Clusters of Galaxies

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Big Cluster Questions

- What is dark matter?
- What is accelerating the universe?
- How do galaxies form and evolve?
- What is the relationship between black holes and their galaxy and cluster hosts?
- Where are the baryons?

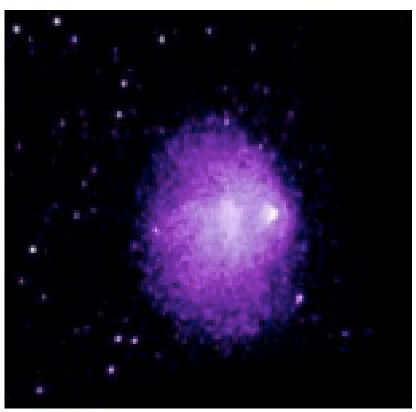
Dark Matters

- 3 independent methods to estimate cluster masses: galaxy dynamics, hydrostatic X-ray gas, gravitational lensing.
- Nature of the dark matter may be revealed in M(r) (e.g. testing NFW M(r) predictions, constraints on self-interacting dark matter; MOND)
- Baryon/DM ratio if clusters are fair (or predictably biased) samples

Dark matter test

Bullet cluster
1E0657-56
Markevitch et al. 2004;
Clowe et al. 2004

Difference between gravitational lensing and the main baryonic mass (the X-ray gas) contradicts MOND



Navarro-Frenk-White Profiles

- Clusters should be nearly self-similar throughout the cluster mass range.
- Concentration (r_{virial}/r_{scale}) depends on formation epoch.
- Simulated clusters have c_{500}~3 (2-6)

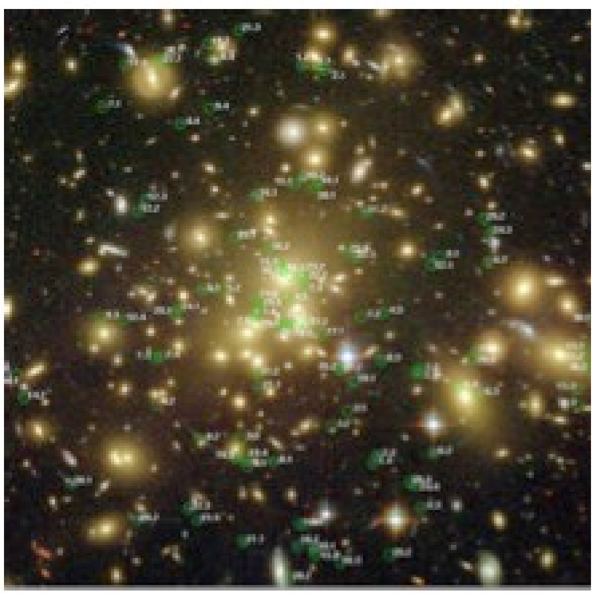
Abell 1689

Broadhurst et al. 2004

30 galaxies, multiply lensed over 100 images

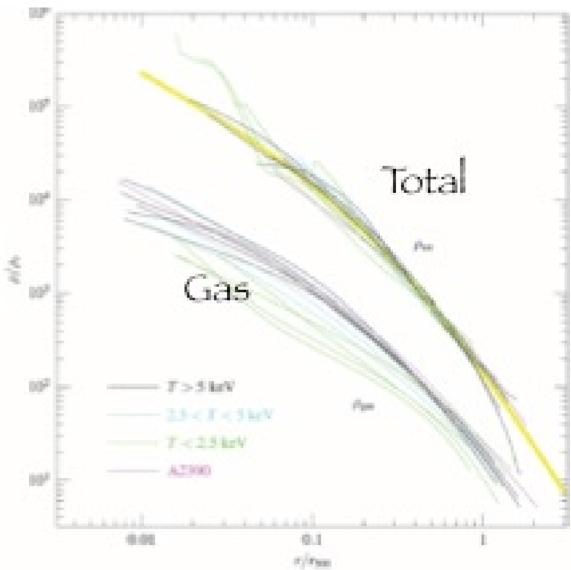
NFW c=12.5-15.5 but c_{pred}~ 3-4!

(Be careful of how c is defined ...)

