The Imaging X-Ray Polarimetry Explorer (IXPE)
X-ray polarimetry and VHE Astronomy

By

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Hands-on the Extreme Universe with High Energy Gamma-ray data

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New and old messengers

Physics and Astrophysics are in a phase of fast evolution due to the show-up of new messengers, namely gravitational waves and neutrinos. But the eventual understading of the physics of the emitters of these new messengers always is always accomplished through data in the em band.

The extension of the em band to ranges ill covered and the extension of the spectropolarimetric capabilities is very important.

Cherenkov telescopes have allowed for a breakthrough in the last 20 years. An effort is spent to extend the gamma-ray capabilities to lower energies.

An important extension of the em capabilities is in progress. IXPE, the first mission dedicated to X-ray polarimetry is in orbit since December 9 2021. More missions performing X-Ray Polarimetry are under study.

I order to figure how X-ray Polarimetry and Cherenkov Telescopes can cooperate to solve some hot topics of High Energy Astrophysics I show the IXPE capabilities and a [very] few preliminary results.

Big Hopes Meager Results

The first attempts of X-ray polarimetry were started soon after the beginning of X-Ray Astronomy.

At the time vast theoretical literature predicted a wealth of results from X-ray Polarimetry.

In 40 years only one positive detection of X-ray Polarization: the Crab (Novick et al. 1972, Weisskopf et al.1976, Weisskopf et al. 1978) $P = 19.2 \pm 1.0$ %; $\theta = 156.4^{o} \pm 1.4^{o}$

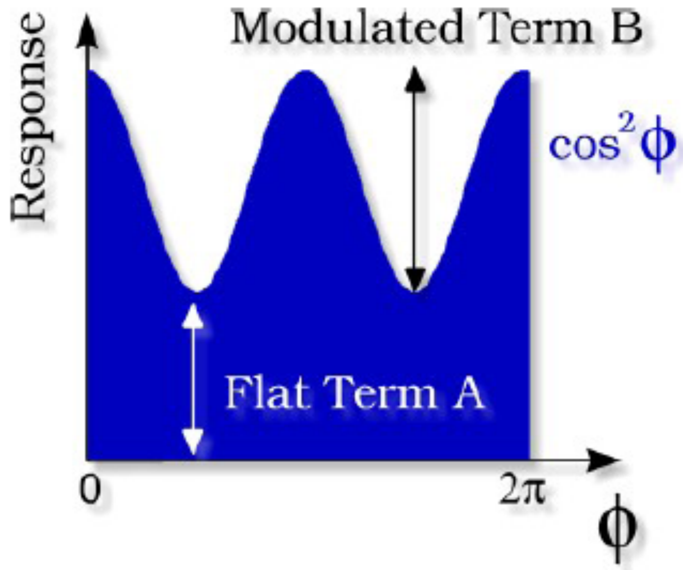
Polarimeters were proposed for XMM and foreseen for Einstein and Chandra, XEUS and IXO but systematically disembarked. The Stellar X-Ray Polarimeter was built and tested for the Spectrum X-Gamma mission but the satellite was never flown.

A missiono dedicated to X-ray polarimetry (GEMS) was selected by NASA but stopped after three years.

A few results were published on Hard X-ray or soft Gamma-Ray polarimetry.

Data on Crab with OSO-8 were still the only valuable result in the classic range 2-8 keV

The conventional formalism



Fit function: $\mathcal{M}(\phi) = A + B\cos^2(\phi - \phi_0)$

Modulation: $\frac{\mathcal{M}_{\max} - \mathcal{M}_{\min}}{\mathcal{M}_{\max} + \mathcal{M}_{\min}} = \frac{B}{B + 2A}$

Polarization: $\frac{1}{\mu}\frac{B}{B + 2A}$

μ is the modulation factor, i.e. the modulation for 100% polarized radiation

The first limit: In polarimetry the sensitivity is a matter of photons

MDP is the Minimum Detectable Polarization

$$MDP = \frac{4.29}{\mu R_S}\sqrt{\frac{R_S + R_B}{T}}$$

R_S is the Source rate, R_B is the Background rate, T is the observing time
μ is the modulation factor: the modulation of the response of the polarimeter to a 100% polarized beam

If background is negligible: $$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N_{ph}}}$$

To reach MDP=1% with μ=0.5: $$N_{ph} = \left(\frac{4.29}{\mu\,\mathrm{MDP}}\right)^2$$ = 736 10^3 ph

Source detection > 10 photons
Source spectral slope > 100 photons
Source polarization > 100.000 photons

Caution: the MDP describes the capability of rejecting the null hypothesis (no polarization) at 99% confidence. For a significant meaurement a longer observation is needed. For a confidence equivalent to the gaussian 5σ the constant is higher 4.29→7.58

X-Ray Polarimetry from a concept [dream] to reality

These numbers on sensitivity are frankly discouraging but the situation was even worse.

If the counting rate from the source r_s is comparable to the rate from background r_b the source is near to the limit of detectability.

Only a polarimeter with imaging capability can observe weak sources. The X-Ray telescopes were available but imaging detectors with polarimetric capability were not.

OSO-8 data have been the only data for around 46 years.

25 years later an imaging detector for polarimetry was invented.

15 more years were needed to convince an Agency

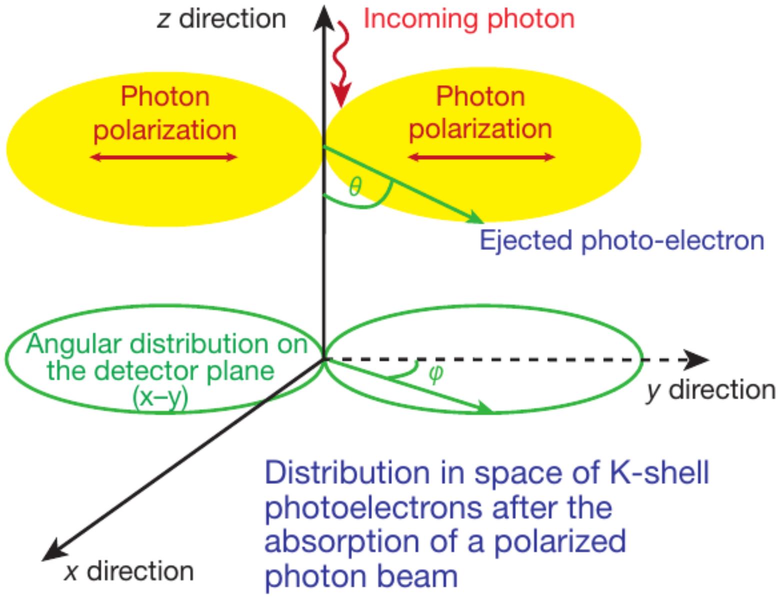
5 more years to build and launch IXPE

IXPE possible thanks to a new detector

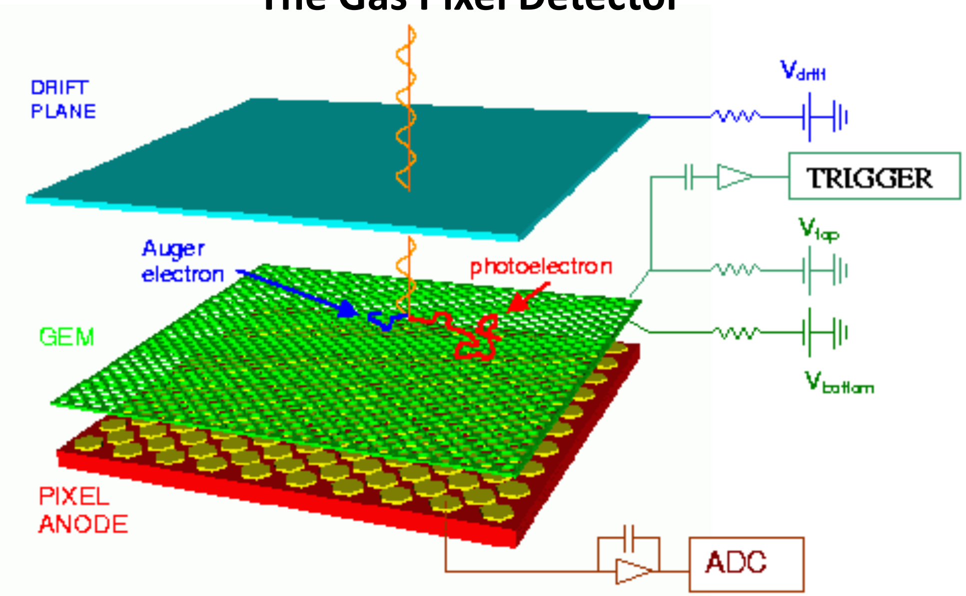
We developed at this aim a polarization-sensitive instrument capable of imaging, timing and spectroscopy

