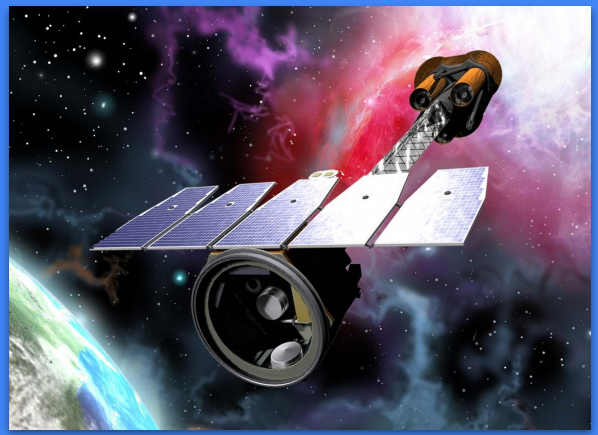
Status of Imaging X-ray Polarimetry Explorer IXPE (2)
（X線偏光撮像衛星IXPEの現状 2）



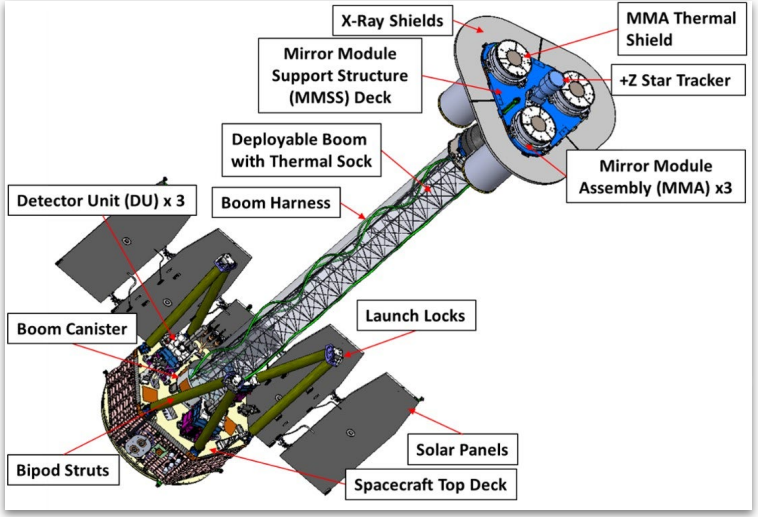
T. Mizuno (Hiroshima Univ.)
on behalf of the IXPE team

2025 Sep. 17, JPS meeting @ Hiroshima Univ.

IXPE Mission

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) + Guest Observer Program; (2024 Feb.-)
- Data are archived by NASA's HEASARC, released 1 week after the completion of the observation



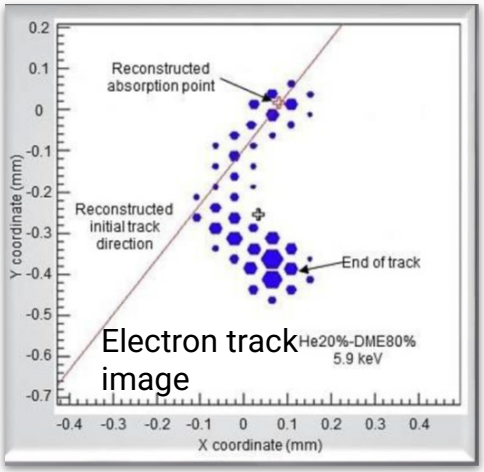
(see Weisskopf 18)

