The extreme Universe viewed in very-high-energy gamma rays
ICRR, Tokyo, Jan 7, 2025

Einstein Probe and Early Results

Hua Feng @ IHEP, CAS

on behalf of the Einstein Probe consortium

Image credit CAS/ESA

X-ray all-sky monitors

X-ray ASMs

- Coded mask detector
- Pinhole/slit camera
- Large field of view
- Low sensitivity

INTEGRAL (credit: ESA)

Focusing telescopes

- Small field of view
- High sensitivity

Scientific drivers

- Look deeper while look wider

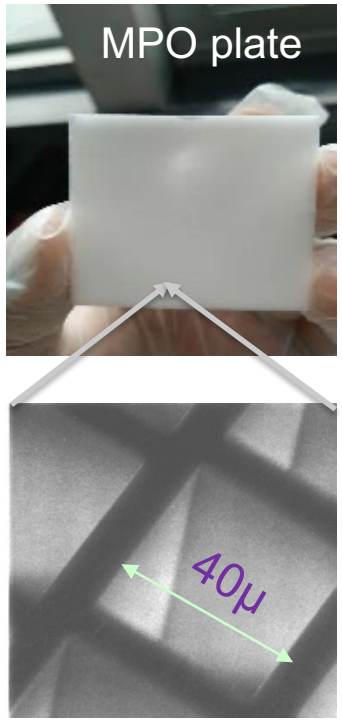
TDE

high-z GRBs

SN shock breakouts

potential X-rays of GW events

Lobster-eye micro-pore optics (MPO)



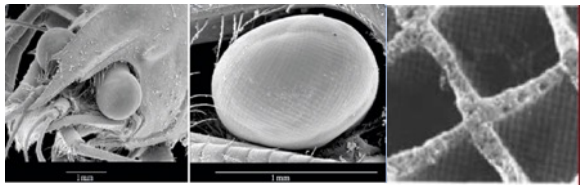
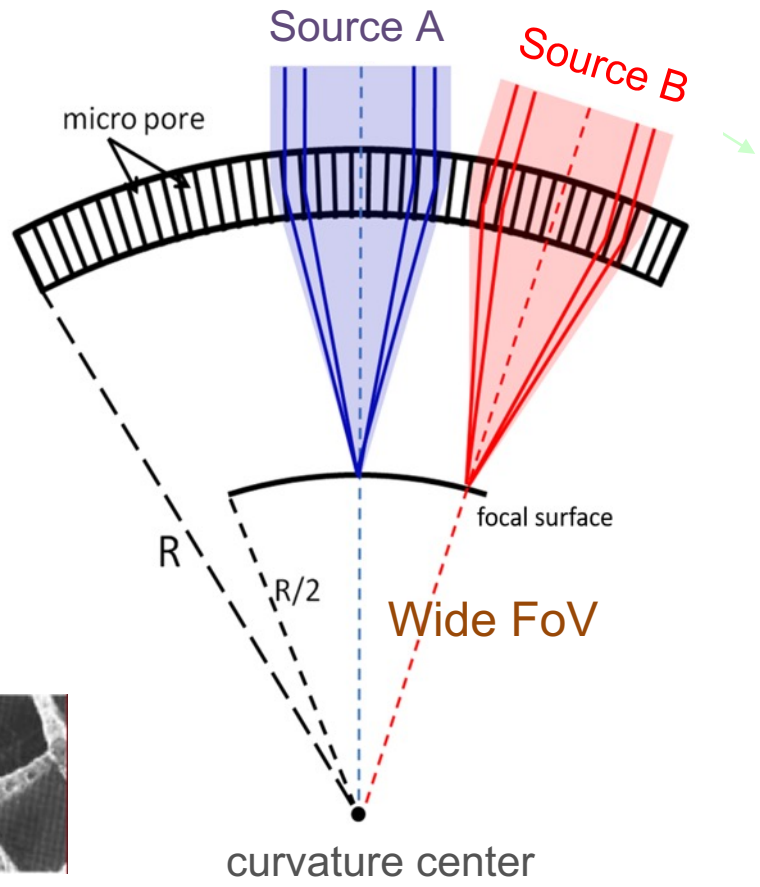
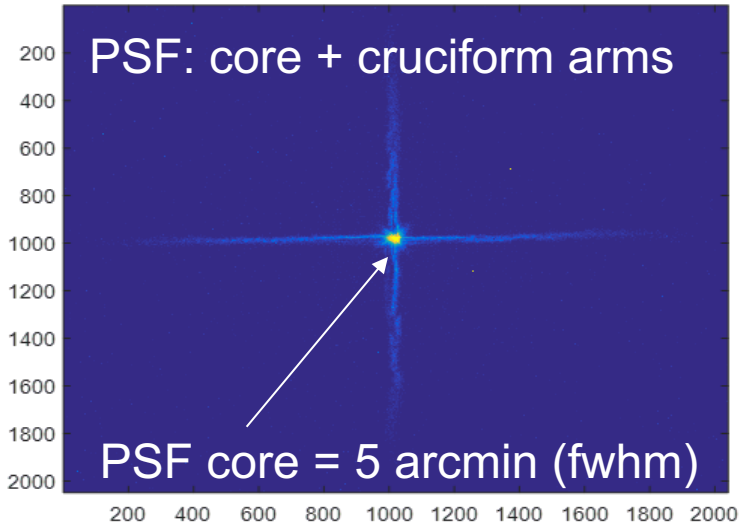


image credit:
http://www.as.utexas.edu/lectures/great_lecture_twenty.html

grazing incidence reflection



- Wide FoV (no vignetting theoretically)
- Angular resolution (several arcmin)
- Soft X-ray passband



- First proposed by R. Angel (1979 ApJ)

Einstein Probe (EP) mission

Goals space X-ray observatory for time-domain astronomy

- Discover soft X-ray transients & monitor source variability at an unprecedented sensitivity
- Characterize transients/variables by quick X-ray follow-up onboard
- Disseminate transient alerts to community in time, quick response ToO

Milestones

- 2010- Lobster-eye R&D @ XIL/NAO
- 2012 Mission concept (PI: Weimin Yuan)
- 2017/12 Adoption
- 2018 Joined by ESA & MPE; 2022 CNES
- 2022/07 Pathfinder *LEIA* launched
- 2024 Jan. 9 launch
- 2024/01-07 commissioning & calibration
- 2024/07- nominal mission (lifetime: 3 yr, goal 5 yr)

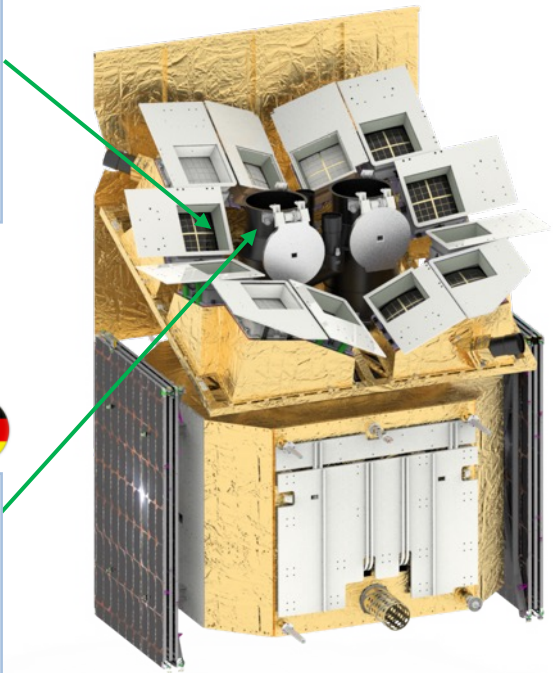
Instruments & spacecraft

Wide-field X-ray Telescope
WXT (12 modules)

Lobster-eye MPO + CMOS
FoV: ~3,600 sq deg (1.1 sr)
Band: 0.5 – 4 keV
Resolution: ~ 5’ (FWHM)
Sensitivity: ~1mCrab @1ks

Follow-up X-ray Telescope
FXT (2 units)

Wolter-1 + pn-CCD (eROSITA)
FoV: ~1 deg
Band: 0.3 -10 keV
Resolution: 24” (HPD, on-axis)
Effe. area: ~300 cm^2 @1keV (x 2 units)



Spacecraft

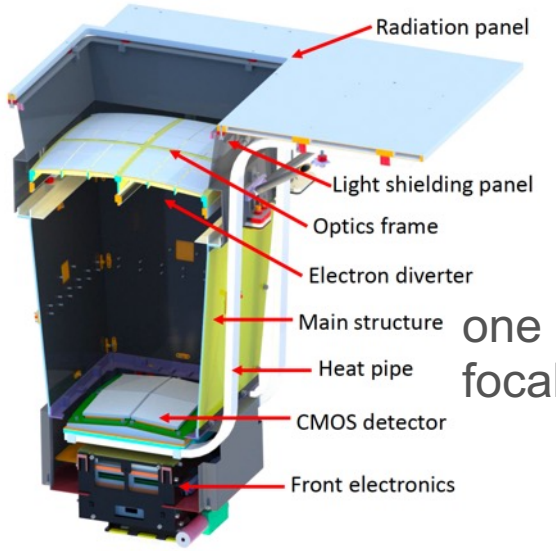
On-board data processing
Quick slew & autonomous follow-up

Telemetry

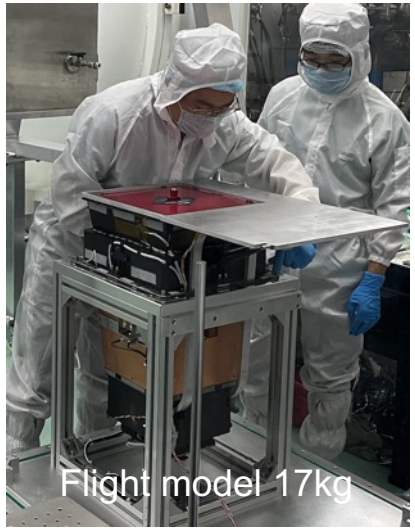
X/S-band (several hours)
BD (down/up-link; minutes)
VHF (down-link; minutes)

Yuan, et al. 2022 *Handbook of X-ray and Gamma-ray Astrophysics*

Wide-field X-ray Telescope

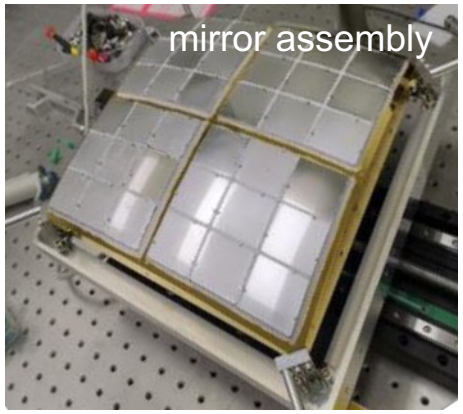


one module
focal length 375 mm



Lead of LE mirrors
Chen Zhang (NAO/CAS)

WXT chief designer
Xiaojin Sun (SITP/CAS)



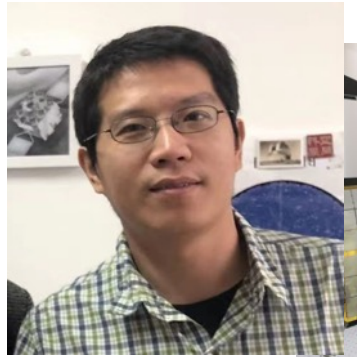
MPO plates (developed by NNVT jointly with NAO/CAS)

41mm x 41mm each

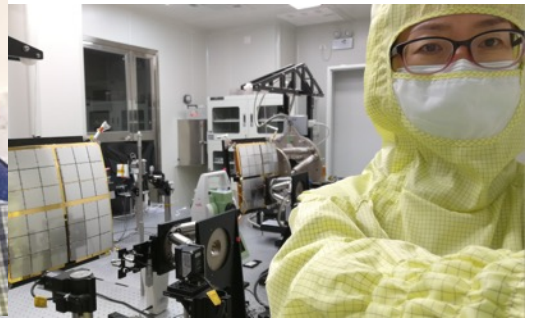
BI CMOS sensors 61mm*61mm

Time resolution 50ms

ΔE ~ 122eV @1.25keV

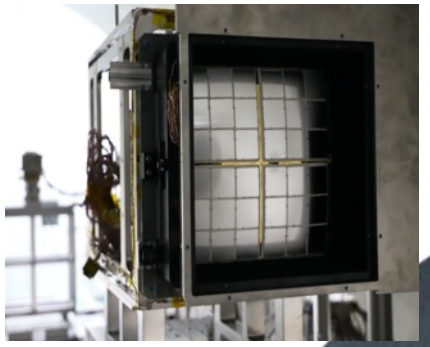


Instrument scientist &
lead of CMOS
Zhxing Ling (NAO/CAS)



MA engineer
Yanfeng Dai (NAO)

EP-WXT pathfinder LEIA (Lobster Eye Imager for Astronomy)

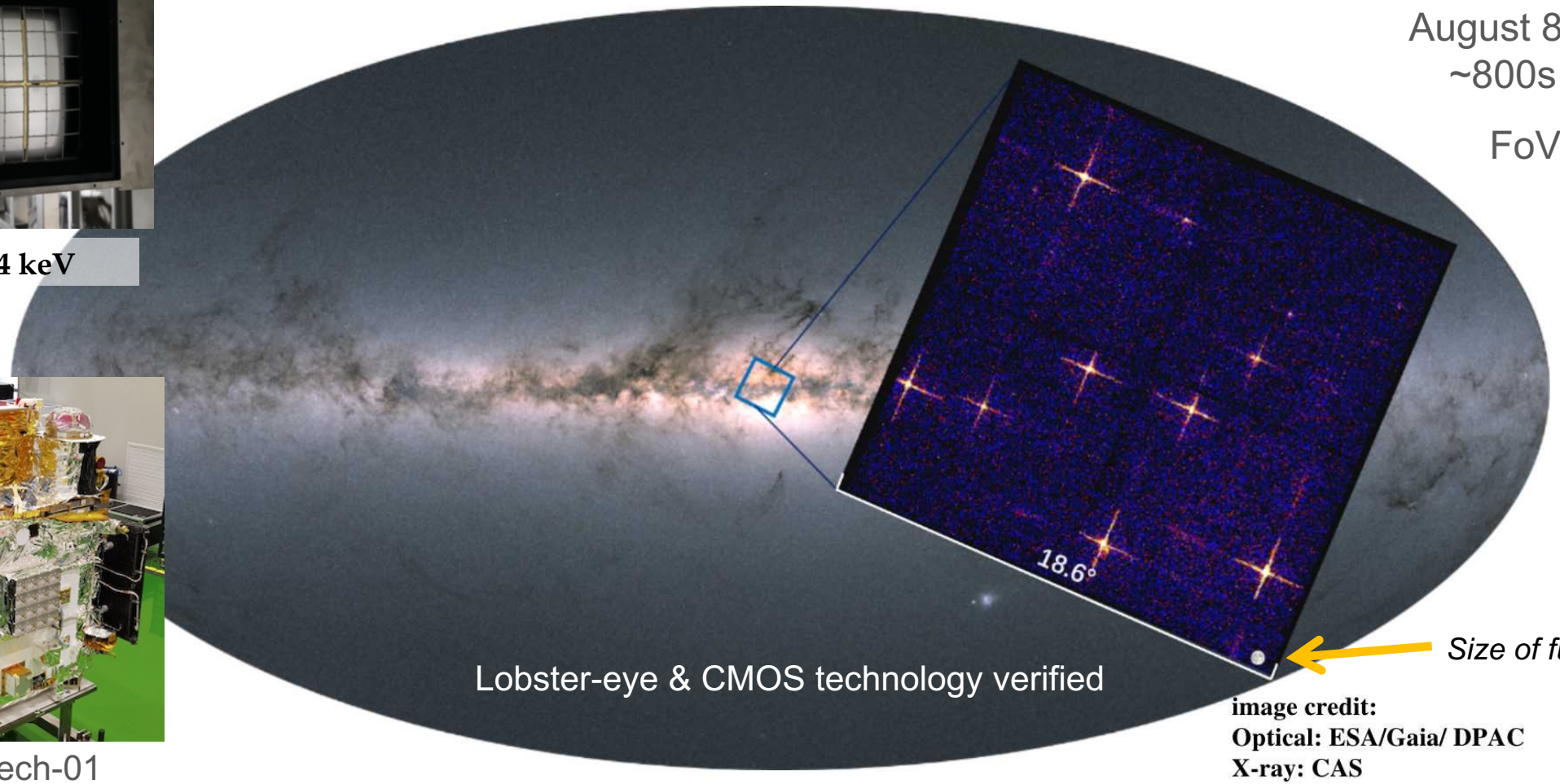


LEIA 0.5 – 4 keV

CAS's SATech-01 experiment satellite
Launched 2022-07-27
credit: MicroSAT

Instrument test observations
August 8-10, 2022
~800s exposure

FoV 340 deg^2

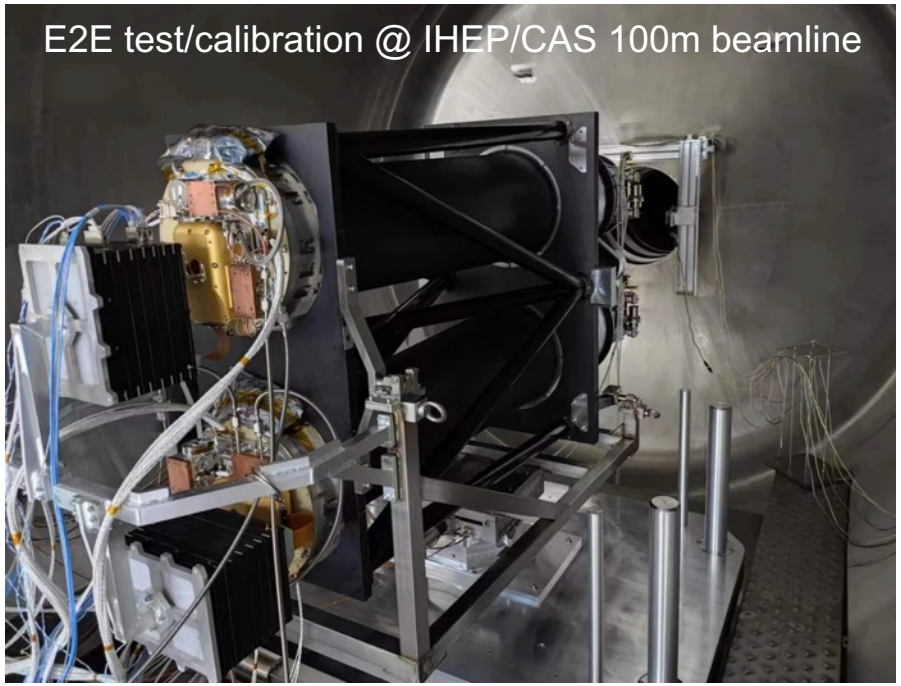


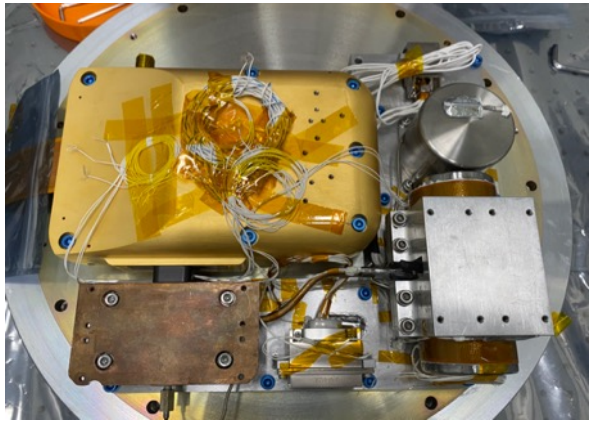
Frist wide FoV X-ray observations by a lobster-eye focusing X-ray telescope in orbit
Zhang et al. 2022 ApJL, 941, L2

