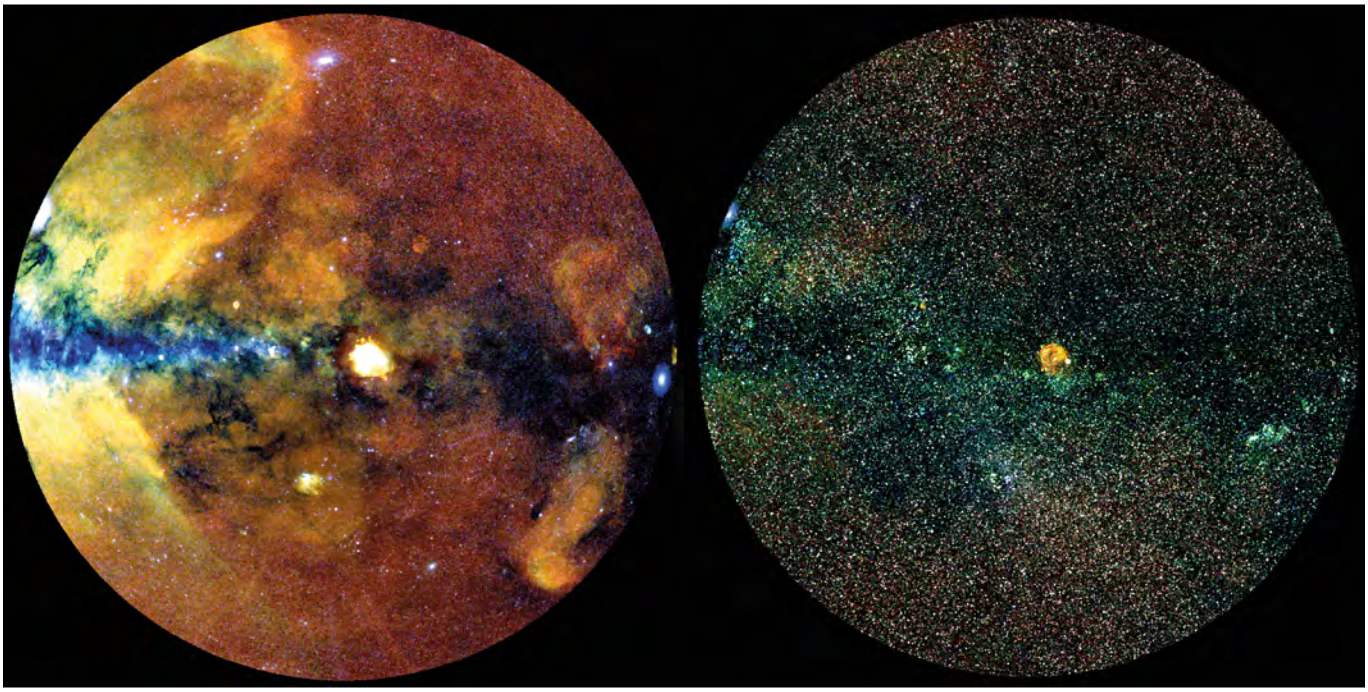

THE HOT UNIVERSE REVEALED BY eROSITA

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eROSITA onboard the Spectrum-Roentgen-Gamma (SRG) orbital observatory is the most powerful X-ray survey telescope ever built, thanks to its unique combination of large effective area and degree-wide field of view. Its survey has already led to several discoveries and groundbreaking results covering essentially all fields of astrophysics. Here, we review a few of them.

Between December 2019 and February 2022 X-ray telescope eROSITA [1,2] performed an almost uninterrupted survey of the entire sky, from its vantage point along a wide halo orbit around the second Lagrange point (L2) of the Sun-Earth system. Observations were carried out in a simple scanning mode, with the telescope slowly rotating (90 degrees per hour) around its axis, gathering photons along overlapping great circles in the sky. By combining the images of these great circles, the entire sky is imaged every six months. Individual X-ray photons with an energy between approximately 0.2 and 10 keV are recorded, their energy and arrival times measured with great accuracy by the pnCCD detectors with which eROSITA is equipped.

The recently released first eROSITA All-Sky Survey (eRASS1) [3] shown in Fig. 1 was carried out from December 2019 to June 2020, and represents the most accurate and sensitive view of the X-ray sky to date. In the most sensitive energy range of eROSITA (0.2-2 keV), the telescope detected approximately 340 million X-ray photons, most of them produced by diffuse background emission of astrophysical origin - either from the solar wind, from Milky Way hot gas, or from faint, distant unresolved black holes at cosmological distances.

