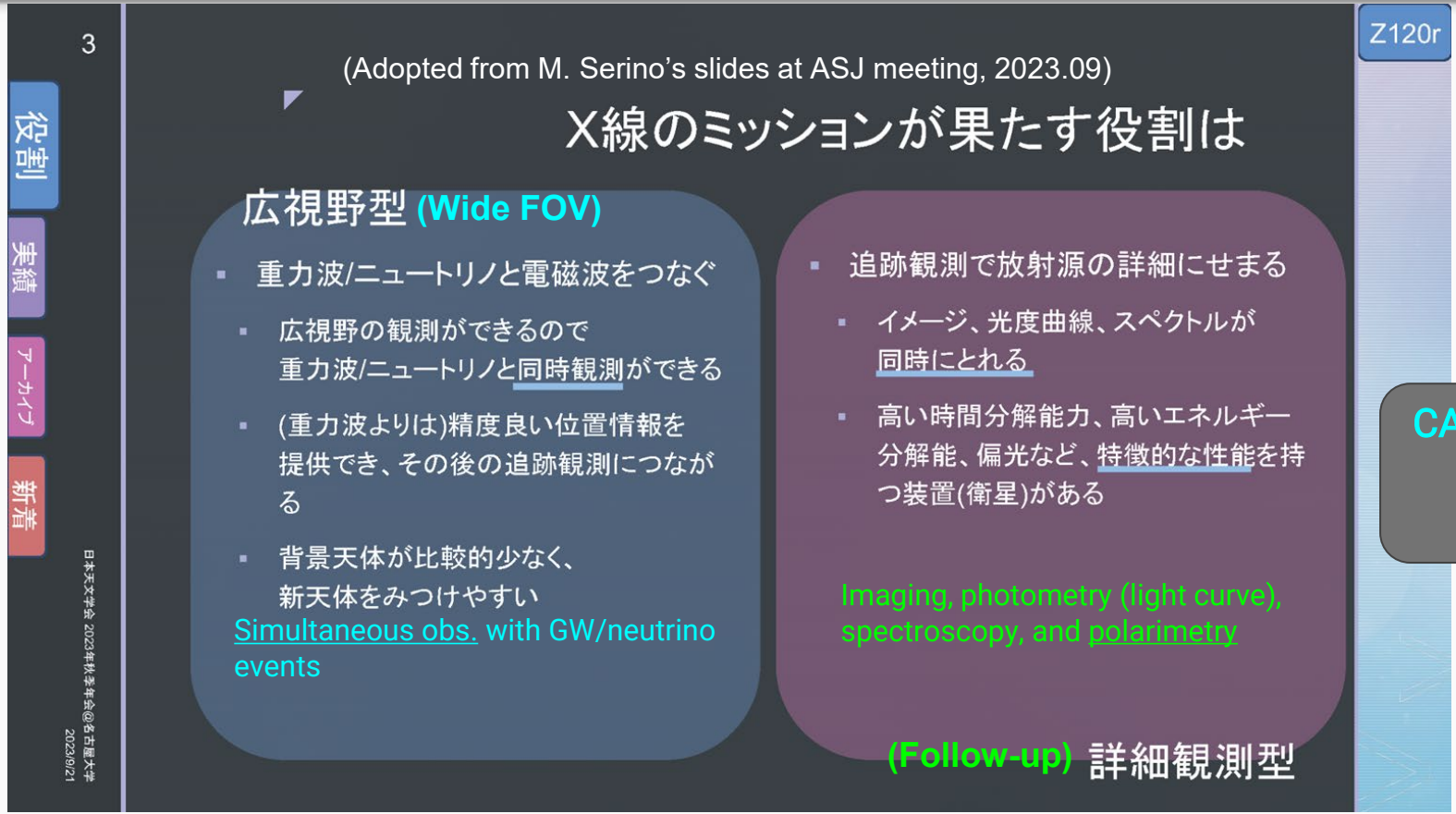
CAMELOT and IXPE: All-Sky Monitoring and Polarimetry for Multimessenger Astrophysics (3)

T. Mizuno (Hiroshima Univ.)
on behalf of the CAMELOT and IXPE team

2025 Nov. 19, Annual Conference on Multi Messenger Astrophysics @ Miyagi

Introduction: Role of X-ray Missions in MM Astrophys

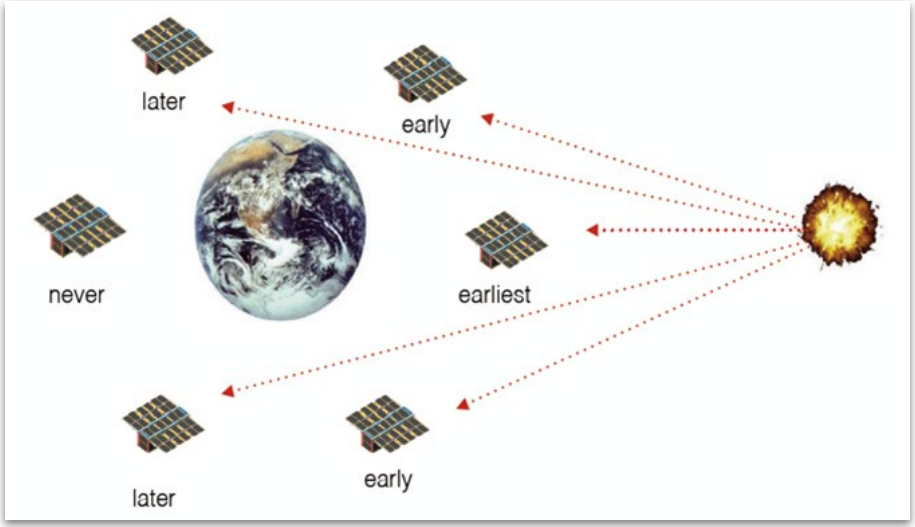


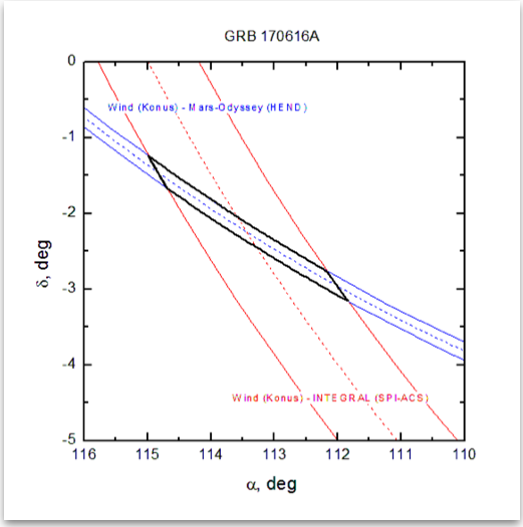
CAMELOT and IXPE

Wide FOV Obs. with a Fleet of Nano Sat.

