The X-ray View of High-z Clusters

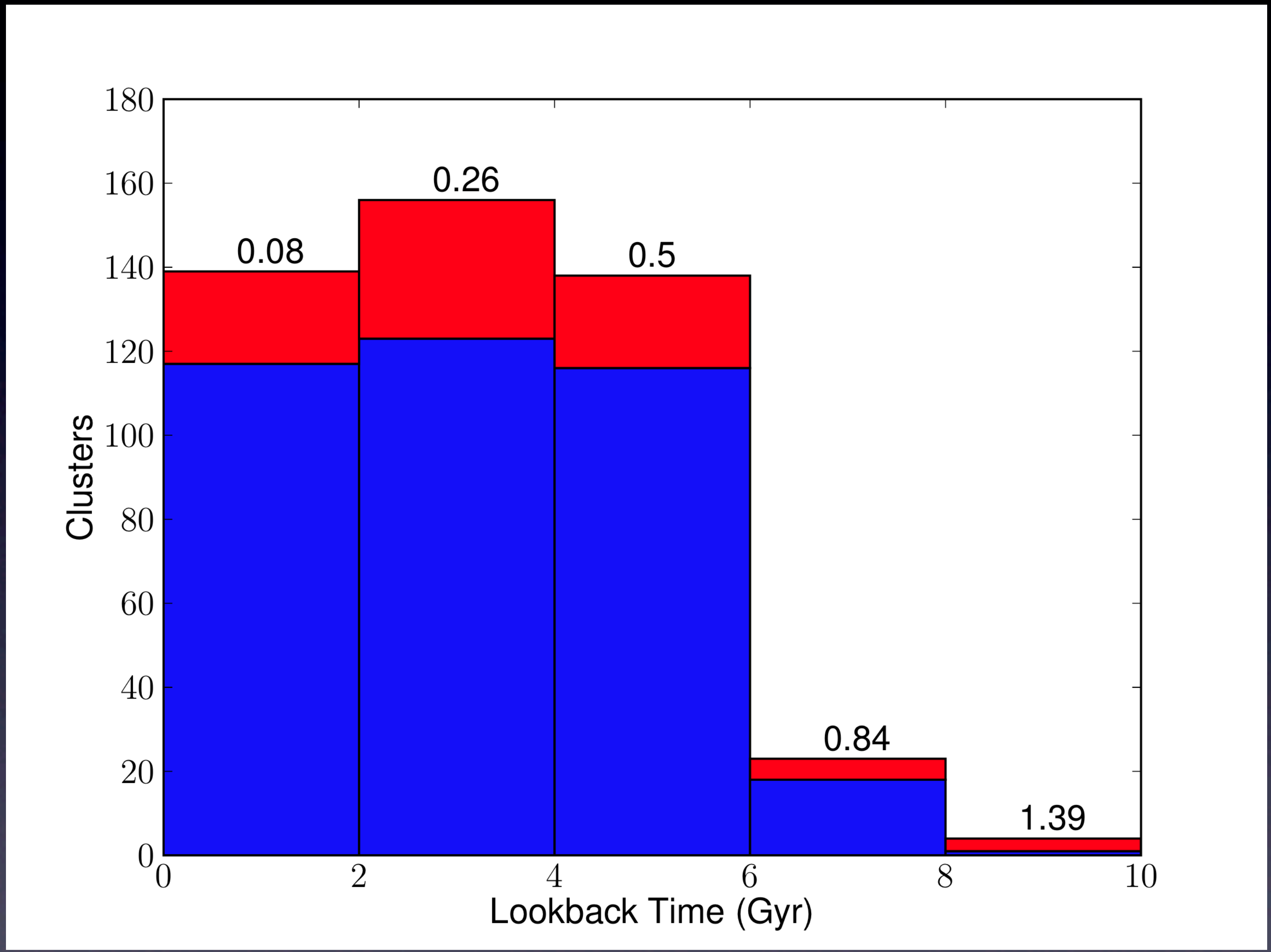
Kathy Romer (University of Sussex, UK)
on behalf of the XCS collaboration

Talk Overview

- Review of results from X-ray observations of $z>0.8$ clusters (with a focus on XCS)
- Discussion:
  - ⋆ for cosmology and scaling relations, wouldn't we be better off at $z<0.7$?
  - ⋆ I'm ready to get over X-rays; lets prove that optical/IR surveys are fine for cosmology
  - ⋆ we can do cluster X-ray astronomy from the ground much cheaper with SZ

Warning/Apology: I have concentrated on cosmology and scaling relations as science drivers/results and have not included anything about the properties of the gas (e.g. metal abundance vs z).

Why z>0.8?



Current XCS redshift histogram

Talk Overview

- Review of results from X-ray observations of *$z>0.8$* clusters
  - ★ X-ray: Before XMM & Chandra
  - ★ X-ray: After XMM & Chandra
  - ★ Other: red sequence + SZ

Warning/Apology: The following review is broadly correct, but there are likely to be omissions and errors. Not all are my fault, but please shout when you spot anything missing or wrong!

How to catch a cluster (X-ray before XMM & Chandra)

- Einstein (EMSS)
- ROSAT All Sky Survey
- ROSAT pointed observations (PSPC)
- ROSAT pointed observations (HRI)

How to catch a cluster (X-ray before XMM & Chandra)

- Einstein (EMSS)
- ROSAT All Sky Survey
- ROSAT pointed observations (PSPC)
- ROSAT pointed observations (HRI)
  - ⋆ a promising project that ran out of steam (or money, or telescope time), Panzera et al. 2002

In my view....

Cluster surveys need more than good ideas or new datasets to get done. They need a dedicated team who will work for years without papers coming out; preferential access to telescopes; cash to pay students and postdocs.

How to catch a cluster (X-ray before XMM & Chandra)

- Einstein (EMSS)
  - ★ MS1054.4, z=0.83, T=8.3keV
  - ★ Discovery paper: Gioia & Luppino 1994
  - ★ Latest X-ray analysis: Branchesi et al. 2007
  - ★ Importance:
    - ✦ proved 15 years ago that distant clusters are out there was used on its own to disprove Omega=1.
    - ✦ It is still used in ensemble studies (scaling relations, galaxy evolution etc.)

In my view...

MS1054 is a lovely cluster, and case studies are very useful (and generate nice publicity images), but when doing statistical work, we have to stop being so precious about individual high redshift clusters and be prepared to “waste” a few. We should concentrate on homogeneous samples with selection functions.

How to catch a cluster (X-ray before XMM & Chandra)

- ROSAT All Sky Survey
  - ★ None from the regular RASS
    - ✦ But later I will give a nod to MACS (Ebeling et al. 20??) [In the long term, I think the extended REFLEX is likely to overshadow MACS]
  - ★ NEP Region got deeper coverage than the rest of the sky.
    - ✦ RXJ1821 (z=0.81, T=4.7keV) [Gioia et al. 2004]
    - ✦ RXJ1716 (z=0.81, T=6.5keV) [Gioia et al. 99, Branchesi 07]
  - ★ Importance: These clusters are regularly used in ensemble work.

In my view...

We shouldn't write off datasets just because they are old. RASS produced a few z>0.8 clusters, but its real impact is at z<0.5. Not only does it provide the low z counterparts needed for evolution work, but on its own it can do kick ass cosmology. Peter Schneider showed that 10 years ago with the power spectrum, the MACS folk are showing it today with number density evolution.

eROSITA could be amazing, but its hard not to feel grumpy about it since few us will have access to the data!

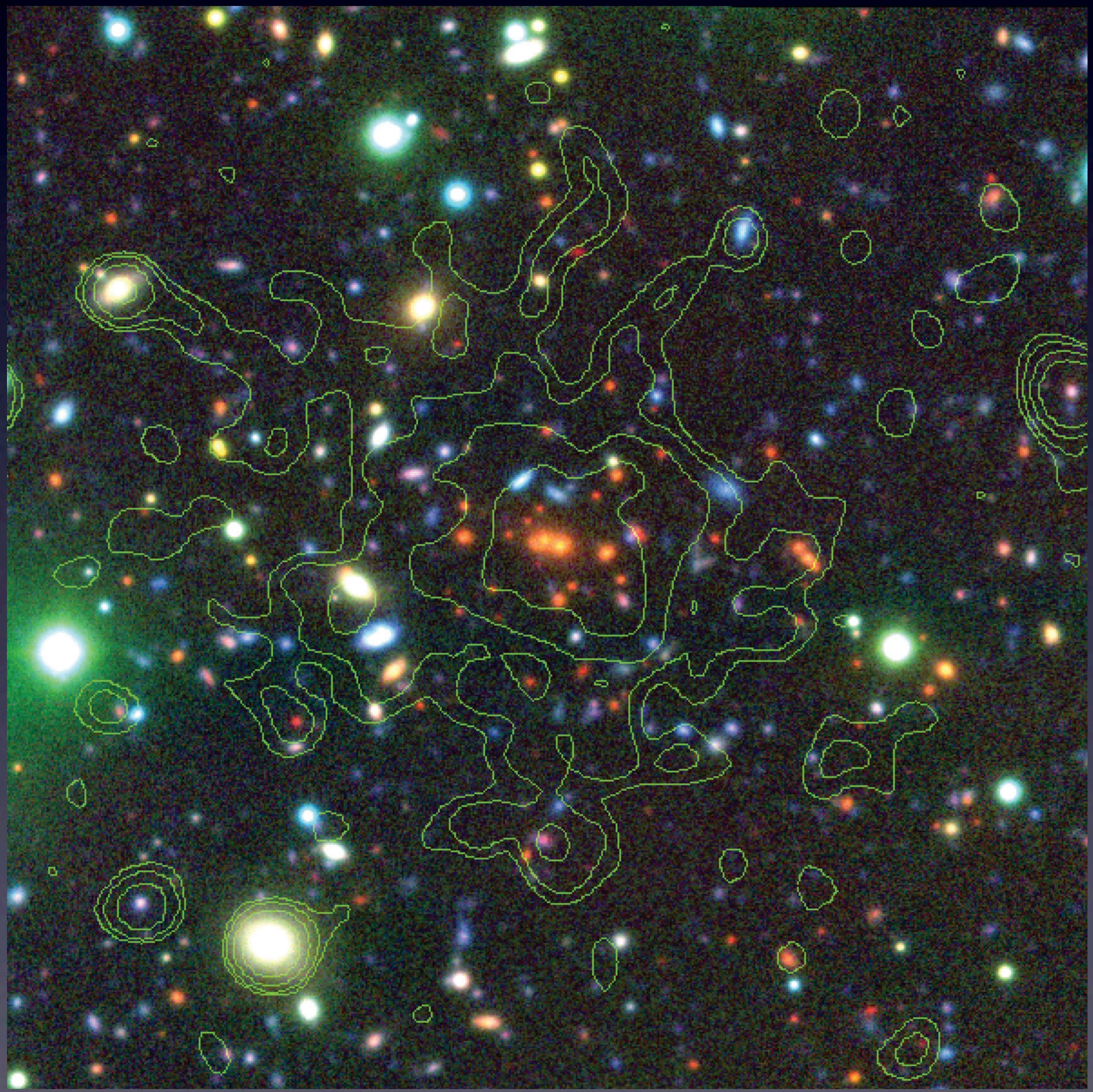
How to catch a cluster (X-ray before XMM & Chandra)

- ROSAT pointed observations (PSPC); from serendipitous detections
- RDCS and WARPS got the most (their samples overlap)
  - ★ RDCS + WARPS: 6 @ 0.8<z<1 plus 3 @ z>1
  - ★ A few of these were also [p]re-discovered by SHARC (Romer et al. 00) & 400SD (Burenin et al. 2006). I will later give a nod to 400SD survey.
- WARPS z>0.8 discoveries in Ebeling et al 99 & 01, Perman 2002)
  - ★ XMM/Chandra followup papers: Maughan et al. 05
- RDCS z>0.8 discoveries in Stanford et al. 97; Rosati et al. 98.
  - ★ XMM/Chandra followup papers: Stanford et al. 00; Holden et al. 02; Stanford et al. 02; Rosati et al. 04

How to catch a cluster (X-ray before XMM & Chandra)

- Importance of PSPC serendipitous surveys
  - ★ still leading the way on ensemble studies of X-ray scaling relations
  - ★ generating controversy: ensemble measurements of scaling relations are giving conflicting answers wrt evolution (e.g. Holden et al. 2002 vs Vikhlinin et al. 2008).
  - ★ demonstrates that XMM/Chandra follow-up is essential
  - ★ providing test cases for detailed follow-up:
    - ✤ Lynx Supercluster
    - ✤ RXJ0152, z=0.83, Tx~5keV
    - ✤ RXJ1222, z=0.89, Tx=10keV: hottest z>0.8 cluster know
  - ★ Inspired some of us to do it all over again for XMM

RDCS cluster at z=1.24
colour composite with Chandra contours
(now that's what I call a *real* cluster!)



Rosati et al. 2004

in my view....

Doing this review has shown me that Chandra is really useful for high-z cluster studies. I apologise for my XMM bias. We'll never have it so good in X-ray astronomy, so we need to make the best use of the time we have left.

How to catch a cluster (X-ray after XMM/Chandra)

- Dedicated surveys Chandra
- Dedicated surveys XMM
- Serendipitous detections Chandra
- Serendipitous detections XMM

Gratuitous Image of XMM!

