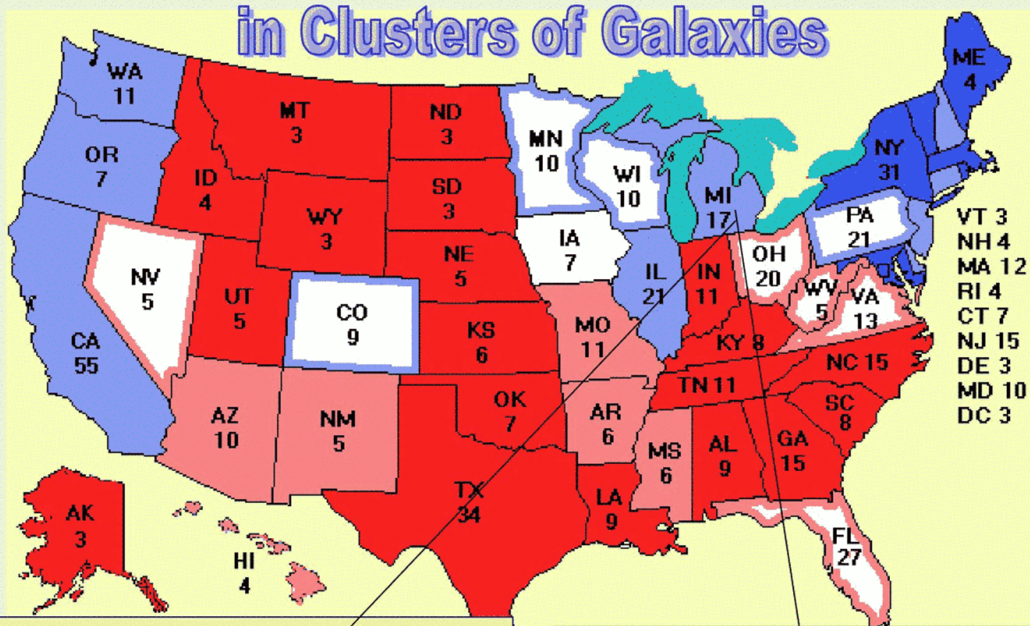
Thermodynamics of the ICM in Clusters of Galaxies



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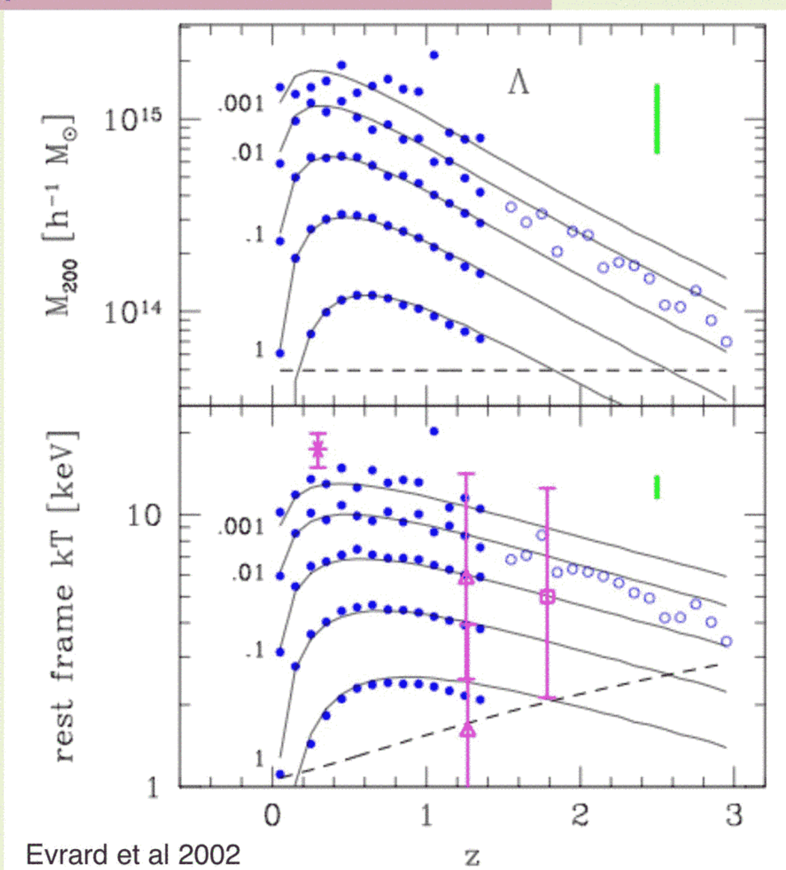
early emergence of groups/clusters in ΛCDM model

