Any Questions?

H_0 from Galaxy Clusters

- There's been lots of discussion about H_0 tension between SNe and CMB.
- Back in the day, people used to think about doing H_0 from galaxy clusters.
- How would we do this, and what would it take experimentally?
- We can work this out from minimal facts - cluster are young, and σ_8 is a bit less than one.

How do Clusters Form?

- If I have a spherically symmetric structure in the universe, it evolves on its own (Birkhoff's theorem, although first published by Jørg Jepsen)
- So, overdensities evolve just like closed universes if their local $\Omega > 1$
- In a matter-dominated universe, what would the density be of a galaxy cluster?

Cluster Formation 101

- In matter-dominated, background universe keeps expanding while overdensities collapse. Key concept is turnaround radius - size of cluster overdensity stops expanding and starts collapsing.
- What is final radius of cluster relative to turn-around radius?
- Virial theorem: T=-1/2 U for self-gravitating.
- At turnaround, energy is purely potential.
- When virialized, I must have double potential energy and turned into kinetic. Double potential means half radius
- Half radius means 8x density *relative to turnaround*.

Background Density

- Background density keeps dropping as surrounding universe expands. Plus, expansion rate slower inside cluster than outside.

- So, say background scale factor up by 3. Density down by ~3^3=27.

- Cluster density then enhanced vs. background by 8*27~200.

- If universe keeps expanding while cluster stays put, this ratio would increase. However, clusters are young.

How Big?

- Parameter σ_8 is fractional (linearized) RMS density fluctuation on 8 Mpc scales. It's ~0.8, with larger density fluctuations on small scales, smaller on large.
- Scales where σ_x is <<1 can't form nonlinear structure. So, largest things today should have come from ~10 Mpc regions.
- Current size ~10/($200^{1/3}$)~1.5 Mpc
- Critical density: $3H^2/8\pi G$. H0~70 km/s/Mpc~70e5/3.08e24=2.3e-17. $\rho_c \sim 10^{-27}$ g/cm^3.

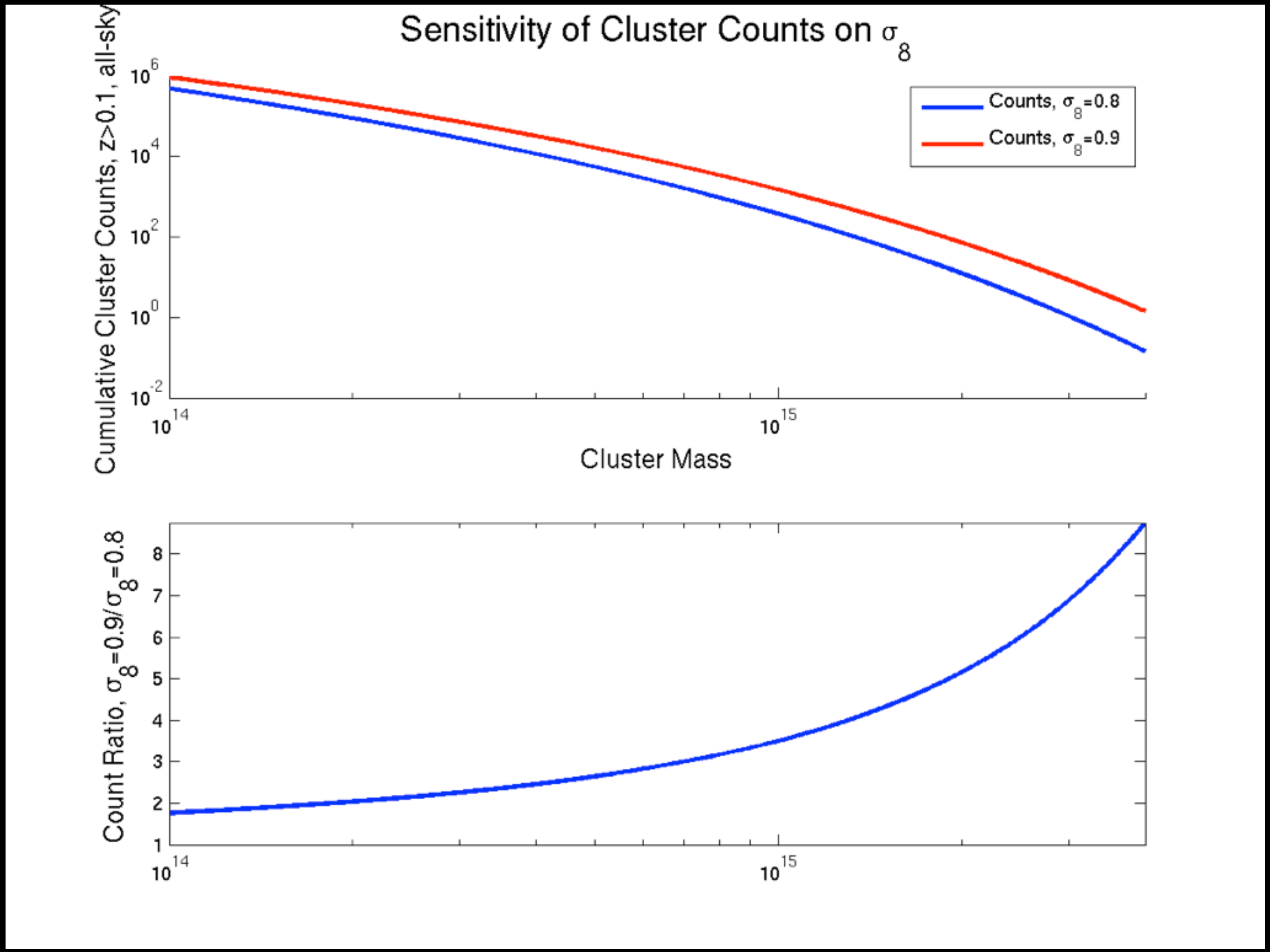
How Heavy?

