Einstein Probe and its role in multi-messenger astronomy

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National Astro. Obs.， CAS

on behalf of the EP consortium

Image credit CAS/ESA

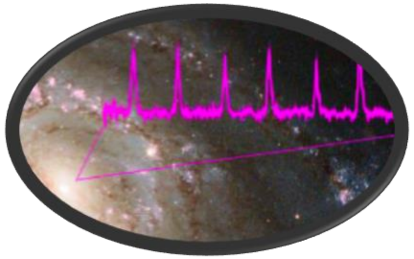
Outline

- Scientific & technical background
- Einstein Probe (EP) & science capabilities
- Selected discoveries of transients by EP
- Its role in multi-messenger astronomy

New high-energy transients & science questions

BH tidal disruption event

Demography of Black holes
How matter falls onto BH?
How jets form?



Quasi-periodic eruption

EMRI as GW sources?

High-redshift GRB

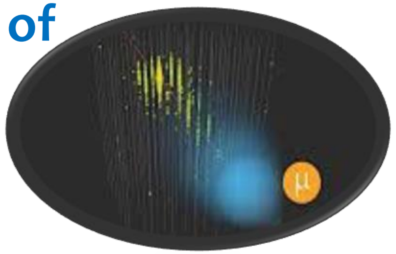
When first stars formed?
metal enrichment in early universe

Next generation X-ray monitors needed to see

- **deeper/further**
- **High cadence**

EM counterpart of neutrino events

How particles Accelerated?



Supernova shock breakout

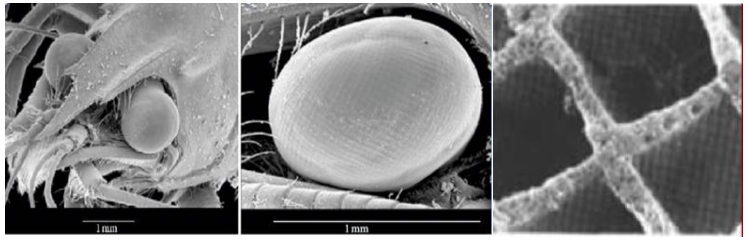
Supernova physics & progenitors

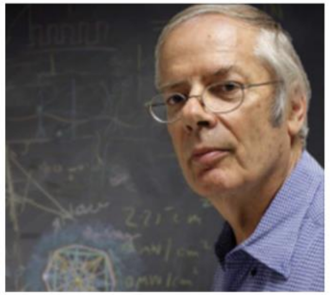
EM counterpart of gravitational waves

What are EM counterparts?
How compact objects merge?

Lobster-eye optics for X-ray focusing imaging

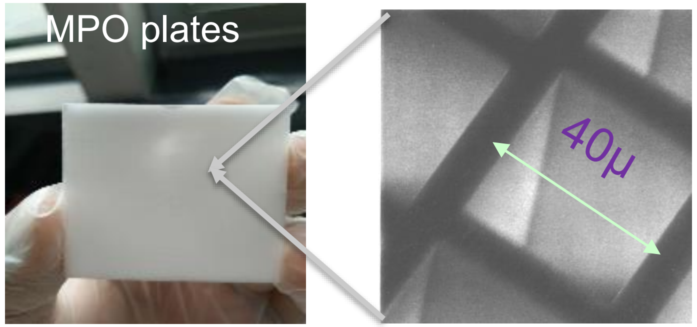
grazing incidence reflection by Lobster-eye Micro-Pore Optics (MPO)

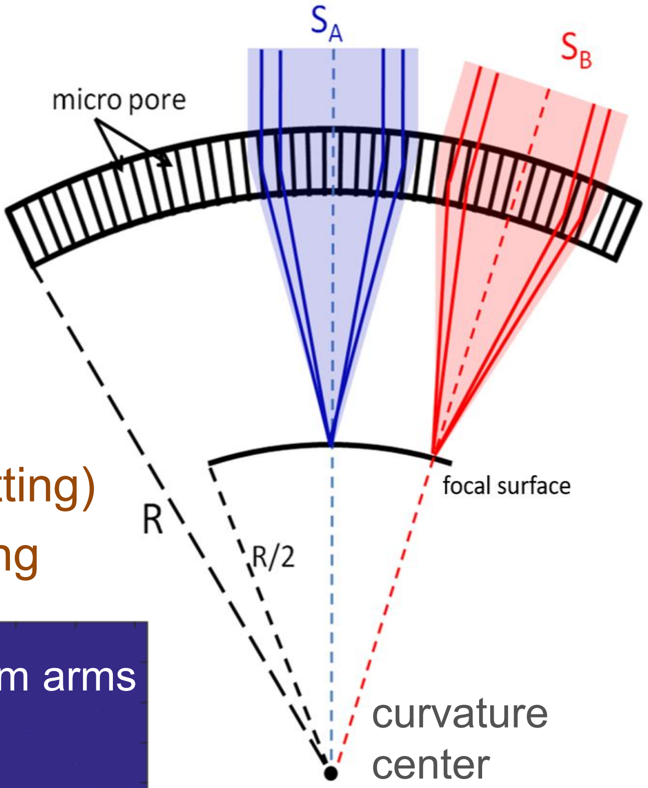




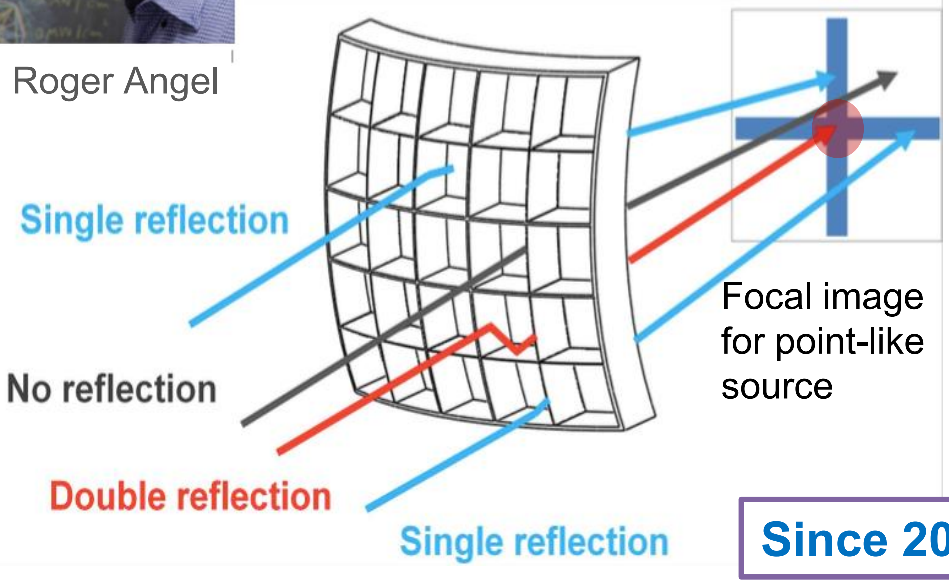
Dr. Roger Angel

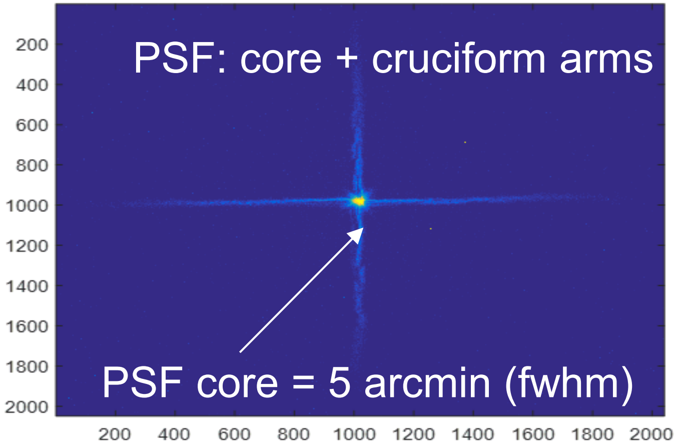
image credit:
http://www.as.utexas.edu/lectures/great_lecture_twenty.html





- Wide FoV (no vignetting)
- True focusing imaging





measured X-ray PSF mage @XIL/NAO/CAS

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

Einstein Probe (EP) - Tianguan (天关) 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

- 2011 Lobster-eye R&D @ XIL/NAO & X-ray ASM on CSS
- 2012 Mission concept
- 2017/12 Funded by the 2nd phase of the Space Science Programme (CAS)
- 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

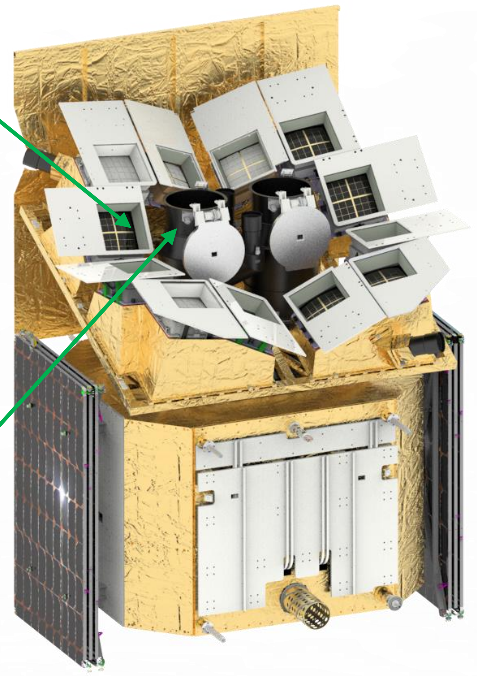
Wide-field X-ray Telescope
WXT (12 modules)

Lobster-eye MPO + CMOS
FoV: 3,850 sq deg
Band: 0.5 – 4 keV
Effe. area: ~3 cm^2 @1keV
Resolution: ~ 5' (FWHM)

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

esa

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



Spacecraft

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

Telemetry

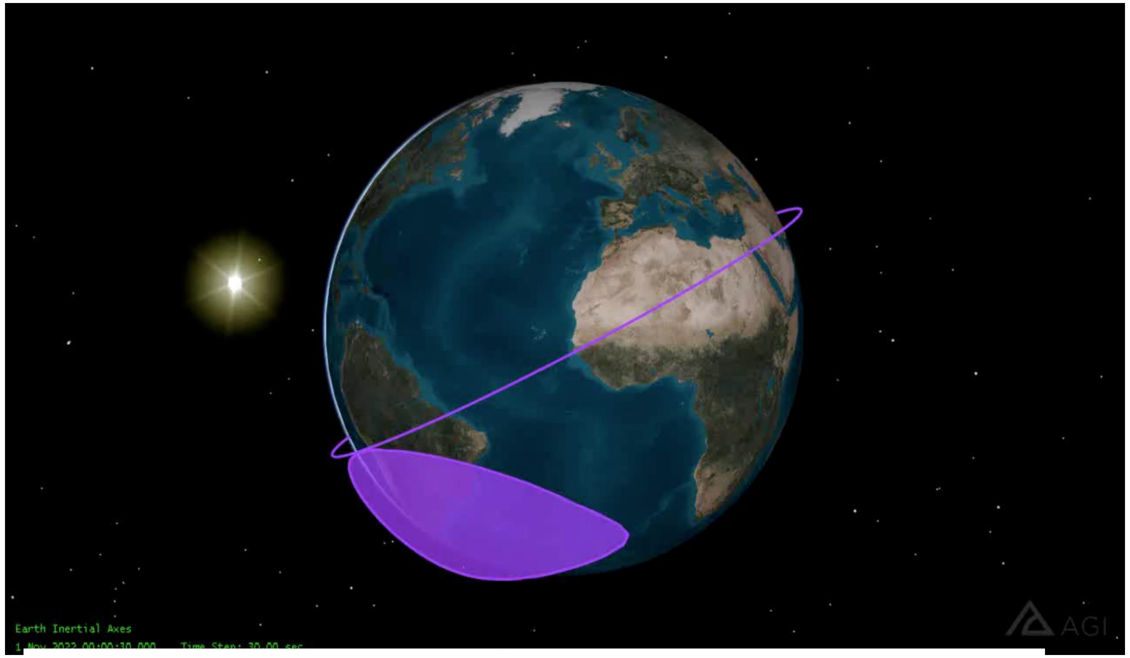
esa

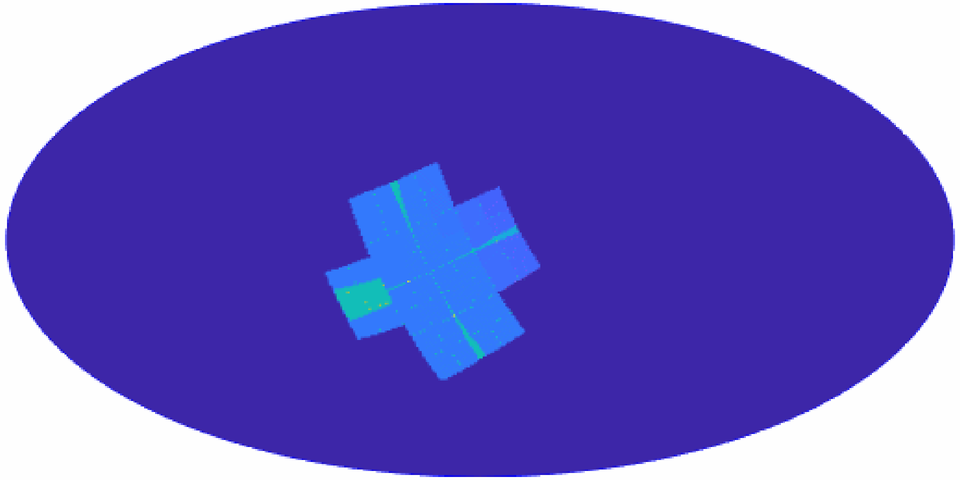
X/S-band (several hours)
BD (down/up-link; minutes)
VHF (down-link; minutes)