expect ~50 per sq deg
kT>1 keV halos
@ z=2-3

M ~ few x10^{13} $h^{-1}M_{sun}$
R ~ 0.5 h^{-1} Mpc

Steidel et al's search
area ~1 sq deg

next generation X-ray
telescopes will detect
this hot gas

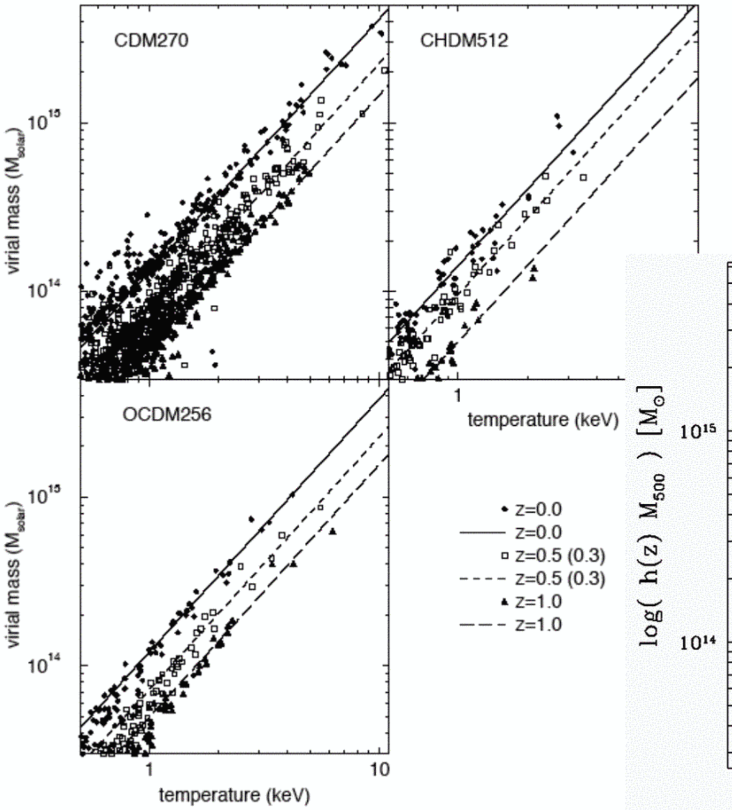


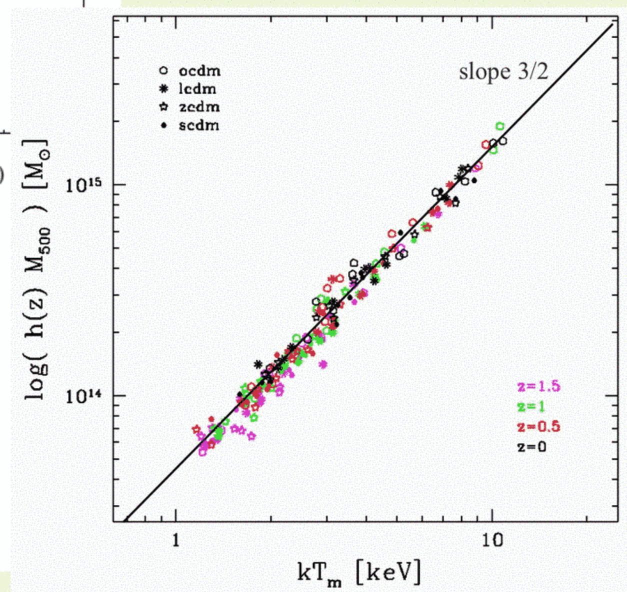
Evrard et al 2002

ICM virial relation: computational calibration

Evrard, Metzler & Navarro `96
Bryan & Norman `98
Mathiesen & Evrard `01

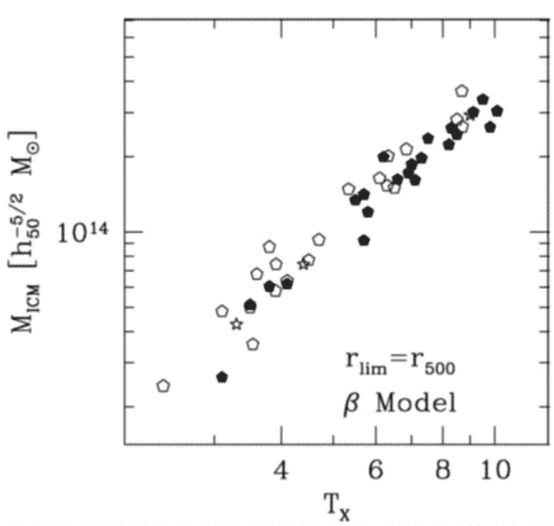
T alone is a low-noise mass estimator:
~11 % scatter in $h(z)M_{500}$ at fixed kT





