Baryon Budget in 2 keV clusters

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Overview

- Introduction
- The 400 sq deg serendipitous survey of clusters of galaxies
- The groups selected from the survey
- Example of observation of one group from the sample
  - X-ray observations
  - Optical observations
  - Results of baryon determination
- Summary

Introduction

- Scope: Accurate mass determinations and baryon census in 2keV galaxy clusters (groups)
- Why:
  - Clusters and groups of galaxies are the best systems for accurate observational determination of the relative contribution of the different components of matter.
  - Clusters (rich, massive) have been used intensively as representative samples of the Universe as a whole, however
  - Groups are much more numerous and contribute more to the total mass density in the Universe than do the rich clusters, thus
  - Need to study groups in detail to confirm details of cosmological parameters.

Introduction

- Important issues:
    - Selection of a good statistical sample of groups – choose from a high quality survey, more confident to extrapolate results from measurements of just a few groups.
    - Need X-ray observations to get total mass and T. Need to extend observations to large radii to ease separation of non-gravitational heating; the low mass in groups of galaxies makes the X-ray properties sensitive to the presence of that kind of heating of the intracluster medium, e.g. early energy input from SNe ("preheating") or radiative cooling and associated energy feedback from star formation.
    - Need optical observations to allow for determination of stellar mass which in groups typically contributes more than 25% of the total mass. Groups are also a good choice here: the limited number of galaxies in a group compared to a cluster makes it feasible to examine spectroscopically (most of) the galaxies.

The 400 sq deg survey

- The 400 sq deg *ROSAT/PSPC* galaxy cluster survey is an extension to the well-known 160 sq deg survey (Vikhlinin *et al* 1998, Mullis *et al* 2003).
  - Serendipitous survey, i.e. using pointing observations with the original target different from survey members.
  - High galactic latitude ROSAT/PSPC observations: |b|>25·
  - $N_H < 10^{21}$ cm^{-2}
  - t_{exp} > 1000 s (corresponds to detection threshold: $f_X \sim 3x10^{-13}$ erg s^{-1} cm^{-2} [0.5-2keV])
  - 10· away from LMC, SMC
  - Detection threshold for this survey is $f_X > 1.4x10^{-13}$ erg s^{-1} cm^{-2} [0.5-2keV]

The 400 sq deg survey

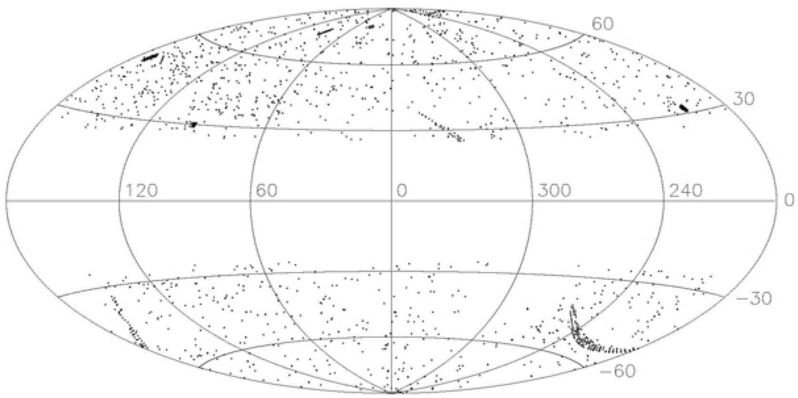
- Compared w. the 160 sq deg survey, the 400 sq deg survey goes closer to the Milky Way, accepts less exposure time, and has included the recent archival release of pointings to cover the original lack of coverage of the all-sky survey.

- Result is 1610 fields vs. 646 in the 160 sq deg survey, but due to higher flux threshold, only 84 more extended objects detected (while at all fluxes, the detection of extended objects is as expected, ~2.5 times the number from 160 sq deg).
- The total number of clusters in the survey is now 266 – for the same flux limit in 160 sq deg we had 188.
- Removing non-serendipitous candidates leaves 242 clusters.
- Thus, the survey is optimized towards richer, more massive clusters at higher redshifts.

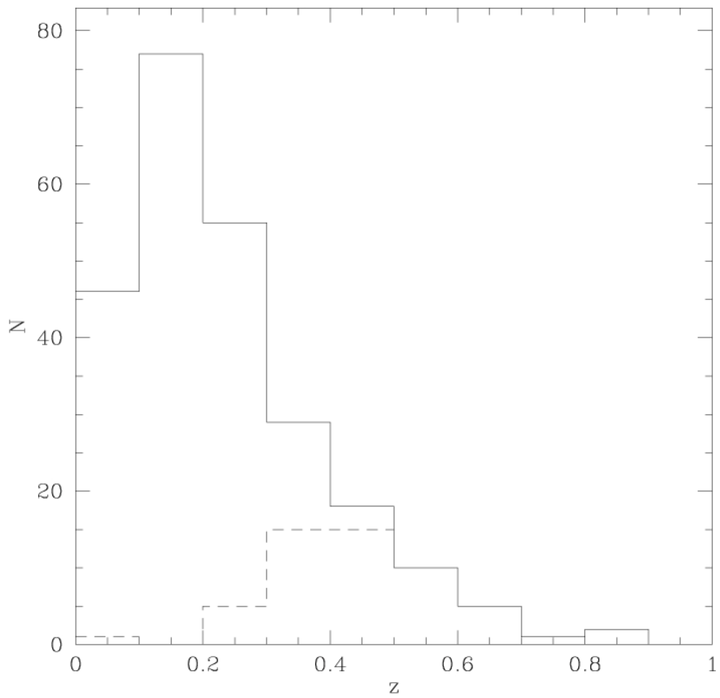
The 400 sq deg survey

- However, it is useful for selection of galaxy groups (having lower mass, lower flux) in the nearby Universe (lower z).
- Within z<0.2 the coverage of the survey is total and includes also (high and low flux) groups of galaxies.
- Compare to ROSAT All-Sky Survey, which is only complete up to z<0.04
- Optical confirmation of cluster by imaging, and spectroscopically determination of the redshift (based on 2 or more bright galaxies). Note, this is only a confirmation, not a selection criteria!

- The survey will be published soon, look for Burenin *et al* 2006 (X-ray) and Hornstrup *et al* 2006 (optical).



