Towards the 2020 vision of the baryon content of galaxy groups and clusters

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1 The baryon budget of clusters: importance and scientific context

Groups and clusters of galaxies occupy a special position in the hierarchy of large-scale cosmic structures because they are the largest and the most massive (from $\approx~10^{13}\,M_{\odot}$ to over $10^{15} \,\mathrm{M_{\odot}}$) objects in the universe that have had time to undergo gravitational collapse.¹ The large masses of clusters imply that their contents have been accreted from regions of \approx 8 - 40 comoving Mpc in size and should thus be representative of the mean matter content of the universe. Thus, in contrast to galaxies, clusters are expected to retain the cosmic fraction of baryons within radii accessible to current and next generation observations in sub-mm, optical/NIR and X-ray wavelengths, even if their diffuse gas was significantly heated by supernovae (SNe) and active galactic nuclei (AGN).

The gaseous atmospheres of clusters (the intracluster medium or ICM) therefore contain a wealth of information about galaxy formation processes, including the efficiency with which intergalactic gas is converted into stars and the chemical and thermodynamical effects on the evolution of galaxies and the surrounding intergalactic medium (IGM) driven by ensuing feedback mechanisms. Suppose, for example, that AGN feedback significantly heats the ICM in the central regions and the gas expands. The density of the gas in the center would be lower, but we should still observe the expanded gas in the outer regions of the cluster and should be able to observe the signature of heating in its entropy. Likewise, if a certain fraction of ICM gas has cooled in the past, we should be able to observe these baryons either in the form of cold gas or in the form of stars. Some fraction of gas processed by galaxies is returned to the intracluster medium via winds

and ram pressure stripping, as is evidenced by the high abundance of heavy elements in the intracluster plasma. The distribution of metals as a function of radius provides a record of the baryons recycled through galaxies and the exchange of material between galaxies and surrounding gas. Multi-wavelength, holistic studies of baryon contents of groups and clusters *as a function of radius* thus shed light on many key processes accompanying galaxy formation, one of the central unsolved problems of modern astrophysics. Most of these processes are difficult to observe or constrain by other means.

Knowledge of the baryon content of clusters is also a key ingredient in the use of clusters as cosmological probes. First, it is the observed stellar and hot gas components of clusters that are most often used as proxies for their total mass, which can be connected to theoretical predictions and used to constrain cosmology via evolution of the cluster abundance and spatial distribution. Second, measuring the fraction of the total mass in baryons within clusters is one of the most powerful methods of measuring the mean matter density of the universe and is important in the interpretation of the cluster signal contribution to the small-scale CMB anisotropies in terms of the power spectrum normalization. Third, since the mass fraction of hot gas measured from observations depends on the luminosity distance at the cluster redshift, tracing evolution of this fraction as a function of redshift is a powerful independent geometrical constraint on the dark energy content of the universe. All of the above measurements require good understanding of the evolution of the stellar and hot gas fractions in clusters.

Study of the baryon budget of groups and clusters across cosmic time is thus a truly important scientific theme with a wealth of connections to other areas of astronomical research, such as cosmology, galaxy formation and evolution, AGN physics, etc., and is therefore of tremendous scientific interest.

¹ The space limitations do not allow us to provide a representative list of references for the topics we discuss. A version of the paper with extensive references included will be posted on the arXiv.

During the past two decades, the advent of new observational facilities and theoretical models have allowed us to uncover some very interesting puzzles in this area (see § 2) and to formulate specific questions, which we are poised to address in the next decade:

- Does the baryon fraction of groups and clusters reflect that of the universe as a whole at radii and epochs probed by observations?
- ▷ What are the radial distributions of different mass components of clusters (stars and cold gas, diffuse hot gas, and dark matter)?
- ▷ How does the observed baryon budget in clusters and groups constrain models of galaxy formation and feedback?

