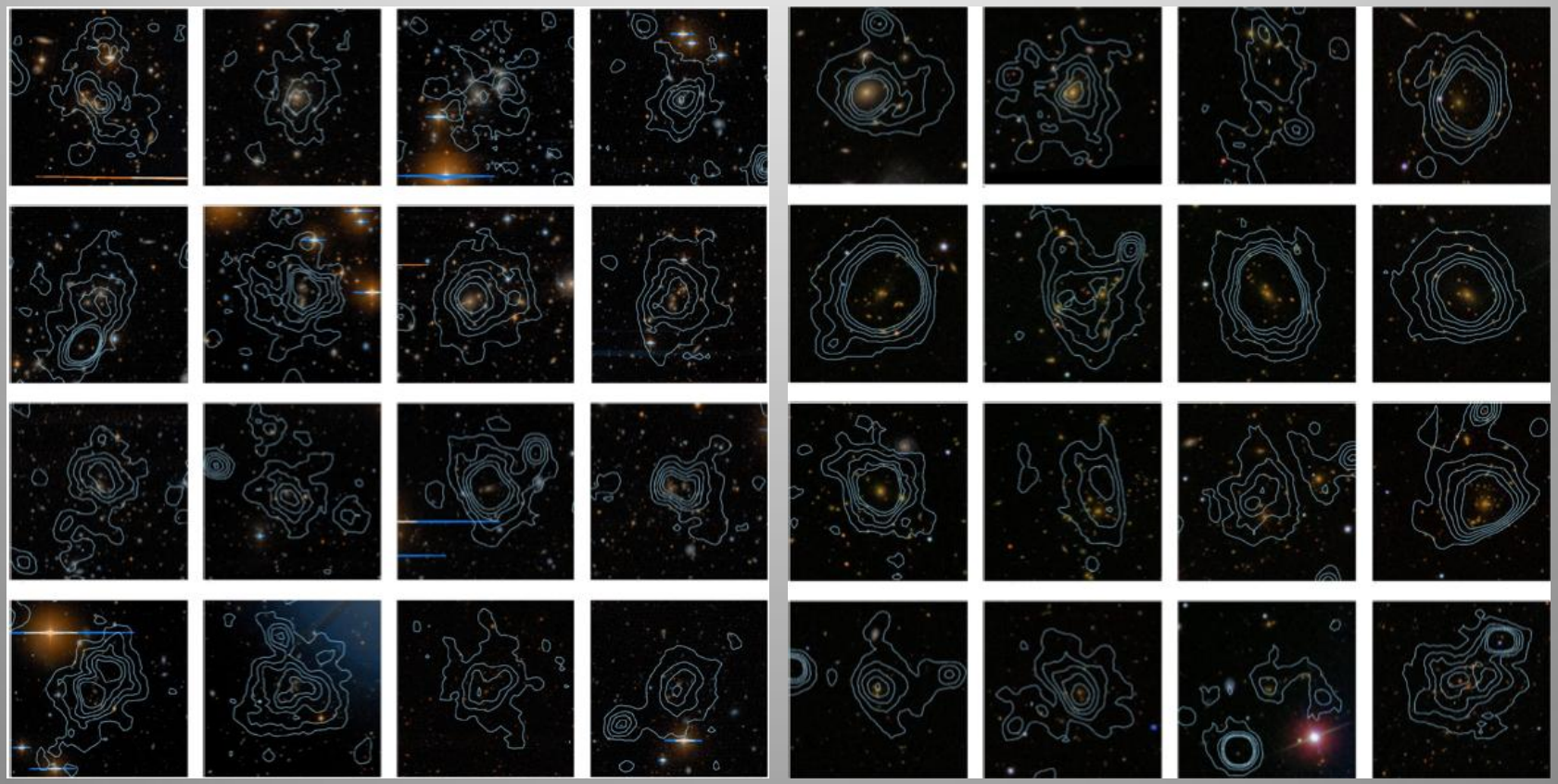
XMM Cluster Survey: First Data Release

Kathy Romer (University of Sussex)
On behalf of the XCS collaboration



September 13th 2011, Stockholm Clusters Meeting

XCS
XMM Cluster Survey

- **First a brief introduction to XCS…**
- We are searching for serendipitous detections of X-ray clusters using **all the data** in the XMM-Newton public archive.
- XCS Goals:
  - Cosmological parameters: σ_8 (5%), Ω_M (10%), Ω_Λ (15%).
  - Cluster scaling relations
  - Galaxy evolution
  - High quality data products for community use

ArXiv: 1010.0677; 1106.3056

13th September 2011

OUTLINE

- A. Development of XCS-DR1
- B. Applications of XCS-DR1
- C. Future plans for XCS

OUTLINE

- A. Development of XCS-DR1 [26 slides]
- B. Applications of XCS-DR1 [15 slides]
- C. Future plans for XCS [5 slides]

OUTLINE

- A. Development of XCS-DR1
- **B. Applications of XCS-DR1**
  - Already submitted [or about to be]
    - Studies of Fossil Groups (Harrison et al.)
    - Overlap with Planck (Viana et al.)
    - [AGN-ICM-BCG connection (Stott et al.)]
  - Analysis well underway
    - Optical to X-ray scaling relations (Mehrtens et al.)
    - Cosmological parameters (Sahlen et al.)
    - X-ray scaling relations (Hilton et al.)
- C. Future plans for XCS

What I hope I get across today

- The science we are doing is interesting
- The catalogue we have produced is high quality: please use it! You can do that independently or with "inside help". Several groups are already working with us: VHS, AMI, DES.
- We'd welcome help with one or more of the following: XMM proposals, Mass Estimates, Ground based follow-up, Chandra analysis.
- Respect for other X-ray clusters surveys (past, present and future)

A. Development of XCS-DR1

- For XCS-DR1, we wanted to get as many clusters out to the community as possible:
  - 503 optically confirmed, serendipitously detected X-ray clusters (402 with measured X-ray temperatures).
  - The candidate list that XCS-DR1 is drawn from is complete (in the sense that it can be modeled with a selection function).
  - But, because the optical follow-up is patchy, only sub-sets of XCS-DR1 clusters form “statistical” samples.

find images and data at xcs-home.org

The XMM Cluster Survey: Optical analysis methodology and the first data release

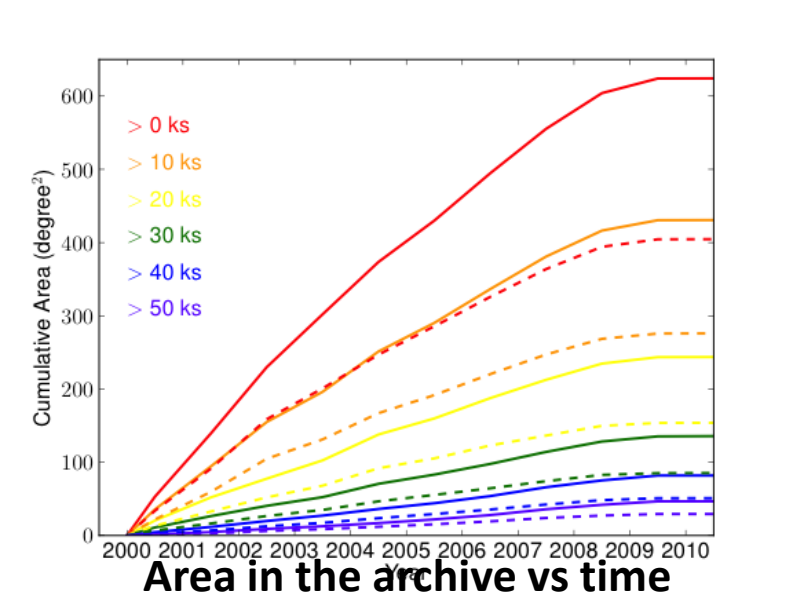
Nicola Mehrtens, A. Kathy Romer, E. J. Lloyd-Davies, Matt Hilton, Christopher J. Miller, S. A. Stanford, Mark Hosmer, Ben Hoyle, Chris A. Collins, Andrew R. Liddle, Pedro T. P. Viana, Robert C. Nichol, John P. Stott, E. Naomi Dubois, Scott T. Kay, Martin Sahlen, Owain Young, C. J. Short, L. Christodoulou, William A. Watson, Michael Davidson, Craig D. Harrison, Leon Baruah, Mathew Smith, Claire Burke, Paul-James Deadman, Philip J. Rooney, Edward M. Edmondson, Michael West, Heather C. Campbell, Alastair C. Edge, Robert G. Mann, David Wake, Christophe Benoist, Luiz da Costa, Marcio A. G. Maia, Ricardo Ogando

(Submitted on 15 Jun 2011 (v1), last revised 17 Jun 2011 (this version, v2))

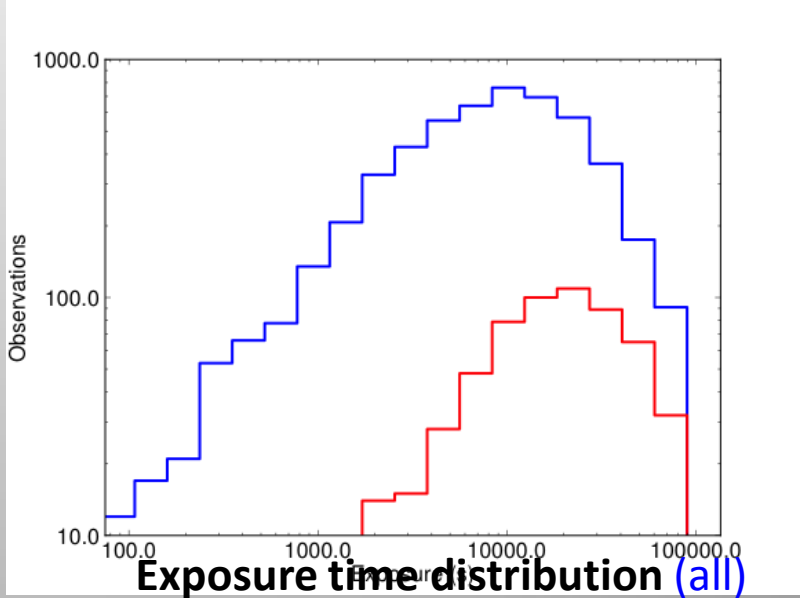
The XMM Cluster Survey (XCS) is a serendipitous search for galaxy clusters using all publicly available data in the XMM-Newton Science Archive. Its main aims are to measure cosmological parameters and trace the evolution of X-ray scaling relations. In this paper we present the first data release from the XMM Cluster Survey (XCS-DR1). This consists of 503 optically confirmed, serendipitously detected, X-ray clusters. Of these clusters, 255 are new to the literature and 356 are new X-ray discoveries. We present 464 clusters with a redshift estimate ($0.06 < z < 1.46$), including 261 clusters with spectroscopic redshifts. In addition, we have measured X-ray temperatures (Tx) for 402 clusters ($0.4 < Tx < 14.7$ keV). We highlight seven interesting subsamples of XCS-DR1 clusters: (i) 10 clusters at high redshift ($z > 1.0$, including a new spectroscopically-confirmed cluster at $z = 1.01$); (ii) 67 clusters with high Tx (> 5 keV); (iii) 131 clusters/groups with low Tx (< 2 keV); (iv) 27 clusters with measured Tx values in the SDSS `Stripe 82' co-add region; (v) 78 clusters with measured Tx values in the Dark Energy Survey region; (vi) 40 clusters detected with sufficient counts to permit mass measurements (under the assumption of hydrostatic equilibrium); (vii) 105 clusters that can be used for applications such as the derivation of cosmological parameters and the measurement of cluster scaling relations. The X-ray analysis methodology used to construct and analyse the XCS-DR1 cluster sample has been presented in a companion paper, Lloyd-Davies et al. (2010).

Looking forward to XCS-DR1+n

- There are thousands more clusters waiting to be discovered in the archive: the XMM archive just keeps on growing.