Simultaneous observation using GW/neutrino and EM wave is essential for MM Astrophys (e.g., GW170817, IC-170922A)

- We need to monitor <u>all sky</u> (~4π sr) with <u>good angular resolution</u> (<=1deg)



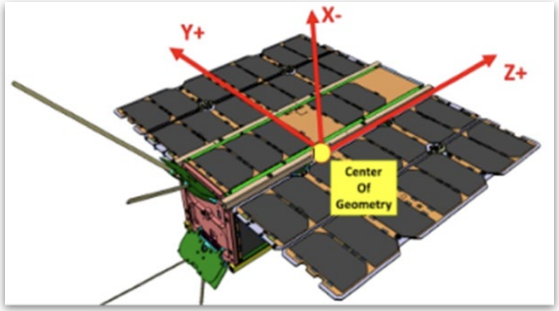


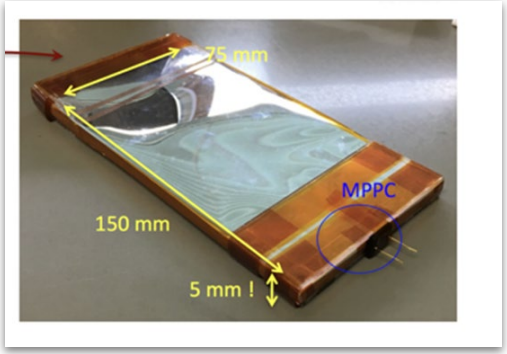
~10 nano satellites allow all-sky monitoring in hard X-ray and gamma rays

Timing-based localization; triangulation principle with different arrival time (<=0.1 ms) enables sub-degree localization

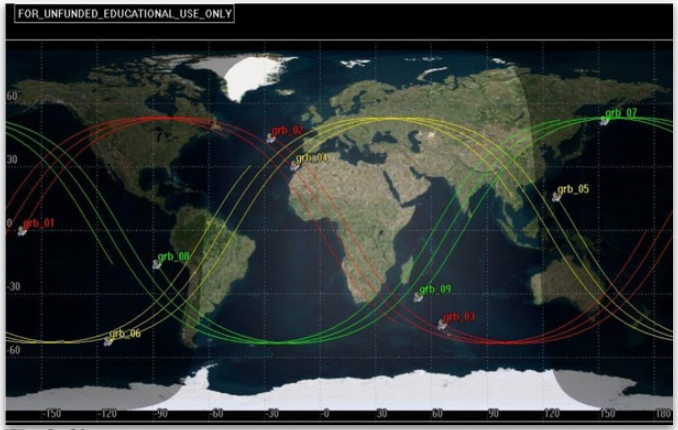
CAMELOT Mission

Hungarian-Japanese-Czech-Slovak project using standardized nanosatellites





Werner+18
Ohno+20

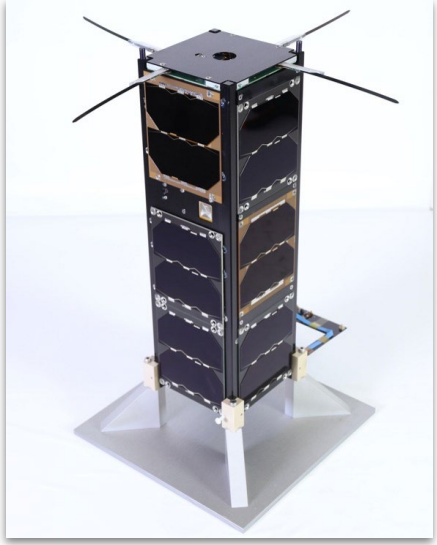


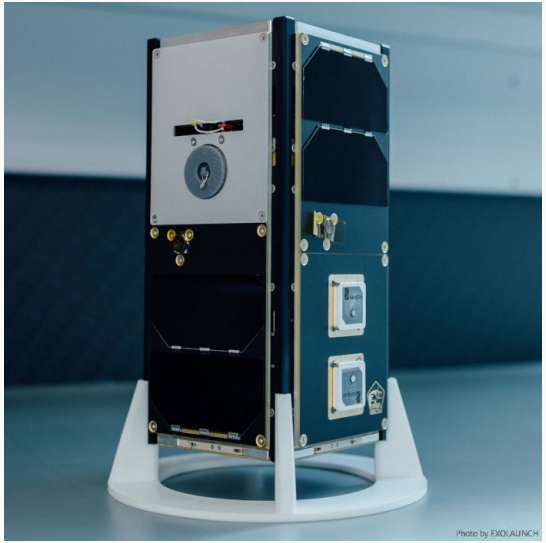
Satellite platform	3-U cubesat platform
Target orbit	>=9 satellites constellation in LEO with various orbital configuration
Payload	150x75x5 mm^3 CsI readout by multi-channel MPPCs
Goal	Degree-scale timing-based localisation with a similar sensitivity to the Fermi-GBM

Mission Status

Pal+23; Ripa+22; Münz+24

3 demonstration satellites in/completed operation





GRBalpha (2021.03-2024.06); 1U-sized prototype satellite (https://grbalpha.konkoly.hu/)
・has smaller detector, but the same basic concept

VZLUSAT-2 (2022.01-); 2 prototype detectors as 2ndary payloads (https://www.vzlusat2.cz/en/)
・allows simultaneous GRB detection using nanosatellites

GRBbeta (2024.07-); 2U-sized technological precursor (https://grbbeta.tuke.sk/index.php/en/)
・tests several technologies such as attitude control and UV camera

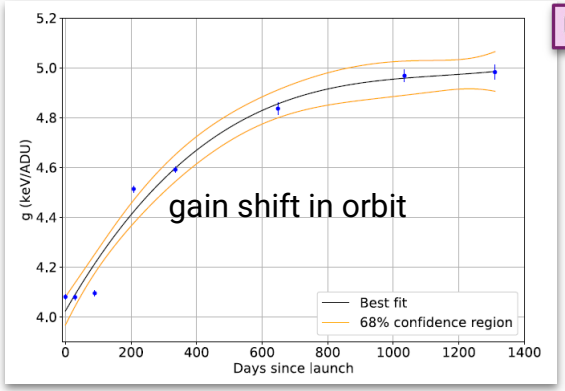
In-orbit Performance

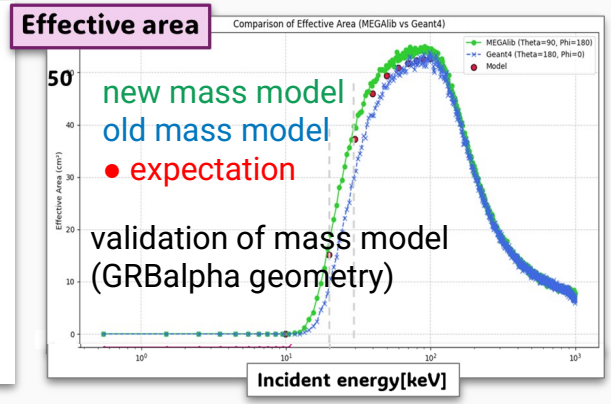
Pal+23; Ripa+22&25; Münz+24

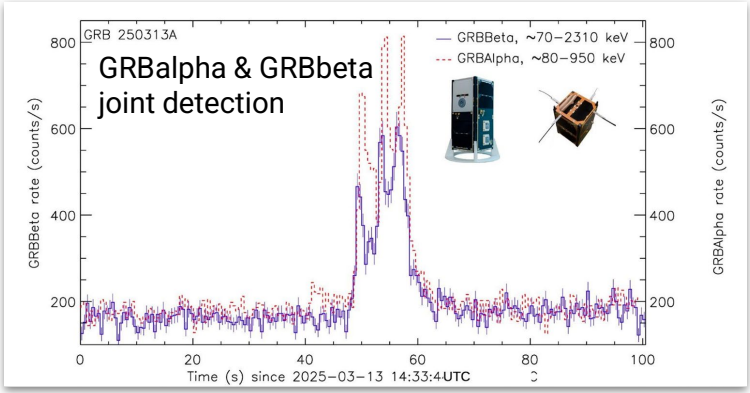
GRBalpha completed >4 yrs operation successfully

