IXPE 衛星による「かに星雲・パルサー」のX線偏光観測
(IXPE view of Crab Nebula and Pulsar)

T. Mizuno (Hiroshima Univ.)

Y. Fukazawa, H. Takahashi, S. Zhang (Hiroshima Univ.), S. Gunji, E Watanabe, M. Terashima, Y. Kan, M. Kamikobayashi (Yamagata Univ.), T. Tamagawa, T. Kitaguchi, T. Enoto (RIKEN), K. Uchiyama, T. Takeda (Tokyo Univ. of SCIENCE/RIKEN), I. Mitsuishi, K. Kashiwagura, Y. Tawara (Nagoya Univ.), W. Iwakiri (Chuo University), K. Hayashida, K. Asakura (Osaka Univ.), M. Weisskopf, B. Ramsey, S. O'Dell (NASA/MSFC), P. Soffitta (IAPS/Rome), L. Baldini (INFN/Pisa) and IXPE Team

2022 Sep. 7, JPS meeting @ Okayama Univ. of Science

Crab nebula is a supernova remnant (SN1054) and pulsar wind nebula (PWN) in the constellation of Taurus

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

One of the most studied astrophysical systems (from radio through optical to X-ray/γ-ray, imaging, photometry, spectroscopy and polarimetry)

Promising environments where the physics of particle acceleration and relativistic outflows ($\Gamma=10^6$) can be investigated


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

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

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)
- 3 x (mirror + detector), 2-8 keV, HPD=25", 100 times more efficient than OSO-8
- Imaging-spectro-polarimetry in X-rays for the first time => Crab PWN&PSR

(Weisskopf18)
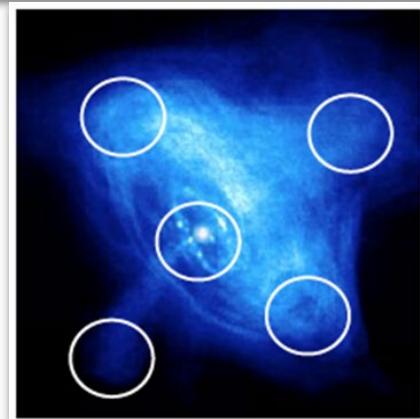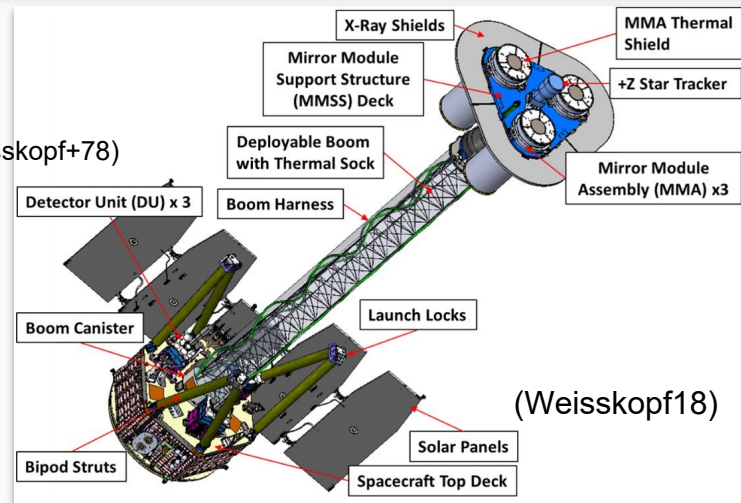
PSR polarization (phase-resolved, 20" from the PSR, OP subtracted) revealed <u>distinctive features</u>

