Reading the Metal Diaries of the Universe

Tracing Cosmic Chemical Evolution from the reionization epoch till the present

Metals are essential for star formation and their subsequent evolution, and ultimately the formation of planets and the development of life, as we know it. Reconstructing the cosmic history of metals, reaching from the first population of stars to the processes involved in the formation of galaxies and clusters of galaxies, is the framework of this White Paper. Most baryons reside in diffuse structures, in (proto)-galaxies and clusters of galaxies, and are predicted to trace the vast filamentary structures created by Dark Matter and Dark Energy. X-ray spectroscopy of diffuse matter has the unique capability of simultaneously probing all the elements (C through Fe), in all their ionization stages and all binding states (atomic, molecular, and solid), and thus provides a model-independent survey of the metals. A medium-size cosmology mission, *Xenia* – named for the Greek word for hospitality – will combine cryogenic imaging spectrometers and wide field X-ray optics with fast repointing to collect essential information from three major tracers of these cosmic structures: the Warm Hot Intergalactic Medium (WHIM), Galaxy Clusters, and Gamma Ray Bursts (GRBs).

"We are stardust, we are golden; we are billion-year-old carbon; and we got to get ourselves back to the garden."
Joni Mitchell, Woodstock 1969

Submitted by**:** D. Hartmann[1], C. Kouveliotou[2], L. Piro[3], J-W. den Herder[4], T. Ohashi[5], T. Abel[6], L. Amati[7], S. Barthelmy[8], J. Beacom[9], J. Bloom[10], M. Bonamente[11], E. Branchini[12], G. Branduardi-Raymont[13], J. Bregman[14], M. Briggs[11], V. Bromm[15], A. Burkert[16], D. Burrows[17], S. Campana[18], C. Carilli[19], R. Cen[20], P. Coppi[21], C. Danforth[22], R. Diehl[23], S. Ettori[7], M. Fall[24], X. Fan[25], G. Fishman[2], B. Fields[26], C. Forman[27], G. Ghisellini[18], M. Galeazzi[28], N. Gehrels[8], G. Ghirlanda[18], J. Grindlay[27], A. Heger[29], P. Henry[30], W. Hermsen[4], A. Holland[31], J. Hughes[32], J. Kaastra[4], N. Kawai[33], B. Keel[34], R. Kelley[8], M. Kippen[35], A. Kusenko[36], A. Loeb[27], P. Madau[46], F. Matteucci[37], G. Mathews[38], C. Meegan[39], P. Meszaros[17], T. Mineo[40], K. Mitsuda[41], S. Molendi[18], L. Natalucci[3], K. Nomoto[42], P. O'Brien[43], S. O'Dell[2], F. Paerels[44], G. Pareschi[18], V. Petrosian[6], N. Prantzos[45], J. Primack[46], J. Prochaska[46], E. Ramirez-Ruiz[46], B. Ramsey[2], A. Rasmussen[6], S. Savaglio[23], J. Schaye[47], S. Snowden[8], V. Springel[48], Y. Suto[42], G. Tagliaferri[18], Y. Takei[41], Y. Tawara[49], F. Timmes[50], L. Townsley[17], P. Ubertini[3], A. van der Horst[2], J. Vink[51], M. Weisskopf[2], R. Wijers[52], C. Wilson-Hodge[2], S. Woosley[46], N. Yamasaki[41]

[1]Clemson University, [2]NASA/MSFC, [3]INAF-Rome, [4]SRON, [5]Tokyo Metropolitan University, [6]Stanford University, [7]INAF-Bologna, [8]NASA/GSFC, [9]Ohio State University, [10]UCB, [11]UAHuntsville, [12]Roma Tre University, [13]MSSL, [14]University of Michigan, [15]University of Texas, [16]University of Munich, [17]Penn State University, [18]INAF-Milano, [19]NRAO, [20]Princeton University, [21]Yale University, [22]University of Colorado, [23]MPE, [24]STScI, [25]University of Arizona, [26]UIUC, [27]Harvard/SAO, [28]University of Miami, [29]University of Minnesota, [30] University of Hawaii, [31]Open University, [32]Rutgers University, [33]Tokyo Institute of Technology, [34] UATuscaloosa, [35]LANL,[36]UCLA, [37]INAF-Trieste, [38]University of Notre Dame, [39]USRA, [40]INAF-Palermo, [41]JAXA/ISAS, [42]University of Tokyo, [43]University of Leicester, [44]Columbia University, [45]IAP Paris, [46]UCSC, [47]Leiden University, [48]MPA, [49]Nagoya University, [50]University of Chicago, [51]Utrecht University, [52]University of Amsterdam

