AGN in dense environments:
Cluster AGN Topography Survey (CATS)

Becky Canning

Allen, Brandt, Ehlert, King, von der Linden, Luo, Mantz, Morris, Noordeh, Xue + SPT
Environmental effects

Figure 1: Empirical evidence suggests a close link between super-massive black holes (SMBHs) and their host galaxies.

Left: The SMBH mass-velocity dispersion ($M$) relation for galaxies with dynamical mass measurements (figure from Gultekin et al. 2009). The integrated growth of SMBHs correlates with that of their host galaxy.

Right: In many of the most massive galaxies we directly observe SMBHs interacting with the surrounding interstellar or intracluster medium (ICM). The SMBH in the central galaxy of MS 0735.6+7421 hosts powerful radio jets (pink) that are depositing energy into the ICM (blue) out to a distance of 200 kpc (McNamara et al. 2008). SMBHs influences the evolution of their host galaxies. In the most massive galaxies at low redshift, AGN jets are directly observed to blow bubbles filled with relativistic particles, providing a heat source that can, in principle, balance the radiative cooling rates of the X-ray emitting gaseous halo (Fig. 1; for a review see e.g. Fabian 2012). This 'mechanical feedback' from AGN is required in simulations to recover the cut off at the bright end of the galaxy luminosity function (Sijacki et al. 2006).

There are also strong empirical correlations between the masses of SMBHs and the properties of their host galaxies, such as the mass (Magorrian et al. 1998; Haring & Rix 2004), velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Gultekin et al. 2009, Fig. 1) and luminosity (Kormendy & Richstone 1995; Marconi & Hunt 2003) of the host galaxy bulge. The global histories of SMBH accretion rates and star-forming activity over cosmic time are remarkably similar (Silverman et al. 2008; Aird et al. 2010; Merloni & Heinz 2013). These observations support the idea that the stellar growth of galaxies and the growth of SMBHs is strongly coupled. However, they may also spring from a non-causal origin (e.g. Peng 2007; Jahnke & Maccio 2011).

Despite these clear links, recent studies have found inconclusive results when directly comparing AGN activity and star formation. While high luminosity AGN ($>10^{46}$ erg s$^{-1}$) have been found to be associated with star-forming galaxies (e.g. Lutz et al. 2008; Bonfield et al. 2011), the hosts of moderate and lower luminosity AGN are observed to have a wide range of IR and UV properties (e.g. Silverman et al. 2009; Goulding et al. 2014). These diverse findings have frustrated attempts to uncover the processes responsible for triggering AGN and the detailed nature of the AGN-host galaxy interaction.

Observations of AGN-galaxy properties are further complicated by the varying time-scales for AGN activity and star formation processes, variability and potential changes in the accretion mode.
AGN in dense environments

- Ram pressure stripping, evaporation, starvation, tidal effects
- Rates of mergers and interactions

Depend on:
- Position within host cluster
- Mass of host cluster

![Graph showing dependence of AGN fraction on redshift.](image)

Adapted from Krishnan+2017
Challenges

Cluster AGN rare - background dominated

Incomplete redshifts = differential measurements

Need large survey but can leverage cluster self similarity
Challenges

- Cluster AGN rare - background dominated
- Incomplete redshifts = differential measurements

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Fortunately people enjoy looking at clusters with Chandra!
Challenges

Cluster AGN rare - background dominated

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Need large survey but can leverage cluster self similarity

Abundant X-ray data!

**Blessing:** Can use X-ray data to characterize environment and AGN.
Challenges

Cluster AGN rare - background dominated
Incomplete redshifts = differential measurements

Need large survey but can leverage cluster self similarity

Abundant X-ray data!

Blessing: Can use X-ray data to characterize environment and AGN.

Curse: Diffuse X-ray emission increases background. Affects both completeness and purity of AGN sample.
CATS - Cluster AGN Topography Survey

Adapted from Brandt & Alexander 2015

2–10 keV flux limit (erg cm$^{-2}$ s$^{-1}$) vs. $\Omega$ (degrees$^2$)

- HEAO1 A–2
- ASCA Medium
- HELLAS
- ASCA Deep
- XBootes
- ChaMr
- COSMOS
- C–COSMOS
- CDF–S
- E–CDF–S
- SSA 22
- AEGIS–X Deep
- CDF–N
- CDF–S
- 3XMM
- All Sky
CATS Selection

X-ray: 550 clusters 
~40,000 point sources 
(27 Ms Chandra Data)

Radio: 183 clusters 
(FIRST survey)

IR and UV: WISE 550 clusters; Spitzer 320 clusters; Galex 550

Spectroscopy: 7
z=0.4, 12 z=0.8, 1 z=2 clusters

Noordeh. in prep

Einstein Symposium
AGN number densities

**X-Ray**
Canning+ in prep

**Radio**
King+ in prep

Number density (deg⁻²)

Radius (r/r₅₀₀)

COSMOS
AGN fractions

![Graphs showing AGN fractions in X-Ray and Radio modes.](image)
AGN fractions

How do these evolve?