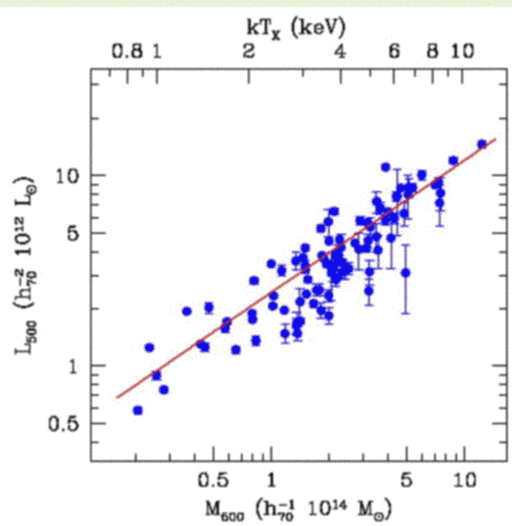
X-ray and optical scaling relations for X-ray flux-limited samples

Mohr, Mathiesen & Evrard 99



14 % scatter in M_{ICM} at fixed T_X

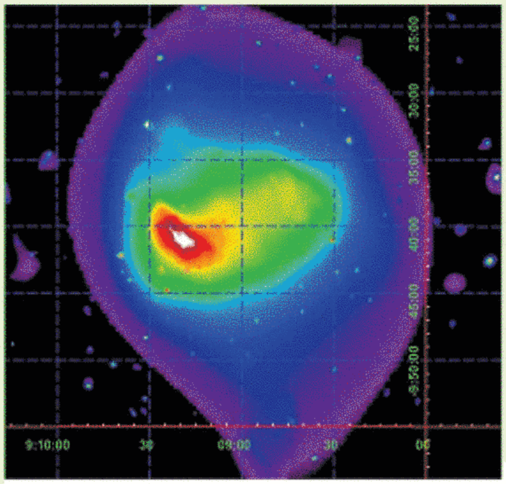
Lin, Mohr & Stanford 2004

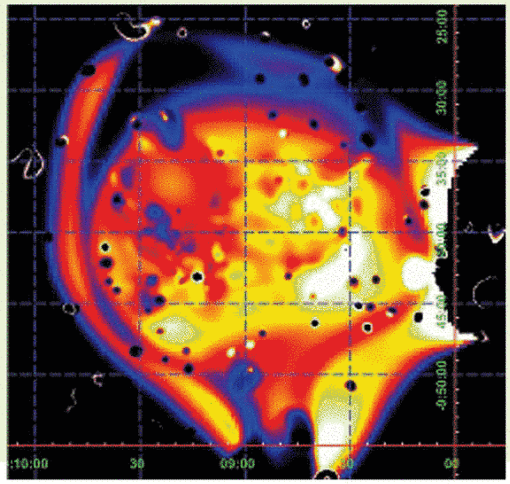


25 % scatter in L_K at fixed T_X

Chandra/XMM offer increasing detailed views of hot ICM

Henry et al 2004





September 28, 2004

New York Times

When Clusters Collide

By HENRY FOUNTAIN

As collisions go, the one taking place in the vicinity of the constellation Hydra is a doozy. Out there, some 800 million light-years from Earth, two galactic clusters - one with about 1,000 galaxies, the other with 300, totaling trillions of stars - have gone bump in the night.

Astronomers have released the clearest picture yet of this collision, one of the most energetic events in the universe after the Big Bang. Data from the XMM-Newton satellite, an X-ray observatory operated by the

