The Properties of Cool Cores in Galaxy Clusters at z > 0.5

New Insights From SZ, Optical and X-ray Surveys

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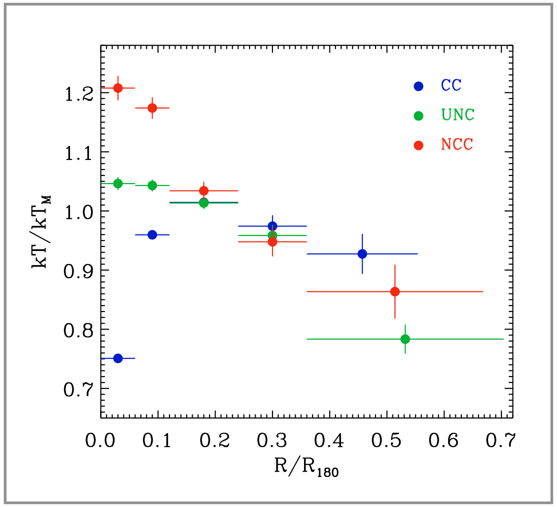
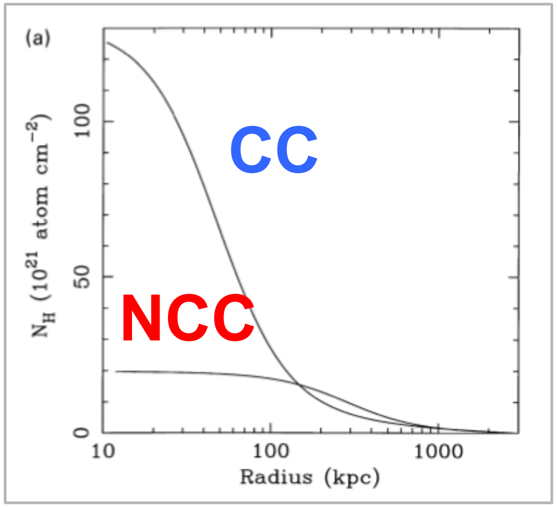
Introduction – The Cooling Flow Problem

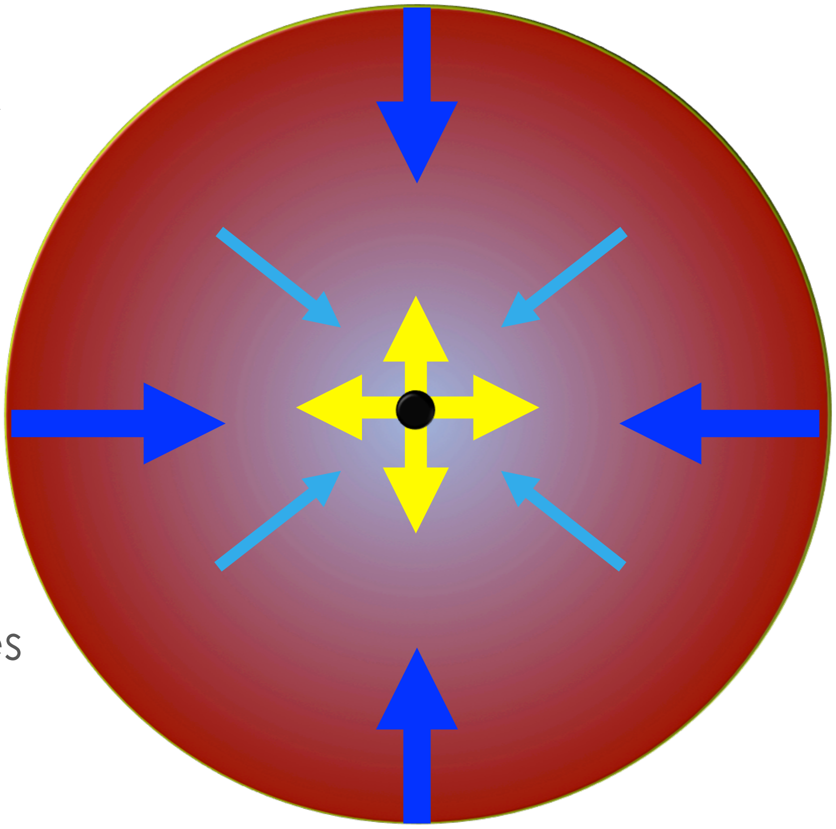
- Some galaxy clusters have L_X high enough in the center that the X-ray plasma should cool radiatively in less than a Hubble time.
  - $t_{cool} \propto kT^{1/2}/n_e$
- Implies cooling rates of ~ 100-1000 $M_\odot$/yr
  - Expect to see huge amounts of cold gas and star formation
  - The "cooling flow problem"
- Solution:
  - Assume that energy is injected into the core, effectively balancing the energy losses due to radiative cooling.
    - e.g. AGN feedback, mergers, conduction from outer layers…
    - Feedback-included cooling rates in more reasonable rate of ~1-10 $M_\odot$/yr