How to catch a cluster (X-ray after XMM/Chandra)

- Dedicated surveys Chandra, e.g. CFDS
- Dedicated surveys XMM
- Serendipitous detections Chandra, e.g. CHAMP (Barkhouse 2006) and BMW (Romano et al. 2009)
- Serendipitous detections XMM

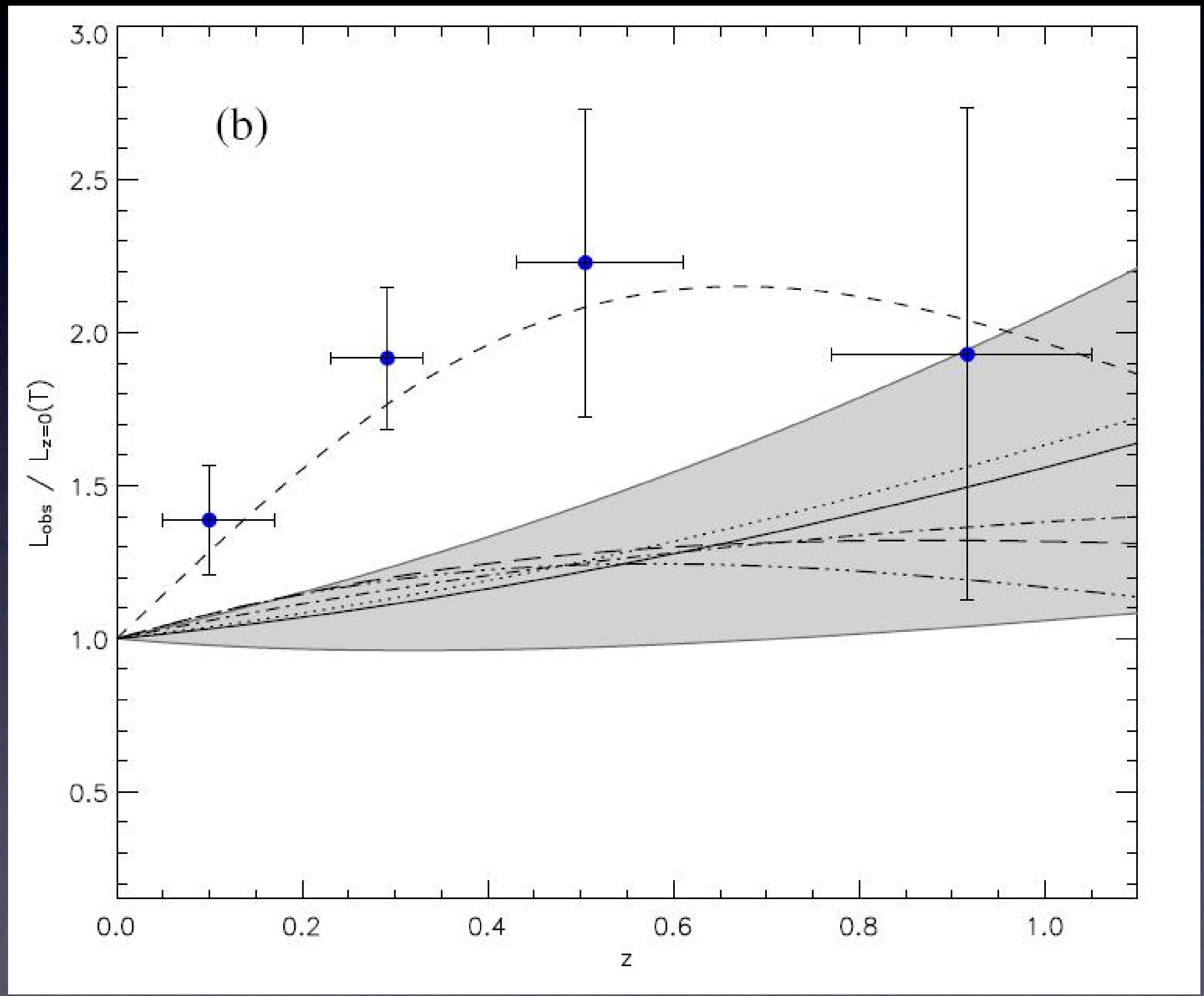
How to catch a cluster (X-ray after XMM/Chandra)

- Dedicated surveys XMM
  - ⋆ XMM-LSS
  - ⋆ COSMOS

How to catch a cluster (X-ray after XMM/Chandra)

- Dedicated surveys XMM (XMM-LSS)
  - 29 spectroscopically confirmed clusters (few square degrees)
    - 3 @ $0.8<z<1$ (Pierre et al. 2006)
    - 3 @ $z>1$ (Bremer et al. 2006; Pacaud et al. 2008)
  - Importance:
    - scaling relation evolution analysis was corrected for selection function (Pacaud et al. 2008)
    - demonstrates efficiency of multi-wavelemgth approach
    - but... not enough area for cosmology or scaling relations

XMM-LSS scaling relations corrected for selection functions

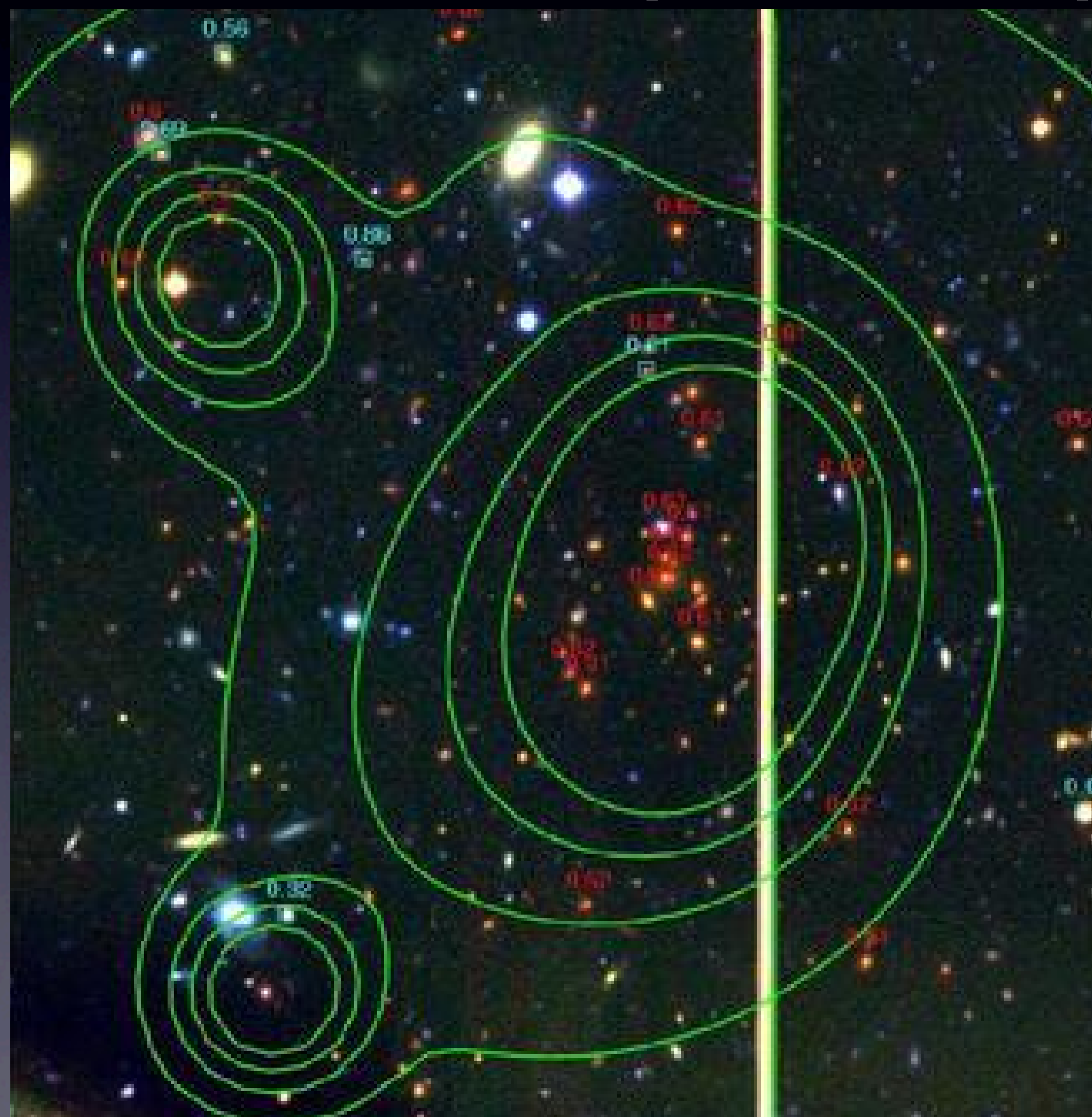


in my view....

Any scaling relation derived from incomplete and/or inhomogeneous samples should be seen as preliminary work. Scaling relation evolution is vital; it tells what physics is going on in the gas and messes with our ability to do cosmology.

The optical/IR selection methods don’t need to worry nearly so much about evolution.

One of XMM-LSS clusters (z=0.6)

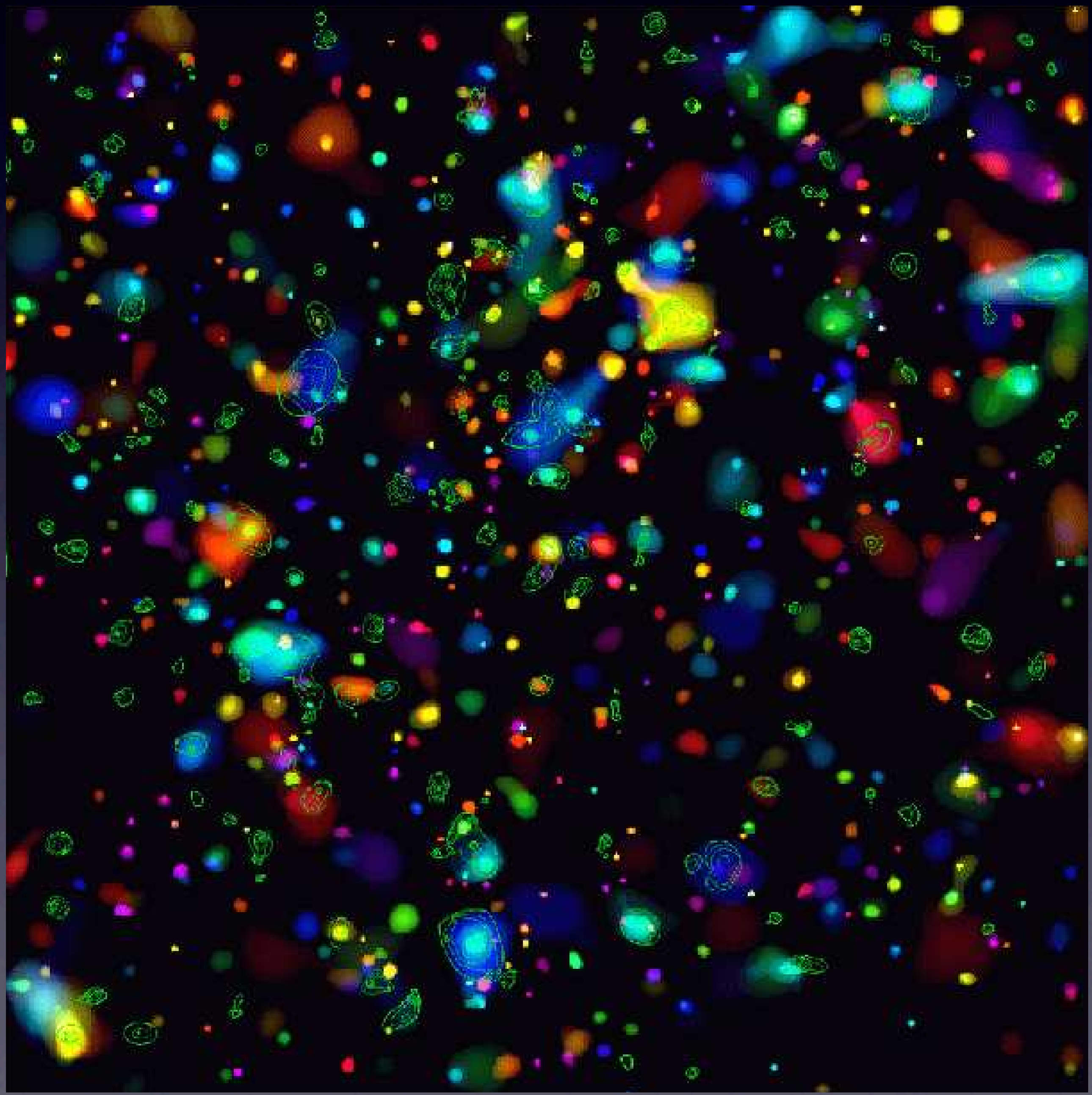


See the stripe? That happens a lot. We go so deep to get these images that bleed trails from stars are inevitable. Its a real pain. Some XCS candidates will never be identified because of them.

How to catch a cluster (X-ray after XMM/Chandra)

- Dedicated surveys XMM (COSMOS)
  - ~2 square degrees, more than 70 clusters (Finoguenov et al. 2006)
  - ~14 clusters/groups @ $0.8<z<1.$ and ~6 @ $z>1$
    - bigger than all the rest so far put together!
  - Importance
    - shows importance of multi-wavelength f'up
    - shows importance of going deep
    - shows problems with source crowding
    - not big enough to do scaling relations or cosmology

Cosmos field (galaxy overdensities)



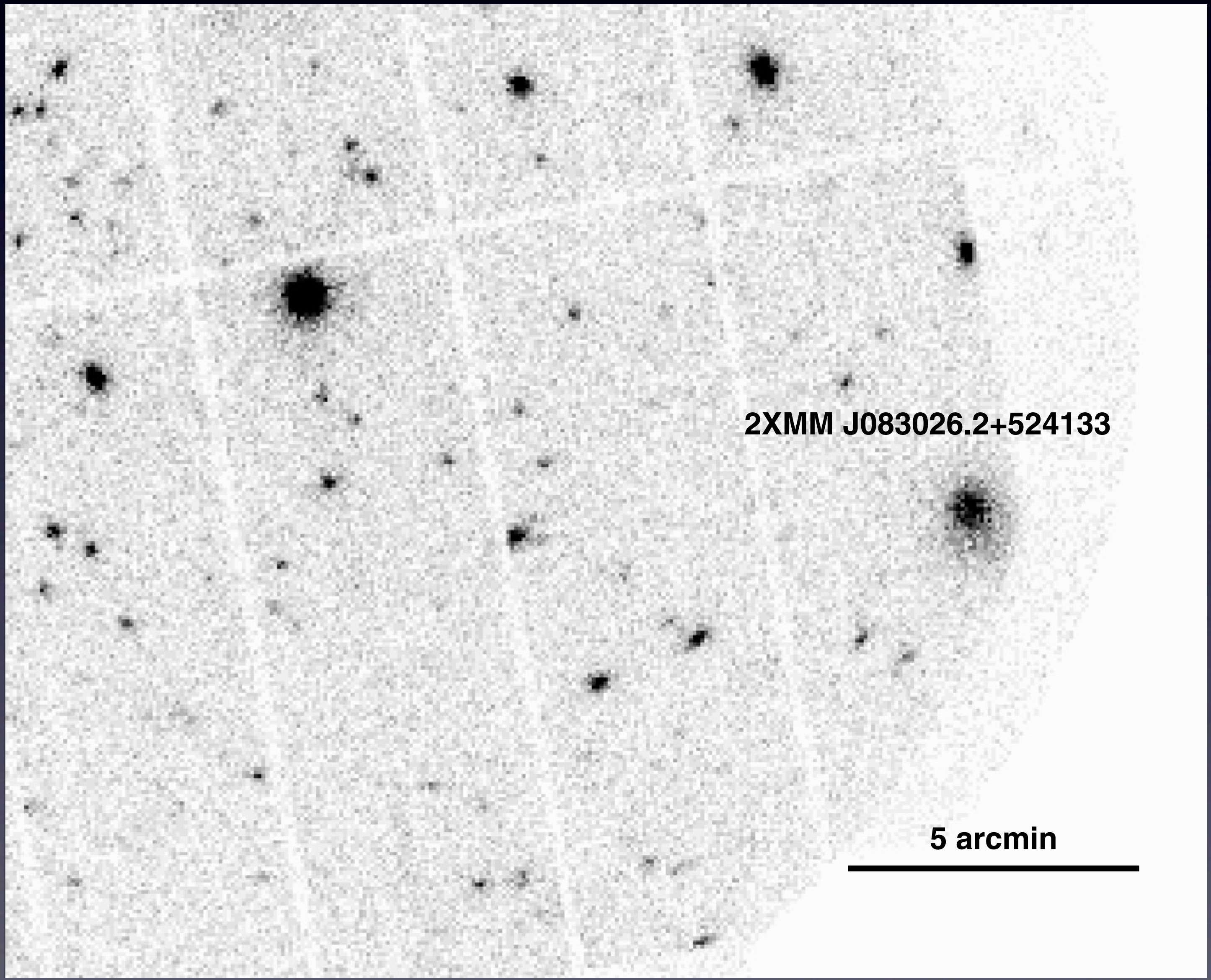
How to catch a cluster (X-ray after XMM/Chandra)

- Serendipitous detections XMM
  - ★ 2XMM+SDSS non detections
  - ★ XDCP
  - ★ XCS

How to catch a cluster (X-ray after XMM/Chandra)

- Serendipitous detections XMM (2XMM+SDSS non detections)
  - Lamar et al. 2008 took off the shelf XMM catalogues from 2XMM and looked for places where extended sources had no SDSS counterpart, then followed up.
  - Simple, but effective at finding high z clusters
  - 2XMM J0830 z=0.99 and Tx=8.2 keV
  - Importance:
    - used X-ray's to measure the redshift (saves time)
    - limited use for scaling relations and cosmology: selection function cannot be determined for this selection method.