- 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 is significantly polarized (PD~15 % and PA~105 deg)
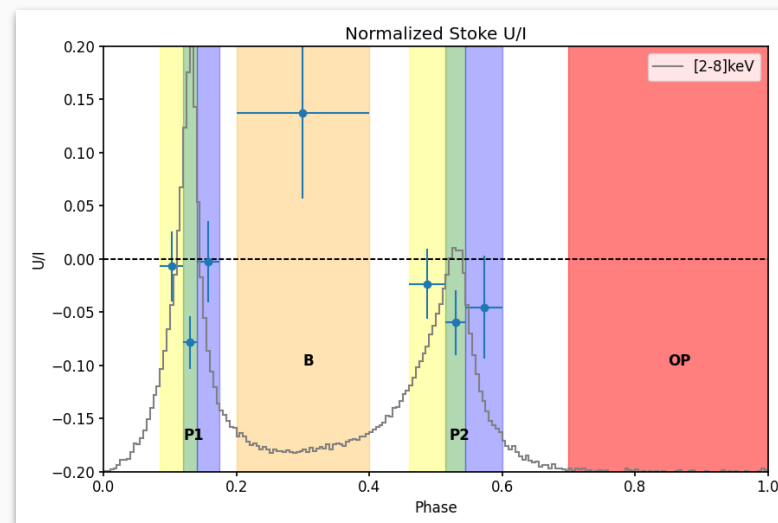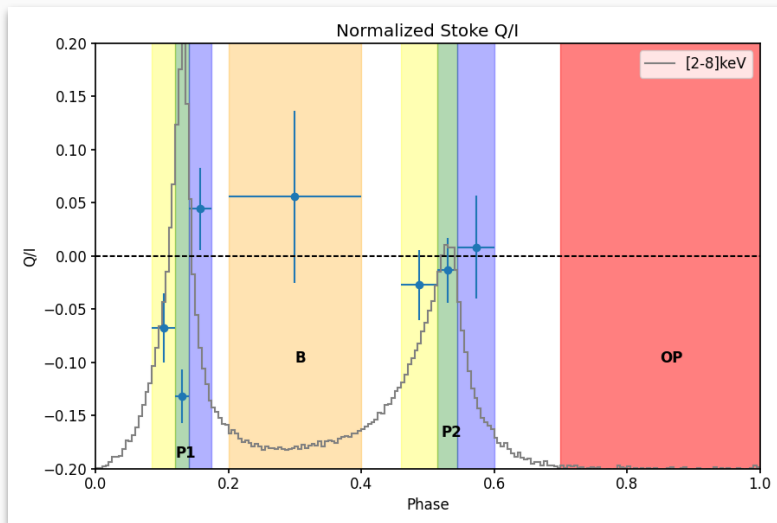
Total PSR gives Q/I= -0.018 +/- 0.019 and U/I= -0.019 +/- 0.019, giving 99 % <u>UL of PD</u>~5.7 %

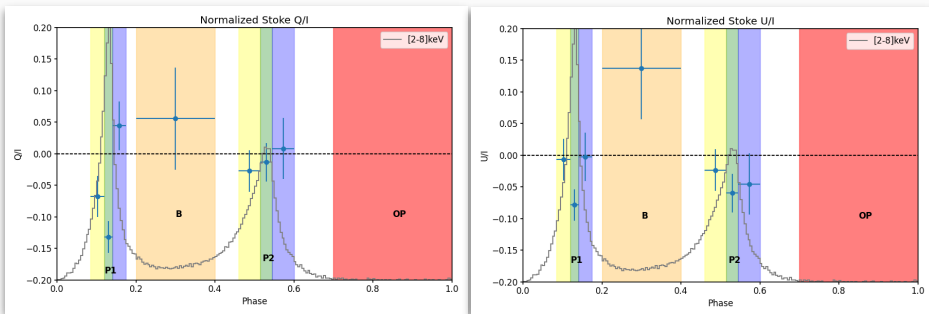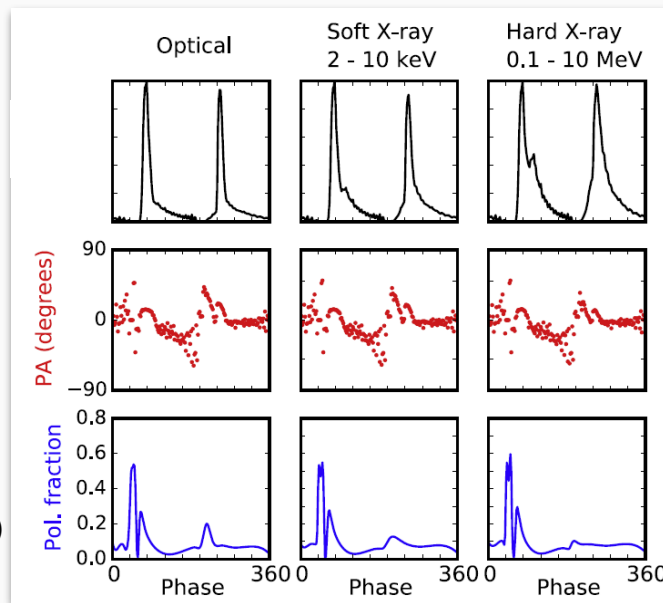<u>Only</u> P1 center is significantly polarized (PD~15 % and PA~105 deg)

- Low PD seems not compatible with optical (PD=5.5 %; Slowikowska+09) and most of models
- High PD only in P1 center also difficult to explain
- =>Need detailed comparison with (new) model calc.