Introduction: Cool Core Clusters @ z ~ 0

- Current picture:
  - $>10^7$K gas cools radiatively via a combination of thermal bremsstrahlung and line cooling
  - AGN feedback counters this cooling, somehow depositing the right amount of energy over large physical scales
    - Radio-blown bubbles
    - Jets
    - Sound waves
  - Some fraction of the cooling ICM (a few %), which represents the imbalance between cooling and feedback continues to cool



Introduction: The Evolution of Cool Cores

- We know a lot about cool cores at z ~ 0…
  - How does this population evolve?
    - Important question, because it gives insight into how the heating/cooling balance has evolved over time

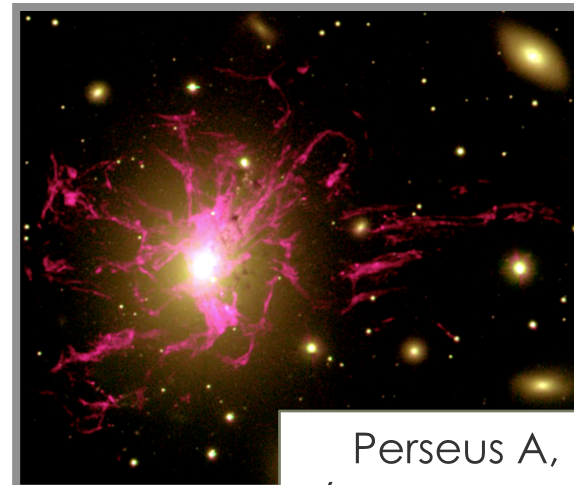
- What do we know so far?
  - Very few strong cool cores at z > 0.5
    - Vikhlinin et al. 2007, <z> ~ 0.5 ** 0/20 strong cool cores*
    - Ebeling et al. 2007, <z> ~ 0.55 ** 0/12 strong cool cores*
    - Santos et al. 2008, <z> ~ 0.8 ** ~1/15 strong cool cores*
  - Implies rapid evolution, but how rapid?
  - X-ray surveys may be biased
    - Conventional wisdom says they should be biased towards detecting cool cores, as the SB is higher
      - But! Strong cool cores at high-z may look like X-ray point sources, wouldn't be classified as clusters in shallow surveys

A Convenient, New Probe of ICM Cooling?

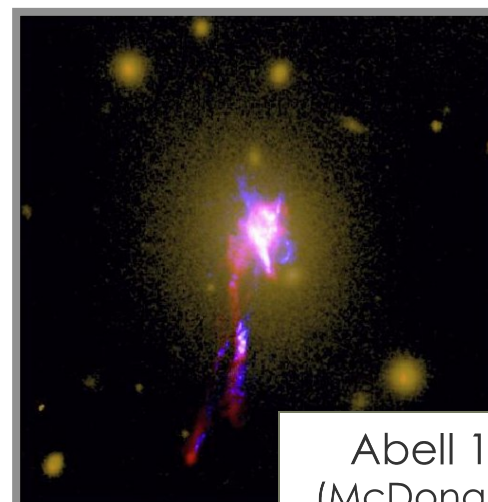
- The presence of emission-line nebulae strongly correlates with the ICM cooling properties
  - $dM/dt \propto L_{H\alpha}$ *(e.g., McDonald+10,11)*
  - $K_0 \propto L_{H\alpha}$ *(e.g., Cavagnolo+08)*
  - $R_{cool} \propto R_{H\alpha}$ *(e.g., McDonald+10,11)*
  - *Hα emission where t_{cool} is minimal (McD+10)*

