CAMELOT and IXPE: All-Sky Monitoring and Polarimetry for Multimessenger Astrophysics (2)

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on behalf of the CAMELOT and IXPE team

2024 Nov. 18, Annual Conference on Multi Messenger Astrophysics @ Gunma

Introduction: Role of X-ray Missions in MM Astrophys.

3

役割 / 実績 / アーカイブ / 新着

Z120r

X線のミッションが果たす役割は

広視野型 (Wide FOV)

- 重力波/ニュートリノと電磁波をつなぐ
  - 広視野の観測ができるので重力波/ニュートリノと同時観測ができる
  - (重力波よりは)精度良い位置情報を提供でき、その後の追跡観測につながる
  - 背景天体が比較的少なく、新天体をみつけやすい

Simultaneous obs. with GW/neutrino events

(Follow-up) 詳細観測型

- 追跡観測で放射源の詳細にせまる
  - イメージ、光度曲線、スペクトルが同時にとれる
  - 高い時間分解能力、高いエネルギー分解能、偏光など、特徴的な性能を持つ装置(衛星)がある

Imaging, photometry (light curve), spectroscopy, and polarimetry

CAMELOT and **IXPE**

(Adopted from M. Serino's slides at ASJ meeting, 2023.09)

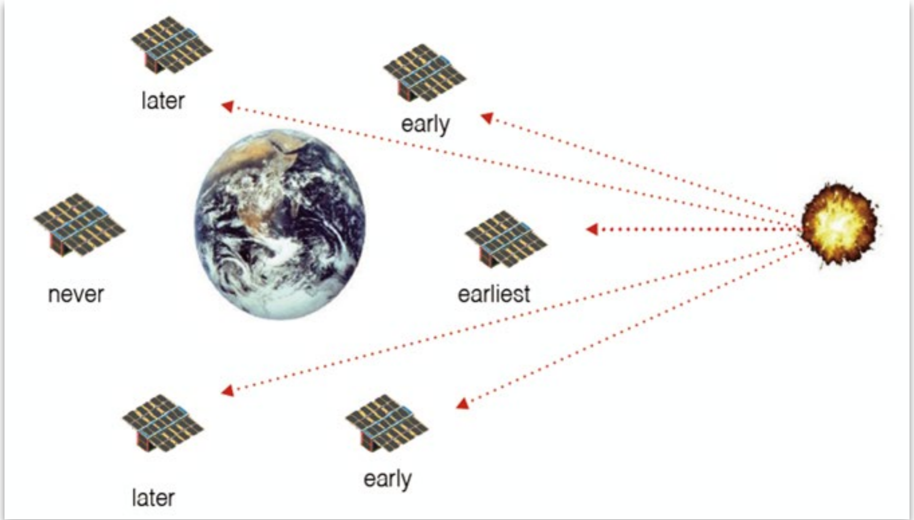
日本天文学会 2023年秋季年会@名古屋大学

2023/9/21

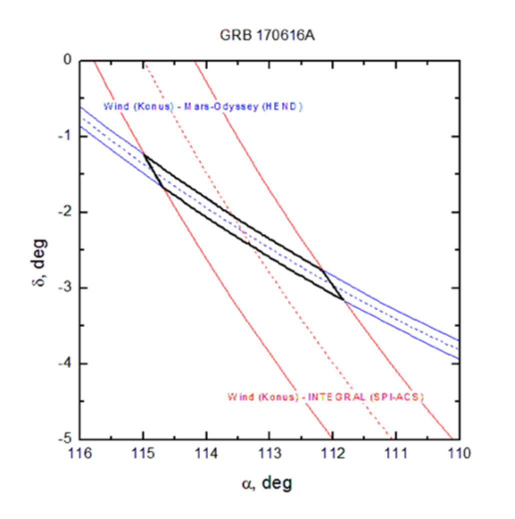
All-Sky Monitoring with a Fleet of Nano Sat.

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)



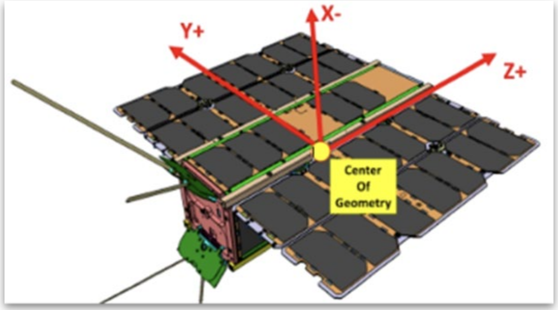
~10 nano satellites allow all-sky monitoring in hard X-ray and gamma rays

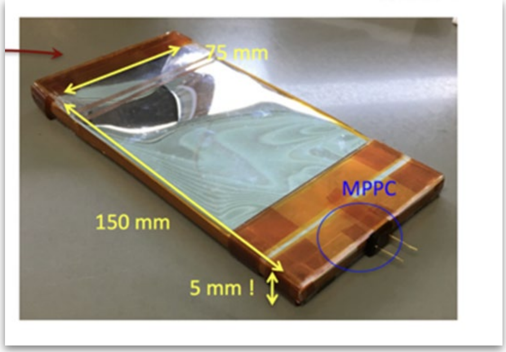


Timing-based localization; triangulation principle with different arrival time (<=0.1 ms) enables sub-degree localization