Follow-up X-ray Telescope (FXT)

IHEP/CAS + ESA + MPE

- 2 Wolter-I mirror assemblies
  - ★ 1 by ESA (Media-Lario, eROSITA design)
  - ★ 1 by MPE (eROSITA FS)
- X-ray cameras (IHEP)
  - ★ PN-CCD detector modules by MPE based on eROSITA tech.

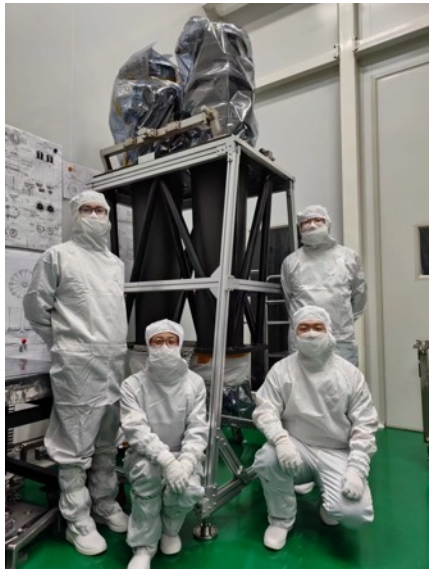




X-ray camera built @ IHEP/CAS

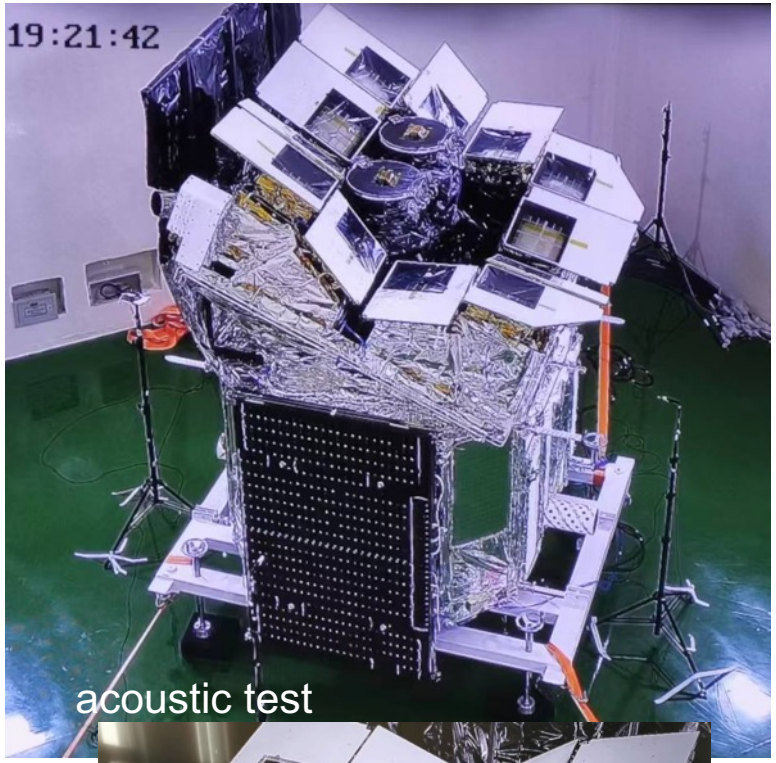
PI: Yong Chen (IHEP/CAS)

Camera lead: Weiwei Cui (IHEP/CAS)



FXT Delivered by IHEP team to MicroSAT on May 26, 2023

EP satellite



acoustic test


thermal vacuum tests

S/C developed @ MicroSat/CAS, Integration & tests

Satellite weight	1430 kg
Power	1150 W
Dimension	3.418(H) × 2.591(D) × 10.309(W) meters


thermal vacuum tests


just before launch

Launch of EP Jan. 9, 2024

height 592 km
orbital period 96min
inclination angle 29 deg.

LM-2C @Xichang

S/C-launcher separation

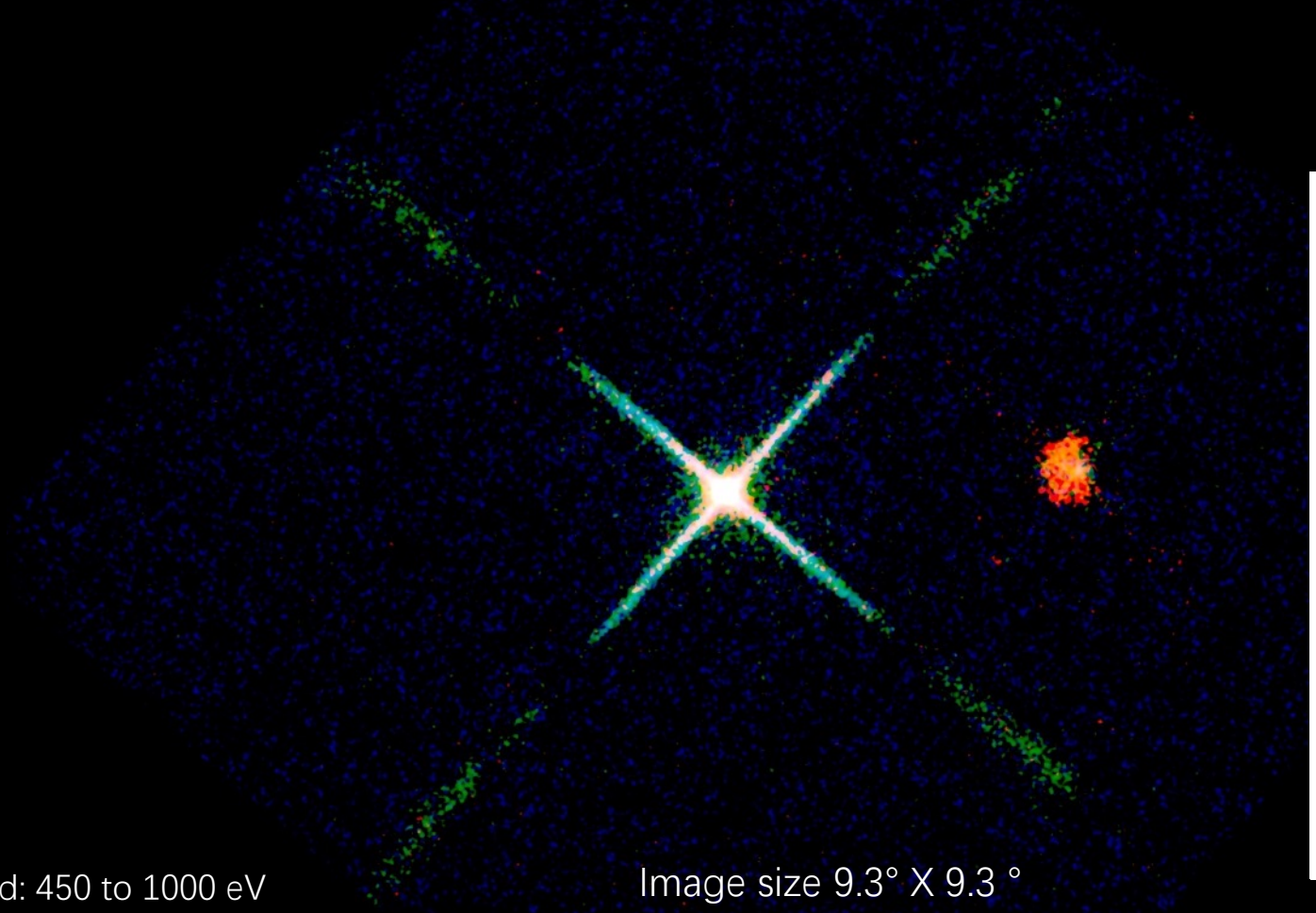
height 592 km

orbital period 96min

inclination angle 29 deg.

X-ray First light 2024 Feb. 19

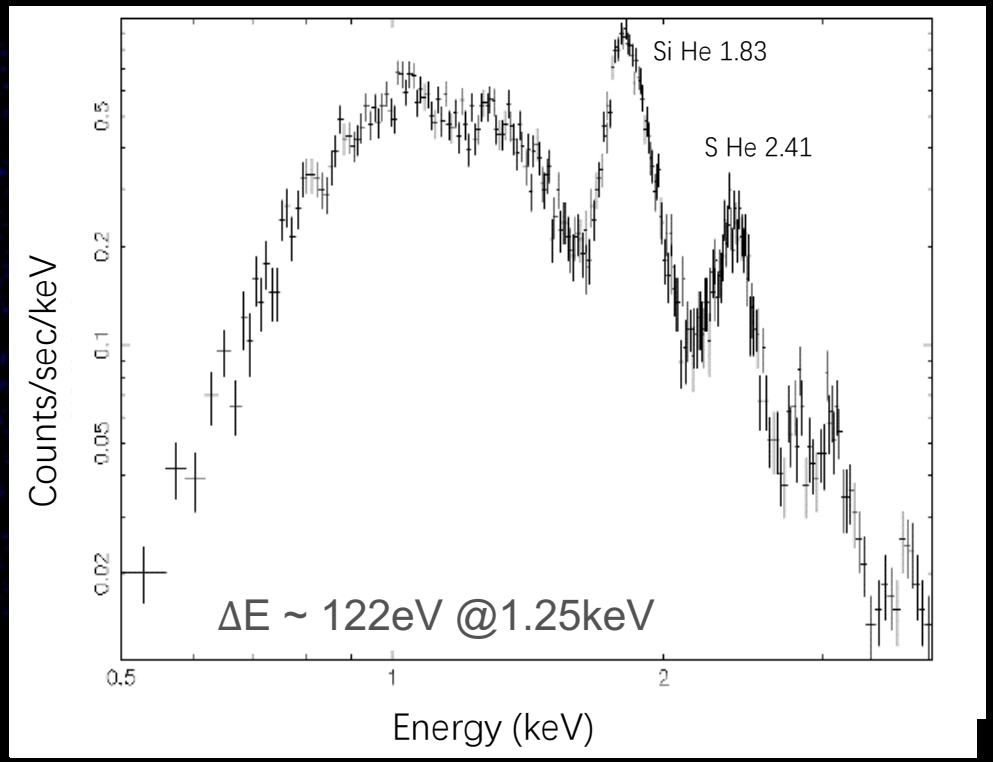
Cassiopeia A supernova remnant



Red: 450 to 1000 eV
Green: 1000 to 2000 eV
Blue: 2000 to 5000 eV

Image size 9.3° X 9.3 °
exposure 22 kilo-seconds

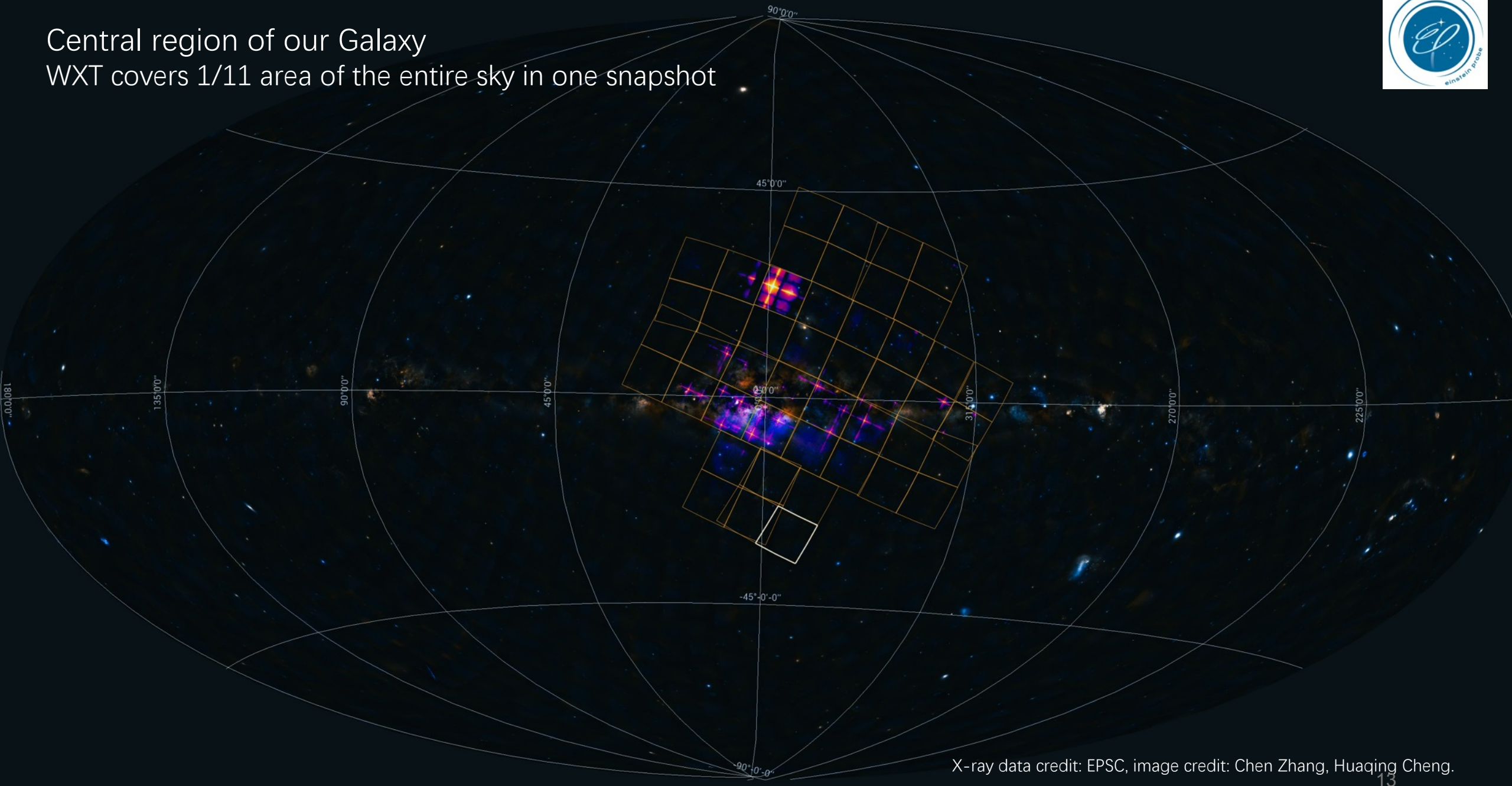
X-ray spectrum obtained at the same time



X-ray data credit: EPSC, image credit: Chen Zhang, Huaqing Cheng.