- *Maybe we can use the presence of optical line emission to classify a galaxy cluster as cool core or non-cool core?*
  - *Advantages:*
    - *Less expensive observations*
    - *Large online databases (e.g., SDSS)*
    - *Different biases in optically-selected samples*

(See also, Megan Donahue's PhD Thesis, circa 1990)



Perseus A, (Conselice+01)

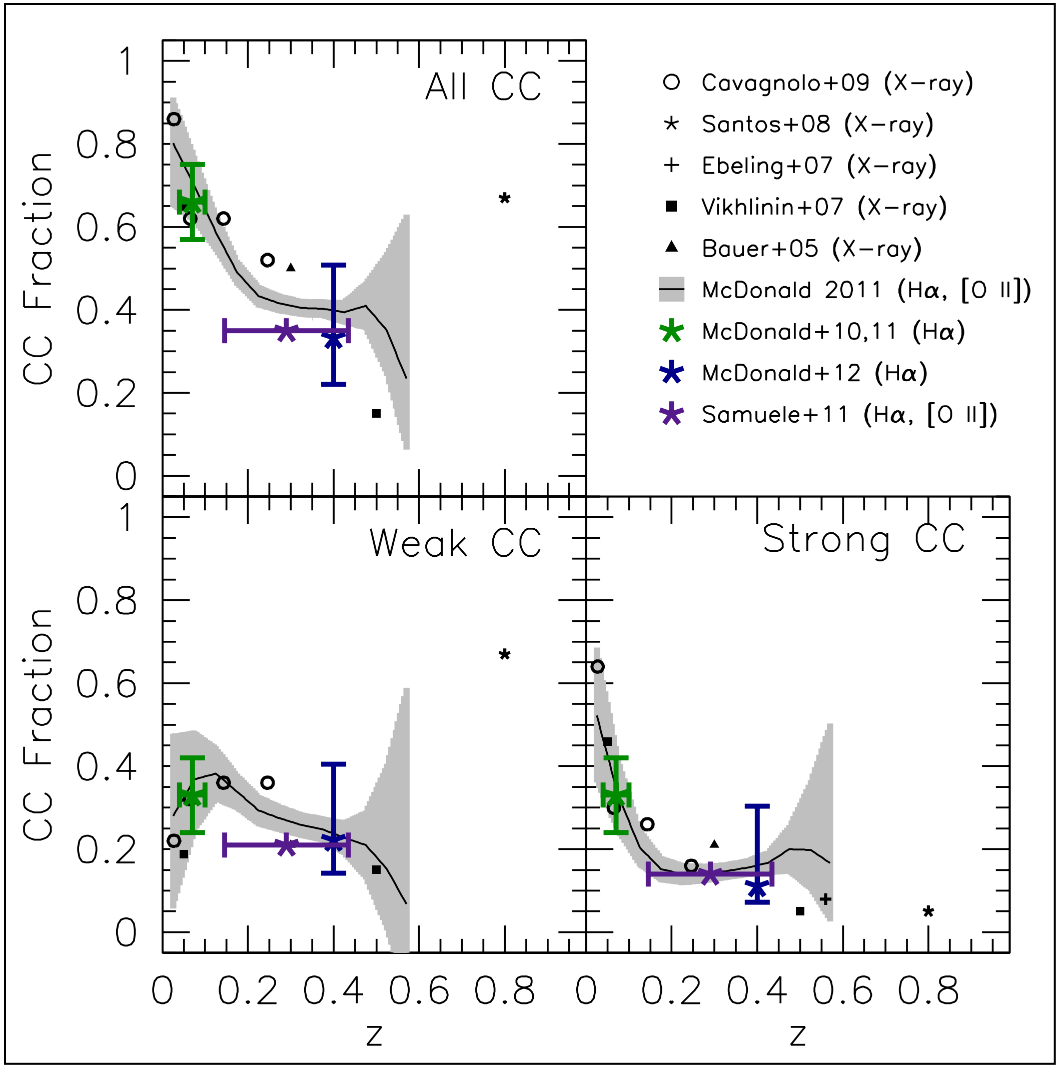


Abell 1795 (McDonald+09)

A Convenient, New Probe of ICM Cooling?

