Astro2020 Science White Paper

Supermassive Black Hole Feedback

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: Understanding the processes that drive galaxy formation and shape the observed properties of galaxies is one of the most interesting and challenging frontier problems of modern astrophysics. We now know that the evolution of galaxies is critically shaped by the energy injection from accreting supermassive black holes (SMBHs). However, it is unclear how exactly the physics of this feedback process affects galaxy formation and evolution. In particular, a major challenge is unraveling how the energy released near the SMBHs is distributed over nine orders of magnitude in distance throughout galaxies and their immediate environments. The best place to study the impact of SMBH feedback is in the hot atmospheres of massive galaxies, groups, and galaxy clusters, which host the most massive black holes in the Universe, and where we can directly image the impact of black holes on their surroundings. We identify critical questions and potential measurements that will likely transform our understanding of the physics of SMBH feedback and how it shapes galaxies, through detailed measurements of (i) the thermodynamic and velocity fluctuations in the intracluster medium (ICM) as well as (ii) the composition of the bubbles inflated by SMBHs in the centers of galaxy clusters, and their influence on the cluster gas and galaxy growth, using the next generation of high spectral and spatial resolution X-ray and microwave telescopes.

Supermassive Black Hole Feedback and Galaxy Evolution

Understanding the processes that drive galaxy formation and shape the observed properties of galaxies is one of the most important and challenging frontier problems of modern astrophysics. A consensus has emerged over the last two decades of observations and modeling that the evolution of galaxies is critically shaped by the energy injection from supernovae and active galactic nuclei (AGN). These processes are collectively known as "feedback." Understanding the transition from star-forming to quiescent galaxies, known as "quenching," and the physical processes that shape quiescent galaxies, is key to understanding the most fundamental properties of galaxies. The most common hypothesis is that both the initial quenching of galaxies and their maintenance in a quiescent, non-star-forming state is due to the effects of sub-relativistic wide-angle AGN winds during high accretion rate stages of evolution (quasar/ejective mode) and collimated relativistic AGN jets during the low accretion rate stages (radio/maintenance mode) (e.g., [1, 2]). However, despite its paramount importance, the physics of AGN feedback is not well understood and the question

How does the supermassive black hole feedback affect galaxy evolution?

remains a major unanswered question in astrophysics. While recent simulations demonstrated that it is possible to tune phenomenological AGN feedback prescriptions to produce massive galaxies that resemble the observed quiescent ellipticals (e.g., [3–5]), we do not have a satisfactory understanding of the actual physics of the AGN feedback.

In this white paper, we focus on the maintenance mode of the AGN heating (see [6–8] for a review, white papers). AGN jet powers are in principle sufficient to offset the cooling observed in X-rays in ellipticals and galaxy clusters (e.g., [9, 10]). However, this power is released in the very vicinity of the central SMBHs (on scales on the order of a gravitational radius, i.e., $\sim$20 AU for a billion solar mass black hole, which is comparable to the size of the Solar System) and must be distributed over scales comparable to cooling radii, where the cooling time is comparable to the Hubble time ($\sim$100 kpc). Thus, **one major challenge is to unravel how the energy released near the supermassive black holes is distributed over nine orders of magnitude in distance**. Furthermore, it is uncertain how much energy can be transferred from the AGN to the ambient medium and what physical processes are responsible for its thermalization in the ICM and intragroup medium. All of these issues have fundamental bearing on shaping the properties of galaxies.

The best place to study the impact of SMBH feedback is in the hot atmospheres of massive galaxies, groups, and galaxy clusters, which host the most massive black holes in the Universe, and where we can directly image the impact of black holes on their surroundings. Novel measurements of the thermodynamical and kinematic properties of the ICM and intragroup medium are needed to constrain models of AGN feedback. Specifically, we identify the following **critical new measurements that are needed to transform our understanding of the physics of supermassive black hole feedback**: (i) detailed measurements of the density, temperature, pressure fluctuations and velocity field in the ICM with the aim of unambiguously probing the energetics of feedback and establishing the dominant mechanisms of energy transport from black holes to the ICM (e.g., sound waves and shocks vs turbulence, sloshing and/or buoyancy waves), and (ii) direct measurements of the composition of AGN bubbles inflated by SMBH in the centers of galaxy clusters with the aim in unravelling the impact of the direct cosmic ray (CR) heating on the ICM.

