Einstein Probe:

status and preliminary detection results

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on behalf of the Einstein Probe consortium

Image credit CAS/ESA

Einstein Probe (EP) mission

Goals space X-ray observatory for time-domain astro.

Discover soft X-ray transients & monitor source variability at unprecedented sensitivity

Characterise transients/variables by quick X-ray follow-up onboard

Disseminate transient alerts to astro. community in time, quick response ToO

Milestones

2010- Lobster-eye R&D @ XIL/NAO (est. by Prof. S.-N. Zhang)

2012 Mission concept

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)

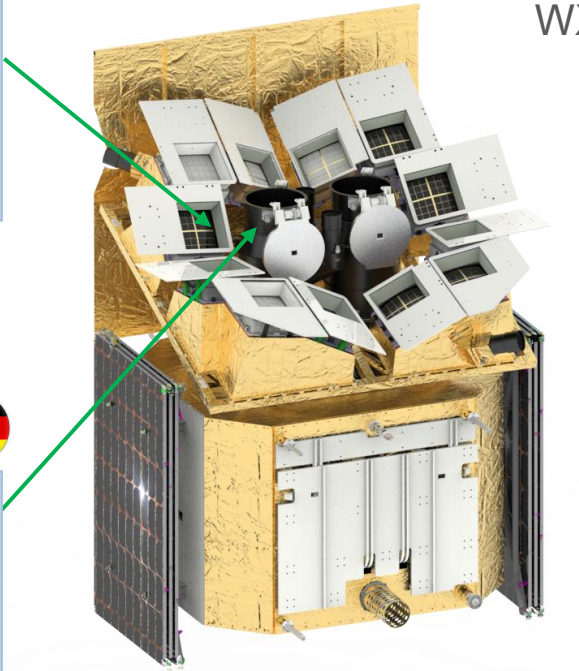
Instruments & spacecraft

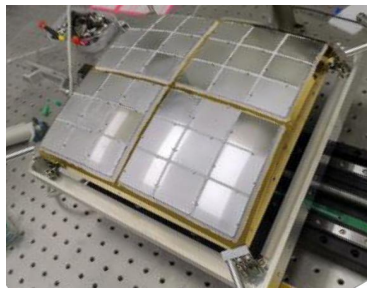
Wide-field X-ray Telescope
WXT (12 modules)

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 -10keV
Resolution: 24” (HPD, on-axis)
Effe. area: ~300 cm^2 @1keV (x 2 units)





WXT mirror & CMOS detectors (1 module)

Spacecraft

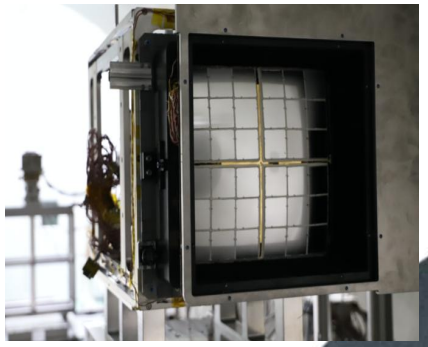
On-board data processing
Quick slew & autonomous follow-up

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*

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

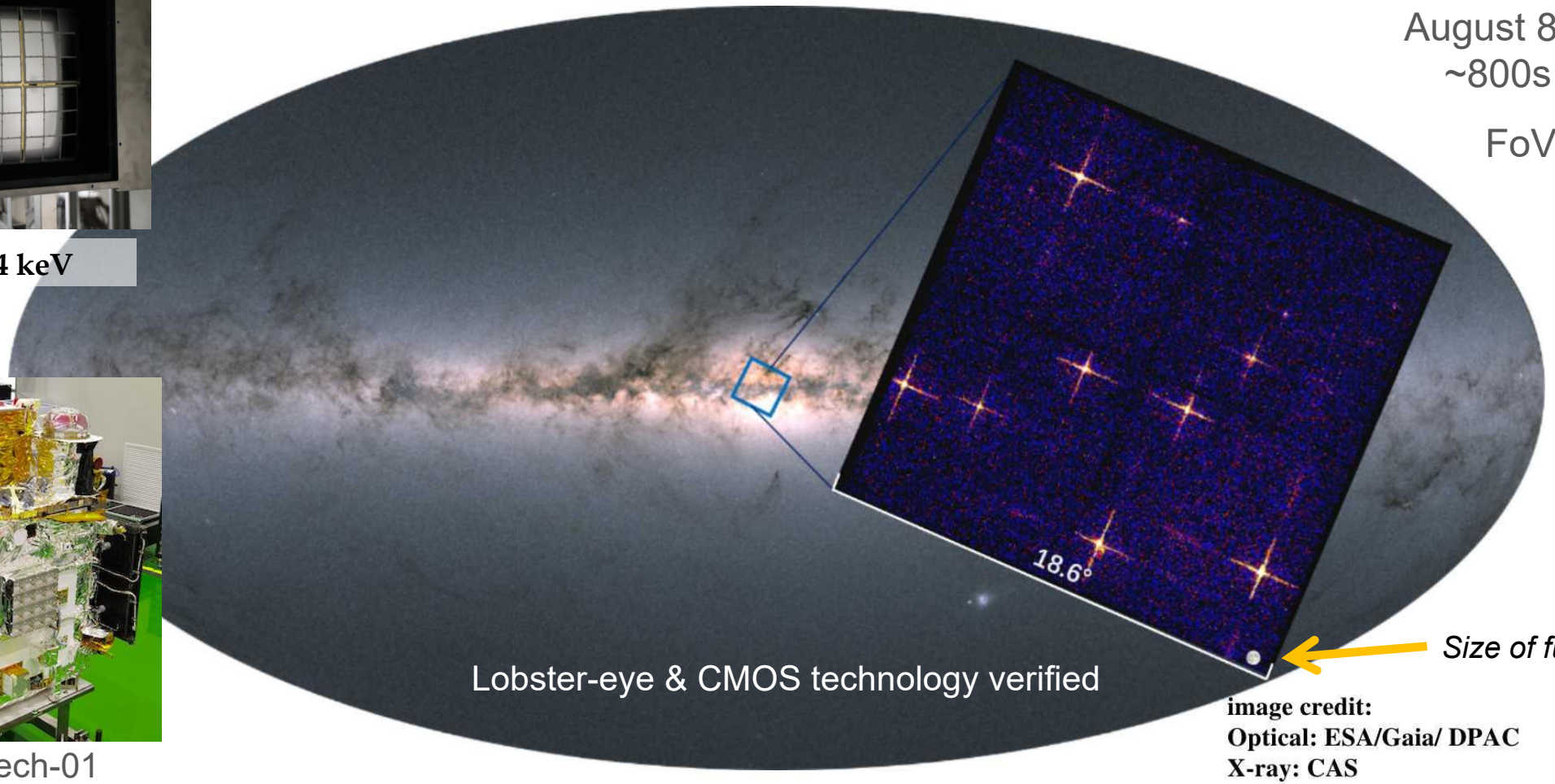


LEIA 0.5 – 4 keV

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

see Dongyue Li and Hui Sun's talks

Launch of EP

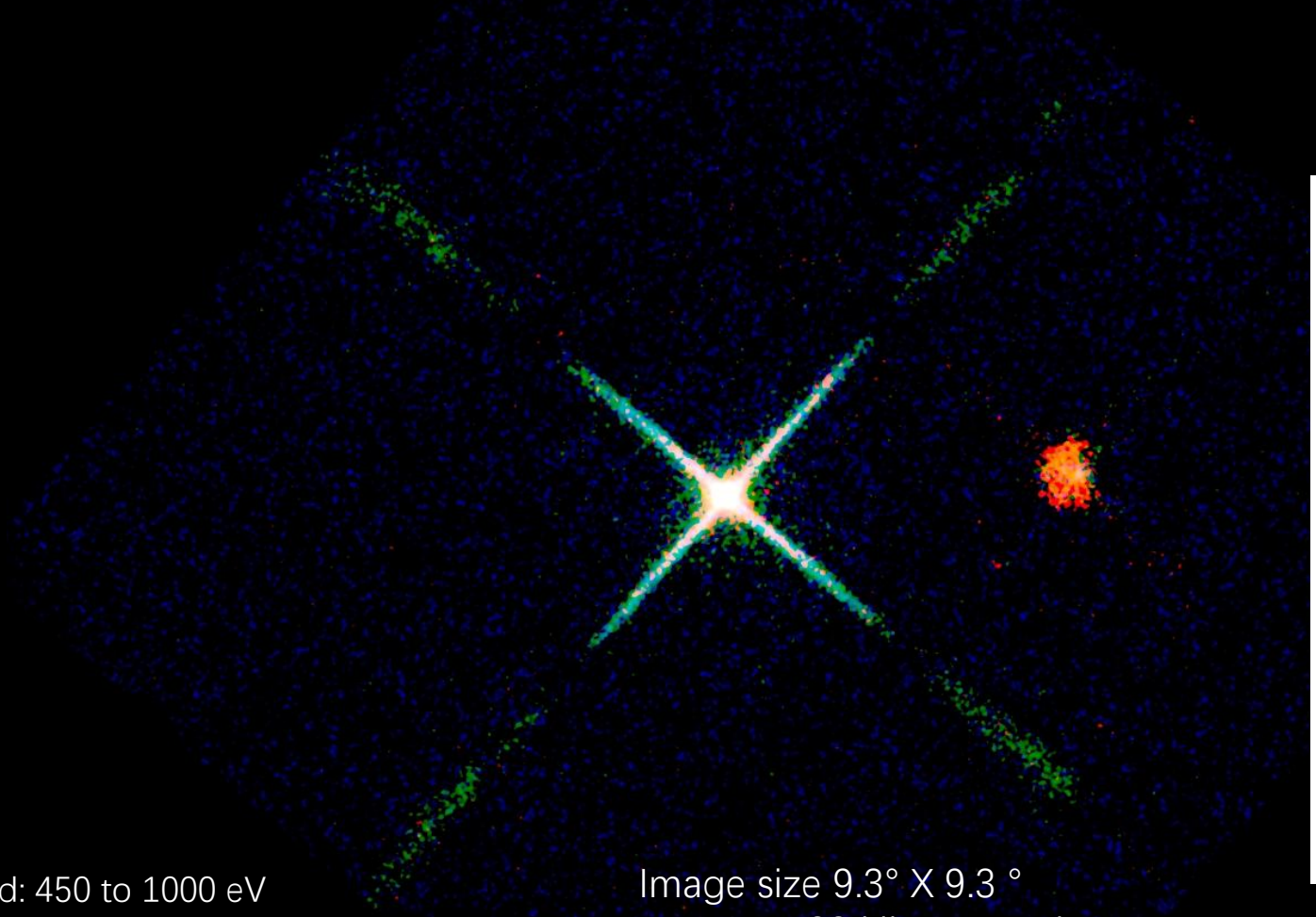
Jan. 9, 2024

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

LM-2C @Xichang

X-ray First light 2024 Feb. 19

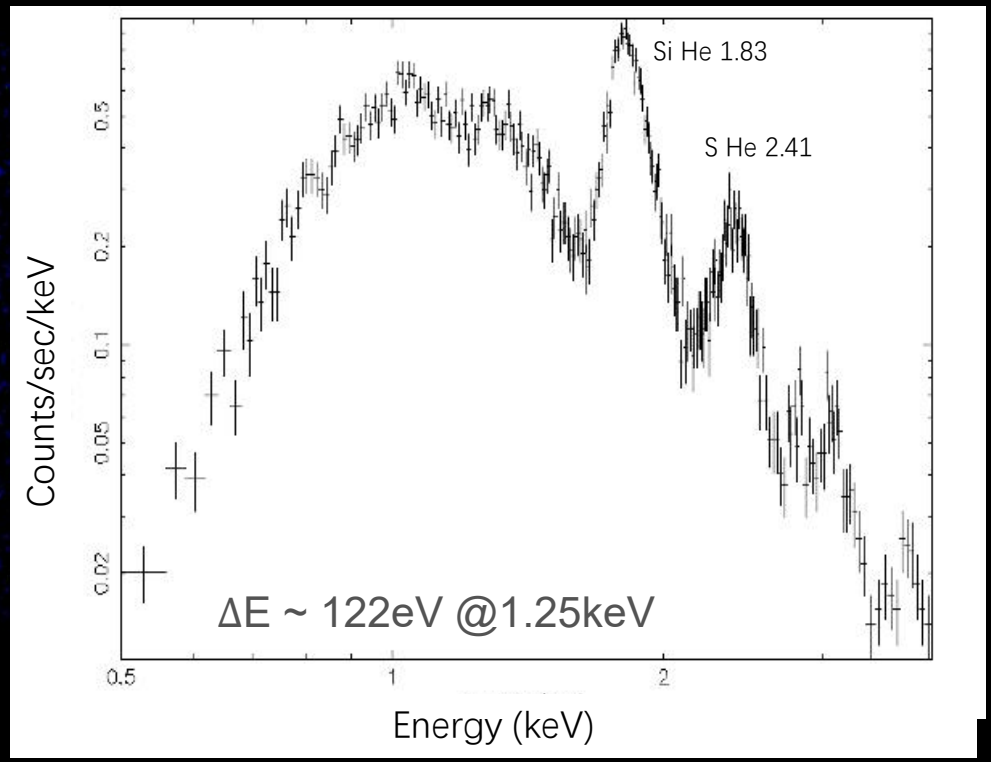
Cassiopeia A supernova remnant (nebula)



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

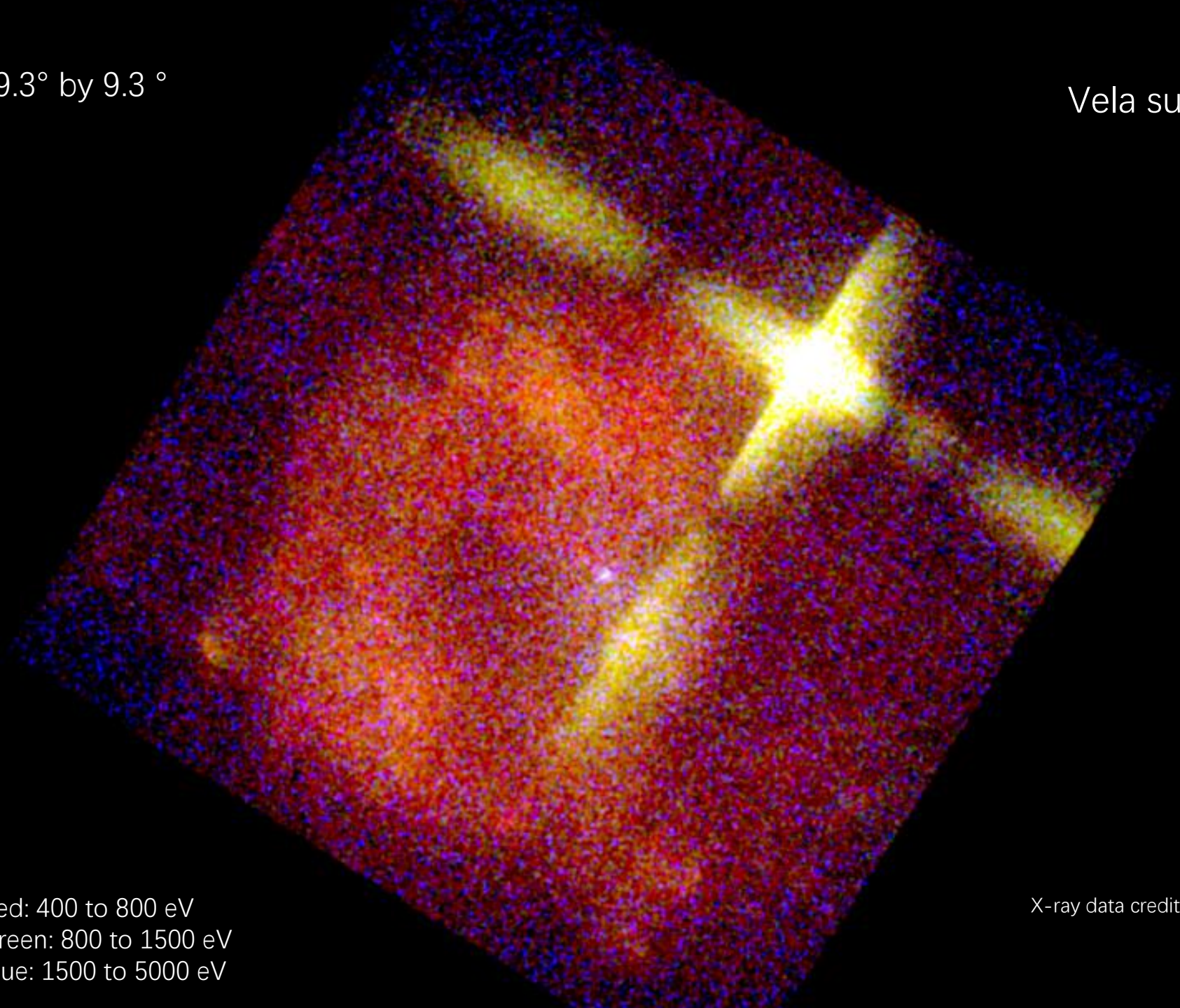
X-ray spectrum obtained at the same time



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

9.3° by 9.3 °

Vela supernova remnant X-ray (nebula)



exposure 9.3 kilo-seconds
mage size 9.3° X 9.3 °

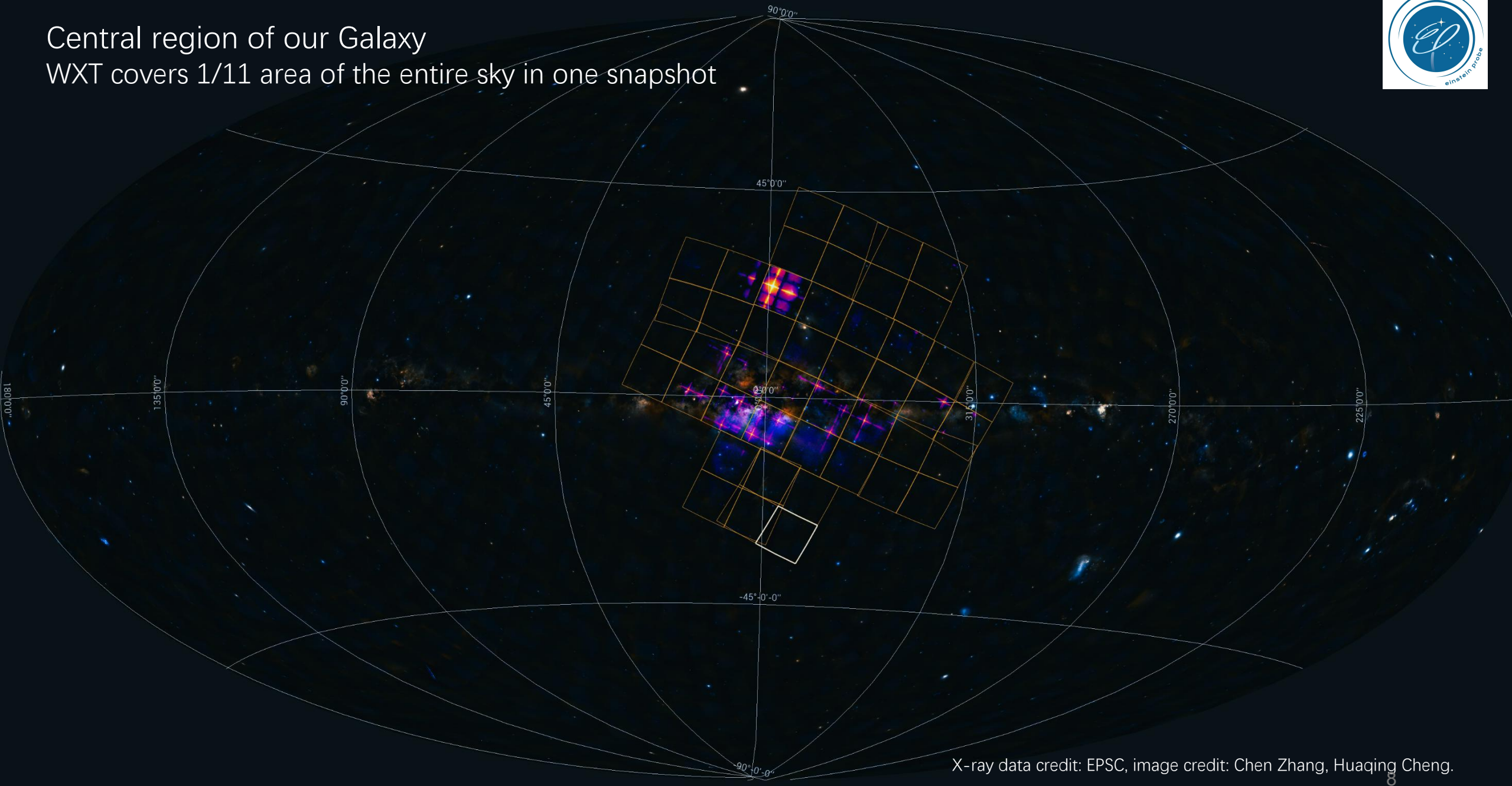
Vela supernova exploded about 11000 yr ago
936 light years to Earth

