Einstein Probe

---- a lobster-eye observatory to monitor the soft X-ray sky

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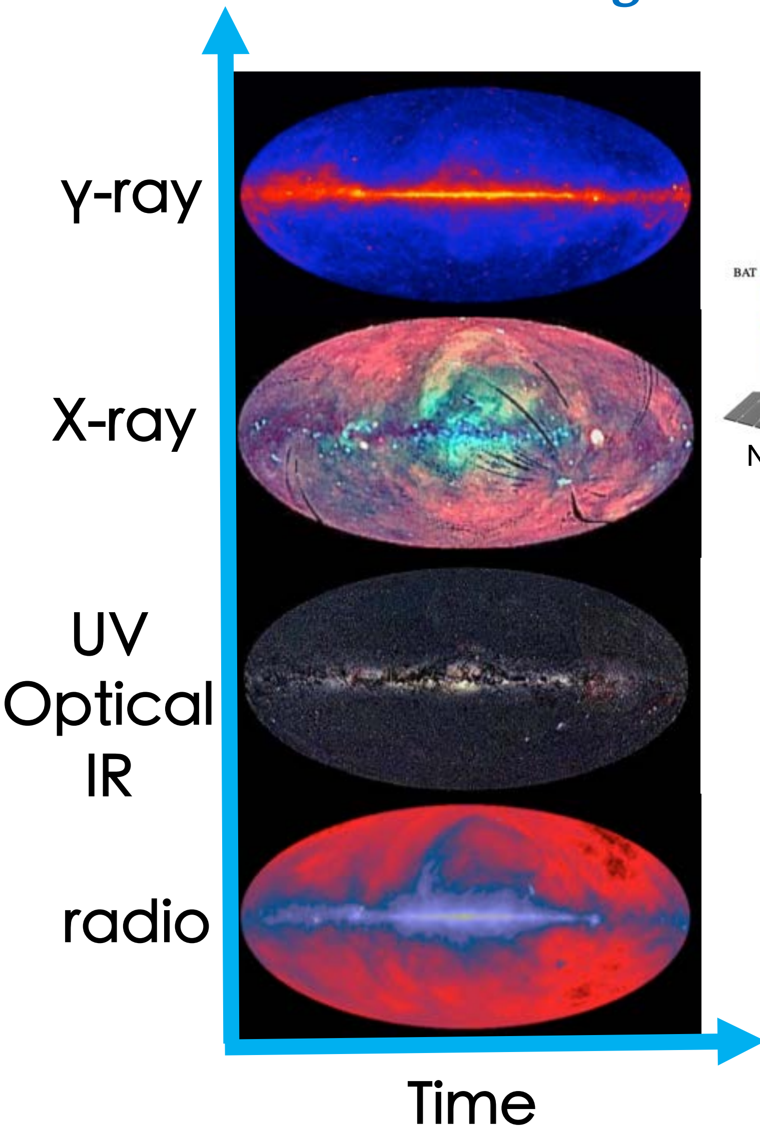
Outline

- Science driver
- Methodology and instrumentation
- Mission concept and status
- Scientific capability & prospects

Time-domain astronomy in 2020’s : M-λ & M-M

Multi-wavelength



Transients & variables

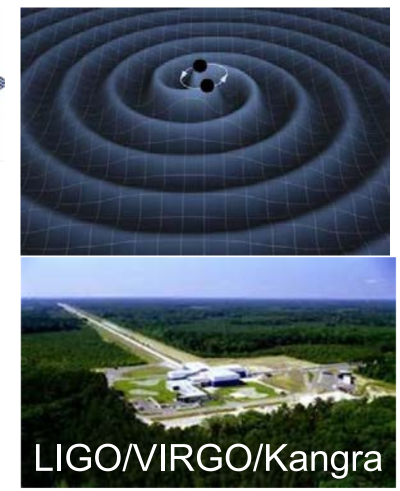
soft X-ray is to be covered

LSST,ZTF,
and more …

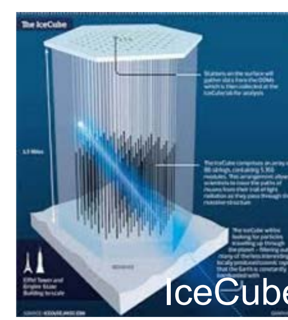
LOFAR、SKA

Multi-messenger

GW, neutrino

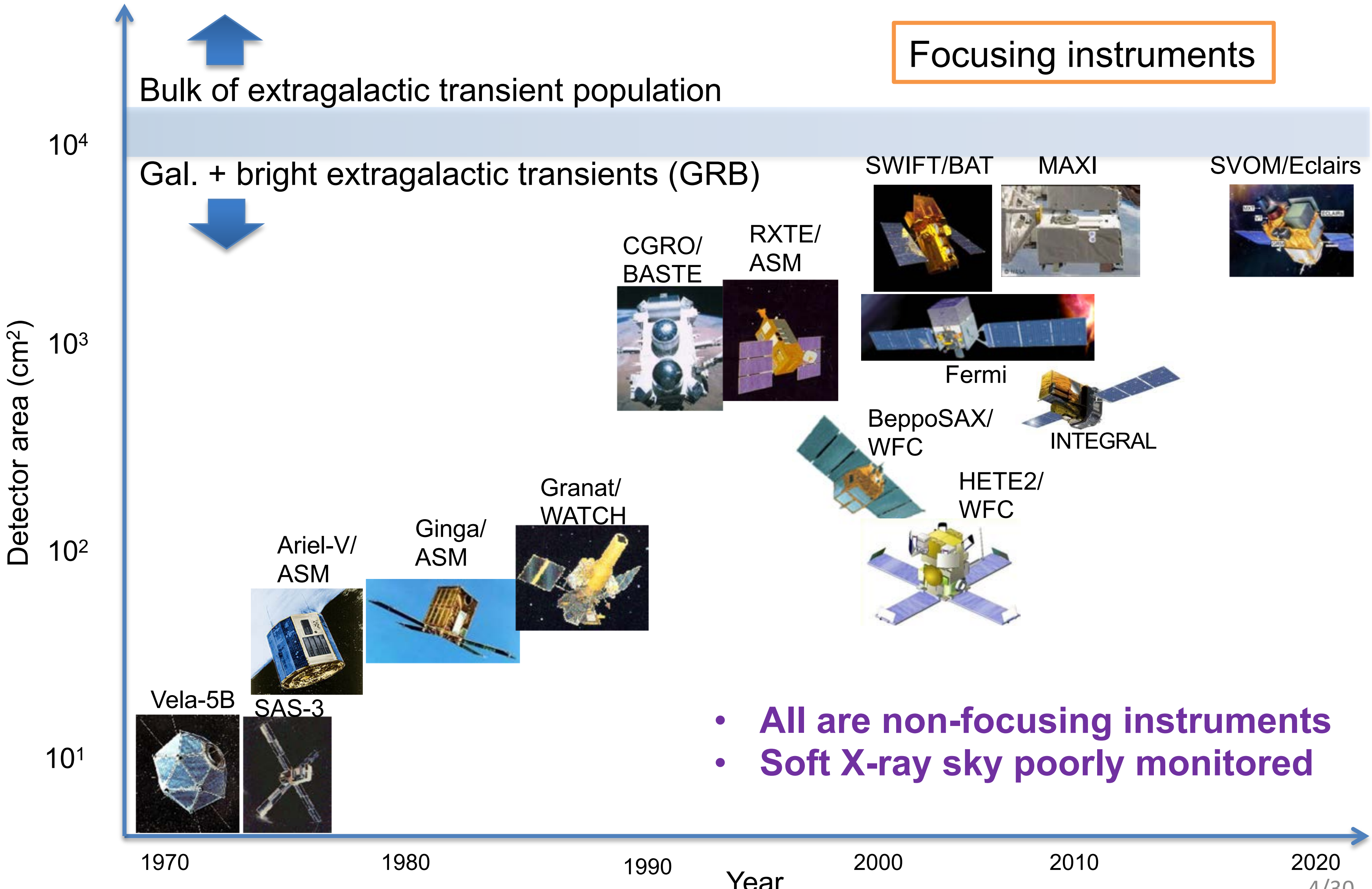


credit: LIGO



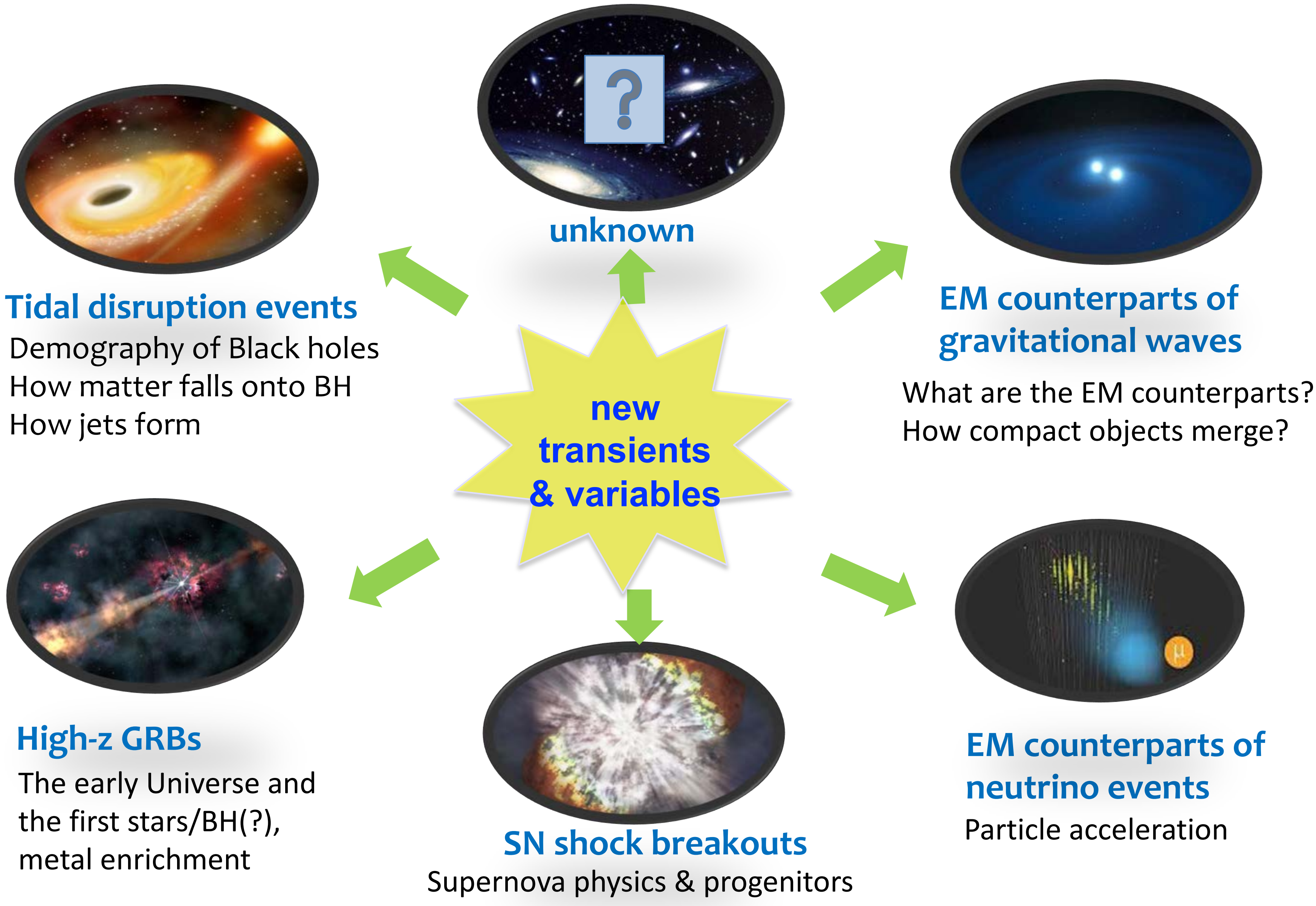
credit: IceCube

An incomplete history of X/ γ-ray wide-field monitors

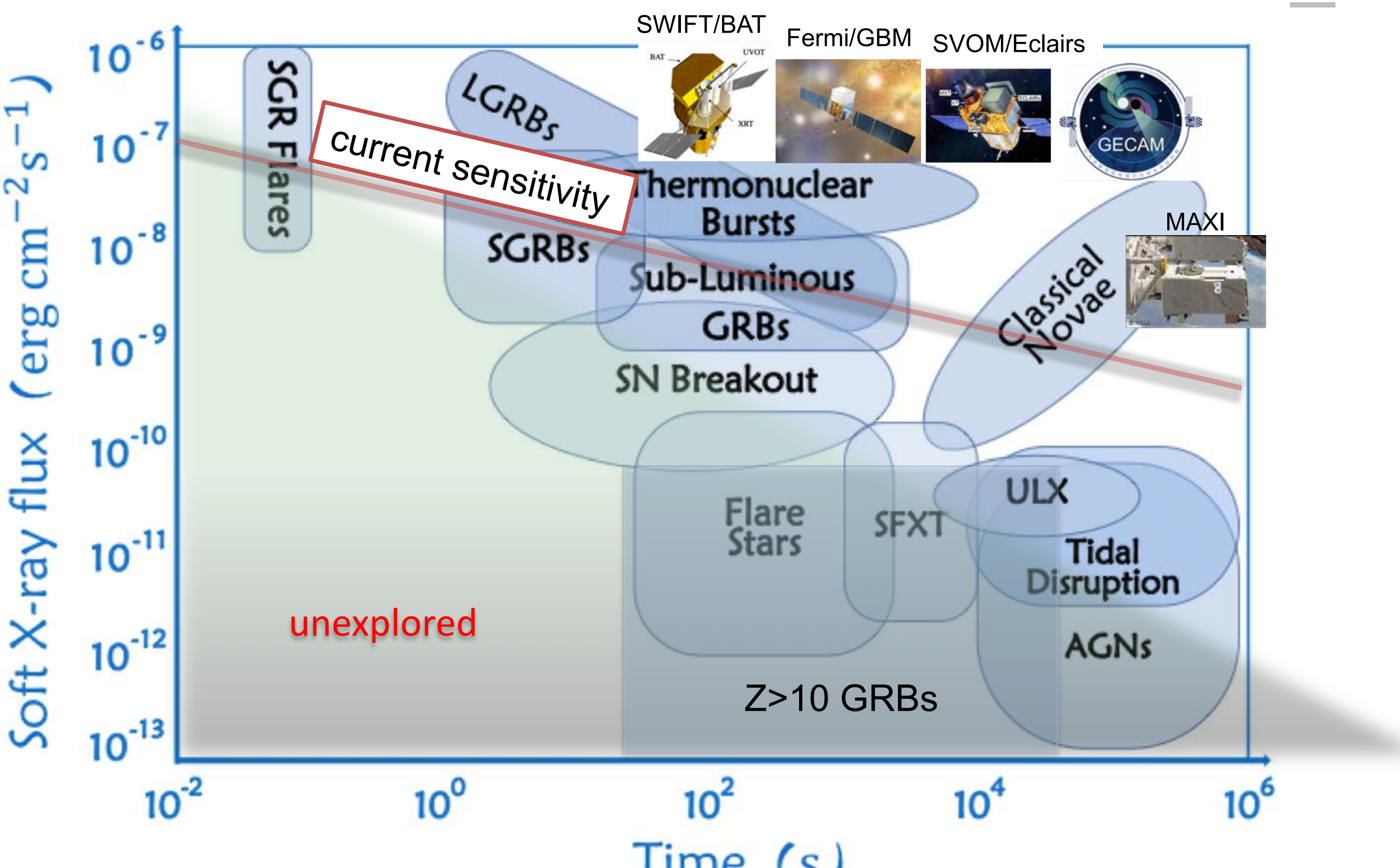


- **All are non-focusing instruments**
- **Soft X-ray sky poorly monitored**

New types of high-E transients await discovery and characterization in large numbers



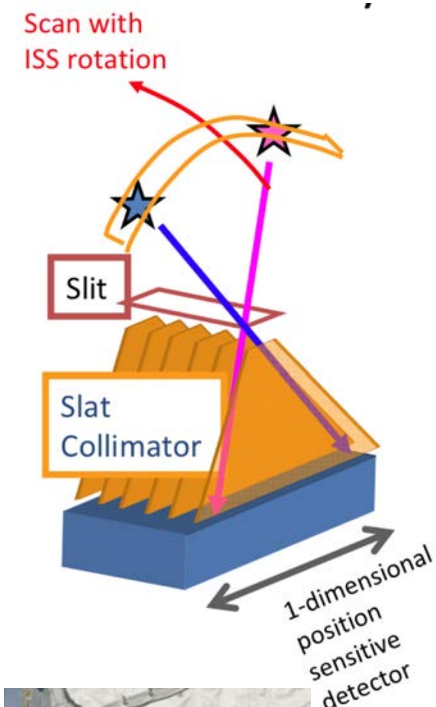
Challenges in finding faint high-E transients



Next generation X-ray ASM: higher sensitivity and higher cadence

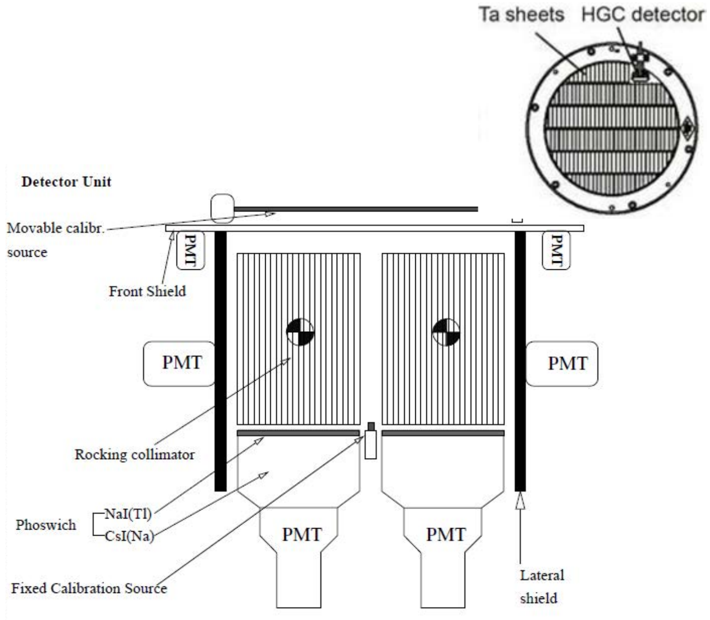
current wide-field X-ray monitors: non-focusing

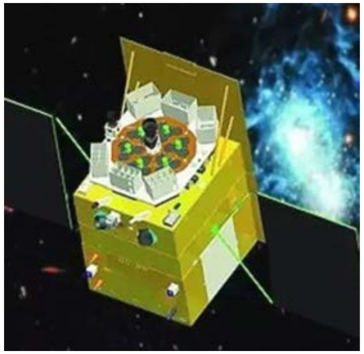
pinhole/slit



MAXI (credit: JAXA)

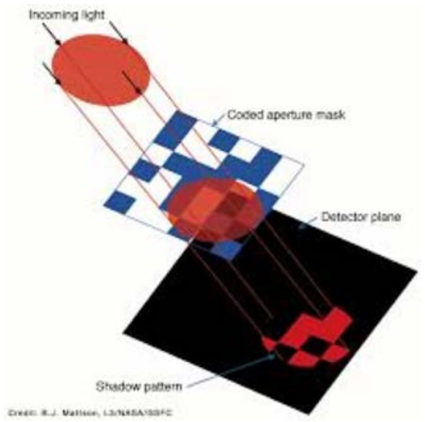
collimator + scan

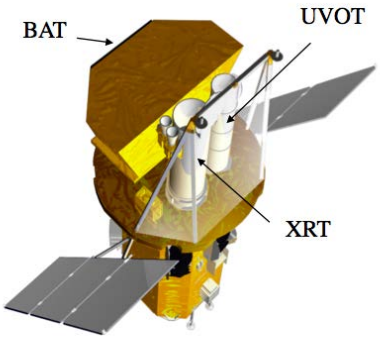




HXMT-Insight (credit: CAS)

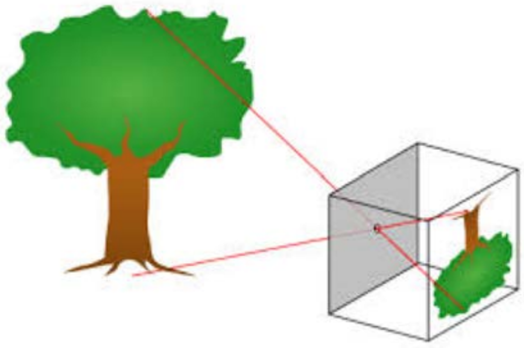
coded masks





Swift/BAT (credit: NASA)

Non-focusing wide-field X-ray monitors



pinhole imaging

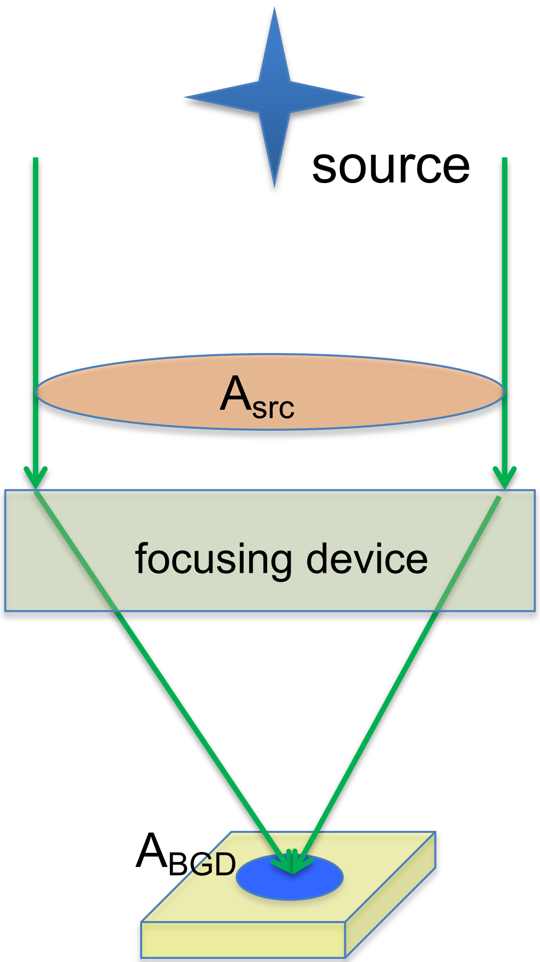
$$\frac{S}{N} \propto \frac{N_{src}}{\sqrt{N_{BGD}}} \propto \frac{A_{src}}{\sqrt{A_{BGD}}}$$

$A_{src}/A_{bgd} \sim 1$

increasing A_{src} also enlarges A_{bgd} at the same time （spatial resolution decreases)

Low angular resolution (~ degree), high background, low signal/noise

A focusing optic



$$\frac{S}{N} \propto \frac{N_{src}}{\sqrt{N_{BGD}}} \propto \frac{A_{src}}{\sqrt{A_{BGD}}}$$

$$A_{src} \gg A_{BGD}$$

A_{BGD} and hence the detector background is reduced, thus S/N increased

From the point of view of its instrumentation, X-ray astronomy possesses a certain moral simplicity. It is a perpetual battle of good versus evil; that is of signal versus noise.

