Perseus in Sicily: From Black Hole to Cluster Outskirts
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The Hot Universe with XRISM and Athena

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Abstract. X-ray spectroscopy is key to address the theme of "The Hot Universe", the still poorly understood astrophysical processes driving the cosmological evolution of the baryonic hot gas traceable through its electromagnetic radiation. Two future X-ray observatories: the JAXA-led XRISM (due to launch in the early 2020s), and the ESA Cosmic Vision L-class mission *Athena* (early 2030s) will provide breakthroughs in our understanding of how and when large-scale hot gas structures formed in the Universe, and in tracking their evolution from the formation epoch to the present day.

Keywords. space vehicles: instruments, telescopes, X-rays: general

1. The Hot Universe

The last few decades have witnessed a momentous improvement in our understanding of the origin and evolution of the Universe. According to the standard ΛCDM cosmology, the Big Bang was followed by a short (a fraction of a second) phase of strongly accelerated expansion ("inflation"), followed by a phase of slower but continuing expansion. Density fluctuations in the early Universe led to the formation of the first structures. These seeds grew over cosmic time via hierarchical collapse. While the evolution of large scale structures is primarily driven by the cosmological parameters and by the interaction with the gravitationally dominant dark matter, still poorly understood astrophysical processes drive the evolution of the **"Hot Universe"**, the baryonic hot gas traceable through its electromagnetic radiation. Accretion onto the dark matter potential wells heated gas to million degree temperatures. Galaxy clusters (the largest gravitationally bound structures in the Universe) lay at the nodes of the cosmic web (Schaye *et al.* 2015). While about 80% of their total mass is in the form of dark matter, the remainder is dominated by diffuse, hot, metal-enriched X-ray emitting plasma (the "Intergalactic Cluster Medium, ICM), with stars constituting only 15% of visible baryons. Furthermore, it is now ascertained that a Super-Massive Black Hole (SMBH) sits at the center of most, if not any, galaxies. SMBHs can inject sufficient energy into the ICM to substantially affect its structure, dynamical state and chemical abundance (Fabian 2012). This "feedback" process can be augmented by SuperNova (SN) winds, coupling the ICM evolution with the life cycle of stars in galaxies. The evolution of the ICM can be therefore shaped by processes beyond the pure gravitational collapse. By tracing clusters and groups from the local Universe back to their formation epochs (at z$\sim$2–3), observational cosmology can be put on a solid experimental grounds because a full understanding of the entire range of astrophysical process at play is required to get a consistent picture of the evolution of cosmic structures. Last, but not least, the census of baryons is largely incomplete, $\simeq$40% at z<2 still eluding detection despite intense observational efforts (Nicastro *et al.* 2017; see, however, Nicastro *et al.* 2018).

Major astrophysical questions remain therefore to answer (Nandra *et al.* 2013):

- How do baryons in groups and clusters accrete and dynamically evolve in the dark matter halos?
- What drives the chemical and thermodynamic evolution of the Universe's largest structures?
- What is the interplay of galaxies, super-massive black holes, and intergalactic gas evolution in groups and clusters?
- Where are the missing baryons at low redshift, and what are their physical states?

X-ray is the only band of the electromagnetic spectrum allowing to probe physical properties of this plasma such as temperature, densities, abundances, velocity field, and ionisation state. All these quantities can be reliably measured only with high-resolution X-ray spectroscopic observations able to characterize recombination transitions of highly ionized (He- and H-like) ions of a wide range of metals. Such measurements allow us to fully characterize the physical state of the plasma as well as the relative share of the energy going into thermal and non-thermal processes in the ICM, the latter generating turbulence and kpc-scale bulk motions. These processes have still to be observed at the relevant spatial scales (corresponding to a few arc-seconds in the local Universe). Furthermore, comparing abundances in the local and high-redshift Universe will trace the evolution of the chemical enrichment and the impact of SN feedback on the growth of large-scale structure in the Universe. Comparing abundances in galaxies, galaxy groups and clusters and in the intergalactic medium is needed to model the life-cycle of matter. All these measurements require a significant improvement in the performance of X-ray spectroscopic instruments over several parameter spaces: energy resolution, spatial resolution, and collecting area.