Red: 400 to 800 eV
Green: 800 to 1500 eV
Blue: 1500 to 5000 eV

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

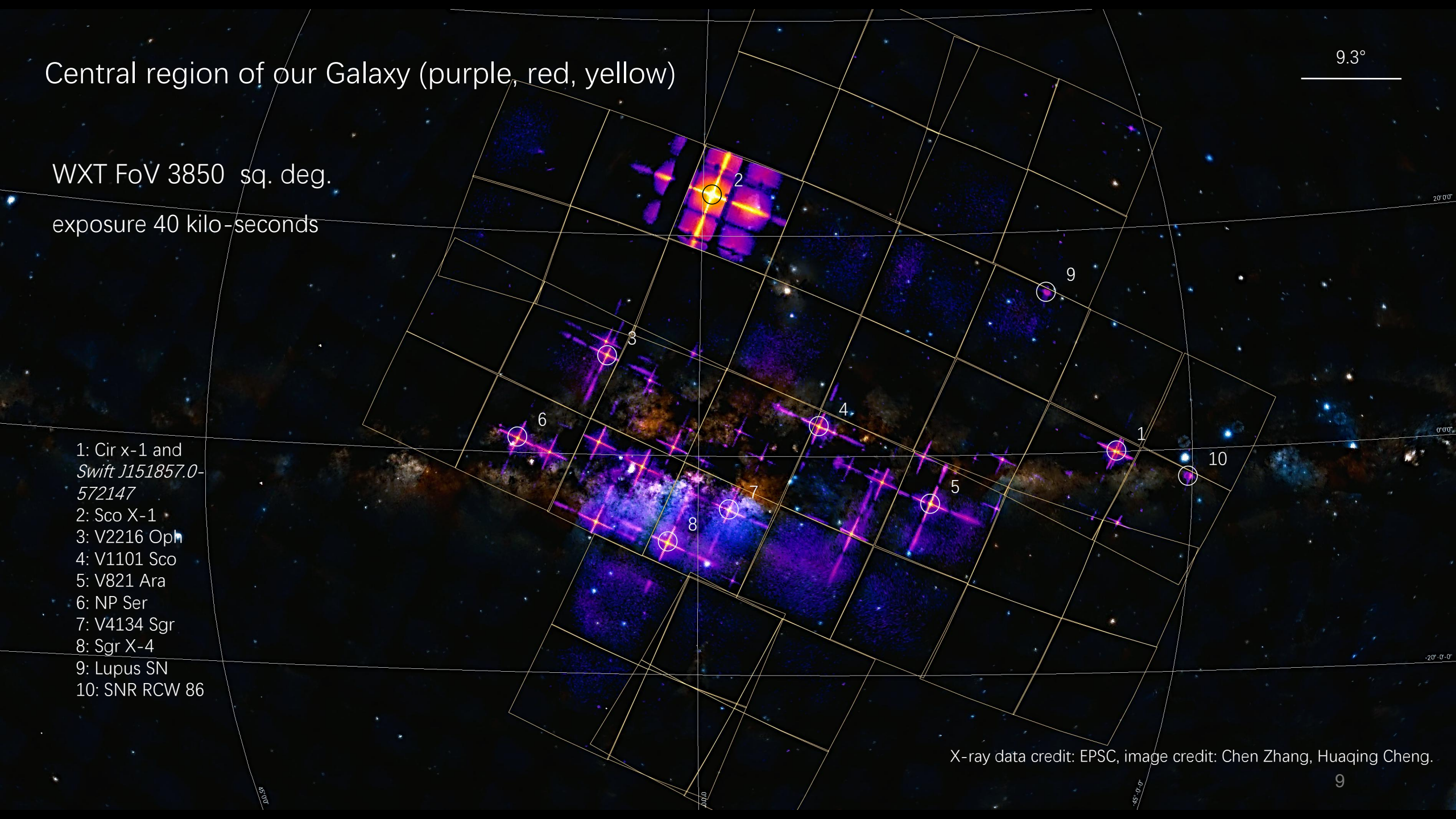


X-ray data credit: EPSC, image credit: Chen Zhang, Huaqing Cheng.

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

WXT FoV 3850 sq. deg.

exposure 40 kilo-seconds



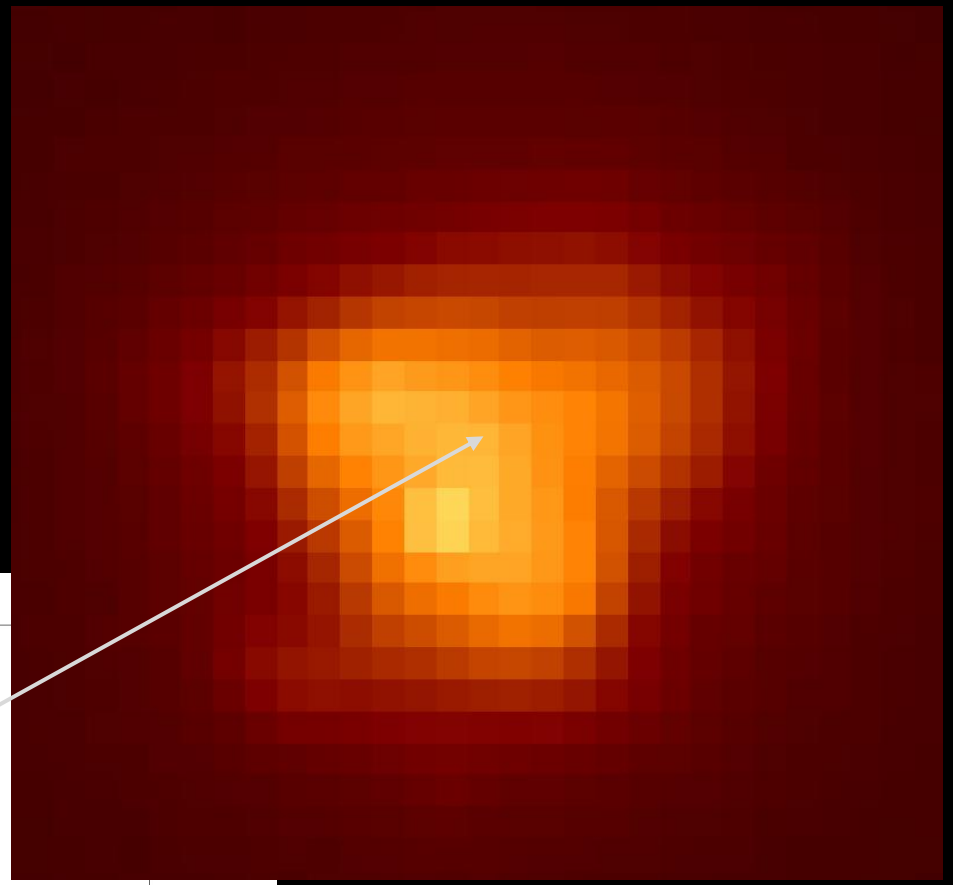
1: Cir x-1 and *Swift J151857.0-572147*
2: Sco X-1
3: V2216 Oph
4: V1101 Sco
5: V821 Ara
6: NP Ser
7: V4134 Sgr
8: Sgr X-4
9: Lupus SN
10: SNR RCW 86

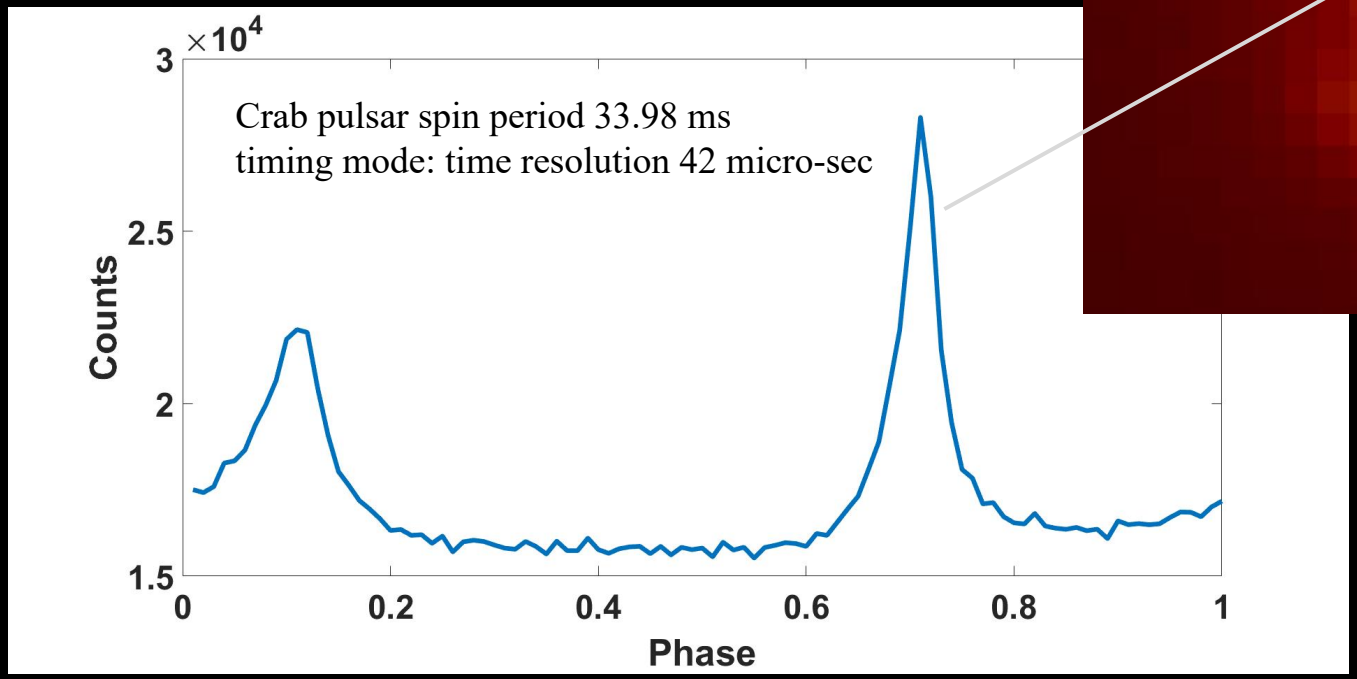
X-ray data credit: EPSC, image credit: Chen Zhang, Huaqing Cheng.

FXT X-ray First light

Crab nebula supernova remnant

Band 0.3-10 keV
Exposure 2600s

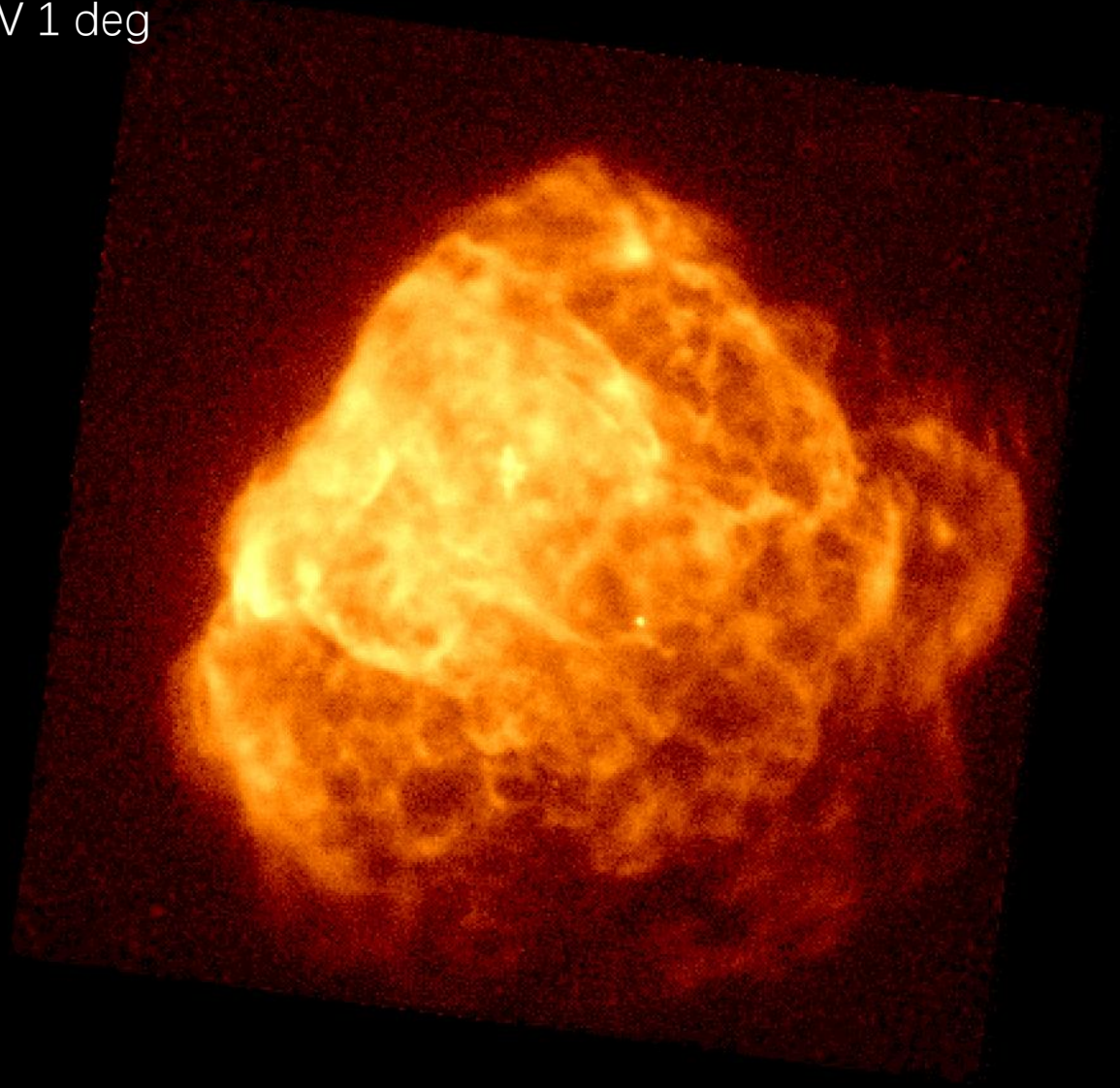




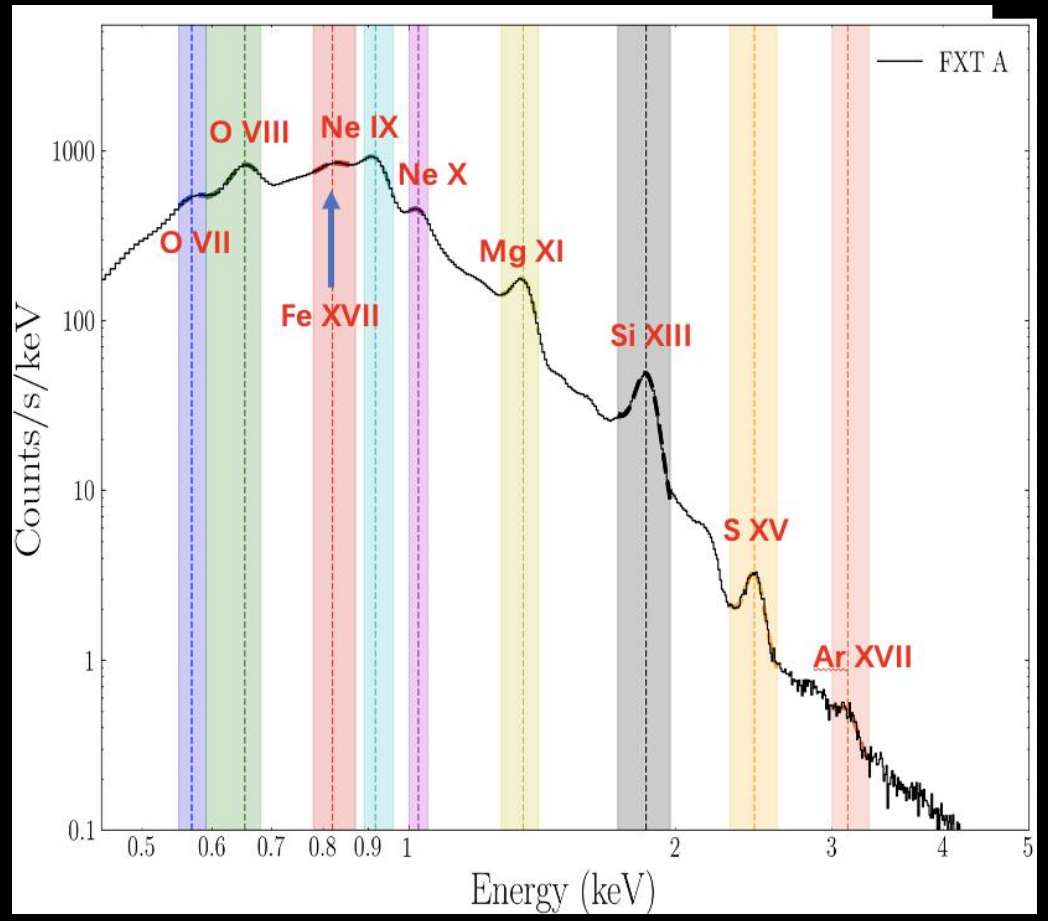
FXT X-ray First light (0.3-10 keV)

Puppis A supernova remnant (nebula)

FoV 1 deg

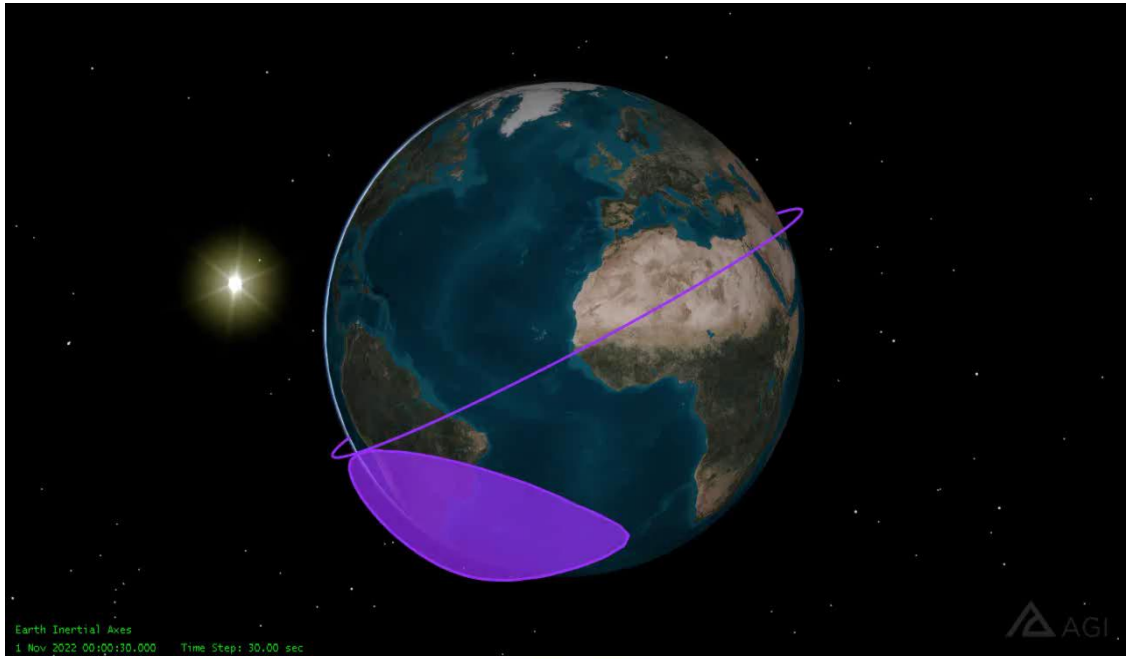


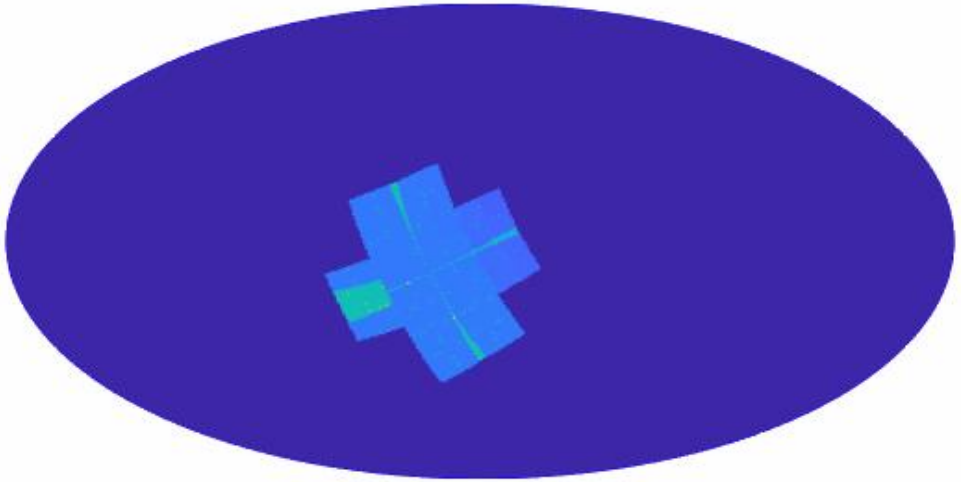
FXT X-ray spectrum obtained at the same time



