Magnetic Field Structure of the Crab Pulsar Wind Nebula Revealed with IXPE (X線偏光衛星IXPEによる「かに星雲」の磁場構造)

T. Mizuno (Hiroshima Univ.),
H. Ohno (Tohoku Bunkyo Univ.), E. Watanabe, S. Gunji, S. Shibata (Yamagata Univ.), N. Bucciantini (INAF Osservatorio di Arcetri), P. Slane (CfA), M. Weisskopf (NASA MSFC) on behalf of the IXPE team

2023 Sep. 16, JSP meeting @ Tohoku Univ.

Crab Nebula

Pulsar (PSR) and pulsar wind nebula (PWN) produced by SN 1054

- d=2 kpc, L=10^{38} erg/s
- PWN powered by PSR at the center (Crab pulsar, P=33 ms)

Promising environment to study relativistic outflows ($\Gamma=10^6$) and particle acceleration

- Magnetic field (B) turbulence plays important role in acceleration and emission from radio to gamma-rays (e.g., Luo+20)

X-ray imaging-polarimetry will provide vital information about the B structures where particle acceleration is taking place

Crab Nebula (Radio—IR—Optical—UV—X-ray)

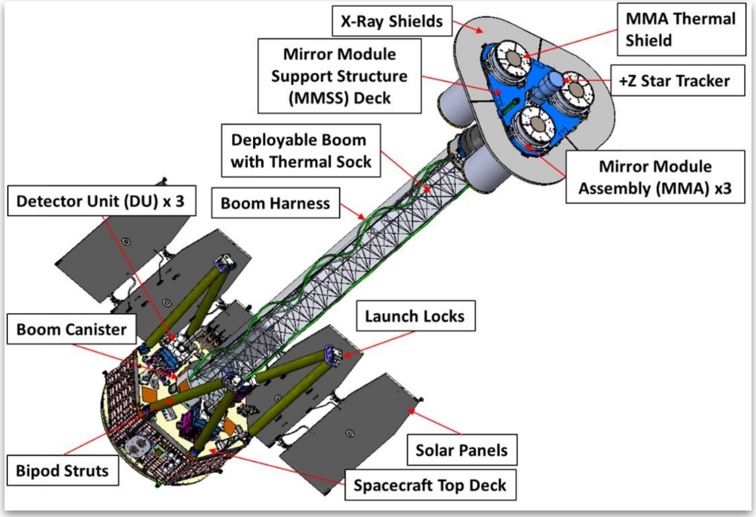
(https://svs.gsfc.nasa.gov/30944)

IXPE Mission+Instruments

The first mission devoted to <u>spatially-resolved X-ray polarimetry</u>

(cf; Weisskopf 18, Soffitta+21 and Baldini+21)

- 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.-)
- 3 sets of (mirror + detector) enable <u>imaging-polarimetry</u> in 2-8 keV for the first time
  - FOV=12.9’ x 12.9’, HPD=25”, m_{100}>0.5
  - <u>Event-by-event Stokes parameter</u> to use imaging-polarimetry capability (Kislat+15, Vink & Zhou 18)
- Initial report of Crab obs. (Bucciantini+23)



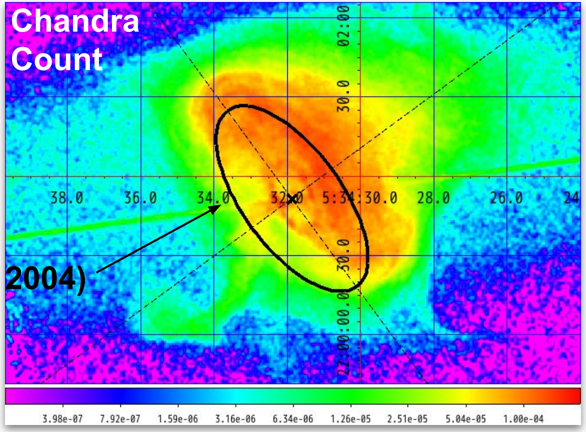
- Equatorial orbit (600-km altitude)
- 100 times more efficient (less exposure required) than OSO-8 (Weisskopf+78)

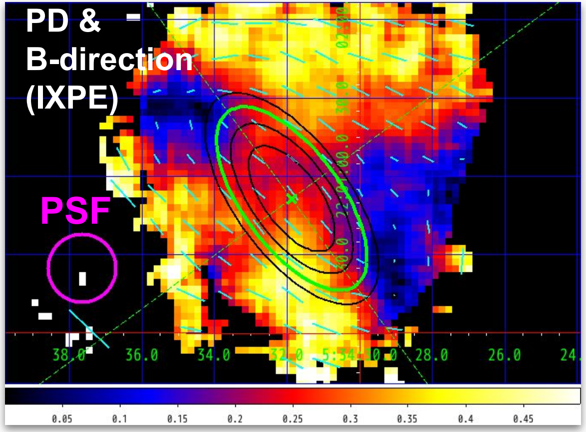
Crab PWN Polarization (Overview)

Following the initial report (Bucciantini+23), we carried out in-depth analyses of the Crab PWN observed in 2022 Feb/Mar w/ 90ks exposure (Mizuno+23, submitted to PASJ)

- B-direction deviates from torus major axis, in particular outside of torus but already inside
- High PD (polarization degree) areas in high latitudes (cf. Bucciantini+23)
- Areas of very-low PD seen in east and west of torus. That in west does not positionally coincide with the edge of torus (where geometrically depolarization expected)
- Moderately low PD areas positionally coincide with north/south jets

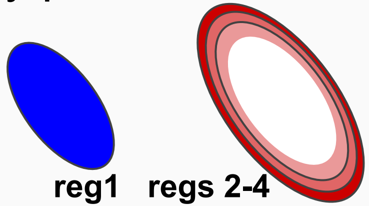
X-ray torus (Ng&Romani 2004)