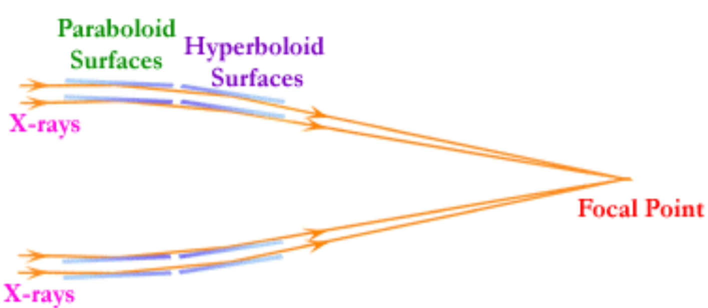
G.W. Fraser "X-ray detectors in astronomy"

X-ray focusing optic systems

- X-ray reflection： grazing incidence $\theta < \theta_c \propto \frac{\sqrt{n_e}}{E_{pho}}$

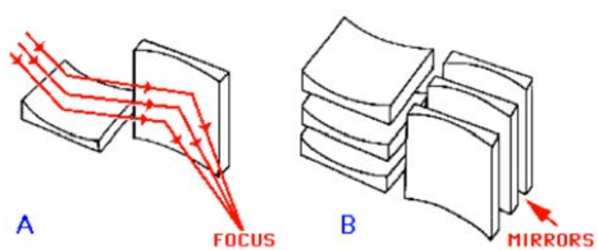
  critical angle θ_c ~ a few degrees @ 1keV

- always 2 reflections for imaging
- two basic options:
  - Wolter type I (Wolter 1952)
  - Kirkpatrick-Baez (K-B) geometry (Kirkpatrick & Baez 1948)
    - Angel – square pore lobster-eye



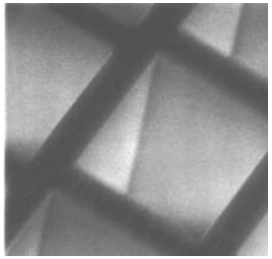
Wolter-I

credit: NASA



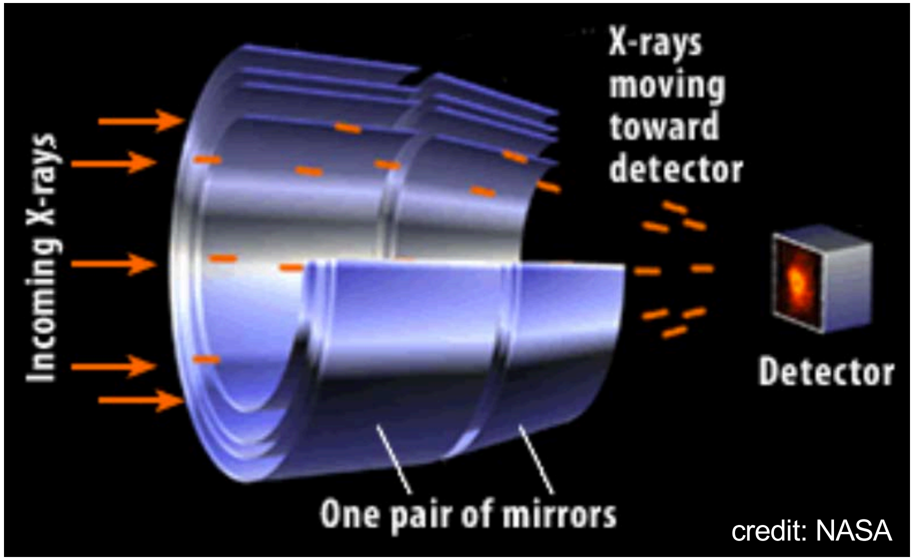
K-B

credit: from NASA/GSFC webpage after Kirkpatrick & Baez (1948)

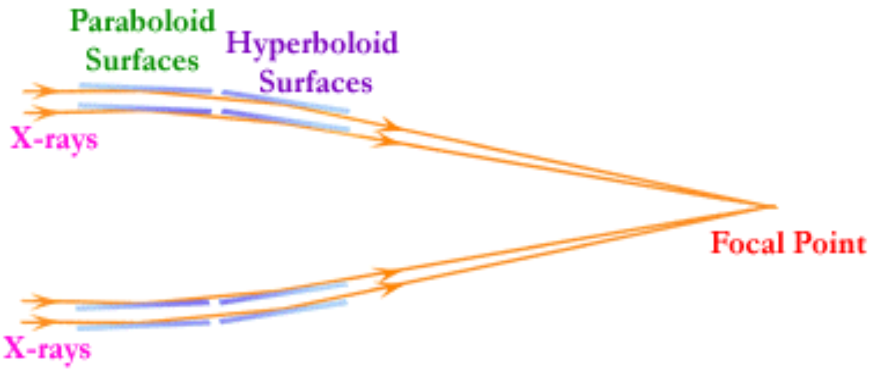


Angel lobster-eye

Wolter-I type focusing optic



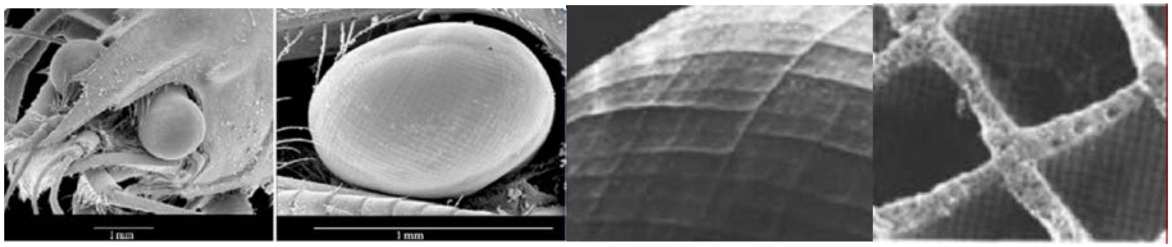
- Large light collecting area
- High spatial resolution
- Small field-of-view (<1 deg)
- Heavy



credit: NASA

widely used: Chandra, XMM-Newton, NuStar, Swift/XRT, eROSITA

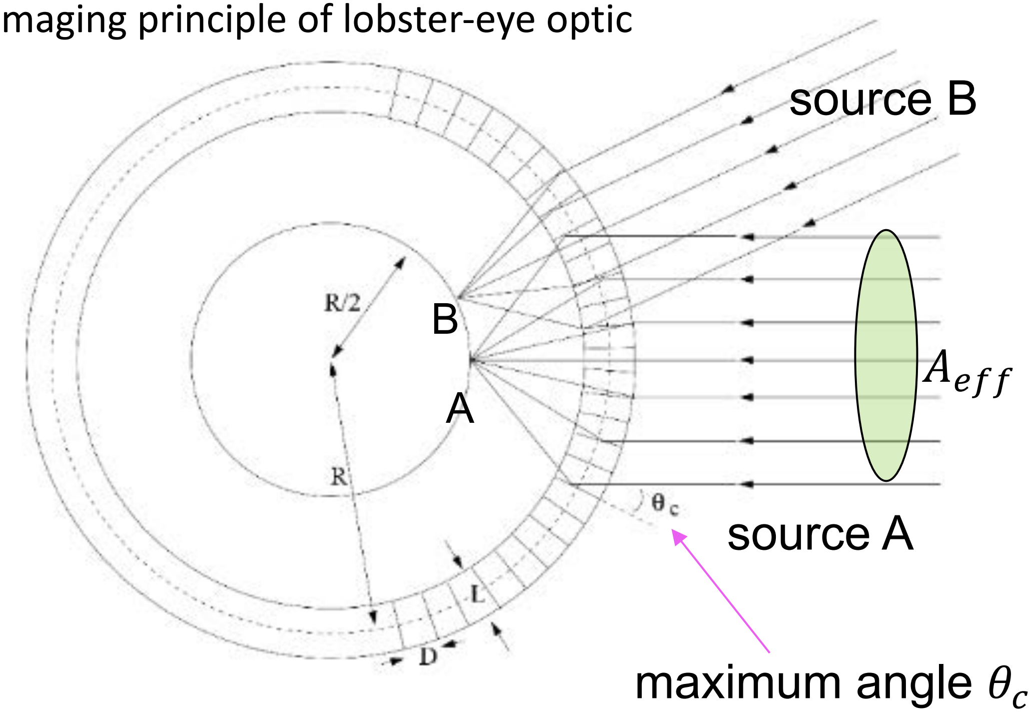
Lobster-eye micro-pore optic (MPO)



a SEM image of a lobster eye (from Gaten 1994) (also other crustaceans)

light is reflected from the adjacent walls of the square packed pores (tunnels) and is brought onto the focal surface (sphere)

imaging principle of lobster-eye optic



- grazing incidence focusing
  - same as for X-ray
- spherical symmetric optic
  - wide-field up to 4π
- light-collecting area
  - $A_{eff} \propto sphere\ area \propto R^2$

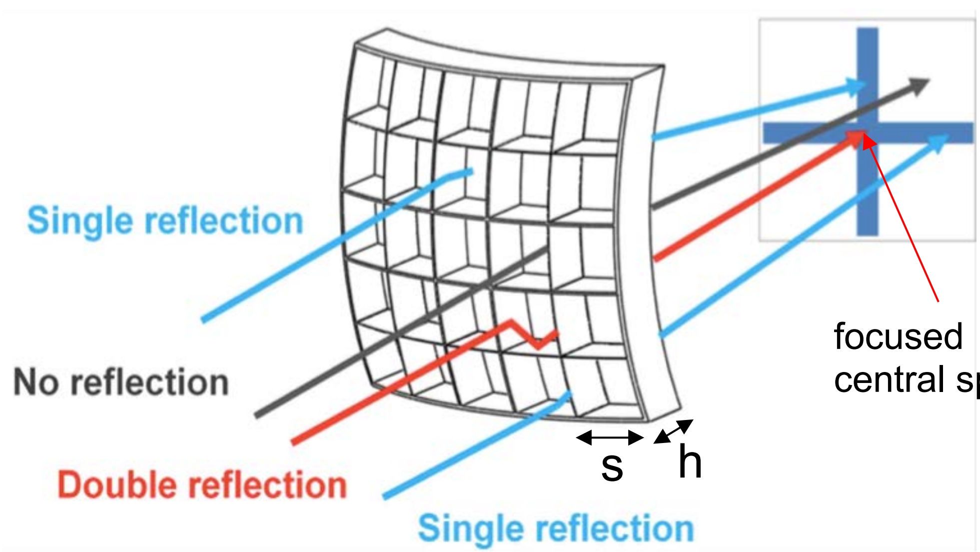
an ideal optic for X-ray wide-field monitors

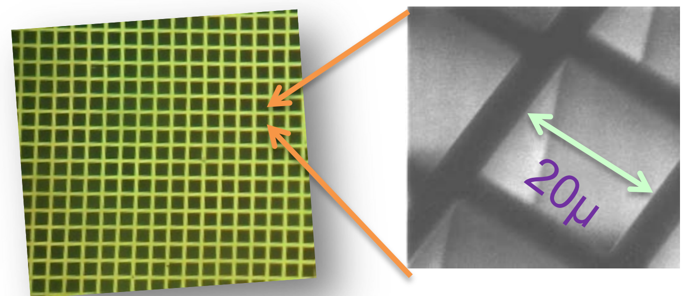
Concept of lobster-eye MPO for wide-field monitor

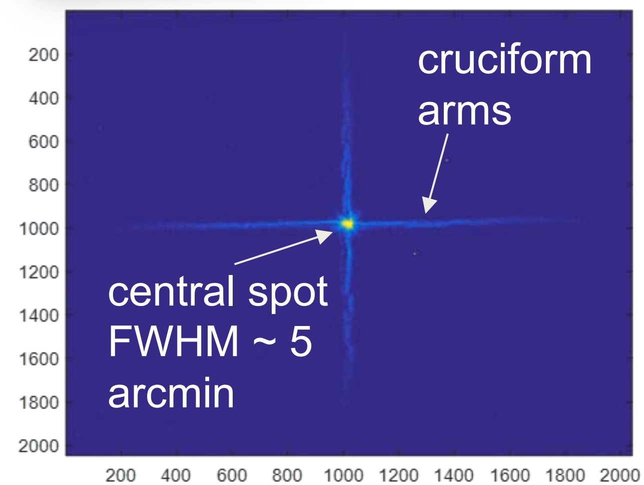
First proposed by R. Angel (1979), and later studied theoretically and experimentally by a number of groups e.g. Wilkins et al. (1989) ; Fraser et al. (1992); Kaaret (1992)

also known as micro-channel plates (MCP)

Light path of MPO

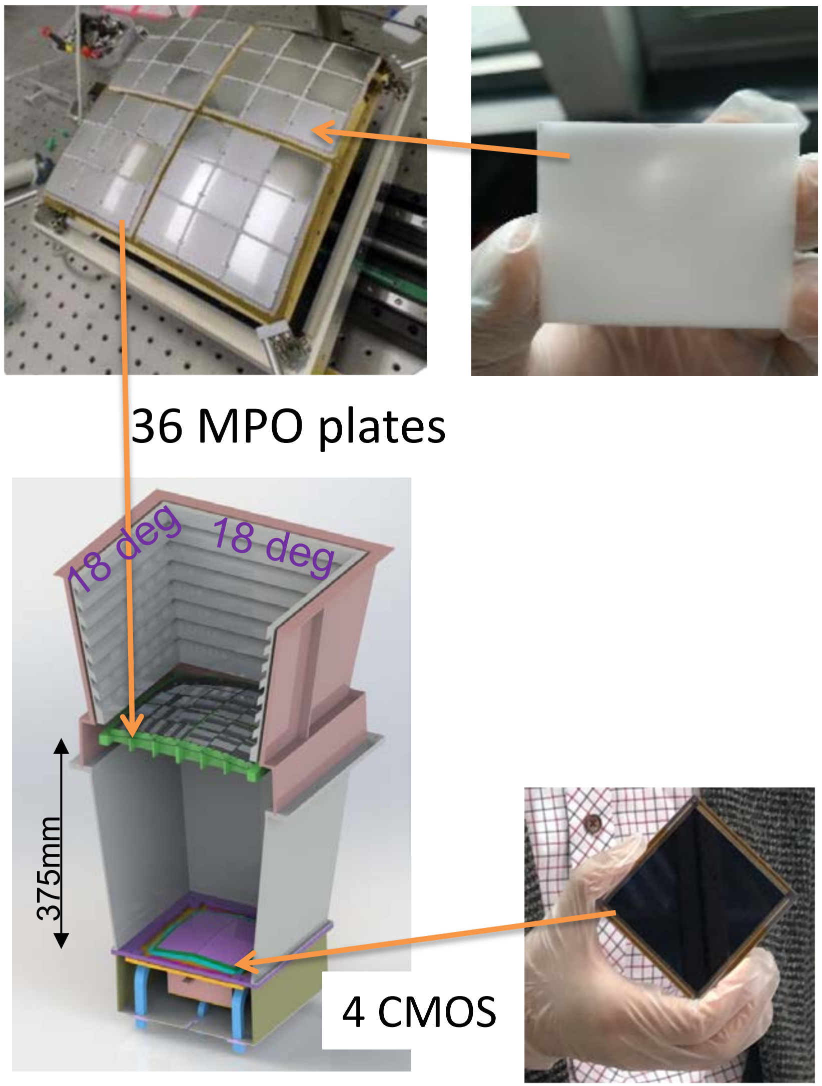






long square tube, aspect ratio h/s = 40-60 : 1

A lobster-eye telescope： ideal X-ray wide-field monitor



FoV 324 sq. deg.

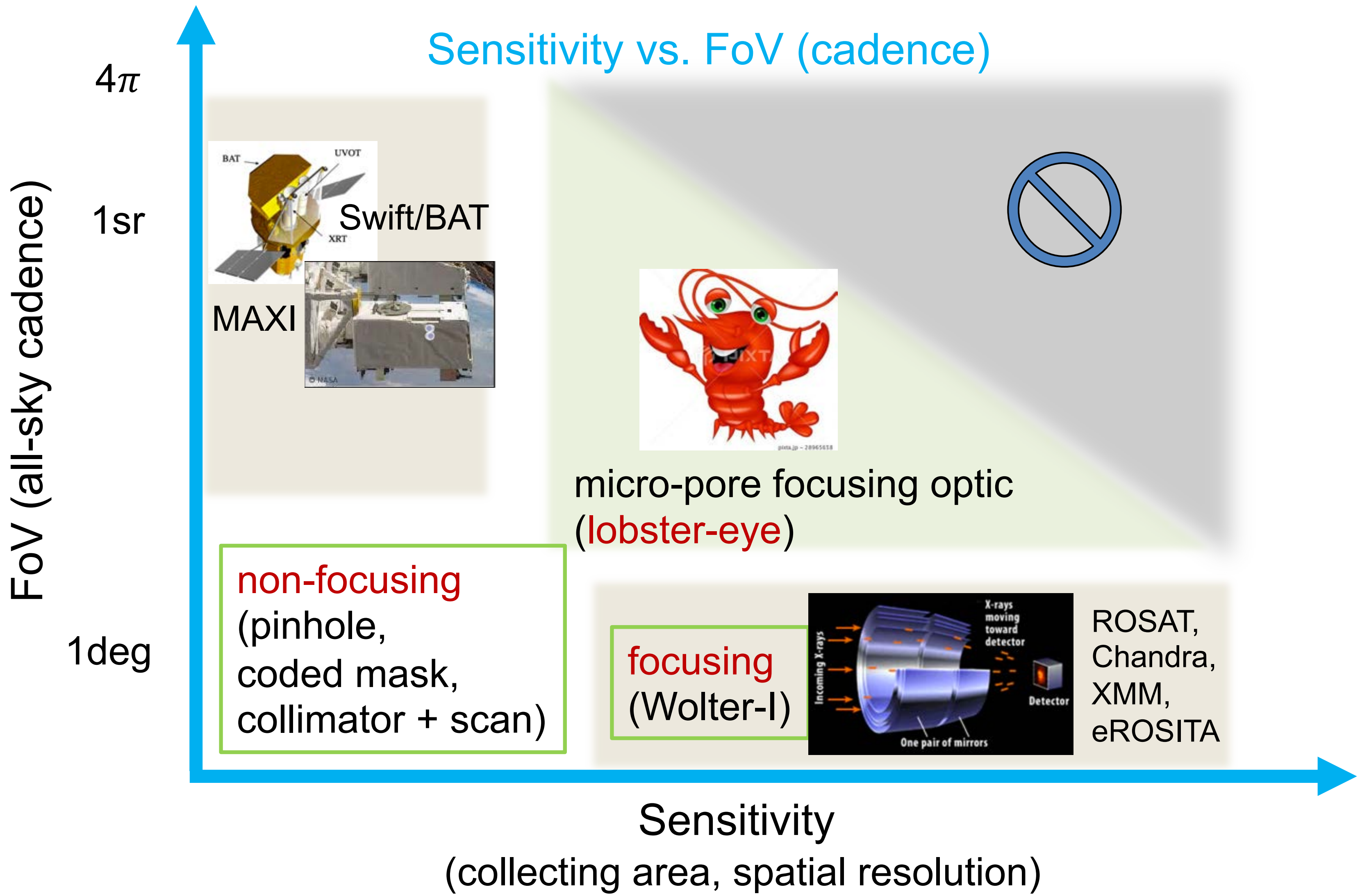
Pros

- True imaging by focusing X-rays
- Wide FoV (almost un-vignetted)
- good resolution: ~ 5 arcmin
- good sensitivity
  - reduced noise in source area (detector)
  - more photons in soft X-ray
- Low weight
  - lead glass with millions of holes