Observation modes

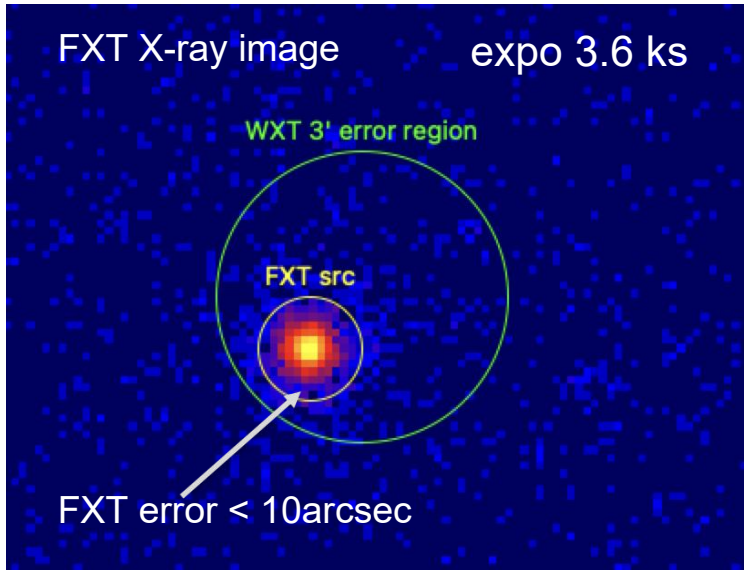
- Circular orbit
  - Height 592km, period 96min
  - inclination angle 29 deg.
- Observation modes
  - Survey (primary WXT)
  - Autonomous follow-up (FXT)
  - ToO (FXT, WXT)
  - Calibration
- WXT survey mode
  - Pointing to night sky
  - 3 pointings/orbit, ~20min each
  - ~ 1/2 sky covered in 3 orbits (~ 5 hr)
  - Whole sky coverage in ½ year
  - FXT pointed to pre-selected targets





Onboard trigger for FXT automated follow-up

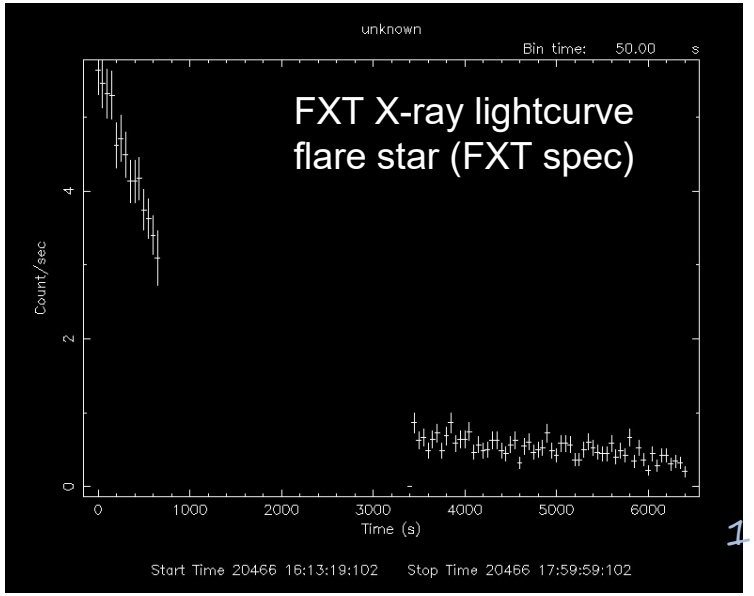
- 1st successful test: EP240605a June 5 UTC 16:10:30,
- transient info downlink within minutes (BD & VHF)
- triggered FXT obs @ UTC 16:11:44
  - 1 min after triggering



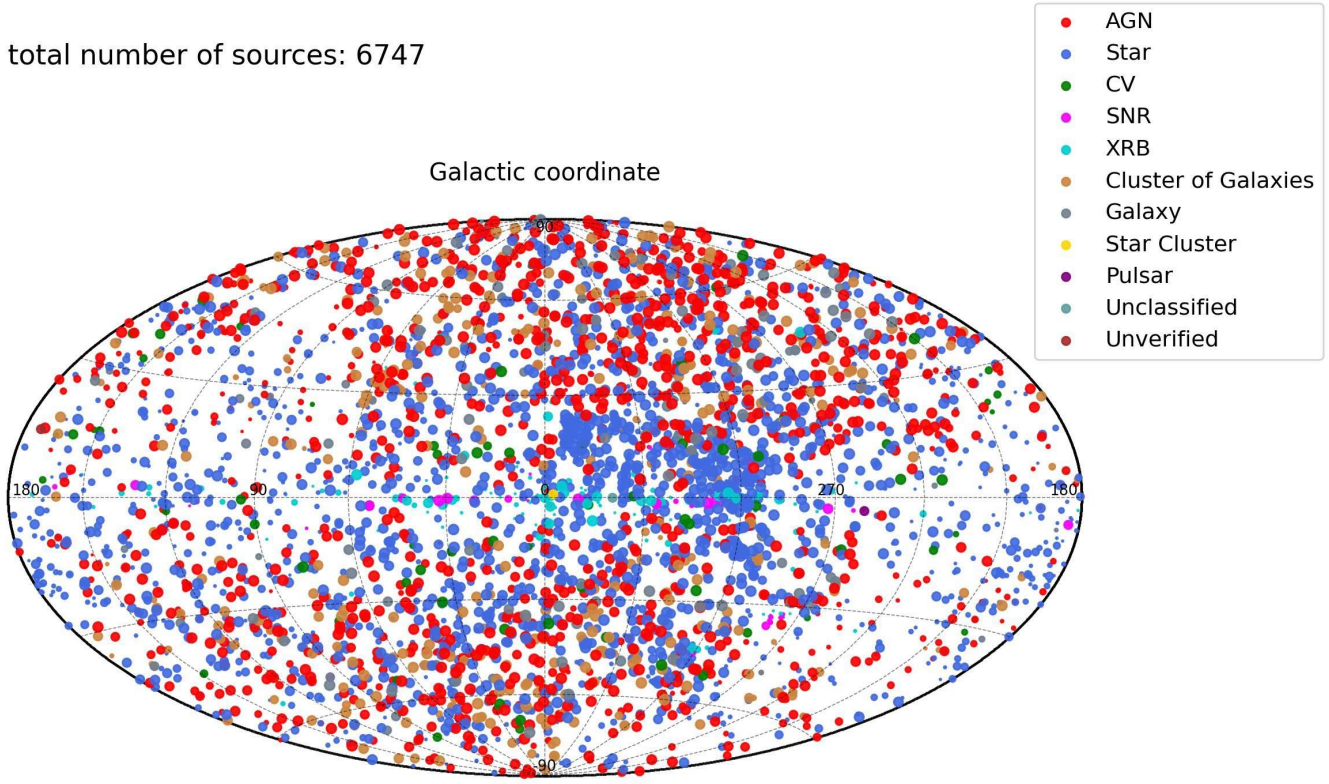
alert information downlinked via BD

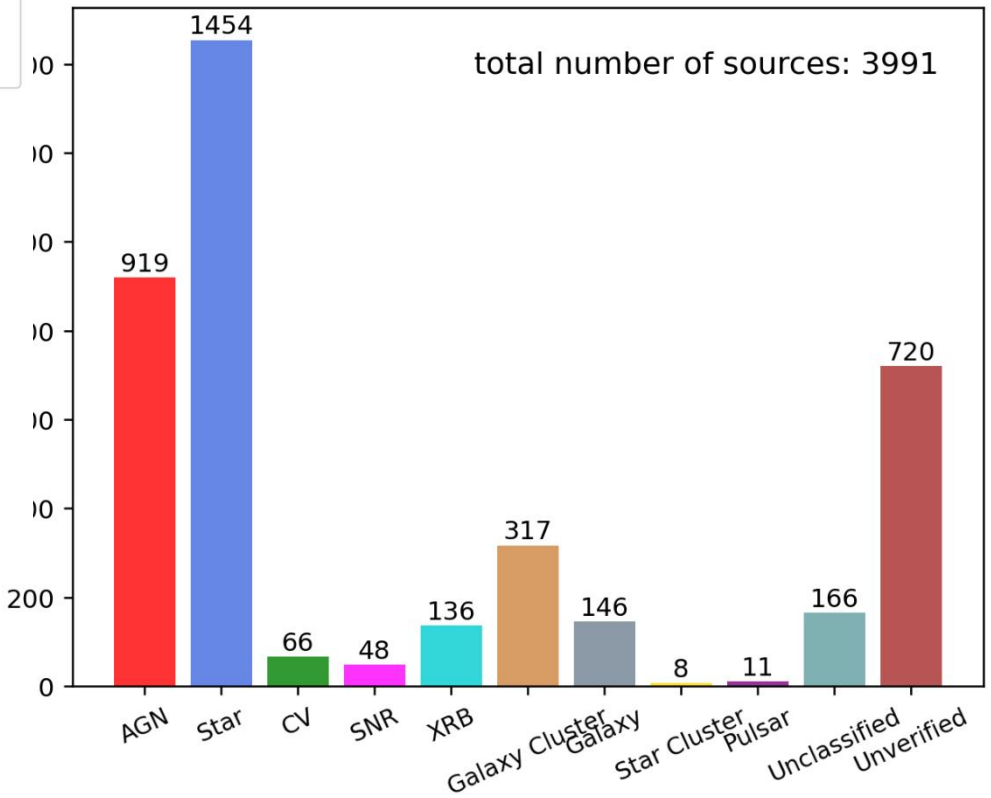
Beidou Alert: 01708918013 CMOS14

RA, Dec	19.907, -68.695	**Galactic l, b**	299.095, -48.223
RA (HMS), Dec (DMS)	01h19m37.7s,-68d41m42.0s	**1 σ Pos Err (arcmin)**	0.692
Observation Time (UTC)	2024-06-05 16:00:40	**Trigger Time (UTC)**	2024-06-05 16:10:30
X	2674.2	**Y**	3576.6
Net Rate	0.06	**Variance**	13.34
Significance	8.1	**HR**	0.18



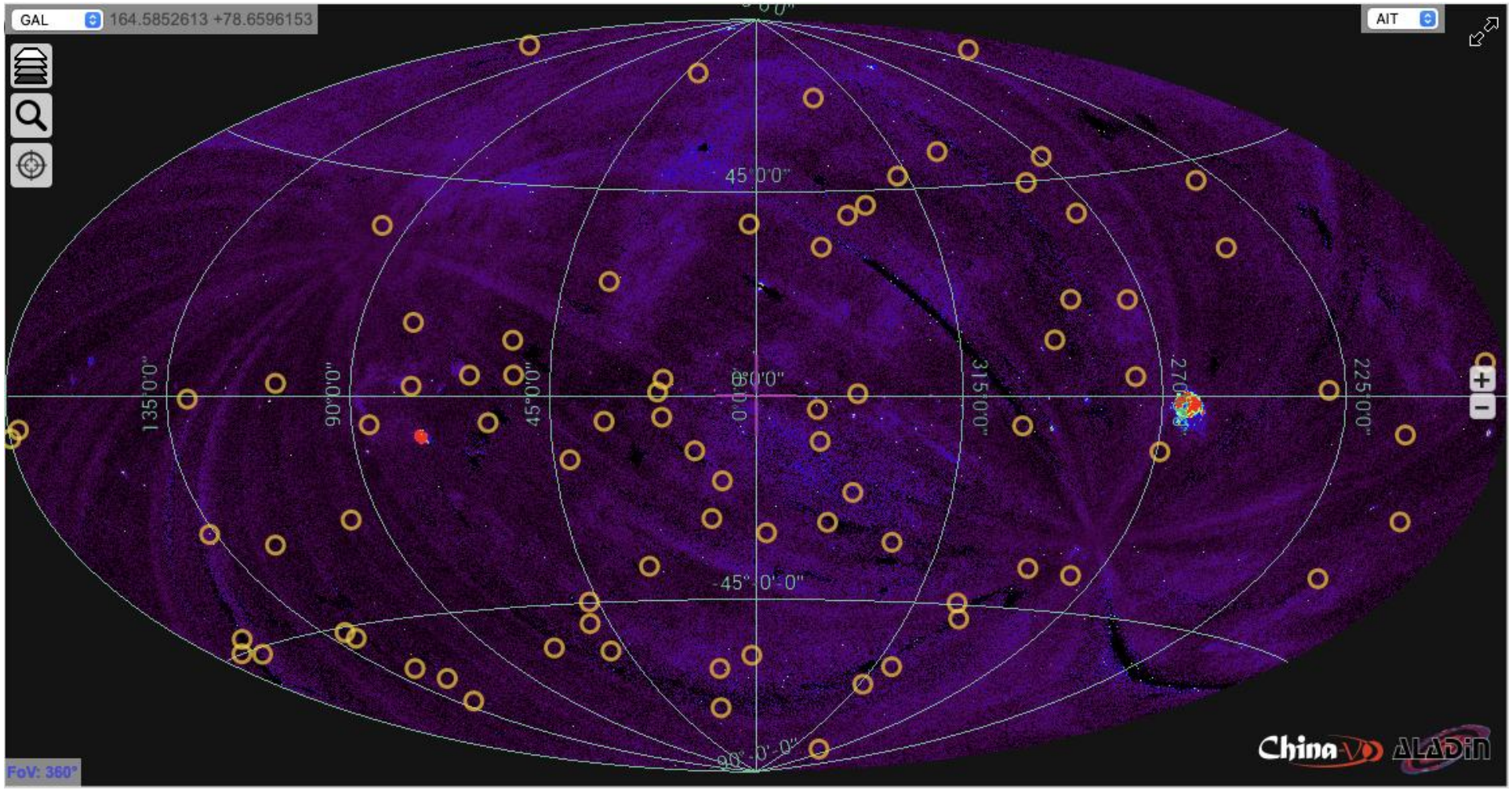
Statistics on X-ray sources detected with EP



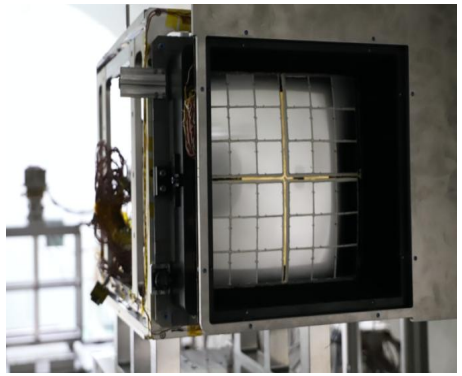


- Bright sources detected with WXT: 6747
- Transients：55 high S/N (3200 low S/N)
- Stellar flares：488
- New X-ray sources detected with FXT: ~20,000

Transients detected with EP-WXT (high S/N)

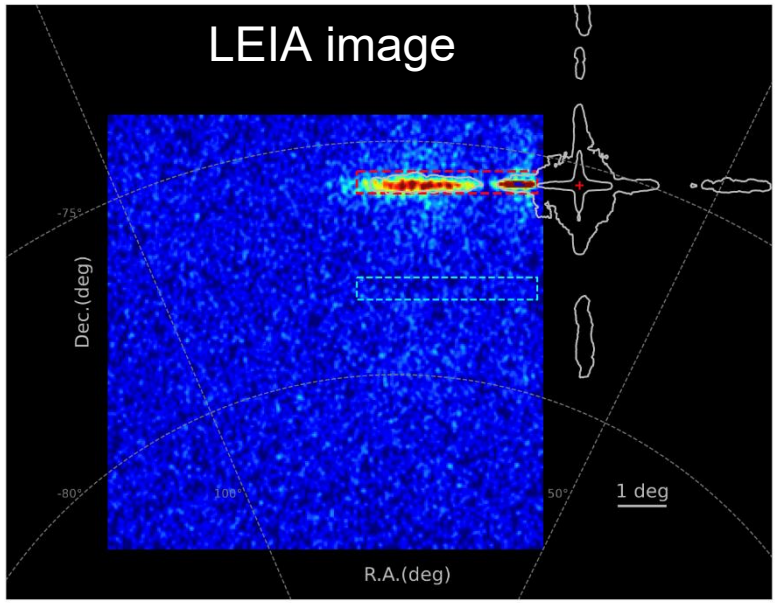


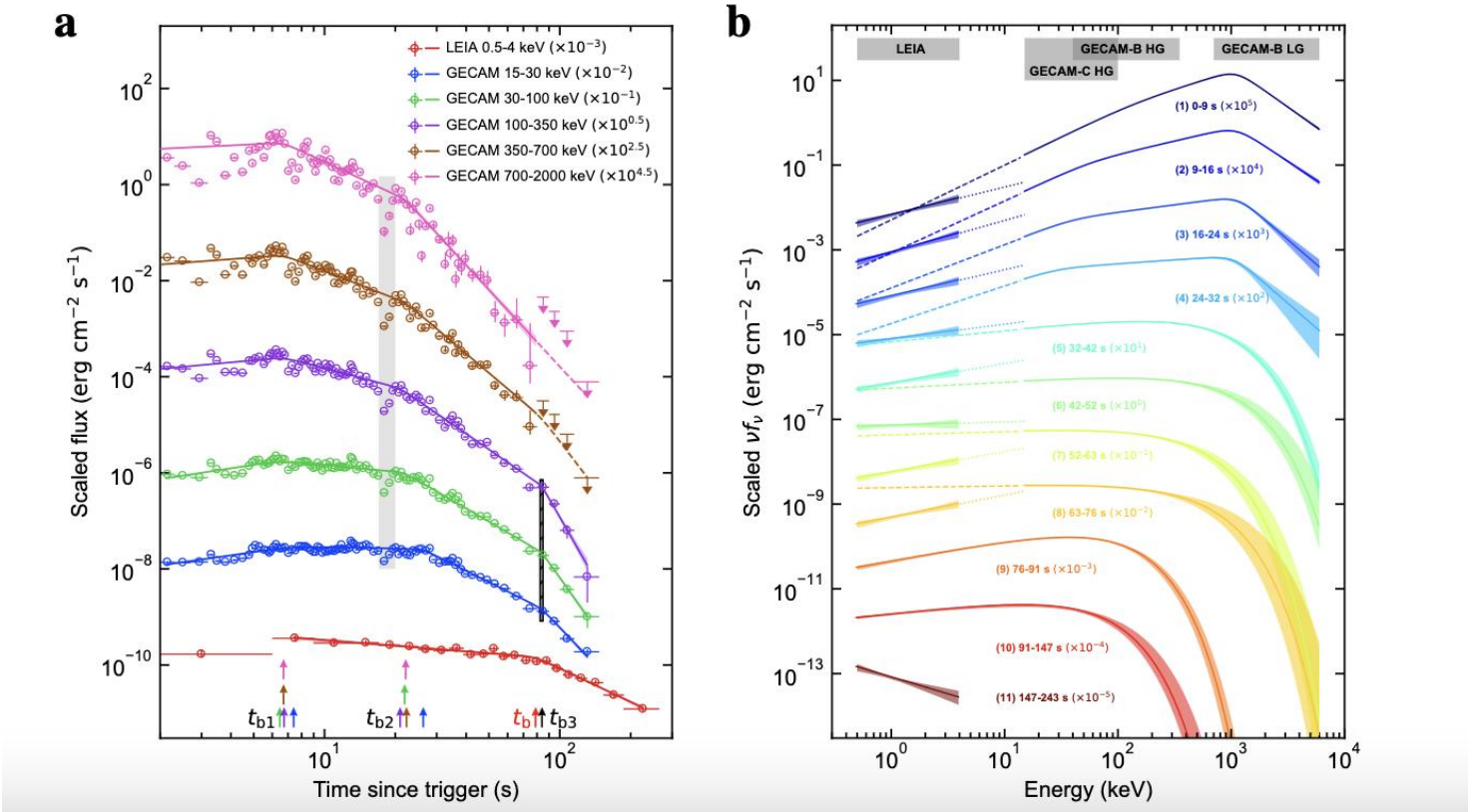
LXT 230307A: transient powered by NS merger



EP pathfinder LEIA 0.5 – 4 keV

- Hard X-rays and gamma-rays powered by relativistic jet
- Soft X-rays likely powered by a magnetar, emerging from burst onset
- Consistent with the association of kilonova signature found by JWST