Physics of Feedback: Fluctuations in the Intracluster Medium

One plausible ICM heating mechanism is the thermalization of gas motions. These motions could be generated by propagating sound waves, rising bubbles of relativistic plasma, mergers, or galaxy motions. Their importance lies not only in their association with the heating processes, but also in their ability to reshape galaxies by propelling molecular outflows to galaxy-scale distances.

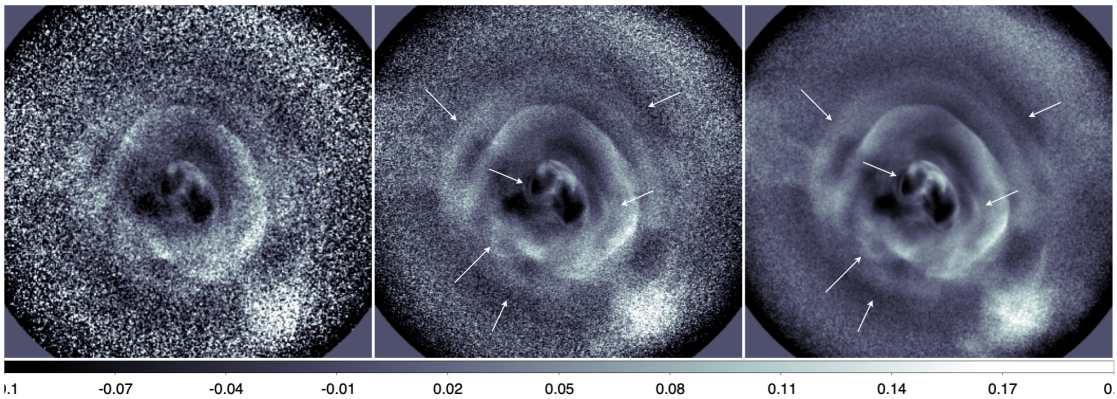

Figure 1: Maps of adiabatic (sound waves) and isothermal (bubbles) fluctuations based on mock X-ray observations of a Perseus-like cluster. Photon counts in the soft and hard X-rays are processed such that isobaric fluctuations are removed [see 11, for details]. *Left:* 300ks *Chandra* observation *Center:* 300ks *Lynx* observation *Right:* 10Ms *Chandra* observation equivalent to a 1Ms observation with the next generation X-ray mission characterized by $\sim$10 times larger effective area. White arrows identify sharp structures associated with shocks, which will be detectable with future X-ray missions.

Black Hole–Generated Sound Waves, Sloshing Motions, and Turbulence Supermassive black holes could deliver heat to the surrounding gas by generating sound waves and weak shocks. Coherent large-scale, approximately concentric ripples have been observed in the Perseus [12] and Virgo clusters [13], and other objects, and have been tentatively interpreted as sound waves. The dissipation of the mechanical energy of these waves could heat the ICM. This potential mode of heating is particularly appealing as the sound waves are expected to distribute the AGN energy very quickly (i.e., on the cool core sound crossing time) and in a quasi-isotropic fashion, thus offseting cooling while not violating the gas velocity dispersion constraints ($\sim$200 km s^{-1}) from the *Hitomi* mission [14]. Furthermore, sound waves and weak shocks can carry a substantial fraction of the enthalpy contained in AGN cavities (e.g., [15]). Interestingly, the fraction of AGN energy channeled into the waves should be systematically smaller for a given source power when the bubbles are dominated by CR pressure because, for a given bubble size, the bubble enthalpy is larger for a relativistic rather than thermal fluid. Direct measurements of AGN bubble expansion speeds with future high spectral and spatial resolution X-ray instruments could help to establish what fraction of the AGN energy is channeled to the rapidly propagating waves (see Figure 2; [16]).