Distribution of the 1610 ROSAT fields used in the survey projected in galactic coordinates



The distribution of redshifts of the clusters in the survey. (Dashed line represents bright clusters, L_{44}>1)

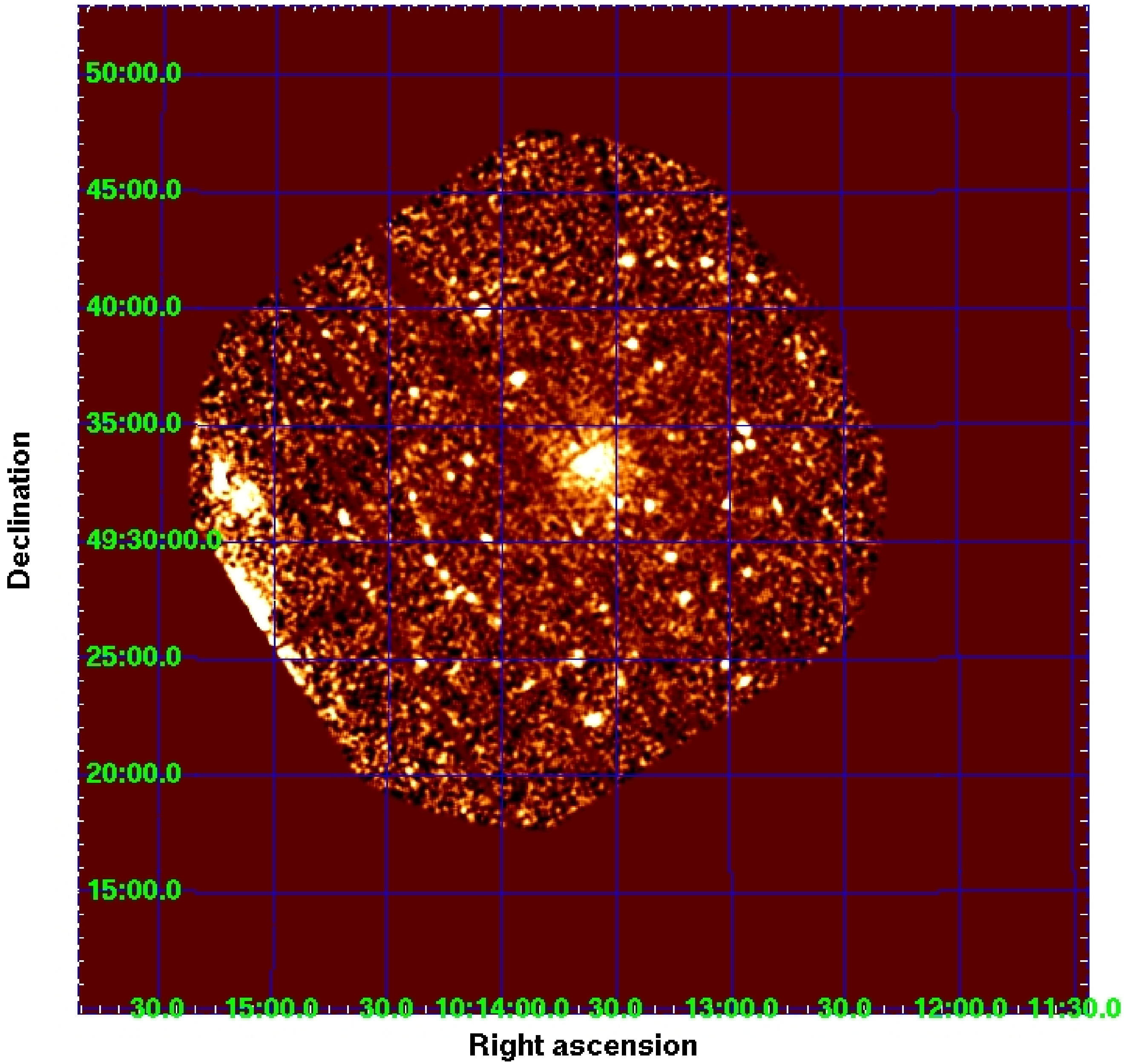
Groups selected from 400 sq deg survey

- Decided to select a sub-sample of the groups, which had
  - *T ~ 2 keV* (based on f_X -> L_X -> T using local L-T relation (Markevitch, 1998))
  - $f > 3 \times 10^{-13}$ erg s^{-1} cm^{-2}
    - To make sure the selection is within the complete coverage area of the survey
  - $0.05 < z < 0.15$
    - To also allow for a single or at least only a few mosaic observations with available telescopes (optical, X-ray) to cover the cluster to r_{vir}. This helps establish the background more firmly.
  - More than 10 groups
    - To improve the statistics.
- Final selection covers 14 groups.
- These 14 are observed with optical telescopes, using Danish 1.5 m telescope (La Silla) and Nordic Optical Telescope (NOT, La Palma).
- 2 observed with *XMM.* ~33 ks asked for; only about 1/3 useful ☹
- 1 accepted for observation with *Chandra,* 1 observed.

Example: Analysis of one group (cl1013p4933)

- Observed for 33 ks with XMM, thin filter, 2xMOS, and PN.
- Observed in R, V, B with NOT
  - Spectra from ~35 of the brightest galaxies, of which about 25 belongs to the system – confirms that z=0.134
- The X-ray observation reductions briefly:
  - Used 10-15 keV band to determine where the flares provide a particle background too high to allow usage of the data. That reduced the effective observation exposure to 13 ks.
  - Used closed detector data to estimate residual particle background from background in the Out of FOV areas on the three detectors.
  - Identified and blocked out non-cluster sources.
  - Resulting profiles not sufficiently “clean” – had to remove 20% more of the particle background to get an acceptable profile.
  - X-ray background defined from 8-10 arcmin annulus

CL1013P4933



X-ray profile

- The particle and X-ray background corrected image was then used to create the surface brightness profile.
- The profile was initially attempted to be fit with a classical beta profile:

$$S(r) = S_0 \left[1 + (r / r_c)^2 \right]^{1/2-3\beta}$$

- However, the beta model profile did not provide a good fit – as has become the general trend in most recent X-ray observations of clusters.
- A 2D beta model was attempted using SHERPA, same result, although the 2D revealed, that there was no serious deviation from circular distribution of the flux.