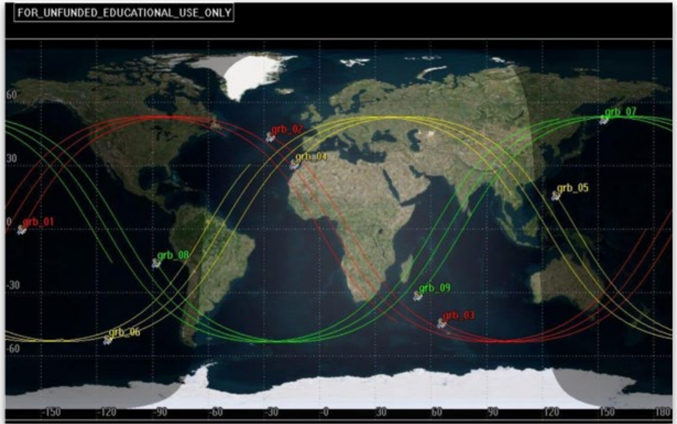
CAMELOT Mission

Hungarian-Japanese-Czech-Slovak project using <u>standardized nanosatellites</u>





Werner+18
Ohno+20



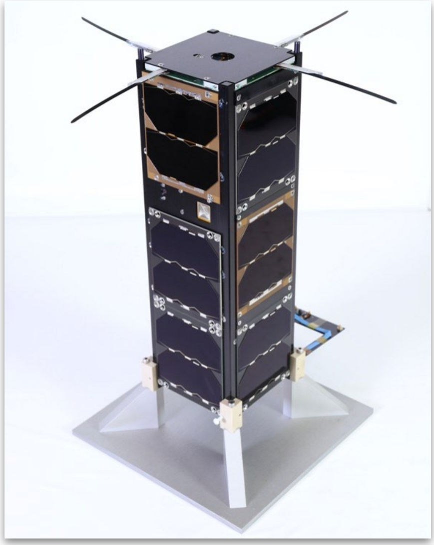
Satellite platform	3-U cubesat platform
Target orbit	>=9 satellites constellation in LEO with various orbital configuration
Payload	150x75x5 mm^3 CsI readout by multi-channel MPPCs
Goal	Degree-scale timing-based localisation with a similar sensitivity to the Fermi-GBM

Mission Status

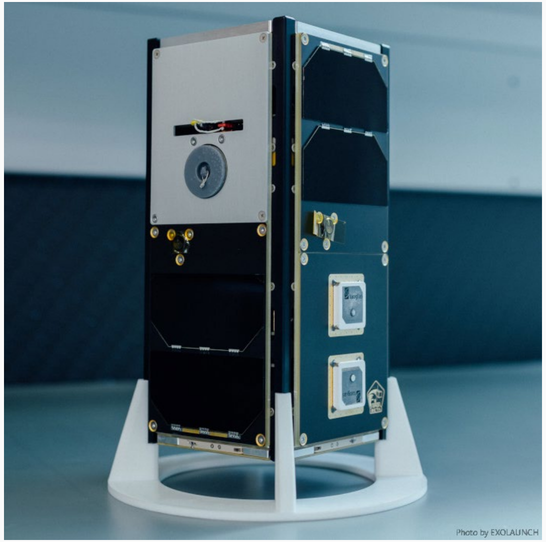
Pal+23; Ripa+22; Münz+24

3 demonstration satellites in operation

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

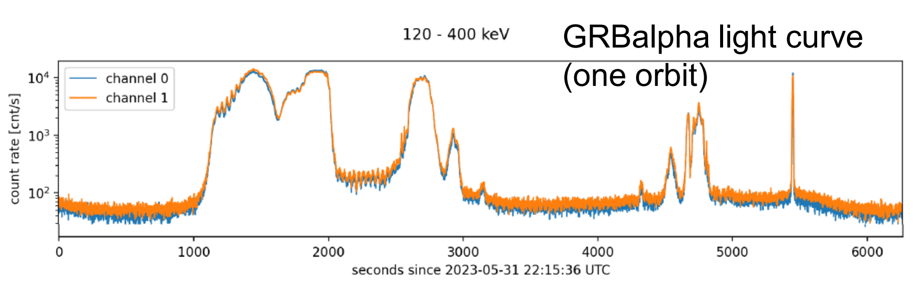


VZLUSAT-2 (2022.01-); 2 prototype detectors as 2ndary payloads (https://www.vzlusat2.cz/en/)
・allows simultaneous GRB detection using nanosatellites



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

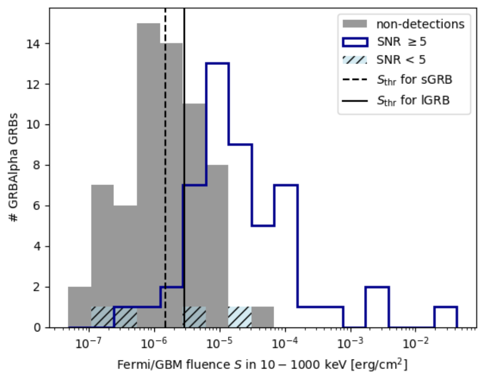
In-orbit Performance



GRBalpha light curve (one orbit)

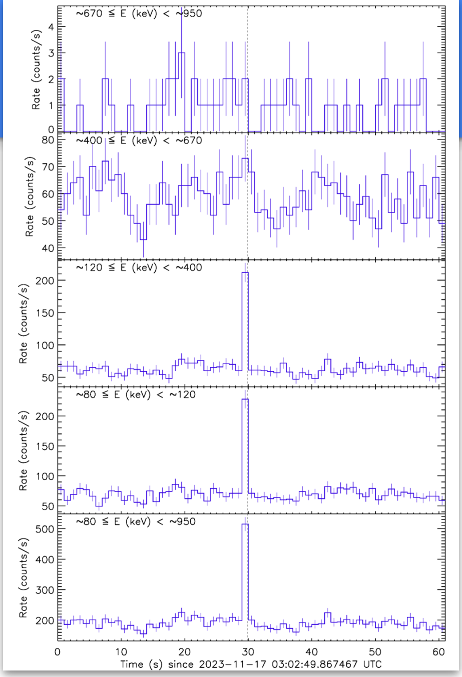
Pal+23; Ripa+22; Münz+24

~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

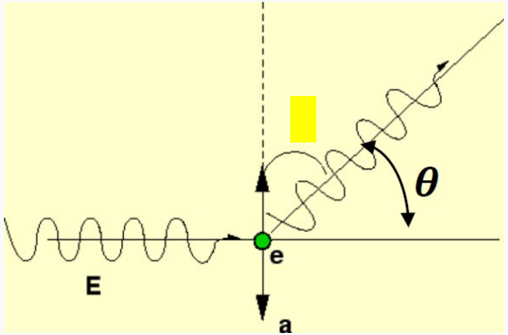
X-ray Polarimetry for Probing Disk/Corona