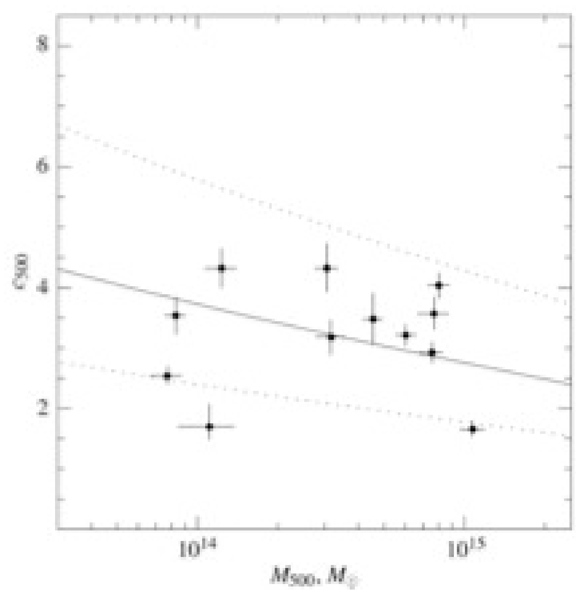


Chandra: Scaled mass density profiles, 13 clusters

Vikhlinin et al. 2006



Concentration index from X-ray mass profiles (Vikhlinin et al 2006)



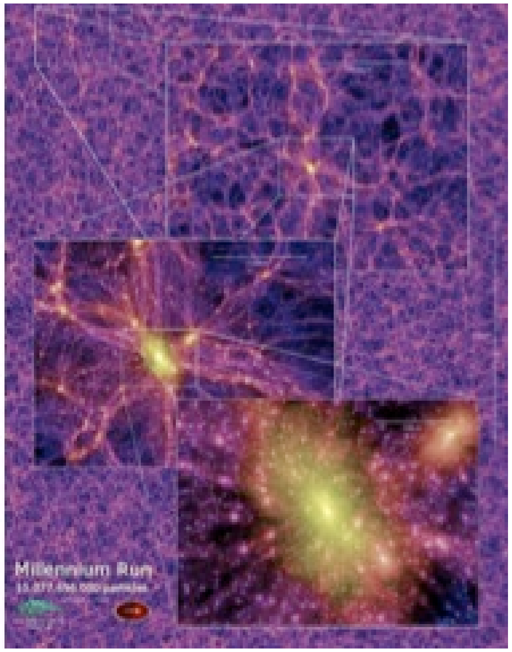
Lensing and X-rays

- X-rays reveal baryons responding to a dark matter potential well: method can only work for a (TBD) sub-sample of clusters.
- Lensing shows photons responding to matter along the line of sight, regardless of virialization state.
- Chandra and HST/ACS are ideal to provide the data for detailed comparisons.

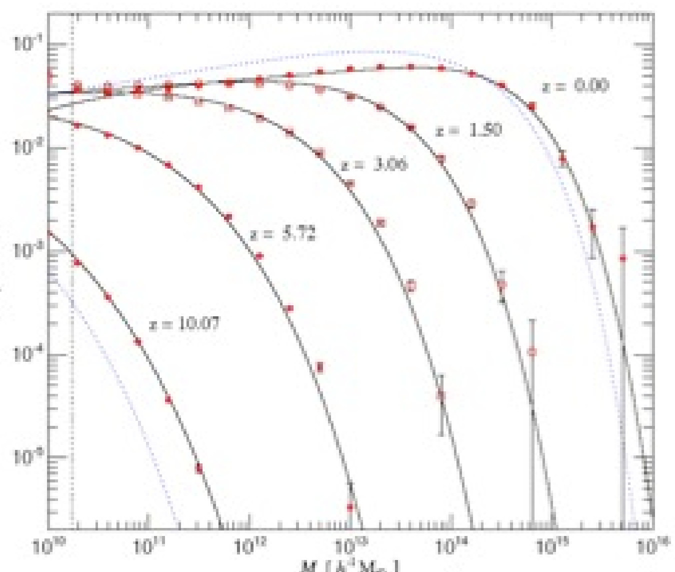
Accelerating the universe

- N(M,z) of clusters is extraordinarily sensitive to Ω_M and σ_8.
- Geometrical volume element z<0.5
- Gravitational growth factor z>0.5
- Evolution of the cluster mass function can distinguish "dark energy" models from modifications to gravity theory.