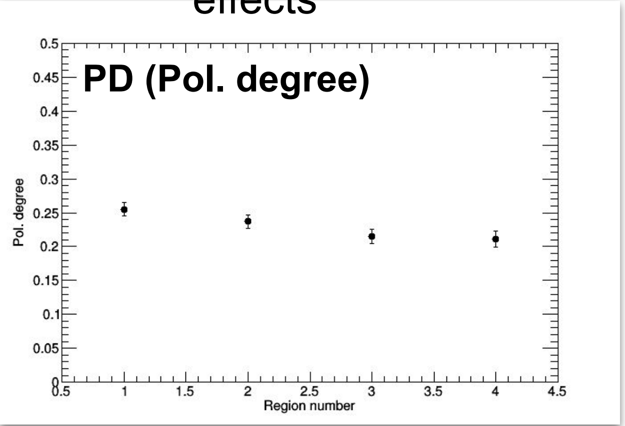


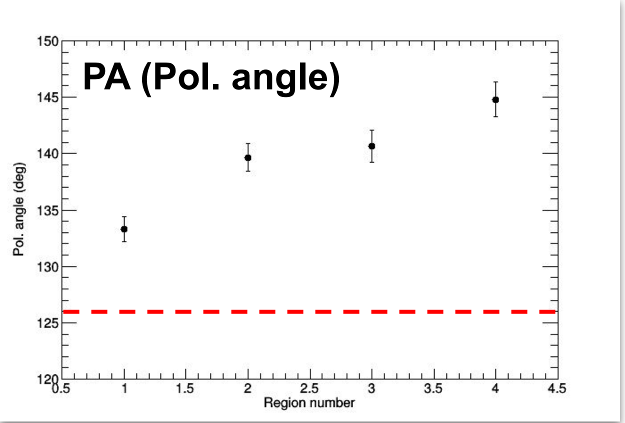
Positional Dependence of Polarization (X-ray Torus)

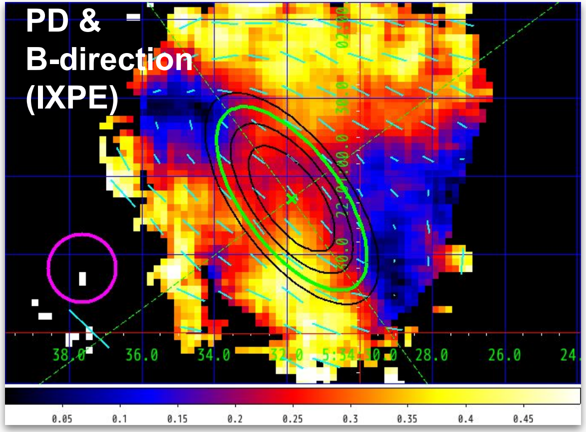
We defined an ellipse (reg 1) and elliptical rings (regs 2-4) to study positional dependence of polarization



- PA of the innermost region is closest to the projected torus axis
- PD/PA gradually decrease/increase as we go away from the PSR
- => Toroidal-B direction is perpendicular to PSR spin axis close to the termination shock, then B direction gradually deviates to an east-west direction likely due to environmental effects







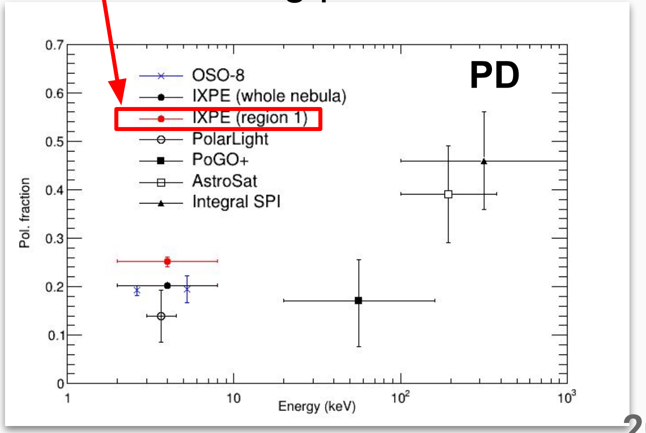
Comparison with Past High-Energy Polarimetry

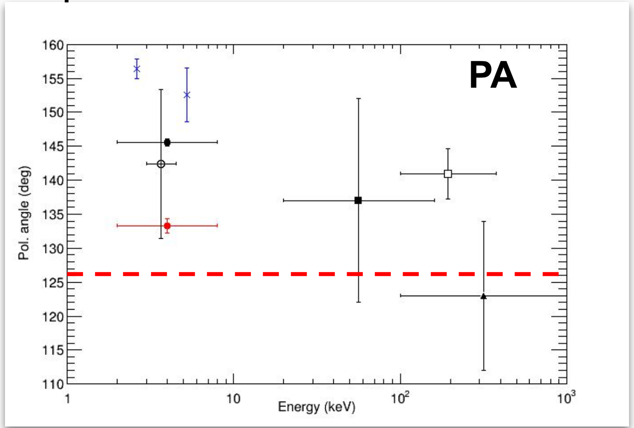
Before IXPE, (non-imaging) X-ray and γ-ray polarization used to study B-structures

- OSO-8, PolarLight (soft X-ray); PoGO+ (hard X-ray); AstroSAT, Integral SPI/IBIS (γ-ray)
- Higher energy observations gave "larger PD" and "PA closer to torus axis", as expected due to synchrotron cooling. However, not conclusive due to lack of spatial information

IXPE shows how the B-structure develops for the first time

- In the vicinity of PSR, PD is larger than average and PA is closer to the projected torus axis, confirming past discussion about B development