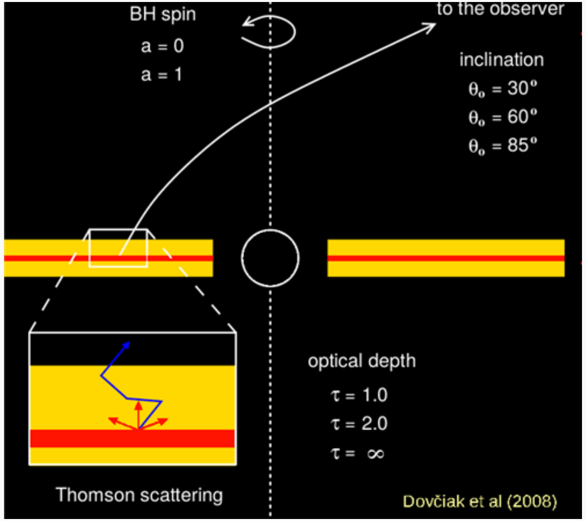
Scattered photons are polarized
($\Pi = \frac{1-(\cos\theta)^2}{1+(\cos\theta)^2}$)

Unique probe for geometry of compact objects (accretion disk and corona not accessible by imaging)

Also probes relativistic effects (light bending) around a black hole (BH)

We can investigate <u>disk, corona and space-time geometry</u> close to BH using <u>X-ray polarimetry</u> by **IXPE**



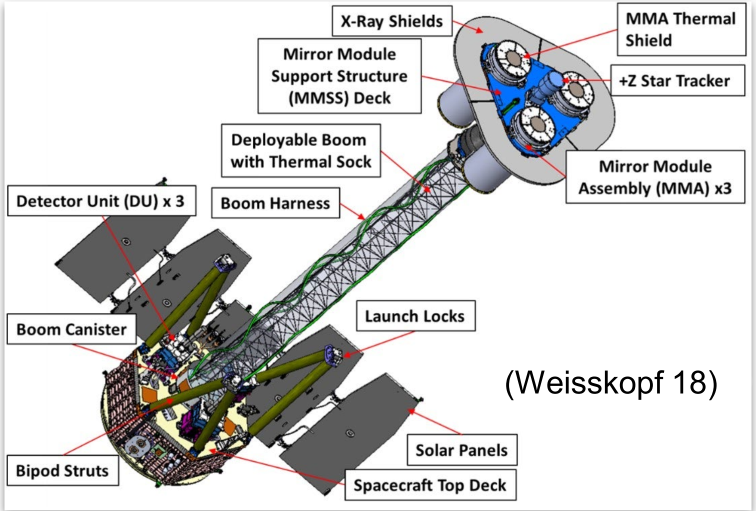


IXPE Mission+Instruments

(see Weisskopf 18 for details)

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

- NASA SMEX mission, launched in 2021 Dec
    - Bilateral collaboration between NASA/MSFC and Italian Space Agency (w/ Japanese group providing key devices)
- 2 year mission (baseline) +1.5 year extension (Guest Observer Program; 2024 Feb.-) Unanticipated ToOs can be requested via the IXPE ToO website
- 3 sets of (mirror + detector) enable 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

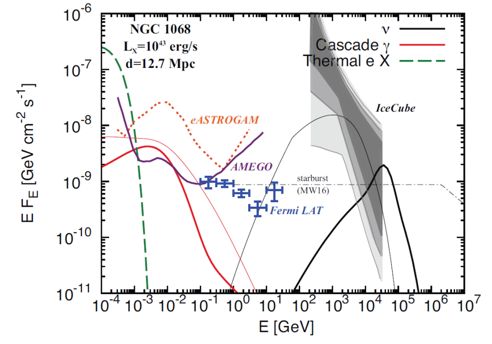


(Weisskopf 18)

- Equatorial orbit (600-km altitude)
- 100 times more efficient (less exposure required) than OSO-8 (Weisskopf+78)

Science w/ IXPE : Geometry of Seyferts

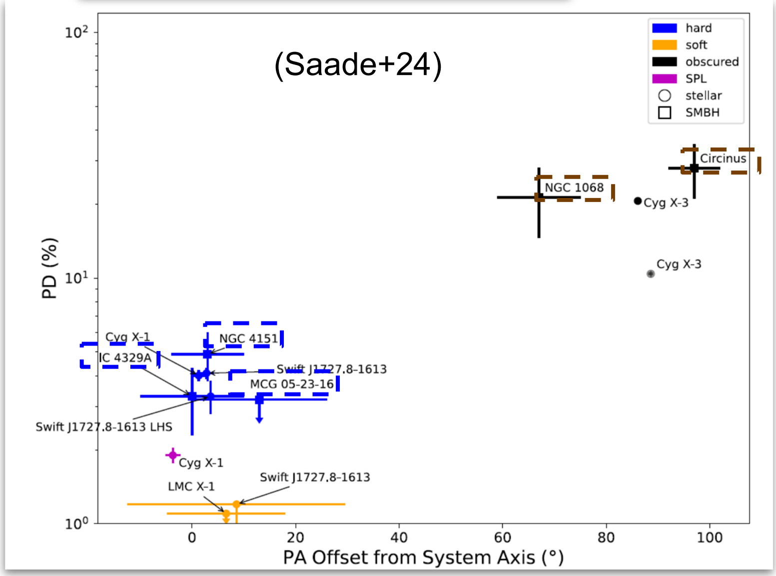
IceCube detected high-energy neutrinos from Seyfert galaxy NGC 1068 (IceCube collab. 2022). GeV gamma-ray flux is much smaller, indicating that Seyferts accelerate CR protons in areas opaque for gamma-rays, likely hot corona



(Murase, Kimura+20)