Cosmological simulations: the Millennium Run (Springel et al. 2005)



Differential Halo Number Density

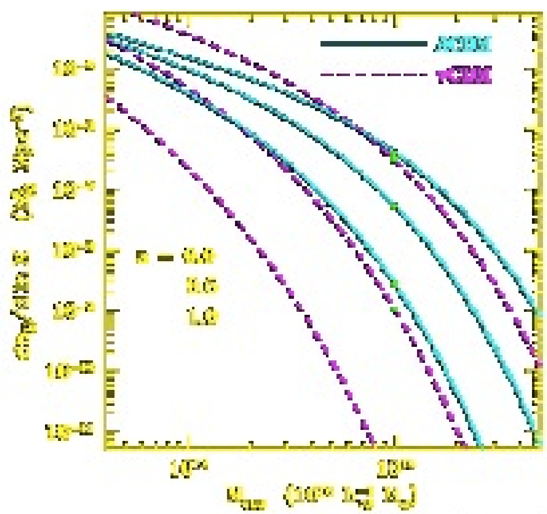


Millennium Simulation

Cluster observables break parameter degeneracies multiple ways

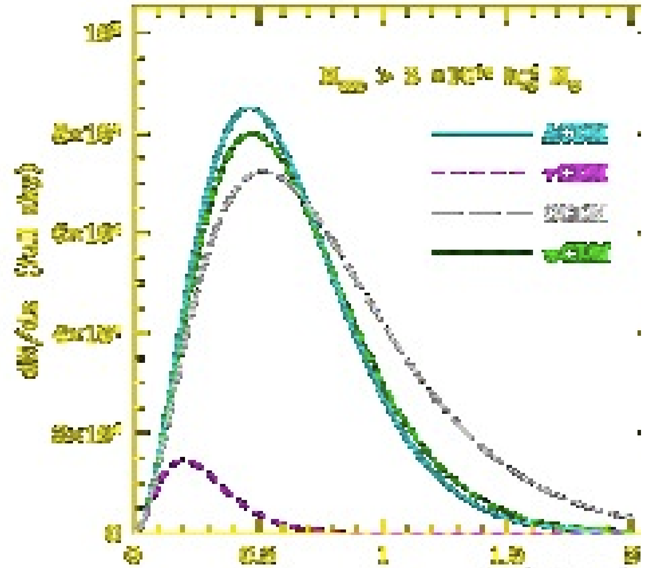
- Normalization and shape of the luminosity or temperature function.
- Evolution of the luminosity or temperature function.
- Cluster spatial correlation function

Cluster evolution is extremely sensitive to Ω_M



Voit 2005

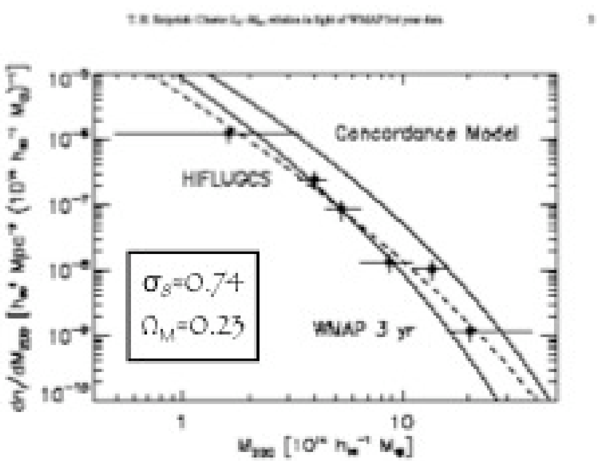
A large survey can distinguish w=-1 from w=-0.8



Voit 2005

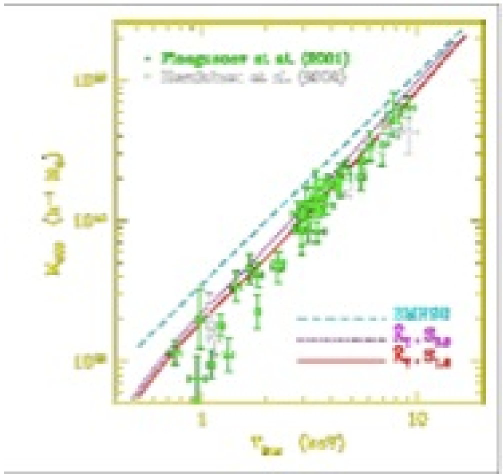
Recent WMAP result: σ_8 and Ω_M:

Lx-M has small scatter & Mx may not need a fudge factor.

