The Evolution of Galaxy Clusters Across Cosmic Time

A Science Working Paper for the 2010 Decadal Survey

M. Arnaud[1], H. Bohringer (MPE), C. Jones (CfA), B. McNamara (University of Waterloo), T. Ohashi (Tokyo Metropolitan University), D. Patnaude (CfA), K. Arnaud (NASA/GSFC), M. Bautz (MIT), A. Blanchard (Laboratorie d'Astrophysique de Toulouse-Tarbes), J. Bregman (University of Michigan), G. Chartas (Penn State University), J. Croston (University of Hertfordshire), L. David (CfA), M. Donahue (Michigan State University), A. Fabian (IfA, Cambridge), A. Finoguenov (MPE), A.Furuzawa (Nagoya University), S. Gallagher (University of Western Ontario), Y. Haba (Nagoya University), A. Hornschemeier (NASA/GSFC), S. Heinz (University of Wisconsin), J. Kaastra (SRON), W. Kapferer (University of Innsbruck), G. Lamer (Astrophysikalisches Institut Potsdam), A. Mahdavi (San Francisco State University), K. Makishima (The University of Tokyo), K. Matsushita (Tokyo University of Science), K. Nakazawa (The University of Tokyo), P. Nulsen (CfA), P. Ogle (Spitzer Science Center), E. Perlman (University of Maryland, Baltimore County), T. Ponman (University of Birmingham), D. Proga (University of Nevada, Las Vegas), G. Pratt (MPE), S. Randall (CfA), T. Reiprich (Argelander-Institut für Astronomie), G. Richards (Drexel University), K. Romer (University of Sussex), M. Ruszkowski (University of Michigan), R. Schmidt (Astronomisches Rechen-Institut), R. Smith (CfA), H. Tananbaum (CfA), A. Vikhlinin (CfA), J. Vrtilek (CfA), D. Worrall (University of Bristol)

[1]CEA-IRFU
Service d'Astrophysique
Ormes des Merisiers
91191 Gif sur Yvette Cedex
France
email: Monique.Arnaud@cea.fr

The large scale structure of the present Universe is determined by the growth of dark matter density fluctuations and by the dynamical action of dark energy and dark matter. While much progress has been made in recent years in constraining the cosmological parameters, and in reconstructing the evolution in the large–scale structure of the dark matter distribution, **we still lack an understanding of the evolution of the baryonic component of the Universe.** How normal, baryonic matter collects in dark matter gravitational wells and forms galaxies and clusters is not understood well enough to make precise predictions about what we see, from first principles.

Present observations, as well as theoretical work, indicate that baryonic structure formation on various scales is deeply interconnected: galaxy formation depends on the large scale environment in which galaxies are found, and on the physical and chemical properties of the intergalactic gas from which they form, which in turn is affected by galaxy feedback. Due to the complex behavior of the baryonic matter, progress has been driven largely by observations and requires us to study simultaneously the evolution of the hot and cold components of the Universe.

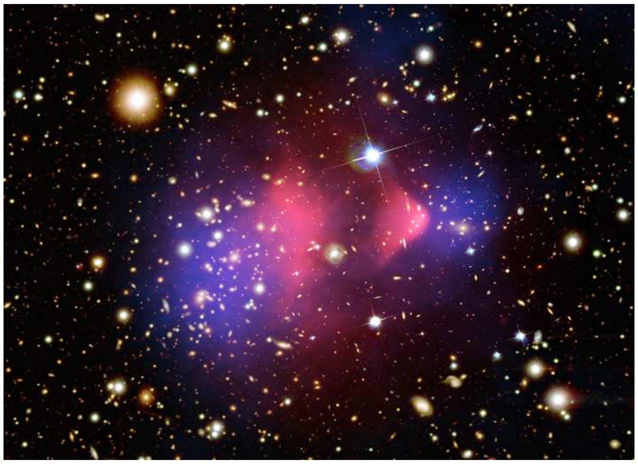
Located at nodes of the cosmic web, clusters of galaxies are the largest collapsed structures in the Universe with total masses up to 10^{15} $M_{\odot}$. Over 80% of their mass resides in the form of dark matter. The remaining mass is composed of baryons, most of which (about 85%) is a diffuse, hot T $> 10^7$ K plasma (the intracluster medium, ICM) that radiates primarily in the X-ray band. Thus in galaxy clusters, through the radiation from the hot gas and the galaxies, we can observe and study the interplay between the hot and cold components of the baryonic matter and the dark matter. X-ray observations of the evolving cluster population provide a unique opportunity to address such open and fundamental questions as:

- How do hot diffuse baryons dynamically evolve in dark matter potentials?
- How and when was the excess energy which we observe in the intergalactic medium generated?
- What is the cosmic history of heavy-element production and circulation?

