NEW CONSTRAINTS ON
GALAXY CLUSTER
EVOLUTION FROM THE
SOUTH POLE TELESCOPE

THE X-RAY UNIVERSE
DUBLIN, IRELAND – JUNE 24, 2014

MICHAEL MCDONALD
HUBBLE POSTDOCTORAL FELLOW, MIT

In collaboration with: B. Benson (Chicago), M. Bautz (MIT), E. Miller (MIT), A. Vikhlinin (CfA), B. Stalder (CfA), J. Hlavacek-Larrondo (Montreal), A. C. Edge (Durham), H. Lin (Harvard U) and the rest of the South Pole Telescope Collaboration
Background

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 $\rightarrow$ Inner 100 kpc $\rightarrow$ 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

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
    - ~10^-5-10^-1 cm^-3
    - At large radii, ~10 e^- per m^3!

- **Extent/mass**
  - Extends for several Mpc
  - Total mass in gas ~10^{14} M_☉

- **Morphology**
  - Retains imprint of major events

- **AGN Feedback**
  - Bubbles in ICM

- **Relaxed**
  - Smooth, symmetric

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

- **Recent interaction**
  - Single-peaked, spiral structure
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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?

\[ z \approx 2 \quad \text{to} \quad z \approx 0 \]

Cooling Flow Prediction
**The Cooling Flow Problem**

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**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?*
  - Radio-mode AGN feedback appears to be perfectly offsetting cooling in every nearby galaxy cluster
  - Deviations from energy balance are $\sim 1\%$ (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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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 $1/d_L^2$

Michael McDonald - "The X-ray Universe" - Dublin, Ireland - June 24, 2014
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 $\sim (1+z)^4$
  - 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 $z < \sim 0.5$
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

June 24, 2014
Michael McDonald - "The X-ray Universe" - Dublin, Ireland - June 24, 2014
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!

Figure 1. Visual representation of the SPT-SZ data and matched filtering process described in Sections 2 and 3. Panels (a) and (b) show 6×6 cutouts of 95 and 150 GHz maps from the ra21hdec-60 field; the displayed temperature range is ±300 µK. The maps are made from data that have been only minimally filtered (scan-direction high-pass filter at `⇠50) and show the main features of SPT-SZ survey data: large-scale primary CMB fluctuations, emissive point sources, and SZ decrements from galaxy clusters. Panel (c) shows the azimuthally averaged spatial-spectral filter optimized for detection of ✓c=0.

3.1. Cluster Extraction

As described in §2, the SPT-SZ survey fields are observed at 3 frequency bands centered at approximately 95, 150 and 220 GHz. These maps contain signal from a range of astrophysical sources. For the purposes of this analysis, we characterize the observed temperature, T, in the maps at frequency ✓i and location x by:

\[ T(x, ✓i) = B(x, ✓i) \ast [f_{SZ}(✓i) T_{CMB} y_{SZ}(x) + n_{astro}(x, ✓i)] + n_{noise}(x, ✓i). \]
Background

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**The South Pole Telescope – 2500 deg² Survey**

- SPT recently completed 2500 deg² survey of the southern sky
  - 516 clusters at \( M_{500} > \sim 2 \times 10^{14} M_\odot \)
    - 416 new discoveries!
    - \( z_{\text{median}} = 0.55 \)
    - Bleem et al. (~July 2014)
  - Relatively insensitive to redshift
    - \sim 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!

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The Survey

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

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The SPT-SZ Survey (2007-2011):

- The highest resolution and sensitivity map of the CMB
  (covering 2500 deg² ~ 6% of sky)

- **Final survey depths of:**
  - 90 GHz: 40 uK_CMB-arcmin
  - 150 GHz: 18 uK_CMB-arcmin
  - 220 GHz: 80 uK_CMB-arcmin

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SPT–SZ 2500 deg² ×

ROSAT–All sky

Planck–DR1

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**Notable Individual Systems**

- **SPT-CL J0509-5342:** First identified SPT-CL J0509-5342, SPT-CL J0546-5345
- **SPT-CL J0540-5744, SPT-CL J0330-5228:** Menanteau et al. 2010b
- **SPT-CL J0102-4915:** First reported in Marriage et al. (2011), this cluster is also known as “El Gordo” (Menanteau et al. 2012).
- **SPT-CL J2344-4243:** This system, first reported in Bleem et al. (~July 2014), is also known as the “Phoenix Cluster.” This massive cluster at \( z = 0.0596 \) exhibits an exceptionally high rate of star formation and is the most X-ray luminous cluster known. The properties of this system are explored in detail in McDonald et al. (2012, 2013a, 2014b).
- **SPT-CL J0658-5556:** This cluster is the well-known “Bullet” cluster (1ES 0657-558). Detected in the SPT-SZ sample.
- **SPT-CL J2248-4431:** First reported as ACO S1063, Böhringer et al. (2004), is the second most massive cluster in the REFLEX X-ray catalog and is the second most significant detection in the SPT-SZ sample.
- **SPT-CL J2011-5228:** SPT-SZ Journal, 2010. SPT-SZ Journal, 2011. This cluster is also known as “El Gordo” (Menanteau et al. 2012). Detected in the SPT-SZ sample. This cluster, more X-ray luminous than the Bullet Cluster and the second most X-ray luminous cluster in the SPT sample. This cluster, more X-ray luminous than the Bullet Cluster and the second most X-ray luminous cluster in the SPT sample.
- **SPT-CL J0102-4915:** First reported in Marriage et al. (2011), this cluster is also known as “El Gordo” (Menanteau et al. 2012).
THE SOUTH POLE TELESCOPE – X-RAY FOLLOW-UP

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

Couples pristine SZ selection with high-angular resolution of Chandra

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

McDonald+12,13a
**Evolution of Cluster Cores**

**Thermodynamics of cool cores:**
- Minimum entropy at \( \sim 10 \text{ keV cm}^2 \) has not changed since \( z \sim 1 \)
  - Same trend found for \( t_{\text{cool}} \) and \( dM/dt \)
- Cool gas is stuck in “semi-cool” state

*See also: Cavagnolo+09*

**Size of cool cores:**
- Cool cores have grown in density by factor of \( \sim 10 \) 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 $z = 1 \rightarrow 0$

A SIMPLE PICTURE?

Interpretation:

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

### Graph

- **$\rho / \rho_{\text{crit}}$** vs. $r / r_{500}$
- $K_\phi > 150$ keV cm$^2$
- $K_\phi < 30$ keV cm$^2$

### Diagram

![Diagram of cool core growth and feedback](image)

- **$\dot{M}_{\text{hot}} \sim L_X$**
- **$\dot{M}_{\text{cold}} \sim \text{SFR}$**
- **$z \sim 1$** Feedback!
- **$z \sim 0$**
- **$\sim 100%$ cooling (classical cooling flow)**
- **$\sim 10%$ cooling**
- no feedback vs. w/ feedback

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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 \( z \sim 1 \)

- 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

![Graph showing pressure profiles at different redshifts](image)
**Strong AGN Feedback**

- Quantify the mechanical feedback strength by measuring power required to inflate X-ray cavities: $P_{\text{cav}}$
  - Negligible evolution in $P_{\text{cav}}$ over past $\sim 8$ Gyr
  - AGN feedback has been important since at least $z \sim 1$
  - 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)
**Take-Home Points**

1. Between $z \sim 1$ and $z \sim 0$:
   i. Cool cores have grown by a factor of $\sim 20$ 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 ($\sim 2000$ 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)

   …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?*