The photoelectric effect

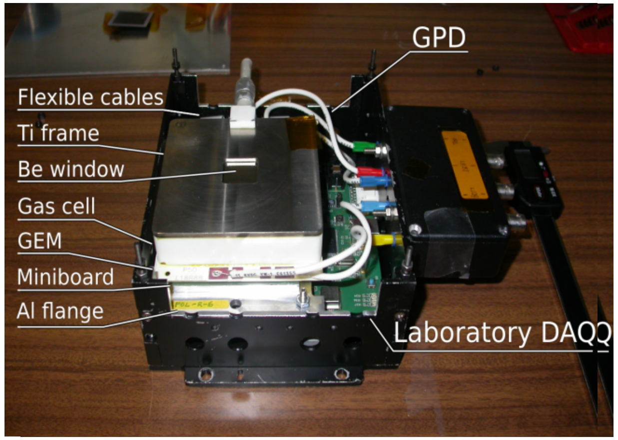
$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$



The Gas Pixel Detector



E. Costa et al. 2001, Bellazzini 2006, Bellazzini 2007



Exploiting the photoelectric effect in a gas

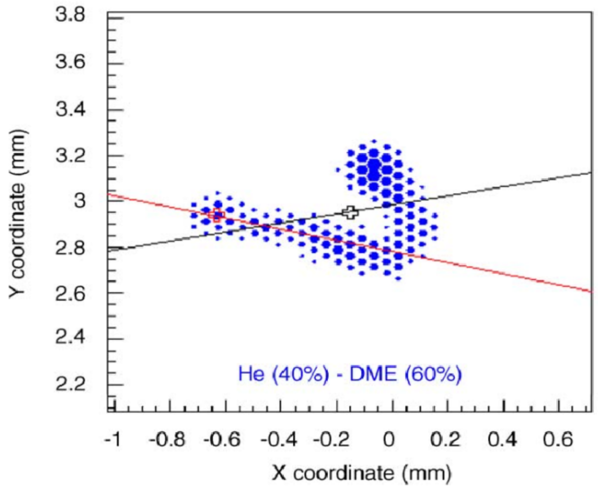
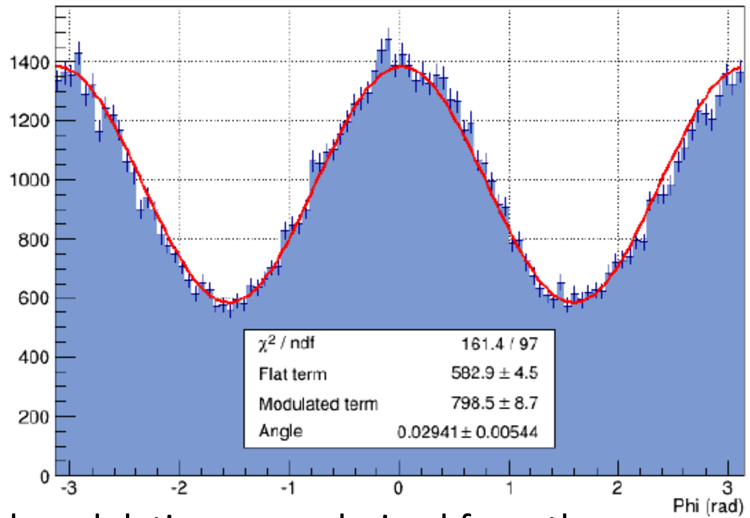
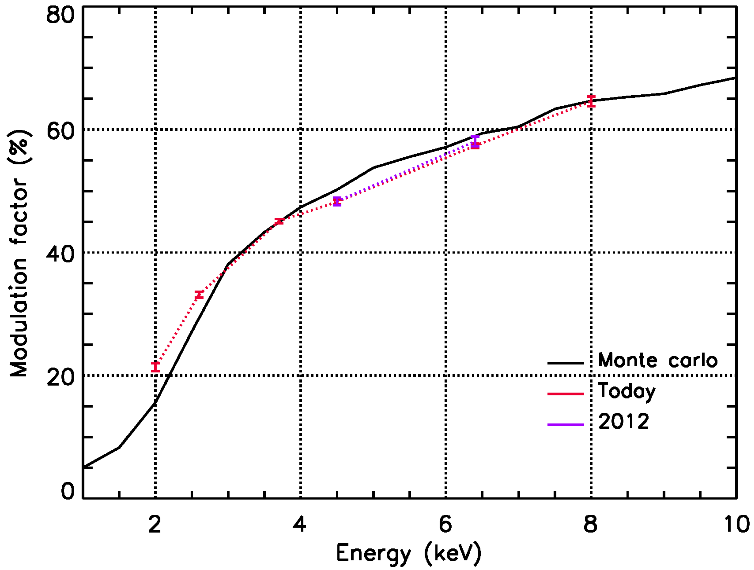


Image of a real photoelectron track. The use of the gas allows to resolve tracks in the X-ray energy band.

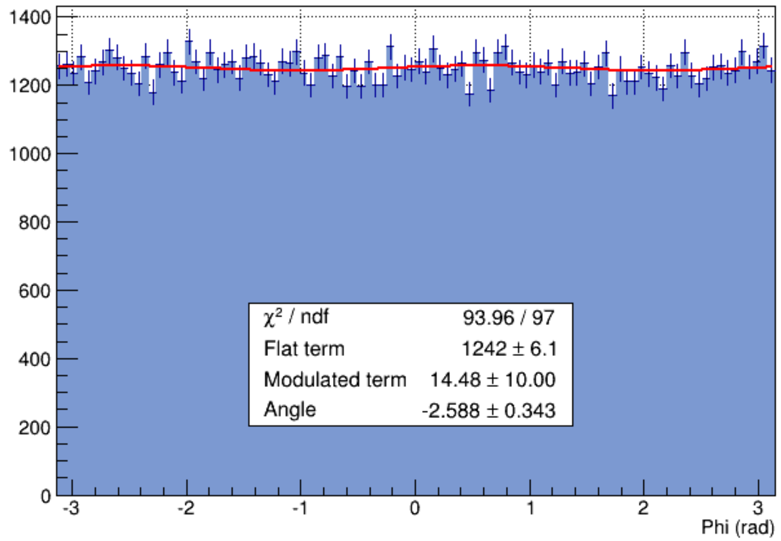


Real modulation curve derived from the measurement of the emission direction of the photoelectron.



Muleri et al. 2008,2010

Modulation factor as a function of energy.



Bellazzini et al. 2012

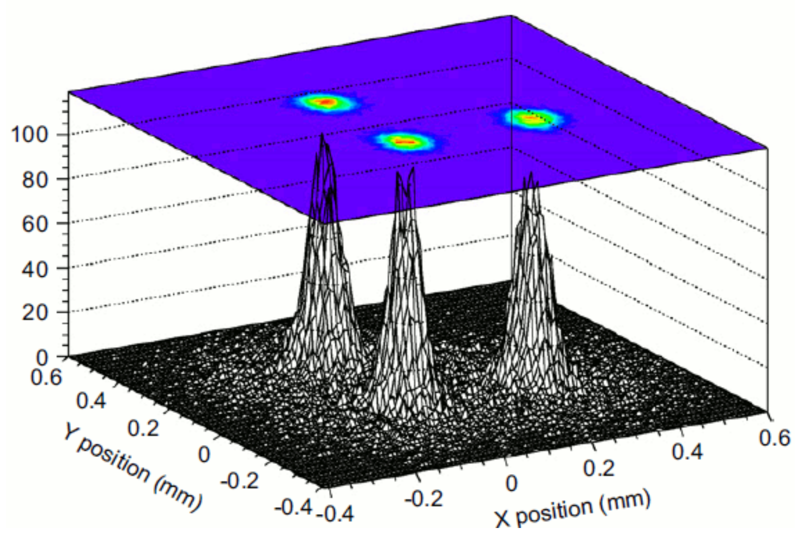
Residual modulation for unpolarised photons.

