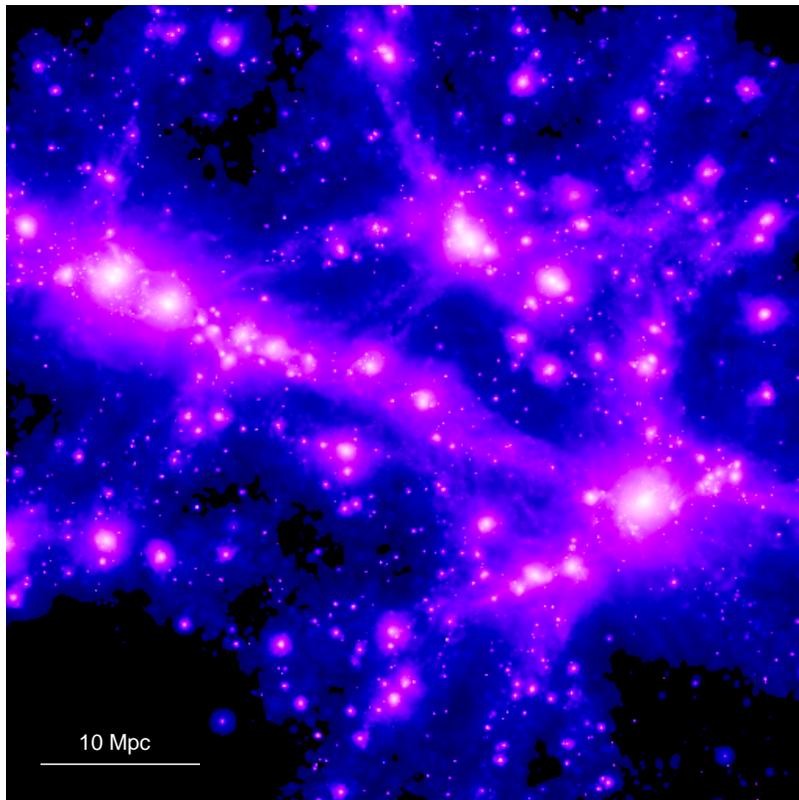


DIFFUSE BARYONIC MATTER BEYOND 2020

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ABSTRACT

The hot, diffuse gas that fills the largest overdense structures in the Universe — clusters of galaxies and a web of giant filaments connecting them — provides us with tools to address a wide array of fundamental astrophysical and cosmological questions via observations in the X-ray band. Clusters are sensitive cosmological probes. To utilize their full potential for precision cosmology in the following decades, we must precisely understand their physics — from their cool cores stirred by jets produced by the central supermassive black hole (itself fed by inflow of intracluster gas), to their outskirts, where the infall of intergalactic medium (IGM) drives shocks and accelerates cosmic rays. Beyond the cluster confines lies the virtually unexplored warm IGM, believed to contain most of the baryonic matter in the present-day Universe. As a depository of all the matter ever ejected from galaxies, it carries unique information on the history of energy and metal production in the Universe. Currently planned major observatories, such as *Astro-H* and *IXO*, will make deep inroads into these areas, but to see the most interesting parts of the picture will require an almost science-fiction-grade facility with tens of m^2 of effective area, subarc-second angular resolution, a matching imaging calorimeter and a super high-dispersion spectrograph, such as *Generation-X*.

1 OVERVIEW AND RECENT ADVANCES

Most of the visible matter in the Universe is in the form of diffuse gas that fills dips and valleys of the Universe’s gravitational potential. It is heated to $T \sim 10^5 - 10^8$ K by shocks generated by the growth of Large Scale Structure (LSS). At present, we can study only the hottest and densest phase of this matter, found in central regions of galaxy clusters ($r < r_{500} - r_{200}^*$), which comprises only a small fraction of the total. The gas within these regions is close to hydrostatic, and its X-ray observables can be used to estimate the cluster total (dark

*Radii of the average overdensity of 500 and 200 above the critical density of the Universe

matter dominated) masses,^{1,2} providing the basis for sensitive cosmological tests (§2).