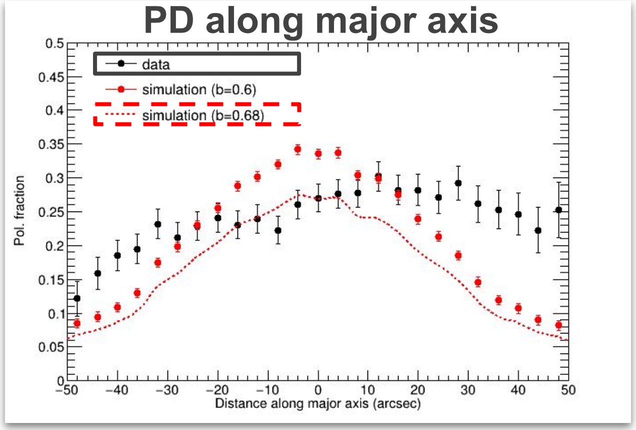
Study of B-Turbulence

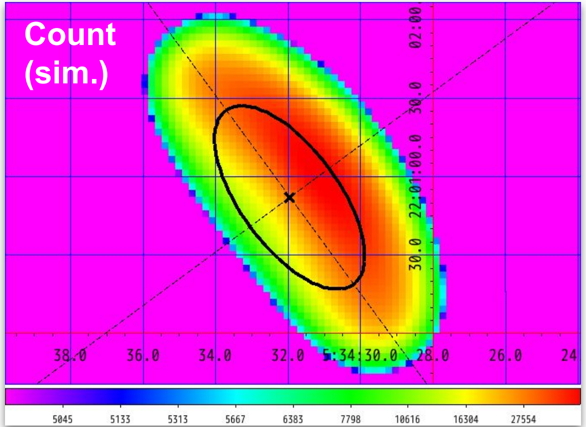
Although B-turbulence is not taken into account in the standard KC model (Kennel&Coroniti 84), it could play important role in Crab PWN

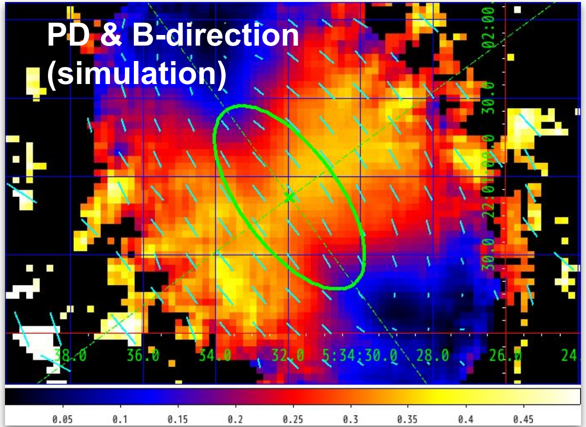
- It can explain X-ray surface brightness (Shibata+03) and spectrum from radio to γs (Luo+20)

We developed a phenomenological model and compared PD between data and model at the PSR position where contamination from high/low-PD areas is minimal

- b (fractional energy of turbulent-B) ~2/3 obtained; turbulent-B dominant







Summary and Future Prospect

IXPE is the first dedicated X-ray imaging-polarimetry observatory and provides rich information of Crab PWN (observed in 2022 Feb/Mar)

- Toroidal-B direction is perpendicular to PSR spin axis, then B-direction gradually deviates to an east-west direction due to some environmental effects
- Turbulent B is dominant in the inner nebula (accounting for ~2/3 of the B-energy), in agreement with image (X-ray) and spectrum (radio to gamma-rays)
- （More results/discussions in the paper submitted）

New observation in 2023/Feb. More results to come

Thank you for your attention

References & Useful Links

- Bucciantini et al. 2023, Nature Astronomy 7, 602
- Feng et al. 2020, Nature Astronomy 4, 511; Chauvin et al. 2017, Scientific Reports 7, 7816; Vadawale et al. 2018, Nature Astronomy 2, 50; Dean et al. 2008, Science 321, 1183; Forot et al. 2008, ApJL 688, 29
- Kennel & Coroniti 1984, ApJ 283, 694
- Kislat et al. 2015, Astroparticle Physics 68, 45; Vink & Zhoug 2018, Galaxies 6, 46
- Luo et al. 2020, ApJ 896, 147
- Mori et al. 2004, ApJ 609, 186; Martin et al. 2021, MNRAS 502, 1864
- Nakamura & Shibata 2007, MNRAS 381, 1489
- Ng & Romani 2004, ApJ 601, 479
- Shibata et al. 2003, MNRAS 346, 81
- Soffitta et al. 2021, AJ 162, 208; Baldini et al. 2021, Astropart. Phys. 133, 102628
- Weisskopf et al. 1978, ApJL 220, 117
- Weisskopf 2018, Galaxies 6,33
- Xi et al. 2022, Nature 612, 658

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- IXPE Archive (https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/)
- IXPE Long Time Plan (https://ixpe.msfc.nasa.gov/for_scientists/ltp.html)

Backup Slide

Initial Result of Crab PSR+PWN

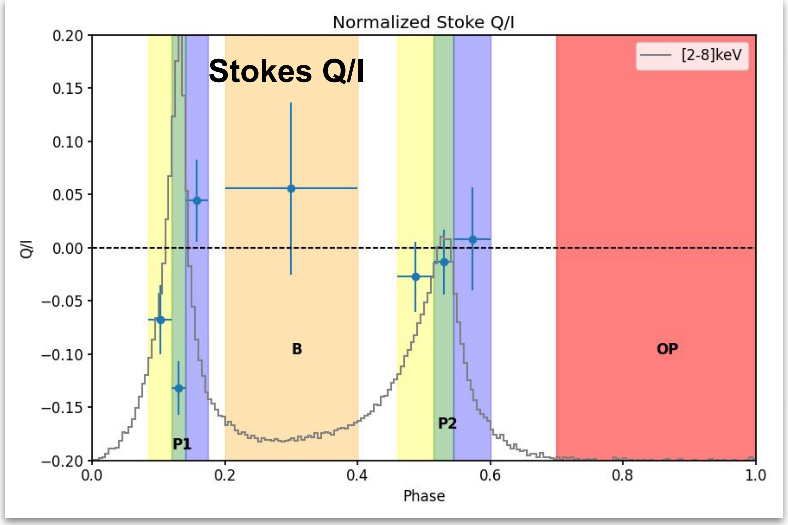
(Bucciantini+23)