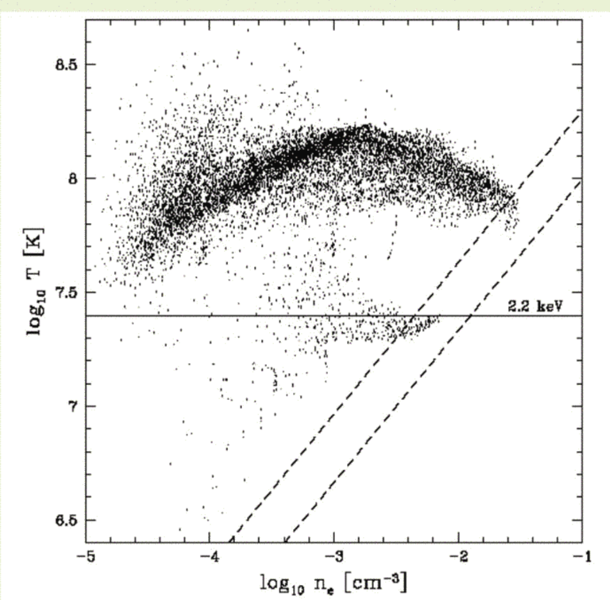
ICM is a multi-temperature atmosphere

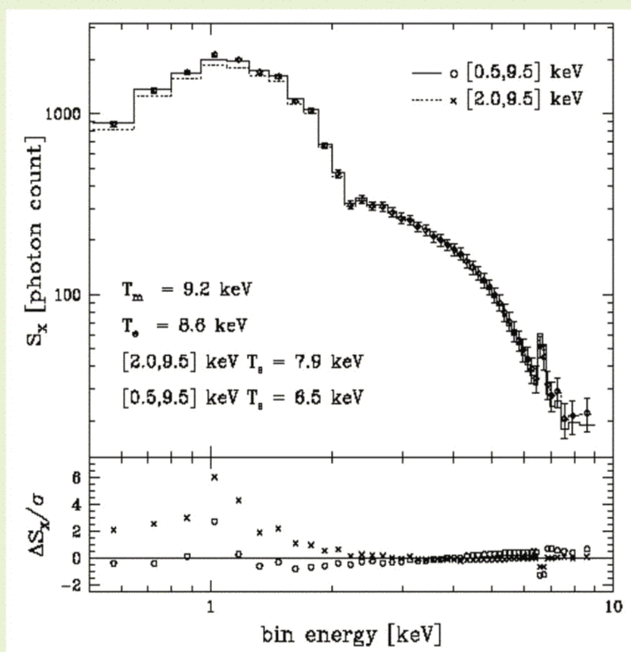
Mathiesen & Evrard 2001

Mazzotta et al 2004

cool cores or merging satellites can exist for ~Gyr within r_{500}

– excess emission at low photon E
– best-fit T_X sensitive to E_{min}



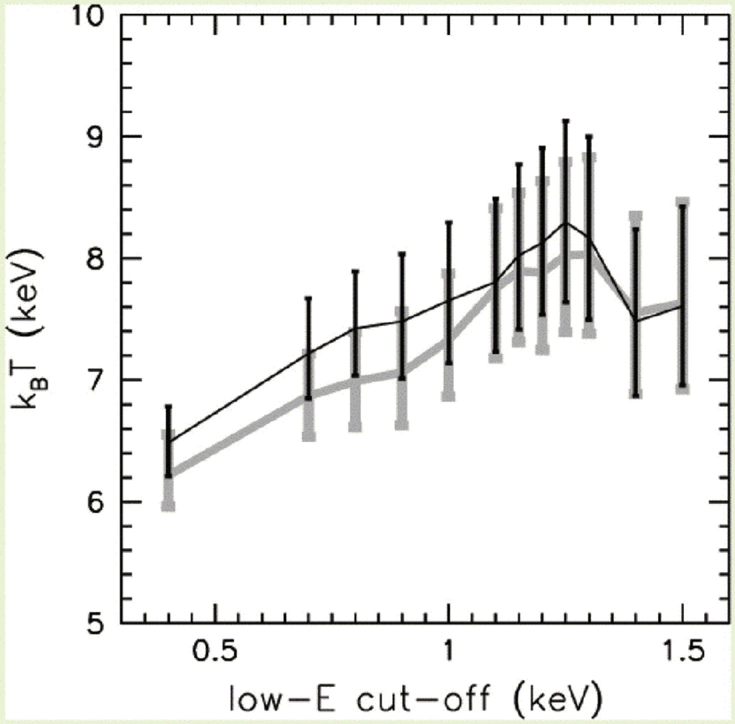


XMM-Newton spectral evidence for cool substructure?

