

Einstein Probe: Unveiling the Transient X-ray Universe

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Abstract The Einstein Probe (EP), a Chinese-led international X-ray astronomy mission with key contributions from ESA, MPE, and CNES, is advancing time-domain astrophysics through its unprecedented wide-field soft X-ray monitoring capability to discover and characterize cosmic X-ray transients. Launched in January 2024, EP carries two complementary instruments: the Wide-field X-ray Telescope (WXT), which employs lobster-eye micro-pore optics to monitor approximately 11% of the sky with exceptional sensitivity, and the co-aligned Follow-up X-ray Telescope (FXT), which provides high-resolution imaging, spectroscopy, and timing observations for rapid follow-up studies. During more than two years of in-orbit operations, EP has detected over 230 X-ray transients, including Tidal Disruption Events (TDEs), Gamma-Ray Bursts (GRBs), rare compact binary systems, and previously unknown types of transients, thereby opening a new observational window for high-energy time-domain astrophysics. Major scientific achievements include the first demonstration of lobster-eye micro-pore focusing X-ray imaging over an extremely large field of view, the discovery of an intermediate-mass black hole through a tidal disruption event, the detection of a high-redshift gamma-ray burst with complex soft X-ray precursor emission, the identification of a weakly relativistic jet associated with a type Ic-BL supernova, and the discovery of unusual X-ray transients that highlight previously unrecognized manifestations of stellar collapse and compact-object interactions. These discoveries provide new insights into some of the most energetic and rapidly evolving astrophysical phenomena, ranging from stellar explosions and relativistic jets to tidal disruption events and black-hole accretion. Enabled by its unique instrumentation, autonomous rapid-response capability, and extensive international collaboration, EP is expected to continue delivering major discoveries and to remain a major facility for time-domain and multi-messenger astrophysics.

Key words Einstein Probe, Wide-field X-ray survey, Time-domain astronomy, X-ray transients, Lobster-eye optics, Multi-messenger astrophysics

Classified index P172.4, P145.8

1 Mission Overview

The Einstein Probe (EP), designated “Tianguan” in Chinese, represents an international collaboration in X-ray astronomy led by the Chinese Academy of Sciences (CAS) with key contributions from ESA, MPE, and CNES. Launched on 9 January 2024, *via* an LM-2C rocket from the Xichang Satellite Launch Centre, the

1.4-ton satellite occupies a 570 km low-Earth orbit with a 96-minute period, with a nominal 3-year operational lifetime and a goal extended to 5 years.

EP’s scientific payload features two synergistic instruments: the Wide-field X-ray Telescope (WXT) employs 12 lobster-eye modules to achieve an unprecedented 3850 square degrees field of view (approximately 11% of the sky) with 5-arcmin resolution at 0.5–4 keV,

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delivering a 1–2 orders of magnitude sensitivity improvement over prior monitors. The co-aligned Follow-up X-ray Telescope (FXT) utilizes dual conventional Wolter-I mirrors providing $>300\text{ cm}^2$ effective area each at 1.5 keV and sub-30-arcsecond resolution, enabling precision localization and spectral and timing studies^[1]. An artist's impression of the Einstein Probe in space is shown in Figure 1.

These capabilities directly support EP's core science objectives: (i) to discover and characterize cosmic X-ray transients, particularly faint, distant and rare types of X-ray transients, in large numbers; (ii) to discover and characterize X-ray outbursts from otherwise normally dormant black holes; (iii) to search for X-ray sources associated with gravitational-wave events and precisely locate them.

2 In-orbit Performance and Science Capabilities

Following its launch, EP demonstrated robust operational capabilities through efficient power management and precise attitude control. During the six-month commissioning phase, the WXT and FXT completed comprehensive in-orbit calibrations while validating the satellite's capacity for coordinated observations and autonomous rapid-response maneuvers. This phase ended with formal science verification on 22 July 2024, transi-

tioning EP to routine operations while already delivering significant early results. Instrument verification confirms all specifications are exceeded. The specifications for the WXT and FXT models are shown in the Table 1.

