Einstein Probe

exploring the dynamic X-ray universe

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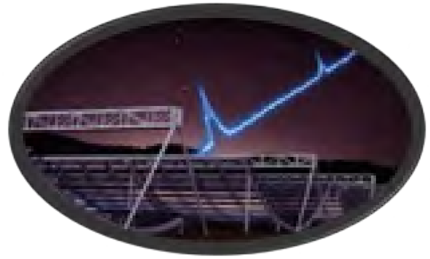
NAOC, 2020-12-02

Outline

- Introduction and science driver
- Methodology and technology
  - micro-pore optics for X-ray focusing
- Mission concept and status
- Scientific capability & prospects

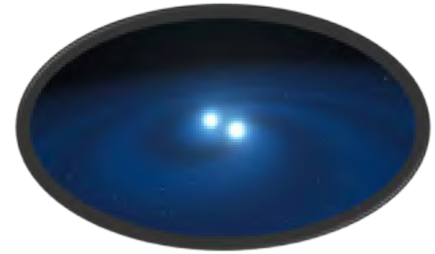
New types of high-E transients & science questions



Fast radio bursts

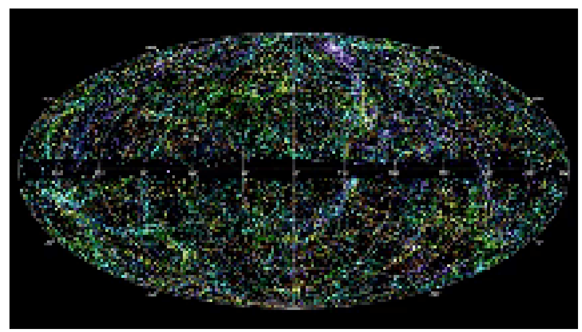
Tidal disruption events

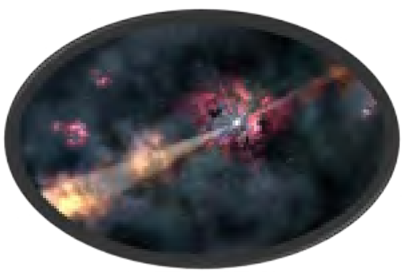
Demography of Black holes
How matter falls onto BH
How jets form



EM counterparts of gravitational waves

What are the EM counterparts?
How compact objects merge?



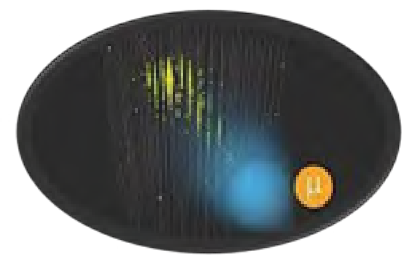


High-z GRBs

The early Universe and the first stars/BH(?), metal enrichment

SN shock breakouts

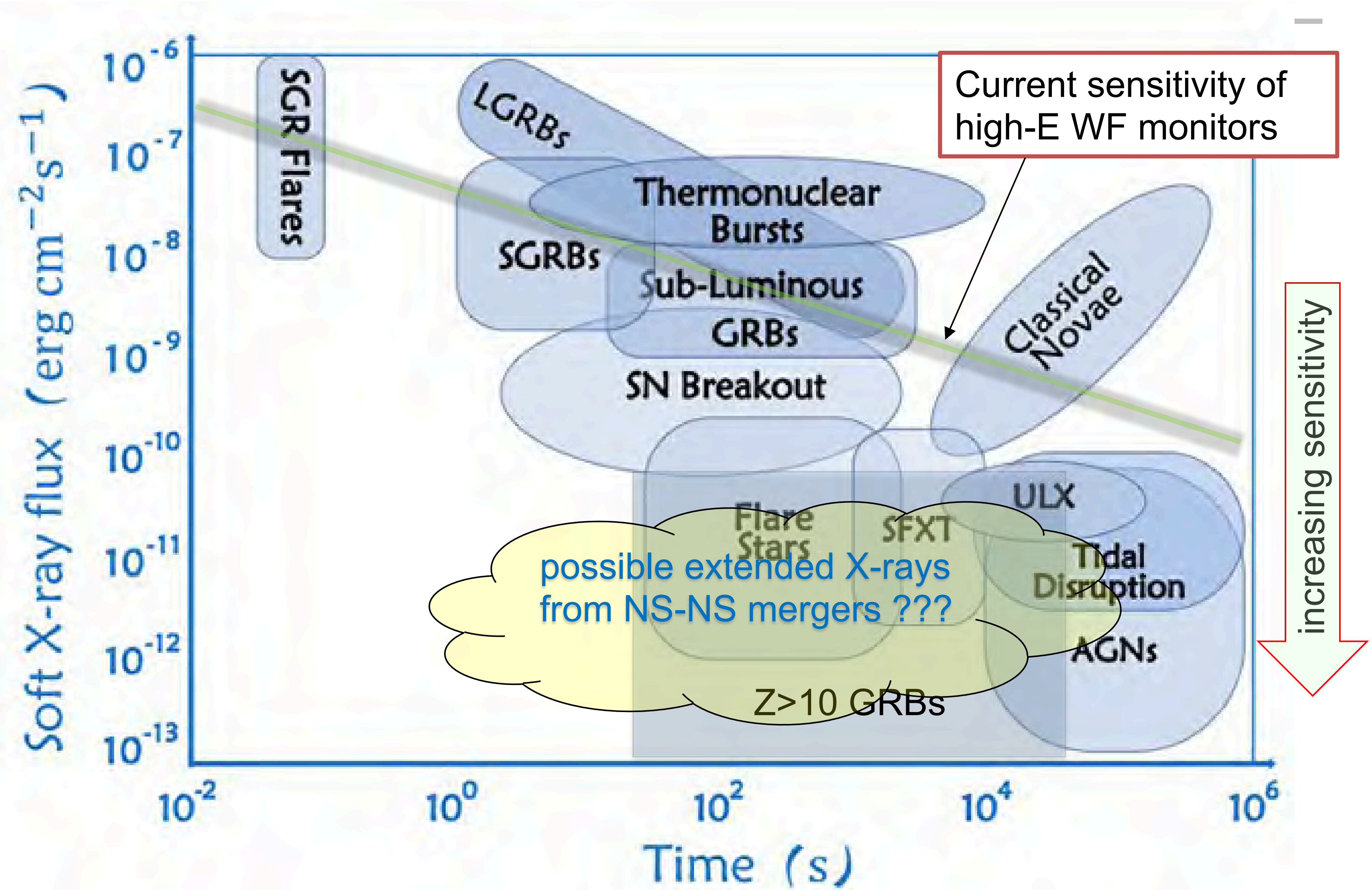
Supernova physics & progenitors



EM counterparts of neutrino events

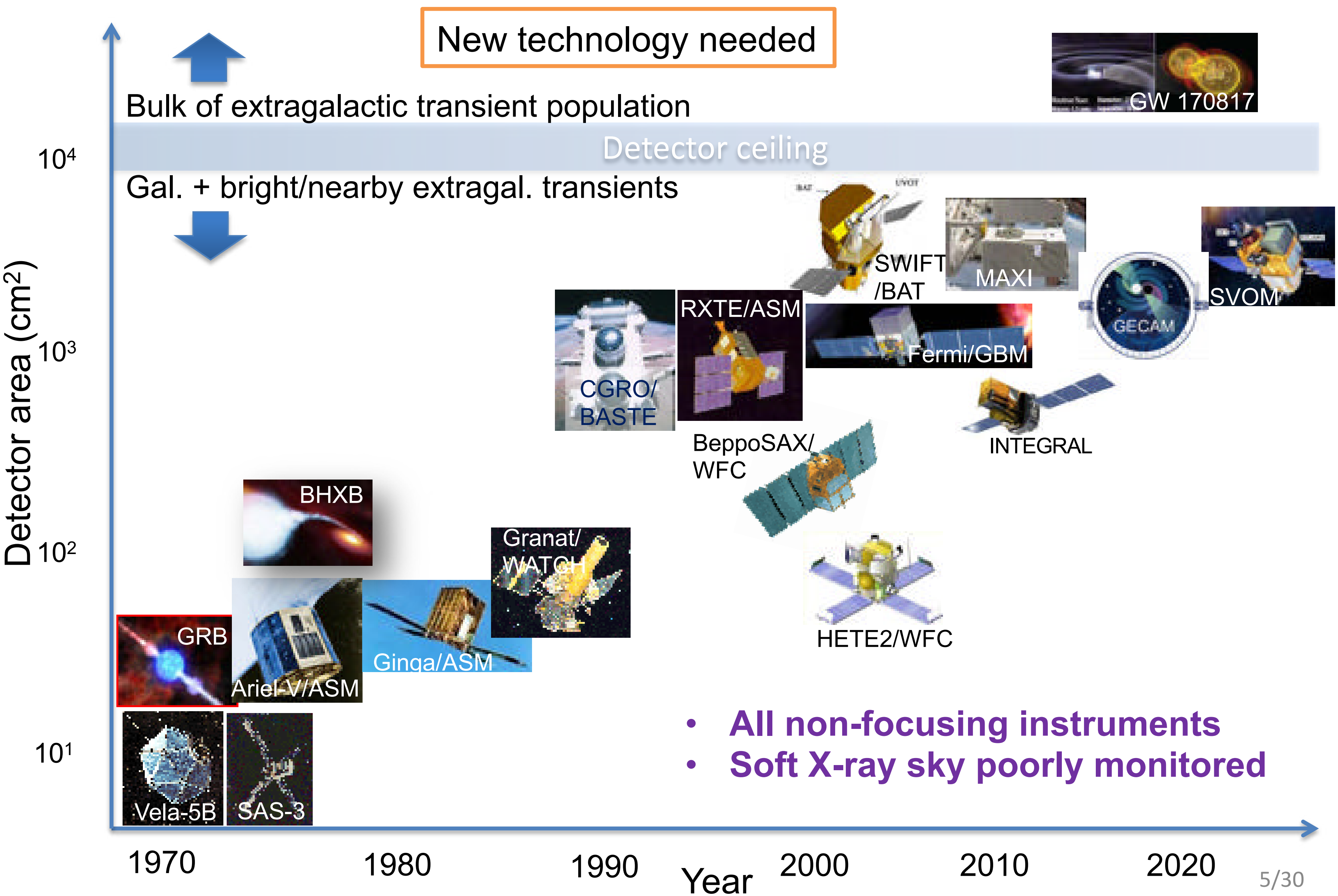
Particle acceleration

Challenges in finding faint high-E transients



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

A (incomplete) history of high-E **wide-field** monitors



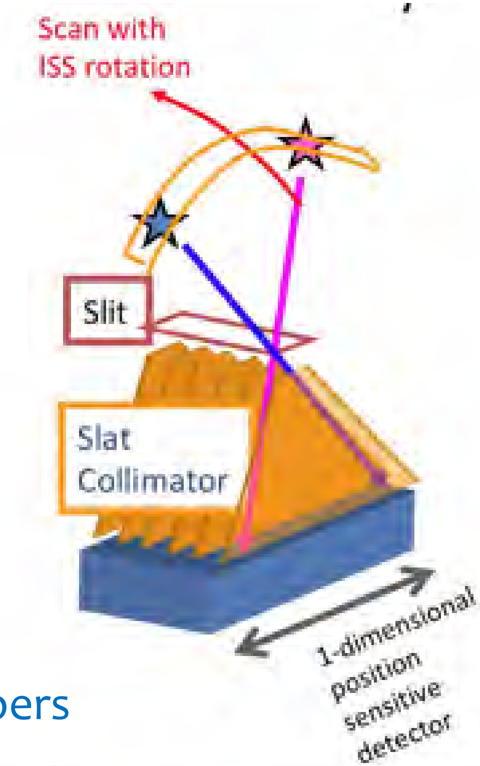
- **All non-focusing instruments**
- **Soft X-ray sky poorly monitored**

MAXI on ISS

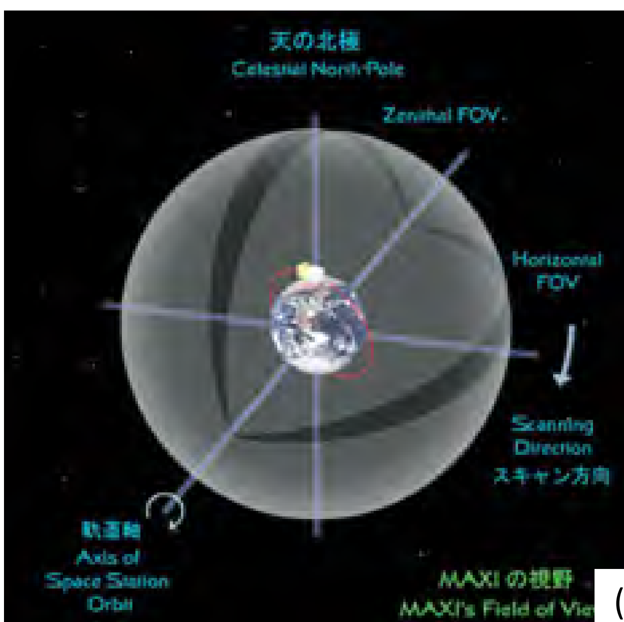

MAXI of JAXA (2009 -)

pinhole/slit camera

Simple but beautiful

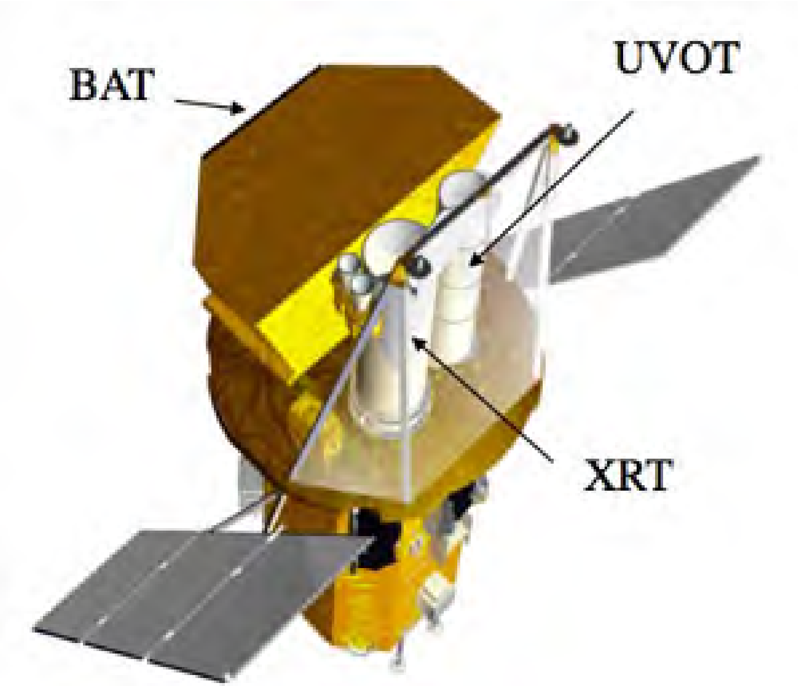


Scan whole sky twice every 90min (2-30keV);
Discovered transients & monitored sources in large numbers