Area in the archive vs time

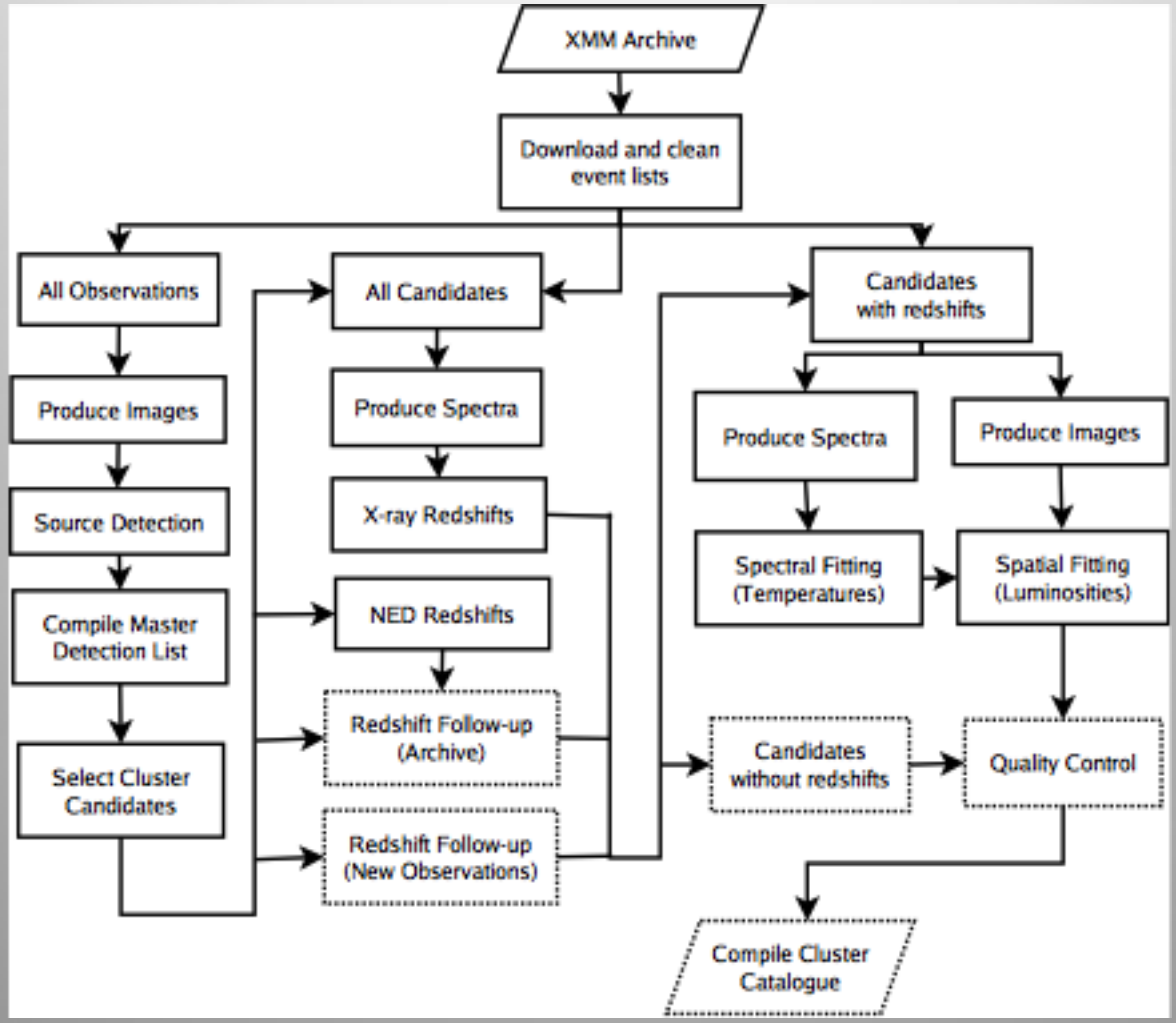


Exposure time distribution (all)

(for DR1 clusters with temperatures)

- Funding allowing, XCS will keep delivering clusters to the community as long as XMM does. We expect the total area covered to be ~500 square degrees.

Our USP: Automated Pipelines



But they took many years to write.

The XMM Cluster Survey: X-ray analysis methodology

E. J. Lloyd-Davies, A. Kathy Romer, Nicola Mehrtens, Mark Hosmer, Michael Davidson, Kivanc Sabirli, Robert G. Mann, Matt Hilton, Andrew R. Liddle, Pedro T. P. Viana, Heather C. Campbell, Chris A. Collins, E. Naomi Dubois, Peter Freeman, Craig D. Harrison, Ben Hoyle, Scott T. Kay, Emma Kuwertz, Christopher J. Miller, Robert C. Nichol, Martin Sahlen, S. A. Stanford, John P. Stott

(Submitted on 4 Oct 2010 (v1), last revised 15 Jun 2011 (this version, v2))

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But they took many years to write.

The XMM Cluster Survey: X-ray analysis methodology

E. J. Lloyd-Davies, A. Kathy Romer, Nicola Mehrtens, Mark Hosmer, Michael Davidson, Kivanc Sabirli, Robert G. Mann, Matt Hilton, Andrew R. Liddle, Pedro T. P. Viana, Heather C. Campbell, Chris A. Collins, E. Naomi Dubois, Peter Freeman, Craig D. Harrison, Ben Hoyle, Scott T. Kay, Emma Kuwertz, Christopher J. Miller, Robert C. Nichol, Martin Sahlen, S. A. Stanford, John P. Stott

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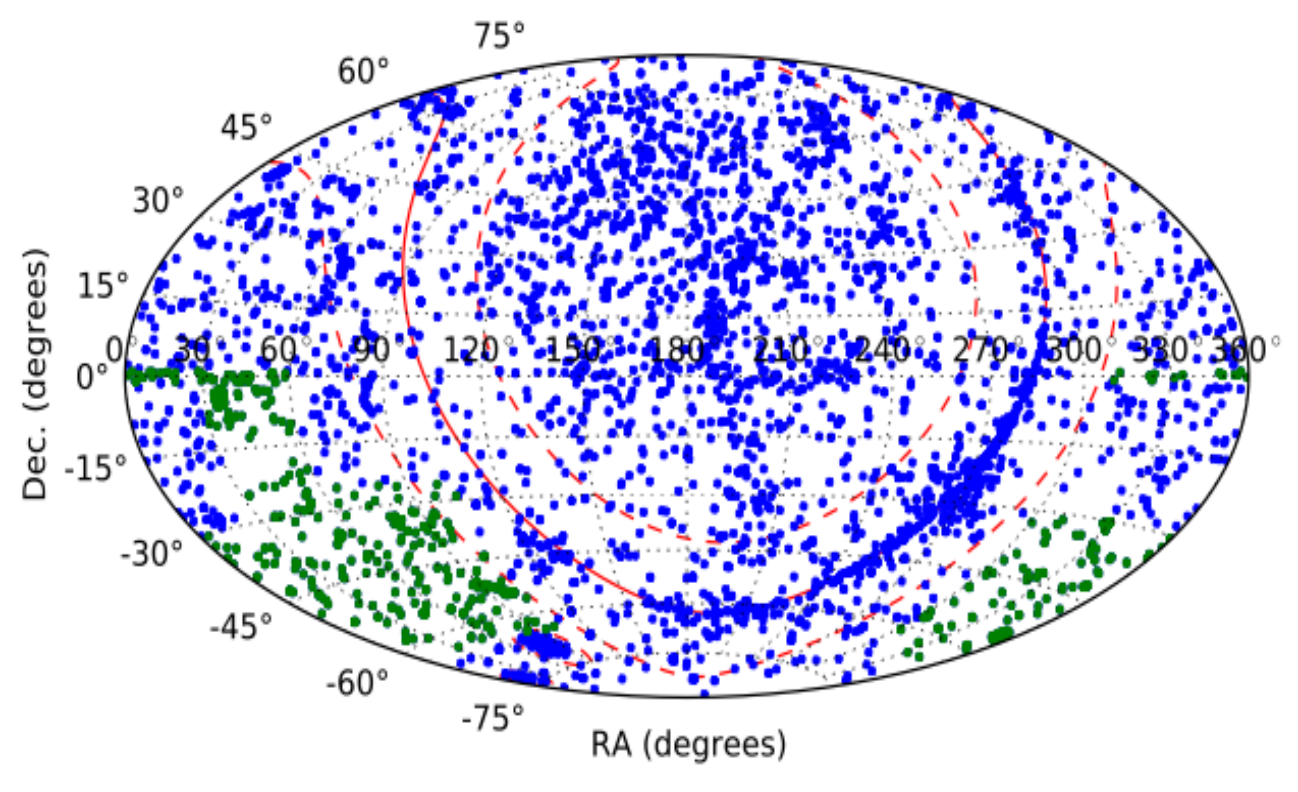
Observations processed



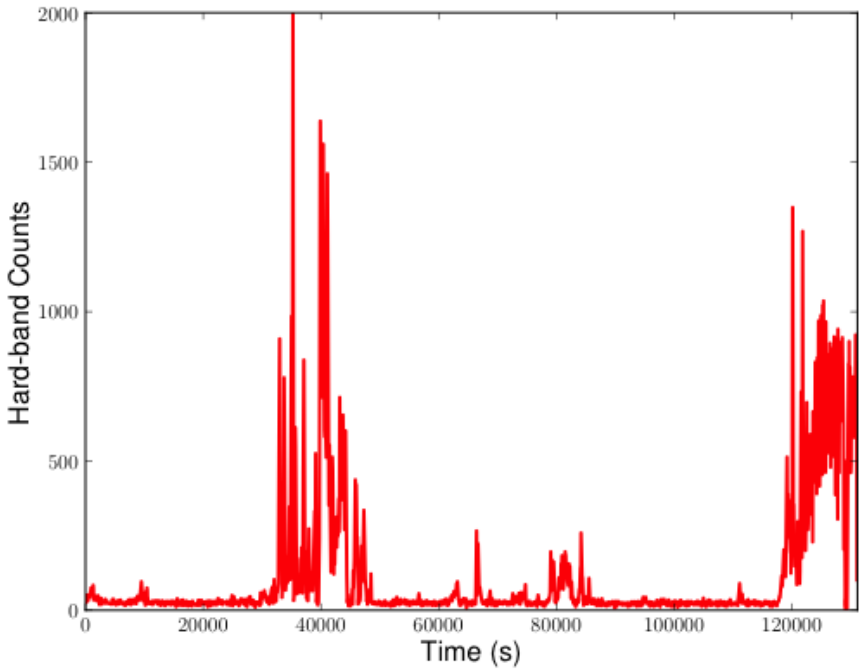
More than 4,000 XMM observations have been processed so far.

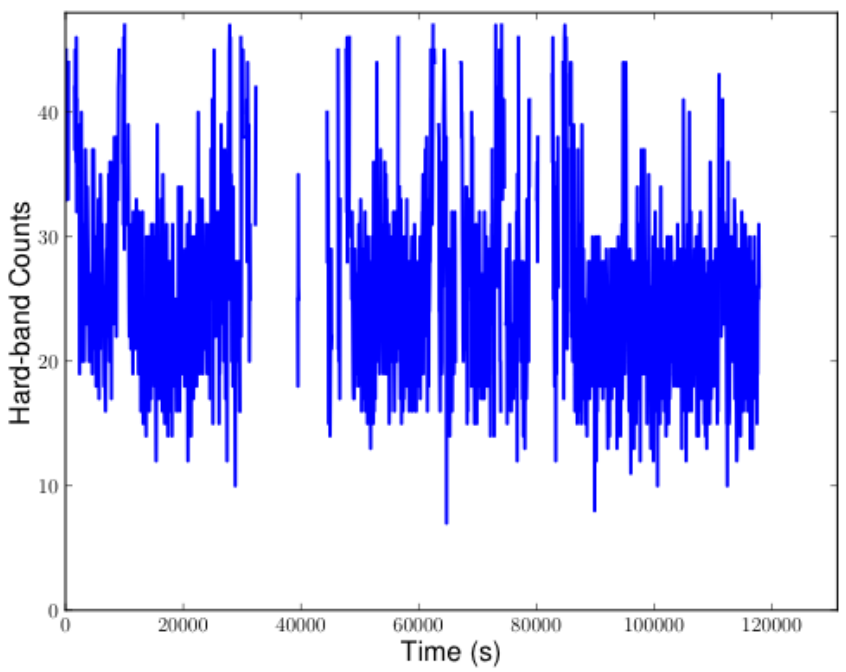
For cluster searching we exclude: Galactic Plane (b±20°), Magellanic clouds, XMM targeted clusters etc.

For cluster searching we cover: 410 sq. deg. (non-overlapping)