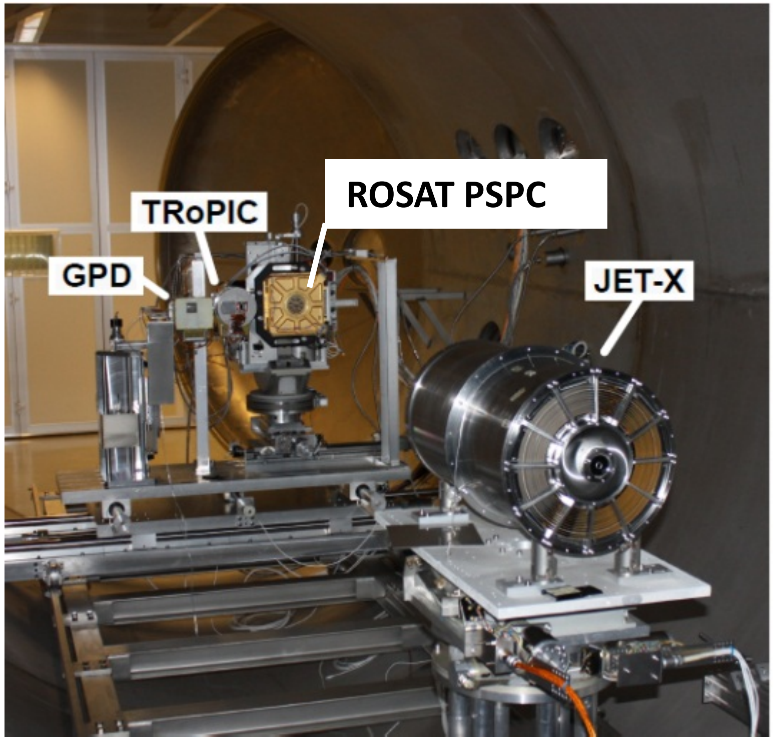
IMAGING

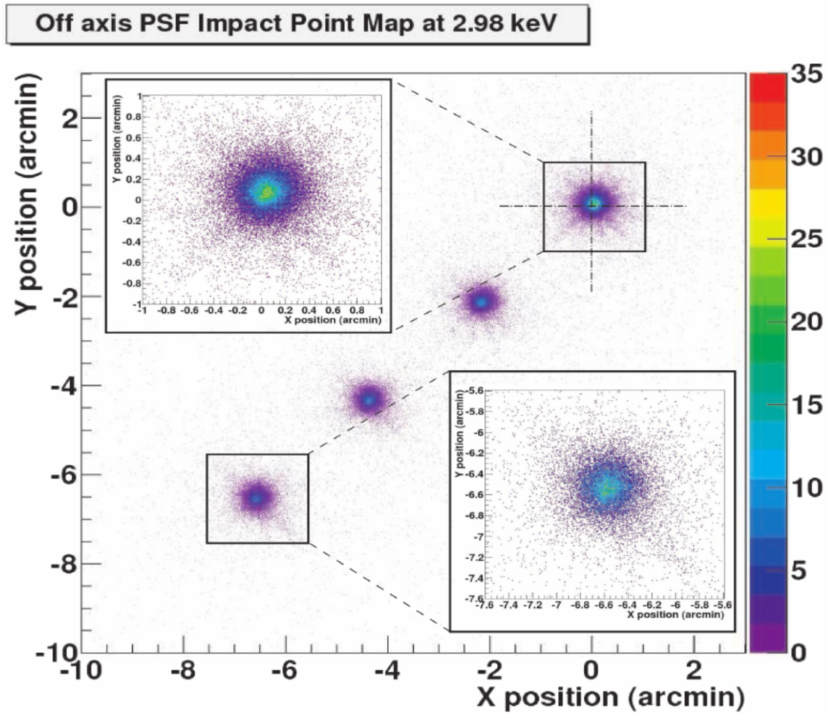
- Good spatial resolution: 90 μm Half Energy Width

- Imaging capabilities on- and off-axis measured at PANTER with a JET-X telescope (Fabiani et al. 2014)

- Angular resolution for IXPE: <30 arcsec







Position Sensitive Detector → Imaging Experiment

A position sensitiv detector in the focus of an X-Ray telescope provides an imaging experiment that:

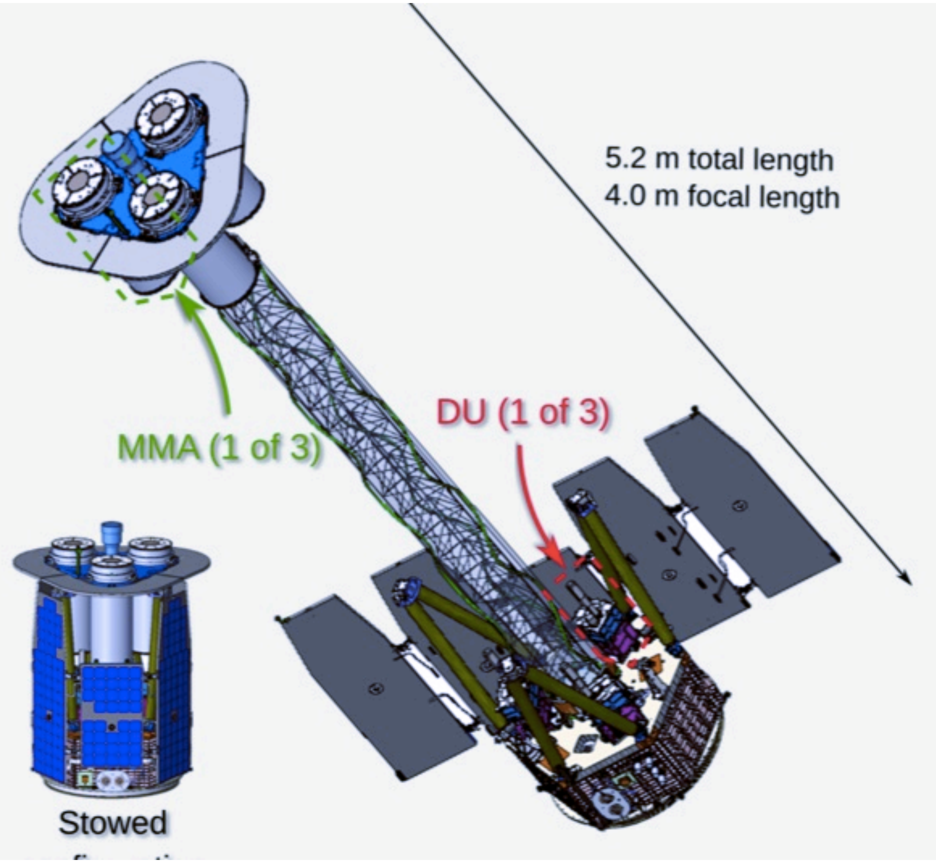
1) Can perform angular resolved Spectroscopy/Timing/Polarimetry of extended sources
2) Can perform Spectroscopy, Timing and Polarimetry of point-like sources with hih sensitivity. The photons from the source are concentrated within the point spread function in the focal plane. They are to be compared with the background within the same p.s.f.. With a psf of 0.2 - 0.5 mm tha background corresponds to a fraction of mCrab.

This jump in sensitivity was performed by IXPE.

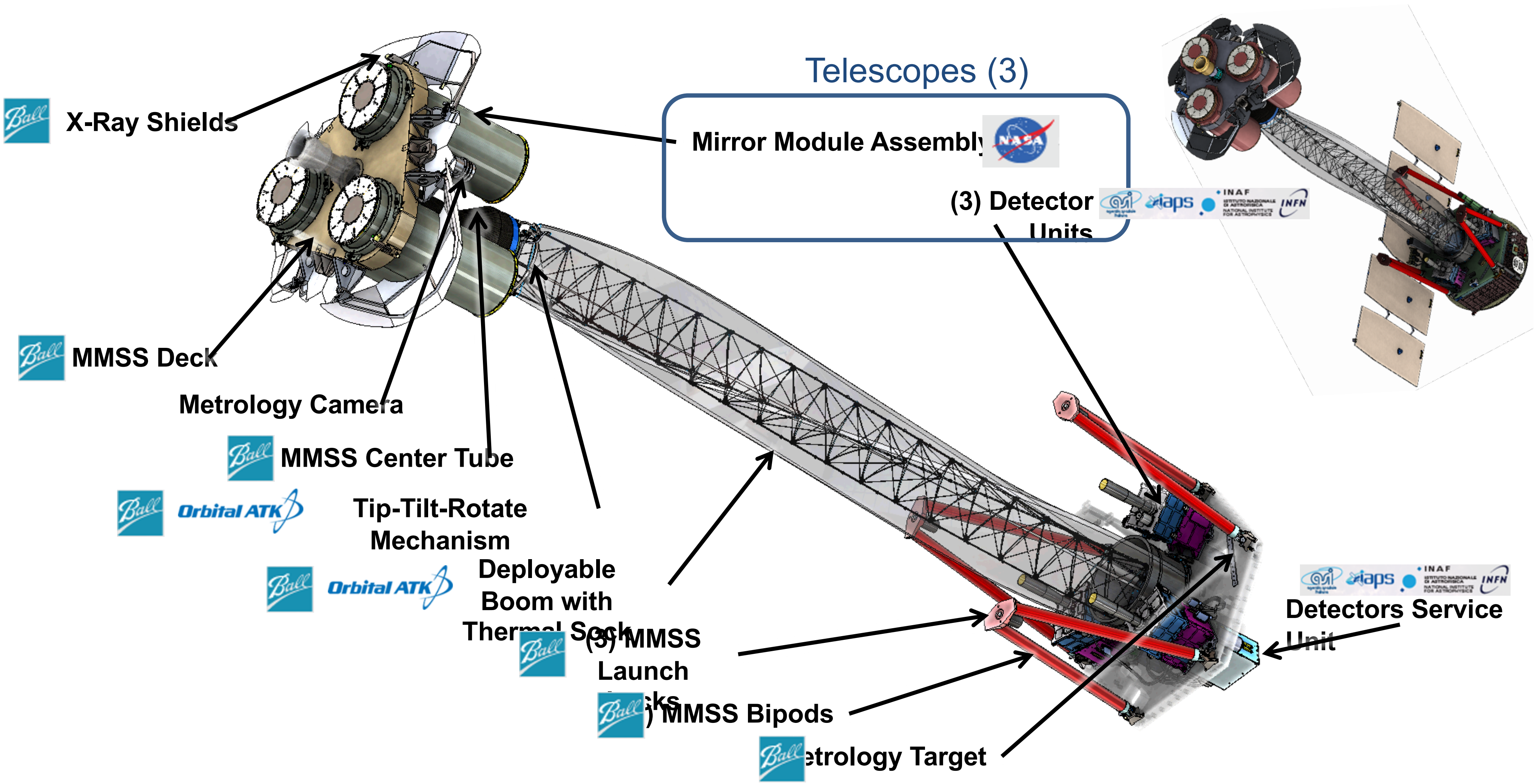
X-Ray Polarimetry is no more a dream but a new window in the Sky.