- >200 transients detection
- Characterization of MPPC degradation in LEO (Ripa+25)

Mass model and detector response of GRBalpha&VZLUSAT-2 being developed (Yokota)







Statistics of significant detection

(as of 2025.11.13)	GRBalpha	VZLUSAT-2
GRB (short)	127(23)	70(10)
Solar flare	101	74
SGR	2	3

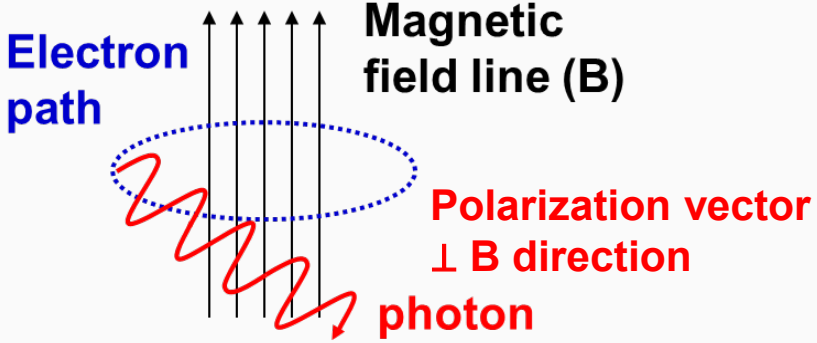
Light curves of detected events are in public (one transient per ~5 day)

GRB beta: commissioning completed

- testing UV camera (precursor for future UV obs.) and attitude control
- also confirming transient detection (12(L)+1(S) GRBs since 2025.03)

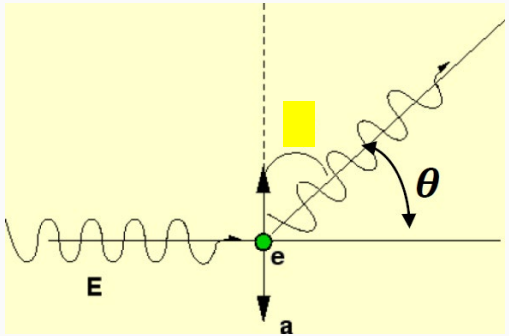
HE e- + B-field produce synchrotron radiation polarized ($\Pi_{\max} = \frac{p+1}{p+7/3} \sim 0.7$) on electron's orbital plane

- Unique probe for B-configuration (and accelerated electrons)



Scattered photos are polarized ($\Pi = \frac{1-(\cos\theta)^2}{1+(\cos\theta)^2}$) along the plane of scattering

- Unique probe for geometry of disk/corona around compact objects

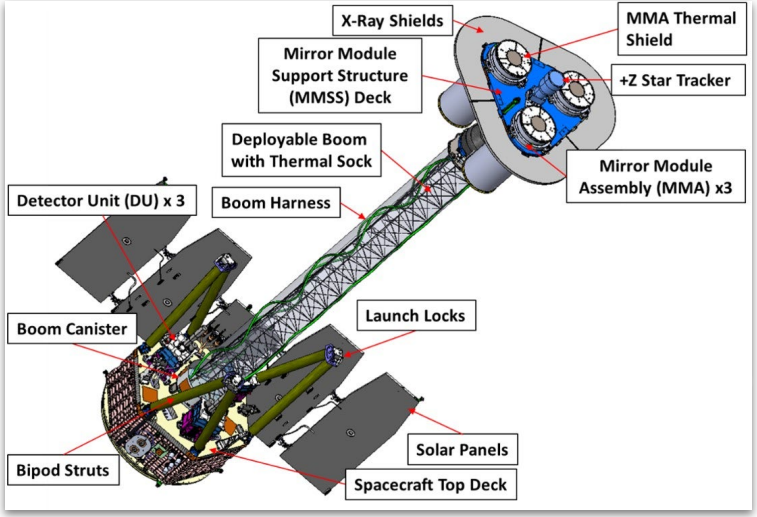


We can investigate B-field & disk/corona using X-ray polarimetry by IXPE

IXPE Mission

The first mission devoted to spatially-resolved X-ray polarimetry

- NASA SMEX mission, launched in 2021 Dec
  - Bilateral collaboration btw. NASA/MSFC & Italian Space Agency (w/ Japanese group providing key devices)
- 2 year mission (baseline) + Guest Observer Program (2024 Feb.-)
- Imaging-polarimetry in 2-8 keV for the first time
- Data are archived by NASA's HEASARC, released 1 week after the completion of the observation
- Unticipated ToO can be requested via IXPE website; latest example is that for Crab PSR after glitches (see also Goya's poster for PWN analysis)



3 x (Mirror + Gas Pixel Detector)
FOV=12.9' x 12.9', HPD=25", μ_{100}>0.5 achieved (see Weisskopf 18)

Notes on Detector Performance in Orbit

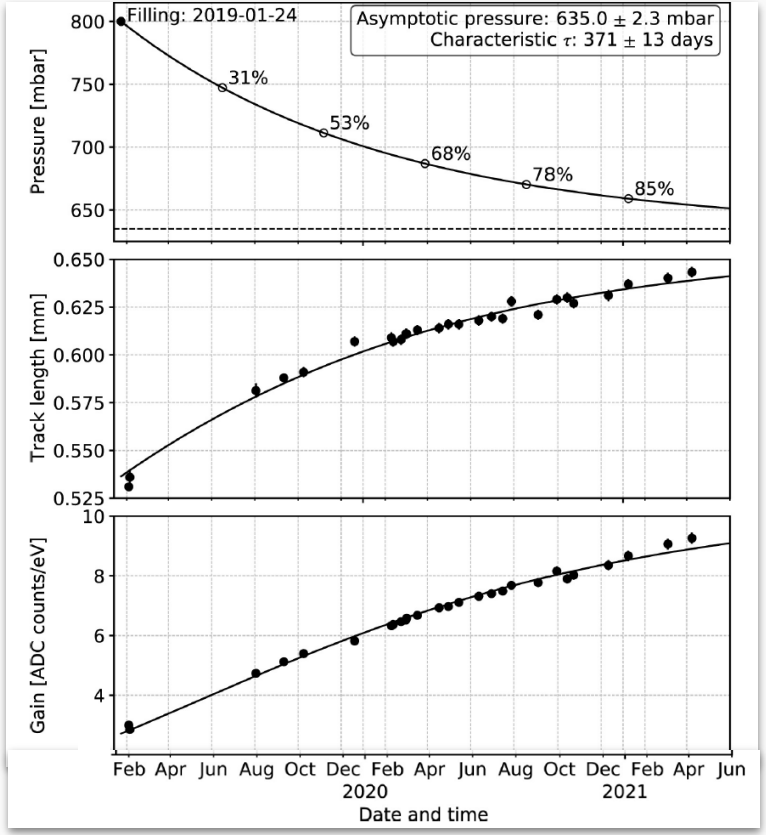
GPD pressure decrease gradually (known issue before the launch)

- will affect efficiency, track length, and gain (and instrumental response)
- We continuously monitor the efficiency and update responses

DU2 anomaly since 2025.04

- Part of readout ASIC not work
- We continuously take data, but need to re-calibrate the spurious modulation correction
- DU2 date (after 2025.05) removed temporary.