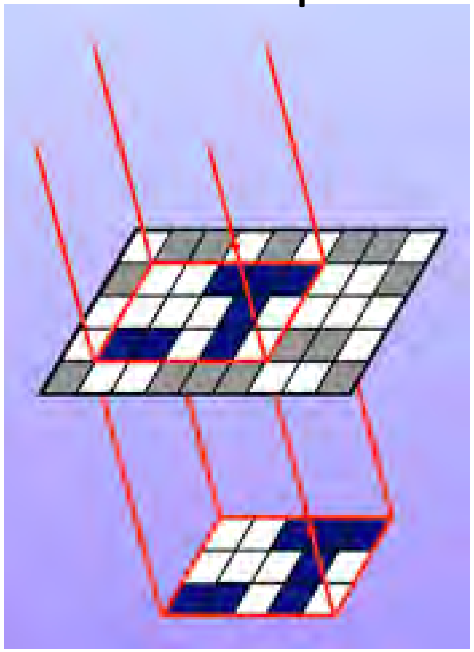
(credit: MAXI team RIKEN/JAXA)

Swift



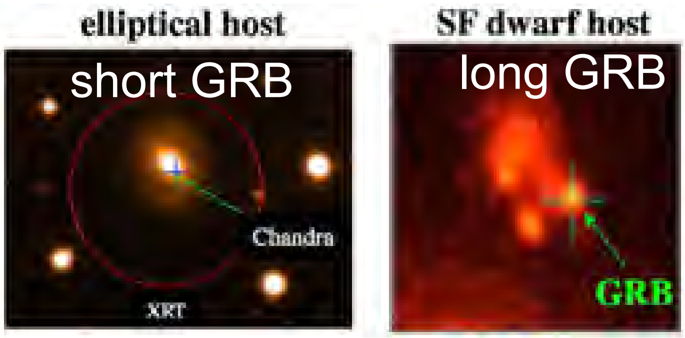
Credit NASA

BAT: coded aperture



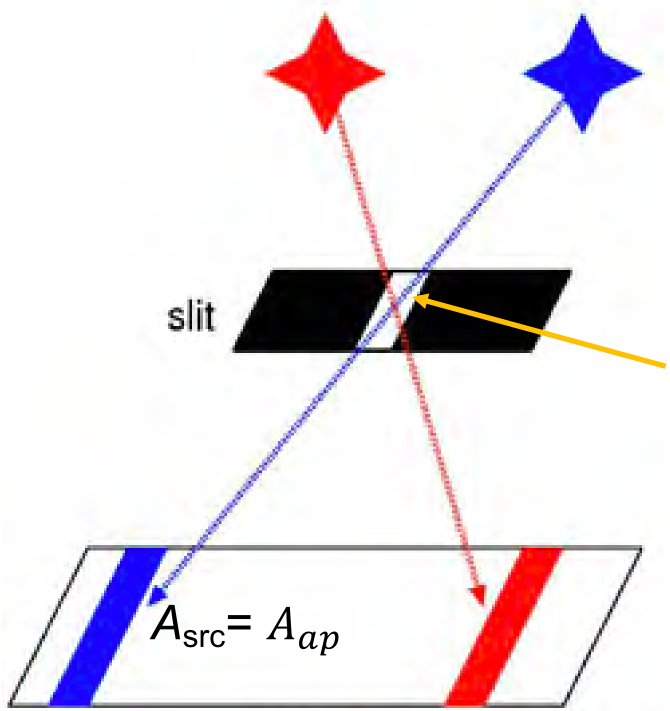
Credit: N. Gehrels

- NASA's GRB mission (2004-)
- BAT: 14-300keV, FoV ~ 2 sr
- ~100 GRB and several tens of other transients per year



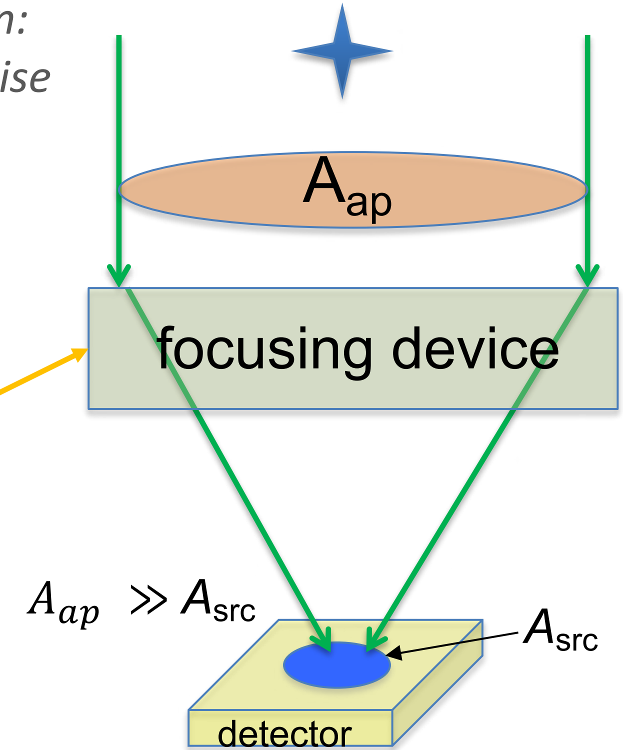
Focusing vs. non-focusing X-ray optics

X-ray source detection: battle of signal vs. noise



credit: MAXI team

photon collecting aperture A_{ap}



$$\frac{A_{ap}}{A_{src}} = 1$$

Background-limited case

$$\boxed{\frac{S}{N} \approx \frac{N_{src}}{\sqrt{N_{bgd}}} \propto \sqrt{A_{ap}}\sqrt{\frac{A_{ap}}{A_{src}}}}$$

$$\frac{A_{ap}}{A_{src}} \gg 1$$ ~ focusing gain

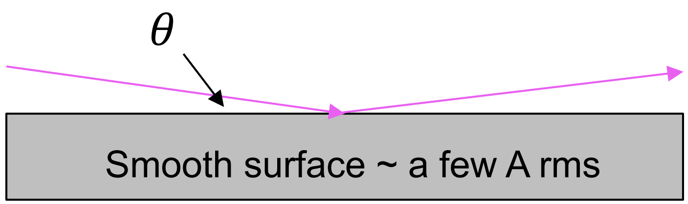
angular resolution matters

less efficient increase S/N with $\sqrt{A_{ap}}$

efficient Increase of S/N with $\sqrt{\frac{A_{ap}}{A_{src}}}$

X-ray focusing optics: Wolter type

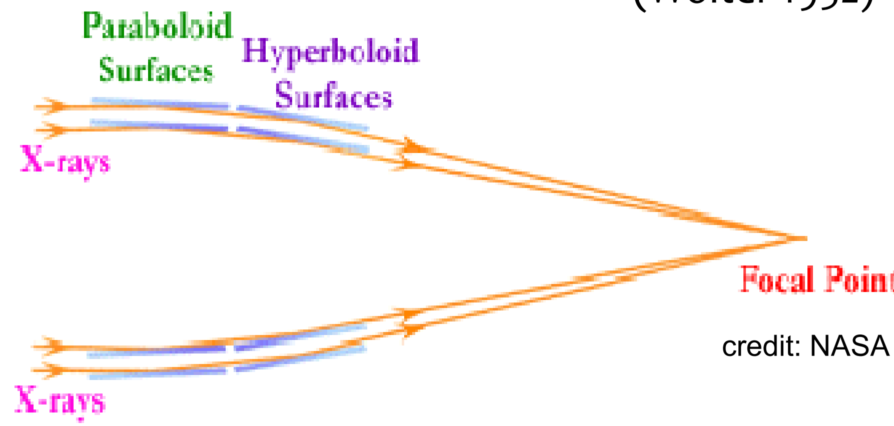
X-ray reflection by grazing incidence, and optimized for soft X-rays



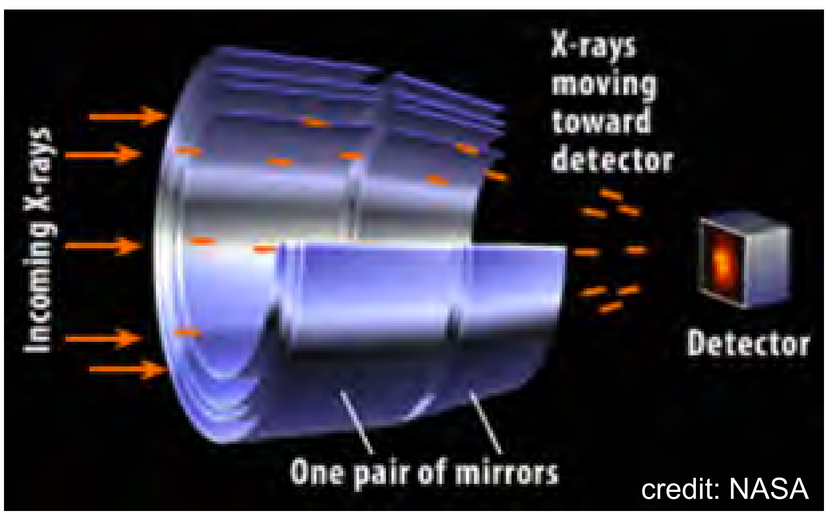
$\theta < \theta_c \propto \frac{\sqrt{n_e}}{E_{pho}}$ critical angle θ_c ~ a few degrees @ 1keV

Wolter-I X-ray mirror

(Wolter 1952)



credit: NASA



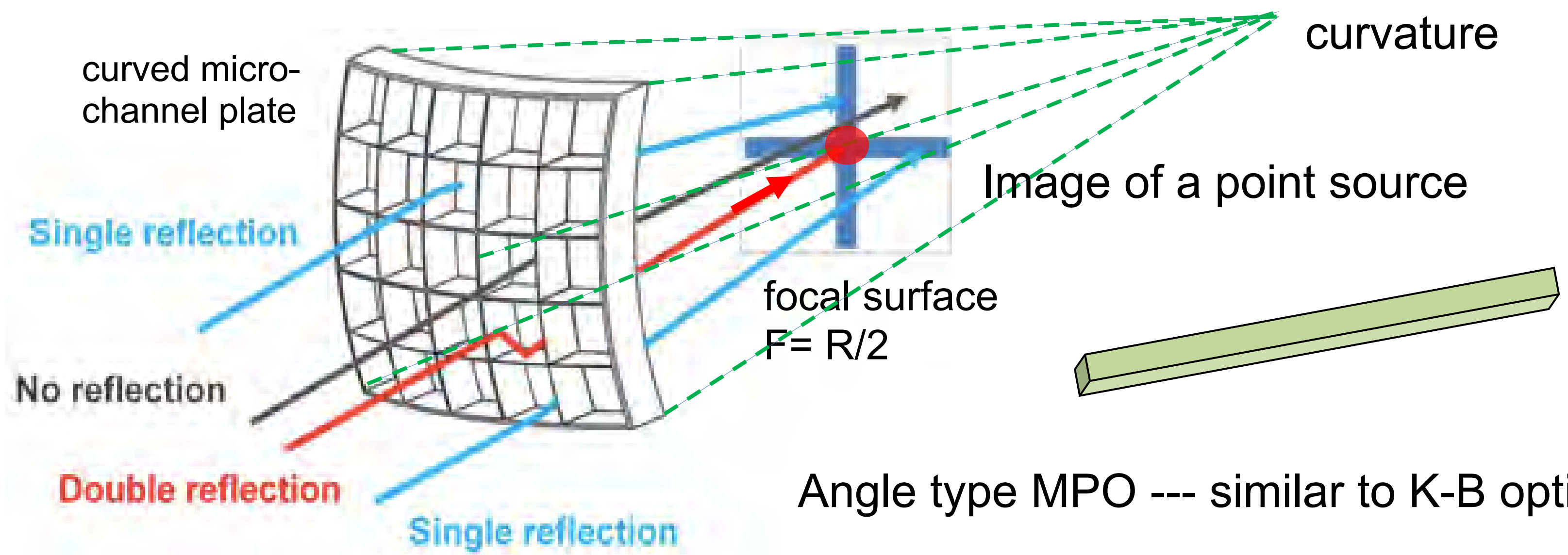
credit: NASA

- Large light collecting area
- High spatial resolution (arcmin-arcsec)
- Small FoV (< 2x grazing angle, 1-2 deg)
- Heavy