Imaging X-Ray Polarimetry Explorer

- NASA-ASI SMall EXplorer mission dedicated to (linear) X-ray imaging polarimetry
  - ➥ Energy range: 2–8 keV
  - ➥ Polarimetry: MDP>5.5% in 10 days for 10^{-11} cgs
    - + Imaging (< 30 arcsec)
    - + Timing ($\sim 10\mu s$)
    - + Spectroscopy (<20% at 5.9 keV)
- 3 identical telescopes
  - ➥ Grazing-incidence X-ray mirrors (3+1 spare)
  - ➥ Imaging X-ray photoelectric polarimeters based on GPD design (3+1 spare)
  - ➥ The two are separated by an extensible boom



The IXPE Components

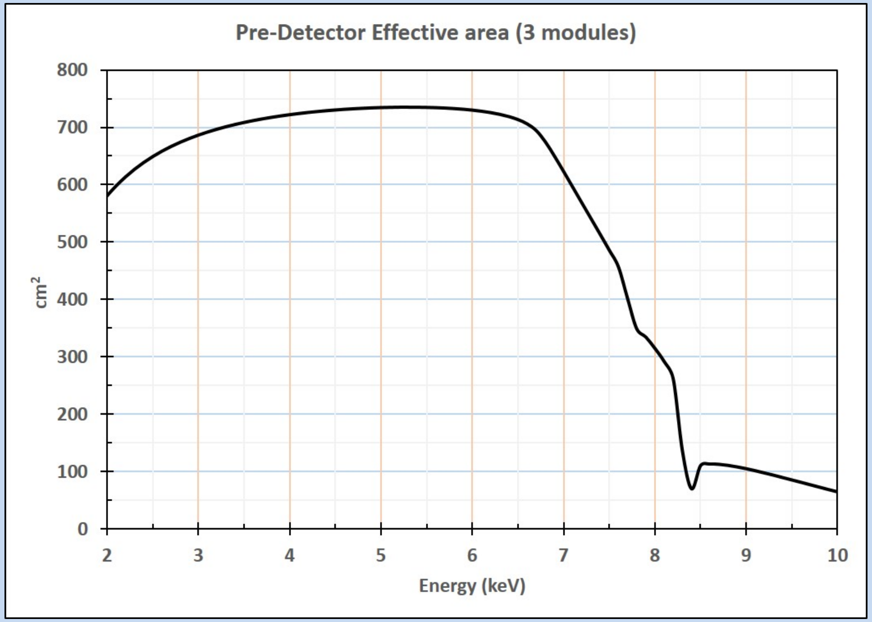


Mission Description

Parameter	Value
Launcher	Falcon-9
Launcher Date	Decmber 9 2022
Mission Duration	25 months including 1 month commissioning/payload verification
Orbit	Low Earth orbit (LEO) Altitude =600km, circular Eccentricity = 0 Inclination = 0 degrees (equatorial)
Ground Stations	Malindi, Kenya (primary station) Singapore NEN station (backup)
Communications	2.0 Mbps downlink via S-band LGA (to ground) 32 kbps downlink via S-band LGA (to ground) 1 kbps downlink via S-band LGA (to TDRS) 2 kbps uplink via S-band LGA (from ground)

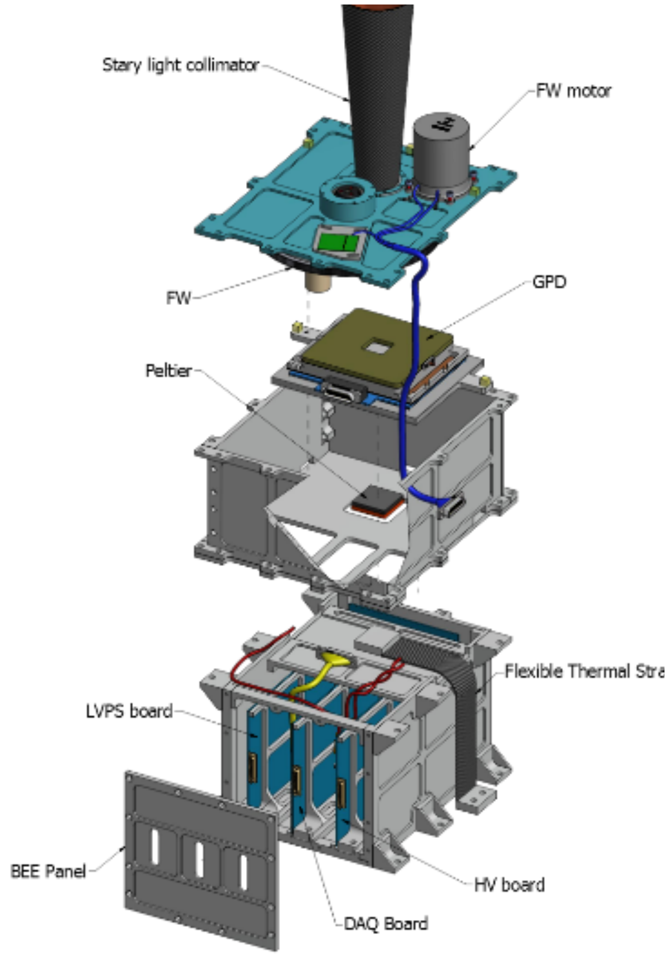
MIRROR MODULE ASSEMBLY PROPERTIES

Property	Value
Number of modules	3
Mirror shells per module	24
Inner, outer shell diameter	162, 272 mm
Total shell length	600 mm
Inner, outer shell thickness	180, 260 µm
Shell material	Nickel cobalt alloy
Effective area per module	210 cm^2 (2.3 keV) > 230 cm2 (3-6 keV)
Angular resolution	≤ 25 arcsec HPD
Detector limited FOV	12.9 arcmin
Focal length	4 m
Mass (3 assemblies)	97 kg



IXPE

Polarization sensitivity (MDP)	<5.5 % for 1x10^{-11} erg/s/cm^2 (10 days observation)
Spurious modulation	< 0.3 %
Energy band	2-8 keV
Number of telescopes	3
Angular resolution	< 30’’
Field of view	12.9 x 12.9 $arcmin^2$
Focal length	4 meters
Effective area at 3 keV	700 cm^2
Spectral resolution	< 25 % @ 5.9 keV
Operational phase	2 yr + extension (1 yr)
Sky coverage	40 %
Orbit	LEO 600 km (0^o inclination)



What can X-Ray Polarimetry Test?

Astrophysics:

• Non thermal emission processes producing intrinsically polarized photons.

• Deviation from spherical geometry of the matter close to the emitting regions polarizing by transfer in a variety of situations and classes of sources: jets, accretion disks and columns, reflection, archeoastronomy, etc.

Fundamental Physics:

Matter in extreme magnetic fields

Matter in strong gravity fields

Lorenz Invariance Violation effects

Axion Like Particles

Timing & spectroscopy may provide ambiguous and model dependent information.

- **Resolved sources**: Emission mechanisms and mapping of the magnetic field: PWNs, SNR and extragalactic jet
- **Unresolved sources**: Geometrical parameter of inner part of compact sources: X-ray pulsars, Coronae in XRB and AGNs.

