ACCRETING BINARY POPULATIONS AND ISM EVOLUTION IN GALAXIES

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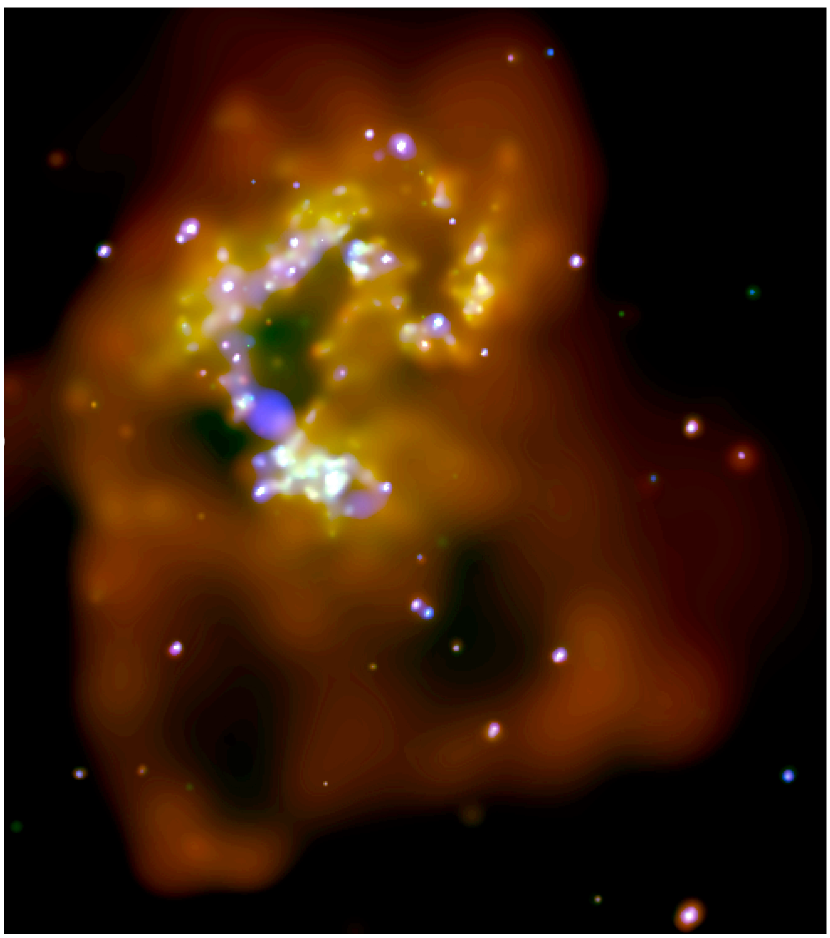

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I. A high-resolution view of energetic phenomena in galaxies

X-rays provide a unique window to the energetic phenomena related to the stellar and gaseous components of galaxies. These phenomena carry information about the star-formation and chemical enrichment history of galaxies, the formation and evolution of their compact object populations and the behavior of matter at extreme gravitational and/or magnetic fields. Understanding these processes is fundamental to modern astrophysics and the driver of multiple theoretical and observational studies.

The current generation of X-ray observatories (Chandra and to some extent XMM-Newton) has provided an exceptional picture of the phenomenology of the discrete source populations (accreting compact objects and supernova remnants) and the hot gaseous component in nearby galaxies (e.g. Fabbiano 2006 and references therein). These observations showed conclusively the link between the total number of X-ray binaries and star-formation rate, and galaxy mass (e.g. Grimm et al 2003; Gilfanov et al 2004), that had been suggested by earlier studies of the integrated emission properties of galaxy samples (e.g. Fabbiano 1989; Eskridge et al. 1995; Fabbiano & Shapley 2002). The same data provided for the first time evidence for localized enrichment of the ISM associated with star-forming activity (e.g. Baldi et al 2006a,b), and set the first constraints on the hot gas component of low-luminosity "X-ray faint" elliptical galaxies (e.g. Trinchieri et al 2009). These advances required very long (~0.5Msec) Chandra observations which reached point source luminosities of $\sim 10^{37}$erg/s, at the limit of what can be achieved with Chandra for these 'background-limited' observations (due to the hot ISM and unresolved much fainter sources). Observations of lower-luminosity populations are possible only for the nearest objects (e.g. 200ksec on M81 reach $\sim 10^{35}$erg/s), but our local volume (<5Mpc) contains only a handful of galaxies appropriate for these studies. Doing "resolved stellar population work" in the X-ray band has just barely become possible with Chandra, however, increased collecting area and higher spatial resolution will allow us to extend these studies to a larger volume of galaxies and to currently inaccessible, fainter types of populations.