Central region of our Galaxy

WXT covers 1/11 area of the entire sky in one snapshot

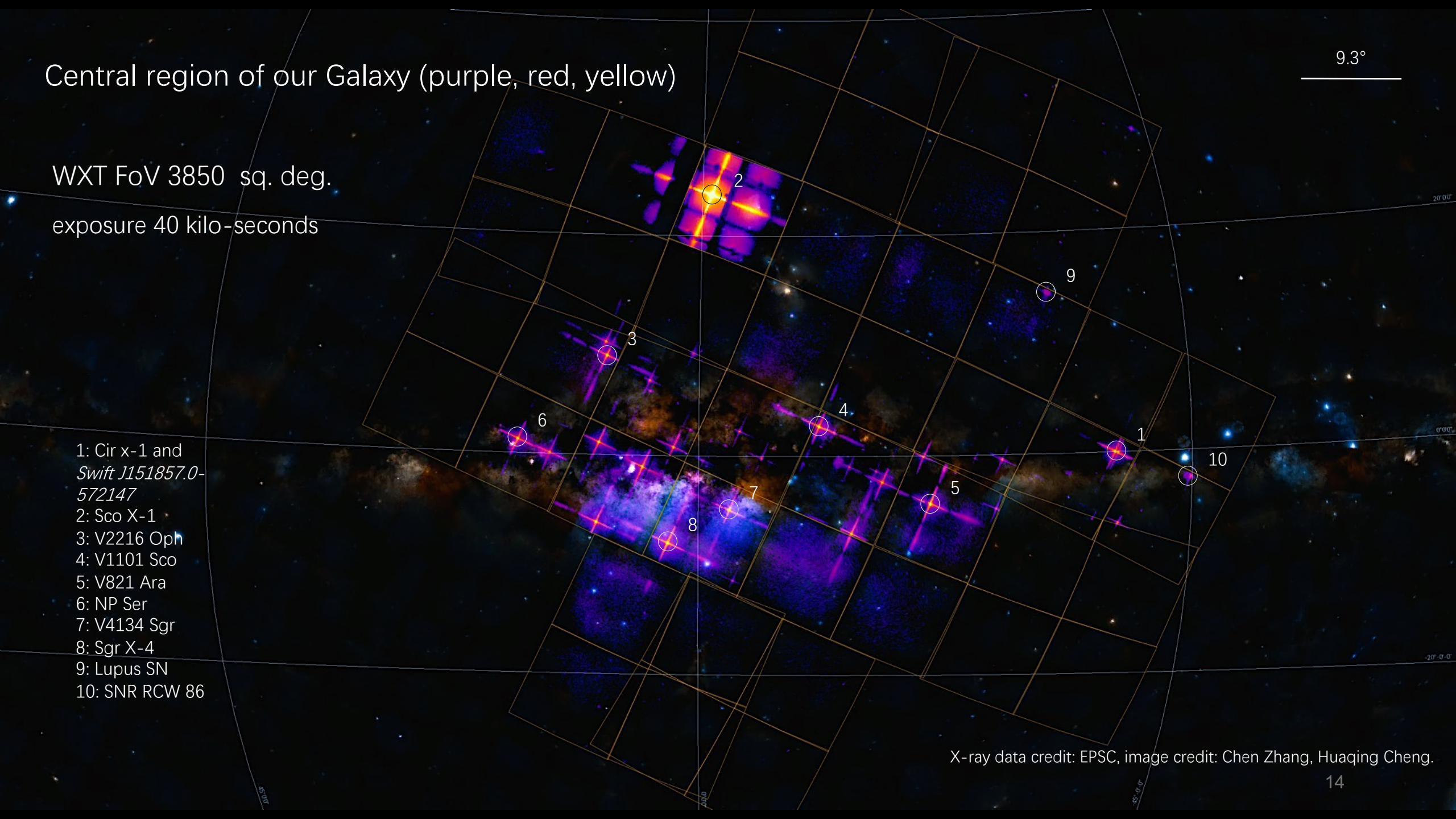


X-ray data credit: EPSC, image credit: Chen Zhang, Huaqing Cheng.

Central region of our Galaxy (purple, red, yellow)

WXT FoV 3850 sq. deg.

exposure 40 kilo-seconds



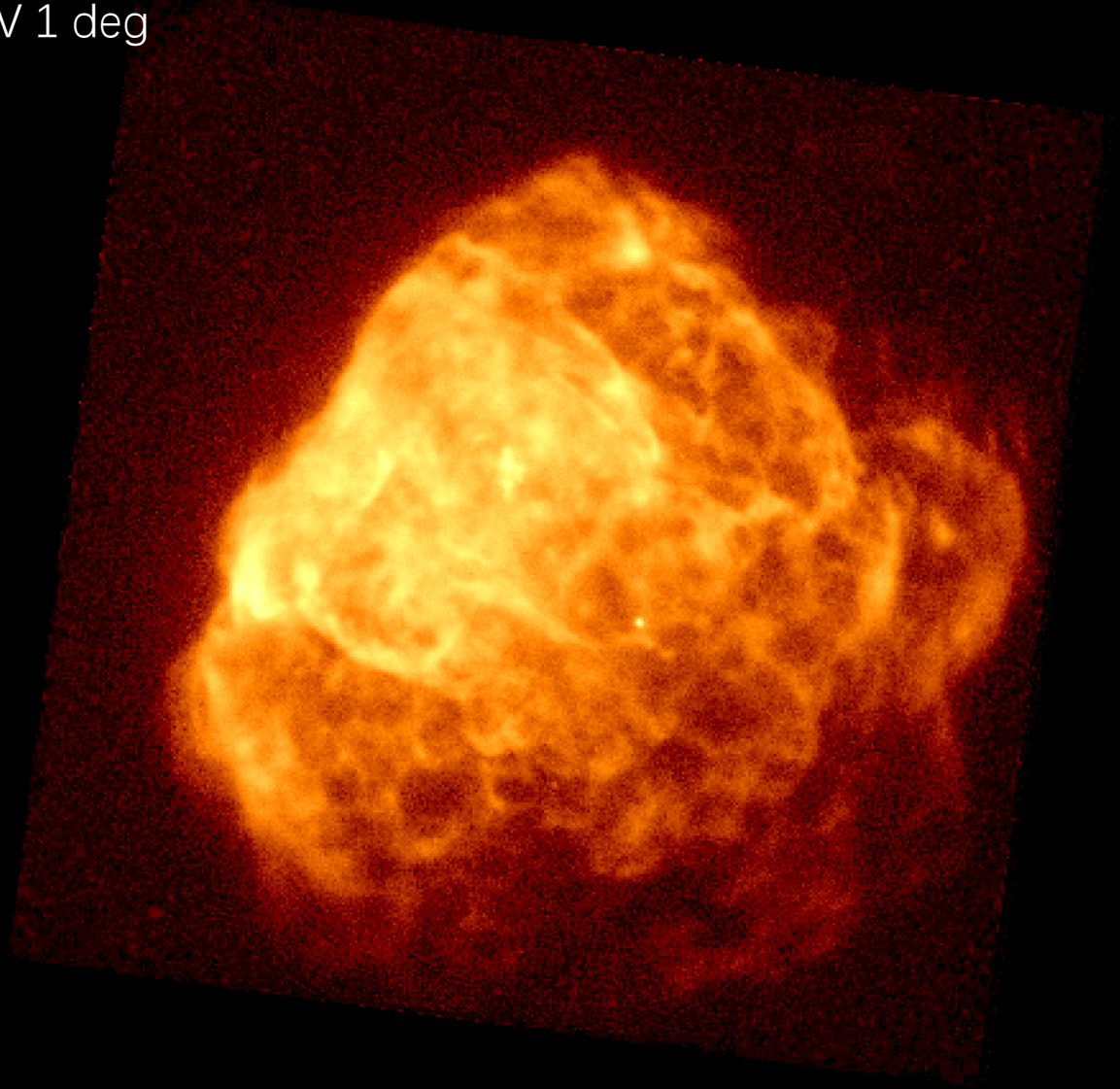
1: Cir x-1 and *Swift J151857.0-572147*
2: Sco X-1
3: V2216 Oph
4: V1101 Sco
5: V821 Ara
6: NP Ser
7: V4134 Sgr
8: Sgr X-4
9: Lupus SN
10: SNR RCW 86

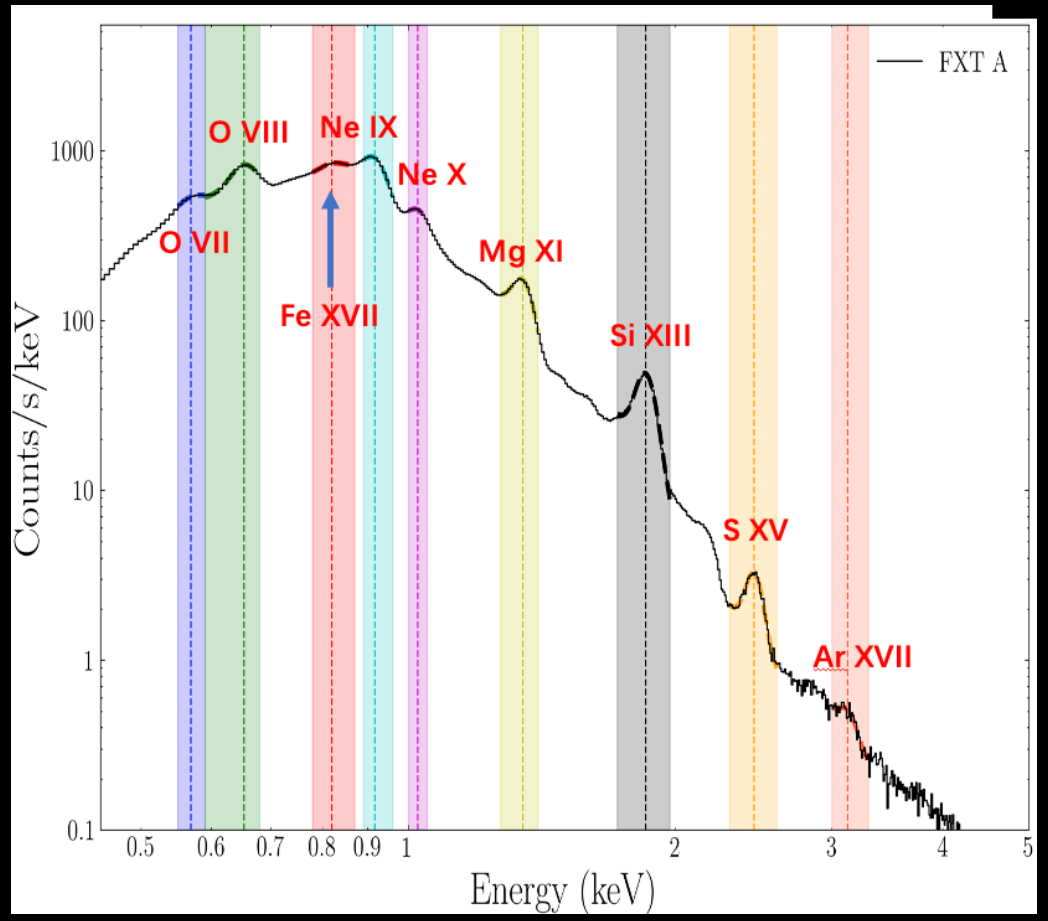
X-ray data credit: EPSC, image credit: Chen Zhang, Huaqing Cheng.

FXT X-ray First light (0.3-10 keV)

Puppis A supernova remnant

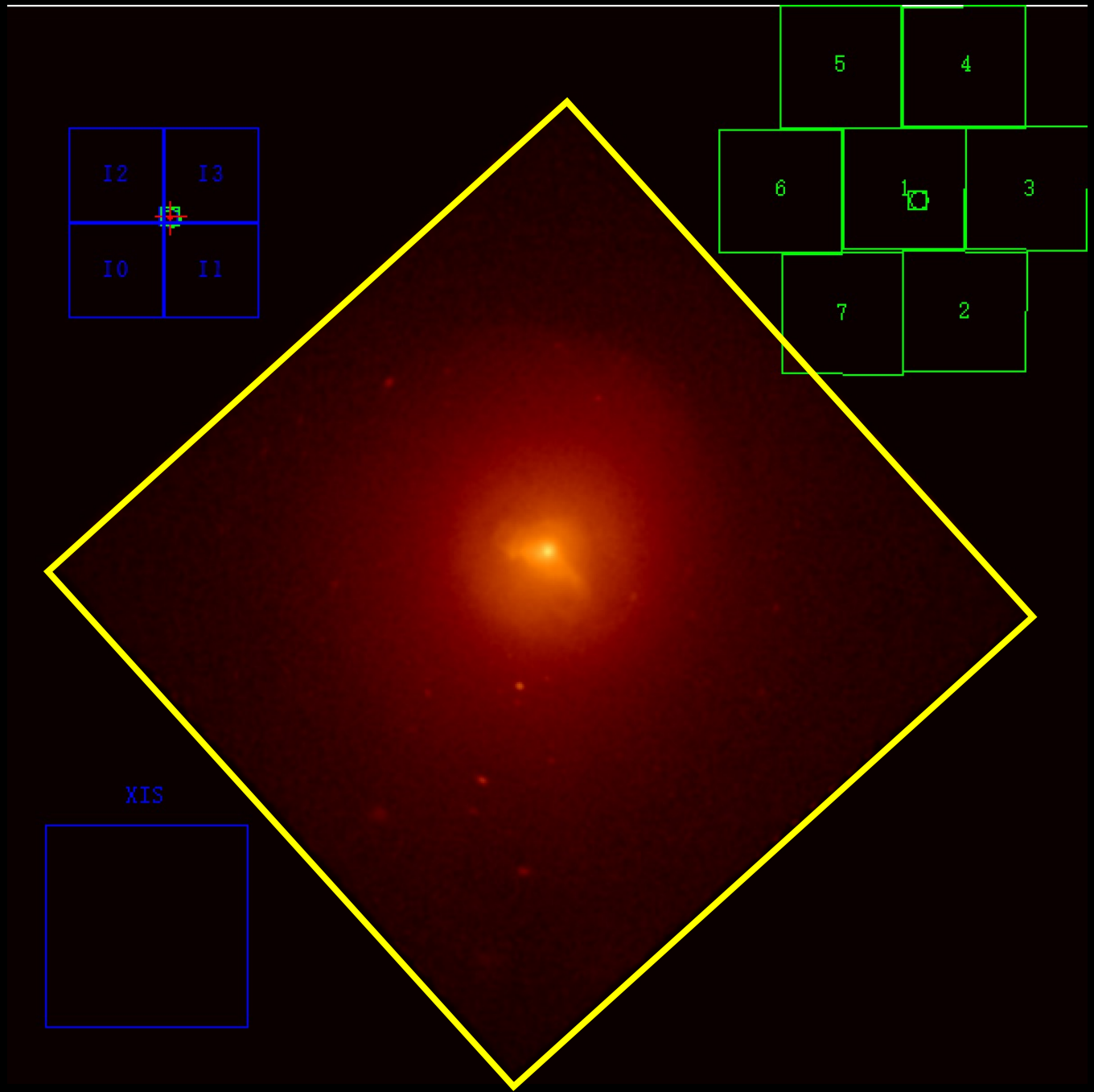
FoV 1 deg





M87

Chandra
ACIS-I
FoV



XMM-Newton
MOS FoV

Suzaku
XIS FoV

Observation modes

Circular orbit

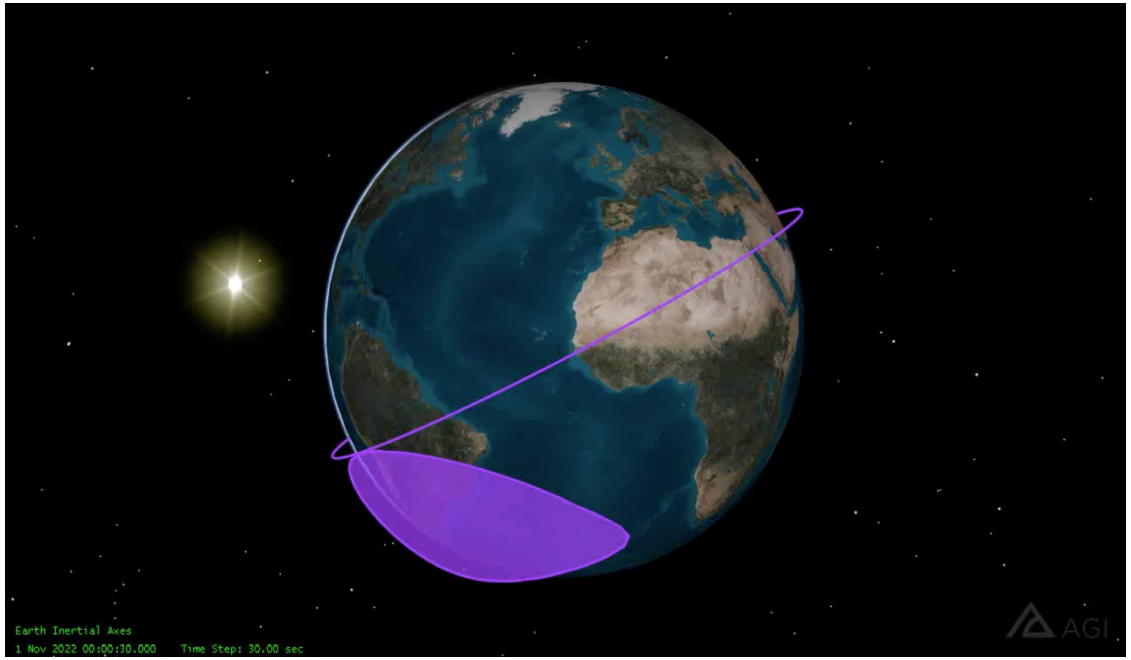
- Height 592 km, period 96 min
- inclination angle 29 deg.

