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

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

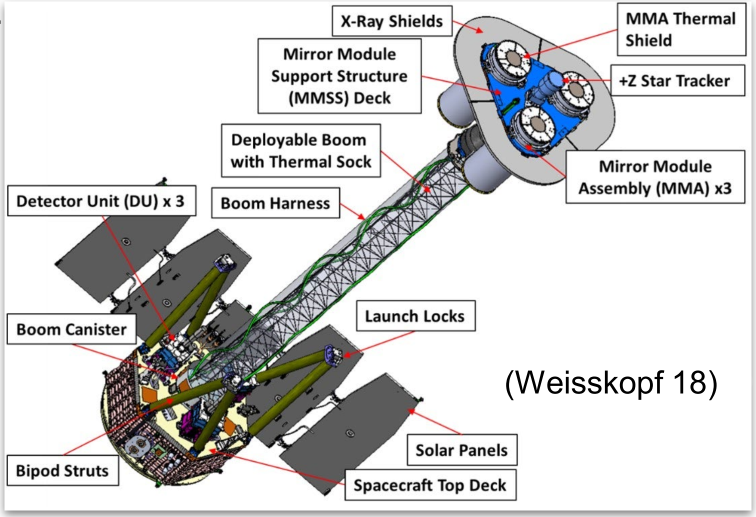
2024 Sep. 16, JPS meeting @ Hokkaido Univ.

IXPE Mission

(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.-)
- Data are archived by NASA's HEASARC, released 1 week after the completion of the observation



(Weisskopf 18)

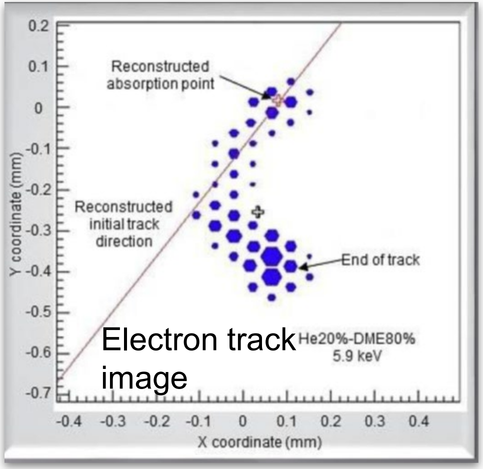
- Equatorial orbit (600-km altitude)
- 100 times more efficient (less exposure required) than OSO-8 (Weisskopf+78)

IXPE Instruments

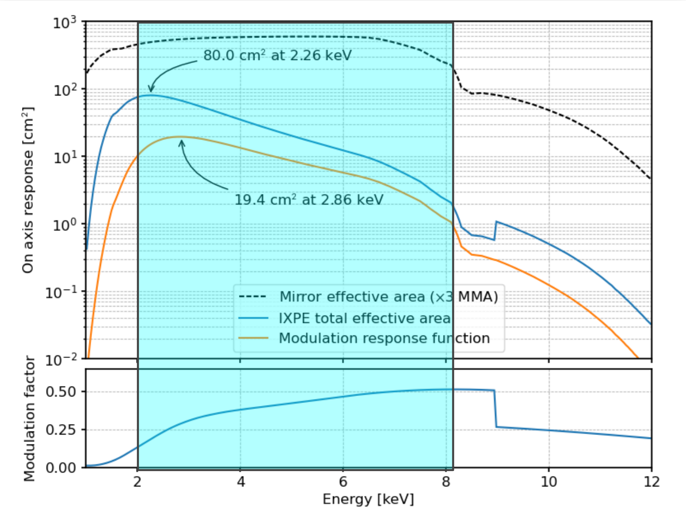
(see Soffitta+21 and Baldini+21 for latest information)

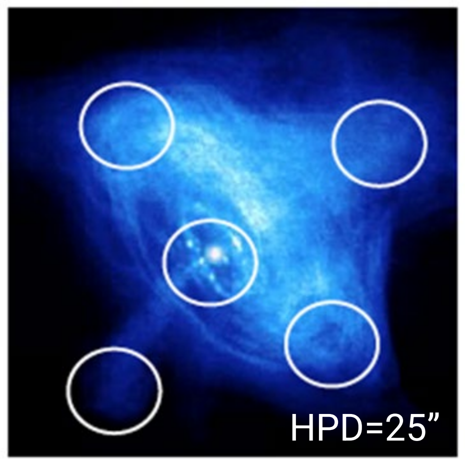
2-8 keV, 3 Mirror Module Assemblies (MMAs) and Detector Unites (DUs)

