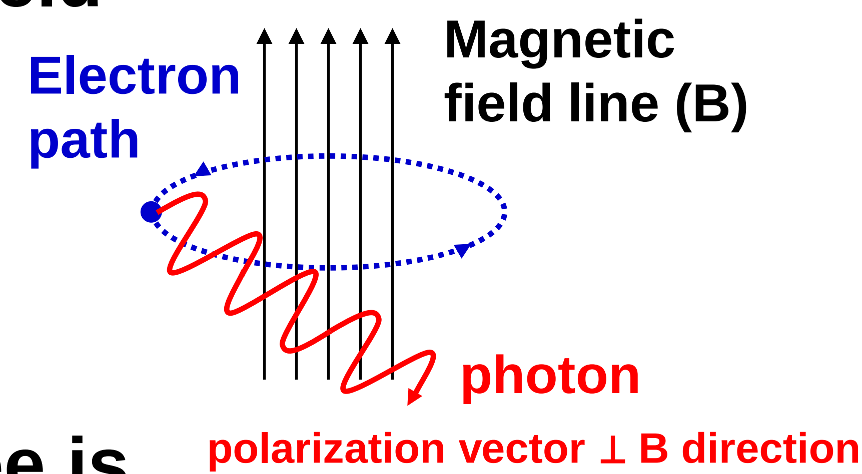
X-ray Polarimetry Mission IXPE
(X線偏光観測衛星測IXPE)

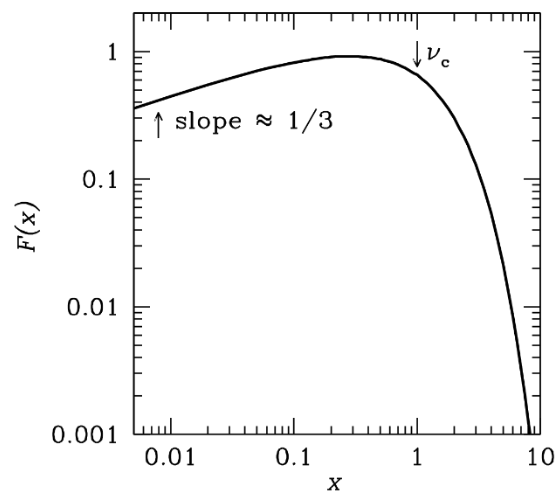
November 11, 2020 @ 11th OISTER WS

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

Polarization (1)

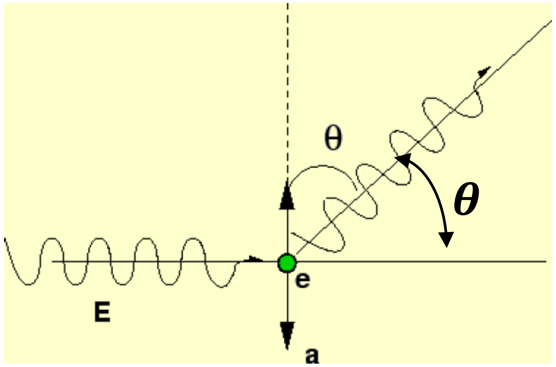
- Electrons + magnetic field produce synchrotron radiation
- Unique probe to B (and accelerated electrons)
- High polarization degree is expected ($\Pi_{\mathrm{max}} = \frac{p+1}{p+7/3} \sim 0.7$)
- X-ray polarimetry can probe B-field configuration around freshly-accelerated electrons ($h\omega_{\mathrm{p}} \sim 0.29 \frac{3\gamma^2 eB}{2m_{\mathrm{e}}c}$)

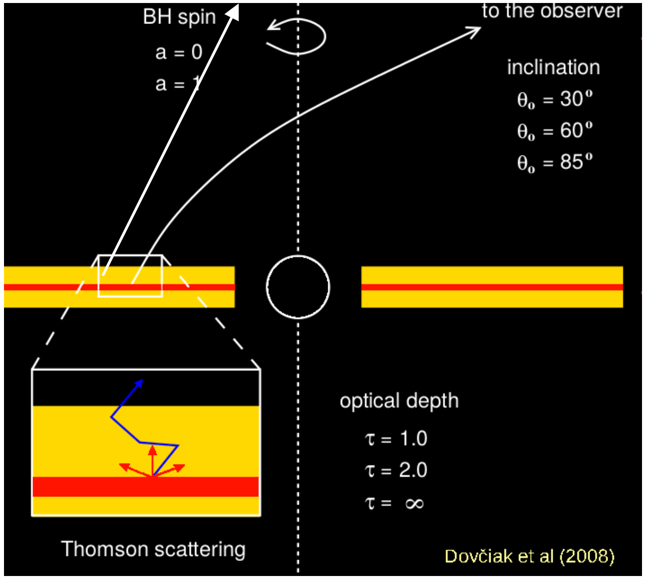




Polarization (2)

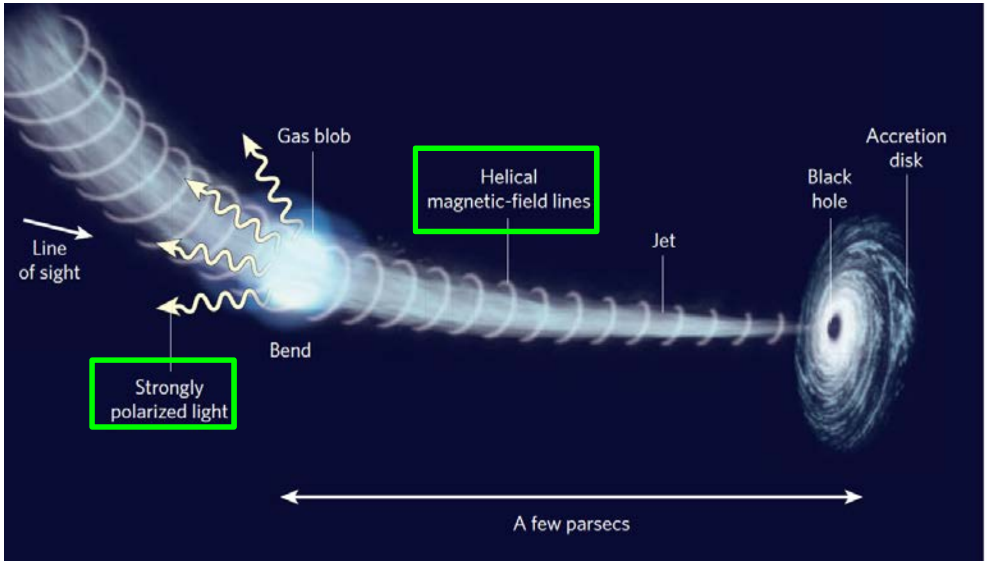
- **Reflected photons are polarized ($\Pi = \frac{1-(\cos\theta)^2}{1+(\cos\theta)^2}$)**
- **Unique probe to geometry of compact objects (light source and accretion disk) not accessible by imaging**
- **Also probes relativistic effect around a black hole (BH)**
- **We can investigate disk & space-time geometry using X-ray polarimetry**

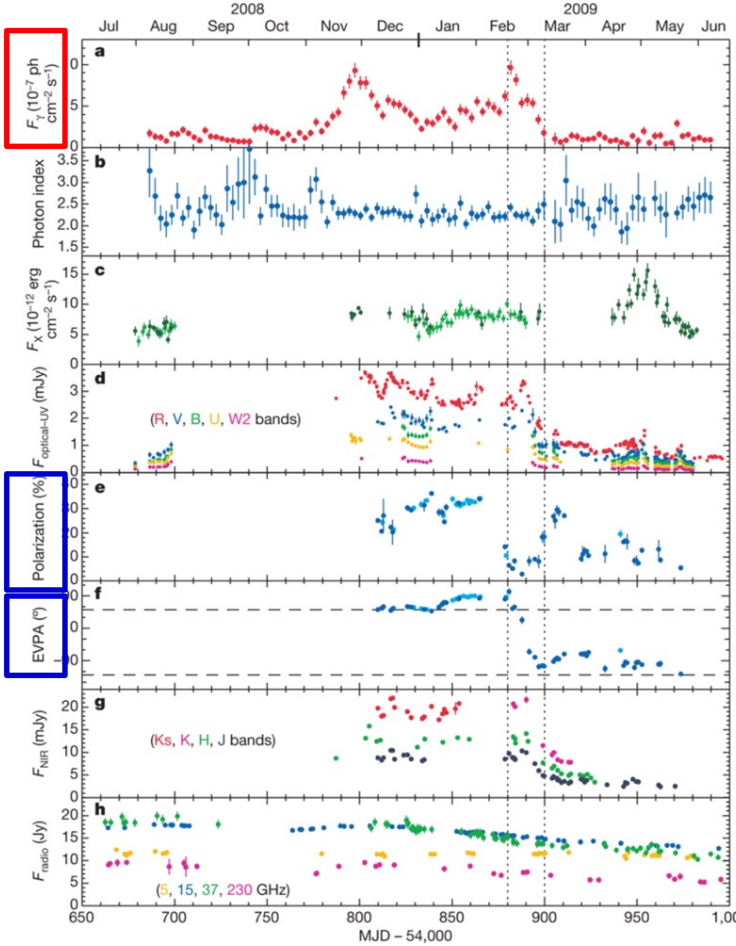




3C279 (Abdo +10, Nature 463, 919)

- **Optical polarization aided with MW obs. revealed (possible) helical magnetic field associated with flare**





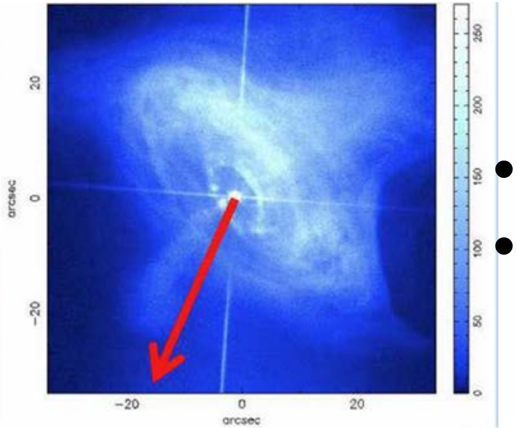
Imaging-Spectro-Polarimetry

- **Polarization is powerful probe to magnetic field and source geometry**
  - **It improves our understanding of objects**
  - **Multiwavelength observation is important**
- **X-ray polarimetry has been unexplored but is key in high-energy astrophysics**
  - **Probes B-field around freshly-accelerated electrons, geometry (disk & space-time) in the vicinity of BH**
- **IXPE is the first dedicated X-ray imaging-polarimetry observatory**