  Stay tuned



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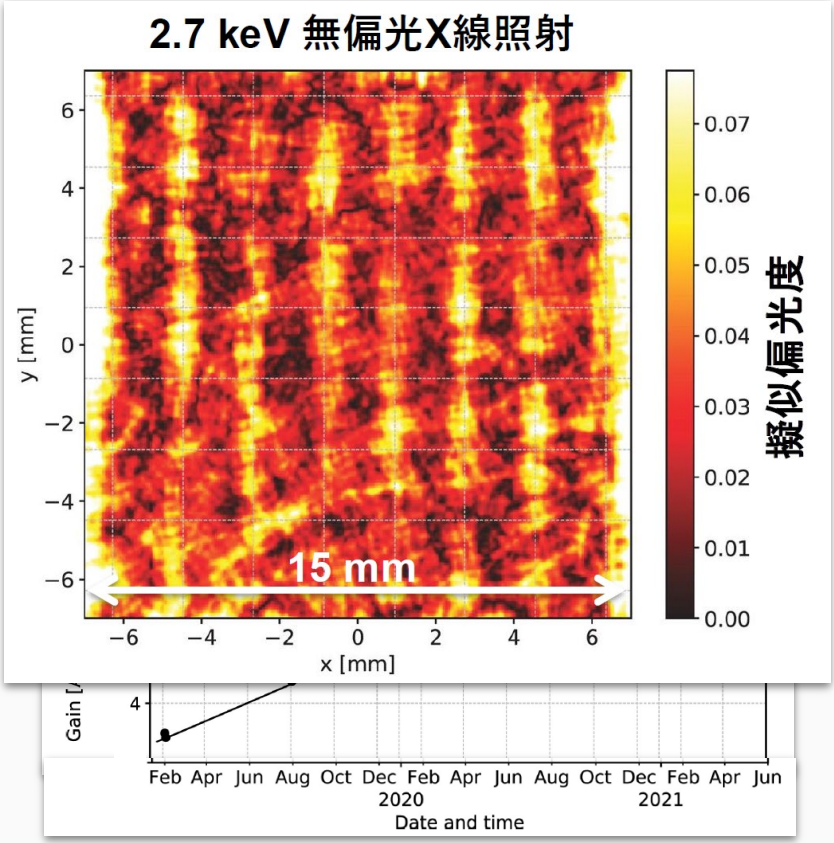
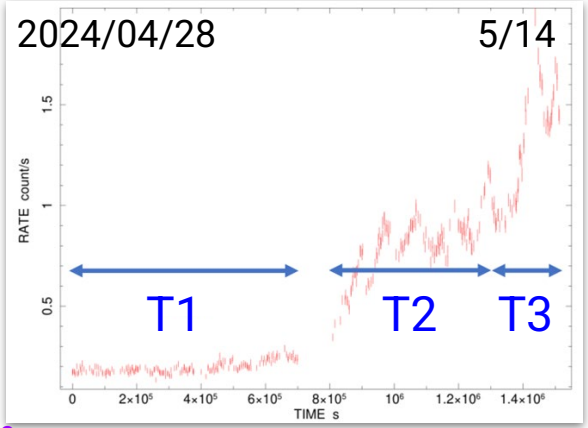


Science w/ IXPE : Multi-λ Polarimetry of Mrk 421

High-synchrotron-peaked blazar (at z=0.031)

Flux increased by x10 in 2024; Coordinated polarimetry in X-ray (IXPE) and IR&opt. (Kanata)

(Tochihara+25 @ASJ meeting)

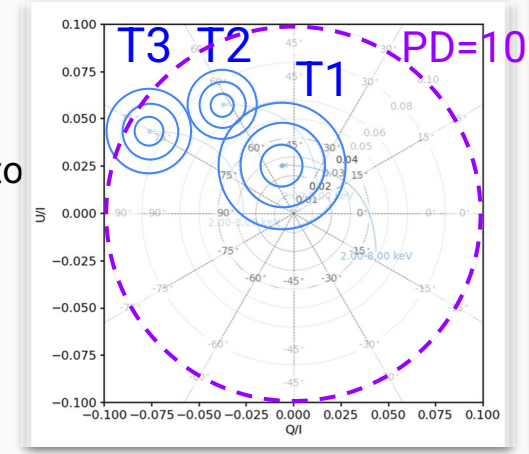


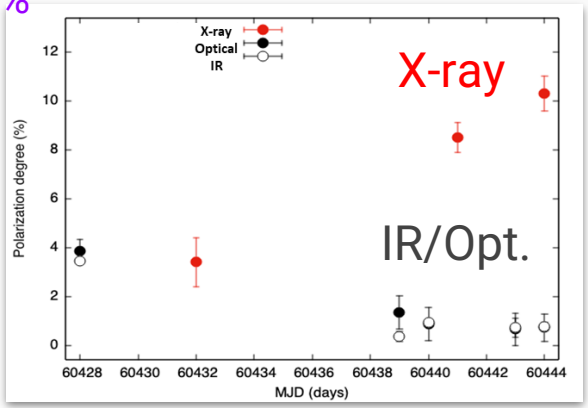
Significant change of PD_X by Q/U analysis

During the flare, only PD_X increased

(PD_{IR} & PD_{opt} stayed low and stable)

- HE particles are localized and unrelated to those producing IR/opt.
- PD_X of T1 is lowest among past observation; likely depends on the flux





Summary and Future Prospect

All-sky monitoring and X-ray polarimetry are crucial in multimessenger (and multiwavelength) astrophysics

CAMELOT mission enables all-sky monitoring in hard X-ray with good spatial resolution using fleet of nanosatellites

- Demonstration satellites; GRBalpha, VZLUSAT-2 and GRBbeta
  - GRBalpha completed operation successfully
  - One transient per ~5 day and light curves are publicly available (GRBalpha and VZLUSAT-2)
  - GRBbeta was launched last year; testing technologies and detecting transients

IXPE is the first mission devoted to spatially-resolved polarimetry in soft X-rays

- Data are made public after completion of observation, ToO also possible upon request
- GPD pressure change and DU2 anomaly (no need to worry once you understand them)
- It reveals B-configuration of AGN, PWN, etc. (also reveals disk/corona geometry)