(Harding and Kalapotharakos 17)

Total PWN+PSR maps (PSR contribution small); <u>Polarization PWN map in X-ray for the first time</u>

- Left: PD/100 (smoothed)
- Right: Intensity map with polarized B-direction
    - B-direction broadly follows the emission torus, w/ unpolarized regions at NE/SW edges
    - More polarized regions found outside of main torus (north&south;PD~45 % and PA~160 deg)
   - PD is more asymmetric than intensity with respect to the nebula axis
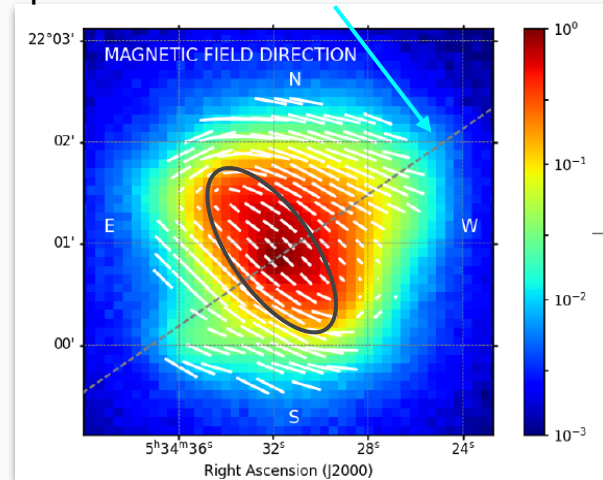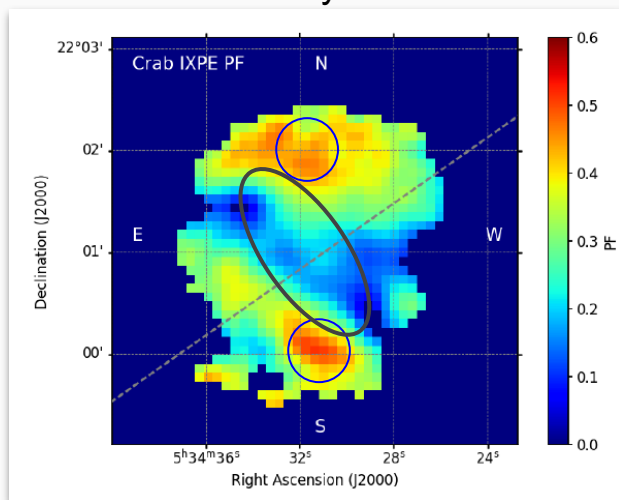
B-direction broadly follows the emission torus, w/ unpolarized regions at NE/SW edges

(More polarized regions found in north/south of main torus w/ PD~45 %)

(PD is more asymmetric than intensity wrt. nebula axis)

- Unpol. regions at edges expected due to rapid swing of PA (Nakamura & Shibata 07) who obtained turbulent-B fraction to be 60 % to reproduce integrated PD by OSO-8
- With IXPE, we can directly compare PD/PA profiles and better constrain turbulent B
- (Other interesting features also to be investigated to study development of B turbulence, etc.)

(Nakamura & Shibata 07)

b=0.6
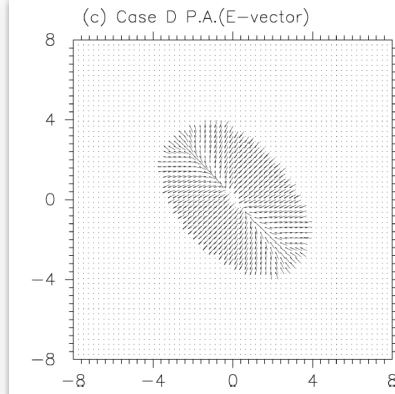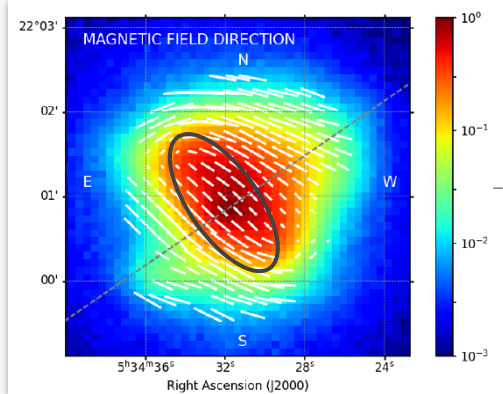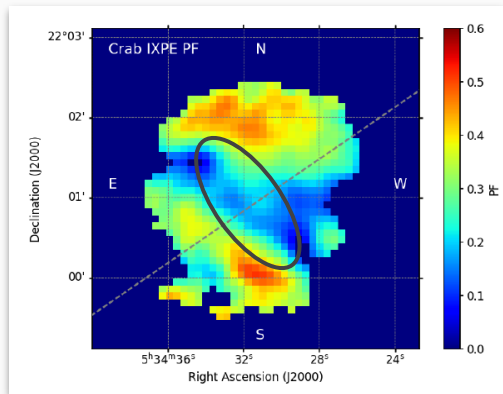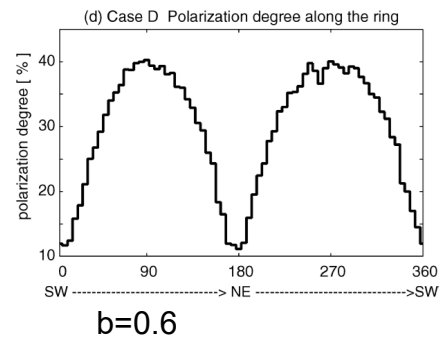
IXPE was launched in 2021 Dec. and allowed for the first time the simultaneous phase and space resolved X-ray polarimetry of the Crab PSR/PWN