Cons

- small effective area
  - $3cm^2$ @ ~ 1keV for 37cm focal length
- large focal surface (detector)
  - ¼ mirror area
- narrow bandpass (<5keV)
  - fast drop of reflectivity for E>5keV
- cruciform PSF

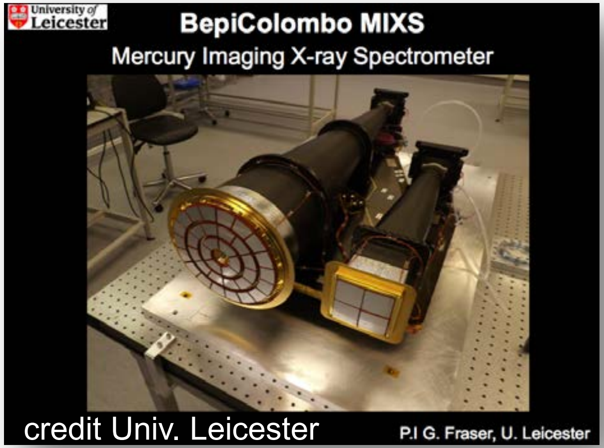
lobster-eye MPO: a compromise of FoV & sensitivity



MPO missions proposed, planned, and built

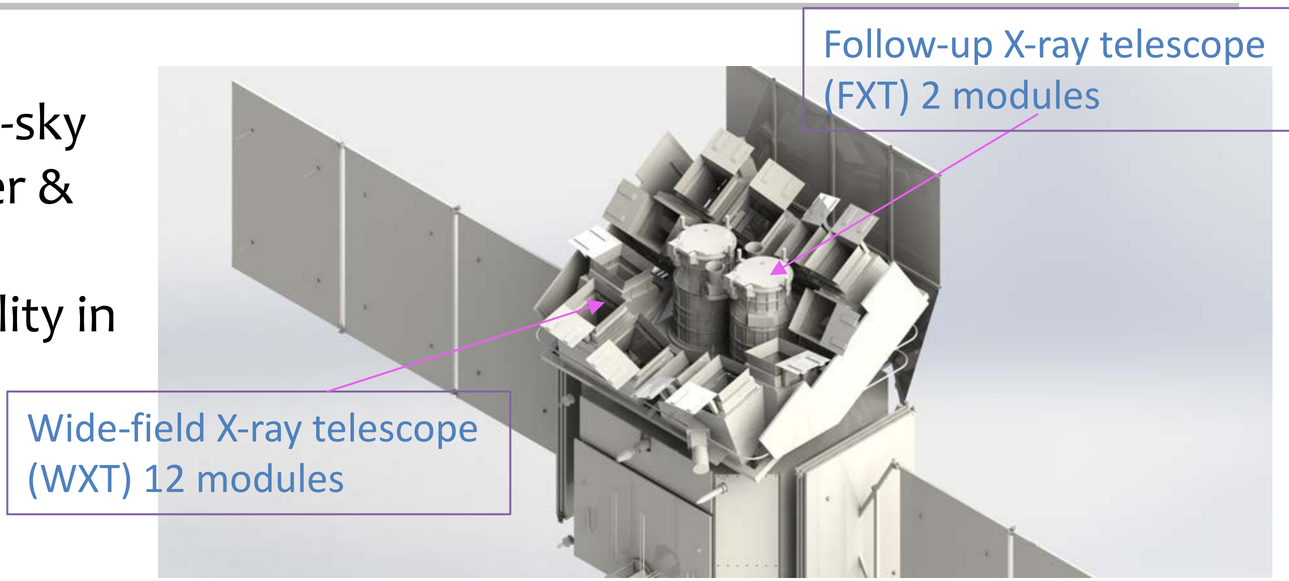
- Conceptual designs of X-ray ASM
  - Priedhorsky, et al. (1996, MNRAS)
  - Fraser et al. (2002)
- mission proposals to use MPO for astrophysics (others include planetary science and Earth magnetosphere studies)
  - ASM (to ESA, Fraser et al. 1990)
  - Lobster (Priedhorsky et al. 1997, NASA SMEX)
  - Lobster on ISS (Fraser et al. 2000)
  - WFT on SRG mission (UK, Fraser et al.)
  - A-STAR (ESA)
  - Einstein Probe (CAS) approved
  - Lobster (NASA)
  - Theseus (ESA)
  - ISS-Lobster and TAP (NASA)
  - HiZ-GUNDAM (JAXA)
- launched
  - STORM rocket experiment (US; upper atmosphere)
  - Mercury mission BepiColombo MIXS (ESA)
  - a cubeSat (Nanjing Univ. China)

incomplete!



Einstein Probe (EP) mission

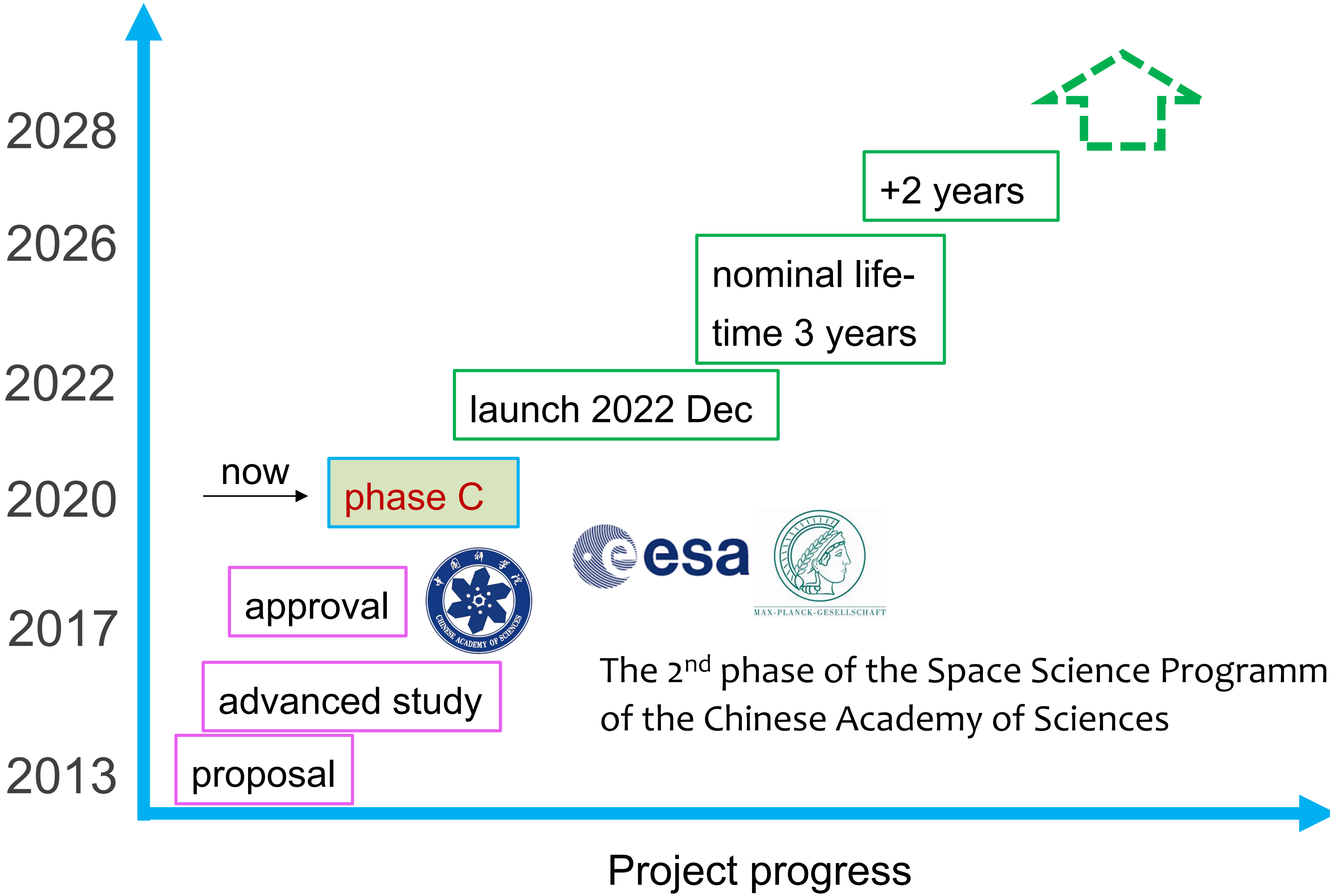
An observatory for all-sky monitoring to discover & study high-energy transients and variability in soft X-rays



The 1st X-ray monitoring observatory with *all* focusing instruments

- Field of View: 3600 sq. deg.; grasp: ~10,000 $deg^2.cm^2$
- Monitoring band: soft X-ray 0.5-4 keV
- Sensitivity: > 1 order of magnitude higher than those in orbit
- Good angular resolution: (~5 arcmin) and positioning accuracy (<1 arcmin)
- Autonomous 0.3-10keV X-ray follow-up within < ~ 3min (localisation <10 arcsec)
- Fast alert data downlink and fast uplink (ToO)

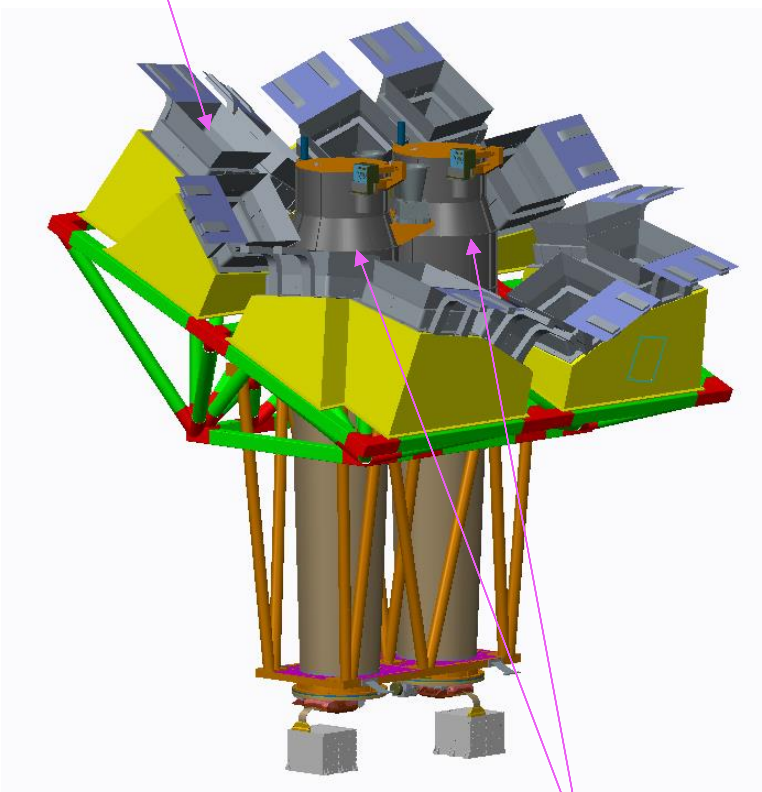
Project status



The 2nd phase of the Space Science Programme of the Chinese Academy of Sciences

Instrument configuration & fields of view

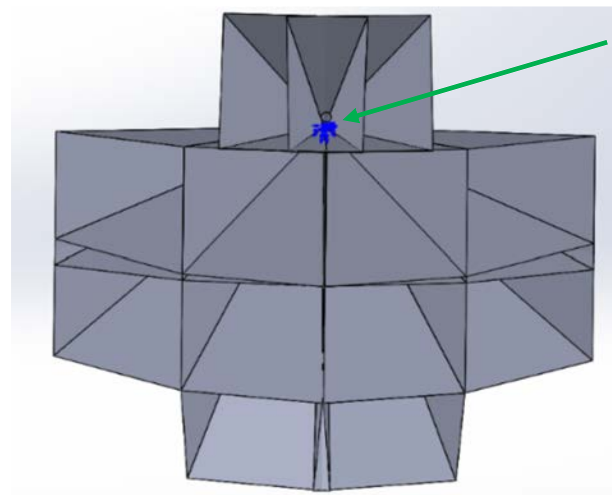
WXT (12 modules)



FXT(2 telescopes)

WXT FoV (1.1sr)

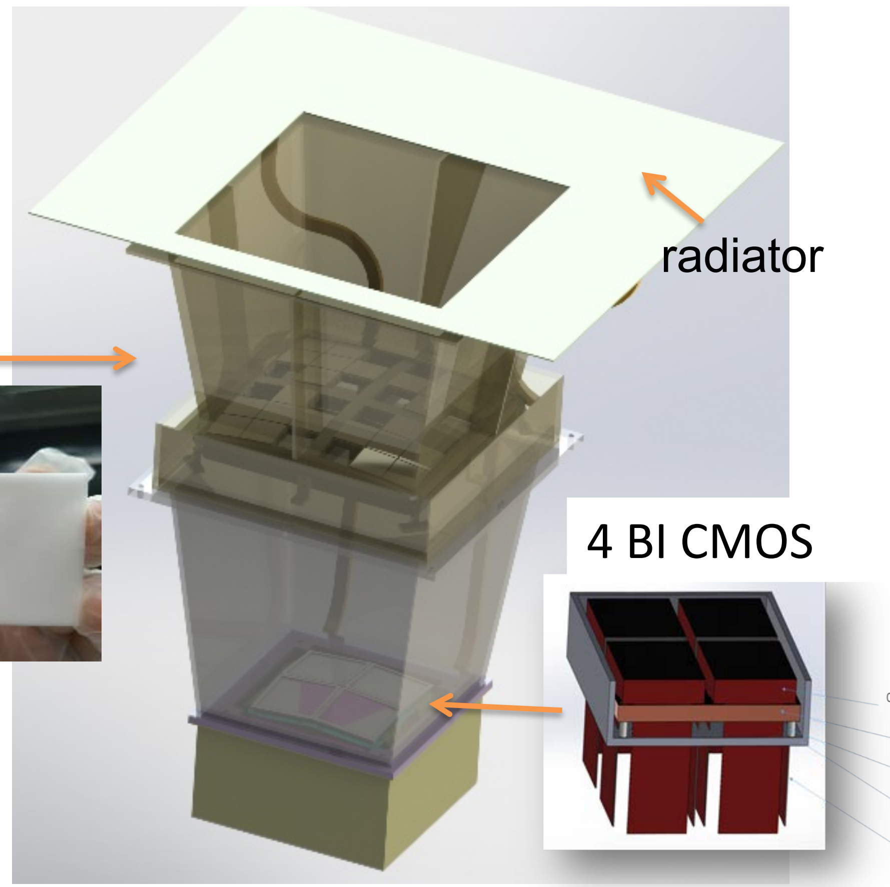
FXT FoV (38')



Wide-field X-ray Telescope (WXT)

- X-ray optics: lobster-eye MPO
- Detector: BI CMOS array
- Focal length: 375mm
- Eff. area: ~3cm2 @1keV
- FoV: 3600 sqr. deg.
- FWHM: ~ 5 arcmin
- Bandpass: 0.5-4 keV
- E-resolution: 170eV @1.25keV

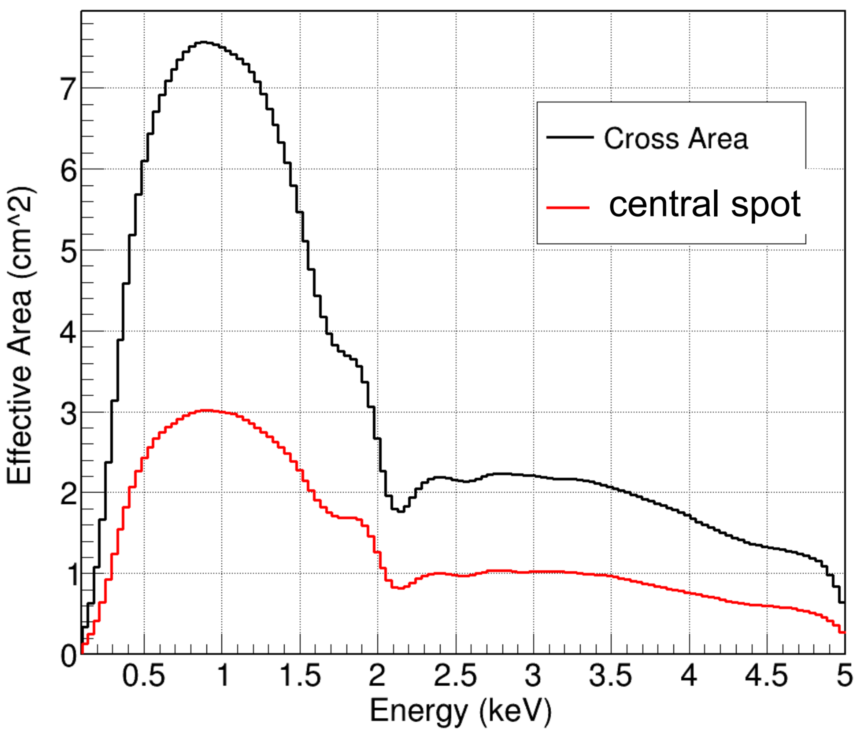
One WXT module



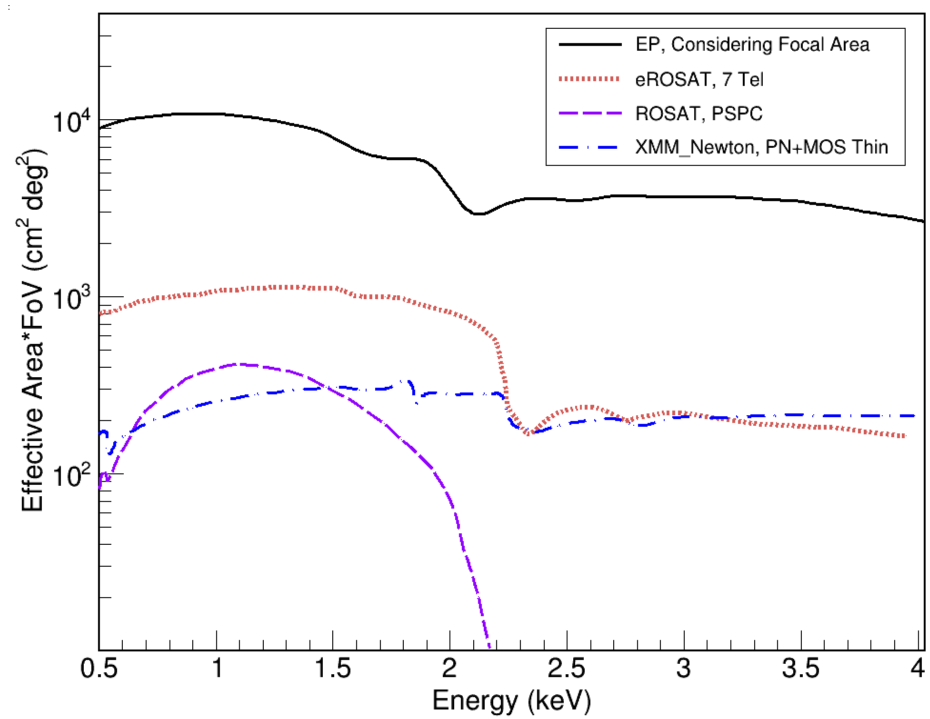
The largest-format detector for focusing X-ray telescopes to date (total 432 cm^2)