X-ray/γ-ray Polarimetry

- **Only a few measurements in X-ray/γ-ray**
  - **Integral (Crab, Cyg X-1) in >100 keV**
  - **PoGO+ (Crab, Cyg X-1) in 20-160 keV**
  - **ASTROSAT (Crab, Cyg X-1) in > 100 keV**
  - **Hitomi SGD (Crab) in >60 keV**
- **In soft X-ray (<10 keV), Crab Nebula is first and only positive detection**

Weisskopf 18



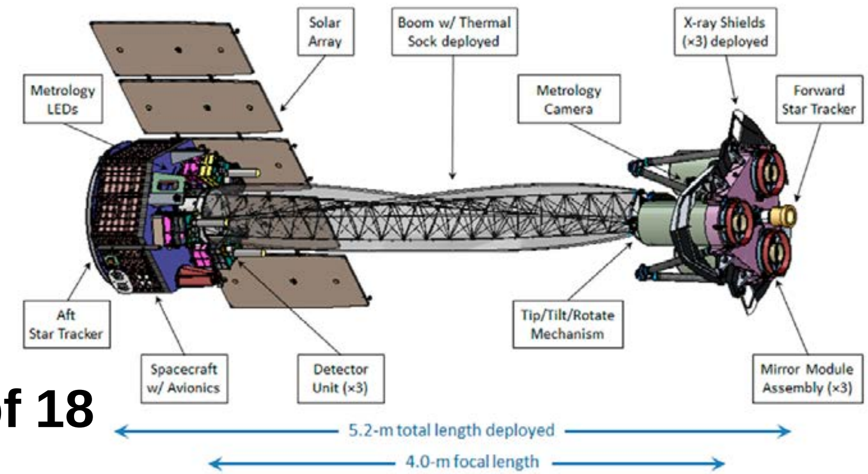
OSO-8 satellite (1975-)

- **Graphite Bragg crystal**
- **Crab nebula (w/o pulsar):**

$$PD = 19\% \pm 1\%$$
$$PA = 156^\circ \pm 2^\circ$$

IXPE Mission

- **With IXPE, we can study several 10s sources in soft X-ray polarization**
  - **NASA SMEX mission, launch in late 2021, baseline duration 2 years**
  - **Japanese group provides key devices of the instruments**
- **Data are made public after validation**



2-8 keV
FOV=12.9’ x 12.9’, HPD=25”
3×(mirror + detector)

Weisskopf 18

IXPE Imaging X-Ray Polarimetry Explorer

Team and Mission Description

- **Bilateral collaboration between NASA/MSFC and Italian Space Agency (ASI)**
- **Japanese group provides key devices; mirror thermal shield and Gas electron multiplier**

NASA Marshall Space Flight Center	PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving
asi agenzia spaziale italiana	Detector system funding, ground station
Ball	Spacecraft, payload structure, payload, observatory I&T
iaps, INAF Istituto Nazionale di Astrofisica / National Institute for Astrophysics, INFN, OAC, OHB Italia	Polarization-sensitive imaging detector systems
CU LASP	Mission operations
Roma Tre Università degli Studi, Stanford University	Scientific theory
McGill	Co-Investigator
MIT Massachusetts Institute of Technology	Co-Investigator

Science Advisory Team

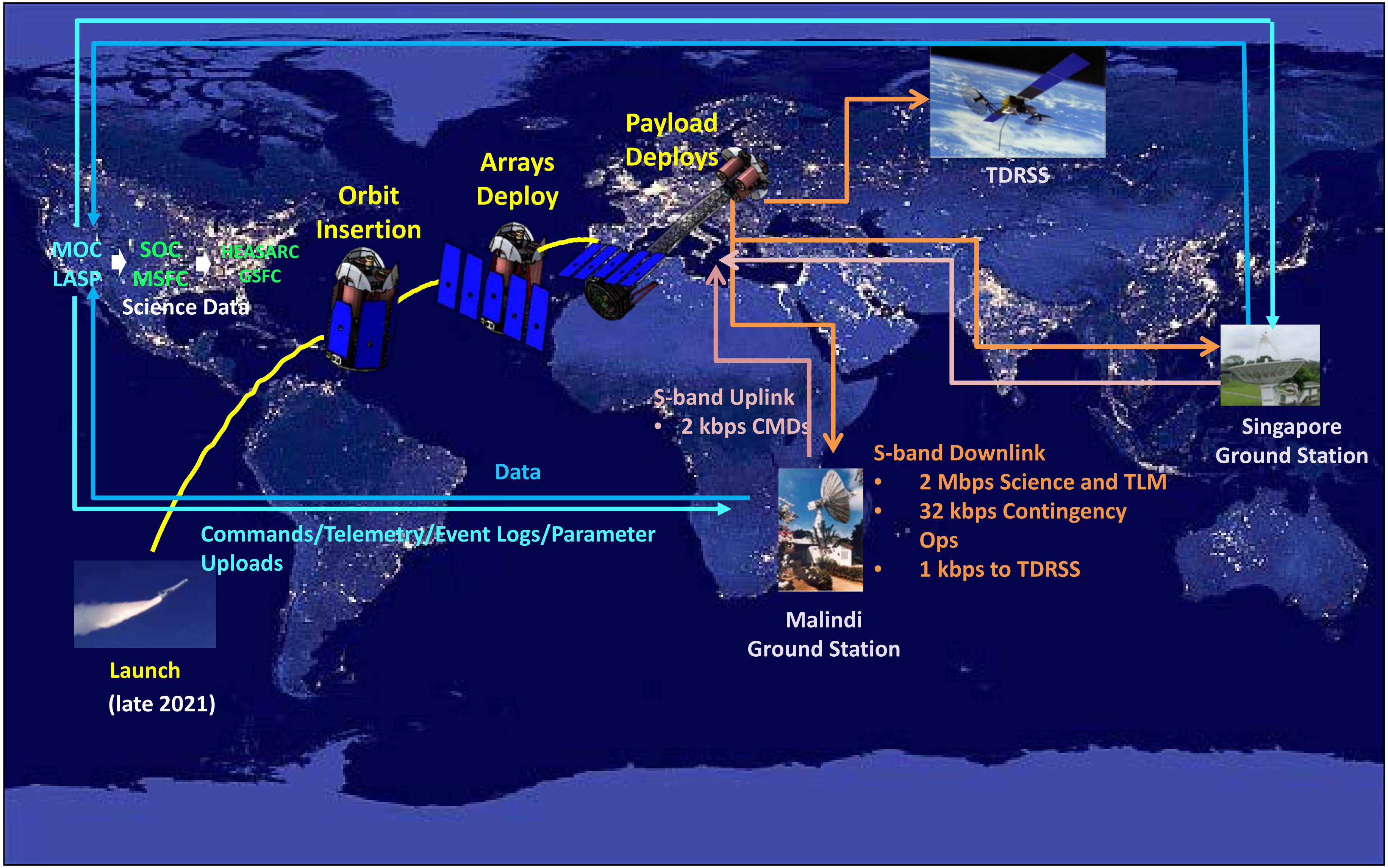
PI: Martin Weisskopf
(NASA Marshall Space Flight Center)

- **Launch on a Falcon 9 from KSC**
- **600-km circular orbit at 0.1 deg inclination**
- **2 year baseline mission, 1 year optional extension with GO program**
- **Point-and-state at pre-selected target**
- **Science Operation Center (SOC) at MSFC**
- **Mission Operation Center (MOC) at CU/LASP**
- **Malindi ground station (Singapore Backup)**

Operation and Data Archive/Release

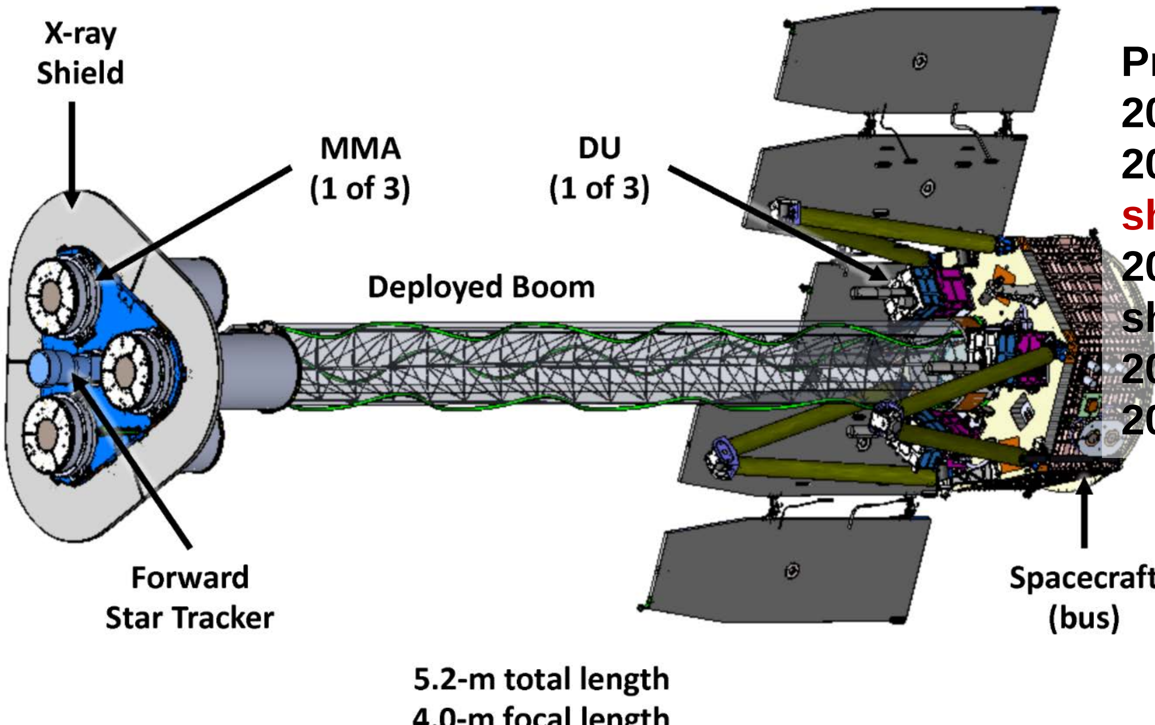
- 2+1 years mission, point-and-state at pre-selected target
- Observing plans (OPs) for 1^{st} and 2^{nd} years are defined by the IXPE team
  - If mission is extended, OP will be GO-based
- MOC generates OP every week (TOO possible)
- Data are archived by NASA's HEASARC and released with the following timing:
  - (First three months) 1 months after completion of the observation (data for 90% of the scheduled observing time are received by MOC)
  - (After that) 1 week after the completion of the obs.