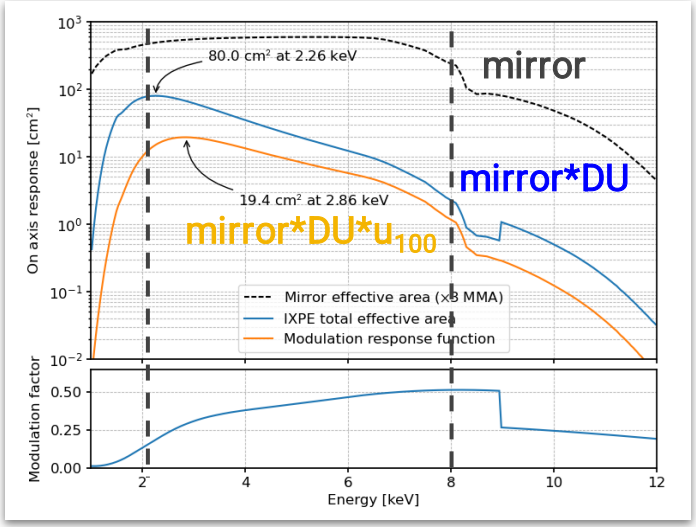
IXPE Instruments

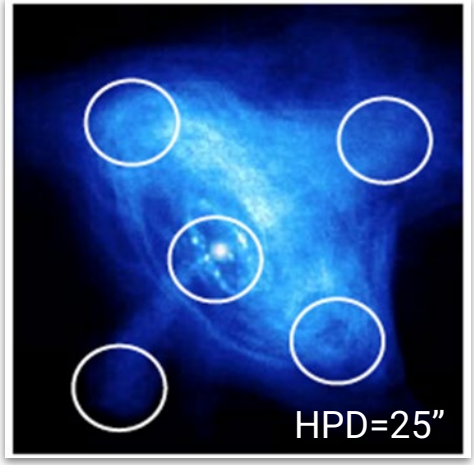
(see Soffitta+21 and Baldini+21)

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

- MMAs: each has >200 cm^2 (3-6 keV)
- DUs: Gas pixel detector, measure photoelectron track (polarization) direction
  - FOV=12.9' x 12.9', HPD=25", μ_{100}>0.5 achieved. (Aeff*μ_{100}~20 cm^2, ΔE~20%@3 keV)
  - Event-by-event Stokes param. to use imaging-polarimetry capability (Kislat+15, Vink & Zhou 18)







Mission Status

Baseline mission completed successfully

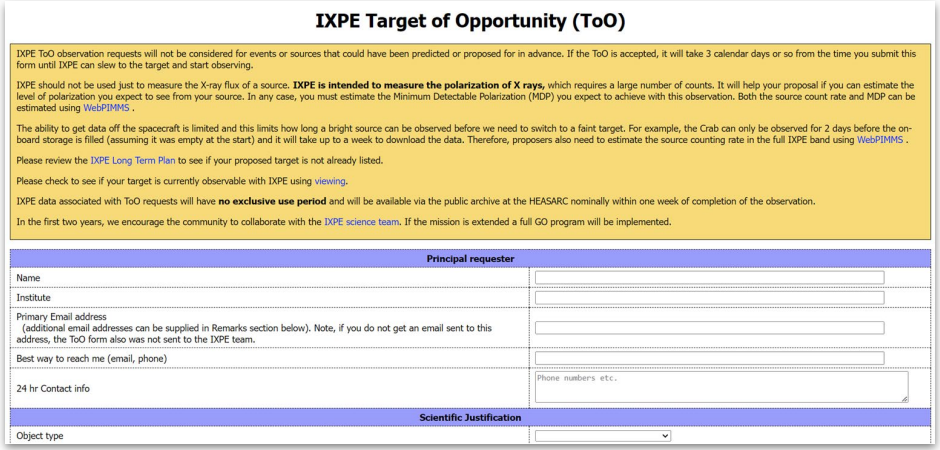
- Almost all classes of sources observed; >70 discovery papers (3 in Nature, 2 in Science)
- Data are released 1 week after completion of obs.

GO phase started in 2024/Feb, now cycle 2 (2025/Feb-), cycle 3 will start in 2026/Feb