▲ **FIG. 1:** The eROSITA X-ray all-sky survey hemisphere view; two wavelet-filtered false-color images are shown to highlight extended and diffuse structures (left) and point sources (right). In both images, the half-sky is projected onto a circle (so-called Zenithal Equal Area projection) with the centre of the Milky Way on the left and the galactic plane running horizontally. Photons have been colour-coded according to their energy (red for energies 0.3-0.6 keV, green for 0.6-1 keV, blue for 1-2.3 keV). Courtesy of J. Sanders (MPE).

A catalogue was then constructed – after careful processing and calibration – by detecting concentrations of photons in the sky against the large-scale, diffuse background. The eRASS1 catalogue covers half the X-ray sky, the data share of the German eROSITA consortium. It consists of more than 900,000 sources, including some 710,000 supermassive black holes in distant galaxies (Active Galactic Nuclei, AGN), 180,000 X-ray emitting stars in our own Milky Way, 12,000 clusters of galaxies, plus a smaller number of other exotic classes of sources like X-ray emitting binary stars, supernova remnants, pulsars, and white dwarfs. This catalogue increases the number of known X-ray sources in the published literature by more than 60%, the largest single progress in the demographic of high-energy celestial objects since the launch of eROSITA's predecessor, the German-UK-USA ROSAT X-ray mission in 1990.

After eRASS1, eROSITA has continued scanning the sky and accumulated 3.5 additional all-sky surveys. Those data will also be released to the world in the coming years.