The radial distributions of all main mass components of groups and clusters (stars, cold, warm, and hot gas and total mass) at different redshifts out to the virial radius are the main required observational measurements. During the next decade sensitive multi-wavelength observations, capable of accurately probing all the major matter components of clusters, should allow us to tackle or make substantial progress on all of the outlined questions. Increasingly sophisticated simulations of clusters will explore a range of plausible scenarios and assumptions about the physics of galaxy formation and ICM and their effect on resulting distribution of baryons and total mass. Multi-wavelength, comparative studies of real and simulated cluster samples would allow us to use clusters as veritable astrophysical laboratories for studying galaxy formation and testing our theoretical models of structure formation and underlying assumptions about fundamental physics governing the universe.¹ At the same time, reliable

and detailed knowledge of the baryon content of clusters would provide the necessary basis for their use as precision cosmological probes.

2 Current status

2.1 Observations. Over the past decade, dramatic progress has been made in observations of all the main components of clusters. Deep high-resolution wide-field imaging has dramatically improved the accuracy of strong and weak lensing measurements of cluster mass profiles and the number of systems with lensing data has been increasing dramatically. Such measurements provide a powerful independent method of measuring the distribution of total mass in clusters. Statistical measurements of the shear profiles around large numbers of clusters in the SDSS survey have determined the average mass profiles around clusters of different richness with exquisite precision out to ~ 10 Mpc.

Deep imaging in multiple optical bands, in particular in the near infrared (NIR), has permitted a systematic census of the stellar component in clusters, including the low surface brightness intracluster light (ICL). At the same time, measurements of stellar kinematics with the panoramic integral field spectrograph SAURON have provided the first direct constraints on the mass-to-light ratios of stellar populations of some nearby cluster galaxies.

New, high-resolution, sensitive X-ray observations by *Chandra* and *XMM*-Newton have revolutionized our knowledge about properties of the hot ICM gas by reliably mapping gas density, temperature, and metallicity out to a significant fraction of virial radius. These observations show that the ICM is not isothermal and that the widely used β -model does not describe the radial distribution of the hot gas density in the outer regions of clusters.

¹ The Bullet cluster, the system in which hot gas in one of the merging clusters is clearly offset from center of total mass and galaxies, is a fine example of a system where

multi-wavelength mapping of different components of cluster region provides powerful information about underlying physics of the system and properties of dark matter.

Qualitatively better data about the thermal state and cooling of the gas, especially in cluster cores, has revealed both new insights and puzzles (e.g., lack of very cold gas in the centers, high gas entropy in the outskirts, etc.). Deep, targeted X-ray observations of carefully selected relaxed clusters have determined the total mass profiles of groups and clusters under the assumption of hydrostatic equilibrium and put constraints on the halo concentrations and cuspy inner density profiles predicted by Cold Dark Matter (CDM) structure formation simulations.

Measurements of the Sunyaev-Zeldovich effect (SZE) with interferometric techniques have produced independent constraints on the thermal state of the gas in dozens of clusters. At the same time, technological breakthroughs in building large bolometric detector arrays have improved the mapping speed of the SZE receivers by an order of magnitude. Such instruments now provide unique constraints on the ICM gas distribution in the outermost regions of clusters, to the virial radius and beyond.

Deep 21 cm imaging of the Virgo cluster has constrained the amount of cold HI gas, while observations of molecular emission have revealed the presence of some cold gas in cluster centers. These measurements have started to elucidate the way in which the interstellar medium of galaxies gets stripped by the hot ICM as they enter clusters and the balance of heating and cooling in cluster cores. UV spectroscopy of background quasars has given first constraints on the amount and properties of warm gas ($T \sim \text{few} \times 10^5 \text{ K}$).

Figure 1 shows three representative examples out of many exciting developments outlined above: measurement of the contribution of the central galaxy and ICL stars to the total stellar budget of clusters out to the virial radius, recent high signal-to-noise measurements of the SZE signal out to the virial radius, and measurements of ICM gas density profiles and total mass profiles from deep targeted *Chandra*



Fig. 1— Distribution of mass fraction of stars in the brightest cluster galaxies and ICL in clusters of different mass (top,[1]), accurate SZE profile measurement for cluster AS1063 out to the virial radius, $\approx 2r_{500}$ (middle, SPT team, in prep.), and hot gas and total mass profiles derived from deep *Chandra* data for a sample of relaxed clusters (bottom, [2]).