- 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", μ_{100}>0.5 achieved
  - Event-by-event Stokes parameter to use imaging-polarimetry capability (Kislat+15, Vink & Zhou 18)



Electron track image





HPD=25"

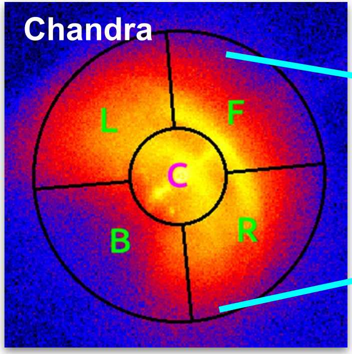
Science w/ IXPE: Case of Vela PWN

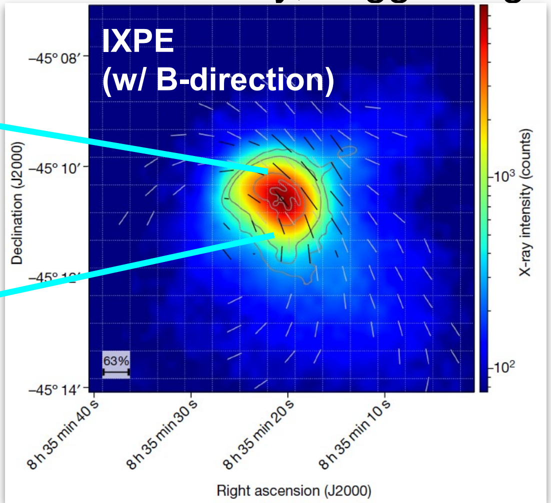
Closest middle-aged PWN (d=0.3 kpc, t=11 kyr, $L_{sd}=10^{37}$ erg/s)

- Chandra showed double torus and jet-like structure (angle=130 deg)

IXPE revealed PD of ~70% in some regions, close to sync. Limit

- High PD disfavors diffusive-shock accel. at termination shock (reconnection?). PA distr. in radio match with X-ray, suggesting similar B-structure in larger volume





	Center [C]	Front [F]	Right [R]	Left [L]	Back [B]
PD (%)^{S}	49.6±2.5	70.0±3.6	56.0±3.1	42.0±3.0	33.3±3.6
PD (%)$^{S+B}$	48.8±2.5	65.4±3.6	53.1±3.1	39.9±3.0	31.1±3.7
PA (°)^{S}	−50.2±1.5	−48.8±1.5	−64.9±1.6	−30.1±2.1	−59.4±3.1
PA (°)$^{S+B}$	−50.3±1.5	−48.8±1.6	−64.9±1.7	−30.2±2.2	−59.4±3.4

(Xie+22)