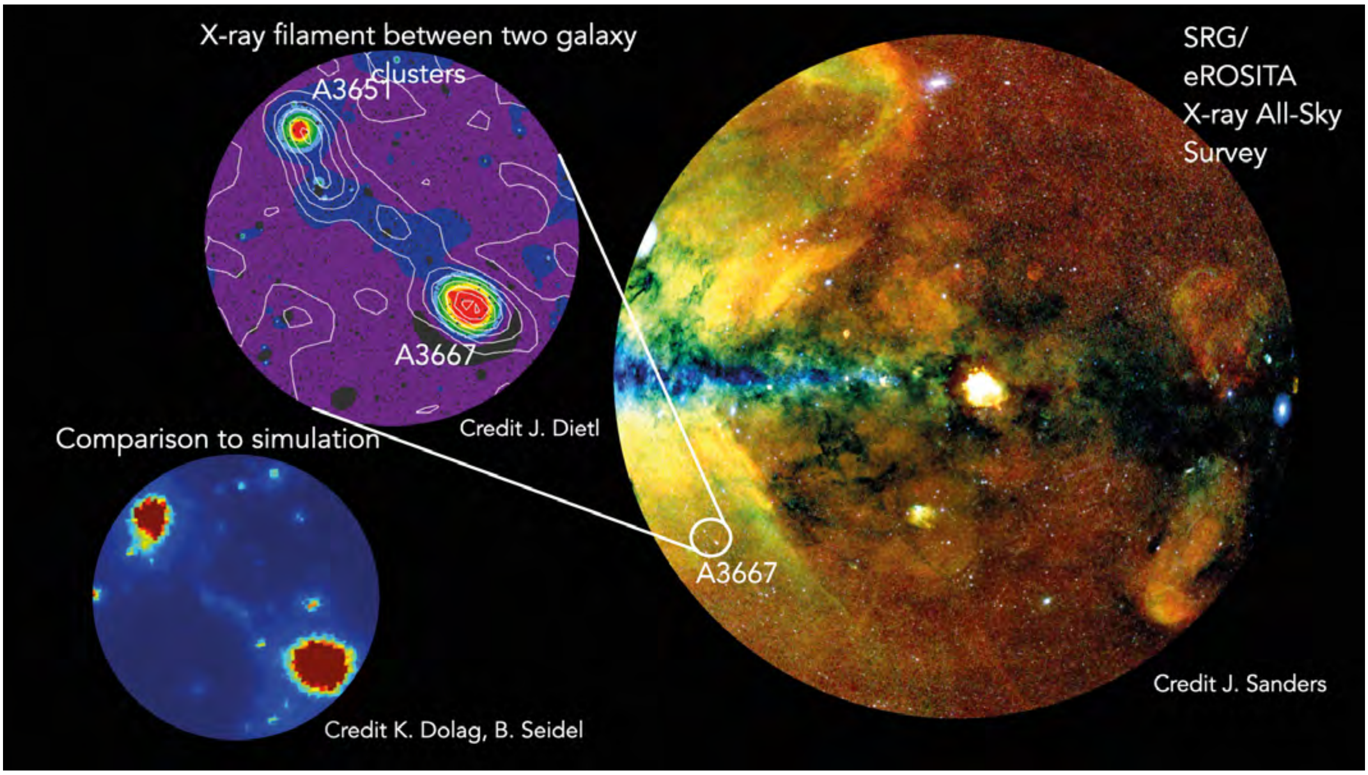
Hot gas in our Galaxy

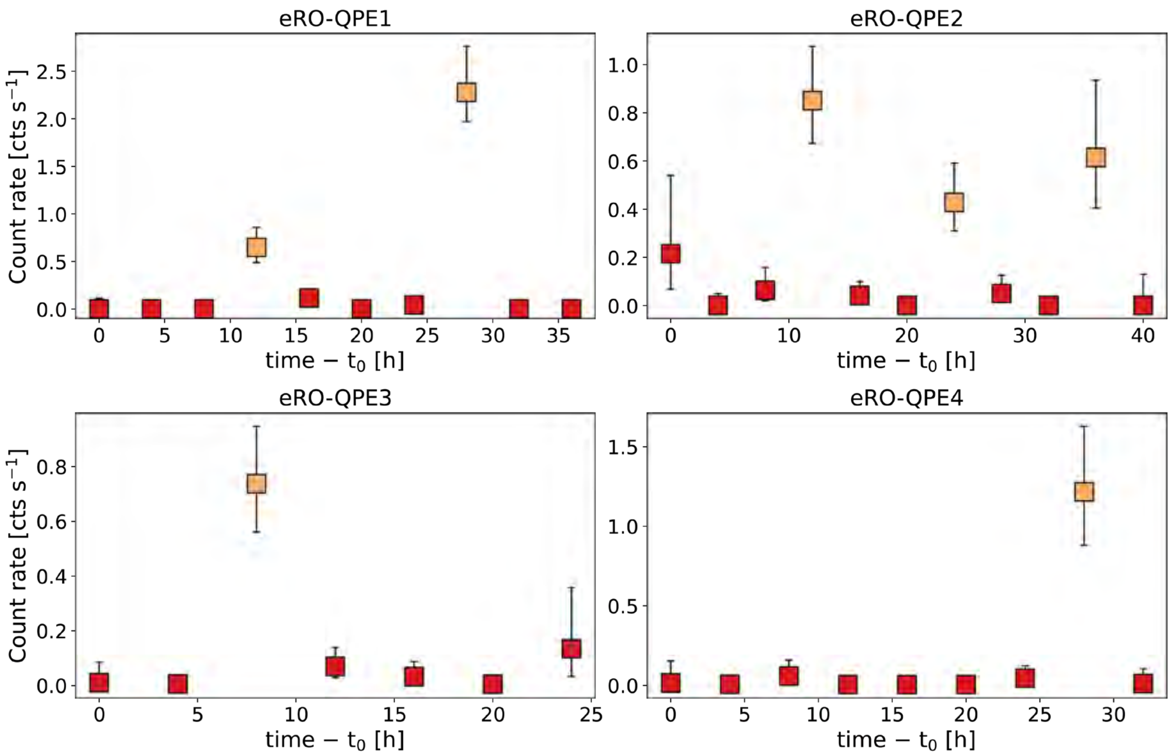
One of the first discoveries based on eRASS1 were the "eROSITA Bubbles"[4], huge regions of hot X-ray emitting gas in our own Milky Way, presumed to be caused by previous outbursts of our supermassive black hole at the centre or, more likely, by previous central bursts of star formation and subsequent supernova explosions. Half of the northern and southern Bubble can be seen in the half-sky image in the left panel of Fig. 1 (the yellowish emission on the left). Cosmological galaxy formation models predict such "feedback". In fact, both outflowing hot gas and inflowing cooler gas as well as a large-scale hot gas halo filling the gravitational potential of galaxies are generic predictions. The detailed physical processes are not fully understood, though, and these gas phases have been challenging to detect and characterise in the past. The eRASS data are, therefore, a treasure trove to study processes involving gas at temperatures of >1 million Kelvin at high spatial resolution in our own galaxy (as well as in large statistical samples of other galaxies, *e.g.* [5]). And, indeed, eROSITA measured the distribution of multiple emission components from this diffuse gas. The instrument detected not only the local emission from the solar wind in our solar system, but also the "Local Hot Bubble", a structure produced by a number of supernovae in the vicinity of our Sun. eROSITA also measured diffuse gas at 1-2 million Kelvin in our Galaxy, as well as a somewhat surprising "supervirial" component of even hotter, >6 million Kelvin gas, see for example [6]. The exact origin of the latter is not, yet, completely understood; it might be dominated by hot gas in a "corona" around the disk of the Milky Way or by the summed unresolved emission of billions of stars.