X-ray observations of relaxed clusters. The figure demonstrates that current observations are becoming capable of mapping profiles of different cluster components to a significant fraction of the virial radius.

2.2 Theory. During the last two decades selfconsistent cosmological simulations of cluster formation following the dynamical evolution of collisionless dark matter and diffuse baryons in the non-radiative regime and including various processes accompanying galaxy formation have improved in mass resolution and dynamic range by about 4 and 2 orders of magnitude, respectively. Despite the fact that many aspects of galaxy formation remain poorly understood, notable successes of the simulations include correct predictions of the gas density and temperature profiles outside of cluster cores, and the radial distribution of cluster galaxies. Prediction of these quantities in an ab initio model of ACDM structure formation is convincing evidence that modeling of cluster formation is on a firm theoretical footing. Cosmological simulations of clusters have demonstrated that the baryon fraction outside cluster cores is expected to be within $\approx 10\%$ of the universal baryon fraction $\Omega_{\rm b}$. However, stellar and hot gas fraction profiles do depend sensitively on the details of the physical processes included in simulations.

Figure 2 illustrates the current observational measurements of stellar and hot gas mass fractions, and their sum – the total baryon fraction, within r_{500} (the radius enclosing an overdensity of $500\rho_c$, $\rho_c \equiv 3H(z)^2/8\pi G$, $r_{500} \approx 0.5r_{\rm vir}$), and compares these measurements to high-resolution simulations of clusters with dissipative physics of galaxy formation [3].

Stellar mass fractions in observed groups and clusters (bottom panel) steadily decrease with increasing cluster mass. Clusters from cosmological simulations shown in the figure exhibit at best a very weak trend. The actual values of f_* for groups ($M < 10^{14} \,\mathrm{M_{\odot}}$) are in rea-



Fig. 2— The stellar (bottom), gas (middle) and total baryon (top) mass fractions in units of the mean baryon fraction (Ω_b/Ω_m) in cosmological cluster simulations with (blue) and without (red) galaxy formation (points with no error bars) and in observed clusters [2, 1, 4, 5] (points with error bars). within the radius r_{500} enclosing overdensity of 500 times the critical density. The figure shows fairly good agreement of observed and predicted gas fractions, but large discrepancies in the stellar fractions. The total baryon fractions of most of the observed clusters are significantly below the theoretical expectation.

sonably good agreement. For massive clusters, however, the f_* in simulated clusters is a factor of ~ 2 - 5 larger than observed. This is an illustration of the well-known "overcooling problem."¹

Surprisingly, despite the glaring discrepancy in f_* , the comparison of hot gas fractions in the middle panel shows rather good agreement between simulations and data, both in the average trend and in the actual values. The top panel

¹ This problem should be distinguished from the "cooling flow" problem. The latter refers to the lack of cold gas in cluster centers, while the overcooling problem refers to a too high fraction of cooled, condensed gas produced in simulations *over the entire formation history* of clusters, including all of its progenitors.

shows comparisons of the total baryon fractions in simulations performed both in non-radiative regime (red triangles) and with galaxy forma $tion^{1}$ (blue circles) to observations. The total baryon fractions of both observed and simulated clusters do not show a detectable trend with mass. For observed systems this, by itself, is a striking fact as gas in the shallower potential wells of groups is expected to be more susceptible to AGN feedback. Another noteworthy fact is that observed baryon fractions are lower than the universal value and the values predicted by simulations for this radius. Although there is a scatter in values of f_{bar} from cluster to cluster, a large fraction of them is significantly below the universal value measured by the WMAP satellite.

There are several different potential explanations for the low observed baryon fractions, although none of them have been convincingly proven yet. One key theoretical issue is systematic errors in stellar masses derived from stellar population synthesis models (SPS), but other unknown systematics in estimates of stellar and gas masses are possible. The X-ray estimates of the latter, for example, depend on the Hubble constant as $f_{gas} \propto h^{-1.5}$ so a value of h = 0.65 (2σ lower than h = 0.72 – the best fit value to the WMAP 5 yr data) would explain a significant fraction of the difference.