On 27 April 2024, EP released its first-light images. The initial observations, which targeted the Galactic Centre, M87, Omega Centauri, and the Crab Nebula, successfully validated EP's dual instrumentation capabilities, demonstrating the capabilities of WXT's panoramic imaging and high sensitivity, as well as FXT's excellent light-collecting power, imaging quality and spectral resolution, large field-of-view for Wolter-I-type X-ray telescope, and millisecond timing resolution.

EP's commissioning and early observations have demonstrated its excellent science capabilities, including a large field of view and high sensitivity, a novel detecting window in soft X-rays, powerful follow-up capabilities, fast two-way spacecraft-ground telecommunications, and quick response and flexible observation scheduling. The unparalleled combination of such capabilities makes EP a promising game-changer in the field of high-energy time-domain astrophysics. This promise has been partly demonstrated by the exciting discoveries achieved already in the one and a half years of EP operations.

3 Science Operations

The EP Science Center (EPSC) is responsible for the sci-

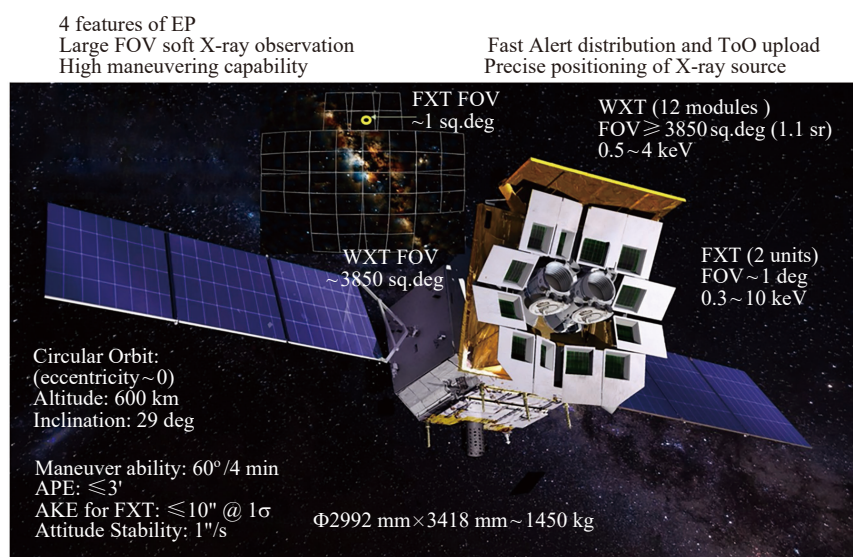


Fig. 1 Artist's impression of the Einstein Probe in space (Credit: IAMCAS)

Table 1 Specifications of the instruments

Parameters	Wide-field X-ray Telescope	Follow-up X-ray Telescope
Number of modules	12	2
Telescope optic	lobster-eye MPO	Wolter-I
Detector	CMOS	pn-CCD
Field of view	≥ 3600 square degrees	$\geq 60'$ (diameter)
Focal length / mm	375	1600
Effective area/ cm^2 (@1.25 keV)	2–3	~ 300 (one unit)
Spatial resolution (@1 keV)	5' (FWHM)	20"–24" (HPD, on-axis)
Bandpass /keV	0.5–4	0.3–10
Energy resolution /eV	122@1.25 keV	100@1.5 keV
Limiting flux /(erg·s ⁻¹ ·cm ⁻²)	$\sim 8.9 \times 10^{-10}$ (27.65 mCrab) @10 s $\sim 1.2 \times 10^{-10}$ (3.9 mCrab) @100 s $\sim 2.6 \times 10^{-11}$ (0.8 mCrab) @1 ks	$\sim 1 \times 10^{-14}$ @10 ks
Time resolution	50 ms (full-frame)	50 ms (full-frame) 2 ms (partial window) 42 μ s (timing)