2. The *Hitomi* heritage

However, high-resolution X-ray spectroscopy is just in its infancy. Only with the advent of modern X-ray observatories such as *Chandra* and XMM-Newton at the beginning of the century, X-ray detectors with a resolving power higher than 100 became routinely operational (Paerels & Kahn 2003). These missions, still enormously successful, carry grating systems able to disperse the incoming X-ray photons onto energy-sensitive detectors. In the soft X-ray band (E$\leqslant$2 keV) resolving powers of $\sim$3–400, and $\sim$1000 were achieved by the grating systems on board XMM-Newton (den Herder *et al.* 2001) and *Chandra* (Brinkman *et al.* 1987; Canizares *et al.* 2005), respectively. In the energy range around $\simeq$6 keV, where the all-important K-shell transitions of iron occur, the *Chandra* high-energy gratings achieve a resolving power of $\simeq$170, albeit with a tiny effective area ($\simeq$30 cm^2).

A huge step forward was expected with the JAXA-led X-ray observatory *Hitomi*, whose successful launch on 2016 February 17 led to hope that a new era in observational X-ray spectroscopy had started. *Hitomi* carried the *Soft X-ray Spectrometer* (SXS), a pixellated micro-calorimeter detector with an unprecedented $\leqslant$5 eV energy resolution over the 0.3–12 keV energy band (Kelley *et al.* 2016). Such a performance corresponds to an improvement in resolving power larger then one order of magnitude at 6 keV with respect to the *Chandra* high-energy transmission gratings, together with an one-order-of magnitude larger effective area at the same energies. Regrettably, the spacecraft was lost after only six weeks of operations due to a chain of anomalies of the attitude control system coupled to human errors (JAXA 2016). However, careful planning during the commissioning phase led to *Hitomi* observing for almost one week the core of the Perseus

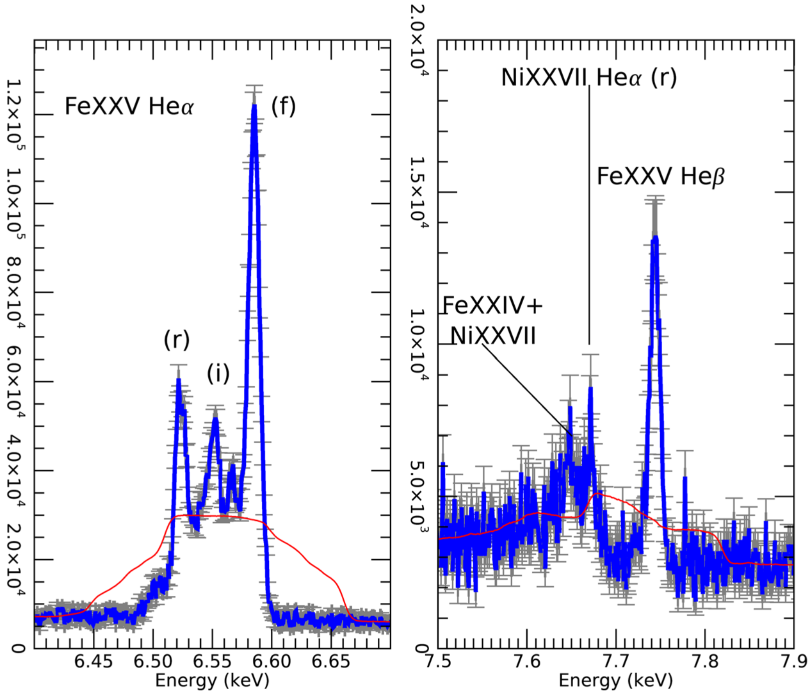

Figure 1. *Hitomi*/SXS spectrum of the Perseus Cluster in the 6.4–6.7 keV (*left panel*) and 7.5–7.9 keV energy range (*right panel*), respectively. The main emission lines discussed in the manuscript are labeled. The error bars correspond to 1σ Poissonian uncertainties. The *red lines* represent the same spectrum at CCD-resolution. Technical details: the spectrum was extracted from the combined calibrated event lists of Obs.# 100040020, -30, -40, and -50 ($\simeq 2.43\times10^5$ s net exposure time), downloaded from the *Hitomi* science archive. It corresponds to a circular extraction region around the cluster core with a 150” radius. It was generated with HEASOFT version 6.22, and the calibration files version 10, released on 15 February 2018.