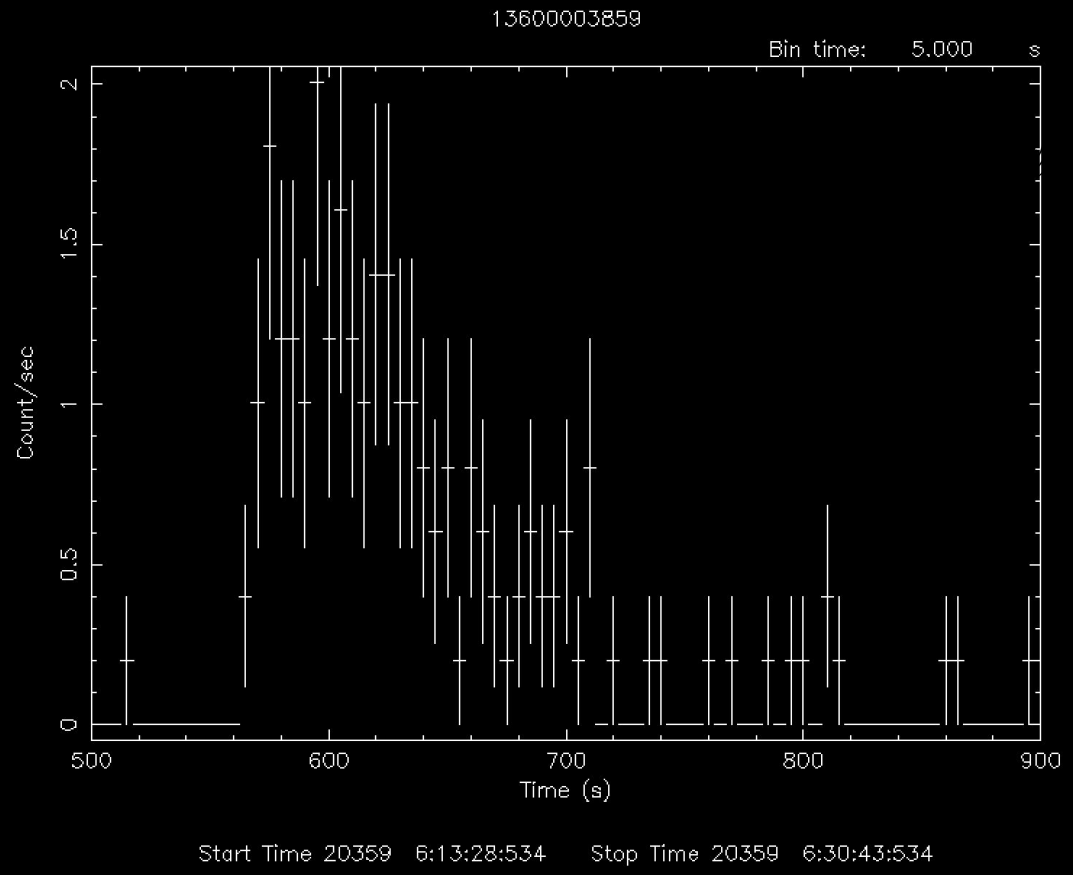


Sun H. et al. submitted arXiv:2307.05689

EP240219a

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

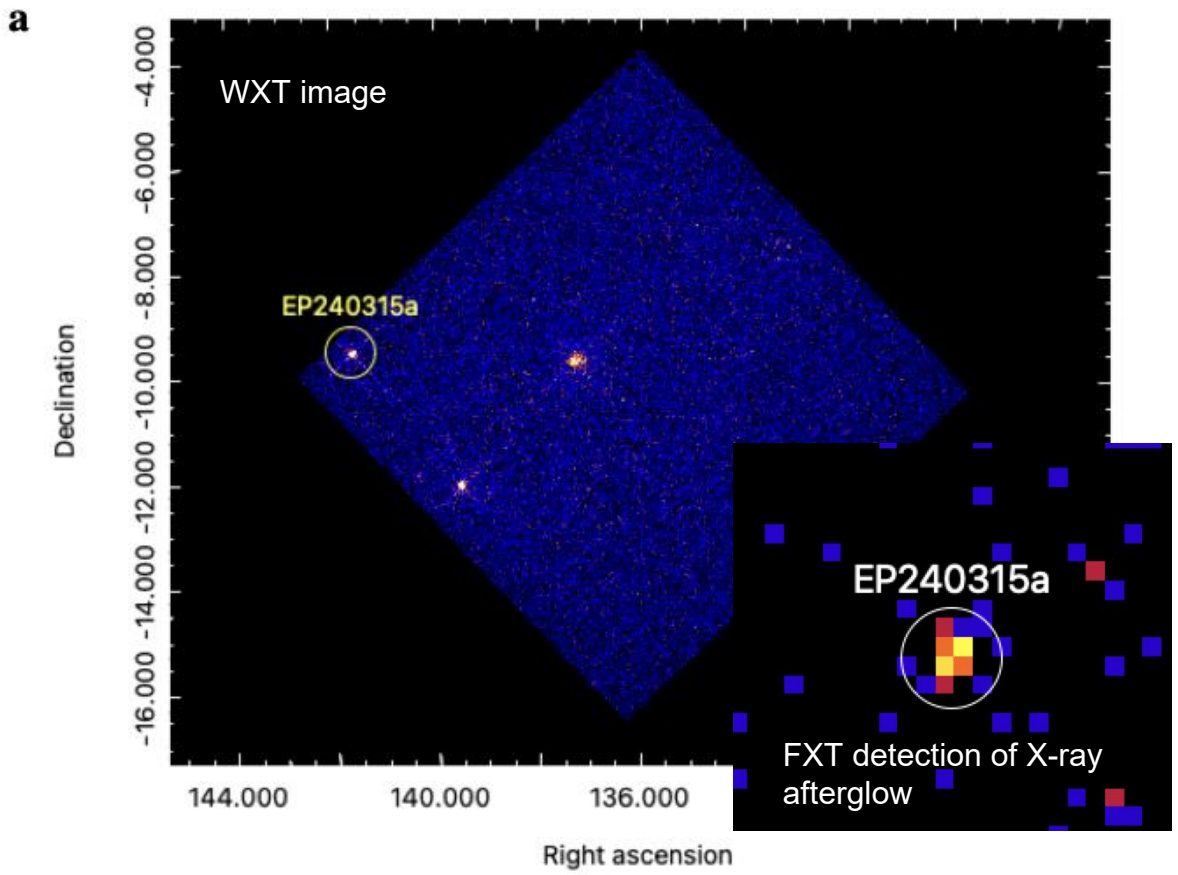
- Duration < **200s**
- Subthreshold GRB signal found in Fermi/GBM data (Zhang ATel #16473)
- Atel sent from EPSC: 1st EP alert!
- No optical counterpart found (starting T0+3days)
- An X-ray rich GRB



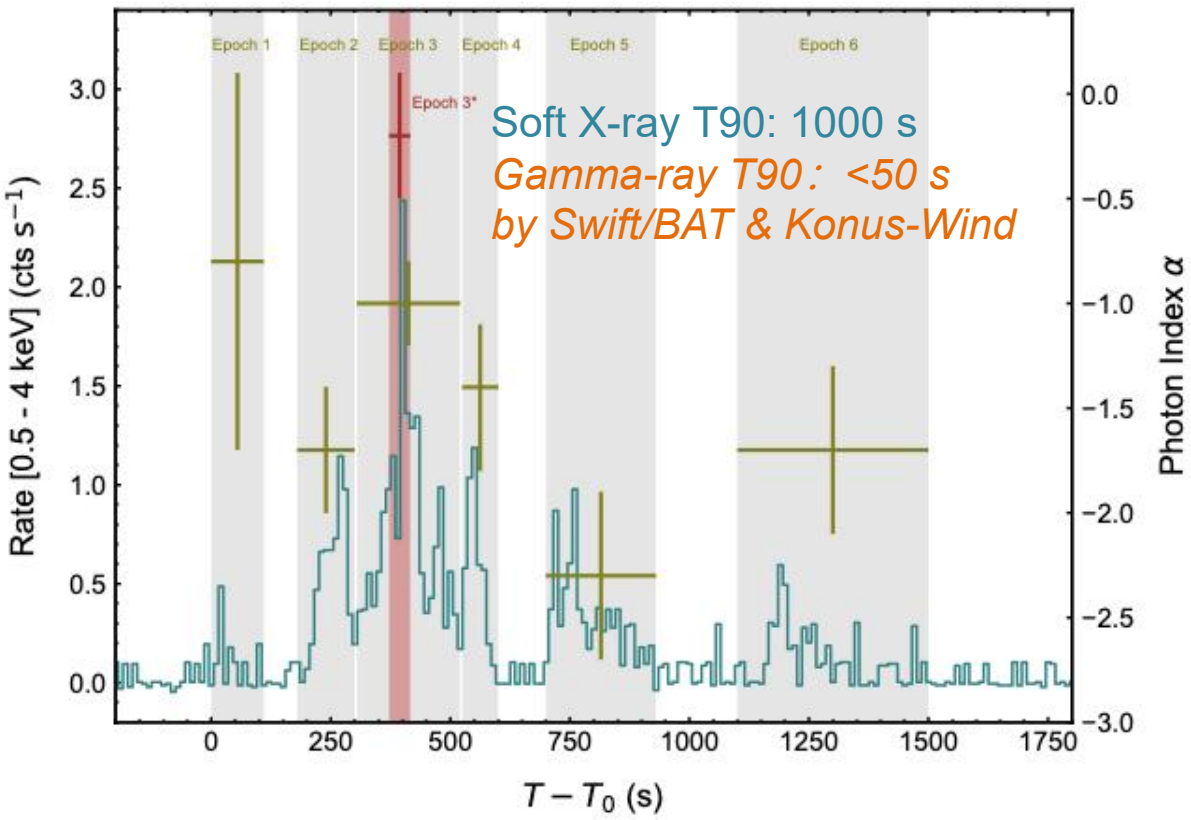
9.3° by 9.3 °, 1 time-frame = 33.3 sec

Yin et al. to appear in ApJL
https://arxiv.org/abs/2409.12613

EP240315a: GRB @redshift 4.859



Onboard trigger, confirmed by on-ground analysis



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)

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

detectable by WXT at z~7.5
EP's potential of detecting high-z GRB !

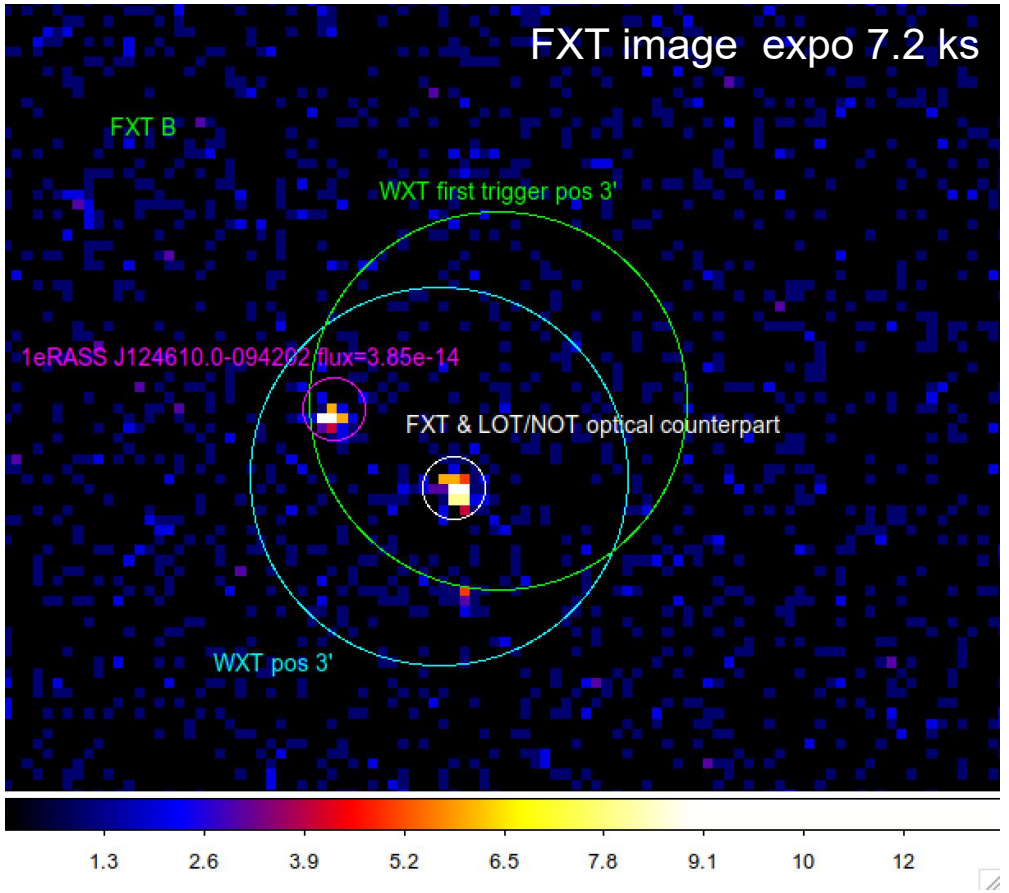
EP240414a: the quickest follow-ups

- WXT onboard trigger (VHF/BD)
  (Lian et al. GCN 36091)

- T0+ 2hrs: FXT follow-up (uplink ToO)
  A new source 1.5'away

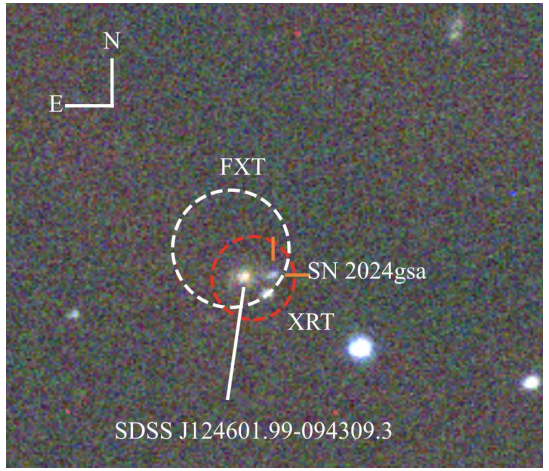
- Optical follow-up
  - LOT + 3.13 hr (AT2024gsa, r= 21.52 mag)
  - NOT +2.29 hr
  - GTC +5 hr
  - BOOTES-4/MET +5.56 hr
  - Pan-STARRS1 +2/3 d
  - GSP + 3.66 d

- Later time detection of associated supernova (Levan et al. GCN 36355)
- Host galaxy z = 0.41
- Projected offset ~25 kpc (Jonker et al. GCN 36110)



90% positioning errors
WXT: 2.1 arcmin
FXT: < 10 arcsec

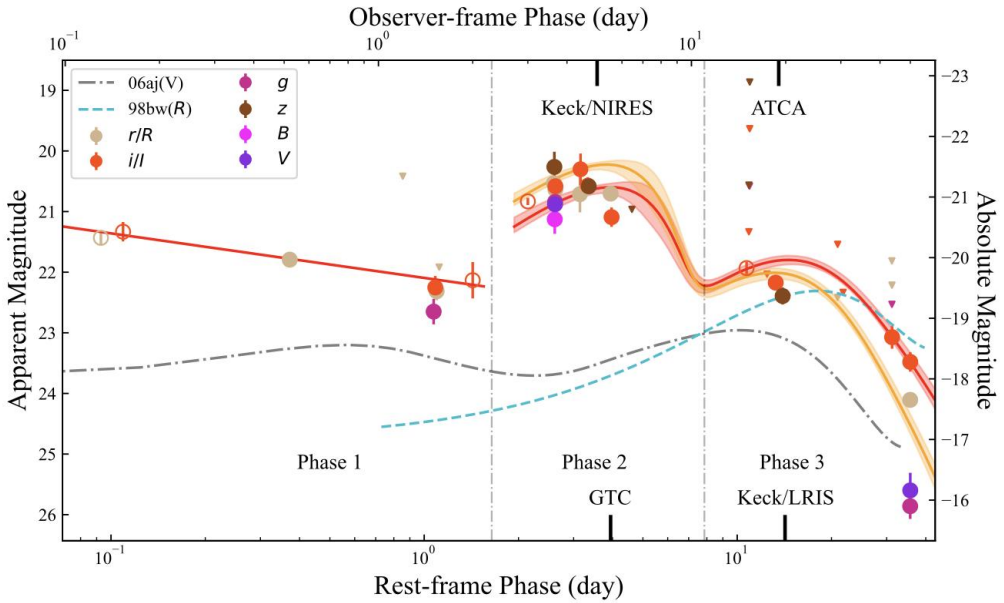
EP240414a: a new type of fast X-ray transient ?

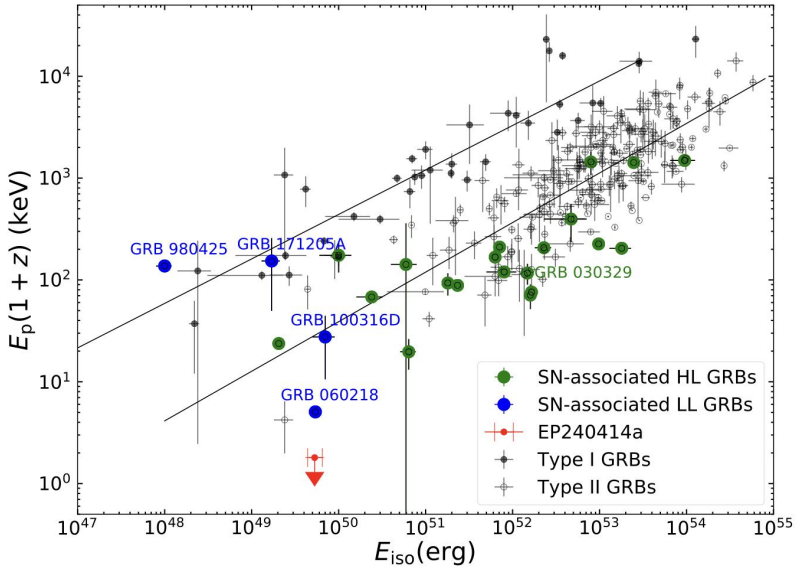


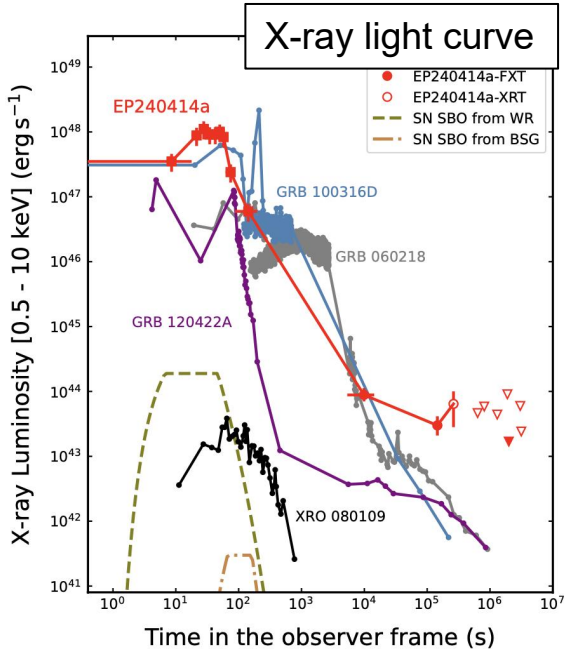
- Associated of a Type Ic-BL supernova SN 2024gsa (z=0.4)
- No significant γ-ray signals associated
- Very soft energy spectrum Ep< 1.3 keV