Lamar et al. 2008 z=0.99 cluster

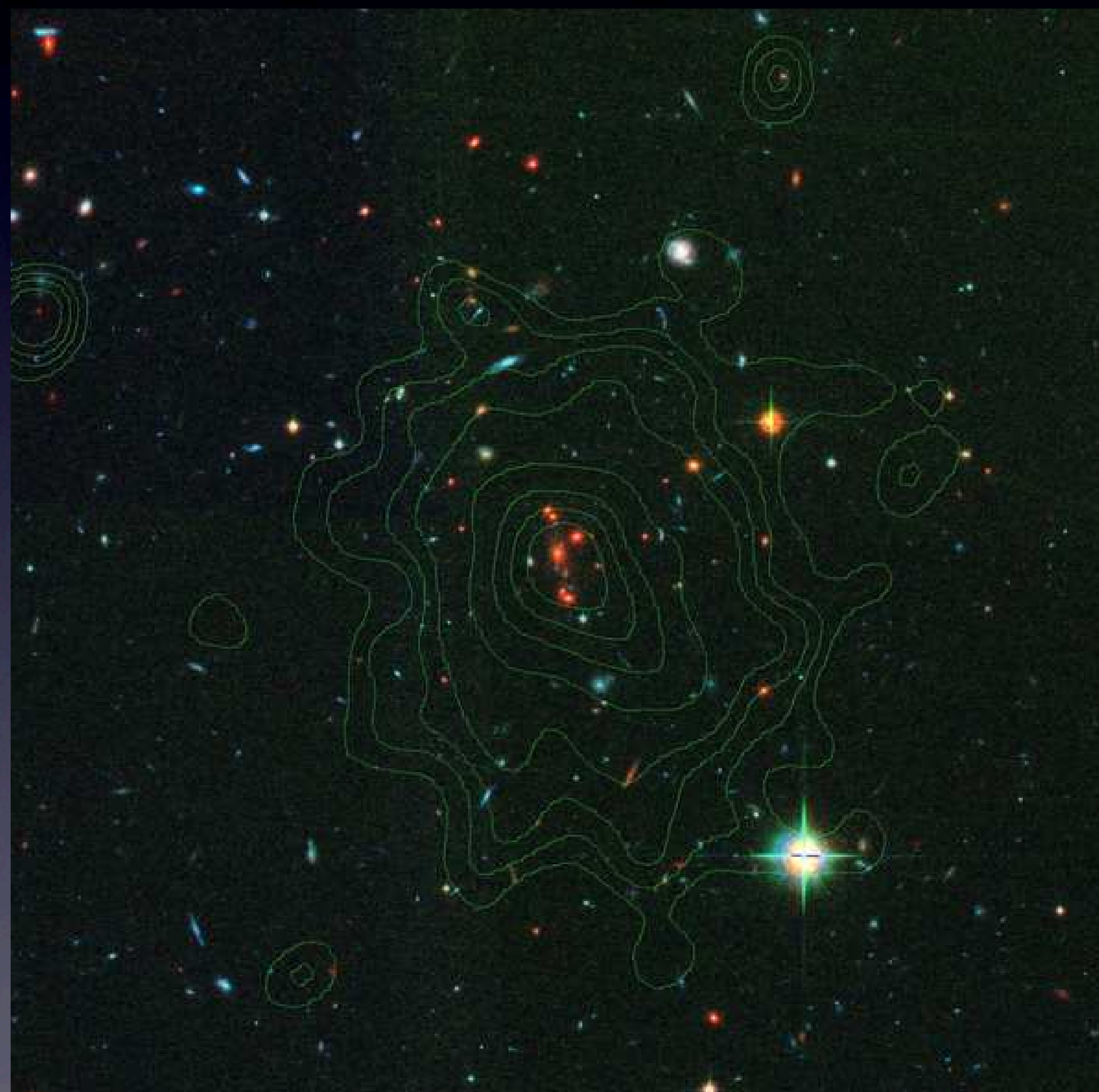


In my view...
It seems strange that the various surveys keep finding the monsters first (this one, the XCS 1.45 cluster, the XDCP 1.39 cluster, Andreon's 1.9 cluster...). I don't know what it means, but it is a bit creepy.

How to catch a cluster (X-ray after XMM/Chandra)

- Serendipitous detections XMM (XDCP)
  - Combines deepest XMM pointings with ESO followup to select high-z clusters
  - Early success with XMM J2235 (Mullis et al. 2003); z=1.39, Tx= 8.6 keV (Rosati et al. 2009)
  - Continuing success with major ESO follow-up campaign e.g. poster by Hoon (z=1.08). From a talk at Bonn in July: 8 @ 0.8<z<1 and 10 @ z>1: all *spectroscopically confirmed.* Dozens with photo-z's at z>0.8
  - Importance:
    - The X-ray selection technique works (but Chandra data helps)
    - The area large enough for cosmology and scaling relations
    - They can do a selection function (work already started)

z=1.39 cluster with Chandra contours. (that's still what I call a *real* cluster)



in my view...

XDCP is an excellent project. It is our (XCS) closest rival. I cannot fault their X-ray analysis. The reason they are beating us at the high z end is that they got lots of ESO time. So thank you ESO for supporting cluster surveys (and please give us time too!).

How to catch a cluster (Red Cluster Sequence)

- Using optical data: Chandra follow up of **Red Cluster Sequence** Survey
  - ★ Hicks et al. 2008; 8 @ $z>0.8$, including one $z>1$ detection
  - ★ Importance: they have examined scaling relation evolution independent of ROSAT detection
  - ★ Importance: demonstrates the future potential of DES etc. samples.
- Using IR data:
  - ★ **SpARKS** (Ellingson et al. 09; ~4 with X-ray detections @ $z>1$)
  - ★ UKIDDS (Andreon et al. 09; $z\sim1.9$ with Chandra confirmation)
- Using optical + SZ data: Blanco Cosmology Survey + SPT survey (Staniszewski et al. 09; 2 @ $z>0.8$)
  - ★ Importance: SZ follow-up can be as good as X-rays, and its a lot cheaper!

How to catch a cluster (X-ray after XMM/Chandra)

- Serendipitous detections XMM
- The XMM Cluster Survey
- Romer et al. 2001, Liddle et al. 2001

XCS

- Aims (Data):
  - find all the clusters in the XMM archive (regardless of redshift)
  - measure their redshifts
  - measure their X-ray properties
  - determine their selection function

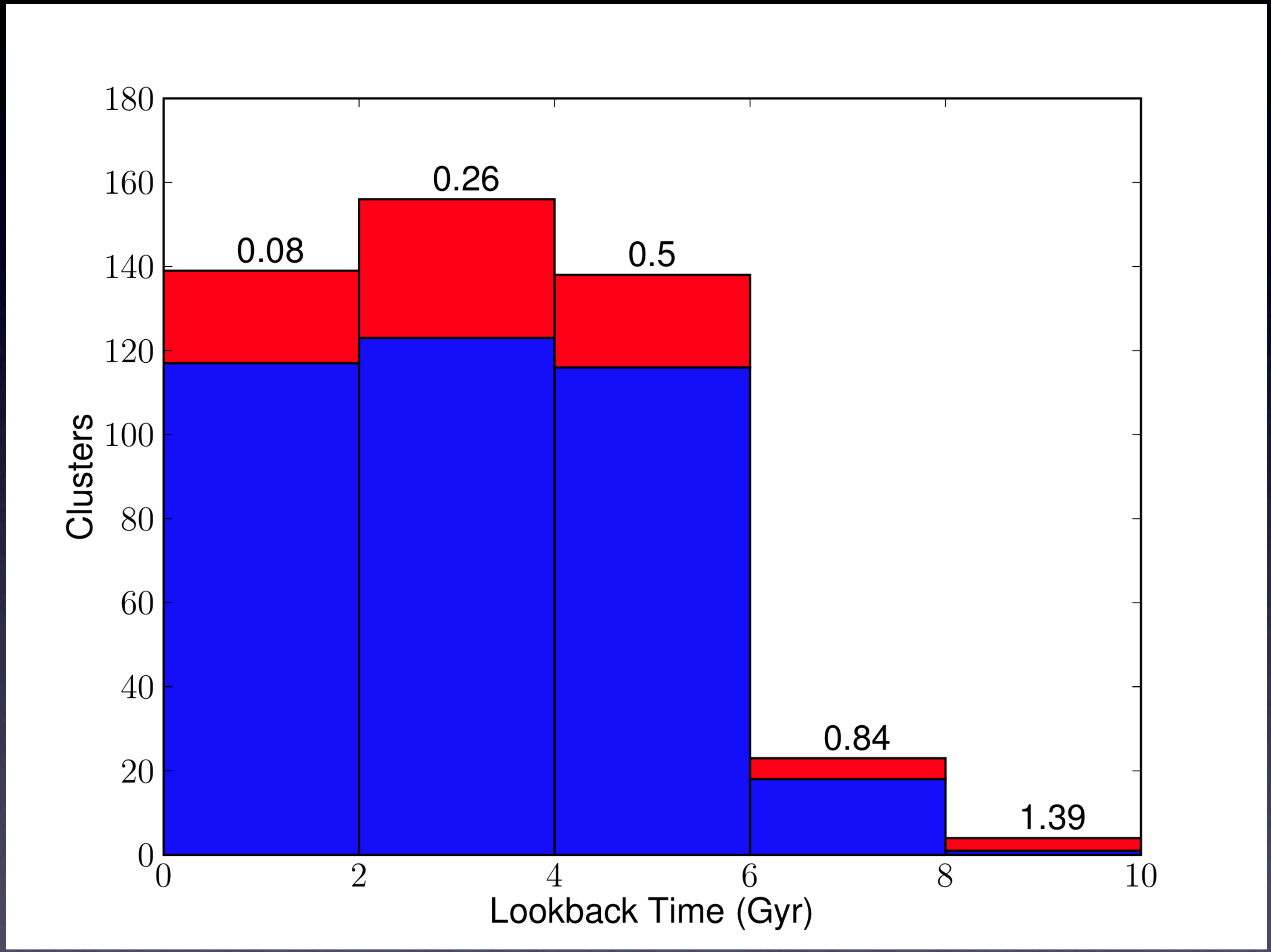
XCS

- Aims (Science):
  - cosmological parameters
  - X-ray scaling relations
  - find z>1 clusters
  - Galaxy evolution (John Sott's talk yesterday)

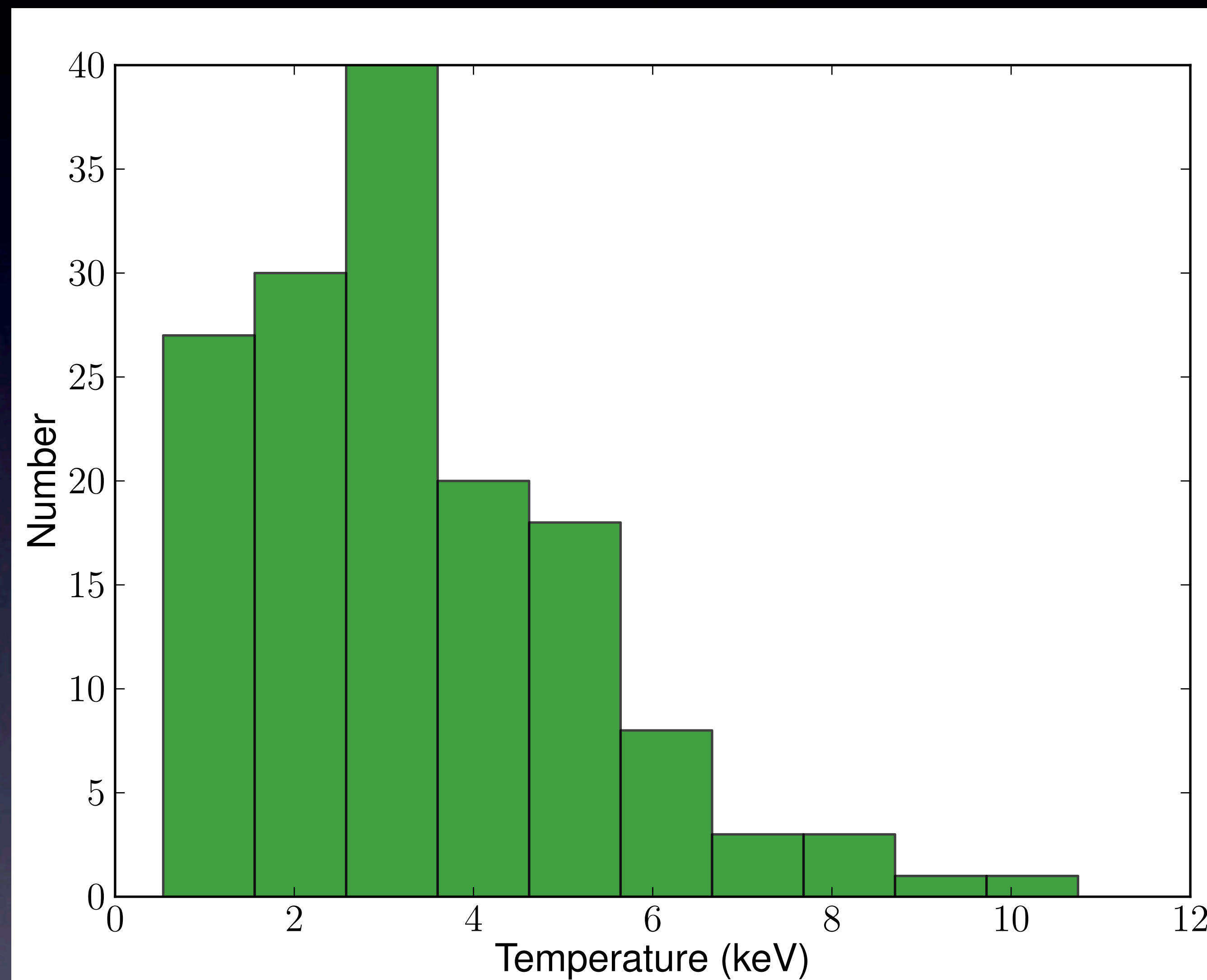
XCS

- Results (Data)
  - ★ Whole XMM archive has been processed (~5000 observaions)
  - ★ 130,000 sources detected over 520 sq.deg (non contiguous, non overlapping)
  - ★ 5,800 extended sources (cluster candidate) over 230 sq.deg
  - ★ 2,100 with sufficient counts to get Tx
    - ✦ 460 have measured redshifts (all will have Tx) Lloyd Davies et al. in prep.
    - ✦ 205 have measured Tx (error less than 50%)