Ground Station Summary



IXPE Observatory (Deployed)

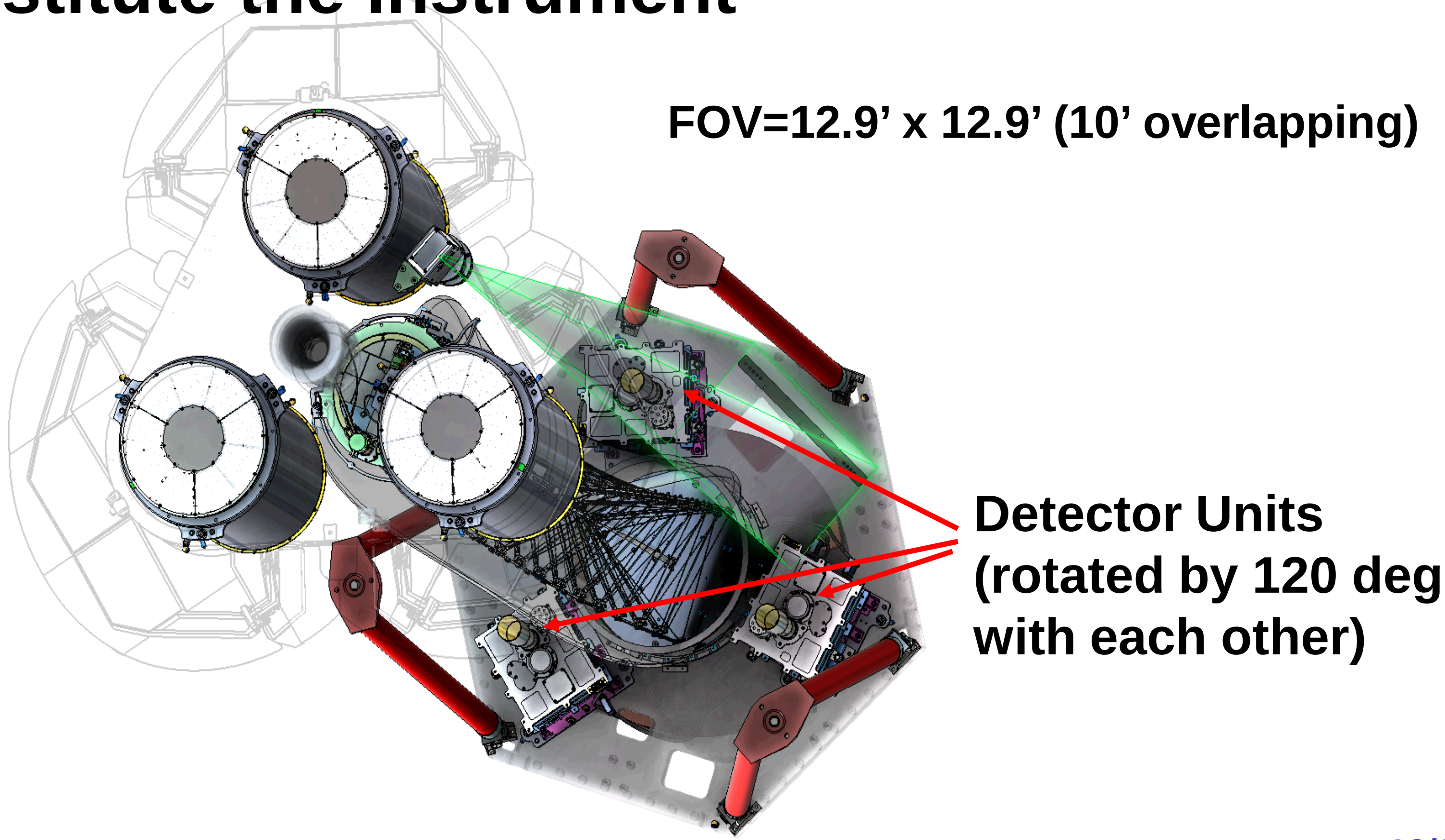
- **2-8 keV, 3 Detector Units (DUs) and Mirror Module Assemblies (MMAs)**
- **Japanese group provides key devices (GEM for DU and thermal shield for MMA)**



Project Status:
2017/1 accepted for NASA SMEX
2020/3E production of TS completed, shipped to US
2020/3-5, NASA/MSFC almost shutdown due to COVID-19
2020/6 env. test of MMA completed
2021/E launch

Detector Instrument

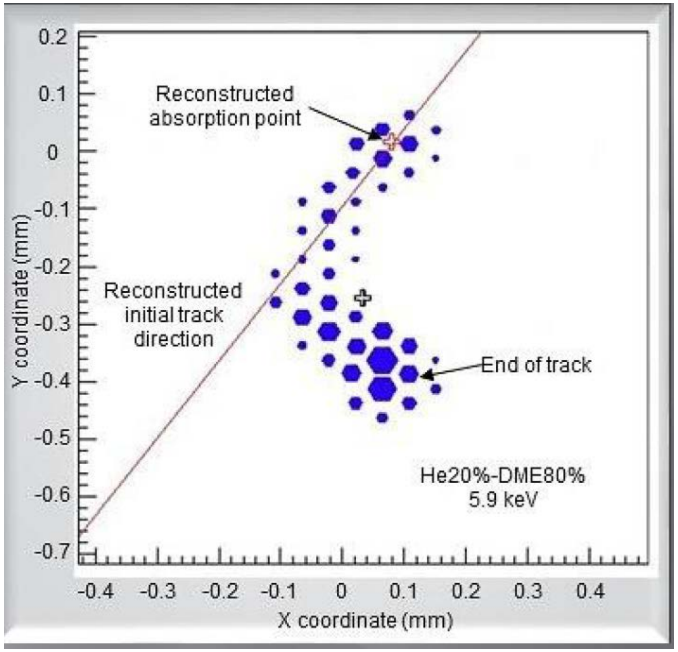
- **Three Detector Units (DUs) and single Detector Service Unit (on underside of deck) constitute the instrument**



Pol. Measurement Principle

- **Direction of photoelectron is parallel (on average) to incident X-ray polarization**

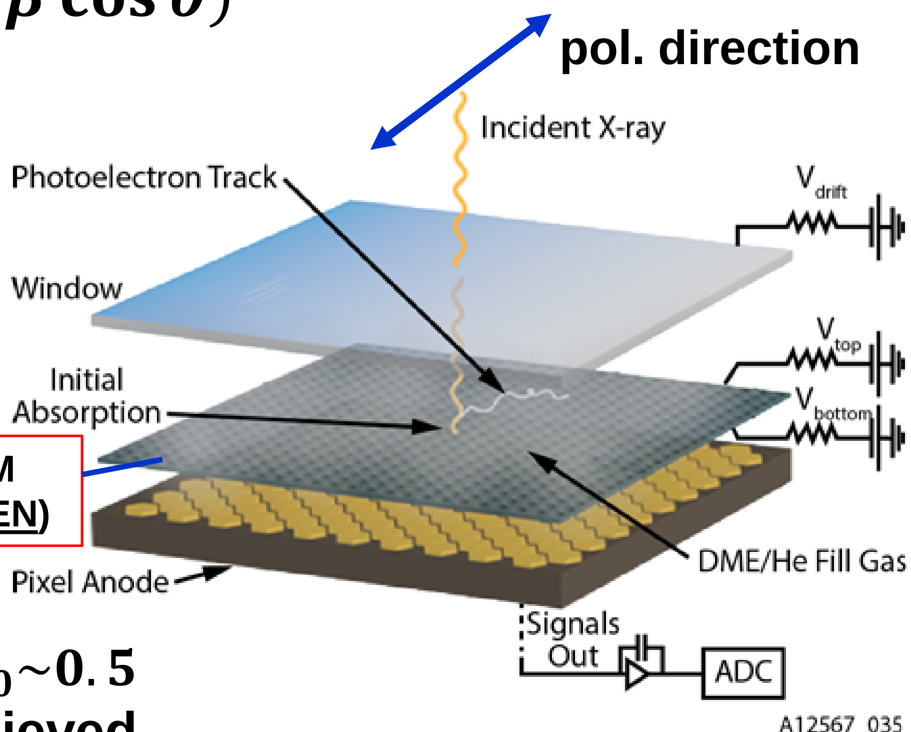
$$\frac{d\sigma}{d\Omega} \propto \frac{(\sin\theta\cos\varphi)^2}{(1-\beta\cos\theta)^4}$$



Electron track image

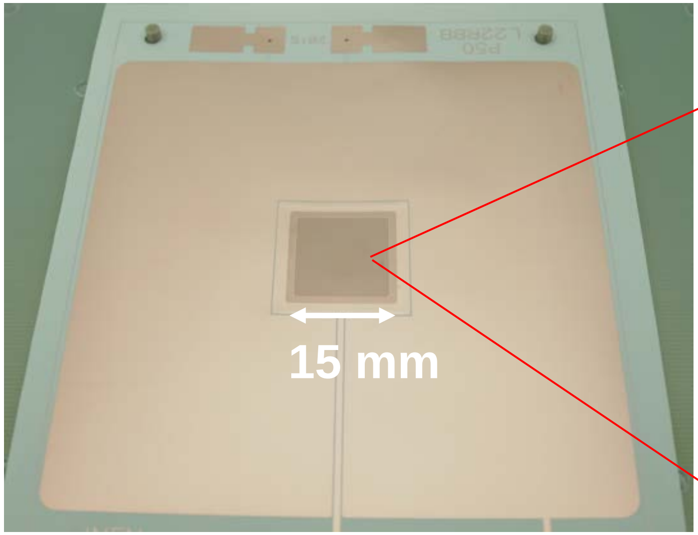
GEM (RIKEN)