Chandra, XMM-Newton, ROSAT, NuStar, Swift/XRT, eROSITA

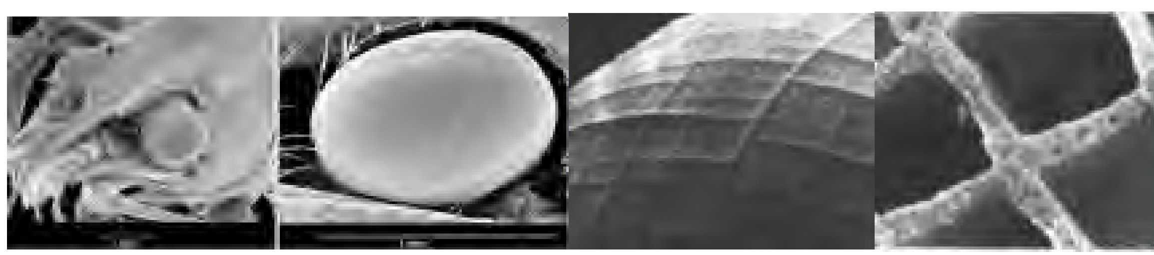
X-ray focusing optics: Micro-Pore Optics - Angel

Light path of MPO focusing



Angle type MPO --- similar to K-B optics

Lobster eye



(also other crustaceans) SEM image (Gaten 1994)

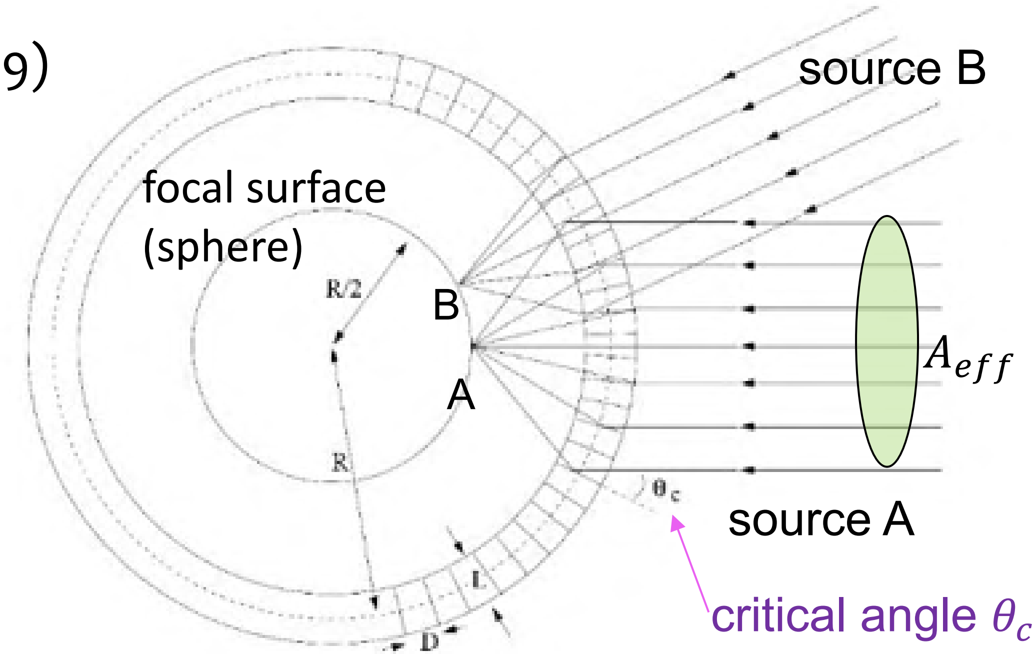
Lobsters see by light reflection (grazing incidence) rather than refraction !

Lobster-eye Micro-Pore Optics

first proposed by R. Angel (1979)

ideal optics for wide-field X-ray monitor

Studied by a number of groups
e.g. Wilkins et al. (1989) ; Fraser et al. (1992); Kaaret (1992)



- Spherically symmetric optics, wide field-of-view up to 4π
- effective area (a small fraction of sphere) $A_{eff} \propto R^2 \propto F^2$
- Practically A_{eff} ~ 10 cm² (all directions)
- Angular resolution ~5 arcmin (c.f. 1.5 deg MAXI)
- Light weight

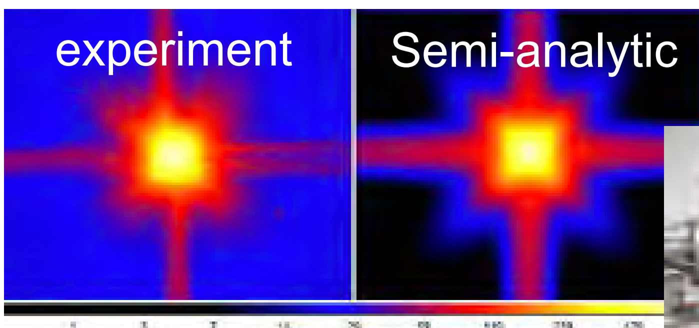
$$\sqrt{\frac{A_{ap}}{A_{src}}} \sim 20$$

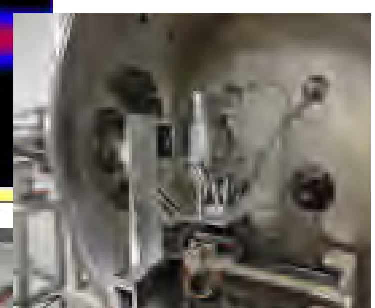
Not matured until recent years !

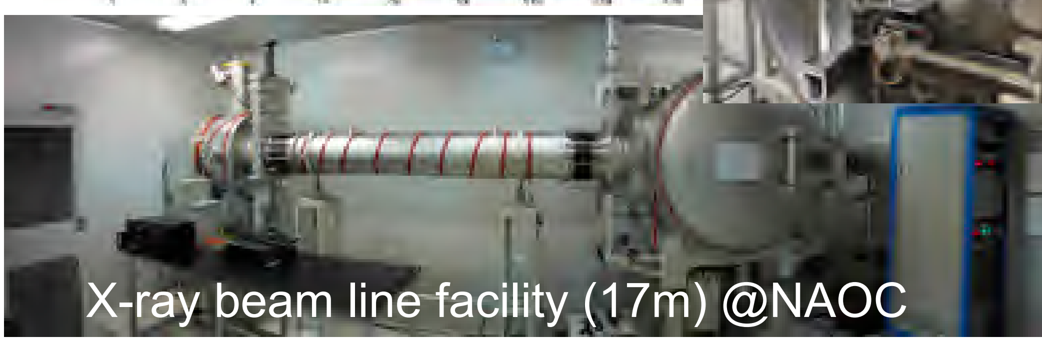
X-ray imaging technology development at XIL/NAOC

- Theoretical and experimental study of MPO imaging optics
  - Developed ray tracing simulation code using Geant4
  - Semi-analytic calculation
- Developing MPO devices (collab. with NNVT)
- Developing technology to build LE-MPO X-ray mirrors
- Testing X-ray detectors for use of lobster-eye telescopes

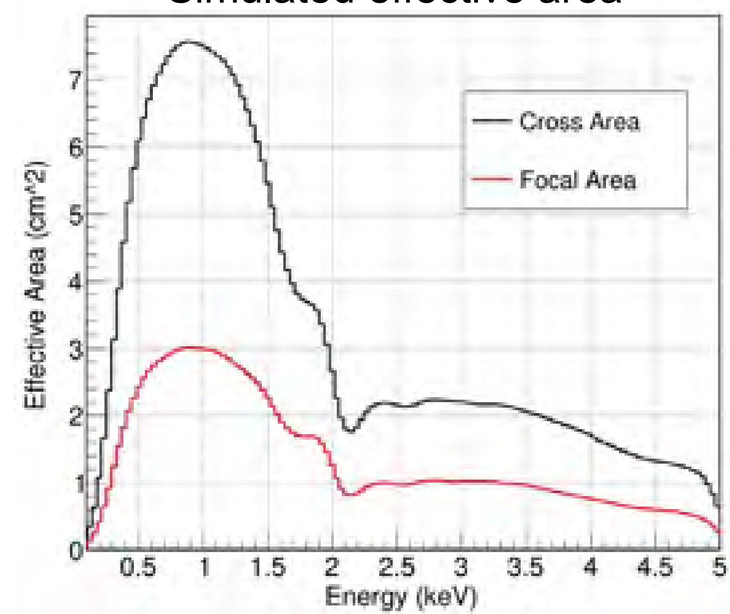
Since ~2010





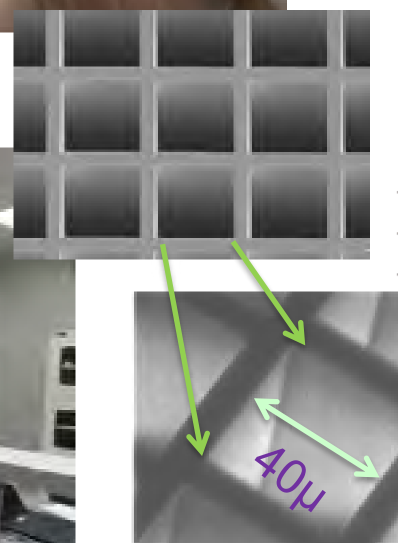


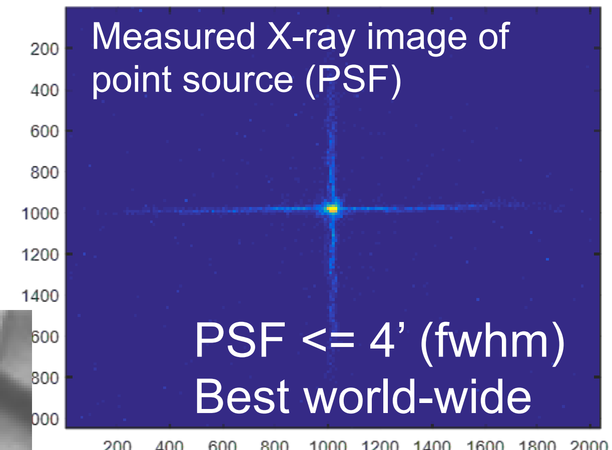
Simulated effective area



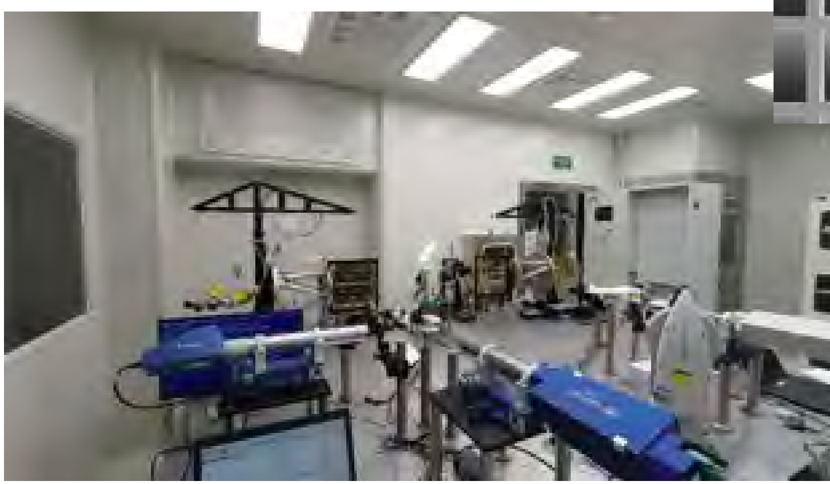
张臣、凌志兴、赵东华、贾振卿、等

X-ray imaging technology development at XIL/NAOC





surface roughness ~ 5 Ang rms!



Designed & built laser-guided automatic assembling facility, mouthing precision: 20" for each MPO plate

A brief introduction to Einstein Probe ……

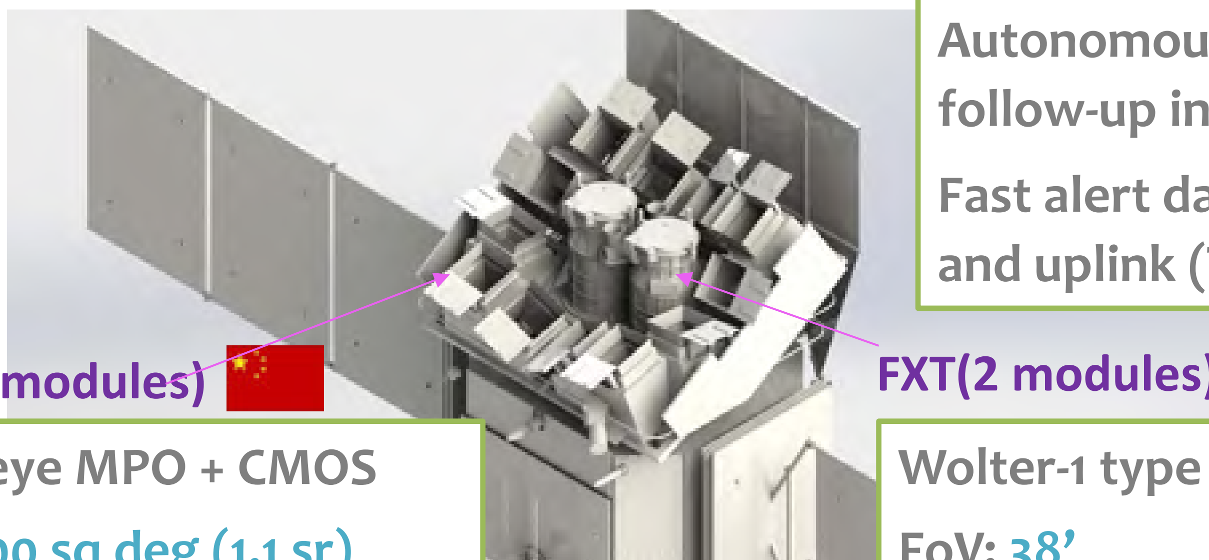
Einstein Probe (EP) mission

- A space observatory for all-sky monitoring to discover & study high-energy transients and variability in X-rays
- CAS's mission with international participa

On-board data processing

Autonomous slew & follow-up in 3-5 min

Fast alert data downlink and uplink (ToO)



WXT (12 modules)

lobster-eye MPO + CMOS

FoV: 3600 sq deg (1.1 sr)

band: 0.5 – 5 keV soft X-ray

eff. area: ~3 cm^2 @1keV

FWHM: ~ 5', positioning <1'

Sensitivity: 10-100 x increase

FXT(2 modules)

Wolter-1 type + CCD

FoV: 38'