Our current knowledge comes primarily from detailed studies of clusters in the relatively nearby Universe (z$<$0.5). **Major advances will come from high throughput, high spectral and spatial resolution X-ray observations that measure the thermodynamic properties and metal content of the first low mass clusters emerging at z $\sim$ 2 and directly trace their evolution into today's massive clusters.** X-ray observations at high spectral resolution also will open completely new vistas in discovery space by directly probing the dynamics of the hot gas by mapping the velocity field and turbulence.

How do hot baryons dynamically evolve in dark matter potentials?

Clusters grow via accretion of dark and luminous matter along filaments and the merger of smaller clusters and groups. X-ray observations show that many present epoch clusters are indeed not relaxed systems, but are scarred by shock fronts and contact discontinuities, and that the fraction of unrelaxed clusters likely increases with redshift. Although the gas evolves in concert with the dark matter potential, this gravitational assembly process is complex, as illustrated by the temporary separations of dark and X-ray luminous matter in massive merging clusters such as the "Bullet



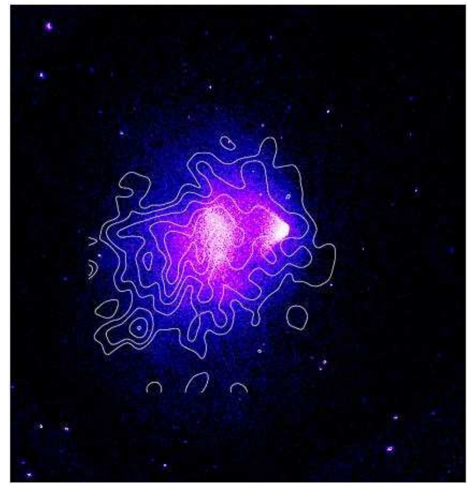


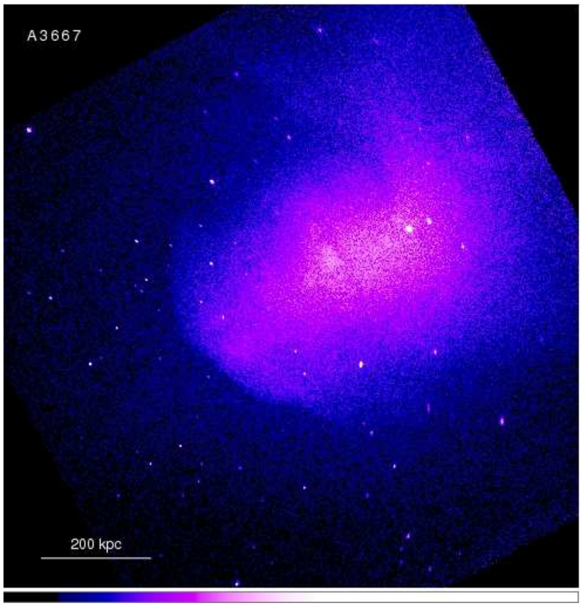
Figure 1: **Left:** As shown here for the "Bullet Cluster" (1E 0657-56), following the subcluster – cluster collision, the X-ray gas (in pink) and the dark matter as traced by the lensing (in blue) can become separated. **Right:** Contours of radio synchrotron emission due to relativistic particles, possibly (re)accelerated by shocks and gas turbulence, overlaid on the Bullet cluster X-ray image.

Cluster" (see Figure 1, left). In addition to the X-ray emitting hot gas, the relativistic plasma seen through synchrotron emission in merging clusters (Figure 1, right) is an important ICM component with at present few observational constraints.

Major mergers are among the most energetic events in the Universe since the Big Bang, releasing up to 10^{64} ergs of gravitational potential energy through the merger of two large subclusters. There are important questions to be answered, both to understand the complete story of galaxy and cluster formation from first principles and, through a better understanding of cluster physics, to increase the reliability of the constraints on cosmological models derived from cluster observations (see white paper by Vikhlinin et al.). These include: (1) How is the gravitational energy that is released during cluster hierarchical formation dissipated in the intracluster gas, thus heating the ICM, generating gas turbulence, and producing significant bulk motions? (2) What is the origin and acceleration mechanism of the relativistic particles observed in the ICM? (3) What is the total level of nonthermal pressure support, which should be accounted for in the cluster mass measurements, and how does it evolve with time? To answer these questions, more than an order of magnitude improvement in spectral resolution is required, while keeping good imaging capabilities, to map velocities and turbulence.