Note The typical limiting fluxes in 0.5–4 keV are derived for a point like source from simulations, assuming a power-law spectrum with a photon index of 2 and a Galactic absorption column $3 \times 10^{20} \text{ cm}^{-2}$. MPO: Micro-Pore Optics. FWHM: Full Width at Half Maximum. HPD: Half-Power Diameter. mCrab: 1/1000 of the strength of the X-ray flux of the Crab nebular.

ence operations of the mission, including the planning and scheduling of EP observations, instrument calibration and health monitoring, data reduction and analysis of quick-look data, transient alerts handling and dissemination, ToO proposal handling, and user support. EPSC is operated predominantly at the National Astronomical Observatories, CAS (NAOC) and partly at Institute of High Energy Physics (IHEP), CAS for the operations of FXT.

EP employs dynamically prioritized observation modes. During survey operations, WXT executes 3 sequential 20-minute pointings per orbit, achieving full night-sky coverage every 3 orbits and completing all-sky mapping within six months. Simultaneously, FXT conducts Survey Target Observations (FSTOs) by observing an object close to the nominal pointing direction and selected from pre-approved targets in the annual call for proposals (currently, cycle-2 observations just started). Both modes remain interruptible by higher-priority events. When WXT detects transients exceeding on-board thresholds, the satellite immediately enters autonomous follow-up mode, terminating ongoing low-priority observations, slewing to the target coordinates, and initiating tiered FXT exposures lasting from one to sev-

eral orbits. Meanwhile, the transient information, including the source coordinates, time and X-ray fluxes, is sent to EPSC in real-time *via* the Beidou satellite navigation system as well as the VHF system provided by CNES. Target-of-Opportunity (ToO) observations can be requested by EP users by submitting proposals to EPSC, which will be reviewed and, if approved, scheduled and executed. Time-critical ToO observations can be performed within 10 minutes of approval *via* BeiDou. Throughout all modes, WXT maintains persistent monitoring. The complete science and housekeeping datasets are downlinked *via* X-band, received by one of the ground stations at Sanya, Singapore, and Western Australia (the service of the latter stations is two provided by ESA).

EP starts to establish collaborations with other facilities to develop standardized response protocols, which will enable coordinated multi-wave studies aimed at maximizing the scientific yield from transient detections.

To date, EP has issued over 400 alerts through GCN and ATel circulars, which have prompted rapid multi-wavelength follow-up campaigns at by many space and ground-based telescopes, large and small, in-

cluding Swift, XMM-Newton, NICER, NuSTARS, VLT, HST, JWST, ZTF, GMT, SALT, LCOGT, ALMA, VLA, ATCA, MeerKAT, demonstrating the broad interests of the astronomy community in transients discovered by EP.

4 Scientific Highlights

First realization of lobster-eye micro-pore focusing imaging with extremely large Field Of View (FOV, see Figure 2). EP-WXT achieved, for the first time, long-awaited lobster-eye micro-pore focusing imaging observations with a huge field of view of thousands of square degrees.

EP240222a (22 Feb. 2024). An intermediate-mass black hole of several tens of thousands solar masses lurking in the halo of a nearby large galaxy, caught alive *via* tidally disrupting a star [2].

EP240315a (15 Mar. 2024). A high-redshift ($z = 4.859$) GRB exhibiting complex soft X-ray variability preceding and following the γ -ray emission, demonstrating WXT's capability to trace GRB evolution [3].

EP240408a (8 Apr. 2024). Intermediate-timescale transient featuring a 12-second flare ($300\times$ flux increase) with anomalous spectral-temporal properties, suggesting a new transient class [4].

EP240414a (14 Apr. 2024). Extragalactic transient ($z = 0.401$) associated with type-Ic supernova SN

2024 gsa, revealing a weakly relativistic jet from massive stellar collapse—a new category distinct from the known GRB-supernova association [5]. Figure 3 shows the rest-frame peak energy–isotropic energy correlation (Amati relation).