- PSR:
  - Total PSR signal gives 99 % UL of PD~5.7 %; not compatible with existing modeling to explain energy dependence (opt.―soft X―hard X)
  - Only P1 is significantly polarized; also difficult to explain
- PWN:
  - B-direction follows the torus and shows low PD areas at edges, likely due to rapid swing of PA. We can directly compare data and model to constrain turbulent-B
  - Larger and more asymmetric PD outside of torus; give constraints on development of B turbulence

Thank you for your attention

- Bucciantini et al. arXiv:2207.05573
- Weisskopf et al. 1978, ApJL 220, 117
- Weisskopf 2018, Galaxies 6,33
- Kislat et al. 2015, Astroparticle Physics 68, 45
- Vink & Zhoug 2018, Galaxies 6, 46
- Dean et al. 2008, Science 321, 1183
- Feng et al. 2020, Nature Astronomy 4, 511
- Slowikowska et al. 2017, MNRAS 397, 103
- Vadawale et al. 2017, Nature Astronomy 2, 50
- Harding and Kalapotharakos 2017 ApJ 840, 73
- Nakamura and Shibata 2007, MNRAS 381, 1489
- Bucciantini et al. 2017, MNRAS 470, 4066
- 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

With IXPE, we can study tens of sources in soft X-ray polarization (positive detection only for Crab nebula by OSO-8; Weisskopf+78)
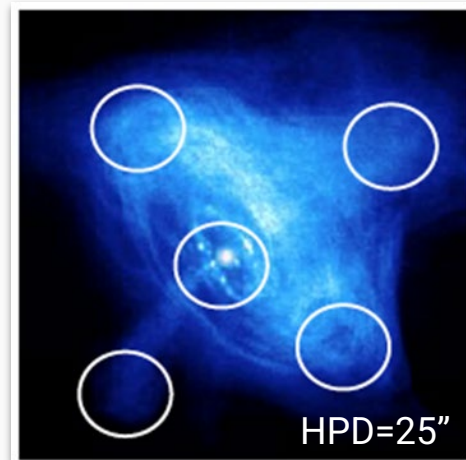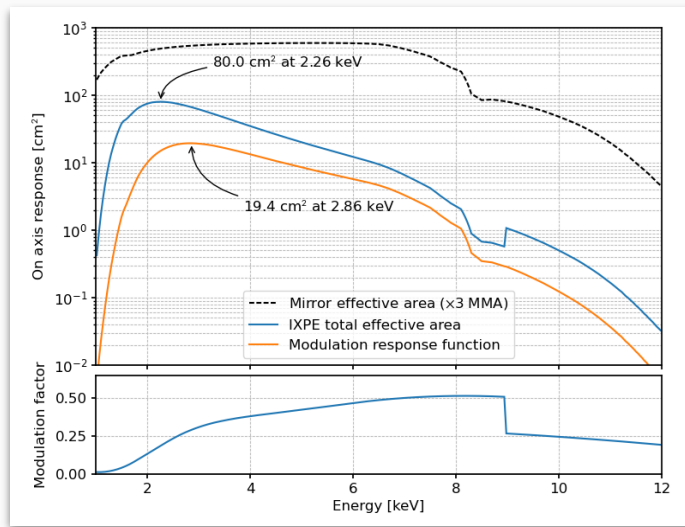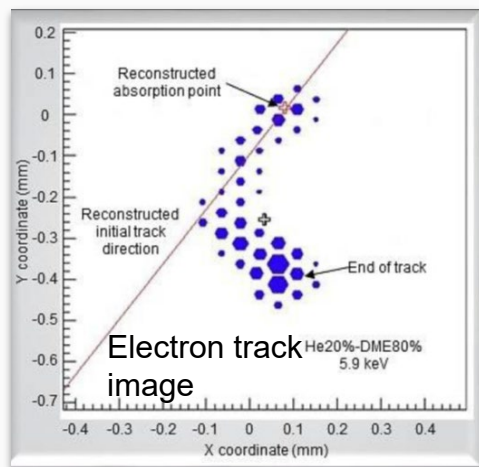
- NASA SMEX mission, launched in 2021 Dec, 600-km circular orbit, 0.1 deg inclination
  - Bilateral collaboration between NASA/MSFC and Italian Space Agency (w/ Japanese group providing key devices)
- Baseline mission (2 year): point-and-stare at pre-selected targets (defined by the IXPE team)
- Extended mission (1 year): Guest Observer Program
- Data are archived by NASA's HEASARC, released 1 week after the completion of the observation