Submitted to Science Frontier Panels: CFP and GCT

Associated Mission: *Xenia* **(**http://sms.msfc.nasa.gov/xenia/)

Synergy with: *JWST, IXO, ALMA, eVLA, LSST*, and developments in super-computing

KEY QUESTIONS

When were the first metals created?
How does metallicity change on cosmic time scales?
How are the baryons in clusters and cosmic filaments distributed?
What are the thermodynamic conditions in large-scale structures?

Not too long ago, the most distant objects known were quasars, but recent sensitive surveys with space- and ground-based telescopes have turned up ordinary galaxies beyond the farthest quasars. Since then, the race has been on to find the most distant stars and their explosions that drive the cycle of chemical enrichment. Tomography of the structured Universe with bright background light sources, such as quasars and Gamma-Ray Bursts (GRBs), probes the large-scale distribution and physical state of the gas, coupled dynamically to the stars and dark matter underlying the basic building blocks of the Universe. Relative to the predictions derived from the Big Bang Nucleosynthesis and the Cosmic Microwave Background (CMB), not all of the baryons in the local Universe are currently accounted for (e.g., Gonzalez et al. 2007), with the rest believed to reside in the warm-hot tenuous gas that traces the underlying dark matter. Understanding cosmic chemical evolution is best advanced with sensitive UV-X-ray studies of the diffuse baryons inside galaxy clusters, and in the theoretically predicted cosmic web that stretches between clusters and super-clusters (e.g., Paerels et al. 2008). The dark side of the Universe and its more familiar luminous aspects are coupled, and probing the links between these components will lead to a fundamentally better understanding of how the Universe transitioned from the dark ages to the rich structures of the present. The objective described in this White Paper is mapping the build up of cosmic structures on various scales from the high-z Universe to the present time (stars, galaxies and the cosmic web), with emphasis on the distribution and state of the baryonic component.

Fundamental questions in cosmology are related to the global dynamics of the Universe, and the need to unravel the nature of its components, especially dark matter (DM) and dark energy (DE). Enormous progress on these questions has been made with studies of the CMB (e.g., Spergel et al. 2007) and direct probes such as Type Ia supernovae (see Linder 2008 for a review). To derive key parameters and determine the z-dependence of the equation of state of dark energy, one must carry out precision measurements to z~2. Beyond that range leverage diminishes, as DE is of decreasing dynamical importance. Deep surveys of quasars and galaxies have revealed, however, that some (proto)-galaxies were already in place at redshifts beyond 6. The first generation of accreting black holes and massive stars, which reionized the Universe prior to z ~ 6 (e.g., Fan et al. 2006; Gallerani et al. 2008) may have begun forming as early as z ~ 10-20 (e.g., Loeb, Ferrara, & Ellis 2008). The cosmic cycle of star formation, evolution, and death is a well-established concept, and easy to trace observationally in the Milky Way and the local group. *Bridging the gap, however, from Galactic Chemical Evolution to Cosmic Chemical Evolution is a formidable challenge*. A study of how abundances evolved from the initial (primordial) conditions emerging from Big Bang Nucleosynthesis to those of present stars and galaxies *will be possible for the first time due to advances in cryogenic X-ray detectors.*

The study of *star formation* in the young Universe is in its initial stages. Simulations suggest a bias of the Initial Mass Function (IMF) to larger stellar masses with decreasing metallicity (e.g., Bromm & Loeb 2007), possibly leaving an IR signature in the extragalactic background (Primack et al.

2008). While most massive stars today explode as Type II core collapse supernovae, a near zero-metallicity star of ~ 150 M_{sun} more likely dies by pair instability (Heger et al. 2003). Feedback on the environment from the first generation of supernovae is different than in a present-day galaxy, and star formation today takes place in dense molecular clouds, while in the early Universe it was hampered by inefficient cooling in pristine H-He environments. The first generation of supernovae quickly enriched the gas, and with GRBs we can trace the metallicity of their host galaxies as a function of redshift. How the Universe cools, and the evolution of (linear) perturbations that imprint angular structures on the CMB, is well understood. But this gratifying simplicity ends when primordial density contrasts evolve into the non-linear regime. The Universe entered a dark age about 300,000 years after the big bang, and darkness persisted until the first non-linear structures developed into stars, whose demise after only a short life defines the end of the cosmic dark ages.