- Mass going into cluster is $4/3\pi(10/2\ \mathrm{Mpc})^3\rho \sim 1.1e50\Omega_m$ grams ~2e15 $M_\odot$.

- So, big cluster should be ~1-2 Mpc across, weigh ~2e15 $M_\odot$ and have a density ~200 times the background.

- Velocity dispersion $\sim(GM/r)^{1/2}$ $\sim(6.67e\text{-}8*2e15*2e33/1.5*3.08e24)^{1/2} \sim 2000$ km/s.

Cluster Masses from Sims



- Indeed, biggest things we expect to see from n-body sims are few e15 solar masses.
- Counts at most massive end extremely sensitive to σ_8, less so for smaller clusters, since they form from more non-linear scales. Only rarest fluctuations can form most massive clusters.

Scaling Relations

- How would velocity dispersion scale with mass?
- $V \sim (GM/r)^{1/2}$, $M \sim \rho r^3$, $r \sim (M/\rho)^{1/3}$.
- $V \sim (GM/(M/\rho)^{1/3})^{1/2}. \sim (G\rho M^{2/3})^{1/2} \sim M^{1/3}(G\rho)^{1/2}$.
- $T \propto V^2 \propto M^{2/3}$.
- How would this scaling law change if smaller clusters were older?

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- $T \propto V^2 \propto M^{2/3}$.
- How would this scaling law change if smaller clusters were older?
  - Their density would be higher since they formed in younger universe. So, velocity would be relatively higher, and temperature would scale less steeply than $M^{2/3}$.