High-resolution X-ray spectral imaging can determine the subcluster velocities and directions of motions by combining redshifts measured from X-ray spectra (which give relative line-of-sight velocities) and total subcluster velocities deduced from temperature and density jumps across merger shocks or cold fronts [1]. These measurements combined with high quality lensing observations from instruments such as the LSST will probe how the hot gas reacts in the evolving dark matter potential.

X-ray line width measurements will allow the level of gas turbulence to be mapped in detail for the first time. As an example, Figure 2 shows that the 2.5 eV resolution of the *IXO* calorimeter can distinguish line widths of 100, 300, and 500 km s^{-1} in a small (1 arcmin^2) region of the very



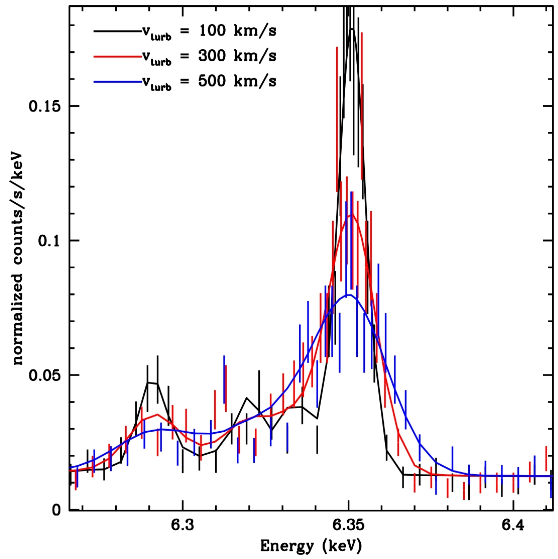


Figure 2: **Left:** 500 ksec *Chandra* image of the z=0.055 merging cluster A3667. **Right:** The 6 keV Fe line region of three simulated (*IXO*) calorimeter spectra for a 1 arcmin^2 region in the very faint shock southwest of the A3667 merging subcluster. The exposure time of the simulations is 200 ksec. The three spectra correspond to different levels of turbulence, with line widths of 100, 300, and 500 km s^{-1}. Since this cluster is undergoing a merger, we also expect to see line shifts due to gas bulk motions.

faint shock of the merging cluster A3667. For a high redshift cluster (with a luminosity of $\sim 10^{44}$ erg s^{-1} at z = 1), the line width could still be measured to an accuracy of 70 km s^{-1} in a 100 ksec exposure, and more precisely if more time is invested.

Sensitive hard X-ray (10–40 keV) imaging can reveal inverse Compton emission from the ICM. Although this emission has so far not even clearly been detected, it promises unique information on the energy density of the relativistic particles, and when combined with next generation radio observatories like SKA, would probe the history of magnetic fields in clusters. Capabilities like those of *IXO* are needed to understand these observationally elusive, but important components of the ICM.

Further crucial insight into cluster assembly can be gleaned from measurements of the *dark matter* distribution in the most relaxed systems. Cosmological numerical simulations of large-scale structure collapse robustly predict that the dark matter distribution should be cuspy, vary with system mass, and evolve with time. Current X-ray observations of bright, local systems confirm the cuspy nature of the distribution, and show some indication for a variation with mass [2,3]. With *IXO*, we can dramatically increase the mass range available for these tests, and, for the first time, tackle the question of evolution by determining the mass profiles up to high redshift ($z \sim 2$), even for low mass systems .

How and when was the excess energy in the intergalactic medium generated?

One of the most important revelations from X-ray observations, supported by recent optical and IR studies, is that non-gravitational processes, particularly galaxy feedback from outflows created by supernovae and supermassive black holes (SMBH), must play a fundamental role, both in the history of all massive galaxies and in the evolution of groups and clusters as a whole. Galaxy feedback is likely to provide the extra energy required to keep the gas in cluster cores from cooling all the way down to molecular clouds, to account for the energy (i.e. entropy) excess observed in the gas of groups and clusters, to cure the over-cooling problem, to regulate star formation, and to produce the red sequence (Note the additional discussion in the "Cosmic Feedback" white paper by Fabian et al.).