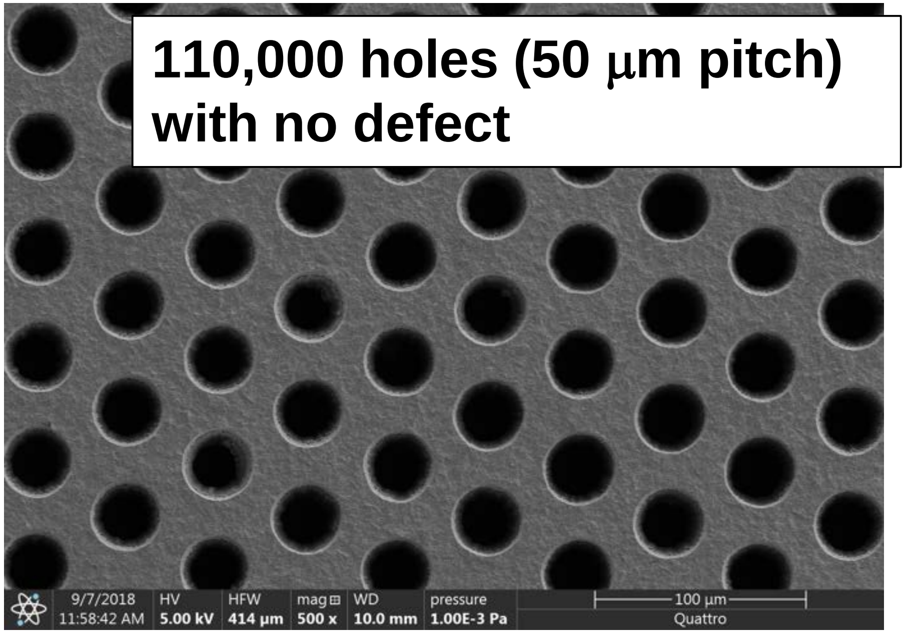
μ_{100}~0.5 achieved



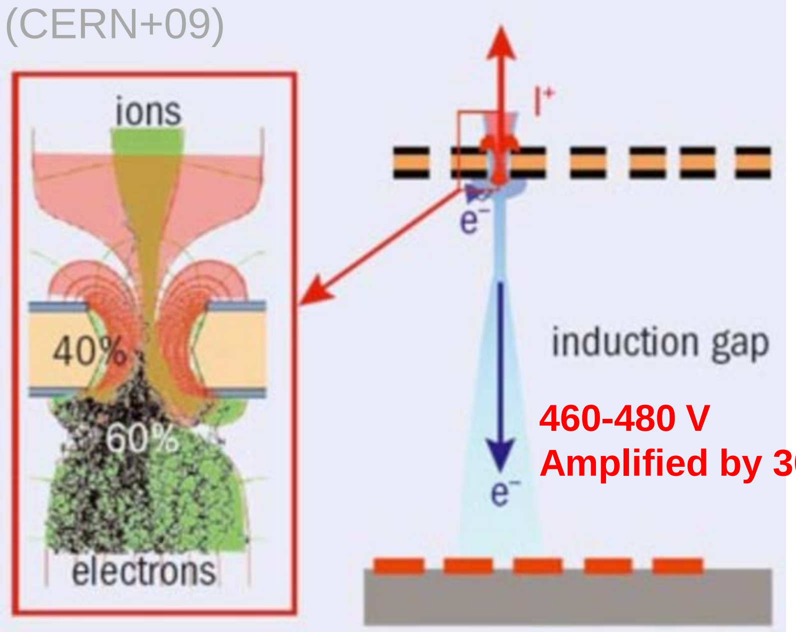
Gas pixel detector (GPD)

Gas Electron Multiplier (GEM)

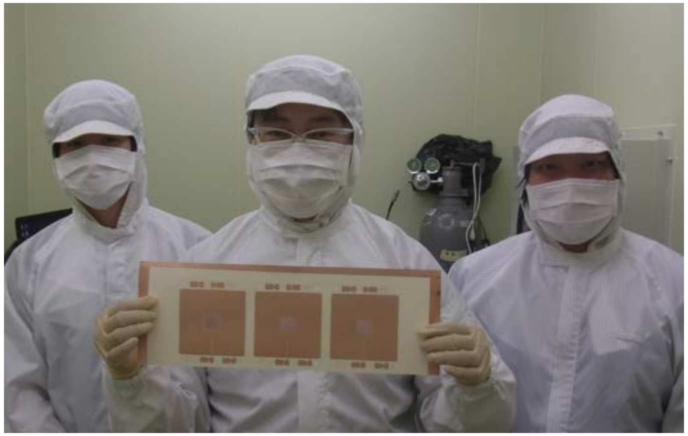




110,000 holes (50 μm pitch) with no defect

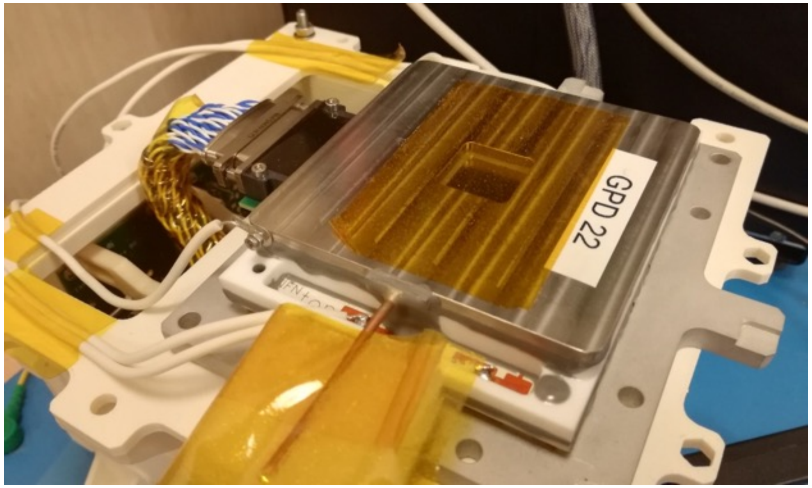


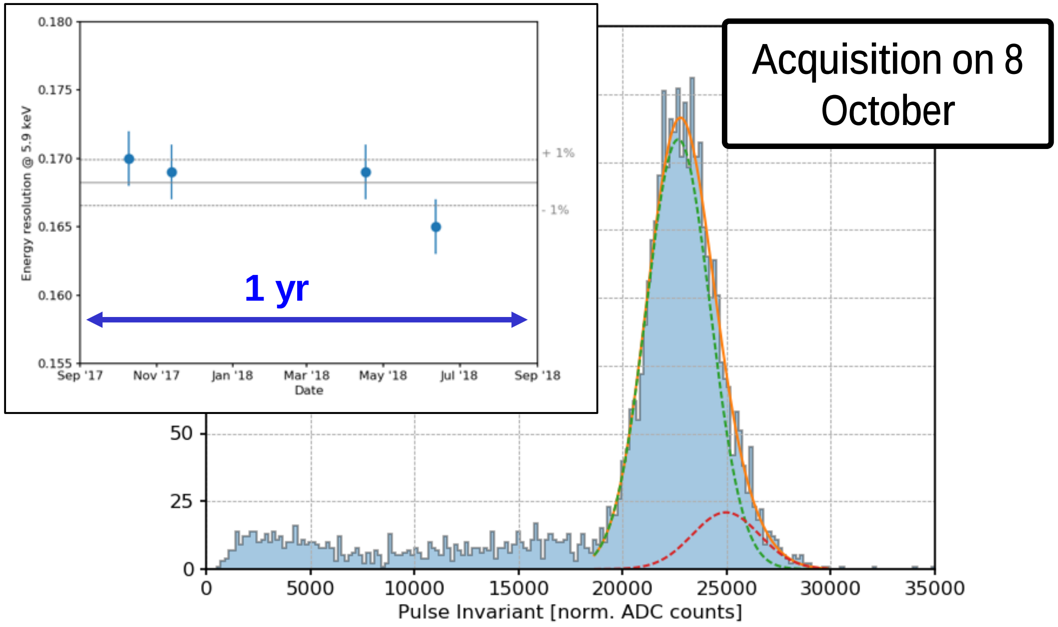
460-480 V
Amplified by 300-500

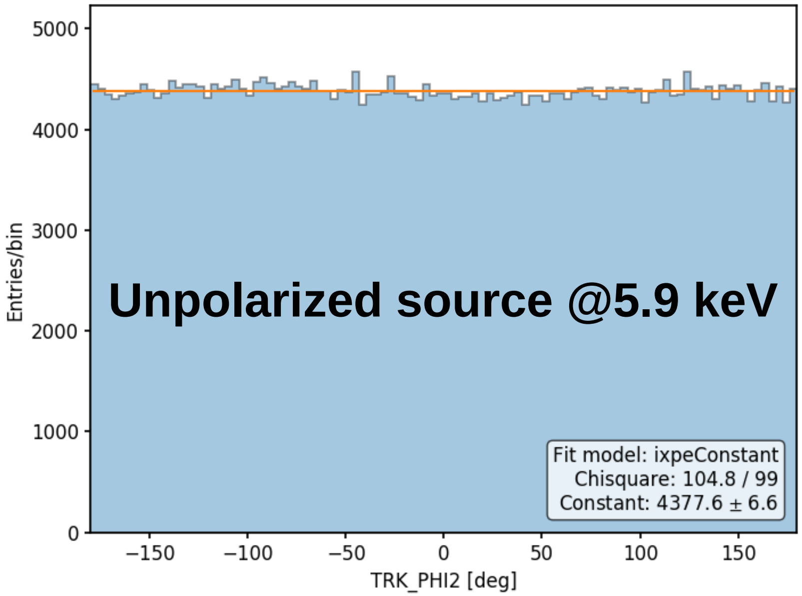


Screening and test at RIKEN

EM X-ray Polarimeter





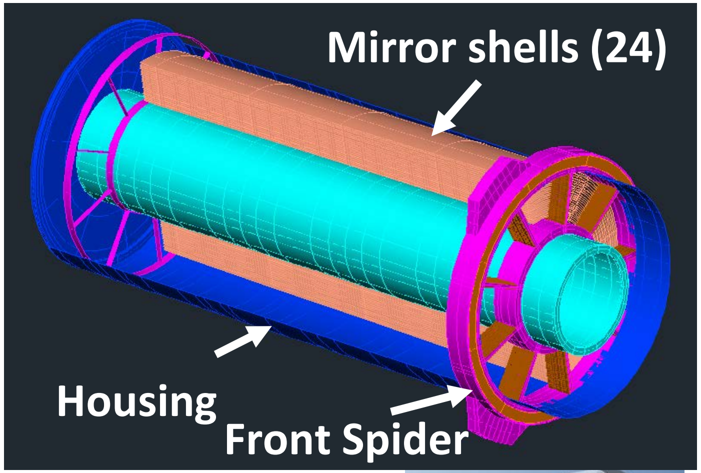


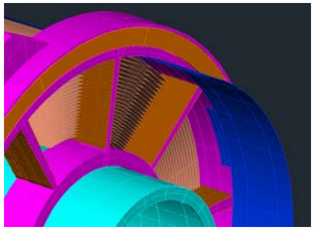
<u>Long term stability and uniformity checked with Fe-55 source</u>