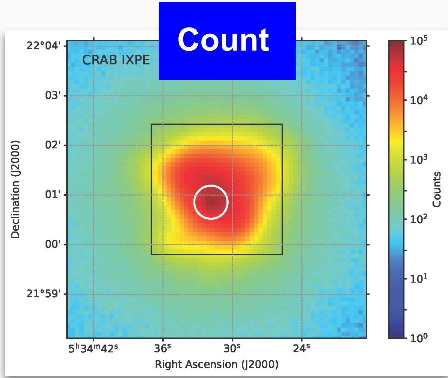
IXPE revealed distinctive features of PSR polarization

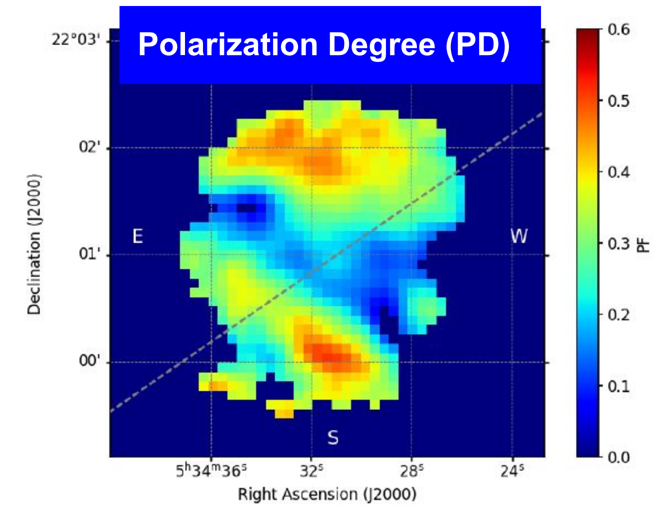
- Total PSR gives 99% upper limit of PD~5.7%; only P1 center is significantly polarized (PD~15%)

IXPE also revealed distinctive features of PWN polarization

- Toroidal B structure around PSR; PD distribution very asymmetric about the torus axis







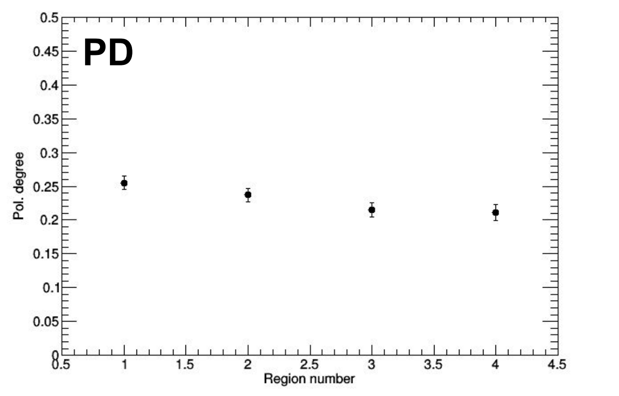
Crab PWN Polarization (Cont'd)

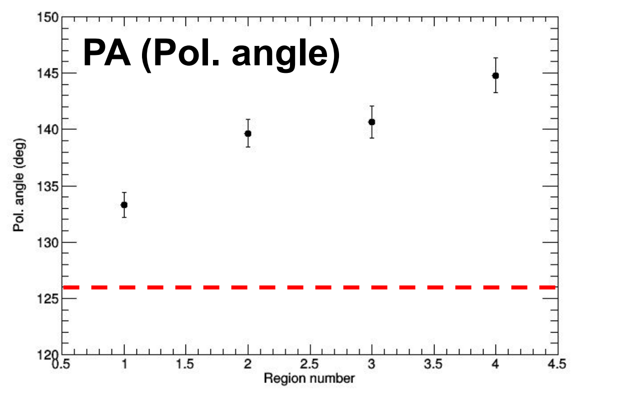
We defined a ellipse and elliptical rings (equal area) to study positional dependence

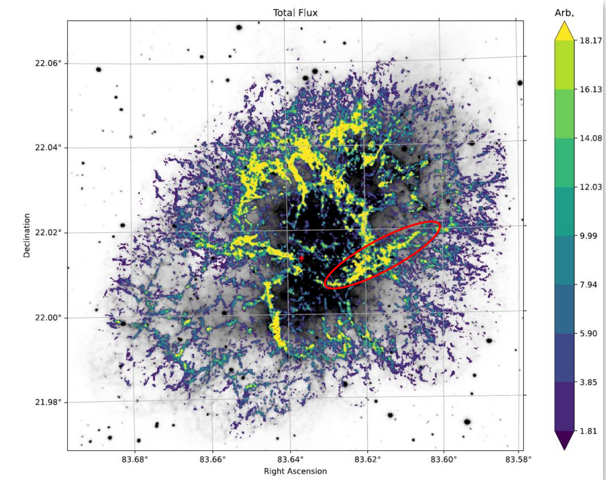
- PA of the innermost region is closest to the projected torus axis
- PD/PA gradually decrease/increases as we go away from the PSR
- => Toroidal-B direction is perpendicular to PSR spin axis close to the termination shock, then gradually deviates to an east-west direction likely due to environmental effects

PD may be intrinsically high in high latitudes (like Vela PWN; Xi+22)

- A filament of high column density (Mori+04, Martin+21) runs almost perpendicular to pulsar wind; it may change B-direction and produce low PD area







Possible Polarization of Jets

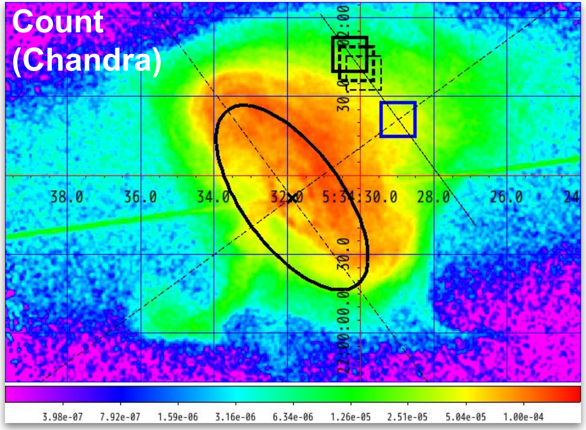
Moderately low PD areas are seen along the axis of the jets at high latitudes where PD is very high (~50%)