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

Sun et al. submitted, arXiv: 2410.02315



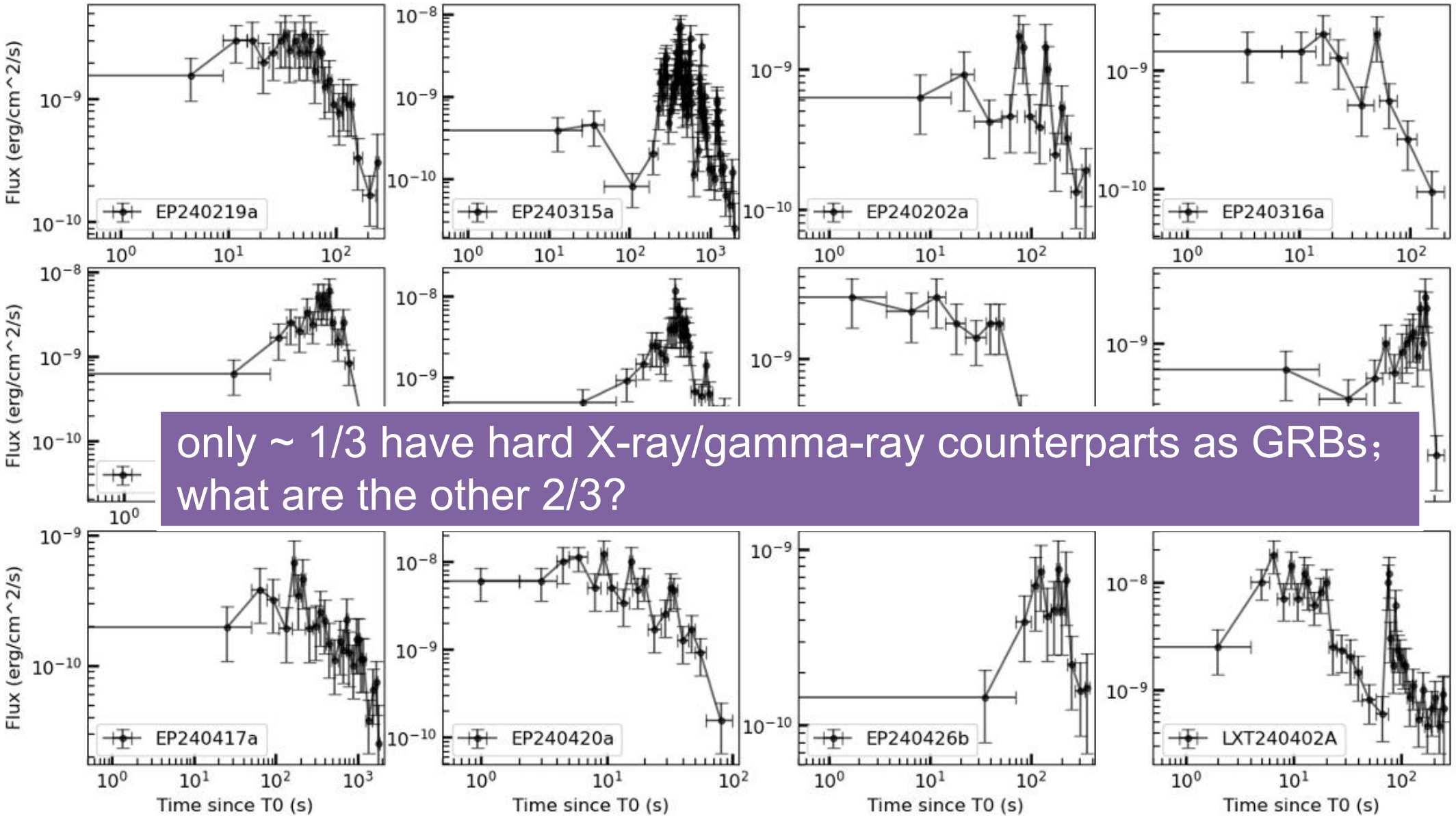




GRBs(4)/Fast X-ray transients (10) by EP & LEIA

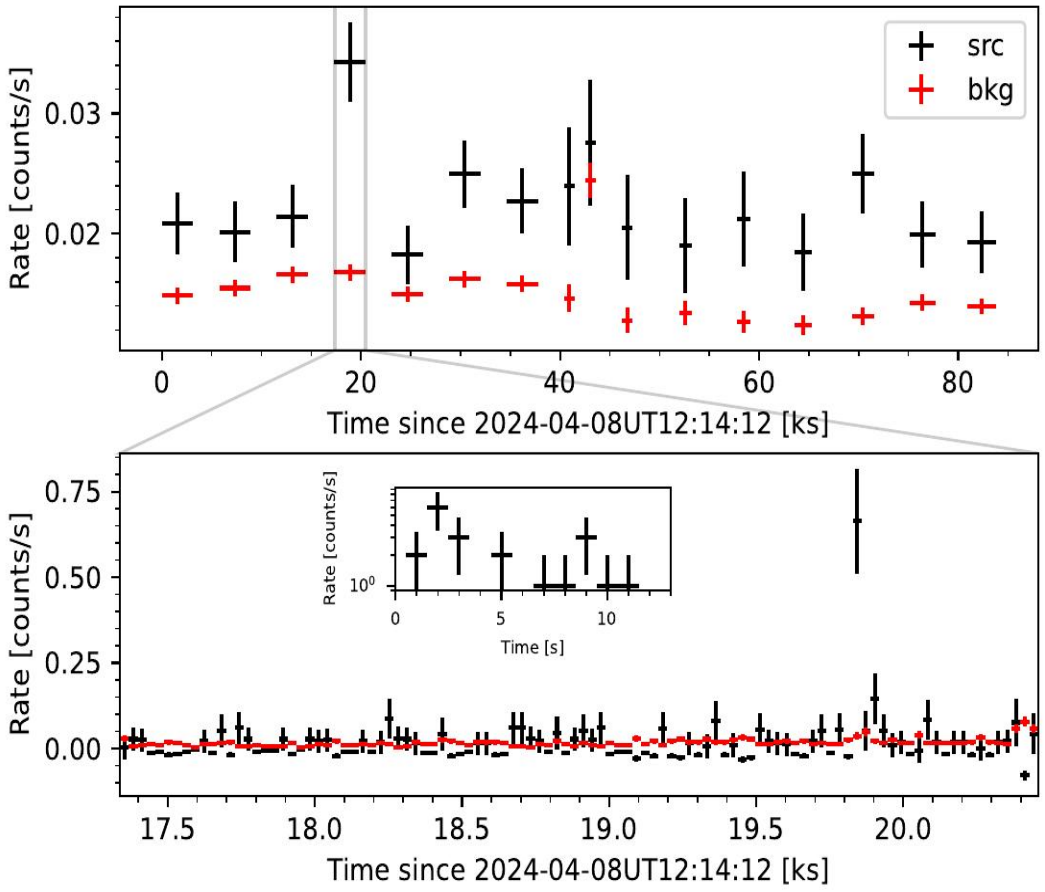
Transient	Duration	Peak Flux erg cm^{-2}s^{-1}	Fluence erg cm^{-2}	γ-ray counterpart	X-ray afterglow	Optical afterglow	z
LXT/GRB 230307A	~180 s	4E-7	2E-5	Y	Y	Y	0.065
EP240219a	~200 s	5E-9	1E-7	Y	X	N	-
EP240315a	~1600 s	3E-9	1E-6	Y	Y	Y	4.859
EP240202a	~300 s	4E-9	9E-8	N	N	N	-
EP240316a	~160 s	3E-9	1E-7	N	N	N	-
EP240331a	~100 s	4E-9	2E-7	N	possible?	N	-
LXT240402a	~200 s	3E-8	5E-7	Y	Y	Y	1.551
EP240413a	~200 s	7E-9	2E-7	N	possible?	N	-
EP240414a	~150 s	3E-9	2E-7	N (GBM off)	Y	Y	0.4
EP240416a	> 200 s	1E-9	1E-7	N (GBM off)	N	N	-
EP240417a	> 1500 s	3E-10	1E-7	N	N	N	-
EP240420a	~80 s	8E-9	3E-7	N	Y	Y	-
EP240426b	~300 s	9E-10	2E-7	N	N	N	-
EP240506a	~50 s	1E-8	5E-8	N	N	N	-

Example light curves of EP fast transients



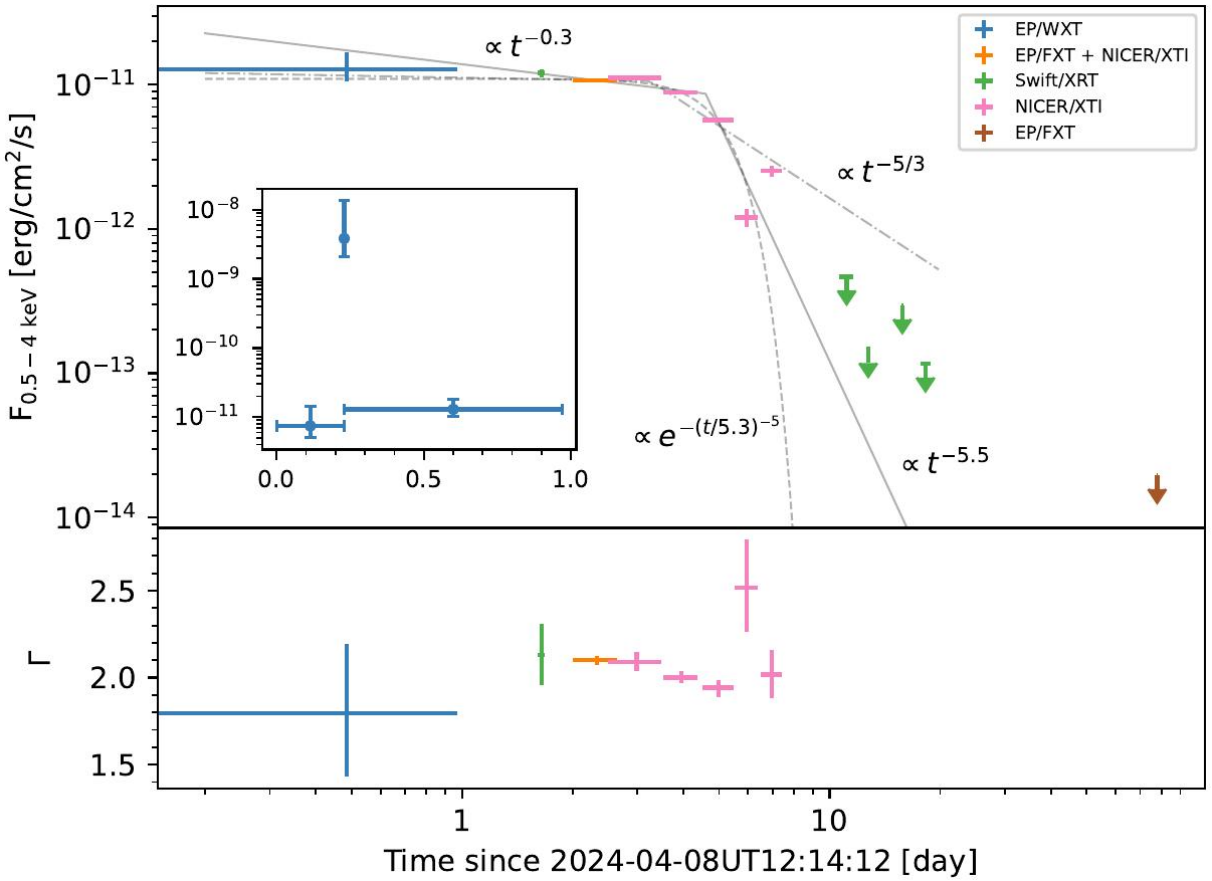
only ~ 1/3 have hard X-ray/gamma-ray counterparts as GRBs; what are the other 2/3?

EP240408a: peculiar intermediate-timescale transient



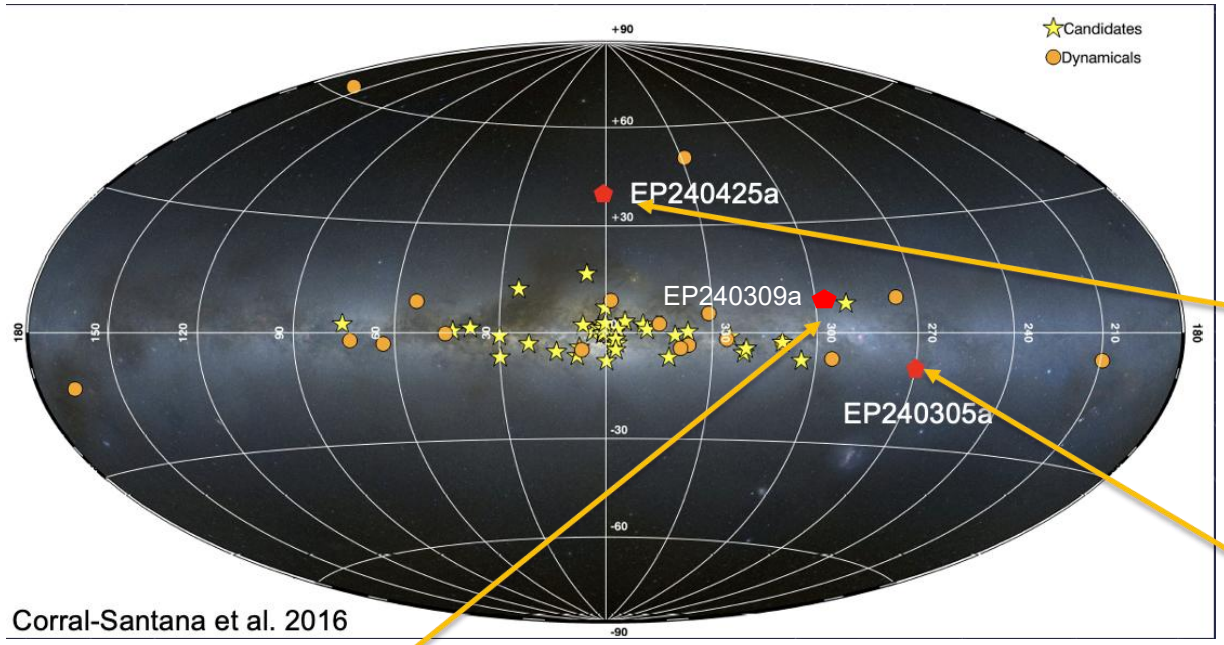
Persistent X-ray emission before flare:
hard to explain as a GRB

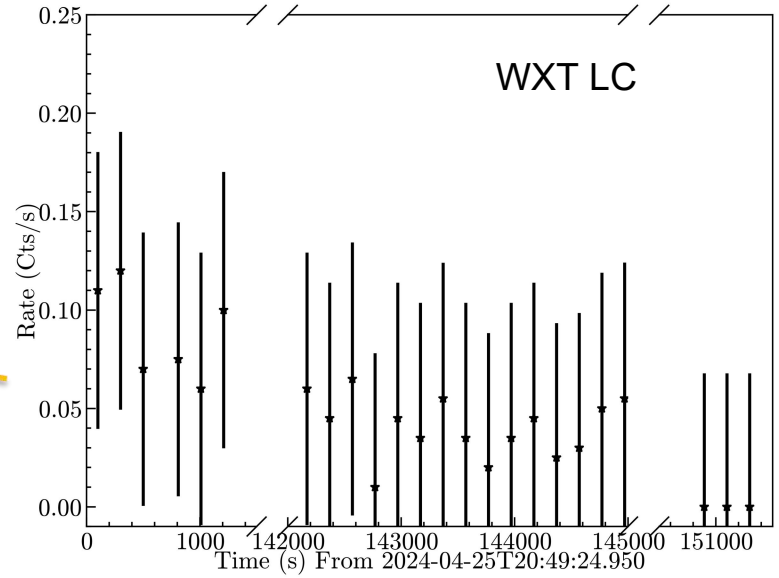
Broken-PL decay in the X-ray light curve



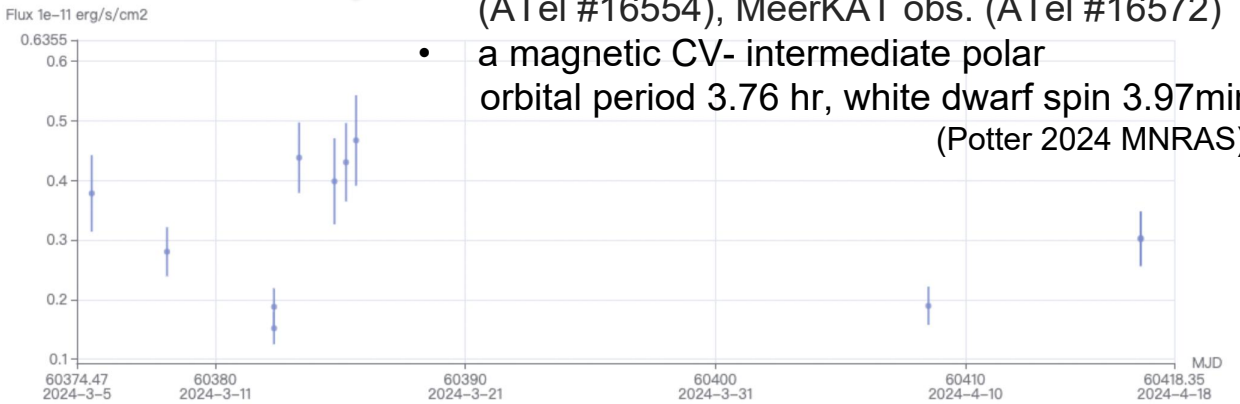
see Dongyue Li's presentation

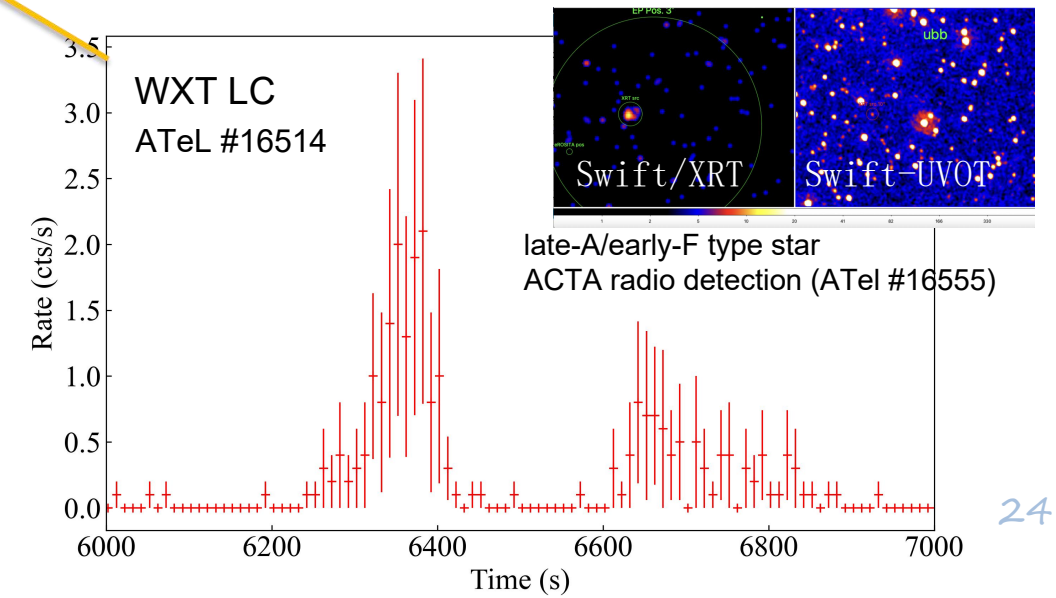
Galactic transients



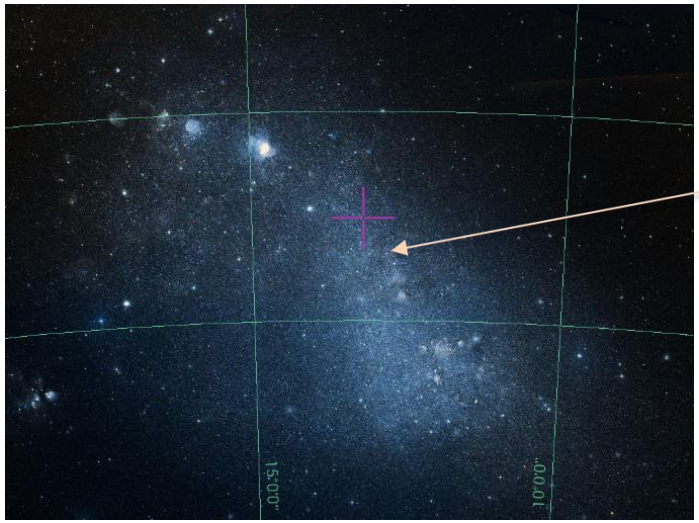


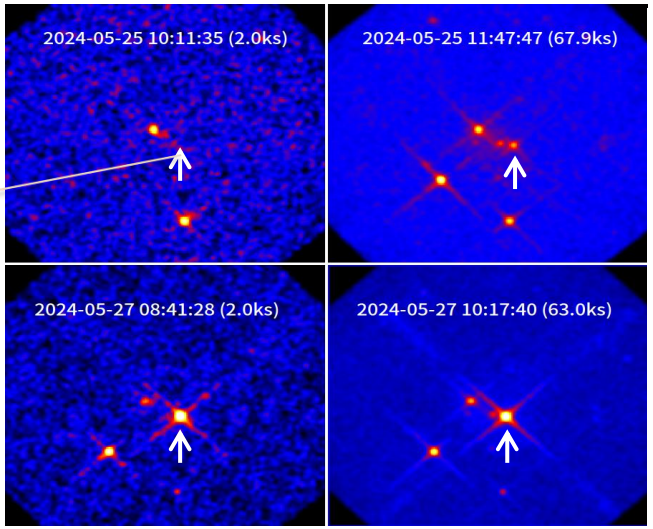
- A bright UV source and highly variable in optical (ATel #16554), MeerKAT obs. (ATel #16572)
- a magnetic CV- intermediate polar
  orbital period 3.76 hr, white dwarf spin 3.97min
  (Potter 2024 MNRAS)