It is now well established from *XMM-Newton* and *Chandra* observations of local clusters and groups that their hot atmospheres have much more entropy than expected from gravitational heating alone [4,5,6]. Determining when and how this non-gravitational excess energy was acquired will be an essential goal of the next generation X-ray observatory. Galaxy feedback is a suspected source, but understanding whether the energy was introduced early in the formation of the first halos (with further consequence on galaxy formation history), or gradually over time by AGN feedback, SN driven galactic winds, or an as-yet unknown physical process, is crucial to our understanding of how the Universe evolved.

The various feedback processes, as well as cooling, affect the intergalactic gas in different ways, both in terms of the level of energy modification and the time-scale over which this occurs. Measuring the evolution of the gas entropy and metallicity from the epoch of cluster formation is the key information required to disentangle and understand the respective role for each process. Since non-gravitational effects are most noticeable in groups and poor clusters, which are the building blocks of today's massive clusters, these systems are of particular interest.

A major challenging goal of a future next generation X-ray observatory is thus to study the properties of the first small clusters emerging at $z\sim2$ and directly trace their thermodynamic and energetic evolution to the present epoch.

Future wide-field Sunyaev-Zel'dovich, X-ray (e.g. SRG/eRosita) and optical-IR surveys will discover many thousands of clusters with $z<2$, but will provide only limited information on their individual properties. These surveys will provide excellent samples of clusters for follow-up IXO studies. In addition, $\sim$ 4 low mass clusters per deg^2, with $M > 10^{13}\ M_\odot$, will be detected serendipitously within the $18' \times 18'$ field of the *IXO* Wide Field Imager. Deep *IXO* observations will determine the X-ray properties of even these low mass systems.

The power of a high throughput, high resolution X-ray mission to study in detail high z clusters is illustrated in Figure 3 which shows simulated, deep spectra for high redshift systems as would be obtained with the *IXO* calorimeter. These will provide gas density and temperature profiles, and thus entropy and mass profiles to $z \sim 1$ for low mass clusters ($kT \sim 2$ keV, Fig. 3, middle) and for rarer more massive clusters, such as JKCS 041 (Fig. 3, right) up to $z \sim 2$, with a precision currently achieved only for local systems. Measurements of the global thermal properties of the first poor clusters in the essentially unexplored range z = 1.5–2 also will become possible (Fig. 3, left).