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

Mission profile

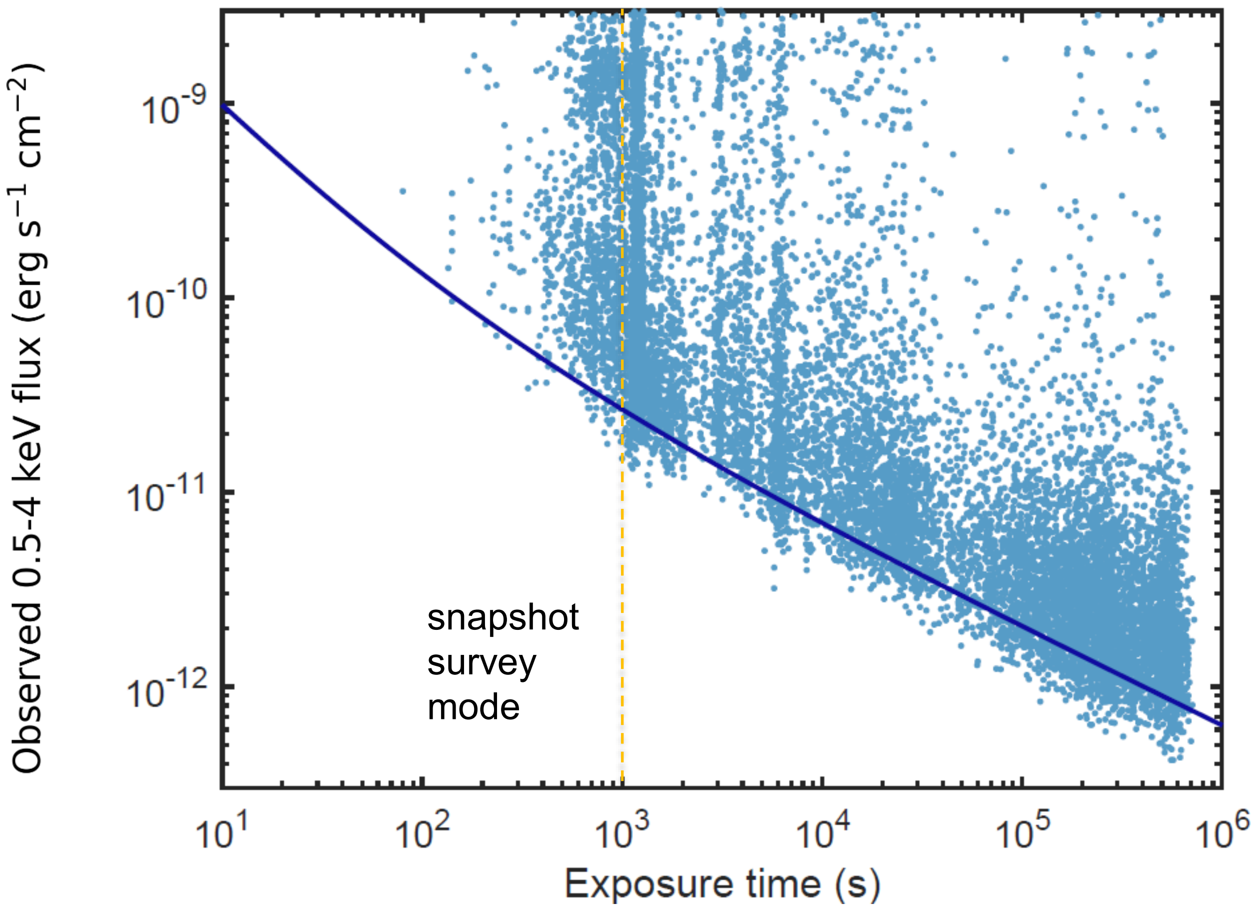
- Orbit: 590 km (P ~97min),   i = 29 deg
- Observation modes
  - Survey: 3 snapshots per orbit in the night-sky, each ~20 min exposure
  - cover most of night sky in 3 orbits
  - Cover whole sky in half a year
  - Autonomous follow-up: FXT (3-5 min)
  - ToO
- On-board data processing & transient search
- Alert data rapid downlink & triggering (Beidou & VHF)
- Fast ToO uplink (Beidou)



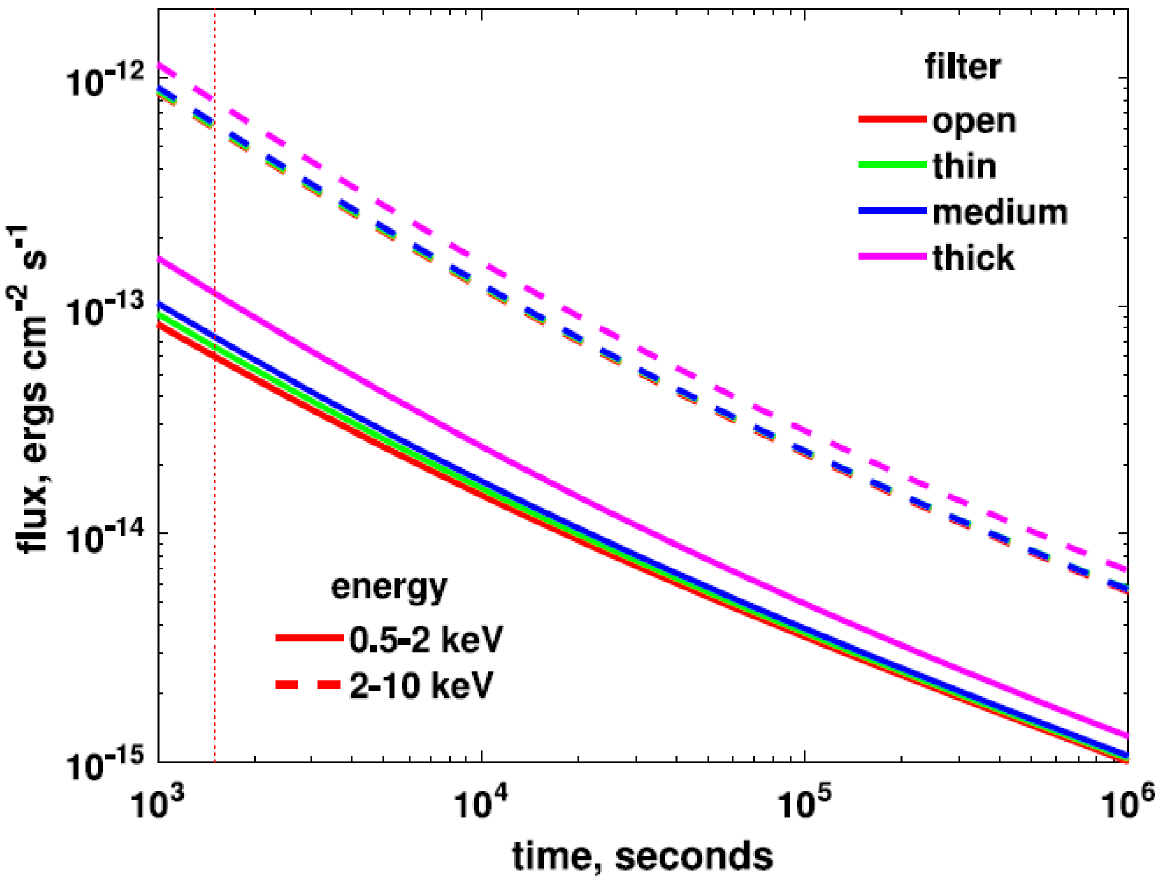


Sensitivity

WXT

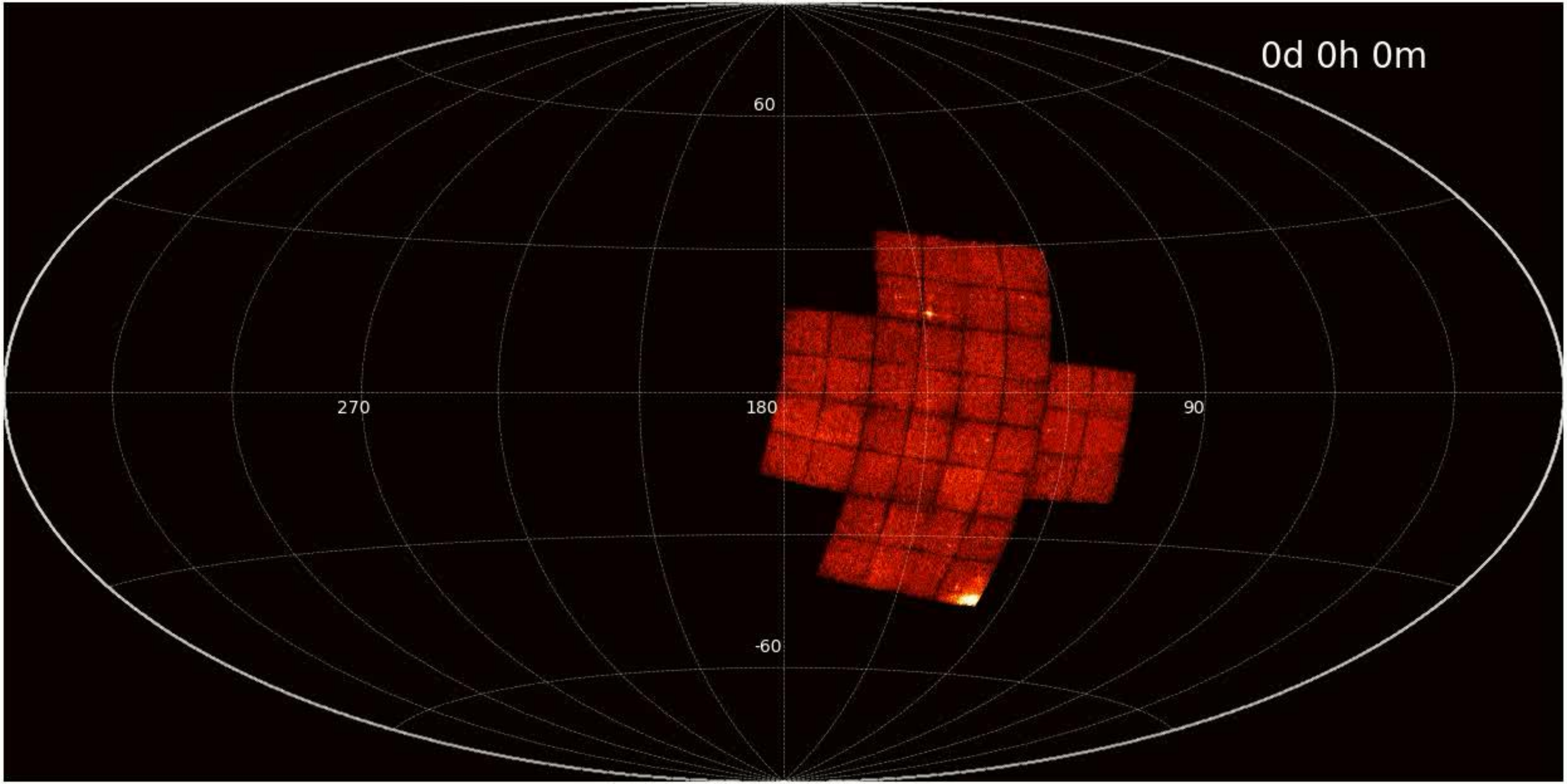


FXT (1 unit)

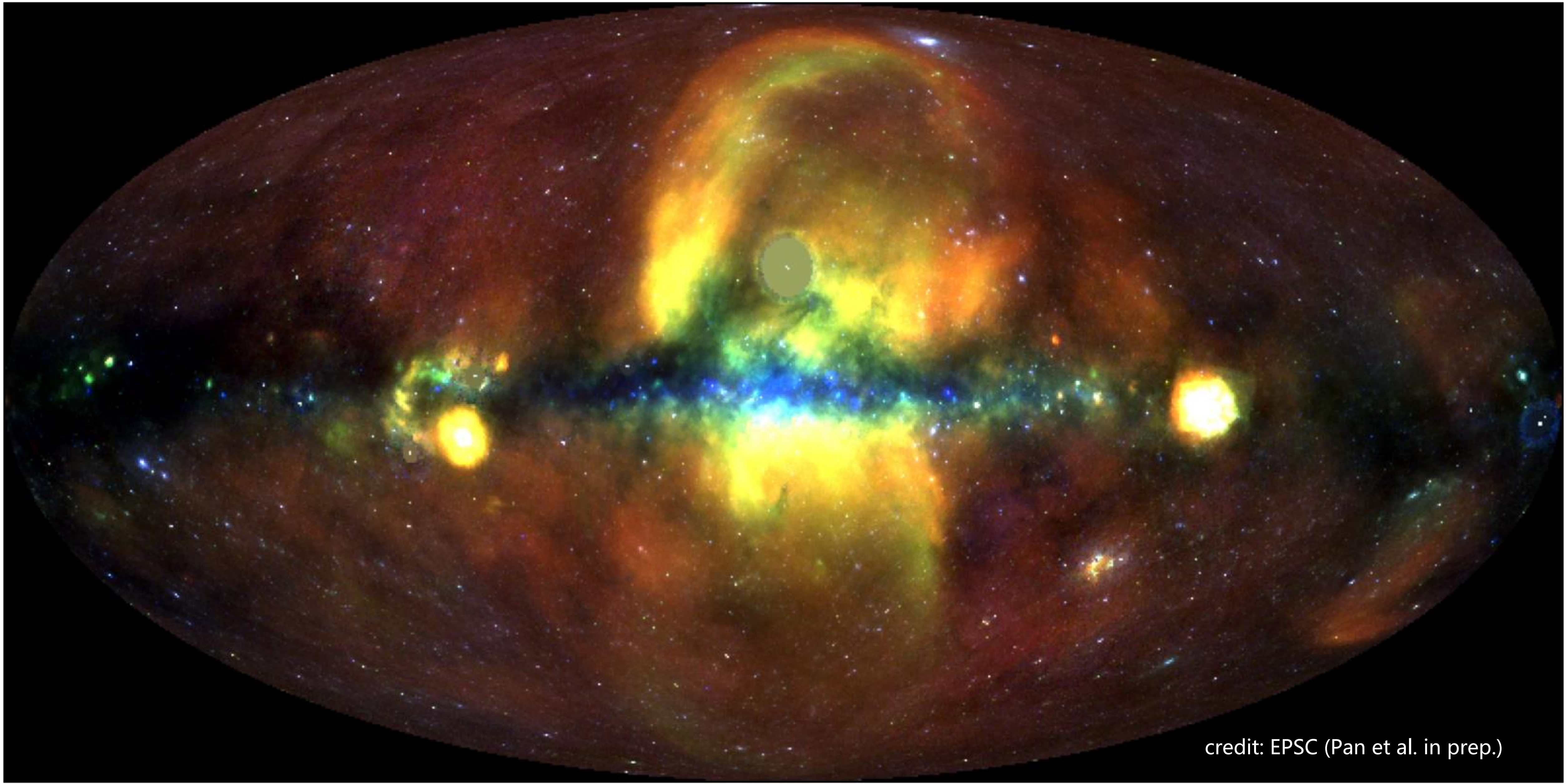



Central region of our Galaxy (purple, red, yellow)
WXT FoV 3850 sq. deg.
exposure 40 kilo-seconds
9.3°
1: Cir x-1 and *Swift J151857.0-572147*
2: Sco X-1
3: V2216 Oph
4: V1101 Sco
5: V821 Ara
6: NP Ser
7: V4134 Sgr
8: Sgr X-4
9: Lupus SN
10: SNR RCW 86
1
2
3
4
5
6
7
8
9
10
X-ray data credit: EPSC, image credit: Chen Zhang, Huaqing Cheng.