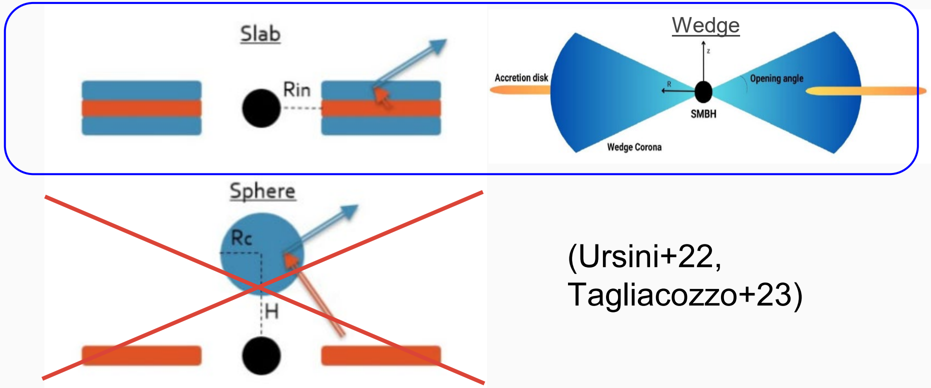
IXPE observed 5 Seyferts to constrain source geometry

- Two **obscured Seyferts** have large PD and PA perpendicular to system axis, very likely due to scattering by torus surrounding SMBH/corona
- Three **unobscured Seyferts** have moderate PD and PA parallel to system axis, allowing us investigating corona's geometry of Seyferts

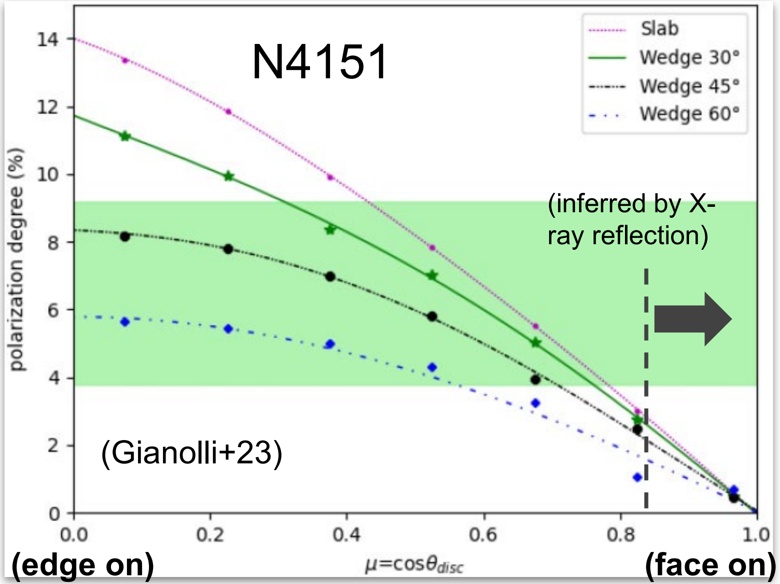


Popular "lamp post" model predicts PA perpendicular to system axis (PA shall be parallel to disk for X-rays to reach observer) and is ruled out. Slab and Wedge geometries are possible in terms of PA

Although inclination is uncertain (Marin 2016), rather flat geometry is preferred by observed PD



(Ursini+22, Tagliacozzo+23)



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) in operation
  - One transient per ~5 day and light curves are publicly available (GRBalpha and VZLUSAT-2)
  - GRBbeta was launched and is under commissioning

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

- It revealed common trends for Seyferts, preferring rather flat geometry of corona
- Data are made public after completion of observation, ToO also possible upon request

Thank you for your attention

References & Useful Links

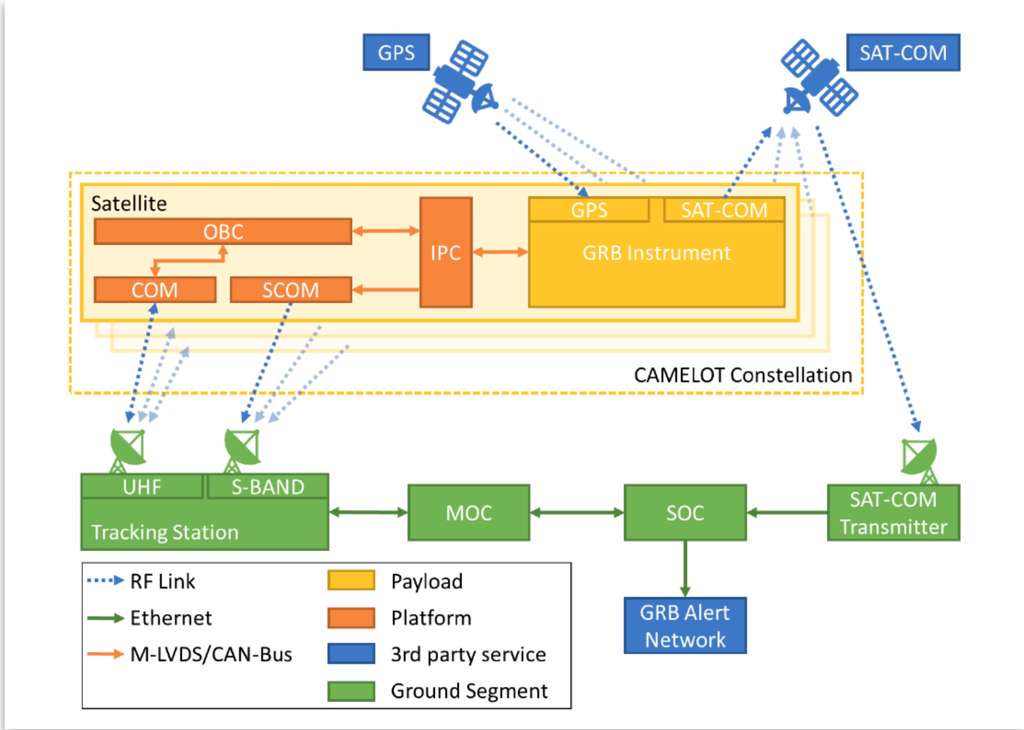
- GRBalpha transient light curves (https://monoceros.physics.muni.cz/hea/GRBAlpha/) and website (https://grbalpha.konkoly.hu/)
- VZLUSAT-2 transient light curves (https://monoceros.physics.muni.cz/hea/VZLUSAT-2/) and website (https://www.vzlusat2.cz/en/)
- Werner et al. 2018, Proc. SPIE 10669, 2;Ohno 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