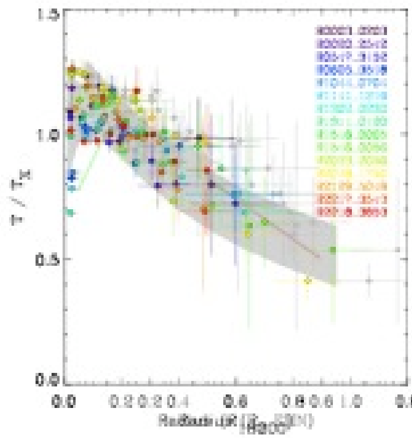


Concordance model (σ_8=0.9, Ω_M=0.3) predicted 200; WMAP 3 yr predicts 50

M-T_x Relation



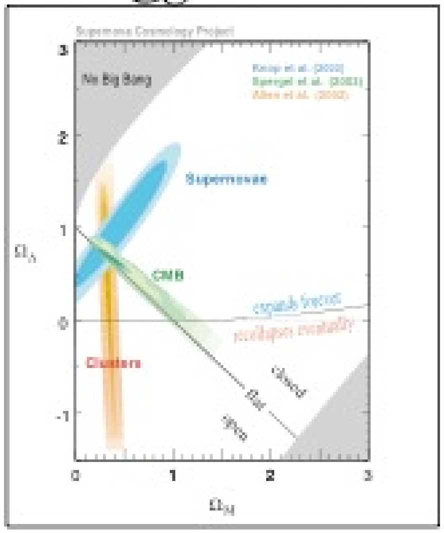
2006: Excellent agreement found between XMM (Arnaud et al. 2005) and Chandra (Vikhlinin et al. 2006)



Pratt et al. 2006 (points), grey band (ASCA), Beppo/SAX (green), Chandra (red)

Cluster cosmology

- Baryon fraction (Allen et al. 2002)
- N(M,z=0) (Reiprich, Bohringer, Henry)
- Evolution of N(T), N(Lx) (Eke, Cole, Frenk, Henry, Donahue)
- Cluster correlation function (Mohr)
- Cluster simulations (Evrard, Borgani)



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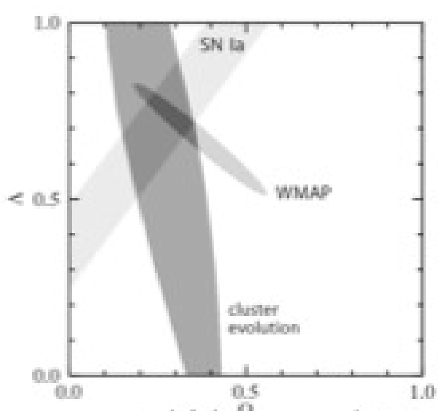

Vikhlinin et al, 2005

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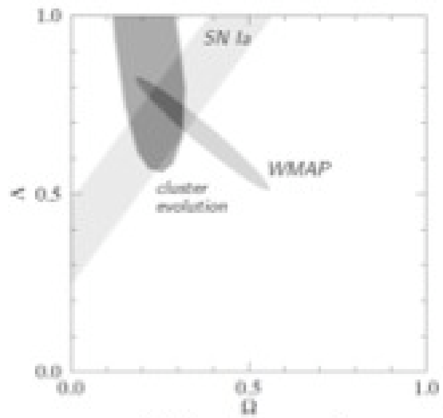
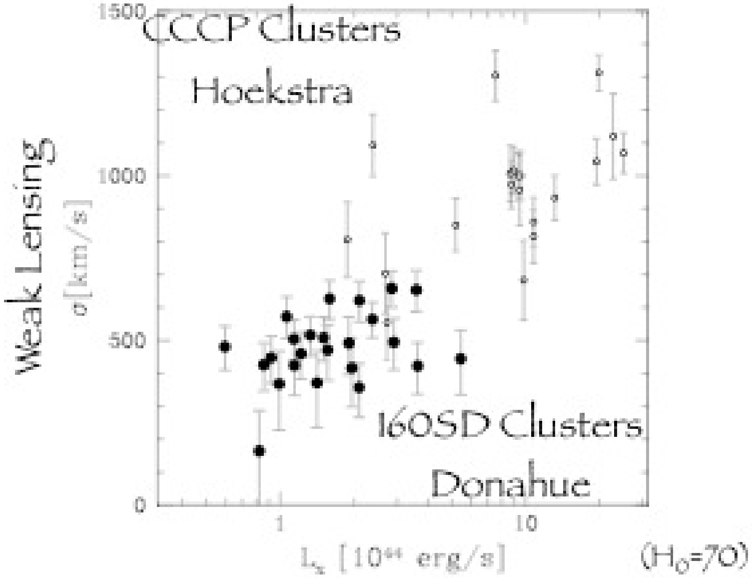