(Weisskopf18)
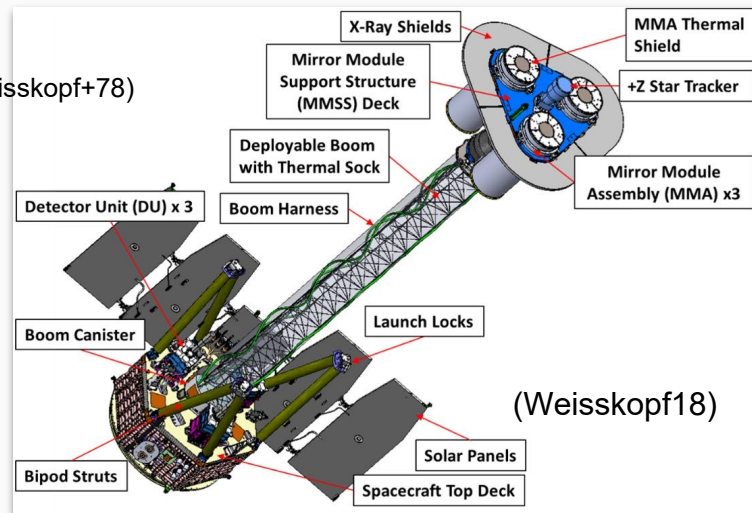
- 3 x (mirror + detector)
- 2-8 keV
- 100 times more efficient (required exposure is shorter) than OSO-8

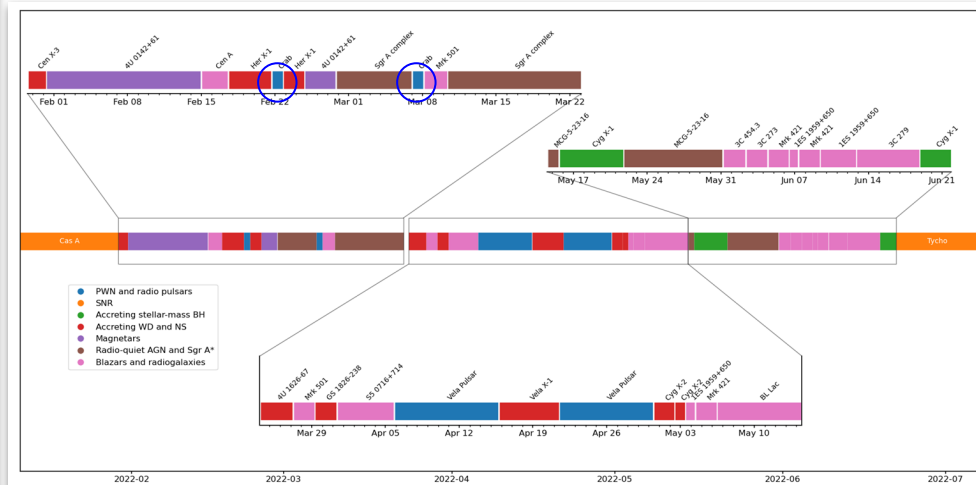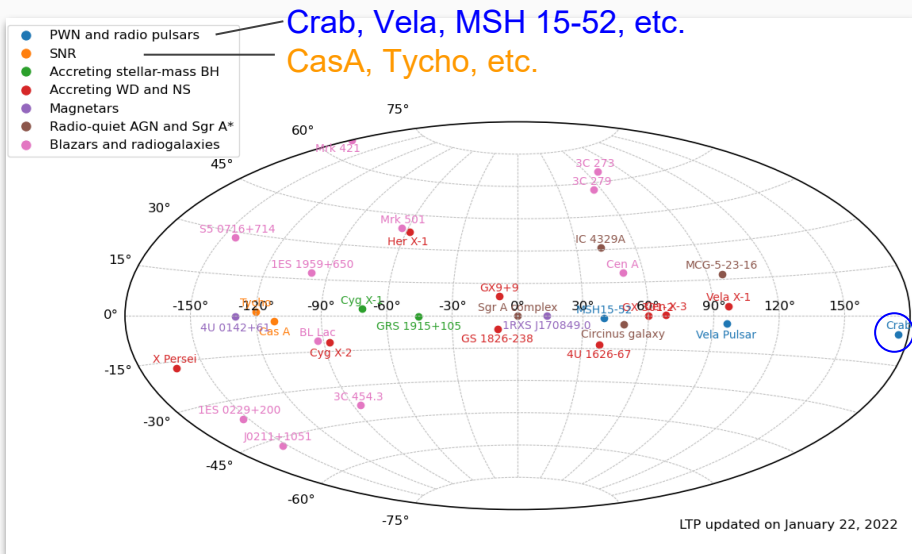2-8 keV, 3 Detector Unites (DUs) and Mirror Module Assemblies (MMAs)

- 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
  - Stokes parameter based analysis to use imaging-polarimetry capability (Kislat+15, Vink & Zhou 18)