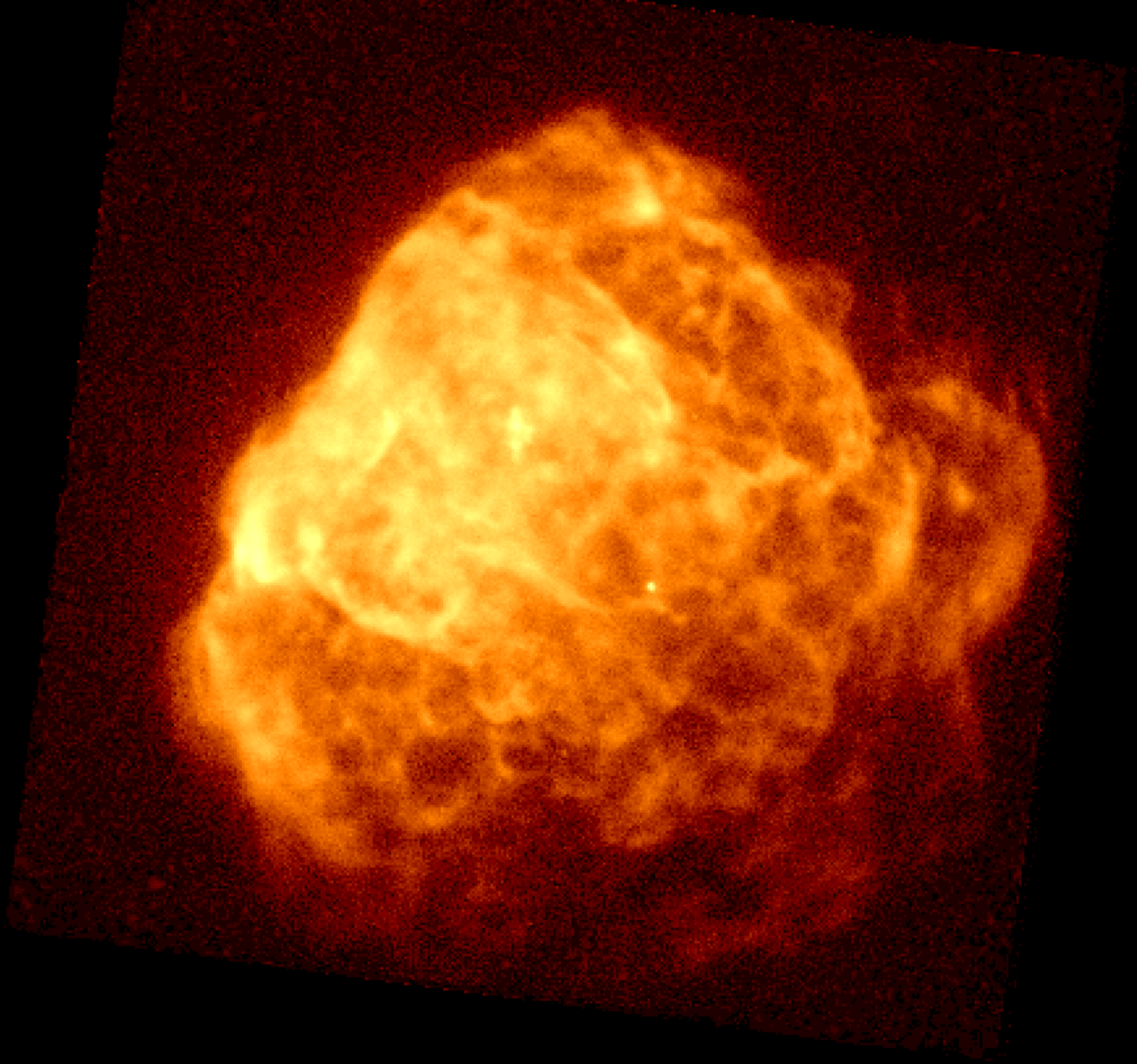
EP-WXT 1 day sky coverage



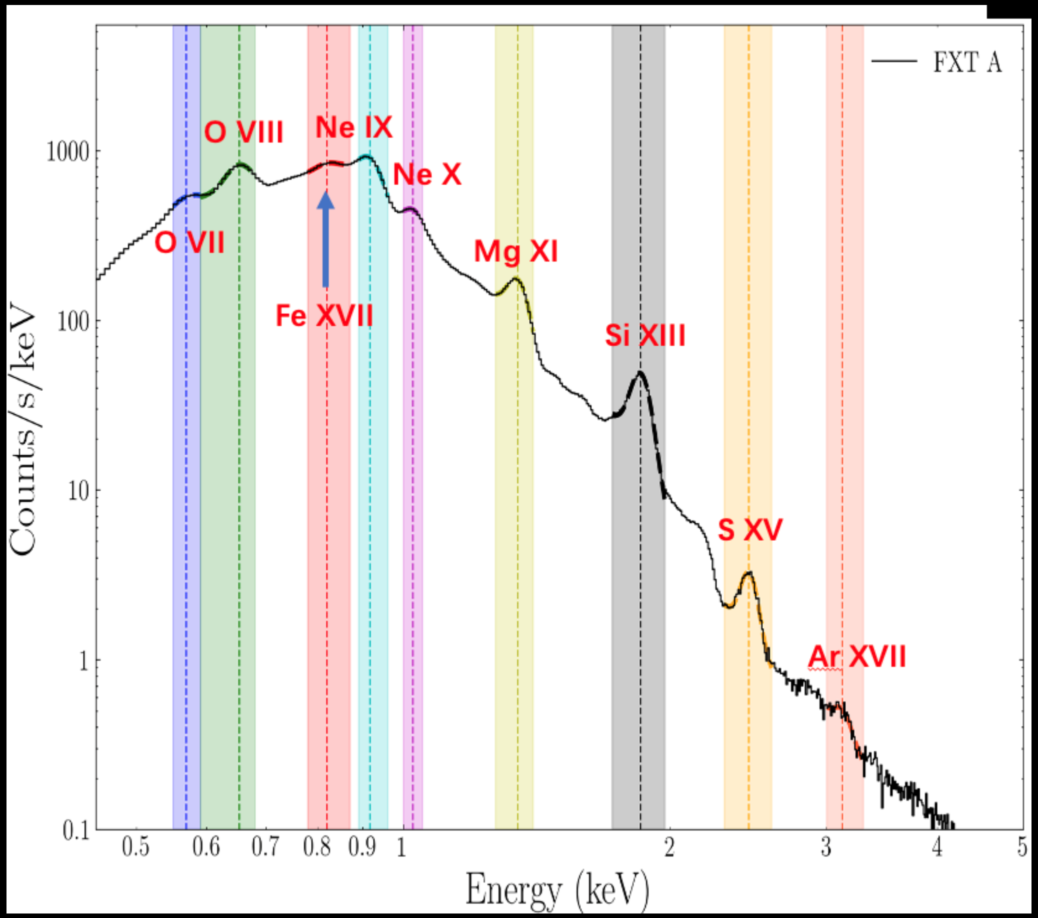
EP-WXT all-sky map (RGB: 0.5-0.8-1.0-2.0 keV)



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

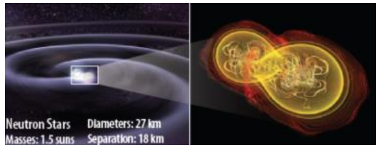


Main science goals

Carry out systematic survey of soft X-ray transients and variability of X-ray sources at unprecedented sensitivity and high cadence

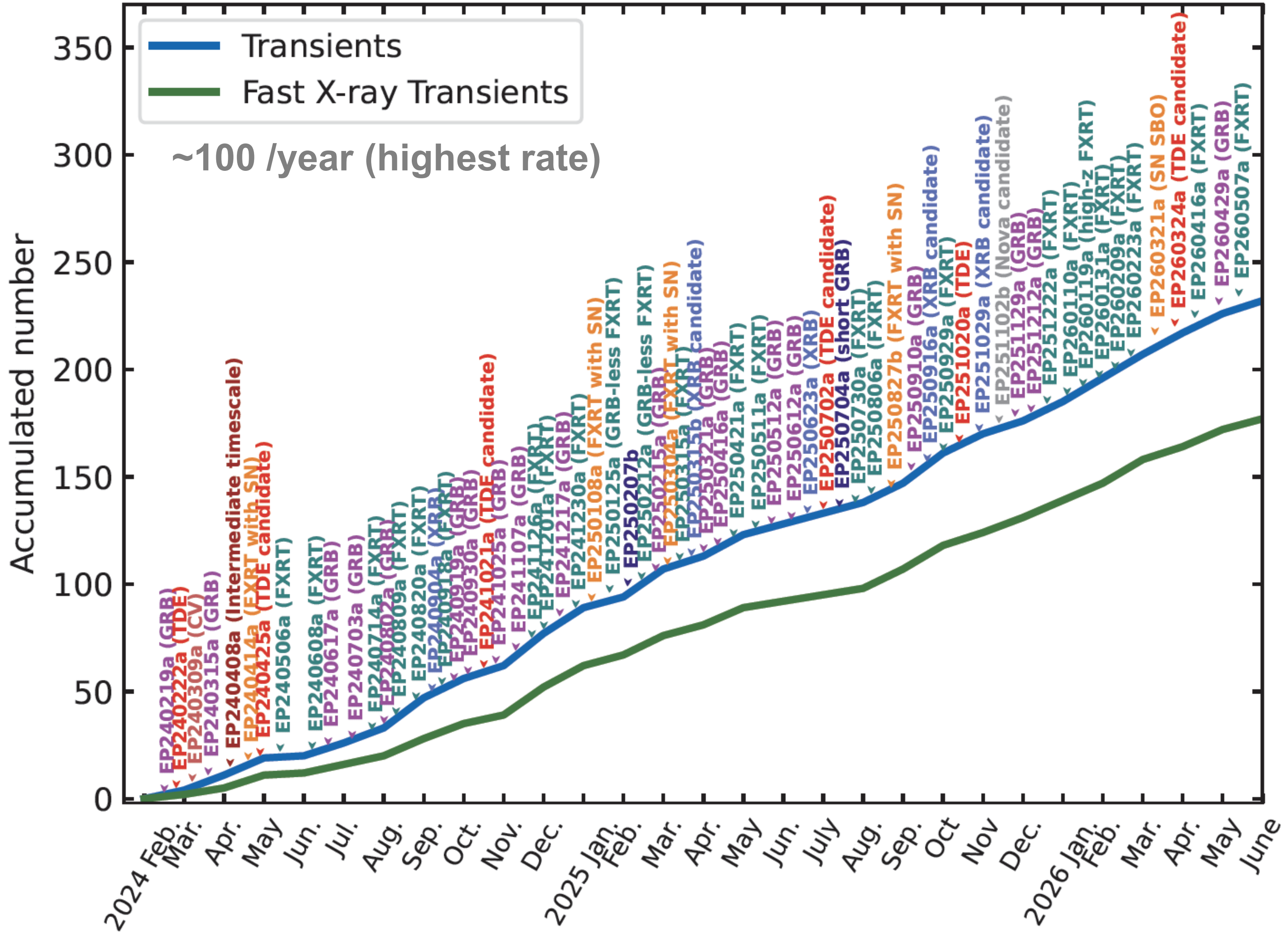
Discover otherwise quiescent Black holes at almost all astrophysical mass scales and other compact objects by capturing their transient flares

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



defined in proposal of 2013 Jan

EP transients in 1st two years



- X-ray transients: 232
  - **> 400 GCN/ATel**
  - **follow-ups by multi-W telescopes worldwide**
  - **102 optical counterparts, 55 redshifts**

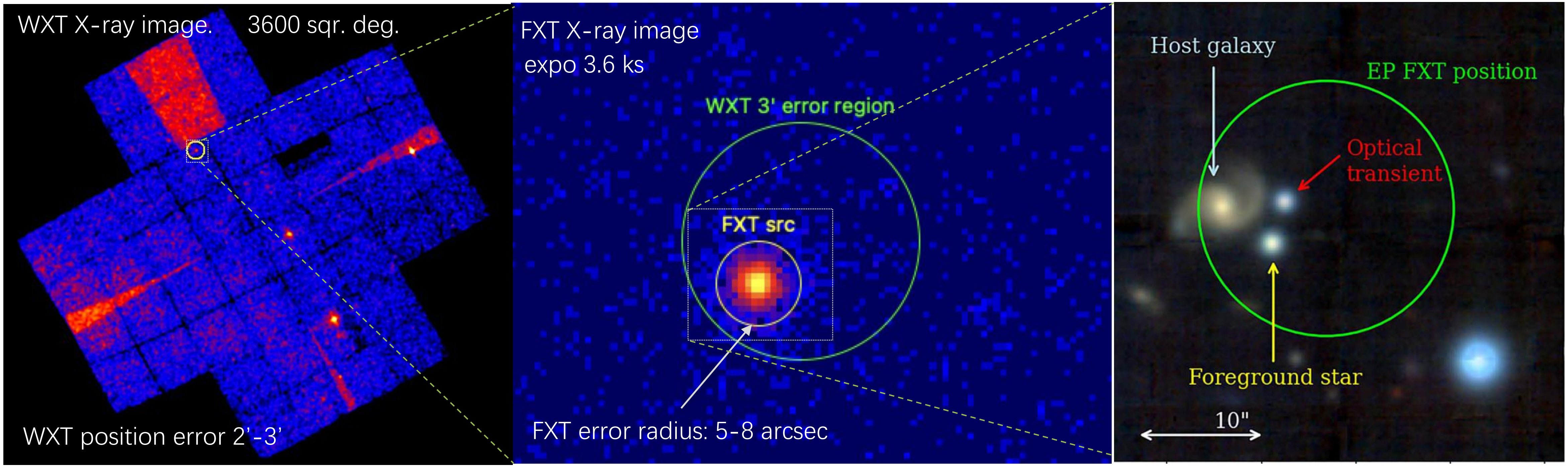
- FXT 177
- the rest: 55
  - **FXRTs with long afterglow**
  - **TDEs**
  - **compact object flares**
  - **unknown classies**