These studies demonstrated that we can use observations of the accreting source populations and the hot ISM in galaxies to address basic questions such as:

1. What is the mass spectrum and number density of stellar compact objects and on what parameters do they depend?
2. What are the evolutionary paths of binary stellar systems and how are they related to gravitational-wave sources and γ-ray bursts?
3. How did the compact object populations and ISM of galaxies evolve over cosmic time?
4. What are the cycles of the elements of life (how stars enrich the ISM and how galactic outflows regulate star-formation)?

These questions are of fundamental importance for many areas of traditional astrophysics including evolution of galaxies and stellar evolution, but also reach in the realm of studies of the physics of stellar remnants, properties of γ-ray burst progenitors and gravitational wave sources.

II. Compact object populations and their relation to gravitational-wave sources and γ-ray bursts

a. <u>The mass spectrum and number density of compact objects</u>

Current studies of accreting binaries in our Galaxy give us only a partial view of the populations of compact objects due to: (a) uncertainties in the distance of the X-ray sources; and

(b) limited sampling of the (metallicity, age, IMF) parameter space. Observations of external galaxies are essential to achieve the complete picture necessary for understanding stellar evolution, compact object formation, compact object mergers and γ-ray bursts. Two major pieces of this puzzle are the demographics of stellar compact objects (neutron stars and "stellar mass" black holes), and the evolutionary channels of binary stellar systems.

Observations with Chandra and recent theoretical developments (e.g. Belczynski et al. 2008) have shown that we can set constraints on the types of objects that constitute the accreting source populations of nearby galaxies by studying their summary statistics (X-ray luminosity functions, average X-ray spectra, variability patterns; e.g. Bilstden & Deloye 2004; Piro & Bildsten 2002, Fragos et al 2008). The availability of large area ground and space telescopes in the future (e.g. JWST, 30m class telescopes) opens new possibilities through identification of the spectral types of the optical counterparts of the accreting sources detected in X-ray observations of nearby galaxies. We will be able to classify the accreting sources, on the basis of their donor stars, as High-Mass X-ray binaries (HMXBs; based on the detection of O/B-type counterparts), or Low-Mass X-ray binaries (LMXBs; based on their association with globular clusters, low-mass stars or the non-detection of any early-type counterpart).

For objects in the Local Group we will be able to measure their mass functions based on optical spectroscopic monitoring. Current efforts in the case of a few very bright objects led to the discovery of an eclipsing X-ray binary in M33 consisting of a $15.65\pm1.45M_\odot$ black hole orbiting a $70.0\pm6.9M_\odot$ companion (Orosz etal, 2007), and a Wolf-Rayet X-ray binary in the Local Group galaxy IC10 (pin-pointed with Chandra, Prestwich etal, 2007), with a mass function of $7.64\pm1.26M_\odot$, which corresponds to a minimum compact object mass of $23.1\pm2.1M_\odot$, (the most massive black-hole known so far; Silverman & Fillipenko 2008). These two discoveries, which were based on the initial detection of X-ray eclipses, demonstrate the potential of constraining the black hole mass distribution by studying sources beyond the Milky Way.