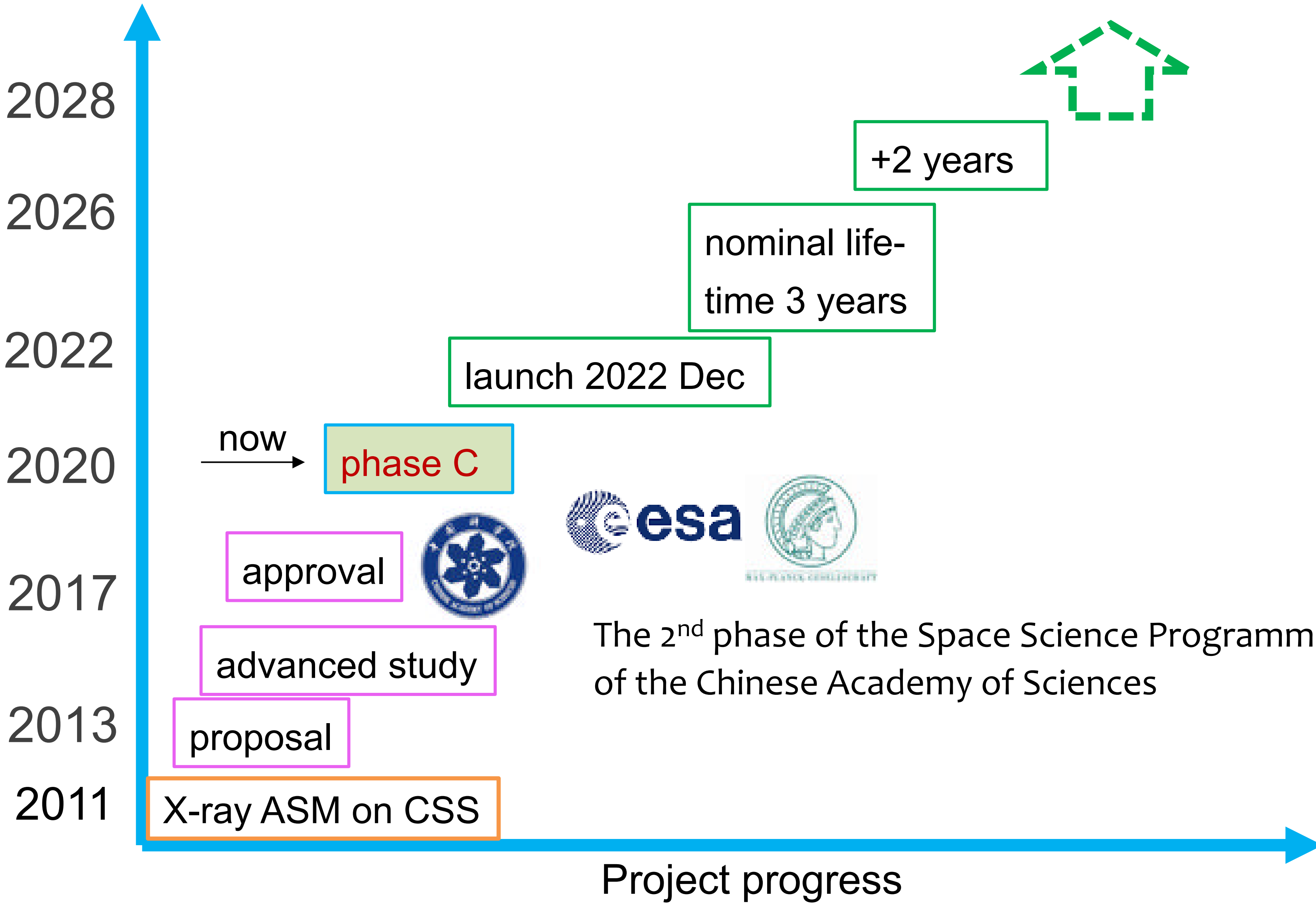
band: 0.3-10keV

eff. area: 2x 300cm^2 @1keV

angular FWHM: 30"

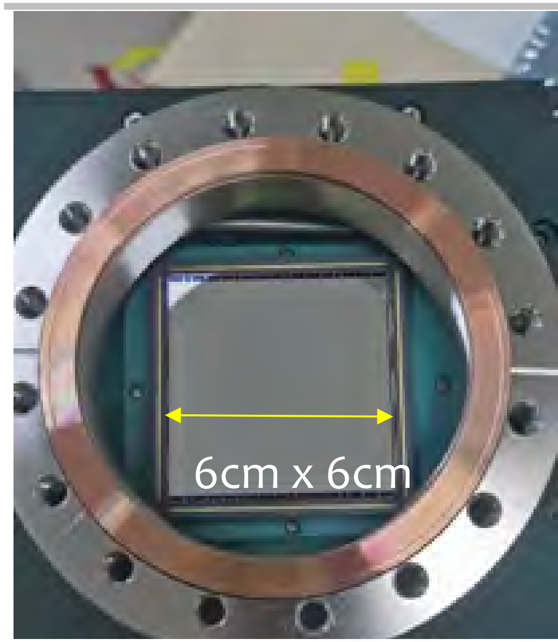
positioning accuracy: <10"

Project status



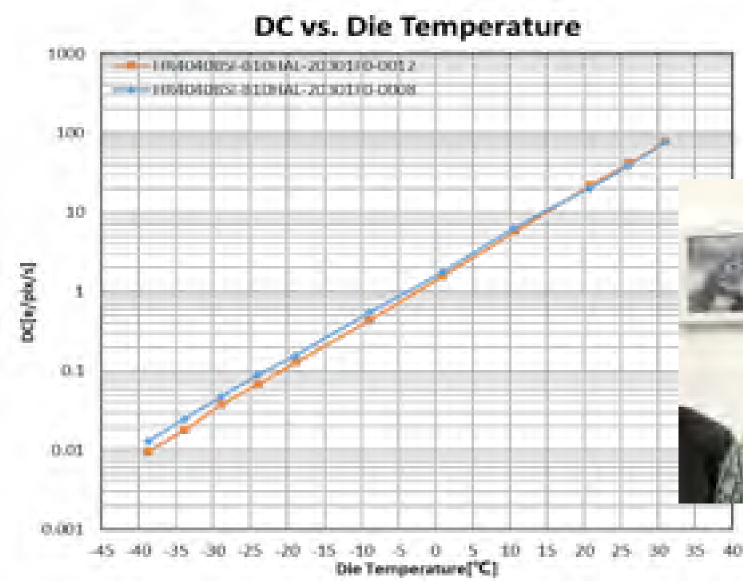
The 2nd phase of the Space Science Programme of the Chinese Academy of Sciences

CMOS testing and camera building



- Back-illuminated CMOS (Gpixel)
- 6cm x 6cm [4k x 4k]

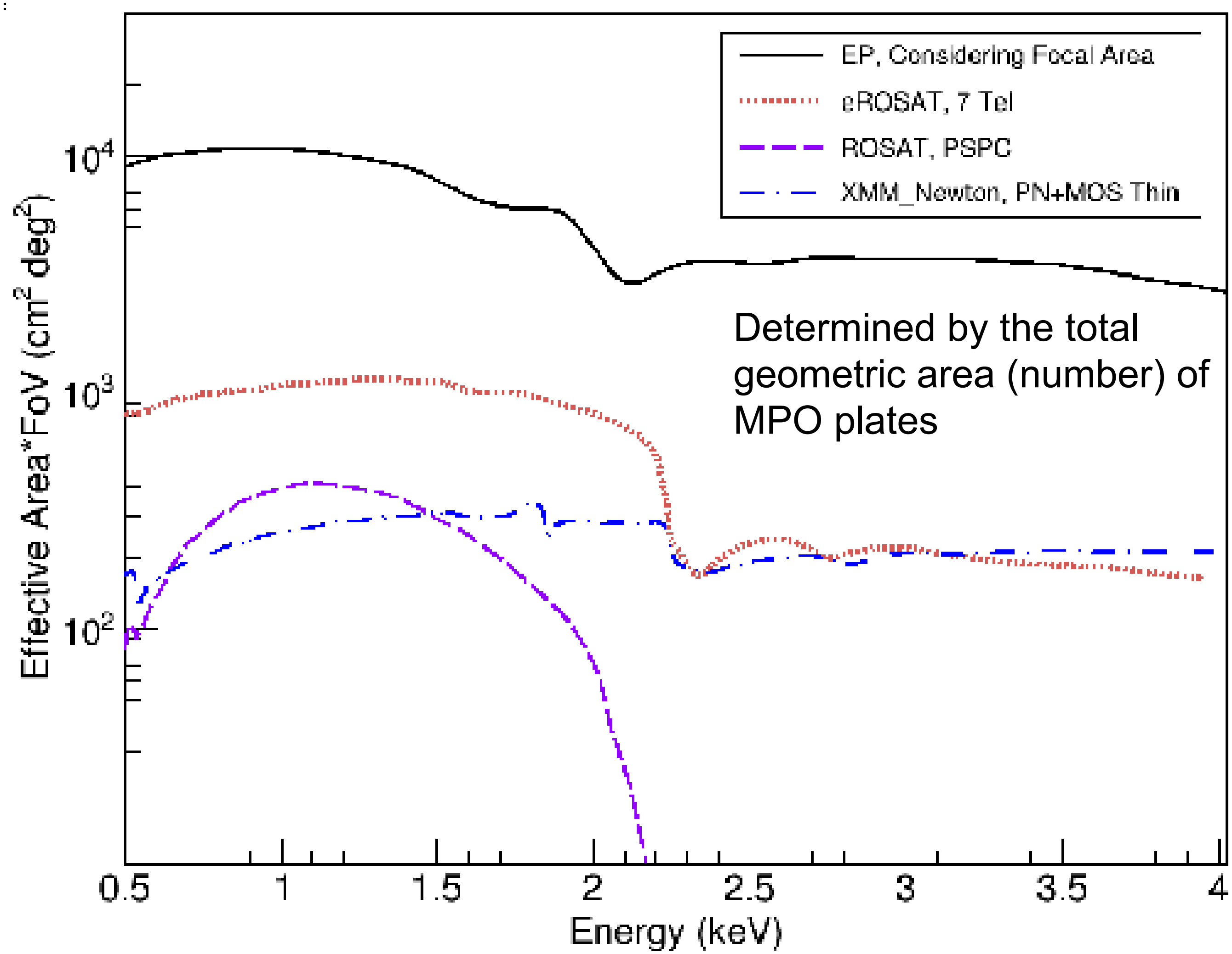
First time CMOS used for X-ray detection in space ever!
Testing, testing, testing ……



凌志兴、王文昕、张臣、等

Grasp of WXT

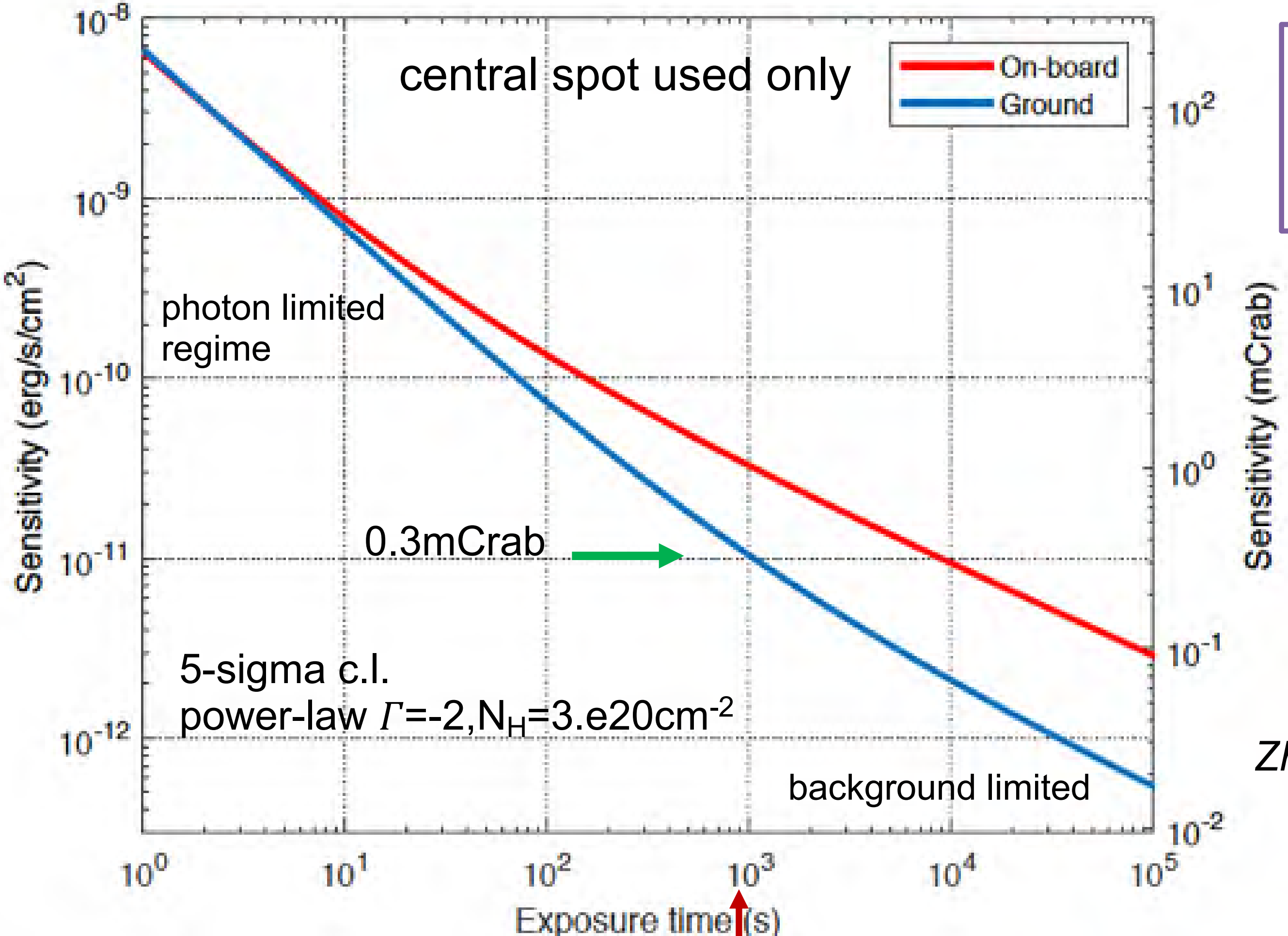
Grasp: a measure of monitoring capability