WXT monitoring survey + FXT automated follow-up

WXT obs. and onboard search

FXT automated follow-up

multi-waveband follow-ups

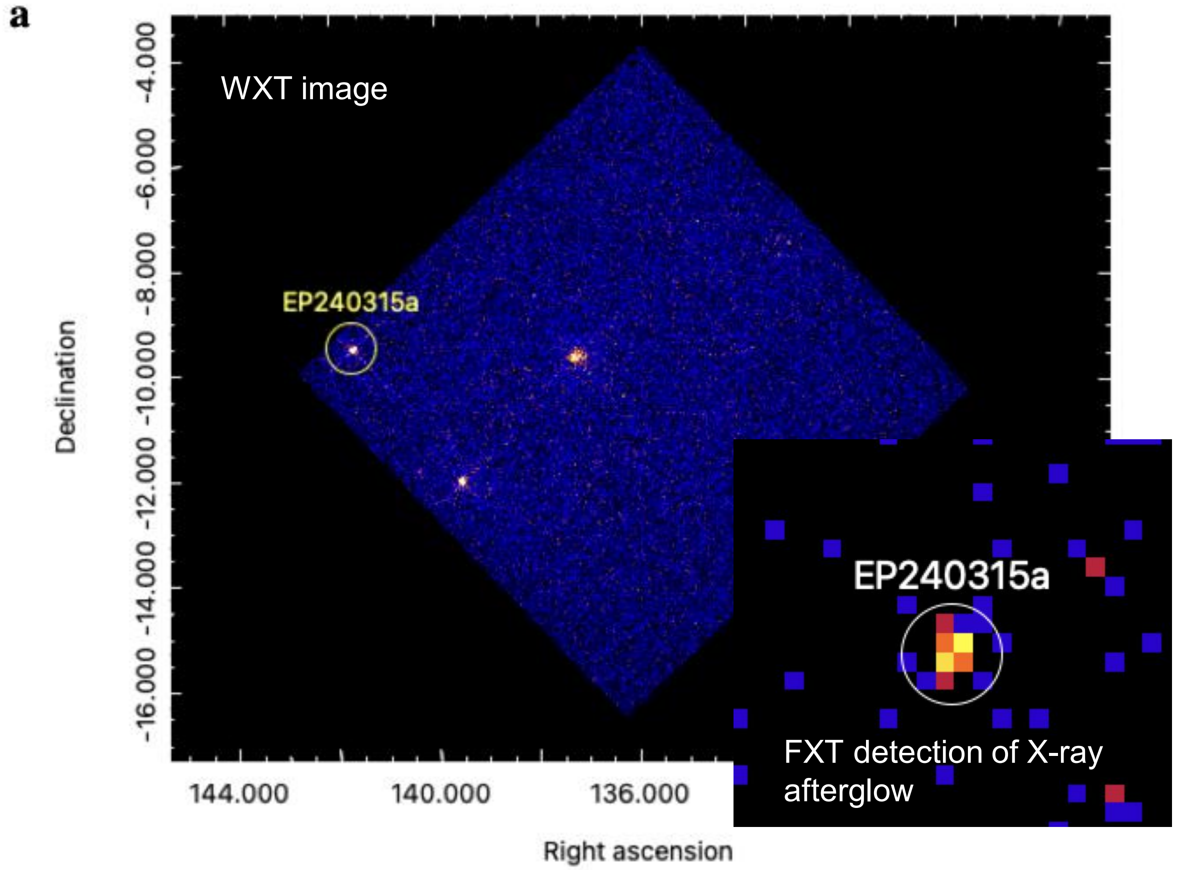


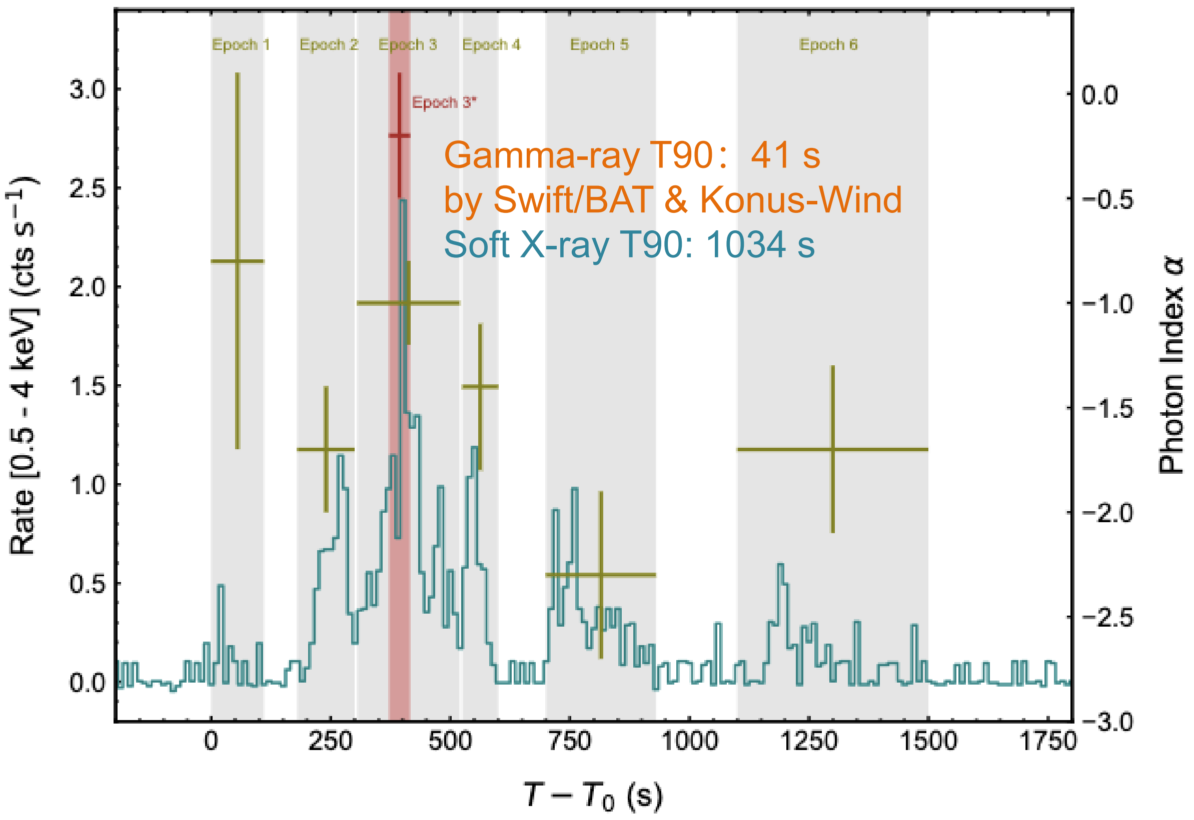
van Dalen et al. 2025

several minutes

transient alert downlinked to EPSC and automatically disseminated via GCN/notices in minutes

EP240315a: GRB @redshift 4.859



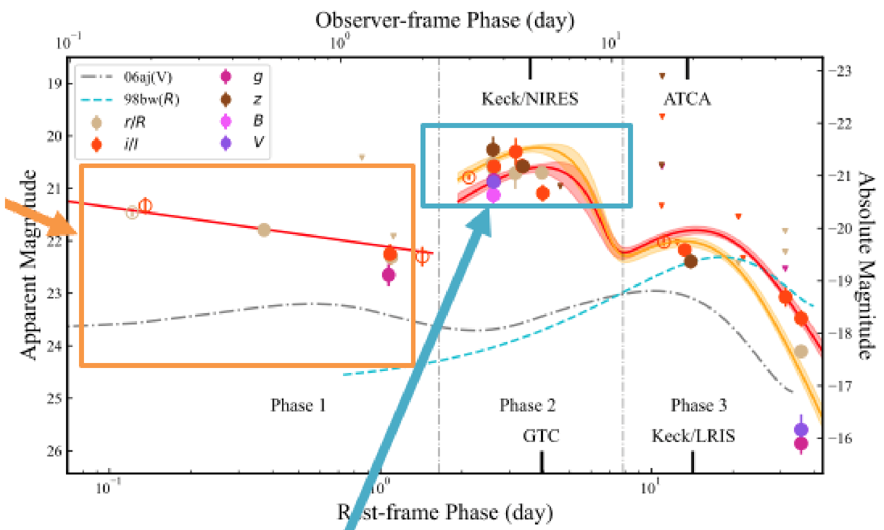


Marked difference in soft X-ray and hard X/γ rays

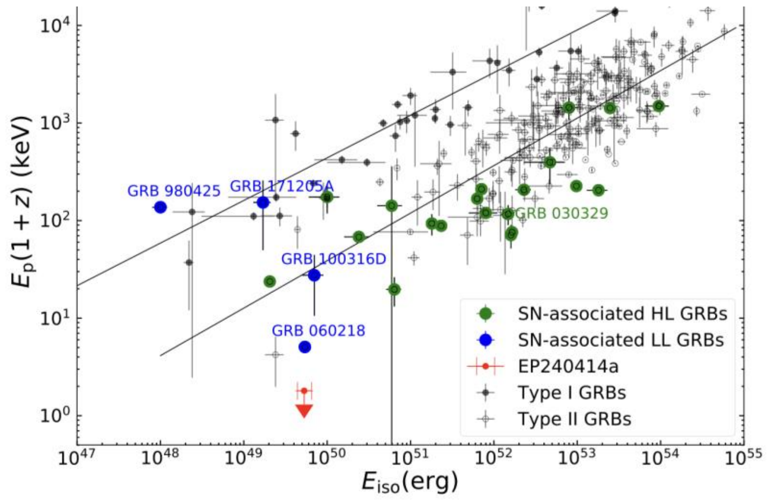
Liu Y., et al. 2025 Nature Astronomy, 9, 564
Levan A., et al. 2025 Nature Astronomy, 9, 1375
Gillanders J.H., et al. 2024 ApJ

Redshift 4.859 by VLT (Levan et al. 2025)
Fast X-ray transient & GRB
Central engine activity before detection

EP240414a: possibly new type of fast X-ray transients with SN

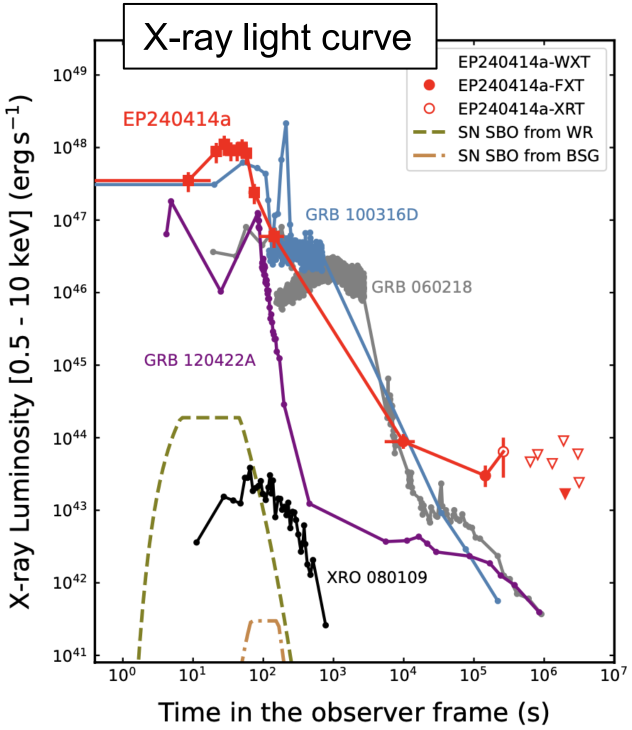


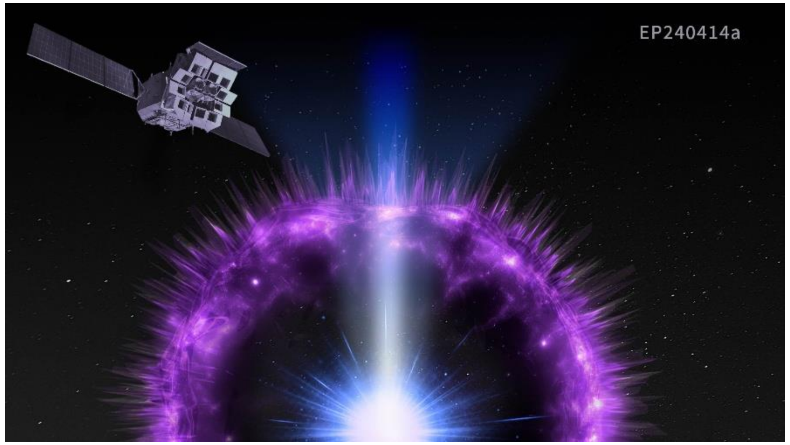
Shock breakout and cooling emission from the expanding hot material at large radii **an extended shell**



- No GRB, very soft spectrum
- Associated with Ic-BL supernova 2024gsa z=0.4
- No similar previous events

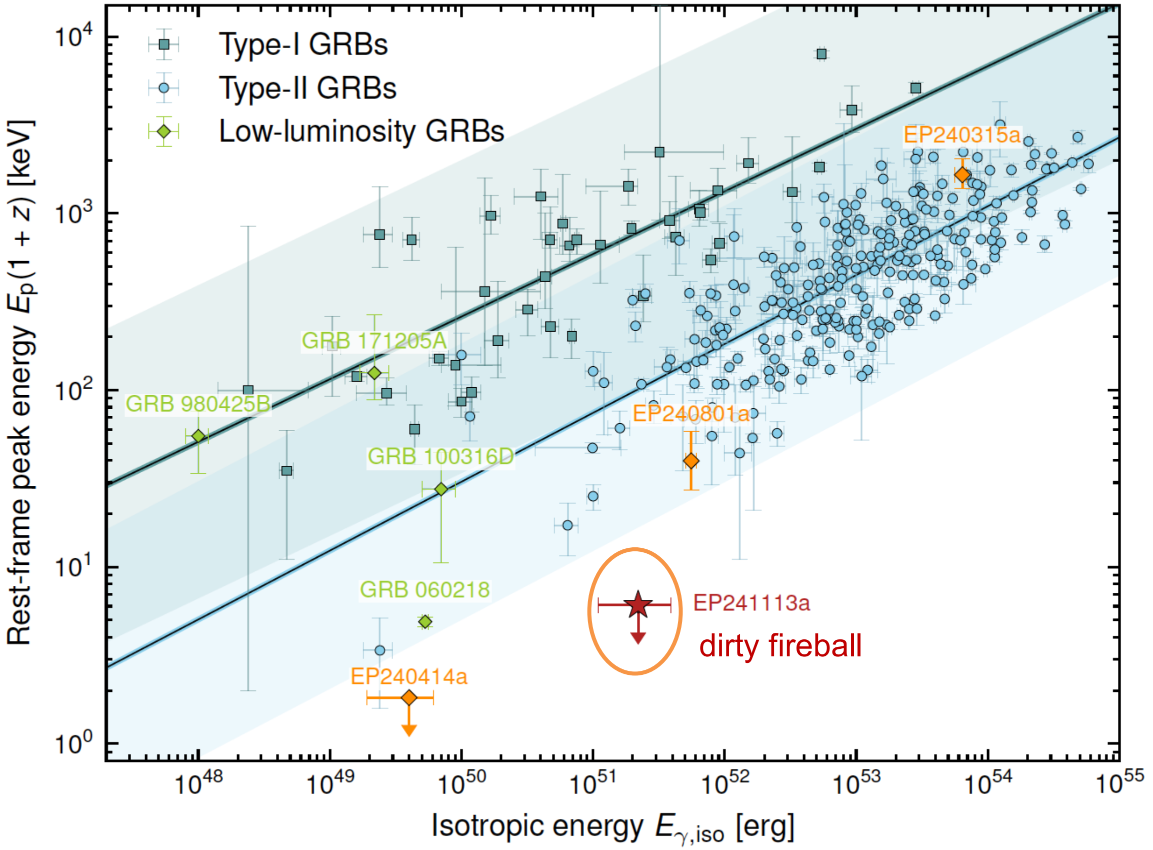
A weak relativistic jet that interacts with an extended shell surrounding the progenitor star