There are deviations from hydrostatic equilibrium, however, observed in clusters undergoing a growth event and in many cool-core clusters, where jets and relativistic plasma from the central supermassive black hole stir the gas. Enormous progress in understanding these phenomena has been made in the past decade with the advent of powerful X-ray imaging spectrographs such as *XMM* and *Chandra*. *XMM* has determined that radiative cooling of the dense cores must be compensated by some heating mechanism.³ *Chandra* provided a leap in angular resolution that has led to the discovery of the ubiquitous AGN-blown, radio-filled bubbles in most cool cores.⁴⁻⁶ It called into question the old paradigm that gravity is the only important source of thermal energy for the intracluster medium (ICM) — apparently, AGN can inject as much mechanical energy into the core gas as it loses via radiative cooling.⁷⁻⁹ Precisely how this injection works, and how much of the cluster volume is affected, is unclear (§2.1).

Merging clusters revealed a wealth of gas motion-related phenomena — subcluster infall, shocks, “cold fronts”, cool core sloshing, ram pressure stripping — all deduced indirectly using *Chandra*’s high-resolution imaging and modest spectral information.¹⁰⁻¹⁴ These phenomena await an imaging calorimeter, which will measure the gas velocities directly (§3.1). One of the surprises was the ubiquity, sharpness and symmetry of “cold fronts” and the stability of AGN bubbles, indicating that mixing and instabilities in the ICM are suppressed by some unexpected microphysical properties of the intracluster plasma.

But perhaps the most interesting regions of clusters lie beyond the reach of the current X-ray instruments, because of their extremely low surface brightness. These are regions where the intergalactic medium (IGM) that flows along giant filaments of the Cosmic Web meets the intracluster gas. Physical processes in those regions hold the key to a num-

ber of important astrophysical and cosmological questions. Most of the baryonic matter in the present Universe is located still further into the low-density regions of the Cosmic Web. It is accessible only via FUV and X-ray line absorption studies that require very large collecting areas and very high spectral resolution (§4.1). So far only a few tentative detections of such absorption lines have been reported.^{15–19}

In this paper, we consider which fundamental questions in this field will remain *beyond* the capabilities of the near-term, trail-blazing X-ray facilities such as *Astro-H* and *IXO*. To answer them, technological leaps such as those proposed in the *Generation-X* mission concept (White Paper by Schwartz et al.) are needed during the coming decade.

2 COSMOLOGY WITH GALAXY CLUSTERS

Clusters are the most massive virialized structures in the Universe, which makes them sensitive cosmological probes. Two avenues have been actively pursued — the *growth of structure* test based on the evolution of the cluster mass function,^{20–22} and the *geometric* test based on the cluster baryon fraction.²³ At the present accuracy, the results strongly support the need for Dark Energy and are uniquely complementary to other studies (CMB, SNe, galactic surveys). Given the breadth of survey and cosmology missions planned for the near future, it is impossible to foresee what parameters of the current cosmological model will still be of interest 1-2 decades from now. In a model-independent way, clusters can uniquely trace the growth of LSS from $z \sim 1.5–2$ to the present. Its precise behavior depends on the nature of Dark Energy (WP by Vikhlinin et al). High- z clusters for these studies will be found in large numbers by the forthcoming SZ and/or X-ray survey missions, but to estimate cluster masses, an angular resolution and collecting area of *IXO* or, for higher z , *Gen-X* will be required.

Statistical uncertainties arising from small sample sizes remain the dominant uncertainty in current studies. It is increasingly clear, however, that any precision cosmological studies

in the next 1-2 decades, which will take advantage of many hundreds of clusters, will need cluster mass estimates with a systematic accuracy of $\sim 1–3\%$ (this is not the accuracy of *individual* cluster masses, but biases for sample averages). A promising approach is to use future sensitive weak lensing mass measurements to calibrate a well-behaved combination of X-ray observables and use it as a mass proxy (WP by Vikhlinin et al). While this can be done on a purely statistical basis, experience tells us that understanding and adequate numerical modeling of the underlying physics is key to obtaining robust constraints. Hence, ***cluster precision cosmology in the next decades will look more like cluster physics.*** The necessary new physical knowledge will come from combining gravitational lensing, SZ, low-frequency radio, and gamma-ray observations, all of which will come of age in the next decade, with vastly improved X-ray capabilities. For example, the currently identifiable questions that may affect cosmological constraints are:

- Why is cluster f_{bar} , the fraction of baryons (gas + stars) in the total mass, slightly lower than the Universal average?
- How relaxed are “relaxed” clusters? What is the fraction of turbulent and nonthermal pressure components (cosmic rays, magnetic fields) in the total gas pressure?