Despite the promising features of this mode of heating, it is far from certain that the ripples are indeed sound waves. Coherent large-scale and approximately concentric fluctuations in the ICM could alternatively be caused by spiral sloshing gas motions [17, 18] (see also white paper by [19]) or gravity waves and turbulence induced by the AGN in the gravitationally stratified ICM (e.g., [20–23]). In the latter case, turbulence is expected to be weakly anisotropic with the preference for motions orthogonal to the radial direction. By measuring velocities of gas motions indirectly through the analysis of X-ray surface brightness fluctuations (which are consistent with direct ve-

locity measurements from *Hitomi*, see [14, 24]), it was shown that the dissipation of these motions provides enough heat to the ICM to offset radiative cooling (e.g., [23, 25]). In order to unravel the true nature of the fluctuations, and in particular to unambiguously determine the nature of the coherent ripples, the equation of state of the ICM fluctuations must be measured on small spatial scales. While the sound waves are adiabatic fluctuations ($dT/T = (2/3)d\rho/\rho$; where T and ρ are the temperature and density, respectively), the sloshing motions and turbulence generate predominantly isobaric ones ($dT/T = -d\rho/\rho$; e.g., [11, 26–28]). Although current measurements show that fluctuations are mostly isobaric, the nature of fluctuations on small spatial scales dominated by ripple-like structures remains unknown due to a relatively poor spectral resolution and small effective area of current X-ray telescopes.

Figure 1 shows mock X-ray observations of a Perseus-like cluster processed using a method designed to filter out isobaric ICM fluctuations [11] based on hydrodynamical simulations of AGN feedback of [29]. Panels show 300 kilosecond *Chandra*, 300 kilosecond *Lynx*, and 10 million second *Chandra* mock observations. While an exposure of 10 Ms is not within the reach of *Chandra*, collecting a comparable photon counts in a Ms observation may be within the grasp of future flagship X-ray missions characterized by high spatial resolution and $\sim$10 times larger effective area. This is a conservative estimate as the effective area is photon energy-dependent and may be even larger. This figure demonstrates that (adiabatic) sound waves could be unambiguously detected by future X-ray missions. Similar techniques could also be used to identify isobaric fluctuations, thus enabling one to **distinguish between contributions to the ICM heating from AGN feedback (via sound wave heating) and bulk gas motions (via dissipation of isobaric ICM fluctuations).**

Microphysics of AGN Feedback Detailed physics of AGN feedback on microphysical spatial scales is largely unknown, which limits our ability to reproduce realistic feedback in numerical simulations. Therefore, one of the goals for the next decade is to unravel the nature of the ICM microphysics. Over the next decade, significant improvements in the capabilities of X-ray observatories are anticipated. The *XRISM* observatory, with the X-ray calorimeter, will be launched in early 2022. It will deliver spectra of extended X-ray sources with the resolution at least 30 times better than *Chandra*'s. However, in order to understand transport processes in the ICM, it is necessary to study the statistical properties of gas density fluctuations and velocities on spatial scales that are comparable to the Coulomb mean free path (typically, $\sim$kpc to a few tens of kpc) and below. On these scales, theoretical predictions for the behavior of the ICM vary substantially depending on the properties of transport processes. The next-generation *Lynx* observatory would be the best mission for such science. It will have an effective area at least a factor of 10 larger than *Chandra*, a subarcsecond spatial resolution, and spectral resolution even better than *XRISM*. By measuring the **ICM fluctuation power spectra** in density, temperature, and velocity fluctuations, next generation missions may allow us to probe the mean-free-path scale and below and quantify the level of

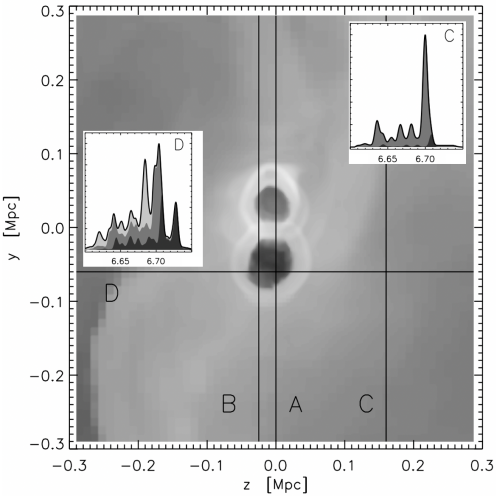

Figure 2: Simulation of AGN bubble inflation. Inlets show iron line profiles along the lines intersecting the bubble (D) and ambient medium (C). Line width $\sim$10 eV will be resolved by *Lynx*.; Adopted from [16].

thermal conduction and viscosity of the ICM (e.g., [24, 30]).