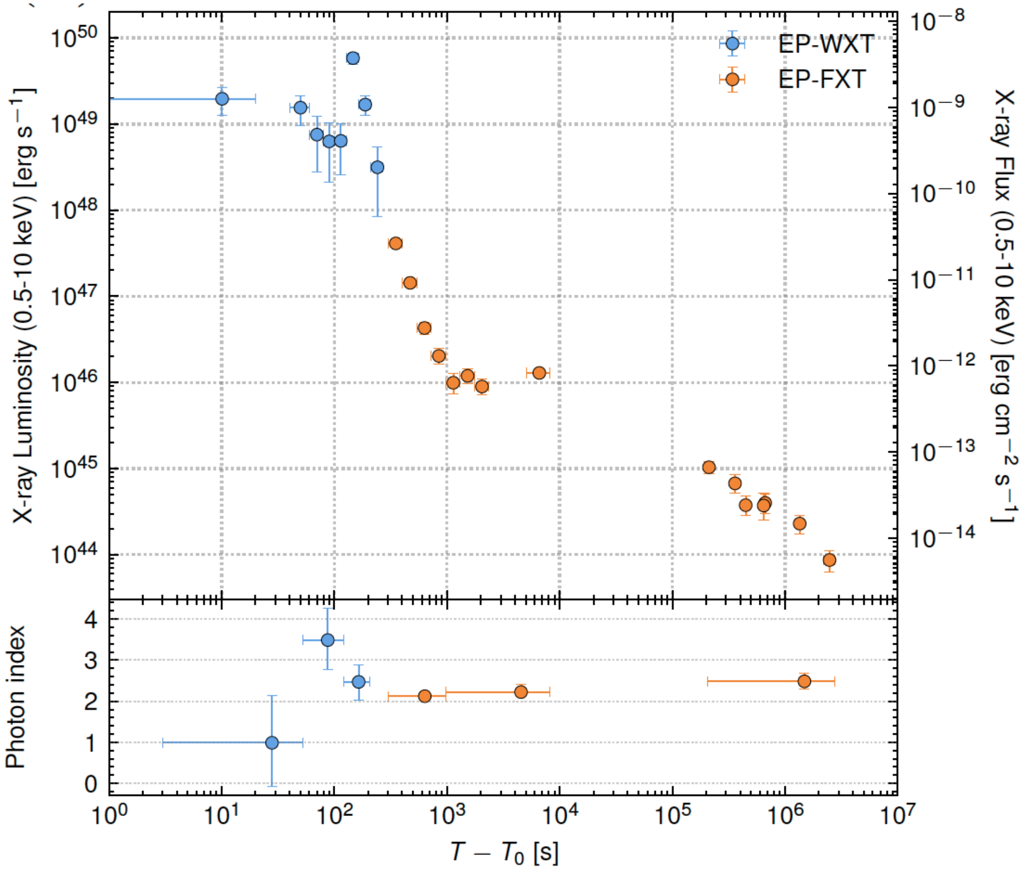




Sun H. et al. 2025 Nature Astronomy 9, 1073

EP241113a: an energetic dirty fireball in X-ray

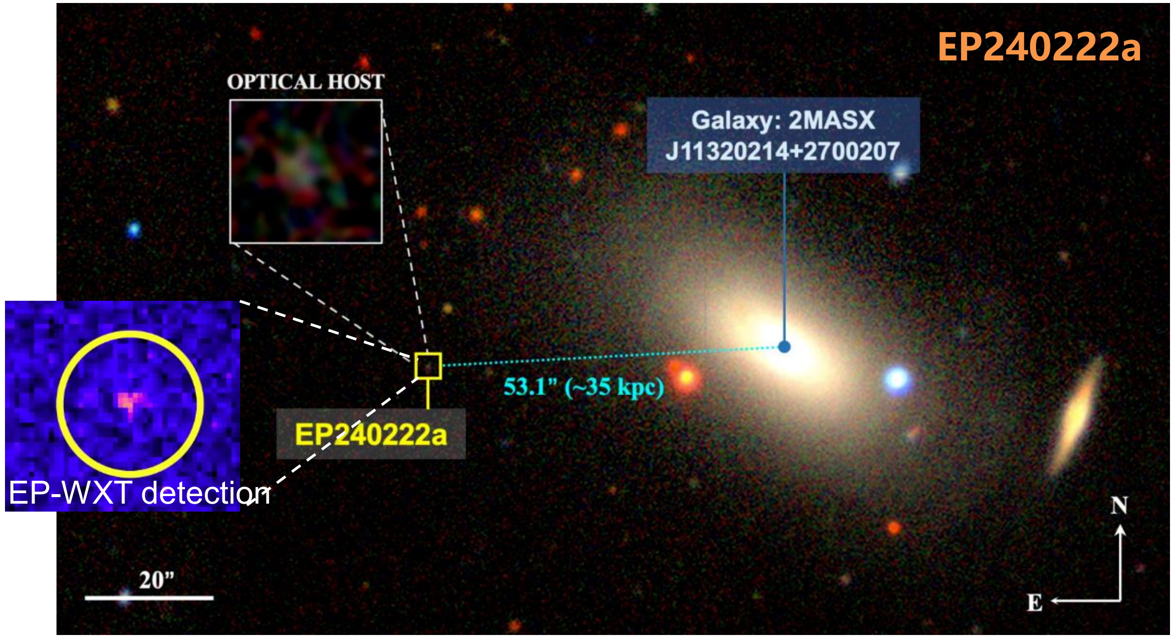




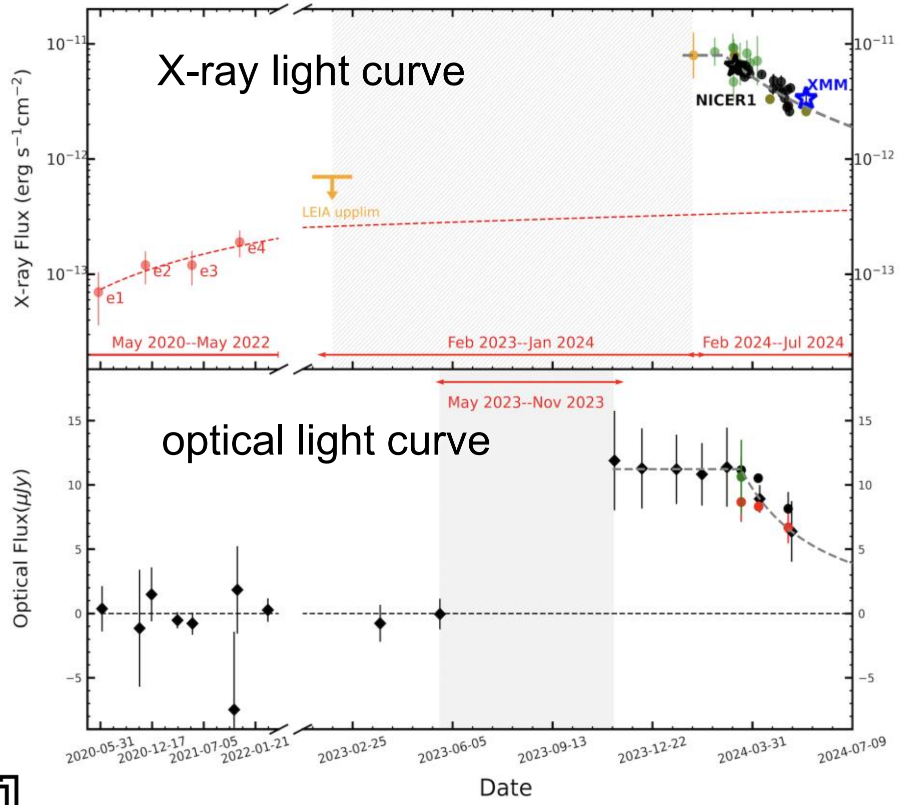
Dai C., et al. arXiv/2603.26213, Science, under review

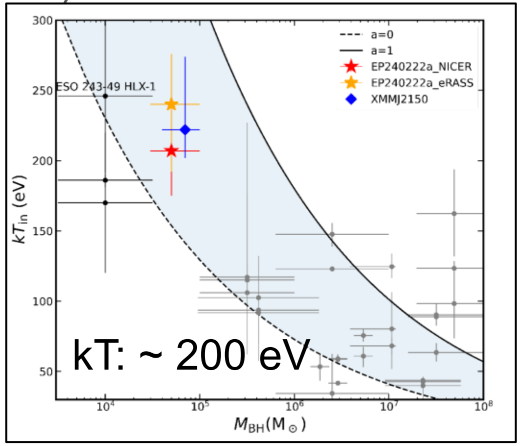
- No GRB, very soft spectrum
- Lorentz factor ~ 20, viewed on axis
- Long-predicted dirty fireball: relativistic jet contaminated by baryons

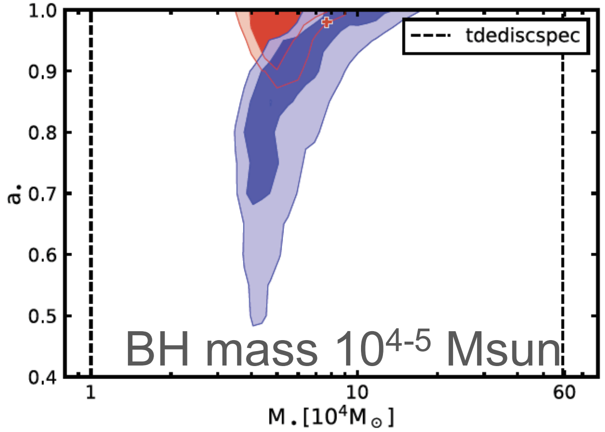
EP240222a: TDE by Intermediate-mass black hole



35 kpc projected distance from the center of a massive galaxy (z=0.033)