- 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, Astroparticle Physics 68, 45; Vink & Zhoug 2018, Galaxies 6, 46
- IceCube collaboration 2022, Science 378, 538; Murase et al. 2020, PRL 125, 011101; Saade et al. 2024, ApJ 974, 101
- Ursini et al. 2022, MNRAS 510, 3676; Tagliacozzo et al. 2023, MNRAS 525, 4735; Gianolli et al. 2023, MNRAS 523, 4468, Marin 2016, MNRAS 460, 3679
- Weisskopf 2018, Galaxies 6,33; Soffitta et al. 2021, AJ 162, 208; Baldini et al. 2021, Astropart. Phys. 133, 102628

Backup Slide

Mission Concept

Data flow for CAMELOT constellation



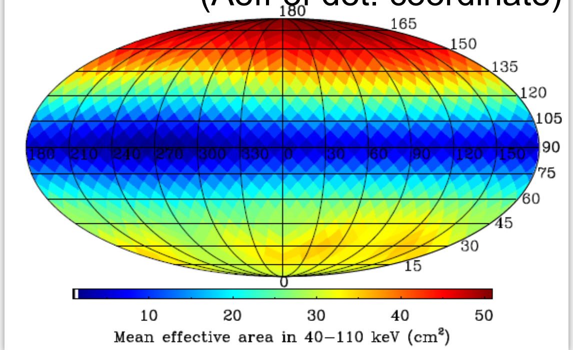
- Following on-board trigger, satellite payload will downlink data using global satellite communication module
- After the localization of GRB, the SOC will send GRB alert

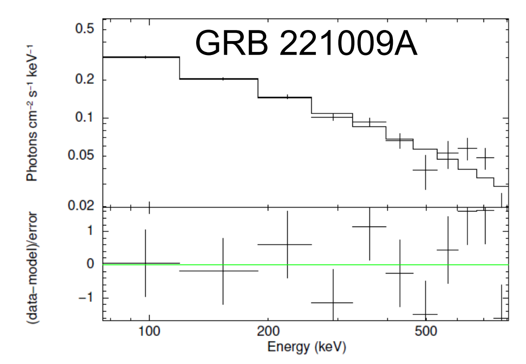
Mission Status (2)

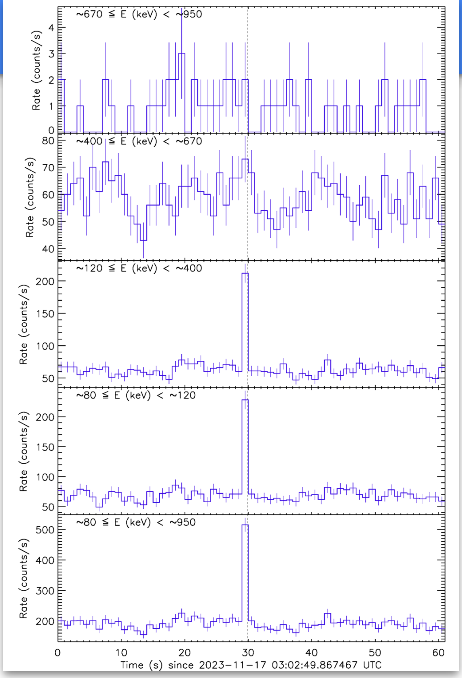
2 demonstration satellites in operation

Pal+23
Ripa+22,23

(Aeff of det. coordinate)







Almost transparent to hard X-rays; ~2/3 of orbit is suitable for GRB detection

Peak flux was measured without strong saturation

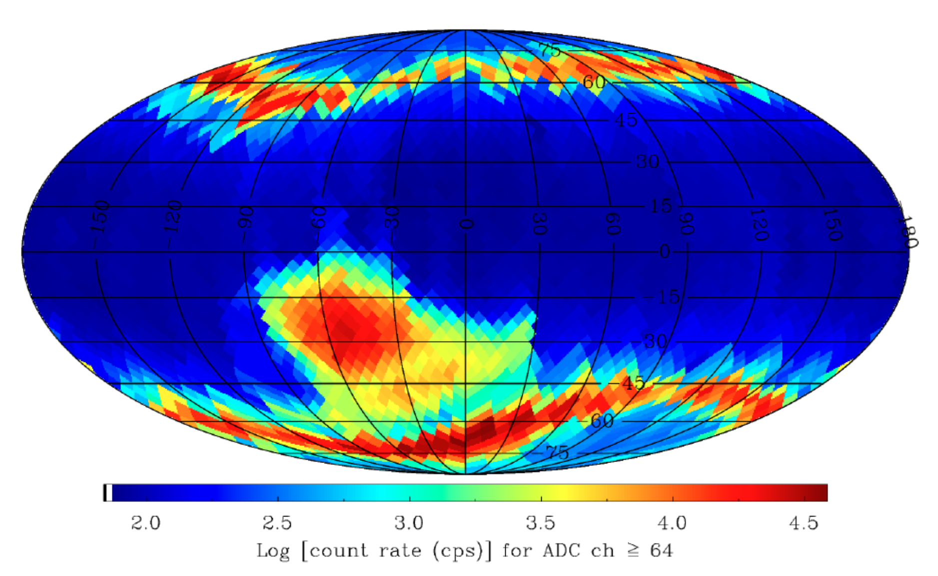
Light curves of detected events are in public; one transient per ~5 day