- 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	

Notes on Detector Performance

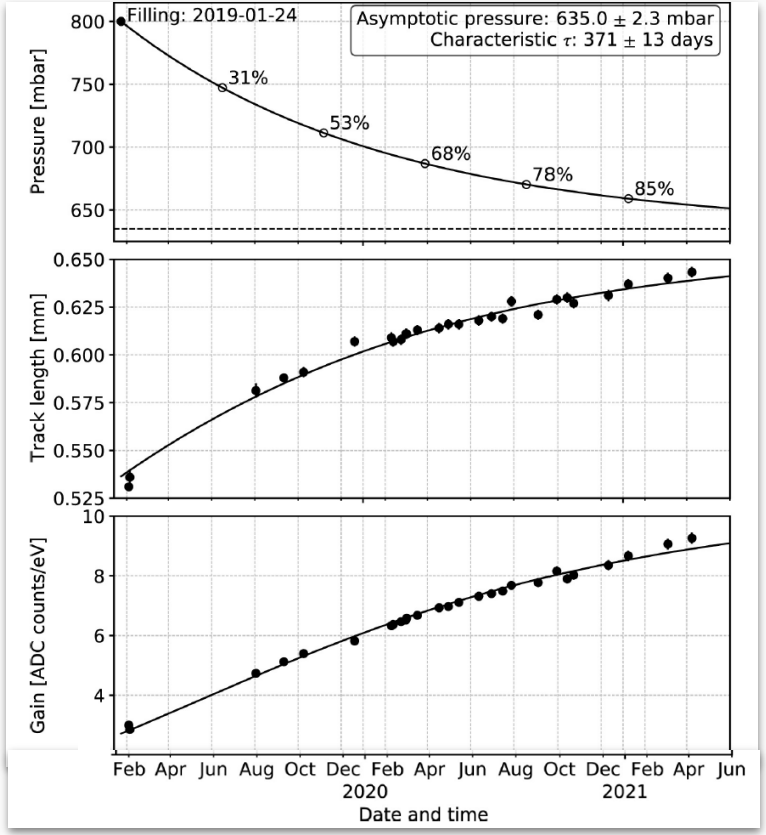
GPD pressure decrease gradually (known issue before the launch)

- will affect efficiency, track length, and gain (and instrumental response)