X-ray profile

- In stead, we used the modified beta-model introduced by Vikhlinin *et al* (2005):

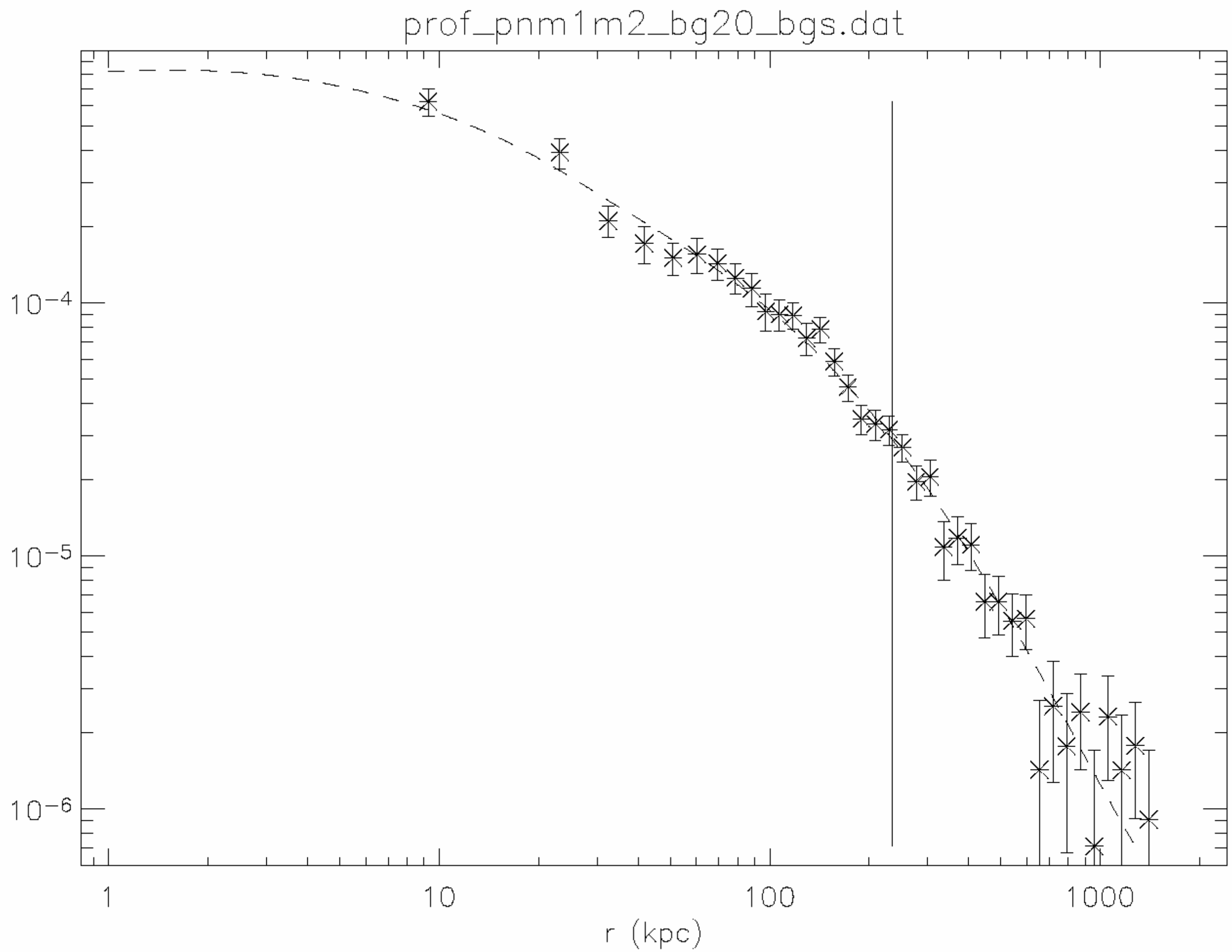
$$n_e n_p = n_0^2 \frac{(r/r_c)^{-\alpha}}{(1+r^2/r_c^2)^{3\beta-\alpha/2}} \frac{1}{(1+r^\gamma/r_s^\gamma)^{\varepsilon/\gamma}} + \frac{n_{02}^2}{(1+r^2/r_{c2}^2)^{3\beta_2}}$$

This model, obviously, has a lot of degrees of freedom.

The advantage is, that it does fit the observation (properly corrected due to integration along line of sight and folding with point spread function).

The disadvantage is the high interdependence of the parameters, making simple progressive error-estimates from each of the parameters hard.

Best way will be to do a series of monte-carlo simulations to estimate error; here, we just assume (based on previous similar group analysis's), that the error in the mass-estimates rely mostly on the T-determination.


prof_pnm1m2_bg20_bgs.dat
10⁻⁴
10⁻⁵
10⁻⁶
1
10
100
1000
r (kpc)

Mass-determination

- The X-ray image of the group indicates a relaxed X-ray gas. Thus we assume the classical hydrostatic equilibrium, where the mass is found by:

$$M(r) = -3.71\times 10^{13} M_{\odot} T(r) r \left(\frac{d\log\rho_g}{d\log r} + \frac{d\log T}{d\log r} \right)$$

- The gas-density profile is derived from the fit to the surface profile, which gave $n_e n_p$:

$$\rho_g = 1.252 m_p (n_p n_e)^{1/2}$$

- And we get the total density from:

$$\rho(r) = (4\pi r^2)^{-1} \frac{dM}{dr}$$

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Mass determination

From the ρ_g relation, we derive the gas-mass-profile through:

$$M_g(R) = 4\pi \int_0^R r^2 \rho_g(r) dr$$

- The temperature profile is obtained from the spectral fit to the X-ray emission from annuli, centered on the max X-ray flux, so that the central part has at least 1000 counts, and the radii of the annuli are defined so that $r_{out}/r_{in} = 1.5$.