Zhang et al. 2004

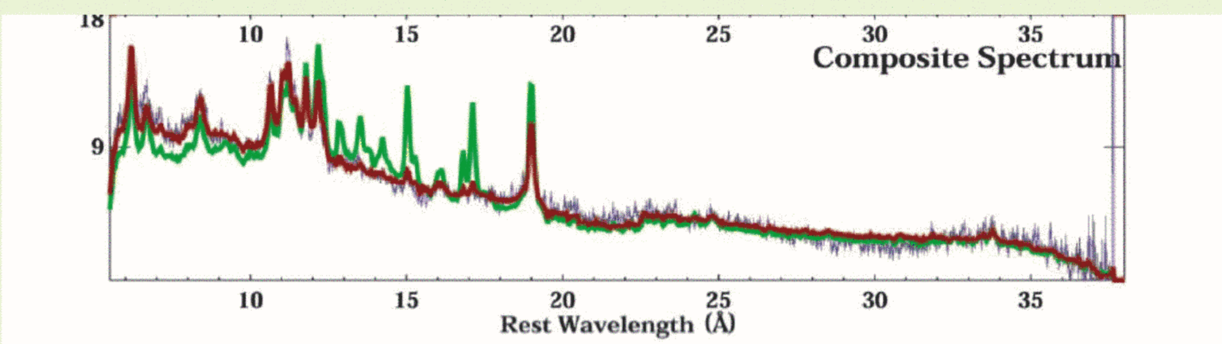
RXCJ0528.9-3927

best fit increases with min energy cutoff

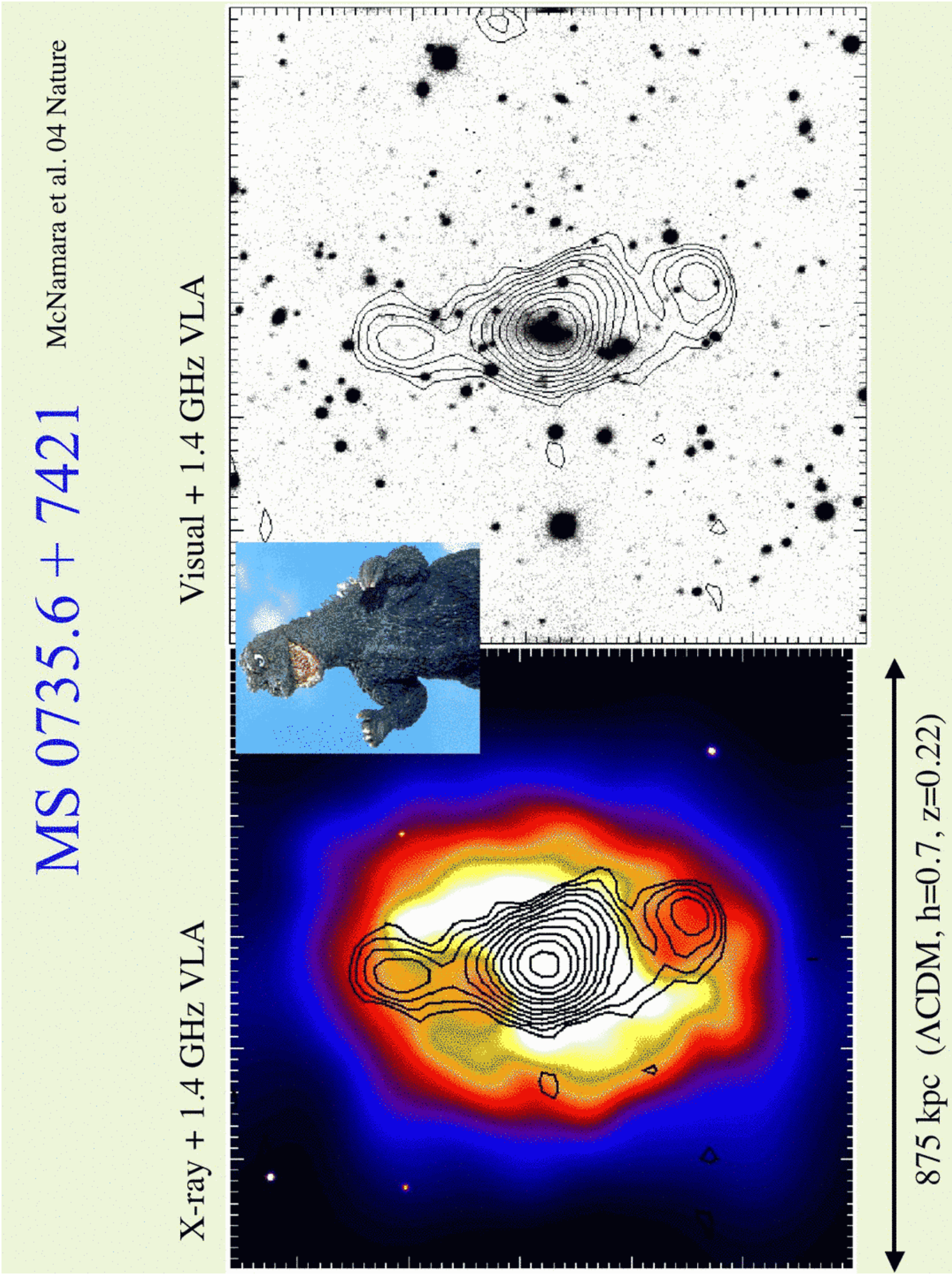


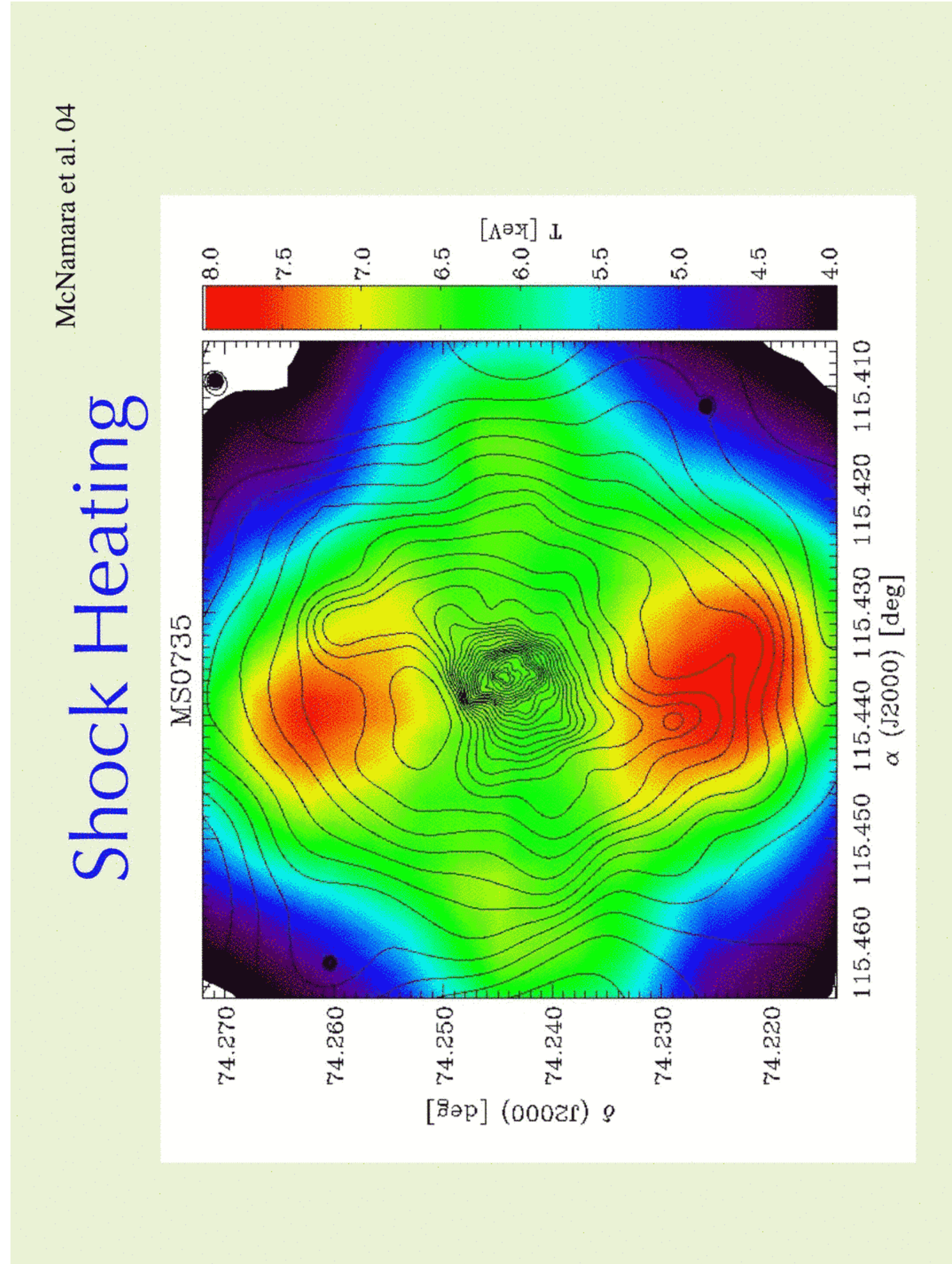
cool cores remain a mystery

Peterson et al 2003



– 14 groups/clusters observed with XMM RGS
– no evidence for low T ions (below ~T_0/3) in core
– what's heating the gas?
conduction?
mergers?
AGN?