Vikhlinin et al, 2005

Cluster Cosmology

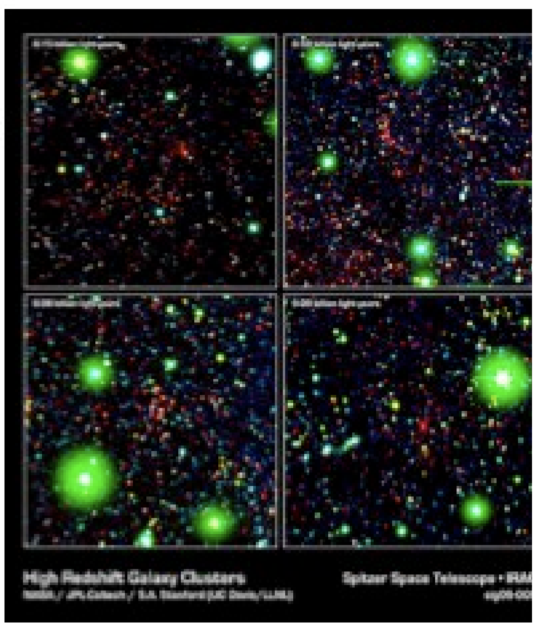
- Multiple, independent observables constrain cosmological parameters: cross-calibration is an effective test of the validity of the approach.
- Limited by the accuracy of the mass-observable calibration.
- Limited by the small catalogs of clusters at z~0.5



Spitzer spies high-z clusters in 90 second IRAC exposures

Stanford et al. 2005, z~1.4

1-2 micron peak, highly visible in near - mid IR



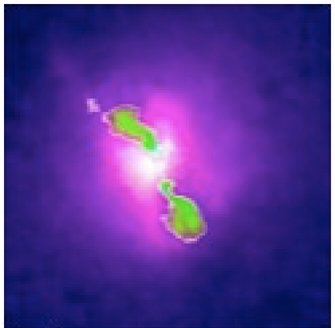
Cluster Cosmology

- The time for calibration is now, while Chandra and XMM still work.
- Key future cluster surveys: South Pole Telescope (4000 sq deg).
- HST: gravitational lensing
- Spitzer: high redshift cluster discovery.

Black holes and clusters

- Bubbles and shocks in the IGM are allowing the total kinetic output and duty cycle of an AGN to be measured for the first time. (e.g. McNamara, Nulsen, Fabian)
- AGN feedback appears to play a crucial role in determining the high L cutoff in the galaxy luminosity function. (e.g. Springer, Kauffmann, Somerville)
- AGN feedback appears to play a crucial role in moderating the thermal properties of the gas in the "cooling flows." (e.g. Donahue, Voit, Fabian)
- The biggest black holes in the universe are expected to reside in the biggest galaxies (e.g. Springer et al). Do they?