2.1 “Missing baryons” inside clusters

The baryon fraction f_{bar} derived from the X-ray data within $r < r_{2500} - r_{500}$, is too low by $\sim 30\%$ compared to the Universal value from *WMAP*.^{24,25} This is lower than expected if gravity and LSS shocks were the dominant heat source for the ICM. As this assumption is basic for cluster cosmology studies, we need to map this discrepancy to greater radii, investigate its evolution with z , explain its cause and eventually include adequate modeling into numeric codes (for a discussion see WP by Kravtsov et al). Among the possible explanations are (a) some cosmological parameters involved in the cluster f_{bar} derivation, such as H_0 , or even the universal f_{bar} it-

self, are incorrect; (b) a systematic overestimate of cluster total masses; (c) large mass in unseen stars into which the ICM has been converted, or a gross underestimate of the stellar M/L ratio; and (d) energy injection from supernovae or AGN before or during cluster formation. As suggested by the recent discovery of half-Mpc size “ghost cavities” in some clusters,^{26,27} feedback from the central AGN can affect ICM over a much greater cluster volume than thought.⁹ The first three possibilities will be addressed by forthcoming cosmology missions and sensitive gravitational lensing and optical measurements. The last possibility will be probed in the course of a fundamental study of the growth of supermassive black holes in the cluster centers over the cosmic time.

2.2 Cosmological history of AGN feedback

X-ray cavities, filled with relativistic plasma, serve as “calorimeters” of the total power emitted by the cluster central black hole as it accretes the intracluster gas.^{8,9} To see the emergence and evolution of these monster black holes will involve surveying for AGN bubbles in the cores of clusters at $z = 1-2$. Because the CMB energy density grows as $(1+z)^4$, at some redshift we may see the young X-ray cavities fill up and become bright spots, because of the increased Inverse Compton emission from the cosmic rays inside the bubbles. Combined with radio synchrotron data, this would open a unique window into the content and energetics of cosmic rays (currently completely uncertain) and their effect on the ICM.

These high z observations will pose a technical challenge, because the X-ray brightness contrast of the subtle “ghost bubbles” is very low, while young bubbles are very small. An instrument with *Chandra* or better angular resolution but a much larger effective area is required. These studies will be synergistic with sensitive low-frequency radio observations, e.g., *LOFAR*, *LWA*, *SKA*.

2.3 Cluster outskirts

A solution to the cluster missing baryons problem, and clues to the cluster nonthermal en-

ergy content, may well be found in the cluster outskirts, between the currently observable region within $r < r_{500}$ from the cluster center and the infall shock region around $r \sim 2r_{200} \sim 3-5$ Mpc, where the IGM, flowing along the Cosmic Web, meets the cluster. Fig. 1 shows a simulated X-ray image of a supercluster; a circle marks the central r_{500} region of a massive cluster and the brightness contour corresponds to $r \sim 2r_{200}$. The area between them is clearly where most of the action is — shocks and turbulence are generated, small infalling gas halos are stripped from their collisionless dark matter hosts, the near-pristine IGM is mixed (or not) with metal-rich halos and heated to $T > 1$ keV. By combining weak lensing mapping of the total mass and X-ray + SZ mapping of the gas, we may find that the gas fraction does indeed approach the Universal value, or find clues why it does not. We are also sure to discover a lot more.