The standard scenario of early star formation assumes a Cold Dark Matter (CDM) cosmology, in which dark matter ("mini")-halos admit star formation, producing ionizing light (from massive stars) responsible for some or all of the reionization transition. From the Gunn-Peterson effect in high redshift quasars and GRBs one finds that the Universe was already highly ionized by $z \sim 6$, but we do not yet know the detailed temporal and spatial evolution of this transition. It may have started with Population III stars at $z > 20$, and may have undergone several episodes (e.g., Fan et al. 2006). Establishing the origin of the ionizing radiation is an outstanding challenge, and a direct method to do so is the use of GRBs for which the delay between the formation of their massive progenitors and their collapse (the burst) is short. The GRB phenomenon provides precious but short-lived sources of light that can be used to probe intervening matter to very large distances. GRBs serve as brilliant beacons for spectroscopic investigations of the abundances in early star forming (proto)-galaxies that are much too faint for detection in regular surveys.

Gravity leads from the first population of stars in small galaxies to large-scale clusters of galaxies today. The production and distribution of elements within these evolving dynamic structures needs to be mapped in greater detail than has been achieved to date. Simulations of large-scale structure by Springel et al. (2006), and others, beautifully demonstrate how the power spectrum of matter evolves, and how voids and filaments emerge as natural features of the dynamic Universe. Simulations of dark matter on the scale of our Milky Way's halo (Diemand et al. 2008) show that the dark matter dominated local environment is highly structured as well. Baryons, making up only about 4% of the cosmic energy density, trace some of these structures, and are essential to our ability to gather knowledge of how and when the universe produces stars and gaseous flows that we can probe directly with light. Only a fraction of the baryons end up in stars, most remain in diffuse structures; and some baryons that did end up in stars, re-emerge in the diffuse component after nuclear processing in the explosive final stages of massive stars. Recycling gas within galaxies, i.e., infall into and outflow from galaxies and similar processes on the scale of clusters, created a rich distribution of metal enriched gas on small and large scales. We need an accounting of the whereabouts and the conditions of the cosmic baryon component to better understand the feedback processes responsible for the density-temperature-abundance patterns that are observed in galaxies, clusters of galaxies, and the filamentary bridges between clusters predicted in simulations. Thermodynamic conditions of these baryonic environments are often such that their small column density or low surface brightness make it hard to detect them, and even harder to establish their chemo-thermo-dynamic state. Shocks in these gaseous structures, caused by large-scale flows, AGN activity, or star bursts, also cause significant deviations from thermal equilibrium, and create non-thermal particle populations, whose properties have been simulated (e.g., Cen & Ostriker 2006; Bykov, Paerels, and Petrosian 2008), but not yet observationally confirmed.

X-ray spectroscopy of diffuse matter has the unique capability of simultaneously probing all the elements (C through Fe), in all their ionization stages and all binding states (atomic, molecular, and solid), and thus provides a model-independent survey of the metals. Fig. 1 provides an overview of how various building blocks evolved, and how high-resolution X-ray spectroscopy and imaging advances this field with technology that is ready to go. The most distant star forming regions can be probed with rapid response spectroscopy of bright GRBs, and local cluster structures can be studied with a wide Field of View (FoV) imaging survey. The filamentary Warm Hot Intergalactic Medium (WHIM) is probed along these sight lines in absorption. Thus a combination of near-field cluster surveys with far-field GRB response-spectroscopy provides an optimal strategy to address the key questions posted above and map cosmic chemical evolution from reionization to the present.