IXPE organization

Scientific Working Groups

1. Wayne Baumgartner: **Science Calibration WG** (Co-Chair Fabio Muleri IAPS/INAF)
2. Allyn Tennant: **Science Data Processing WG** (Co-Chair Matteo Perri INAF c/o SSDC)
3. Luca Baldini: **Science Analysis and Simulation WG** (Co-Chair Herman Marshall MIT)
4. Giorgio Matt (Universita’ Roma III) and Roger Romani (Stanford): **Science Advisory Team** chairs

Topical Working Groups

- Niccolò Bucciantini (O. Arcetri): **PWNe and isolated pulsars**
- Patrick Slane (Harvard Univ.) : **SNR**
- Michal Dovčiak (Czech Academy of Sciences): **Accreting stellar-mass BH**
- Juri Poutanen (Tuorla Obs.): **Accreting NS & WD**
- Roberto Turolla (Padua Univ.): **Magnetars**
- Frédéric Marin (Astron. Obs. of Strasbourg): **Radio-quiet AGN & Sgr A***
- Alan Marscher (Boston Univ.): **Blazars & radio galaxies**

First Year of observation plan (notional)

Source Class	
AGN	4 Seyfert 6 Blazars
Galactic Center	Sgr B2
Microquasars	6
Pulsar Wind Nebulae + Pulsar	3
Supernova Remnants	3
Magnetars	2
Classical Accreting X-ray pulsars	8
Accreting Millisecond X-ray pulsars and Low B binaries	7

Launch Date April 2021→December 2021

IXPE performs as predicted

Scientific Measurement Requirements		Scientific Requirements		Projected Performance
Physical parameters	Observables	Property	Value	
Linear polarization	Degree Π, angle ψ	Sensitivity MDP_{99} ($F_{2\text{-}8} = 10^{-11}$ cgs, Δt = 10 d)	≤ 5.0%	4.4%
		Systematic error in polarization degree Π	≤ 0.3%	0.2%
		Systematic error in position angle ψ	≤ 1°	0.2°
X-ray flux	F	Absolute calibration error in F	≤ 20%	< 10%
Energy dependence	$F(E)$, $\Pi(E)$, $\psi(E)$	Energy band E_{min}–E_{max}	2–8 keV	1.5–9 keV
		Energy resolution ΔE (E = 2 keV), $\propto \sqrt{E}$	≤ 0.7 keV	0.54 keV
Spatial dependence	$F(k)$, $\Pi(k)$, $\psi(k)$	Angular resolution HPD (system-level)	≤ 30″	28″
		Field of view FOV >> HPD	≥ 8′ ∅	12.8′ × 12.8′
		Onboard pointing accuracy << FOV	≤ 1′	< 0.5′
Time dependence	$F(t)$, $\Pi(t)$, $\psi(t)$	Time accuracy << source pulse periods	≤ 0.25 ms	< 0.1 ms
Areal background rate	R_B/A_{det}	R_B/A_{det} << R_S/A_S for low-intensity source	< 0.04 $s^{-1}cm^{-2}$	< 0.01 $s^{-1}cm^{-2}$

1

Courtesy of F.Muleri

Minor Troubles

Alignment of the three mirrors with detectors.

A first problem is an oscillation of the order of one arcminute due to thermal effects on the boom during the orbit. It took some time to quntify and correct.
The alignment performed at the Commissioning was not optimal. In the first observations we found that each detector is not positioned at the center of the field of view of the corresponding telescope.
Given the vignetting of the optics at off-set angles this introduces a small uncertainty in absolute calibration, which is more prominent at higher ennergies when the vignetting is larger. In general in the sources at 6-8 keV IXPE measures spectra softer than those measured from other satelites.
The mirrors have been re-aligned in June. Data will be re-processed so that they will be available to the community with the correct normalization.

In any case the measurement of polarization is totally unaffected by these pointing troubles.

Solar Activity

The High Voltage Power Supplies are reduced below the multiplication threshold with time-tagged commands during the transit of the saellite in the South Atlantic Anomaly.
We found that, following solar flares and episodes of Coronal Mass Ejection, the extension of the South Atlantic Anomaly increases, so that an increase of counts is found before the swith off. These counts must be removed. A careful analysis of data is needed to prevent the possibility that such an increase of background, not adequately removed, could spoil the observatin of very weak extended sources. In

A long term plan

In practice with IXPE we evolve from the situation of a unic polarized source known, the Crab, to the possibility of studying sources belonging to many different classes. Beside the obvious target of Crab Polarimetry could result an important tool of diagnostics but the coverage of literature is very discntinous. Theory is fed by data!

Moreover IXPE

1) Is a narrow field instrument pointing a source at a time. If the observation gives an upper limit of dubious significance the time is almost lost.
2) In the general frame of a very tight budget the capability of repointing on the basis of data of other observatories or of IXPE itself is limited to a few per year. E.g. if we discover that the source is in a very low state and the nmber of detected photons is too meagre for a meaningful measurement, there is no chace to skip the pointing.

High significance detections

24 sources observed so far
8 high–significance detections (>6σ)
from quick-look analysis

4U0142+61
Her X-1
Crab PWN
Mrk 501
Vela PWN
Mrk 421
Cyg X-1
Cen X-3

But also some result of lower statistical significance but of clear astrophysical impact have been performed.
See e.g.CasA

Which overlap with Cherenkov Telescopes?

Any target of ixp the list is a high energy object emitting X-rays or γ-rays via a non thermal process. The point is that not all the sources arrive to emit in the TeV range.

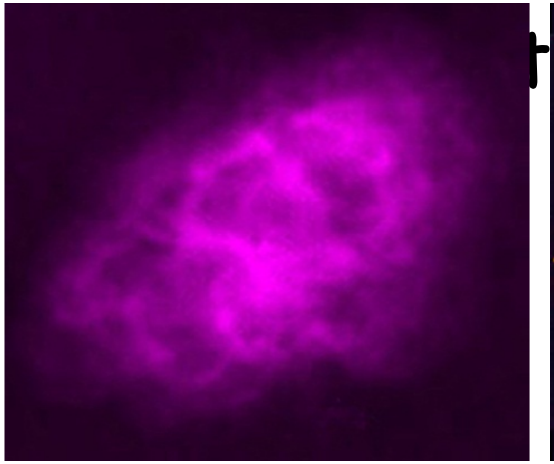
Also given that the two ranges are far for 9-10 orders of magnitude the process/mechanism providing the polarized X-rays is not necessarily the same giving the γ-rays. In most cases it will be different. But in many cases the different emission mechanism will be effective in the same phyisical system. E.g. in some flare of blazars all the energies rise at the same time.

So the data from X-ray Polarimetry and from Cherenkov Telescopes can cooperate to improve our understanding of sources.

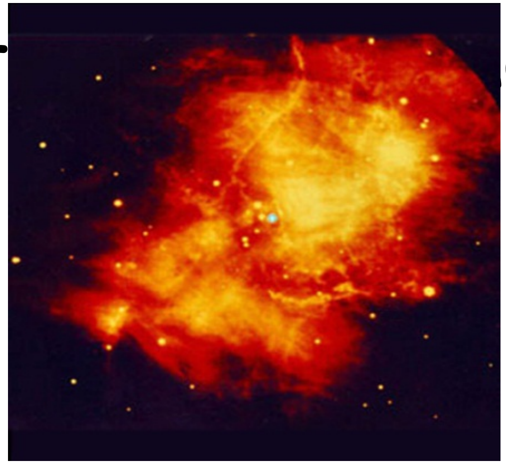
Since the production of VHE photons pass through acceleration the most straightforward candidates are:

- Pulsar Wind Nebulae
- SuperNova remnants
- Blazars

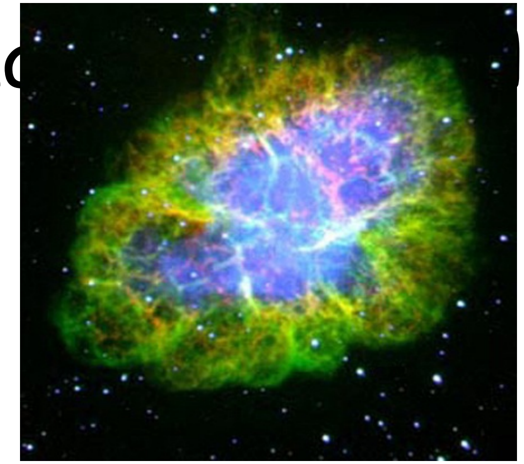
Why X is better? The prototypical accelerator



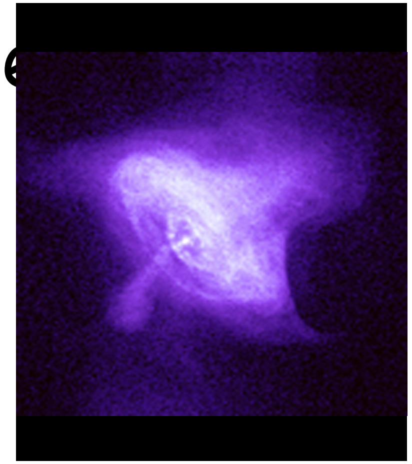
Radio (VLA)



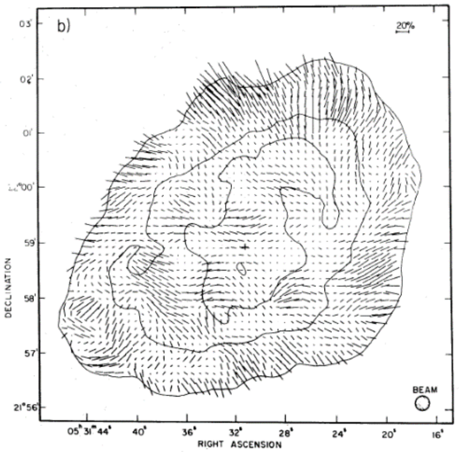
Infrared (Keck)