Electron track image

He20%-DME80% 5.9 keV

80.0 cm^2 at 2.26 keV

19.4 cm^2 at 2.86 keV

Mirror effective area (x3 MMA)
IXPE total effective area
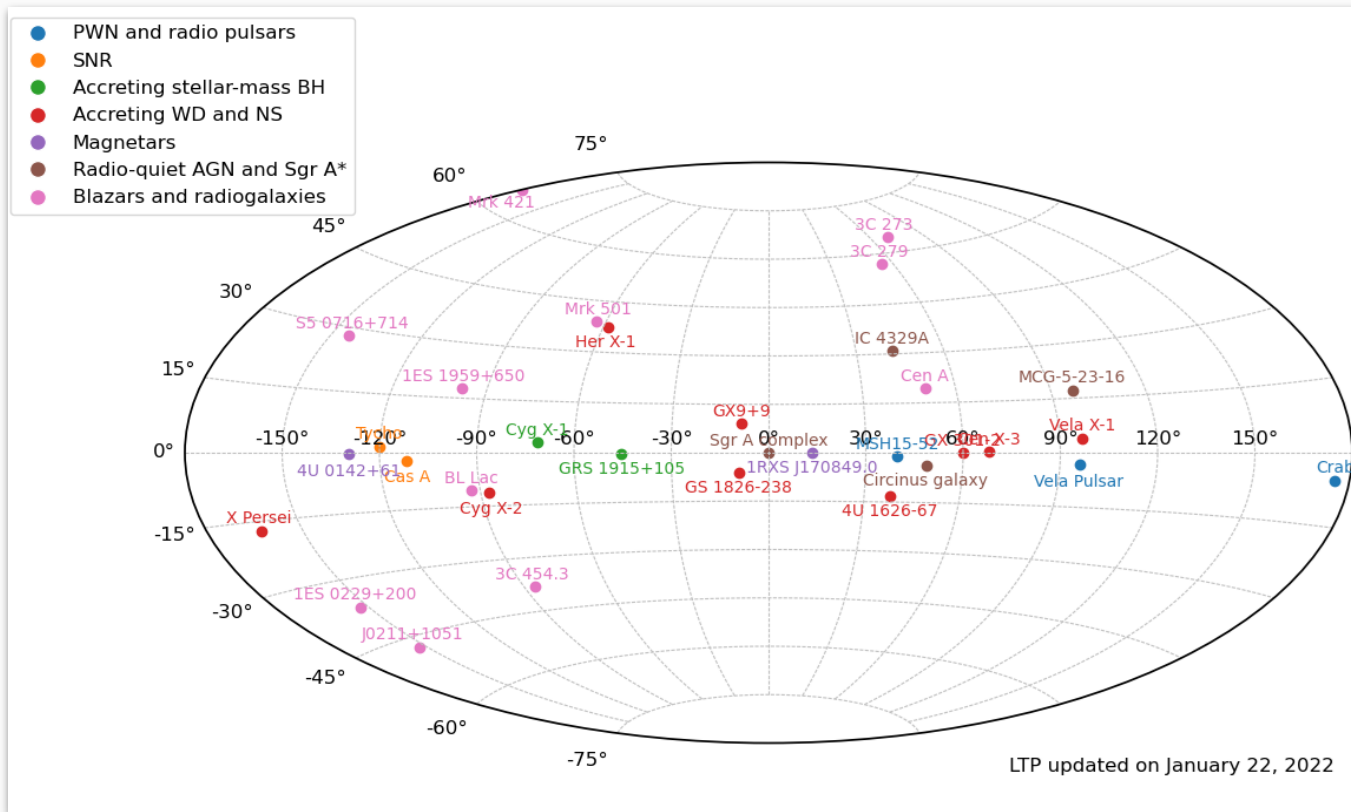Modulation response function

HPD=25"

Almost all classes of celestial sources will be observed

- PWN/PSR, SNR, BHB, WD/NS, Magnetar, RQ-AGN (and Sgr A*), Blazar/RG
- Crab was observed twice (btw. Feb. 21st and Mar. 7th) with total exposure ~92 ks
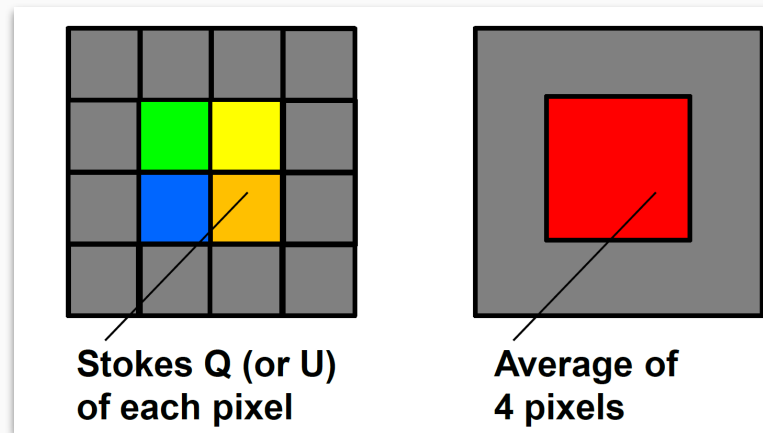
Almost all classes of celestial sources will be observed