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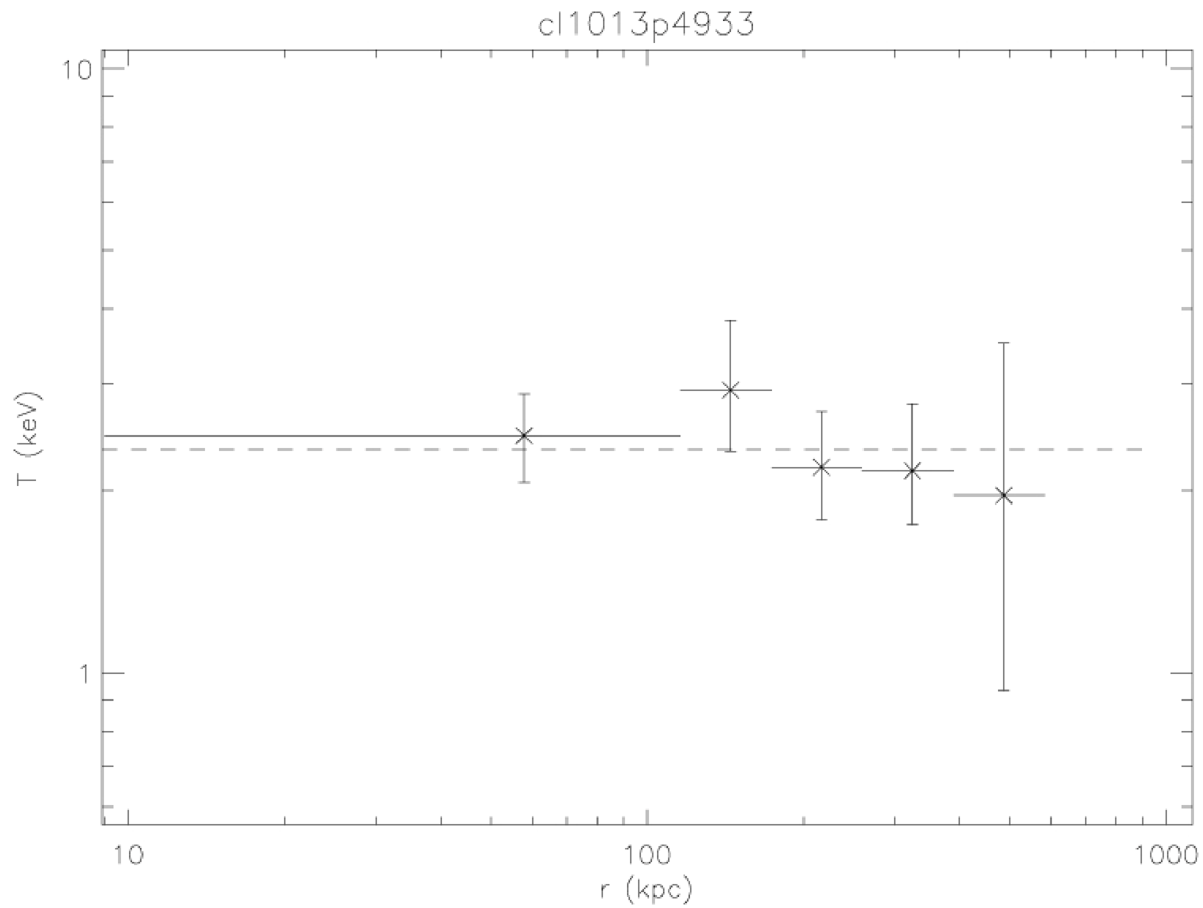
Temperature plot



X-ray results

- Data allows for assuming T_e konstant; $T_e = 2.34 \pm 0.40$ keV.
- Using the Evrard *et al* (1996) model for r_{vir} :
  - $r_{vir} = 2.78/h_{0.7} \times (T/10\text{keV})^{1/2} \times (1+z)^{-3/2} = 1.11\text{Mpc}$.

- M_{gas}, M_{total}, ρ_{gas}, ρ_{total} determination from equations mentioned above gives
  - $r_{500} = 402$ kpc
  - At r_{500} we have
    - $M_{tot} = (5.1 \pm 0.9)\ 10^{13}\ M_\odot$
    - $M_{gas} = (4.1 \pm 0.8)\ 10^{12}\ M_\odot$
    - $f_{gas} = 0.08 \pm 0.02$
- CMB observations constrains the baryon content to $\Omega_b/\Omega_m = 0.175 \pm 0.023$ (Readhead et al,2004, Spergel et al, 2003).