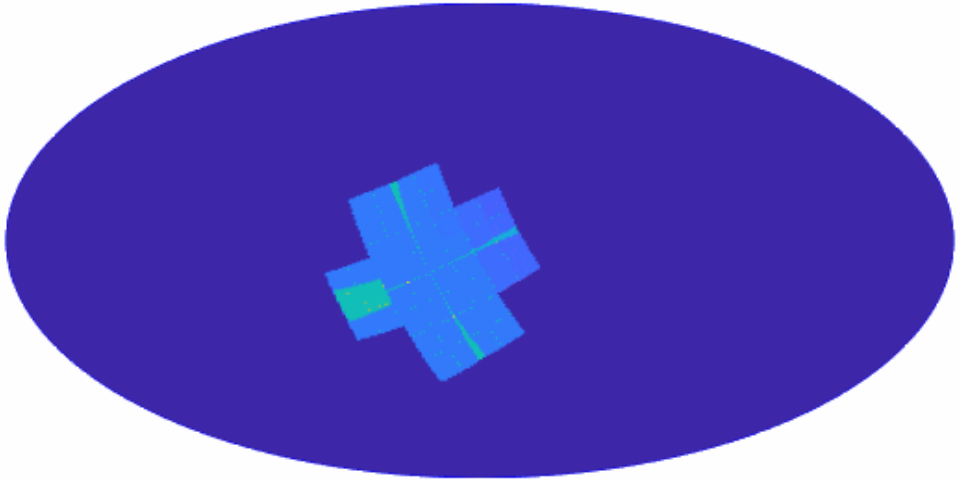
Observation modes

- Survey (primary WXT)
- Autonomous follow-up (FXT)
- ToO (FXT, WXT) – quick response

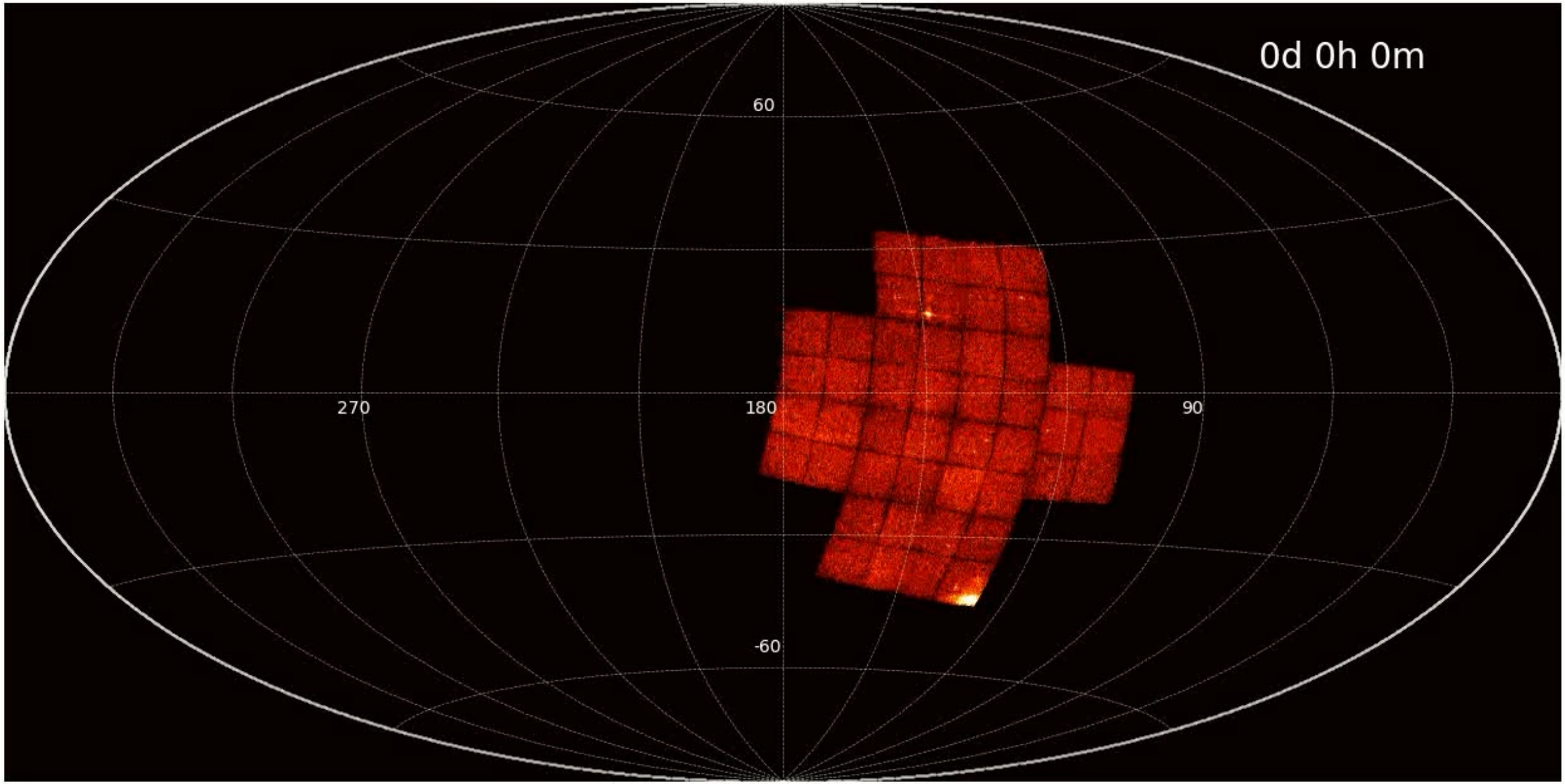
WXT survey mode

- Pointing to night sky
- 3 pointings/orbit, ~20min each
- ~ 1/2 sky covered in 3 orbits (~ 5 hr)
- Whole sky coverage in ½ year
- FXT pointed to pre-selected targets

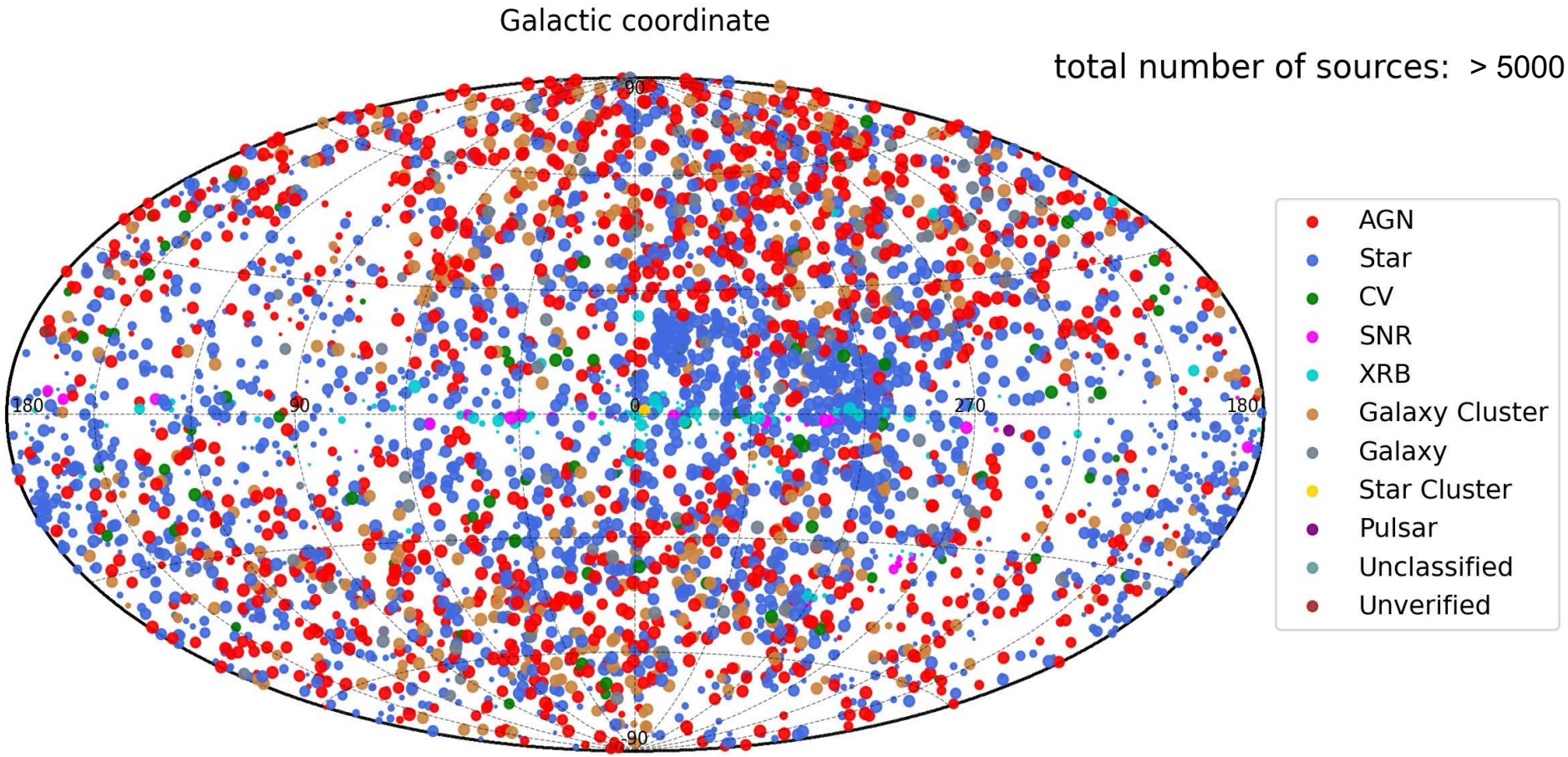




WXT one-day data taking

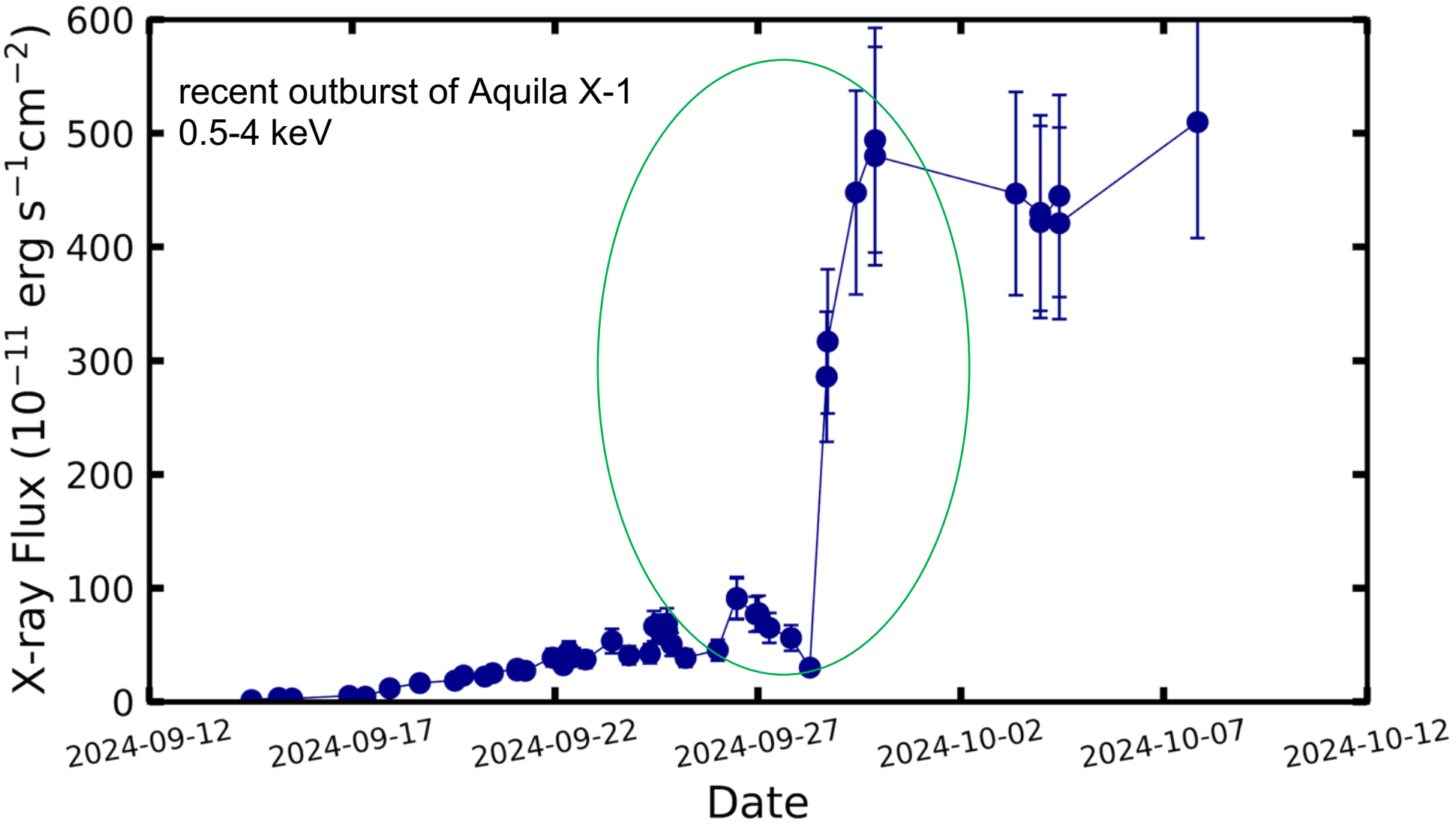


Statistics on X-ray sources detected with EP

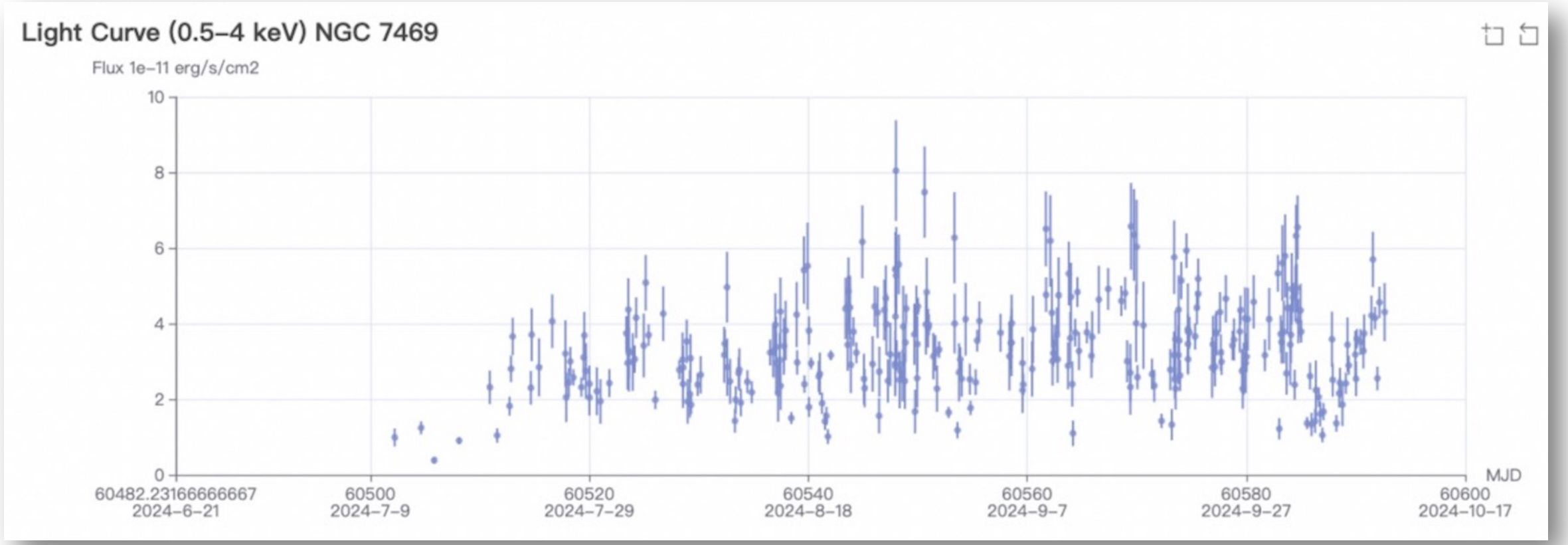


- Transients： ~80 high S/N (many low S/N)
- Stellar flares： ~500
- FXT sources: ~30 k (~20 k new)

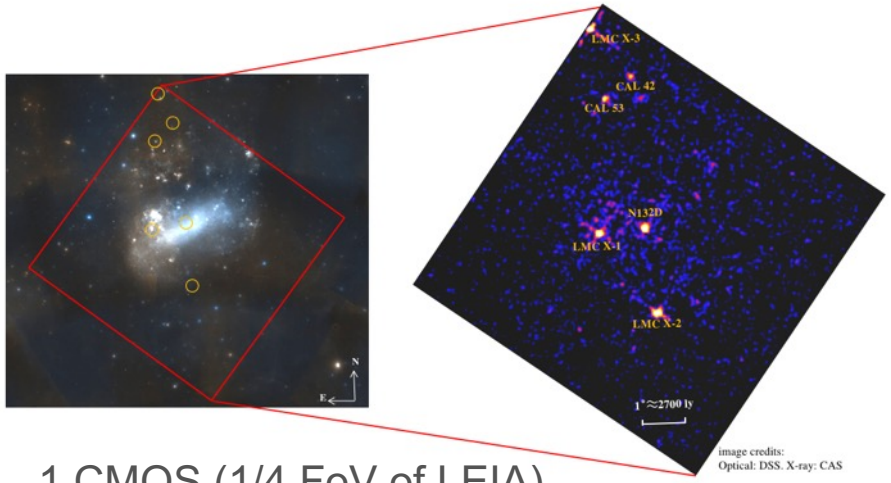
EP-WXT monitoring X-ray sources: NS XRB Aql X-1