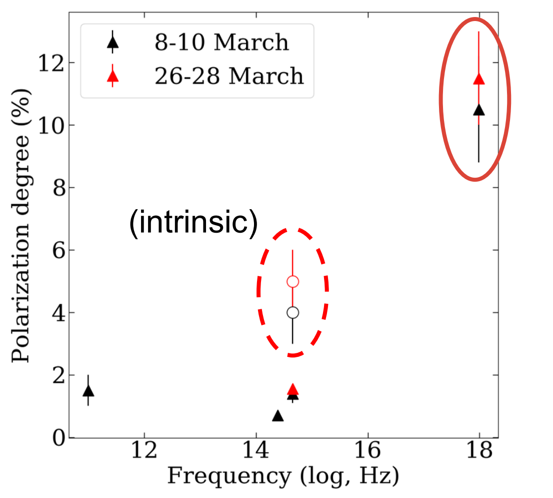
Science w/ IXPE : Case of Mrk 501

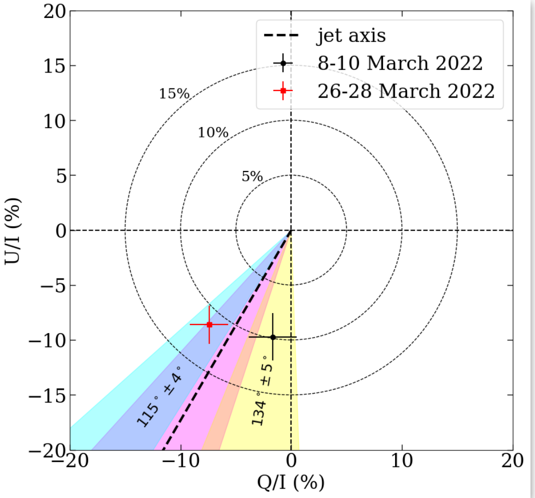
High-synchrotron-peaked blazar (at z=0.034)

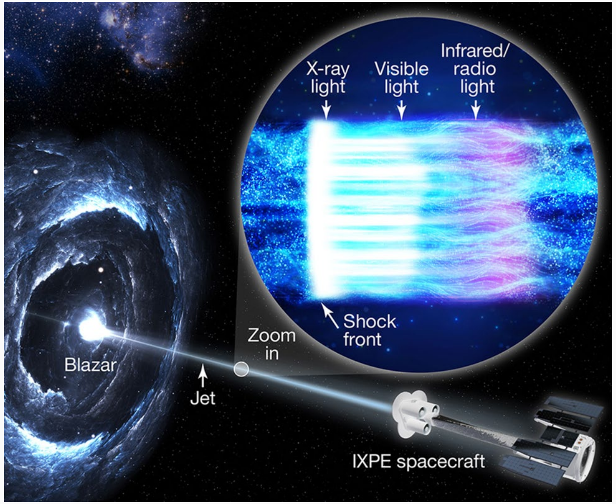
Coordinated polarimetry in radio, optical, and X-ray

- PD_X= (10+/-2) %, ~2.5 times larger than PD_{radio} and PD_{opt}
- PA_X= (134+/-5) deg, parallel to radio jet

in tension with single-/multi-zone and magnetic reconnection models, but supports energy-stratified electron scenario (shock)







(Liodakis+22)