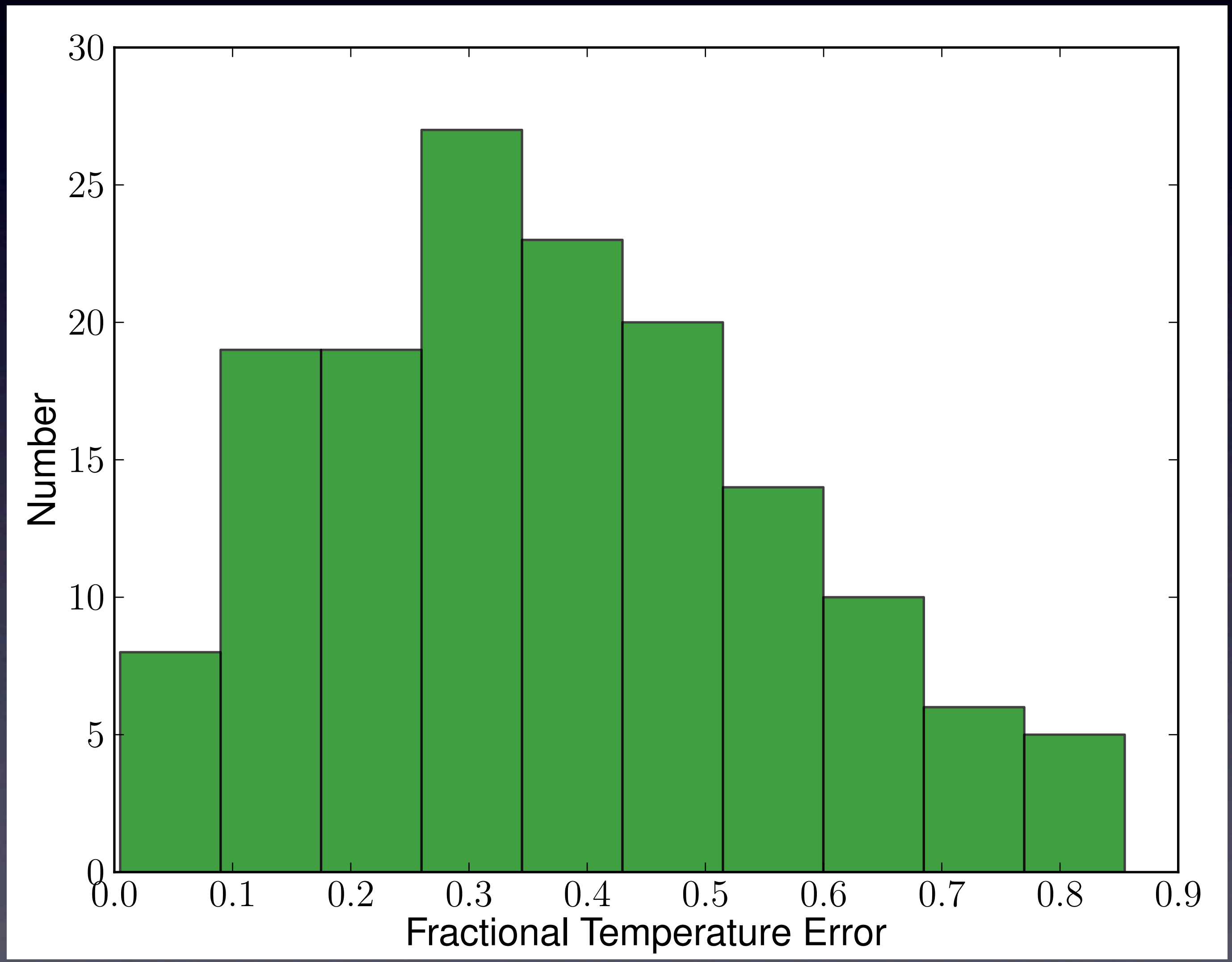
XCS Age Histogram



XCS Tx histogram



XCS Tx errors



in my view...

once the temperature error exceed 40%, you might as well be using richness. We have asked for 3MS of XMM time to shrink all errors to 10%, but these sorts of proposals never go down well with the TACs, so chances are slim (co-I's welcome).

XCS

- Results (Science):
  - cosmological parameters
  - X-ray scaling relations
  - find z>1 clusters
  - Galaxy evolution (John Sott's talk yesterday)

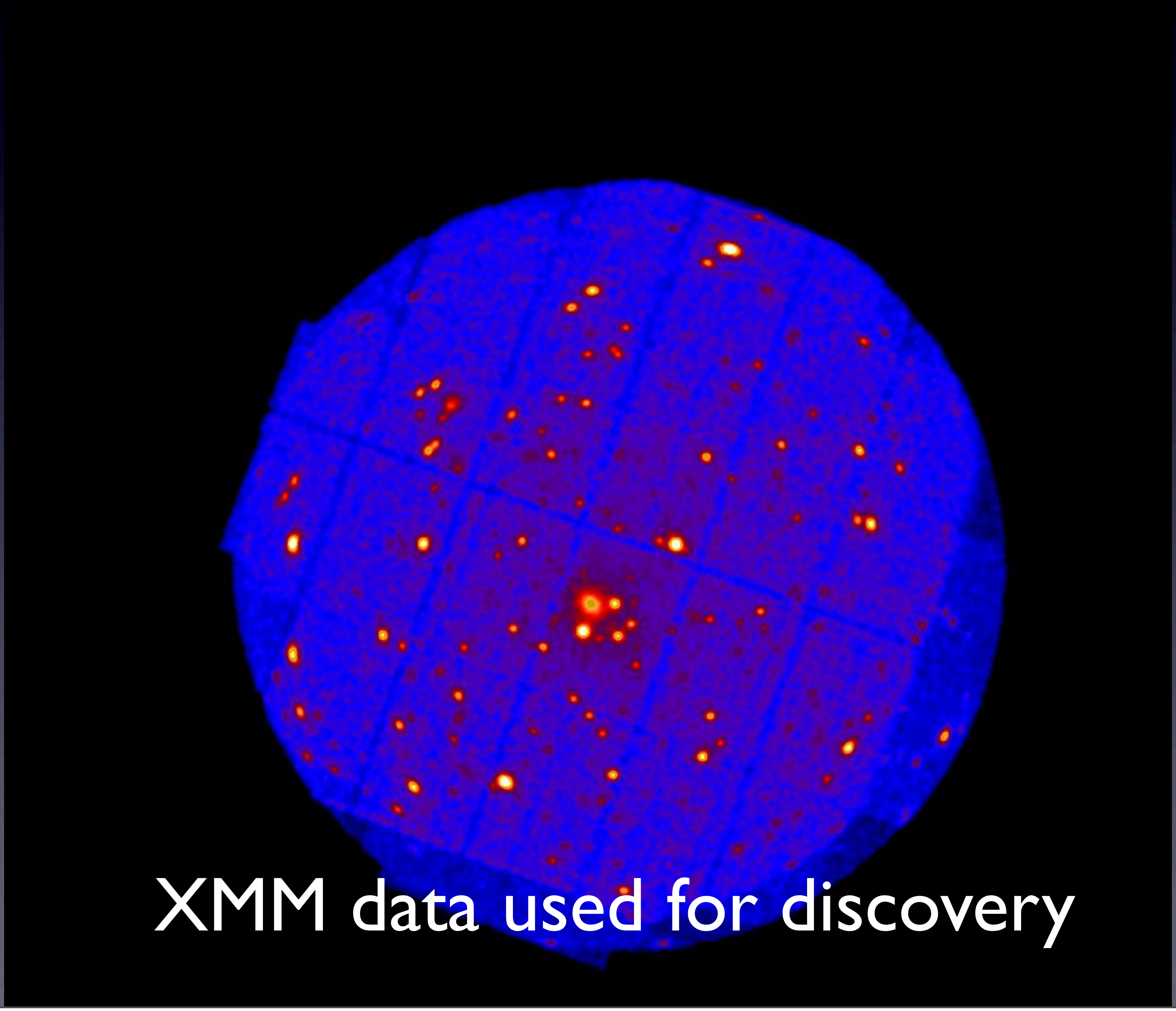
XCS

- Results (Science)
  - Find z>1 clusters (Stanford et al. 2006, Hilton et al. 2007)
    - 14 z>1 clusters (not all spectroscopic z's)
    - Including the record holder for the highest z spectroscopically confirmed cluster
    - [30 0.8<z<1 (not all spectroscopic z's)]

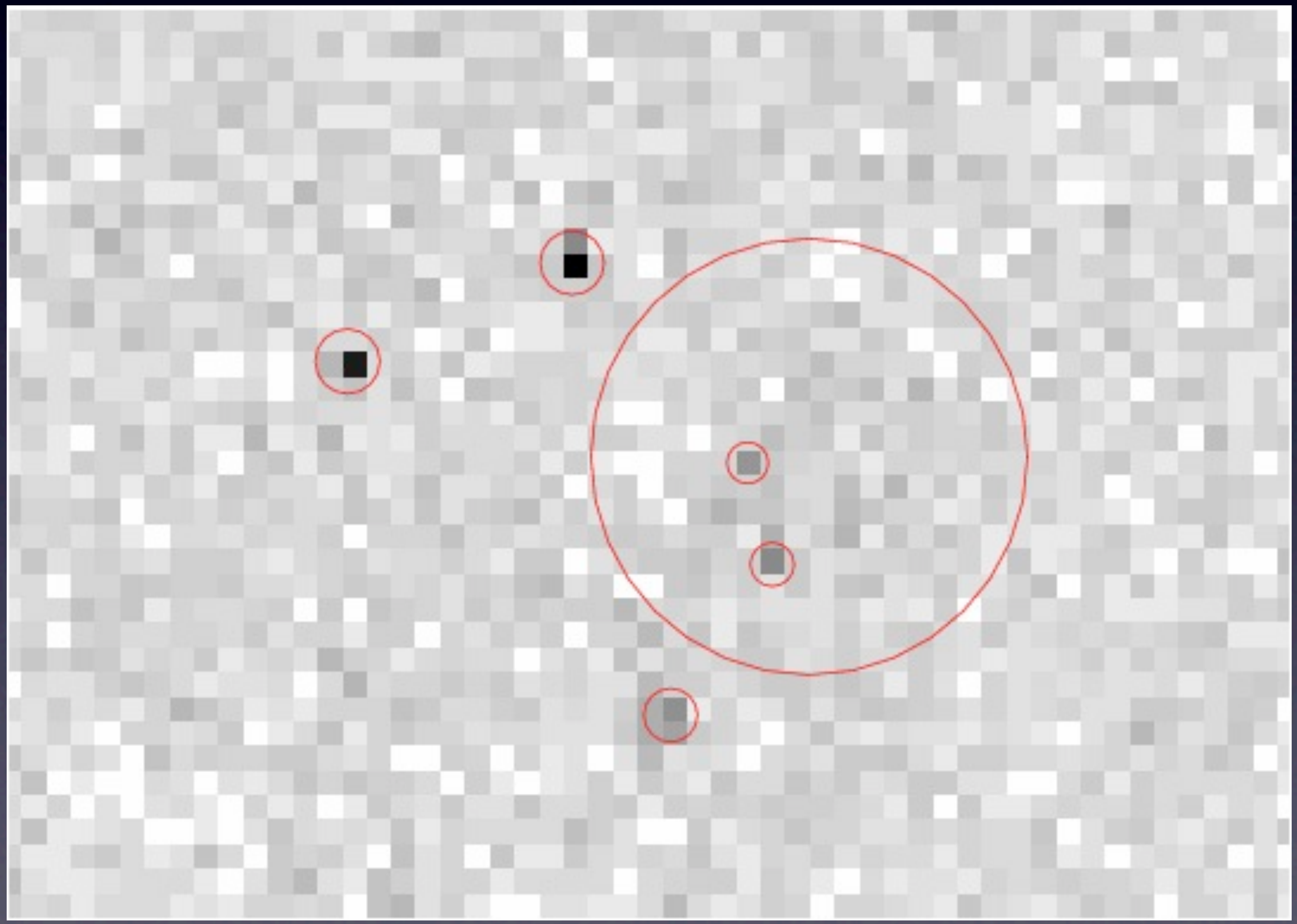
The highest z cluster (at least until January '10)

Not even I would call this one pretty!

The highest z cluster (at least until January '10)



The highest z cluster (at least until January ’10)