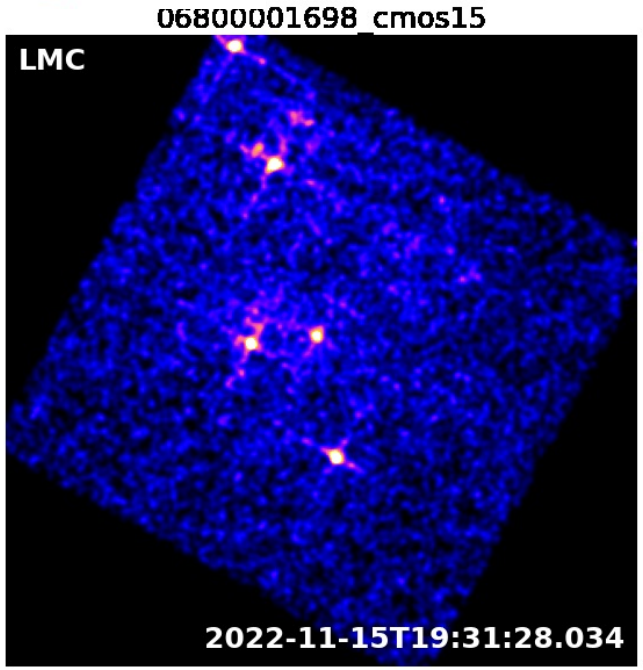
EP-WXT monitoring X-ray sources: Seyfert 1 AGN

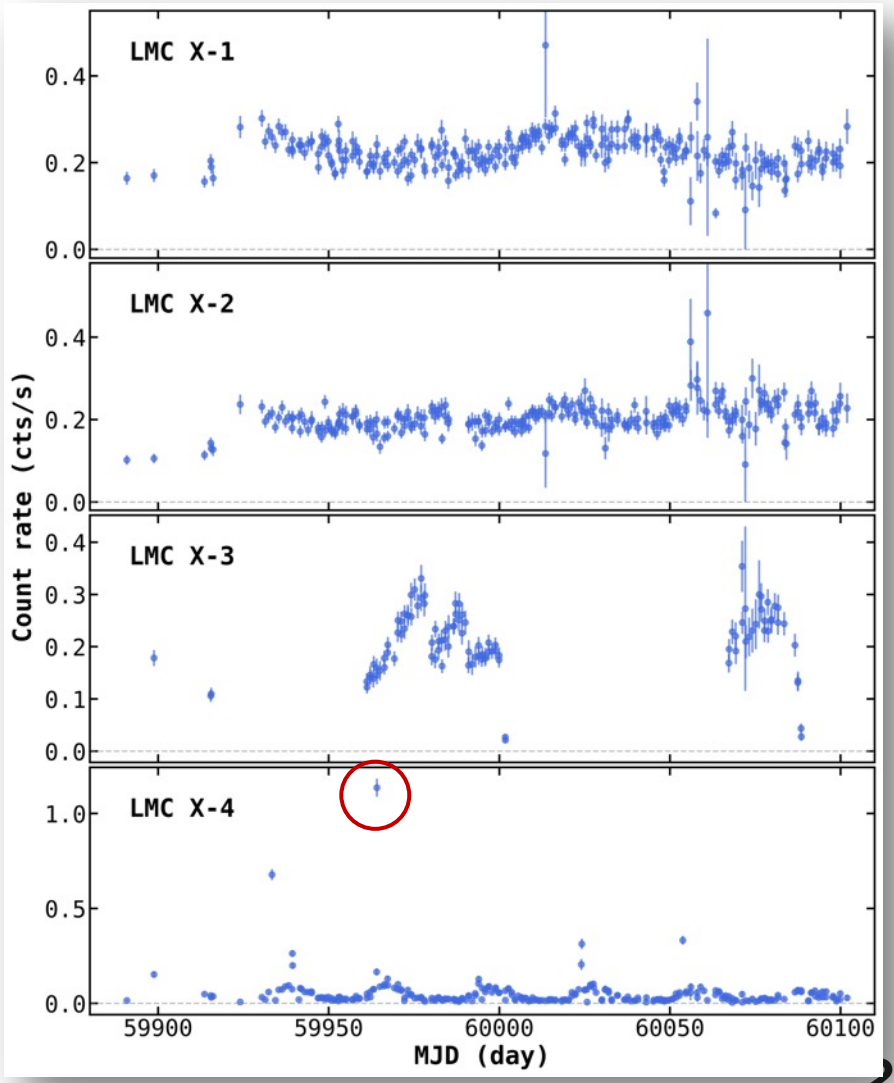


LEIA Monitoring of Large Magellanic Cloud

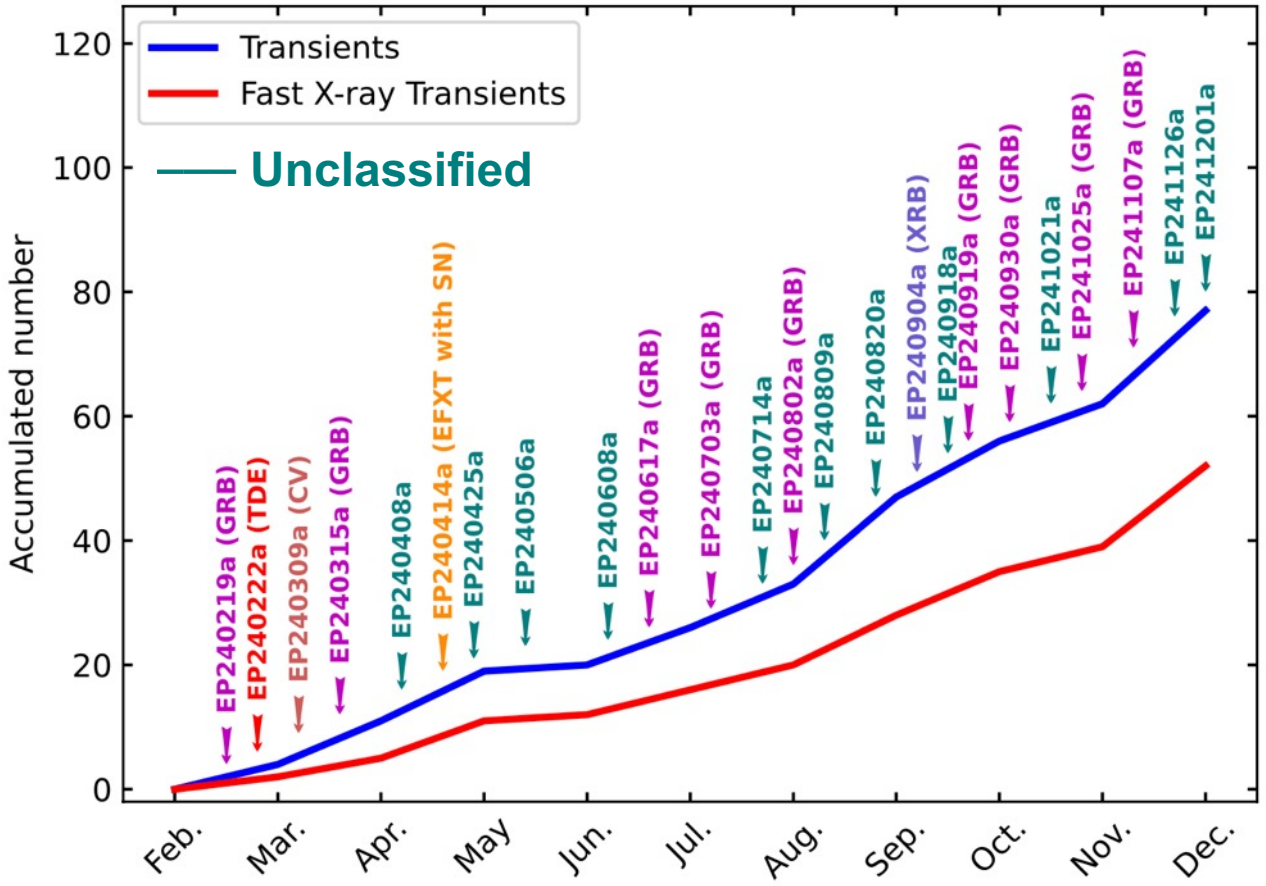


1 CMOS (1/4 FoV of LEIA)

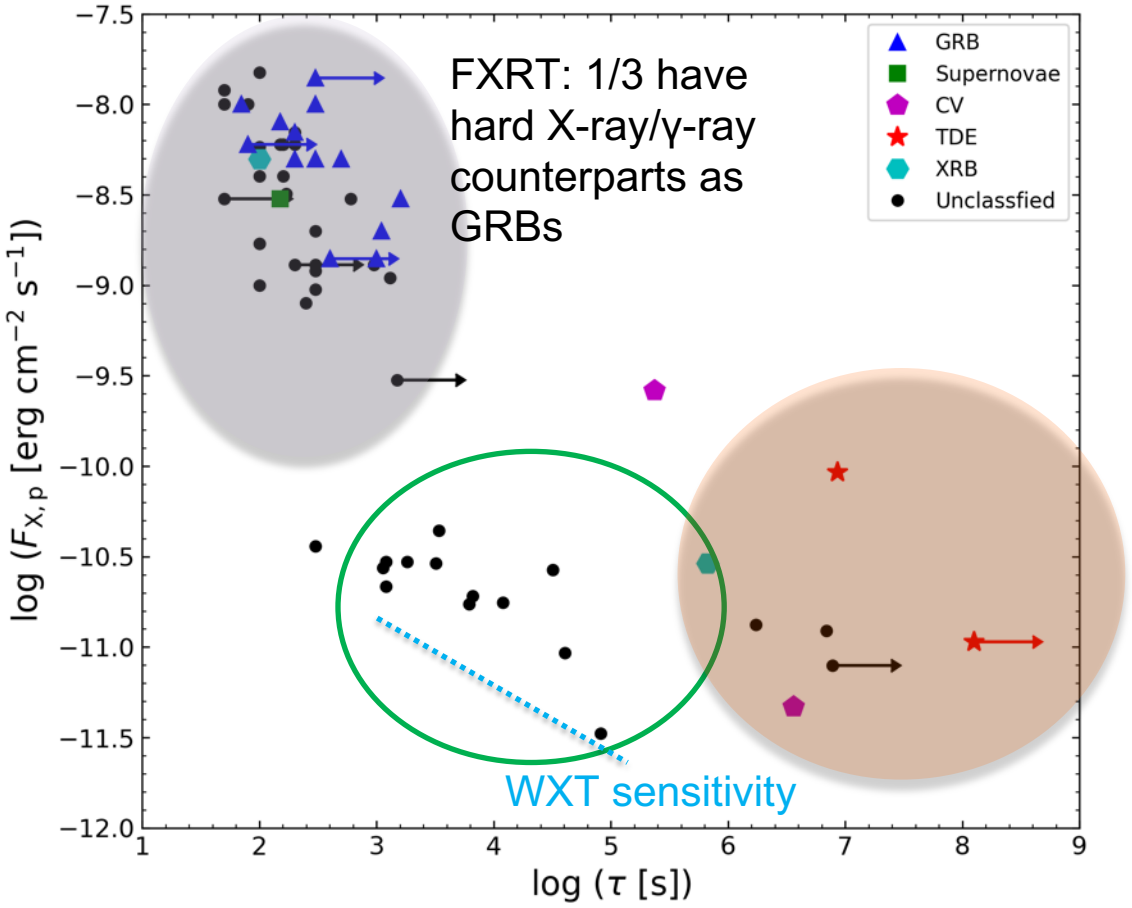




Statistics on X-ray sources detected with EP

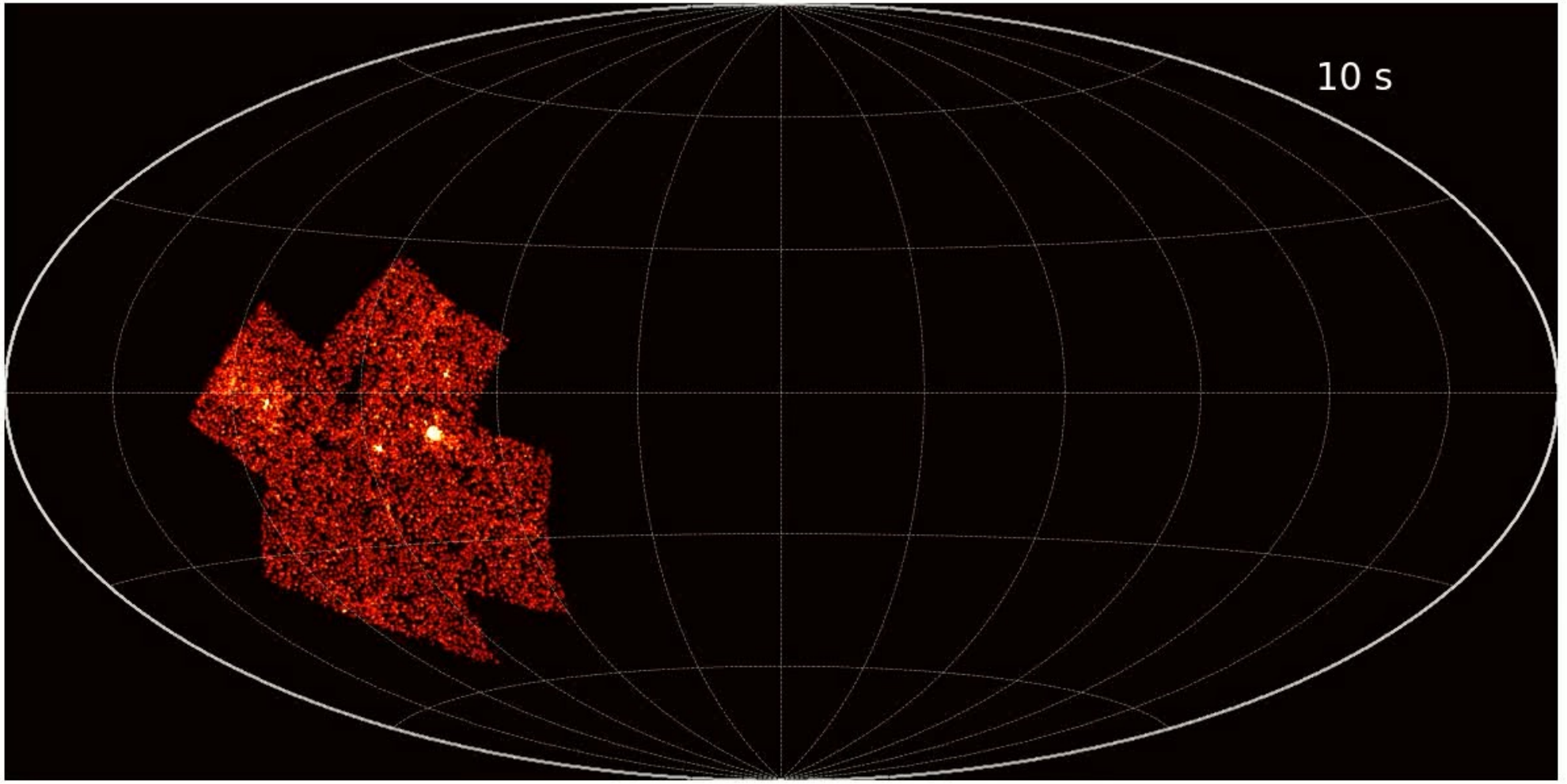


peak flux vs. timescales for EP-WXT transients



Onboard FXT automated follow-up

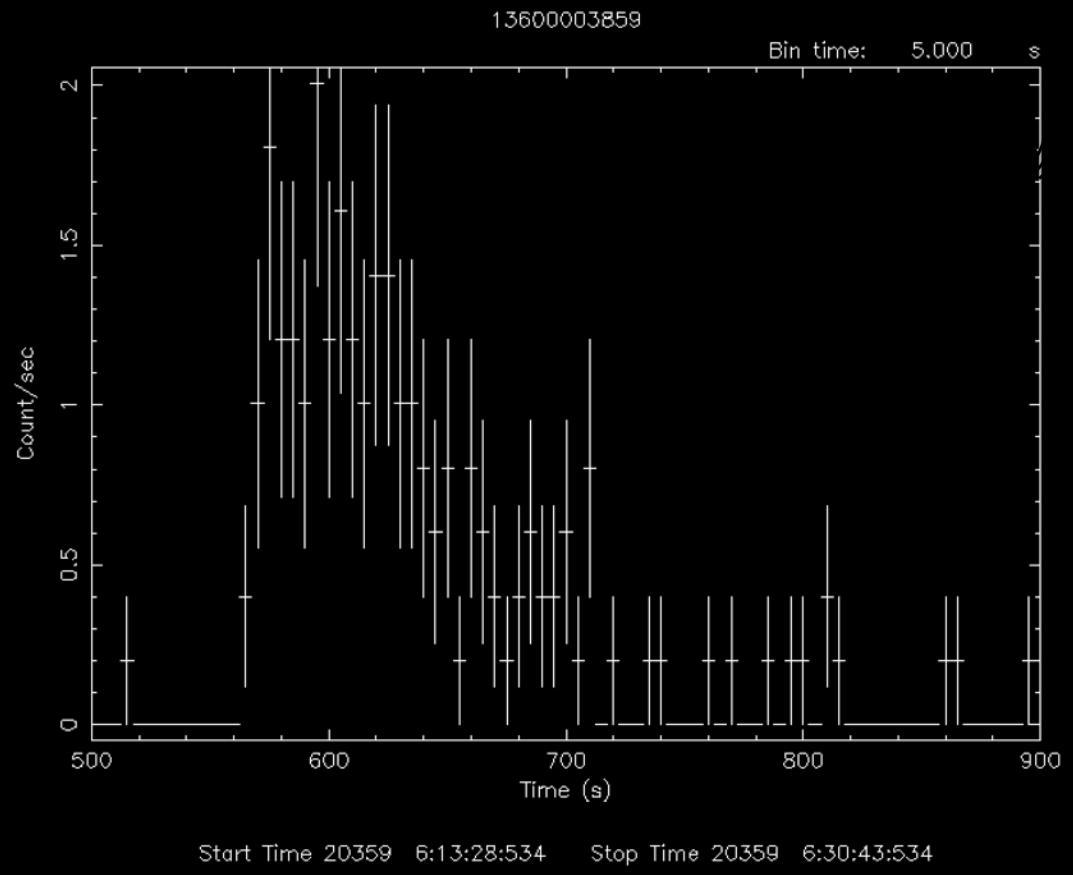
- onboard triggers：~70 (total 75 hr obs.)
- ToO obs：~500 (total 778 hr obs.)