Green: DES overlap region

Image making complicated by flaring

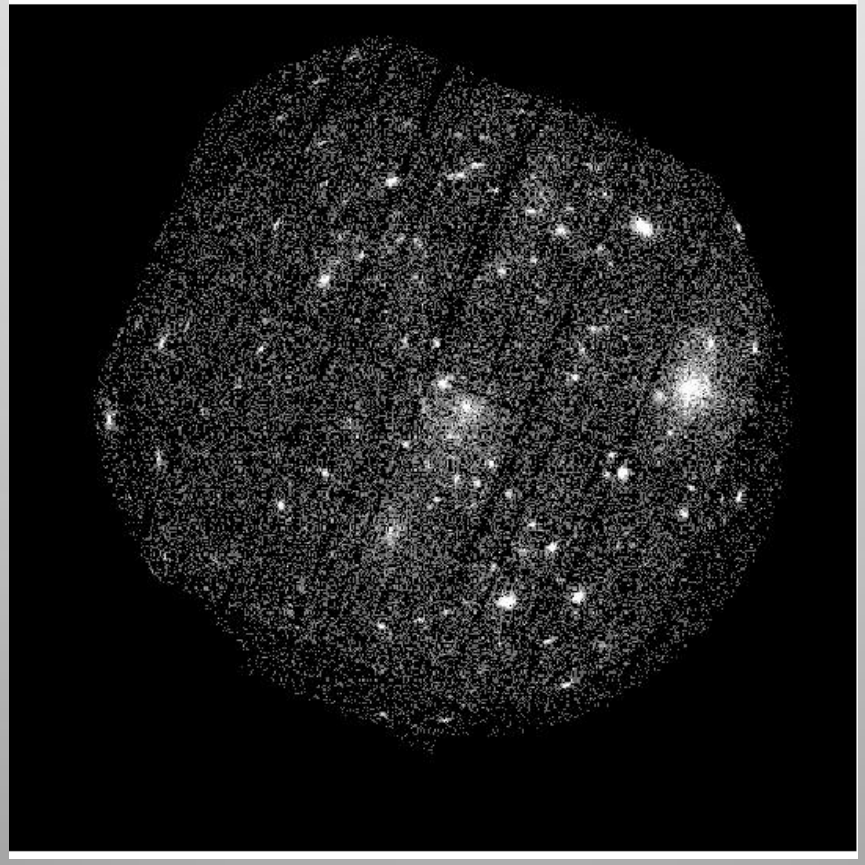




Time stream before flare correction

Time stream after flare correction

After flare cleaning the images look like this, now we find the sources



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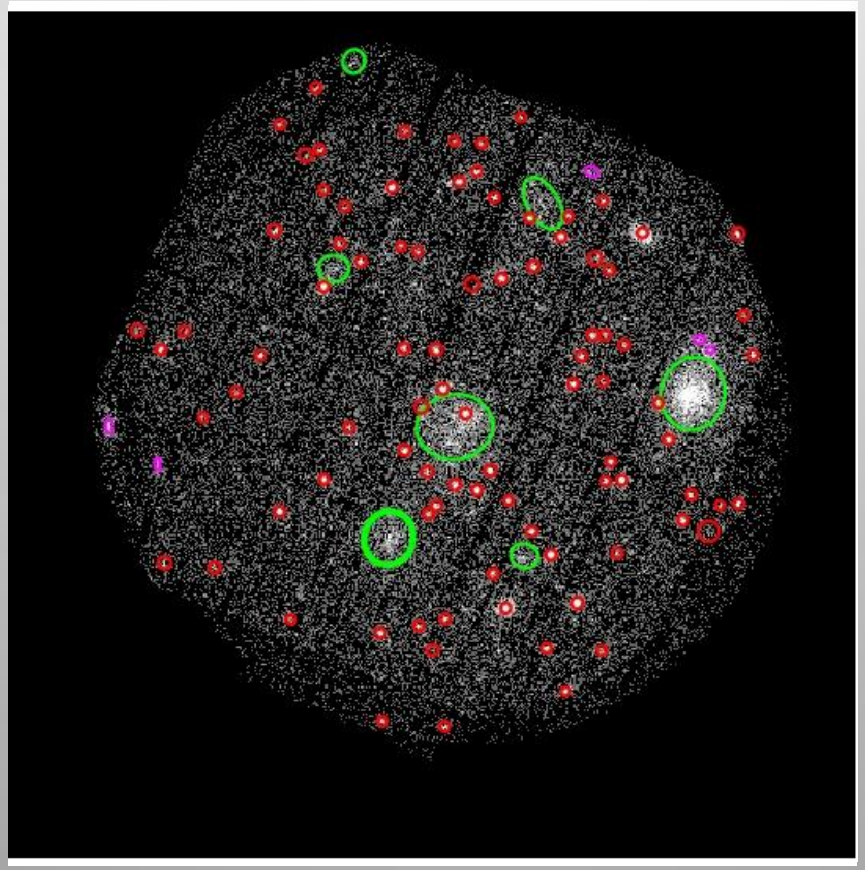
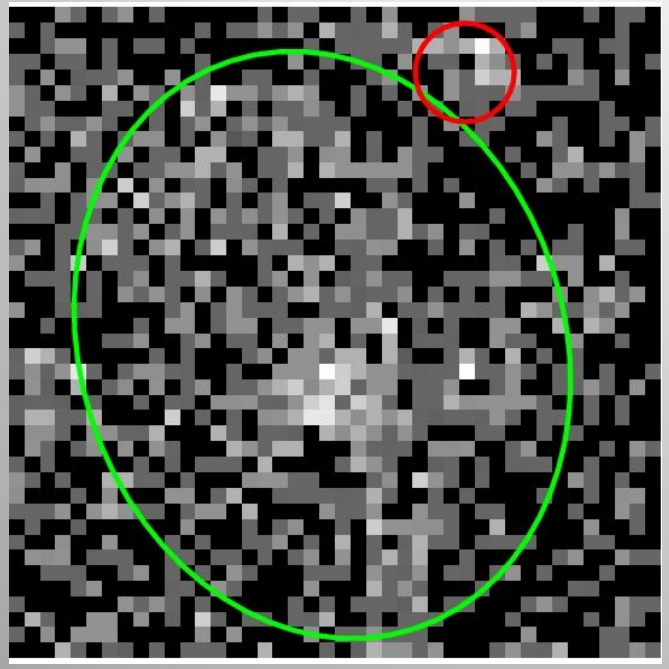
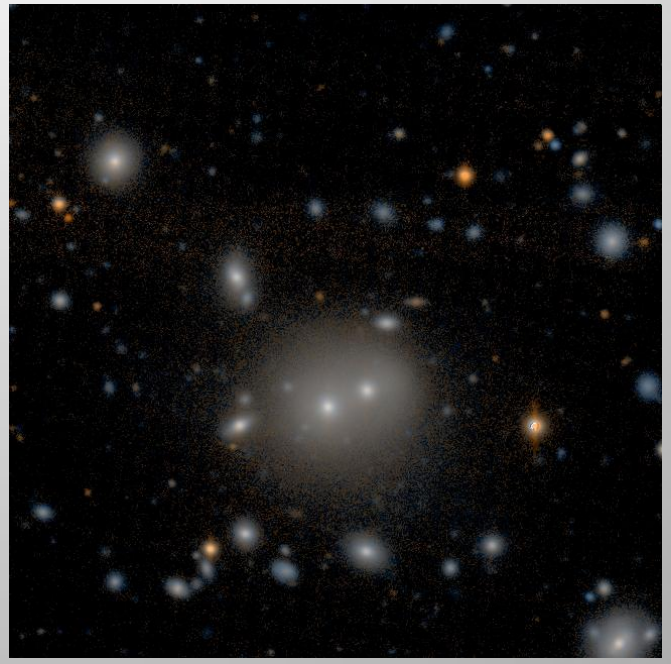


So far, we have >3,500 **Cluster candidates** and >100,000 **Point sources.**

Now we check the identifications of the cluster candidates

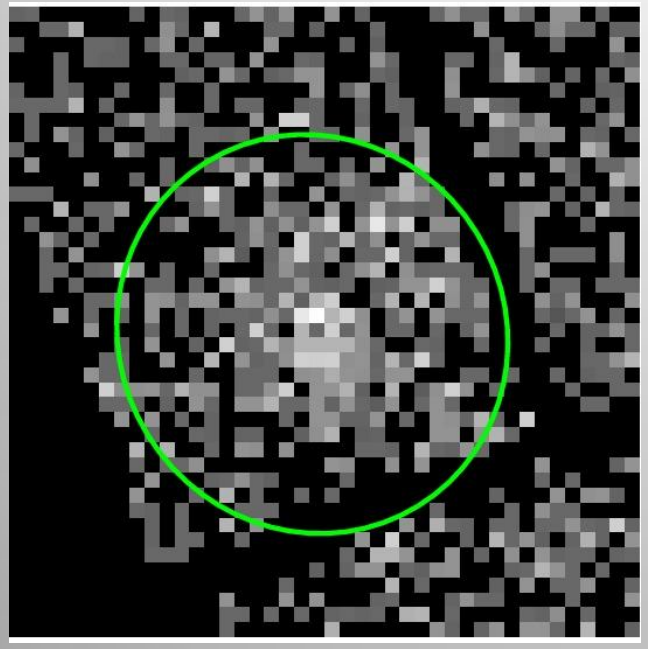


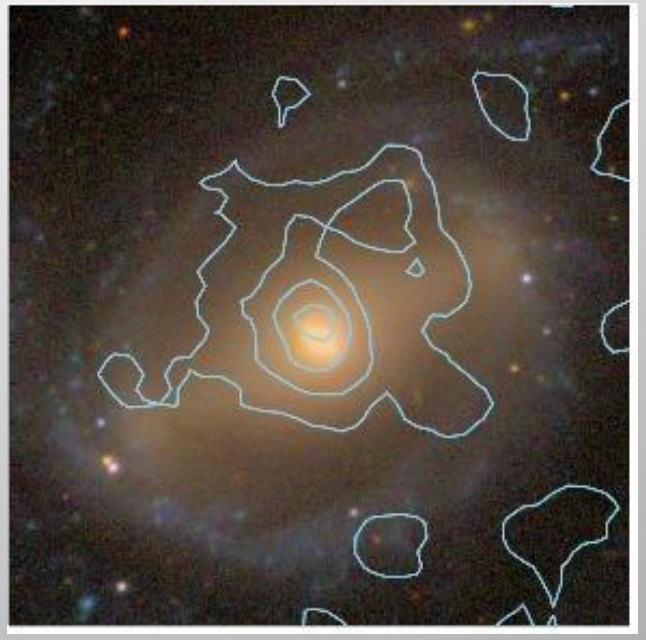


The 503 clusters in XCS-DR1 have been confirmed in two ways:

- Eye-ball programme (similar to *Galaxy-Zoo*) for candidates using:
  - SDSS-DR7
  - Stripe 82 co-add
  - The NOAO-XCS Survey (NXS) (our own imaging/photo-z survey)
- Detailed checks of the literature.

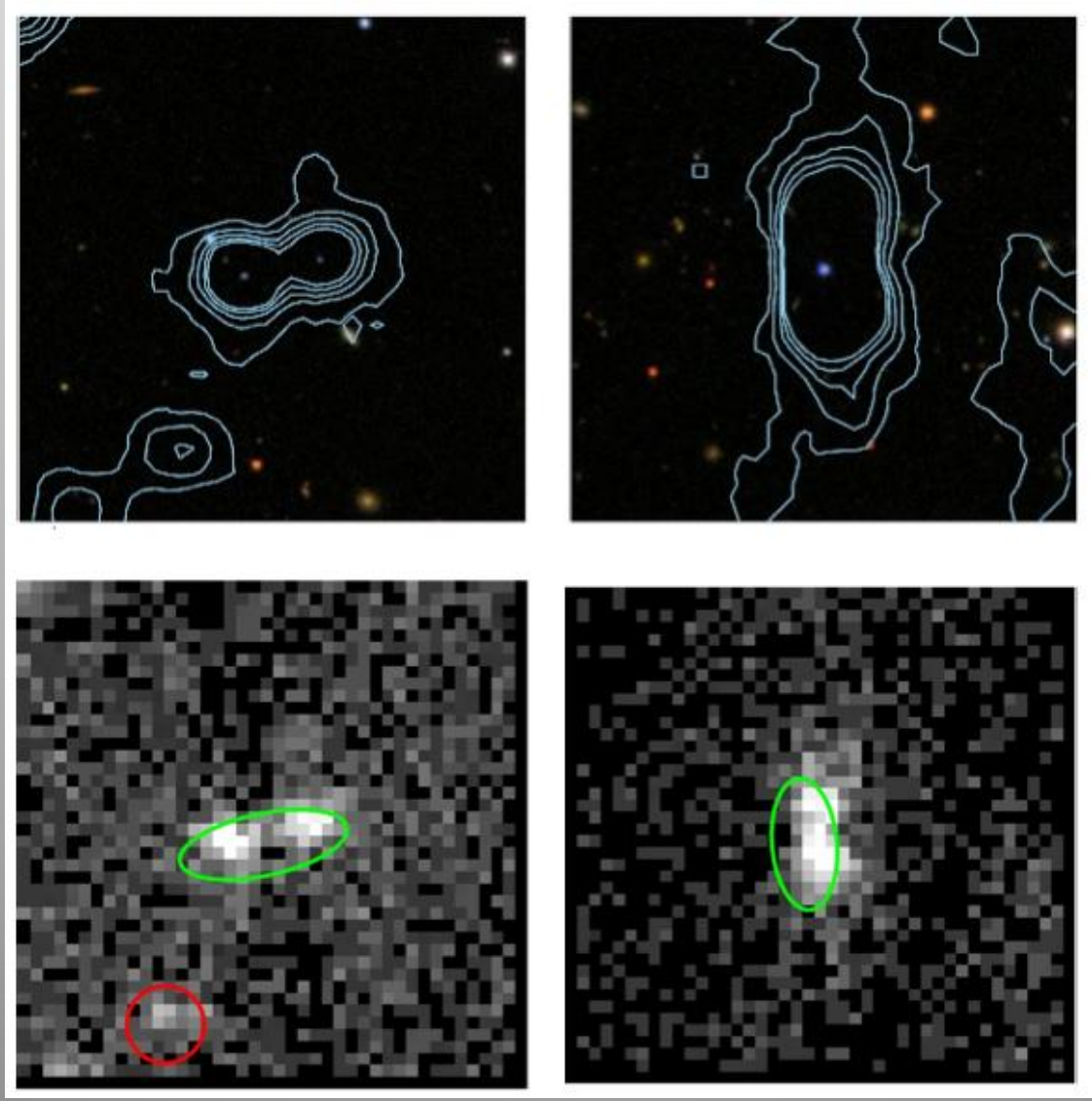
This is important because…





Not all extended XMM sources are clusters!

And not all sources labeled as extended are actually extended…



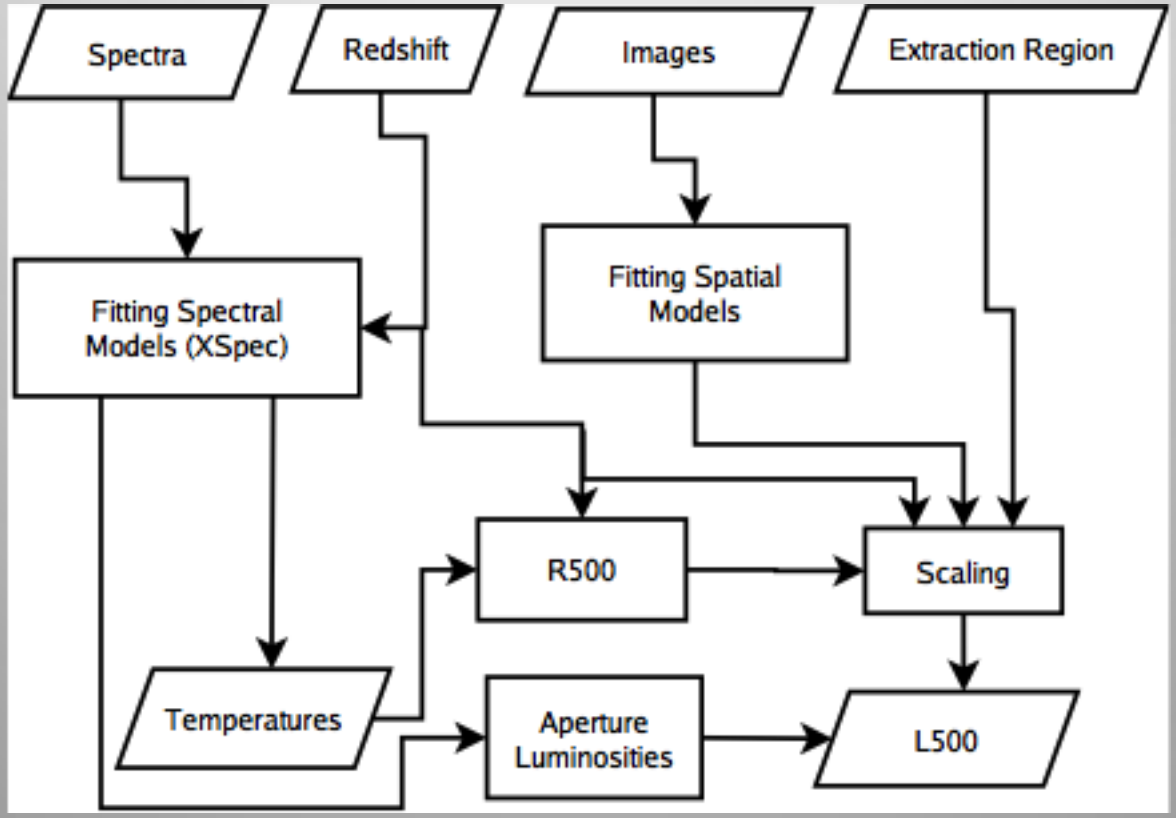
the need for a confirmation step impacts completeness…

- In regions where there is no imaging, we cannot confirm candidates as clusters
  - Unless a particular candidate is associated with a known cluster
- Even in regions where there is imaging, some of the clusters are too far away to show up as galaxy over densities.
  - We are trying to get deeper imaging of such objects in the SDSS region
  - We are using IR data (UKIDDS, VISTA, WISE)

After identifying the clusters, we need redshifts….