The discussed comparisons of expectations and observations show that our current "vision" and understanding of the baryon budget within virial radius are not yet as clear as we would like them to be. The possibility remains that we may be missing key details of the picture. However, the situation can be dramatically improved in the next decade with the advent of a new generation of surveys and instruments at different wavelengths.

3 Studying baryon budget in the next decade

3.1 Observations. The next generation of observations to constrain baryon budget of groups and clusters should cover a representative range of redshifts (0 < z < 2). This would allow to study formation of these systems as it occurs (and where sensitivity to dark energy is greatest in cosmological tests). Additionally, observations should probe a wide range of masses, as smaller systems merge and are incorporated into larger ones, so their properties are key to understanding of the baryon content of the larger systems. Lastly, it is very important to trace mass components as far in radius as possible, as cluster outskirts may contain key information both about accretion of matter onto clusters and about the prior thermal history of baryons. The observational program can address the scientific questions formulated in § 1 by a combination of statistical studies of clusters in large wide-area surveys to study mean trends and deep targeted observations of individual systems to study variations as a function of specific physical properties.

Stellar content. To obtain robust stellar mass measurements for cluster galaxies and ICL, deep, multi-band photometry is needed, with filters spanning the peak in the stellar component of the SED. This implies a combination of optical and infrared imaging for the redshifts 0 < z < 2. Such imaging can be carried out efficiently using a combination of a large wide area optical ground-based or space imaging survey, and NIR imaging with JWST from space. Large area multi-band optical surveys could constrain ICL in low-z clusters for which X-ray and SZ data are available by stacking clusters within a given range of total mass. Independent constraints on the mass-to-light ratios of a large number of cluster galaxies with IFU spectroscopy on large telescopes would usefully extend upon the work of SAURON project in the recent years. Development of better SPS models and stellar mass

¹ The f_{bar} values in these two types of simulations are close to the universal but are somewhat different. Physical processes behind these differences are understood, but their explanation is beyond the scope of this paper.

estimators and good understanding of the associated systematic error is a must. Spectroscopic measurements of velocities in cluster fields in conjunction with theoretically-motivated mock catalogs could constrain the 3d distribution of cluster galaxies. Efficient execution of such a spectroscopic measurement program requires a highly multiplexed spectrograph capable of dense spatial sampling (e.g. an instrument like GISMO+IMACS at Magellan) or a wide-area IFU, on an 8 – 10 m or larger telescope.

Hot ICM gas. Targeted deep observations of individual groups and clusters by Chandra, XMM-Newton, and Suzaku will continue to provide measurements of gas density and temperature profiles out to $r_{500} - r_{vir}$. The number of possible targets will increase dramatically after completion of the currently ongoing X-ray and SZ surveys and those planned for the near future. It would be extremely helpful if by the end of the next decade a more sensitive, low background, high-resolution (< 10'') X-ray telescope capable of mapping the gas distribution to larger radii (to $r_{\rm vir}$ and perhaps beyond) at 0 < z < 2, such as IXO (see white paper by Vikhlinin et al.), would become available. Sensitive X-ray observations would help to trace evolution of hot gas fraction very accurately over the main epochs of cluster formation and for a wide range of masses, which would provide a larger lever arm for comparisons with models. They would also provide robust estimate of total cluster mass using established robust, low-scatter observable mass proxies.

SZE observations of hot ICM will play an increasingly important role in the next decade (see white paper by S. Golwala et al.), as a combination of new sensitive interferometers and single-dish telescopes with large, multi-band \sim *mm* focal plane detector arrays should be coming online. The unprecedented combination of high angular resolution (~arcsecond) and spatial dynamic range of the new planned interferometers will allow detailed imaging of the ICM thermal pressure within inner regions of

clusters ($\theta < 1'$) with resolution well matched to that of the *Chandra* X-ray observations. Such high-resolution observations will also be able to estimate the contribution of background sources to the SZE signal, thereby eliminating one of the main sources of systematic uncertainty. Continuing development and deployment of SZ receivers with large bolometric detector arrays (> 10⁴ detectors) on telescopes with wide fields is critical to map out thermal pressure of the ICM to the virial radius and beyond for representative samples of clusters.