J005245.1-722843 (27 May 2024). A rare binary consisting of a Be star and a white dwarf in the Small Magellanic Cloud caught through outburst, providing the first full thermonuclear flash light curve from a near-Chandrasekhar-mass O-Ne white dwarf accreting from a $12 M_{\odot}$ companion [6].

EP J182730.0-095633/EP240904a (4 Sept. 2024). A new candidate black hole in a binary system in the Milky Way was unveiled *via* capturing a faint outburst [7].

EP241021a (21 Oct. 2024). a new type of X-ray transient with month-duration evolution timescales with possible origin from a tidal disruption event with relativistic jet or unusually long-duration GRB [8].

LXT230307a (7 Mar. 2023). The EP pathfinder LEIA (Lobster Eye Imager for Astronomy) detected the prompt X-ray emission likely originated from a temporary highly magnetized neutron star resulting from merger of two neutron stars, which was accompanied by a long GRB [9]. Figure 4 shows the multi-band light curve and spectral energy distribution obtained from the coordinated observations by LEIA and GECAM.

EP250702a (2 Jul. 2025). X-ray precursor hours be-

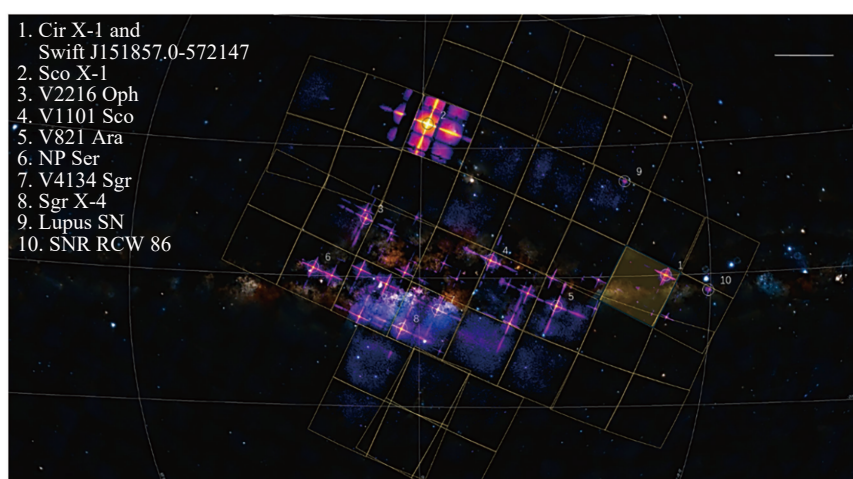


Fig. 2 Observation of WXT pointed to the center of the Milky Way Galaxy with an exposure time of about 4×10^4 s. The X-ray sources are drawn with color purple, which is stacked with Digitized Sky Surveys image provided by the Association of Universities for Research in Astronomy. The squares outline the FOV of WXT, mosaicked by 12 modules composed of 4 CMOS sensors each (Credit: EPSC/NAOC) (DSS image credit: AURA)