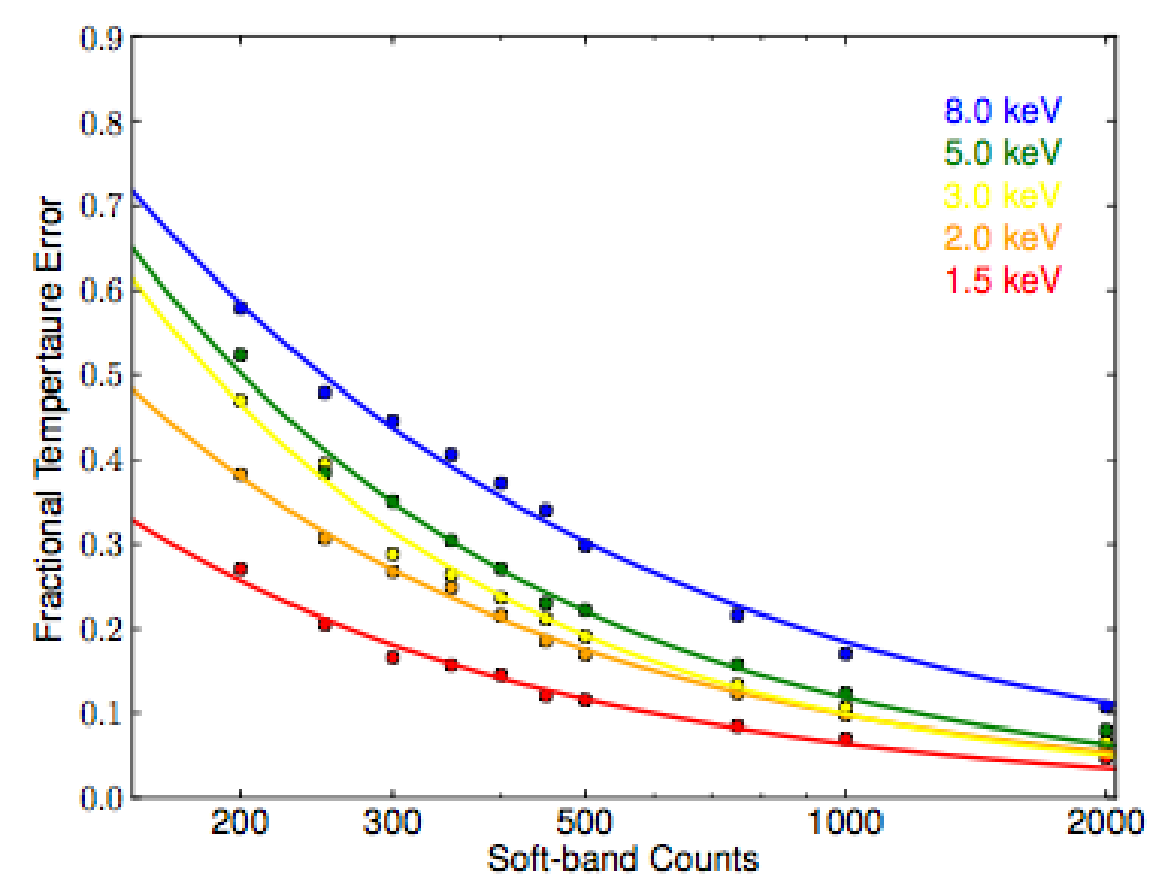
- This has been a painstaking process, taking many years. So far, we have gathered **464 redshifts** for the 503 confirmed clusters:
- **Spectroscopic redshifts (261)**
  - From our own work (Keck, Gemini, NTT, WHT).
  - From SDSS LRGs.
  - From the literature.
- **Photometric red-sequence redshifts (203**, excluding overlaps**)**
  - From our own work (NXS).
  - From SDSS-DR7.
  - From Stripe 82.

After gathering redshifts, we need temperatures and luminosities….



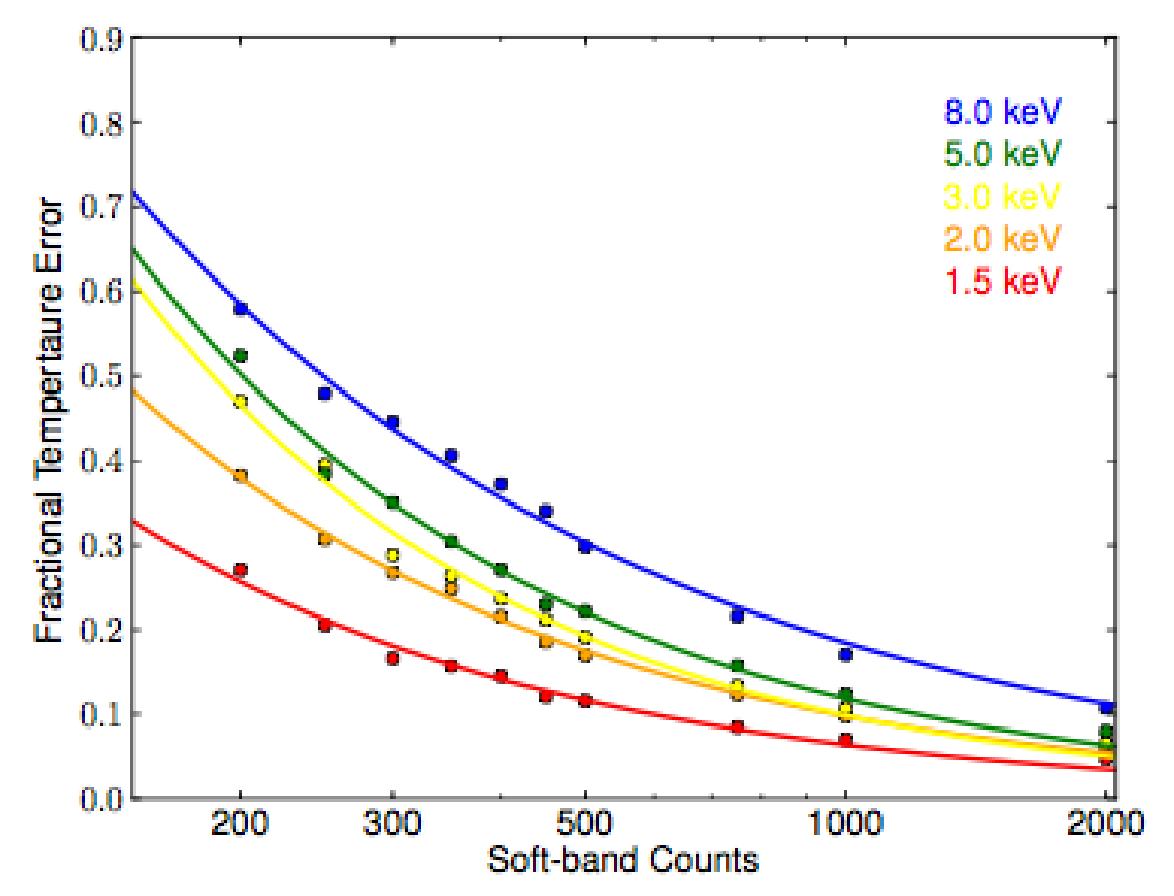
Overview of the “post processing” strategy

Automating X-ray analysis is unusual, why do we think it'll work?



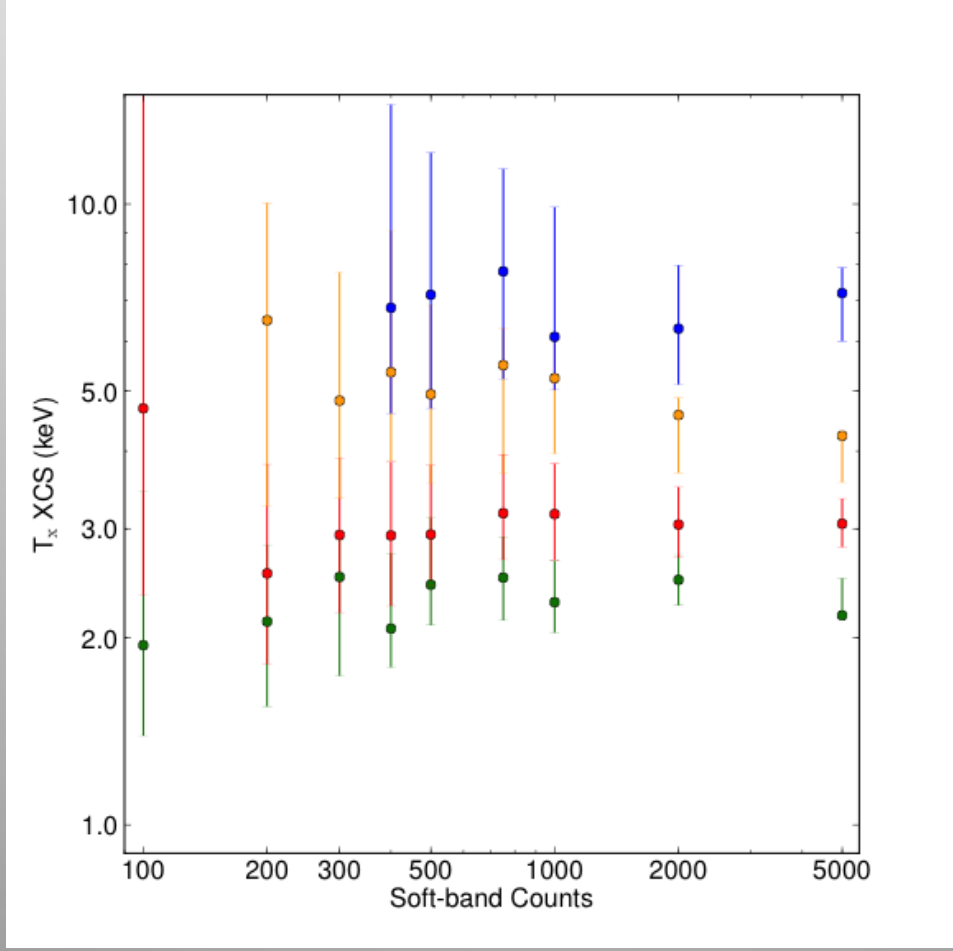
Using [realistic] simulated spectra, **we can predict the Tx errors** as a function of T and counts.

Automating X-ray analysis is unusual, why do we think it'll work?