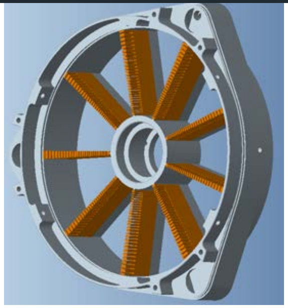
Energy resolution <17%, integrated over the entire detector surface (after gain equalization)

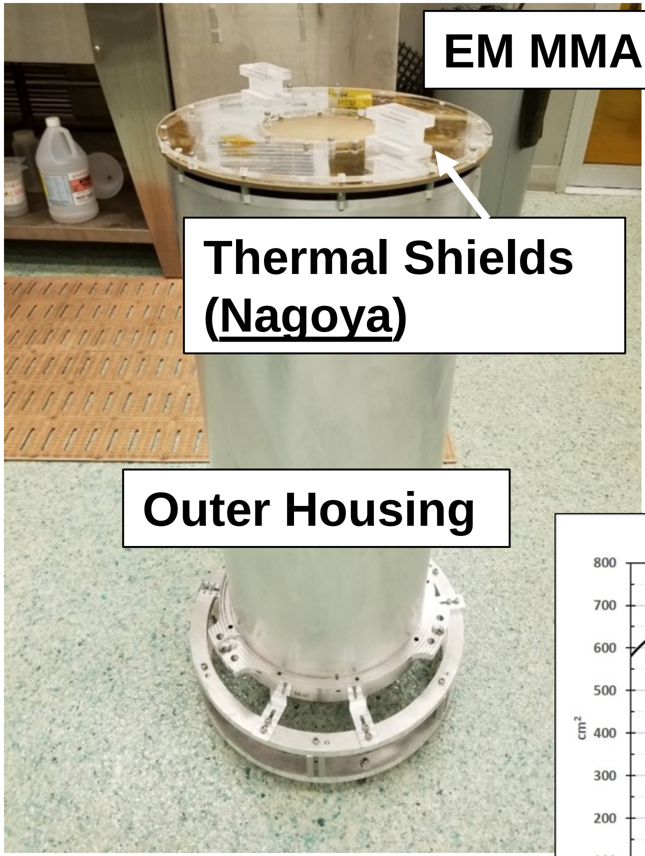
IXPE Imaging X-Ray Polarimetry Explorer

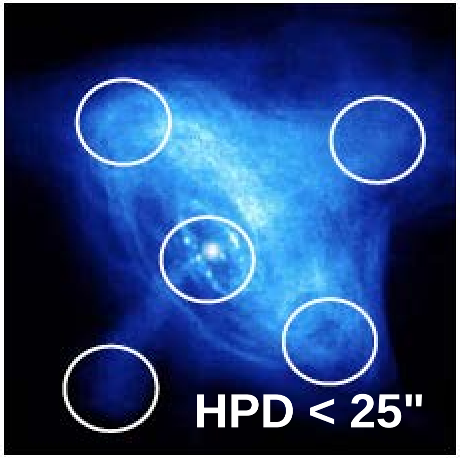
Mirror Module Assembly

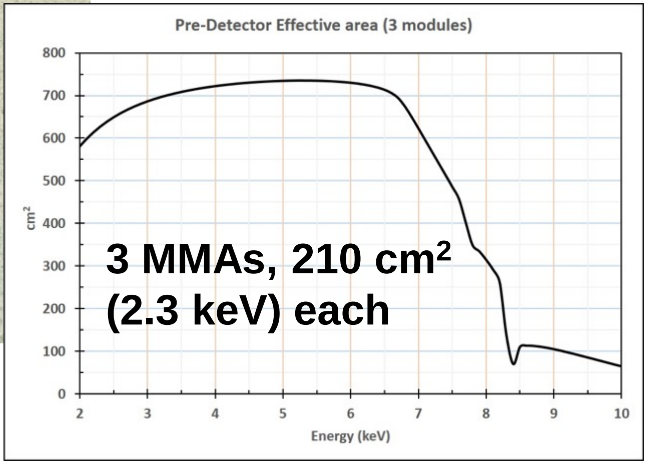






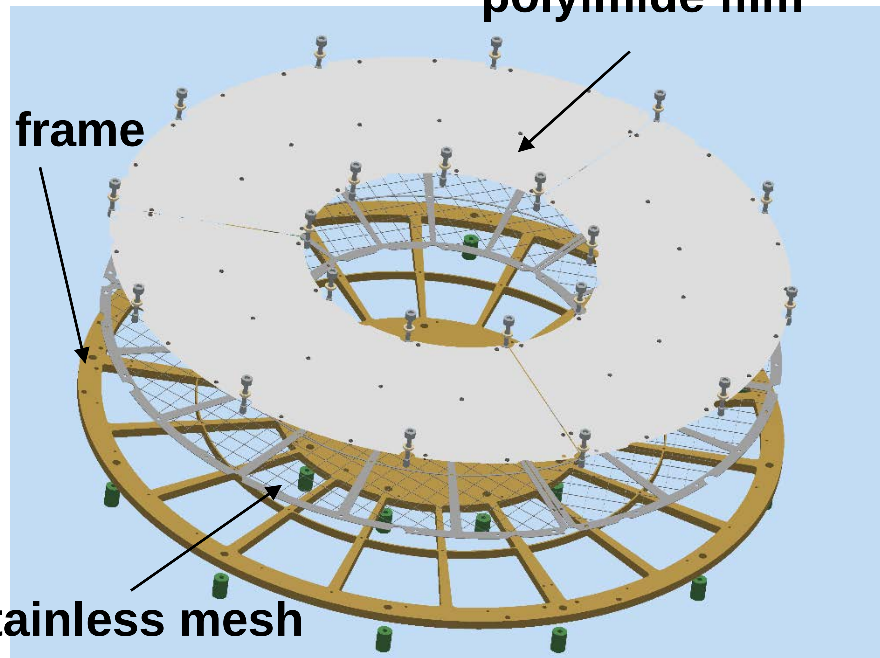


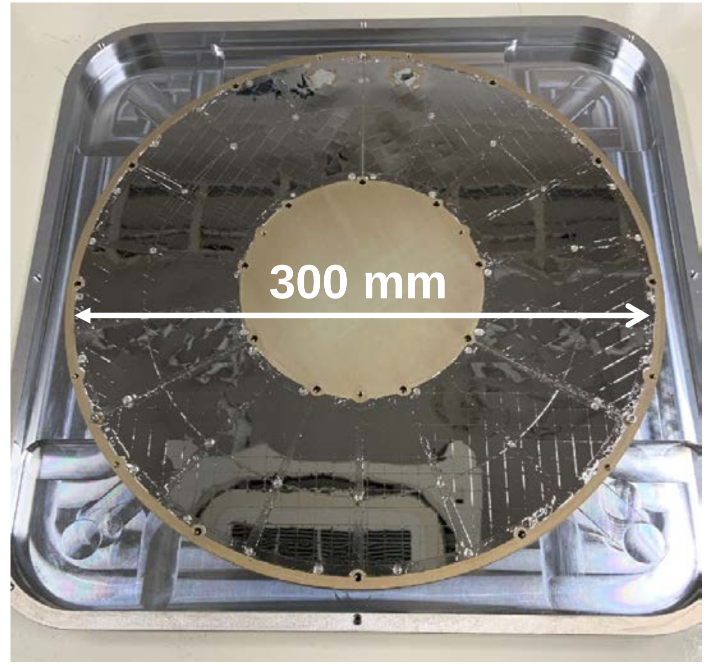




- 3 modules, each uses a single rigid spider to support 24 shells
- light weight housing for thermal control

Mirror Thermal Shield

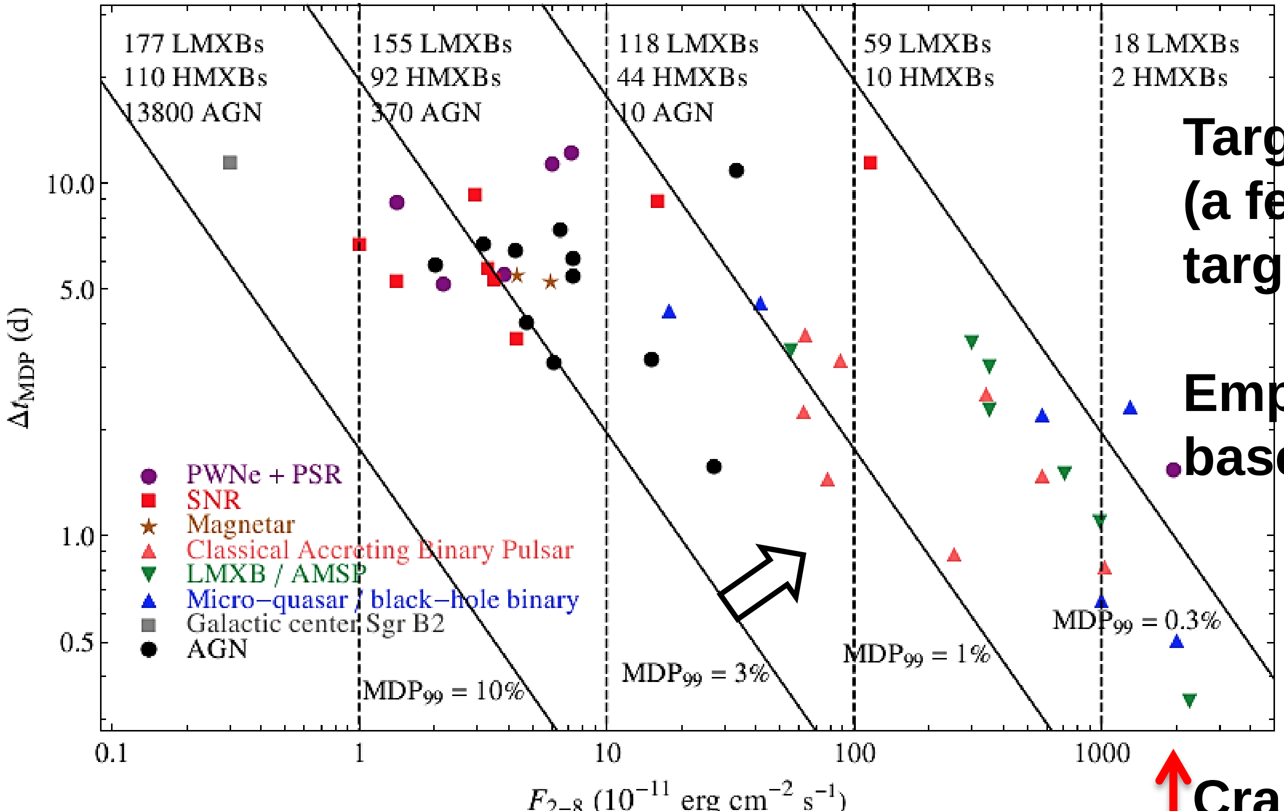




- 1.4 μm Polyimide film, coated with 50 nm alminium
- Supported on 97.5% transparent stainless-steel mesh (on Al frame)
- Transmission factor 90% at 2 keV
- Similar to shields flown on Hitomi

