Science horizons & technology challenges beyond the Chandra X-ray Observatory

When we think about directions for astrophysics in the next 10–30 years, one of the overarching priorities is to reach into previously unexplored realms of the Universe. Several directions, identifiable today but mostly beyond the capabilities of anything currently planned, fit into this category. One is achieving a panchromatic view of the quickly emerging population of galaxies and supermassive black holes at $z \sim 10$. Another is tracing formation of galaxies and their assembly into large-scale structures starting from the earliest possible epochs. Yet another is observing baryons and large-scale physical processes outside of the very densest regions in the local Universe. Sensitive X-ray observations are critical for achieving the necessary breakthroughs in these areas:

- Observations of the first generation supermassive black holes are key for understanding their progenitors and the relation between SMBHs and host galaxies, as well as solving the puzzle of $10^9\,M_\odot$ black hole "monster" formation by z=6–7. The lower-z experience indicates that a large fraction (perhaps, >50%) of SMBHs in high-z galaxies will be highly obscured in the optical and near-IR bands, limiting what even JWST can accomplish in this area. The envisioned X-ray observatory described below will detect 2–100 keV X-rays (rest frame, mostly unaffected by absorption) from z=10 SMBHs with masses as low as a few × $10^4\,M_\odot$, thus providing a unique view into very early stages of the SMBH growth.
- Objects at a mass scale of >> 1 galaxy are expected to first form at redshift ~ 6. The next generation X-ray observatory should spatially resolve the emission and measure the temperature and mass of hot gas in these protoclusters, even if their central galaxies host luminous quasars. Thus, we will be able to "write" a complete history of the largest bound structures in the Universe and understand the role of SMBHs in their evolution.
- HST/COS detection of low-z OVI absorption lines confirms the presence of $10^{5.5}$ K gas in the intergalactic medium and/or halos of ~ $0.3L^*$ galaxies. However, this technique is insensitive to the higher-T IGM expected at higher densities and more massive galaxy halos. Deep *Chandra* exposures detect the $T > 10^7$ K gas near the virial radius (r_{200}) of galaxy clusters where the density is ~150 times higher than the cosmic mean. The next step should be *mapping in emission* the intergalactic medium at lower temperatures (>10^6 K) and overdensities (≈ a few × 10's). For the first time, these observations will bring to light ~ 15% of all baryons in the local Universe and reveal structures ranging from denser parts of the filamentary Cosmic Web to the "hot-mode" IGM accretion onto massive galaxies.

Recent technological developments support the feasibility of building in the 2020s an X-ray observatory with angular resolution comparable to Chandra and with 30 to 100-fold increase in sensitivity in the 0.2–10 keV energy band. This gain in sensitivity is precisely what is needed to address the topics described above. Moreover, such an X-ray observatory will provide an incredibly powerful capability for a wide variety of cutting-edge science where X-ray information is indispensable — supernova remnants, accretion onto black holes and neutron stars, atmospheres of active stars, quasar winds, etc.

Angular resolution and sensitivity go hand-in-hand for X-ray telescopes. Chandra-scale angular resolution (1″ or better) is essential in building more powerful, higher throughput observatories to avoid source confusion and remain photon rather than background-limited. Building this next-generation X-ray observatory presents significant challenges. Technology developments for potential instruments such as microcalorimeters, wide-field active pixel detectors, and transmission gratings show great promise, but further progress is required and appears feasible[a,b,c]. The most daunting task is development of lightweight, high-resolution X-ray optics. Current technology for thin segmented mirrors is approaching ~ 10″ angular resolution, near its projected limit. Several NASA-funded studies aimed at high-resolution, lightweight X-ray optics are underway. One approach is based on making the mirrors adjustable using a thin piezoelectric layer deposited on the back surface of the segments[*]. Teams are also investigating corrections of mirror distortions through differential deposition of a filler material[†]. Another technique involves precision-cutting of thin, distortion-free mirror segments out of large silicon crystals[‡].

There are promising early indications for the feasibility of achieving 1″-scale resolution with lightweight optics. Of course it will take several years before any of the currently studied techniques or their combination becomes a proven way to build lightweight, high-resolution X-ray mirrors. Nevertheless, with ongoing investments in optics and detectors, there is a real possibility that the technology for realizing the vision for a true successor to *Chandra* will be demonstrated before the end of the current decade. We believe that such an observatory will be instrumental for expanding the discovery space for all of astrophysics in the upcoming decades.

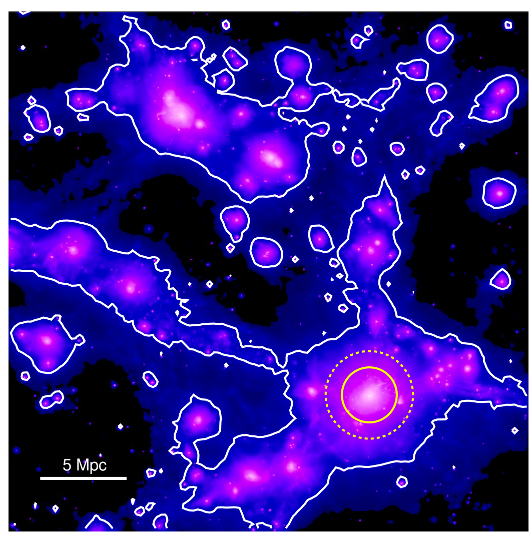

Illustration of sensitivity gain with the next-generation X-ray observatory: The figure shows 0.5–2 keV X-ray brightness for a simulated 30×30 Mpc region[*]. The dotted circle shows the r_{200} radius for the most massive cluster in this box ($M \approx 10^{15}\,M_\odot$). *Chandra* has detected X-rays to this radius in the deepest, ~ 10^6 s exposures. The large-scale white contour locates the X-ray brightness level, ~1/30 that at r_{200}, accessible with the X-ray observatory discussed here.

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