Measurements of **sound wave** density, temperature, and velocity fluctuation amplitudes as a function of the distance from cluster centers could also help to **put constraints on the ICM transport processes**. Theoretical arguments suggest that ICM electron (and ion) conduction and ion viscosity should be significantly suppressed below their respective Spitzer-Braginskii values if the waves are to propagate out to significant distances from the AGN bubbles (e.g., [31]) as appears to be the case if the ICM ripples are indeed sound waves.

Data from *XRISM* will also enable measurements of the gas motions generated by AGN and probe the velocity amplitudes, scales, anisotropy, and power spectra for a moderate sample of low-z clusters. It will enable studies of **non-equilibrium plasmas and put constraints of non-thermal electrons accelerated in AGN shocks** by measuring line ratios in high-resolution spectra [32].

Physics of Feedback: Composition of AGN–inflated Bubbles

A major uncertainty in determining the power supplied by the AGN jets is associated with the fact that the composition of radio lobes inflated by the jets is unknown (e.g., [33, 34]). This poses a problem for future radio surveys that attempt to quantify the cosmological evolution of the energy injected by the supermassive black holes. It has recently been suggested that the composition of radio lobes in Fanaroff-Riley I and II radio galaxy populations (FR I and FR II, respectively) is systematically different. While FR I sources are likely dominated by hadronic CRs (mostly protons), FR II sources tend to be dominated by leptons (mostly electrons/positrons; [35]). This implies that translating the jet radio power to its total power is very uncertain. For a given radio power, the total jet power can be orders of magnitude larger when the jets are heavier, i.e., hadron-dominated. Interestingly, recent multi-messenger neutrino and gamma-ray observations reported by the IceCube Collaboration [36] suggested that blazar jets can be sources of hadronic CRs.

Importantly, the amount of coupling between the energy contained in the AGN-inflated bubbles and the ambient ICM depends sensitively on the composition of the plasma filling them and on the physics of the CR transport processes (e.g., [37, 38]). Consequently, the effective heating rates are expected to be different in the lepton- and hadron-dominated jet cases. Bubble composition will also have an impact on CR transport rates with dramatic consequences for the ICM dynamics and spatial uniformity of the distribution of AGN energy [37, 39]. Thus, it is imperative to unravel the composition of AGN cavities to understand how effectively the AGN energy is utilized in the ICM.

As discussed below, the composition of the cavities inflated by black holes has recently been probed more directly using the Sunyaev–Zel'dovich (SZ) effect (i.e., the inverse Compton (IC) scattering of CMB photons by the ICM). As we argue below, the composition of AGN outflows in clusters could be measured independently in X-rays using similar principles. Thus, the next generation X-ray and SZ instruments may contribute to **(i) solving the long standing problem of the unknown composition of relativistic jets, and (ii) constraining the environment of the central AGN engine (jet launching, conversion of the black hole spin energy to the mechanical energy of outflows), thus ultimately linking the scales of gravitational radii ($\sim$Solar System scales) to the scales of cool cores ($\sim$100 kpc)**.