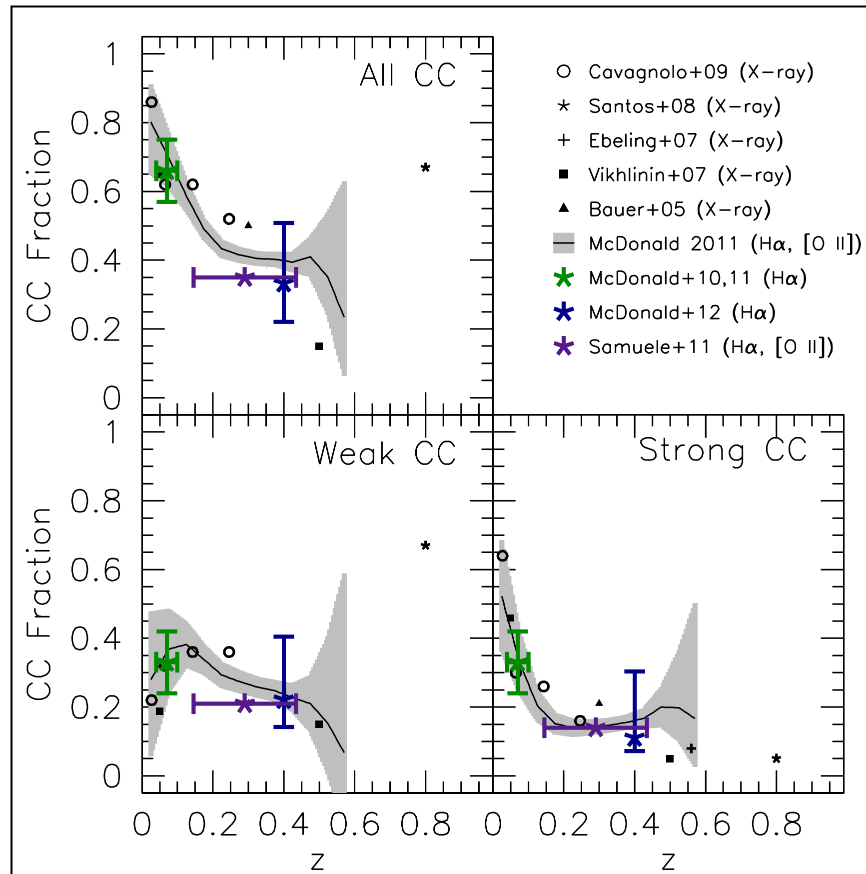
- Grey regions (McDonald 2011)
  - SDSS spectroscopy of >50,000 optically-selected BCGs
- Green point (McD+10,11a)
  - Hα survey of ~30 galaxy groups and clusters
- Purple point (Samuele+11)
- Blue point (McD in prep)
  - Hα survey of 10 distant galaxy clusters

These results confirm rapid evolution of strong cool cores observed in X-ray



Evolution of Emission-Line Nebulae From z=0 to z=0.5

- What does it mean?
- ~3-4 Gyr ago, strong cooling and multi-phase gas in the ICM was rare
  - Implies that:
    - ICM heating was more effective at early times (e.g., higher rate of mergers)
    - Cooling began to dominate around z ~ 1
      - Assuming initial central cooling time is several Gyr



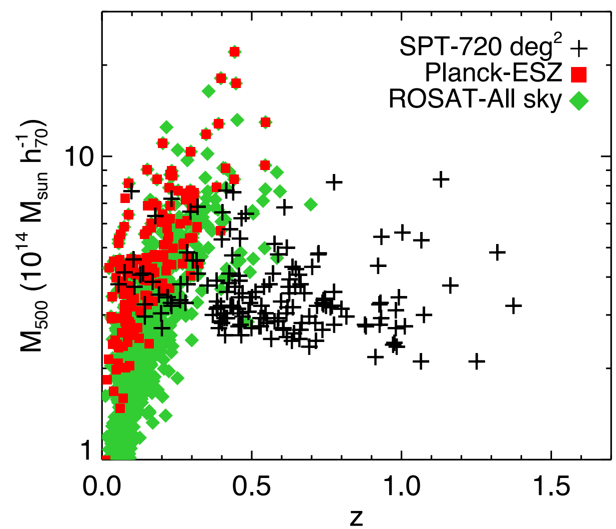
- May be an epoch of strong cooling at z > 0.5, but current surveys suffer from biases in both sample selection and methodology
  - E.g., difficult to spatially separate cool cores from AGN at these redshifts.

