New Constraints on Galaxy Cluster Evolution from the South Pole Telescope

The X-ray Universe
Dublin, Ireland – June 24, 2014

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Background

(Galaxy Clusters, Cooling Flows)

Galaxy Cluster Surveys

(Optical, X-ray, SZ)

The South Pole Telescope

(2500 deg^2, SPT-XVP surveys)

Early SPT-XVP results

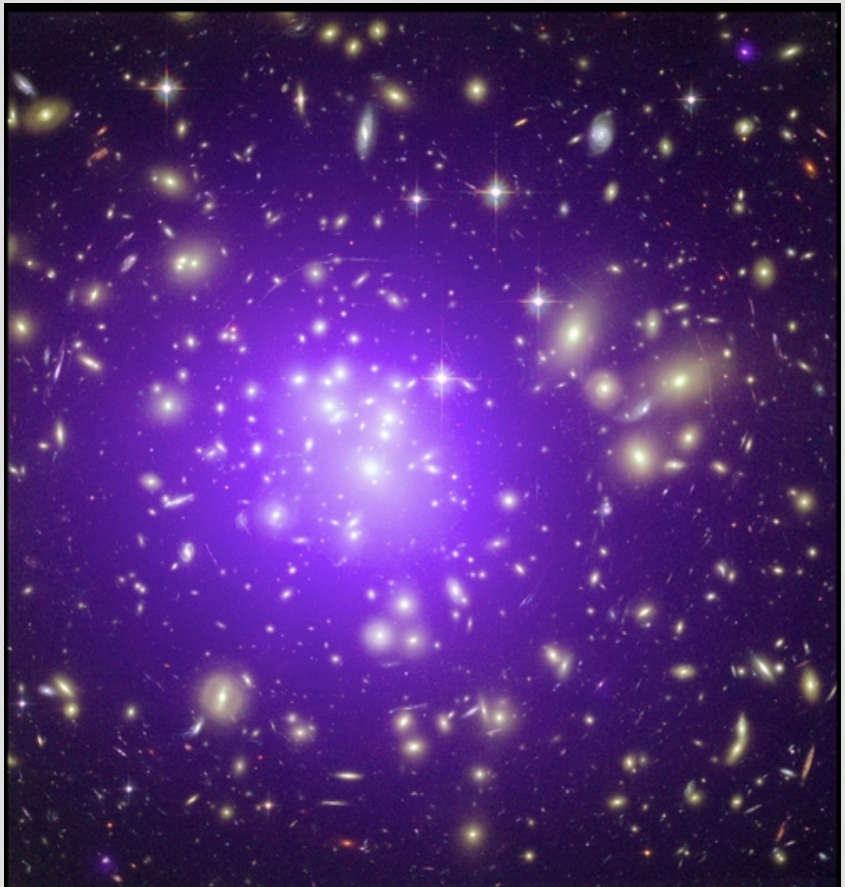
(Central Galaxies → Inner 100 kpc → Outer Mpc)

WHAT IS A GALAXY CLUSTER?

~2-5% stars:
- 90% in galaxies, ~10% diffuse
- Single galaxy (BCG) typically dominates optical light

~15% hot gas:
- "intracluster medium"
- visible in X-rays

~80% dark matter:
- Mapped via strong & weak lensing, dynamics



Abell 1689: A Galaxy Cluster Makes Its Mark - Chandra (X-ray) and Hubble Space Telescope
NASA/CXC/MIT/E.-H. Peng et al and NASA/STScI Release Date: Sept. 11, 2008 ASU-IPF-2903

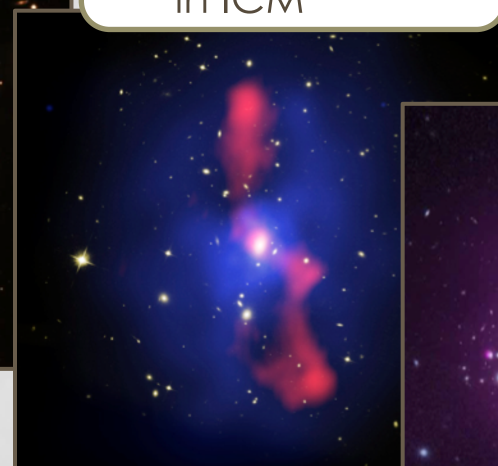
The ICM is subdominant in mass, but tells us the most about the history of the cluster!

The Intracluster Medium

- Temperature/Density
  - $>10^7$K plasma
  - Low density
    - $\sim10^{-5}$-10^{-1} cm^{-3}
    - At large radii, ~10 e^- per m^3!
- Extent/mass
  - Extends for several Mpc
  - Total mass in gas $\sim10^{14}$ $M_\odot$
- Morphology
  - Retains imprint of major events

Ongoing merger
- Double-peaked, elongated X-ray emission

Recent interaction
- Single-peaked, spiral structure



AGN Feedback
- Bubbles in ICM

Relaxed
- Smooth, symmetric

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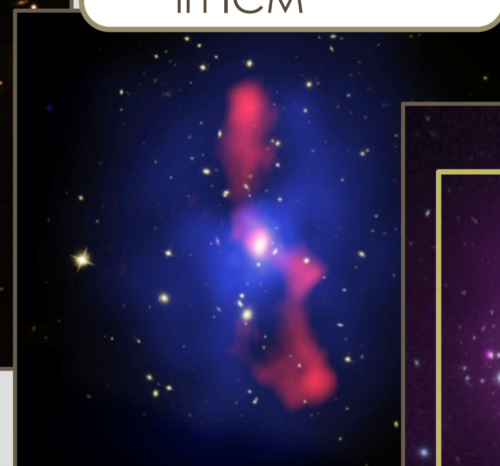

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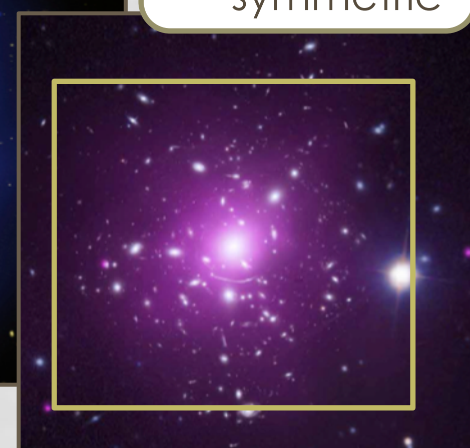


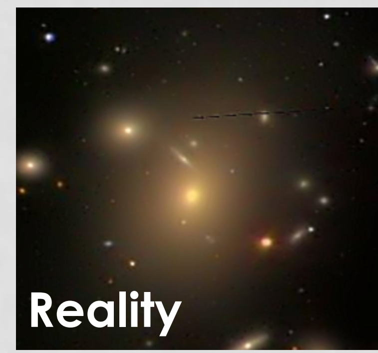
<u>Relaxed</u>
- Smooth, symmetric

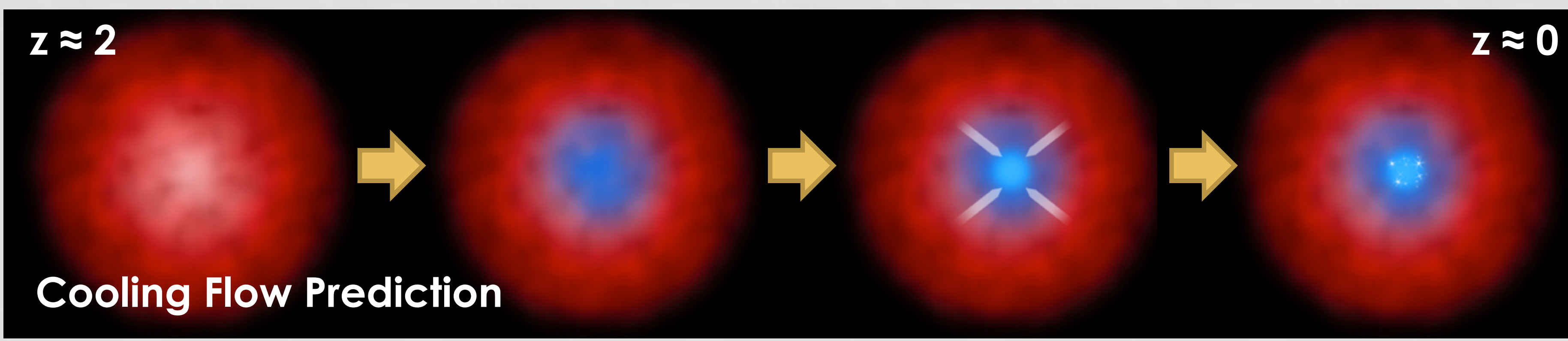
THE COOLING FLOW PROBLEM

- Intracluster plasma is cooling radiatively ($\varepsilon_{ff} \sim n_e^2$)
- In some clusters, central cooling time is < 1 Gyr
  - Should lead to 100-1000 $M_\odot$/yr in cooling

BUT: 99% of cooling is somehow suppressed

- Massive amounts (>$10^{12} M_\odot$) of low-entropy material is "frozen" in cool cores. But how/why?