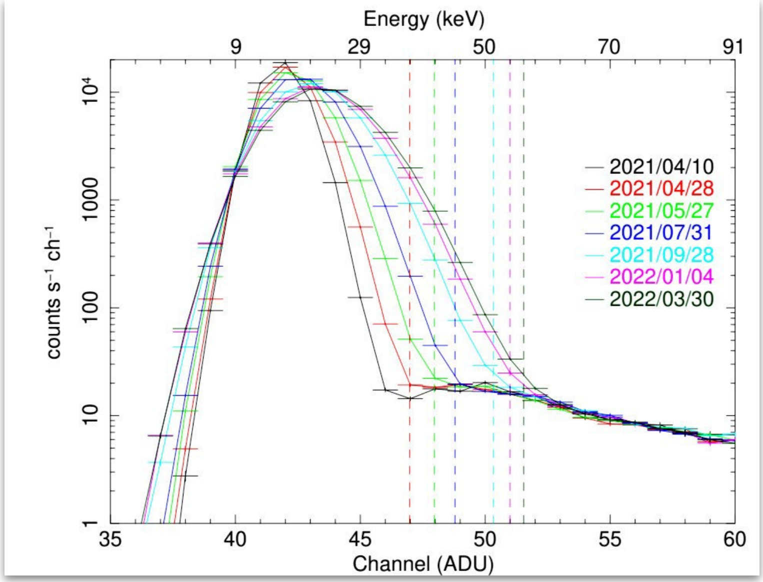
(as of 2023.11.20)	**GRBalpha**	**VZLUSAT-2**
GRB (short)	49(9)	31(3)
Solar flare	23	21
SGR	2	5

GRBbeta (2024-); 2U-sized next technological precursor

・improved onboard software, inter-sat. communication, attitude determination

GRBalpha also provides useful information about radiation environment and MPPC performance





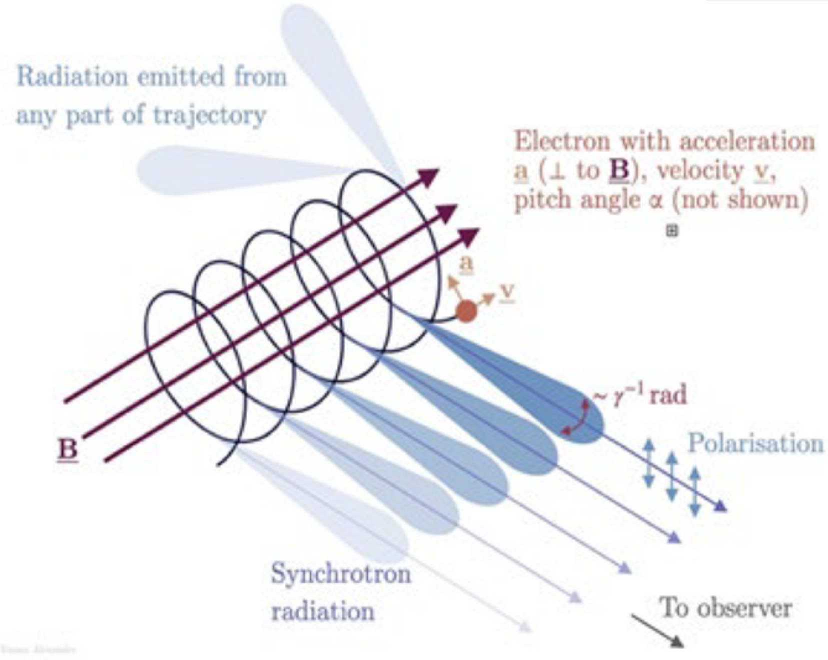
Count rate map by GRBalpha (particle background, CXB, albedo X-ray) => rate trigger algorithm

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

X-ray Polarization to Probe Geometry

Polarization is a vector → measures geometry
Electric vector position angle = EVPA

- Synchrotron radiation →
  EVPA perpendicular to magnetic field lines
- Scattering/reflection →
  EVPA perpendicular to scattering plane
- Strong magnetic fields →
  Opacity different parallel vs perpendicular to B
  EVPA transported along B in strong B
- Strong gravitational fields →
  EVPA parallel-transported along space-time geodesics



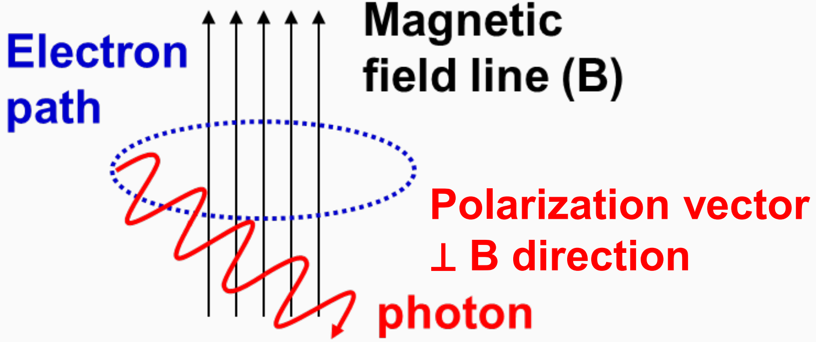
(Slide by P. Kaaret)

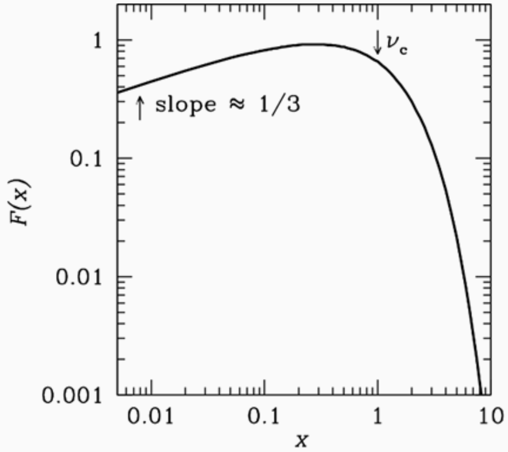
Electrons + magnetic field produce synchrotron radiation

Unique probe for B (and accelerated electrons)

High polarization degree is expected ($\Pi_{\rm max} = \frac{p+1}{p+7/3} \sim 0.7$)

<u>X-ray polarimetry (by IXPE)</u> can probe B-field configuration around freshly-accelerated electrons ($h\omega_{\rm p} \sim 0.29 \frac{3\gamma^2 eB}{2m_{\rm e}c}$)