T. Mizuno

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 Q (or U) of each pixel

Average of 4 pixels

Event-by-event Stokes parameters:

- $i_k=1$, $q_k=2\cos2\theta_k$, $u_k=2\sin2\theta_k$

Stokes parameters of the entire data:

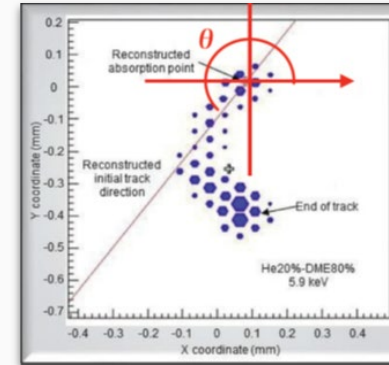- $I=\Sigma i_k$, $Q=\Sigma q_k$, $U=\Sigma u_k$

Normalized Stokes parameters, PD & PA:

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

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)

PSR+PWN's polarized properties by integrating events within 2.5' from the PSR

- Change in PA btw. low (2-4 keV) and high (4-8 keV) energy bands
- Off pulse (OP; phase [0.7-1.0]) gives PD~20 % and PA~145 deg
  - More polarized than total emission (suggesting PSR has lower level of polarization)
  - PA ~20 deg larger than PWN's symmetry axis and those in hard X-ray/γ-ray (~125 deg; Ng & Romani 04, Dean+08)
    - Indicating spatial variation of pol. (and B) direction
  - Also ~10 deg smaller than OSO-8 result (might reflect the variability of the PWN)
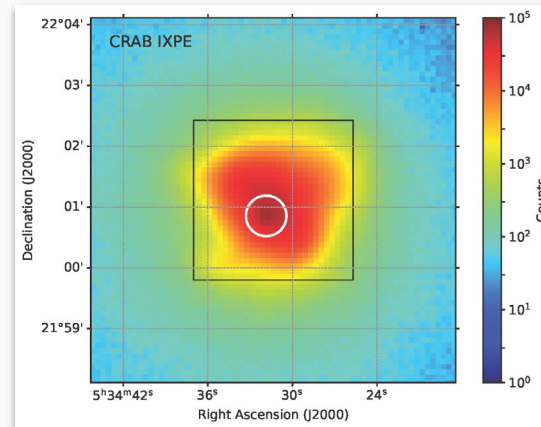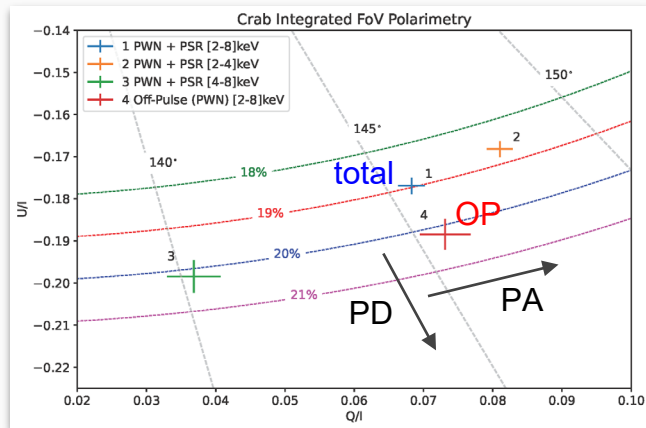
Total gives Q/I= -0.018 +/- 0.019 and U/I= -0.019 +/- 0.019, giving 99 % UL of PD~5.7 %
(Only) P1 center is significantly polarized (PD~15 % and PA~105 deg)