Similar measurements for objects with more typical optical counterparts can be performed with the next generation of optical and infrared telescopes. These observatories can provide the first direct characterization of accreting binaries on the basis of their donors *and* compact objects by enabling determination of the mass function for objects in the Magellanic Clouds (where we will be able to obtain spectra of M,K main sequence donors of LMXBs), M31 or M33 (by obtaining spectra of the main sequence OB-type donors of HMXBs) or even beyond the Local Group (for objects with very massive donors; e.g. Wolf-Rayet stars). Such measurements can open new windows to studies of compact objects by providing constraints to: (a) the upper and lower limit of the mass spectrum of black holes, and (b) their dependence on the parameters of their parent populations (e.g. metallicity, IMF, environment). The latter can be determined from studies of the stellar populations and star-formation history of their host galaxies.

These constraints on the mass spectrum and number density of extragalactic compact objects in concert with characterization of their local stellar populations will test our current theories of compact object formation and their relation to stellar evolution. These are critical elements for understanding gravitational-wave sources through modeling *accreting binary systems which are their progenitors*. This is particularly important for the advanced LIGO and LISA detectors that are planned for the next decades.

Such advances require X-ray data of angular resolution comparable to that of the next generation optical and infrared observatories (0.1″) in order to limit the number of candidate optical counterparts within the error circles, and minimize source confusion in dense stellar environments. This capability is being developed through technology studies of the Generation-X mission (launching cir. 2030). Moreover when high quality X-ray spectral and timing information is available we can obtain independent insights in the nature of their compact objects based on the detection of spectral-state transitions, detection of quasi-periodic oscillations, or the shape of their X-ray power-density spectrum (e.g. McClintock & Remillard 2007). We expect great advances in this area with the large collecting area, and high spectral and timing resolution of the International X-ray Observatory (IXO; circa 2020). However, to constrain the mass spectrum of the compact objects in the Local Group requires the identification of their optical counterparts and therefore a 0.1″ high sensitivity X-ray telescope.

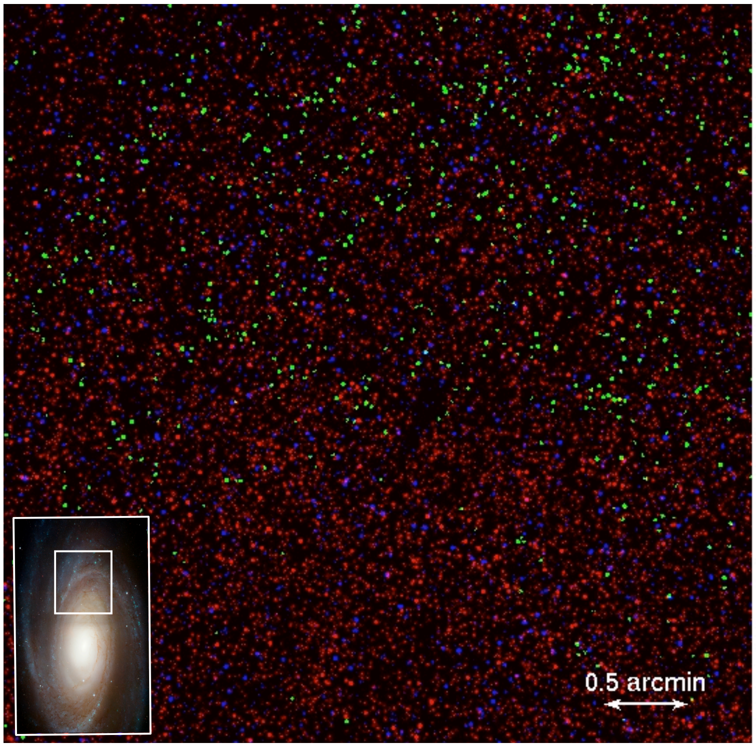
b. Evolutionary channels of X-ray binaries