WXT effective area & Grasp

effective area from simunlations
in all direction within FoV



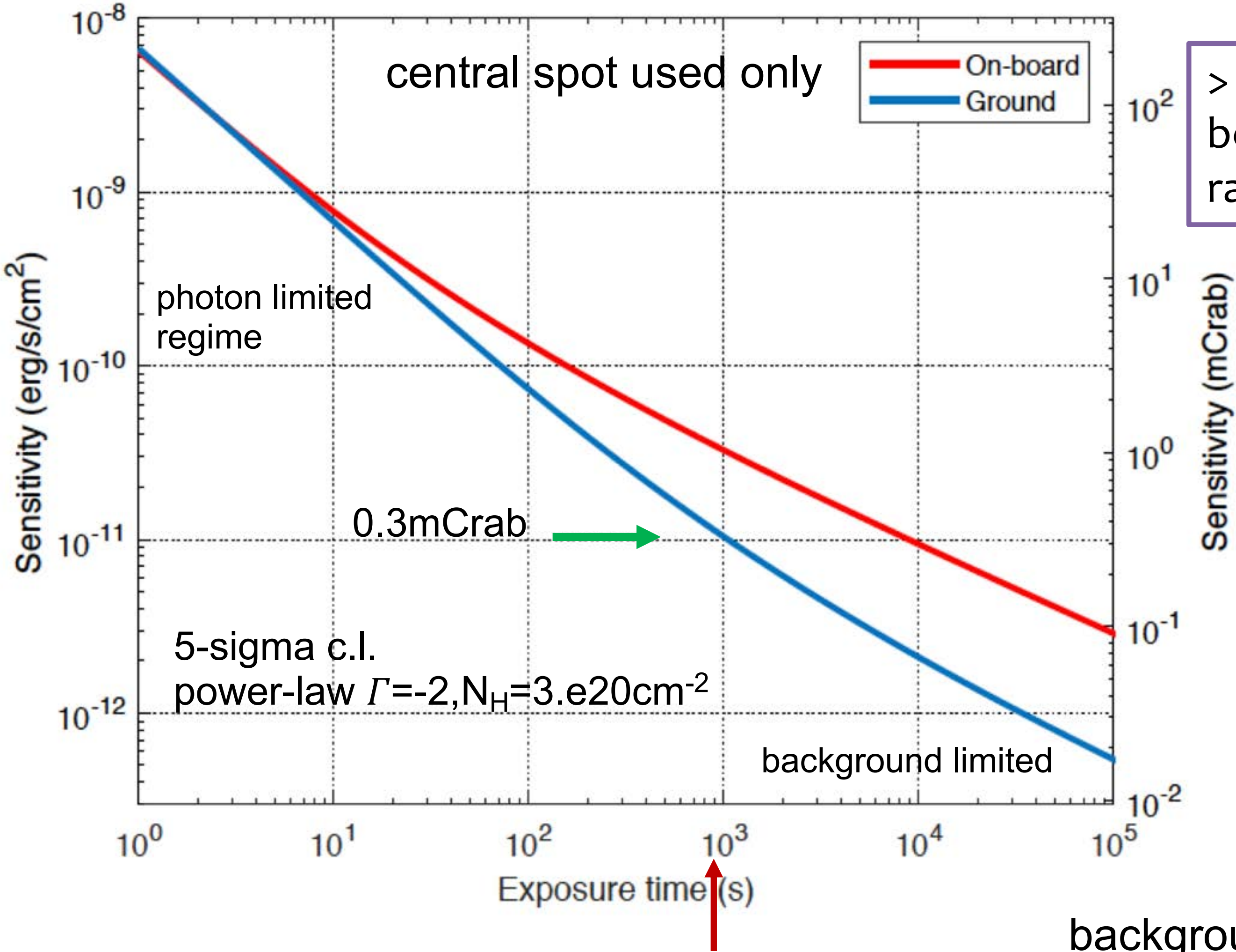
Grasp parameter



MPO pore surface: Ir coating
CMOS detector 200nm Al coating

Zhao D. et al. 2017

Simulated EP WXT sensitivity



> 1 order of magnitude better than current X-ray ASM (MAXI, Swift)

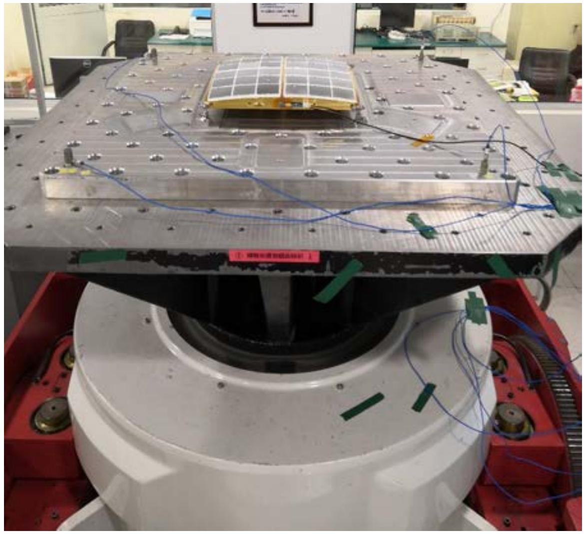
~ 1 survey snapshot

background 3.3 counts @ central spot

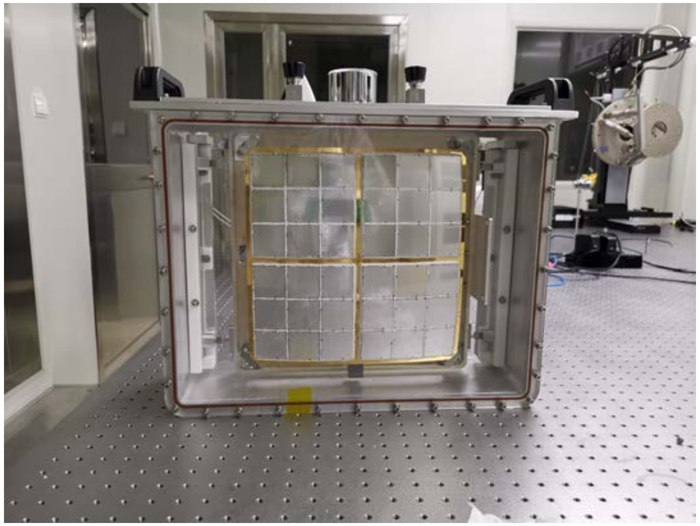
backgrounds : particles, diffuse background, with shielding

Zhao D. et al. 2017

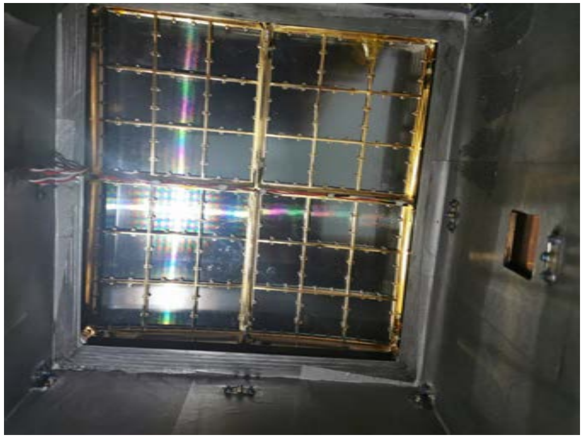
WXT status



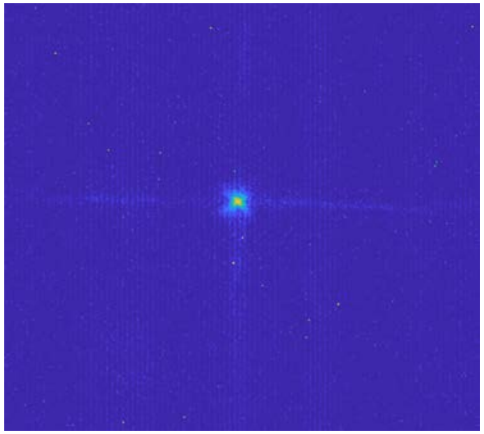
Testing a WXT mirror assembly mechanical-thermal model



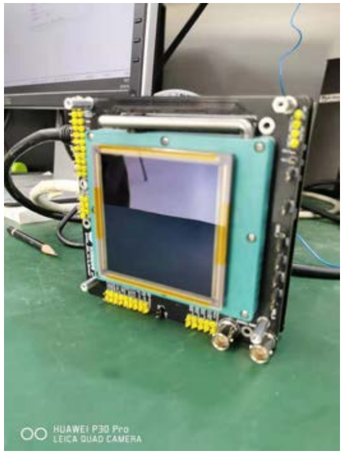
First prototype module of mirror assembly



Second prototype module mirror assembly in thermal vacuum test



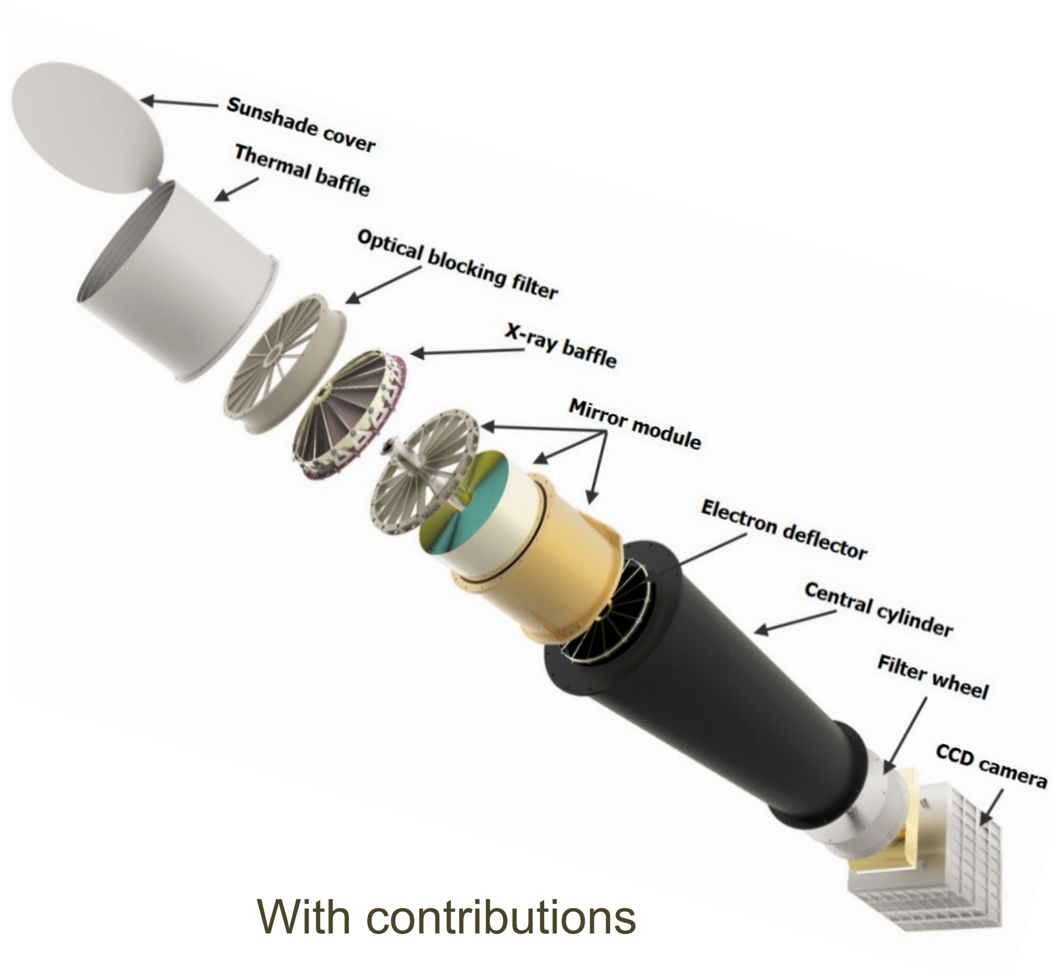
measured one PSF of the mirror assembly



BI CMOS sensor engineering chip

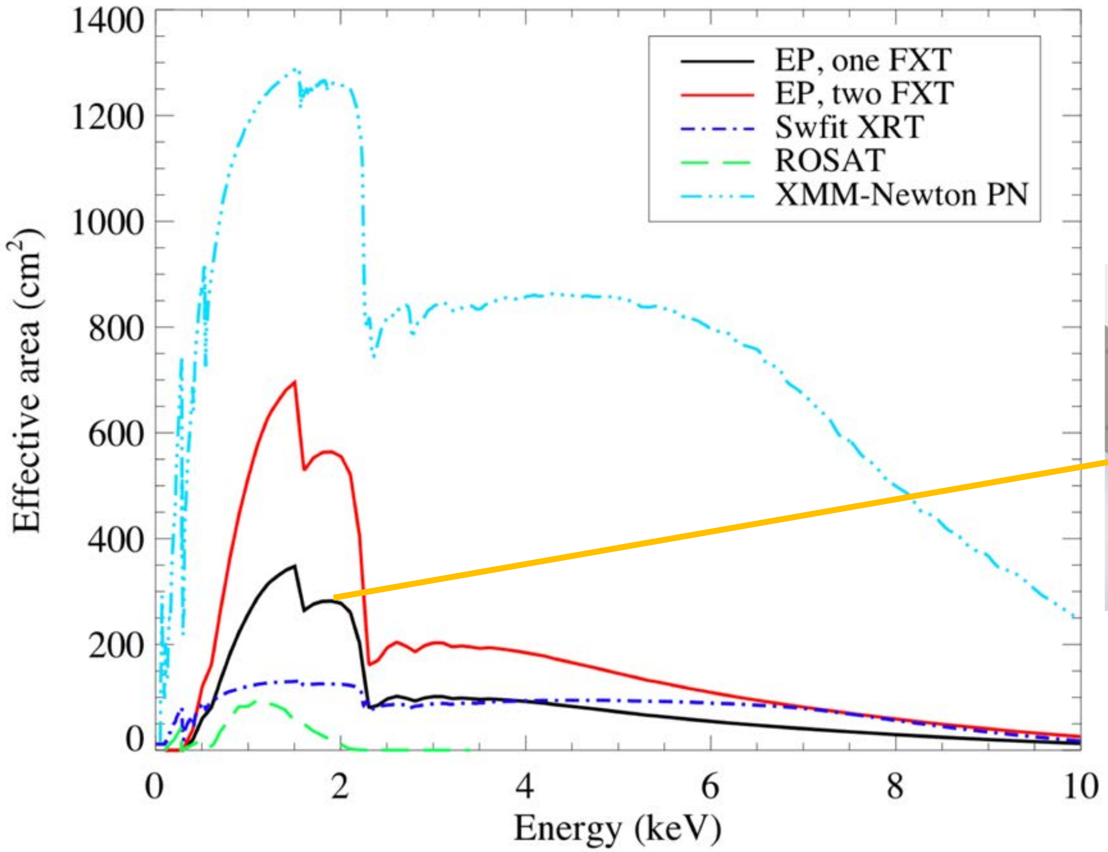
Fellow-up X-ray Telescope (FXT)

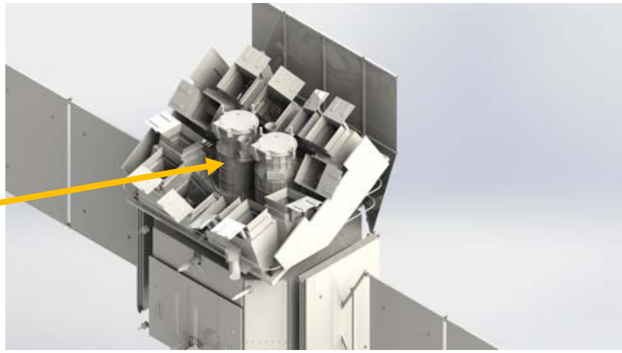
- X-ray mirror: Wolter-I
- Detector: CCD
- Focal length: 1.6m
- Eff. area: 300cm^2 @1keV
- Spatial resolution (HPD): 30”
- FoV: ~38 arcmin
- Bandpass: 0.3-10 keV
- E-resolution: 120eV @1.25keV



With contributions from ESA and MPE

Follow-up capability of EP-FXT

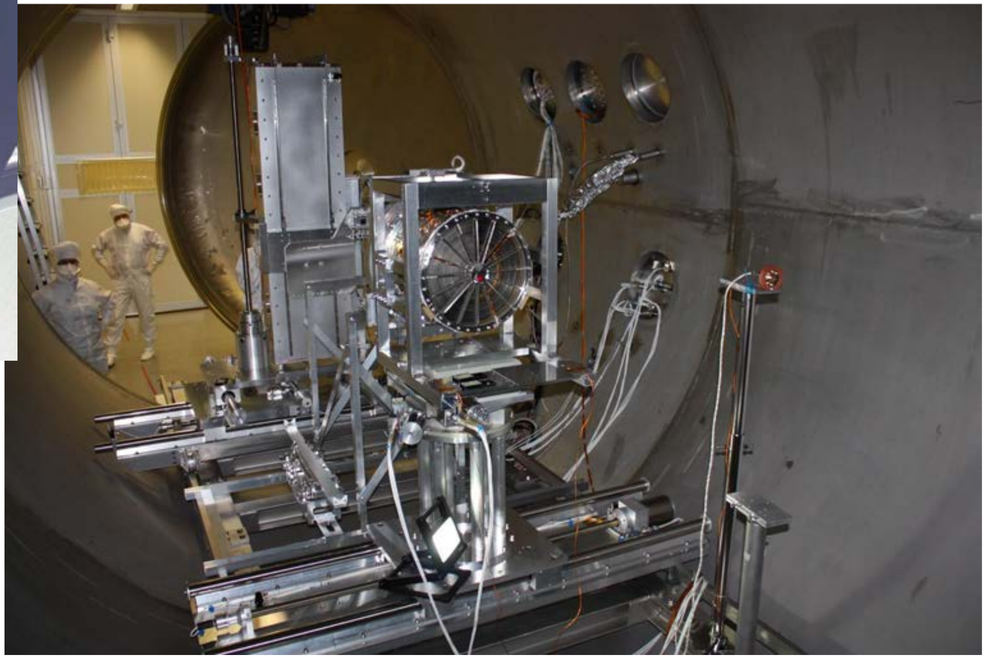




- Source localisation <10”
- Monitoring X-ray spectral/flux evolution
- X-ray follow-up for TDE found in other surveys (e.g. optical, radio)

FXT status

FXT STM Mirrors integration (credit Media-Lario)



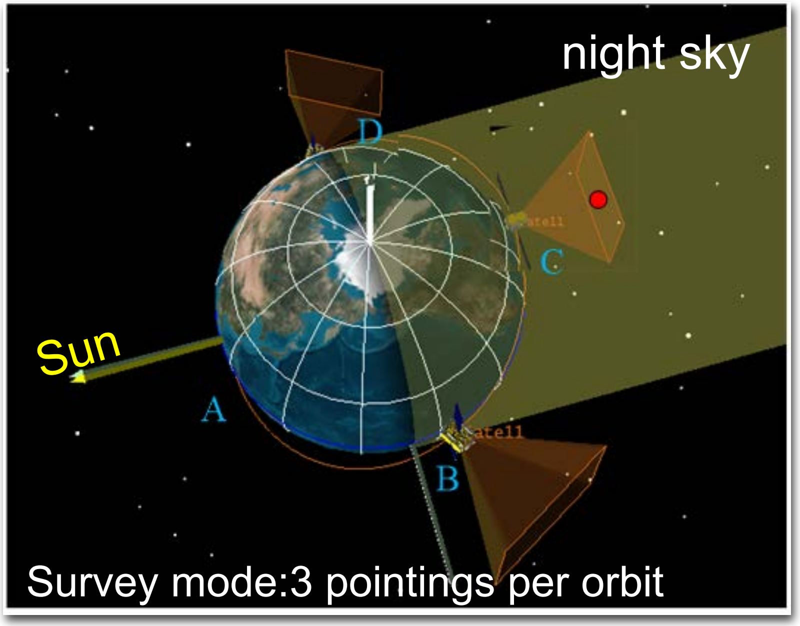
FXT STM Mirror Module at PANTER facility for X-ray tests (credit Media-Lario)

EP satellite STM model

2019 Nov

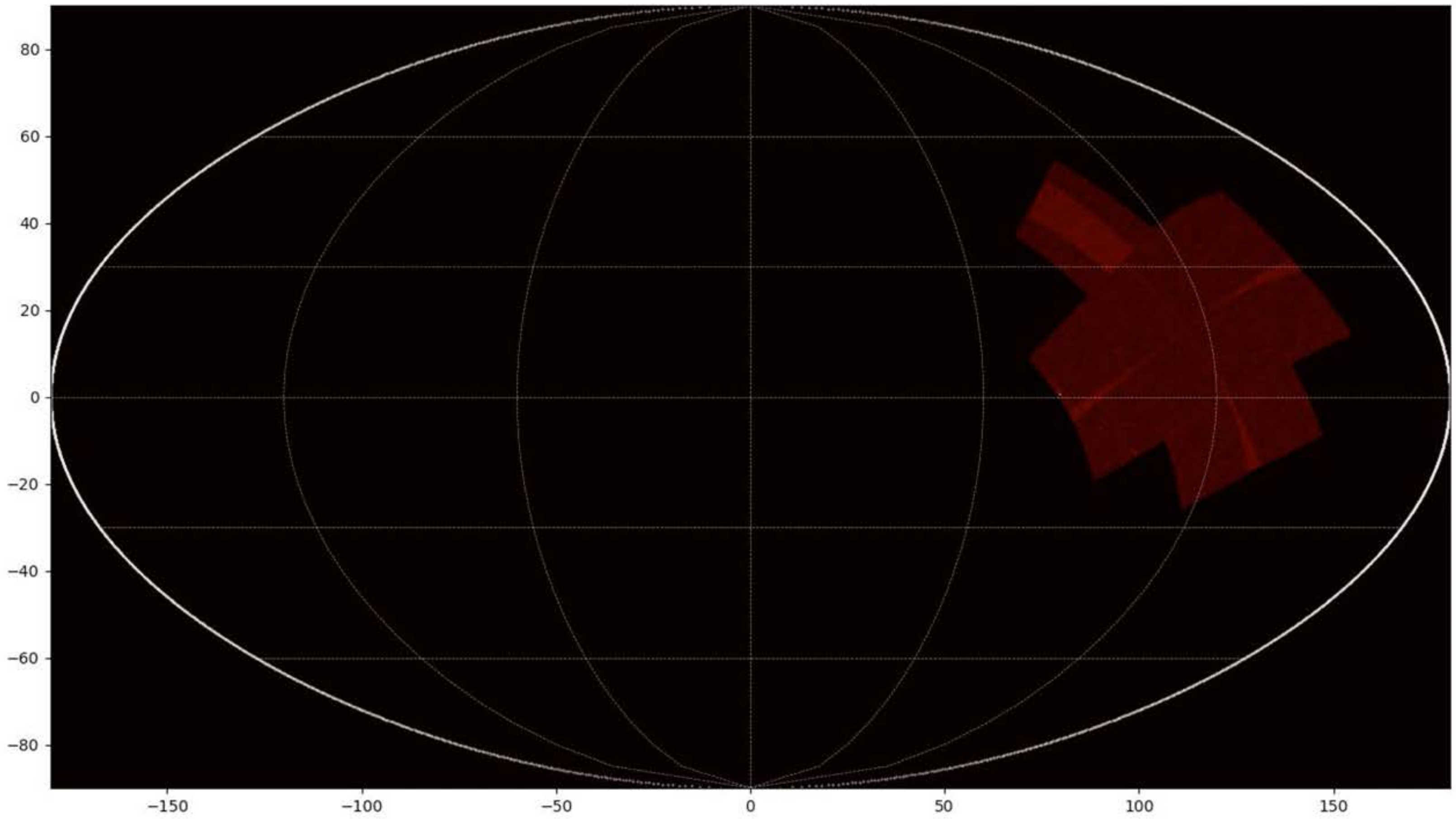
Mission profile

- Orbit: 570 km (P ~97min),   i < 30deg
- 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
- Fast ToO uplink