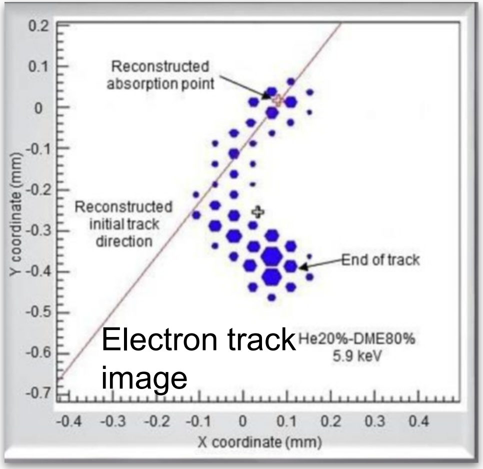


IXPE Instruments

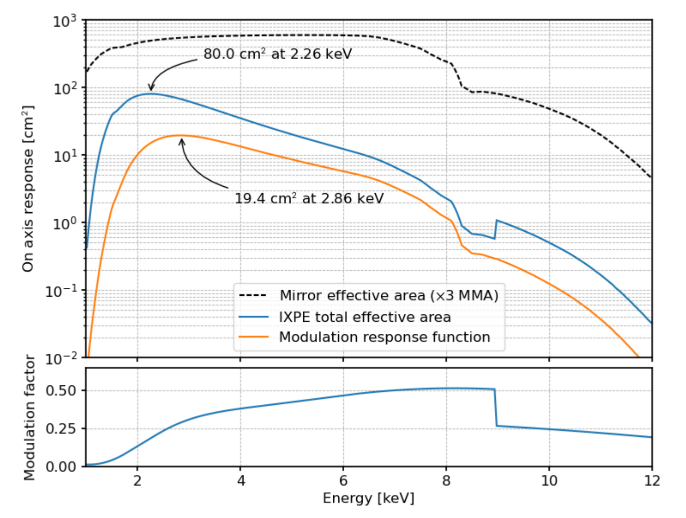
(see Soffitta+21 and Baldini+21 for latest information)

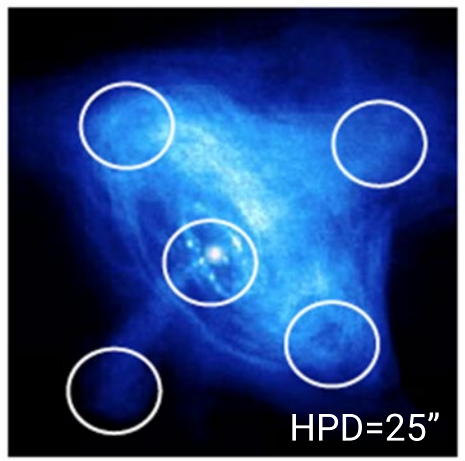
2-8 keV, 3 Mirror Module Assemblies (MMAs) and Detector Unites (DUs)

- 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)



Electron track image





HPD=25"

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.

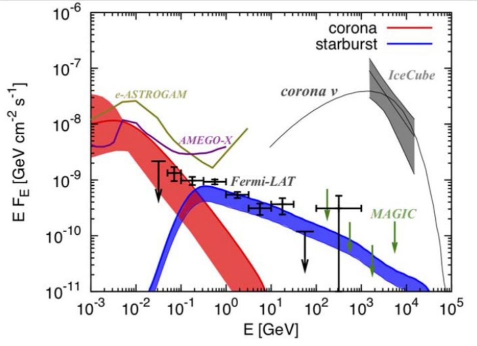
IXPE data associated with ToO requests will have **no exclusive use period** and will be available via the public archive at the HEASARC nominally within one week of completion of the observation.

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	

Science w/ IXPE : Geometry of Seyferts

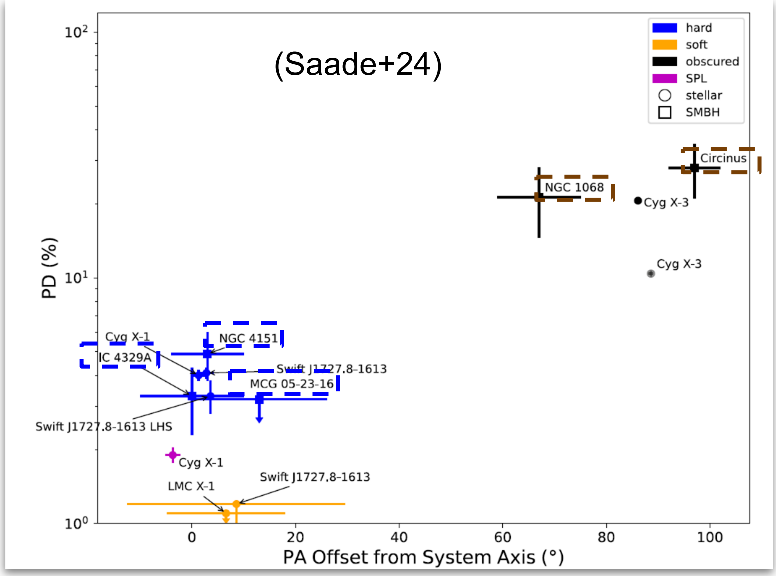
IceCube detected high-energy neutrinos from Seyfert galaxy NGC 1068 (IceCube collab. 2022). Neutrino flux is much larger than that in GeV/TeV gamma-rays, indicating that Seyferts accelerate CR protons in areas opaque for gamma-rays, likely hot corona



(Ajello+23)