One additional element needed for understanding accreting X-ray sources and to constrain sources of gravitational waves as well as γ-ray burst progenitors is the evolutionary paths of accreting binaries. Although detailed modeling of individual sources in our Galaxy has already given a basic framework for the different phases in the evolution of binary stellar systems (e.g. Tauris & van den Heuvel 2006), the small number of objects in combination with the limited parameter space covered by studying only our Galaxy, does not necessarily represent the conditions in other galaxies where the majority of the gravitational wave and γ-ray burst progenitors are expected to originate. Such constraints can be obtained by means of population studies in combination with population synthesis modeling. Already the combination of the deepest Chandra observations of nearby galaxies with state-of-the-art accreting binary population synthesis models has been used to investigate the different populations of sources that are present in these galaxies (e.g. Belczynski et al. 2004; Fragos et al. 2008).

Classification of the different types of sources on the basis of their donor stars (HMXBs or LMXBs; from their counterparts) or on the basis of their compact objects (black-hole or neutron-star X-ray binaries; from their mass functions or X-ray signatures such as pulsations, spectral state transitions, power density spectra etc) can be used to link the different source populations to the properties of their parent stellar populations. This can be done in two ways: either based on phenomenological correlations between the different populations, or using accreting binary populations synthesis modeling. The former can be used for example to examine the still open questions of the properties of HMXB populations of different ages and metallicities (e.g. Zezas et al. 2008), or the field vs. globular clusters scenarios for LMXB formation (e.g. Irwin 2006; Fabbiano 2006 and references therein). Population synthesis models, on the other hand, can constrain the largely unknown underlying physics of accreting binary evolution (e.g. supernova kicks, common envelope phase, winds/mass loss etc) by ruling out the areas of the parameter space that fail to reproduce the observed populations given the measured star-formation histories for each galaxy. This is the *only* way to investigate those parameters and study exotic paths of binary evolution that may lead to different types of gravitational waves or γ-ray burst sources.

Chandra (which is our workhorse for studies of the extragalactic X-ray source populations) is near to the limit of its capabilities in this field due to the small number of galaxies in our local volume, their diffuse X-ray emission, and source confusion in their dense central regions. Any major advances in the above research directions will then require a high spatial resolution, high sensitivity X-ray telescope in order to: (a) detect the bulk of active X-ray binary systems and minimize source confusion problems; (b) increase our sample of galaxies and better cover the parameter space by increasing the accessible volume at those detection limits; (c) classify the X-ray sources based on their optical counterparts and spectroscopic and timing X-ray properties.

Fig. 1: A high resolution, high effective area X-ray telescope will be able to perform detailed population studies of the accreting binaries in nearby galaxies. This is a 100ksec simulation of a 5′×5′ field in M81 observed with a 0.1″ resolution, 50m^2 effective area X-ray telescope. The field is located in the inner disk/outer bulge region of M81 and includes 700 HMXBs, (green sources) and ~14000 LMXBs (red sources) down to a luminosity of ~5×10^{33} erg s^{-1}. *It is clear that the two populations trace the spiral arms, and the red light of the galaxy respectively*. A uniform population of background AGNs (blue sources) is also included. The X-ray sources are based on an extrapolation of the Chandra XLFs of the HMXBs and LMXBs in M81, and the locations of early-type and late-type stars from deep HST observations. Even at those levels the data are barely confusion limited (this is a very conservative scenario assuming no break in either XLF below 10^{35} erg s^{-1}). The insert shows a BVI image from the HST data used to generate the simulation (the white box indicates the simulated region).