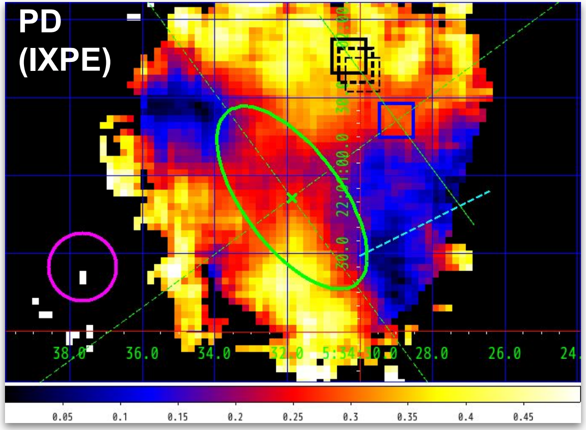
- Jets may have different PA and/or lower PD, producing observed low PD areas

We evaluated possible jet polarizations, using source (blue) and BG (black) regions

- Marginal (2σ) detection of the northern jet polarization with PD~30% and PA~120deg; estimated PA is roughly parallel to the direction of the jet

(Errors are too large for southern jet due to too small source/BG ratio)

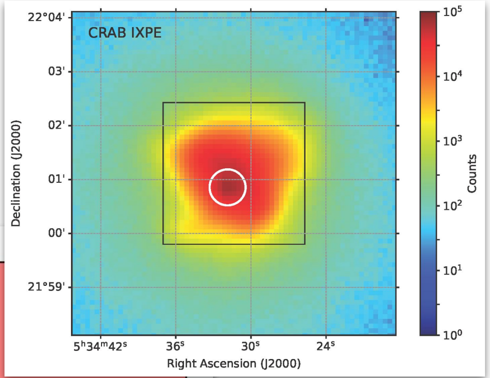


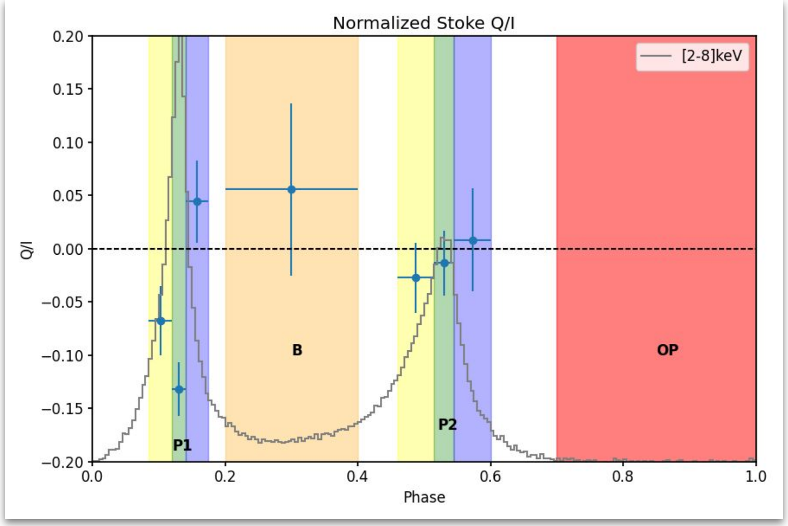


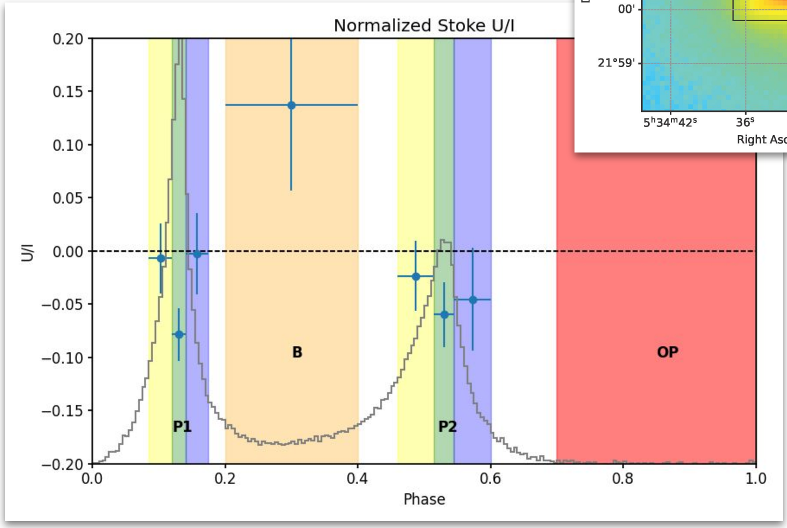
IXPE Observation of Crab PSR

PSR polarization (phase-resolved, 20" from the PSR, OP subtracted) revealed distinctive features

- Total PSR gives Q/I= -0.018 +/- 0.019 and U/I= -0.019 +/- 0.019, giving 99% UL of PD~5.7%
- Only P1 center ([0.12-0.14]) is significantly polarized; PD= (15.4+/-2.5)% and PA= (105+/-18) deg