EP240219a

The first X-ray transient discovered by WXT on Feb 19, 2024, alert released on Astronomer's Telegram

- Duration < 200s
- Subthreshold GRB signal found in Fermi/GBM data (Zhang ATel #16473)
- Atel sent from EPSC: 1st EP alert!
- No optical counterpart found (starting T0+3days)
- An X-ray rich GRB



9.3° by 9.3 °, 1 time-frame = 33.3 sec

Yin et al. 2022 ApJL
https://arxiv.org/abs/2409.12613

Examples of early science results

Gamma-ray bursts (GRBs)

Supernova (SN) explosions

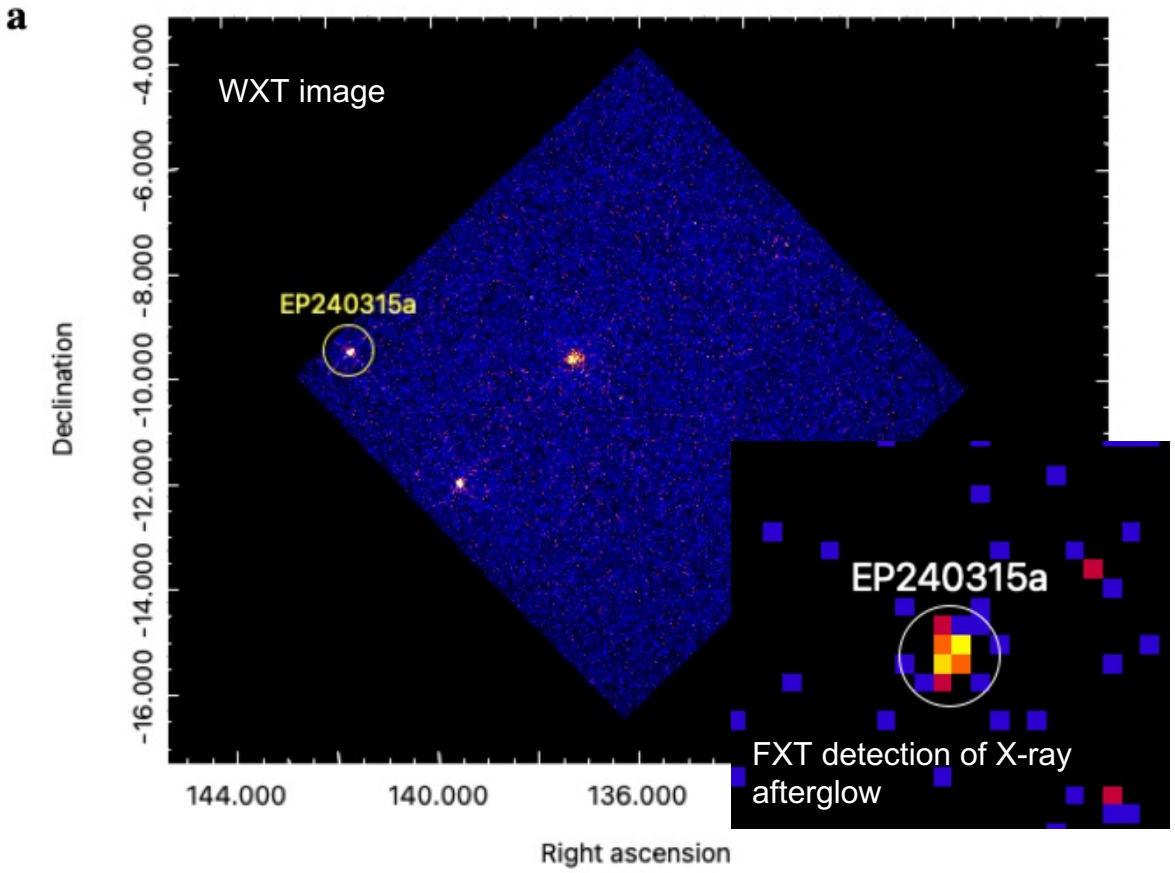
Tidal disruption events (TDEs)

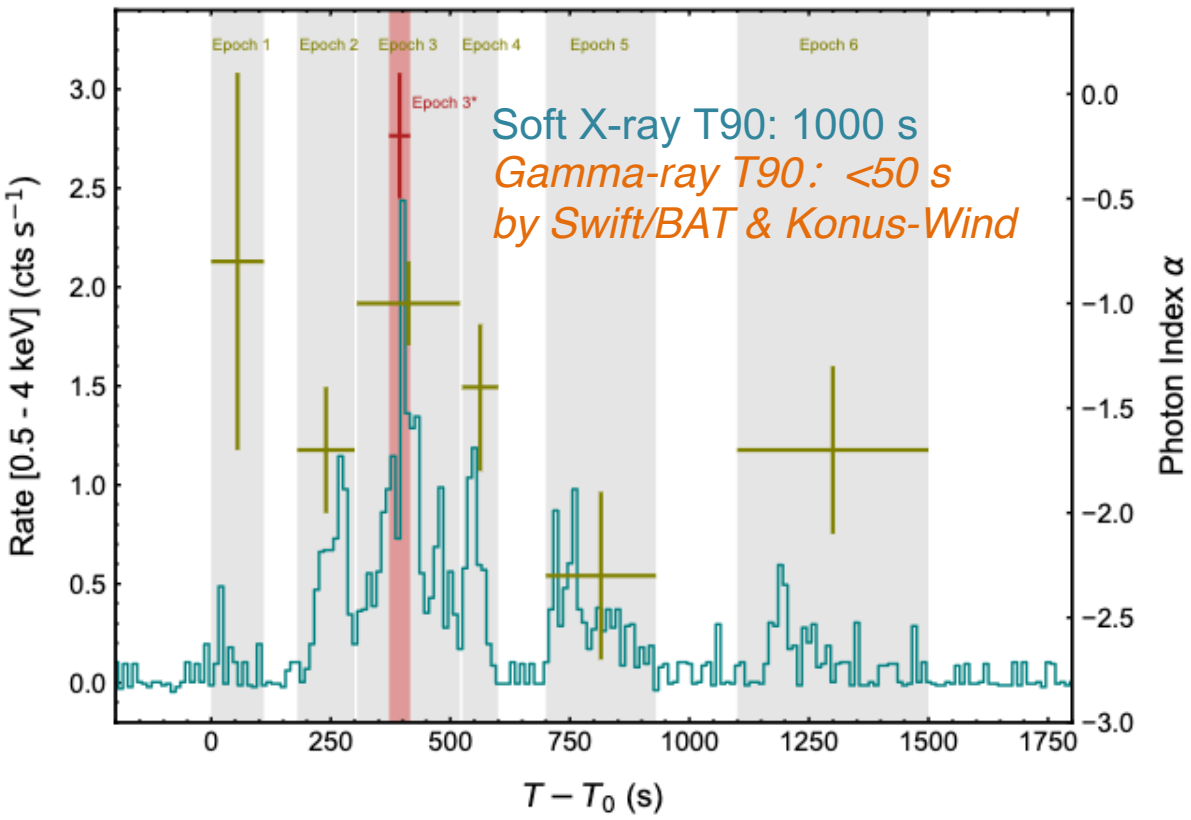
X-ray binaries (XRBs)

Stellar flares

FXT observations of LHAASO sources

EP240315a: GRB @redshift 4.859



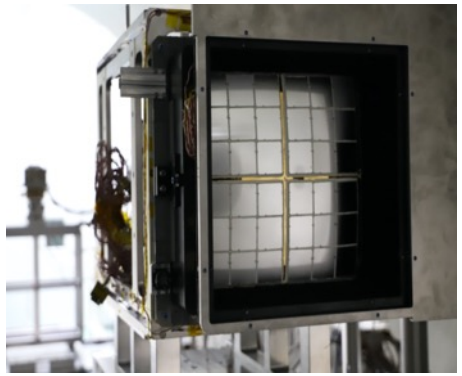


Marked difference in LC of soft X-ray and hard X/γ rays

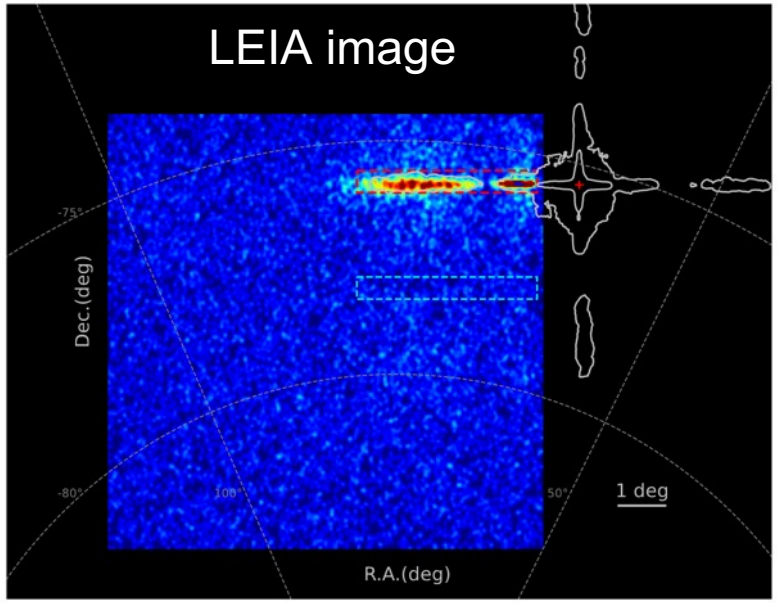
Gillanders J.H., et al. arXiv:2404.10660 (ATLAS optical/radio counterpart, z)
Levan A., et al. arXiv.2404.16350 (Stargate optical pho. and spec., z)
Liu Y., et al. to appear in NA (arXiv:2404.16425)
Ricci R., et al. to appear in ApJL (radio observation)

redshift 4.859 measured by VLT (Levan et al. 2024)

LXT 230307A + GECAM: powered by NS merger



EP pathfinder LEIA 0.5 – 4 keV

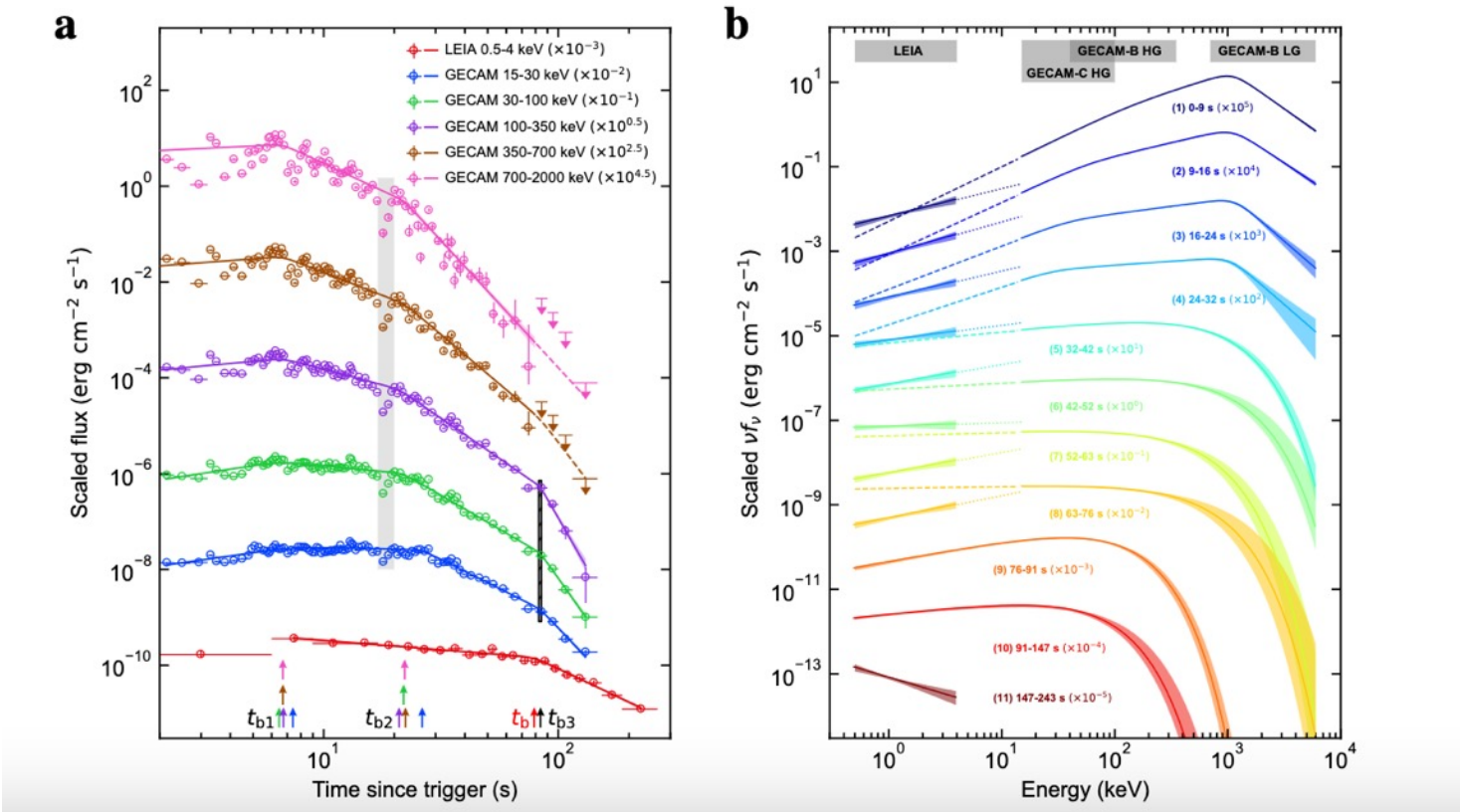


Type I GRB: MVT, Amati relation, spectral lags, location in host

Possible kilonova signature found by JWST

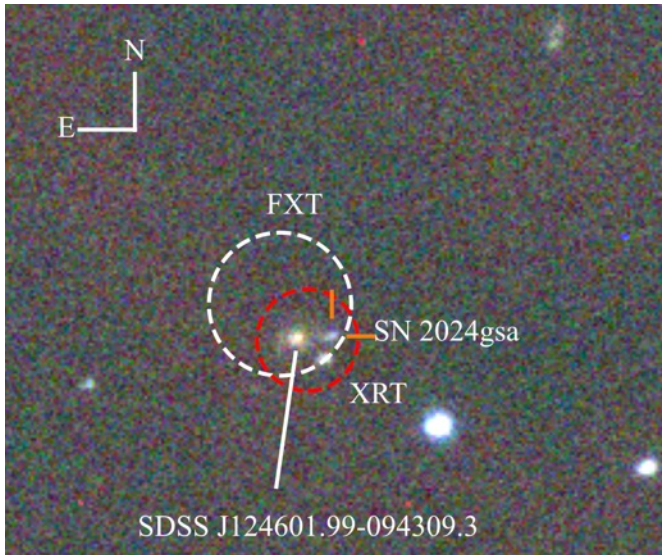
Hard X-rays: emission from a canonical GRB jet

Soft X-rays: likely powered by dipole radiation from a magnetar



Sun H. et al. National Science Review, in press arXiv:2307.05689.

EP240414a: a new type of fast X-ray transient ?