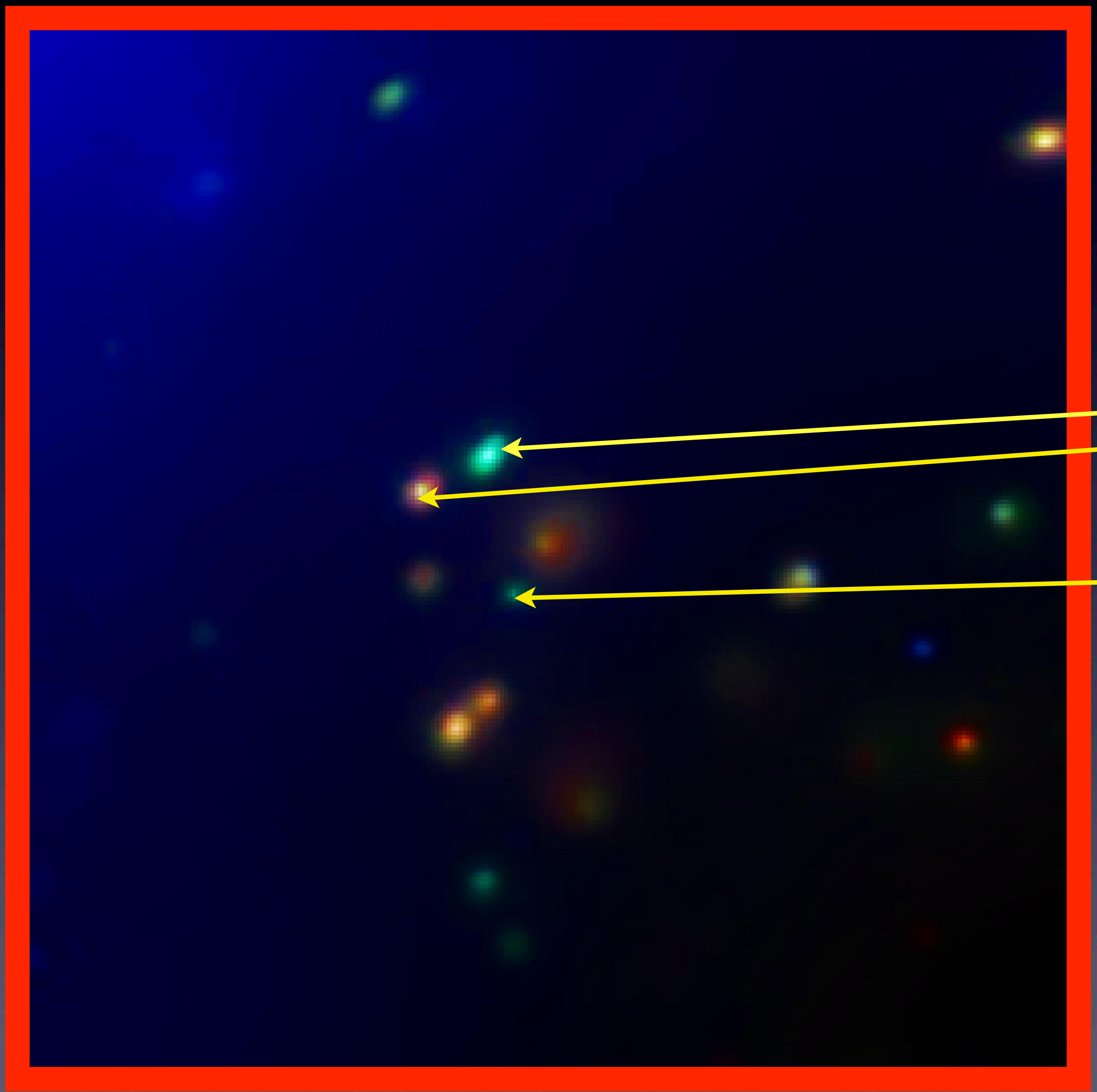


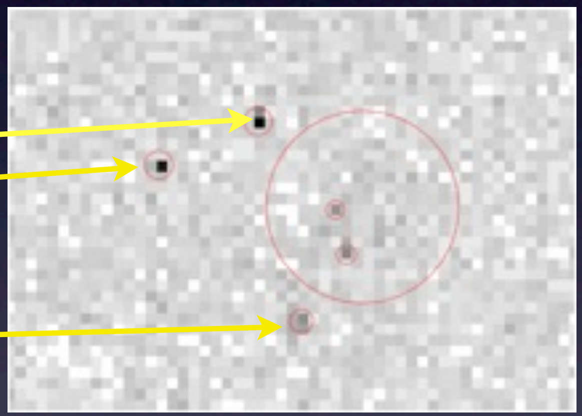
Chandra observation has been used to correct the temperature for point source contamination. Best fit temperature has dropped from Stanford et al. value to 4 keV. (yet to be published)

in my [old] view...
that's why I wasn't much impressed by Chandra for high-z clusters (except for detecting point sources).

Aside: line of sight contamination is a problem for the X-ray surveys. Optical/IR clusters don't have that anymore.

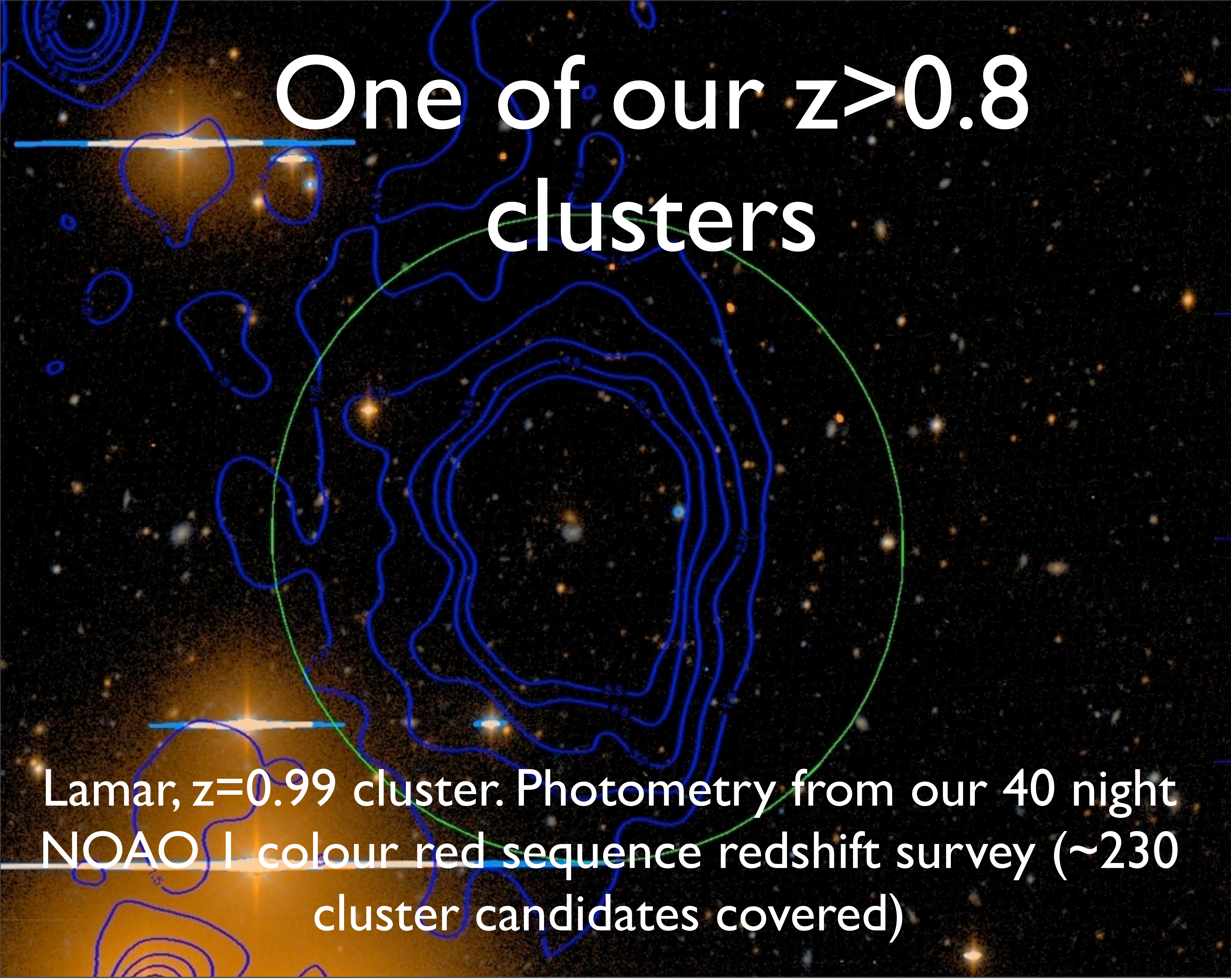
The highest z cluster (at least until January '10)





Comparison with XMM discovery data

One of our z>0.8 clusters

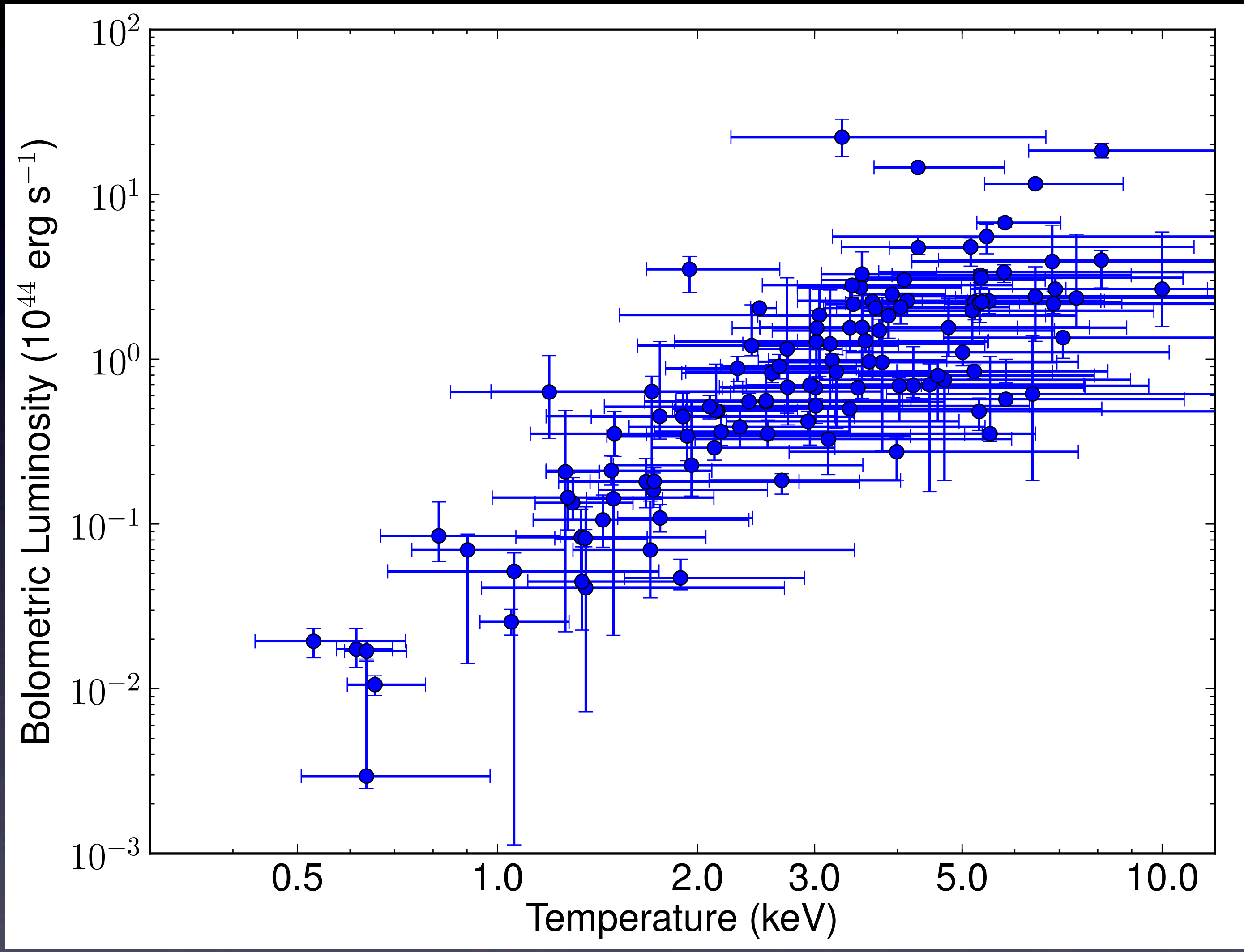


Lamar, z=0.99 cluster. Photometry from our 40 night NOAO 1 colour red sequence redshift survey (~230 cluster candidates covered)

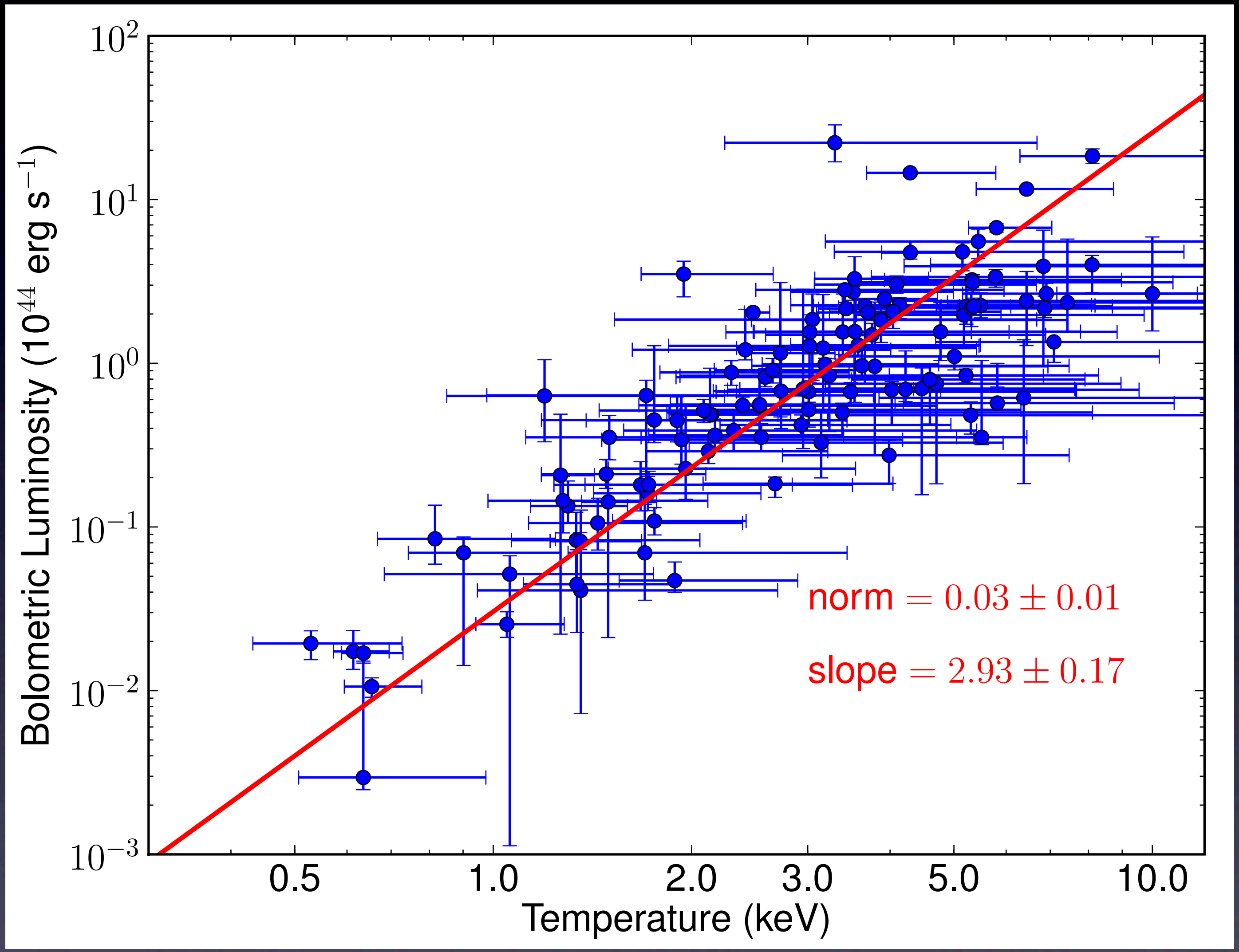
XCS

- Results (Science)
  - ★ Scaling Relations (Lloyd Davies in prep)
    - ✦ largest number of Tx's
    - ✦ need to do selection function corrections
    - ✦ we might need to add target clusters to test evolution at the bright, low z, end. We'll reduce all the data using the same pipeline, but the selection function will be hard to quantify.