MS 0735.6 + 7421
McNamara et al. 04 Nature
Visual + 1.4 GHz VLA
X-ray + 1.4 GHz VLA
875 kpc (ΛCDM, h=0.7, z=0.22)


Shock Heating
McNamara et al. 04
MS0735
T [keV]
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
115.460 115.450 115.440 115.430 115.420 115.410
α (J2000) [deg]
74.270
74.260
74.250
74.240
74.230
74.220
δ (J2000) [deg]

McNamara et al. 04

Giant Cavities in MS 0735.6+7421

$$E_s = 6 \times 10^{61} \text{ erg}$$

Mach 1.4 shock   age = 100 Myr

One trillion Solar masses of gas displaced

50 times larger than the cluster's X-ray luminosity

Five orders of magnitude larger than its 1.4 GHz luminosity

250 times more powerful than Perseus

Four orders of magnitude more powerful than M87

the L_X-M relation in a ΛCDM universe

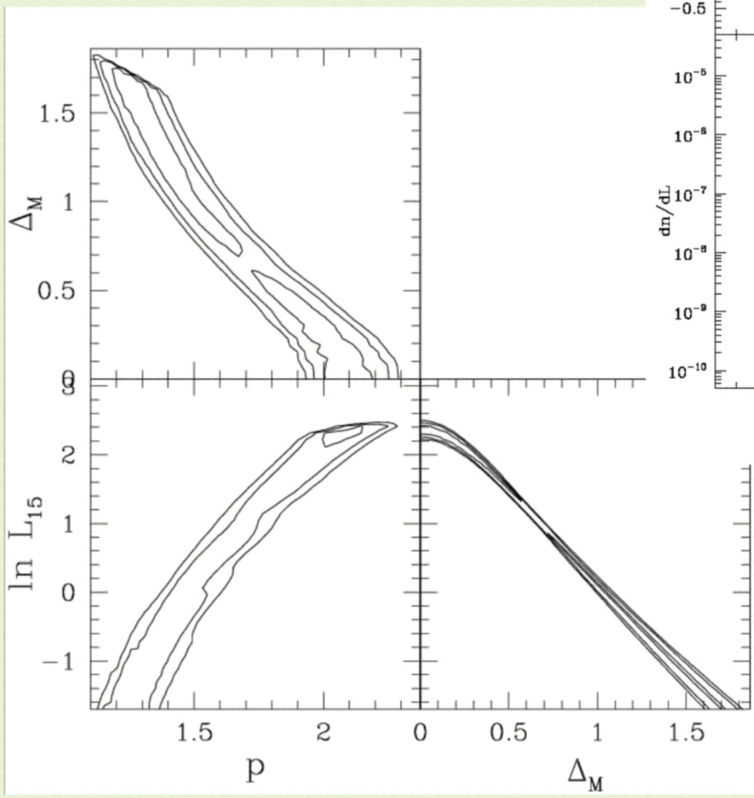
Stanek et al,, in prep

Exercise: transform ΛCDM Jenkins mass function to REFLEX sample luminosity function

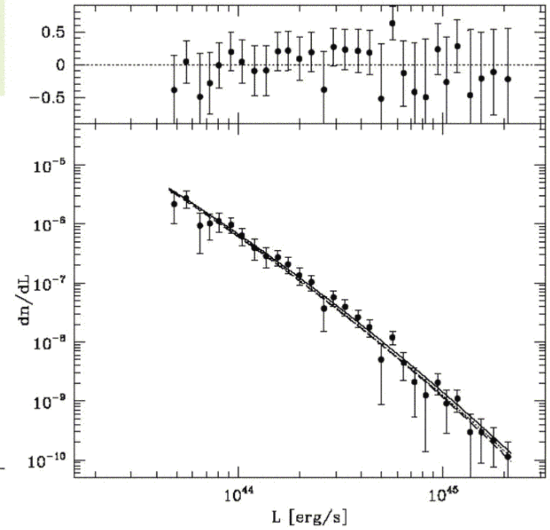
New element: introduce log-normal p(M I L) characterized by power-law median relation $L = L_{15} M^p$ with scatter Δ_M

$$n(L_X)\mathrm{d}\ln L_X = \int \mathrm{d}\ln M\, n(M)\, p(M|L_X)\, \mathrm{d}\ln L_X$$

good fits are easy to find…



Stanek et al, in prep



large range of allowed scatter (up to factor ~4)

range in median scaling relation parameters (L_{15} , p) allow different ICM physics