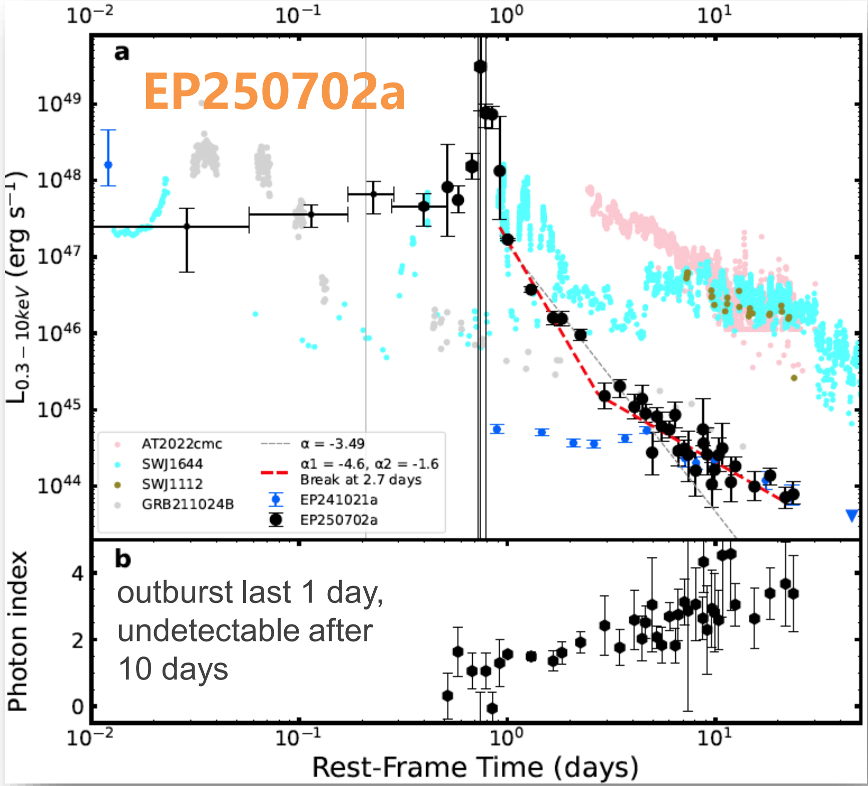


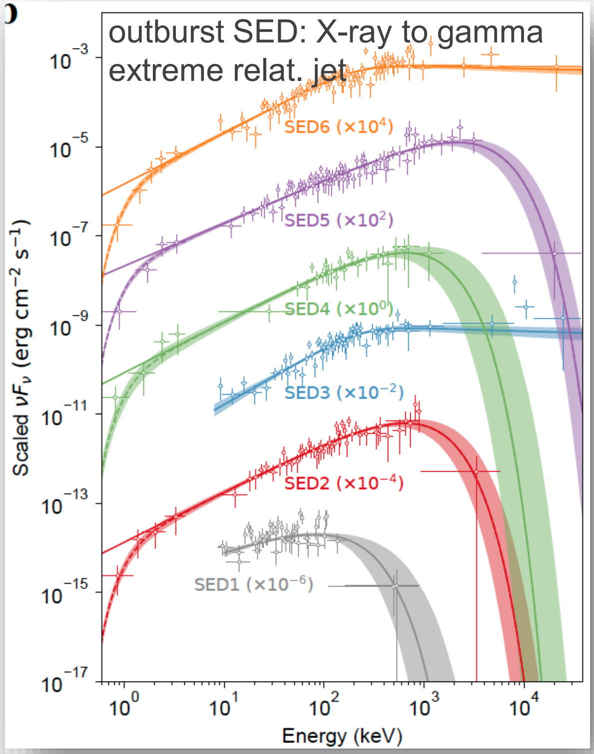


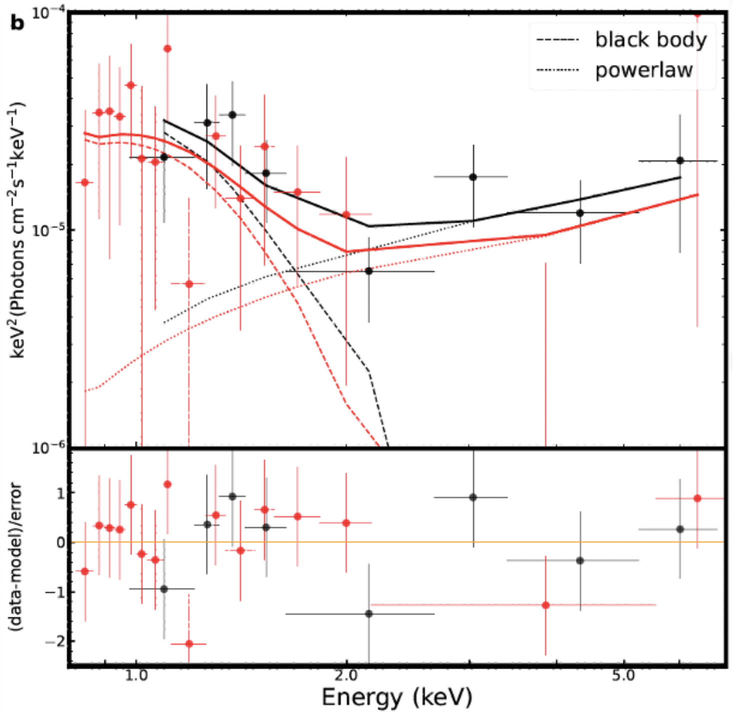
host stellar mass: ~10^7 Msun

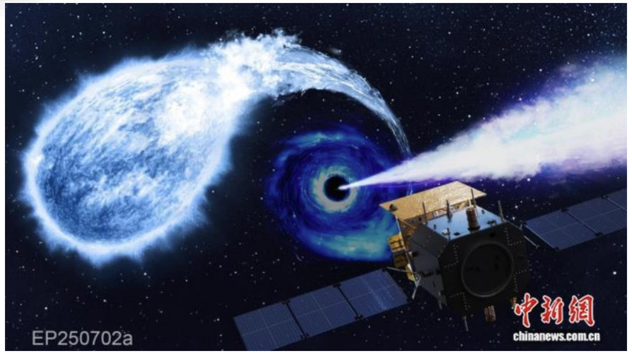
Jin et al. arXiv/2501.09580
Science under review

EP250702a: possible TDE of a white dwarf by IMBH ?







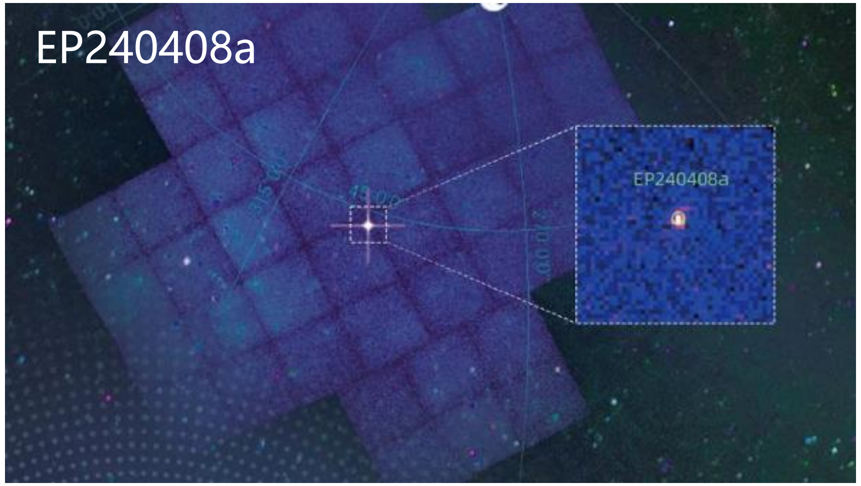


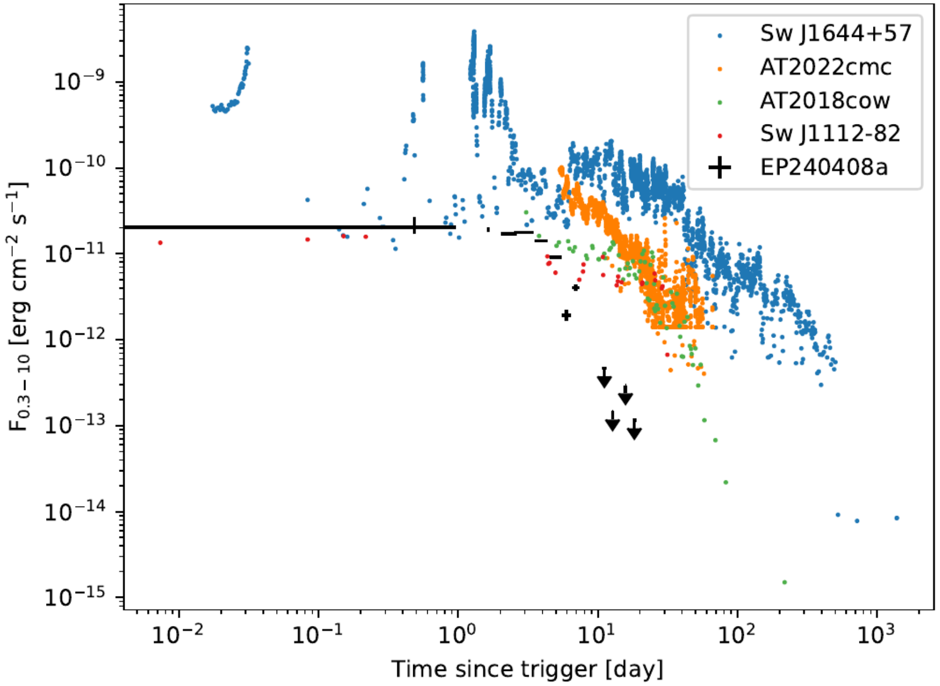
- Unprecedented light curve & spectra
- extreme relativistic jets + thermal/disc
- TDE of a white dwarf by an IMBH

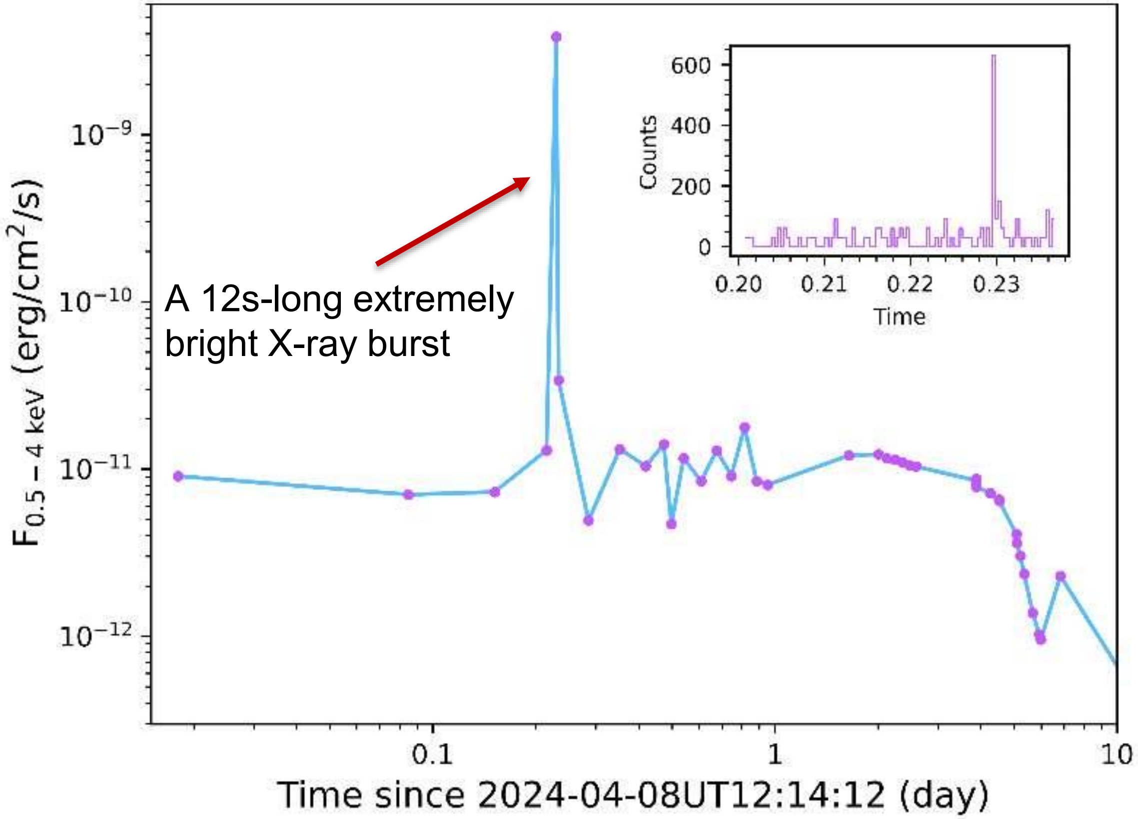
$7.5 \times 10^4\ M_\odot$

Li D. et al. 2026 Science Bulletin

A new transient class?