Going beyond z > 0.5…

- The number of known galaxy clusters at z > 0.5 is relatively small
  - X-ray all-sky surveys are shallow (e.g., ROSAT)
  - Deep, pointed X-ray observations cover relatively small area (Chandra, XMM)
  - SDSS has few BCG redshifts for z > 0.5
- But there's hope!
  - Optical:
    - BOSS – SDSS III
    - DES
    - LSST
    - Plenty of large optical imaging+ spectroscopy surveys coming online
  - Sunyaev Zel'dovich:
    - Surprisingly unbiased for/against CCs!

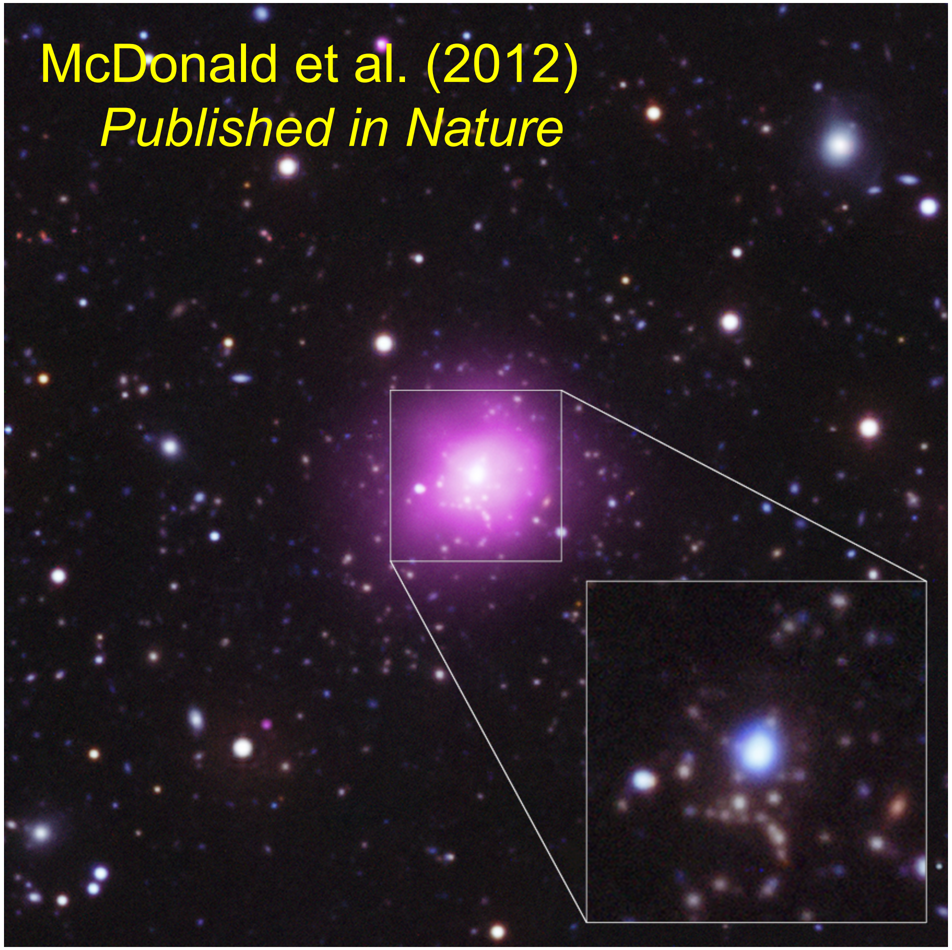
SDSS III

DARK ENERGY SURVEY