Einstein Symposium
Model

Is increased number density related to the mass or redshift of the host cluster?

\[ N_{\text{obs}}(> f, r, z) = A D_A^2 r_{500} \Phi(> L, z) \left( \frac{r}{r_{500}} \right)^\beta + N_{\text{field}} \]

Projected number density of observed X-ray AGN in a cluster field at a given cluster z, r and above flux limit f

\[ A \rightarrow A_0 (1 + z)^\eta \left( \frac{M_{500}}{10^{15} M_\odot} \right)^\zeta \]

\[ \beta \rightarrow \beta_0 + \beta_z (1 + z) + \beta_m \left( \frac{M_{500}}{10^{15} M_\odot} \right) \]

Projecting number density of X-ray AGN expected in cluster above flux limit

Projecting number density of all field AGN above flux limit

'Scale factor' which allows number density to exceed co-moving field AGN

Scaled by radius

Co-moving field AGN number density at z and above luminosity related to flux limit

Some radial dependence
Model

Is increased number density related to the mass or redshift of the host cluster?

\[ N_{\text{obs}}(> f, r, z) = A R^2 r_{500} \Phi(> L, z) \left( \frac{r}{r_{500}} \right)^\beta + N_{\text{field}} \]

Null hypothesis - same as field

Projected number density of observed X-ray AGN in a cluster field at a given cluster z, r and above flux limit f

AGN expected in cluster above flux limit

for all field AGN above flux limit

'Scale factor' for number density of co-moving field AGN

and above luminosity related to flux limit

\[ A \rightarrow A_0 (1 + z)^\eta \left( \frac{M_{500}}{10^{15} M_\odot} \right)^\xi \]

\[ \beta \rightarrow \beta_0 + \beta_z (1 + z) + \beta_m \left( \frac{M_{500}}{10^{15} M_\odot} \right) \]

Ashley’s talk next!
Model

No evolution beyond the field X-ray AGN population with redshift. No radial variation. But...

\[ A \rightarrow A_0 (1 + z)^\eta \left( \frac{M_{500}}{10^{15} M_\odot} \right)^\zeta \]

-4 -3 -2 -1 0
\[ \zeta \]

probability density
0.8 0.6 0.4 0.2 0.0

Observed mass scaling \( \zeta = -1.2 \)

\( \zeta = 0 \) rejected at > 99.9%

Ehlert et al. 2015 (135 clusters)
Model

\[ a_z = 1.20^{+0.86}_{-0.87} \]

\[ a_m = -0.87^{+0.25}_{-0.25} \]

<table>
<thead>
<tr>
<th>Table 2.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
</tr>
<tr>
<td>MACS J0454.1-0300</td>
</tr>
<tr>
<td>MACS J0647.7+7015</td>
</tr>
<tr>
<td>MACS J1427.2+4407</td>
</tr>
<tr>
<td>MACS J2129.4-0741</td>
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<td>MS0015.9+1609</td>
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<tr>
<td>CL J1357+6232</td>
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<tr>
<td>CL J2321.7-0424</td>
</tr>
</tbody>
</table>

More specifically, our model assumes that the projected number density of AGN is given by

\[ n(\theta) = n(\theta)_{\text{obs}} \times \frac{f_{\text{cut}}}{f_{\text{cut},\text{obs}}} \]

where \( n(\theta)_{\text{obs}} \) is the observed number density of AGN, \( f_{\text{cut}} \) is the flux cut-off, \( f_{\text{cut},\text{obs}} \) is the observed flux cut-off, and \( f_{\text{cut}}/f_{\text{cut},\text{obs}} \) is the relative number density of AGN in each cluster field, fully accounting for the variations in the number of AGN detected. Tabulated AGN counts are shown in Table 2.

In detail, we model the number density of X-ray AGN observed, \( n_{\text{X-ray}}(\theta) \), as a function of the redshift, \( z \), of the cluster, \( n_{\text{X-ray}}(\theta, z) \), and the number density of X-ray AGN at the appropriate redshift and luminosity limit, \( n_{\text{X-ray}}(\theta, z, L) \), of the cluster field.

The default luminosity function model chosen to describe the field population in our cluster field is the luminosity density dependent evolution (LDDE) function of Ueda et al. (2014). This function takes the form

\[ \frac{dN}{dL} = A_0 (1 + z)^\eta \left( \frac{L}{10^{15} M_\odot} \right)^\gamma \]

where \( A_0 \) is a normalization constant, \( \eta \) is a redshift dependence parameter, \( \gamma \) is the slope of the luminosity function, and \( L \) is the luminosity of the AGN.

Finally, each cluster field has a different X-ray exposure time and redshift. It is vital to model the number of AGN detected in each cluster field, \( n(\theta)_{\text{obs}} \), accurately to determine the number density of AGN in each cluster field, \( n(\theta) \), as shown in Table 2.
Future...X-ray side - high-z not really possible without Lynx...