References & Useful Links

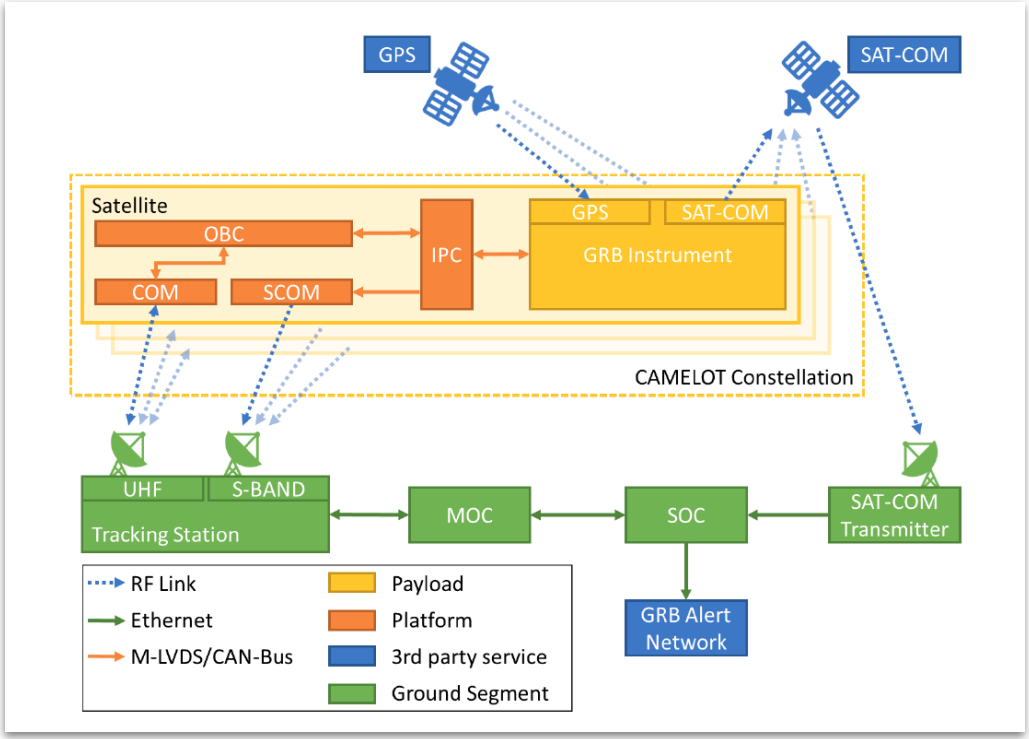
- GRBalpha transient light curves (https://monoceros.physics.muni.cz/hea/GRBAlpha/) and website (https://grbalpha.konkoly.hu/)
- VZLUSAT-2 transient light curves (https://monoceros.physics.muni.cz/hea/VZLUSAT-2/) and website (https://www.vzlusat2.cz/en/)
- GRBbeta website (https://grbbeta.tuke.sk/index.php/en/home/)
- Werner et al. 2018, Proc. SPIE 10669, 2;Ohno et al. 2020, Proc. SPIE 11454, 114541Z
- Pal et al. 2023, A&A 677, 40; Ripa et al. 2022, Proc. SPIE 12181, 121811K; Münz et al. 2024, Proc. SPIE 13093 130936J; Ripa et al. 2025, NIMA 1076, 170513

- IXPE Archive (https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/)
- IXPE technical information (https://ixpe.msfc.nasa.gov/for_scientists/index.html)
- Kislat et al. 2015, Astropart. Phys. 68, 45; Vink & Zhoug 2018, Galaxies 6, 46 (Stokes Param. analysis)
- Di Gesu et al. 2022, ApJL 938, 7; Di Gesu et al. 2023, Nature Astronomy 7, 1245; Kim et al. 2024, Maksym et al. 2025, ApJ 986, 230 (Mrk 421 results)
- Weisskopf 2018, Galaxies 6,33; Soffitta et al. 2021, AJ 162, 208; Baldini et al. 2021, Astropart. Phys. 133, 102628 (Mission & Instruments)

Backup Slide

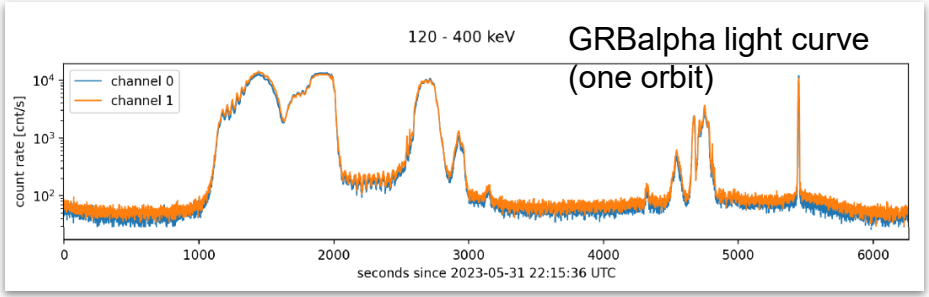
Mission Concept

Data flow for CAMELOT constellation



- Following on-board trigger, satellite payload will downlink data using global satellite communication module
- After the localization of GRB, the SOC will send GRB alert

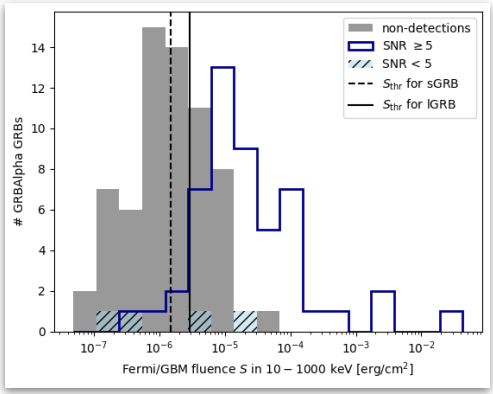
In-orbit Performance



GRBalpha light curve (one orbit)

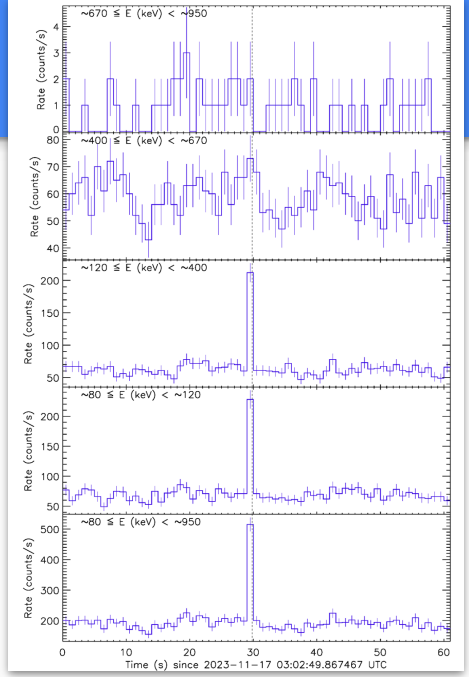
Pal+23; Ripa+22; Münz+24

~2/3 of orbit is suitable for GRB detection



~70% Fermi-GBM GRBs (with fluence of >=3x10^{-6} erg/cm2) will be detected if in FOV and low background region