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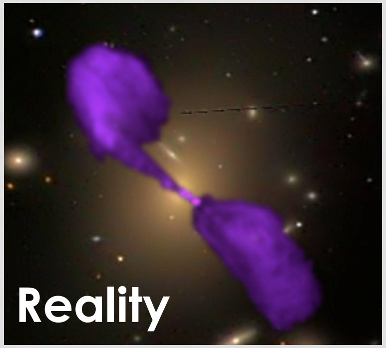
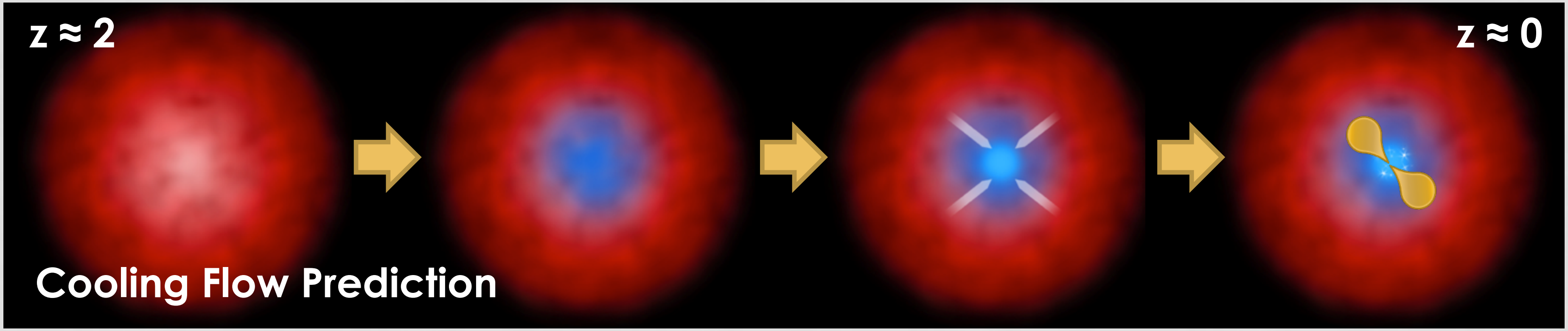
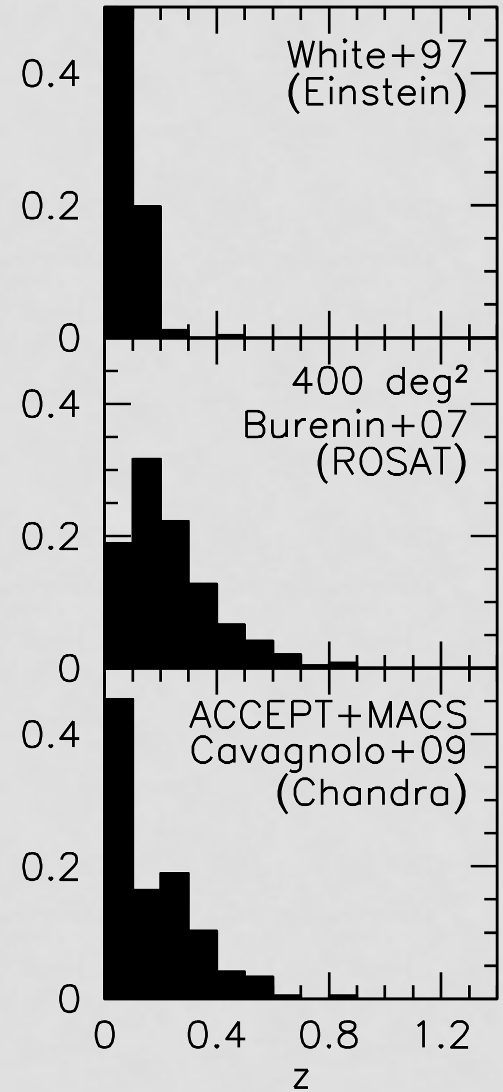
- Massive amounts (>$10^{12} M_\odot$) of low-entropy material is “frozen” in cool cores. But how/why?
  - Radio-mode AGN feedback appears to be perfectly offsetting cooling in every nearby galaxy cluster
  - Deviations from energy balance are ~1% (star formation)





OPEN QUESTIONS

- Did bonafide cooling flows ever exist?
- How has the balance between cooling and AGN feedback evolved over time?
- How and when did cool cores develop?
- How/when did the ICM virialize and/or become enriched?
  Can we observe this evolution?
  (accretion, metal enrichment, etc)?



Need a well-selected sample of high-z clusters!

Previous evolutionary studies of galaxy clusters have been restricted to $0 < z < 0.5$

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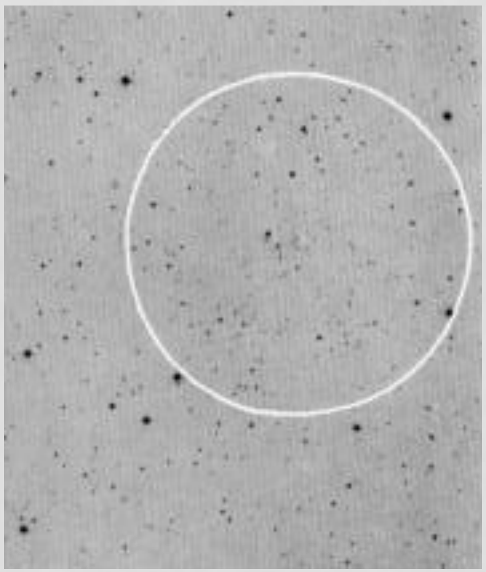
GALAXY CLUSTER SURVEYS: OPTICAL

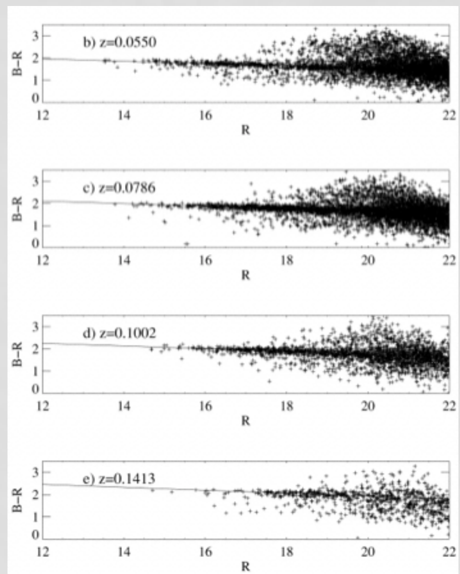
Optical Selection – Tried and True

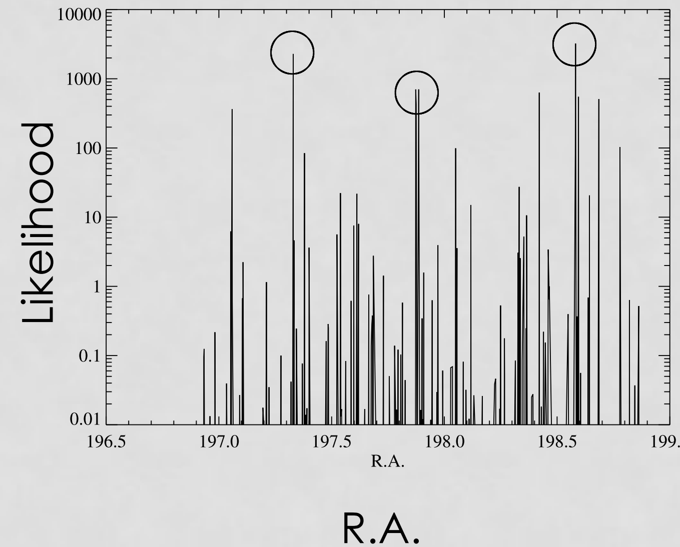
Galaxy overdensity
- E.g., Abell (1958)