add bias & L-T scatter constraints

Stanek et al, in prep

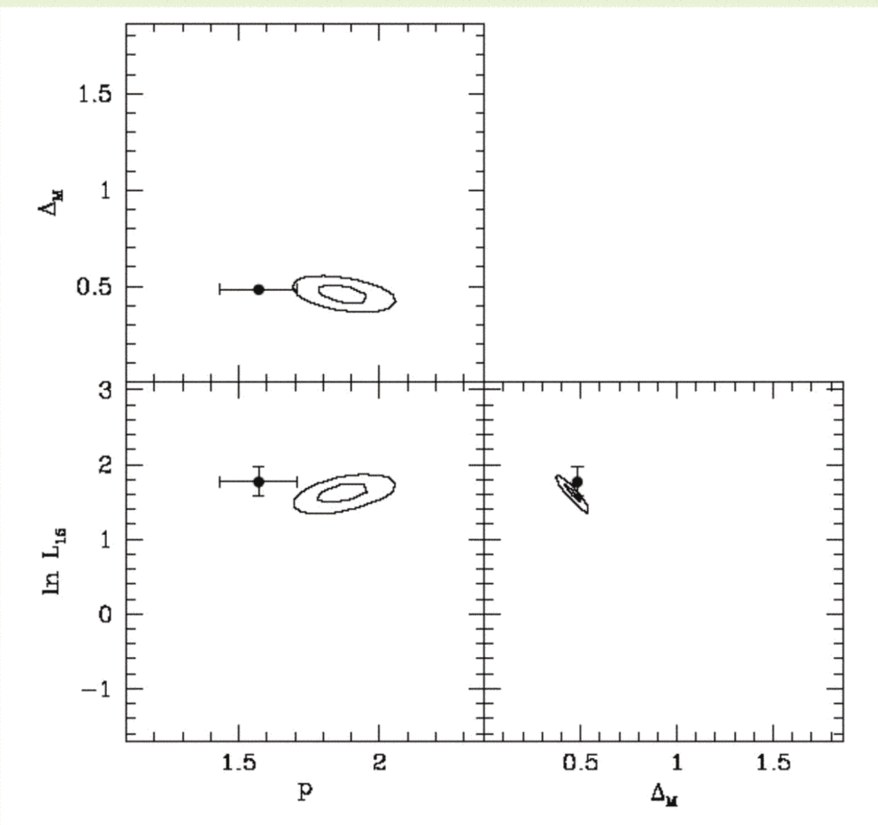
scatter in mass at fixed luminosity

$\Delta_M = 0.45 \pm 0.05$

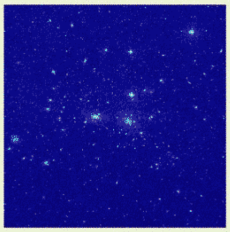
slope in L-M relation steeper than self-similar

$p = 1.85 \pm 0.10$

p= 4/3 for self-similar
Kaiser 1986
p= 11/6 for preheating
Evrard & Henry 1991

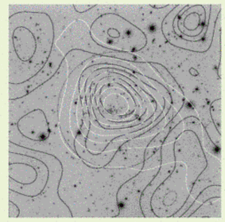


clusters surveys: many efforts in different wavebands



SDSS & 2dFGRS
$N \sim 10^4$ to $z \sim 0.6$

RCSII
$N \sim 10^4$ to $z \sim 1.4$



DLS
$N \sim 10^2$ to $z \sim 1$

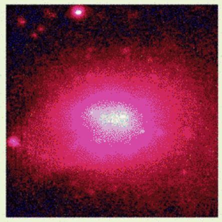
SNAP?
$N \sim 10^4$ to $z \sim 2$?

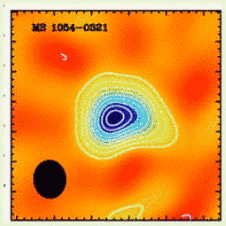
REFLEX/NORAS
$N \sim 10^3$ to $z \sim 0.5$

MACS
$N \sim 10^2$ to $z \sim 1$

XCS
$N \sim 10^4$ to $z \sim 1.5$

DUO (phase A SMEX)
$N \sim 10^4$ to $z \sim 1.5$





APEX-SZ
$N \sim 10^3$ to $z \sim 3$

SZA
$N \sim 10^3$ to $z \sim 3$

AMI
$N \sim 10^3$ to $z \sim 3$

SPT
$N \sim 10^4$ to $z \sim 2$

The Future of Cosmology with Clusters of Galaxies
27 Feb - 2 Mar 2005
Marriott Waikoloa Beach Resort