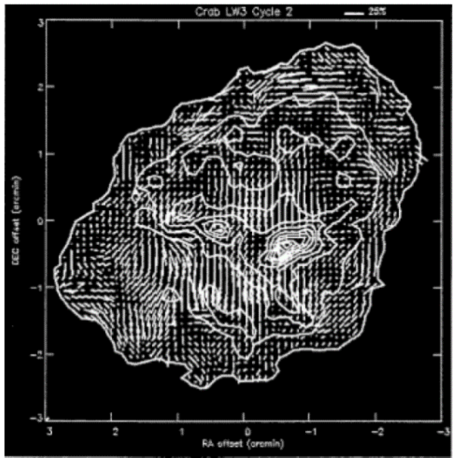
Optical (Palomar)



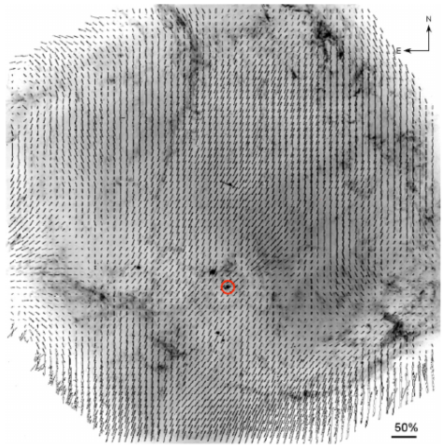
X-rays (Chandra)



Radio polarisation



IR polarisation



Optical polarisation

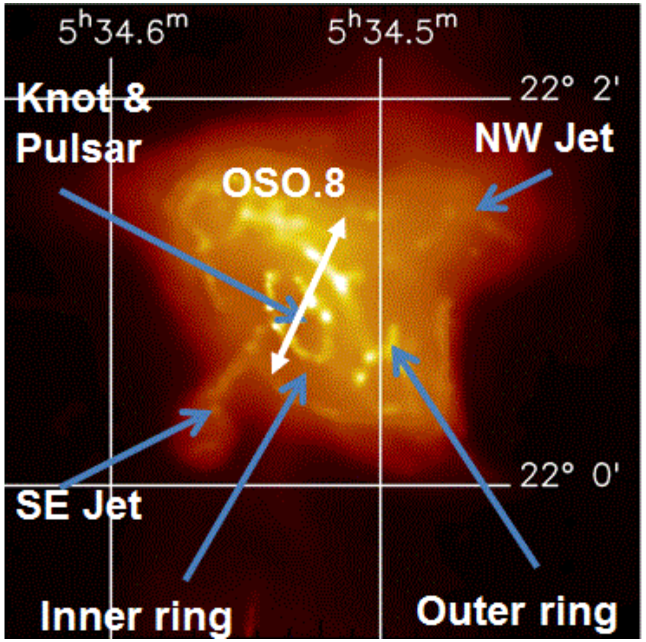
?

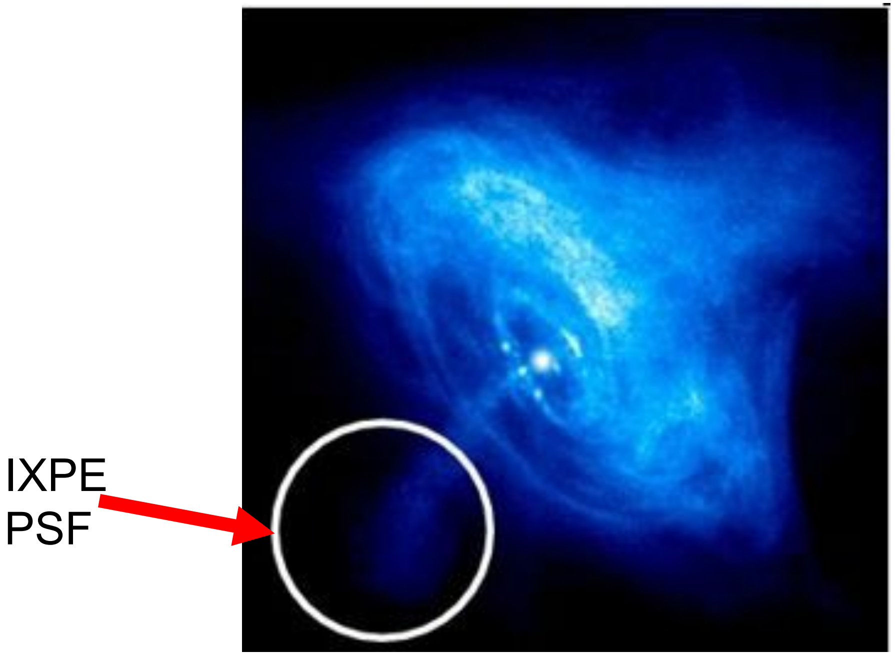
P=19% for the whole nebula (Weisskopf et al. 1978)

X-ray polarisation

X-rays probe **freshly accelerated** electrons and the site of acceleration.
Helas! The angular resolution of IXPE is not that of Chandra but better than that of gamma-ray telescopes and in the range of Cherenkov telescope.

Acceleration phenomena: The Crab Nebula





- The OSO-8 observation, integrated on the whole nebula, measured a position angle which is tilted with respect to jets and torus axes.

- Which is the role of the magnetic field (turbulent or not?) in accelerating particles and forming structures?

- IXPE imaging capabilities will allow to measure the pulsar polarisation by separating fa good fraction of the much brighter nebula emission.

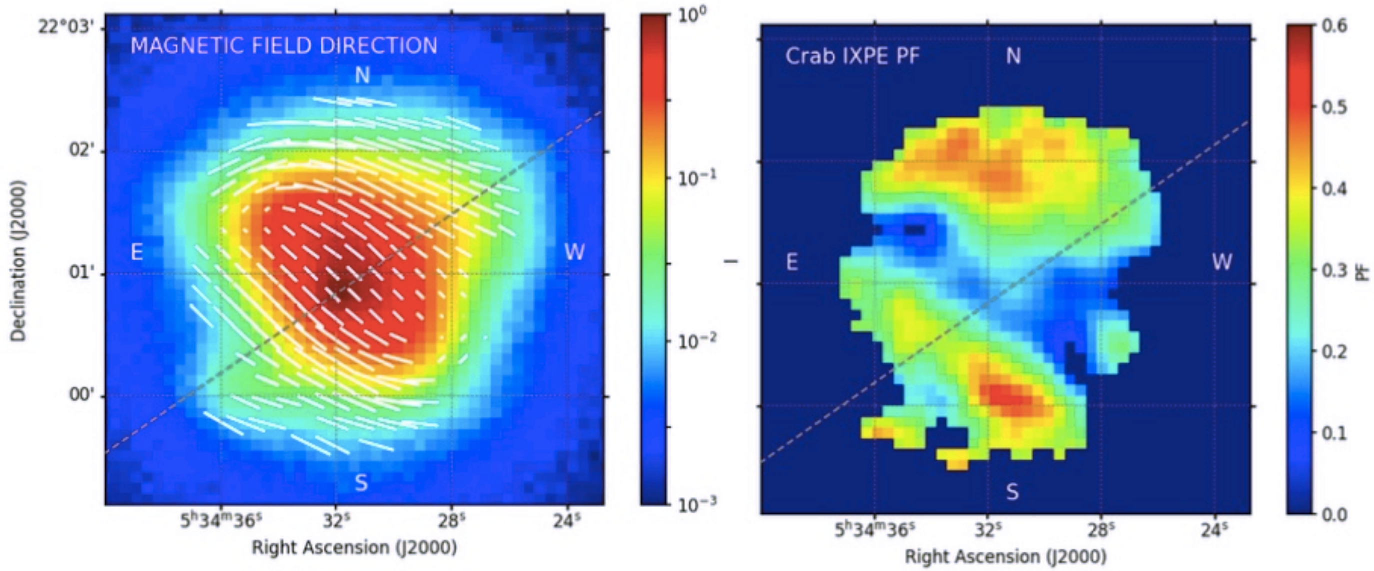
- OSO-8 could not perform polarimetry of the PSR because the nebula is a very bright background.

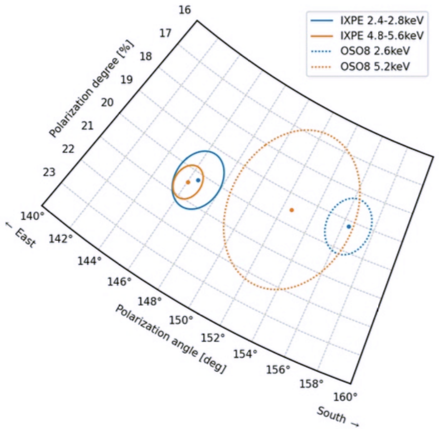
This slide was written before the launch

IXPE is not Chandra but, in combination with Chandra data

The X-Ray Image from Chandra gives the best description of the site of particle acceleration. Polarimetry, even with a poorer angular resolution (25” vs 1”) can give a measurement of the order of the magnetic field.