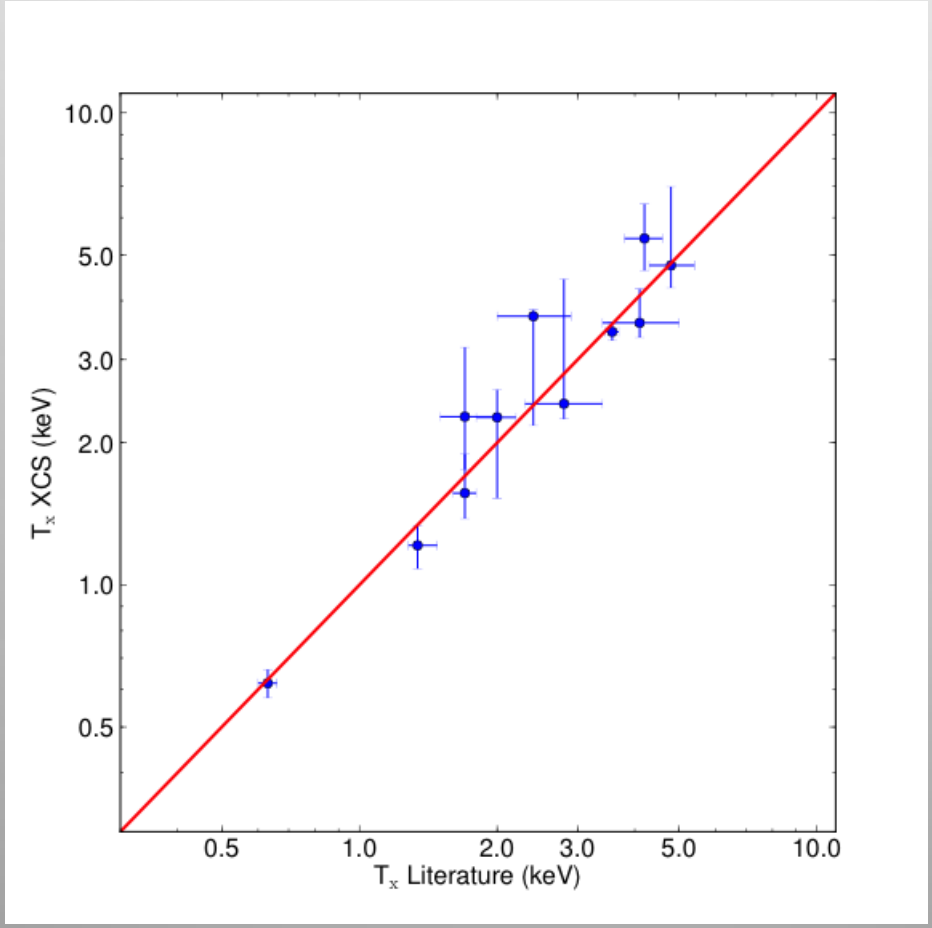
Based on these predictions, we have decided to limit "statistical samples" using a **detection count threshold of 300**: we refer to these clusters as **XCS^{300}** hereafter

X-ray temperatures



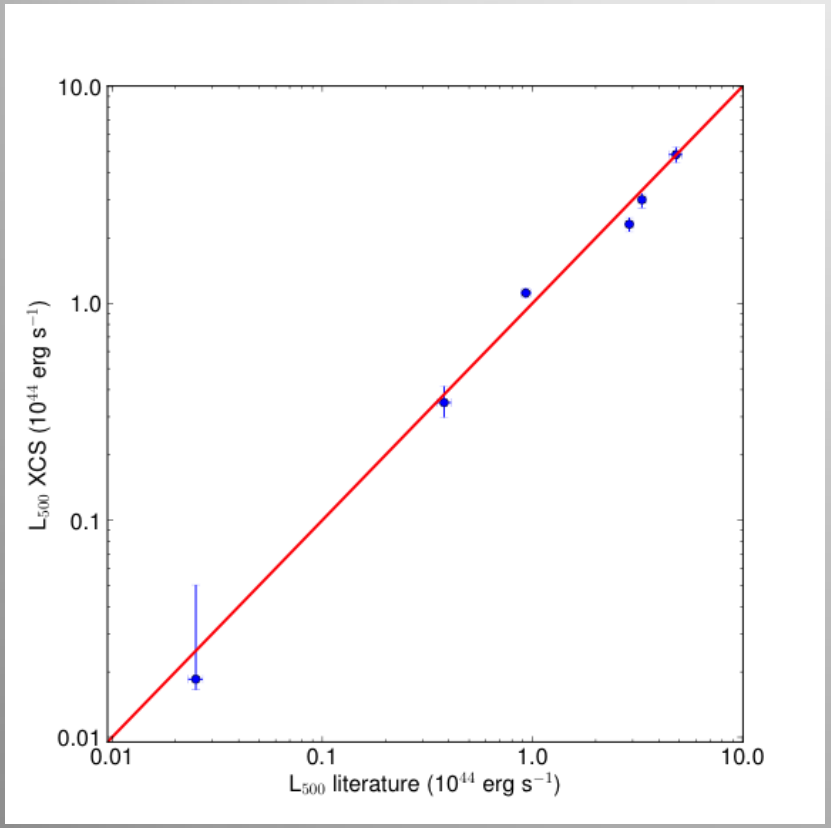
The Tx error predictions have been confirmed using high signal to noise spectra that have been re-sampled to lower count levels.

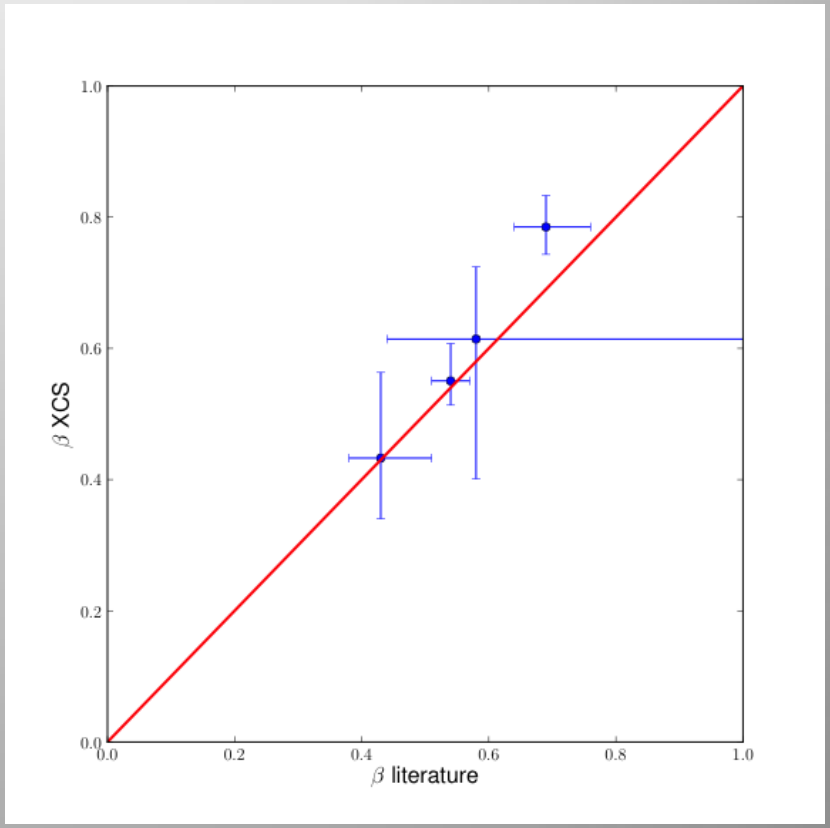
X-ray temperatures



Our Tx values match those in the literature (for the same XMM detected clusters)

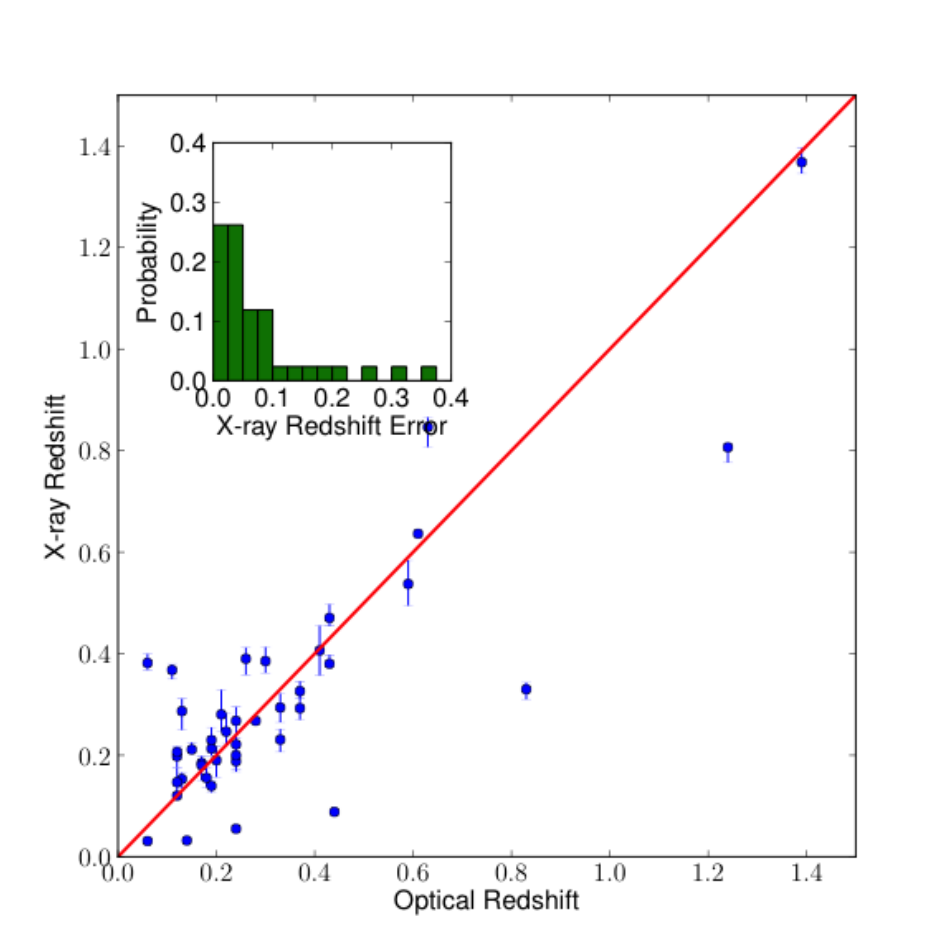
Luminosities and profiles





Our Lx and beta values match those in the literature (for the same XMM detected clusters)

X-ray redshifts

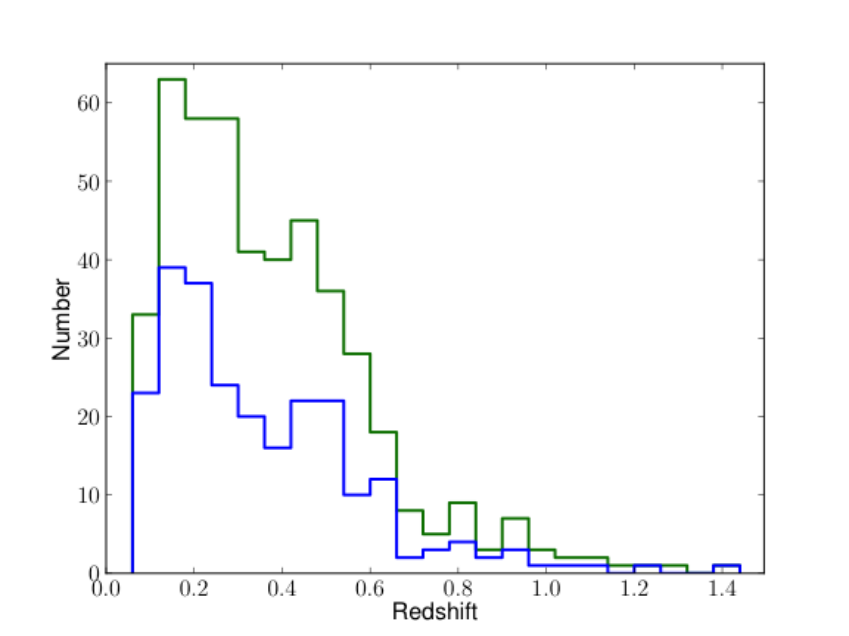


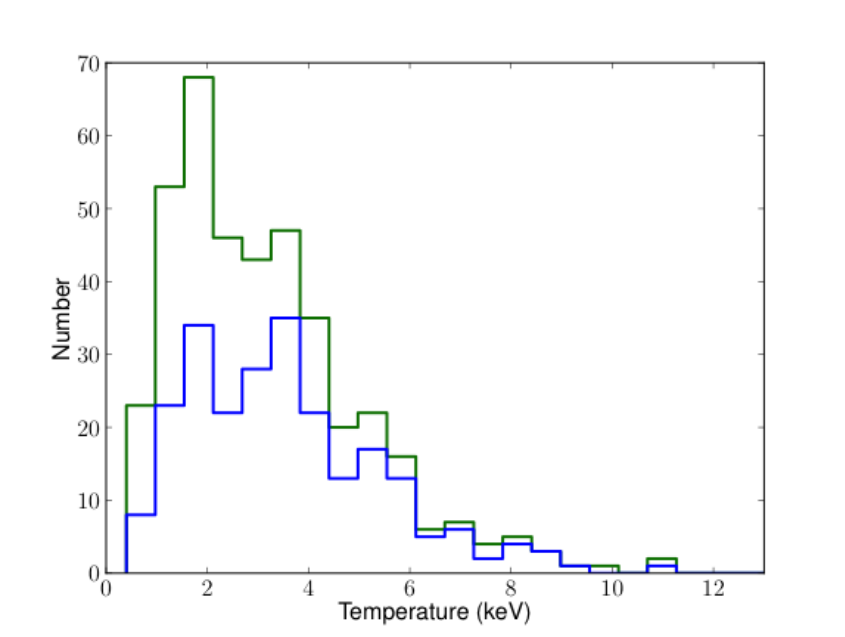
Even our X-ray redshifts estimates also perform well (after applying cuts based on errors): but none of our X-ray redshifts are used in XCS-DR1

Properties of XCS-DR1

503 clusters: 255 entirely new to literature; 356 are new X-ray detections.

464 redshifts (0.06 < z < 1.46); 402 temperatures (0.4 < Tx < 14.7); only 56 had previous Tx in literature. We have doubled the number clusters with Tx within these ranges.





Green line: full sample; Blue line: XCS^{300} sample (255 clusters).