XCS *L-T* relation



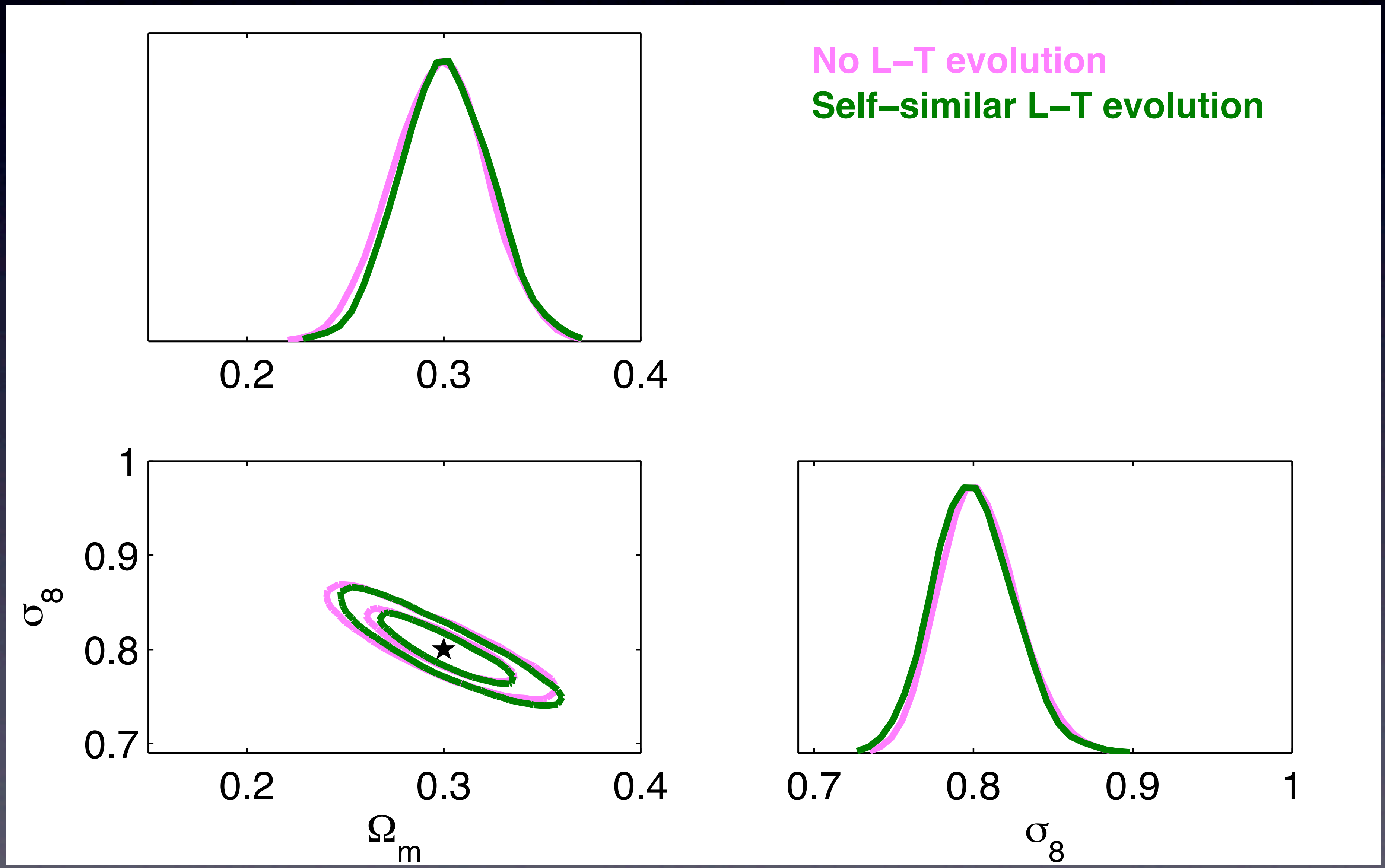
XCS *L-T* Relation



XCS

- Results (Science)
  - Cosmology (Sahlen et al. 2009)
    - So far only forecasts and only for flat cosmologies.
    - We are finally working on actual fits. Will take the Mantz et al. approach (joint parameters and scaling relations).
    - We must be able to do well (based on Mantz et al. and Vikhlinin et al. results).
    - Biggest problem yet to solve is selection functions for non flat cosmologies.

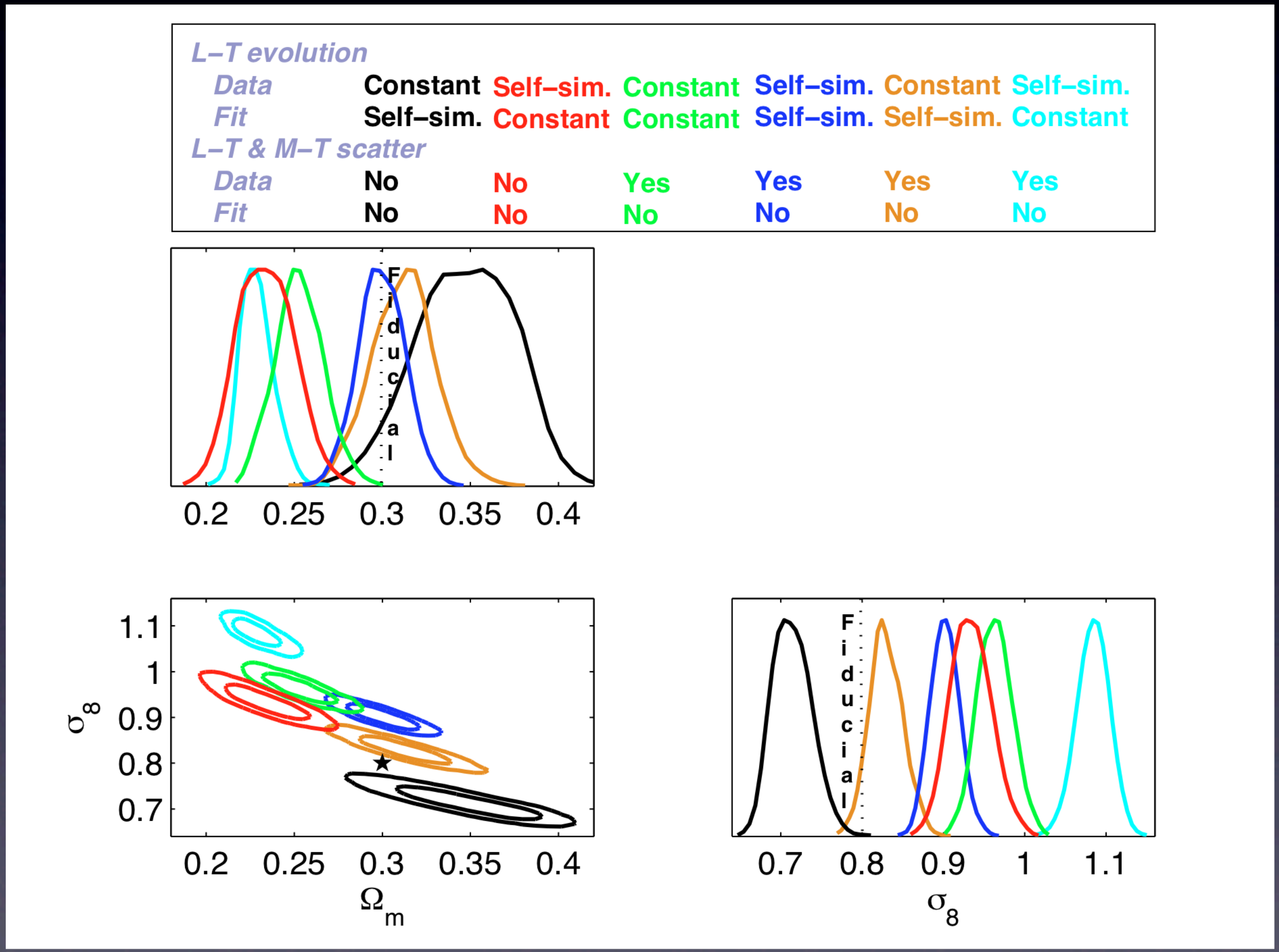
Sahlen et al. 2009, base case scenario (flat universe)



XCS

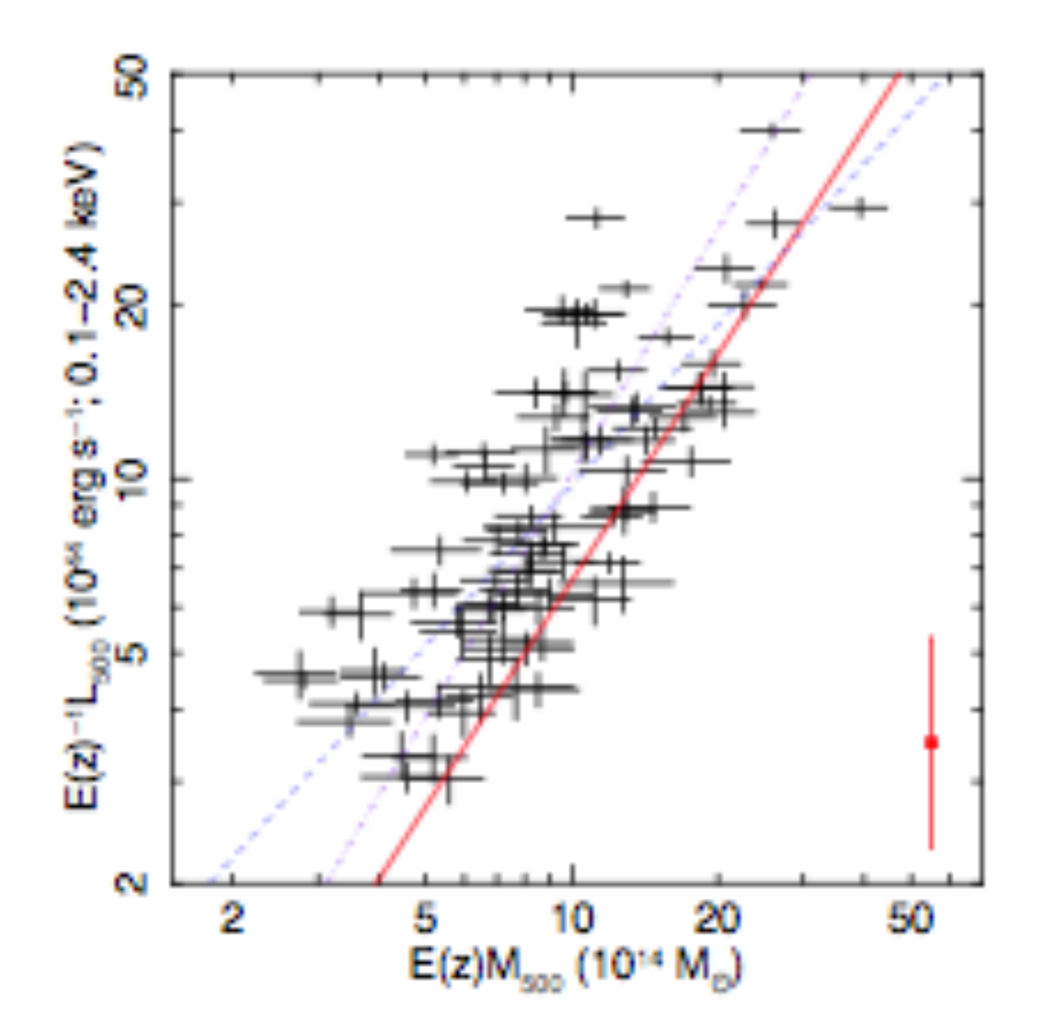
- Results (Science)
  - ★ Cosmology (Sahlen et al. 2009)
    - ✦ So far only forecasts and only for flat cosmologies.
    - ✦ We are finally working on actual fits. Will take the Mantz et al. approach (joint parameters and scaling relations).
    - ✦ We must be able to do well (based on Mantz et al. and Vikhlinin et al. results).
    - ✦ Biggest problem yet to solve is selection functions for non flat cosmologies.

Sahlen et al. Forecasts (why scaling relations matter)

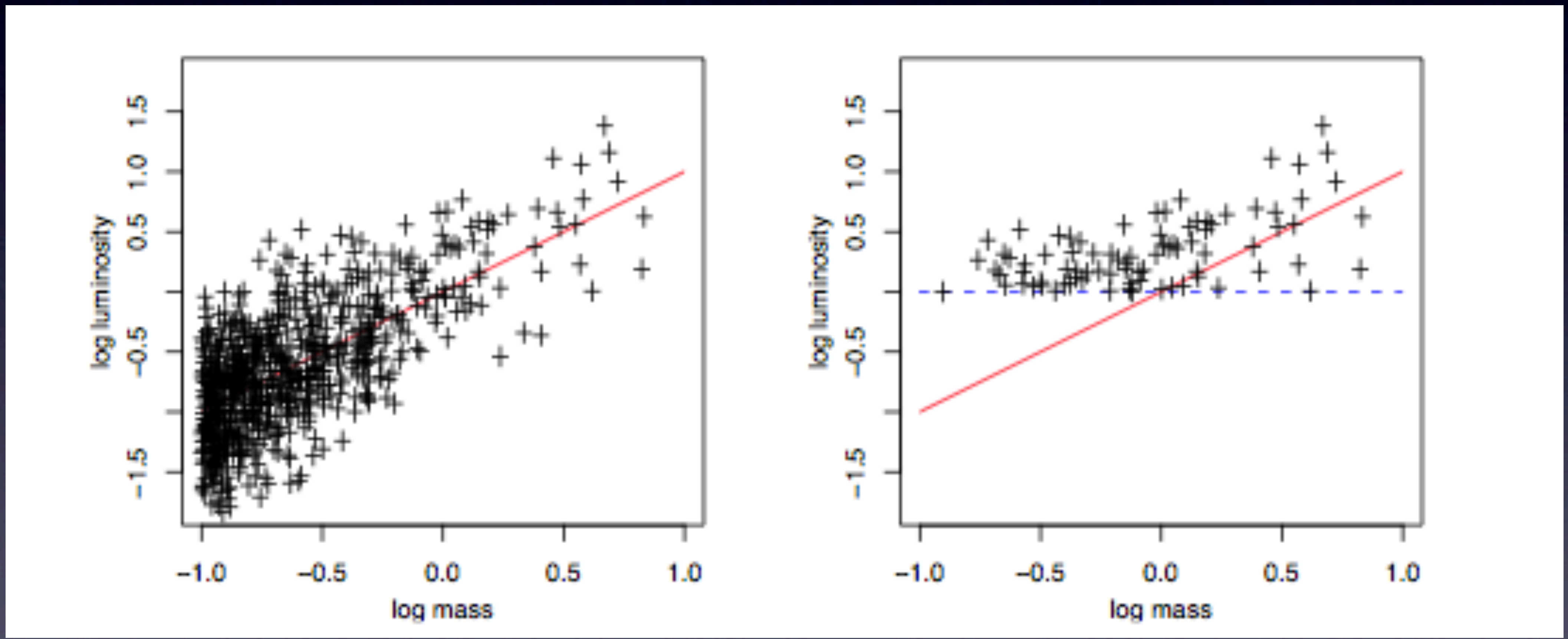


Mantz et al. 2009 (why scaling relations and parameters have to be fit together)

Their best fit looks odd because it account for Malquist bias



Mantz et al. 2009 (why scaling relations and parameters have to be fit together)



"Cartoon" from the Mantz et al. appendix

in my view...

Scaling relations derived without a simultaneous fit to cosmological parameters should be viewed as preliminary.

Also, its a shame XCS can't excise cores, because the results are better when they are cut out.