Determined by the total geometric area (number) of MPO plates

al. 2017

Simulated EP WXT sensitivity



10-100 times better than current X-ray ASM (MAXI, Swift)

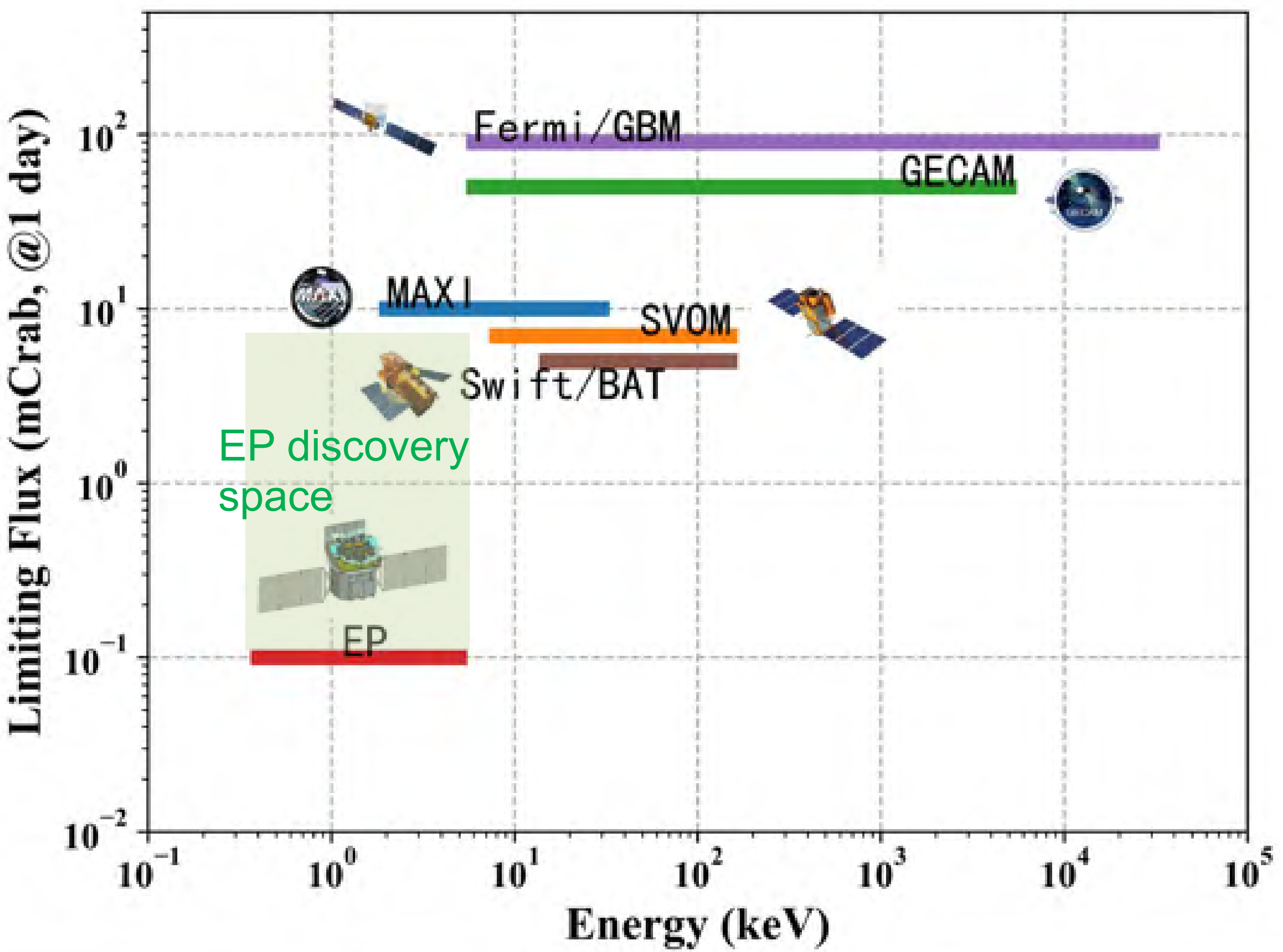
Zhao D. et al. 2017

~ 1 survey snapshot

background 3.3 counts @ central spot

backgrounds : particles, diffuse background, with shielding

EP WXT sensitivity compared with other missions



Sky survey mode considered for EP

Fellow-up X-ray Telescope (FXT)

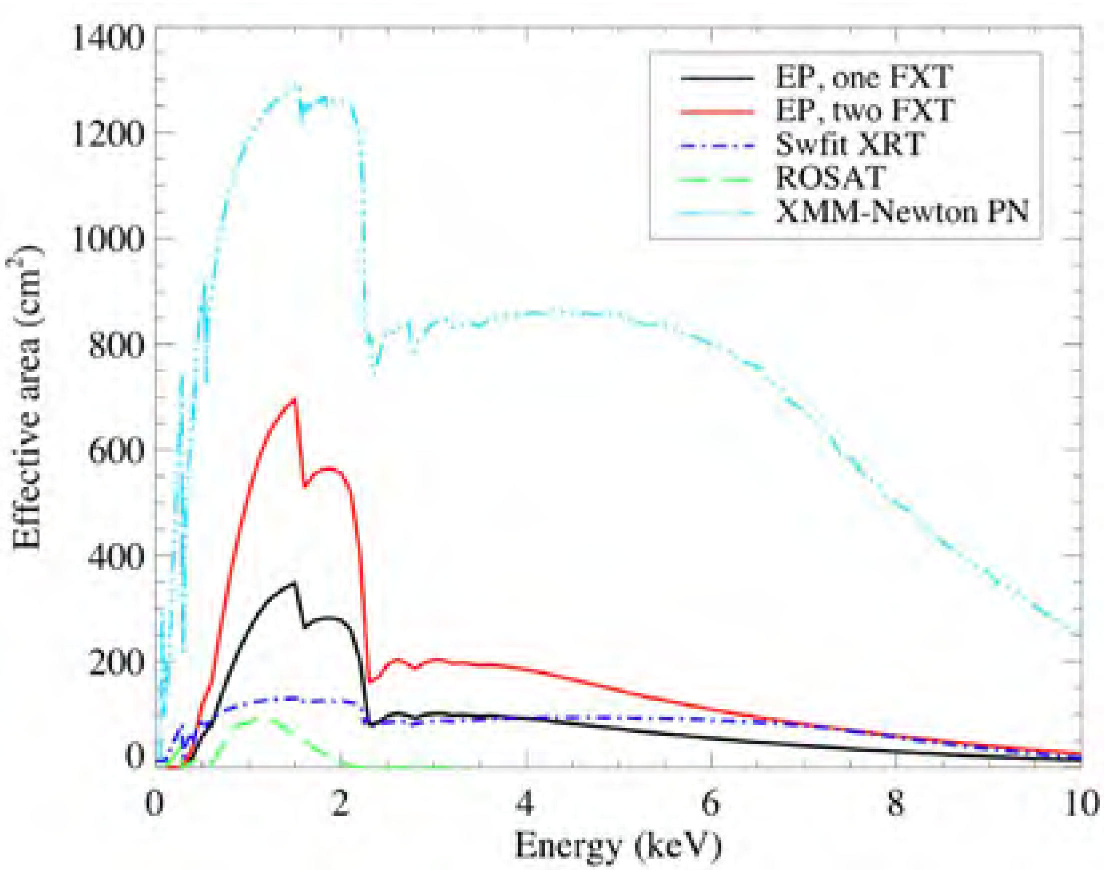
- X-ray mirror: Wolter-I
- Detector: PN-CCD @-90C
- Focal length: 1.6m
- Eff. area: 2x 300cm^2 @1keV
- Spatial resolution (HPD): 30”
- FoV: ~38 arcmin
- Bandpass: 0.3-10 keV
- E-resolution: 120eV @1.25keV

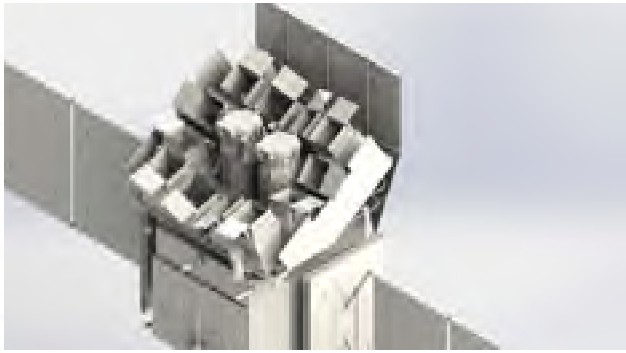
研发单位：高能物理所
+欧空局+马普地外物理所

Led by IHEP, with contributions from ESA and MPE

PI: Yong CHEN (IHEP)

Follow-up capability of EP-FXT



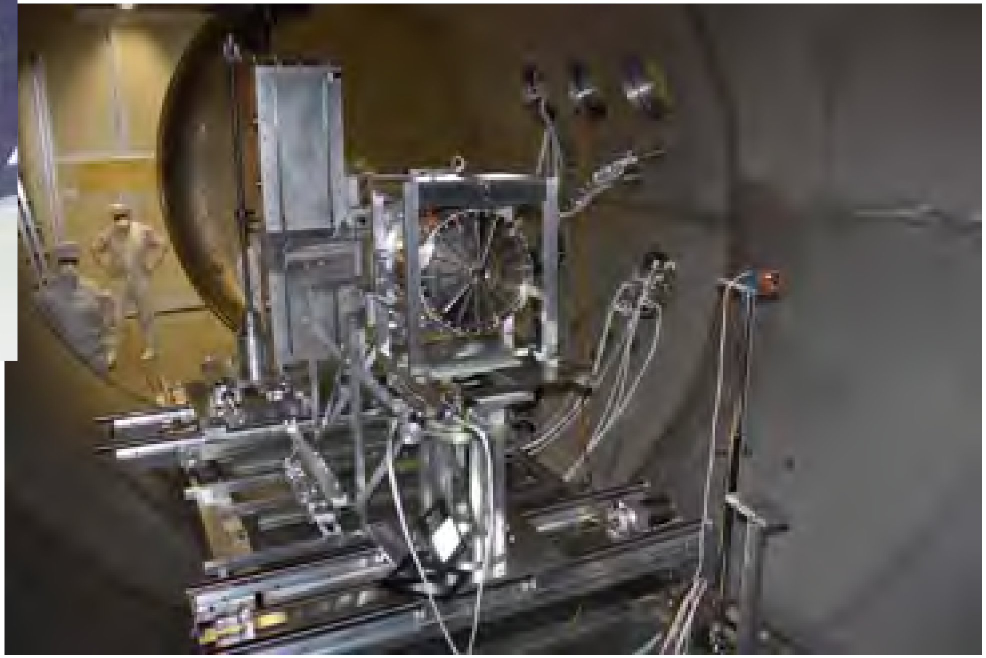


effective area:
5 x Swift XRT @ 1keV,
comparable @ > 6keV

- Source localisation <10”
- Measure X-ray spectra and flux and their evolution
- X-ray observations for transients found in other surveys (e.g. optical, radio)

FXT status

FXT STM Mirrors integration
(credit Media-Lario)

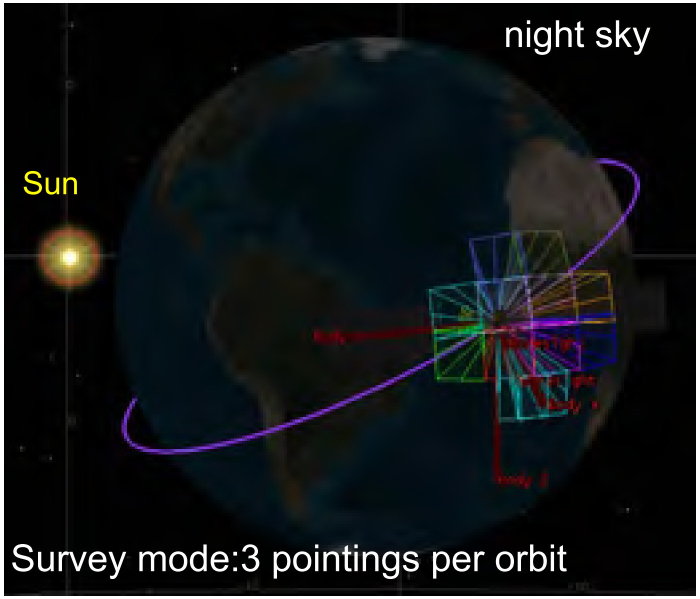


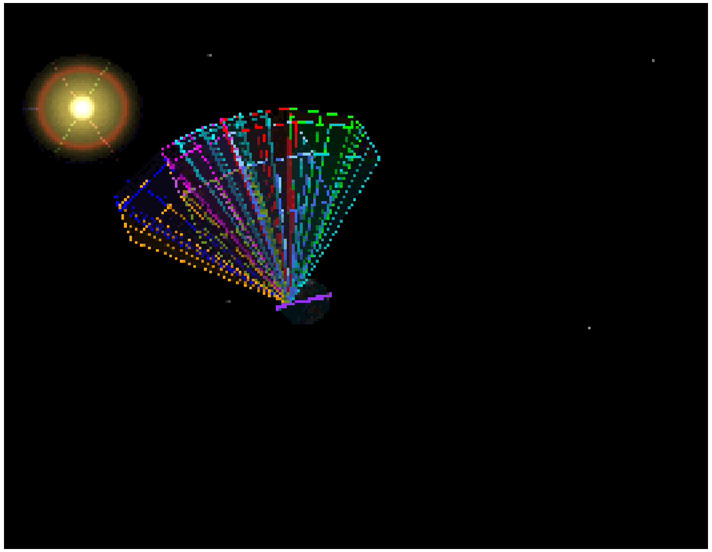
FXT STM Mirror Module at PANTER facility for
X-ray tests (credit Media-Lario)