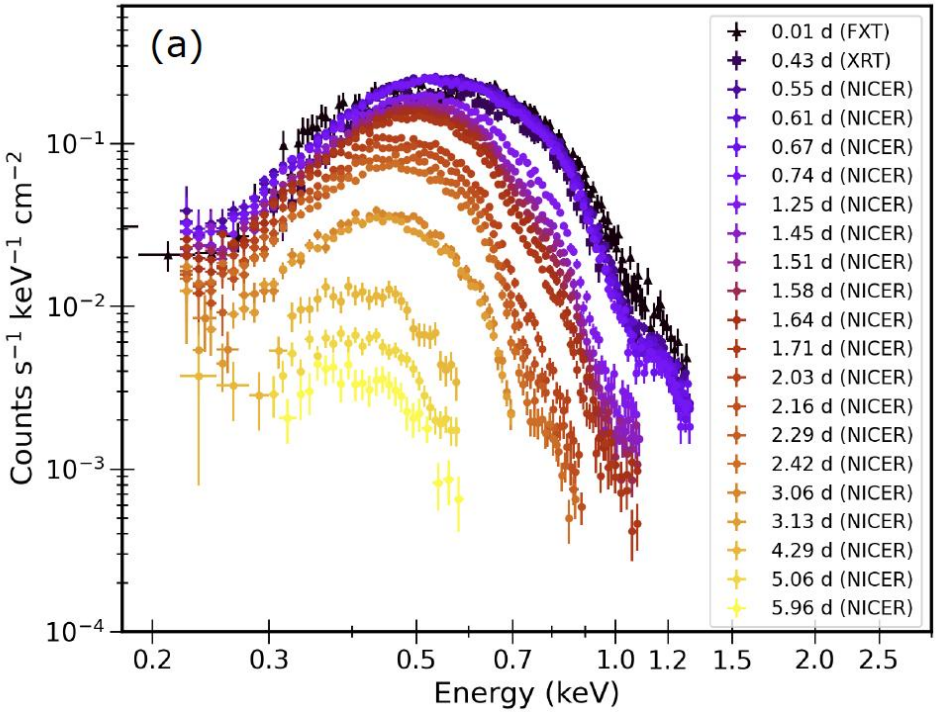


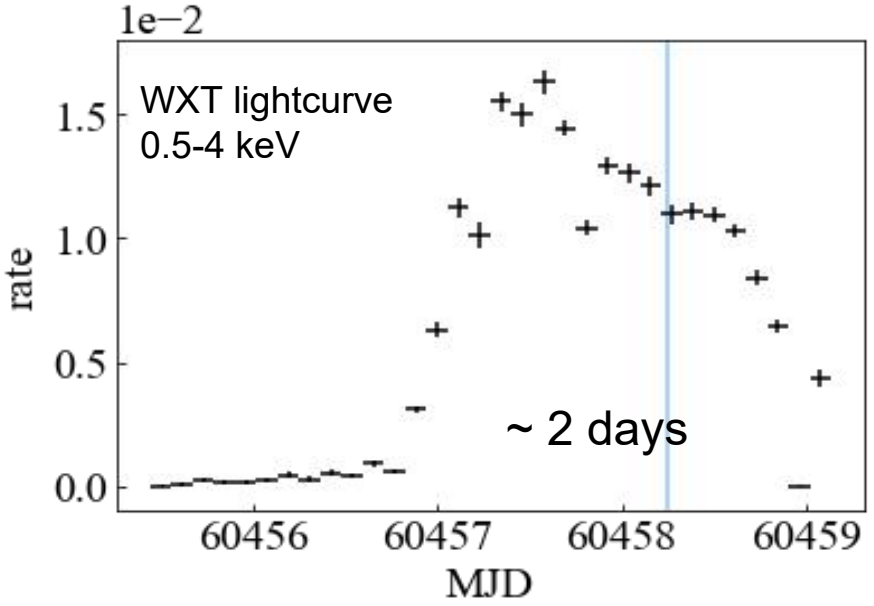


An outburst in Small Magellanic Cloud: Be + WD





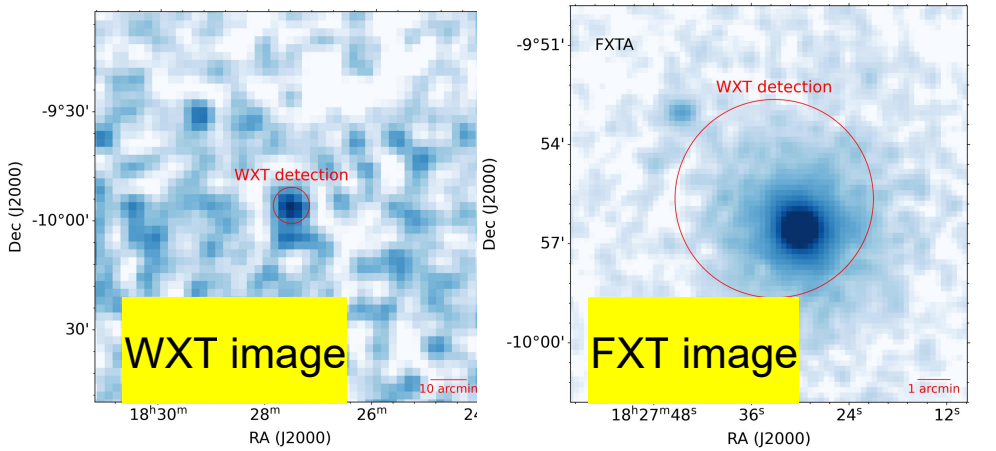


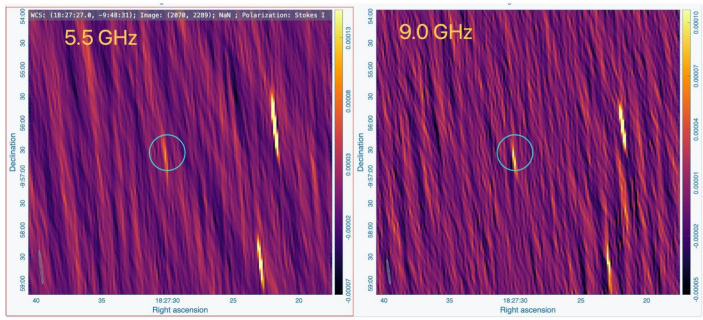


- CXOU J005245.0-722844 a weak Chandra source
- WXT detected its first X-ray outburst (Atel#16631)
- very soft X-ray spectrum
- also by Swift/XRT (ATeL# 16633), follow-up by NICER (ATeL# 16636)
- a possible Be binary system with a WD

Marino, et al. 2024, ApJL submitted, http://arxiv.org/abs/2407.21371

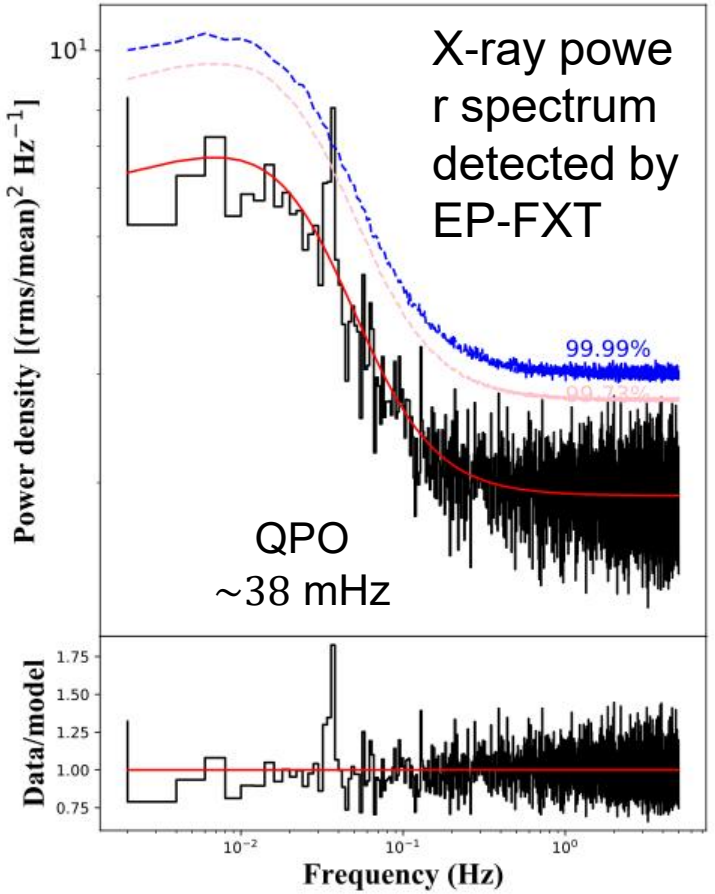
EP240904a: a new X-ray binary (BH?)



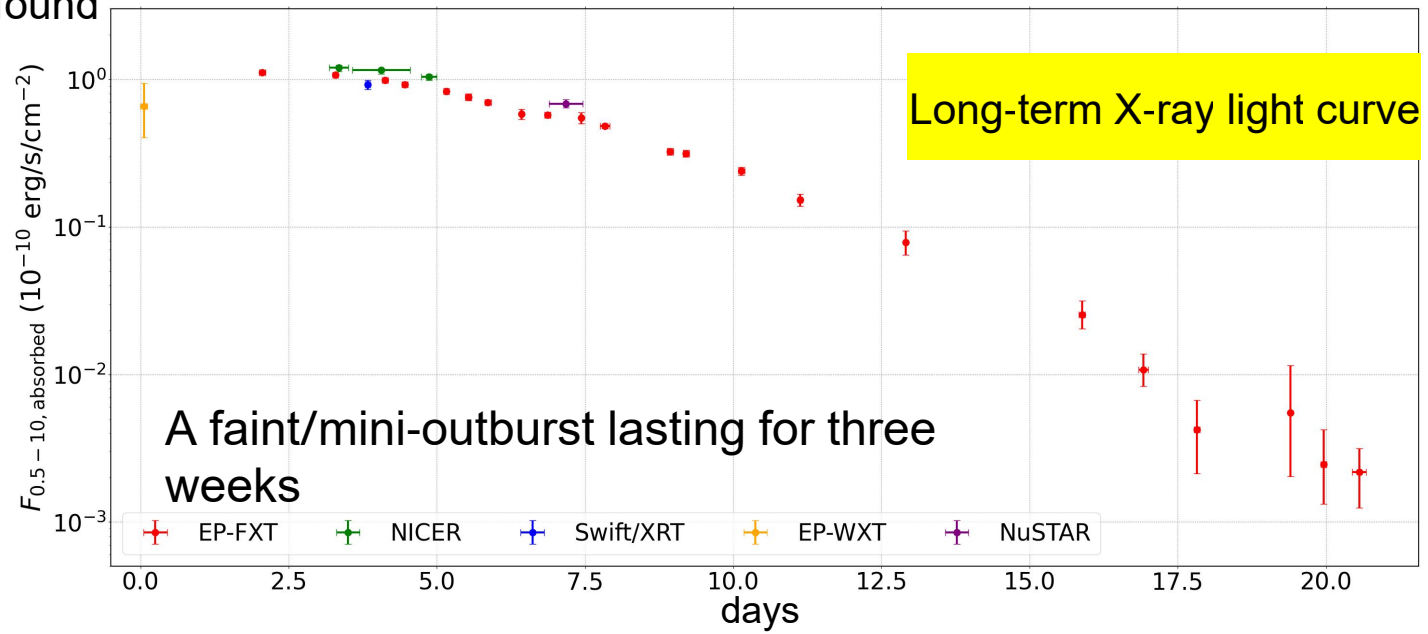


radio: flat spectrum @ X-ray bright state: a compact jet

X-ray spectrum: power-law $\Gamma \sim 2$

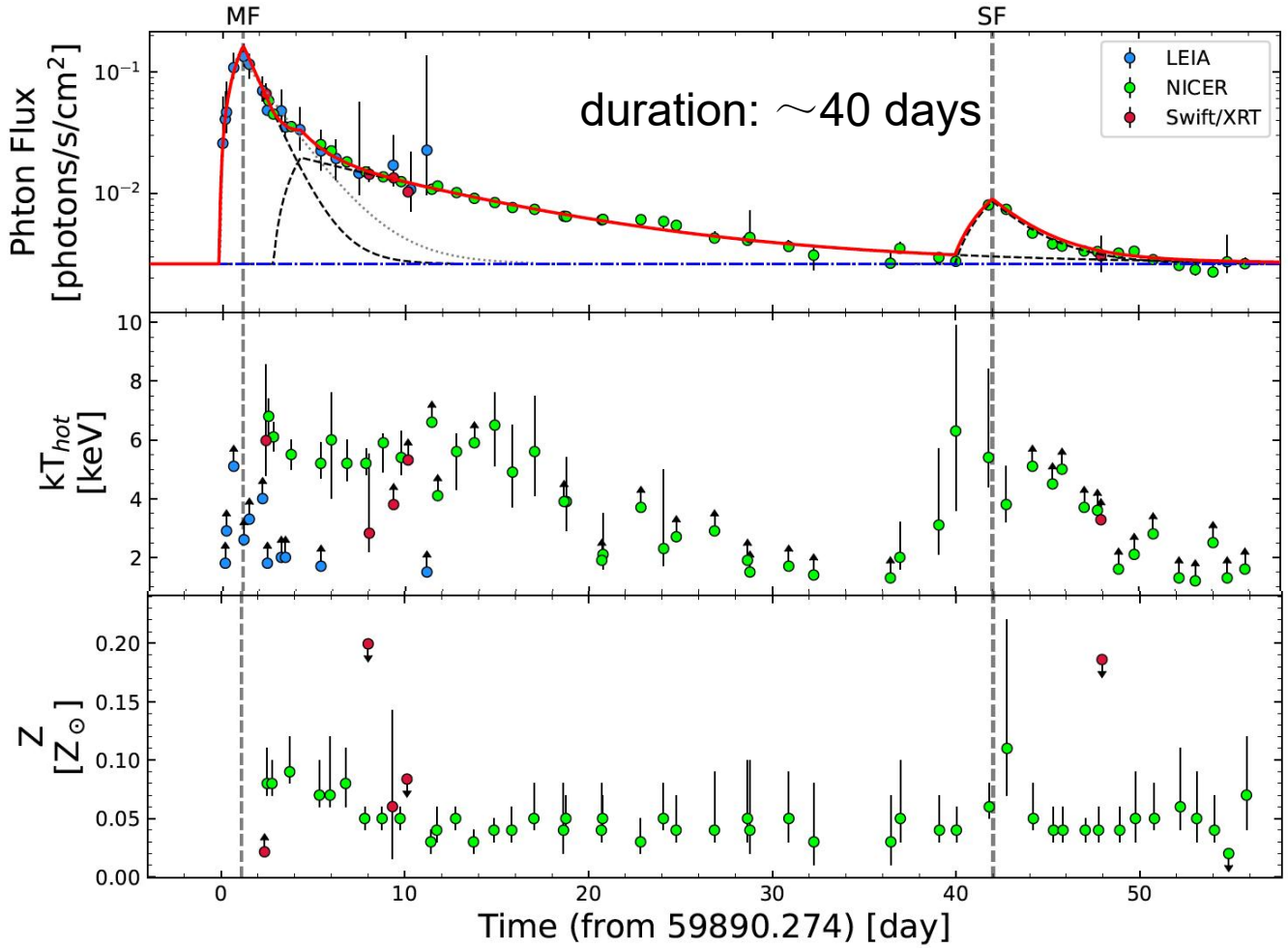


EP J182730.0-095633: Atel # 16805, 16807, 16817, 16825; no optical/NIR counterpart found

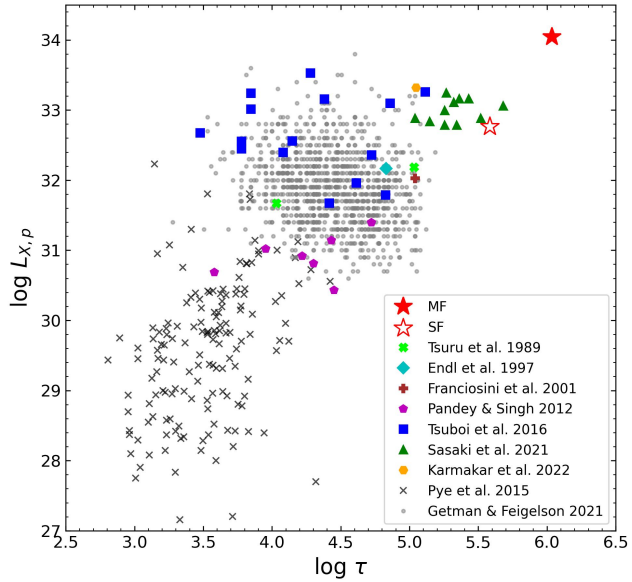


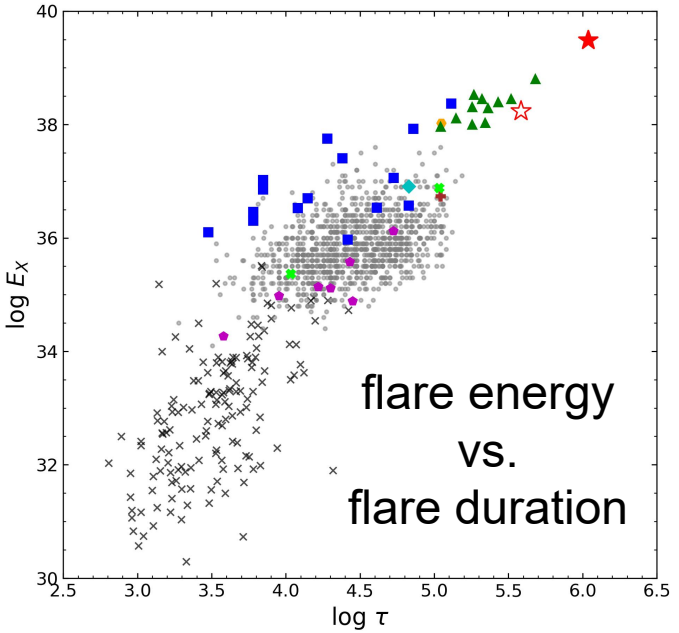
EP team, in prep.