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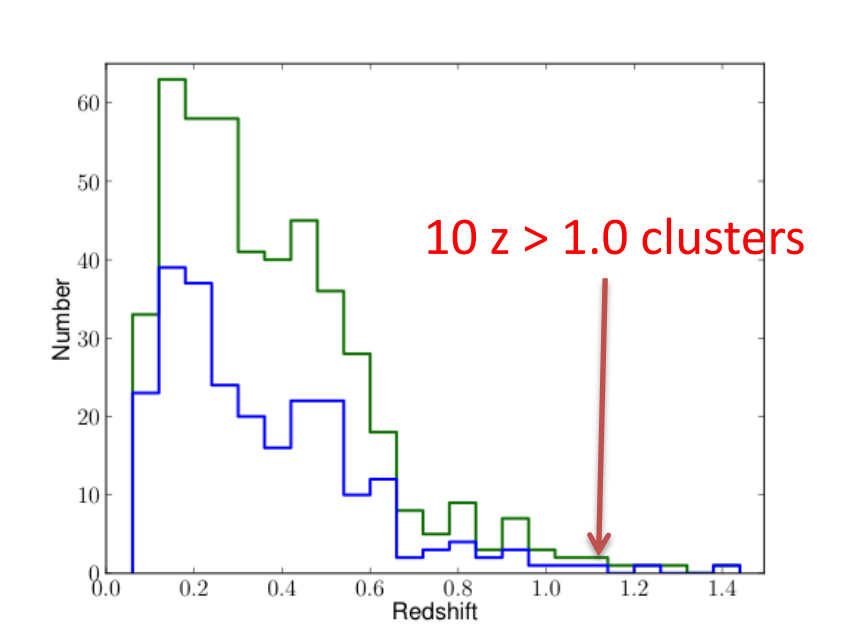
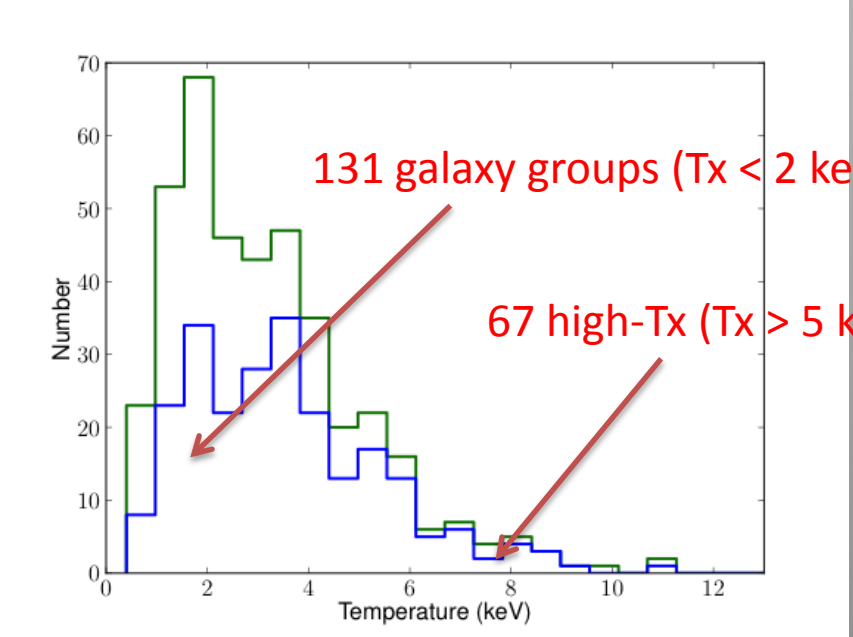
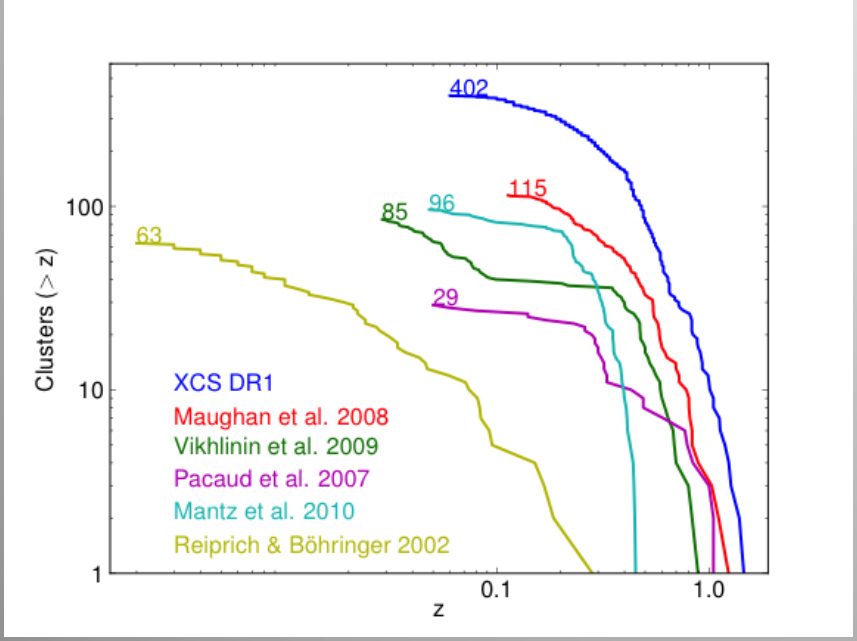


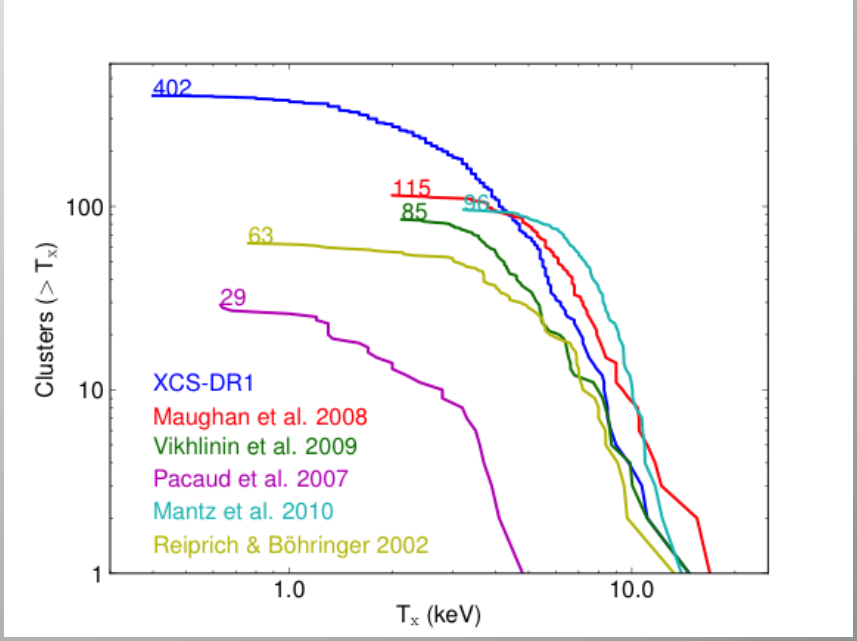


Green line: full sample; Blue line: XCS^{300} sample (255 clusters).

Properties of XCS-DR1

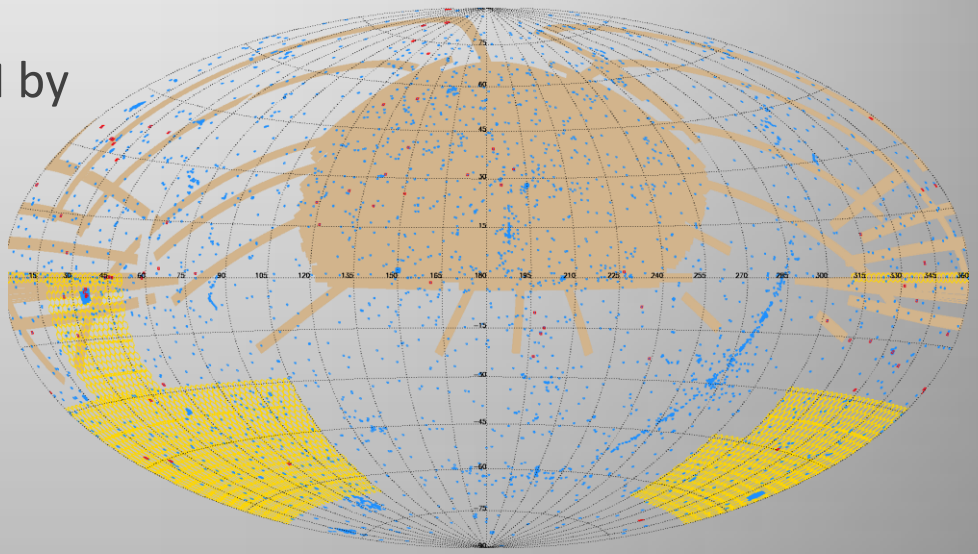
Compared to other data releases with temperatures, XCS contains **more clusters** and probes a **wider range of redshifts** (but that isn't to say its better than any given survey in all respects).



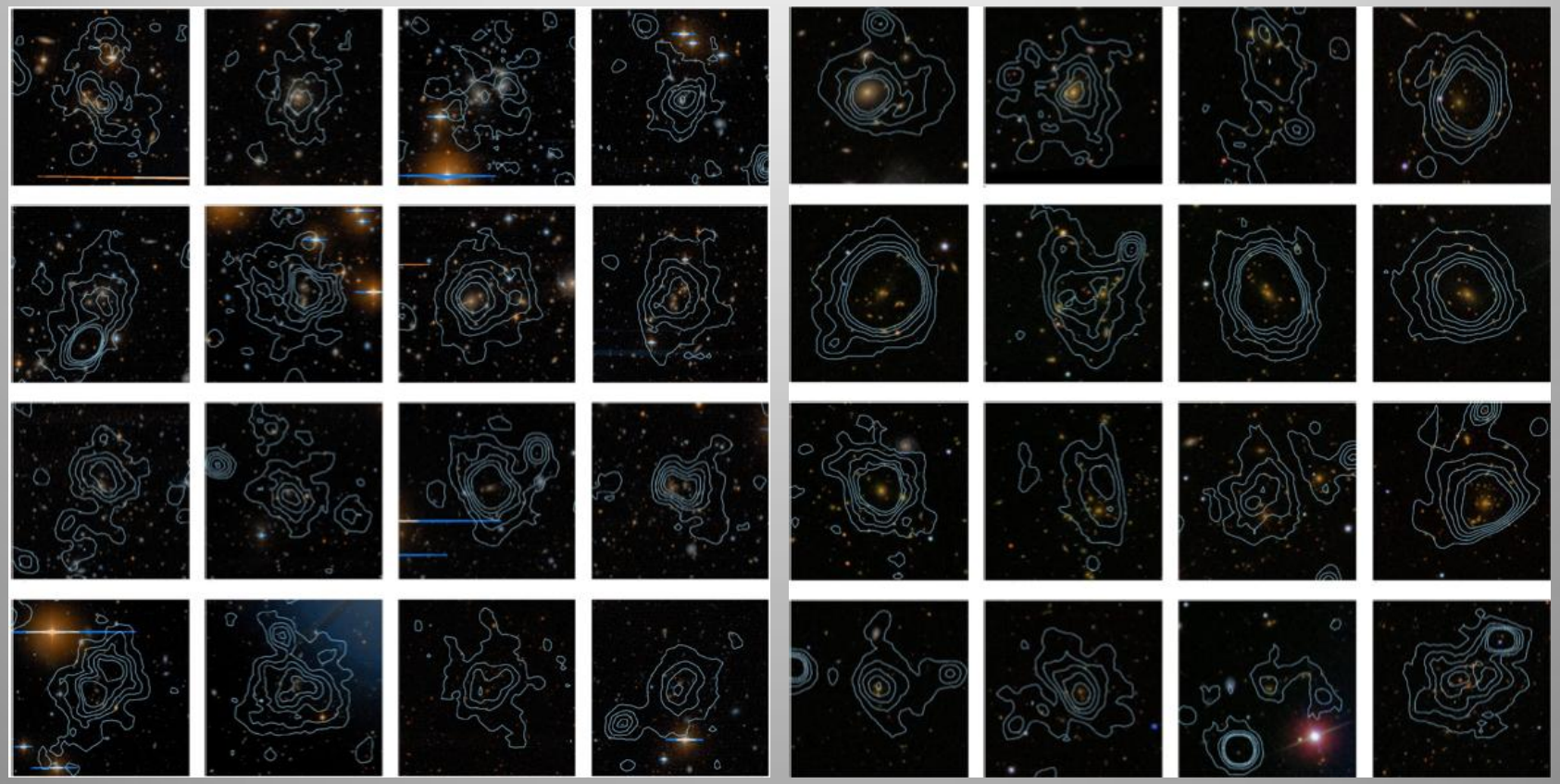


Overlap with deep optical surveys

- **This will enable mass calibration of optical cluster catalogues:**
  - With 200 Tx's it is possible to improve the DES-cluster FoM by 50%; Wu et al. 2010
- 35 XCS-DR1 clusters in Stripe 82
  - 27 with Tx
- 100 XCS-DR1 clusters in the DES region (including S82)
  - 78 with Tx so far (100s more expected once DES z's are available).
  - XCS will also process the targeted (non-serendipitous) clusters in the DES footprint.



B. Applications of XCS-DR1



B. Applications of XCS-DR1

Already submitted [or about to be]

- Studies of Fossil Groups (Harrison et al.)
- Overlap with Planck (Viana et al.)
- [AGN-ICM-BCG connection (Stott et al.)]

Analysis well underway

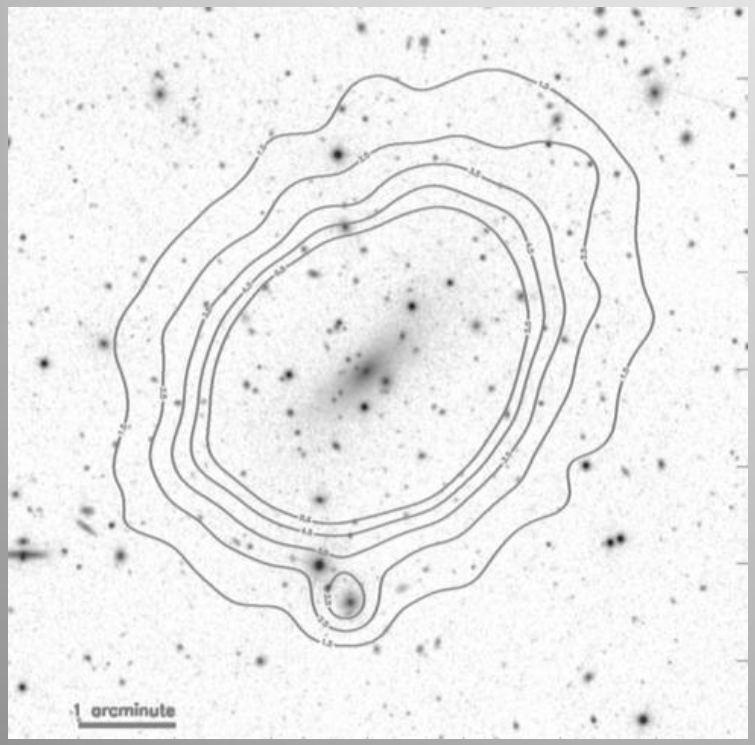
- Optical to X-ray scaling relations (Mehrtens et al.)
- Cosmological parameters (Sahlen et al.)
- X-ray scaling relations (Hilton et al.)