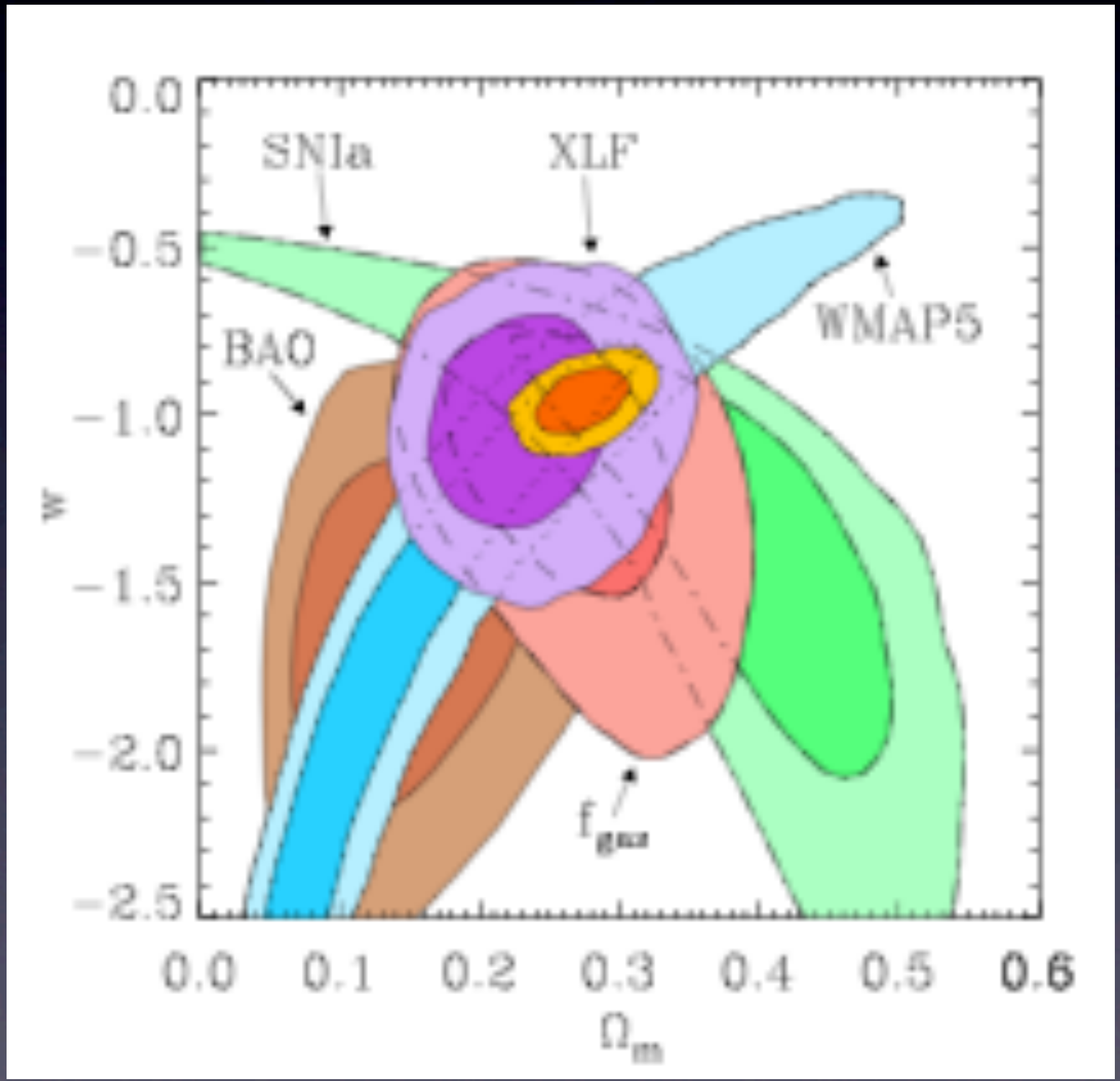
XCS

- Results (Science)
  - ★ Cosmology (Sahlen et al. 2009)
    - ✦ So far only forecasts, but we are finally working on actual fits.
    - ✦ Will take the Mantz et al. approach (joint parameters and scaling relations).
    - ✦ We must be able to do well (based on Mantz et al. and Vikhlinin et al. results).
    - ✦ Biggest problem yet to solve is selection functions for non flat cosmologies.

Mantz et al. 2009 Results

- They get tighter constraints than WMAP! using:
- 238 clusters from RASS at z<0.45 (including MACS)
- 94 with follow-up (ROSAT or Chandra)

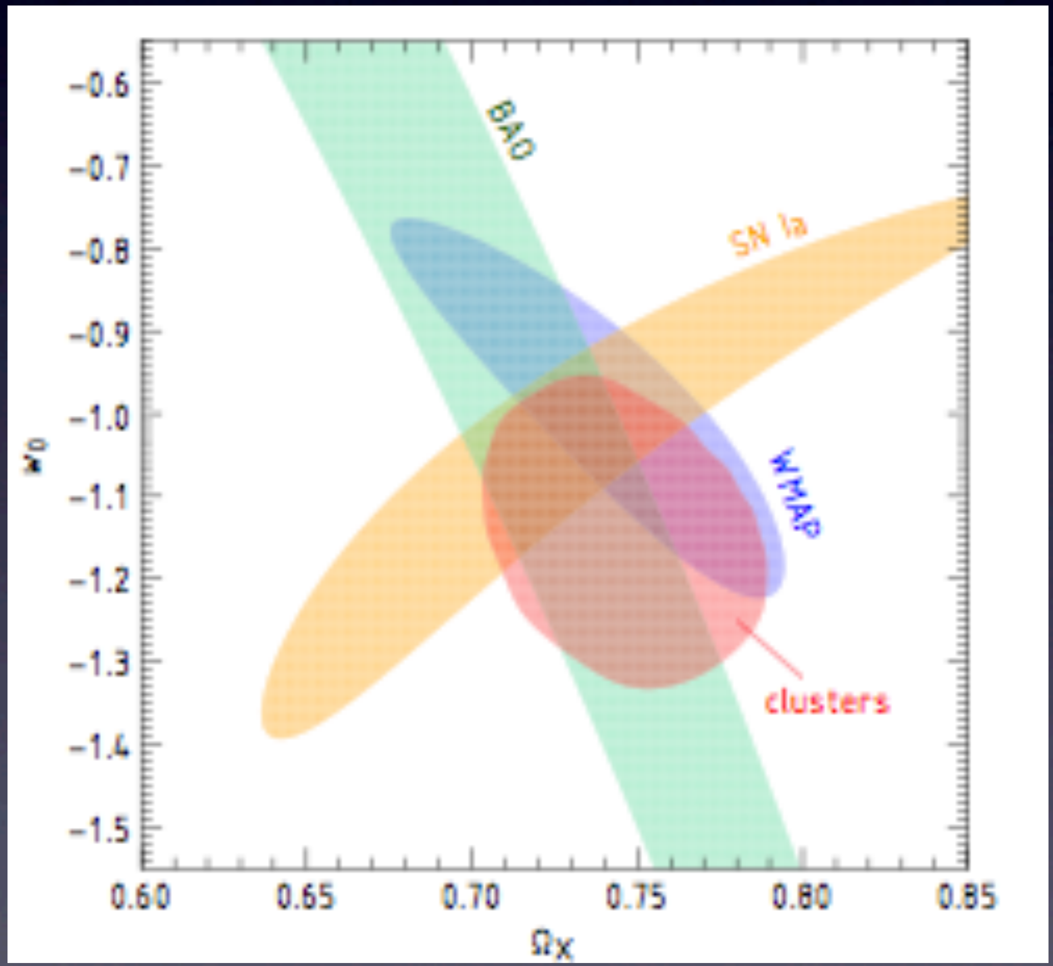
- XCS has more clusters, and goes to higher redshifts, so we must be able to do even better than this!



Vikhlinin et al. 2009 Results

- They get similar constraints to WMAP using:
- 37 400SD clusters <z>~0.5 (2 @ z>0.8)
- 49 RASS clusters z~0.55

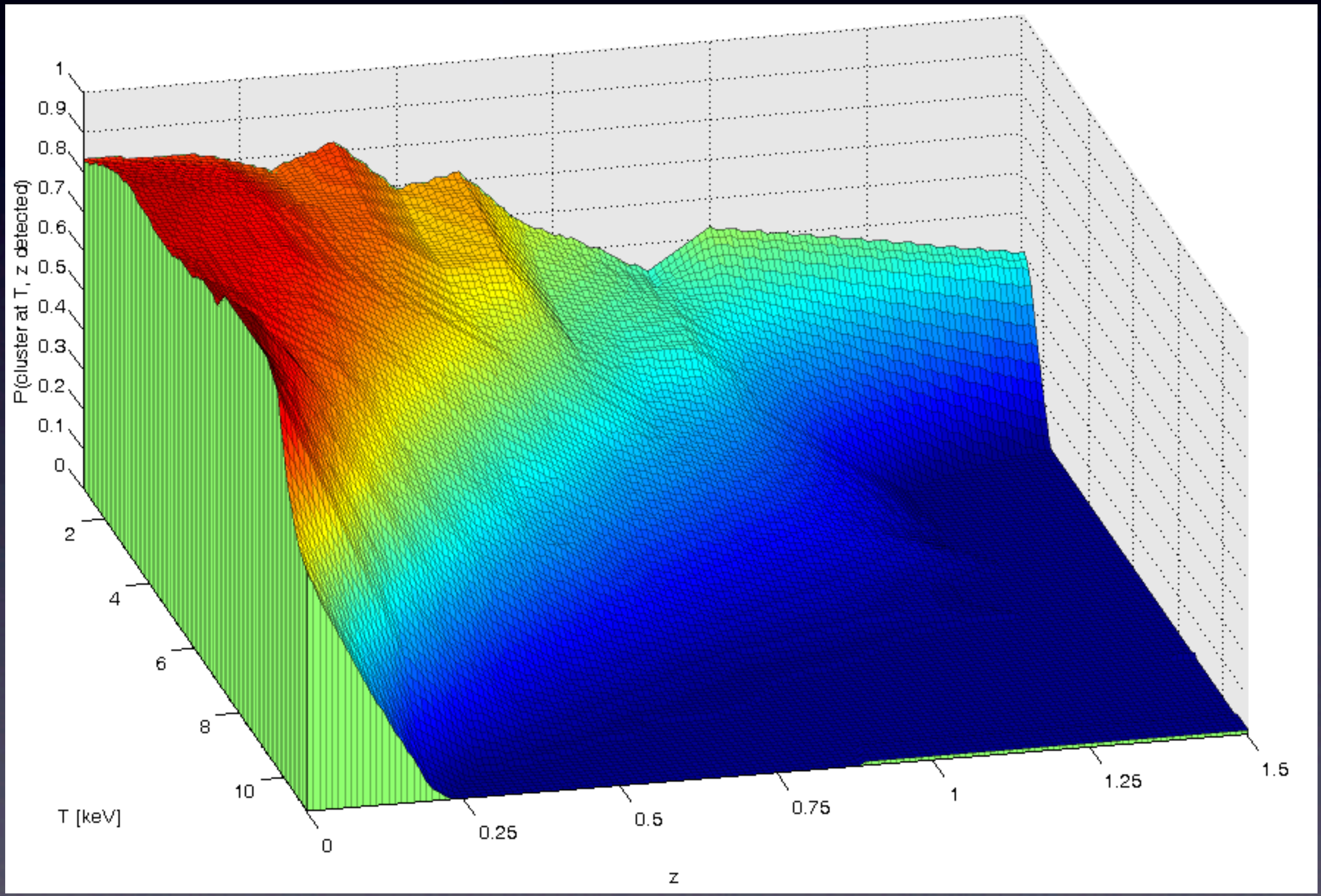
- XCS has more clusters, and goes to higher redshifts, so we must be able to do even better than this!
  - ★ Tx's are worse though



XCS

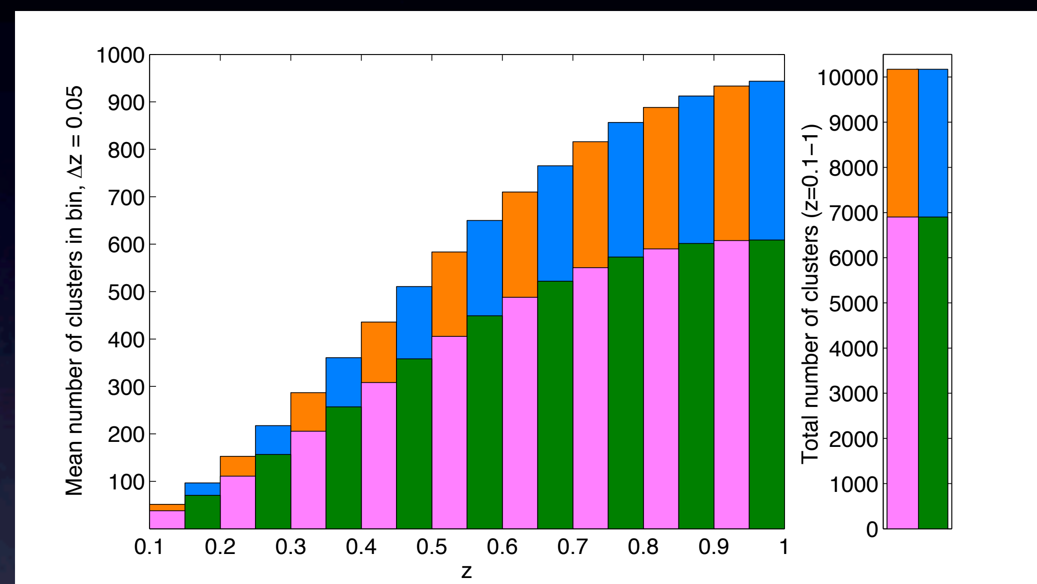
- Results (Science)
  - Cosmology (Sahlen et al. 2009)
    - So far only forecasts, but we are finally working on actual fits.
    - Will take the Mantz et al. approach (joint parameters and scaling relations).
    - We must be able to do well (based on Mantz et al. and Vikhlinin et al. results).
    - Biggest problem yet to solve is selection functions for non flat cosmologies.