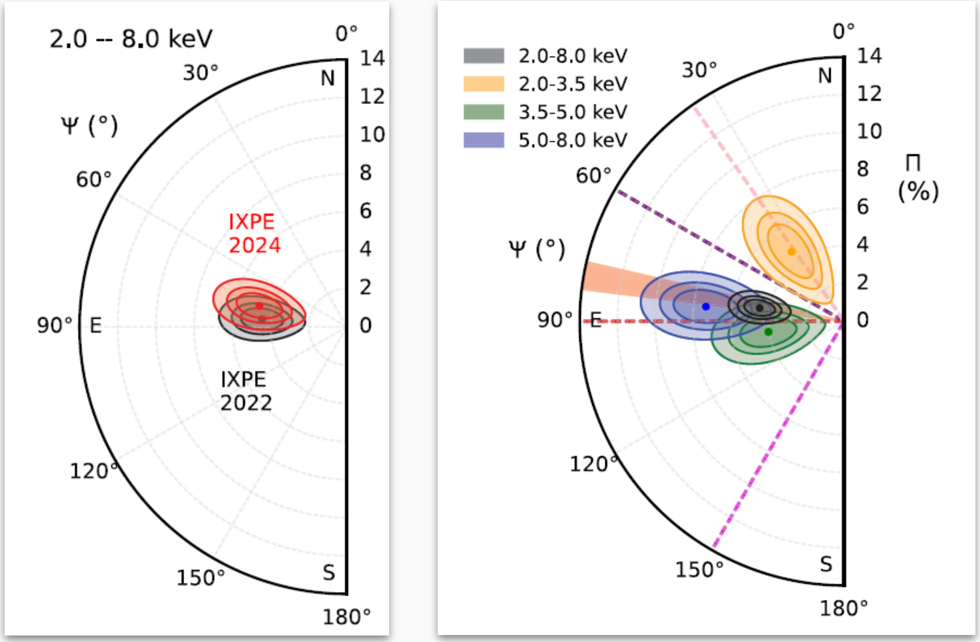
IXPE observed 5 Seyferts to constrain source geometry

- Two **obscured Seyferts** have large PD and PA perpendicular to system axis, very likely due to scattering by torus surrounding SMBH/corona
- Three **unobscured Seyferts** have small PD and PA parallel to system axis, allowing us investigating corona's geometry of Seyferts



Energy-Dependent Polarization

By adding 2022 and 2024 data, IXPE revealed energy dependent polarization from NGC 4151



(Gianolli+23, 24)

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:

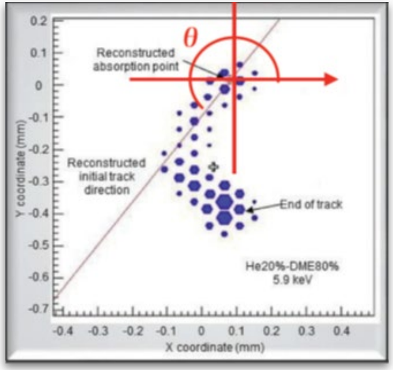
- $I=\Sigma i_k$, $Q=\Sigma q_k$, $U=\Sigma u_k$

Normalized Stokes parameters, PD & PA:

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

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)

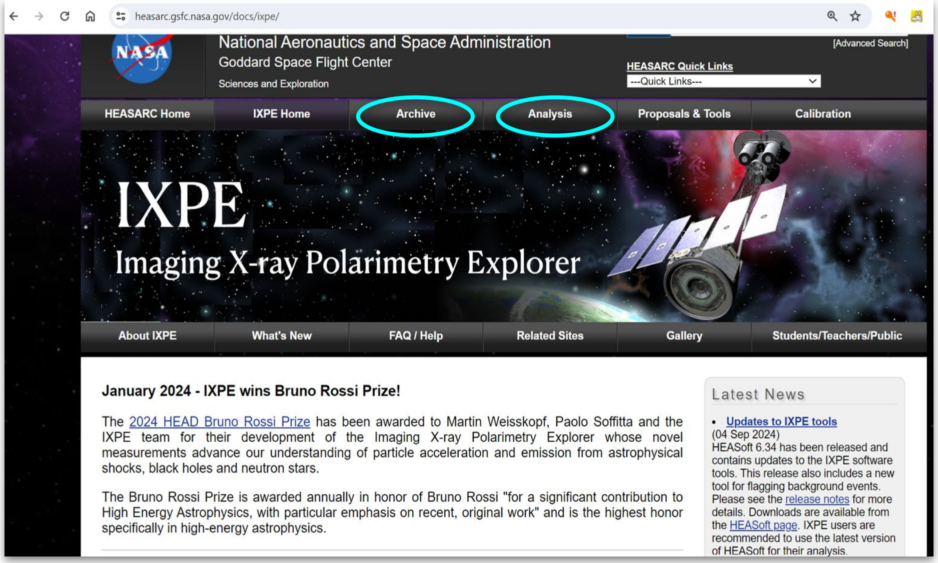
For “Do It Yourself” Persons

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

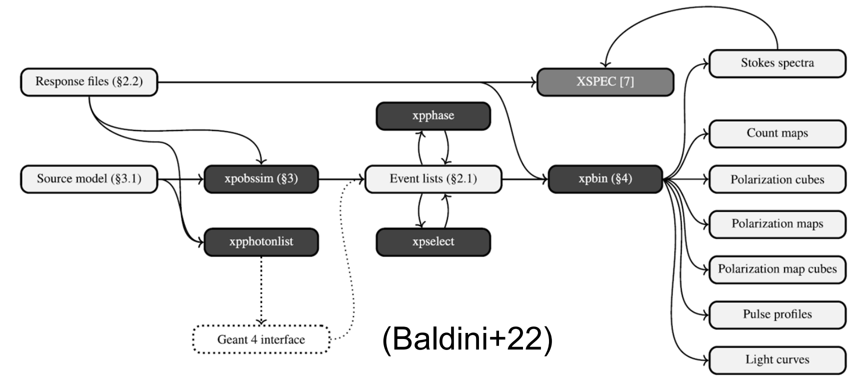


For "Do It Yourself" Persons (Cont'd)

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

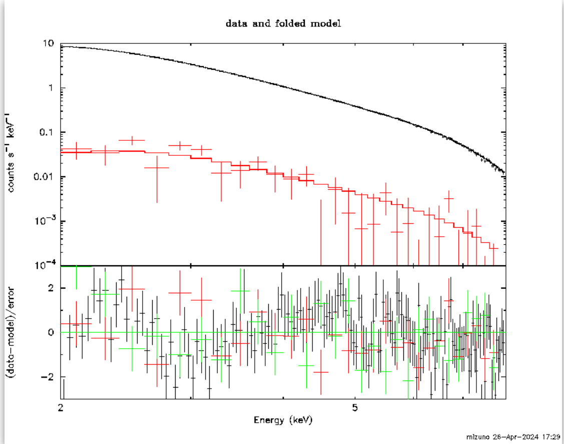
For “Do It Yourself” Persons (Cont’d)

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)