The combination of X-ray and new generation of SZE observations in the next decade would be particularly powerful in mapping the distribution and thermal properties of the hot ICM out to large radii and in cross-checking for systematics. Such observations would decisively constrain or exclude various scenarios of galaxy formation and feedback in clusters, as well as plasma effects, such as helium sedimentation.

Mapping the cold gas. Mass fractions of cold gas are small compared to stars and hot gas, but their measurement is important for understanding just how multiphase the ICM really is. Such measurements will also provide information on the effectiveness of feedback from galaxies and AGN by constraining how much of the central gas actually cools. During the next decade ALMA will revolutionize measurements of molecular gas in clusters over a wide range of redshifts, while Square Kilometer Array pathfinder missions can be used to map diffuse HI gas in distant clusters.

Mapping the total mass distribution. There are now several well-established techniques for deriving the distribution of total mass in clusters. Accurate gas distribution and temperature profiles obtained with existing and future X-ray observatories can provide estimates of the total mass profile for hundreds of relaxed clusters at different redshifts. At the same time, the availability of high-resolution SZ observations would allow application of such techniques to more distant clusters and provide useful crosschecks for lower z clusters, for which both X-ray and SZ data will be available. Additional checks will come from measurements of strong lensing masses in cluster cores, as statistical samples of arcs emerge from the upcoming wide area photometric surveys with follow up from space.

Wide-field deep imaging from large groundbased telescopes, but especially by imaging cameras on space missions, will allow strong and weak lensing measurements of total mass profiles (with potential great synergy between the two). Such measurements for large samples of clusters will provide independent mass measurements and will allow statistical calibration of masses derived from hydrostatic equilibrium analyses of X-ray and SZ data.

3.2 Theoretical modeling. concerted, The observational multi-wavelength campaign outlined above will need to be accompanied by improvements in theoretical modeling of Specific, robust theoretical cluster baryons. predictions of the properties of cluster galaxies, profiles of ICL, and gas density distribution and thermal structure of the hot ICM are required. Simulations are not yet at the point where they can reliably predict properties of cluster galaxies or faithfully model various aspects of galaxy formation and ICM evolution. The focus will therefore be on exploring a wide range of plausible scenarios and different physical processes: efficiency of star formation and its dependence on environment, efficiency of stellar and AGN feedback, generation and evolution of non-thermal components in the form of cosmic rays and magnetic fields (see white papers by Myers et al. and Rudnick et al.), etc. Progress is particularly needed in understanding the role of collisionless effects and deviations from equilibrium in plasma. This will be essential for reliable interpretation of hot gas fraction measurements, especially in the cluster outskirts.

At the same time, advances in available computing power should allow for larger simulations which will better resolve small-scale processes during galaxy formation. Note that cosmological simulations of clusters are particularly difficult in this respect, as scales of kpc (or smaller) need to be resolved to model the ISM and star formation in galaxies reasonably, while modeling volumes in excess of 100 Mpc. To simply resolve the ICM within a virial radius of a massive cluster uniformly to 1 kpc scale requires $\sim 10^{11}$ resolution elements, well beyond capability of the current simulations. Modern methods overcome this daunting requirement by employing either Lagrangian or adaptive mesh refinement techniques, which concentrate resolution elements in small fractions of the volume in cluster center and around densest regions of cluster galaxies. Resolving small-scale turbulence, shocks, cold fronts, and other potentially important phenomena over large volume will challenge the capabilities of these techniques. The wide range of included physical processes also significantly increases requirements for memory, storage, and bandwidth capabilities. This means that substantial tera- and peta-scale computing facilities will be required for successful work in this direction and argues for continuing investment in such facilities. Investment into funding computer science research is also needed, as it would help ensure that simulation codes can effectively use available computing platforms.

References

- [1] Gonzalez, A. H., Zaritsky, D. & Zabludoff,
- A. I., 2007, ApJ, 666, 147
- [2] Vikhlinin, A. et al., 2006, ApJ, 640, 691
- [3] Nagai, D., Kravtsov, A. V. & Vikhlinin, A., 2007, ApJ, 668, 1
- [4] Zhang, Y.-Y. et al., 2006, A&A, 456, 55
- [5] Sun, M. et al., 2008, ApJ in press
- (astro-ph/0805.2320)