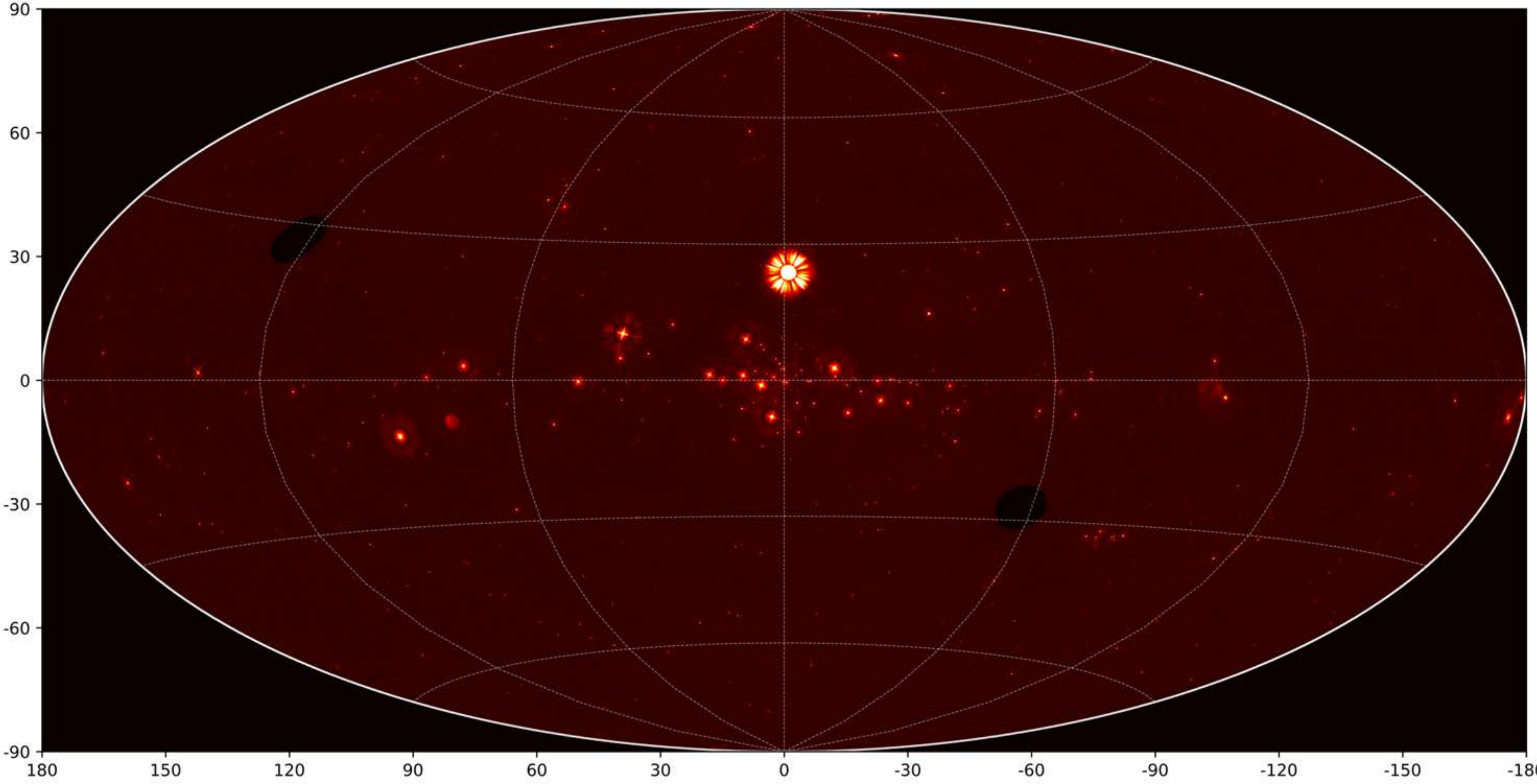
WXT monitoring survey (simulations)

WXT FoV footprints in 1-day (Galactic coordinates)

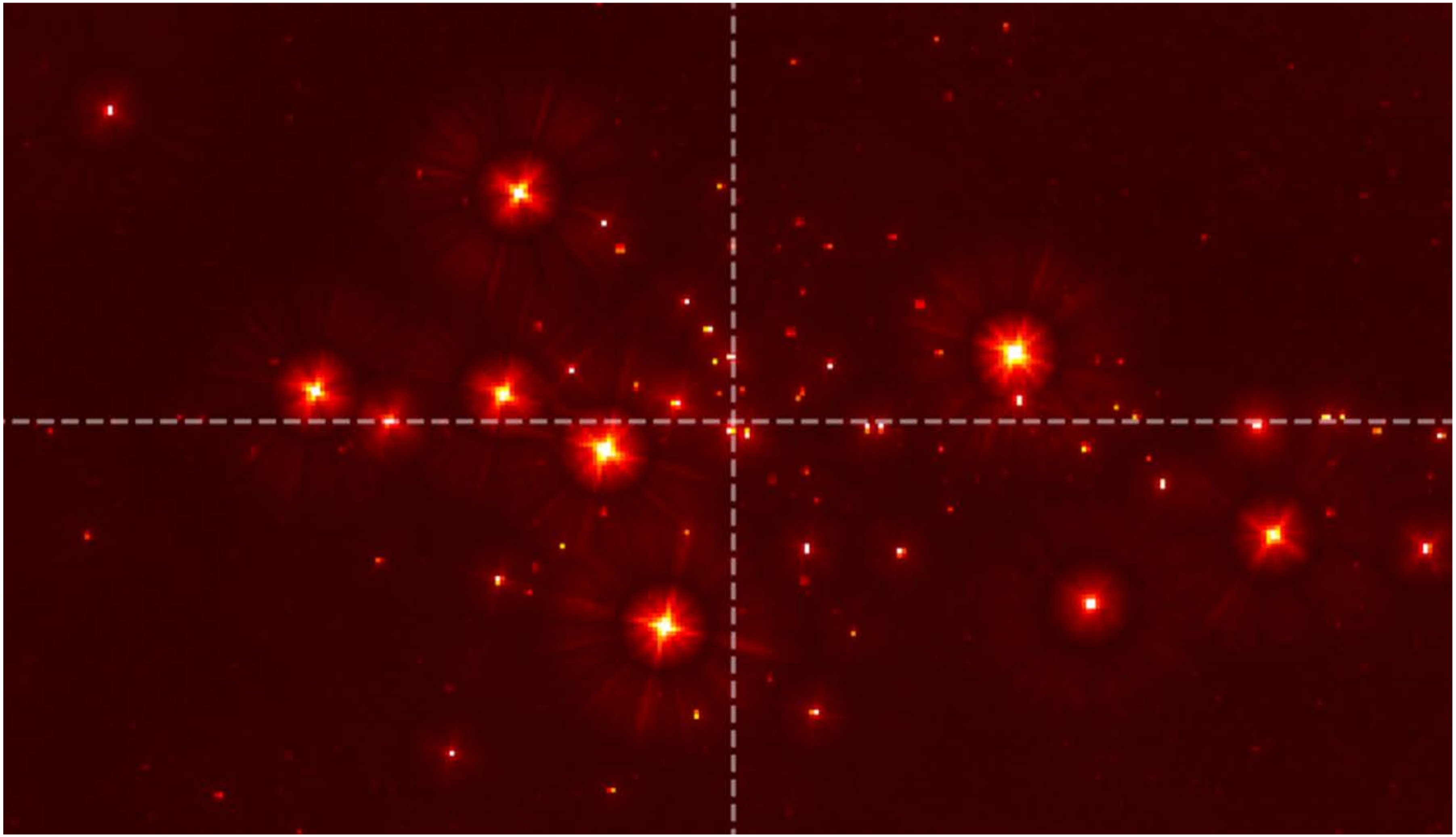


3 orbits (5hr) cover ~1/2 sky

Simulated all-sky image in 1-year operation

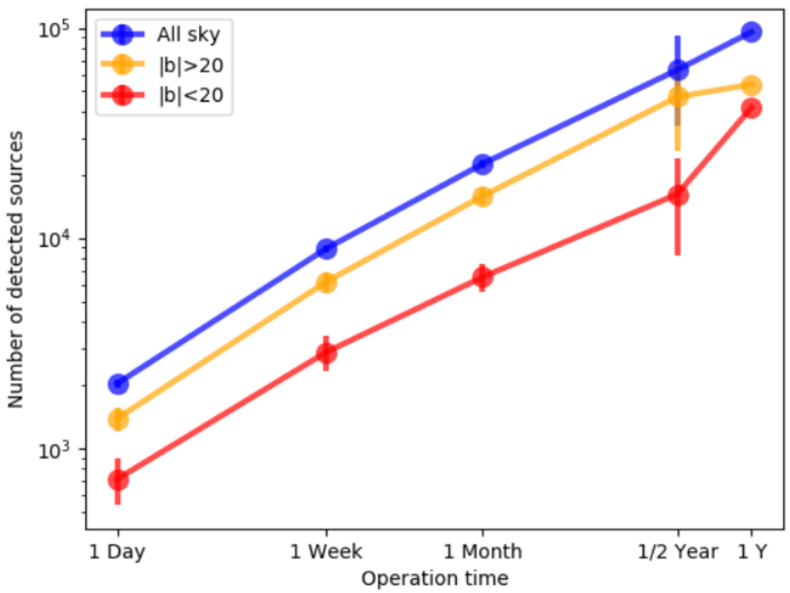


close-up at Galactic center region



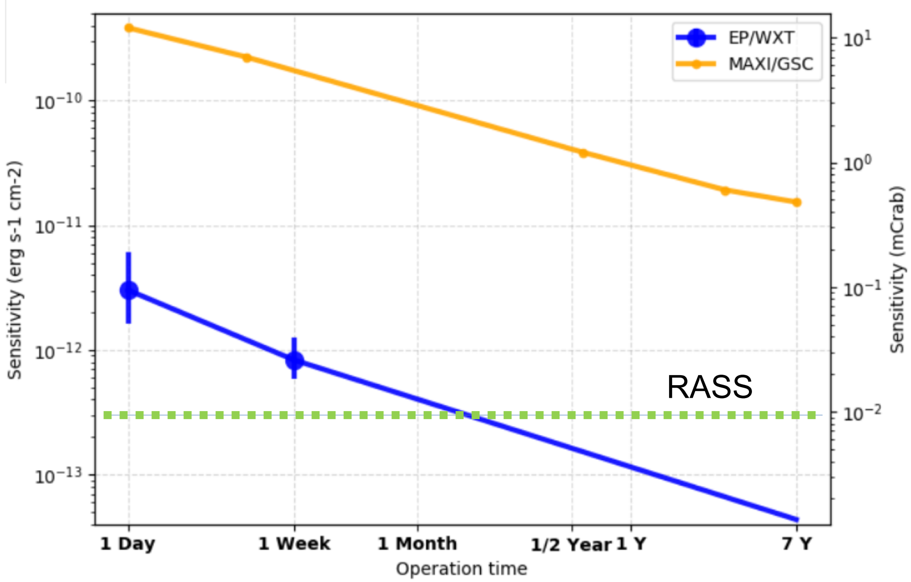
~ 25 deg x 15 deg around GC

Source detection and survey sensitivity (simulations)

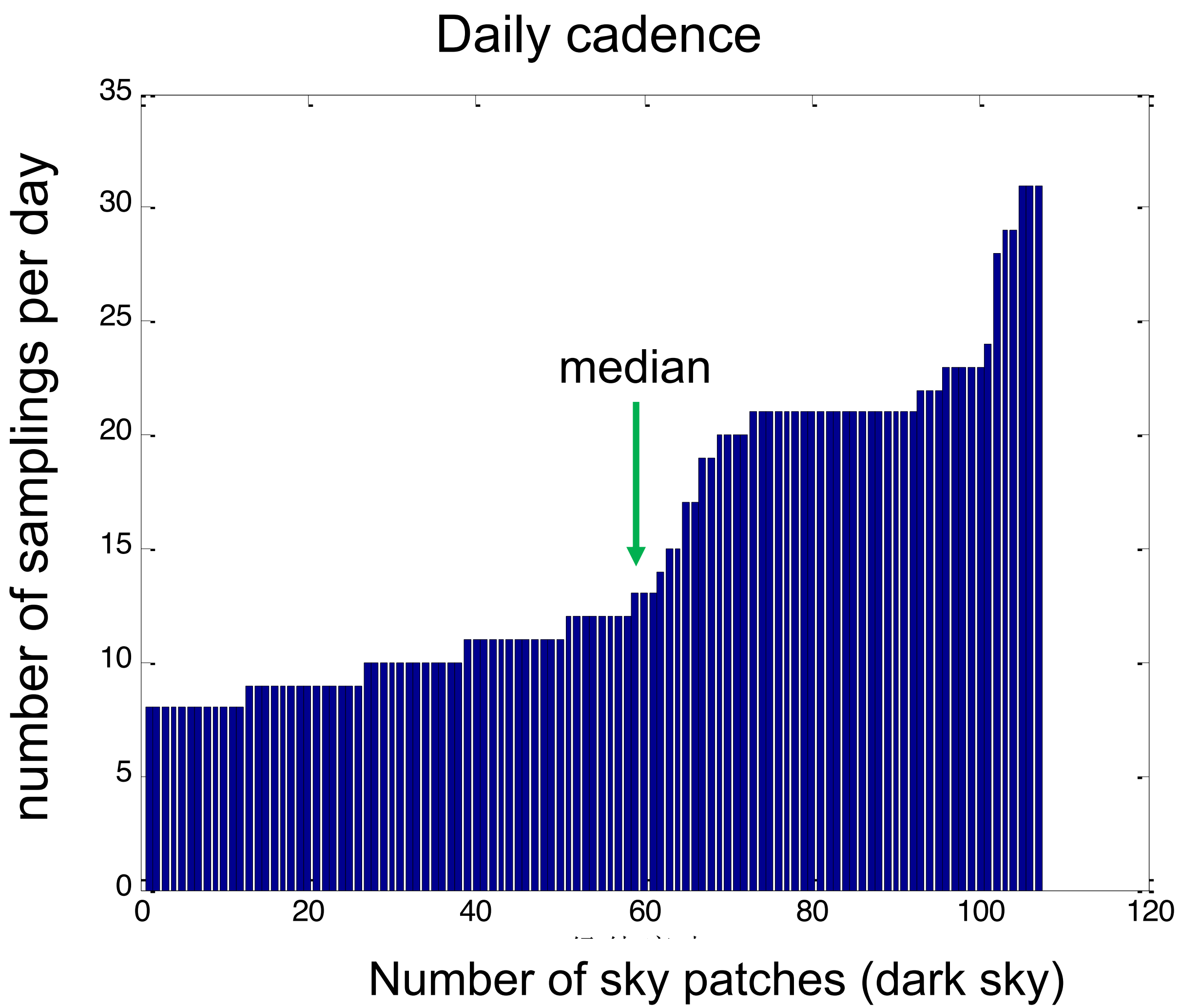


input: the RASS catalogue

~ 2 orders of magnitude deeper than MAXI/GSC



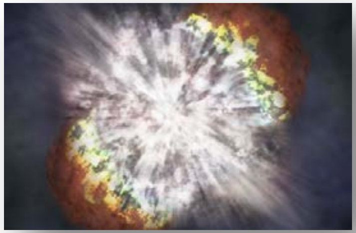
Daily cadence



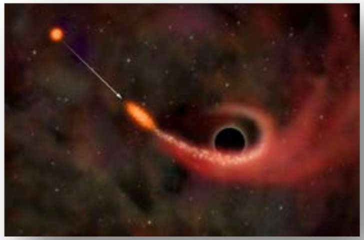
to be updated

Main science goals

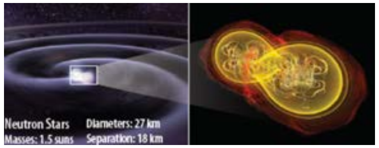
Carry out systematic survey of soft X-ray transients and variability of X-ray sources at unprecedented sensitivity and high cadence



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

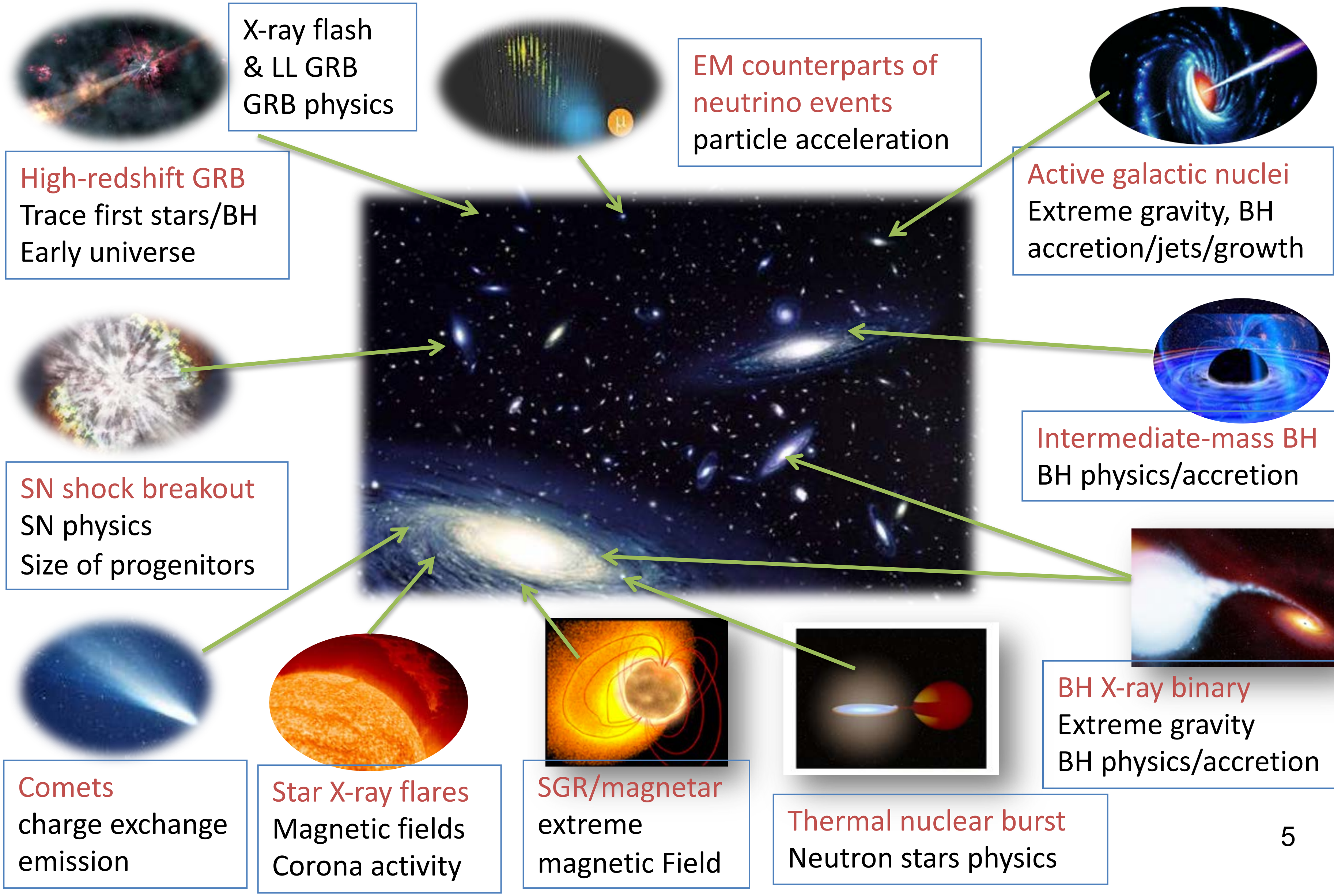


Detect and localize the electromagnetic-wave sources of gravitational-wave events by synergy with gravitational-wave detectors