M. Dafčíková (Ph.D. thesis)



Light curves of detected events are in public; <u>one transient per ~5 day</u>

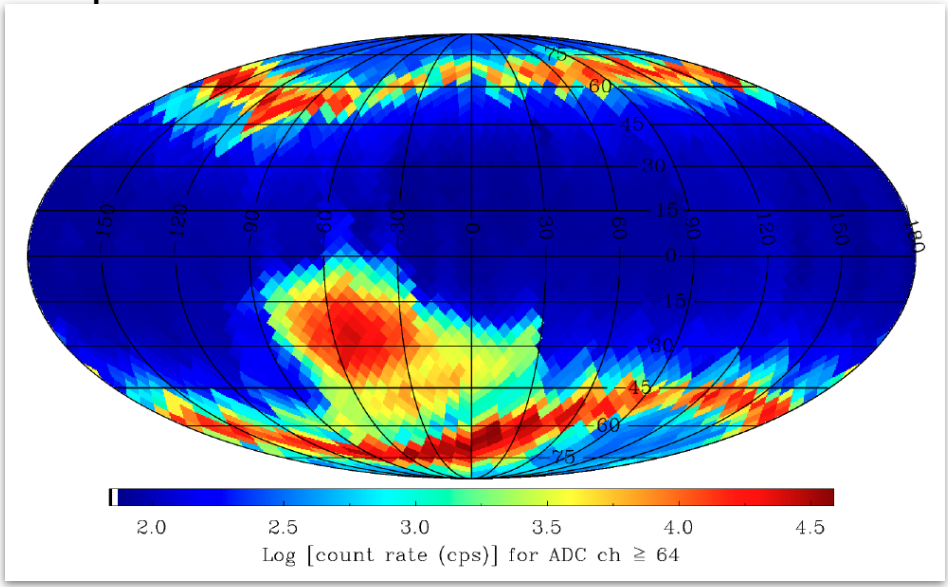
Statistics of significant detection

(as of 2024.11.11)	**GRBalpha**	**VZLUSAT-2**
GRB (short)	102(19)	57(10)
Solar flare	92	58
SGR	2	3

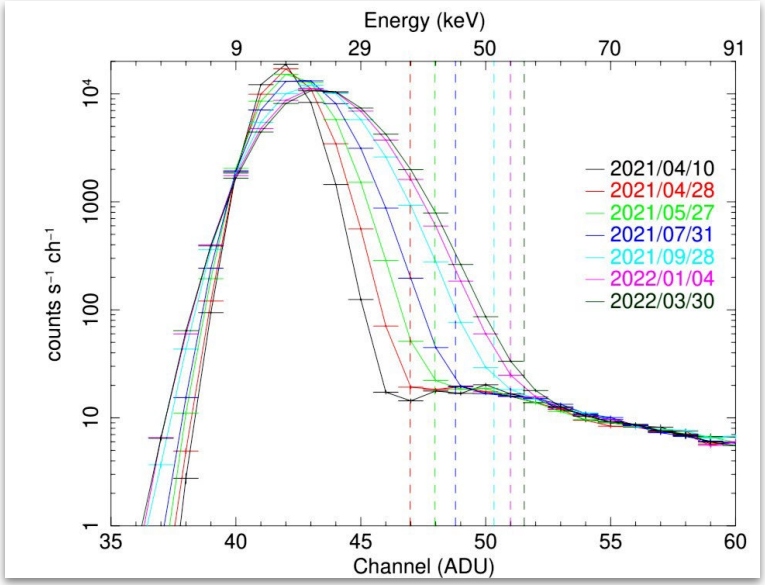
Also in progress: commissioning of GRB beta, characterizing BG
In future: implement a rate trigger algorithm for autonomous detection

Radiation Environment

GRBalpha also provides useful information about radiation environment and MPPC performance



Count rate map by GRBalpha (particle background, CXB, albedo X-ray) => rate trigger algorithm

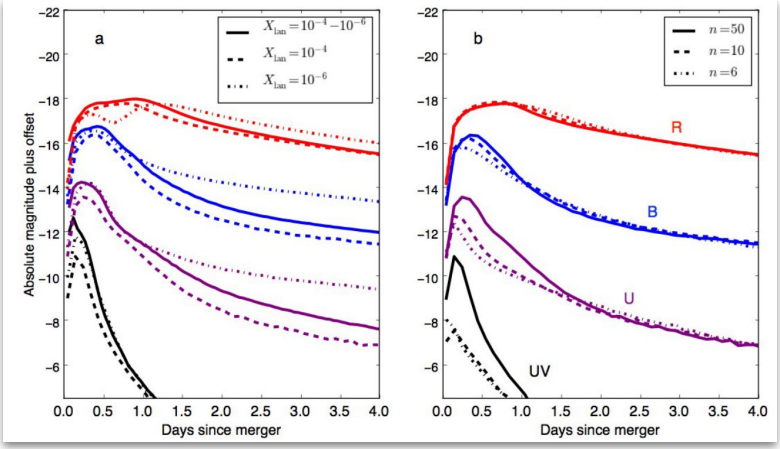


Noise spectrum as measured by GRB in one year operation (degradation of MPPC in LEO)

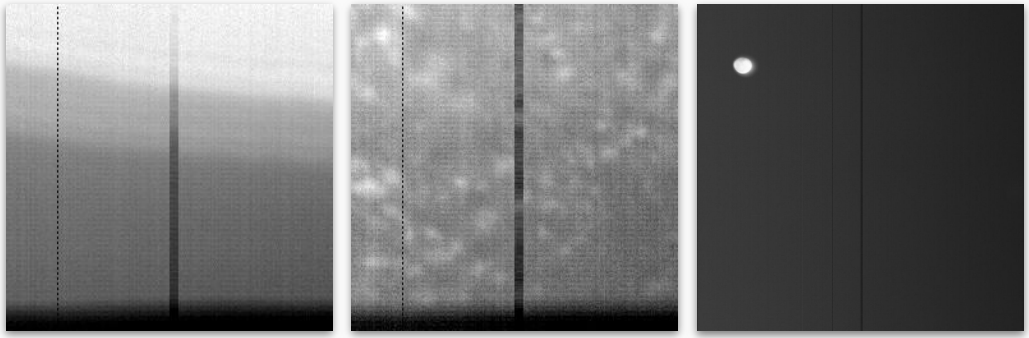
GRBbeta (2024.07-)

2U Cubesat proof-of-concept mission for a technology demonstration

- smaller effective area design to prove CAMELOT mission concept (all-sky monitoring and timing-based localization of GRB)
- experimental UV camera called LUVCam (precursor for future UV observations of kilonova),
- various platform-side features including attitude determination and control subsystem



Kasen+15 (kilonova model lightcurve)