galaxy cluster, one of the X-ray brightest in the local Universe ($z = 0.0179$). While the SXS was still not formally commissioned, it was operated with the closed “gate valve” with a $\sim$300 μm beryllium window along the optical path as contamination prevention (leading to the total suppression of photons at energies $\leqslant$2 keV), and its data were largely self-calibrated (Tsujimoto *et al.* 2018), its spectra provided a transformational view of the properties of the ICM in Perseus (Fig. 1).

The first surprise came from the analysis of the dynamical state of the ICM. Based primarily on the Fe XXV multiplet (see the *left panel* of Fig. 1), the SXS measured a line-of-sight velocity dispersion of the turbulent gas of 164±10 km s^{-1}, in a region 30–60 kpc from the central nucleus, with only a marginally larger velocity in the core (187±13 km s^{-1}) (Hitomi Collaboration 2016). This level of precision is unprecedented in X-ray astronomy. The measured velocities correspond to a turbulent pressure $\simeq$4% (<8%) of the thermal pressure. This is puzzling, because a powerful radio-loud Active Galactic Nucleus (AGN; NGC1275) is present at the cluster core, injecting an amount of energy in the ICM sufficient to evacuate bubbles filled with relativistic plasma (Böhringer *et al.* 1993; Fabian *et al.* 2000): one of the most spectacular examples of “radio-mode” AGN feedback, postulated to prevent radiative cooling of the ICM core gas. The *Hitomi* result is important not only for its implications on the astrophysics of the ICM but also because, if confirmed on a larger sample of clusters at higher redshift, would imply that the deviations from the hydrostatic equilibrium in the ICM are small, and therefore that X-ray derived galaxy cluster masses using this assumption are reliable probes of cosmological parameters (Allen *et al.* 2011).

Another important result came from the study of the chemistry of the ICM in the Perseus cluster. The unprecedented combination of resolving power and effective area allowed the *Hitomi*/SXS to measure the relative elemental abundance of iron-peak elements such as chromium, manganese, and nickel (cf. the *right panel* of Fig. 1). *Hitomi* demonstrated that these abundances are consistent with solar, disproving prior claims of significant over-abundance based on CCD-resolution data (Hitomi Collaboration 2017a). This constrains the progenitor of type Ia SN to be a combination of near- and sub-Chandrasekhar.

Additional papers published on the SXS observation of the Perseus cluster discuss: resonant scattering in the ICM core (Hitomi Collaboration 2018a), tight constraints on the X-ray decay signature of sterile neutrinos, a possible dark matter candidate (Hitomi Collaboration 2017b); the bulk velocity field (Hitomi Collaboration 2018b) and the temperature structure of the ICM (Hitomi Collaboration 2018c). Readers are referred to the contribution by Tamura in these Proceedings for a full description of the whole range of scientific results of the *Hitomi* observations of the Perseus Cluster.

3. The Hot Universe with XRISM

In the light of the extraordinary results obtained by *Hitomi* during its, alas, too short!, operational life, JAXA and NASA decided to propose a mission to recover one of its fundamental scientific objectives: “Resolving astrophysical problems by precise high-resolution X-ray spectroscopy”. This is the **X-Ray Imaging and Spectroscopy Mission** (XRISM, a.k.a XARM) (Tashiro *et al.* 2018). The European and Canadian Space Agencies, as well as European institutes participate in the mission development together with a wide range of scientific institutions in Japan and the United States. The mission is designed to fulfill the main theme: “Revealing material circulation and energy transfer in cosmic plasma and elucidating evolution of cosmic structure and objects” with a payload that closely replicates the soft X-ray telescopes and instruments on *Hitomi*:

- a micro-calorimeter (*Resolve*) with a requirement energy resolution $\leqslant$7 eV in the 0.3-12 keV energy range over a 3’×3’ field-of-view covered by an array of 35 sky sensitive pixels;
- an array of CCD detector (*Xtend*) with a large field-of-view (larger than 30’×30’), and an energy resolution $\leqslant$200 eV at 6 keV at the beginning of the operational life;
- a large-area, light weight soft X-ray telescope with a $\simeq$1.7’ Half Energy Width (HEW) or better, and an area comparable to that of the soft X-ray telescopes on-board *Hitomi*.