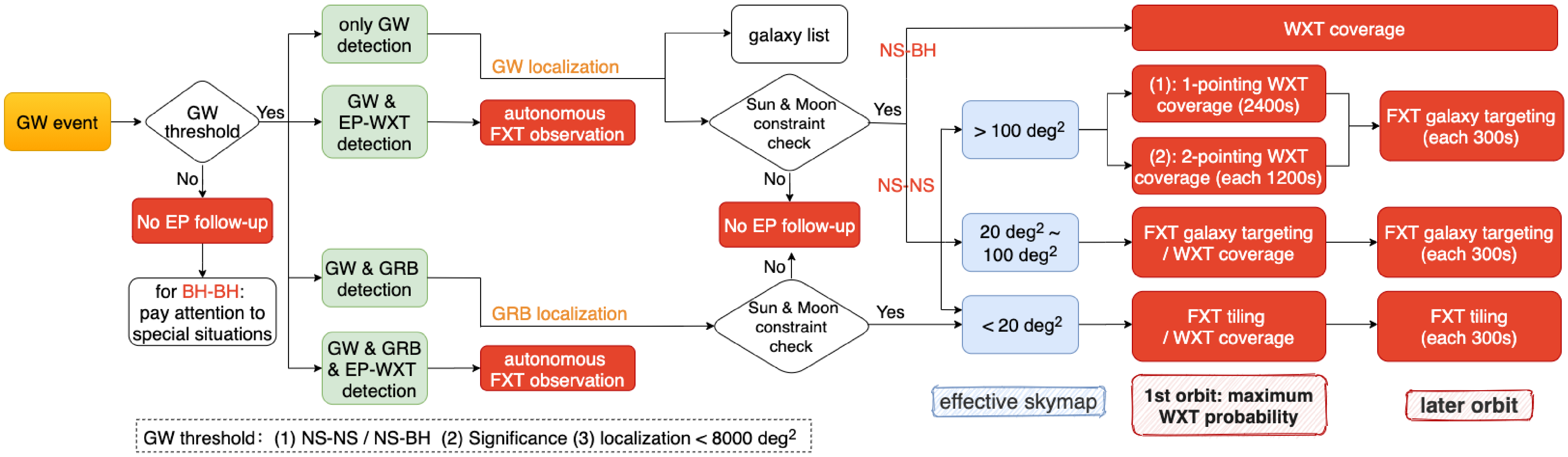




Spectral and temporal properties inconsistent with any known transient types

Zhang W., et al. 2025 Science China
O'Connor B., et al. 2025 ApJL

EP follow-up observation of GW event



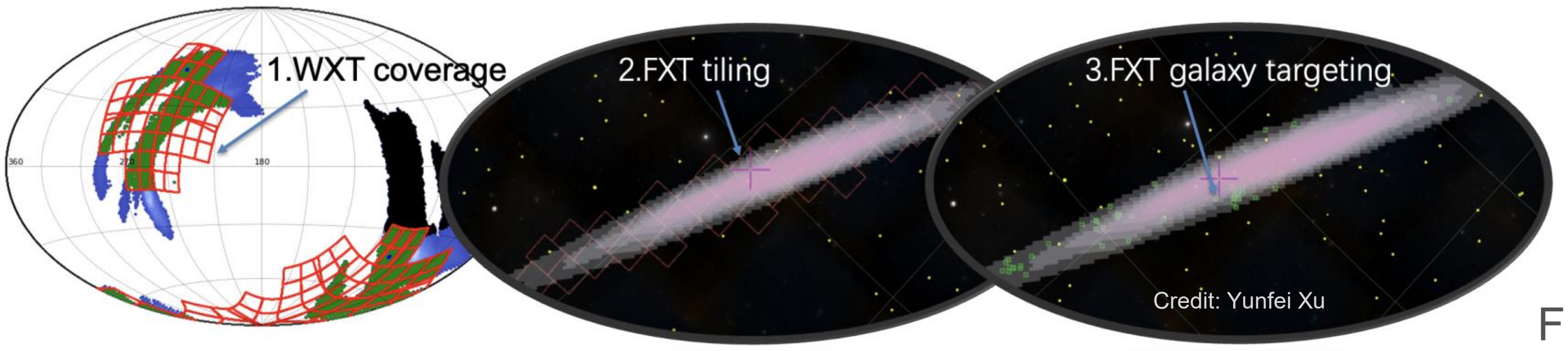


Figure: Jingwei Hu

ToO-MM automated uplink

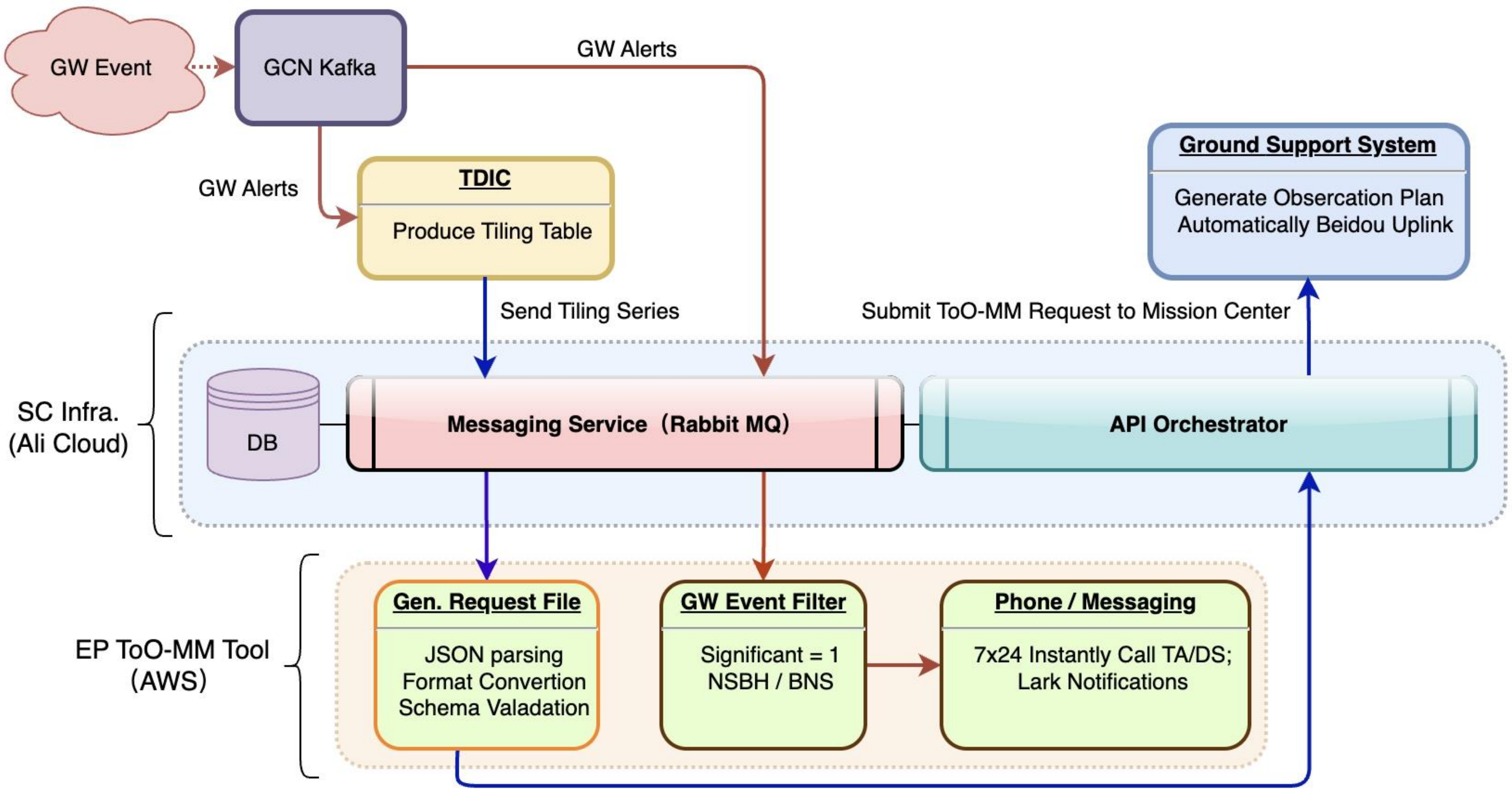


Figure: Mo Zhang Software: Yunfei Xu, Mo Zhang

S250206dm

S250206dm: T0=2025-02-06 21:25:30.439 UTC; NSBH (55%), BNS (37%); 373 +/- 104 Mpc; 90% area=547 deg^2

EP follow-up observations:

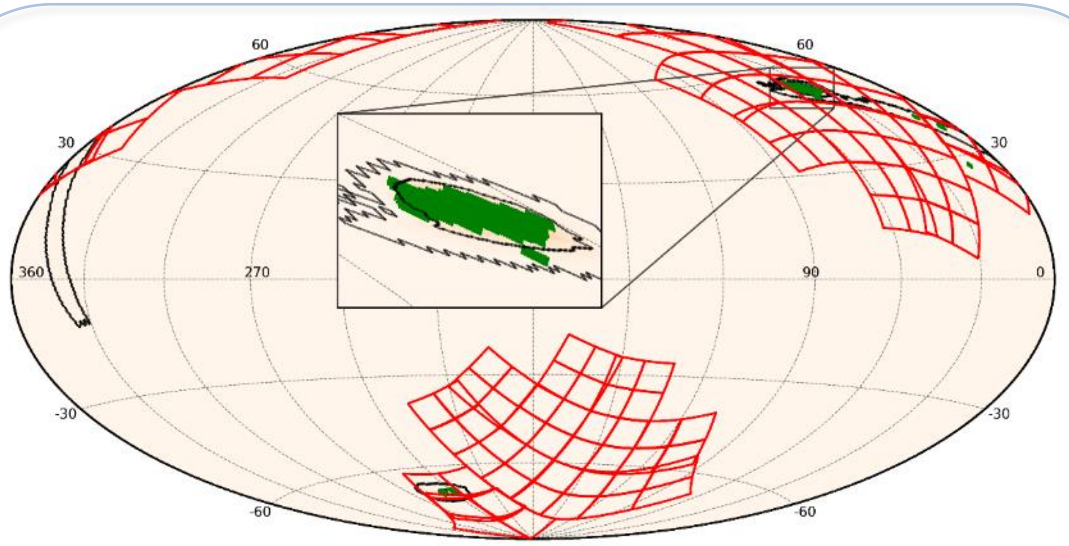
1^{st} round: 2×2400s WXT coverage + 100×300 s FXT targeting galaxies (2025-02-07T02:55:12Z ~ Feb. 8th)

2^{nd} round: 59×2000s FXT tiling (from Feb. 11th to 18th)

Search for transient or variable candidates in the FXT data (apparently associated with the galaxies):

found ~20 uncatalogued sources, two of which exhibit significant flux decay.

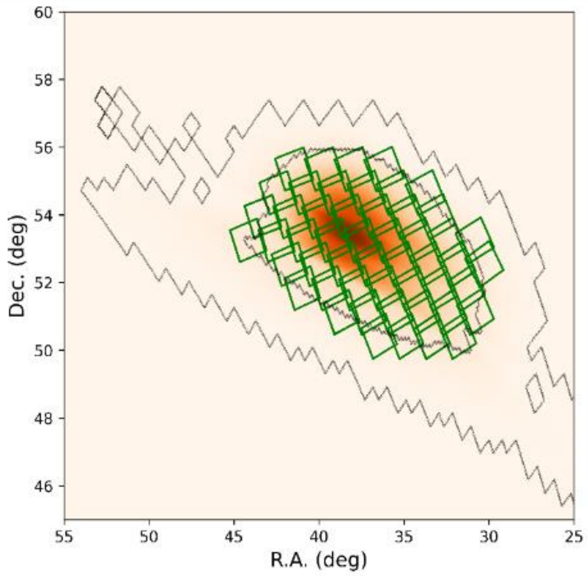
Detailed information: GCN Circular 39545; https://ep.bao.ac.cn/ep/cms/article/view?id=185



1^{st} : WXT covered 302 deg^2 within (55% of) the 90% GW area

WXT 0.5-4 keV flux limits: 1×10^{-11} $\mathrm{erg\,s^{-1}cm^{-2}}$

FXT 0.5-10 keV flux limits: 3×10^{-13} $\mathrm{erg\,s^{-1}cm^{-2}}$

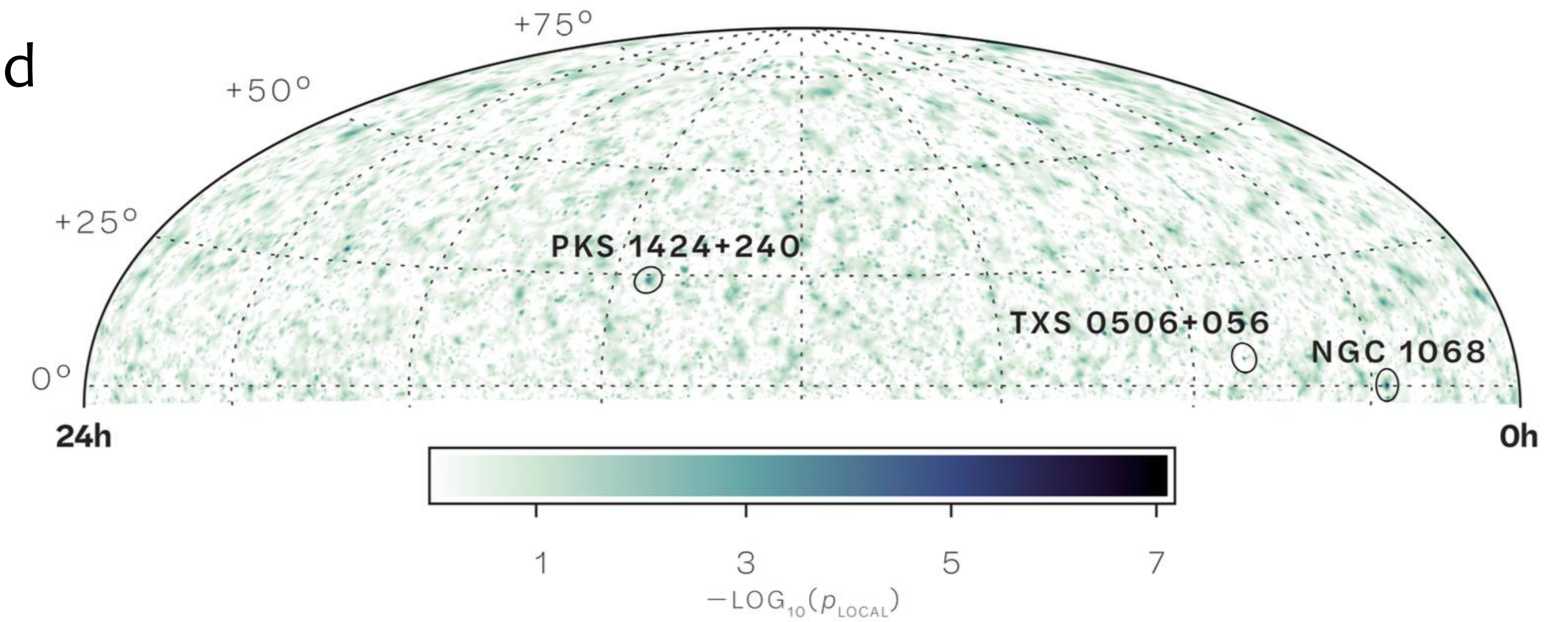


2^{nd} : FXT covered 34 deg^2 within (89% of) the 50% GW area

FXT 0.5-10 keV flux limits: 5×10^{-14} $\mathrm{erg\,s^{-1}cm^{-2}}$

The origin of high-energy astrophysical neutrinos

- Diffuse neutrino background
- Possible sources:
  - Blazar
  - Seyfert
  - Supernova?
  - Low-luminosity GRB ?
  - TDE ?



The IceCube Collaboration(2022)

$$p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^+$$

$\pi^+ \rightarrow e^+\bar{\nu}\nu\nu$

Cosmic rays O(PeV)

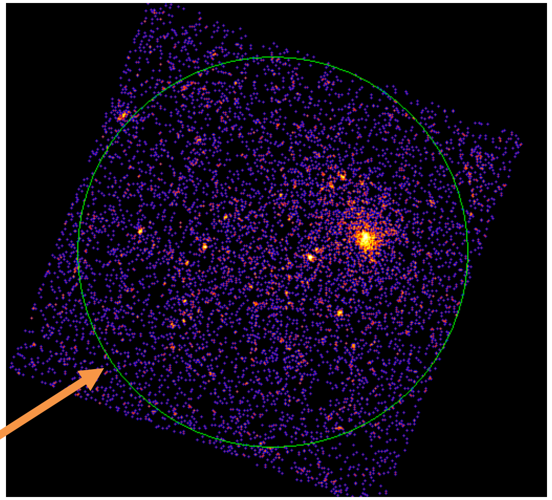
Known invariant mass ~ 1.2 GeV

- γ~ 1 keV (WXT band!)
- Expect association between X-ray transients and neutrinos

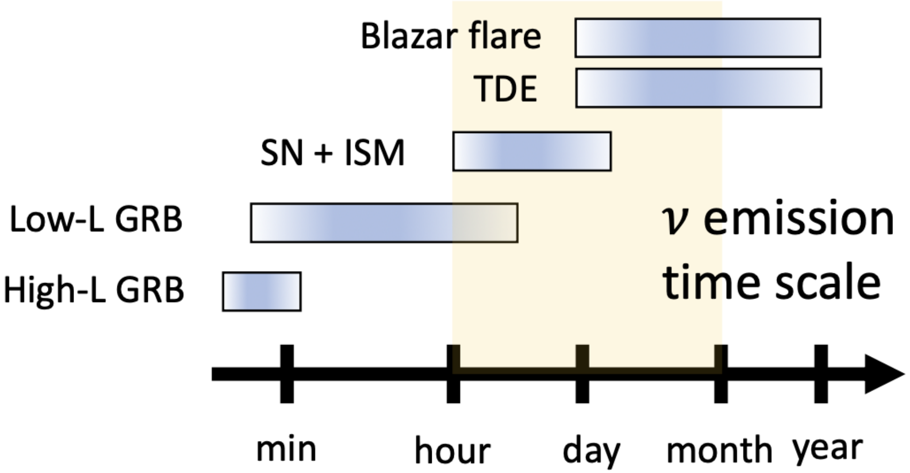
EP observing strategy

- Prompt FXT follow-up
  - IceCube Gold event
  - Automated uploading
  - Latency ~ 40 min
  - Seek evidence counterpart
- FXT monitoring (weekly)
  - Blazar candidates
  - Long-term correlation
- WXT/FXT and neutrino event correlation
  - WXT+ gold/bronze events (collaborate with Chiba University)
  - FXT + low significant events
  - Constrain cosmic-ray loading factor

FXT (1 deg x 1 deg)
IceCube-250706A
(T0+40 min)