Shalen et al. Forecasts (why selection functions matter)



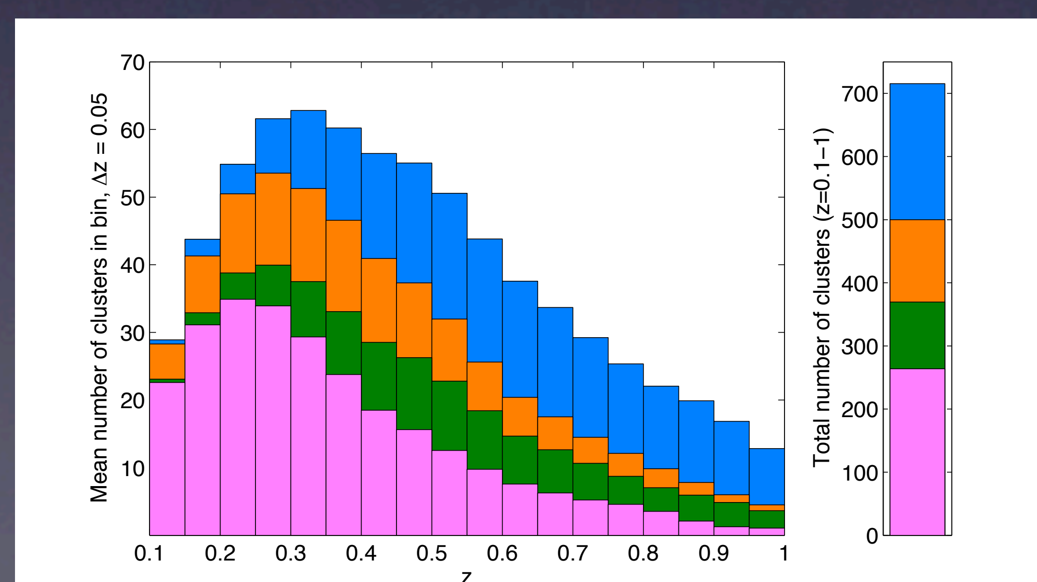
Shalen et al. Forecasts (why selection functions matter)

Number of clusters in the pretend Universe



(a) Underlying cluster distribution. Note that only the M–T relation is relevant for the underlying distribution, and we therefore colour according to both L–T assumptions with the same M–T relation.

Number of clusters in the pretend XCS



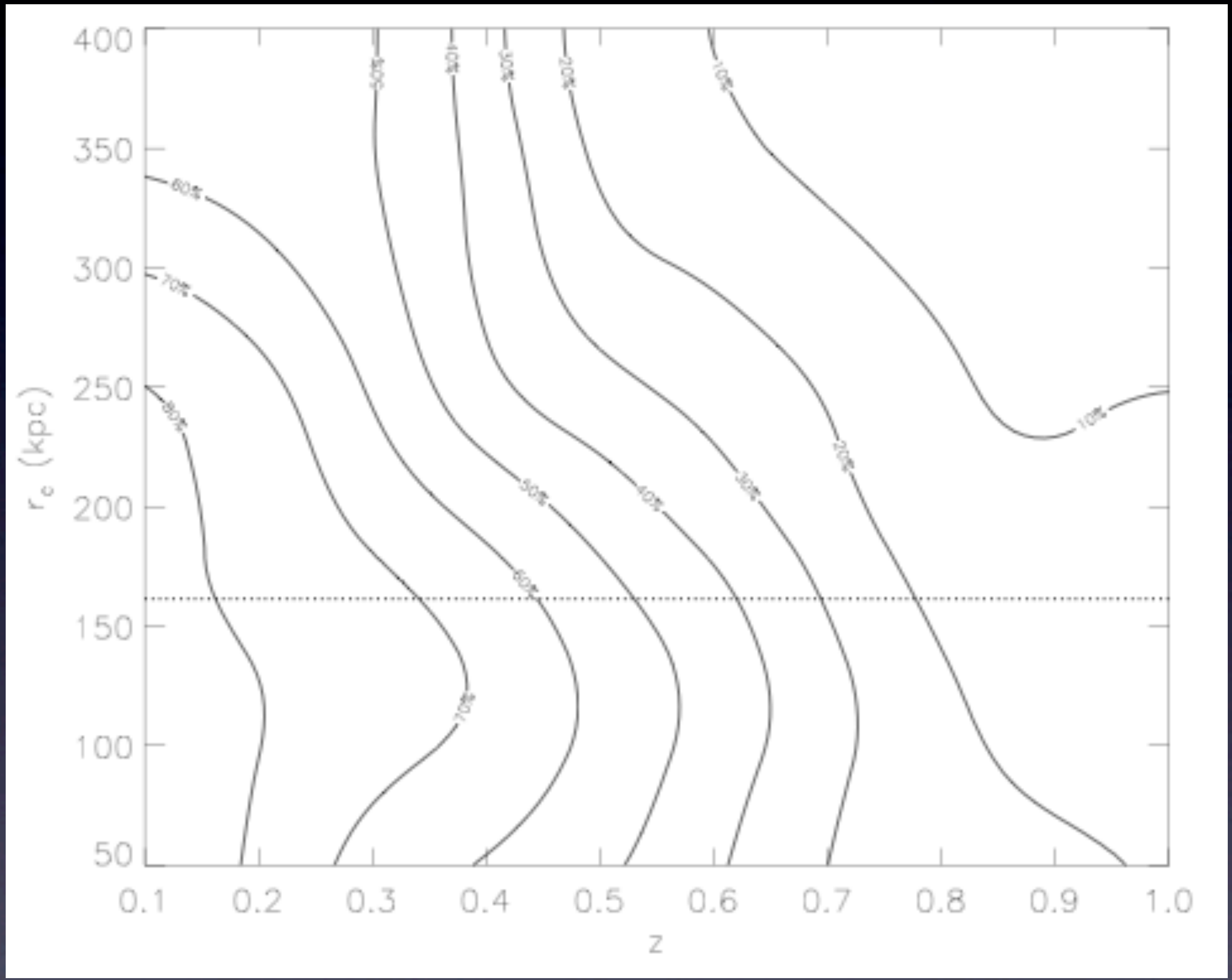
(b) Expected detections using selection function.

Pink & Green: no scatter
Blue & Orange: scatter
Green & Blue:
self similar evolution
Pink and Orange: no
evolution

in my view...
Mike Gladders' point that optical surveys find all clusters is very important. Assuming contamination can be dealt with, this makes optical surveys very appealing.

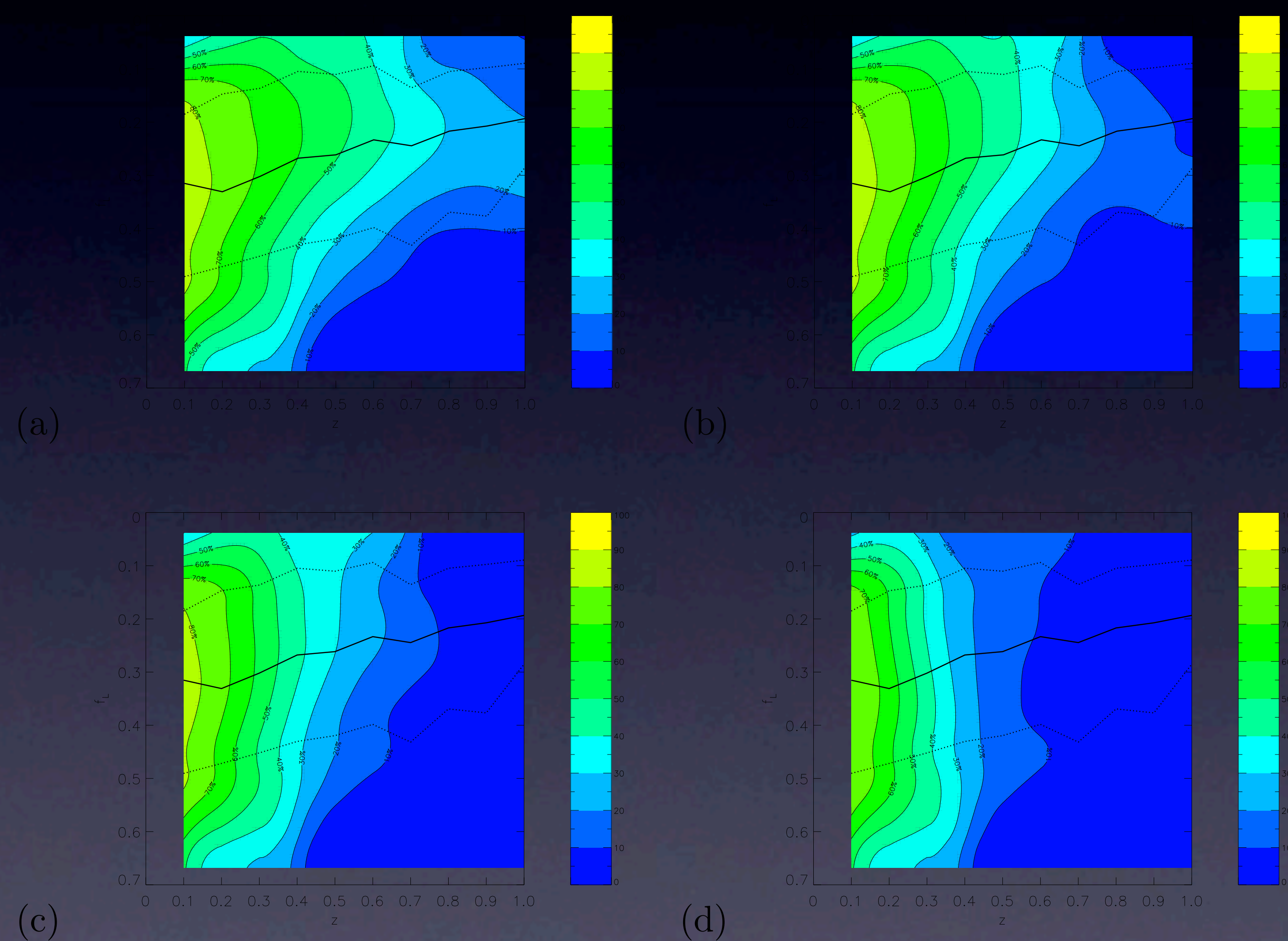
Shalen et al. Forecasts (why selection functions are difficult)

The detectability is sensitive to the core radius



Shalen et al. Forecasts (why selection functions are difficult)

The sensitivity is less for higher count clusters



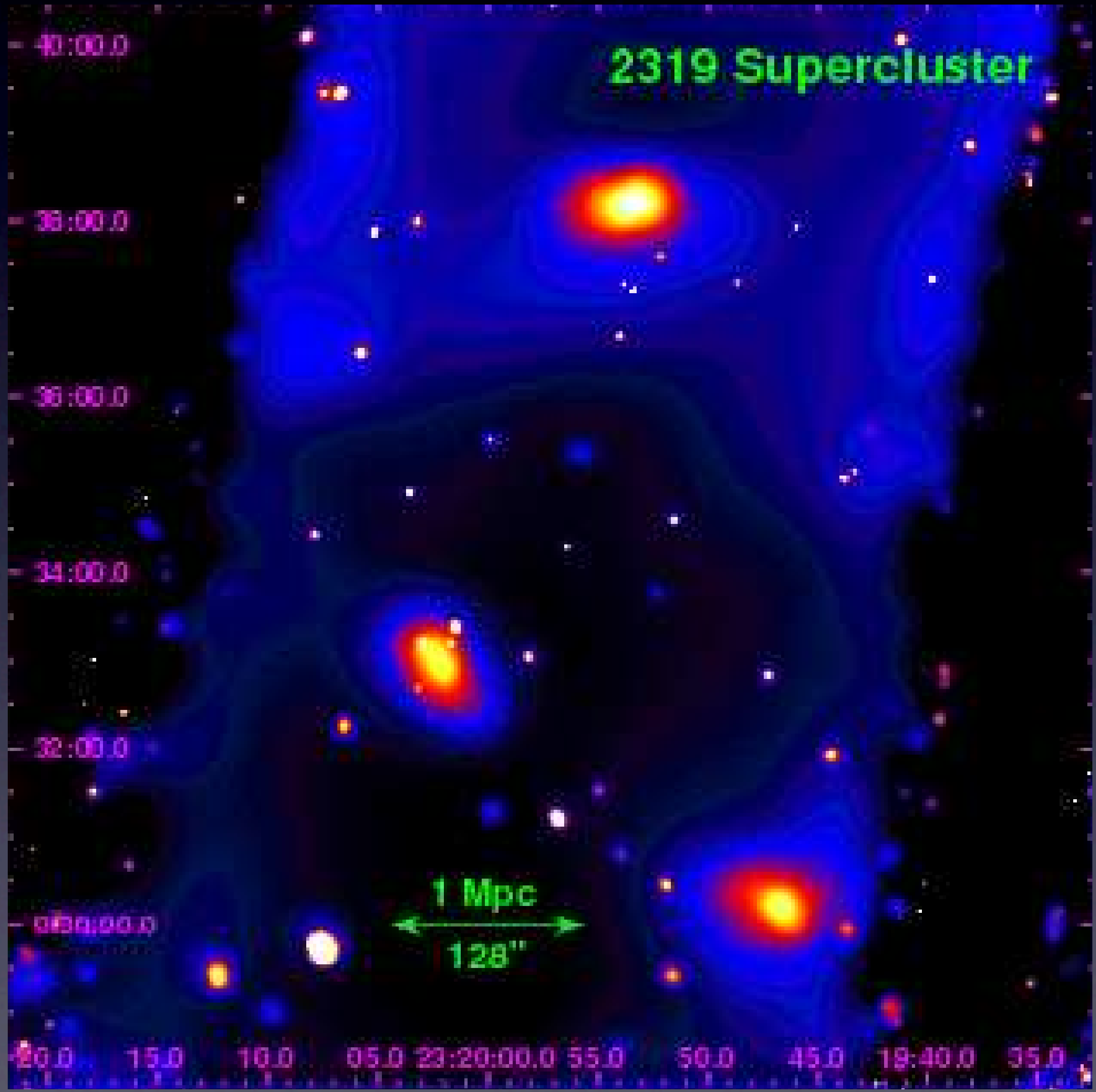
XCS Summary

- The project is now mature. We have thousands of candidates, hundreds of redshifts and two hundred temperatures.
- It probes the high redshift end well, but is held up because of lack of 8m time
- We have selection functions, we are going to attack the cosmological constraints in the coming months.
- The biggest impact is likely to be via mass calibrations for DES clusters.

How to catch a cluster (not X-ray)

- Using optical data: Red Cluster Sequence Survey
  - ★ Hicks et al. 2008; Chandra follow-up 7 @ $0.8<z<1$, plus 1 @ $z>1$
  - ★ Importance:
    - ✦ they have examined scaling relation evolution independent of ROSAT detection
    - ✦ they have demonstrated the future potential of DES etc. samples.

RCS z=0.9 supercluster as seen by Chandra



Hicks et al. 2007

How to catch a cluster (not X-ray)

- Using IR data:
  - ★ SpARKS (Ellingson et al. 09; 4 with X-ray detections @ $z>1$)
  - ★ UKIDDS (Andreon et al. 09; $z \sim 1.9$ with Chandra confirmation)
  - ★ Importance: IR opens up the $z>1$ domain to cluster cosmology (assuming selection functions are available).

How to catch a cluster (not X-ray)

- Using optical + SZ data: Blanco Cosmology Survey + SPT survey (Staniszewski et al. 09; 2 @ $z>0.8$)
- Importance:
  - ★ SZ follow-up can be as good as X-ray follow-up, and its a lot cheaper!
  - ★ SZ detections struggle without optical follow-up. So the combined approach is very important.

Discussion points?

- ★ High redshift clusters are nice, but X-ray resources are limited, so for cosmology and scaling relations, we would be better off at $z<0.7$
- ★ I'm ready to get over X-rays; but more work needs to be done to prove that optical/IR surveys work for cosmology (mass proxies and selection functions)
- ★ We can do cluster X-ray astronomy from the ground, with a decent *facility* SZ instrument. Lets make sure the band 1 instrument on ALMA gets funded.