2 keV, \( z = 3 \) cluster + AGN (5 \( \times \) 10\(^{-17}\) erg/cm\(^2\)/s)
Summary

1. X-ray AGN selection can easily vary with cluster parameters.

2. Mass and redshift degeneracies (and others) complicate our conclusions about environmental quenching.

3. **PRELIMINARY:** Initial results consistent with no evolution beyond that of the field population but evidence for a variation in number density with cluster mass.
Future…

How well will Lynx do?

Assuming:
• Same exposure as current model results (6.3 Ms)
• 10 ks exposure per cluster (630 clusters)
• Flux limit of $5 \times 10^{-15}$ erg/cm$^2$/s (conservative)
• Cluster $M_{500} > 10^{14} M_\odot$ and $z < 2$
Future…

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**Factor of ~10 better constraints!**

Real strength is pushing to high $z$, low mass clusters
Detecting Black Holes

Gibson et al. 2008; Brandt & Alexander 2015

X-rays can penetrate to columns of $N_H \sim 10^{24} \text{ cm}^{-2}$

90% Conf. Limit on Fraction of Quasars

Factor of X-ray Weakness

$N(>S)$ (deg$^{-2}$)

Fraction (>,S)

$S = 2-8 \text{ keV Flux (ergs cm}^{-2} \text{ s}^{-1})$
Spectroscopy

**VIMOS** follow-up program:

**Expect:** 500-700 targets per cluster (~6000 targets)

~860 X-ray AGN

>50 within ~2\(x\) \(r_{500}\),

(15 so far)

Matched by magnitude and cluster centric distance for \(V<23\)

2700 seconds on target
Model

Is increased number density related to the mass or redshift of the host cluster?

\[ N_{\text{obs}}(> f, r, z) = AD^2_A r_{500} \Phi(> L, z) \left( \frac{r}{r_{500}} \right)^\beta + N_{\text{field}} \]

Projected number density of observed X-ray AGN in a cluster field at a given cluster z, r and above flux limit f

\[ = \text{Projected number density of X-ray AGN expected in cluster above } \]

\[ + \text{Projected number density of all field AGN above flux limit} \]

'Scale factor' which allows number density to exceed co-moving field AGN

\[ \times \text{Scaled by radius} \times \text{Co-moving field AGN number density at } z \text{ and above luminosity related to flux limit} \]

\[ \times \text{Some radial dependence} \]
Multi-Spectral Analysis

Towards a more complete census of cluster AGN and host galaxy properties

1. Differences in accretion modes: Radio/IR and Optically selected AGN number densities as a function of host cluster properties. Radio AGN work led by A. King, IR studies in collaboration with SPT.

2. Spectroscopic redshift classification - greatly lowers AGN ‘background’ and enables measurement of AGN fractions as a function of host galaxy stellar mass. VIMOS survey of 10 clusters led by E. Noordeh.

3. Can also use spec-z to train photo-z for large sample. In collaboration with G. Yang and N. Brandt.
Multi-Spectral Analysis

Towards a more complete census of cluster AGN and host galaxy properties

1. Are the obscuration properties of AGN in cluster fields different from field galaxies?

2. How do the number densities of obscured and unobscured AGN in clusters vary with the mass, radial position and redshift of clusters?

3. Are AGN in clusters more or less likely to reside in star-forming hosts.

4. How does the number density of star-forming AGN vary with the cluster radius and redshift?
CATS Selection

- **X-ray**: 550 clusters (27 Ms Chandra Data)
- **Radio**: 183 clusters (FIRST survey)
- **IR and UV**: WISE 550 clusters; Spitzer 320 clusters; Galex 550 clusters
- **Spectroscopy**: 7 clusters (z=0.4, 12 z=0.8, 1 z=2)

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**Einstein Symposium**
1. Are the obscuration properties of AGN in cluster fields different from field galaxies?
2. How do the number densities of obscured and unobscured AGN in clusters vary with the mass, radial position and redshift of clusters?
3. Are AGN in clusters more or less likely to reside in star-forming hosts, and how does the number density of star-forming AGN vary with the cluster radius and redshift?
X-ray detection - blessing and curse

Completeness and purity of the AGN sample
Need to both efficiently and cleanly find point sources in cluster fields.

AGN ONLY

Completeness

Radius from Chandra aimpoint

Purity

Radius from Chandra aimpoint
Completeness and purity of the AGN sample
Need to both efficiently and cleanly find point sources in cluster fields.
Must understand any dependence on cluster properties.
Completeness and purity of the AGN sample
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Figure 2: Top: Gallery of the six model clusters shown in Table 2. Bottom: X-spec spectra extracted from the use emission in model CL1 is shown in the left, bottom panel and the point source emission in the right, bottom panel. All clusters and spectra shown with unrealistic exposure time to highlight spatial and spectral features.