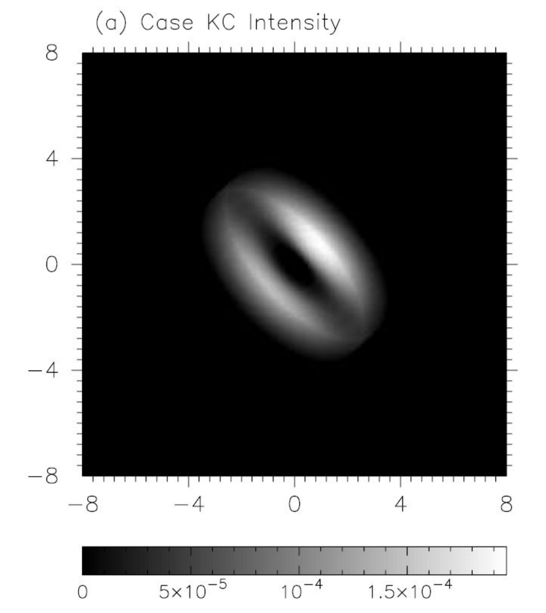


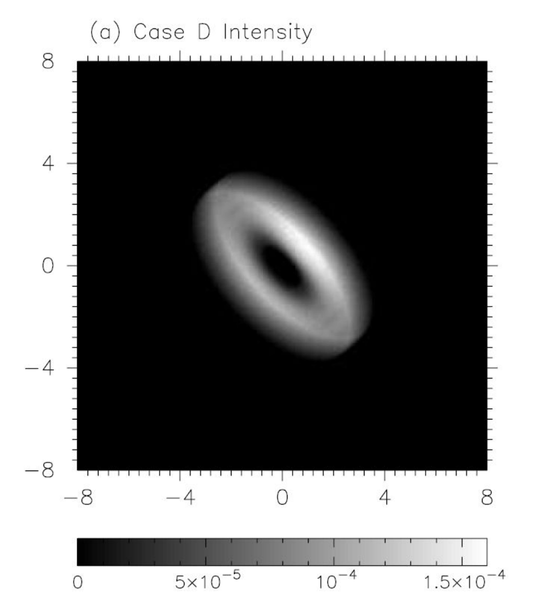


(Bucciantini+23)

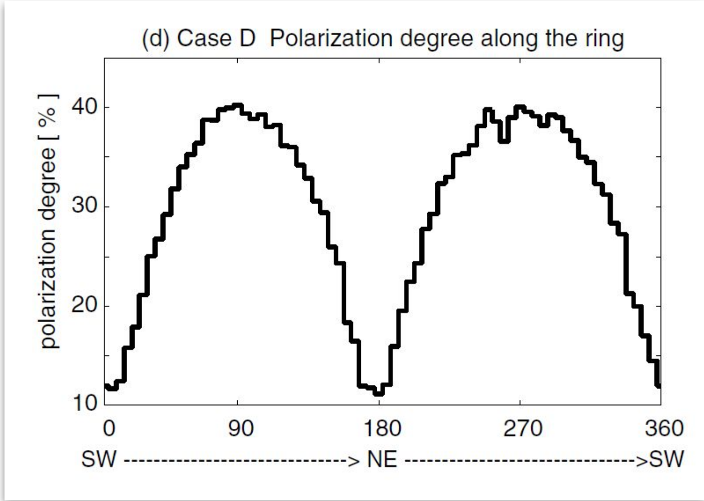
Turbulent-B Effect

While a model with toroidal-B predicts lip-shaped intensity (left), that with turbulent-B gives "ring" (middle). Reduced maximum PD (70 %->40%) predicted (right) by a model compatible with integrated PD by OSO-8





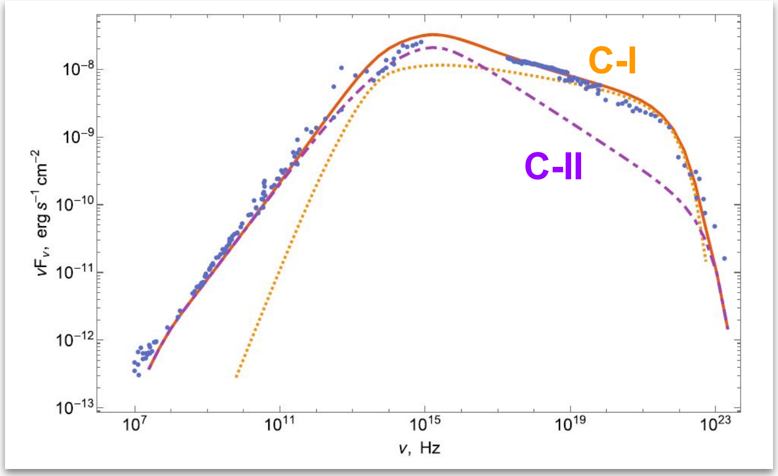
(Nakamura & Shibata 07)



Turbulent-B Model of Crab PWN

Luo+20 constructed a turbulent model of the Crab PWN that solves a long-standing "sigma problem" of the KC84 model

- Nebula contains two population of electrons
  - Component-I is accelerated at the wind termination shock
  - Component-II is accelerated in reconnecting turbulent-B and associated emission extends from radio to gamma-rays



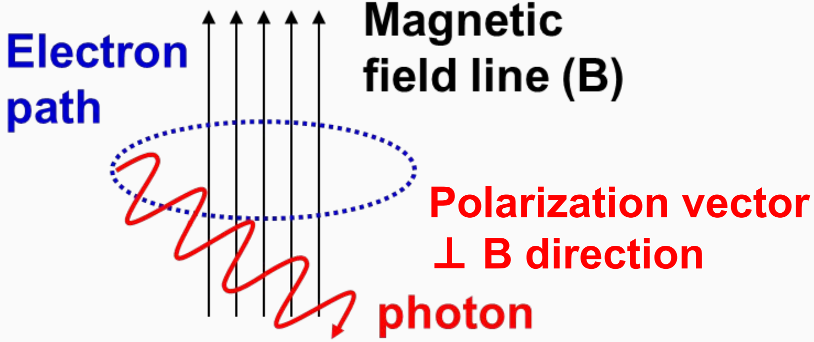
Polarization

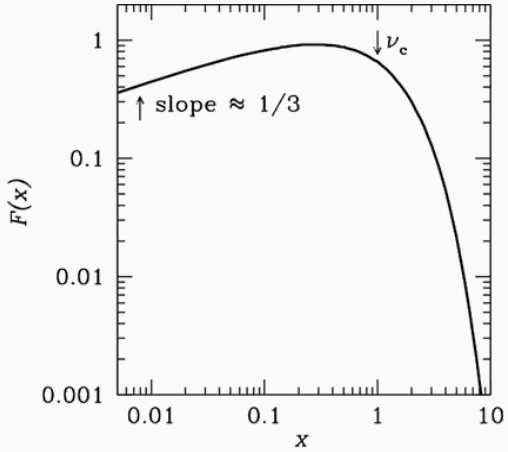
Electrons + magnetic field produce synchrotron radiation