Absolute Temperature

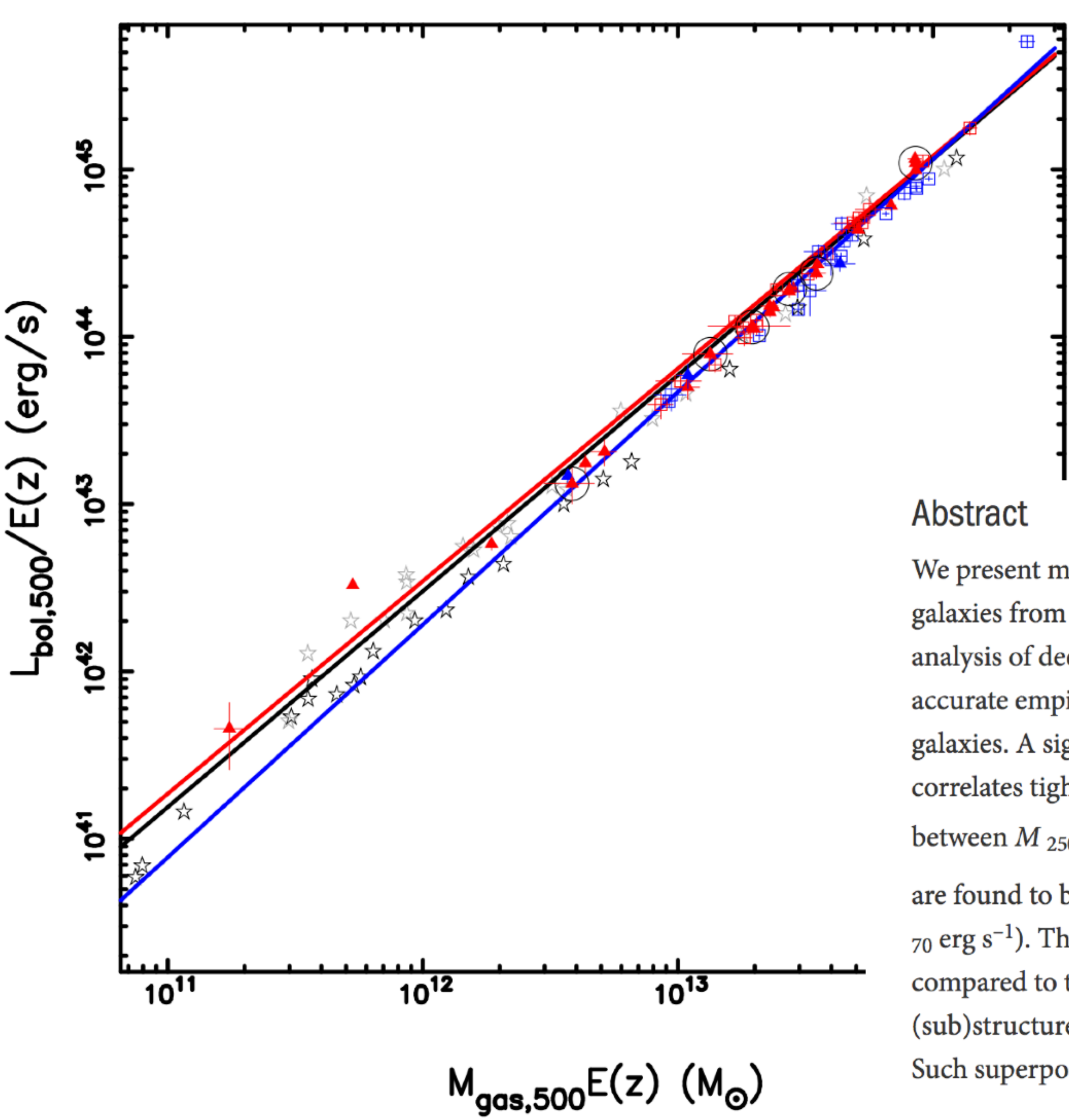
- Massive cluster has dispersion ~2000 km/s. 1/2 $m_p v^2$=3.3e-8 ergs.
- Have 1 proton, 1 electron with E~3/2 kT each, so E~3kT for energy from 1 proton. kT~1.1e-8 erg, T~7 keV
- So, thermal emission from clusters should be in the several keV range

Clusters in X-ray

- Dominant source of emission from clusters is free-free as electrons whiz past ions.
- Emissivity (erg/cm3/s/hz) below. g_{ff} are Gaunt factors which deal with QM effects, etc., and are order unity.
- Total emission is integral over cluster volume, which at fixed density is proportional to mass
- Emission (band-limited) $\sim T^{-1/2} \sim M^{-1/3}$, so $L_x \sim M^{2/3}$.
- NB - total collision rate goes like velocity, so $L \sim T^{1/2}$, but max energy gets spread over larger bandwidth, so emission per Hz goes like $T^{-1/2}$.

$$\epsilon_\nu^{ff} = \frac{2^5 \pi e^6}{3 m_e c^3} \left(\frac{2\pi}{3 m_e k} \right)^{1/2} Z^2 n_e n_i g_{ff}(Z, T_g, \nu) T_g^{-1/2} \exp(-h\nu / k T_g) \qquad (5.11)$$