Mission profile & obs. modes

- 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:

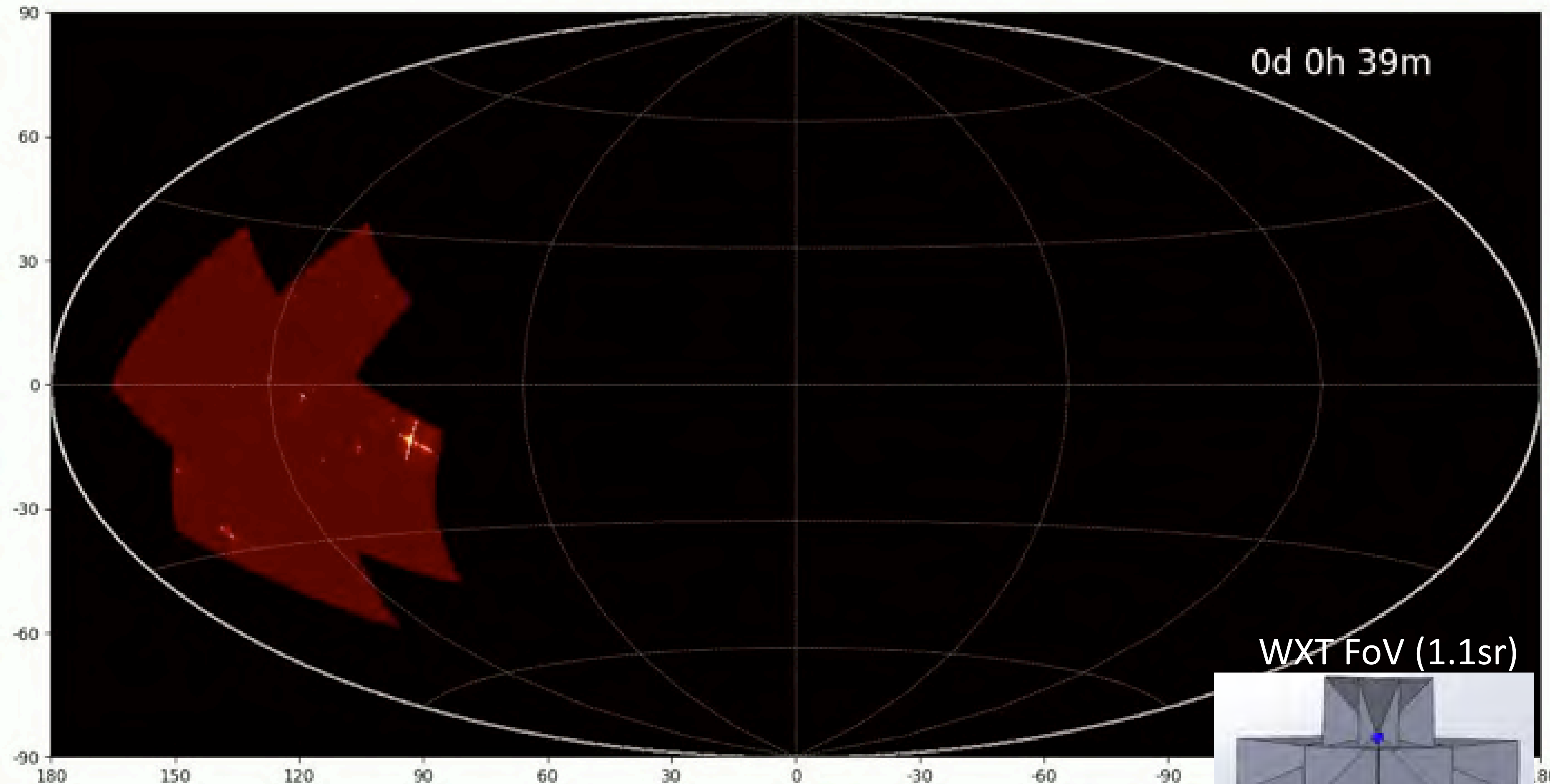
    time for FXT to point (3-5 min)
  - ToO
- On-board data processing & transient search
- Alert data rapid downlink (VHF, Beidou)
- Fast ToO uplink (Beidou)



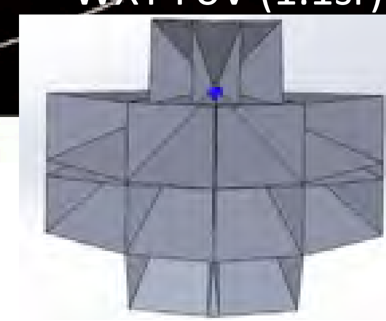


WXT monitoring survey (simulations)

WXT FoV footprints in 1-day (Galactic coordinates)



WXT FoV (1.1sr)



In 3 orbits (5hr) WXT can cover most of the half sky

EP satellite STM model

中科院上海微小
卫星创新研究院

Weight: 1.4 ton

Height 3.4m

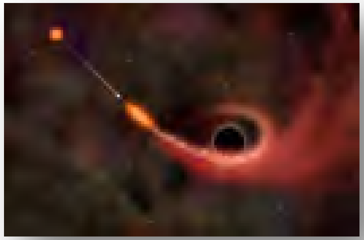
Diameter ~ 3m

satellite mechanical-thermal model (MicroSat)

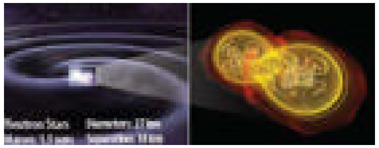
Main science goals

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



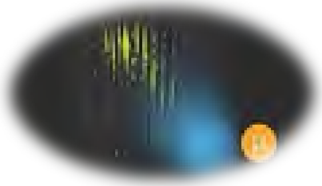
Detect and localize the electromagnetic-wave sources of gravitational-wave events by synergy with gravitational-wave detectors



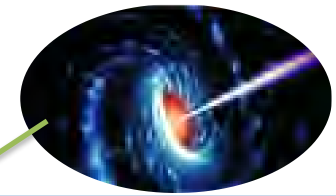
defined in proposal of 2013 Jan

A wide range of X-ray transients & variability

X-ray flash
& LL GRB
GRB physics

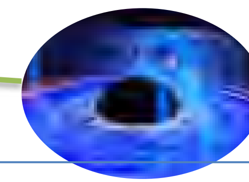


EM counterparts of
neutrino events
particle acceleration



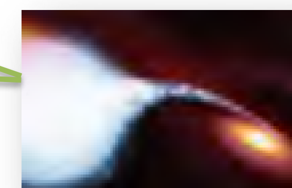
High-redshift GRB
Trace first stars/BH
Early universe

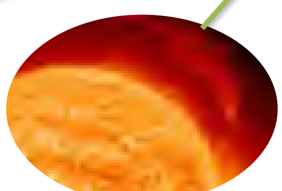
Active galactic nuclei
Extreme gravity, BH
accretion/jets/growth

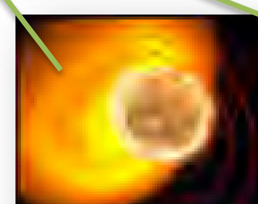


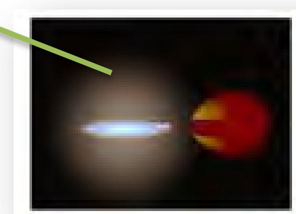
Intermediate-mass BH
BH physics/accretion

SN shock breakout
SN physics
Size of progenitors









BH X-ray binary
Extreme gravity
BH physics/accretion

Fast Radio Burst
X-ray sources

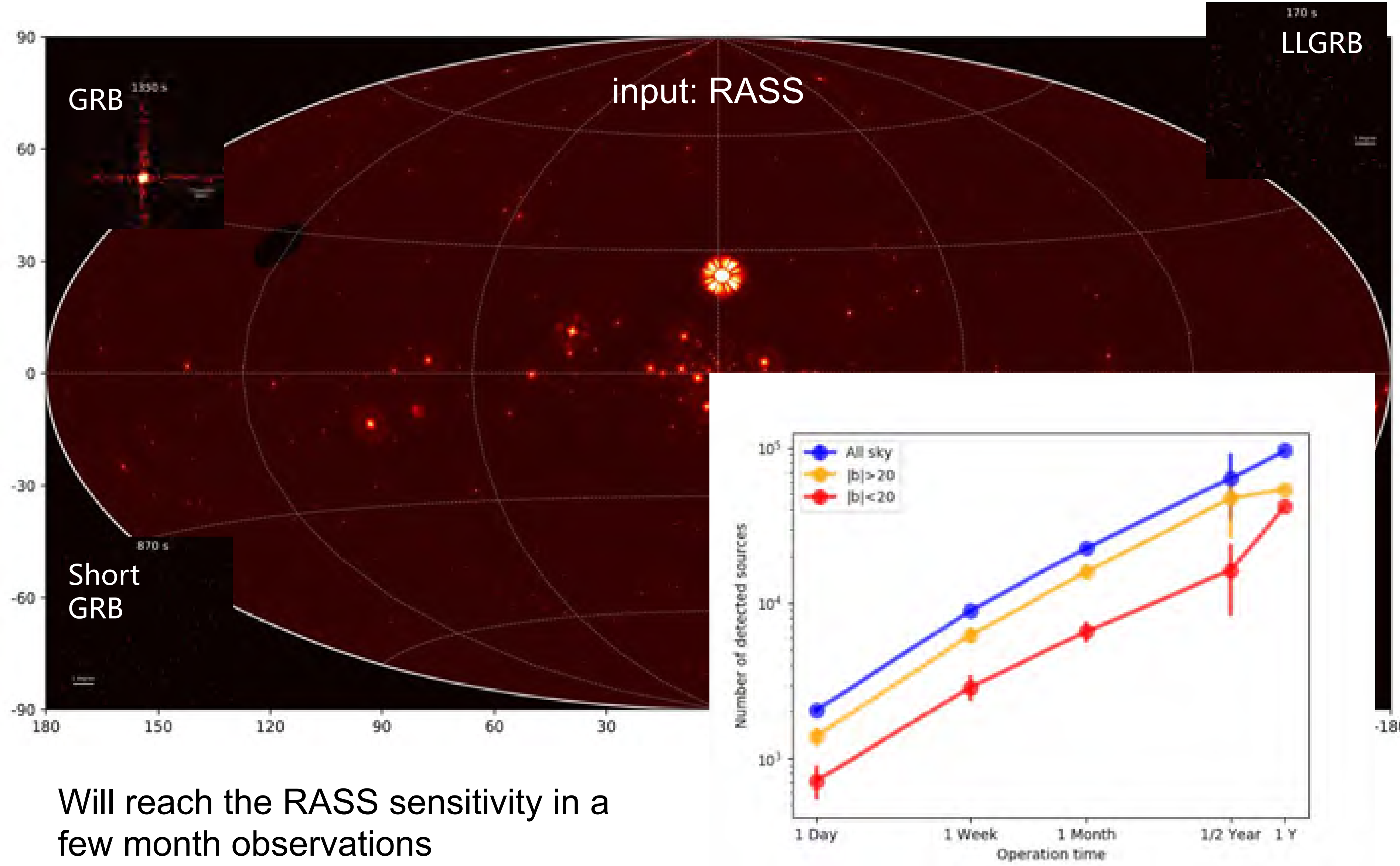
Star X-ray flares
Magnetic fields
Corona activity