This configures a payload whose X-ray spectroscopic performance largely exceeds any currently operational mission (Fig. 2).

One of the XRISM Science Objective is directly related to the “Hot Universe”: “Structure, formation and evolution of cluster of galaxies”. A micro-calorimeter like *Resolve* will be able to address themes that have been only initiated by *Hitomi*. Elucidating how the gravitational energy released by cluster mergers is converted into thermal energies, and how the energy is distributed between particle and collective gas motions is one of the main goals of XRISM. These objectives will be pursued through measurements of the velocity field structure in the central regions of cool clusters to examine local heating sources (AGN jets; magneto-hydrodynamic interaction between the ICM and member galaxies); measurements of temperature and collective motions of gas stripped from galaxy group accreting onto a cluster to investigate if the infalling galaxies contribute to the ICM heating; and measurements of the turbulent velocity in relaxed and disturbed galaxies that will allow us to evaluate how gravitational energy is distributed among thermal energy, kinetic motions of the ICM, and relativistic particles. Not less

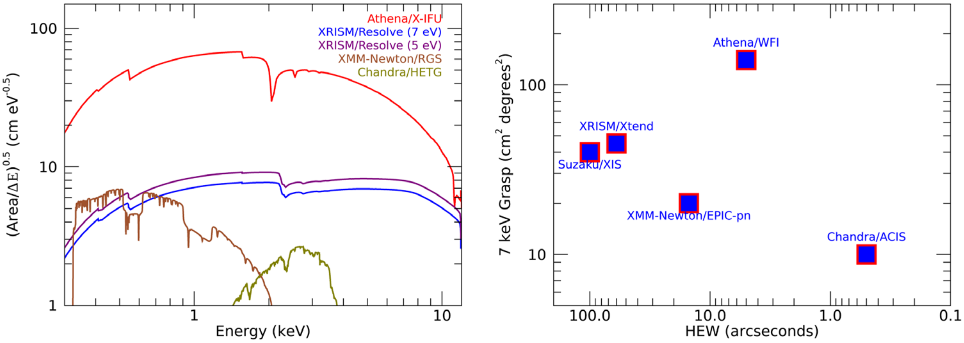

Figure 2. *Left panel:* Weak-line X-ray spectroscopy figure-of-merit for selected operational and future X-ray observatories. The figure of merits is the square root of the ratio between the effective area and the energy resolution. For the *Resolve* instrument on-board XRISM two values are shown, based on the energy resolution requirements (7 eV) and the proven flight resolution of the *Hitomi* SXS ($\leqslant$5 eV). *Right panel*: 7 keV Grasp versus HEW for selected operational and future X-ray observatories. The 1 keV grasp, where the *Athena*/SPO area is optimized, is $\simeq$2800 cm^2 degrees^2 for the *Athena*/WFI, $\simeq$400 cm^2 degrees^2 for the EPIC-pn, and $\simeq$50 cm^2 degrees^2 for the *Chandra*/ACIS.

importantly in a cosmological context, extending the sample of measurements of the ICM turbulent pressure will allow us to correct the hydrostatic bias potentially affecting the X-ray cluster mass functions and therefore remove systematics in the determination of cosmological parameters. XRISM will continue the investigation on the metallicity of the gas trapped in the filament of the cosmic web as a probe of the contribution of different SN explosion types and progenitor populations to the cosmic nucleosynthesis. XRISM is due to launch in the early 2020s (Tashiro *et al.* 2018).