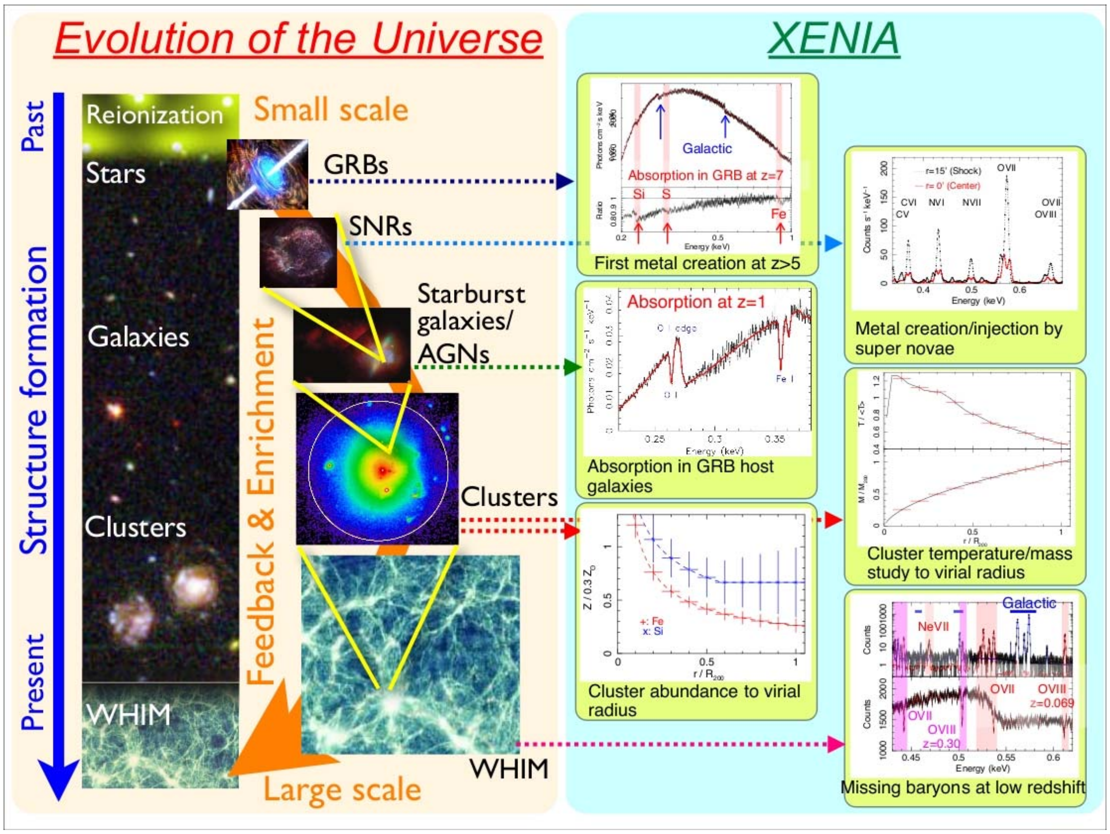

FIG. 1: Much of our knowledge about galaxies and clusters stems from observations of starlight. However, diffuse gas in the Inter-stellar, the Inter-Galactic, and the Intra-Cluster medium is more than a mere bystander in the cosmic cycle of matter.

READING THE METAL DIARIES OF THE UNIVERSE WITH THREE TRACERS

Observationally, the goal to map out the evolution of the metallicity from z=0 to z>6 can be realized with X–ray monitoring, wide field imaging, and high-resolution spectroscopy using three major tracers: the WHIM, Galaxy Clusters, and GRBs in the evolving population of (proto)-galaxies. These tracers unfold the chemo-thermo-dynamical history of the ubiquitous diffuse baryonic component in the Universe that resides in cosmic filaments of the Inter-Galactic Medium (IGM), in clusters (the Intra-Cluster Medium, ICM) and in galaxies (the Inter-Stellar Medium, ISM) and shed light on feedback processes at work in the cosmic multi-component fluid (e.g., Gao & Theuns 2007; Fig.2: state of the art simulations by Branchini et al. 2009).