Optical data

- Cl1013p4933 in three colors
- 1 arcmin ≈ 140 kpc

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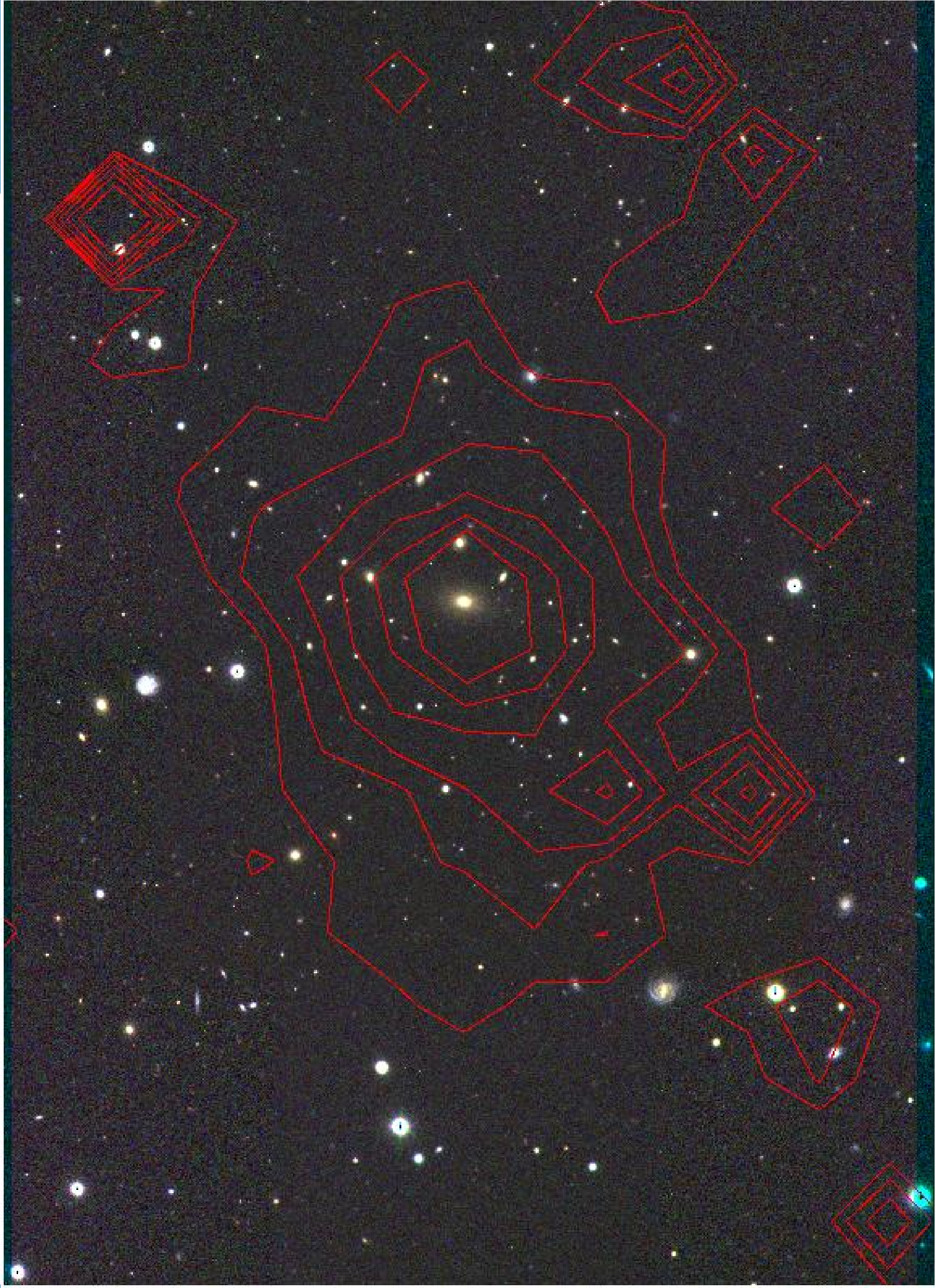
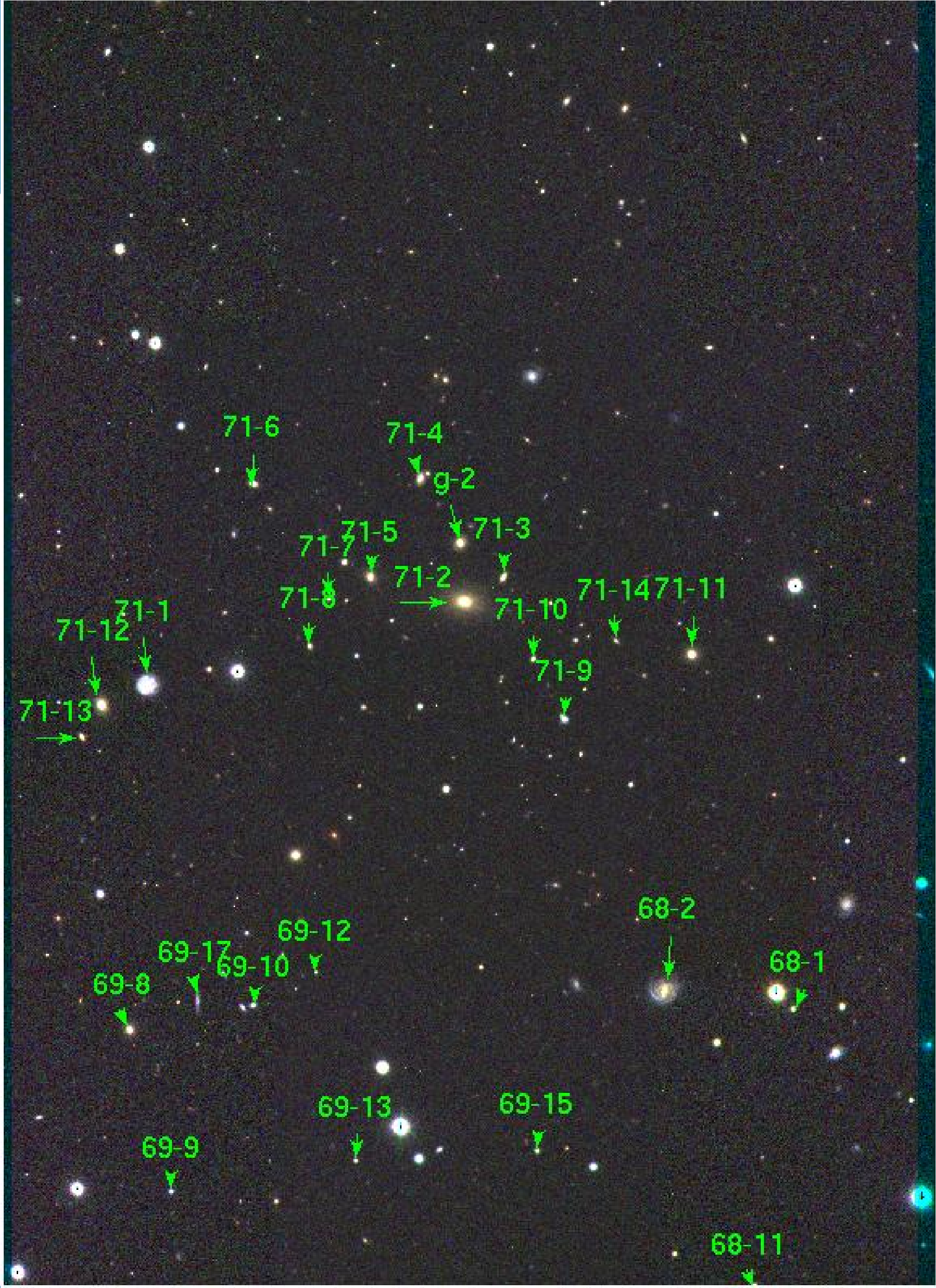
Optical data

- Cl1013p4933 in three colors
- Red contours are X-ray emission (smoothed, 0.5-3 keV emission).