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	

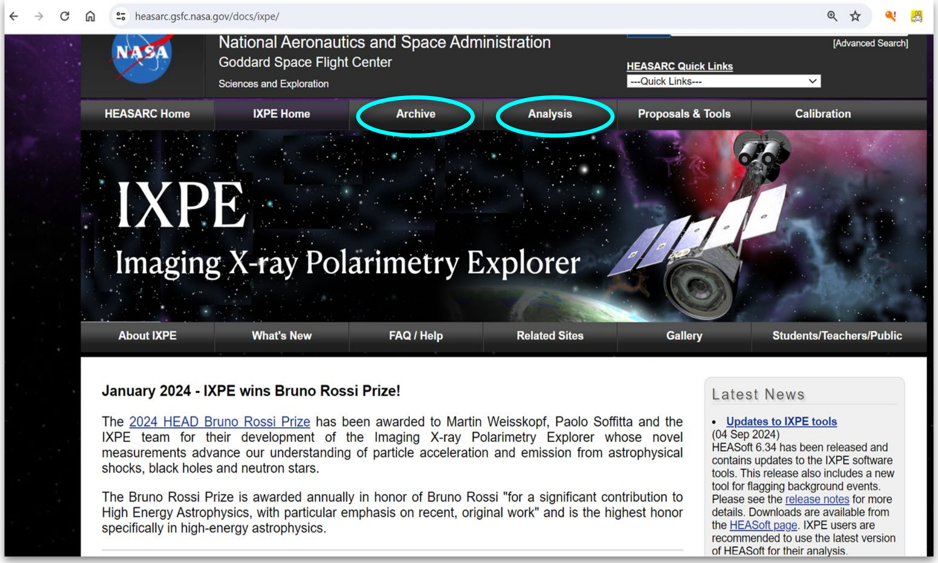
For “Do It Yourself” Persons

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

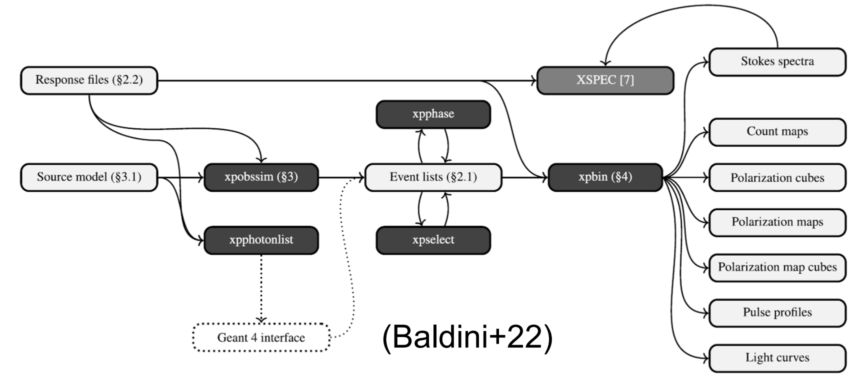


For "Do It Yourself" Persons (Cont'd)

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

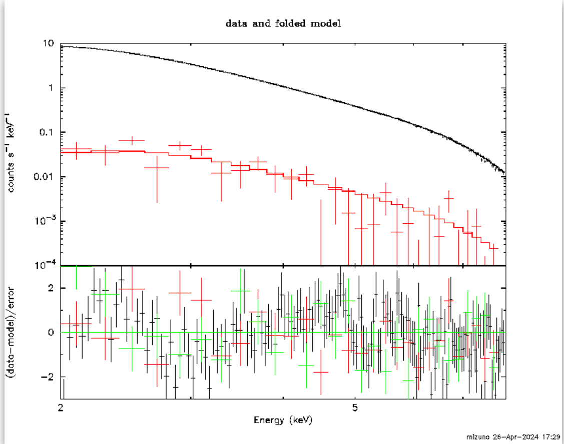
For “Do It Yourself” Persons (Cont’d)

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

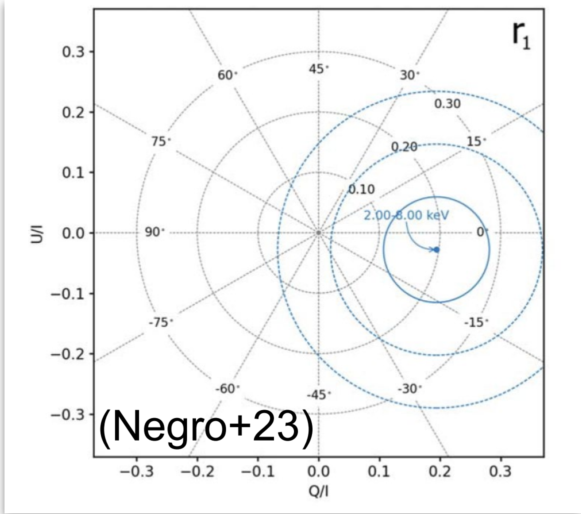
Since PD shall be >=0, PD-PA contour will be skewed when the significance is not so high (σ<=3)

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

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

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)



(Negro+23)

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 B-configuration 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
- (theoretical work or coordinated observation/analysis also very appreciated)