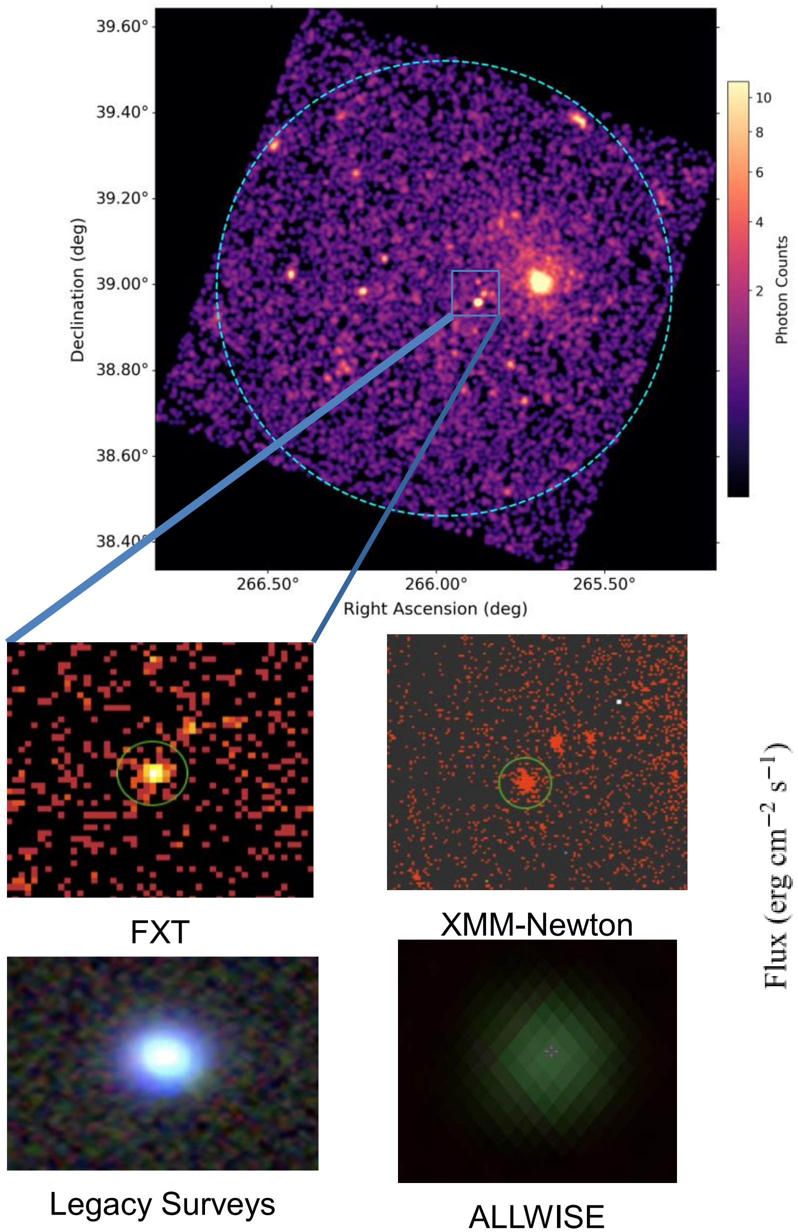


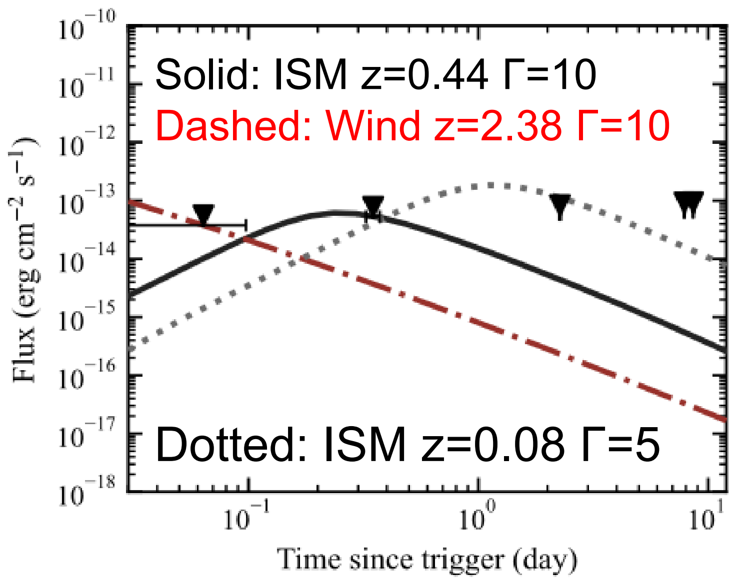
Error circle
radius ~ 0.5 deg

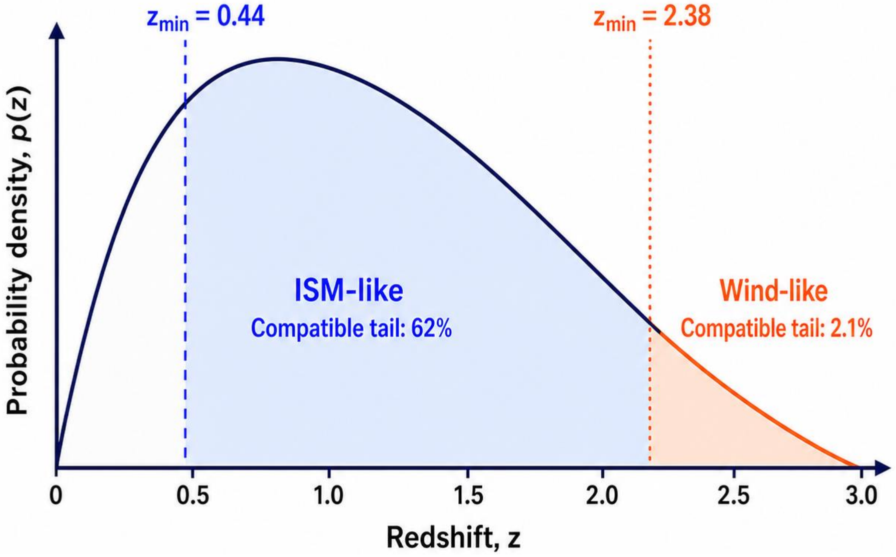


EP-FXT follow-up of IceCube-250706A

- IceCube Gold alert: ~210 TeV and signalness ~65%
- Rapid FXT follow-up: T0+43 min, five epochs, and ~96% localization coverage (90% C.L.)
- 54 X-ray sources: no convincing counterpart
- Flux upper limits + LLGRB afterglow model
- z>0.44 (ISM-like) or z>2.38 (Wind-like)
- Tight constraint with more events

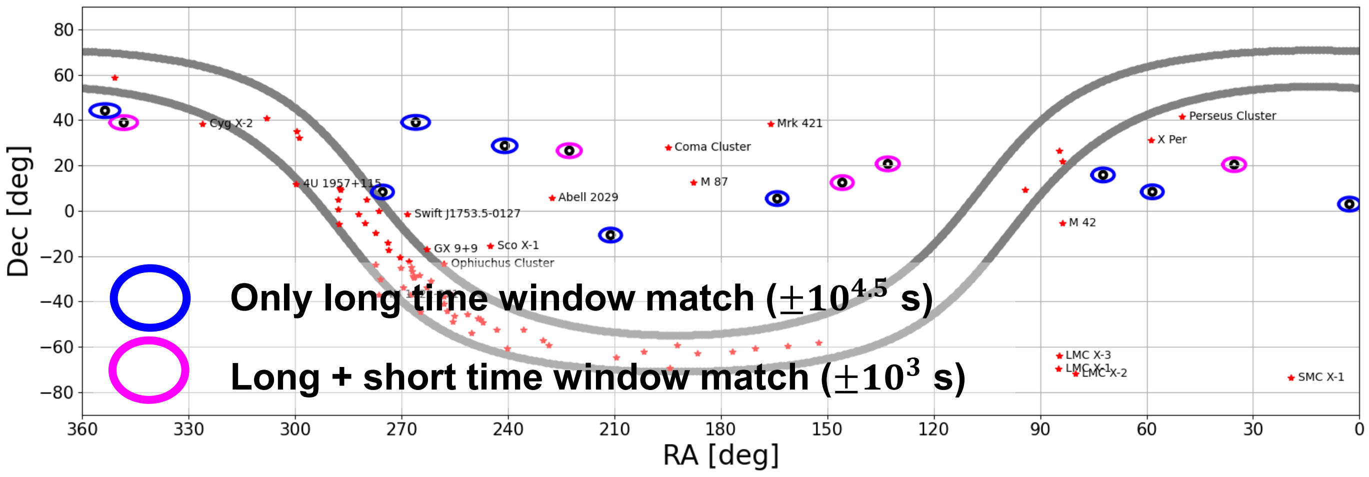






Slide credit: Guojiong Yang

Follow-up analysis of IceCube neutrino alerts by the WXT



- X-ray is a natural target of cosmic rays to produce O(100) TeV ν via p+γ interaction
- Theoretical prediction: $\phi_\nu \propto L_X^{3/2} \rho\, \xi_{CR}$
  (ξ_{CR} is a scaling factor connecting $L_{CR} = \xi_{CR} L_X$)

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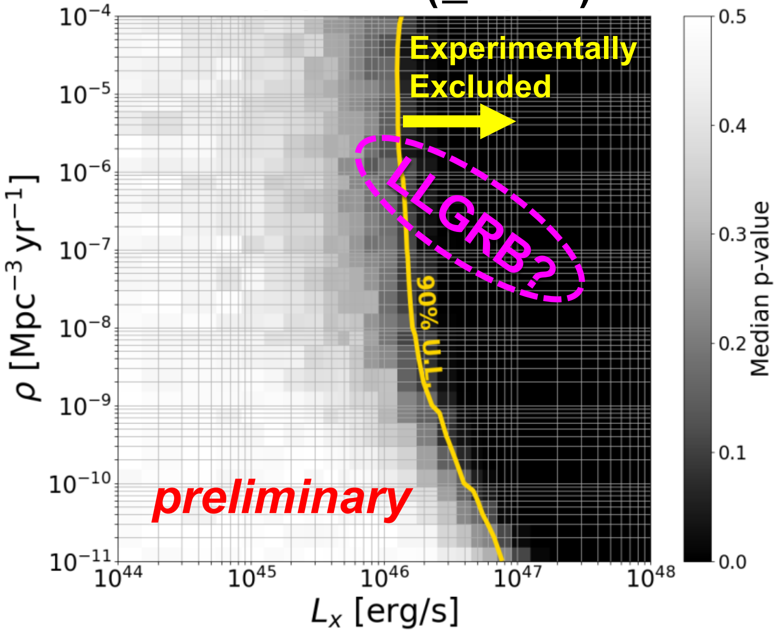
Short time scale transients ($\pm 10^3$ s)



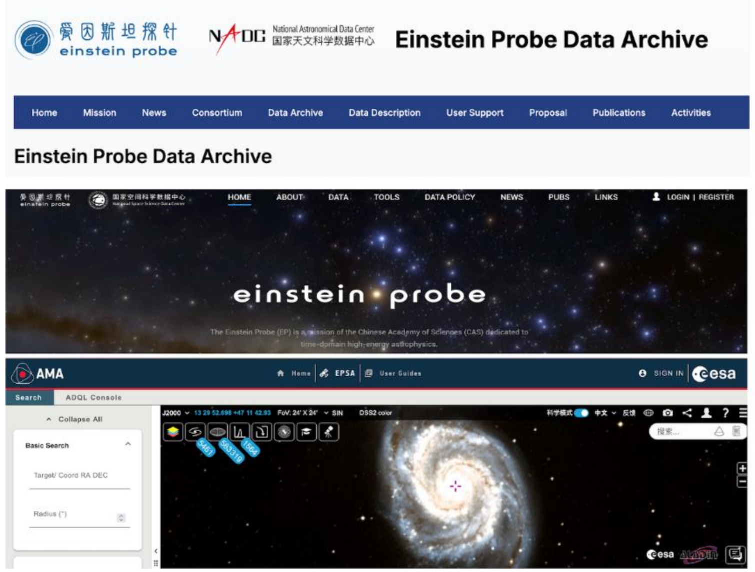
- Performed follow-up analyses on ~2 years of IceCube alerts with EP/WXT to search for X-ray transient counterparts:
  14 alerts : long time window $\pm 10^{4.5}$ s
  5 alerts : short time window $\pm 10^3$
- No X-ray counterpart was observed.
- Assuming IceCube ν are from X-ray transients, we could provide a very strong limit on the X-ray sources: X-ray luminosity, L_X, and rate density ρ.
  => LLGRBs and TDEs as origins of high energy neutrinos are very much disfavored by this analysis

Slide credit: Nobu Shimizu

Release of 1st batch of EP science data

National Astronomical Data Centre (NADC)

https://ep.bao.ac.cn/ep/next/data-release



National Space Science Data Centre (NSSDC)

https://ep.nssdc.ac.cn

2025年12月11日，国家天文科学数据中心、国家空间科学数据中心与天关卫星科学中心联合公开发布“天关”卫星首批科学数据。**此次发布的数据涵盖了2024年7月11日开始科学运行后已达到保护期的后随X射线望远镜（FXT）的1至3级科学数据产品，包含1615个观测号，对深入研究恒星剧烈活动、黑洞及中子星等致密天体的形成、演化、并合等宇宙极端物理过程具有重要的科学意义。**与此同时，欧洲空间局亦同步开放了“天关”卫星科学数据平台，该平台提供经过校准的“天关”卫星高级数据镜像。

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General at National Astronomical Observatories, Chinese Academy of Sciences

OPENING OF DATA ARCHIVES

11 December 2025 EP Science Data are proprietary for a period of one year after which they shall be made publicly available. Access to data is descibed here: There are two institutes in China operating archive interfaces, the National Astronomical Data Centre (NADC) and the National Space Science Data Centre (NSSDC). ESA has now opened the Einstein Probe Science Archive (EPSA) containing public, calibrated *high-level* data, i.e., calibrated data covering level 2 (events files) and level 3 (images, spectra, light curves); for details of ESA mirror archive, see EPSA Documentation.

Data in EPSA are calibrated with the last *major* calibration release. If data need to be processed with the *latest* calibration version, level 1 data must be obtained from the NADC or NSSDC archives and processed with the EP Data Analysis software. Further, PIs of proprietary data need to obtain their data from the NADC archive. At this time, only the FXT data are released while the WXT are planned to be released early 2026.

LAUNCH OF ESA WEBPAGES OF EINSTEIN PROBE

19 July 2022 These ESA webpages with information about Einstein Probe see their first light.

ESA's Einstein Probe Science Archive (EPSA)

https://www.cosmos.esa.int/web/einstein-probe/data

Summary

- Einstein Probe has been operating remarkably well in the past 2 years
- Public availability & data release
  - **FXT data after 1-year proprietary period already made public**
  - **WXT data**
- Some core science objectives have been partly fulfilled
  - **Dramatically enlarged samples, e.g. fast X-ray transients (XRF, SN, …), stellar flares**
  - **Rare or long-predicted transients/objects (IMBH-TDE, WD-TDE, dirty fireball, ..)**
  - **Unexpected: jet-SN connection, other new types of transients**
- EP will continue to advance our understanding of high-energy transients ..
  - **larger samples, new types, multi-messenger transients, ……**

http://ep.bao.ac.cn

https://www.esa.int/Science_Exploration/Space_Science/Einstein_Probe_factsheet