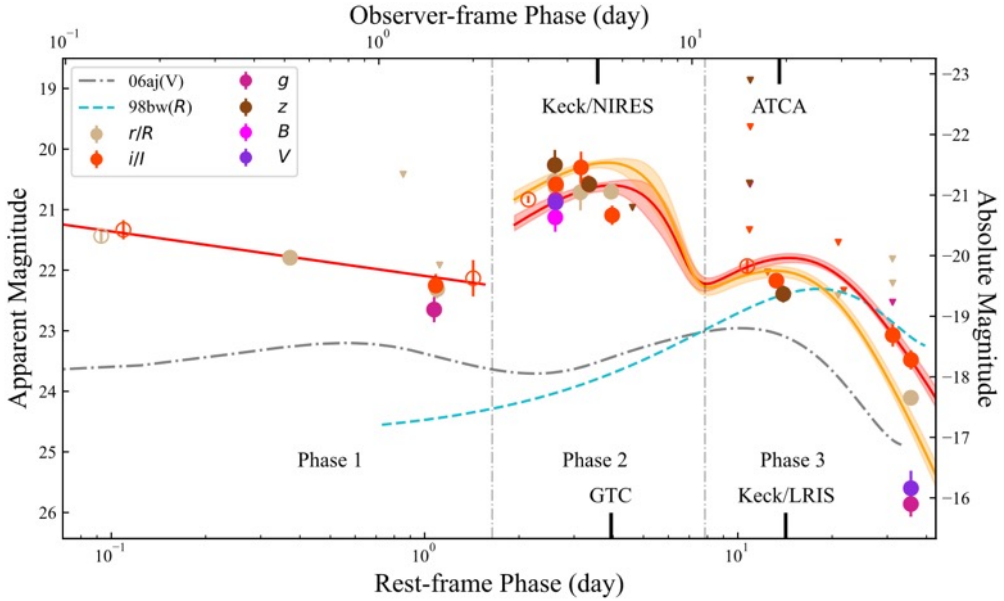
Associated of a Type Ic supernova SN 2024gsa (z=0.4)

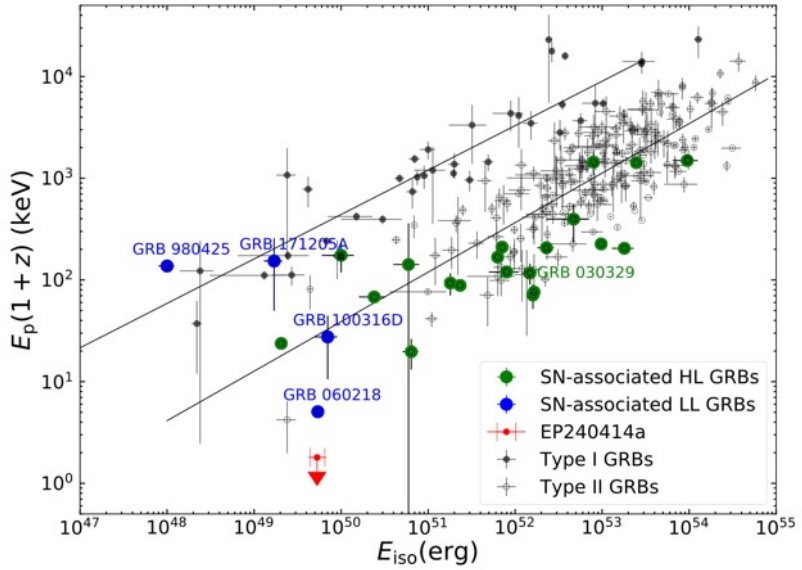
No significant γ-ray signals associated

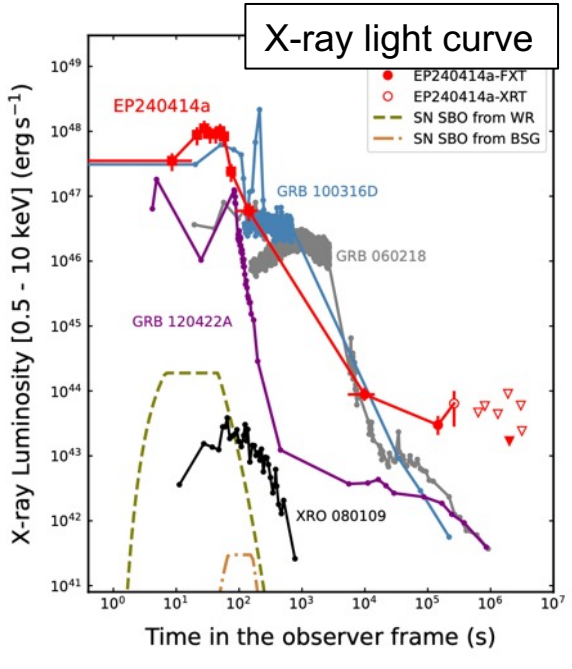
Very soft energy spectrum Ep< 1.3 keV

=> A weak relativistic jet that interacts with an extended shell surrounding the progenitor star

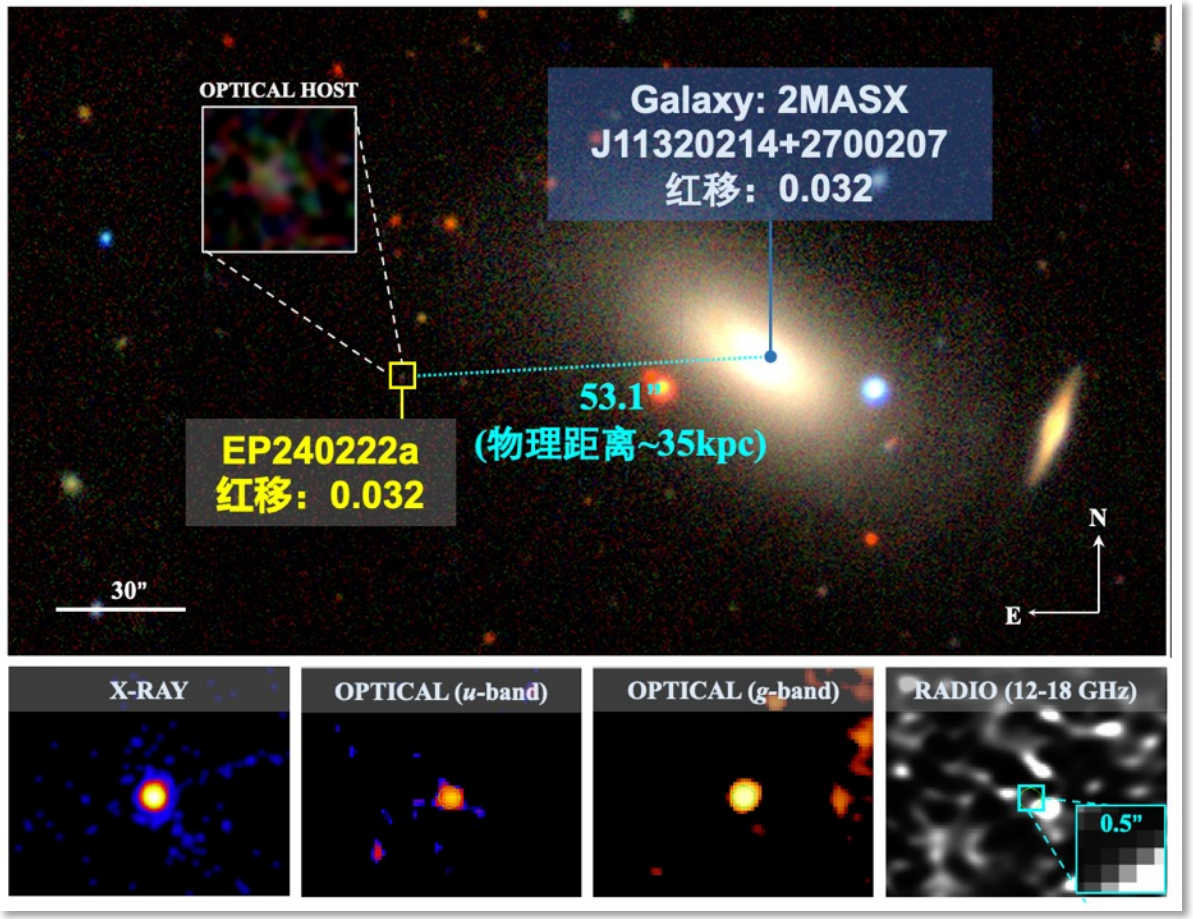
Sun et al. submitted, arXiv: 2410.02315





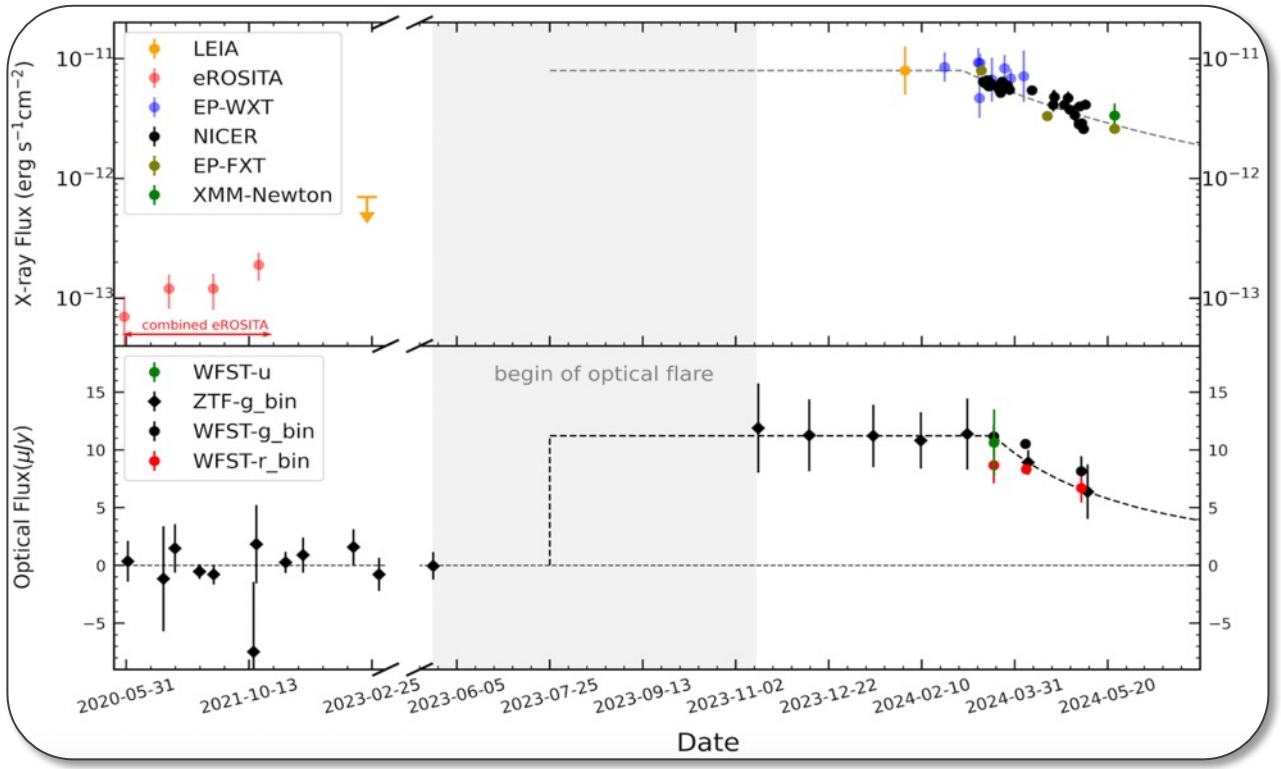


EP240222a: off-nuclear TDE from a candidate IMBH



first TDE detected with EP

GTC + Gemini: z = 0.032



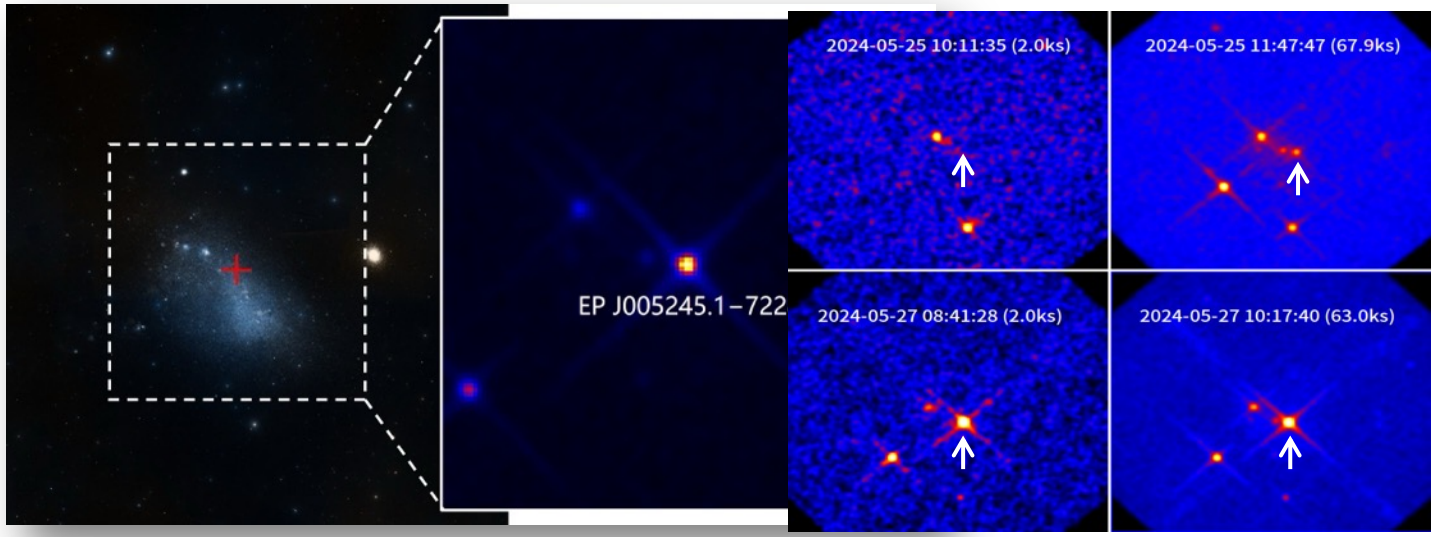
IMBH candidate:

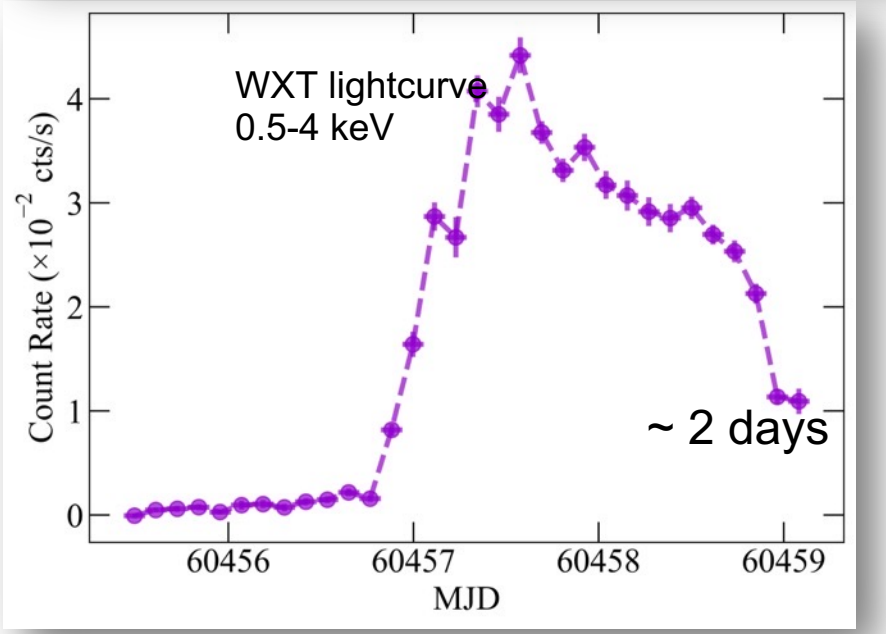
- **X-ray temperature & luminosity**
- **host properties**