IXPE Scientific Capability

- **Time to reach minimum detectable polarization (MDP) ~100 times shorter than that of OSO-8**
- **Various classes of sources accessible**



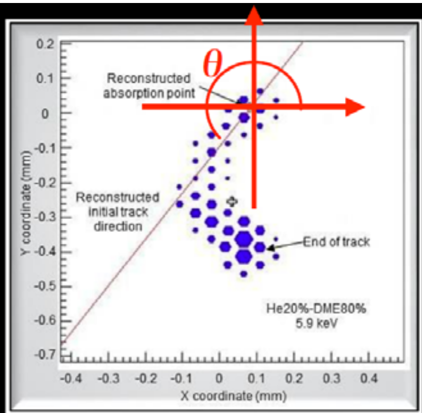
Targets under discussion (a few 10s pre-selected targets + transients)

Employ stokes-param. based analysis

Crab Nebula

(event-by event) Stokes Param. based Analysis

(Slide by S. Gunji for JPS meeting 2019/Mar)



$$q_i = \cos(2\theta_i) \quad u_i = \sin(2\theta_i) \rightarrow Q_r = \frac{1}{N}\sum_{i=1}^{N} q_i \quad U_r = \frac{1}{N}\sum_{i=1}^{N} u_i \rightarrow p_r = \frac{2\sqrt{Q_r^2 + U_r^2}}{\mu} \quad \theta_r = \frac{1}{2}\arctan\left(\frac{U_r}{Q_r}\right)$$

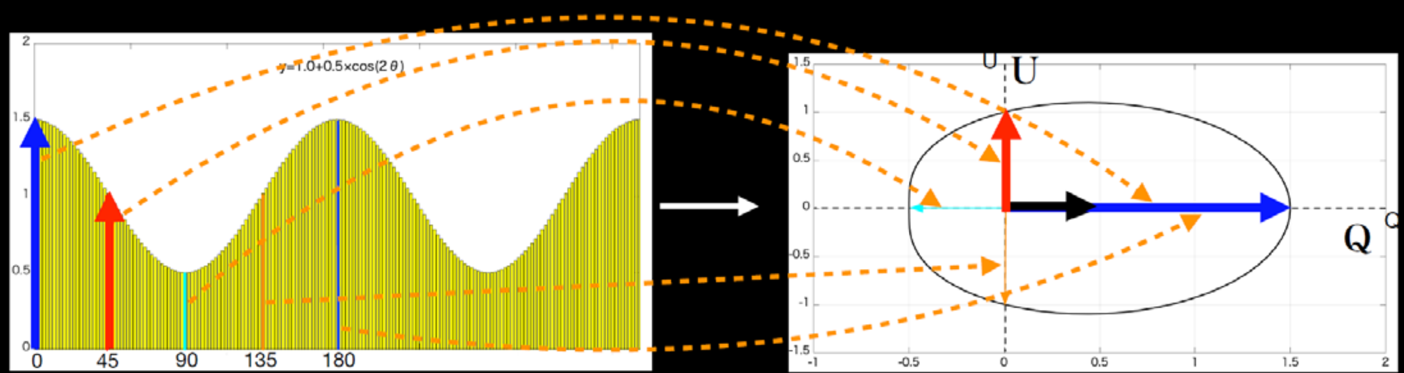
p_r : polarization degree

θ_r : polarization angle

μ : modulation factor

This method is a little difficult to understand.

Intuitively, the counts of each bin are vectorized and the vectors are summed.

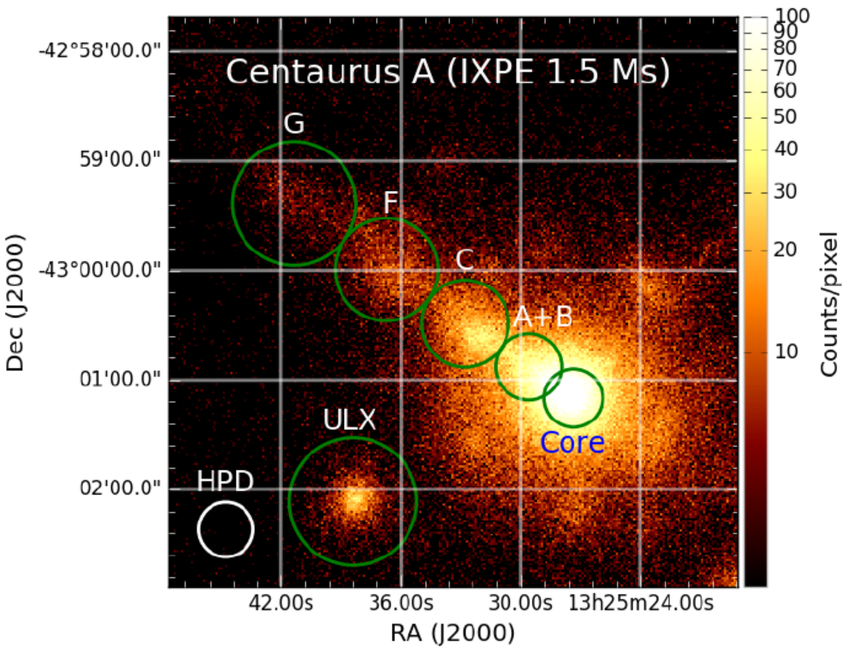


The length and the angle of the summed black vector correspond to the degree and the angle of polarization, respectively.

Stokes parameter is additive => flexible binning in sky coordinate

Case 1: Cen A

- **X-ray imaging polarimetry for the first time**
- **Investigate B-field configuration of jet for Cen A**
  - **Axial vs. transverse, how B-field orientation evolves along the jet**
  - **ULX contamination excluded**

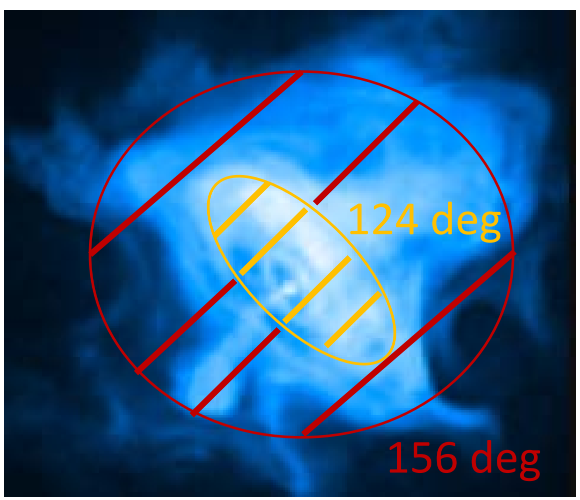


Region	MDP_{99}
Core	**<7.0%**
Jet	**10.9%**
Knot A+B	17.6%
Knot C	16.5%
Knot F	23.5%
Knot G	30.9%
ULX	**14.8%**

Includes effects of dilution by unpolarized diffuse emission

Case 2: Crab Nebula

- **X-ray imaging polarimetry for the first time**
- **Crab Nebula: past measurements (integrated)**
  - **OSO-8: 2.6&5.2 keV, PD=19%, PA=156 deg (Weisscopf +78)**
  - **PoGO+: >20 keV, PD=19%, PA=124 deg (Chauvin +17)**
- **We want to distinguish (possibly) different polarization in inner/outer nebulae by IXPE**



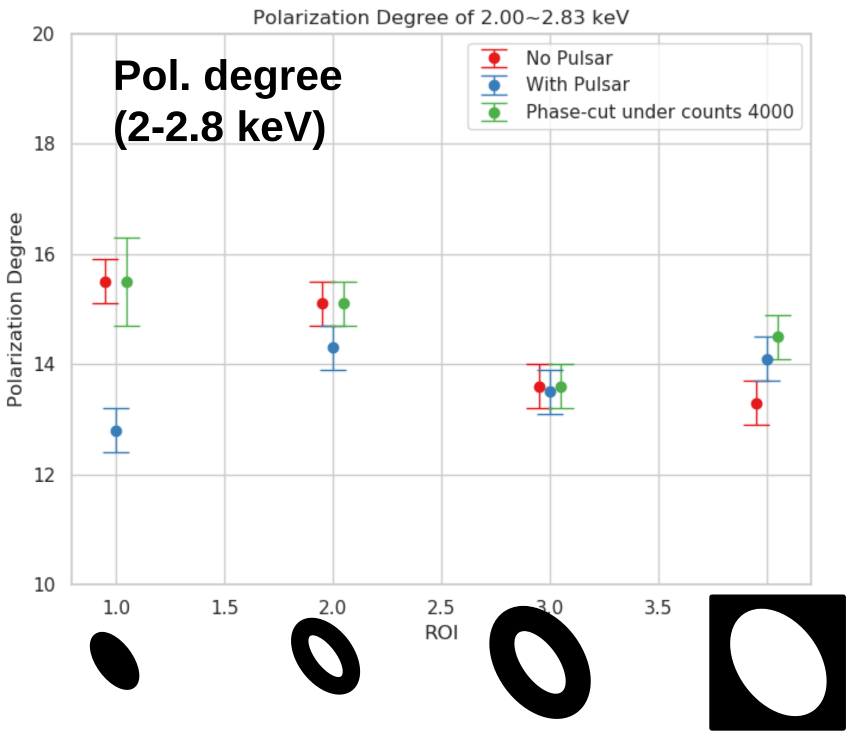
Input polarization model:
PD=19% (uniform)
PA=124 deg (inner), 156 deg (outer)

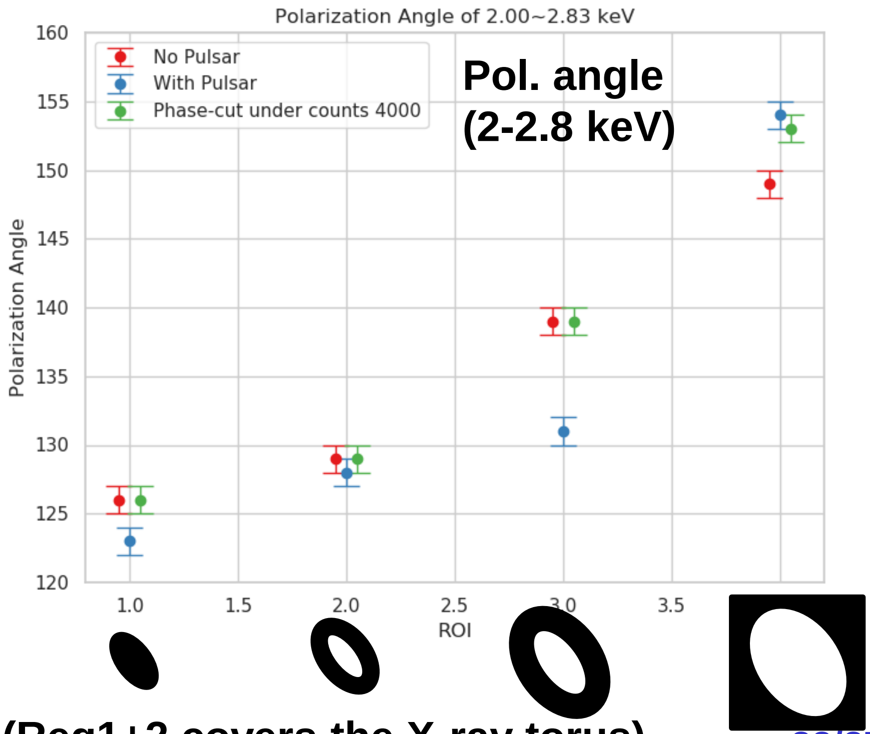
30 ks obs, apply phase-cut (60% remained) to eliminate pulsar contribution

Case 2: Crab Nebula (Contd.)