Physical processes occurring in this region determine the matter and energy content of clusters. For example, infall shocks, with $M \sim 10$, should be efficient accelerators of cosmic rays,²⁹⁻³¹ though much less efficient than strong shocks in supernovae.³² Data on these shocks will be invaluable for studying the CR acceleration mechanisms, with implications throughout astrophysics. These cosmic rays should then be advected into clusters, lurk there for gigayears³³ and provide seeds for reacceleration by merger shocks and turbulence, giving rise to cluster radio halos.³⁴ The cosmic ray content of clusters, especially the relativistic protons, is presently unknown; *Fermi* and Cherenkov telescopes are expected to test the most extreme scenarios. Relativistic electrons accelerated at those far-flung shock fronts should be seen at low radio frequencies by, e.g., *GMRT*, *LOFAR*, *LWA*, and eventually *SKA* (see WP by Rudnick et al). This is the area where combining radio and X-ray data would be extremely synergistic — the SZ providing thermal pressure, the low-frequency radio exploring the nonthermal phenomena, and the X-ray yielding the gas density and temper-

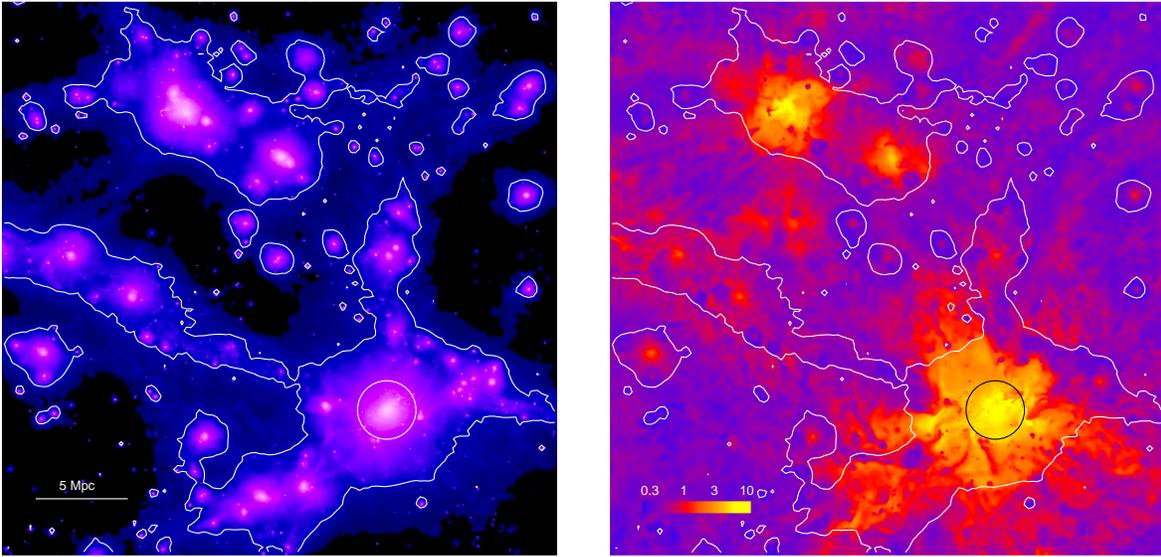


Fig. 1— High-resolution simulations of a 30×30 Mpc region at an intersection of several filaments of the Cosmic Web. *Left*: X-ray brightness in 0.5–2 keV band. *Right*: gas temperature. The color scale bar is in keV. In both panels, the circle shows the r_{500} region for the most massive cluster that is accessible for current telescopes, and the white contour shows the X-ray brightness 30 times below that at r_{200} , encompassing most of the interesting physics (simulations from ref. 28 and E. Rasia)

ature, along with Mach number determination for any shocks discovered.

The gas in the shock regions will have elemental abundances representative of the intergalactic space, but be compressed and heated to an observable state. By comparing the abundances in the shocked gas to those in the intracluster gas, we can learn about chemical history of the Universe.

Because the X-ray surface brightness in these regions is very low, this is uncharted territory. In addition to large effective area and low detector background, it requires one to remove the CXB, whose brightness is much higher. *Chandra* or better angular resolution is needed to resolve its point source component, and a 1-2 eV spectral resolution to resolve the Galactic diffuse foreground, consisting mostly of nonredshifted emission lines. A calorimeter will also be needed to study the IGM emission lines that dominate at $T \lesssim 1$ keV.