c. <u>The cosmological evolution of accreting binaries</u>

The deepest X-ray surveys conducted with Chandra are finding that normal galaxy populations make up an increasingly larger fraction of the X-ray detected sources down to the faintest X-ray fluxes (e.g., Bauer et al. 2004). It is estimated that normal galaxies will begin to outnumber AGNs at fluxes below ~10^{-17} ergs cm^{-2} s^{-1} in the 0.1-10.0 keV band. At present, studies of the evolution of normal galaxies are limited to only X-ray luminous starburst galaxies detected in the deepest Chandra surveys or through X-ray stacking analyses of optical/infrared selected galaxy populations (e.g., Ptak et al. 2007; Lehmer et al. 2008; Tzanavaris & Georgantopoulos 2008). These studies have shown that *the X-ray power output, a tracer of the X-ray binary activity, from normal galaxy populations evolved significantly over z~0-1.5*, consistent with changes in the star-formation activity. Similar high spatial resolution Hubble and Chandra studies of luminous extra-nuclear sources associated with z~0.3 star-forming galaxies showed that their numbers have increased by a factor of 2, in agreement with the enhanced star-forming activity at these redshifts (Hornschemeier et al. 2004; Lehmer et al. 2006). These sources are the high-redshift analogs of the local populations of "Ultra-luminous X-ray sources" (sources with inferred isotropic luminosities above the ~2×10^{39} erg s^{-1} Eddington limit for a 10 M⊙ black hole), which often dominate the total accretion-produced luminosity of a galaxy.

However, because of the very small number of galaxies detected at these redshifts it is unclear if the evolution of their X-ray luminosity is due solely to the enhanced star-formation or is also related to the evolution of the metallicity, IMF or possibly star-formation mode in these galaxies. For example lower metallicity results in weaker stellar winds and therefore more massive compact objects, which can be witnessed by their very high X-ray luminosities. Investigations of the integrated X-ray emission of high redshift galaxies, as well as the emission from their population of luminous sources can directly address the cosmological evolution of the populations of compact stellar remnants.

Deep X-ray surveys conducted with a telescope with a higher spatial resolution and larger collecting area than Chandra will revolutionize our understanding of the evolution of normal galaxies, through the individual detection of thousands of objects over z=0.1-5 (possibly even z~6) in a single 5'×5' field. Such large samples will allow for the first time direct constraints on the X-ray luminosity functions of galaxies selected on the basis of their metallicity, morphology etc (determined from optical and infrared observations) out to and beyond the peak of star-formation activity in normal galaxies at z~1.5-3. These data will show if there is any evolution in their X-ray properties and their X-ray output per unit star-formation rate, and how they are related to either their enhanced star-forming activity, lower metallicity, or environment. Comparison in turn with predictions from X-ray binary population synthesis will provide additional constraints on the cosmological evolution of their populations of compact objects (e.g. Ghosh & White 2001).

III. Cycle of elements of life

The high spatial resolution of Chandra has led to several breakthroughs in studies of the diffuse emission in nearby galaxies. For example deep observations of the Antennae showed for the first time evidence for local metal enrichment of the hot ISM due to star-forming activity (Baldi et al. 2006a,b), while in the case of "X-ray faint" elliptical galaxies deep observations set stringent limits to their gas content (e.g. Trinchieri et al. 2008). IXO in the near future will give a detailed picture of the large scale gaseous component in star-forming and gas-rich elliptical galaxies, including major advances in mapping the metal outflows from starburst superwinds. However, studies of the microphysics of the hot gas in galaxies, or the tenuous gaseous component in gas-poor early-type galaxies requires higher spatial resolution and effective area than is currently available. The high spatial resolution is critical in order to study the properties of the gas close to the regions where it is energized and chemically enriched and to isolate the contaminating X-ray binary population (particularly in the case of early type galaxies).

Understanding the mechanisms of ISM chemical enrichment is important for understanding how the metals are diffused from the star-forming regions where they are produced to the interstellar space and eventually to the regions of the next generations of stars and planets. In addition, understanding of the heating mechanisms of the ISM together with constrains on the physics of large scale outflows provided by IXO, will give us a complete picture of the dynamics of the hot gas in galaxies. In the case of elliptical galaxies in particular, higher sensitivity observations of a larger number of nearby galaxies will allow us to test different scenarios for the retention of their hot haloes (e.g. Pellegrini & Ciotti, 1998; Pellegrini et al. 2007).