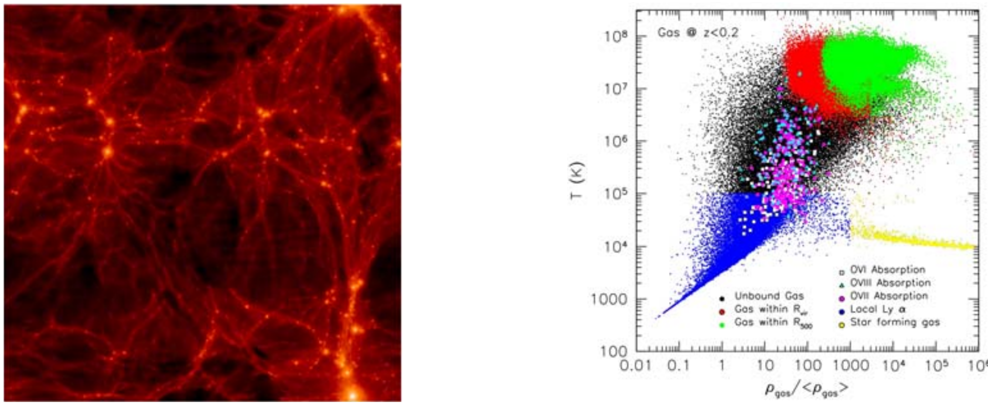

FIG. 2 (Branchini et al 2009): (*Left*) Simulated large-scale structure evolution in ΛCDM-cosmology, with a realistic treatment of feedback. Baryons inside clusters (the nodes) and in the filaments (bridges) sample a range of temperatures and densities, as shown on the right. (*Right*) Simulation of the temperature-density conditions sampled by the baryons: current observations are mostly limited to the detection of hot baryons in cluster cores (green). We advocate observations that can probe cluster outskirts (red), and beyond (light blue and purple) to the filaments and bridges between clusters.

GAMMA RAY BURSTS: A fundamental understanding of star-formation (and ultimately galaxy formation) hinges on tracing the gravitational collapse of diffuse gas in molecular clouds. Although this gas can be studied in exquisite detail in emission within the Milky Way, similar analysis in extragalactic systems demands an alternative approach. Supernovae (SNe) and galaxies are bright enough to be traced deep into the universe, but diffuse gas in their vicinity usually is not luminous enough to be detectable in emission – *this gas can be probed with absorption spectroscopy of GRB afterglows*. In particular, long-soft GRBs are associated with explosions of massive stars (SN Ibc), and thus track star formation. *Thus GRBs may allow us explore the era of Population III ("metal-free") stars at z > 10*. Their enormous brightness gives us the opportunity to measure chemical abundances in early (proto)-galaxies, and to trace changes of these abundances in intervening systems along the sight line to the era of re-ionization at z>6. In contrast to quasars, GRBs are brief transients that only affect their local environment (D < 100 pc) and their afterglows thus record the physical conditions of their mostly unperturbed host galaxy as well as of the intervening IGM. Optical/NIR afterglow spectroscopy already established a significant spread in metallicity at all redshifts (Fig. 3), and indicated that metallicities probed by GRB sight lines are higher than those probed by quasars.

We advocate the use of GRBs as metal tracers to study the buildup of heavy elements and thus determine the cosmic conversion history of gas into stars because: a) their intrinsic spectra are simple, thus line modeling is more straightforward, b) they have not altered their environments over large distances and over long periods of time, and c) they outnumber quasars beyond z~7, offering perhaps the only way to obtain abundances for very small galactic fragments in the early Universe. The X-ray band offers a powerful tool for these studies, as bright X-ray emission follows essentially all GRBs. Afterglows fade fast, thus requiring a rapid repointing capability, which, coupled with a high-resolution spectrometer will open a completely new window on the burst environment, the host galaxy, and the IGM. At high-z the soft X-ray band would reveal absorption edges from intermediate mass elements (e.g., Si, S) in the host, and at more typical redshifts (z~1) those of CNO elements (Fig. 1). Thus, GRBs will be our beacons illuminating Cosmic Chemical Evolution from the pre-galactic phase of the Universe until the large-scale structures of the present.