Studies of X-ray emission from cluster outskirts can be uniquely combined with absorption lines in high-dispersion spectra of the background quasars (see §4.2 below). *Gen-X*

will have the sensitivity to probe to the white contour in Fig. 1, both in emission and absorption, unlike any of the planned missions.

2.4 Particle cosmology

Some of the presently attractive Dark Matter candidates can be discovered by X-ray observations before they are discovered in the laboratory. For example, sterile neutrinos are expected to decay and produce an X-ray emission line.³⁵ Recent observations of large DM concentrations such as clusters and our Galaxy constrained the simple sterile neutrino models (e.g., 36, 37), but a discovery space from the current upper limits down to zero is wide open for a sensitive imaging calorimeter.

3 CLUSTER PHYSICS

Some of the questions posed in the cosmology section (§2) are interesting from the astrophysical perspective. Clusters, as well as hot coronae of groups and massive elliptical galaxies, offer a unique laboratory on plasma physics and hydrodynamics, with applications well beyond the cluster field.

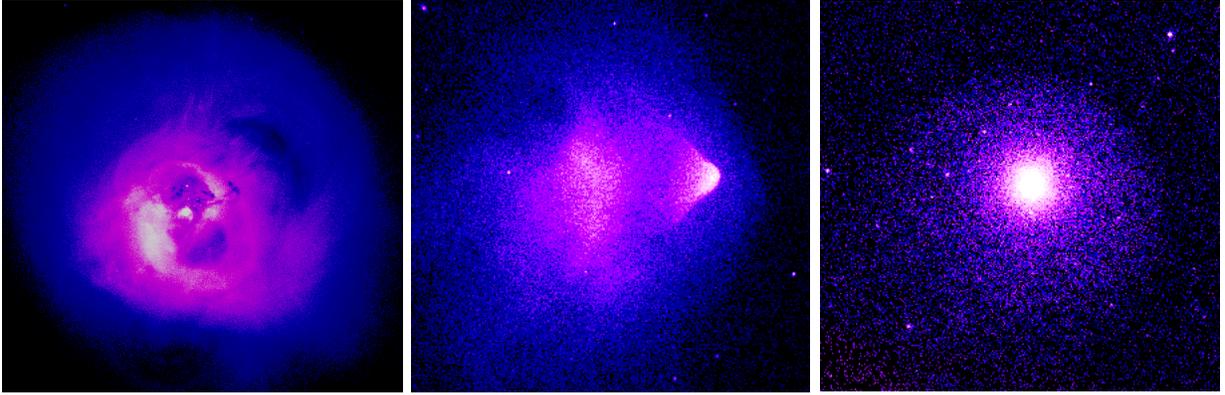


Fig. 2— *Chandra* X-ray images of three classes of high-velocity phenomena in intracluster plasma. Left: AGN bubbles and ripples in Perseus.³⁸ Middle: merger shock front and ram-pressure stripping in 1E0657-56.¹² Right: a cold front apparently stabilized by magnetic draping in NGC 1404 (a circular brightness edge spanning 180° from SW to NE).³⁹ Panels are $5' \times 5'$, approximately the FOV of the *Gen-X* calorimeter.

3.1 Cluster tomography

An imaging calorimeter is the next frontier of cluster astrophysics. *Astro-H* and *IXO* will uncover large-scale gas flows and map the turbulence in merging and relaxed clusters (WP by Arnaud et al). *IXO* will determine whether any turbulence is present in relaxed clusters, such as A1835 and A2029, that are used for the f_{gas} cosmological test. It will also directly test the hypothesis that turbulence is responsible for radio halos.³⁴ An imaging calorimeter such as *IXO* can derive the spectrum of turbulence and disentangle it from bulk flows by sampling multiple, close lines of sight.