Radio sources & the ICM



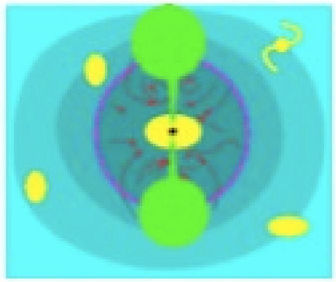
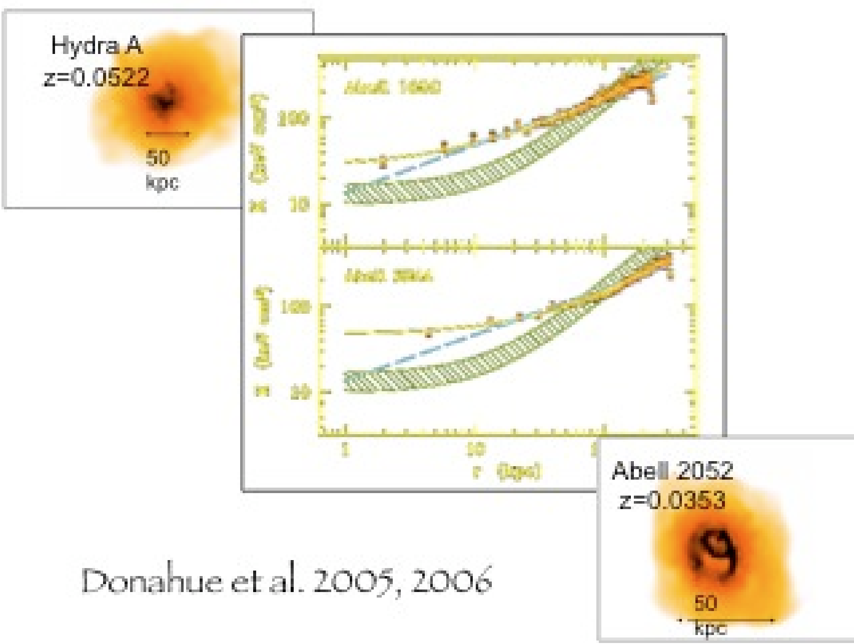