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

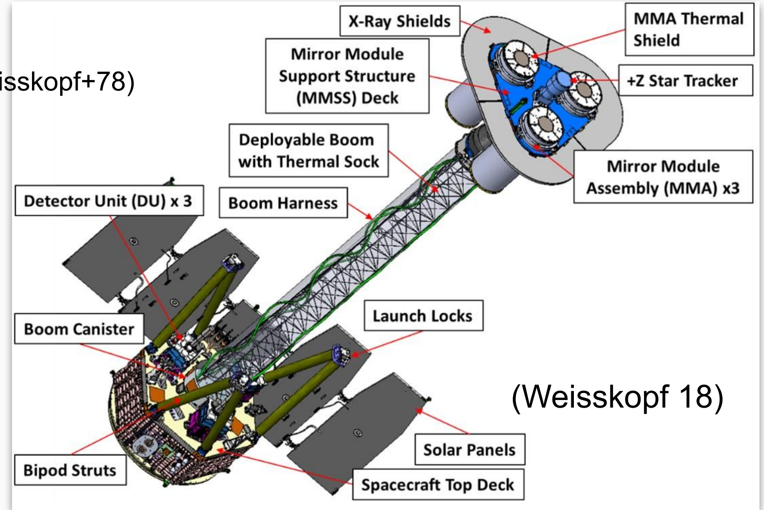




IXPE Mission

With IXPE, we can study tens of sources in soft X-ray polarization (positive detection only for Crab nebula by OSO-8; Weisskopf+78)

- NASA SMEX mission, launched in 2021 Dec, 600-km circular orbit, 0.1 deg inclination
  - Bilateral collaboration between NASA/MSFC and Italian Space Agency (w/ Japanese group providing key devices)
- Baseline mission (2 year): point-and-stare at pre-selected targets (defined by the IXPE team)
- Extended mission (1 year): Guest Observer Program
- Data are archived by NASA's HEASARC, released 1 week after the completion of the observation



- 3 x (mirror + detector)
- 2-8 keV
- 100 times more efficient (less exposure required) than OSO-8

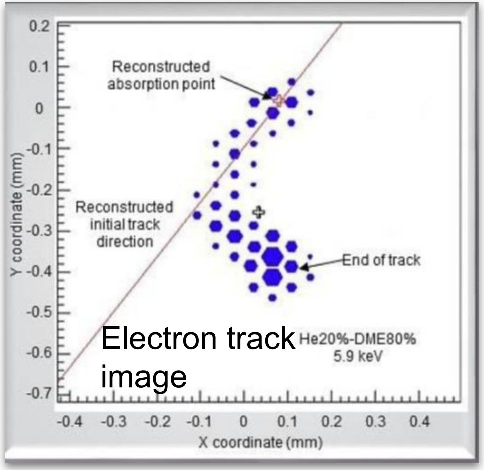
(see Weisskopf 18 for details)

IXPE Instruments

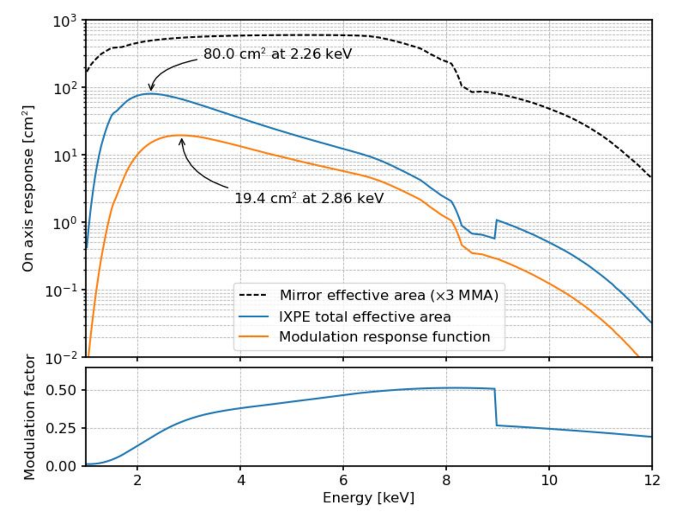
(see Soffitta+21 and Baldini+21 for latest information)

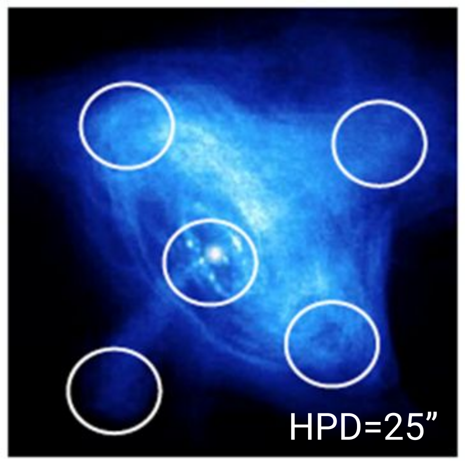
2-8 keV, 3 Mirror Module Assemblies (MMAs) and Detector Unites (DUs)