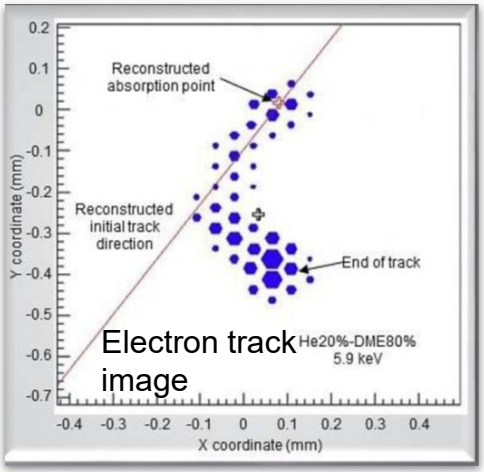
UV image of earth rim, clouds and moon

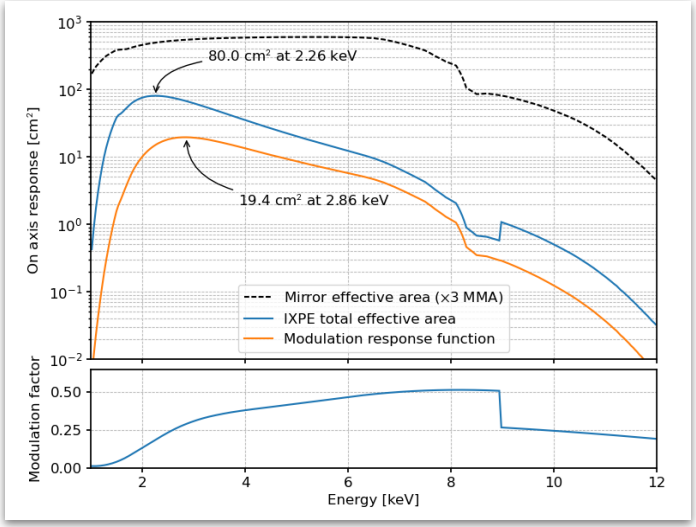
IXPE Instruments

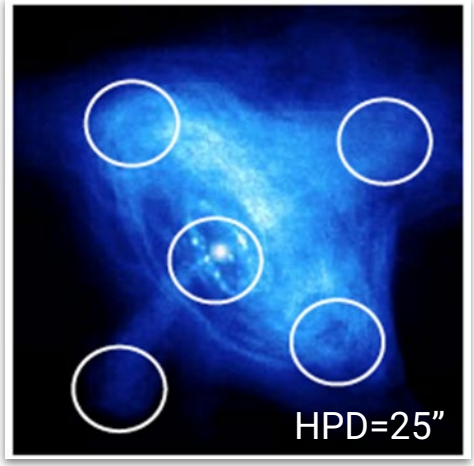
(see Soffitta+21 and Baldini+21 for latest information)

2-8 keV, 3 Mirror Module Assemblies (MMAs) and Detector Unites (DUs)

- MMAs: each contains 24 nested shells and has >200 cm^2 (3-6 keV)
- DUs: Gas pixel detector, measure photoelectron track (polarization) direction
  - FOV=12.9' x 12.9', HPD=25", m_{100}>0.5 achieved
  - Event-by-event Stokes parameter to use imaging-polarimetry capability (Kislat+15, Vink & Zhou 18)







Mission Status

Baseline mission completed successfully

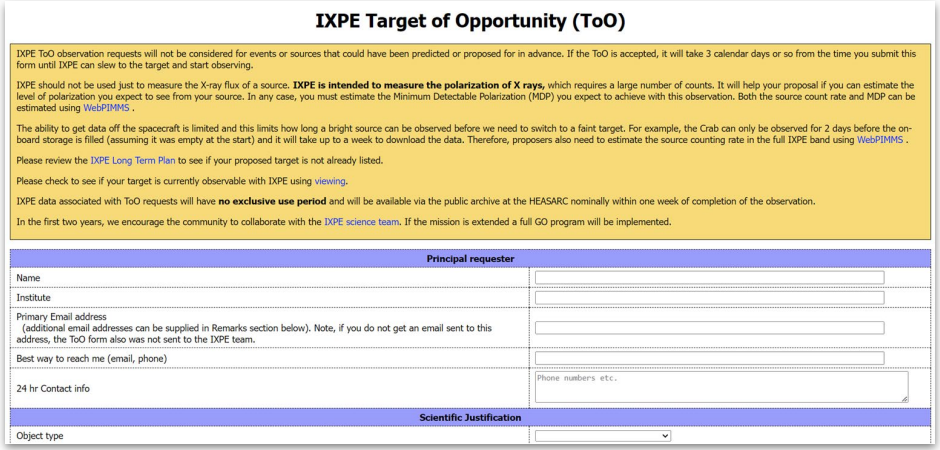
- Almost all classes of sources observed; >70 discovery papers (3 in Nature, 2 in Science)
- Data are released 1 week after completion of obs.

GO phase started in 2024/Feb, cycle2 will be 2025/Feb-Aug

- Call for proposals (incl. ToOs) just closed and being selected
- Unanticipated ToOs can be requested via the IXPE ToO website

(as of 2023.09)

Category	Average Time per Source [ks]	Sources [#]	Observations [#]
PWN	940	4	7
SNR	800	5	7
Stellar BH	670	7	15
NS LMXB	150	9	11
Accreting Pulsar	420	9	17
Magnetar	970	4	4
Blazar | Radio Gal	390	12	17
Radio Quiet AGN | Sgr A	820	5	6
GRB	100	1	1
Total	**540**	**56**	**85**



IXPE Target of Opportunity (ToO)

IXPE ToO observation requests will not be considered for events or sources that could have been predicted or proposed for in advance. If the ToO is accepted, it will take 3 calendar days or so from the time you submit this form until IXPE can slew to the target and start observing.

IXPE should not be used just to measure the X-ray flux of a source. **IXPE is intended to measure the polarization of X rays,** which requires a large number of counts. It will help your proposal if you can estimate the level of polarization you expect to see from your source. In any case, you must estimate the Minimum Detectable Polarization (MDP) you expect to achieve with this observation. Both the source count rate and MDP can be estimated using WebPIMMS .

The ability to get data off the spacecraft is limited and this limits how long a bright source can be observed before we need to switch to a faint target. For example, the Crab can only be observed for 2 days before the on-board storage is filled (assuming it was empty at the start) and it will take up to a week to download the data. Therefore, proposers also need to estimate the source counting rate in the full IXPE band using WebPIMMS .

Please review the IXPE Long Term Plan to see if your proposed target is not already listed.

Please check to see if your target is currently observable with IXPE using viewing.

IXPE data associated with ToO requests will have **no exclusive use period** and will be available via the public archive at the HEASARC nominally within one week of completion of the observation.

In the first two years, we encourage the community to collaborate with the IXPE science team. If the mission is extended a full GO program will be implemented.