This is What You See

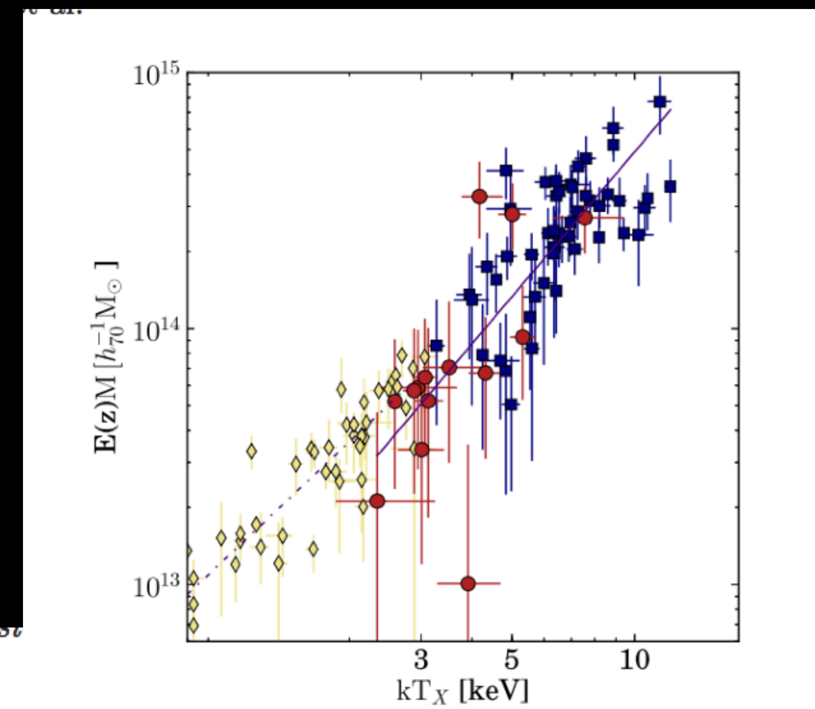


Abstract

We present measurements of the masses of a sample of 25 moderate X-ray luminosity clusters of galaxies from the 160 square degree *ROSAT* survey. The masses were obtained from a weak-lensing analysis of deep *F*814*W* images obtained using the Advanced Camera for Surveys. We present an accurate empirical correction for the effect of charge transfer (in)efficiency on the shapes of faint galaxies. A significant lensing signal is detected around most of the clusters. The lensing mass correlates tightly with the cluster richness. We measured the intrinsic scatter in the scaling relation between M_{2500} and L_X to be $\sigma_{\log L_X|M} = 0.23^{+0.10}_{-0.04}$. The best-fit power-law slope and normalization are found to be $\alpha = 0.68 \pm 0.07$ and $M_X = (1.2 \pm 0.12) \times h^{-1}_{70} 10^{14}\, M_\odot$ (for $L_X = 2 \times 10^{44}\, h^{-2}_{70}$ erg s^{-1}). These results agree well with a number of recent studies, but the normalization is lower compared to the study of Rykoff et al. One explanation for this difference may be the fact that (sub)structures projected along the line of sight boost both the galaxy counts and the lensing mass. Such superpositions lead to an increased mass at a given L_X when clusters are binned by richness.

Mass-Temperature As well

- If T~M$^{(2/3\text{- a bit})}$, M~T$^{(3/2\text{+a bit})}$.
- Again, consistent with data