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



peak luminosity
vs.
flare duration



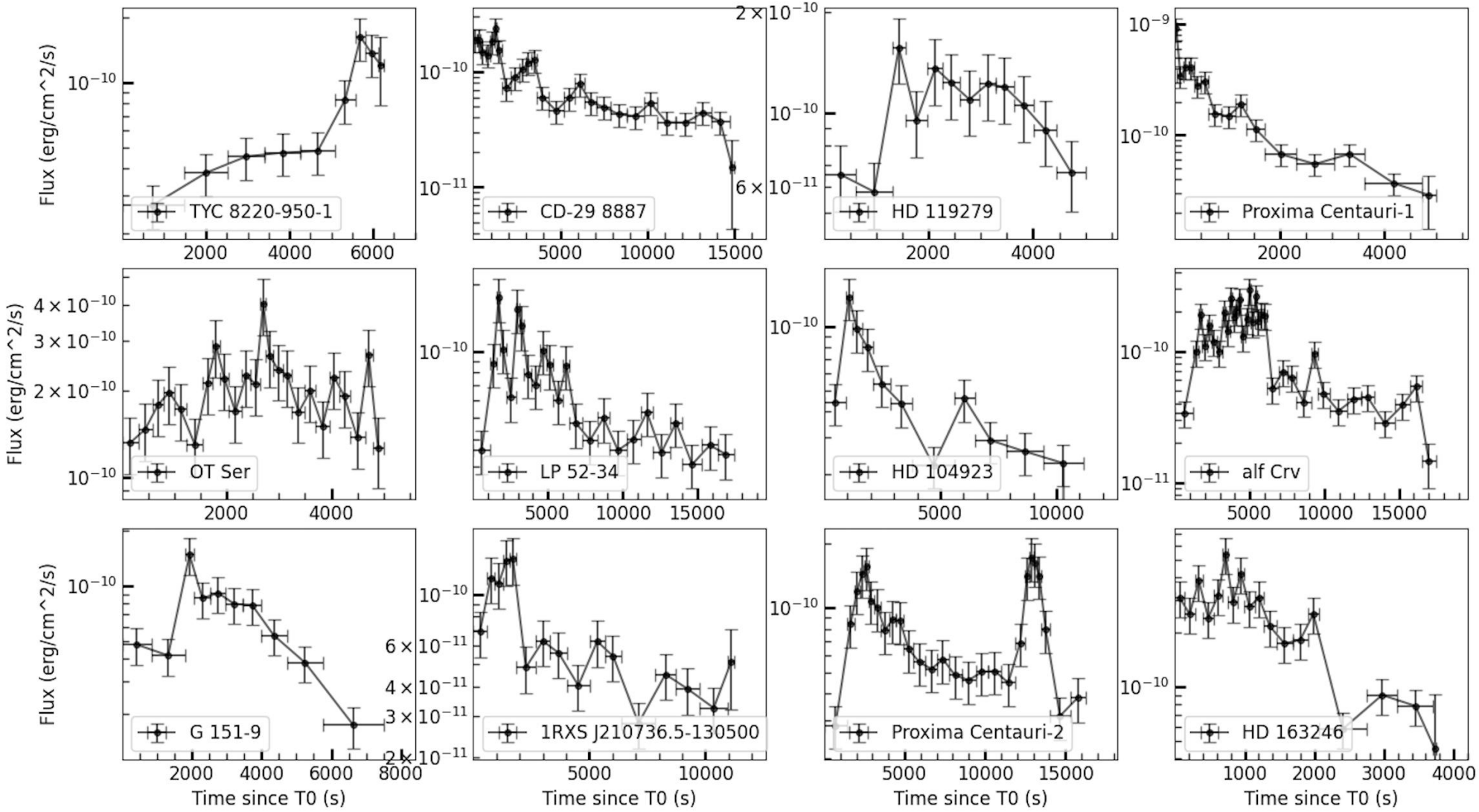


Peak L_X: 1.1E34 erg/s (0.5-4keV); Energy: 3E39 erg (0.5-4keV)

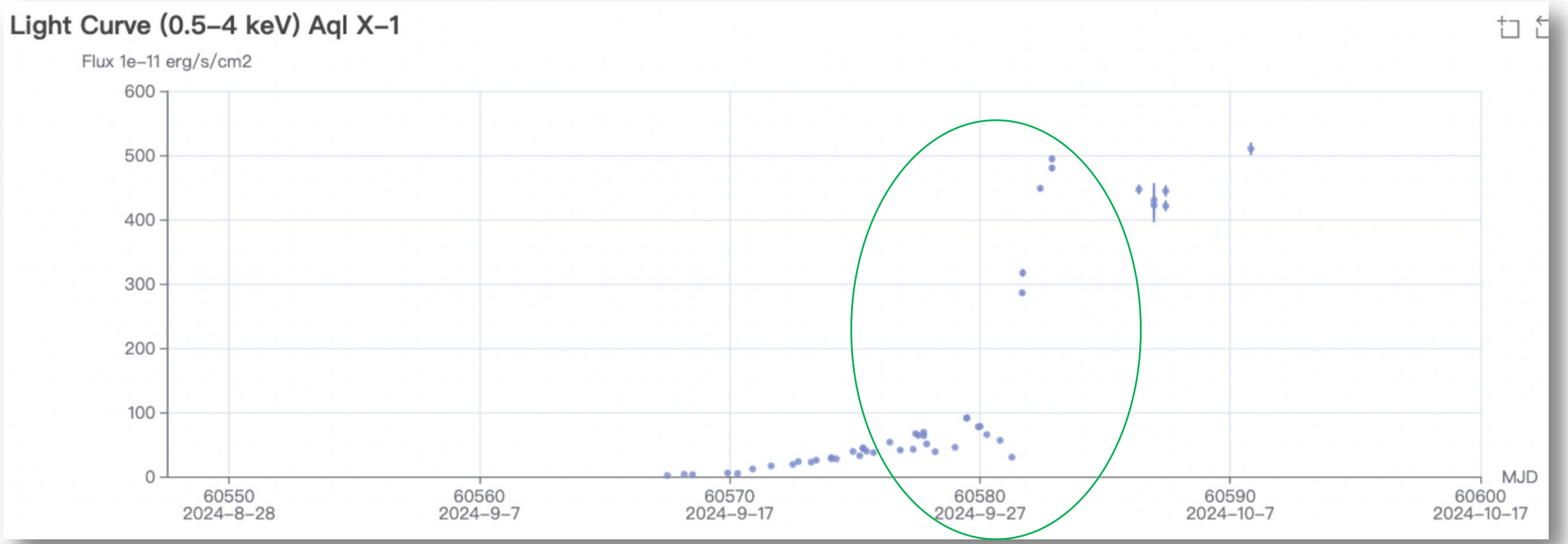
magnetic loop: ~1.9R_star; magnetic field ~ 50 Gauss

Mao X. et al. in prep.

488 Stellar X-ray flares detected with EP-WXT

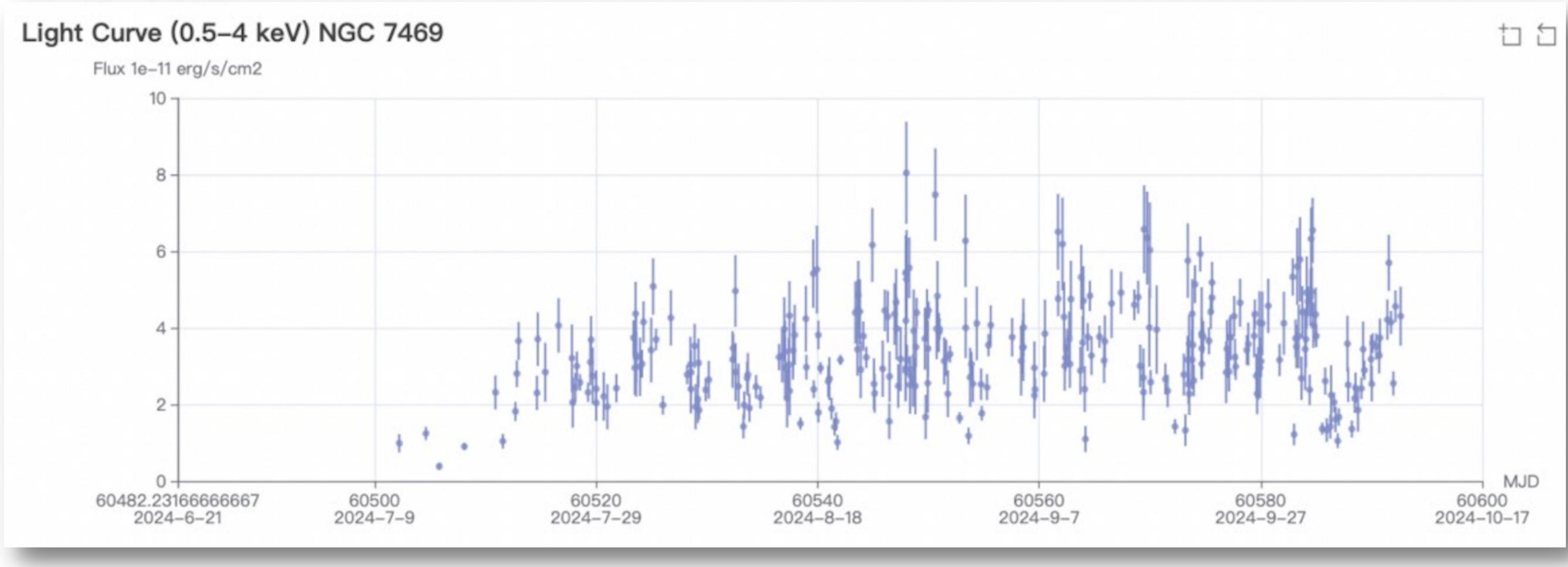


EP-WXT monitoring X-ray sources: NS XRB Aql X-1



recent outburst of Aql X-1

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



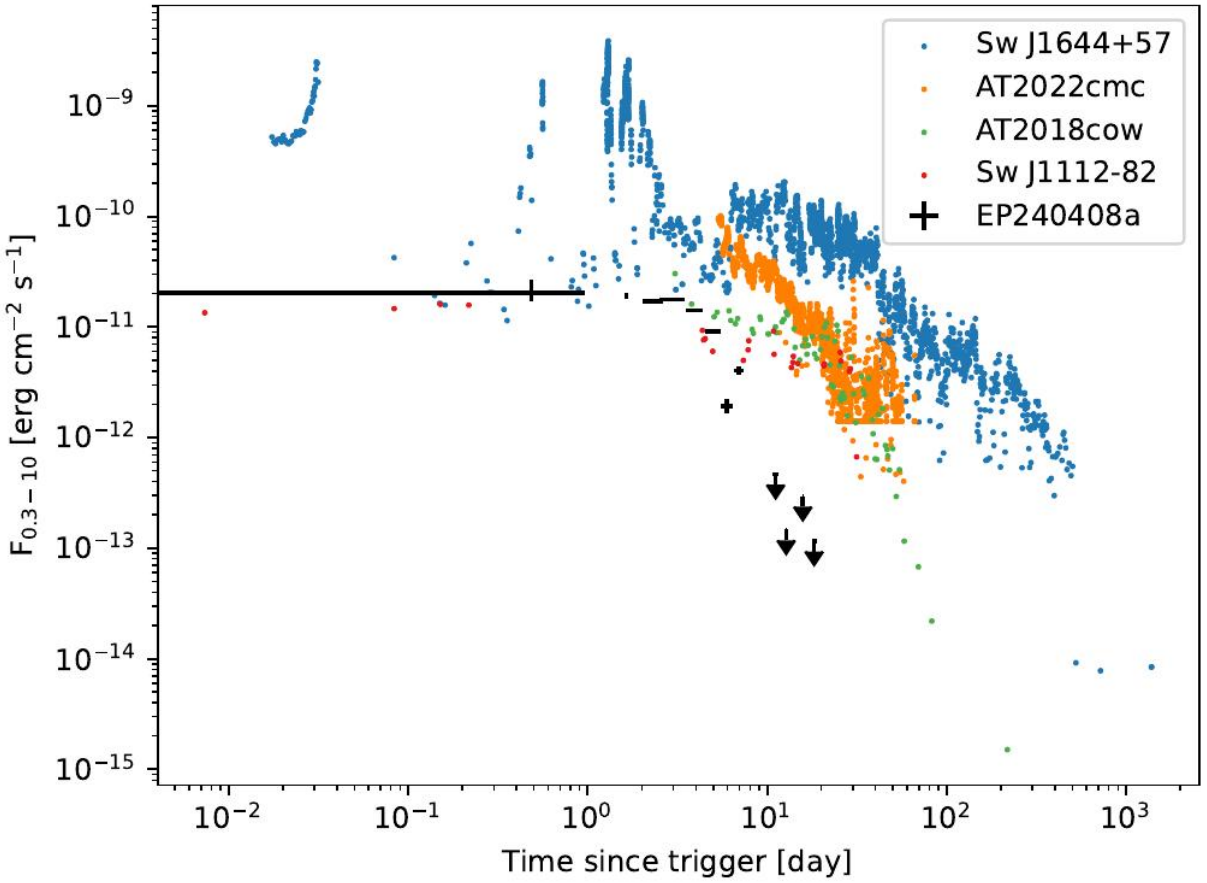
Summary

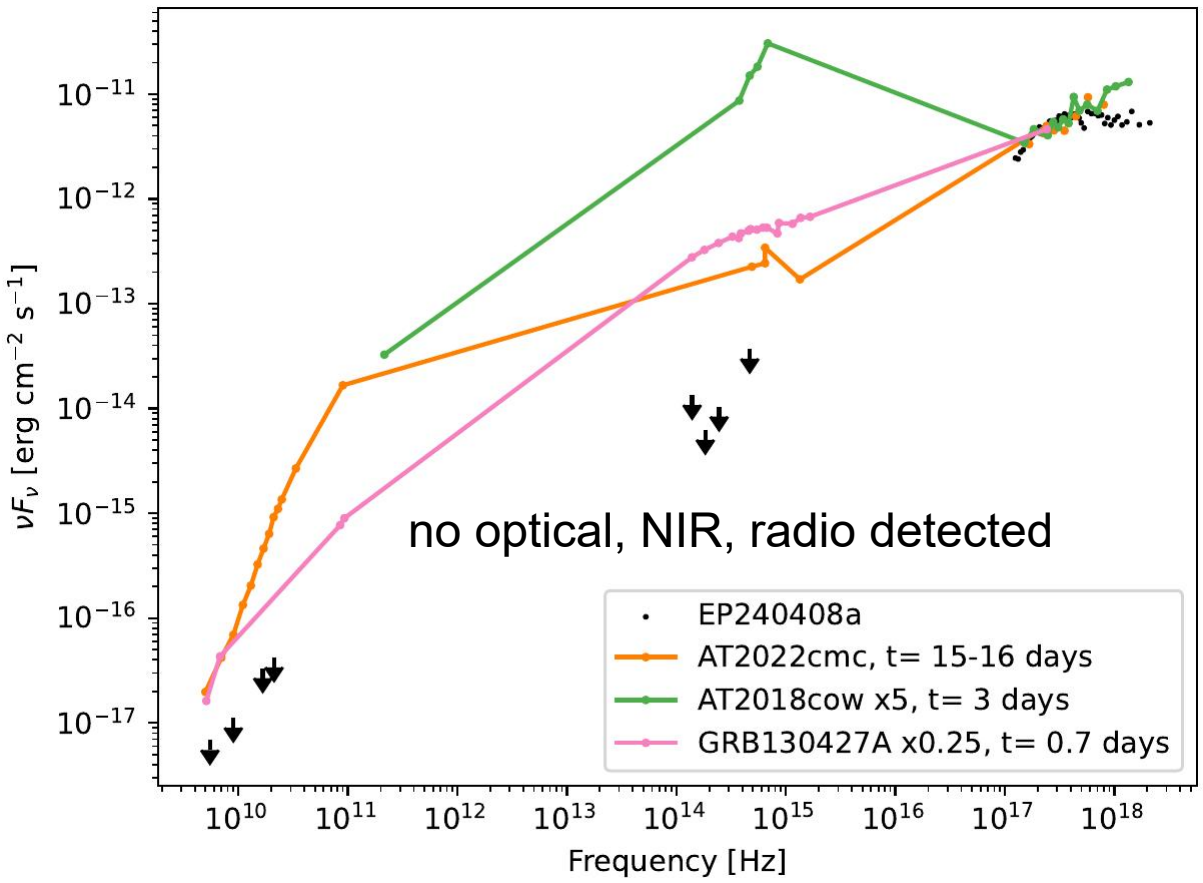
- Since launch on January 9, EP's performance verifications & calibrations have completed
- Nominal science operations just started since July 2024, > 100 GCNs/Atels issued
- ~55 X-ray transients with high/SN (>100 faint ones) have been detected (488 flaring stars)
- A wide range of targets: GRB, SN, TDE, WD+NS+BH in our and nearby galaxy, and more
- Monitored the activity of a sample of known sources
- Great scientific potential in time-domain X-ray astronomy

http://ep.bao.ac.cn
https://www.esa.int/Science_Exploration/Space_Science/Einstein_Probe_factsheet

Thanks to the teams of the Swift, NICER, Chandra, XMM, etc. and ground-based optical and radio telescopes around the world for follow-up observations

EP240408a: peculiar intermediate-timescale transient



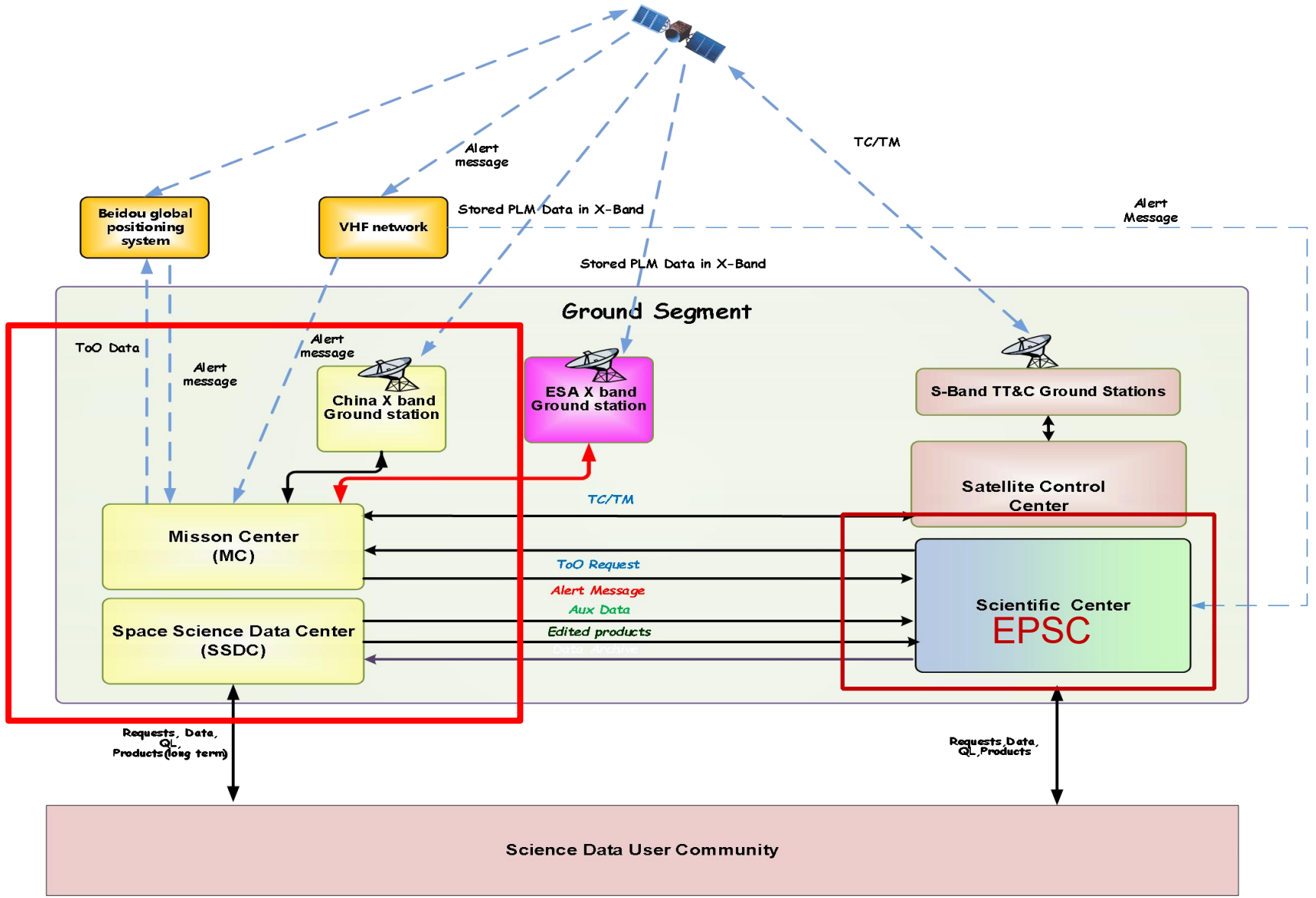


Spectral and temporal properties different from known transients; nature remains unclear!