Optical data

- Cl1013p4933 in three colors
- Galaxies with spectroscopically determined velocities (show only those, who belong to the group).
- z=0.134
- Dispersion:
  - σ_r = 888±150km/s corresponding to
  - T_e = 2.2±0.5 keV (via correlation from Helsdon and Ponman (2000))



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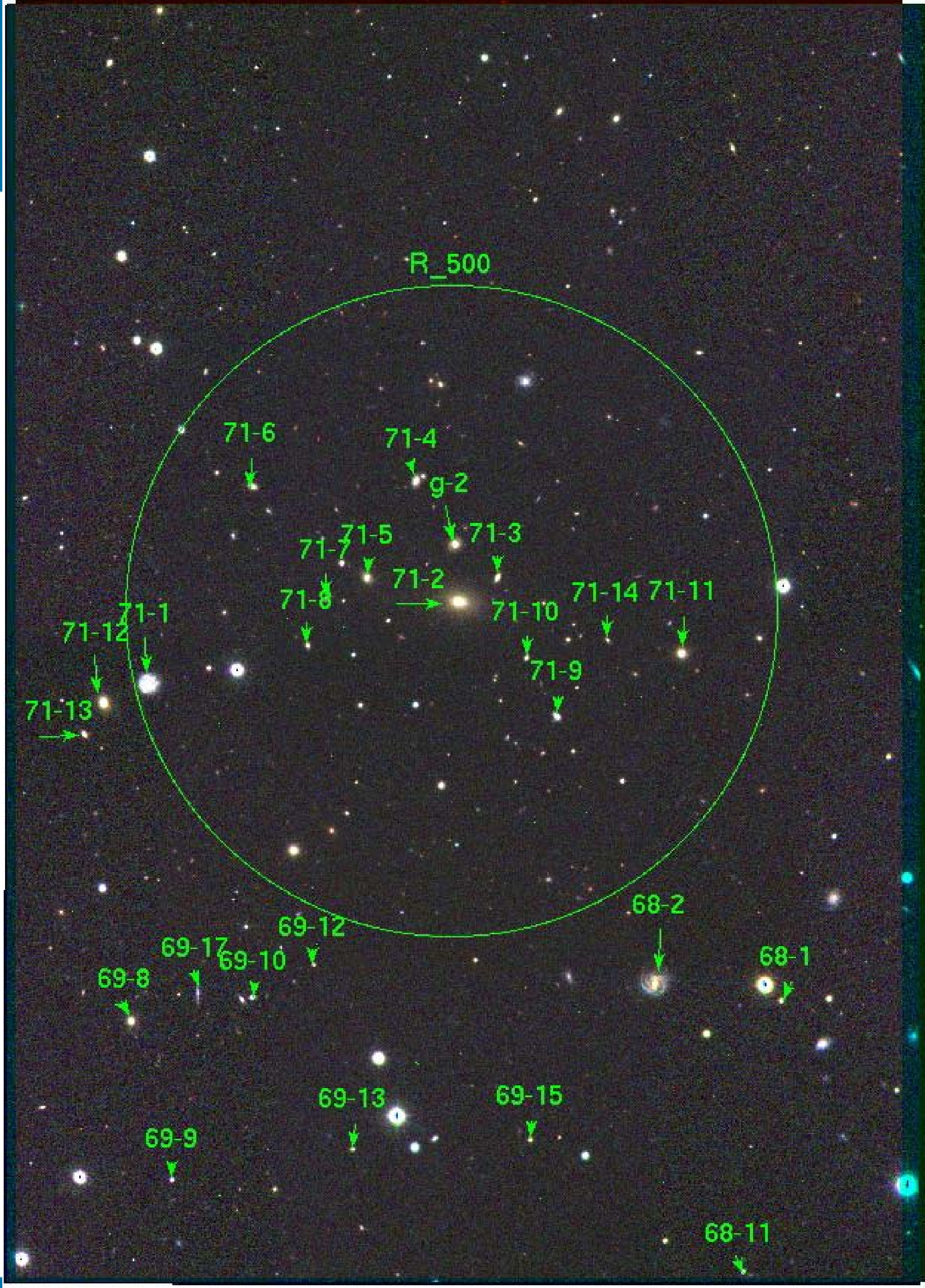
Optical data

- Cl1013p4933 in three colors
- Galaxies with spectroscopically determined velocities (and who are in the group)
- We will for this study concentrate on mass-determination within r_{500}



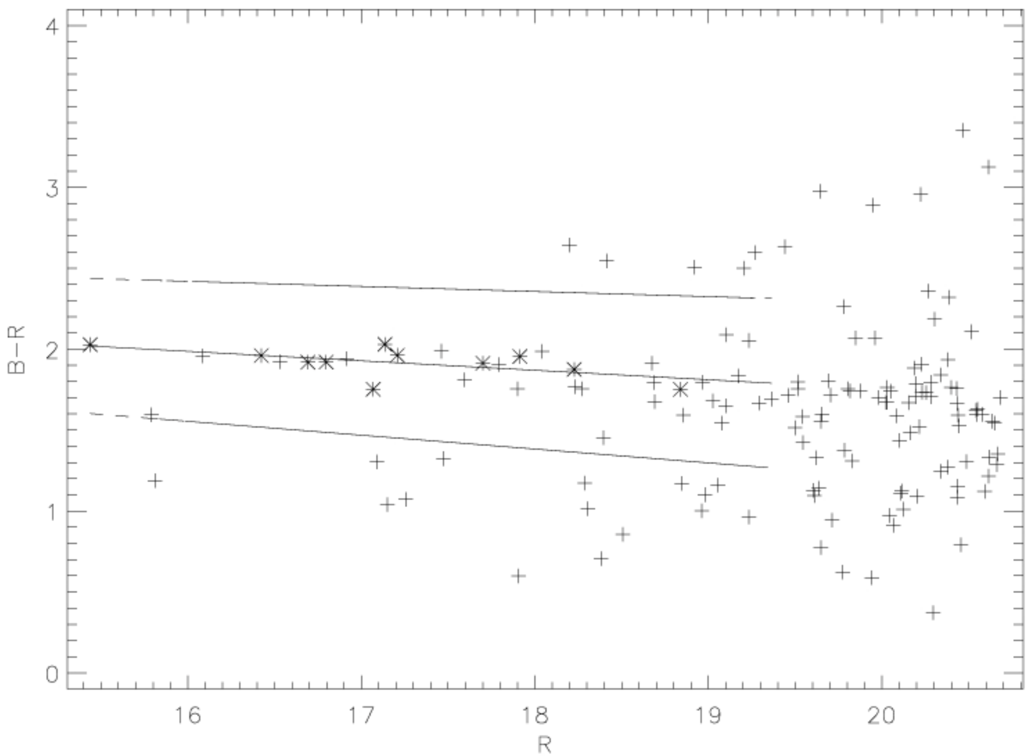
Mass of galaxies

- The galaxies within the r_{500} cirkel are chosen for mass-determination. Their B-R value is derived, correcting to local $(B\text{-}R)_0$ for
  - Atmospheric extinction (sec z)
  - Interstellar extinction (via N_H from Savage and Mathis, 1979)
  - K-correction
  - Evolutionary correction
    - The latter two from Poggianti (1997). These corrections are depending on galaxy morphology, but we have not yet classified the galaxies, and thus for this study, we assumed a mean value.