- Low PD not compatible with most of PSR models (e.g., polar cap and outer gap model)
- Two-pole caustic model predicts depolarization due to rapid swing of PA, but seems not compatible with high PD in the P1 center
  - Intrinsic depolarization is likely required. Need more data and detailed comparison with (new) model calculations
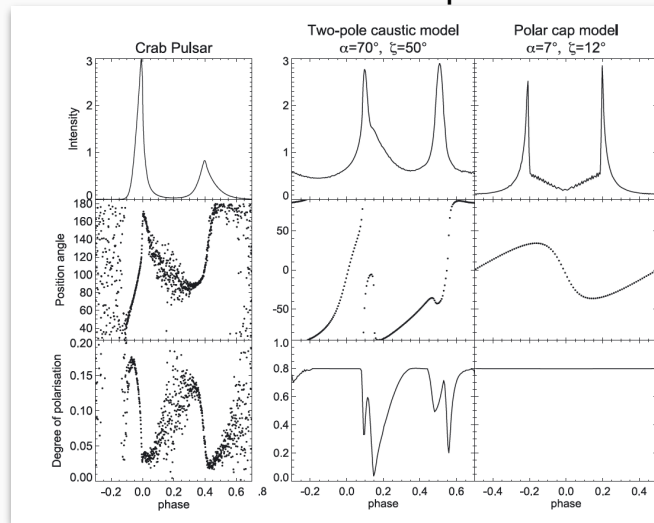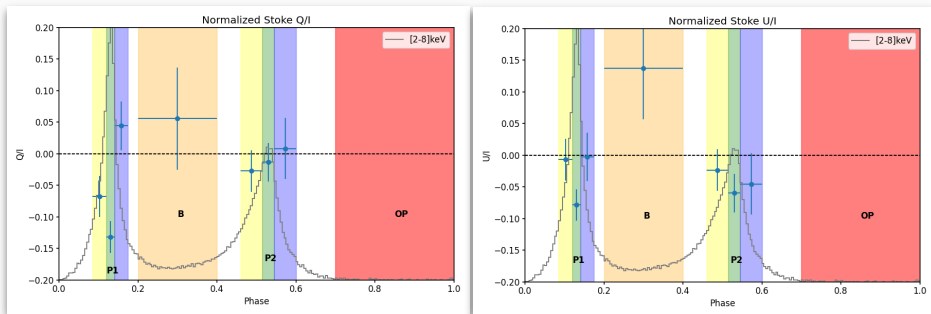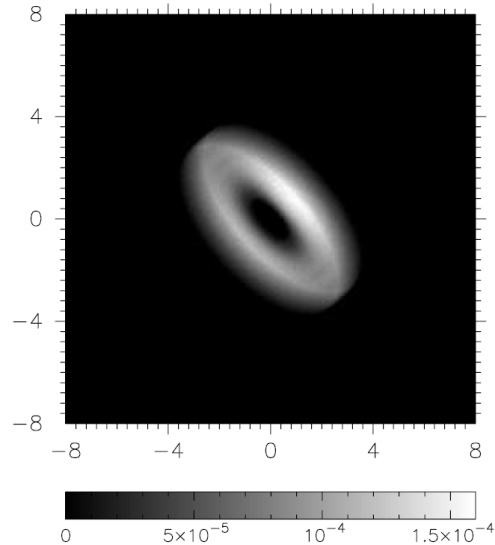

(Slowikowska+09)

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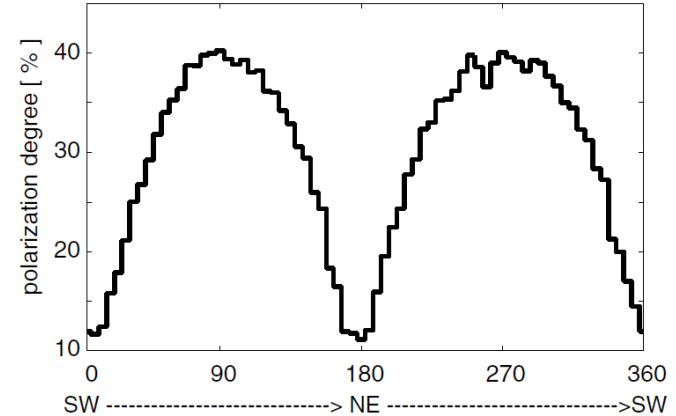

(a) Case KC Intensity
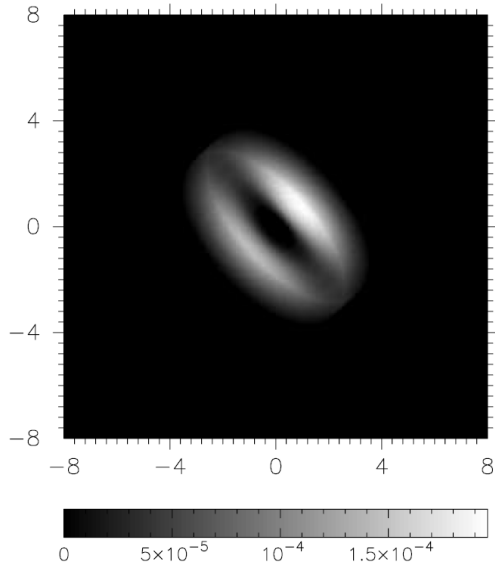
(a) Case D Intensity

(d) Case D Polarization degree along the ring

B-direction broadly follows the emission torus, w/ unpolarized regions at NE/SW edges

More polarized regions found in north/south of main torus (w/ PD=40-50 %)

PD is more asymmetric than intensity (wrt. nebula axis)

- PD outside of torus is ~2 times higher than simple synchrotron turbulent modeling by Bucciantini+17, suggesting level & development of turbulent weaker & patchier
- More asymmetric PD distribution than intensity requires the level of turbulence anti-correlates with ordered B strength

(Bucciantini+17)