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

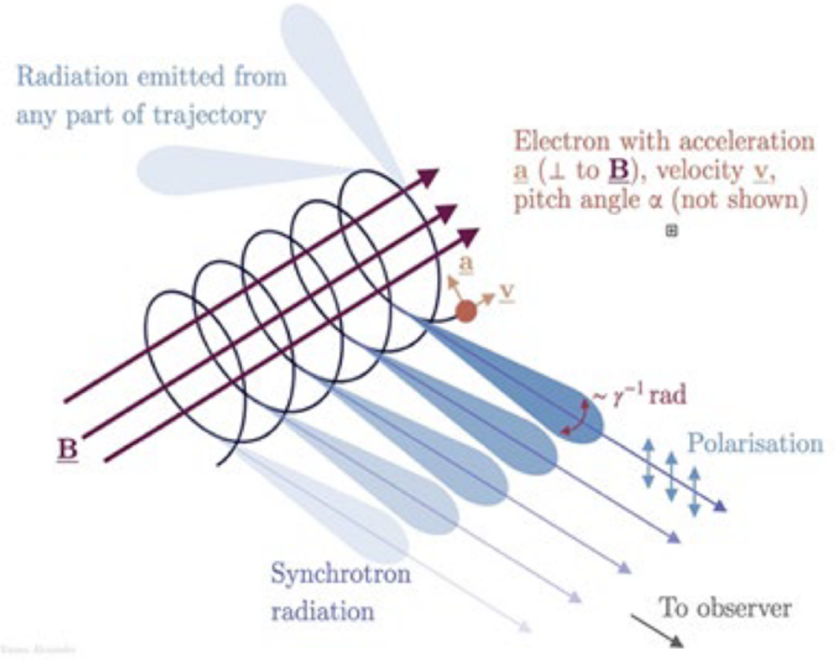
Backup Slide

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)

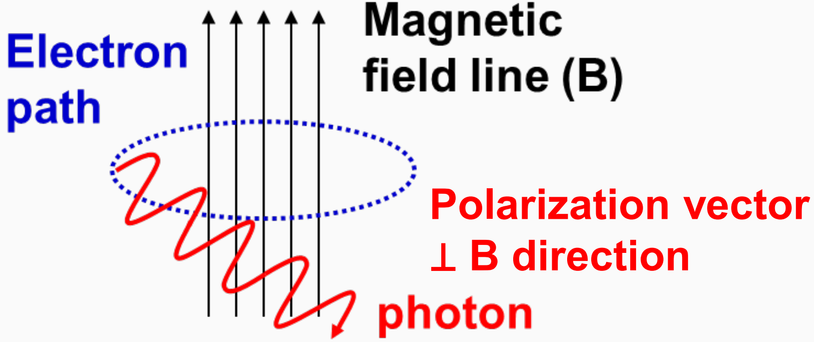
X-ray Polarimetry for Proving B-configuration

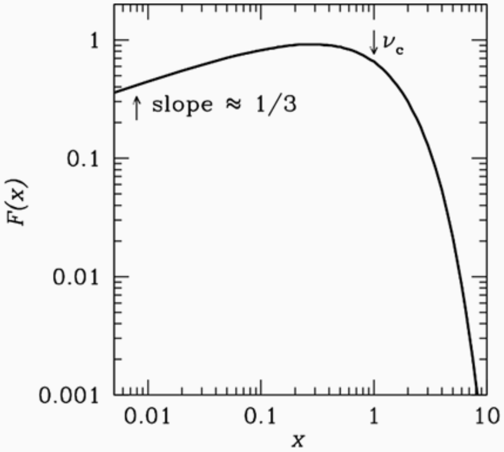
Electrons + magnetic field produce synchrotron radiation

Unique probe for B (and accelerated electrons)

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

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





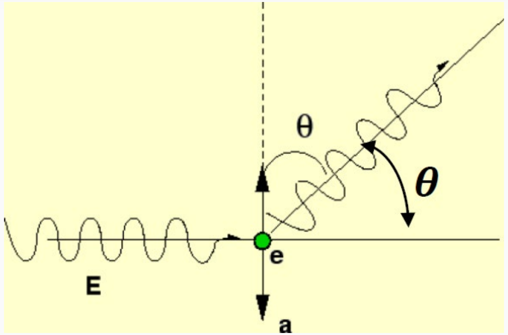
X-ray Polarization for Probing Disk Geometry

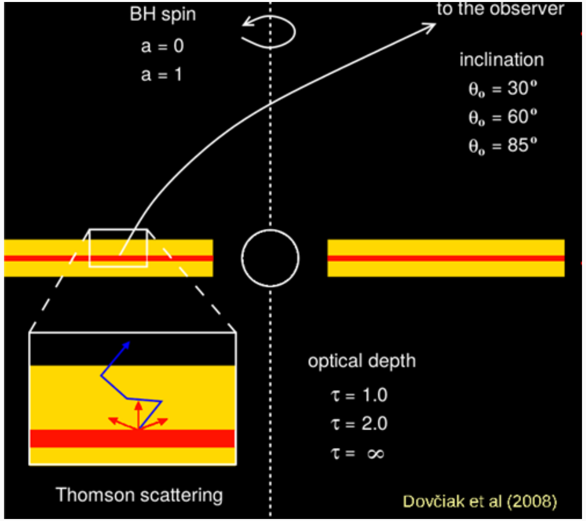
Scattered photons are polarized
($\Pi = \frac{1-(\cos\theta)^2}{1+(\cos\theta)^2}$)