However, there are areas where the calorimetric spectral resolution needs to be combined with arcsecond angular resolution. These include sharp features such as cluster shock fronts (*Is there turbulence behind the shock due to plasma instabilities? What is the post-shock ion temperature?*), cold fronts and buoyant bubbles (*Why are they so stable?*) Resolving these features will provide unique measurements of microphysical properties of the intracluster plasma, such as viscosity, electron-ion equilibration and ionization timescales, and the structure of the magnetic fields. These properties govern mixing and transport processes and possibly heating of the ICM by sound waves from the central

black hole.³⁸ Fig. 2 shows examples of such objects — the discovery potential of calorimetric “data cubes” that map the ICM density, temperature and radial velocity with a super-*Chandra* angular resolution, is obvious.

3.2 Resolving the Bondi radius

Central AGN deposit enough energy into the dense, cool central gas in clusters to prevent it from catastrophic cooling.⁹ To accomplish this, but also avoid blowing up the whole gas core, a feedback cycle is required to link cooling of the hot gas to fueling of the AGN. Understanding this process is of fundamental importance. A key part of a feedback cycle is the feeding of the AGN. The Bondi accretion model, which describes spherical, isentropic accretion onto a black hole, can be radically modified in several ways. Tiny angular momentum can reduce the accretion rate by orders of magnitude.^{40,41} Dissipation of angular momentum can affect the flow significantly.⁴² An X-ray study of the gas flow in the region where it first comes under the dominant influence of the black hole, i.e., near the Bondi radius, would provide important clues to the factors that govern accretion of hot gas by AGN. However, for nearby supermassive black holes, including the important case of M87, the Bondi radius is $\sim 1''$ (e.g., 43), re-

quiring super-*Chandra* angular resolution.

4 INTERGALACTIC MEDIUM

Beyond the cluster infall shock lie giant filaments of the Cosmic Web, filled with tenuous, warm-hot intergalactic medium (WHIM) that should comprise more than half of the baryonic matter in the present-day Universe.^{44–46} The currently unseen extended gas coronae of field galaxies (circumgalactic medium, CGM) may contain an additional significant fraction. As a depository of all the gas ever expelled from galaxies, this vast reservoir of baryons holds unique information on the history of energy and metal production in the Universe. By accurately accounting for these components, we can directly determine the present-day Ω_b , to be contrasted with indirect measures such as those from CMB.

4.1 Absorption line studies

Unfortunately, this gas is very tenuous, which makes its X-ray and UV emission extremely difficult, and for most of the WHIM, virtually impossible, to detect, which is why these “missing baryons” have never been seen. At temperatures $10^{5-6.5}$ K, they can be seen in absorption against background beacons such as quasars and GRB X-ray afterglows. However, the absorbing columns are also very low. Despite extensive observational efforts, the vast majority of this dominant matter component remains undetected. FUV observations of OVI and broad Ly α absorbers^{17–19} probe only the lower-temperature 10% of the missing baryons. The rest should be searched for in the soft X-ray band in absorption by highly ionized O, C, Ne, Fe. Studies with *Chandra* and *XMM* came tantalizingly close to first detections,^{15,16} but much greater sensitivity is required to discover the bulk of the missing baryons.

IXO, as well as some proposed dedicated missions, will have the line sensitivity factor[†] 10–20 times higher than *XMM* and *Chandra*, and can be the discovery facilities for

[†] $S \equiv \sqrt{RA}$, where R is spectral resolving power and A is the effective area.

WHIM studies. *IXO* should detect at least 100 OVII absorbers over the sky (WP by Bregman et al). Looking past *IXO*, the necessary next steps will be (a) to go much deeper in flux and sample the Cosmic Web with thousands of sight lines, (b) to detect different absorption lines of the same element in the same system and use line ratios to derive the gas parameters, such as temperature and density, and (c) ultimately to resolve those spectral lines, probing turbulence, disentangling it from thermal broadening, and possibly determining ion temperatures. A large number of detected absorbers will provide an independent dataset for cosmological studies using the absorber cross-correlation analysis, yielding constraints at redshifts and linear scales very different from those of the CMB or Ly α forest. Line positions and widths will allow us to study the dynamics of WHIM. By separating different physical and kinematics phases of the same WHIM system, one will be able to associate a given metal component with HI systems seen in the UV (by future instruments), and thus measure both the absolute and relative metallicity. This would give a direct measure of the total baryon density Ω_b .