Red Sequence
- E.g., RCS

Red galaxy overdensity
- E.g., maxBCG/GMBCG





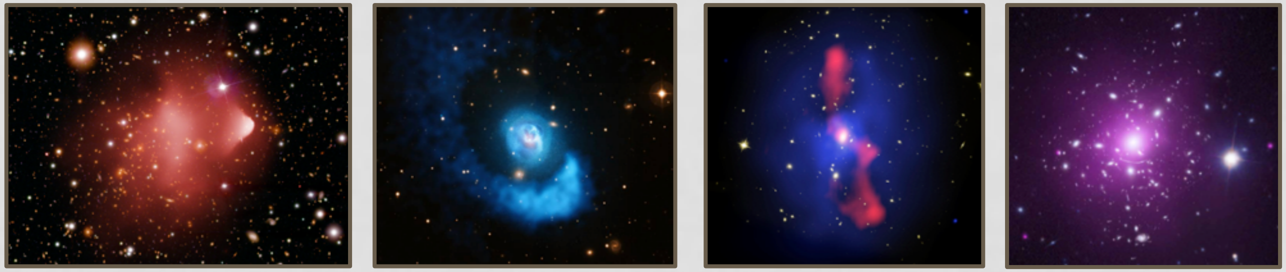


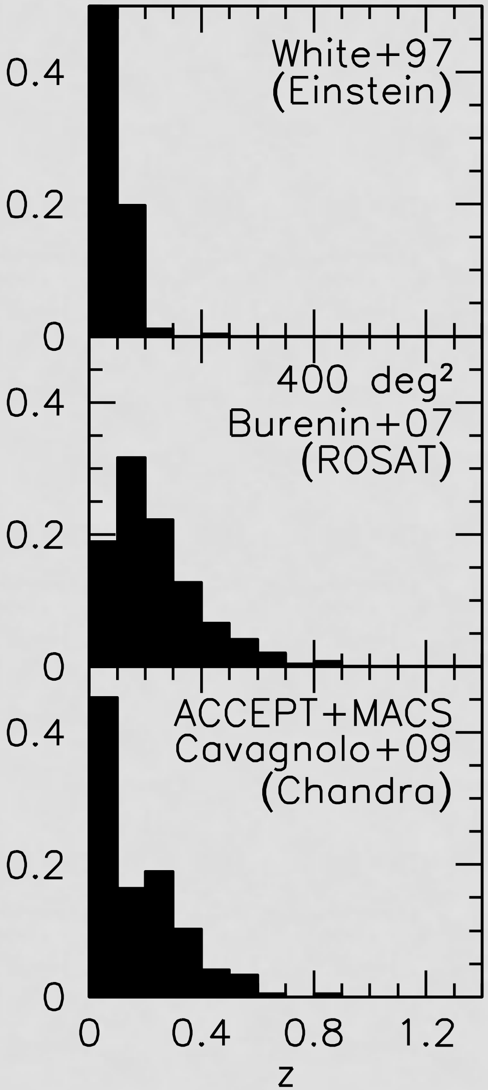
- Relies on an established red sequence
- Galaxy brightness goes like $1/d_L^2$

GALAXY CLUSTER SURVEYS: X-RAY

X-ray Selection – The Local Universe

- Majority of X-ray surveys are still based on pre-selection with ROSAT All-Sky Survey
  - *Exceptions: Serendipitous surveys with Chandra (e.g., ChaMP), XMM (e.g., XCS, XXL), Swift(SWXCS)*
- X-ray surface brightness ~ $(1+z)^4$
  - Very expensive to survey for high-z clusters
- Subtle biases
  - Phoenix cluster misidentified as AGN





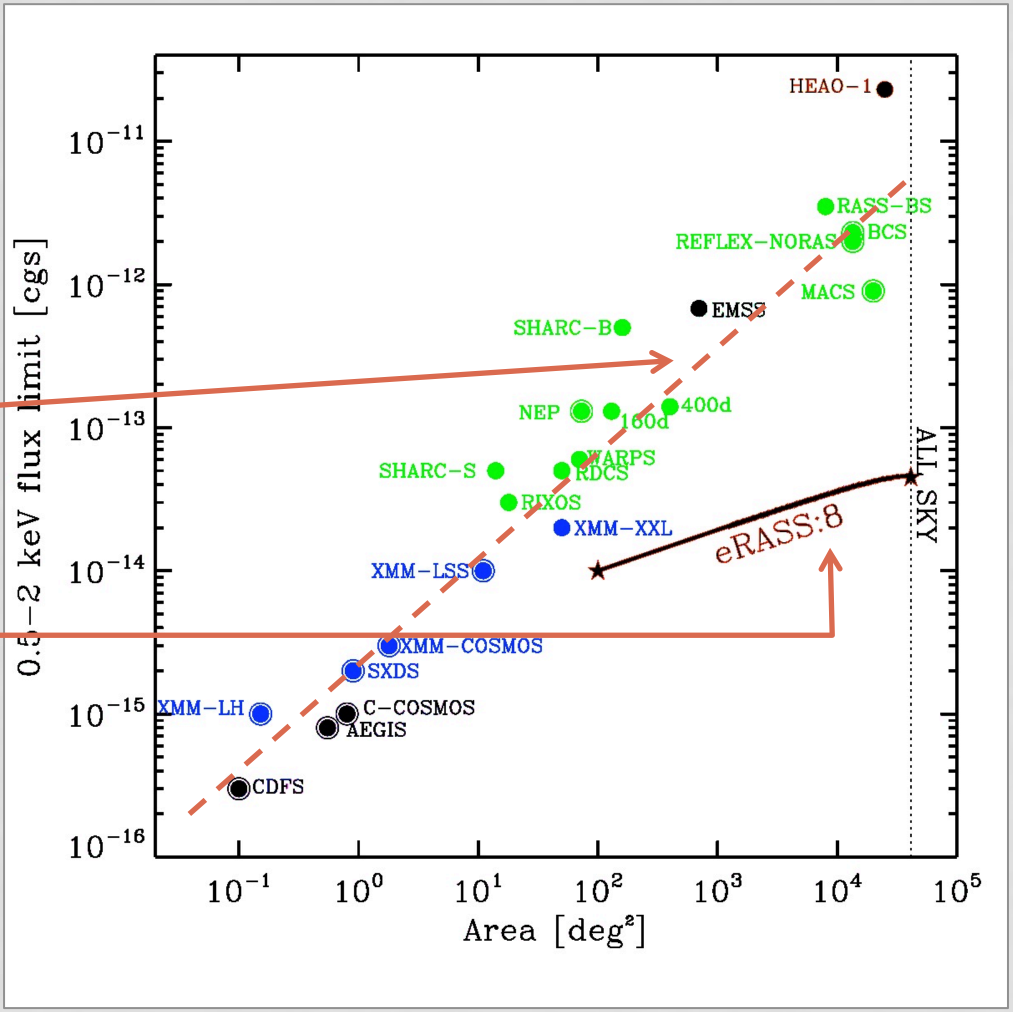
X-ray surveys have enabled our current understanding of galaxy clusters at z < ~0.5

High Redshift Galaxy Clusters

- Would like to understand how galaxy clusters form and evolve
  → Need a sample of "high redshift" galaxy clusters

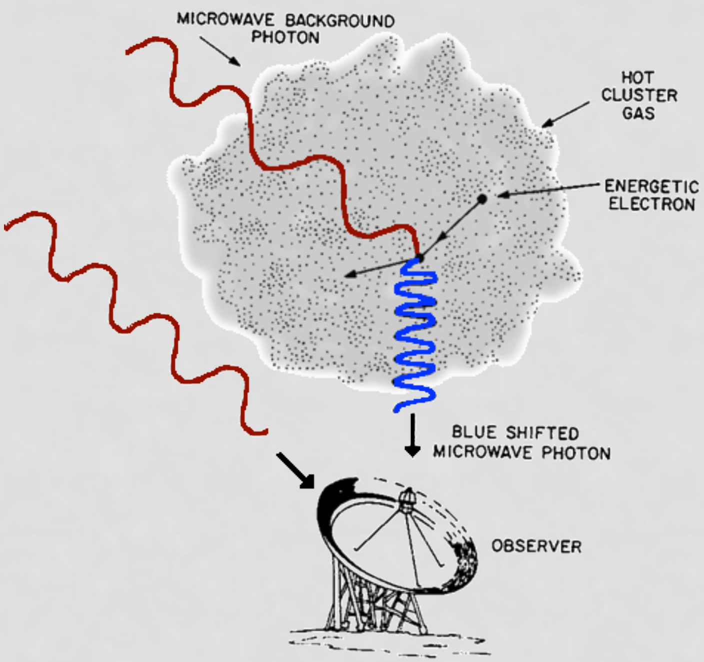
But:

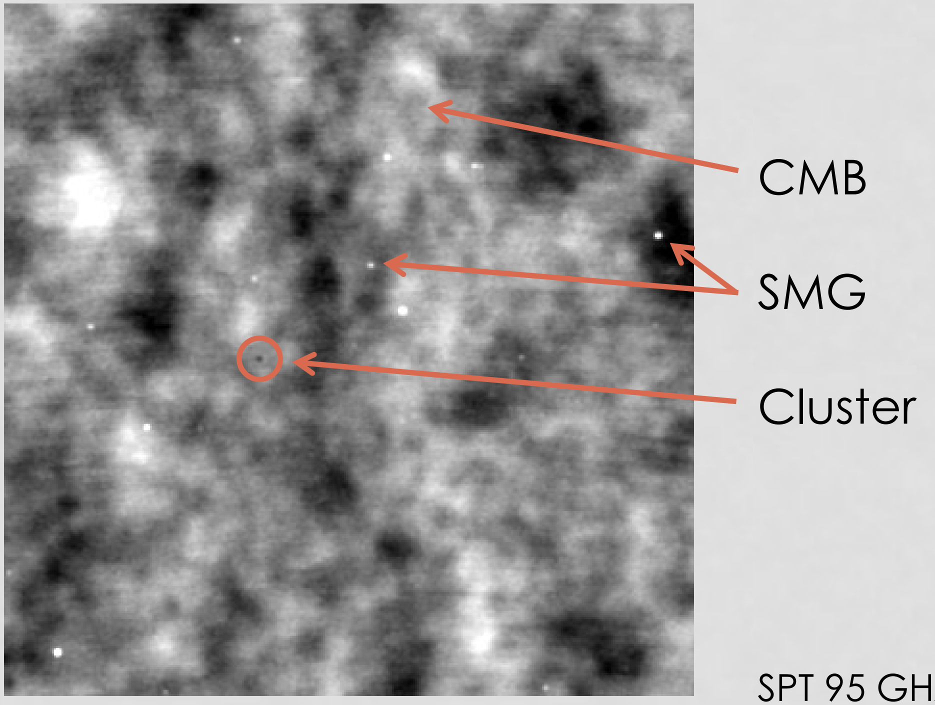
- Deep surveys are narrow
- Wide surveys are shallow
  - Natural result of finite observing time
- How can we do better?
  - Dramatically improve X-ray telescopes
    - More bang for your buck
  - Use a different technique
    - Ideally, get away from $1/d_L^2$ or $(1+z)^4$ sensitivity



Galaxy Cluster Surveys: SZ

- The Sunyaev-Zel'dovich (SZ) effect allows us to detect clusters by their imprint on the cosmic microwave background (CMB)
  - Clusters are "shadows" on microwave background
  - Detection in "color space" is redshift independent!





SPT 95 GHz

Background

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Early SPT-XVP results

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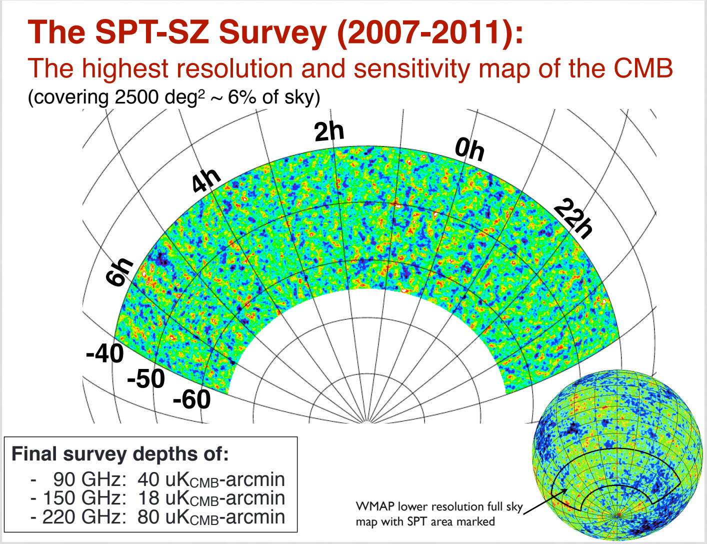
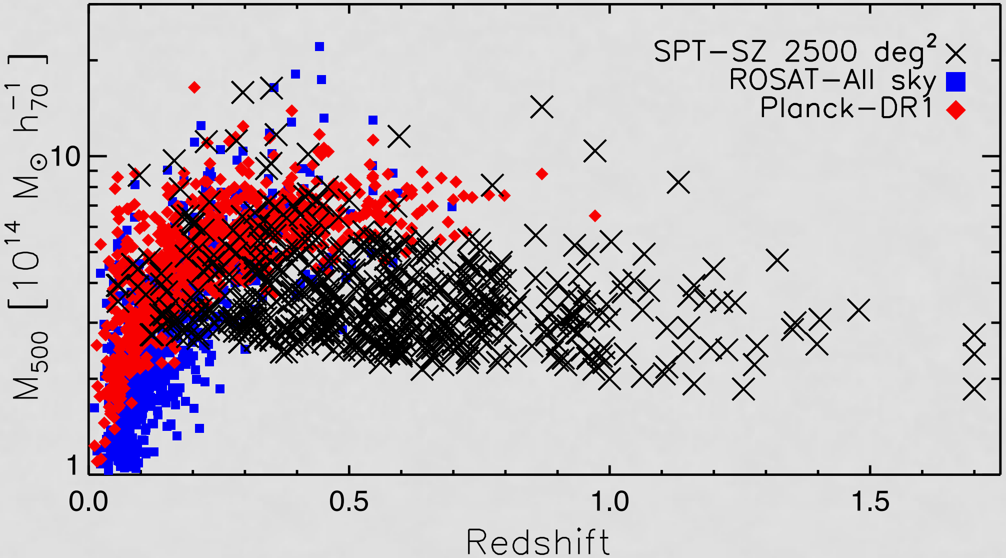
THE SOUTH POLE TELESCOPE – 2500 DEG^2 SURVEY

- SPT recently completed 2500 deg^2 survey of the southern sky
  - 516 clusters at M_{500} > ~2x10^{14} $M_\odot$
    - 416 new discoveries!
    - z_{median} = 0.55
    - Bleem et al. (~July 2014)
  - Relatively insensitive to redshift
    - ~40 new clusters at z > 1
  - Complimentary to eRosita
    - eRosita: low-mass, low-z
    - SPT: high-mass, high-z
      - Lots of overlap, of course!

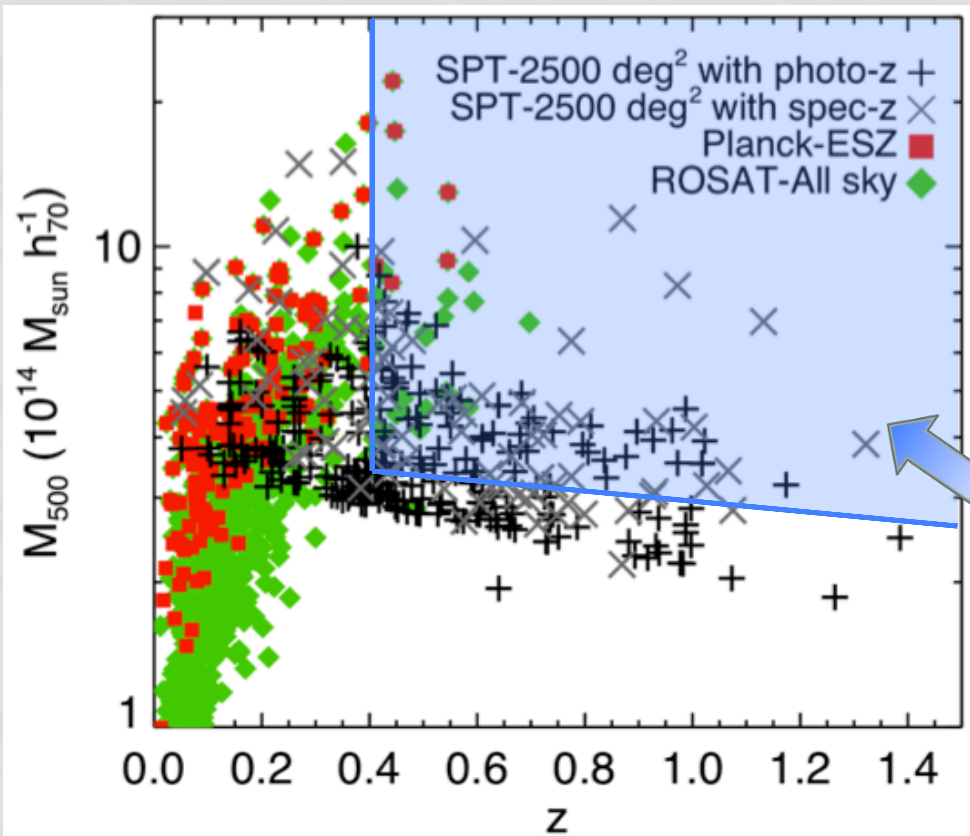


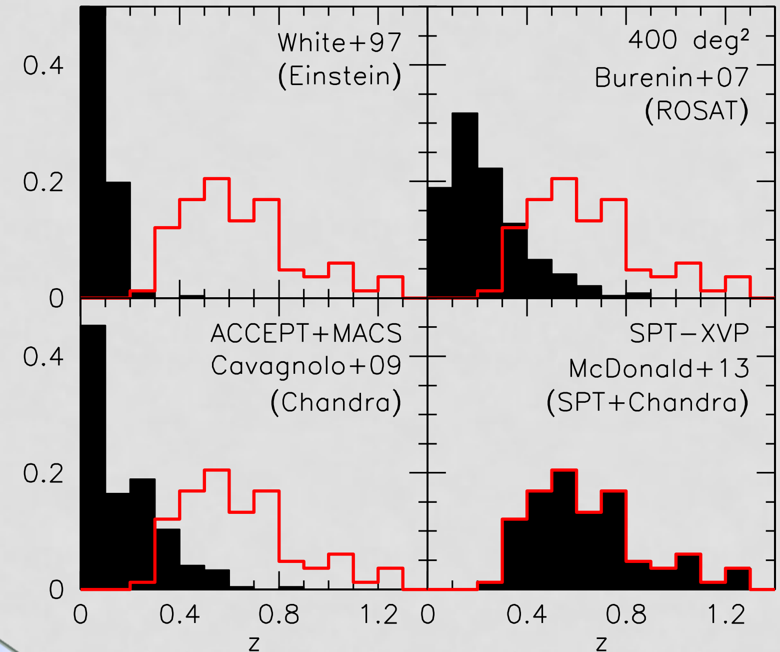
- Problem:
  - Very little additional info from SZ signal!