Observations of galaxies at high redshifts can also provide additional constraints on the evolution of their hot gaseous component which in turn will have important implications for the chemical enrichment of the intergalactic space and regulation of their star-forming activity (e.g. Simcoe et al. 2006). With a telescope with 0.1″ resolution we can measure the spatial extent of galaxies similar to M82 (the prototypical superwind galaxy) or the Antennae at redshifts greater than 0.5 (Fig. 2). For a fiducial galaxy with an X-ray luminosity of 5×10^{39} erg s^{-1} at z~0.5 observed in an 1Msec exposure we will be able to spectrally decompose the thermal and X-ray binary components and therefore measure the evolution of their thermal component as function of star-forming activity and redshift. Similar investigations in the case of elliptical galaxies (identified in optical and infrared deep fields) will test models for halo regeneration (e.g. O'Sullivan et al. 2001).

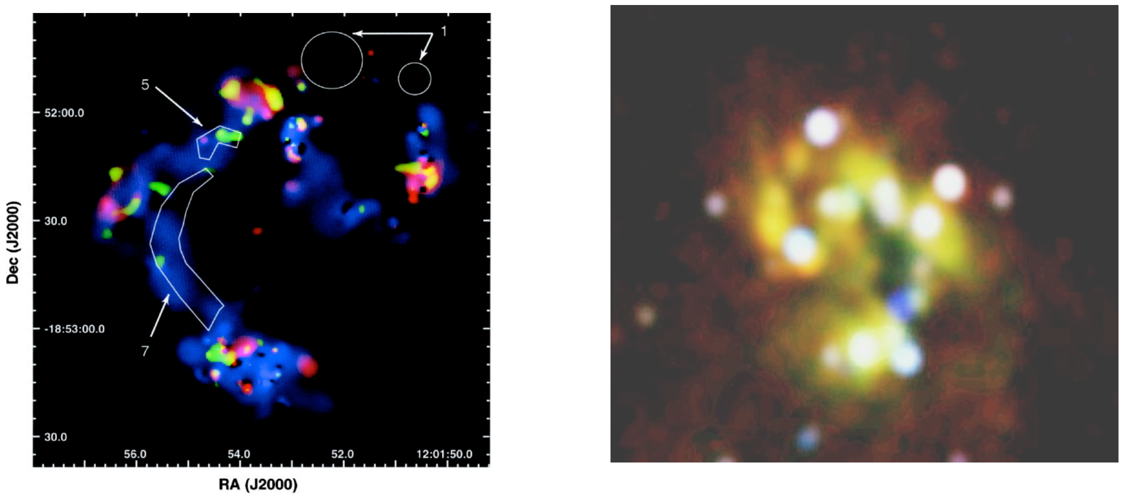


Fig. 2. Left: Evidence for local metal enrichment in the Antennae. This is a composite image of X-ray emission in the Fe-L (red), Si (green) and Mg (blue) X-ray lines measured from deep (411 ks) Chandra observation of the Antennae (adapted from Fabbiano et al. 2004). The peaks of the Si and Fe emission are strong evidence for local metal enrichment associated with on-going star-forming activity. **Right: Generation-X will be able to resolve starburst galaxies at redshifts ~1.** Simulation of a galaxy like the Antennae (L_X~10^{40} erg s^{-1}) at a redhsift of z=1 as it will be seen with Generation-X.