SGR/magnetar
extreme
magnetic Field

Thermal nuclear burst
Neutron stars physics

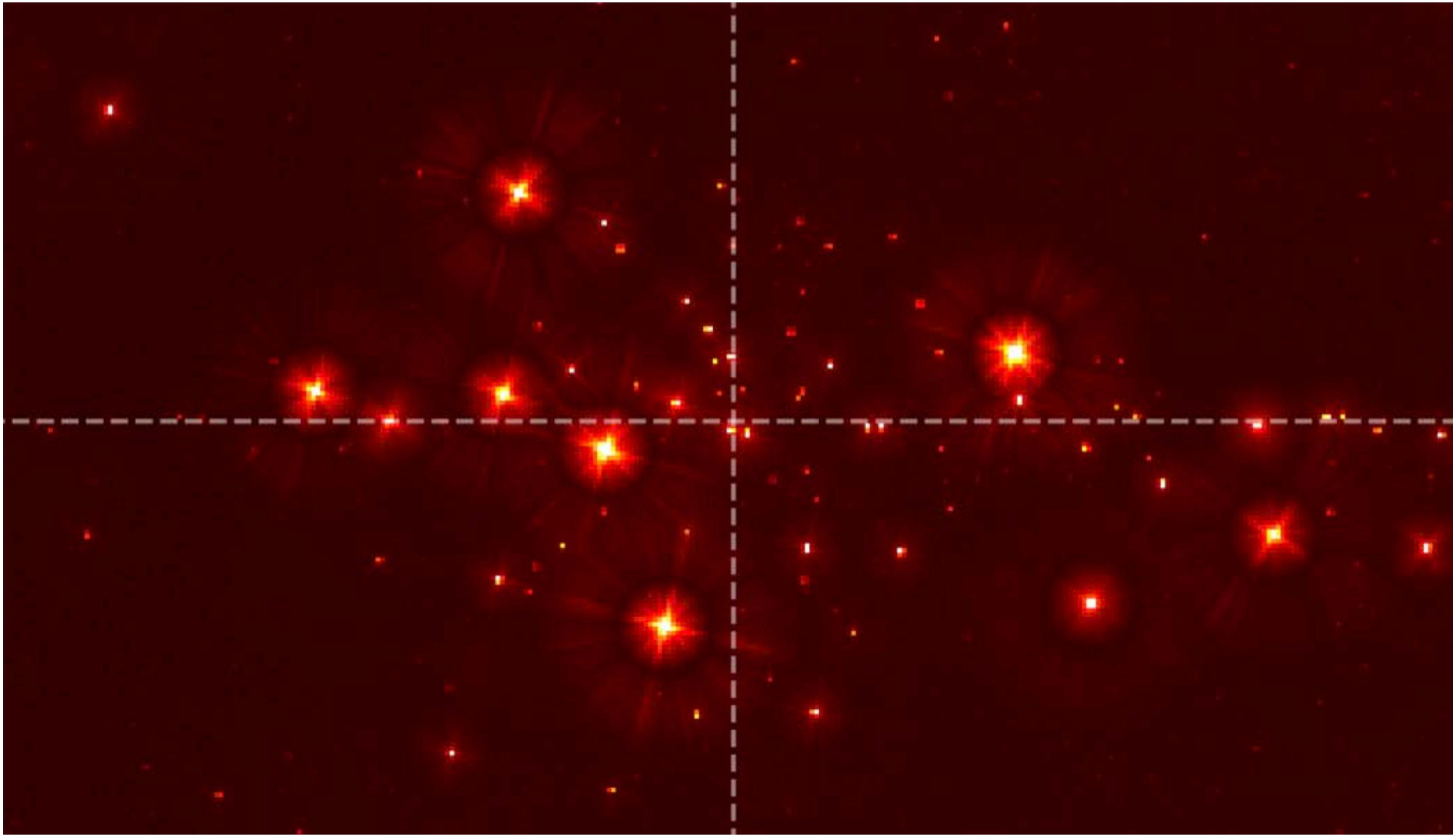
EP special issue
2018

Simulated all-sky image & transients in 1-year



Will reach the RASS sensitivity in a few month observations

close-up at Galactic center region

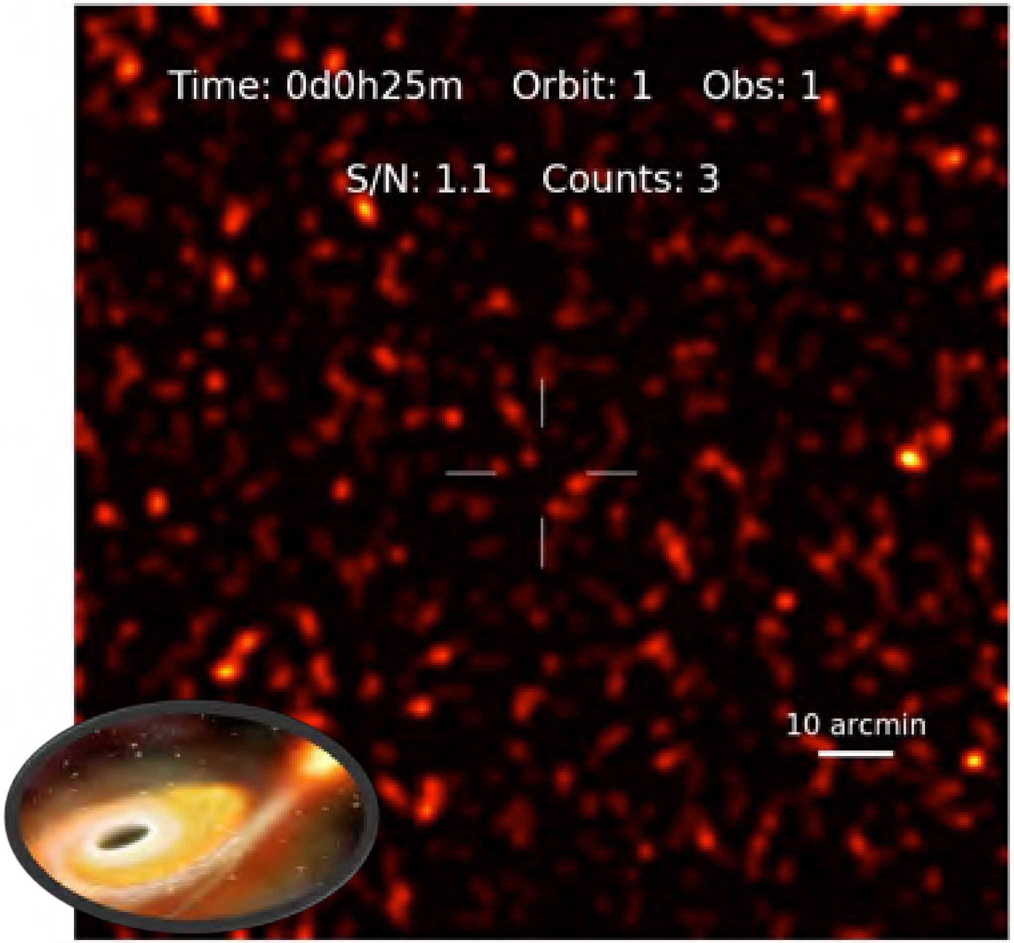


~ 25 deg x 15 deg

Estimated detection rates for some transients

Type of transients	detections per year
Tidal disruption event (TDE)	~100
TDE with jet	10 – ?
Supernova shock breakout	50 (?)
Long GRB	~ 80
High-z GRB (z > 6)	a few ?
Short GRB	~ 10
Low-luminosity GRB	~ 10
Magnetar	~ a few
Stellar flares	several x 10^3
AGN monitored daily/weekly	several tens/hundreds

Simulations: EP-WXT detection of a distant TDE

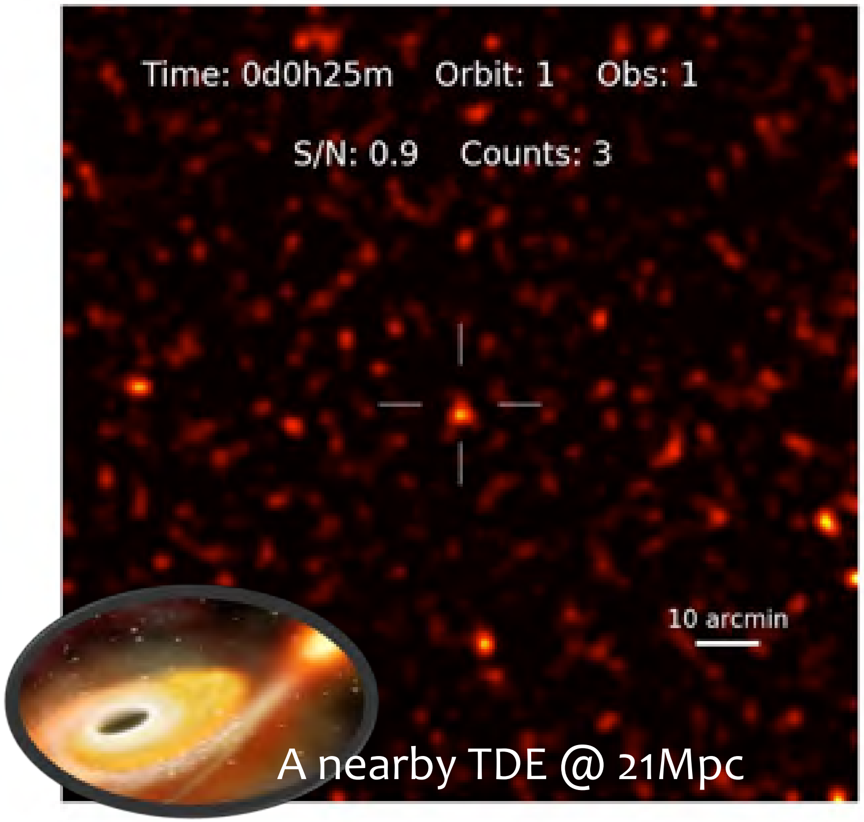


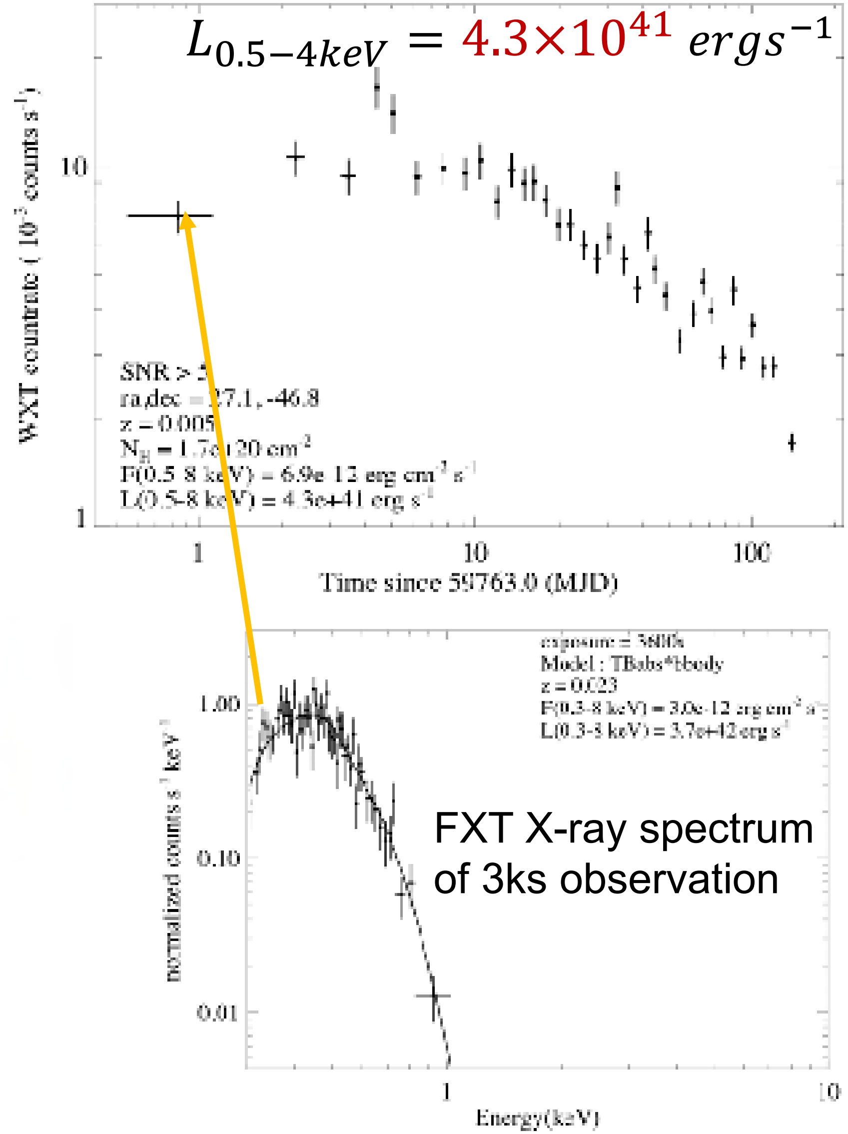
faintest TDE detectable with WXT

@ z = 0.28

- $F_{0.5-4keV} = 1.2\times 10^{-12} erg s^{-1} cm^{-2}$
- $L_{0.5-4keV} = 3.2\times 10^{44} erg s^{-1}$

Simulation: EP-WXT detection of a nearby TDE

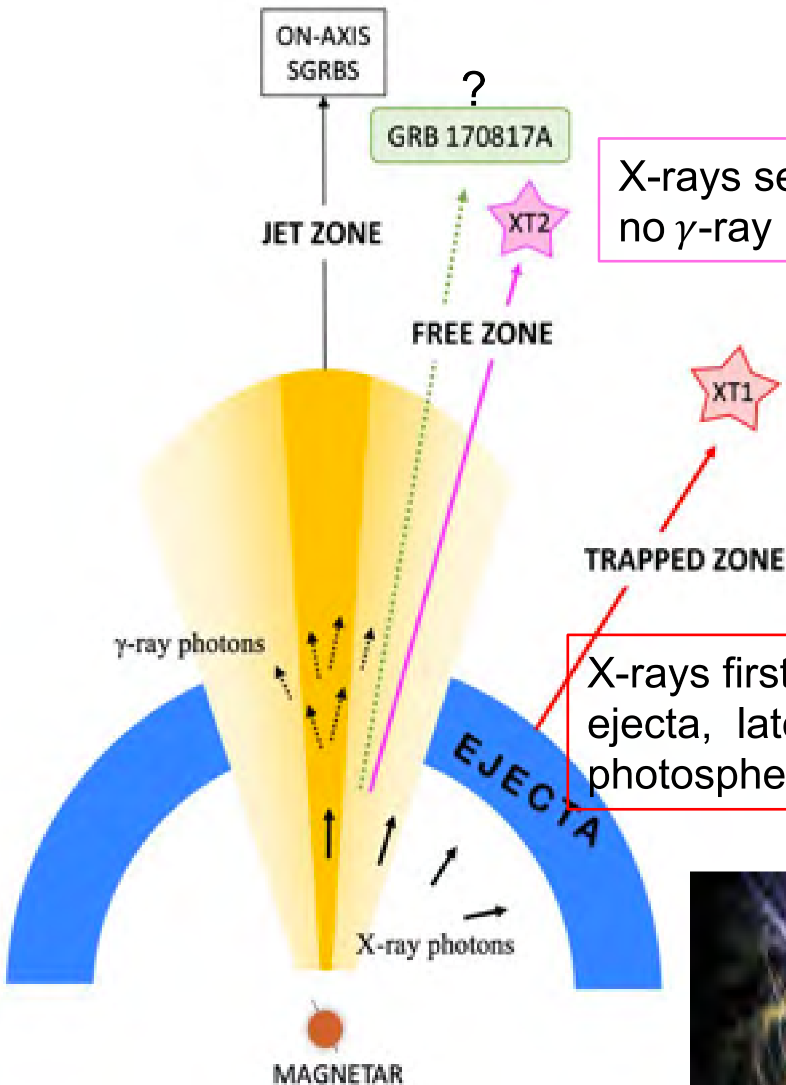




$M_{BH} \sim 10^4\ M_{Sun}$ IMBH

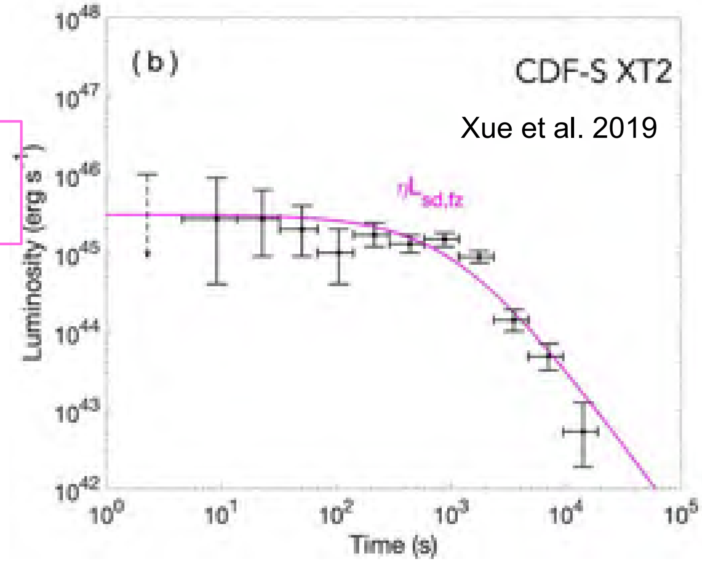
Explore the faint end of the BH mass function