The South Pole Telescope – X-ray Follow-up

- Details about ICM from X-ray follow-up
  - Chandra Cycle 13 XVP (PI: B. Benson)



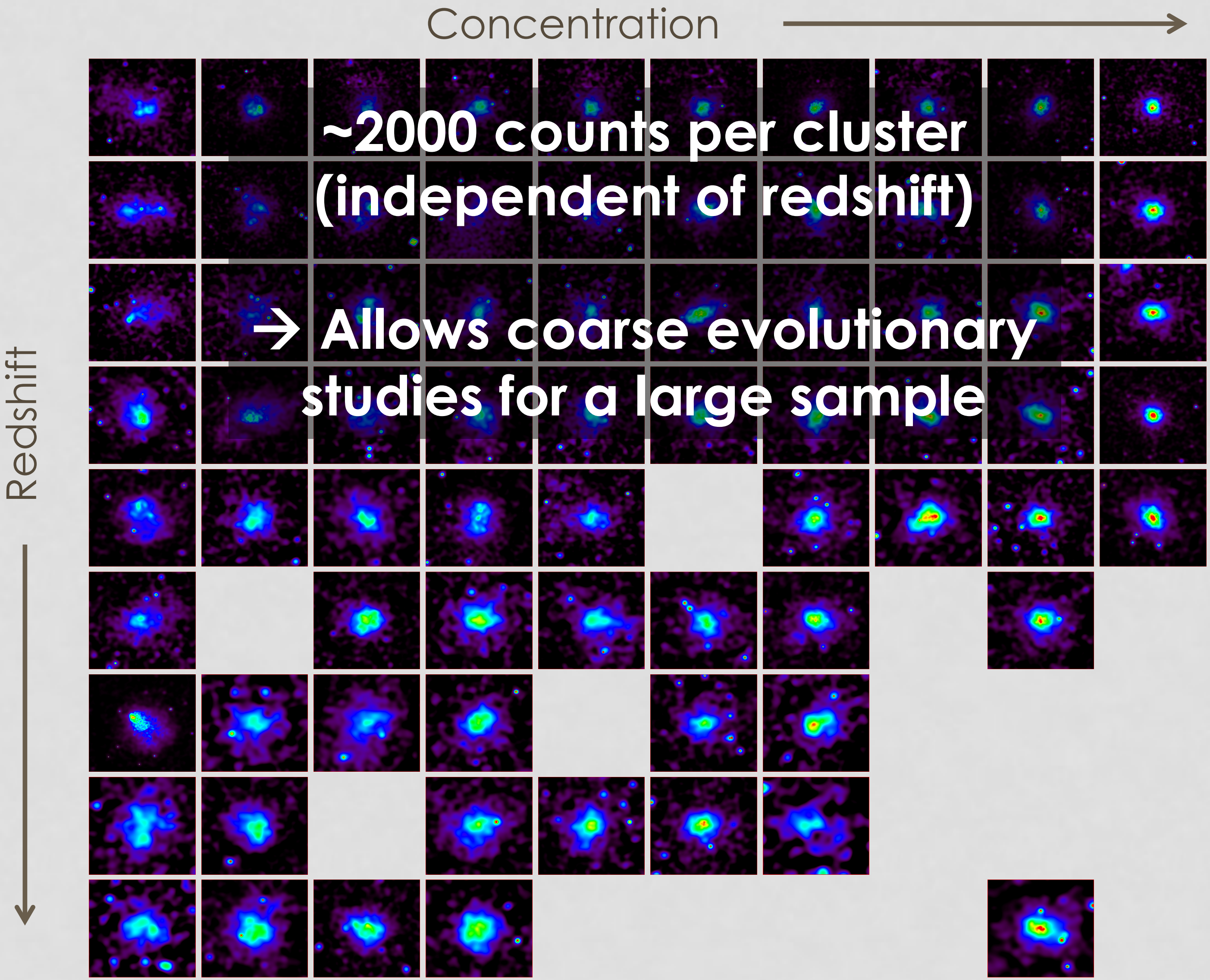


SPT – XVP

- Chandra follow-up of 80 most massive SPT-selected clusters from z=0.4 to z=1.2
- Observations finished in March, 2013

Couples pristine SZ selection with high-angular resolution of Chandra

SPT-XVP Observations



~2000 counts per cluster (independent of redshift)

→ Allows coarse evolutionary studies for a large sample

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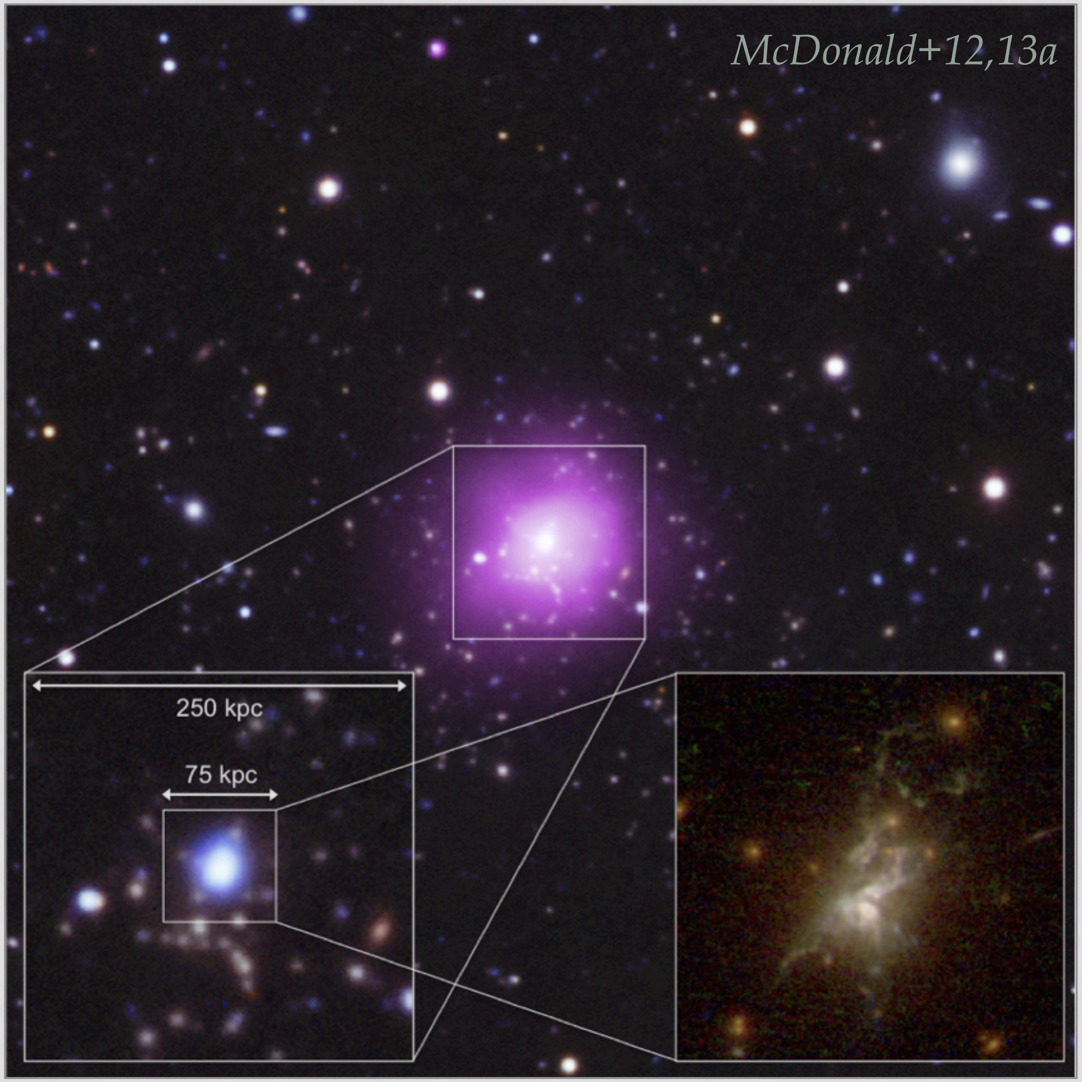
The Phoenix Cluster – A Starburst BCG

- Discovered in 2010 by the South Pole Telescope
  - *z = 0.597*
  - *Williamson+11*

- Most X-ray luminous cluster known
- Top 2-3 most massive clusters known
- Highest X-ray cooling rate known (~3000 $M_{\odot}$/yr)

- **IR/UV-inferred SFR of ~800 $M_{\odot}$/yr in BCG**
  - UV, far-IR, [O II], Ha
  - **30% of cooling flow!!!**

Open questions:
- Why is Phoenix cooling so efficiently?
- Is this cluster unique? Or is this a normal, short-lived phase?
- Is the starburst **really** fueled by the cooling flow?