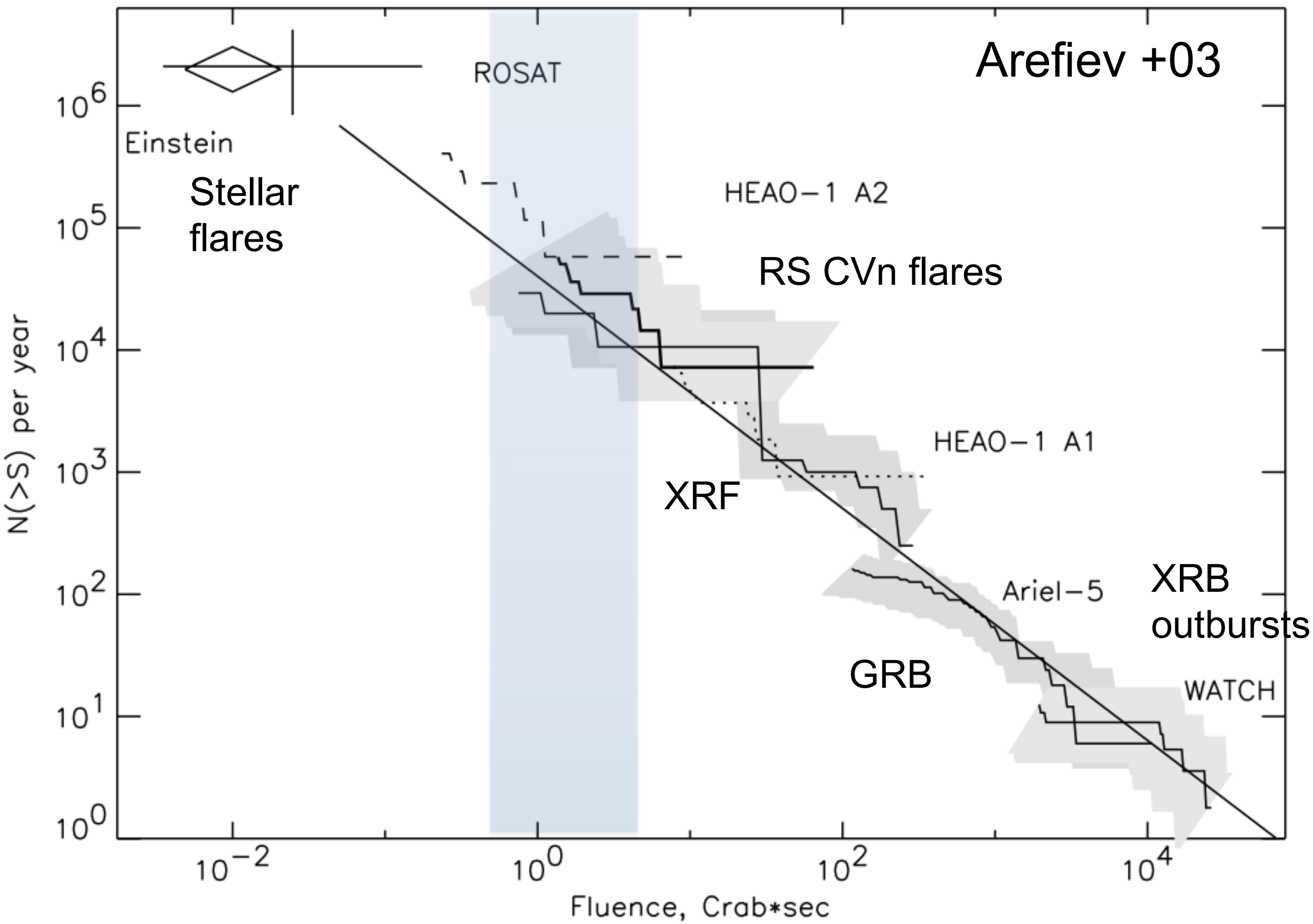


defined in proposal of 2013 Jan

A wide range of X-ray transients & variability



EP detections of Fast X-ray Transients

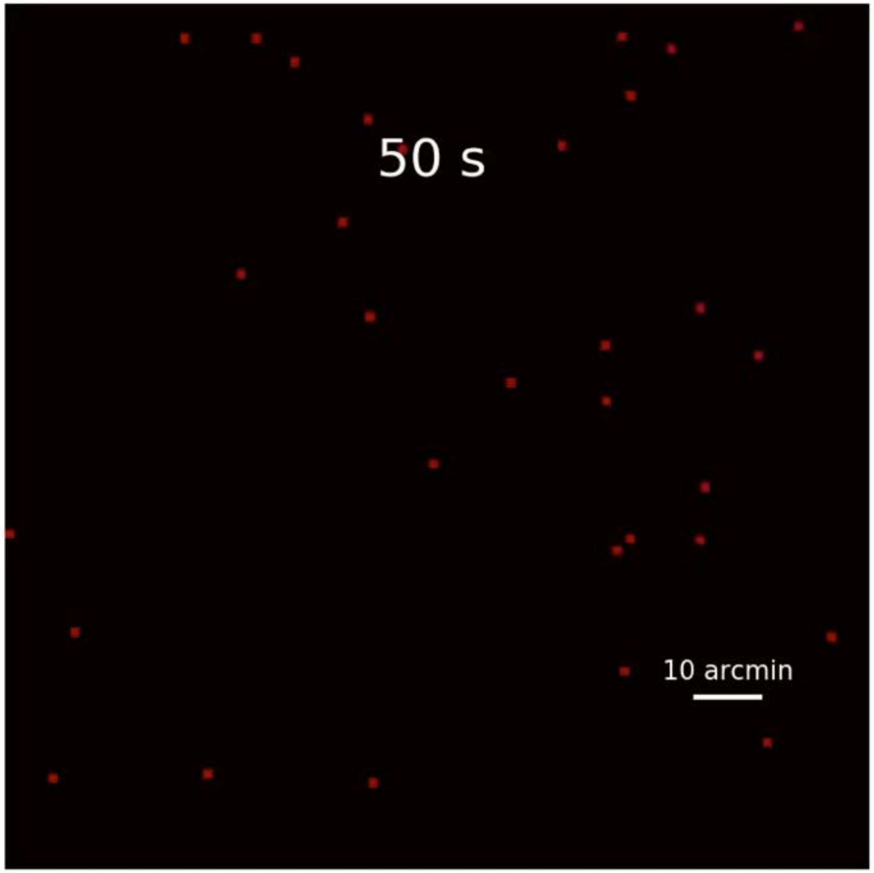


the order of 10^4 FXTs are expected to be detected by EP

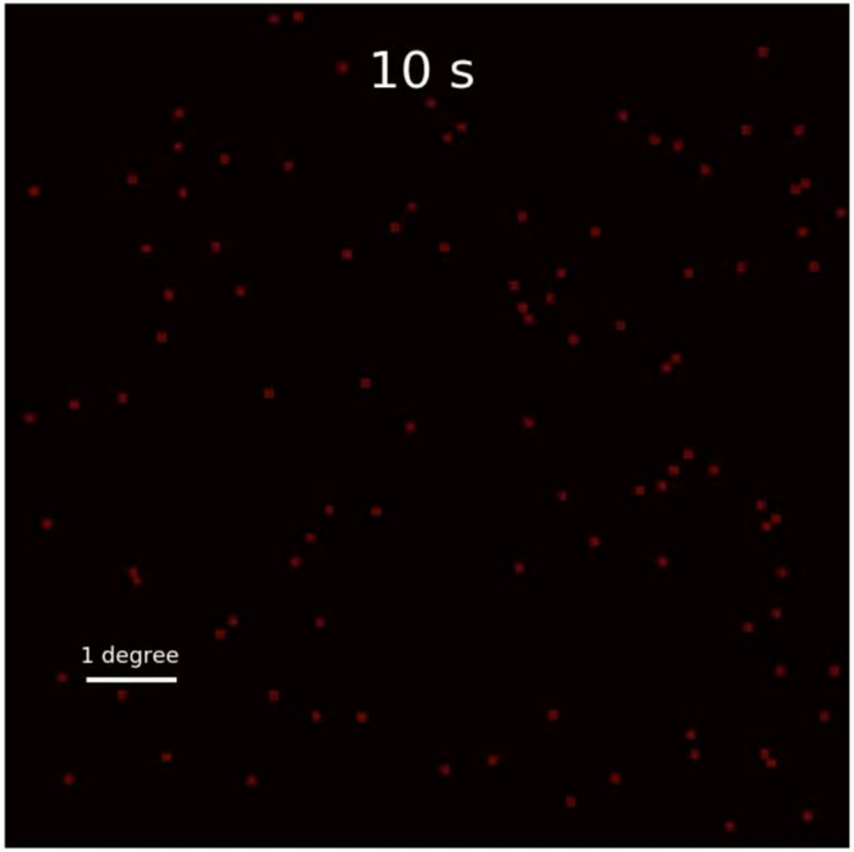
Estimated detection rates for some transients

Type of transients	detections per year
Tidal disruption event (TDE)	100
TDE with jet	10 – 40 (?)
Supernova shock breakout	10 - 200 (?)
Long GRB	80
Short GRB	10
Low-luminosity GRB	10
Super-giant Fast X-ray Transient	10
Stellar flares	5,000
Magnetar	3

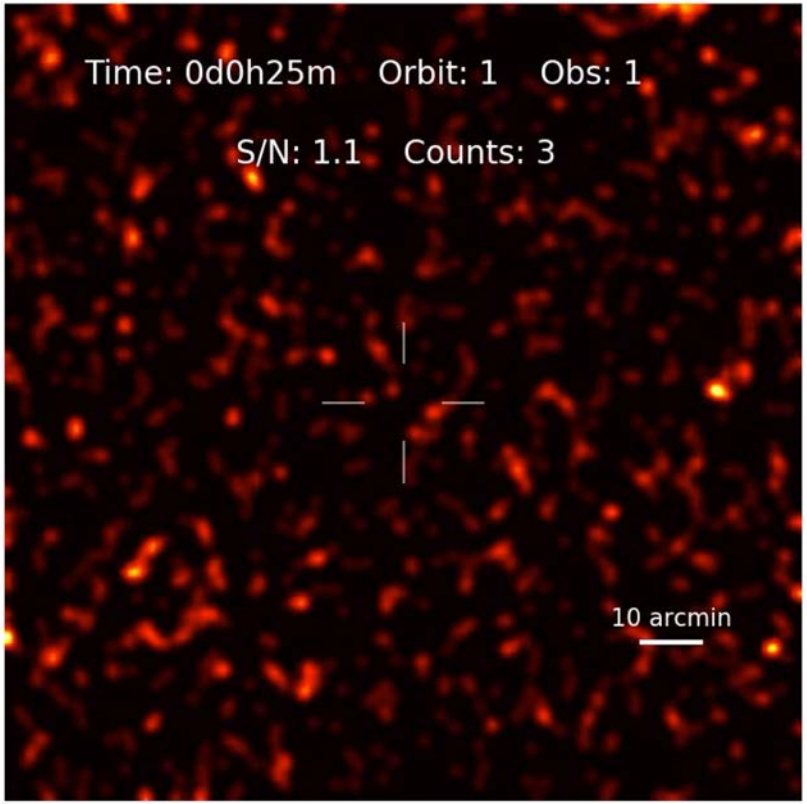
simulated WXT detection of a long GRB



simulated WXT detection of a short GRB



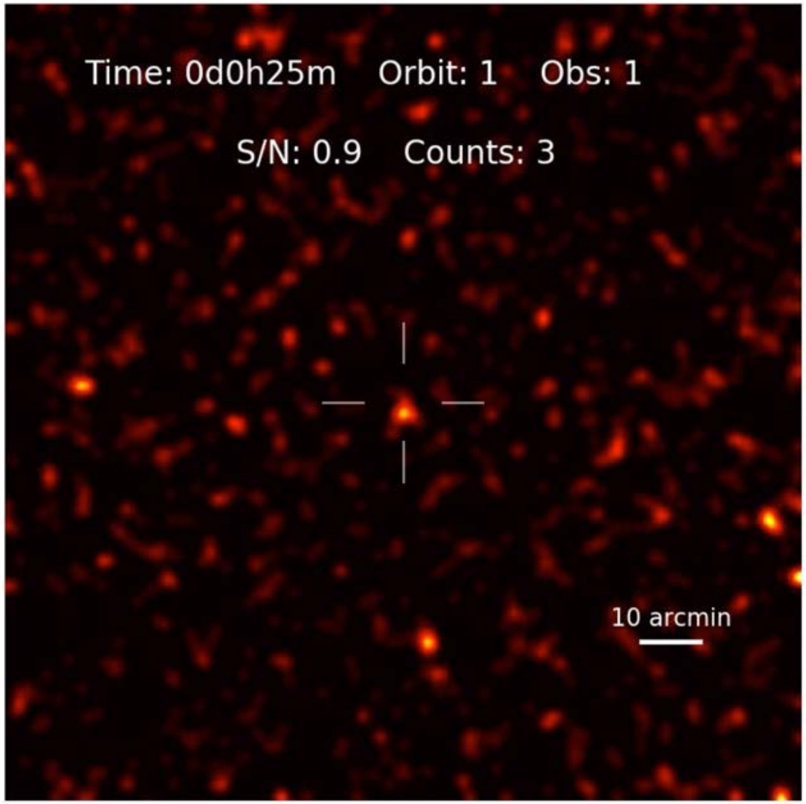
Simulations: EP-WXT detection of a faint TDE

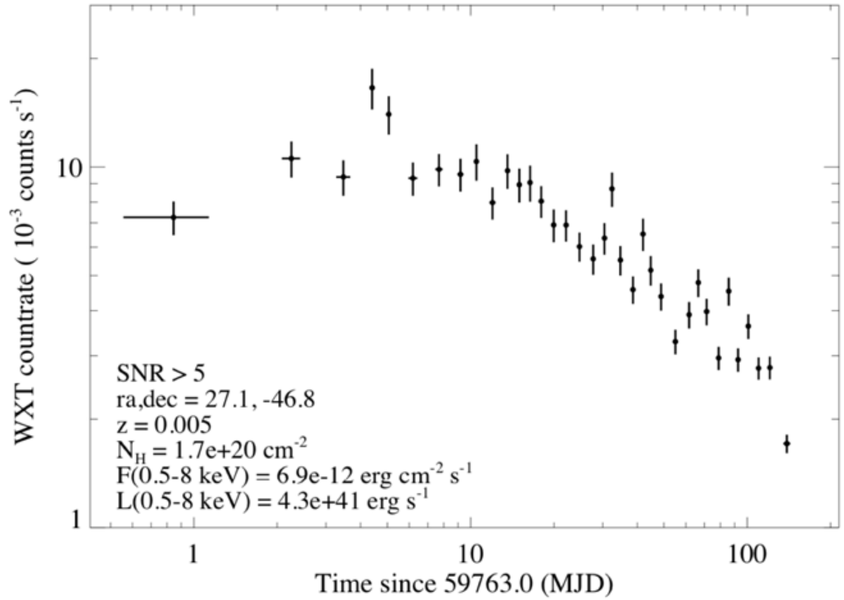


One of faintest detectable TDE

- $F_{0.5-4keV} = 1.2\times10^{-12} erg s^{-1} cm^{-2}$
- z=0.28
- $N_H = 3.4\times10^{20} cm^{-2}$
- $L_{0.5-4keV} = 3.2\times10^{44}\ erg s^{-1}$

Simulation: EP-WXT detection of a bright TDE





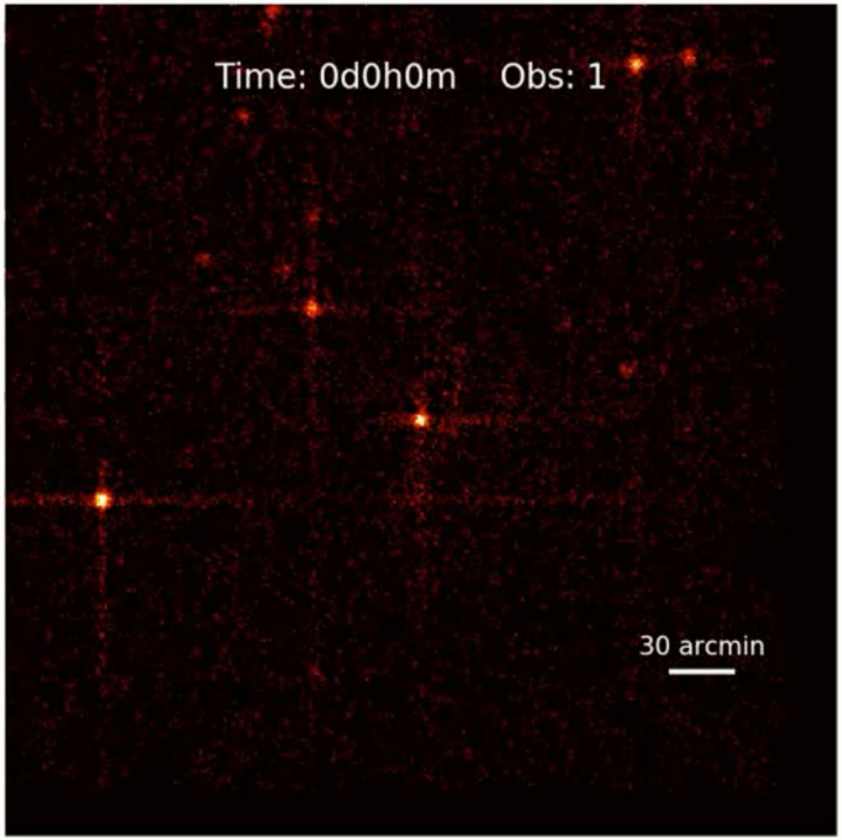
a bright TDE

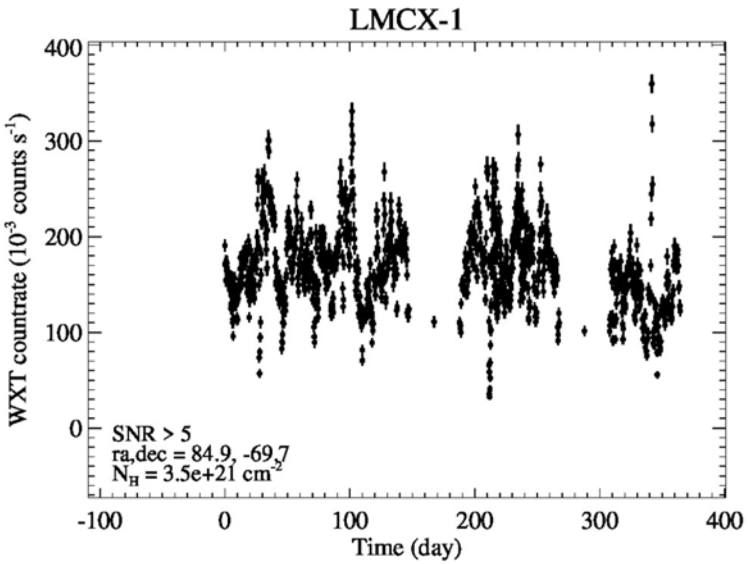
- $F_{0.5-4keV} = 6.9\times10^{-12} ergs^{-1}cm^{-2}$
- D=21 Mpc
- $N_H = 1.7\times10^{20}cm^{-2}$
- $L_{0.5-4keV} = 4.3\times10^{41}\ ergs^{-1}$

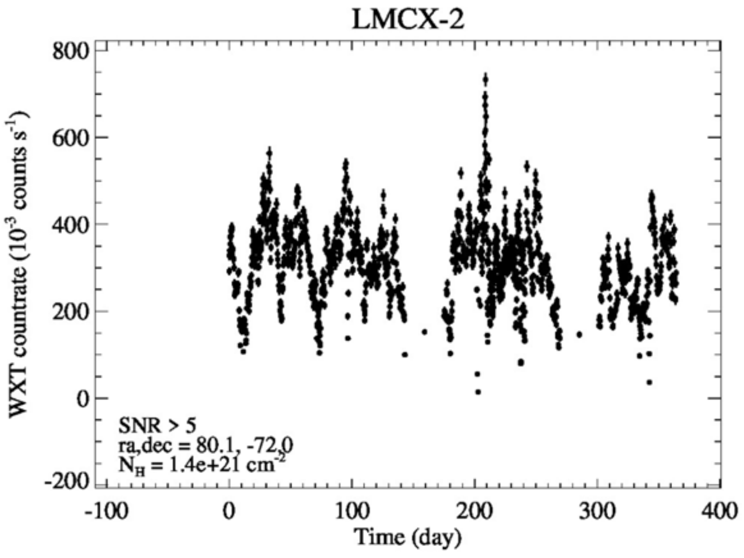
$M_{BH} \sim 10^4\ M_{Sun}$ IMBH ?

faint end of the BH mass function?