- We continuously monitor the efficiency and update responses
- User shall use adequate response files ("quzcif" will help you)

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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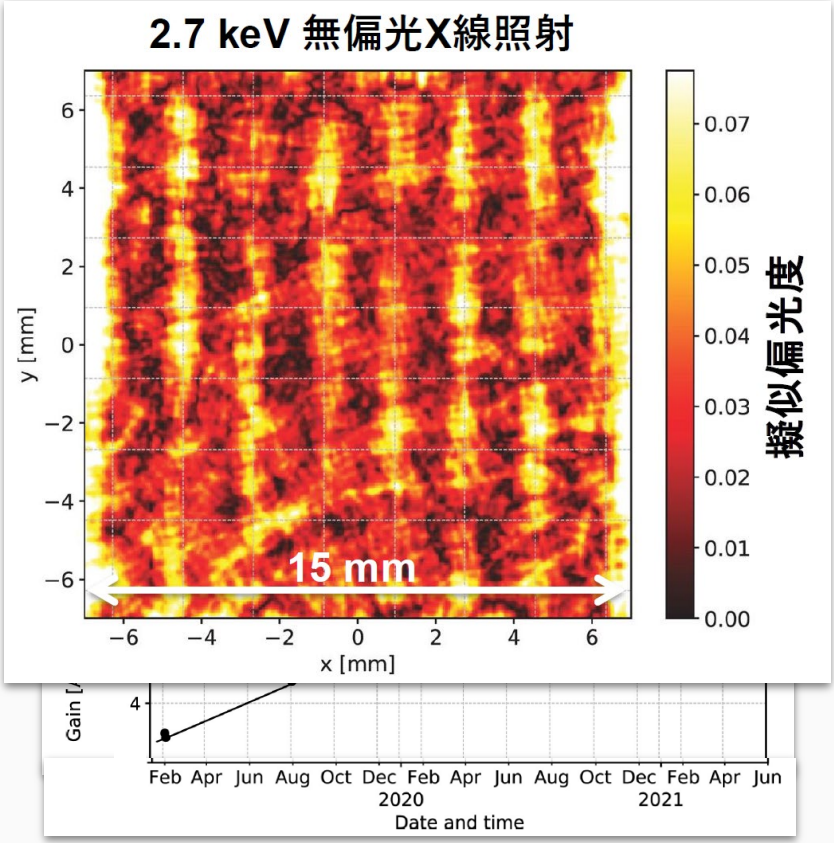
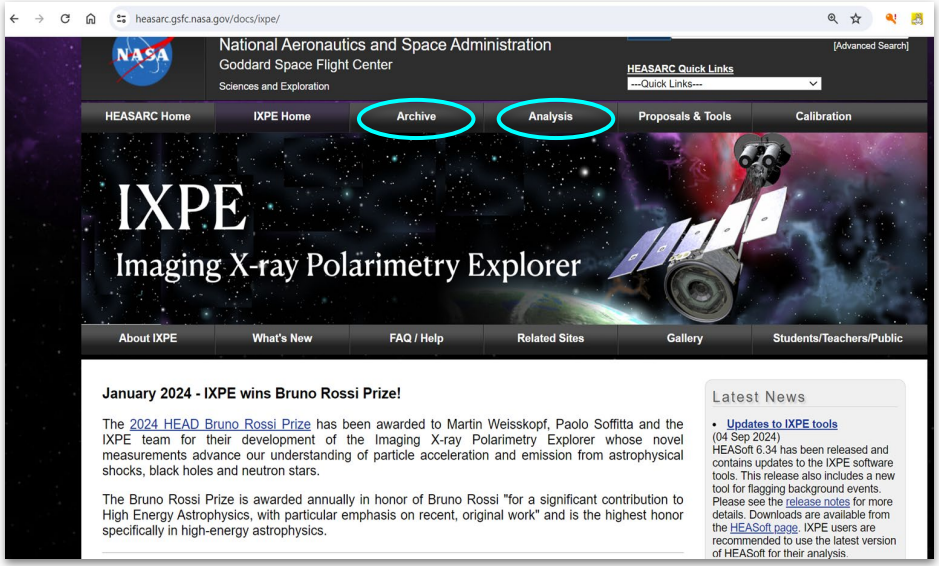