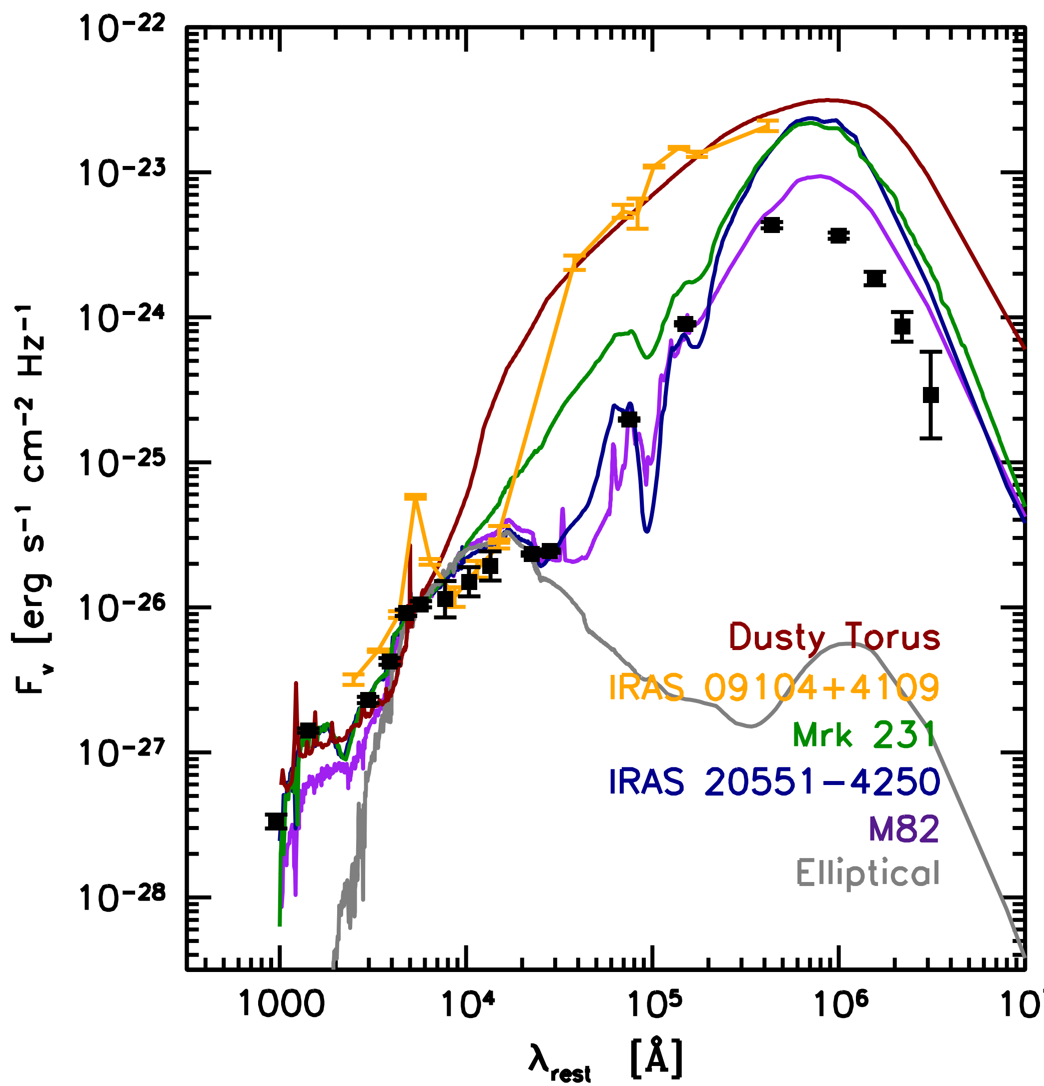
Uncovering High-z Cool Cores with the SPT…

- Common (mis)conception that SZ-selected clusters are all trainwrecks…
- SPT-CLJ2344-4243
  - The "Phoenix Cluster"
  - z = 0.6
  - Classical dM/dt ~ 2200 $M_{\odot}$/yr
    - Accounting for gravitaitonal work done in cooling flow
  - SFR = 740 +/- 160 $M_{\odot}$/yr
    - AGN contribution removed!
  - Central AGN is quasar-like
    - Relatively weak in the radio given strong cooling flow
  - Suggests that, in this cluster, radio-mode feedback is insufficient to halt runaway cooling