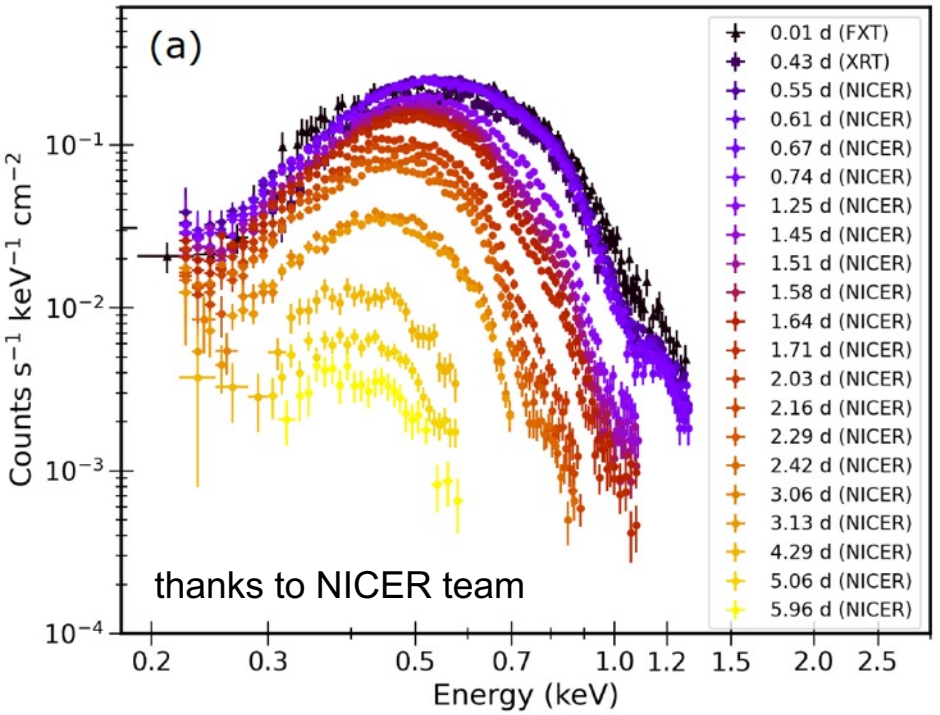
A special TDE with long rising phase

Jin, Li, Jiang, Dai et al., submitted

An outburst in Small Magellanic Cloud: Be + WD



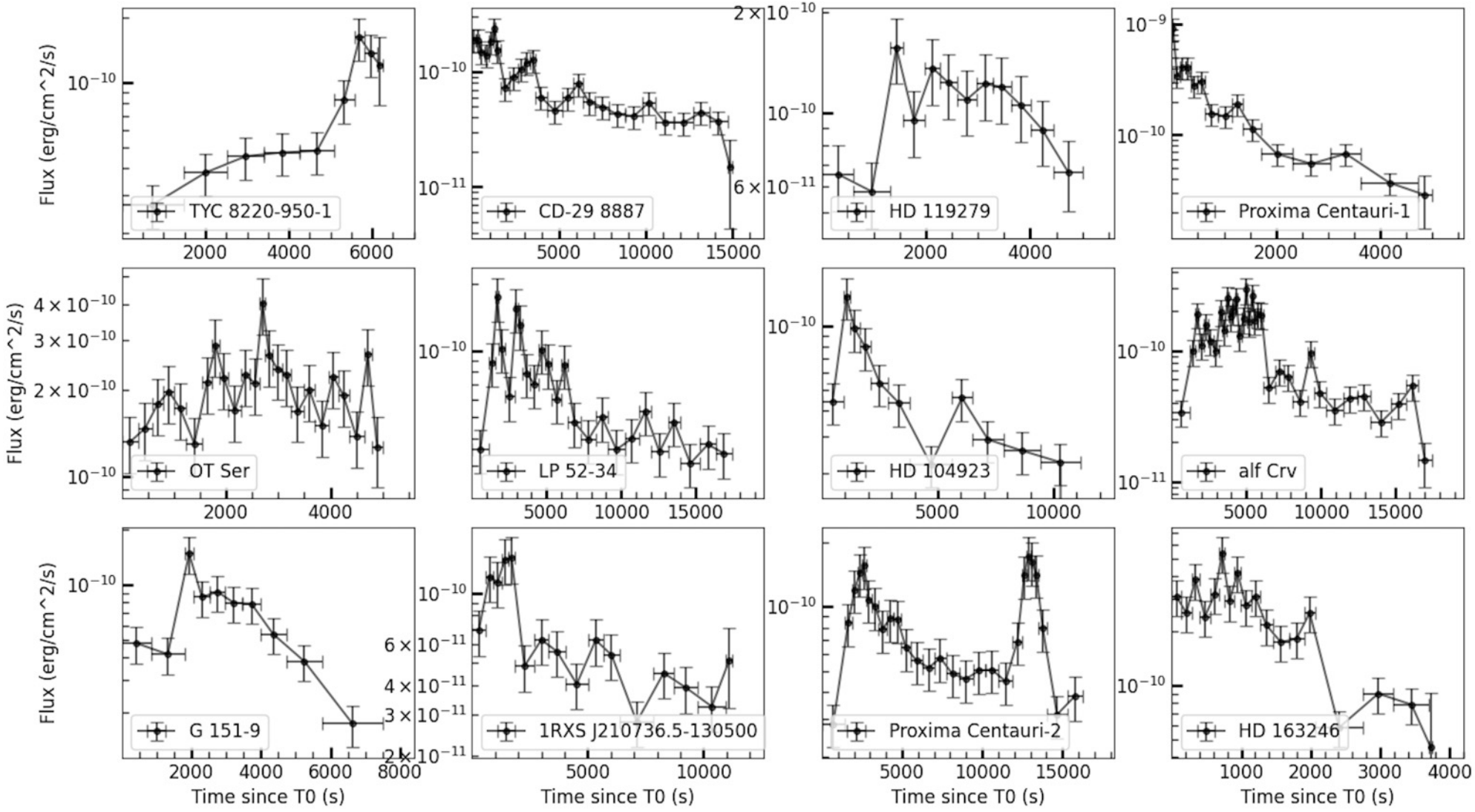




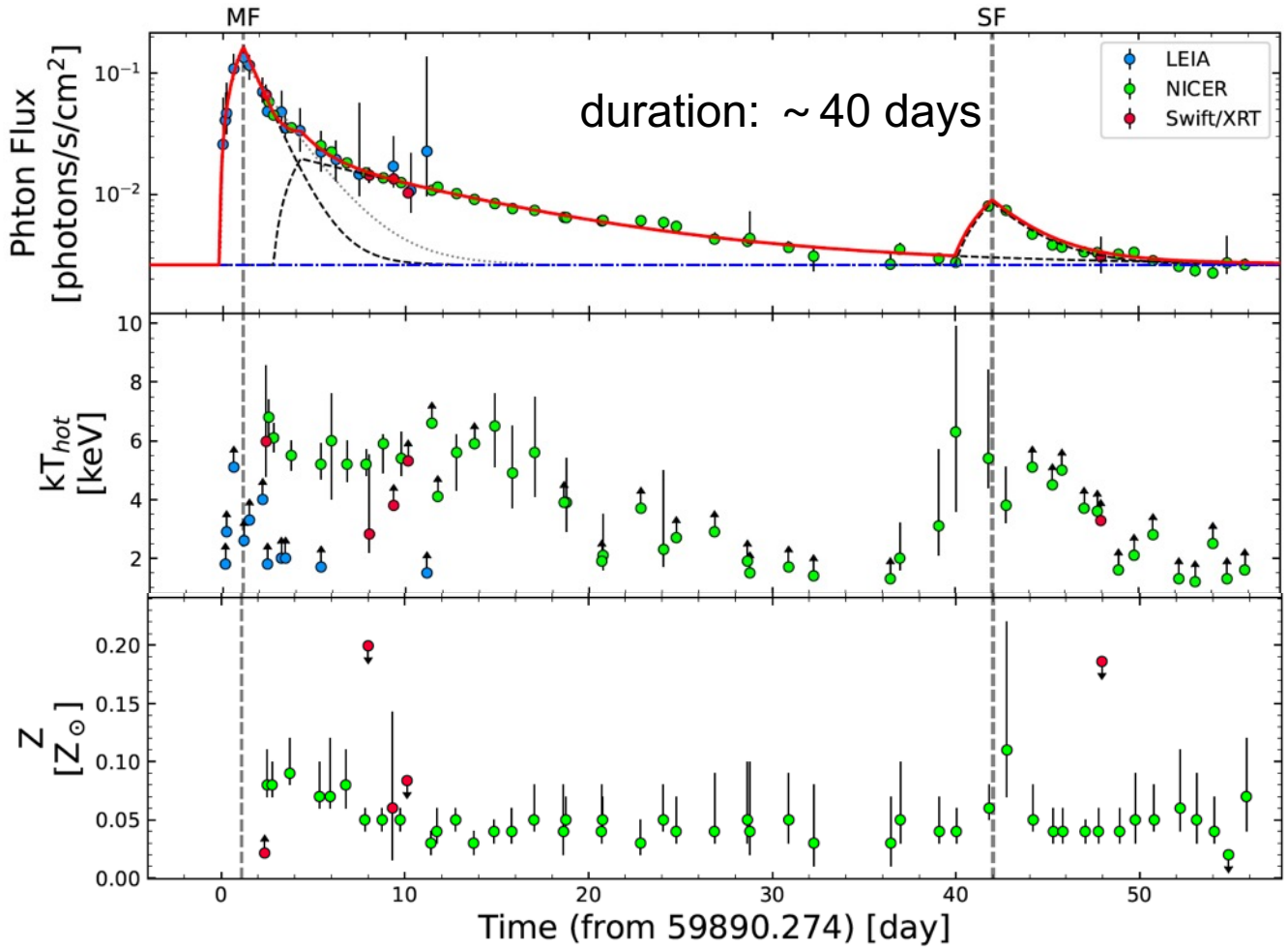
- CXOU J005245.0-722844 a faint Chandra source
- An X-ray outburst detected by EP/WXT (Atel#16631) and Swift/XRT (ATeL# 16633), follow-up by NICER (ATeL# 16636)
- very soft X-ray spectrum
- a possible Be binary system with a WD

Gaudin, Coe, Kennea, et al. 2024 MNRAS 534, 1937 (S-CUBED program)
Marino, et al. 2024, ApJL in press, http://arxiv.org/abs/2407.21371

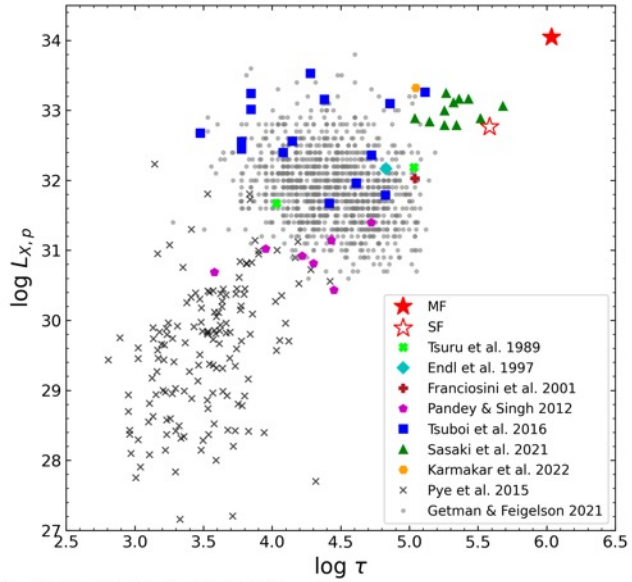
~500 X-ray stellar flares detected with EP-WXT

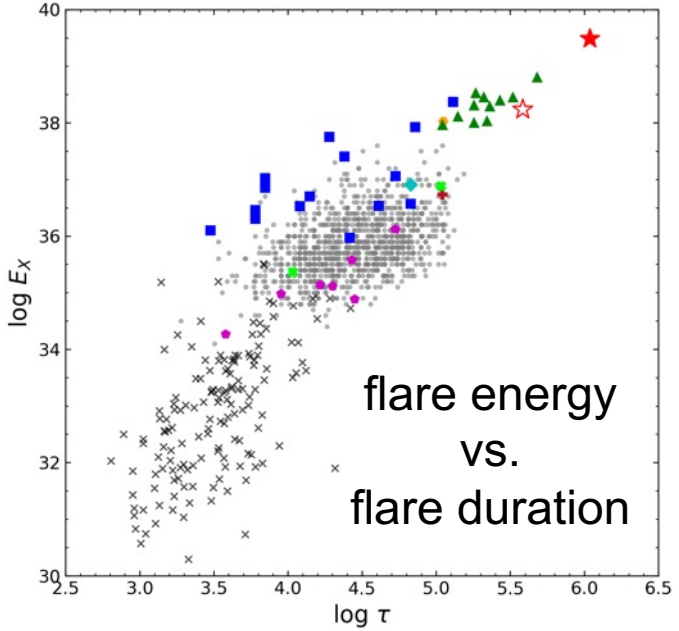


LEIA discovery of the most energetic & long-lasting stellar X-ray flare from RS CVn binary HD 251108



peak luminosity
vs.
flare duration





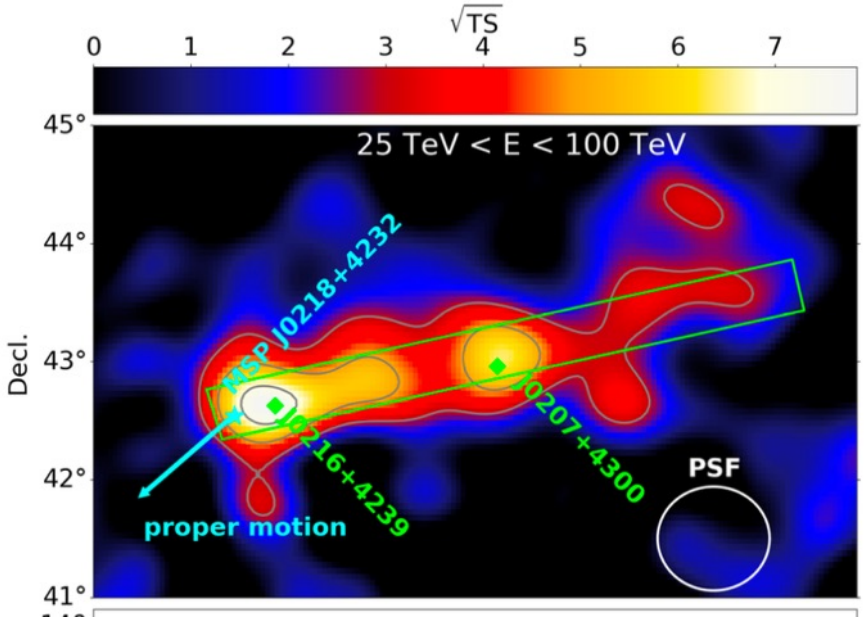
Peak L_X: 1.1E34 erg/s (0.5-4keV); Energy: 3E39 erg (0.5-4keV)

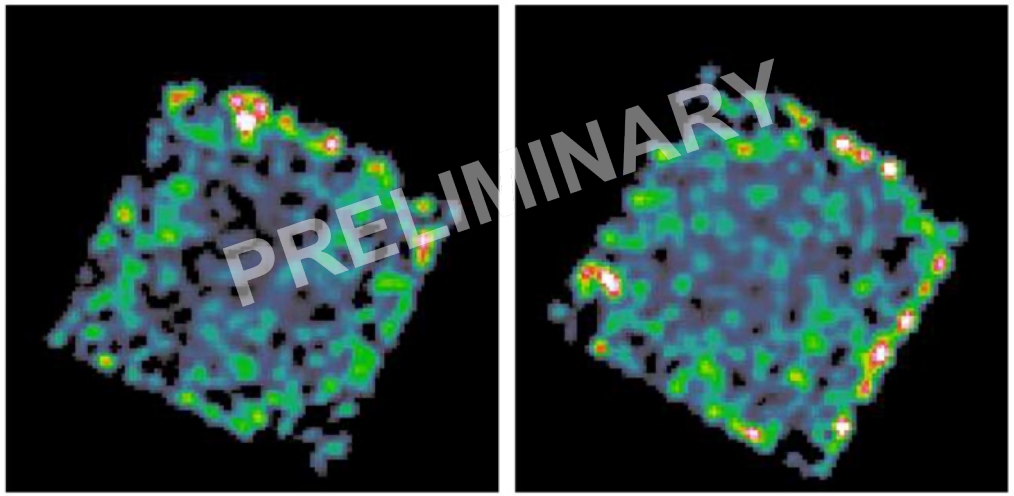
magnetic loop: ~1.9R_star; magnetic field ~ 50 Gauss

Mao X. et al. ApJ submitted

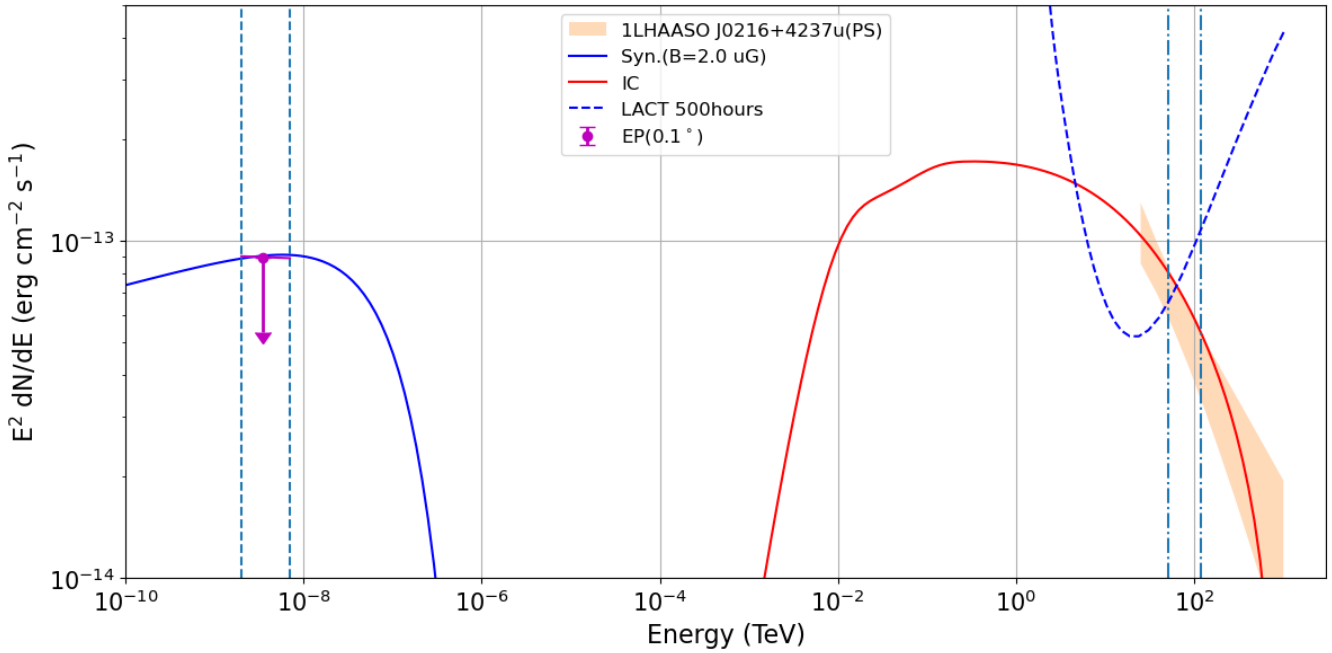
EP-FXT observations of LHAASO sources

A selection of LHAASO sources have been observed with EP-FXT





- **A possible scenario**
  - ➢ **propagation of electrons (must have a low B-field)**
- **EP-FXT: constraints on the B-field**



Summary

A high-sensitivity all-sky monitor

- ~80 X-ray transients with high S/N detected (~500 flaring stars)
- Many rare events: are they really rare?

Unique capability of FXT

- Large field of view + low instrument background

National Key Laboratory of Particle Astrophysics @ IHEP