IXPE has observed the Crab PWN and PSR in February and March for a total live time of the order of 92 ks. (≈1 day).





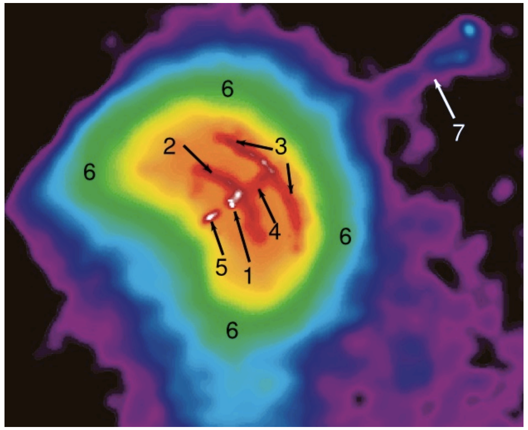
A first lesson from Crab

The degree of polarization integrated on the whole Nebula is consistent with OSO-8, while the angle is changed of around 10°. It is to check whether this is the variability on the few year time scaleof the PWN or is an hstorical trend. From OSO-8 to IXPE a 5% of the life time of the PWN has passed.

From the Imaging Polarimetry the local polarization can arrive to very high values (≈ 40%) . The toroidal field is very regular . The total polarization is determined from the inclination of the torus with respect to the axis. Data suggest that turbolence has not a relevant role.

The imaging allows to search for the PSR with a reduced bkg from the nebula. But the polarization of the nebula is still dominating and the observation is too short to give a good measurement. There is no doubt that the inclusion of the PSR reduces the total polarization.

The Polarimetry of PSR0531+21 and of the jets requires a substantially longer pointing.



Chandra ACIS image from Pavlov 2003

Even more from Vela PWN&PSR

Data from Vela PWN (including the PSR) are even more impressive. As the Chandra image shows the double torus structure is edge-on with respect to the observer.

Vela PWN is the most polarized source detected so far with IXPE and likely will be that also in the future.

Polarization Degree is around 45% although IXPE is integrating regions of different angles.

PWN

The very first results are:

1) The magnetic field is toroidal and extremely ordered.
2) Apparently the order extends to outer regions far from the torus
3) An important turbolence apparently is not there.

Shell Like SuperNova Remnants

SuperNova Remnants are likely the site of acceleration of particles by shocks. The VHE emission shows how efficient the acceleration process can be. The data is of paramount importance for the physics of Cosmic Rays.

X-ray imaging and spectroscopy (mainly by Chandra) are giving a view of the site of acceleration. The spectrum is mainly dominated by lines produced by the thermaization of the energy released but also the front shock is well imaged. And the non thermal components of the spectrum can be singled out in some regions.

X-ray polarization data can give some relevant data on the physcs near the site of acceleration. Of course an imaging polarimetry at energies > 10 keV would be the best but IXPE can select spatially the shock features and perform polarimetry in the continuum between Ca and Fe lines.

Shell-like SNR

Have been sold as one of the main target of IXPE. In practice:

1) The emission at low energy is dominated by emission lines. Although the plasma is not in collisional ionization equilibrium a significant fraction of the continuum is thermal bremsstrahlung (unpolarized). Therefore synchrotron is only a limited fraction.
2) The sensitivity of IXPE is boosted by imaging because the counts from the source compare with counts of background. But this is less true for extended sources. Moreover some features, such as the forward shock are very weak.

While point like sources of many classes can give relevant results with short pointing a significant result from SNR requires pointing of the order of one month.

In the first plan IXPE observed **CasA**, has just observed **Tycho** and will observe a lobe (NE) of S**N1006**.

CAS-A

Cas A has been the first long pointing. In practice the analysis has been the guinea pig to debug all the poblems of IXPE (unequality of gains, pointing misalignment, consequnces of solar activity).
The spectral analysis is needed to extract spectral regions ith less thermal emission.
A firs draft of a paper by J.Vink et al. can be found in arXiv.2206.06713v1 [astro-ph.HE]. Paper is still under revision but principal results hold.

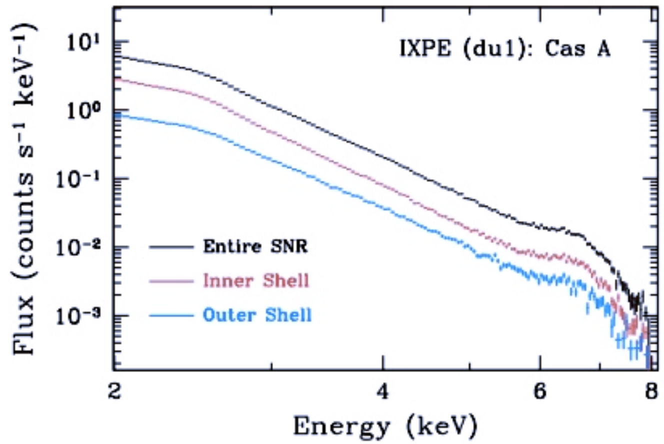


Figure 2. X-ray spectra of Cas A as detected by detector unit 1 of IXPE for three different extraction regions.

IXPE Specral resolution is significantly worse than Chandra or XMM. From the Chandra spectra and with a reasonable level of smoothing to achieve an adequate statstics we derive the regions were the continuum is dominant on lines (Ca line is weak and most o A and Fe lines are exluded) and from the hardness ratio were the synchrotron is dominant.

Search for polarization in maps

For each domain (of the order 42" or 84") so defined we can compute the Mnimum Detectable Polarization and search wether in some this detectin threshold is overcome. We find some"hot spot" were the detection threshold is overcome but this is still compatible with the number of independen ttrials.

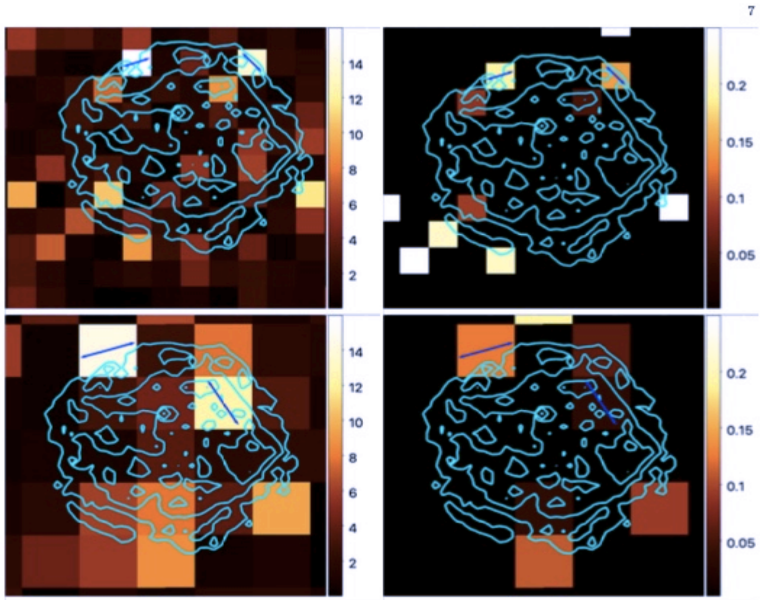


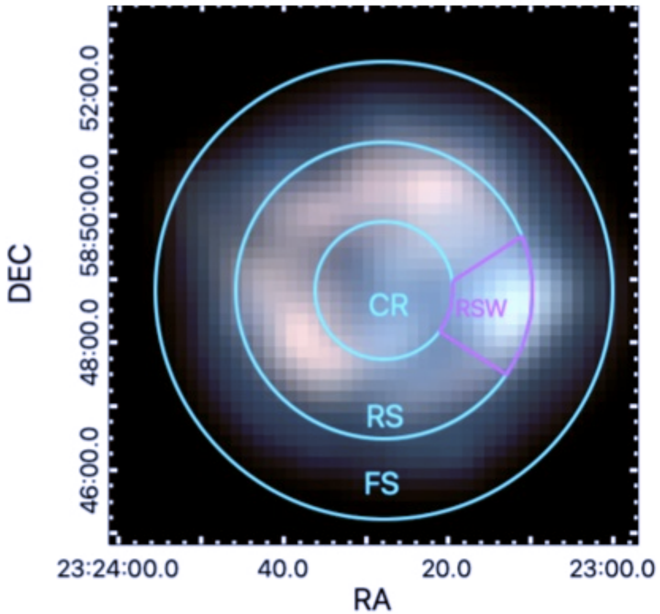
Figure 3. Left: Maps of χ_2^2 (or $S_{i,j}$, see Appendix A) values for the polarization signal for the 3-6 keV band. Right: the corresponding polarization degree maps. Only pixels with pre-trial confidence levels above 2σ ($\chi_2^2 > 6.28$) are shown. For pixels with $\chi_2^2 > 11.8$ (corresponding to 3σ confidence level) the polarization angles are indicated with blue arrows. The errors on these angles are $\sim 8°$. Top row: maps with pixel sizes binned to 42″. Peaks in the χ_2^2 map are $\chi_2^2 = 15.9, 13.6$ corresponding to polarization degrees of 19%, and 14.5%. Bottom row: same plot, but with a larger pixel size of 84″. Peaks in the χ_2^2 map are $\chi_2^2 = 14.4, 12.3$ corresponding to polarization degrees of 12.4% and 3.4%.