Sunyaev–Zel'dovich Effect and the Composition of Black Hole–inflated Cavities The SZ effect measures the integrated pressure along the line of sight in the ICM. While the interactions of thermal ICM electrons with the CMB lead to SZ signal, interactions with CRs contribute very little [39–41]. Recently, based on single-frequency Combined Array for Millimeter-wave Astronomy

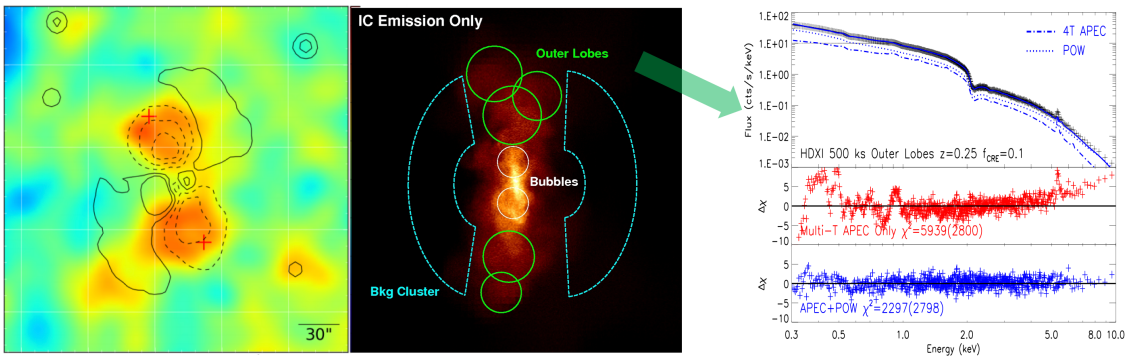

Figure 3: *Left:* Residuals between the SZ the data and model (see text for details). Positive residuals imply deficit of the SZ signal, which is consistent with the picture of CR-dominated AGN bubbles. *Center:* Synthetic image of the inverse Compton X-ray signal from black hole inflated cavities in a galaxy cluster (assuming *Lynx* response) *Right:* AGN lobe spectra (top), multi-temperature fit residuals (middle) and the residuals corresponding to single temperature plus power law component representing IC emission (bottom).

(*CARMA*) observations, [42] reported a suppression of SZ signal from AGN cavities in the galaxy cluster MS 0735.6+7421. Figure 3 (left panel) shows the map of the residuals between the data and model based on the SZ signal corresponding to the smooth gas distribution inferred from X-ray observations and assuming pressure equilibrium between the bubbles and the ambient ICM. Positive residuals imply deficit of the SZ signal, which implies that the cavities may be either supported by very diffuse thermal plasma with temperature in excess of hundreds of keV, or are not supported thermally. **Future high-angular resolution, multi-frequency SZ observations (CCAT-prime, NIKA2, MUSTANG2, TolTEC, AtLAST, LST, CSST, CMB-in-HD) can be expected to provide much sought-after proof of CR heating of the ICM** [see 43–45, for more details].

X-ray Inverse Compton Effect Signal and AGN Bubble Composition AGN cavities are often filled with radio-emitting plasma. The same electrons should be detectable in the hard X-rays (2-30 keV) due to IC scattering of the CMB. Accompanying these electrons may be relativistic protons that could contribute to, or even dominate, the pressure inside the bubbles to support them against the ambient ICM pressure. This theoretically expected IC signal could therefore constrain the particle content of black hole outflows and the long-term impact of these CRs on clusters. While in FR I sources this IC signal has so far eluded detection with *Chandra* or *XMM-Newton* X-ray observatories, such measurements could be within the grasp of future X-ray missions combining large effective area and good spatial resolution, such as *Lynx* or *AXIS* [46]. Figure 3 shows synthetic images (center panel) from a state-of-the-art magneto-hydrodynamical (MHD) simulation of black hole jet feedback that incorporates the effects of CR heating and transport. In these simulations, a small fraction of AGN energy is supplied in the form of CR leptons. Right panel shows spatially resolved spectra (top right panel), large multi-temperature thermal fit residuals (middle right panel), and much smaller residuals corresponding to single temperature gas plus power law component representing IC contribution to X-ray emission (lower right panel). This figure illustrates that this technique has the potential to rule out high-temperature thermal plasma filling the bubbles and can **directly detect non-thermal emission from CRs inside the AGN bubbles.** (Similar type of analysis for *Chandra* instrument response demonstrated that it would be impossible to detect the IC signal.) This method is free from the assumptions of pressure equilibrium between the bubble and the ambient ICM, energy equipartition between the magnetic fields and CRs, and the characteristic bubble rise timescales often assumed to be comparable to the buoyancy timescale (e.g., [34, 35]).

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