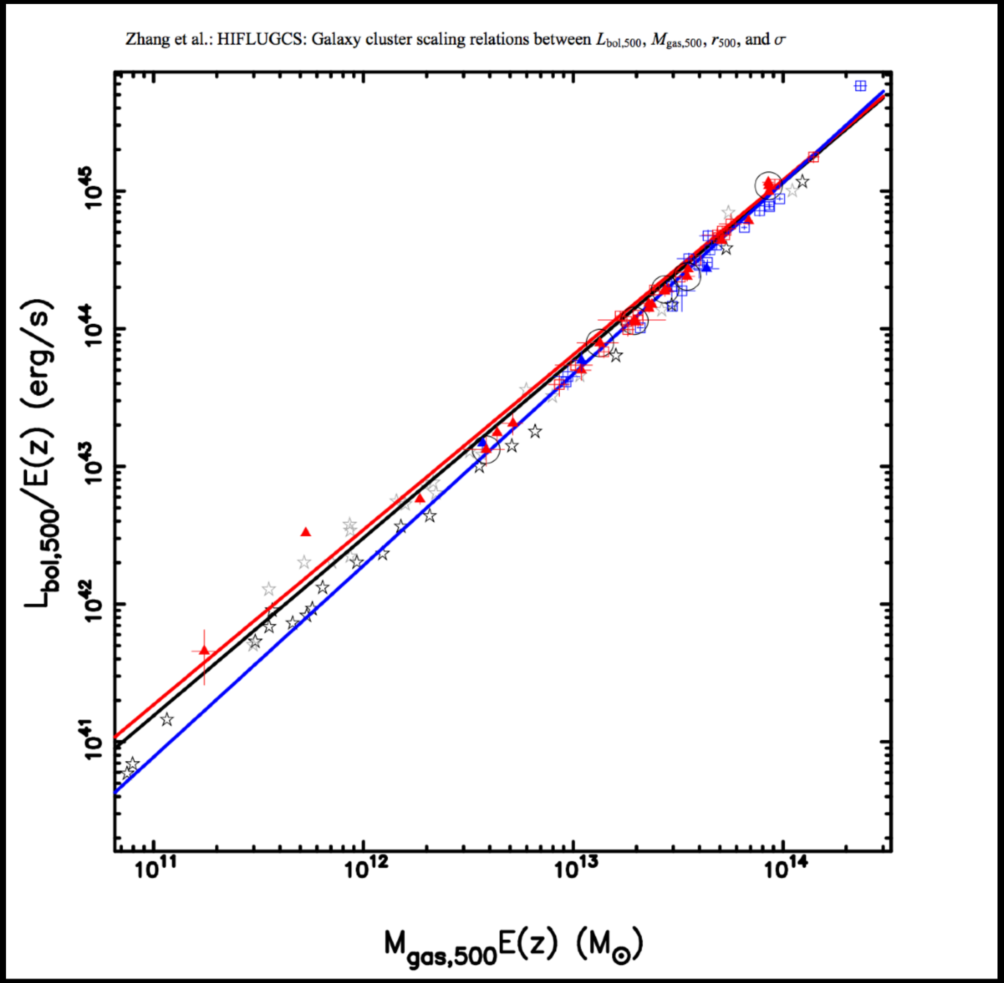
ABSTRACT

We present new X-ray temperatures and improved X-ray luminosity estimates for 15 new and archival *XMM-Newton* observations of galaxy clusters at intermediate redshift with mass and luminosities near the galaxy group/cluster division ($M_{2500} < 2.4 \times 10^{14}\,h_{70}^{-1}\,M_\odot$, $L < 2 \times 10^{44}\,\mathrm{erg\,s^{-1}}$, $0.3 < z < 0.6$). These clusters have weak-lensing mass measurements based on *Hubble Space Telescope* observations of clusters representative of an X-ray selected sample (the *ROSAT* 160SD survey). The angular resolution of *XMM-Newton* allows us to disentangle the emission of these galaxy clusters from nearby point sources, which significantly contaminated previous X-ray luminosity estimates for six of the fifteen clusters. We extend cluster scaling relations between X-ray luminosity, temperature, and weak-lensing mass for low-mass, X-ray-selected clusters out to redshift ~ 0.45. These relations are important for cosmology and the astrophysics of feedback in galaxy groups and clusters. Our joint analysis with a sample of 50 clusters in a similar redshift range but with larger masses ($M_{500} < 21.9 \times 10^{14}\,M_\odot$, $0.15 \leq z \leq 0.55$) from the Canadian Cluster Comparison Project finds that within r_{2500}, $M \propto L^{0.44\pm0.05}$, $T \propto L^{0.23\pm0.02}$, and $M \propto T^{1.9\pm0.2}$. The estimated intrinsic scatter in the M-L relation for the combined sample is reduced to $\sigma_{\log(M|L)} = 0.10$, from $\sigma_{\log(M|L)} = 0.26$ with the original *ROSAT* measurements. We also find an intrinsic scatter for the T-L relation, $\sigma_{\log(T|L)} = 0.07 \pm 0.01$.

Subject headings: galaxies: clusters: general — X-rays: galaxies: clusters

How many Photons?

- Integrate emission function, and get that massive clusters put out ~1e45 erg/s in X-rays.
- How many X-ray photons/s?
- 1e45 erg/s /(5 keV/photon)~10^{56} photons/s.
- At z~0.5, r~150e3 km/s/70 km/s/Mpc ~2 Gpc.
- Surface area ~$4\pi(2*3.08e27)^2$~4.7e56 cm^2. So, massive cluster could give us 1 photon/cm^2/10-100 sec.



Chandra observations of RX J1347.5−1145: the distribution of mass in the most X-ray-luminous galaxy cluster known FREE

S. W. Allen, R. W. Schmidt, A. C. Fabian

X-ray Telescope Mirrors						
Mirror Characteristic	Einstein	EXOSAT	ROSAT	BBXRT/ASCA	Chandra	XMM
aperture diameter	58 cm	28 cm	83 cm	40 cm one module	1.2 m	70 cm one module
mirrors	4 nested one module	2 nested	4 nested	118 nested one module	4 nested	58 nested
geometric area	350	80	1140	1400 two modules	1100	6000 three modules
grazing angles (arcmin)	40-70	90-110	83-135	21-45	27-51	18-40
focal length (m)	3.45	1.09	2.4	3.8	10	7.5
mirror coating	Ni	Au	Au	Au	Ir	Au
highest energy focused (keV)	5	2	2	12	10	10
on axis resolution (arcsec)	4	18	4	75	0.5	20

- What would Chandra photon count rate be?

