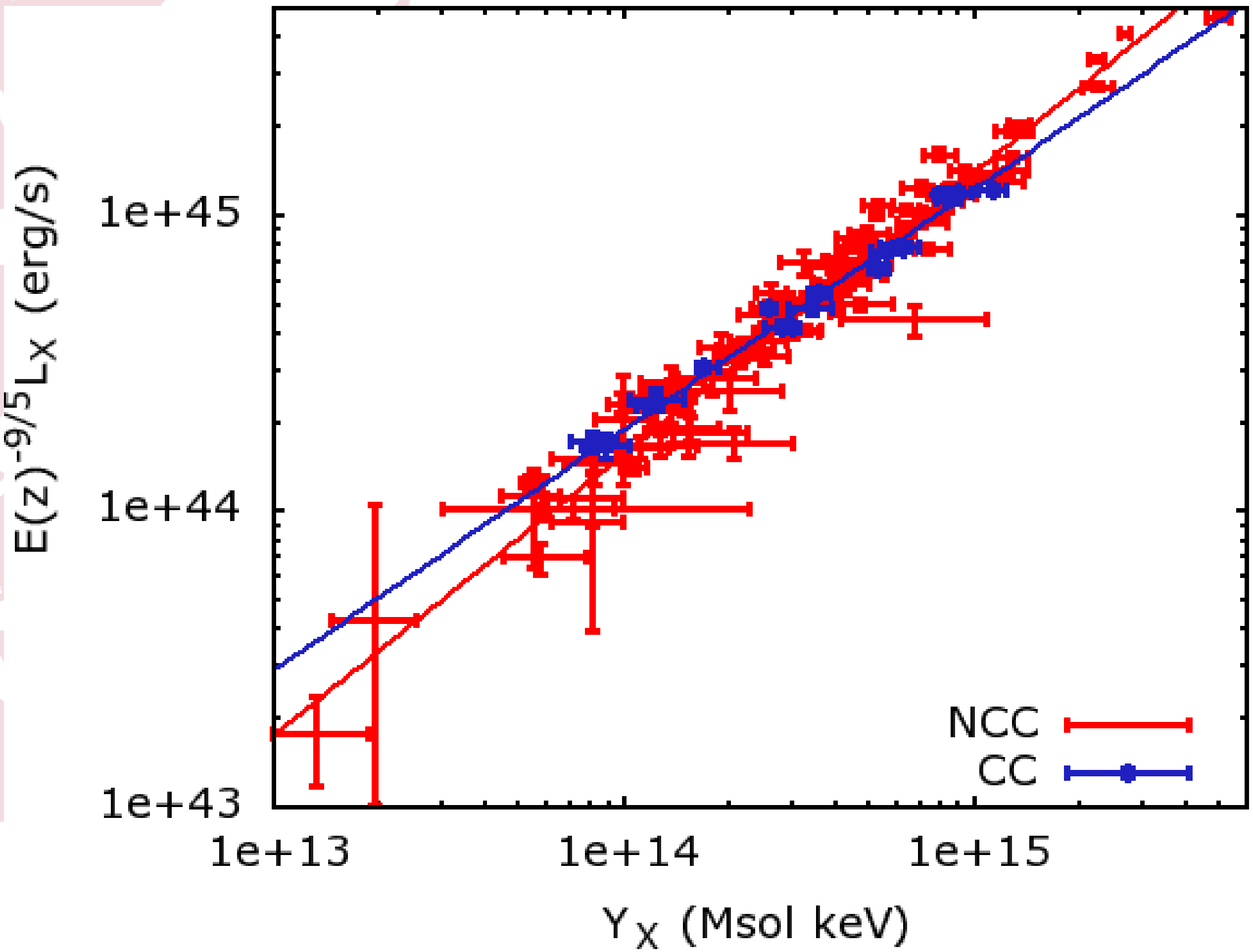
Self Similarity: Slopes

- SS model predicts slopes of Lx scaling relations shallower than observed
- Requires physical process not included in SS model
- e.g. SS model predicts Lx-Yx slope of B=0.8
- Best fit steeper; B=0.94±0.03