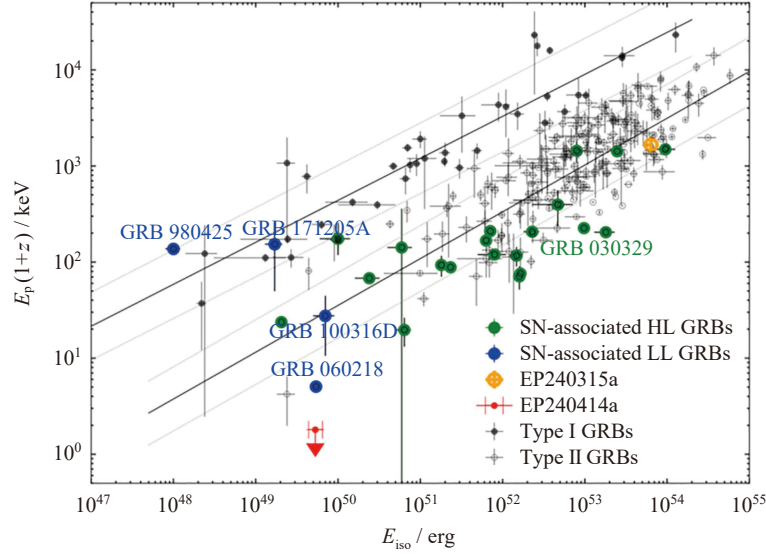


Fig. 3 Rest-frame peak energy and isotropic energy correlation (Amati relation). EP240414a is a significant outlier compared with classical GRBs and some low-luminosity GRBs

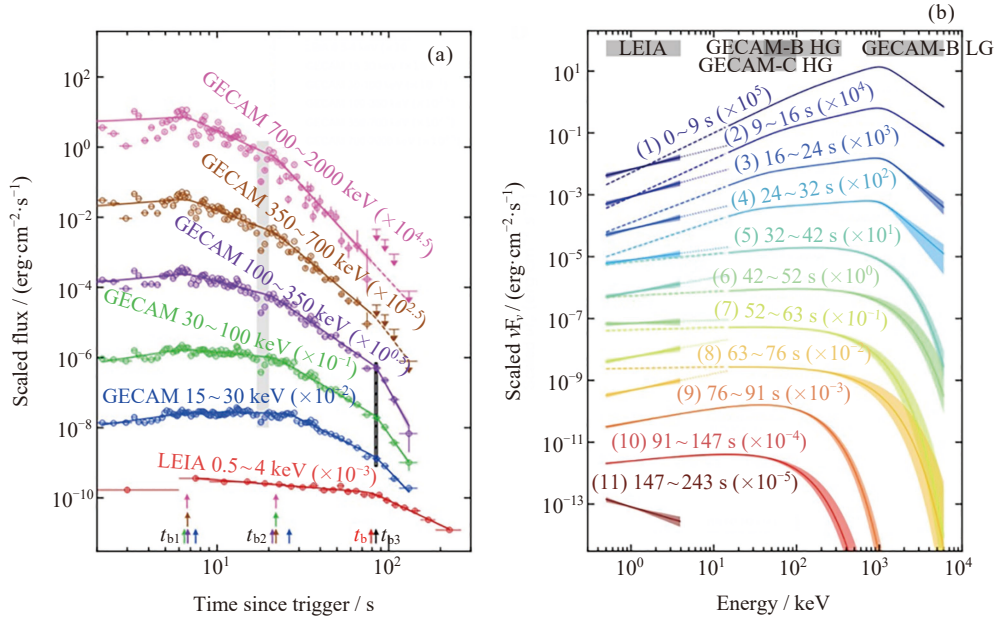


Fig. 4 Multi-band light curve and spectral energy distribution obtained by the coordinated observation by LEIA and GECAM

fore gamma-ray emission, peak luminosity of $3 \times 10^{49} \text{ erg s}^{-1}$, and brightness decline by over five orders of magnitude within 20 days; one of the most plausible interpretations is a white dwarf disrupted by an intermediate-mass black hole ($10^2\text{--}10^5 M_\odot$), a scenario distinct from classical tidal disruption events and gamma-ray bursts^[10]. Figure 5 shows EP250702a's X-ray light curve (with comparisons) and spectral softening^[10].

During the past more than two years of operations

since launch, EP has detected more than 230 X-ray transients with high significance, including ~ 177 fast transients (Figure 6), and over 1800 stellar flares. Some of these transients can only be detected with EP, showcasing its unique ability to detect and characterize fleeting cosmic events. EP is expected to provide valuable insights into the fundamental physics that governs extreme astrophysical environments, ranging from violent stellar deaths to the formative periods of primordial stars

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