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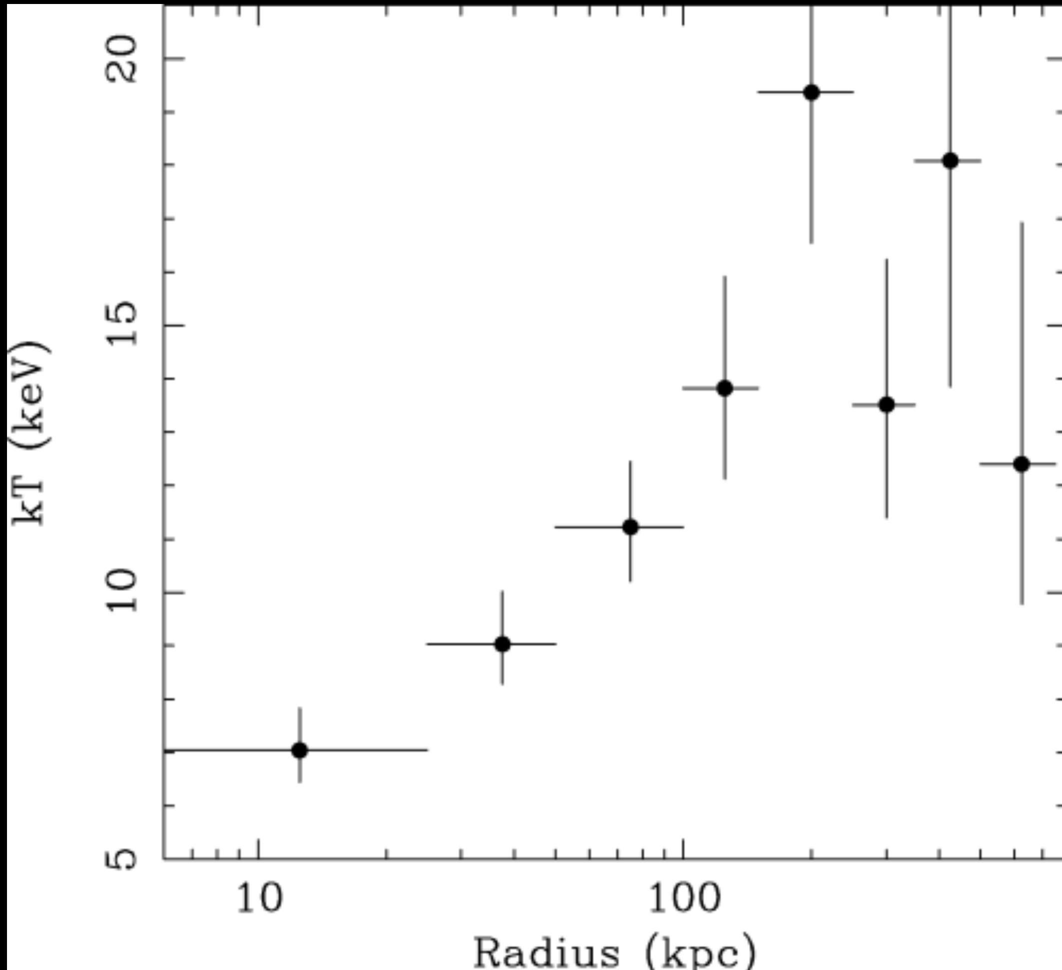
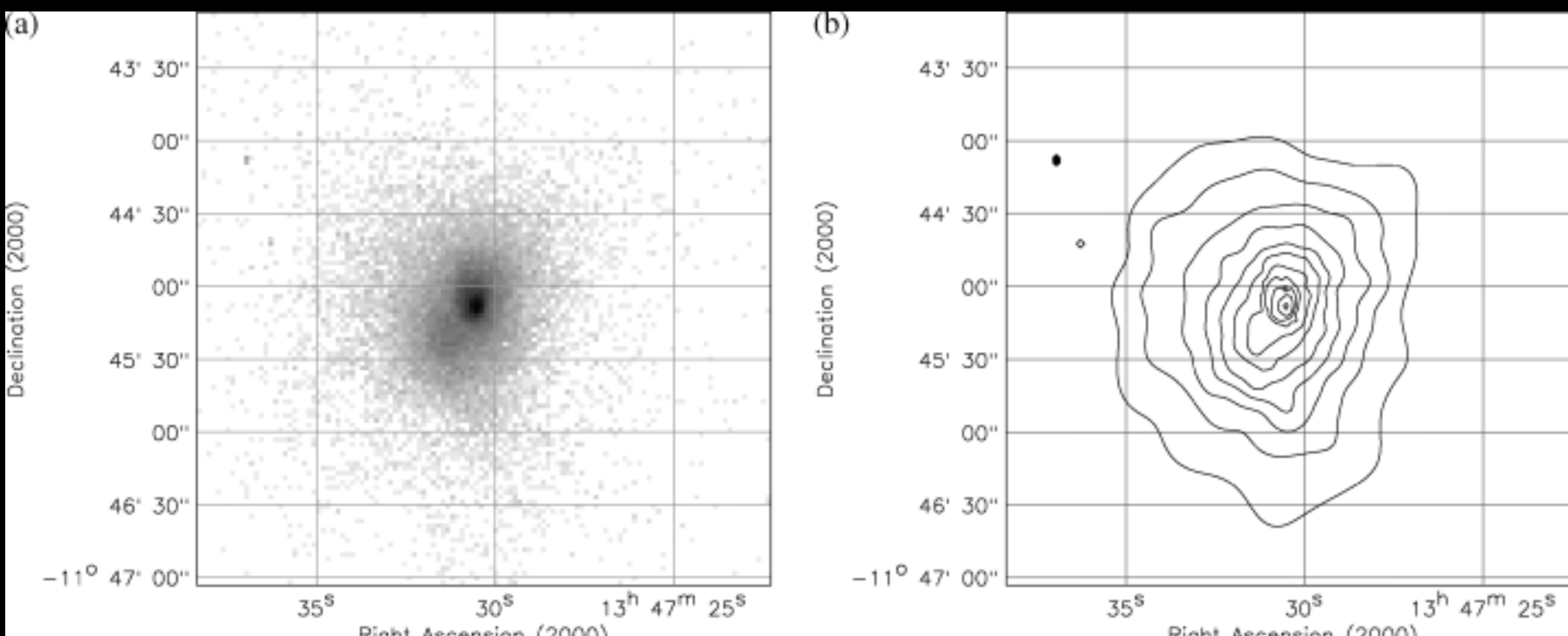
20 ksec of data