4. The Hot Universe with Athena

The next step in this challenge is *Athena*, the second L-class mission of the ESA "Cosmic Vision" program. *Athena* (Nandra *et al.* 2013) is a large area observatory, aiming at addressing the science themes of the "Hot and Energetic Universe". *Athena* aims at tracing the chemical and physical evolution of large-scale cosmic structures from the epoch of their formation (z$\sim$2–3) to the present Universe; and to study the evolution of accreting black holes in the Universe and of the processes through which they affect the cosmological evolution of the galaxy where they reside, by performing a full census of AGN up to the epoch of reionization. However, besides these basic core science themes, *Athena* will be an observatory fully open to the international astronomical community, with fast ($\leqslant$4 hours) and efficient ($\simeq$50%) response to Targets of Opportunity occurring in a random position in the sky. The large majority of its observing time will be allocated on the basis of proposals evaluated in a peer review process. This high-level scientific objectives will be achieved through an innovative payload:

- a single telescope based on Silicon Pore Optics (SPO) technology developed in Europe (Collon *et al.* 2016), with a 12 m focal length, 5" HEW angular resolution at energies lower than 7 keV, and an effective area $\geqslant$1.4 m^2 (0.25 m^2) at 1 (6) keV;
- the Wide Field Imager (WFI; Meidenger *et al.* 2016), an active pixel sensor Si detector with a wide field-of-view (40'×40'), and spectral-imaging capability with a CCD-like energy resolution ($\leqslant$150 eV at 6 keV);
- the X-ray Integral Field Unit (X-IFU; Barret *et al.* 2018) a cryogenic imaging spectrometer with a 2.5 eV energy resolution in the energy range between 0.2 and 12 keV, 5' diameter effective field-of-view and a $\simeq$5" pixel size.

This payload configuration guarantees that the *Athena* performance will exceed any existing or planned X-ray observatory in the decade of the 20s by more than one order-of-magnitude in several parameter spaces simultaneously, such as the photon collecting area or the truly unprecedented combination of spatial resolution, energy resolution and field-of-view enabled by the X-IFU (Fig. 2).

4.1. *Formation and evolution of galaxy group and clusters*

Athena will probe for the first time the physical properties of the ICM in galaxy clusters and group at the epoch of their formation ($z \simeq 2$). Measurement of X-ray surface brightness and temperature with the X-IFU and WFI will allow to derive the entropy profile, and compare it with the expectations of a pure gravitational collapse as opposed to external effects such as feedback by SN winds and/or AGN. These accurate measurements will permit tracing the evolution of scaling relations between the total mass of the cluster with X-ray observables such as the temperature, X-ray luminosity, entropy up to $z\simeq2$ for a wide range of masses (Pointecouteau *et al.* 2013), thus ideally complementing the full census of $z\leqslant1.5$ massive clusters to be achieved by eROSITA (Merloni *et al.* 2012). In the local Universe, the X-IFU will map the non-thermal component of the ICM energy budget through spatially-resolved spectroscopy of the line spectral broadening due to turbulence, and of the line shift due to bulk motion, determining for the first time the large scale properties of the ICM for nearby clusters by resolving the relevant spatial scales. Maps of emission measure, temperature and metallicity in the outskirts of local clusters will unveil the processes occurring where new material is accreting into the dark matter potential and energy is transferred to the ICM via merging events (Ettori *et al.* 2013).

4.2. *Chemical history of hot baryons*

High-resolution spectroscopy of the ICM X-ray line-rich spectrum is the only way to probe the metal abundances of the gas and its cosmological evolution. In the local Universe, *Athena* will map the distribution of the most abundant elements out to the outskirts of galaxy clusters. The peripheral abundance will be used to estimate the contribution of AGN feedback in expelling pre-enriched gas. *Athena* will measure the metallicity of a wide range of elements up to $z\simeq2$, with accuracies ranging from a few percent (Fe, Si) to 10–20% (O, Ca) (Pointecouteau *et al.* 2013). Because the ICM is an almost perfectly isolated system in the dark matter potential well, its abundances are the resultant of the metal synthesis by different types of SNe over cosmic time (a measurement pioneered by *Hitomi* on the Perseus Cluster: Hitomi Collaboration 2017a). Ratios of iron-peak elements such as chromium and nickel against iron trace SN Ia, those of intermediate-Z elements from O to Si trace core-collapsed SN, lower Z elements are mostly sensitive to AGB stars (Werner *et al.* 2008). The *Athena* X-IFU will measure the whole range of these “metals”, and provide a full characterization of the element synthesis history (Ettori *et al.* 2013).