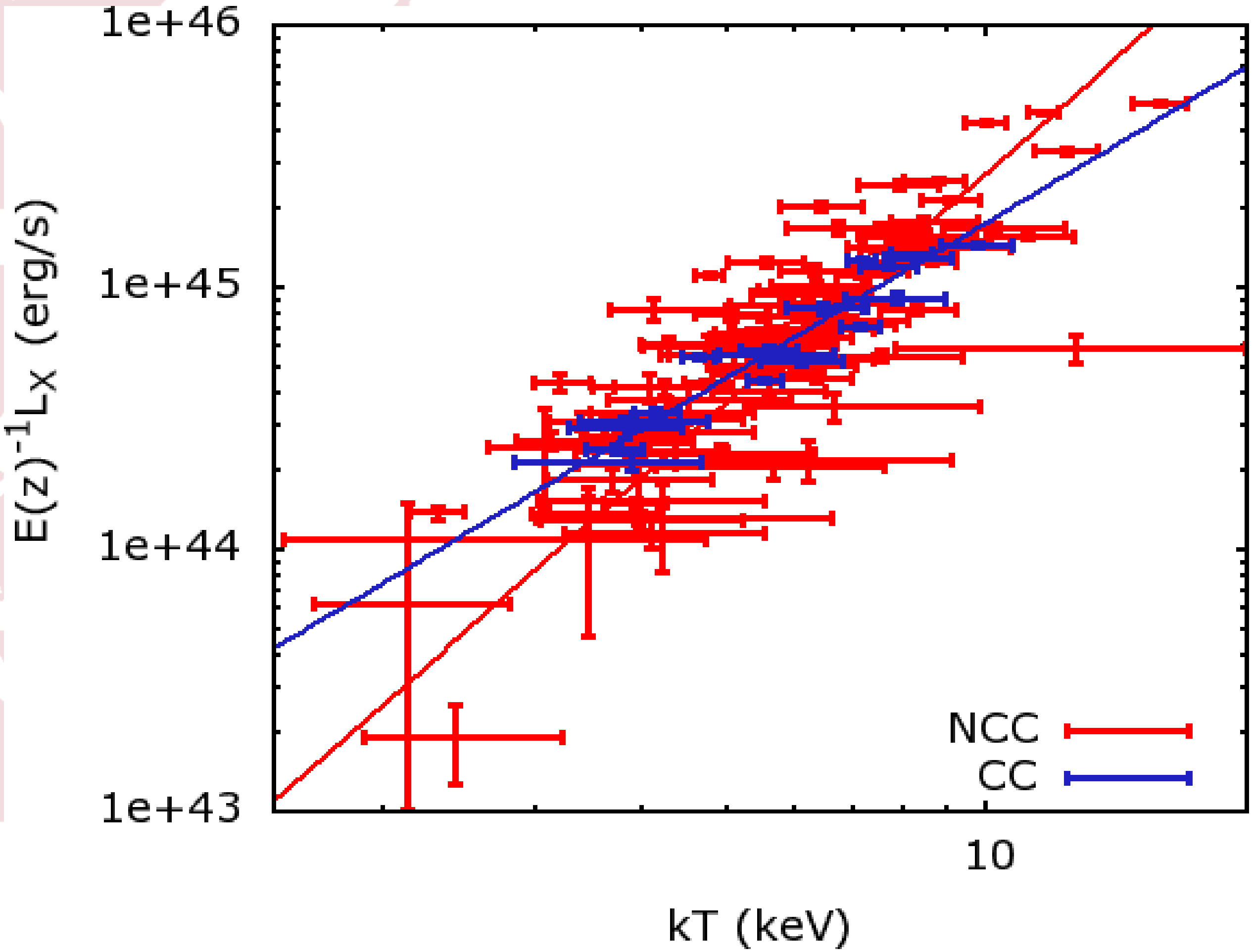
Self Similarity: Slopes

- ★ SS model predicts Lx-Yx slope of B=0.8
- ★ Best fit steeper; B=0.94±0.03
- ★ Split into CC and NCC clusters (using kT difference)
- ★ Cores excluded
  - CC slope (B=0.81) consistent with SS
  - 4σ shallower than NCC slope (B=0.95)



Self Similarity: Slopes

- ★ Same true for LT relation - SS predicts B=2
- ★ NCC clusters → B=2.9±0.2
- ★ CC slope is self similar B=2.1±0.2
- ★ 3σ shallower than NCC slope
- ★ CC clusters tend to be most relaxed
  - – Similarity breaking driven by mergers?



Recap

- ★ Revisited Lx-M relation using Yx to estimate masses
- ★ Scatter (17%) significantly lower than previously thought (60%)
- ★ Scatter remains low if we:
  - Use count rate instead of measured Lx
  - Use (0.15-1)$E(z)^{-1}$ Mpc aperture instead of R500
  - Do not exclude cores for high-z clusters
- ★ Self-similar slopes for CC clusters
  - Similarity breaking driven by mergers?

What's Next?

- ★ Uncertainties on absolute calibration of X-ray masses
- ★ Sunyaev-Zel'dovich effect (SZE) surveys will detect 1000's high-z clusters
  - SZE flux **predicted** to be good mass proxy
- ★ Gravitational lensing probes projected mass along line of sight
  - Systematic uncertainties
- ★ Combine all 3 methods on complete sample of 35 clusters
  - Cross-calibrate mass estimators