Simulated monitoring nearby galaxies: LMC



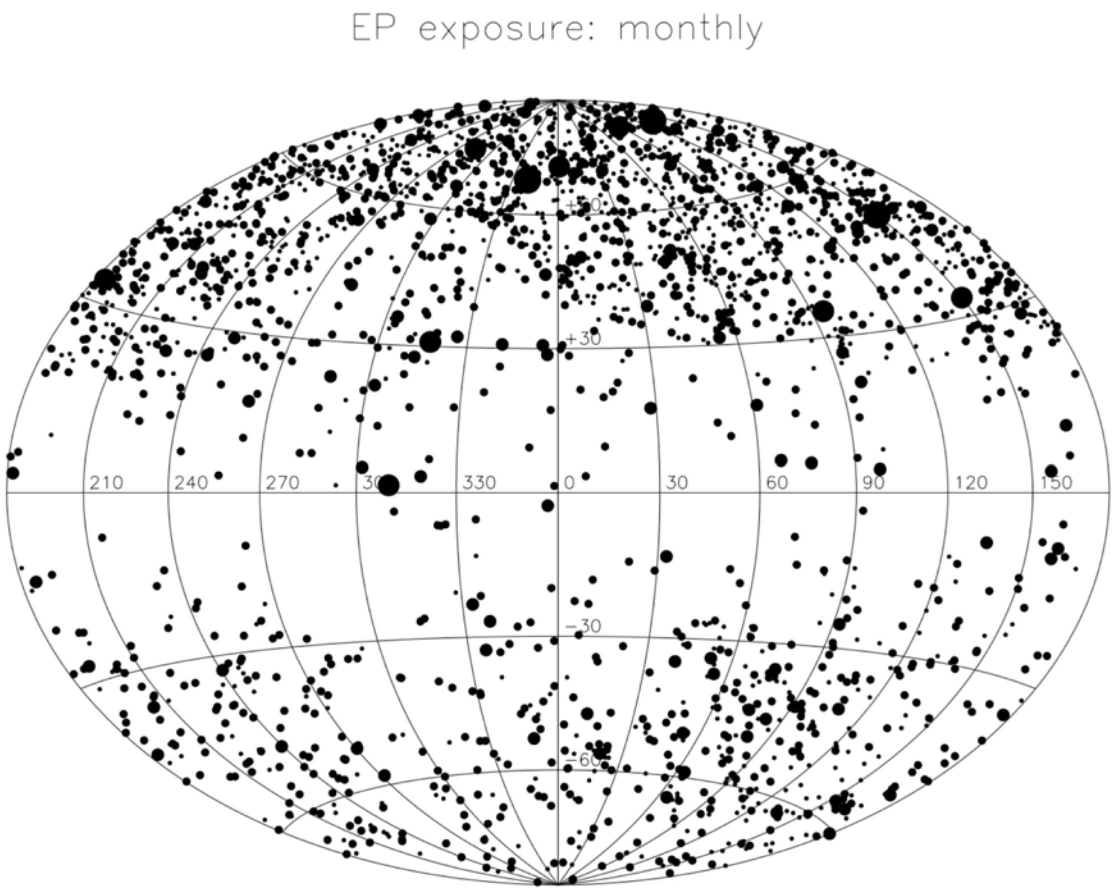




Monitoring of AGN variability

Large samples of AGN to be monitored at various cadences

- variability at timescales from day to months
- flaring AGN, changing-look AGN, state transition ……

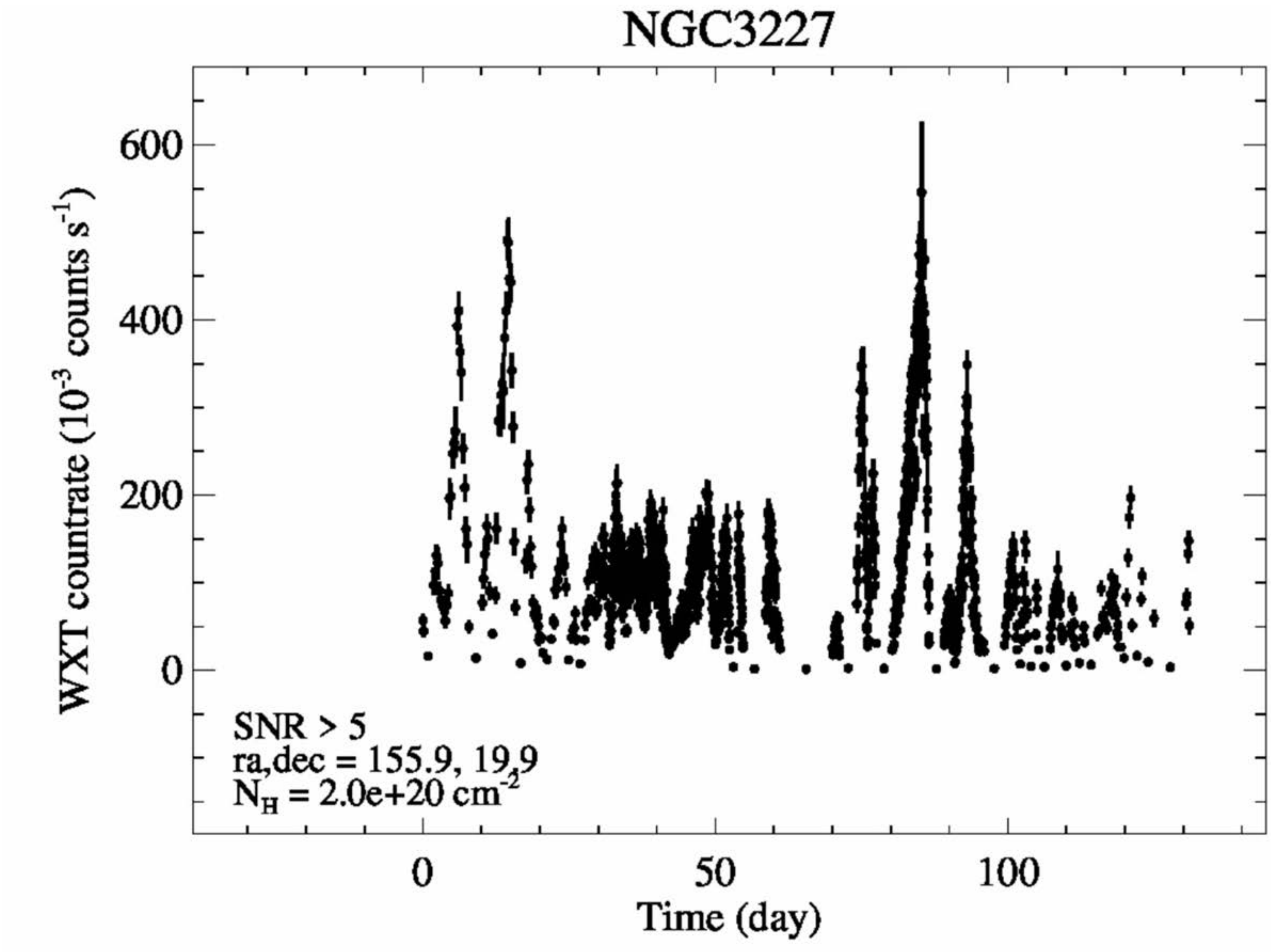


~140 detectable (5 σ)
daily (survey mode)

~700 detectable
weekly

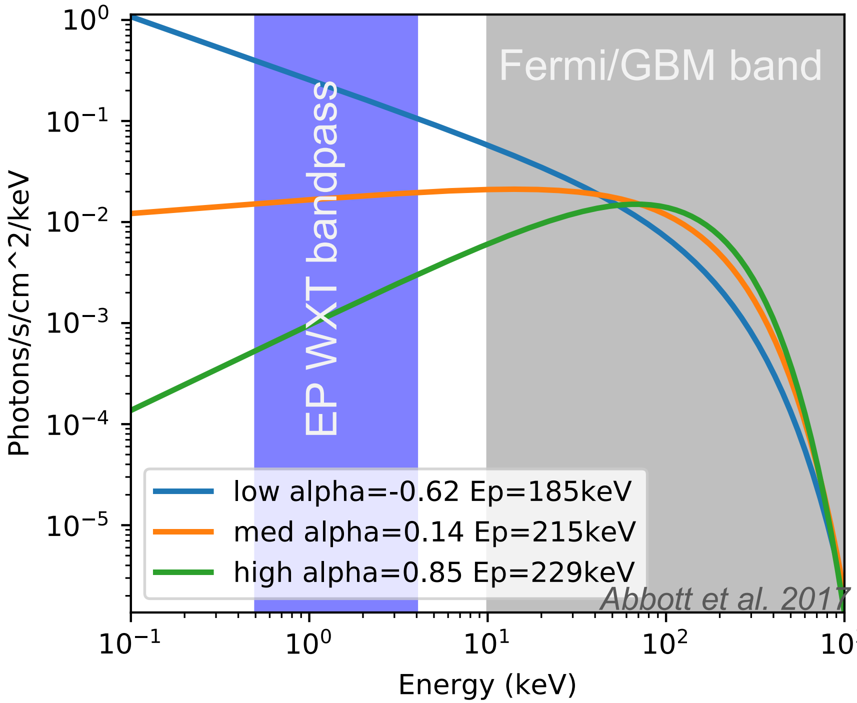
~1,600 detectable
monthly

Simulated EP WXT lightcurve of an AGN

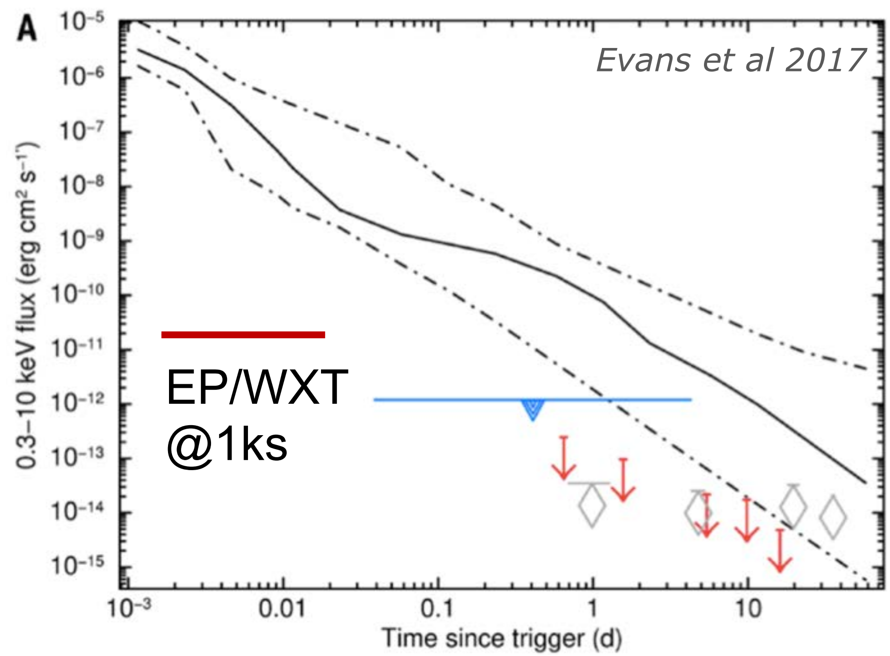


EP detectability for GW 170817: early X-ray

GRB prompt emission: several seconds



ability to detect early X-ray afterglow



Prompt emission: several WXT counts, marginal detection

Early afterglow: ??

magnetar-powered X-ray transients of mergers?

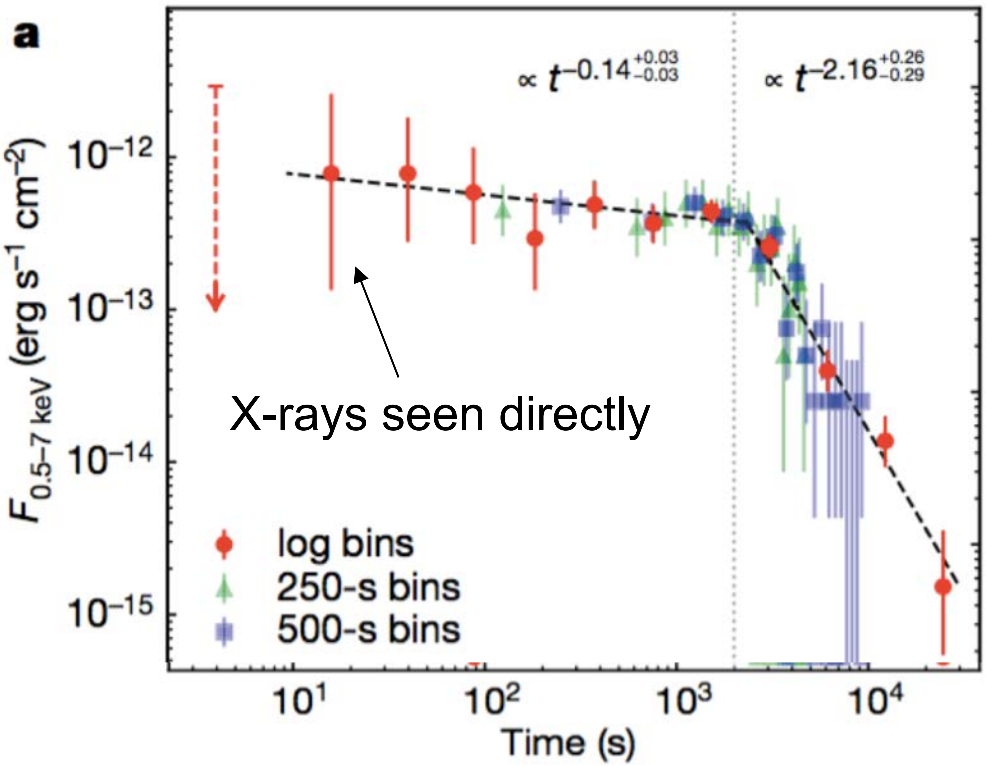
LETTER

https://doi.org/10.1038/s41586-019-1079-5

A magnetar-powered X-ray transient as the aftermath of a binary neutron-star merger

Y. Q. Xue[1,2*], X. C. Zheng[1,2,3*], Y. Li[4], W. N. Brandt[5,6,7], B. Zhang[8,9,10*], B. Luo[11,12,13], B.-B. Zhang[11,12,13], F. E. Bauer[14,15,16], H. Sun[9], B. D. Lehmer[17], X.-F. Wu[2,18], G. Yang[5,6], X. Kong[1,2], J. Y. Li[1,2], M. Y. Sun[1,2], J.-X. Wang[1,2] & F. Vito[14,19]

CDF XT2 @ z=0.738



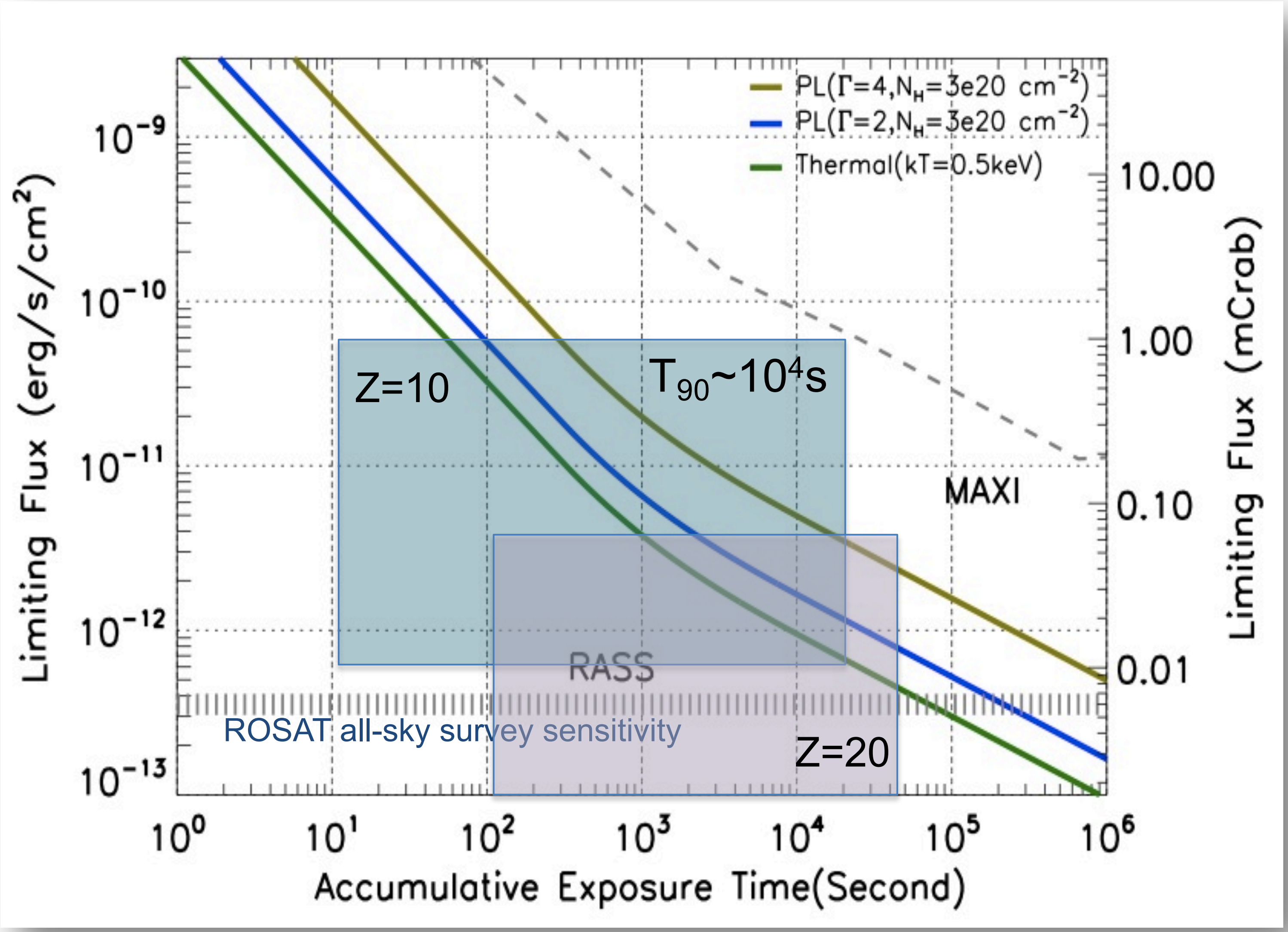
detectable with EP/WXT within ~300Mpc (LIGO horizon for NS-NS mergers)

Summary

- The X-ray sky is rich in violent cosmic events and new types of transients await discovery & characterisation
- Lobster-eye MPO is promising technology to look both deeper & wider in soft X-rays
- EP will be a unique and powerful mission in monitoring the X-ray sky in the years to come, with a combination of
  - Unprecedented monitoring sensitivity
  - Very large FoV & High cadence
  - Unique passband in soft X-ray
  - Rapid response and satellite-ground two-way communication
- Synergy with & follow-up by ground-based telescopes needed