- 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



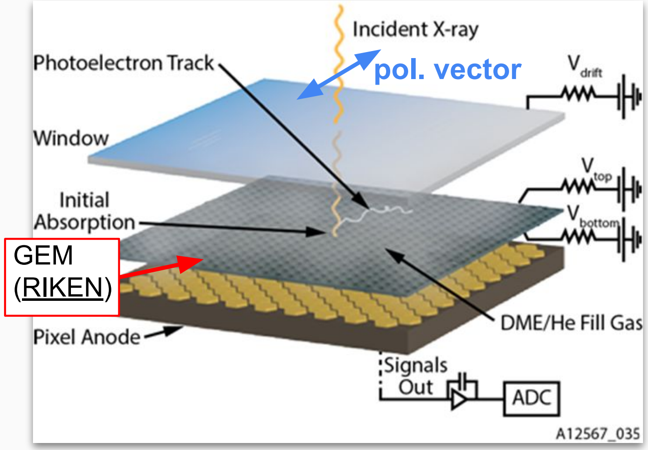


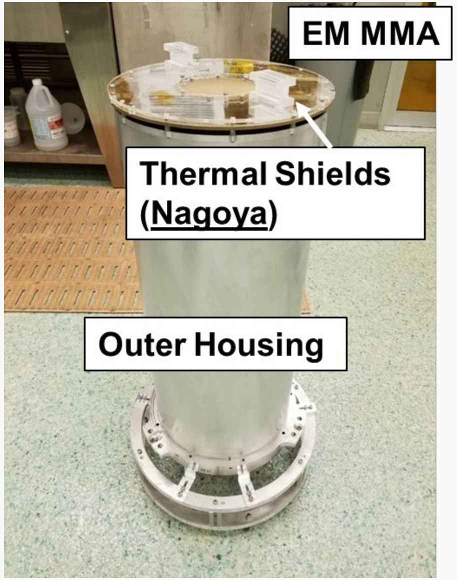
HPD=25"

Team and Mission Description

NASA SMEX mission, launched in 2021 Dec.

- Bilateral collaboration between NASA/MSFC and Italian Space Agency (ASI)
- Japanese group provides key devices





	Investigator	Collaborator	Participant	Total
IT	7	43	13	63
US	9	13	18	40
JP	0	9	9	18
UK	0	3	1	4
DE	0	3	3	6
CA	0	2	2	4
FR	0	2	0	2
CZ	0	2	2	4
NL	0	1	2	3
FI	0	2	6	8
ES	0	1	1	2
CN	0	2	2	4
Sum	16	83	59	158

Year-1 Targets

Almost all classes of sources will be observed

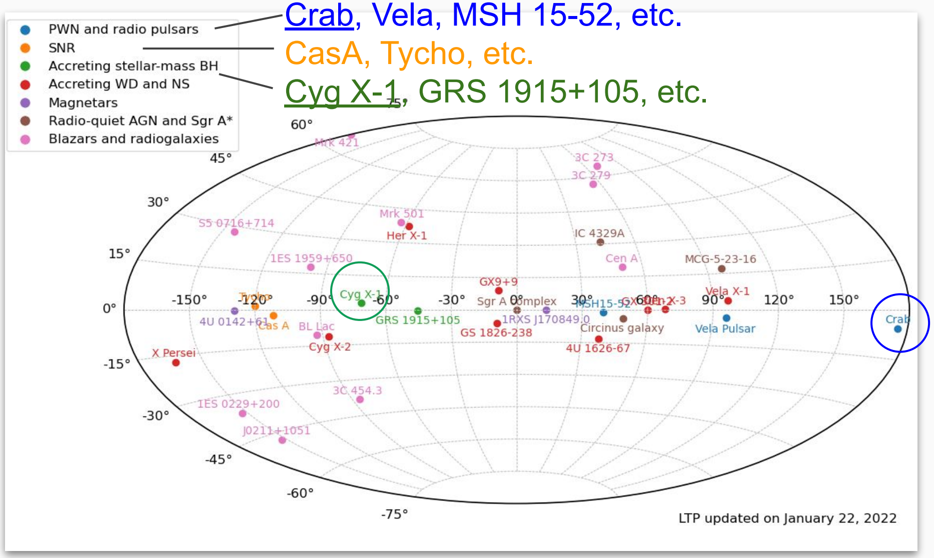
- PWN/PSR, SNR, BHB, WD/NS, Magnetar, RQ-AGN (and Sgr A*), Blazar/RG

Data are released 1 week after completion of ofs.

Crab, Vela, MSH 15-52, etc.

CasA, Tycho, etc.

Cyg X-1, GRS 1915+105, etc.



obsid	name	ra	dec	time
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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
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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/)

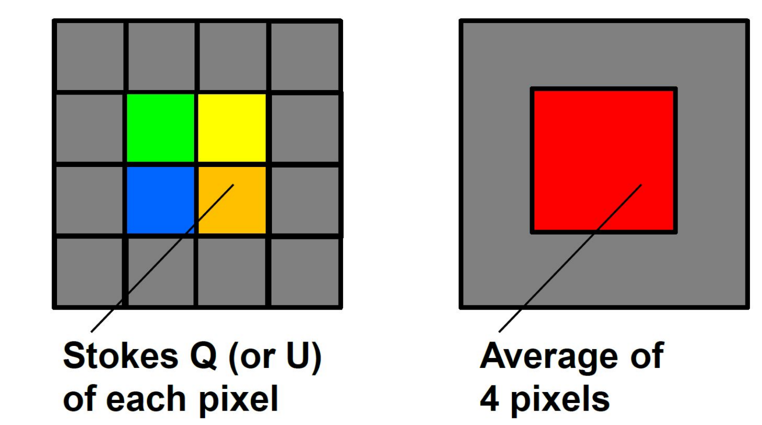
Cyg X-3	308.107	40.958	2022-10-31
MCG-5-23-16	146.917	-30.949	2022-11-06
GRO J1008-57	152.446	-58.293	2022-11-13

(https://ixpe.msfc.nasa.gov/for_scientists/ltp.html)

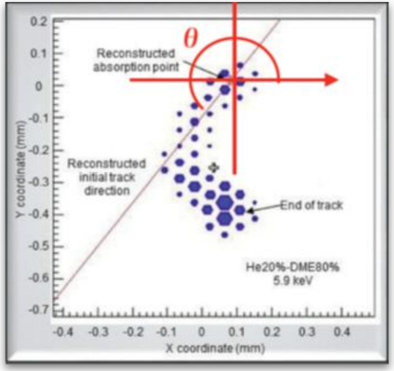
Stokes Parameter Based Analysis

We employed a Stokes Parameter based analysis to fully utilize imaging capability (cf. Kislat+15, Vink & Zhou 18)

Unlike PD/PA, Stokes parameters are additive and allow flexible binning in sky coordinate



Stokes Parameter Based Analysis (Cont'd)



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)