Principal requester	
Name	
Institute	
Primary Email address (additional email addresses can be supplied in Remarks section below). Note, if you do not get an email sent to this address, the ToO form also was not sent to the IXPE team.	
Best way to reach me (email, phone)	
24 hr Contact info	Phone numbers etc.
Scientific Justification	
Object type	

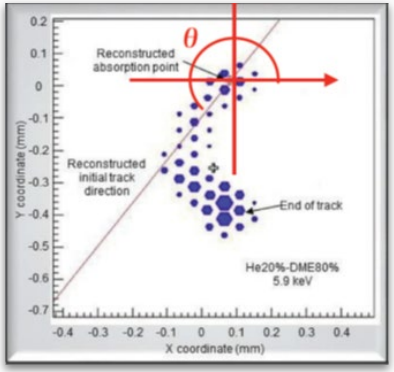
Stokes Parameter Based Analysis

Event-by-event Stokes parameters:

- $i_k=1$, $q_k=2\cos 2\theta_k$, $u_k=2\sin 2\theta_k$

Stokes parameters of the entire data:

- $I=\Sigma i_k$, $Q=\Sigma q_k$, $U=\Sigma u_k$



Normalized Stokes parameters, PD & PA:

- $Q_N=Q/I$, $U_N=U/I$, $PD=(1/m_{100})\mathrm{sqrt}(Q_N^2+U_N^2)$, $PA=(1/2)\arctan2(U, Q)$

Erros:

- $V(Q)=\Sigma q_k^2$, $V(U)=\Sigma u_k^2$

Aeff, m_{100} , and reconstruction quality of each event can also be taken into account

(unlike PD/PA, Stokes params. are additive and allow flexible binning in space and time)

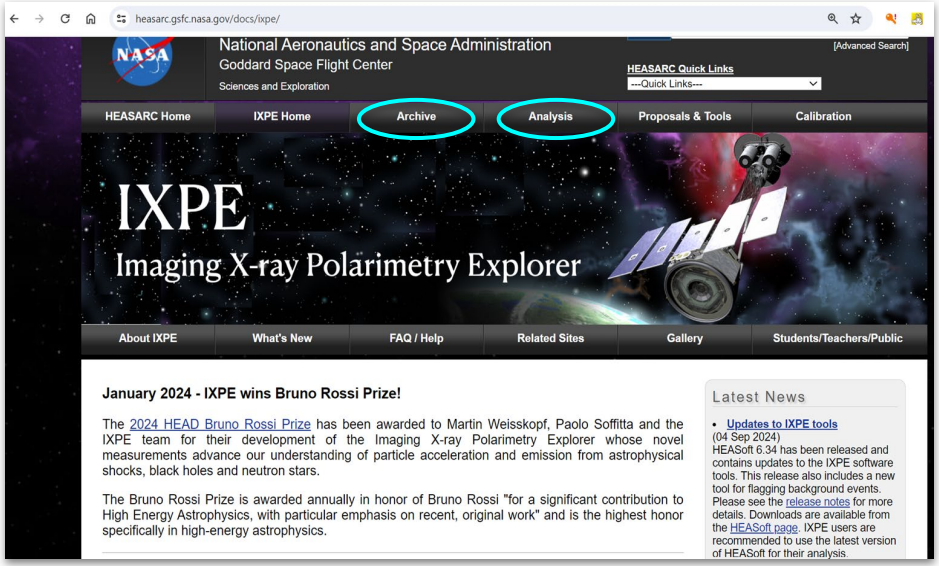
For “Do It Yourself” Persons

IXPE Data archived by NASA’s HEASARC

Data format and HEASOFT analysis tool well documented

Alternative package (ixpeobssim) also available (link under GOF “Contributed IXPE Software” page

Much of analysis can be done in Xspec

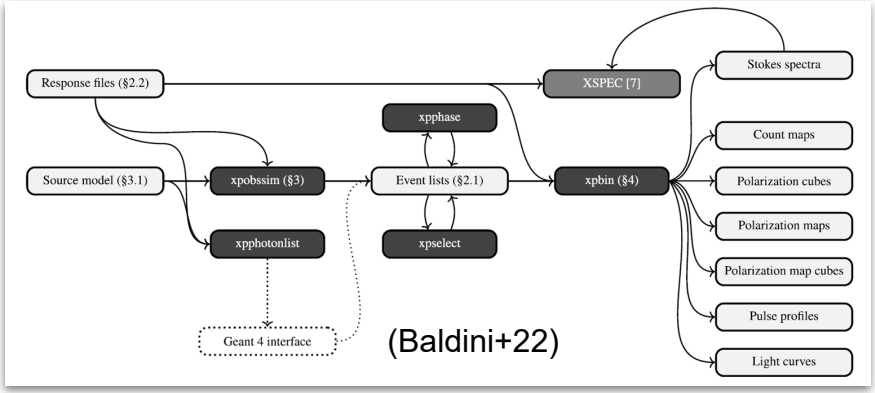


For “Do It Yourself” Persons (Cont’d)

You may use xselect to read/filter events and extract spectrum

```
xsel> read event "./ixpe01004701_det1_evt2_v01.fits.gz"
xsel> filter region "src.reg"
xsel> extract SPEC stokes=NEFF
xsel> save spec ixpe_det1_src_
```

Or, use ixpeobssim to read/select events and bin spectrum



(Baldini+22)

xpselect --regfile src.reg --sufix sel ixpe01004701_det1_evt2_v01.fits

xpbin --algorithm PHA1Q --irfname ixpe:obssim:alpha075_v012 --weights True ixpe01004701_det1_evt2_v01_sel.fits

You will have 3 outputs: Stokes-I/Q/U spectra

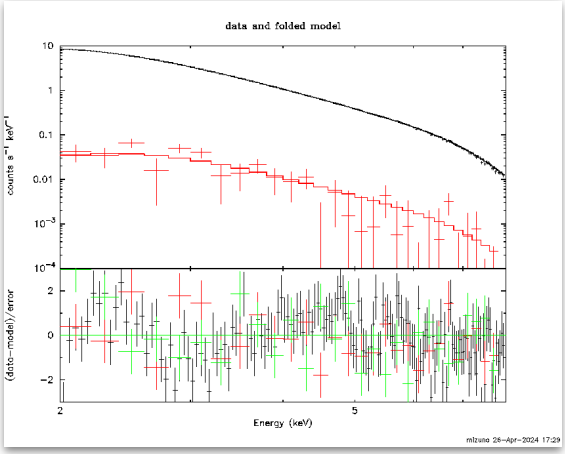
For “Do It Yourself” Persons (Cont’d)

3 responses (not 2) required for each detector: rmf, arf, and mrf

- mrf = arf*μ_{100}
- use ixpecalcarf to generate arf/mrf

```
> ixpecalcarf \
evtfile=ixpe01004701_det1_evt2_v01.fits.gz \
attfile=ixpe01004701_det1_att_v01.fits.gz \
arfout=ixpe_det1_src_Q.mrf \
specfile=none radius=1.0   weight=1   resptype=mrf
```

mrf shall be read instead of arf for Stokes-Q or U spectra. Then you may fit 3 spectra simultaneously with, e.g., TBabs*polconst*powerlaw



Stokes-I (black)
Stokes-Q (red)
Stokes-U (green; negative and not shown in upper panel)

(Ixpeobssim may be more user-friendly for imaging-polarimetry analysis [like Vela PWN])

Note On Statistics

Since PD shall be >=0, PD-PA contour will be skewed when the significance is not so high (σ<=3)

If so, examine Stokes-Q/U plane instead of PD/PA（w/ ixpeobssim）; error contours are circular and you can adequately evaluate significance and errors

- PD=sqrt(Q_N^2+U_N^2), PA=(1/2) arctan2(U, Q)

Use ixpeobssim and Stokes-Q/U for imaging-polarimetry analysis

- See Kislat+15 and Vink&Zhou18 for the formalism (Mizuno+23 may also be useful)