For “Do It Yourself” Persons

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 (xpselect, xpbin) to read/select events and bin spectrum

```
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

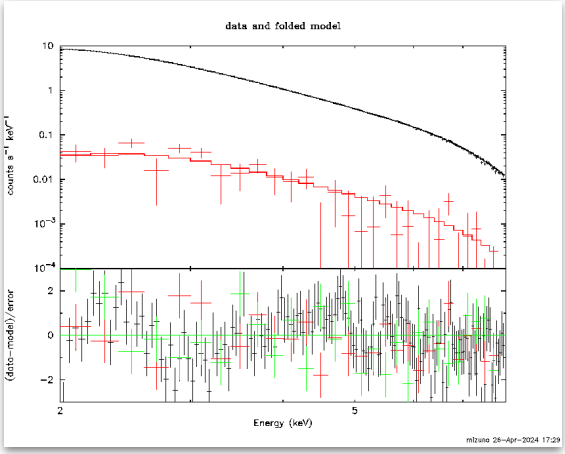
For “Do It Yourself” Persons (Cont’d)

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



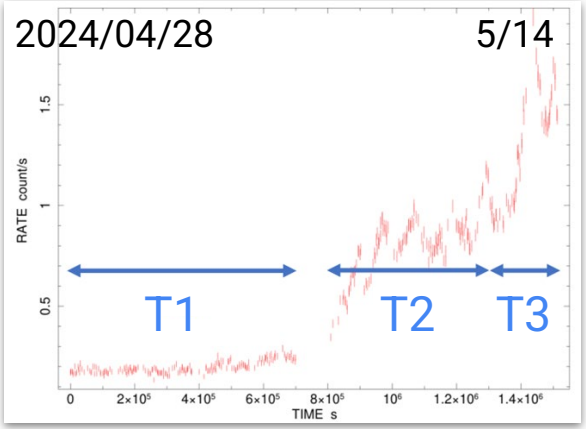
Stokes-I (black)
Stokes-Q (red)
Stokes-U (green; negative and not shown in upper panel)

(use adequate response files by looking at filename or consulting “quzcif” command)

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

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

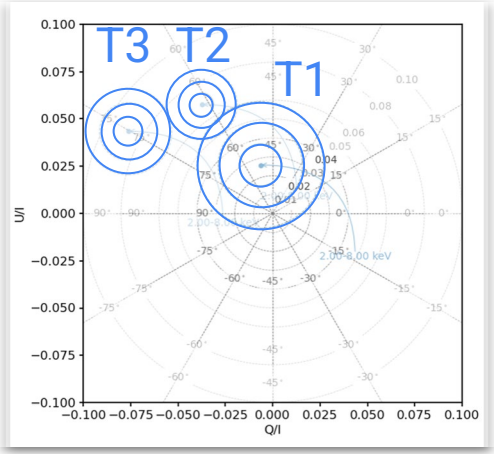
Flux increased by x10; Coordinated polarimetry in IR&opt. (Kanata) and X-ray (IXPE) (Tochihara+25 @ASJ meeting)

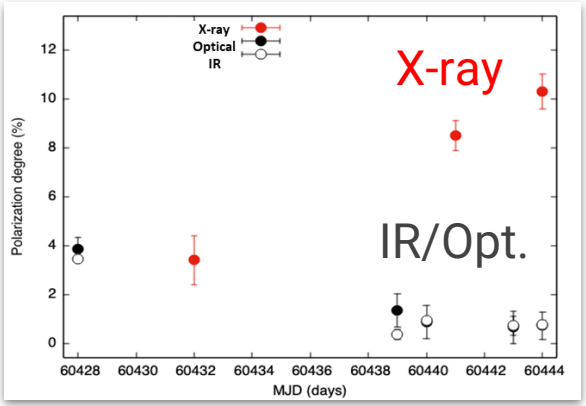


Significant change of PD_X by Q/U analysis

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.





Science w/ IXPE : Other Activities of Japanese Group

Three contributions to this JPS meeting

- Crab PWN B structure in west bay (imaging polarimetry w/ instr. response considered)
- Crab PWN B structure in torus (imaging polarimetry w/ instr. response considered)
- Cyg X-1 corona geometry (dedicated polarization simulation of corona in BHB)

6 **軟X 線偏光撮像観測衛星IXPEの観測データ及びシミュレーションを用いた「かに星雲・パルサー」のWest Bayの磁場評価**

広島大, 山形大[A], 東北文教大[B], Stanford Univ.[C], INAF[D]