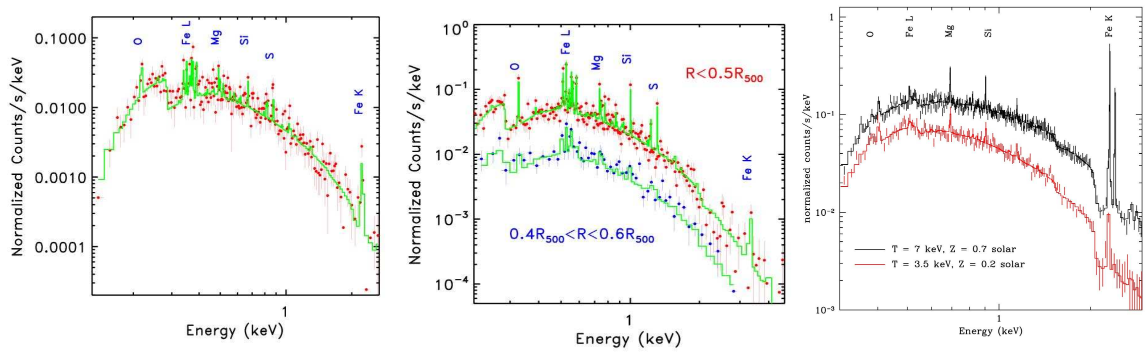


Figure 3: X-ray spectra of high redshift clusters and groups will yield gas temperatures and metallicity profiles. **Left:** *IXO* 250 ksec observation of a low mass (kT=2 keV) z=2 cluster with a bolometric luminosity of 7.7×10^{43} erg s^{-1}. Overall temperature and abundances can be measured accurately: $\pm 3\%$ for kT, $\pm 3.5\%$ for O and Mg, $\pm 25\%$ for Si and S, and $\pm 15\%$ for Fe. **Middle:** The same cluster, but at z=1, observed for 150 ks and for two spectral extraction regions. In the $0.4R_{500}$–$0.6R_{500}$ annulus (R_{500} is a fiducial outer radius of the cluster where the mean cluster mass density is a factor of 500 above the cosmic critical density), the temperature and iron abundances are measured with an accuracy of $\pm 5\%$ and $\pm 20\%$ respectively, illustrating the capability of *IXO* to measure temperature and abundance profiles at z=1, even for low mass systems. **Right:** Simulated *IXO* spectra for the z=1.9 cluster JKCS 041 based on Chandra observations [7]. In an *IXO* exposure of 200 ks, the gas temperature of the core (assumed to be 7 keV) is determined to 3% uncertainty and the overall metallicity to 3%. In the outer region, the gas temperature (assumed to be 3.5 keV) is equally well constrained, while the metallicity is measured to 5%.

What is the cosmic history of heavy element production and circulation?

A fundamental astrophysical question is the cosmic history of heavy-element production and circulation. This is strongly related to the history of star formation, the time and environmental dependence of the stellar initial mass function (and thus the cosmic history of Type I and II SNe) and the circulation of matter and energy between various phases of the Universe. As large 'closed' boxes of the Universe, clusters of galaxies are excellent laboratories to study nucleosynthesis. While the next generation of optical/IR/sub-mm observatories such as JWST, TMT/GMT and ALMA will provide essential information on the star formation history, only sensitive X-ray measurements of lines emitted by the hot ICM, where most of the metals reside, will directly determine the metal abundances in the ICM to high redshifts.

The first open question concerns the production of heavy elements over cosmic time. Chandra and XMM-Newton observations of clusters hint at Fe abundance evolution from z=1 to the present [8,9]. To give a definitive answer on when the metals are produced, we need to extend abundance studies to higher redshifts and for all astrophysically abundant elements. In local systems, the abundance pattern of elements from O to the Fe group, that are produced by supernovae, indicate that both type I and type II SN contribute to the enrichment [10]. However, these measurements only provide a fossilized integral record of the past SN enrichment and thus the evolution of supernovae remains largely unconstrained. Furthermore, the main source of C and N, which can originate from a wide variety of sources (including stellar mass loss from intermediate mass stars,