IV. Conclusion: the need for a high resolution, large area X-ray telescope

Chandra has demonstrated that high spatial resolution is critical for studies of the X-ray source populations and the local properties of the hot ISM in nearby galaxies. IXO will address the nature of the most luminous isolated sources in nearby galaxies and will provide valuable constraints on the physics of accretion onto compact objects as well as the physics of the large scale hot ISM in galaxies. However, progress in the fields of compact object populations and evolutionary channels of binary stellar systems relies on the identification and multiwavelength study of their optical counterparts as well as a deep census of their populations in as diverse environments as possible. This requires sub-Chandra spatial resolution in order to take advantage of the next generation of optical and infrared telescopes and overcome source confusion. Similarly understanding the microphysics of the hot gaseous component in galaxies and their connection to large scale outflows requires high sensitivity and spatial resolution X-ray data.

A facility like Generation-X (Gen-X) with a 0.1″ spatial resolution and 50m^2 effective area will address the fundamental scientific questions discussed earlier and will revolutionize this field by extending the type of studies that are currently possible in our Galaxy to galaxies in our Local Group, and studies in the Local Group out to the Virgo cluster. In each case this is equivalent to a ~1000-fold increase of the accessible volume. It will also vastly increase our sample of high-z galaxies and hence our understanding of the evolution of their gaseous and compact object components. In Fig. 3 we present the different types of sources that we will be able to study in the local Universe with a Gen-X 100ksec exposure. It is clear that these observations will extend our reach to populations currently inaccessible outside our Galaxy (e.g. normal stars, CVs), or outside our immediate neighborhood (e.g. supernova remnants or quiescent accreting binaries). In addition they will extend to the distance of M81 and even the Antennae important X-ray timing and spectroscopic diagnostics that are currently available only for Galactic or Magellanic Cloud sources (e.g. detection of pulsations and spectral state transitions, measurement of power density spectra). This way Gen-X will address diverse and fundamental questions such as compact object demographics, accreting binary evolution, the nature of γ-ray burst and gravitational wave progenitors, the cosmological evolution of galaxies and the microphysics and chemical enrichment of their hot ISM.

Given the project's scale it is clear that Gen-X is a post-2020 mission and that it builds on the technology and scientific legacy of IXO. However, it is important to ensure that it receives adequate funding to meet its technological challenges so that it can progress in tandem with the next generation of optical, infrared, and gravitational-wave observatories.

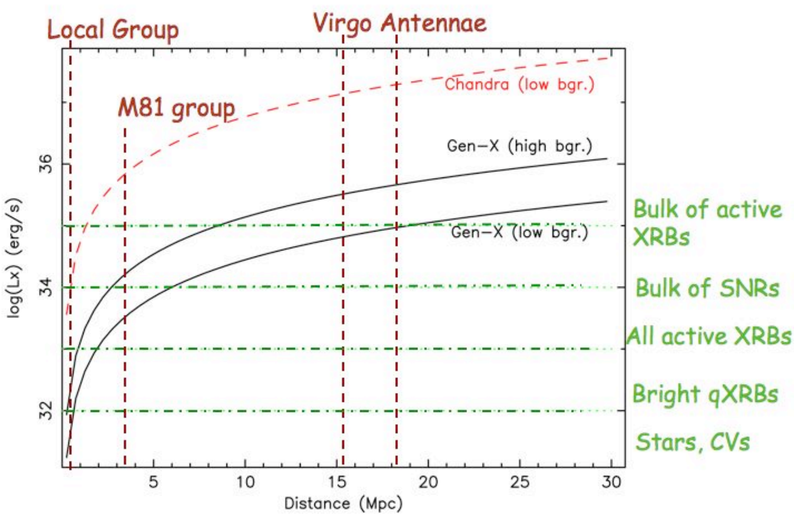


Fig. 3: Discovery space enabled by the Gen-X mission. The black curves show the limiting luminosity (3σ level) as a function of distance for a 100ksec Gen-X observation in the cases of the typical diffuse emission level at the M81 disk and inner bulge (low and high background respectively). For comparison Chandra's liming luminosity in the low-background case is also shown. For reference are indicated the distances of nearby objects and the types of sources that are probed at various luminosities (active and quiescent X-ray binaries, SNRs, cataclysmic variables and normal and active stars).

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