呉屋和保, 水野恒史, 柴田晋平[A], 郡司修一[A], 渡邉瑛里[A], 大野寛[B], J. Wong[C], N. Bucciantini[D], ほかIXPE衛星チーム

休憩　(15:00～15:15)

7 **Polarization Leakageの影響を考慮したCrabのトーラス領域でのX線偏光解析**

山形大, 広島大[A], 理研[B], 理科大[C], 名古屋大[D], 千葉大[E], 大阪大[F], 京大[G], NASA/MSFC[H], IAPS/Rome[I], INFN/Pisa[J], Stanford Univ.[K]

森愛斗, 郡司修一, 渡邉瑛里, 水野恒史[A], Zhang Sixuan[A], 呉屋和保[A], 栃原淑慧[A], 深沢泰司[A], 高橋弘充[A], 武田朋志[A], 玉川徹[B], 北口貴雄[B], 内山慶祐[B,C], 三石郁之[D], 田原譲[D], 岩切渉[E], 林田清[F], 榎戸輝揚[G], Brian Ramsey[H], Philip Kaaret[H], Steven Ehlert[H], Steve O'Dell[H], Paolo Soffitta[I], Luca Baldini[J], Roger W. Romani[K] ほかIXPE 衛星チーム

8 **Constraints on the Corona Geometry of Cyg X-1 in the hard state with Spectrum and Polarimetric Observations in X-rays in 2022**

Hiroshima Univ., Ichinoseki Col.[A], Univ. of Durham[B], Univ. of Tsukuba[C]

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Please listen to their talk and give questions!

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Summary and Take-Home Message

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

- It has observed almost all classes of sources and provided strong constraints on source geometries (of B, disk&corona, torus) and particle acceleration

If you are interested in, please join us in the analysis/interpretation

- Data are made public after completion of observation. ToO also possible upon request
- Analysis tools (heasoft/ixpeobssim) are made public; you may do-it-yourself

Some tips for the analysis presented for reference