4.3. *AGN feedback in galaxy groups and clusters*

The *Athena* X-IFU will measure velocities of the hot ICM gas with a precision of 10-20 km s^{-1}, and temperatures and metallicity with a precision of a few percent on spatial scales of $\simeq$5” in nearby cluster cores. This implies determining the kinematics of the hot gas in galaxies, groups and clusters on scales small enough to be able to resolve the regions where powerful AGN jets impact, and potential affect its dynamical state. This will allow us to assess how the energy carried by relativistic particles is dissipated and distributed to the ICM, and how the balance between heating and cooling is maintained in regions where the most massive galaxies are formed. In other terms, while we have now a good understanding of the macro-physics of the radio mode of AGN feedback in nearby clusters (Hlavacek-Larrondo *et al.* 2015), *Athena* will investigate for the first time the micro-physics of this process thanks to X-IFU spatially-resolved spectroscopy of the hot gas. By estimating the energy stored in cavities, ripples and motions, *Athena* will estimate the energy input of AGN for the first time. On a larger (Mpc) scale, velocity measurements of shocked expanding hot shells around radio lobes will allow an estimate of the integrated jet power, an elusive quantity preventing the whole power of strong shocks from being estimated (Croston *et al.* 2013). Furthermore, the WFI large field-of-view (coupled with the smooth vignetting curve of the SPO, Willingale *et al.* 2013) will enable population studies of AGN-induced disturbances and bow shocks surrounding radio lobes, permitting to characterize morphological disturbances of the surface brightness distribution in tens of clusters at $z \leqslant 0.1$, and to correlate their mechanical energy with the properties of the environment and the AGN jet power (Croston *et al.* 2013).

4.4. *Missing baryons and WHIM*

About one half of the baryons in the Universe are still elusive. Cosmological simulations shows that the bulk of them should be locked in a hot medium, the Warm-Hot Intergalactic Medium (WHIM), with temperature ranging between 10^5 to 10^7 K. However, they have escaped detection so far (see, however, Nicastro *et al.* 2018 for a different view). This cosmic “hide-and-seek” will end with *Athena* that will be able to detect the WHIM, and characterize its physical properties, both in absorption against a bright background source (Gamma-Ray Bursts, GRB; blazars, etc.), or through emissions along tenuous and diffuse filaments. During its nominal 4 year operation life, *Athena* is expected to observe about 90 systems in absorption, follow-up $\simeq$7 GRB in emission, and observe about 100 shallow and 1 deep side-line in emission. Depending of the speed of the spacecraft re-pointing, this will allow to probe filament with Oxygen column densities down to 10^{15-16} cm^{-2} (Kaastra *et al.* 2013).

5. Summary

After the global disarray for the early demise of *Hitomi* operations, the future of X-ray astronomy looks bright again thanks to a plethora of new missions and observatories due launch in the next few years. In this context, the enhanced high-resolution capabilities of the XRISM/*Resolve*, enhanced in the *Athena*/X-IFU by its sharp angular resolution and better energy resolution, and combined to deep wide-field spectral imaging with the XRISM/*Extend* and the *Athena*/WFI will yield a giant leap in our understanding of the formation and evolution of large-scale baryonic structure in the “Hot Universe”. Furthermore, besides their nominal core science goals XRISM and *Athena* are observatories open to the astronomical community. Their observational programs will be primarily driven by the collective scientific wisdom of the community active at the time of their operations. Thanks to the unique capabilities of XRISM and *Athena* - largely exceeding those of any existing or planned spectroscopic X-ray missions - we should “expect the unexpected” - as the far too short *Hitomi* history clearly shows.

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