Supplementary slides

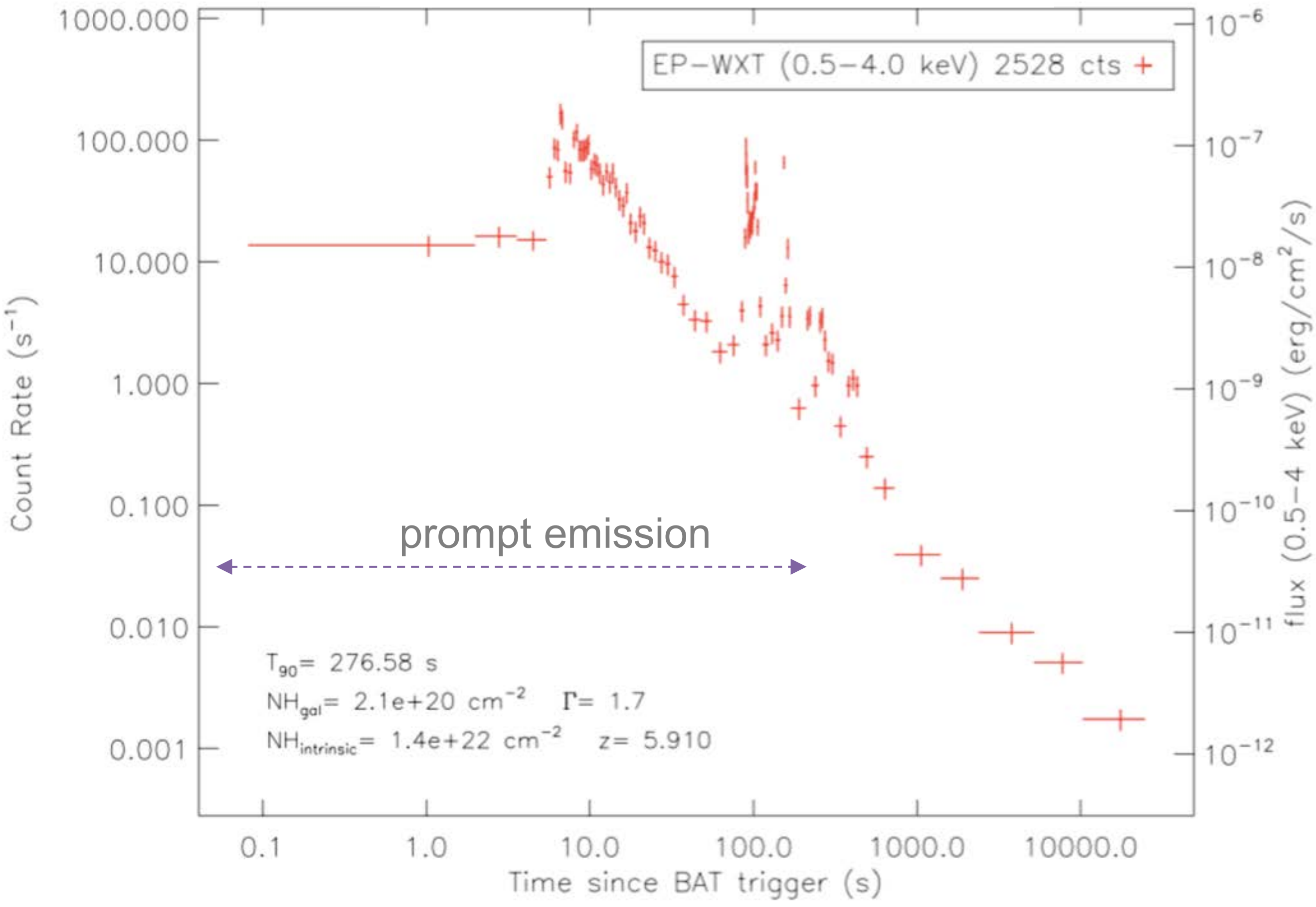
EP detectability of high-z GRBs



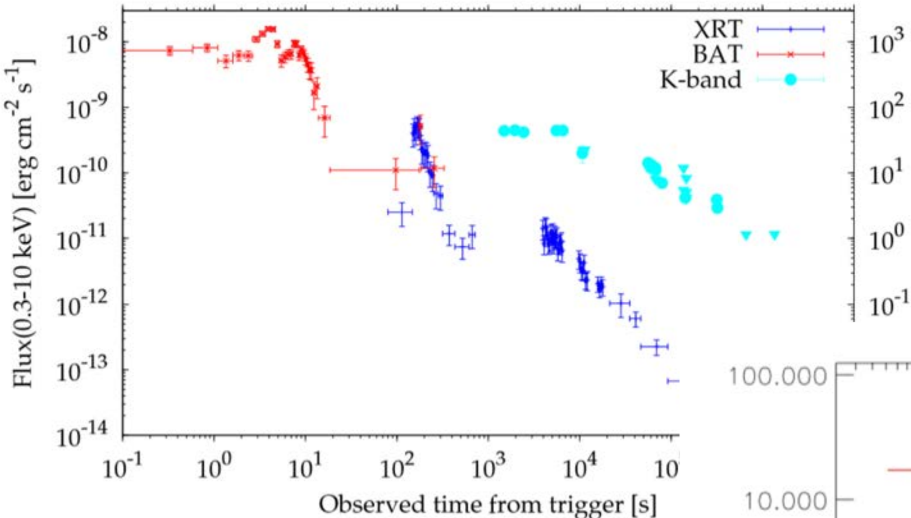
Simulated WXT lightcurves of high-z GRB

Estimated detection rate: N~ 12 @z> 6; N~ 3 @z>8
challenging for optical/IR follow-ups

GRB 130606 @z=5.91

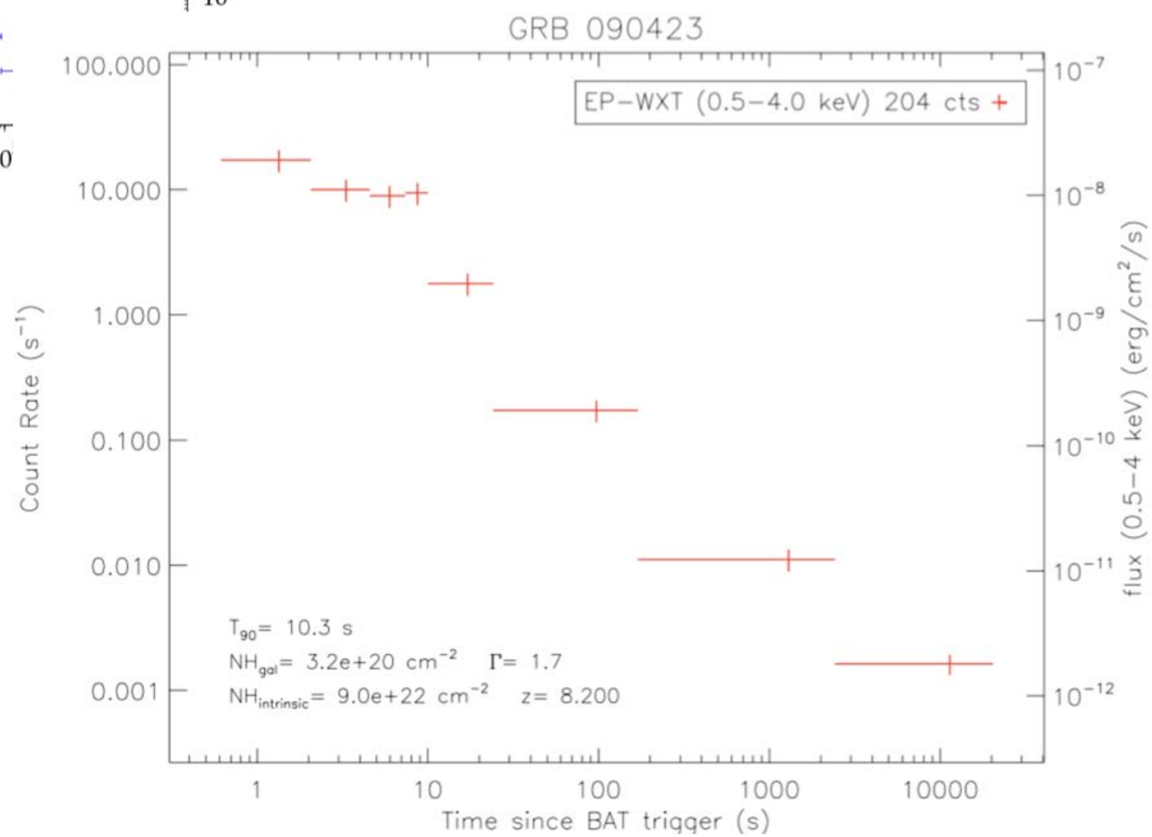


Simulated WXT lightcurves of high-z GRB



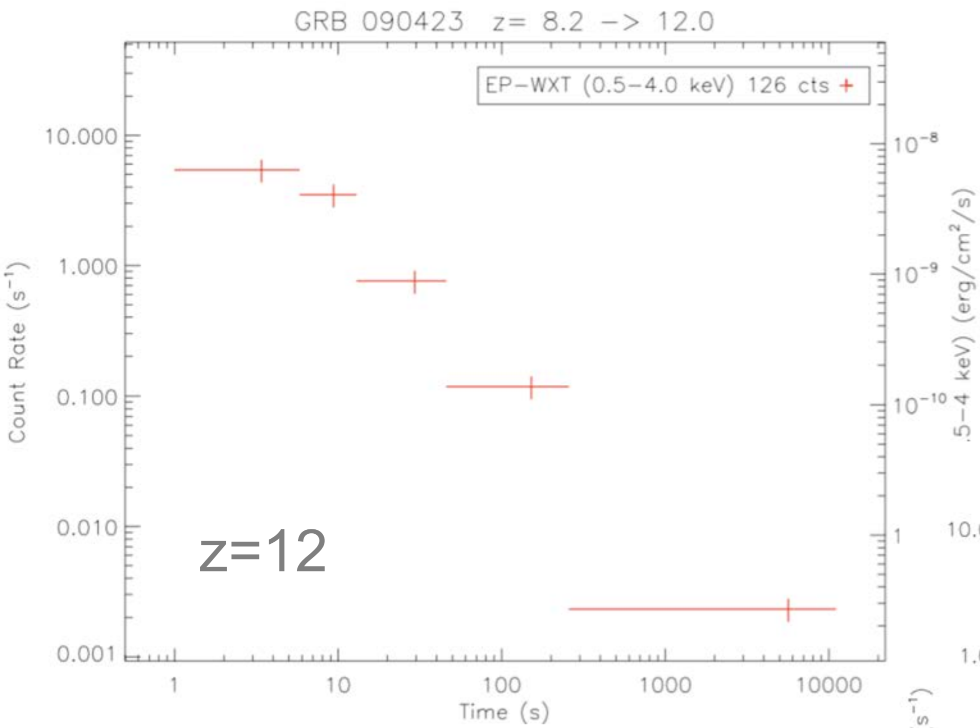
(Salvaterra el. al., 2009)

GRB 090423 @z=8.2

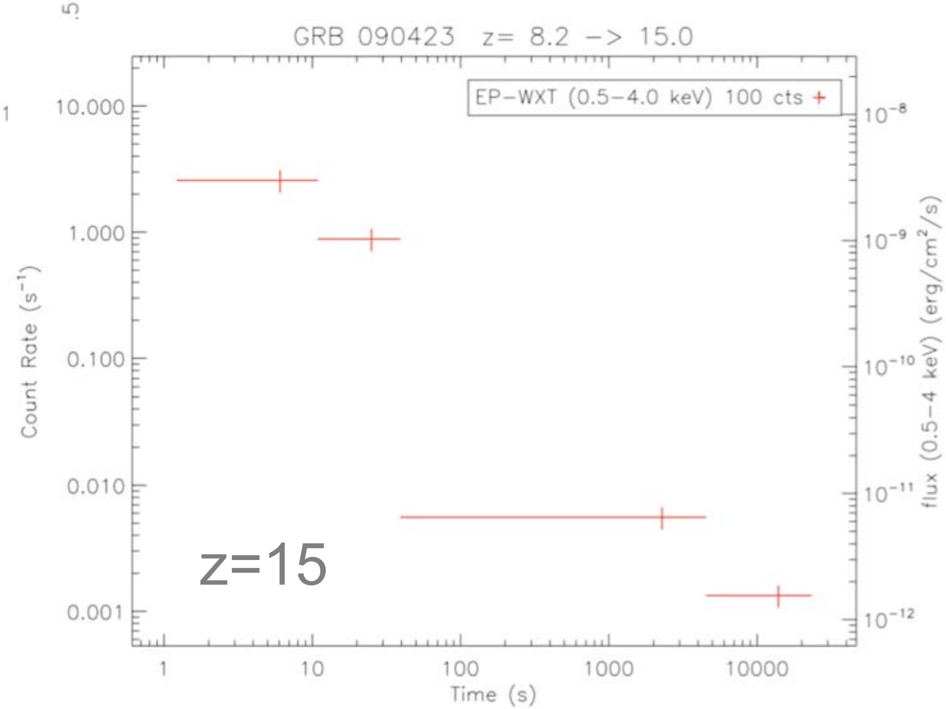


Estimated detection rate:
N~ 12 @z> 6;
N~ 3 @z>8
challenging for optical/IR follow-ups

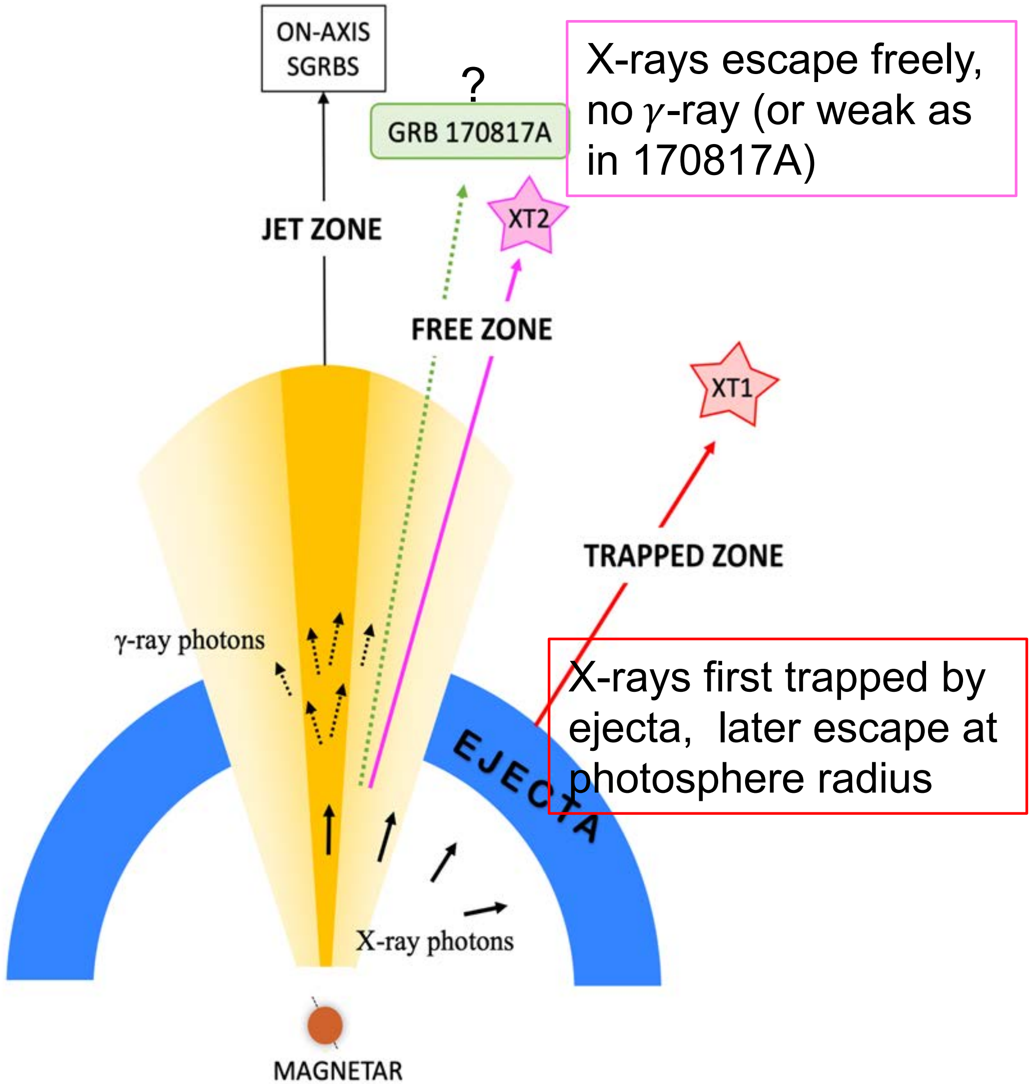
GRB at even higher-z ?

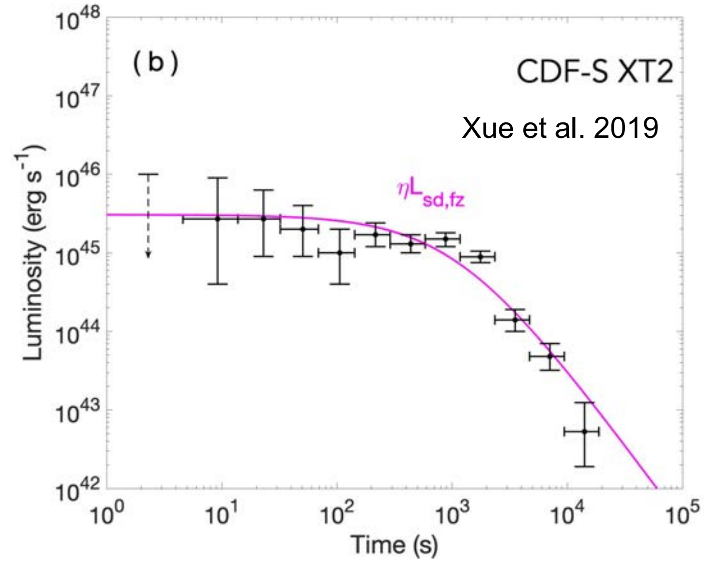


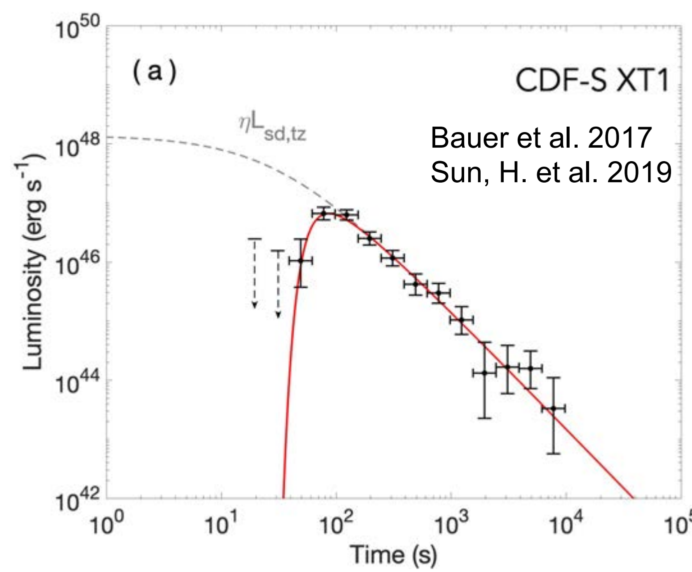
GRB 090423 (@z=8.2) – like can be detectable by WXT at z=12 and 15



magnetar-powered X-ray transients: more event ?

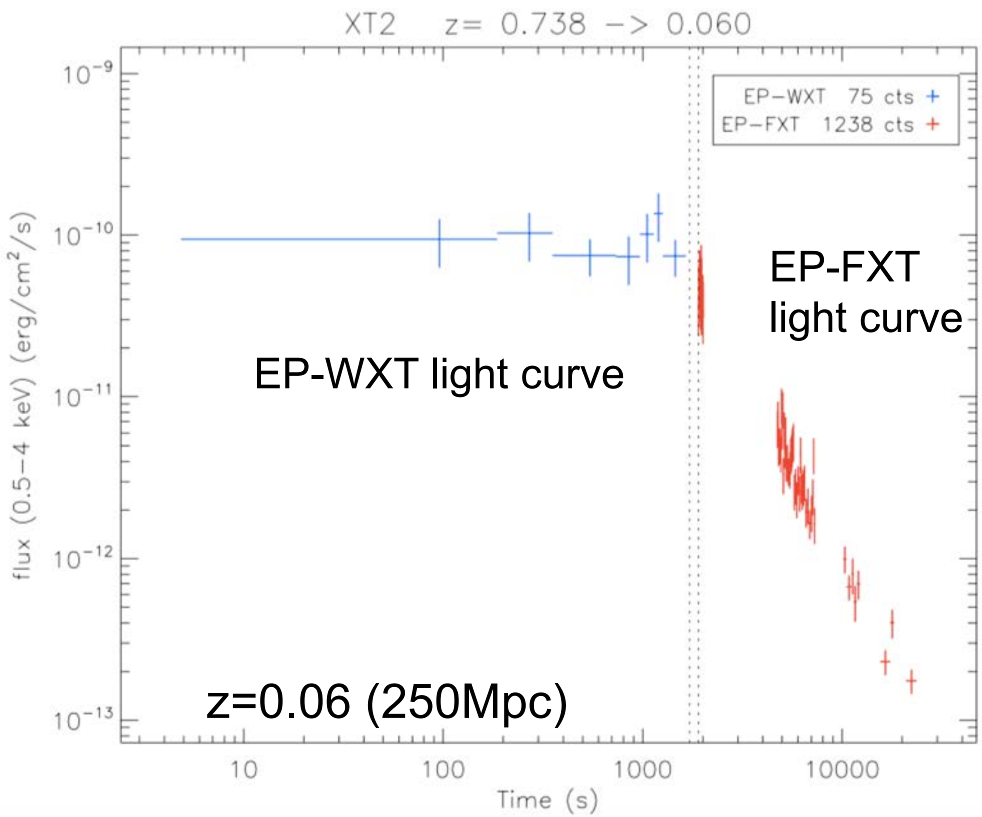




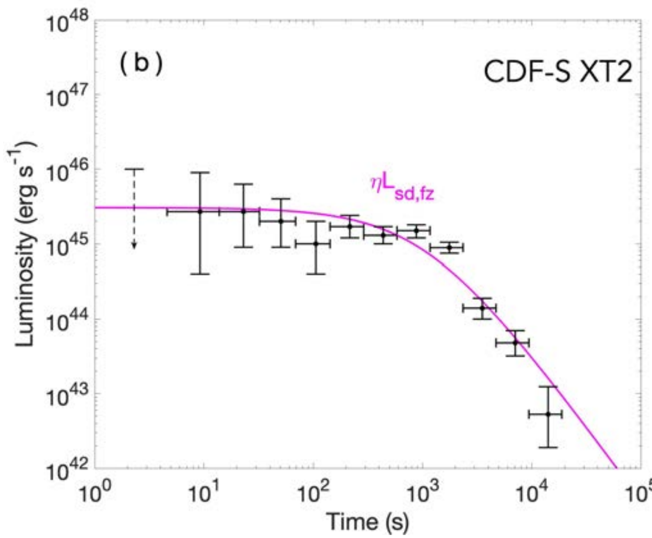


Sun et al., ApJ, 2019, 886, 129

EP detectability of XT2-type transients



Simulated EP observation of XT2 @ z=0.06



- detectable up to ~300Mpc (z~0.07), well match LIGO/VIRGO horizon
- expected rate: 2 – 40 per year (with possible joint GW detection)