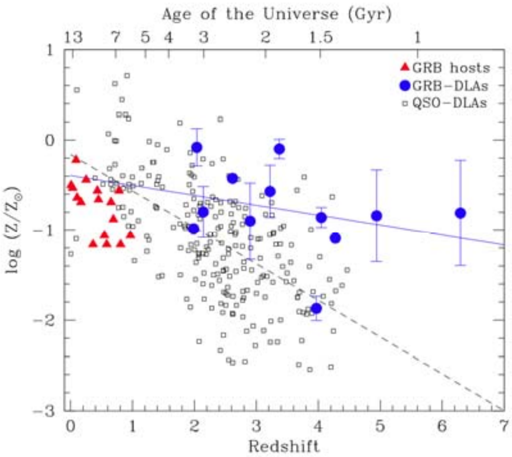

FIG. 3 (Savaglio, Glazebrook & Le Borge 2009): Optical spectroscopy of GRB afterglows finds metal lines in damped Lyman Alpha systems (DLAs) allowing measurements of metallicity (Z) in several cases (filled dots). The trend of Z/Z_{sun} vs. z is marginal, in comparison to that revealed by quasars, and the spread is significant at all epochs. In comparison to QSO-DLAs (open squares, updated sample from that shown in Pettini 2003), GRB-DLAs sample star forming galaxies differently, and to higher redshifts. However, measurements from emission lines in the z<1 host galaxies indicate relatively low metallicities, which is surprising given the high values in GRB-DLAs. This finding is not yet understood and might indicate two different GRB or host populations.

GALAXY CLUSTERS: A Cosmic Chemical Evolution mission would survey nearby galaxy clusters and their outer extensions connecting them with the filamentary structures predicted in large scale structure simulations (while not observing bright GRB afterglows). Evidence for the filaments has been obtained from optical galaxy surveys, but the bulk of the baryons "trapped" in the filaments is not visible in the optical regime. *The tenuous, shock heated filament gas predominantly emits in the X-ray regime*. Cen & Ostriker (1999) were the first to investigate the properties of these WHIM-filled structures, and found that at "low-z" (z<2) about half of all baryons could reside in the filaments connecting galaxy clusters, and their hydrogen densities should be < 10^{-4} cm^{-3}, and temperatures in the range $10^{5\text{-}7}$ K. *This parameter range is not conducive to easy detection*. Still, detections were reported in recent years, albeit with low statistical significance and lack of independent confirmation. Recent *XMM-Newton* observations (Werner et al. 2008; Fig. 4 left panel) of the cluster pair Abell 222/223 (at z=0.2), confirmed the presence of an X-ray emitting inter-cluster bridge (a filament) with conditions expected from simulations (Dolag et al. 2006), and offered impetus to advanced studies with significantly more sensitive instrumentation.

A full understanding of cluster structure and its evolution is essential for the utilization of clusters in cosmology, and a substantial sample size is required to draw statistically significant conclusions. Sensitive wide-field imaging and high-resolution spectroscopy of the next generation X-ray mission must map temperatures, densities, and abundances, beyond the virial radii of many clusters to provide thermo-chemo-dynamical information of diffuse baryons residing inside and even around clusters. With such deep survey data one can study in detail cluster evolution to their formation epochs (z>1), and investigate the role of various feedback mechanisms (e.g., Conroy & Ostriker 2008). *X-ray mapping to large radii is essential for determining the mass and emission profiles of clusters, and to search for baryonic matter that may reside in their outer regions* (connection to the filaments). Next generation X-ray missions must be able to establish a large sample for detailed studies of their structures and abundances, and must reach surface brightness values much below that seen in Abell 222/233 (10^{-16} erg s^{-1} cm^{-2} arcmin^{-2}; Fig. 4 left panel). Future deep, wide Field of View (FoV) surveys will map clusters out to larger distances and allow firm detections of WHIM emission in areas of significantly lower cosmic over densities (Bregman 2007; Paerels et al. 2008).