Perspectives on GRB research

- About 2/3 of the EP fast transients have no significant gamma-ray counterparts
  - detecting GRB in soft X-ray: follow on the legacy of Beppo-SAX and HETE-2
  - previously scarcely detected population, X-ray flash, X-ray rich GRB, ….
- Soft X-ray prompt emission (possible new insight into GRB central engine activity)
  - more extended (longer T90)
  - complicated structure, multiple peaks
- EP240315a: demonstrating the potential in detecting high-z GRB
  - faint flux end of known high-z GRB, detectable at z~7.5 (Liu Y. et al. 2024, Levan et al. 2024, Gillanders et al. 2024)

EP data and information flows

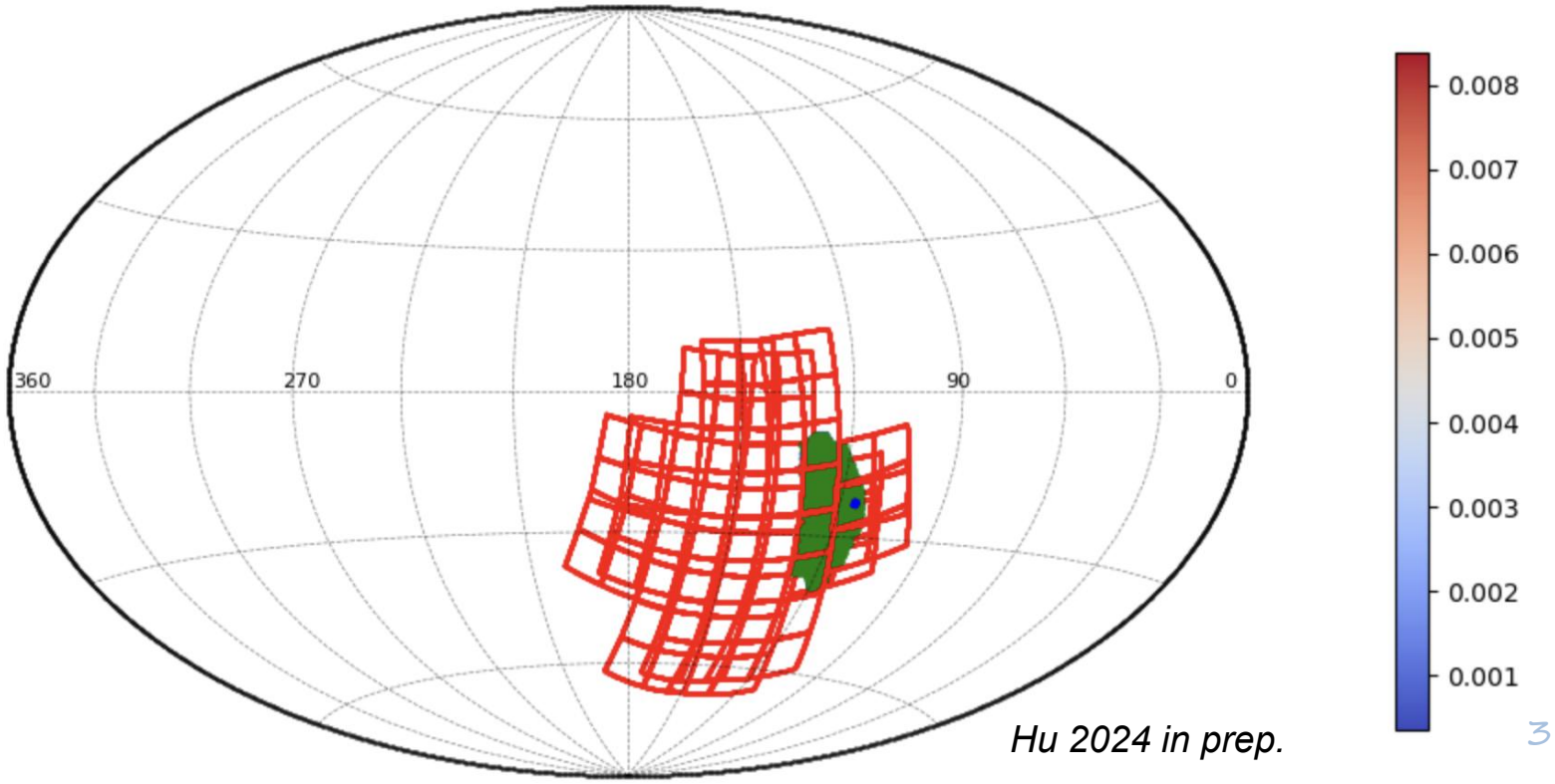


Alerts of transients, ToO & data

- Transient alerts
  - Onboard transient search and trigger unit
  - Alert information quick downlink： minutes
    - VHF (CNES/France)
    - BD system (China)
  - Alert information: release immediately to the community
    - source position, flux, time, spectral parameter
- ToO command uplink
  - Normal (S-band): < 1 day
  - Time critical (BD) < 10 min
- Science data
  - X-band telemetry: it takes about a few hours to reach EPSC
  - Will be made public (community outside EPST) after proprietary periods
  - Non-ToO data: one year
  - ToO by EP science team: 6 months
  - ToO by guest observers: released immediately

Search for potential X-rays from GW event S240422ed

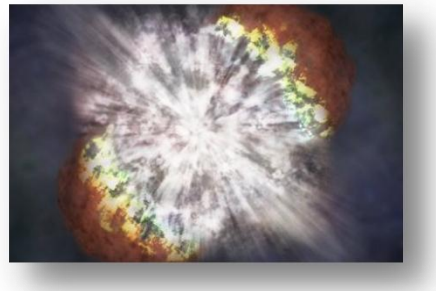
- On April 22, GW event NS+BH (>99%), 214 +/- 64 Mpc
- EP observations: started ~ 3 hrs after GW trigger (yet to be improved)
- Covered with WXT and set X-ray flux upper limits (GCN: 36270, 36277, 36282)
- Searched >100 galaxies with FXT



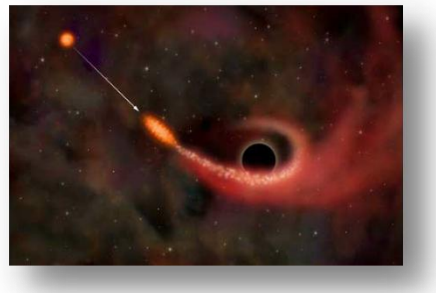
Hu 2024 in prep.

Main science objectives

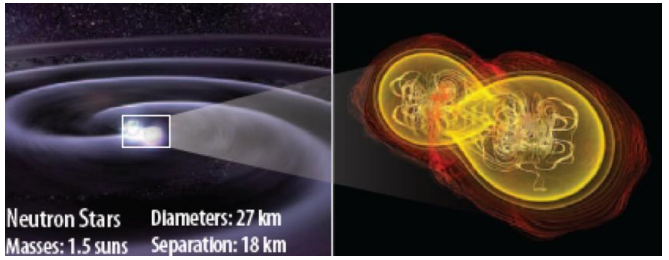
Systematic survey of soft X-ray transients and variability of X-ray sources with unprecedented combination of sensitivity and cadence



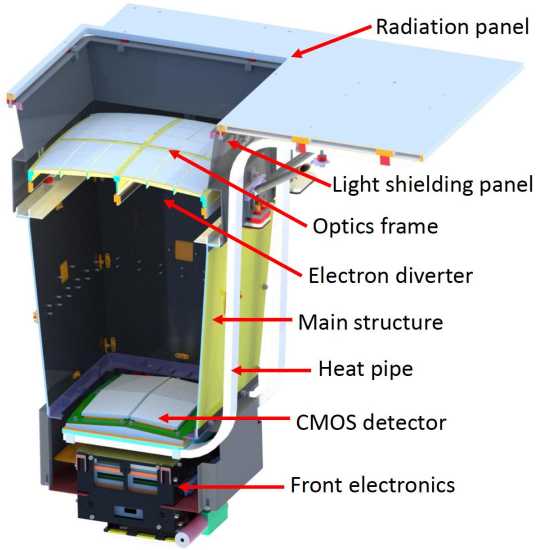
Discover otherwise quiescent black holes at almost all astrophysical mass scales and other compact objects by capturing their transient X-ray flares



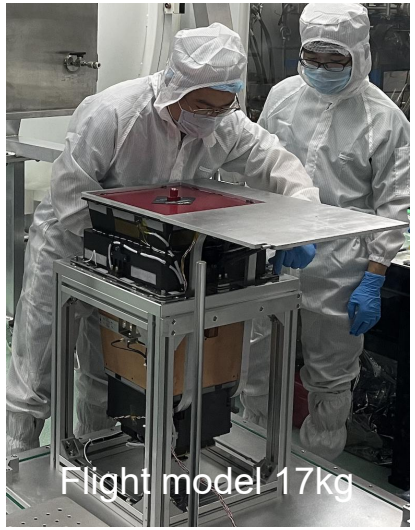
Detect and localise the electromagnetic-wave sources of gravitational-wave events by synergy with gravitational-wave detectors



Wide-field X-ray Telescope

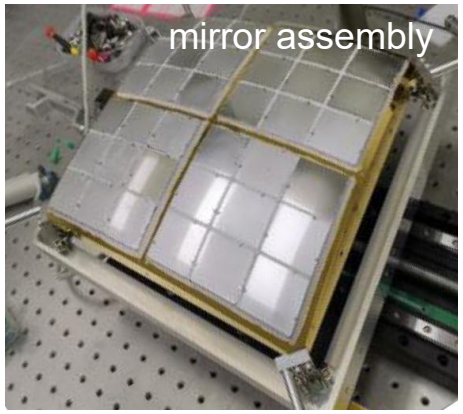


one module



Lead of LE mirrors
Chen Zhang (NAO/CAS)

WXT chief designer
Xiaojin Sun (SITP/CAS)



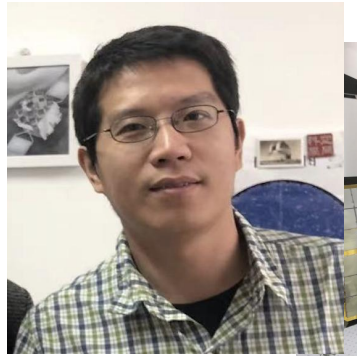
MPO plates (developed by NNVT jointly with NAO/CAS)

41mm x 41mm each

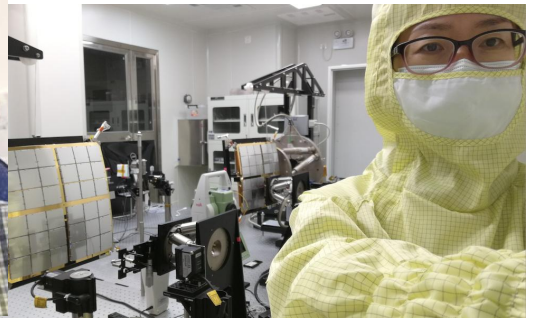
BI CMOS sensors

Time resolution 50ms

ΔE ~ 122eV @1.25keV



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

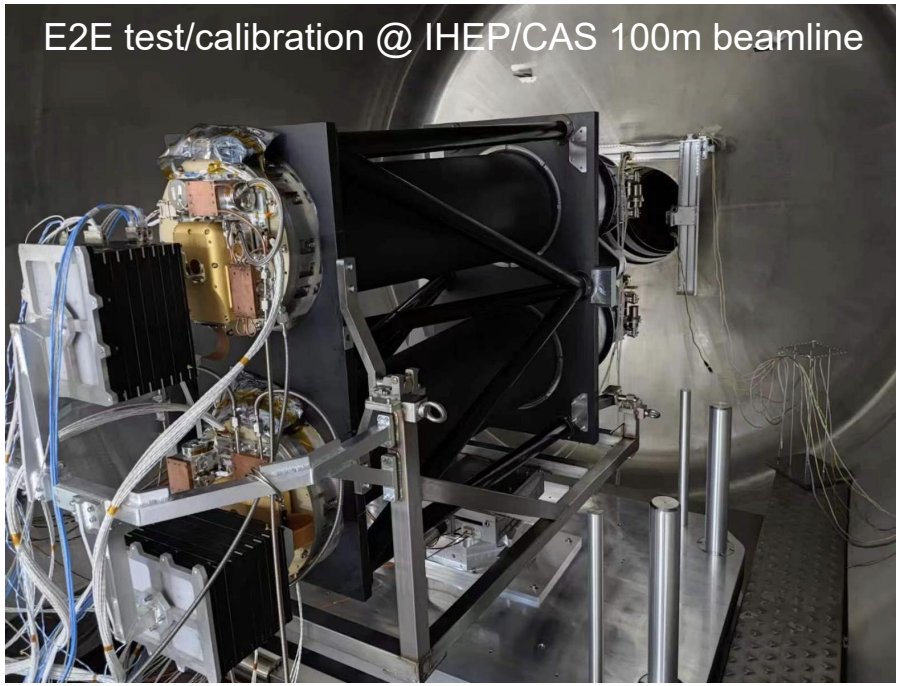


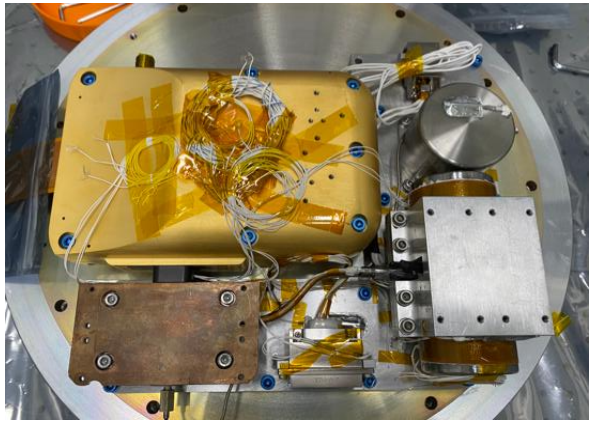
MA engineer
Yanfeng Dai (NAO)

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.

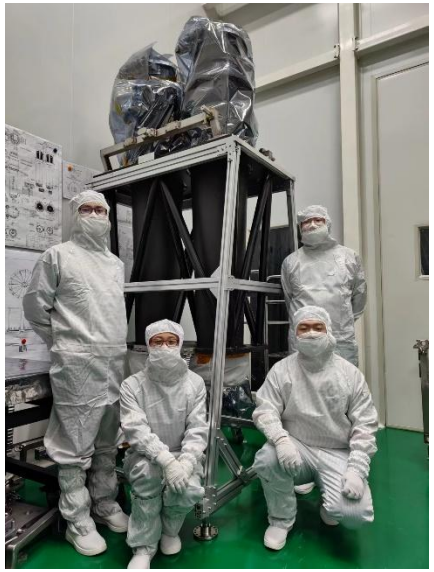




X-ray camera built @ IHEP/CAS

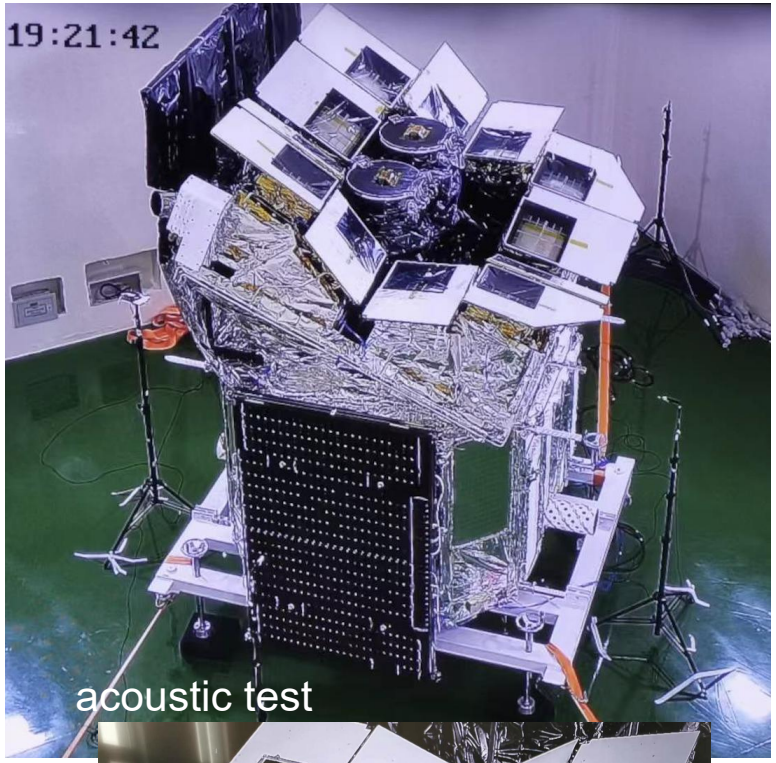
PI: Yong Chen (IHEP/CAS)

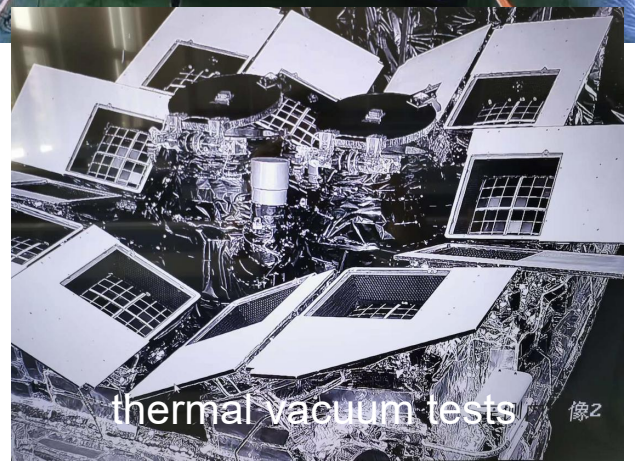
Camera lead: Weiwei Cui (IHEP/CAS)



FXT Delivered by IHEP team to MicroSAT on May 26

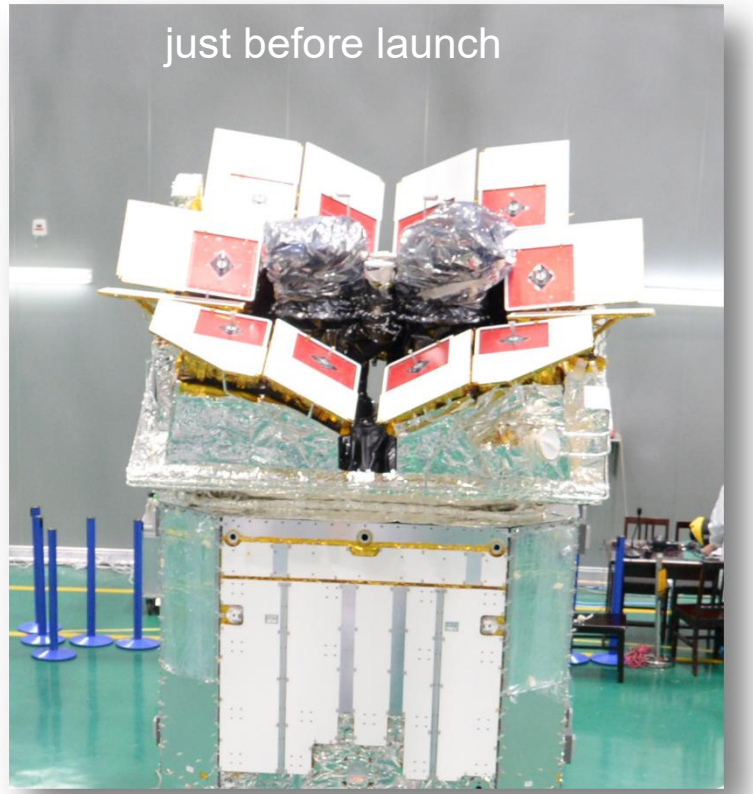
EP satellite





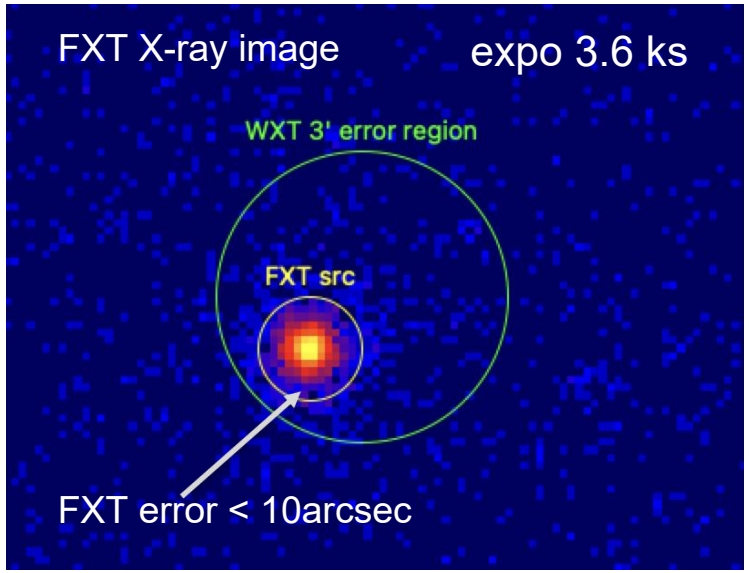
S/C developed @ MicroSat/CAS, Integration & tests

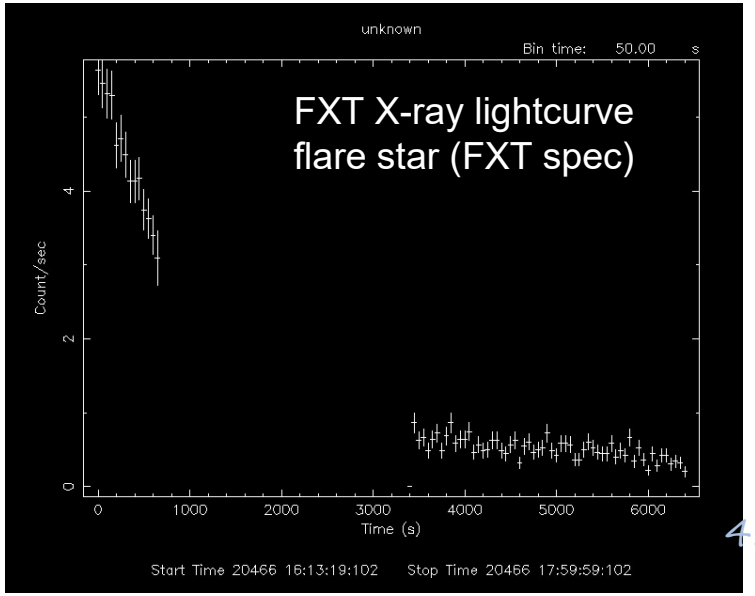
Satellite weight	1430 kg
Power	1150 W
Dimension	3.418(H) × 2.591(D) × 10.309(W) meters



Onboard trigger for FXT automated follow-up

- EP240801a 2024-08-01T09:06:03 (UTC),
- transient info downlink within minutes (BD & VHF)
- FXT follow-up obs.
  - 180s after the WXT trigger





X-ray image of the Moon observed with EP-FXT