The envisioned grating spectrometer on *Gen-X* will provide a further increase in line sensitivity over *IXO* by factor of 40, and a big increase in spectral resolution, opening this nascent field of astronomy to truly quantitative studies.

4.2 X-raying the cluster outskirts

In addition to X-ray emission studies (§2.3), gas in the cluster outskirts can be studied in absorption, just like the WHIM. The gas between $r \sim 1 - 2r_{200}$ should have $T \sim 0.5 - 1$ keV and feature prominent Fe and O absorption lines. It should also have higher column densities than the more tenuous WHIM in the filaments. For *Gen-X*, several hundred suitably bright background sources behind a $1 - 2r_{200}$ region of the Coma cluster will be available for absorption line detection with feasible exposures. Even a $z = 0.2$ cluster such as A2163 should have ~ 10 suitable background quasars

in the corresponding area. This will open a unique possibility to combine emission and absorption by the same medium and directly observe, for example, the ionization nonequilibrium and stripping of metal-rich gas from small halos in the cluster infall region.

4.3 Using clusters as background sources

With a large effective area and an imaging calorimeter with a sufficient FOV, it may be possible to use clusters as background candles for WHIM absorption studies. Clusters are among the brightest X-ray sources in the sky and conveniently reside at the nodes of the Cosmic Web. Thus, cluster sight lines are likely to pass through the densest regions of WHIM. An eV spectral resolution is generally insufficient to detect low-column WHIM systems (see WP by Bregman et al.), but column densities of some filaments along the l.o.s. can be much higher.⁴⁷ They can produce absorption lines blueshifted from the corresponding cluster emission lines. Large angular extent of a cluster would result in volume-averaging over the filament, providing highly complementary information to sparse, pencil-beam sampling of the same filament using quasars.

4.4 IGM in emission

Recent numerical work suggests that metals may not be mixed well into the bulk of the IGM, staying close to the field galaxies that produced them, in the form of 100–200 kpc plumes of the metal-rich galactic wind (e.g., 48). If so, these denser, more metal-rich clouds of “circumgalactic medium” (CGM) may just become detectable in emission. Detecting and confirming their finite extent will provide critical input for galaxy formation models and for the interpretation of the IGM absorption line data. CGM may also contain a significant fraction of the missing baryons.

As outlined in §2.3, in addition to very large collecting area, for such studies one will have to resolve the point-like and Galactic diffuse components of the CXB using a calorimeter with a subarcsecond angular resolution. In particular, CGM will emit a faint

redshifted OVII line that should be disentangled from a non-redshifted, but orders of magnitude stronger, Galactic OVII line.

Finally, a sensitive, low-background imaging calorimeter offers an exotic possibility to observe WHIM in *reflection*, illuminated by a bright blazar that is turned away from us, like a lighthouse in the fog.⁴⁹

SUMMARY

To summarize, we believe that the following fundamental questions in the field of galaxy clusters and IGM will remain unanswered at the end of the next decade:

- How much baryonic matter is hidden in the Cosmic Web, beyond the confines of galaxies and clusters? What is the total amount and distribution of heavy elements and thermal energy in this vast reservoir of baryons?
- What processes occur at the interface between the Cosmic Web filaments and the galaxy clusters, and how do those processes affect cluster physics and energetics?
- What hydrodynamic and plasma processes occur at shocks, cold fronts and buoyant bubbles in clusters? How best to model them to use clusters as a precision cosmology tool?
- How do supermassive black holes at the cluster centers feed on the intracluster gas?

To answer these questions will require a futuristic X-ray facility that combines a mirror with vast effective area and super-*Chandra* angular resolution, a calorimeter array that matches the mirror resolution, and a super high-dispersion grating. Such a combination is envisioned as *Generation-X*. For it to become a reality in our lifetime, key developments in the mirror and detector technologies should occur in the coming decade (see *Gen-X* technical WP). They build upon the *IXO* technologies, but require a huge leap forward from *IXO*, thus depending critically on *IXO* success.

REFERENCES

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