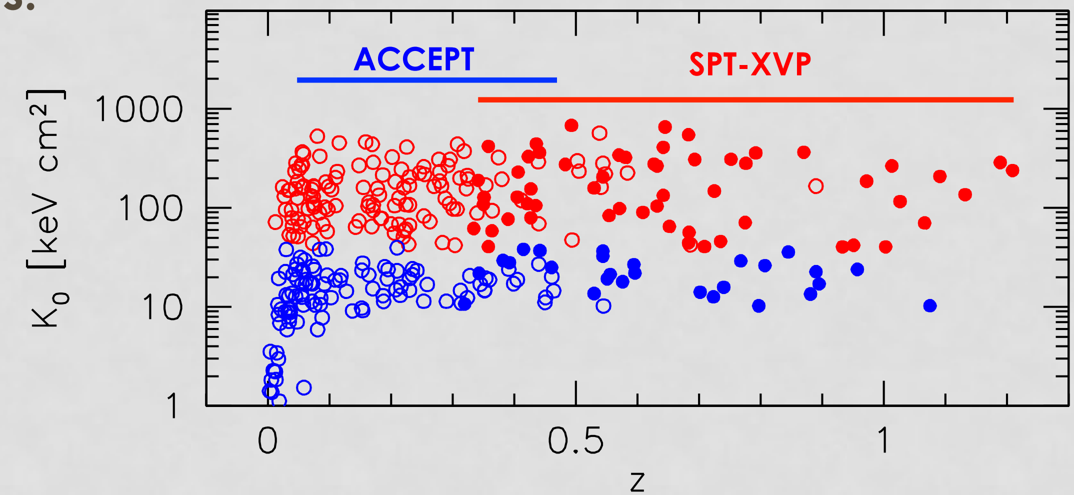
Evolution of Cluster Cores

Thermodynamics of cool cores:

- Minimum entropy at ~10 keV cm^2 has not changed since z ~ 1
  - Same trend found for t_{cool} and dM/dt
- Cool gas is stuck in "semi-cool" state

See also: Cavagnolo+09

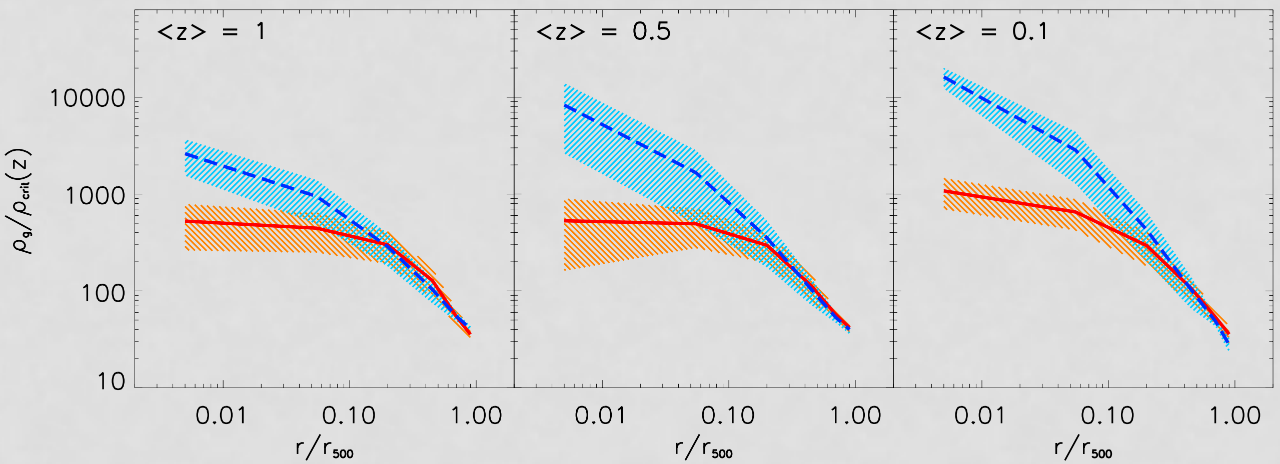
McDonald+13b



Size of cool cores:

- Cool cores have grown in density by factor of ~10 in 8 Gyr
- Above and beyond self-similar expectation

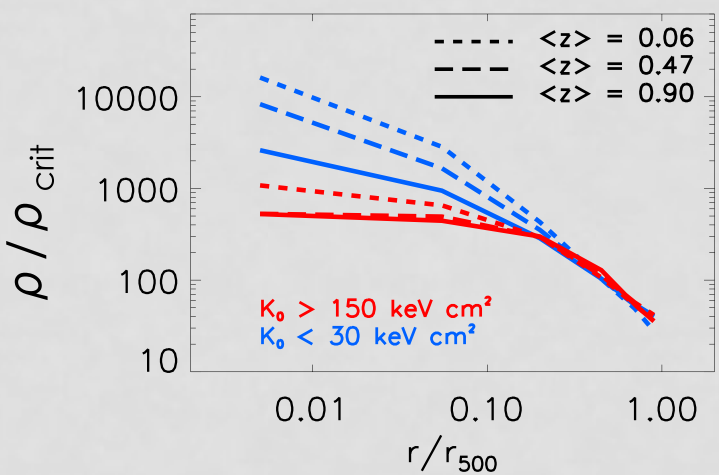
See also: Vikhlinin+07, Santos+10, Samuele+11, McDonald+11

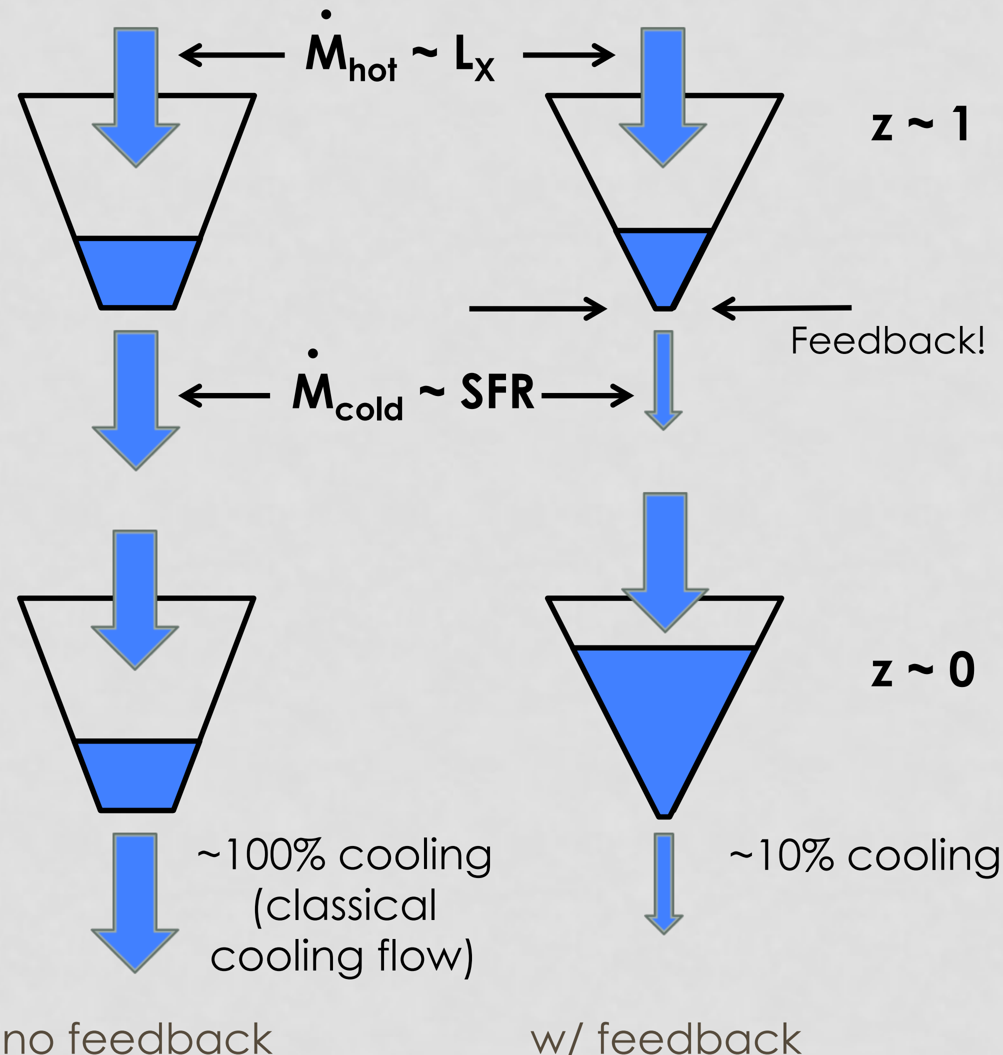


The Evolution of Cool Cores from z = 1 → 0
A Simple picture?