- GPD pressure change and DU2 anomaly (no need to worry once you understand them)
- Stokes Q/U based analysis is useful to adequately evaluate significance and imaging polarimetry

Thank you for your attention

References & Useful Links

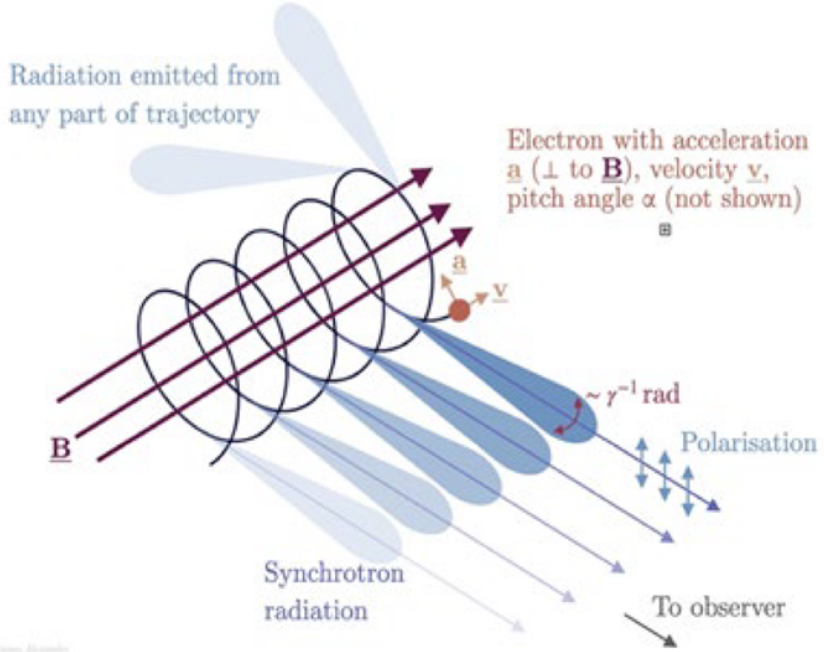
- IXPE Archive (https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/)
- IXPE technical information (https://heasarc.gsfc.nasa.gov/docs/ixpe/analysis/)
- Weisskopf et al. 1978, ApJ 220, L117
- Soffitta et al. 2021, AJ 162, 208; Baldini et al. 2021, Astropart. Phys. 133, 102628
- Weisskopf 2018, Galaxies 6,33
- Kislat et al. 2015, Astroparticle Physics 68, 45; Vink & Zhoug 2018, Galaxies 6, 46; Mizuno et al. 2023, PASJ 75, 2023
- Xi et al. 2022; Nature 612, 658; Liodakis et al. 2022, Nature 611, 677
- Baldini et al. 2022, Software X 19, 101194
- Negro et al. 2023, ApJ 946, 21

Backup Slide

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)

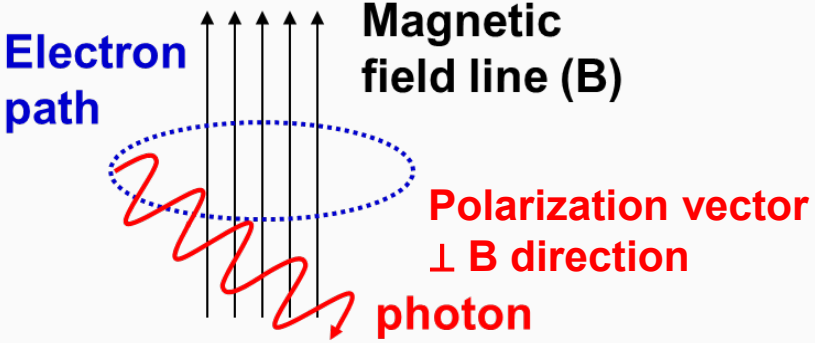
X-ray Polarimetry for Proving B-configuration

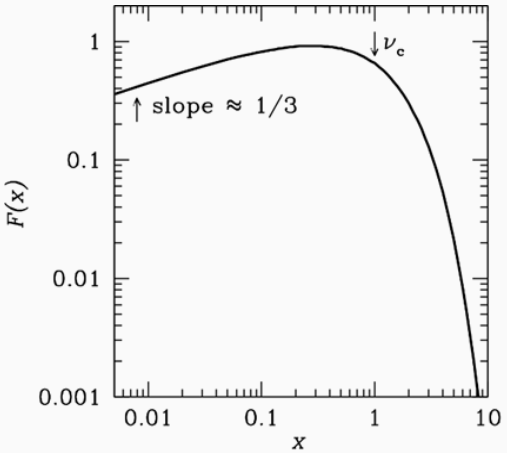
Electrons + magnetic field produce synchrotron radiation

Unique probe for B (and accelerated electrons)

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

X-ray polarimetry (by IXPE) can probe B-field configuration around freshly-accelerated electrons ($h\omega_p \sim 0.29 \frac{3\gamma^2 eB}{2m_e c}$)





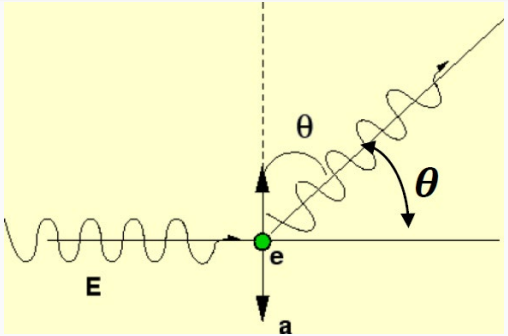