- Galaxies chosen to have B-R within 1σ from the galaxies known to belong to the cluster, and with R < R_{cD}+4
- Final B-R values are used to find M_{gal} via this relation from Bell *et al* 2003:

$$M = 10^{-0.523+0.683(B-R)} L_R$$

- Galaxy masses derived via the B-R are then deprojected to a 3D spherical distribution, before adding the mass to the system.



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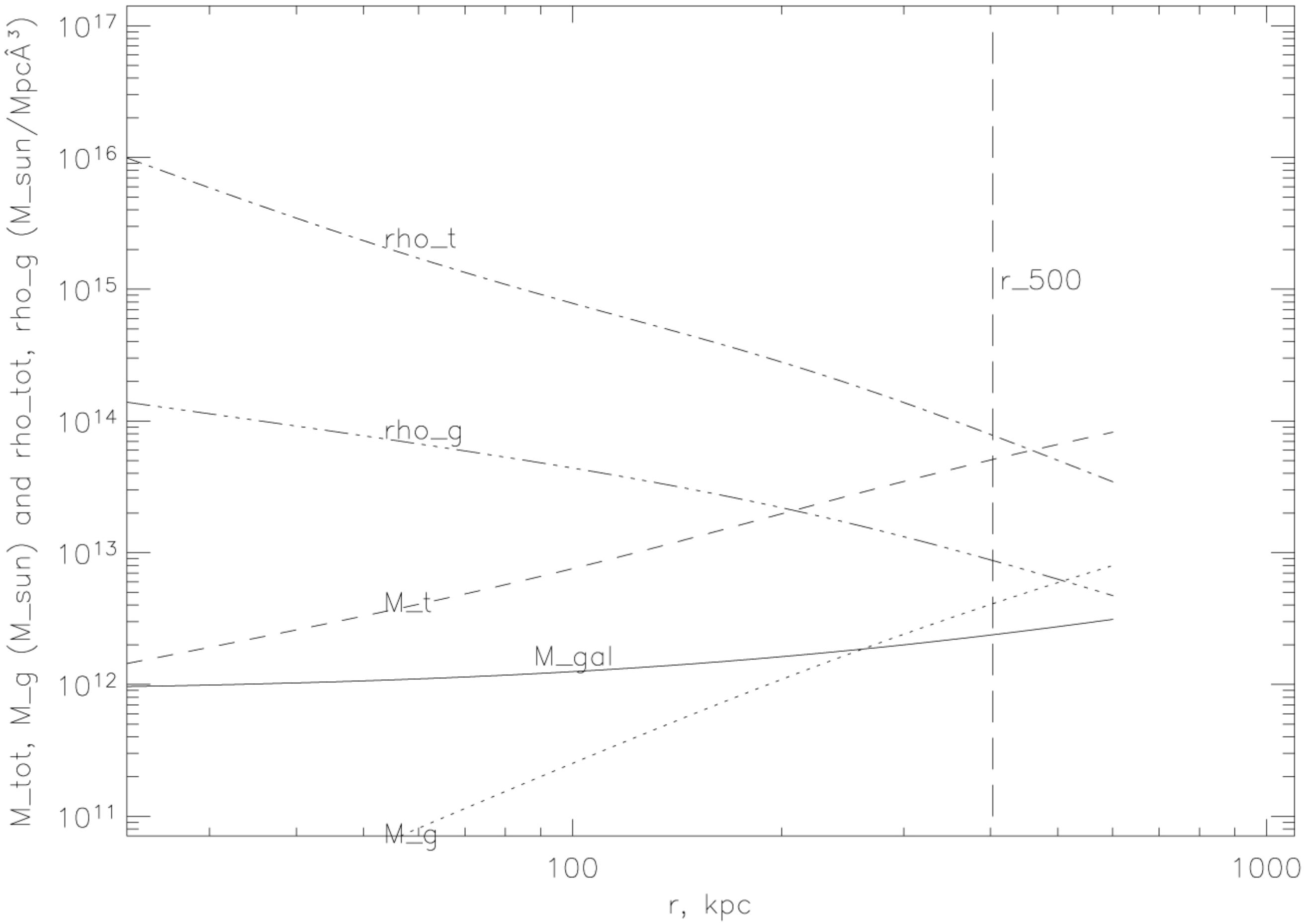
The X-ray and optical determined mass-profiles for cl1013p4933