Interpretation:

- Cool core growth is the result of a **long-standing cooling flow** that is unable to efficiently cool below ~10 keV cm^2
- Low-entropy gas "piles up" over time
  - Mean growth is ~150 $M_\odot$/yr

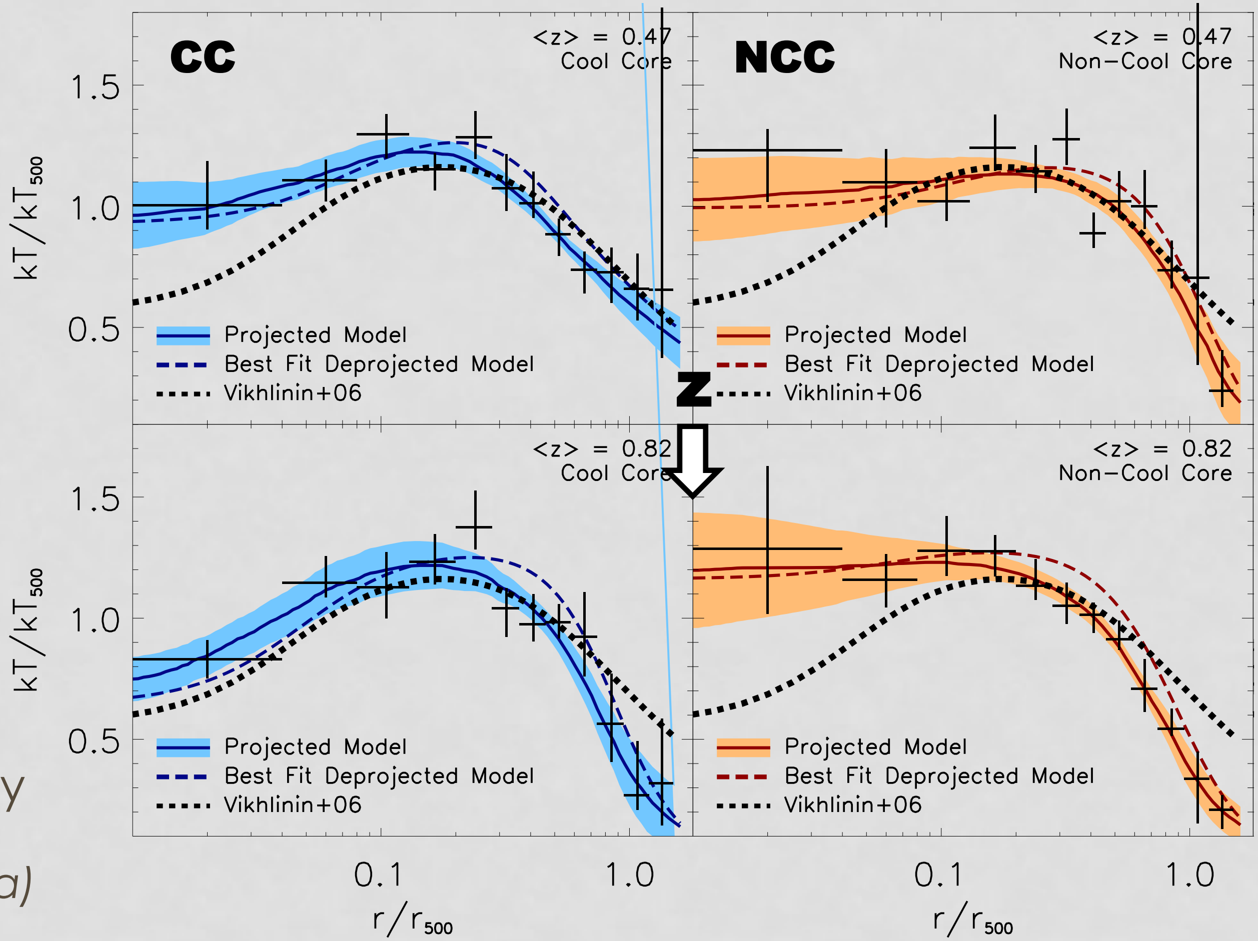




see e.g. Gaspari+11

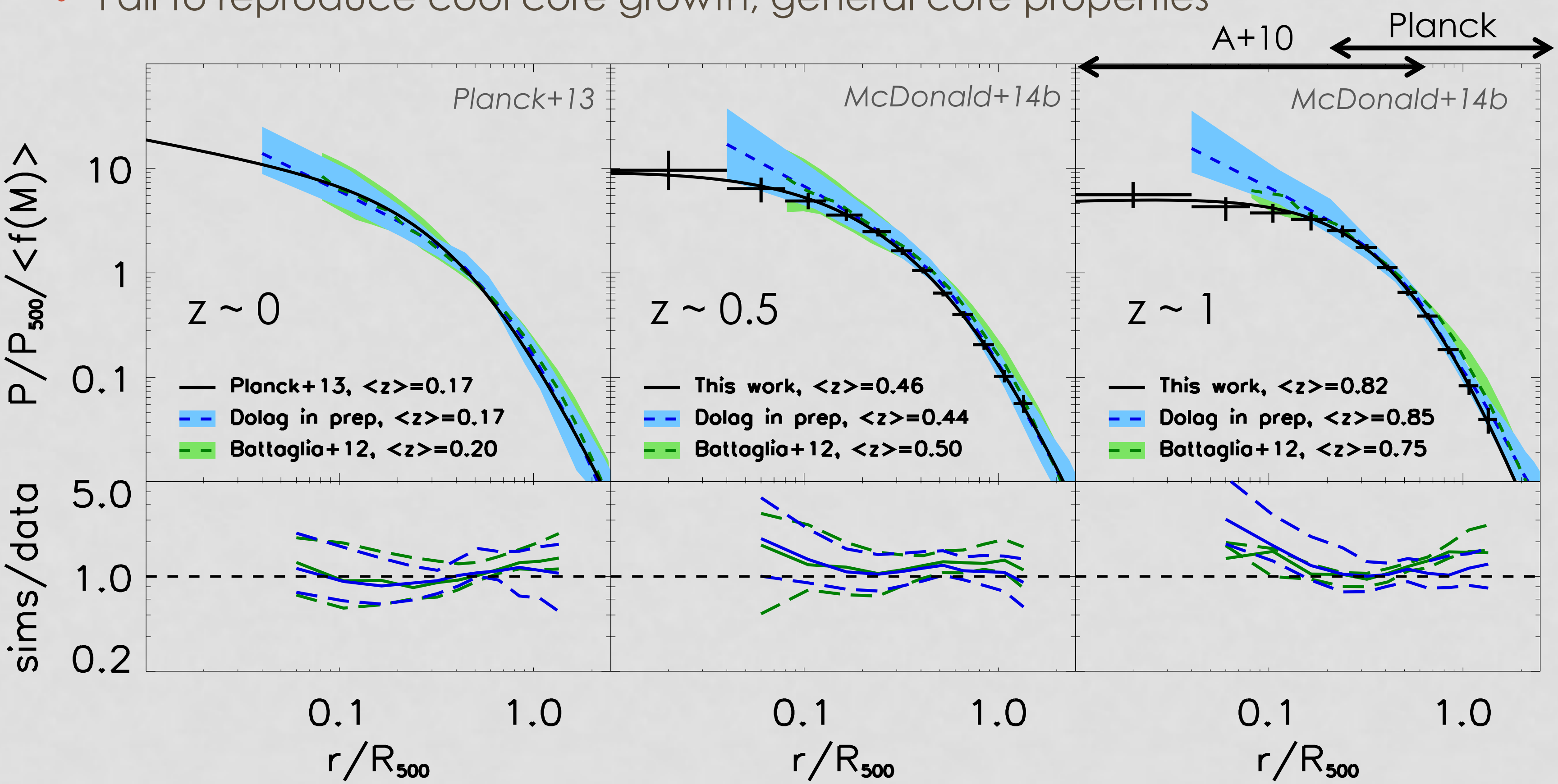
Stacking X-ray Analysis

- Stacking analysis of all 83 clusters allows us to measure the evolution of the average **temperature**, **pressure**, and **entropy** profiles!
- Joint-fit technique allows us to reach $>R_{500}$ at z~1
- Cool cores are cooler at high-z
- High-z clusters seem to have cooler outskirts
- Combine with gas density to get pressure, entropy
- *McDonald et al. (2014a)*