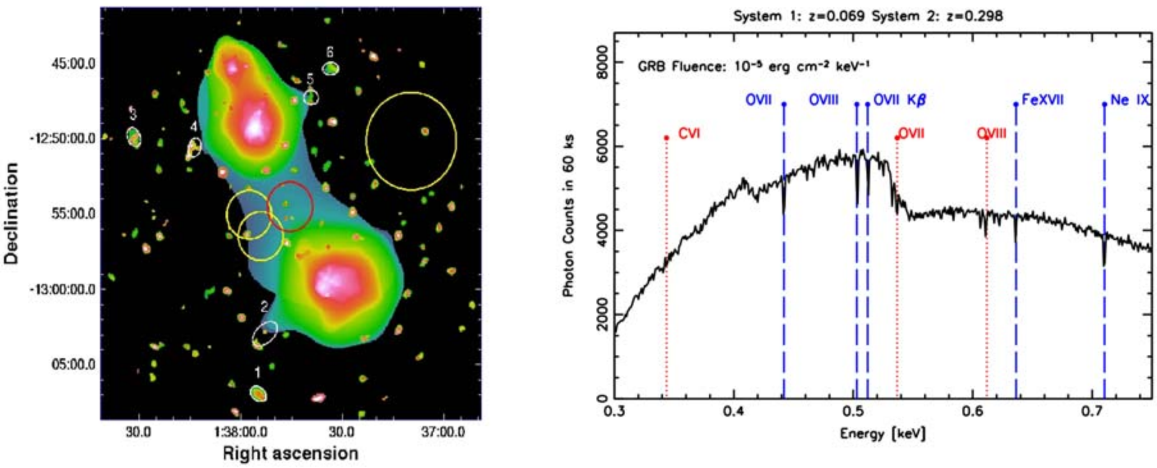

FIG. 4 (*Left;* Werner et al. 2008): The wavelet decomposed *XMM* image of cluster pair Abell 222-223 (0.5 - 2.0 keV), revealing a bridge of kT~1 keV (T is a weak function of the [unknown] metallicity). High sensitivity observations would allow a far more detailed study of the temperature- and abundance distribution. (*Right;* Branchini et al 2009): Simulated absorption lines due to highly ionized oxygen in the local WHIM (z = 0.07 and z = 0.29), probed with a GRB X-ray afterglow at larger redshift (of fluence $S_x \sim 10^{-5}$ ergs/cm^2), complementing measurements in the UV of lower ionization states (C, N, O, Si, S, Fe; e.g., Danforth & Shull 2008).

BARYONS IN THE FILAMENTARY WHIM: Most likely the greatest need for new capabilities to address the ("missing") baryons lies in the X-rays (Prochaska & Tumlinson 2008). A future mission dedicated to revealing baryons must have sufficient sensitivity and energy resolution to detect the spectral fingerprints from highly ionized C, O, and N, by measuring gas densities down to 10^{-5} cm^{-3}, a density ~30 times smaller than currently probed in clusters. The bulk of the WHIM resides in structures with T > 10^6 K. Hints (though not undisputed) of the WHIM in this temperature range were found with *Chandra* observations of the 21.6 Å resonance absorption line of OVII in a bright state of Mrk 421. Evidence for the warm part of the local WHIM exists via absorption line studies with *FUSE*, *HST*, *XMM-Newton*, and *Chandra*. There are other claims of detections of the WHIM, but these results are not yet compelling either. *Sensitive high-resolution X-ray observations will detect the WHIM in emission and in absorption (against the brightest GRBs)*. Sampling WHIM abundances along many sightlines can only be done in X-rays, where the relevant ionization stages of metals have measurable but faint lines; high-resolution and high signal-to-noise spectra are needed to detect them. At T ≥ 10^6 K, *the primary tracers (O VII, O VIII) are only detectable in the soft X-ray regime*. An example of what GRB X-ray spectroscopy would yield is shown in Fig. 4 (right panel). The advantages of using GRBs to probe the WHIM in absorption were pointed out by Branchini et al. (2009), who used hydrodynamic models to simulate the appearance of the OVII line, and found a line-detection rate of 20-80 per year, thus quickly generating a sample exceeding that provided by quasars (see also Gallerani et al. 2008).

FROM OBSERVATIONAL GOALS TO INSTRUMENTAL REQUIREMENTS

The instrumental requirements described below are based on studies carried out for a medium-size cosmology mission, *Xenia* – named for the Greek word for hospitality – which will combine cryogenic imaging spectrometers and wide field X-ray optics with fast repointing to collect essential information from the three major tracers discussed above. The basic technologies, however, are not limited to the concepts investigated by the *Xenia* team.

For bright GRB afterglows with fluence (0.3-10 keV) $\geq 10^{-6}$ erg cm^{-2}, 1000 counts per resolution element are necessary to detect 0.1 eV equivalent width metal absorption lines in the WHIM; this requirement naturally implies an effective area of 1000 cm^2 and a spectral resolution $\leq$3 eV ***(Wide-Field Spectrometer; WFS).*** As GRB afterglows fade quickly, one needs ***rapid localization and repointing*** capability, with a spectrometer pointing at the source within 60 seconds after the trigger. To carry out follow-up observations with high resolution spectroscopy of ~150 bursts over a 3 year mission with sufficient afterglow fluence a ***Wide Field Monitor*** **(*WFM*)** with FoV of 2.5 – 3 sr and sensitivity of 0.5 photon cm^{-2} s^{-1} (5σ for 1 s integration between 15-150 keV) will provide the necessary sample with at least 10 GRBs beyond z>6.