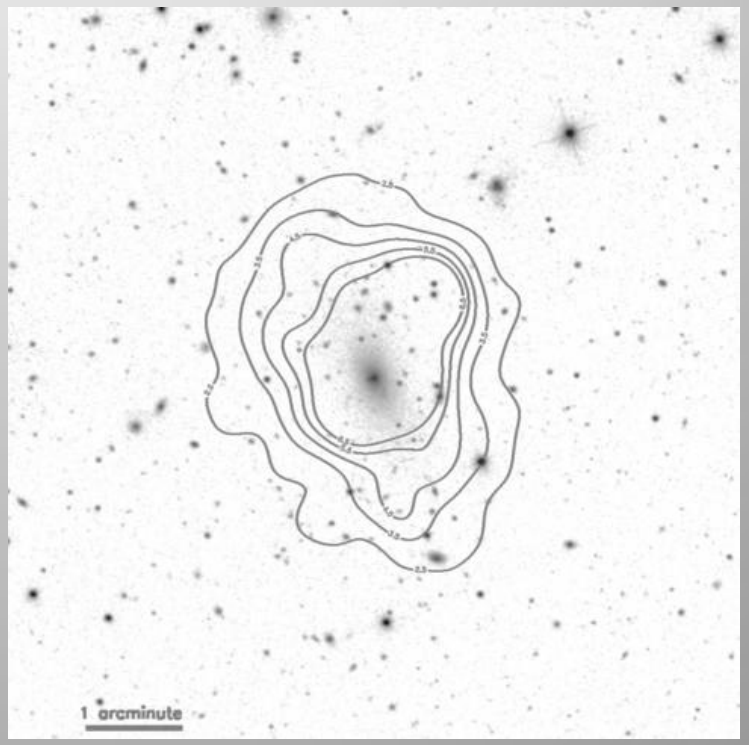
Fossil Groups (Harrison et al.)

- **Status:** about to go back to journal (post ref. report); will be on astro-ph this month.

- 15 XCS-DR1 clusters have been classified as "Fossil Systems"; some are not *groups* but hot *clusters*
- Their central galaxies have higher stellar masses than regular BCG's (for a given cluster mass)
- Our results support previous ideas: *"fossil systems formed early"* and *"fossil galaxies represent the end products of galaxy mergers in groups and clusters"*

Fossil Groups (Harrison et al.)





Examples of Fossil Systems in Harrison et al.

Planck – XCS overlap (Viana et al.)

- **Status:** appeared on astro-ph yesterday: 1109.1828

- 15 XCS-DR1 clusters will be detected by Planck (3 of these are already in Planck-EDR)
- XCS is more sensitive than Planck; but XCS covers only a tiny fraction of the sky
- Even so, XCS should still provide useful checks of the Planck selection function
- Planned XCS analysis of XMM targets will also be of benefit to Planck

Planck – XCS overlap (Viana et al.)

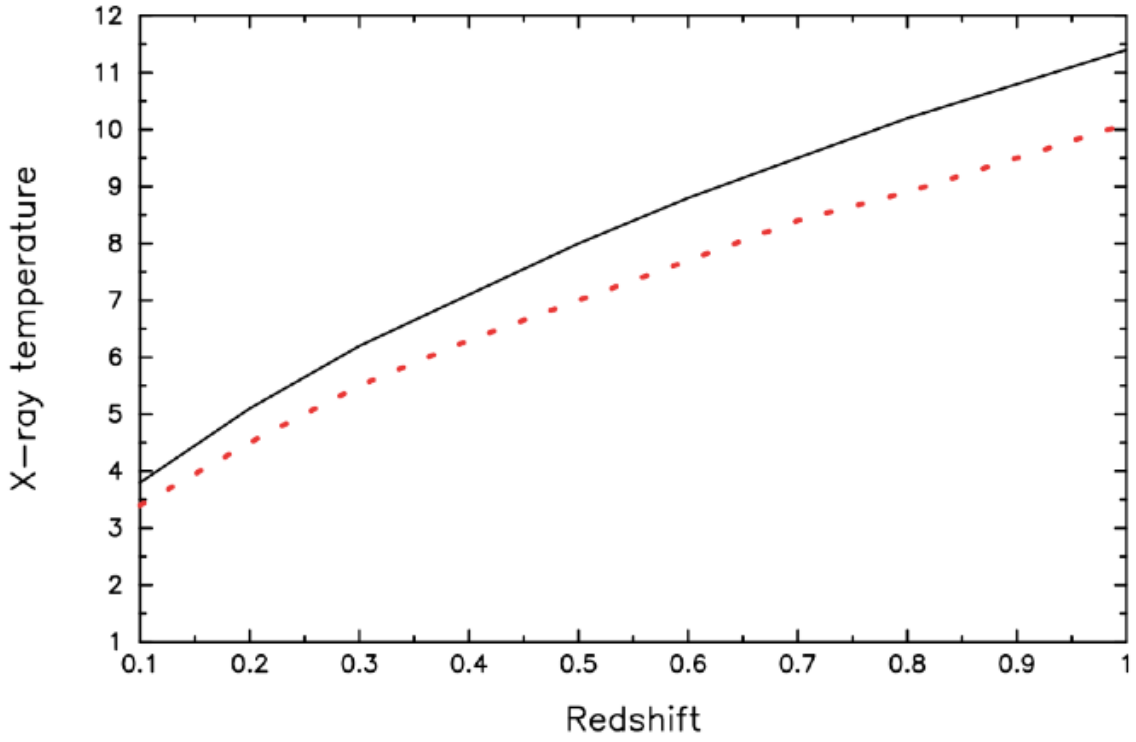


Figure 1. Minimum X-ray temperature, as a function of redshift, that an XCS cluster with over 250 X-ray photon counts needs to have in order to be detected by *Planck* with 0.5 probability (nominal mission - black/full, extended mission - red/dashed).

Planck – XCS overlap (Viana et al.)

The XMM Cluster Survey: Predicted overlap with the Planck Cluster Catalogue

Pedro T. P. Viana, António da Silva, Elsa P. R. G. Ramos, Andrew R. Liddle, E. J. Lloyd-Davies, A. Kathy Romer, Scott T. Kay, Chris A. Collins, Matt Hilton, Mark Hosmer, Ben Hoyle, Nicola Mehrtens, Christopher J. Miller, Martin Sahlén, S. Adam Stanford, John P. Stott

(Submitted on 8 Sep 2011)

We present a list of 15 clusters of galaxies, serendipitously detected by the XMM Cluster Survey (XCS), that have a high probability of detection by the Planck Surveyor satellite. Three of them already appear in the Planck Early Sunyaev-Zel'dovich (ESZ) catalogue. The estimation of the Planck detection probability assumes the flat {\Lambda}CDM cosmology most compatible with WMAP-7 data. It takes into account the XCS selection function and Planck sensitivity, as well as the covariance of the cluster X-ray luminosity, temperature, and integrated comptonization parameter, as a function of cluster mass and redshift, determined by the Millennium Gas Simulations. We also characterise the properties of the galaxy clusters in the final data release of the XCS that we expect Planck will have detected by the end of its extended mission. Finally, we briefly discuss possible joint applications of the XCS and Planck data.

BCG-ICM-AGN connections (Stott et al.)

- **Status:** Waiting for co-author comments; hoping to submit it this month.

- 123 XCS-DR1 clusters (z<0.3) also have radio and SDSS data.
- L-T scaling relations have been constructed as function of the following BCG properties:
  - Mass (correlation found; L-T steepens with mass)
  - Radio luminosity (no correlation found)
  - Centroid offset (correlation found; L-T is shallower with increased offset)
- Interpretations are based on comparisons with OWL simulations.
- The data suggest that *2keV is the boundary* between physics dominated groups and gravity dominated clusters.

BCG-ICM-AGN connections (Stott et al.)

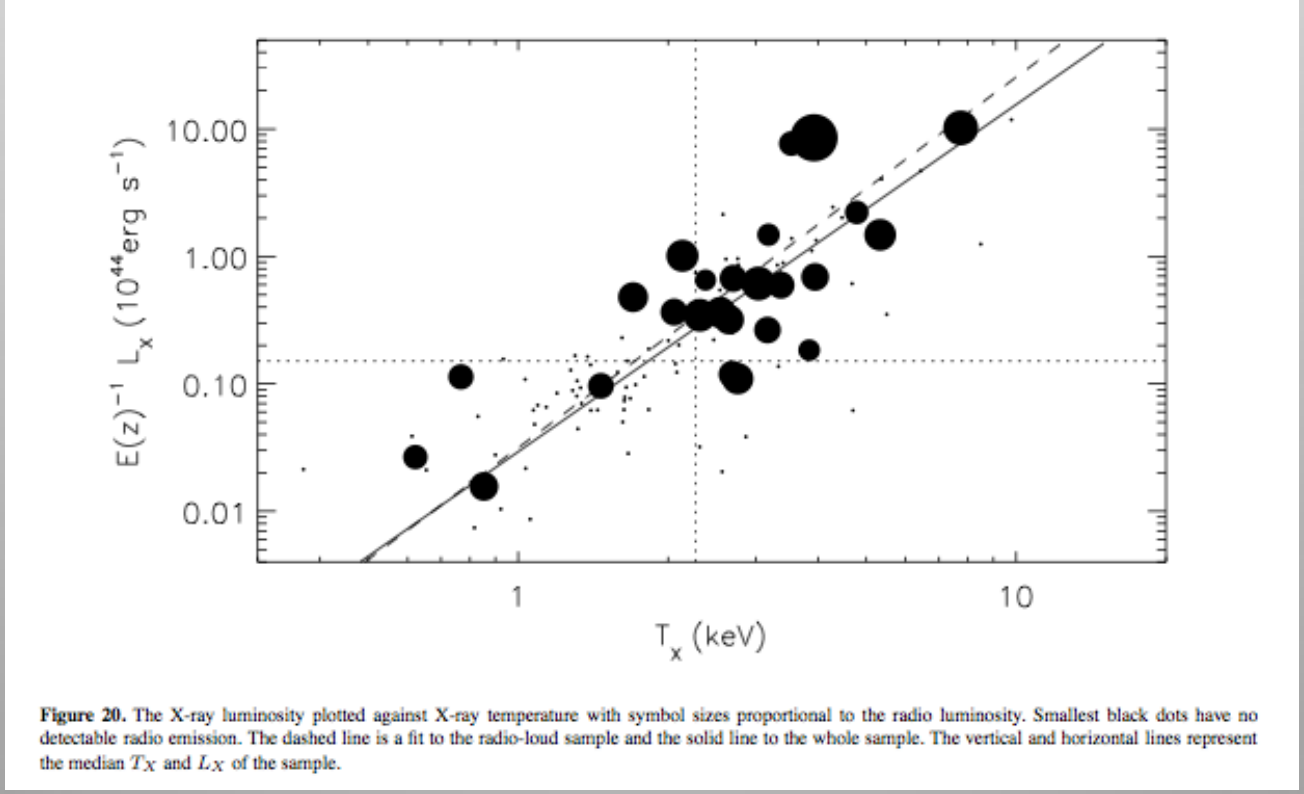
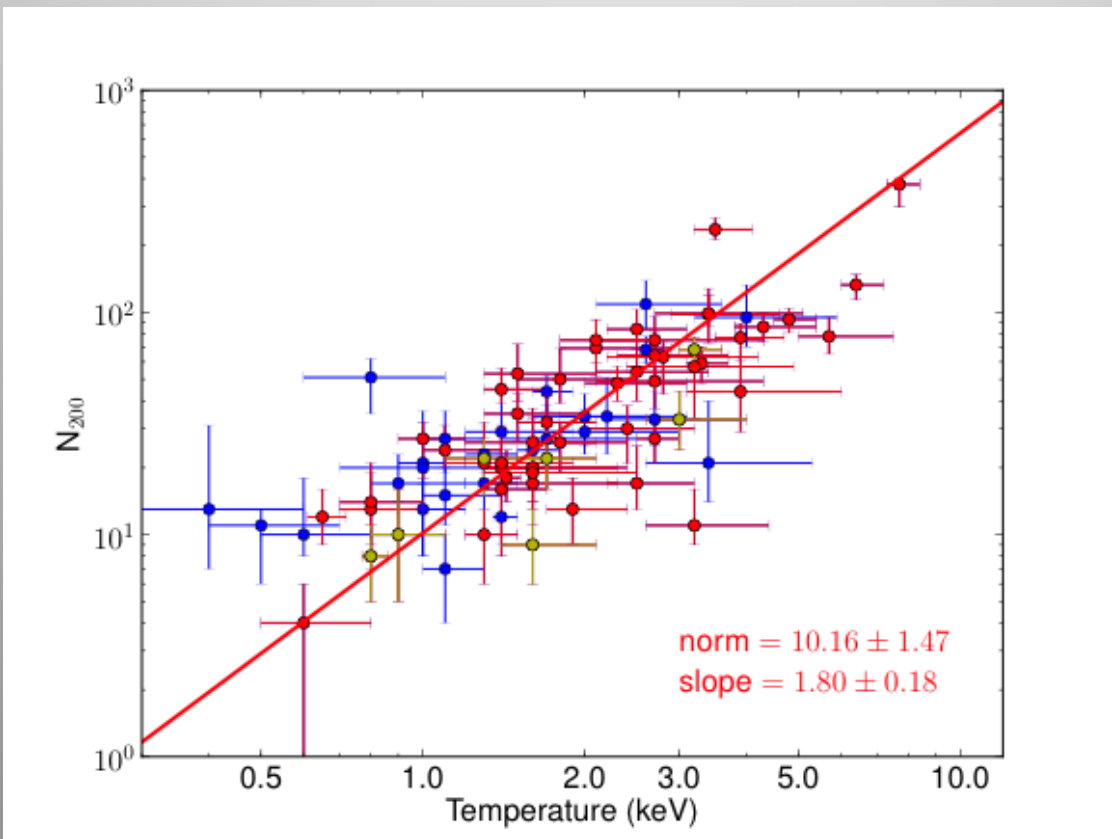


Figure 20. The X-ray luminosity plotted against X-ray temperature with symbol sizes proportional to the radio luminosity. Smallest black dots have no detectable radio emission. The dashed line is a fit to the radio-loud sample and the solid line to the whole sample. The vertical and horizontal lines represent the median T_X and L_X of the sample.