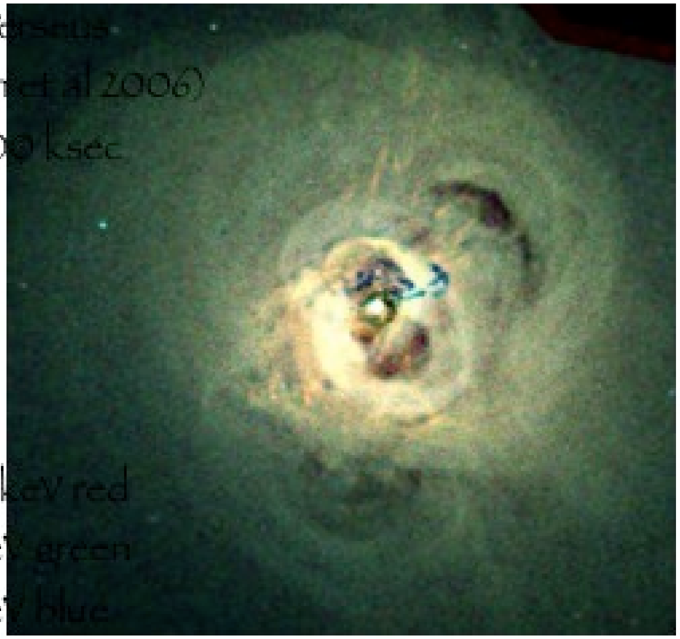
Figure source: Max-Planck-Institute

Hydra A, McNamara et al. 2001



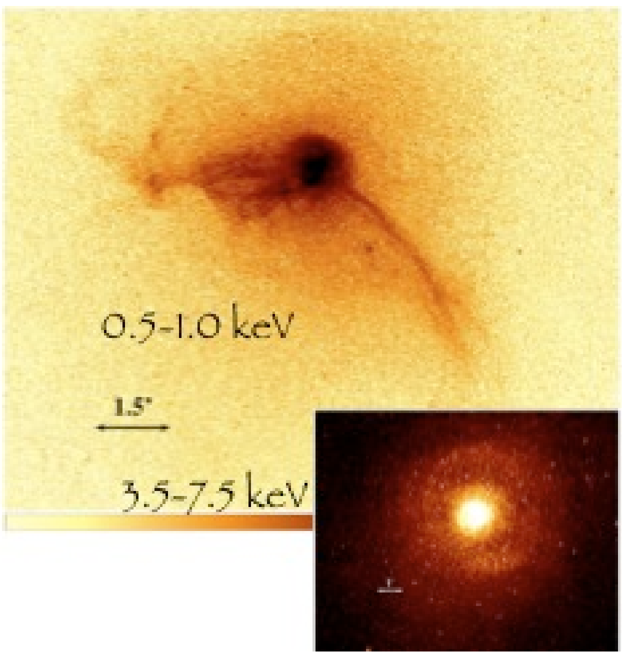
Donahue et al. 2005, 2006

Perseus
(Fabian et al 2006)
900 ksec

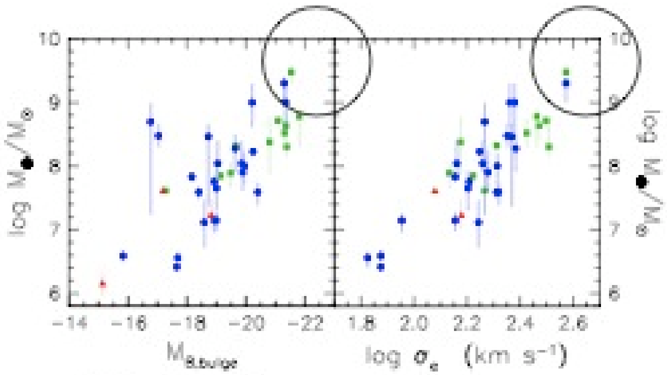


0.3-1.2 keV red
1.2-2 keV green
2-7 keV blue

M87
500 ksec
Forman et al. 2006

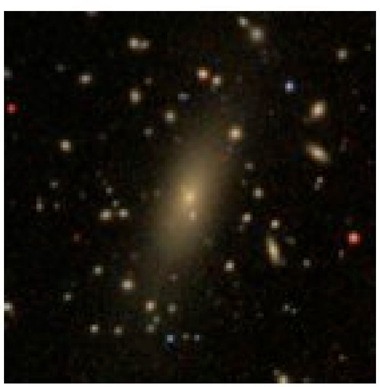


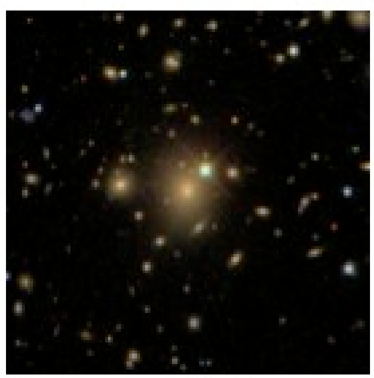
Black hole masses



- Gebhardt et al 2000

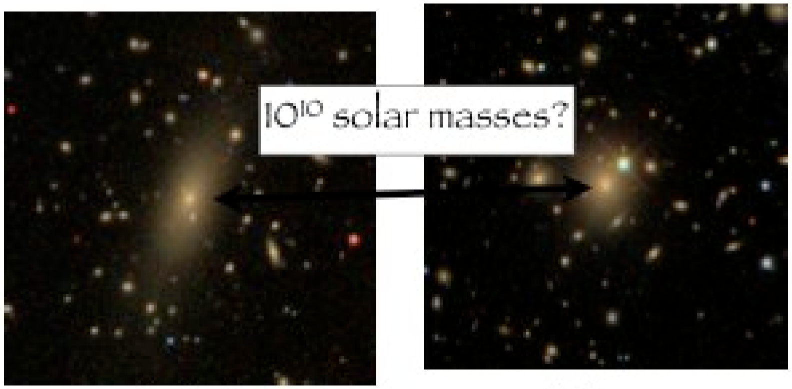
Brightest galaxies in clusters





Abell 1650 M_I ~ -24 Abell 2244

Brightest galaxies in clusters



Abell 1650 M_I ~-24 Abell 2244

Galaxy evolution and star formation

- Ellipticals seem to have a very simple star formation history, and dominate the cores of clusters out to z~1. (Stanford, Postman, Lubin, Dressler)
- Ellipticals in clusters differ morphologically from those in the field. (Conselice, Donahue)
- Field ellipticals have bluer cores (Menanteau / Treu /Pasquali)
- But the bulk of star formation in ellipticals seems to happen before there is much of a cluster (Blakeslee et al.; Mei et al.)
- The highest redshift clusters observed seem well supplied with Fe (Rosati, Mullis).

Great Observatories

- Quantify the star formation rate in cDs, cluster galaxies, groups, and infall regions (Spitzer, followup with NIR ground-based observations)
- Morphological classification in dense environments, z>0 (HST)
- Metal abundances in ICM (Chandra)
- Metal absorption in IGM/ICM (HST/SM4)

Three projects

1. Spitzer high-z cluster search (overlap Chandra & SZ/SPT fields)
2. Chandra & HST cluster mass calibration (overlap SZ/SPT fields): Lx, Tx, optical richness, shear, gas mass, SZ decrement
3. AGN feedback at Chandra resolution. Capture in situ AGN interaction between ICM & AGN: deep Chandra observations, Spitzer star formation rates (black hole masses using STIS?)