- Can distinguish inner- and outer-nebula polarizations with imaging capability of IXPE
- By applying phase-cut, we can recover the change of PD/PA

by R. Yamamoto (Hiroshima)

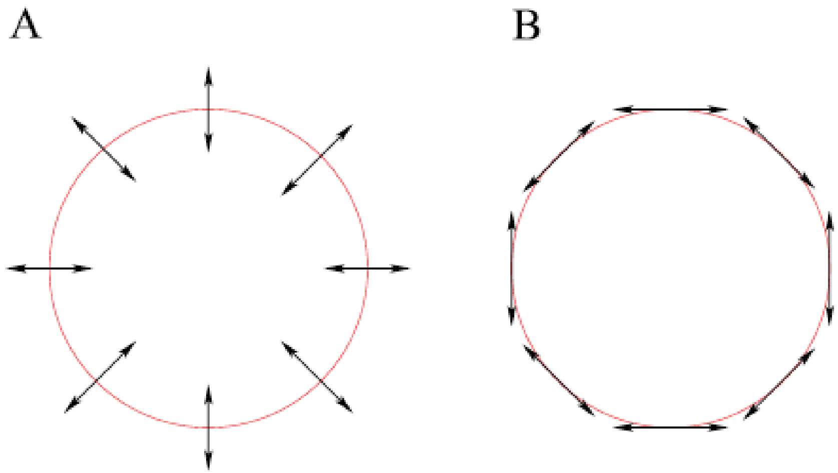




(Reg1+2 covers the X-ray torus)

Case 3: Tycho SNR

- **Turbulent B filed expected at SNR shock. Evolution of B turbulence is under debate**
- **Radio observation generally reveals radial/tangential field for young/old SNRs**
- **X-ray probes thin layer immediately behind the shock**



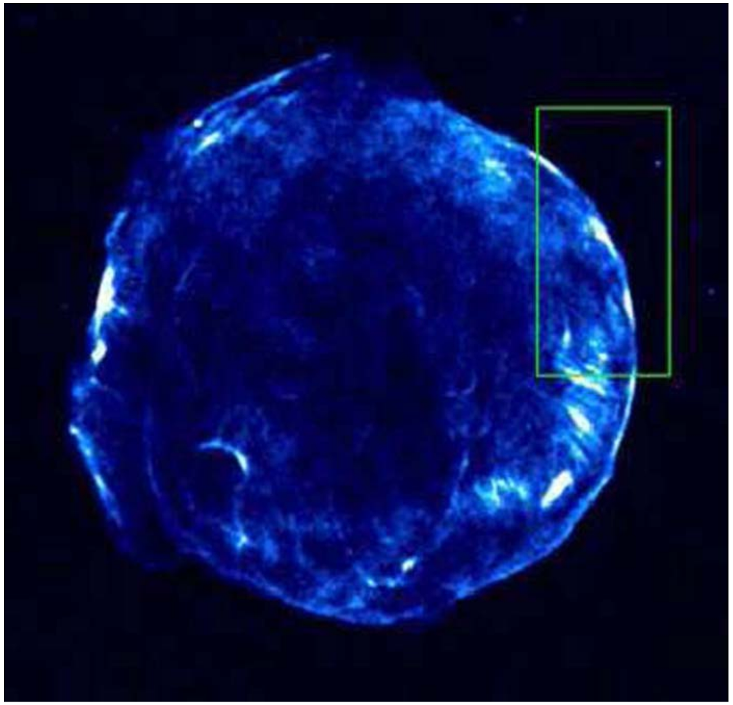
Expected pol. directions for (A) anisotropic turbulence produced by shock compression (B) turbulence produced by anisotropic cascade

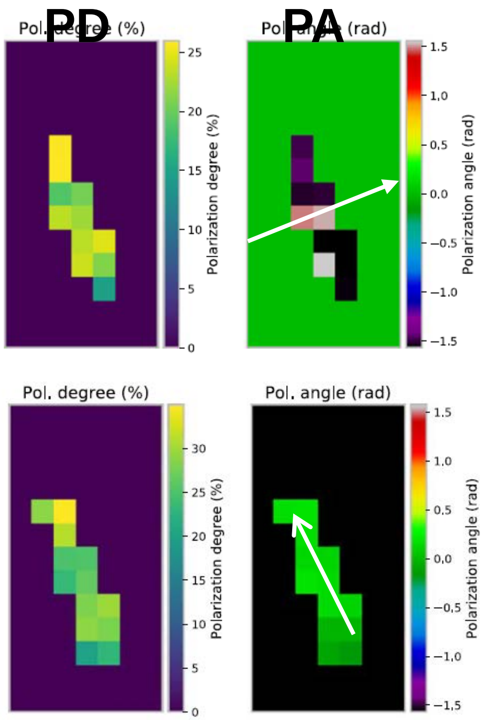
(Bykov +20)

Case 3: Tycho SNR (Contd.)

- **X-ray probes B-filed configuration behind the shock**

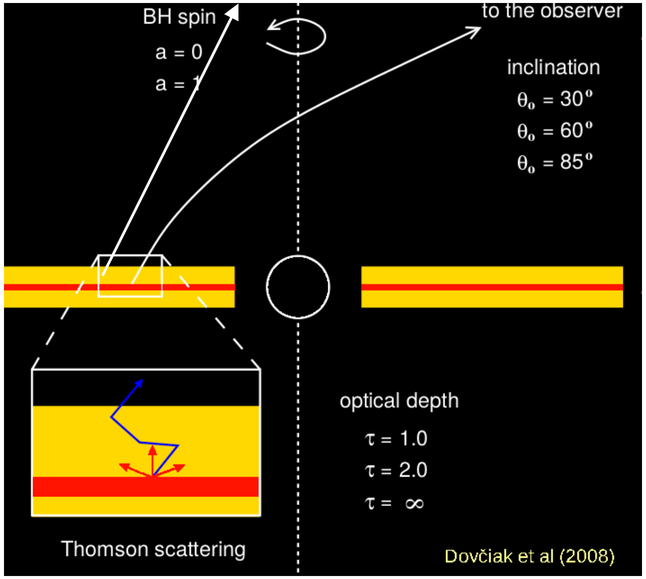
Tycho SNR, pol properties by numerical simulation,
1 MS obs. with IXPE
(A) anisotropic turbulence by shock compression
(B) turbulence produced by anisotropic cascade
Can distinguish A (top) and B (bottom)





Case 4: GRS 1915+105

- **Spectro-polarimetry probes space-time in the vicinity of BH**
  - **Photon scat. produces polarization; PD and PA depend on disk inclination and optical depth**
  - **In general, relativistic effect results in <u>energy-dependent</u> depolarization and change of PA**

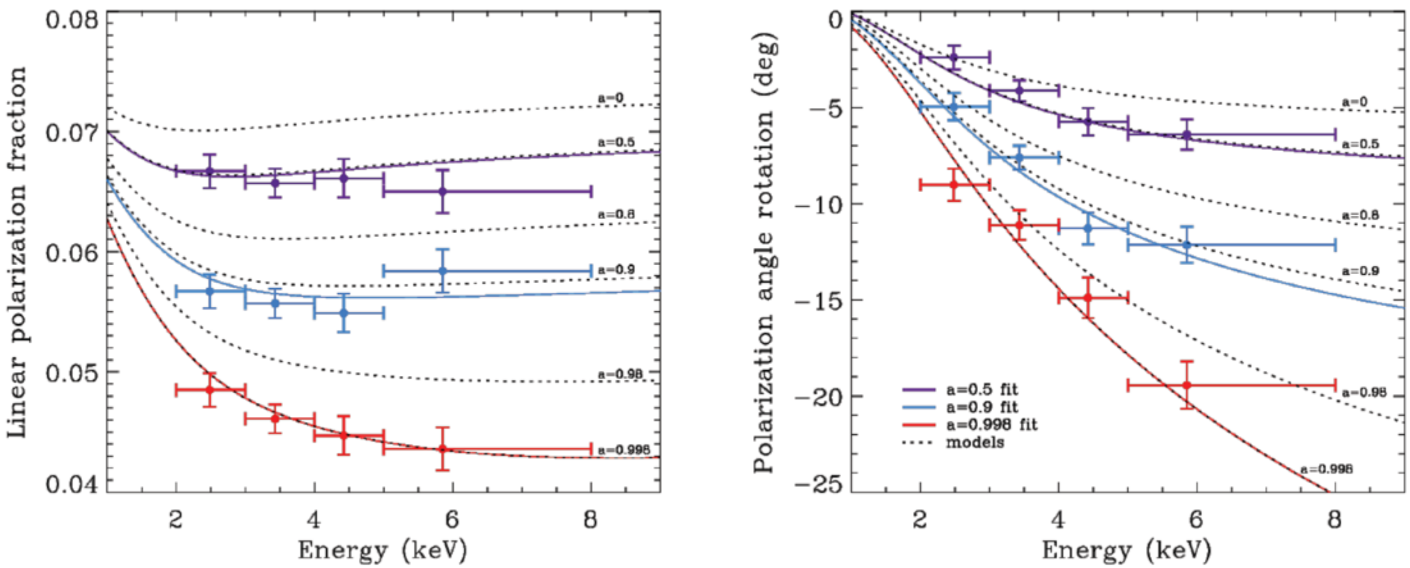


IXPE Imaging X-Ray Polarimetry Explorer

Case 4: GRS 1915+105 (Contd.)