Radio power (indicated by dot size) does not influence the slope of the L-T

Optical to X-ray scaling relations (Mehrtens et al.)

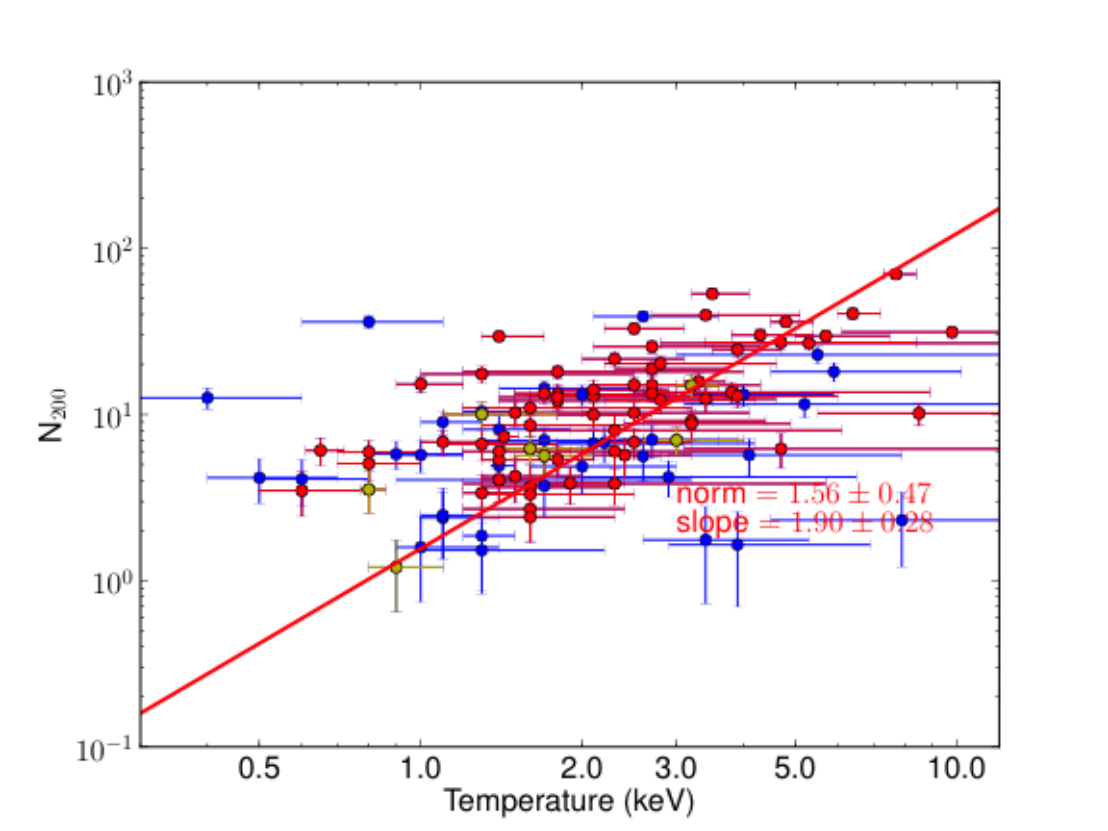
- **Status:** analysis almost done, writing not yet started
- **There is a clear correlation between richness and Tx**



- Photo-z
- Spectral-z (fossil)
- Spectral-z (other)

Optical to X-ray scaling relations (Mehrtens et al.)

- The correlation breaks down if the correct galaxy aperture is not used (this is a challenge to optical surveys)



- **Photo-z**
- **Spectral-z (fossil)**
- **Spectral-z (other)**

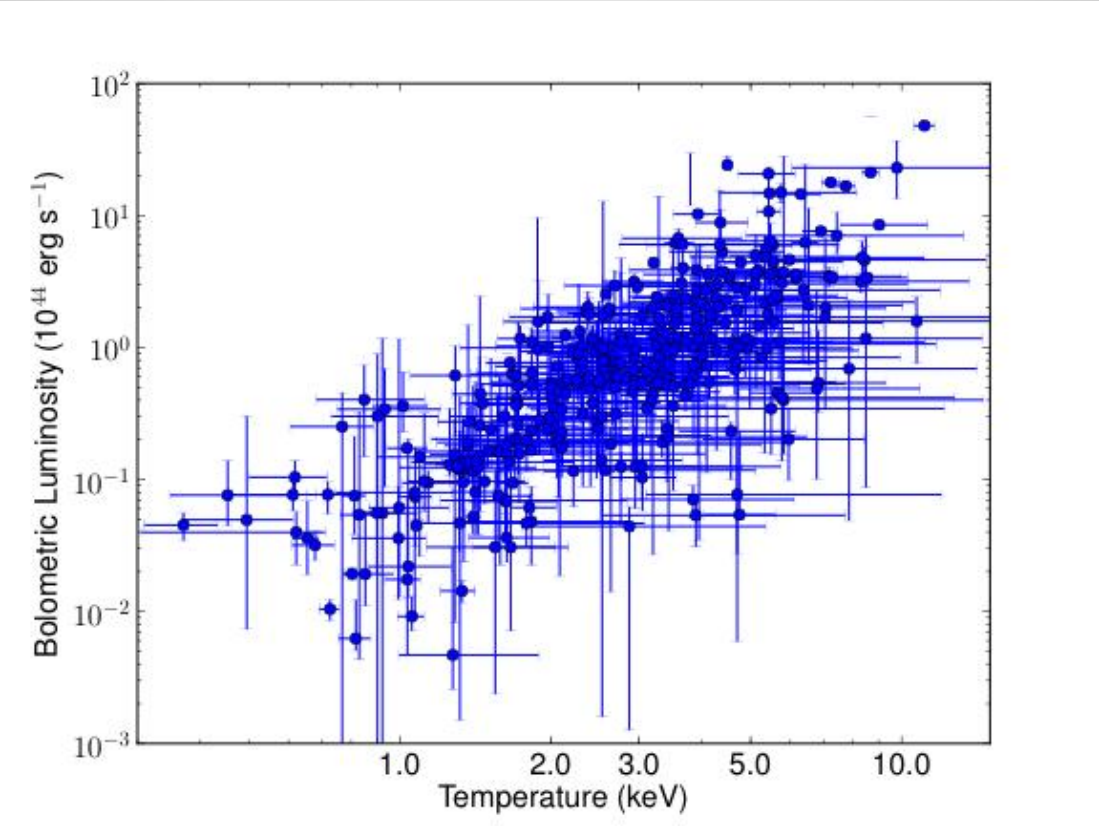
Cosmological parameters (Sahlen et al.)

- **Status:** theory framework ready and tested, we have some work yet to do to define completeness as a function of z.

- See Martin's talk at 11:45!

X-ray scaling relations (Hilton et al.)

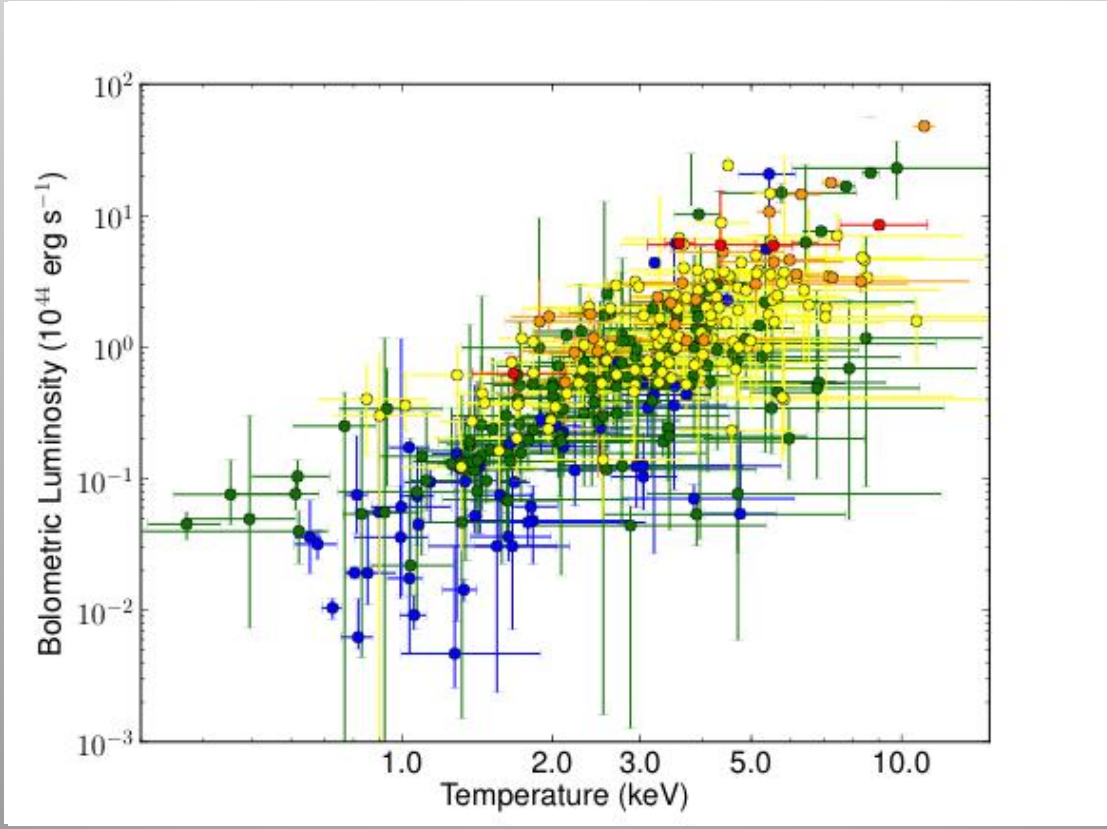
- **Status:** basic analysis is done; correcting for the selection function is now underway.



366 clusters, no selection function

X-ray scaling relations (Hilton et al.)

- The XCS spans 10 Gyr of look back time, so we should be able to probe evolution in a self-consistent manner.



366 clusters, no selection function

Colour coded by look-back time (bins of 2 Gyr)

And there is lots more being done..

Analysis underway (XCS led)

- Halo Occupation Distributions (Mehrtens et al.)
- XCS processing of all XMM “target clusters” (Romer et al.)
- UDS-XCS distant cluster finding/analysis (Stott et al.)
- XCS velocity dispersions (Hilton/Miller et al.)

Analysis underway (not XCS led)

- AMI (S-Z) observations of XCS clusters (Shimwell et al.)
- XCS + (VISTA/VHS & UKIDDS/LAS) (Banerji et al.)

C. Future Plans for XCS

- Confirm more candidates as clusters
- Measure more/better redshifts
- Measure more/better temperatures
- Include mass estimates
- Improve the selection function
- Assist other surveys

Future Plans (short term)

- Confirm more candidates as clusters
  - DR8, UKIDDS, VISTA, WISE, our own imaging
- Measure more/better redshifts
  - DR8, our own spectroscopy (Gemini, Magellan)
- Measure more/better temperatures
  - from new z's, XMM & Chandra archives
- Include mass estimates
  - Lensing from CFHTLS & Stripe 82, velocity dispersions
- Improve the selection function
  - fold in XCS-DR1 results (e.g. on profile parameters)
- Assist other surveys
  - optical cluster surveys (Stripe 82 and pre-DES)

Future Plans (longer term)

- Confirm more candidates as clusters
  - Dark Energy Survey, PanSTARRS
- Measure more/better redshifts
  - DES, PanSTARRS
- Include mass estimates
  - Derive *T(r)* masses, stacked lensing masses
- Measure more/better temperatures
  - from new z's, requested XMM & Chandra data
- Improve the selection function
  - probe more complex clusters and cosmologies
- Assist other surveys
  - Planck, DES, PanSTARRS, XXL, [eROSITA]

Conclusions

- XCS-DR1 contains a lot of clusters and is especially rich in temperature information.
  - XCS-DR1 is not a statistically complete sample, but contains complete sub-samples.
- XCS-DR1 has many applications
  - 3 science papers completed so far
  - several more will be finished soon
  - please use XCS-DR1 for your own science
- XCS has the potential to deliver many more clusters.
  - They are waiting for us in the archive.
  - Optical follow-up is the hardest part (DES and PanSTARRs should solve that in a few years)
  - More large contiguous surveys (like XXL), and additional XMM/Chandra follow-up of XCS clusters, would be of enormous benefit to the cluster community
- If I'd known how hard this was going to be 12 years ago I'd probably have done it anyway (but as photons are precious, lets not waste most of them!)

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