X-ray Polarization for Probing Disk Geometry

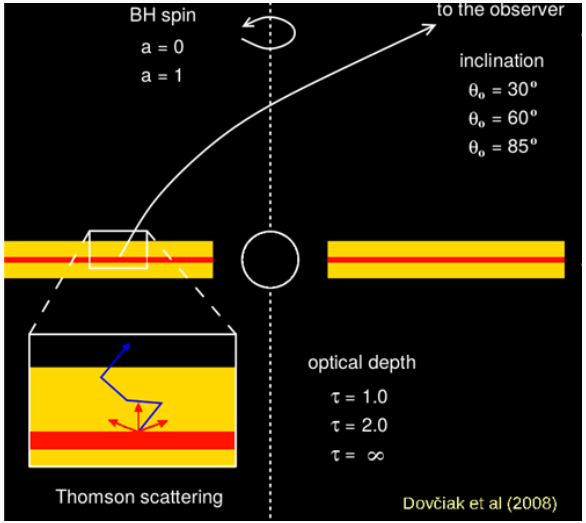
Scattered photons are polarized ($\Pi = \frac{1-(\cos\theta)^2}{1+(\cos\theta)^2}$)

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

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

We can investigate corona, disk and space-time geometry close to BH using X-ray polarimetry





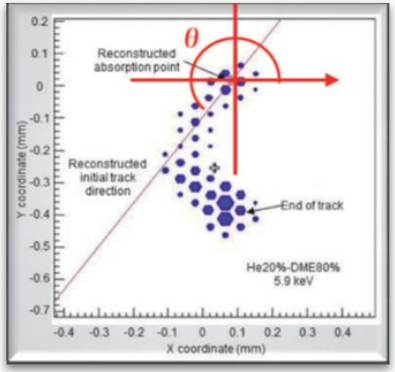
Stokes Parameter Based Analysis

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:

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

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)

Note On Statistics

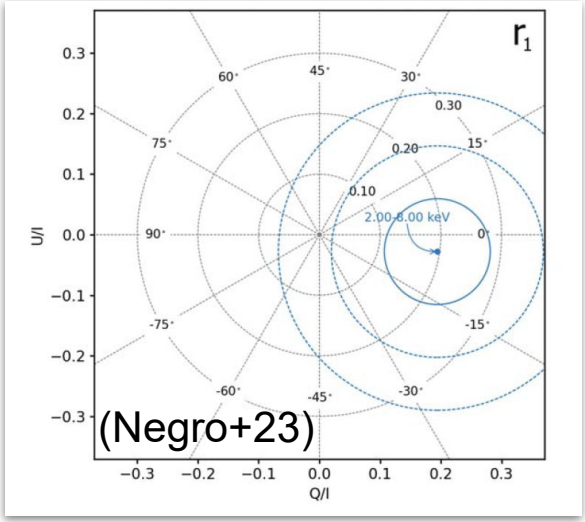
Since PD shall be >=0, PD-PA contour will be skewed when the significance is not so high (σ<=3)

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)

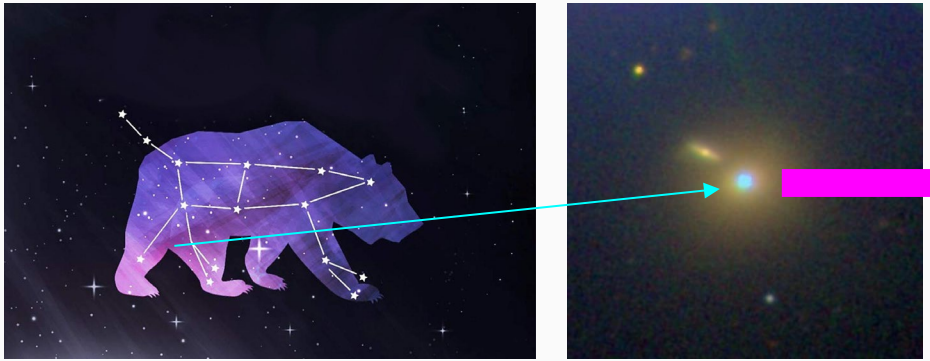
Use ixpeobssim and Stokes-Q/U for imaging-polarimetry analysis

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

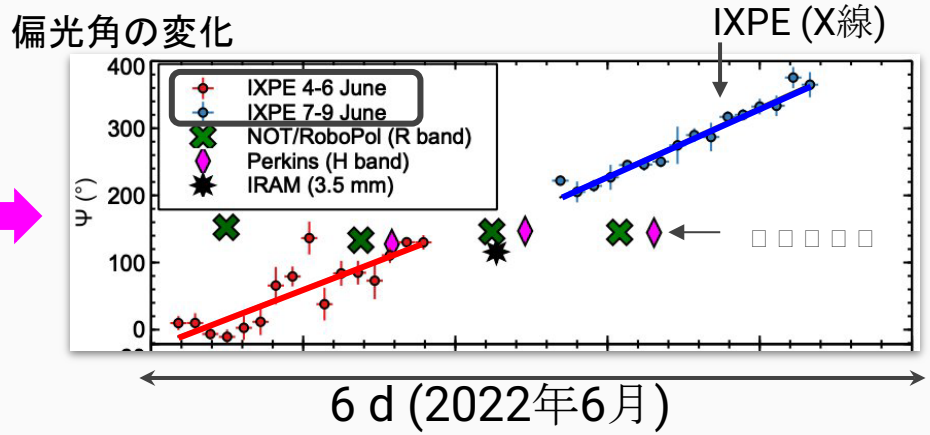


IXPE衛星でみたマルカリアン421

- おおぐま座の方角の超巨大ブラックホール。400万光年彼方にあるため点にしか見えない
- 強力な宇宙ジェットにより電波からガンマ線まであらゆる波長で輝く。X線はジェットの根本から出ている
- 可視・電波・X線で偏光観測をし，IXPEが偏光（磁場）の向きの変化を発見



(Little AstronomyおよびSlone Digital Survey)



IXPE衛星でみたマルカリアン421（２）

- おおぐま座の方角の超巨大ブラックホール。宇宙ジェットにより電波からガンマ線まであらゆる波長で輝き，X線はジェットの根本から出ている
- 可視・電波・X線で偏光観測をし，IXPEが偏光（磁場）の向きの変化を発見
  - ジェットが「らせん状」の磁場を持ち，明るい部分が近づいたためと考えられる
    =>X線で初めてらせん状磁場を捉えた
  - （他の超巨大ブラックホールでは偏光角が変わらない物もあり，個性が豊か）