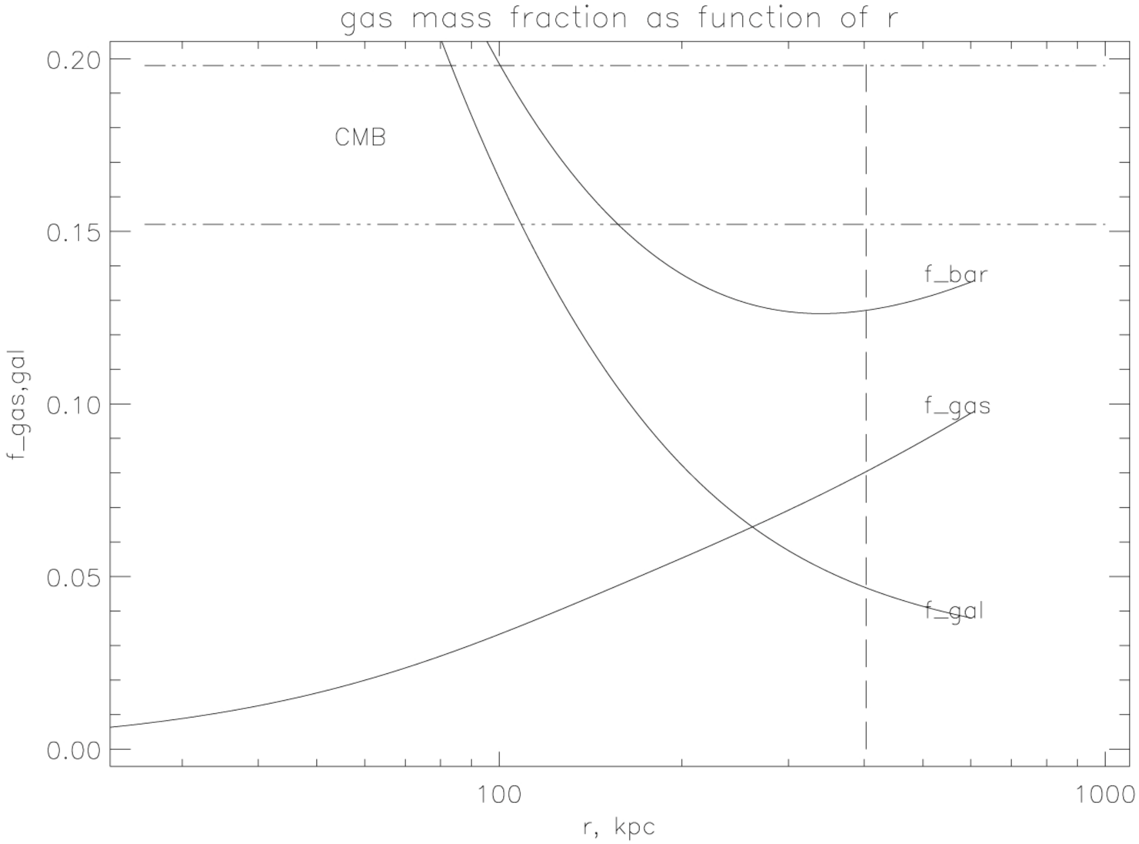


The mass profiles give the fraction profiles

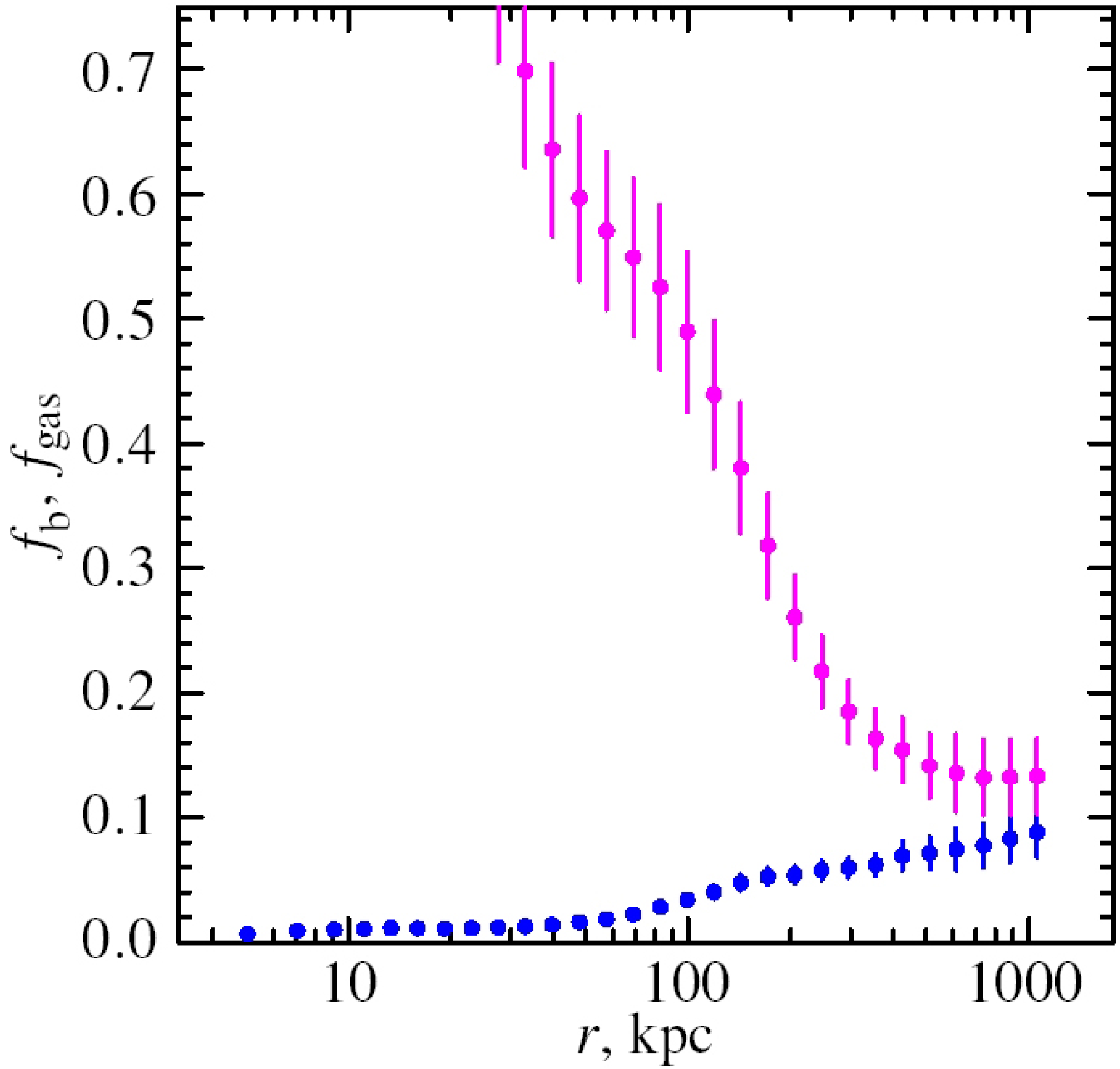
- The R_{500} result:

- $f_{bar} = 0.13 \pm 0.03\ h^{-3/2}$

- CMB:
  $\Omega_b/\Omega_m = 0.175 \pm 0.023$



- And these results are in line with our earlier study of cl1159p5531, (a fossil included in the sample), where optical and Chandra observations exist.
- f_{bar}=0.14±0.03



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Summary

- The project tries to accurately determine the mass distribution in a sample of groups drawn from an X-ray selected survey of clusters of galaxies.
  - In particular determine the baryon content.
  - 14 groups are observed in optical, 4 of those (almost) done in X-rays.
- Preliminary results show, that the values of e.g. M_{total}, M_{gas}, f_{gas}, f_{gal} , σ_r can be determined from these observations, although not quite to the radii aimed for.
- The f_b values for the first groups analyzed are within errors of the value predicted by the CMB observations.
  - Too early to completely rule out non-gravitational processes, more observations and careful analysis needed.