Complementary to the absorption spectroscopy, such a mission will ***image the WHIM and the outskirts of clusters in emission lines*** of H- and He-like C, O, and Ne, and the L shell lines of Fe ***over 1000 lines of sight (4 deg^2)***. Here, spectral resolution is set by the required contrast of the extraordinarily faint emission against the grey background (instrument background, unresolved extragalactic point sources, galactic foreground emission and, in the case of clusters, thermal continuum emission). The expected characteristic emission line intensity is ~0.05 photon cm^{-2} s^{-1}sr^{-1} in the strongest O K-shell line (out to redshift 0.3). An angular resolution of ~4′ matches the typical size of WHIM filaments (1 Mpc~8′ at z=0.1). The low background, crucial for these measurements, is achieved by the selected Low Earth Orbit (LEO), the low focal ratio for the telescope and the optimized detector shielding. The fraction of the cosmic X-ray background due to point sources (AGNs) can be reduced by a further factor ~3 if these point sources are known or can be identified and the relevant pixels of the imaging spectrometer can be rejected. This can be achieved by a ***high resolution imaging camera (Wide Field Imager; WFI)*** with high contrast, large FoV and modest energy resolution, co-aligned with the WFS and with ***a good*** (HPD = 15″, needed to match the confusion limit) ***and constant point spread function over the FoV*** (typical pixel sizes of 60 μm). Such a WFI would be very well suited for studies of the thermodynamical and chemical properties of clusters of galaxies out to the virial radius. The study of a representative sample of clusters, avoiding multiple pointings, requires typically a FoV of 1^o, of the same magnitude as required for the WFS. With an instrumental background as low as <1.5 10^{-5} counts s^{-1} arcmin^{-2} due to the selected LEO and a low focal ratio optics, a point source sensitivity of 1.5 10^{-16} erg cm^{-2} s^{-1} (0.5 – 2 keV) will be achieved for a GRASP (effective area x FoV) of 700 cm^2 deg^2 at 1 keV and 1 Ms observations. A three-year mission will survey the large sample of clusters (>1000) at z>1 needed for the study of their formation and evolution and improve the sensitivity for surveys (i.e., the sky area covered at a given sensitivity and integration time) by about a factor 100 with respect to previous missions.

REFERENCES

Branchini, E., et al. 2009, ApJ, submitted
Bregman, J. 2007, ARA&A 45, 221
Bromm, V. & Loeb, A. 2007, arXiv:0706.2445
Bykov, A.M., et al. 2008, arXiv:0801.1008
Cen, R. & Ostriker, J.P. 1999, ApJ 519, L109
Cen, R. & Ostriker, J.P. 2006, ApJ 650, 560
Conroy, C. & Ostriker, J. P. 2008, arXiv:0712.0824
Danforth, C.W. & Shull, J.M. 2008, ApJ 679, 194
Diemand, J., et al. 2008, Nature 454, 735
Dolag, K., et al. 2006, MNRAS 370, 656
Fan, X., Carilli, C.L. & Keating, B. 2006, ARA&A 44, 415
Gallerani, S., et al. 2008, MNRAS 388, L84
Gao, L. & Theuns, T. 2007, Science 317, 1527
Gonzalez, A.H., et al. 2007, ApJ 666, 147
Heger, A., et al. 2003, ApJ 591, 288
Linder, E.V. 2008, arXiv:0810.1754
Loeb, A, Ferrara, A. & Ellis, R.S. 2008, "*First Light in the Universe*" (Springer)
Paerels, F., et al. 2008, arXiv:0801.1064
Pettini, M. 2003, arXiv:0303272
Primack, J.R., et al. 2008, arXiv:0811.3230
Prochaska, J.X. & Tumlinson J. 2008, arXiv:0805.4635
Savaglio, S., et al. 2009, ApJ 691, 182
Spergel, D., et al. 2007, ApJS 170, 377
Springel, V., et al. 2006, Nature, 440, 1137
Werner, N., et al. 2008, arXiv:0803.2525