- Chandra measures energy of each photon w/ ACIS (CCD).
- Takes many photons for spatially resolved temperatures…
- ~megasecond exposures not uncommon.



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- What would Chandra photon count rate be?
    - 1 photon/10s/cm^2 * 1100 cm^2 = 100 photon/s for brightest cluster in sky. Need collecting area to do this.
    - Collecting area="large" mirror, at grazing incidence=long focal length.

Surface Brightness

- Total X-ray counts per area from a cluster is integral of $\rho^2 T^{1/2} = d\rho^2 T^{1/2}$ where d is cluster depth.
- With x-ray spectroscopy, I can measure T.
- I have two pieces of information from X-rays (T, L), with one more I could break degeneracy and measure d, ρ separately.

SZ

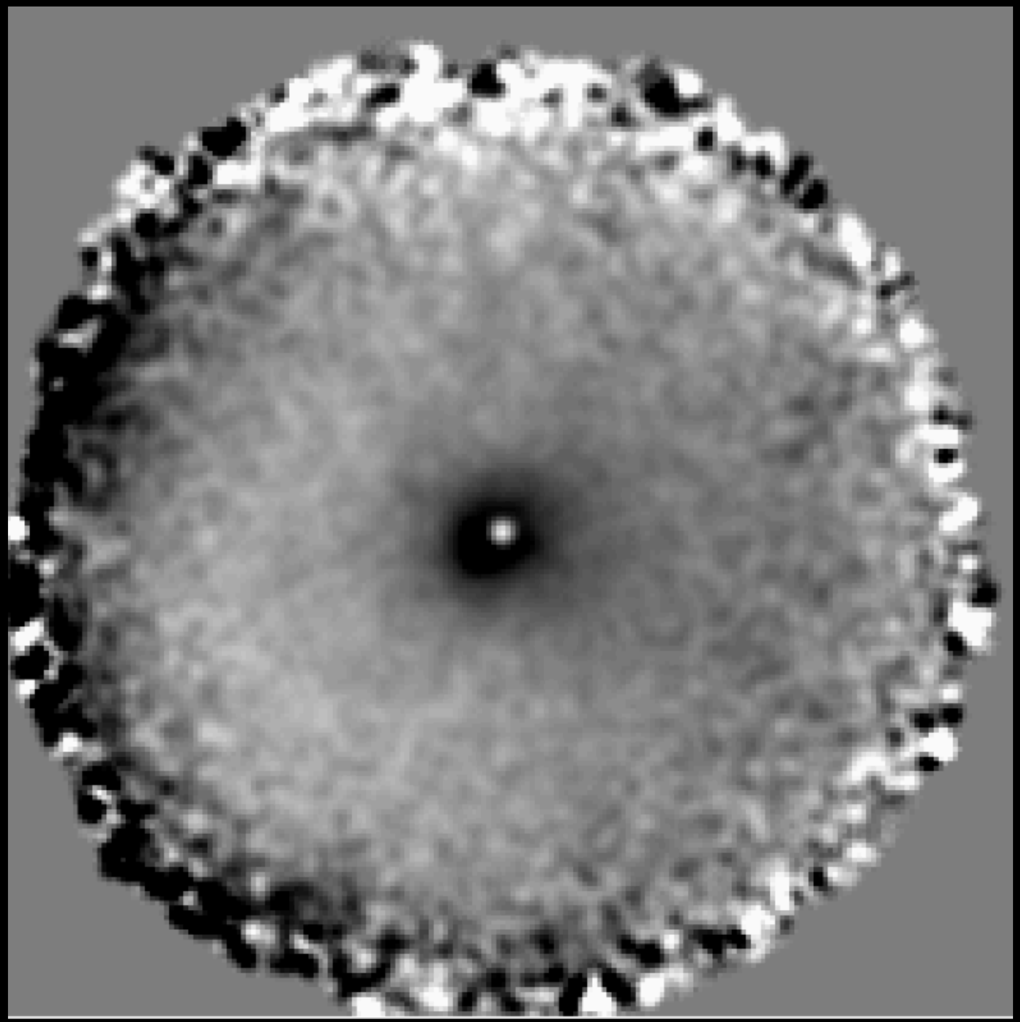
- SZ effect comes from CMB photons scattering off of electron gas.
- What is optical depth through rich cluster?
- M=2e15, r=1.5 Mpc, Mgas~0.2M ~4e14. Electron column density is $4e14*2e33*6e23/(\pi*(1.5*3.08e24)^2)=10^{22}$ e-/cm^2.
- Thomson cross section is 6e-25 cm2, so optical depth ~1e22*6e-25 ~1e^{-3}-1e^{-2}.

Compton Scattering

- As photons bounce off, sometimes red-shifted, sometimes blue-shifted.
- Net effect is to pump energy from low to high frequencies, rate has to be second order in velocity, or first order in temperature.
- So, typical shift will be optical depth time (kT/m_ec^2) ~1e-2*(10/511)~2e-4. CMB temperature is 3K, so typical CMB distortions on order 500μK.
- Effect proportional to # of electrons times temperature.
- Total SZ is $M(M^{2/3})$ $\sim M^{5/3}$, but surface brightness $\sim M^{4/3}$.

SZ Mapping