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





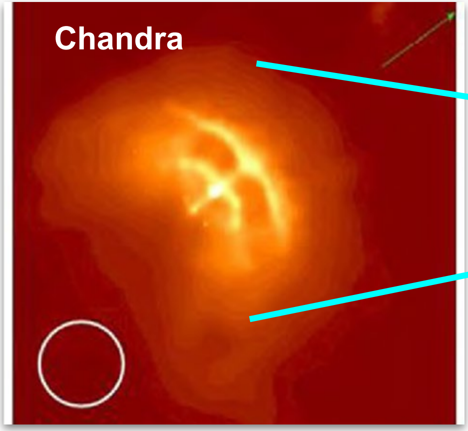
Science w/ IXPE: Case of Vela PWN

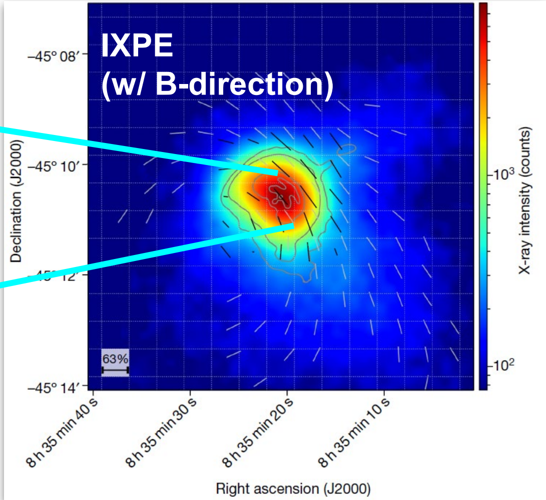
(Xie+22)

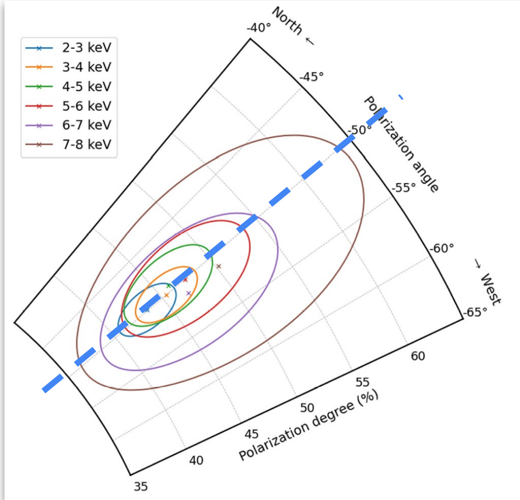
Closest middle-aged PWN (d=0.3 kpc, t=11 kyr, $L_{sd}=10^{37}$ erg/s)

Chandra showed double torus and jet-like structure (angle=130 deg)

IXPE revealed (spatially integrated) PD of ~45% that is >2 x times higher than Crab. PA aligns with torus axis well and symmetric







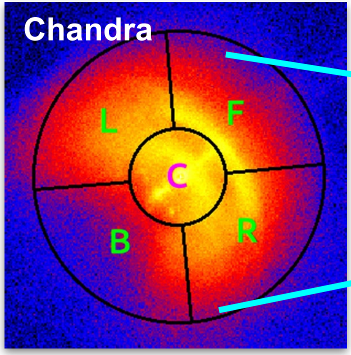
Vela PWN Polarized at Synchrotron Limit

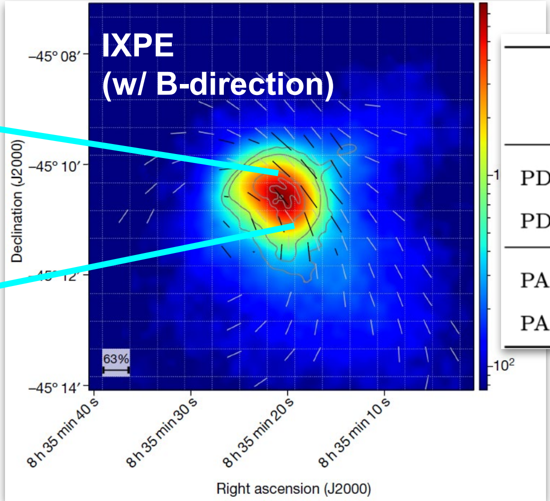
(Xie+22)