- **Spectro-polarimetry probes space-time in the vicinity of BH**
  - **Photon scat. produces polarization; PD and PA depend on disk inclination and optical depth**
  - **In general, relativistic effect results in energy-dependent depolarization and change of PA**

GRS 1915+105 in soft state, IXPE 500 ks (Dovciak +08)



can discuss BH spin w/ IXPE

Summary

- **Polarization is powerful probe to magnetic field and source geometry**
- **IXPE will be launched in late 2021 and make the spectro-imaging-polarimetry in**
  - **Japanese consortium contributes the mission in hardware and science**
  - **A few 10s sources are accessible for the first time (AGN, PWN, SNR, BHB, etc.)**
  - **Coordinated (polarimetric) obs. would provide vital information**

Thank you for your Attention

References

- Bykov et al. 2020, ApJ 899, 142
- Chauvin et al. 2017, Scientific Report , 7816
- Dovciak et al. 2008, MNRAS 391, 32
- Novick 195, SSRv 18, 389
- Kislat et al. 2015, Astroparticle Physics 68, 45
- Vink & Zhou 2018, Galaxies 6, 46
- Weisskopf et al. 1978, ApJL 220, 117
- Weisskopf et al. 2009, Proc. SPIE 7732, 77320E
- Weisskopf 2018, Galaxies 6, 33

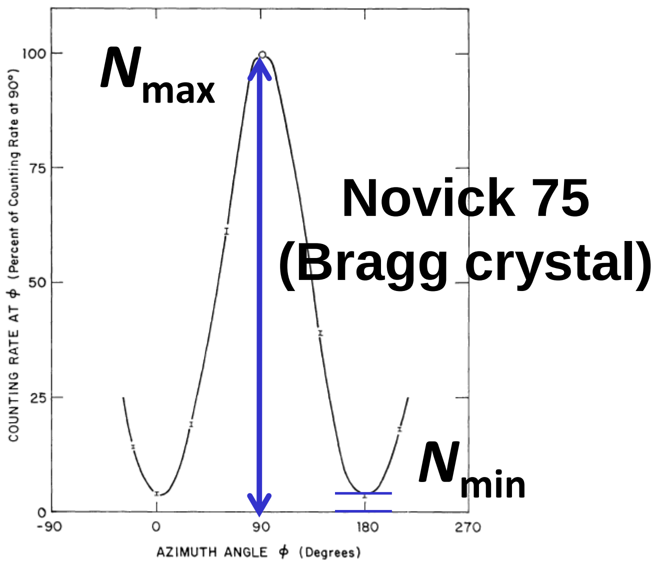
Backup Slides

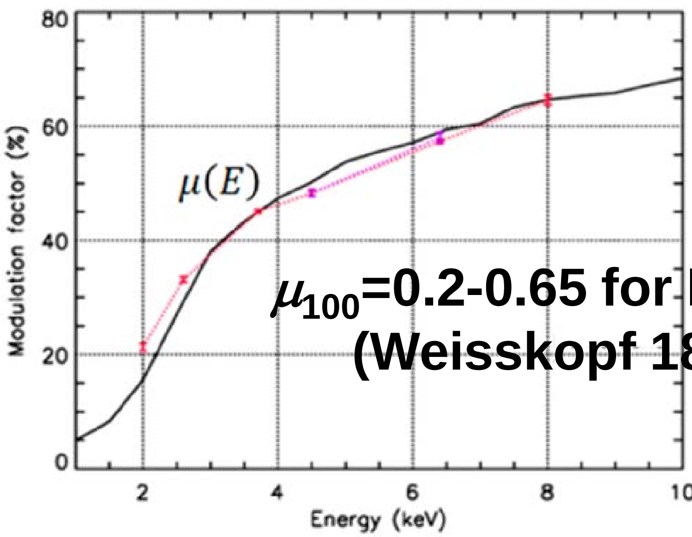
IXPE Imaging X-Ray Polarimetry Explorer

Minimum Detectable Polarization

- **Modulation factor μ_{100} is relative amplitude of modulation curve for 100% polarized signal**
- **Minimum detectable polarization (*MDP*$_{99}$) is the minimum source polarization statistically distinguishable from 0% polarization**

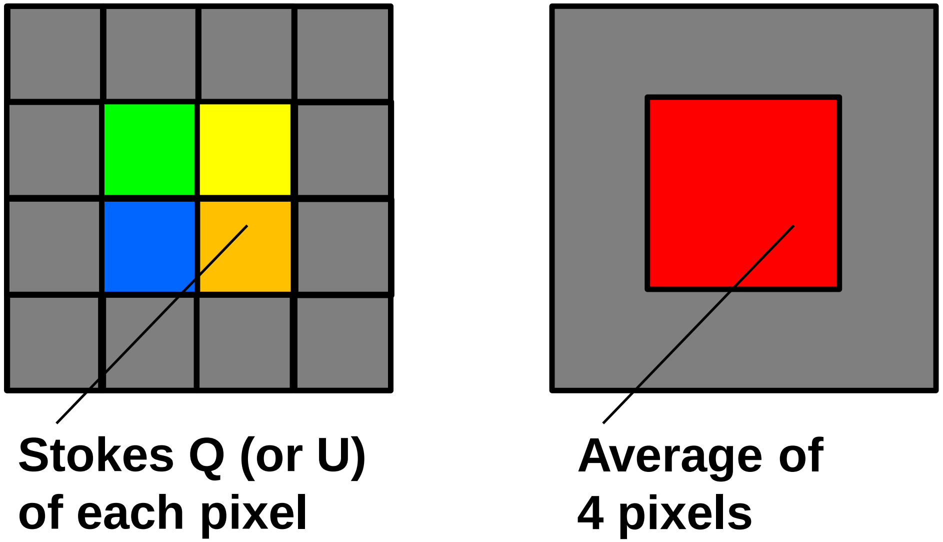
$$\mu_{100} = \frac{N_{max} + N_{min}}{N_{max} - N_{min}} \qquad MDP_{99} = \frac{4.29}{\mu_{100}}\sqrt{\frac{1}{R_S T}\frac{R_S + R_B}{R_S}}$$





Stokes Parameter based Analysis

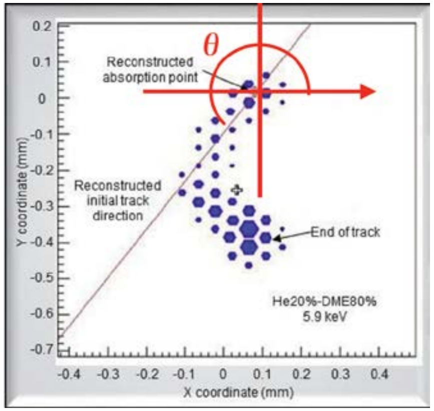
- We employ a Stokes Parameter based analysis to fully utilize imaging capability (cf. Kislat +15, Vink +18)
- Unlike PD/PA, Stokes parameters are additive and allow flexible binning in sky coordinate



Stokes Param. based Analysis (Contd.)

- **Event-by-event Stokes parameters:**

$$i_k = 1, q_k = 2\cos 2\theta_k, u_k = 2\sin 2\theta_k$$



- **Stokes params. of entire data:**

$$I = \sum i_k = N\,, Q = \sum q_k\,, U = \sum u_k$$

- **Normalized parameters, PD and PA:**

$$\hat{Q} = Q/I\,, \hat{U} = U/I \qquad p_r = \frac{1}{\mu_{100}}\sqrt{\hat{Q}^2 + \hat{U}^2}, \theta = \frac{1}{2}\tan^{-1}\left(\hat{Q}/\hat{U}\right)$$

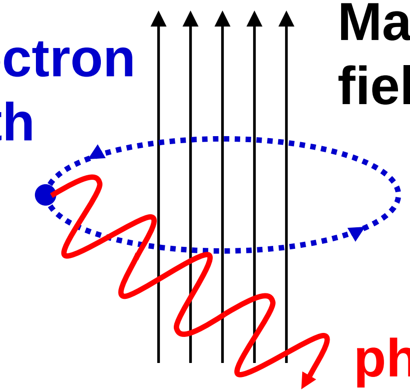
- **Errors:**

$$(Q_{\mathrm{err}})^2 = \sum {q_k}^2 = \sum (2\cos 2\theta_k)^2\,, \hat{Q}_{\mathrm{err}} = \frac{\sqrt{(Q_{\mathrm{err}})^2}}{I}$$

Polarization (1)

- **Electrons + magnetic field produce synchrotron radiation**
- **Unique probe to B (and accelerated electrons)**
- **High polarization degree is expected ($\Pi_{\max} = \frac{p+1}{p+7/3} \sim 0.7$)**
- **Stokes parameters:**

$$\Pi = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}, \chi = \frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right)$$



Japanese Contribution to IXPE

- **Hardware contribution**
  - ✓ **Mirror thermal shield (Nagoya Univ.)**
  - ✓ **Gas electron multiplier (RIKEN)**
- **Partially supported by JAXA's small project program**
- **Japanese contributors**

  T. Tamagawa, T. Kitaguchi, T. Enoto (RIKEN), I. Mitsuishi, Y. Tawara (Nagoya Univ.), S. Gunji (Yamagata Univ.), T. Mizuno, Y. Fukazawa, H. Takahashi (Hiroshima Univ.), K. Hayashida (Osaka Univ.), W. Iwakiri (Chuo Univ.) and students.

Names underlined are assigned as science collaborators.

プロジェクト進捗

- 2017年1月 NASA SMEX 採択
- 2018年6月25-28日 mission PDR (基本設計審査) 通過
- 2018年11月1日 KDP-C 通過
- 2019年6月24-28日 mission CDR (詳細設計審査) 通過
- 2020年3月末 FM 偏光計の較正試験完了、イタリアから米国へ輸送
- 2020年3月末 FM サーマルシールド製作完了、米国納品
- 2020年5月 Online Science Collaborator Meeting 開催
- NASA/MSFC は3-5月の間、大半の実験停止
- 2020年6月 望遠鏡単体試験@MSFC 完了
- FM 望遠鏡、FM偏光計 (3台分) 衛星への integration & test @Ball Aerospace
- FM 望遠鏡+FM偏光計 (1台分) end-to-end 試験@MSFC
- 2021年後半 打ち上げ