- How long would it take 1 ground-based detector (500 μK $s^{1/2}$) to make an SZ map?
- Say 2% measurement, so 50σ, T_{obs} ~1 hr for bright cluster if detector stays on-source.
- Right - just under 1 hour RXJ1347 map w/ Mustang2 on GBT.



Getting H0

- So, we can combine SZ surface brightness ($d\rho T$) and X-ray surface brightness ($d\rho^2 T^{1/2}$), if we have temperature.
- SZ^2/X-ray $\sim dT^{3/2}$.
- With temperature, we now have physical distance through cluster.
- We can measure angular size of cluster as well. If cluster is spherical, we now have measurement of angular diameter distance, gives H_0.

MEASURING THE HUBBLE CONSTANT WITH THE SUNYAEV-ZEL'DOVICH EFFECT

Erik D. Reese

The University of California, Berkeley

Abstract. Combined with X-ray imaging and spectral data, observations of the Sunyaev-Zel'dovich effect (SZE) can be used to determine direct distances to galaxy clusters. These distances are independent of the extragalactic distance ladder and do not rely on clusters being standard candles or rulers. Observations of the SZE have progressed from upper limits to high signal-to-noise ratio detections and imaging of the SZE. SZE/X-ray determined distances to galaxy clusters are beginning to trace out the theoretical angular-diameter distance relation. The current ensemble of 41 SZE/X-ray distances to galaxy clusters imply a Hubble constant of $H_0 \approx 61 \pm 3 \pm 18$ km s^{-1} Mpc^{-1}, where the uncertainties are statistical followed by systematic at 68% confidence. With a sample of high-redshift galaxy clusters, SZE/X-ray distances can be used to measure the geometry of the Universe.