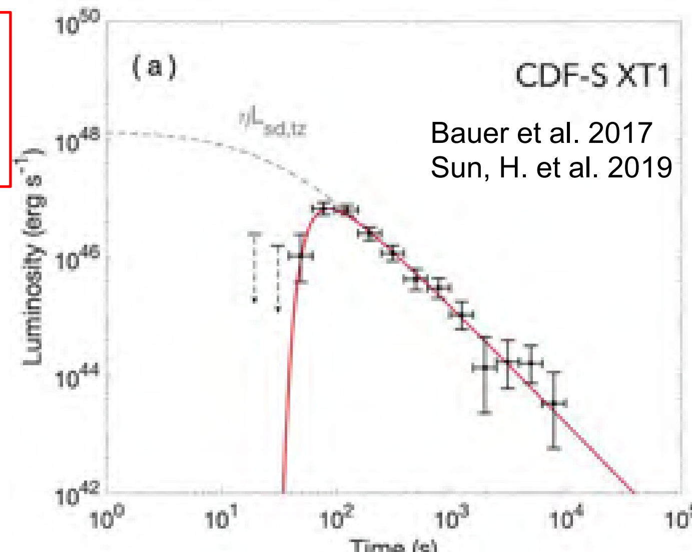
GW X-ray counterparts: magnetar-powered X-ray transients from NS-NS merger?



X-rays seen directly, no γ-ray (or weak)

X-rays first trapped by ejecta, later escape at photosphere radius

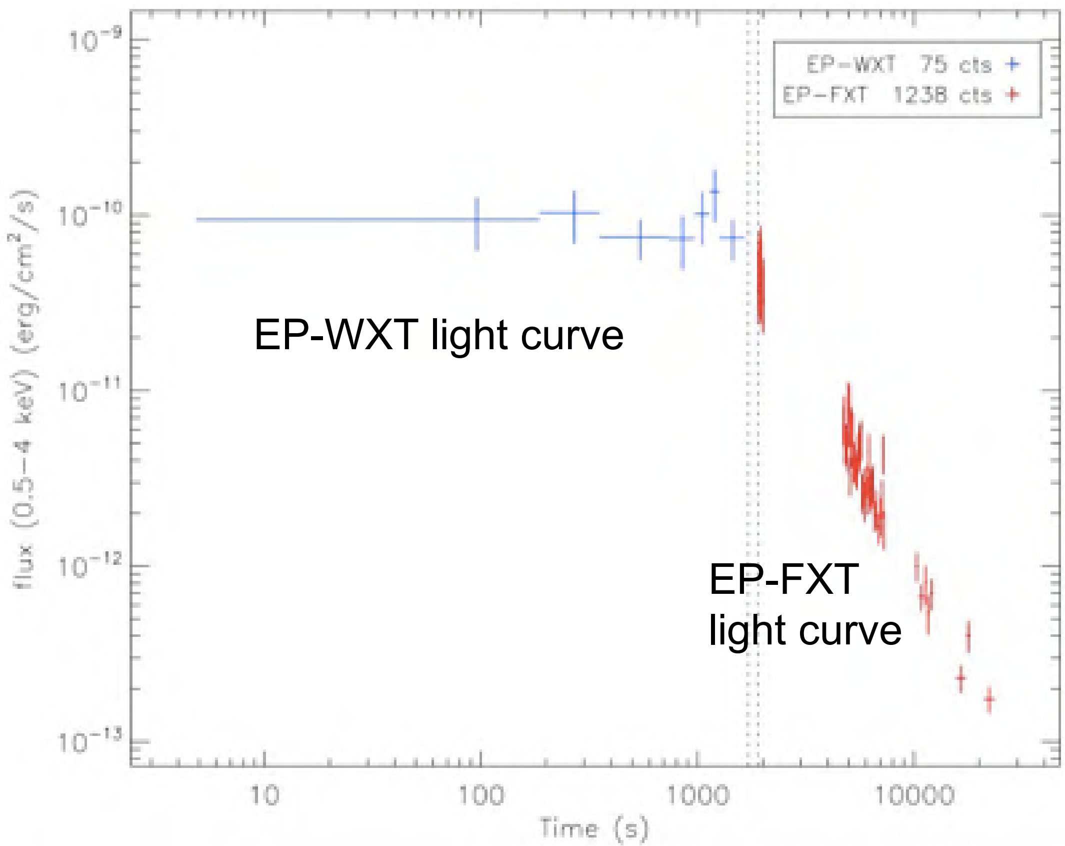




Zhang, et al. 2013, Gao et al. 2014, Xue et al. 2019, Sun et al. 2020

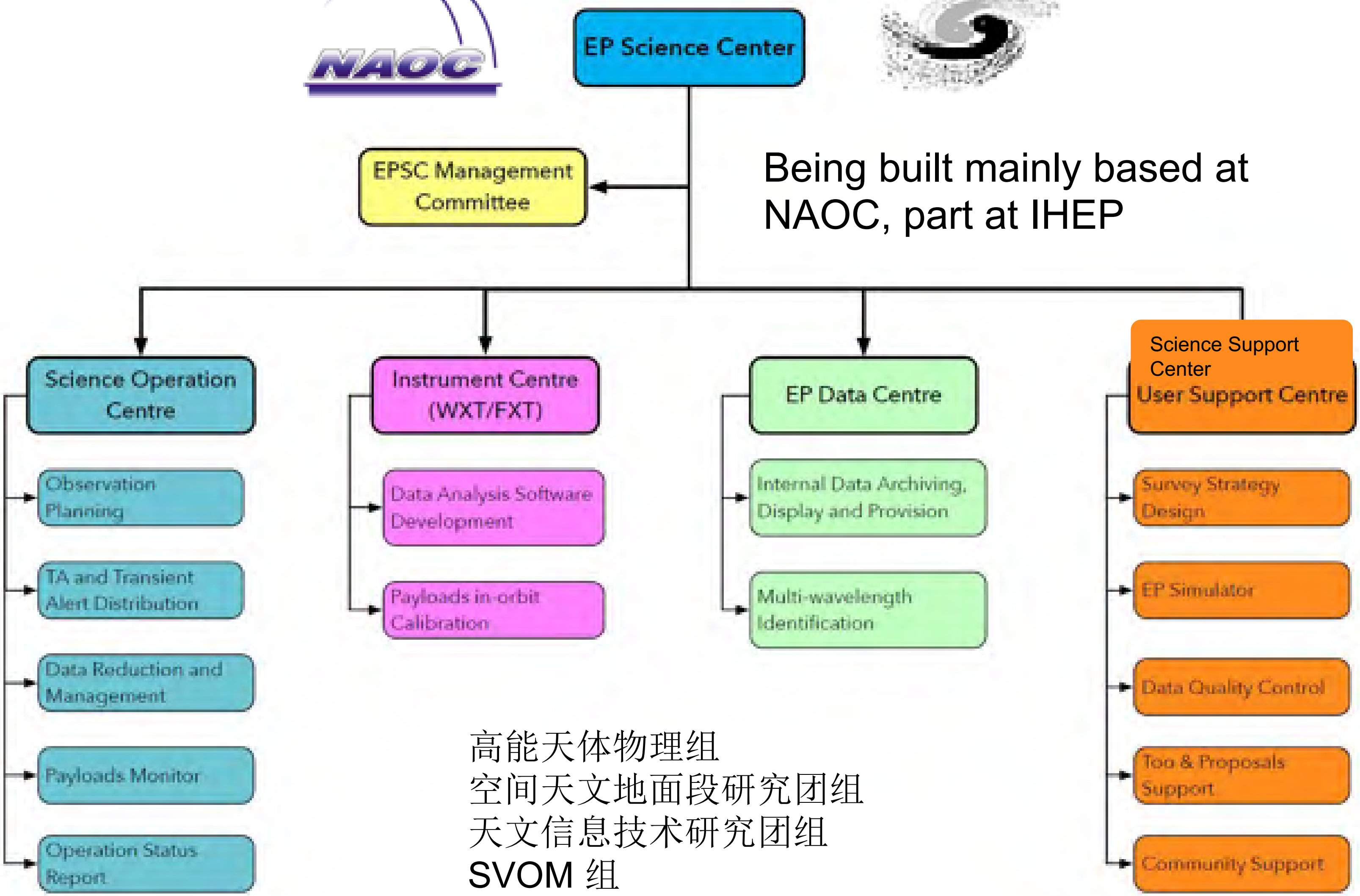
EP detectability of XT2-type X-ray transients

Simulated EP observation of XT2 @ 250 Mpc



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

EP Science Center



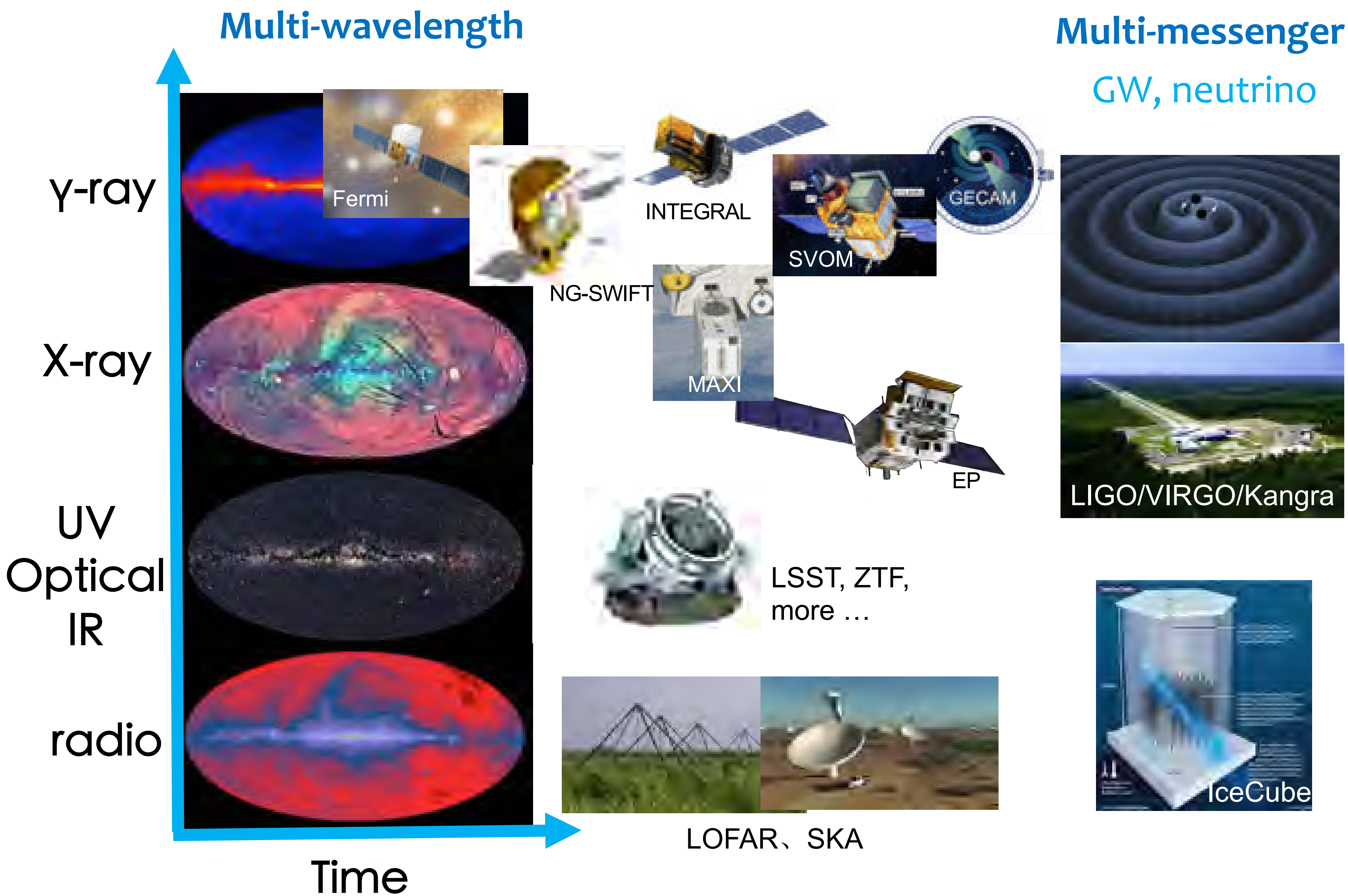
Being built mainly based at NAOC, part at IHEP

高能天体物理组
空间天文地面段研究团组
天文信息技术研究团组
SVOM 组

Summary

- The X-ray sky is rich in cosmic transients, and new types 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 next several years, with
  - Unprecedented monitoring sensitivity
  - Very large FoV & High cadence
  - Unique passband in soft X-ray
  - Rapid response and satellite-ground two-way communication
- We will build and test EP within two years, and then launch and operate it
- Still a long and hard way to go to make it really happen !

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




Thank you for your attention