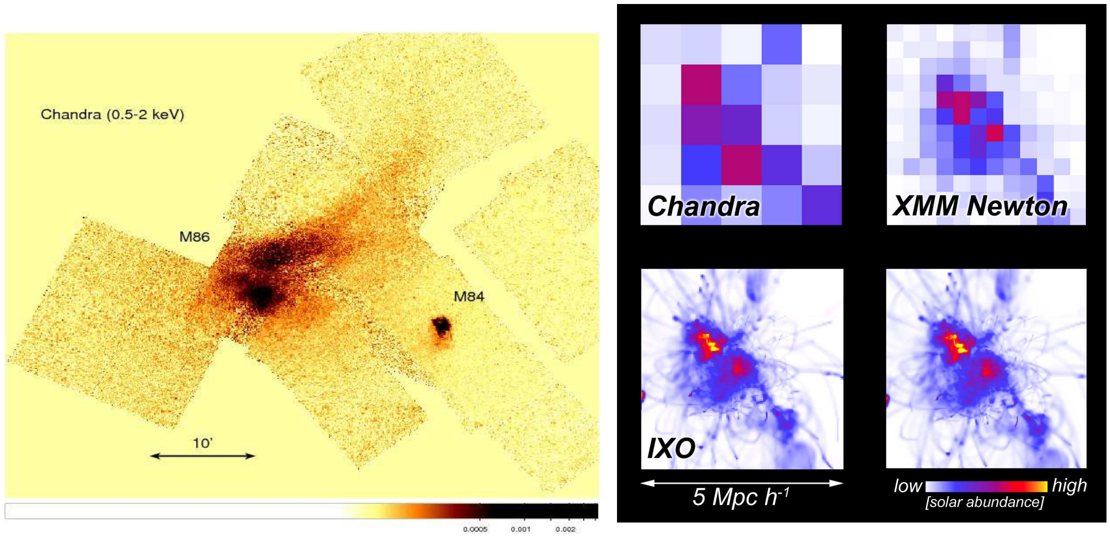


Figure 4: **Left:** X-ray emission from the Virgo elliptical galaxy M86 and its 380 kpc ram pressure stripped tail dominates this mosaic of Chandra images. Sensitive, high resolution X-ray spectroscopy will measure the metallicity along the tail and in the surrounding cluster gas. **Right:** Chandra, XMM, and *IXO* simulations show the metal abundance and distribution in a merging cluster. In this example, a merging 7 keV cluster of $L_X = 2 \times 10^{44}$ erg s^{-1} at z = 0.05 is observed for 30 ksec by each observatory compared to the actual assumed metal distribution (lower right panel). In this example, the calorimeter will image a 0.3$\times$0.3 Mpc region. A similar cluster at z=0.1 would produce a comparable map in $\sim$ 100 ksec and the *IXO* field of view would be 0.54$\times$0.54 Mpc. Several exposures would be required to map the whole region.

whose cosmic history is poorly known) is still under debate.

The second fundamental – and even more complex – open question is how the metals produced in the galaxies are ejected and redistributed in the ICM. Although AGN outflows as well as galaxy–galaxy interactions can add metals to the ICM, studies of local cluster abundance profiles suggest that the metal enrichment of the ICM is due primarily to galactic winds and ram pressure stripping of enriched gas from galaxies by the ICM [10], an example being the ram-pressure stripped tail of the Virgo cluster galaxy M86, shown in Figure 4 (left). These processes would result in different distributions for the metallicity within the cluster and over time. For example, at high redshifts, galactic winds are expected to be effective at enriching the ICM, while at lower redshifts, when massive clusters have formed, the dense ICM, especially in the cluster cores, can ram-pressure strip the enriched gas from galaxies and can even suppress galactic winds and quench star formation. The enriched material is not expected to be immediately mixed with the ICM, and in fact in the brightest, best studied nearby clusters, current X-ray observations show that the metallicity distribution in the ICM is inhomogeneous [11]. Thus by mapping the metallicity in samples of clusters over cosmic time, one can untangle the various transport processes that contribute to the enrichment. In addition, if the mass in metals is calculated assuming that the metallicity is uniform, this will miss estimate the true metal mass in the clusters.

Measurements of the metallicity distribution in clusters, for a wide range of masses, dynamical states, and redshifts, are required in order to understand the ejection and redistribution process within clusters. These studies would also have far reaching consequences for our understanding of the excess energy that is present in the ICM, as some of the transport processes (SNe winds and AGN outflows) also inject energy into the ICM, as well as for our understanding of environmental effects on the galaxy star formation history, when combined with optical and IR observations.

A high-throughput, high-resolution X-ray observatory, such as *IXO*, is required to provide answers to the questions concerning the production, circulation, and evolution of heavy elements in the ICM. The energy resolution of the calorimeter, much smaller than the equivalent width of the strongest emission lines, combined with good spatial resolution will allow a dramatic improvement in the abundance measurements. This is illustrated in Figures 3 and 4. Metal content and abundance patterns could be traced up to z $\sim$ 2 even in low mass clusters (Fig. 3, left). Element profiles will be measured up to z $\sim$ 1 for poor clusters and up to z $\sim$ 2 for more massive objects (Fig. 3, center and right). In addition, in more nearby clusters, we will be able to resolve the 2D metal distribution down to the relevant physical mixing scales (Fig. 4, right), and study in detail the process of metal injection by measuring the metallicity in the core and along the stripped tails of infalling galaxies (e.g. M86, Fig. 4, left). We will also be able to measure for the first time, the abundance of trace elements like Mn to Cr in a significant number of clusters. The production of these elements by SNe Ia is very sensitive to the metallicity of the progenitor star and thus X-ray spectroscopy will provide additional strong constraints on the cosmic history of SNe enrichment.

Concluding Remarks

Numerical simulations have reached a stage where modeling, including all hydrodynamical and galaxy formation feedback processes, is becoming feasible, although AGN feedback modeling is still in its infancy. The appropriate physics of these processes is not always clear, and advances are largely driven by observation. Thus, constant confrontation between numerical simulations of galaxy cluster formation and observations is essential for making progress in the field. *IXO* observations of the hot baryons, the most significant baryonic mass component of clusters, combined with observations of the cold baryons (from Herschel, JWST, ALMA, and ground based optical telescopes) as well as radio observations (e.g. SKA) will provide, for the first time, the details for a sufficiently critical comparison. We expect that the major breakthrough of a detailed understanding of structure formation and evolution on cluster scales, as well as understanding the cosmic history of nucleosynthesis, will come from simulation–assisted interpretation and modeling of these new generation observational data.

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