We defined 5 regions; center (C), front (F), back (B), left (L), and right (R)

- BG-subtracted PD is ~70% for F region, close to sync. limit. Results not affected very much by polarization leakage (Bucciantini+23) and PSR contamination

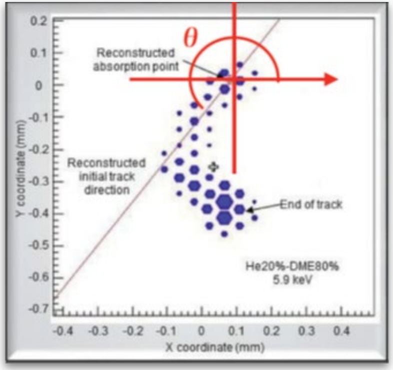
High PD disfavors diffusive-shock accel. at termination shock (reconnection?). PA distr. in radio match with X-ray, suggesting similar B-structure in larger volume





	Center [C]	Front [F]	Right [R]	Left [L]	Back [B]
PD (%)^S	49.6±2.5	70.0±3.6	56.0±3.1	42.0±3.0	33.3±3.6
PD (%)$^{S+B}$	48.8±2.5	65.4±3.6	53.1±3.1	39.9±3.0	31.1±3.7
PA (°)^S	−50.2±1.5	−48.8±1.5	−64.9±1.6	−30.1±2.1	−59.4±3.1
PA (°)$^{S+B}$	−50.3±1.5	−48.8±1.6	−64.9±1.7	−30.2±2.2	−59.4±3.4

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)

Year-1 Targets

Almost <u>all classes of sources</u> have been observed

- PWN/PSR, SNR, BHB, WD/NS, Magnetar, RQ-AGN (and Sgr A*), Blazar/RG

Data are released 1 week after completion of obs.

obsid	name	ra	dec	time
01001301	Cas A	23 23 28.0	+58 48 42	2022-01-11 11:23:47.184
01006501	Cen X-3	11 21 15.1	-60 37 26	2022-01-29 12:39:44.205
01003299	4U 0142+61	01 46 22.4	+61 45 03	2022-01-31 07:23:26.645
01004301	Cen A	13 25 27.6	-43 01 09	2022-02-15 00:13:20.978
01001899	Her X-1	16 57 49.8	+35 20 33	2022-02-17 13:52:46.841
01001099	Crab	05 34 31.9	+22 00 52	2022-02-21 16:12:23.000
01003499	Sgr A complex	17 46 02.4	-28 53 24	2022-02-27 19:14:18.104
01004501	Mrk 501	16 53 52.2	+39 45 37	2022-03-08 02:38:53.767
01002701	4U 1626-67	16 32 16.8	-67 27 39	2022-03-24 01:51:08.024
01004601	Mrk 501	16 53 52.2	+39 45 37	2022-03-27 05:39:23.611
01002801	GS 1826-238	18 29 28.2	-23 47 49	2022-03-29 07:14:28.167
01005301	S5 0716+714	07 21 53.4	+71 20 36	2022-03-31 09:20:06.031
01001299	Vela Pulsar	08 35 20.6	-45 10 35	2022-04-05 19:50:31.503
01002501	Vela X-1	09 02 06.9	-40 33 17	2022-04-15 18:07:09.159
01001601	Cyg X-2	21 44 41.2	+38 19 17	2022-04-30 10:33:42.807
01006601	Cyg X-2	21 44 41.2	+38 19 17	2022-05-02 11:09:14.453
01006201	1ES 1959+650	19 59 59.9	+65 08 55	2022-05-03 11:21:38.273
01003701	Mrk 421	11 04 27.3	+38 12 32	2022-05-04 10:00:28.516
01006301	BL Lac	22 02 43.3	+42 16 40	2022-05-06 11:10:18.035
01003399	MCG-5-23-16	09 47 40.2	-30 56 55	2022-05-14 12:52:30.555
01002901	Cyg X-1	19 58 21.7	+35 12 06	2022-05-15 15:20:54.322

(https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/)