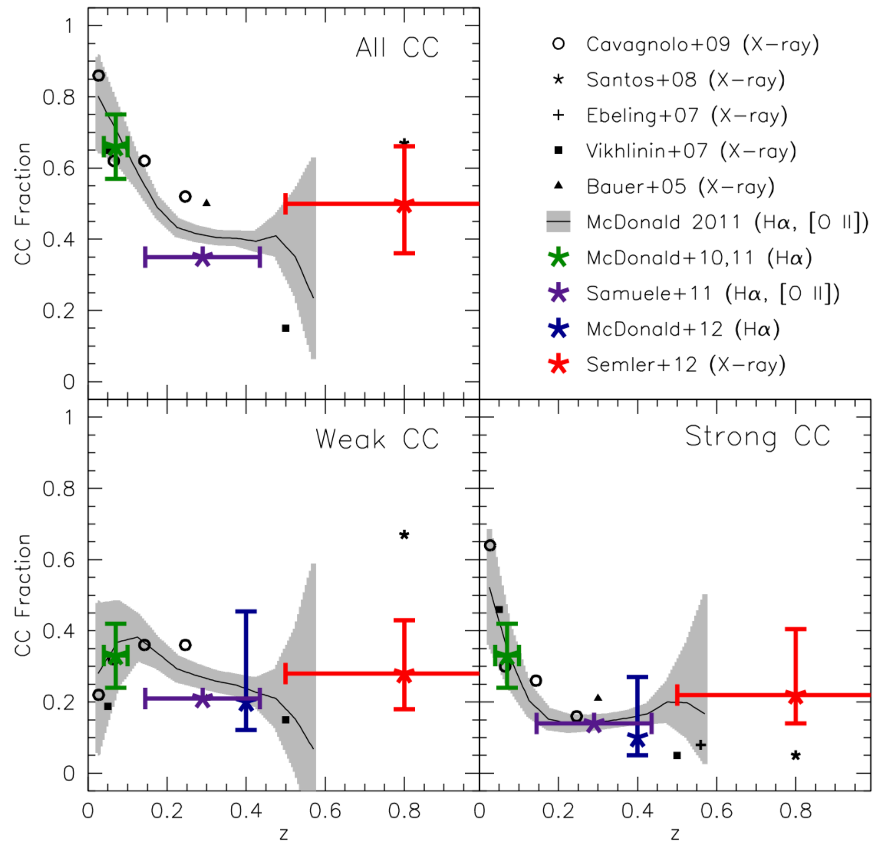
Phoenix A – No Longer Red & Dead

- Combining our ground-based optical data with:
  - GALEX (near-far UV)
  - 2MASS (near IR)
  - WISE (near-mid IR)
  - Herschel (mid-far IR)
- SED is reminiscent of a dusty starburst with a heavily obscured AGN
  - E.g., M82
- Mid-far infrared flux is inconsistent with the picture of only an embedded quasar-like AGN



Uncovering a Population of Strong Cool Cores at z > 0.5

- Semler et al. (2012)
  - 9 SPT-selected galaxy clusters at 0.4<z<1 with Chandra data
    - ~30% strong cool cores
    - ~30% weak cool cores
    - ~40% non-cool cores
  - Suggests only very weak (if any) evolution of cool cores over z=0→1
- Coming soon:
  - Chandra XVP to study 80 most massive SPT-selected clusters.
  - Factor of ~10 increase over Semler+12



Summary:

1. Hα, [O II] emission lines in BCG spectra are an excellent probe of ICM cooling (McDonald 2011)
   - Can be used to efficiently classify large samples of clusters as CC or NCC
   - **Especially useful for large SZ/optical/infrared surveys which have optical spectroscopy of BCGs but no X-ray data!**
2. Systems like Perseus A are rare at $0.3 < z < 0.6$ (McDonald 2011)
   - Most likely due to enhanced rate of mergers and AGN at earlier times
   - May also be due to:
     - Decoupling of multiphase gas and cooling ICM at earlier times
     - Bias against strong cool core detection in optical surveys (unlikely…)
3. **SPT surveys are finding evidence for a significant population of high-z strongly cooling galaxy clusters**
   - Phoenix cluster, at $z = 0.6$, is strongest cool core in the known Universe (McDonald+12)
   - 50% of clusters at $z > 0.6$ have cool cores (Semler+12)