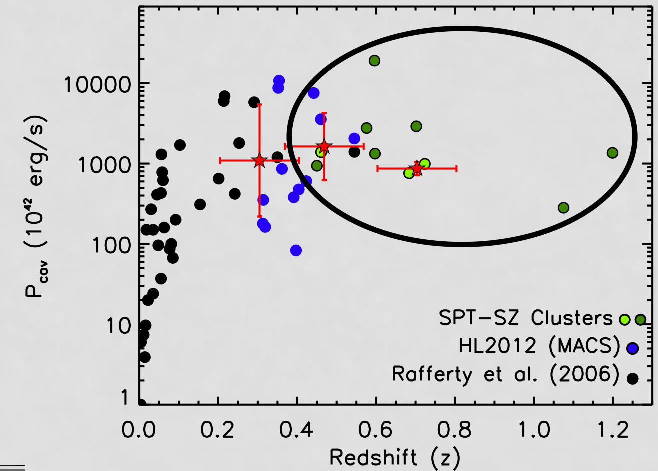
The Universal Pressure Profile

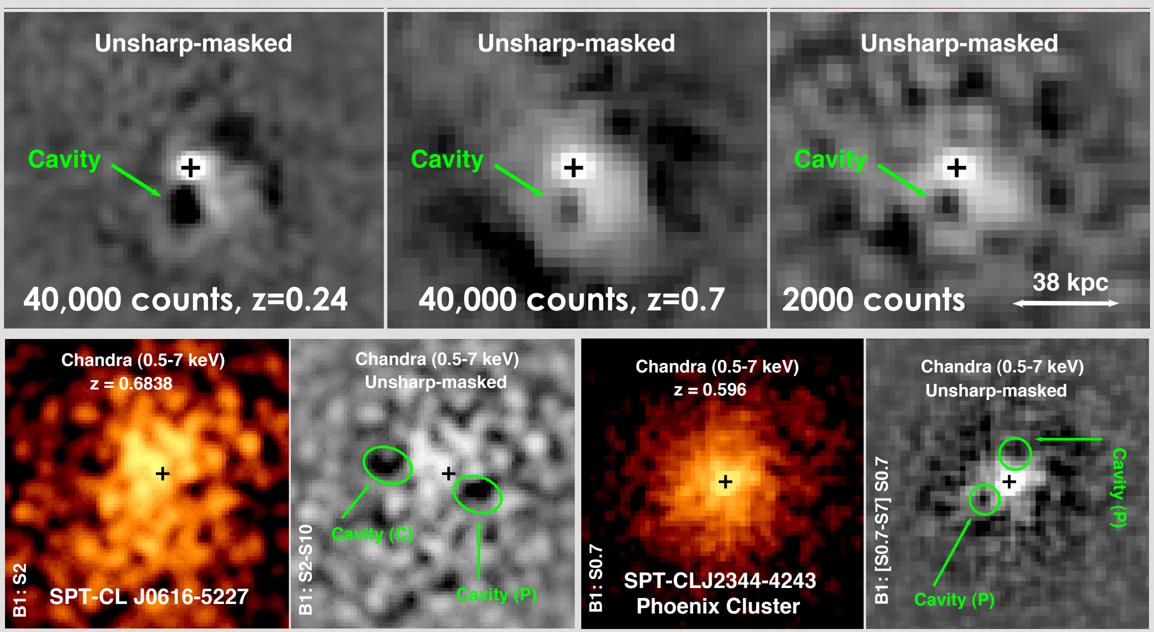
- Pressure profile is constrained from the core ($r < 0.1R_{500}$) to $r \sim 1.5R_{500}$
  - Complimentary to Arnaud+10 and Planck+13 profiles
- Simulations reproduce large-scale pressure profile (self-similarity)
  - Fail to reproduce cool core growth, general core properties

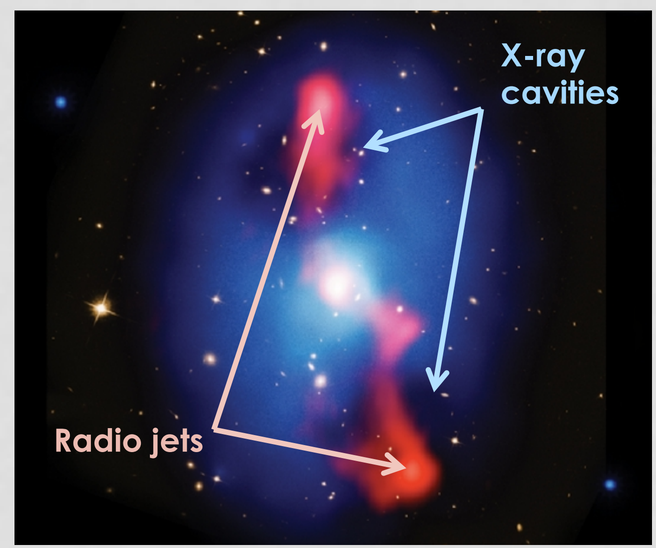


Strong AGN Feedback

- Quantify the mechanical feedback strength by measuring power required to inflate X-ray cavities: P_{cav}
  - Negligible evolution in P_{cav} over past ~8 Gyr
  - AGN feedback has been important since at least z ~ 1
  - *Hlavacek-Larrondo (Summer 2014)*



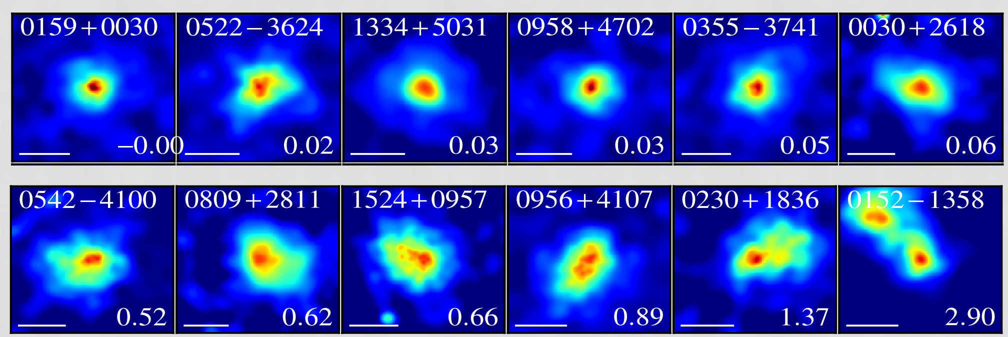




WHAT ELSE CAN YOU DO WITH 2000 COUNTS? A LOT!

- Identify "exciting" clusters
  - Phoenix (McDonald+12,13,14)
    - Extremely star-forming BCG
  - SPT-CLJ2040-4451 (Bayliss+13)
    - High global star formation rate
  - SPT-CLJ0205-5829 (Stalder+13)
    - Fully evolved @ z=1.322
- Measure global properties
  - $T_{X,500}$, $Y_{X,500}$, $M_{g,500}$
    - Assuming Y_X-M scaling relation
    - *Benson et al. (in prep)*
  - Metallicity
    - *Miller et al. (in prep)*
- Study the evolution of the cooling flow problem
  - Is the Phoenix cluster unique?
  - *McDonald et al. (in prep)*
- Stacking analyses!
  - Temperature/Pressure/Entropy
  - Electron density
    - *Nurgaliev et al. (in prep)*

- Cosmology
  - Use Y_X-inferred mass to calibrate SZ mass estimator
  - de Haan et al. (in prep)
- Baryon fractions
  - Combine X-ray + optical to estimate total mass in baryons
  - *Chiu et al. (in prep)*
- Quantify morphology
  - E.g., concentration, centroid shift, asymmetry
    - Nurgaliev et al. (in prep)



Nurgaliev+13

Take-Home Points

1. Between z ~ 1 and z ~ 0 :
   i. Cool cores have grown by a factor of ~20 and (some) BCGs have gone through short-lived phases of vigorous star formation
   ii. Feedback has, for the most part, regulated runaway cooling flows

2. The combined strengths of **SPT (selection)** and **Chandra (follow-up)** provides a powerful sample for studying galaxy cluster evolution

3. Shallow X-ray exposures (~2000 counts) are enough to address many of the interesting questions we have about galaxy cluster evolution

4. There is a lot more to come from the SPT-XVP survey!

1. 2500 deg^2 Survey: Bleem et al. (2014)
2. Cooling flows: McDonald et al. (2014)
3. Cosmology: de Haan et al. (2014)
4. Scaling Rel'ns: Benson et al. (2014)
5. Baryon Fractions: Chiu et al. (2014)
6. Metallicity: Miller et al. (2014)
7. AGN Feedback: H-L et al. (2014)
8. SB Profiles: Nurgaliev et al. (in prep)
9. Morphology: Nurgaliev et al. (2014)

…and much, much more!

Food for thought: SPT-XVP was 80 most massive clusters out of 416

How do we select clusters for X-ray follow-up when we have >>1,000 systems detected with SPT-3G / eRosita ?