Galaxy clusters, cosmology, and missing normal matter

Gas with temperatures in the range 10–100 million Kelvin permeates galaxy clusters and emits copious X-rays. This huge reservoir of ionised plasma – invisible to optical telescopes – contributes much more mass to clusters than the sum of all stars in all cluster galaxies together. It fills the dark matter-dominated gravitational potential of clusters. Therefore, the X-ray luminosity, produced mostly by thermal bremsstrahlung, is correlated with the total ● ● ●

▼ **FIG. 2:** The eRASS image on the right depicts the location on the sky of the A3667/51 system. The zoom-in on the upper left shows the X-ray emission of the filament (blue), which has a projected length of about 40 million lightyears and a likely physical length of more than 60 million lightyears. White contours represent the galaxy density, which is found to align with the gas filament. The figure on the lower left stems from a constrained realisation of the local Universe. After the eROSITA-discovery, a filament (light blue) was also found in this simulation. Based on [13].





▸ **FIG. 3:** eROSITA X-ray lightcurves of the four newly discovered QPEs. In each panel, colored squares represent an eROSITA 40 seconds exposure. Yellow squares mark the X-ray flares, while red ones mark the background/quiescence level. Based on [19-20].

••• cluster mass. As a result, selecting clusters by their X-ray emission resembles selecting them by their mass. Furthermore, the dependence of the X-ray emission on the squared density minimizes projection effects along the line of sight. Taken together, these are ideal conditions for using X-ray clusters as cosmological probes.

eROSITA detected more than 12,000 clusters out of which more than 8000 are new discoveries [7]. Cluster masses were calibrated using major weak gravitational lensing surveys [8,9]. As a result, eROSITA produced the tightest constraints on dark matter and dark energy from clusters to date [10]. The results are consistent with the so-called "Big Freeze" future of the Universe; *i.e.*, eternal accelerated expansion.

Somewhat surprisingly, eROSITA also discovered warm-hot (<10 million Kelvin) gas in the outskirts of nearby massive galaxy clusters. In fact, such gas had been predicted to exist by cosmological hydrodynamical simulations and is believed to be home to the "missing baryons". This term refers to much of the normal matter in the Universe that we know must be there but which escaped detection until now. eROSITA now detects and characterises this gas [11-14]. As an example, a filament of warm-hot gas between two galaxy clusters is shown in Fig. 2. Comparison with simulations of the density and temperature structure of these filaments as well as the abundance of elements heavier than helium that eROSITA reveals, currently indicates a somewhat higher temperature than expected, but analyses of the outskirts of more nearby clusters are needed as well as statistical analyses of large samples, such as that presented in [15], where the first significant (>5 sigma) statistical detection of stacked X-ray emission from cosmic filaments was presented. In the future, the NewAthena X-ray satellite of Europe's Space Agency (ESA), will allow us to study the physical and chemical processes in filaments in even greater detail.

The dynamic X-ray sky

During the survey, every point in the sky is scanned over for about 40 seconds (a "visit") exactly every 4 hours, typically for one day (approximately six visits in total). The same point of the sky is then re-observed (with a similar cadence) after six months. The four eROSITA all-sky surveys completed to date therefore probe variability on interesting astrophysical timescales (from hours to months and years).

On the longest timescales probed (months to years) the variable X-ray sky is dominated by the flickering of accretion onto supermassive black holes in the nuclei of galaxies. Most AGN vary stochastically, but a small fraction of galaxies show dramatic flares triggered by the tidal disruption of stars who wander too close to the nuclear black hole. Several dozens of tidal disruption events discovered by eROSITA have been reported [16], including repeated events in which stars are only partially stripped of mass by the black hole as they orbit around it [17].

However, the most spectacular new discoveries with eROSITA came thanks to its four-hours cadenced visits of the sky. In [18] the serendipitous discovery of the long-predicted fireball X-ray flash of a Nova is reported, revealing the early stages of a thermonuclear explosion on the surface of a white dwarf. Instead [19,20] used the eROSITA surveys to discover four new Quasi Periodic Eruptors (QPE), an exotic class of phenomena associated to repeating short bursts of X-ray emission originating from the nuclei of nearby galaxies. These events have typical durations and recurrence times of hours to days (see Fig.3), and are thought to be produced by the interaction of a star (or a compact stellar remnant) with the accretion disc of a massive black hole. Despite only 8 sources like these are currently known (including the 4 new eROSITA discoveries), they have received the attention of a large number of astrophysicists, as they could be the electromagnetic counterparts of a class of gravitational wave (GW) emitters (so-called Extreme Mass Ratio Inspirals) that will be detected in great numbers by future GW experiments like LISA. ■

About the Author

Thomas H. Reiprich is professor of astrophysics at the University of Bonn. His research focuses on galaxy groups and clusters. He serves on the eROSITA-DE Collaboration Coordination Board, as co-speaker of the Bonn-Cologne Graduate School (BCGS) for Physics and Astronomy, on the Steering Committee of the Transdisciplinary Research Area (TRA) "Matter", as co-chair of the Athena Hot Universe working group, and as co-leader of the External Data Work Package on the Euclid Galaxy Cluster Science working group.

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