In any case CasA is a slowly varying system. Future observations can convert some of these hot spots into positive detections.
They give the idea that the system has a large local variability

Assuming a circular symmetry

The expectation to find polarization from synchrotron was larger for some specific regions such as those where the shock is present. In general, notwithstanding the local diffrences the remnant shows a certain level of spherical symmetry.

Eventhough the local diffrences seem relevant we want to find a possible evidence of this symmetry projected on the map.



We can identify the major regions.
FS Forward Shock
RS Reverse Shock
RSW Reverse Shock West
CR Central Region
And their combinations of any

Collapsing to a 1-D problem

We have a center of symmetry of the CasA image.
To search for a radial (or tangential) component on subregions of the remnant
we can rotate each photon around the center of symmetry

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Table 1. Polarization measurements in annuli and western region after imposing circular symmetry for Stokes U and Q.[a]

	$R_{\rm min}$[b] (arscec)	$R_{\rm max}$ (arcsec)	MDP99 (%)	Pol. Degree (%)	PD Corrected[c] (%)	Angle[d] (°)	Significance
Central region (CR)	0	65	2.4	< 3.1	< 4.0	N/A	0.9σ
Reverse shock (RS)	65	140	1.3	1.6 ± 0.4	1.9 ± 0.5	77.2 ± 7.6	3.1σ
RS West (RSW) [e]	65	140	2.6	< 3.9	< 4.6	N/A	1.9σ
Forward shock (FS)	140	216	2.3	3.5 ± 0.7	4.8 ± 1.0	89.8 ± 6.1	4.1σ
FS + RSW [f]	216	216	1.7	3.0 ± 0.6	3.6 ± 0.7	87.2 ± 5.4	4.8σ
All	0	216	1.0	1.8 ± 0.3	2.4 ± 0.4	85.7 ± 5.2	4.9σ

The result is now significant. The polarization is in average tangential to the shell (angles are consistent with 90°). With our models (and with extrapolation of high energy data) we can make an assumption on the fraction of synchrotron in continuum. In the table this is the PD corrected.

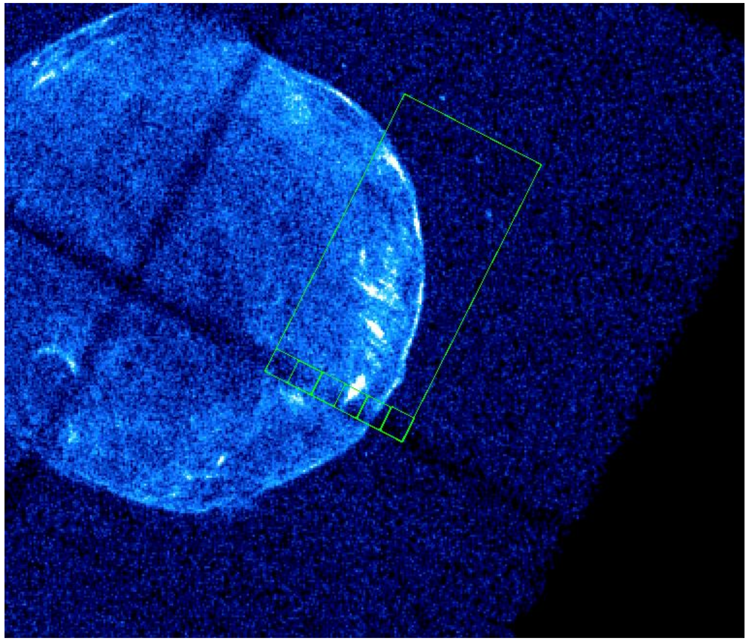
What can we derive?

- The magnetic field is radial
- The Polarization Degree is low (maximum 4.8±1.0% in the FS).

In the paper it is discussed the interpretation of these two features in terms of shock and the impact on the acceleration of electrons to TeV energies.

We can asume in any case that the magnetic field is disrdered below the angular resolutin of around 0.5 arcminutes of IXPE.

What abou Tycho?



Tycho has been just observed
The analysis is slow and complex.
In general the results are not much different fron CasA (notwithstanding Tycho is a Ia).
The presence of polarization in the reions identified as “stripes” in the Chandra image seems more promising than in CasA.

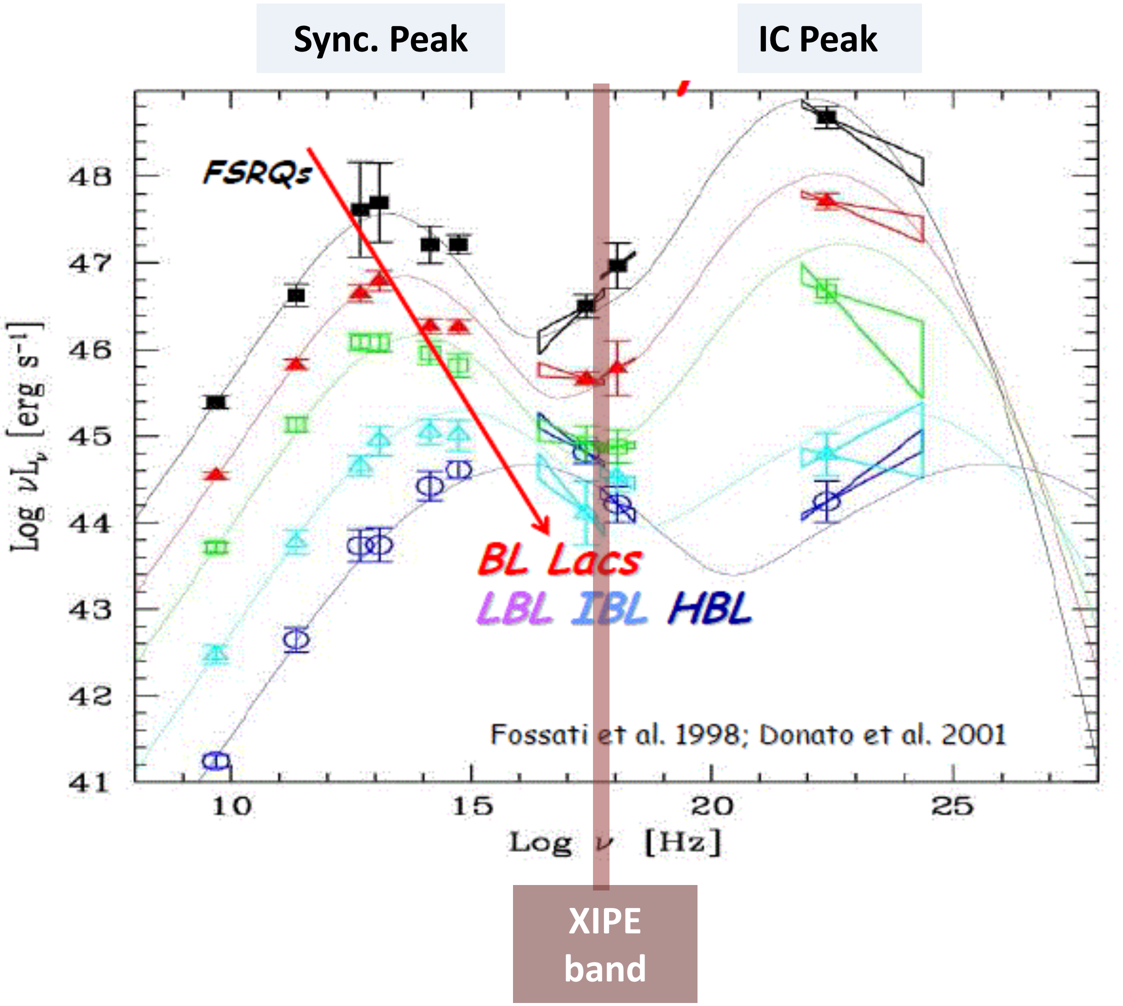
Acceleration phenomena: Unresolved jets

In synchrotron-dominated X-ray blazars, multi-wavelength polarimetry probes the structure of the magnetic field along the jet.

Models predict a larger and more variable polarisation in X-rays than in optical.

Coordinated multi-wavelength campaigns are crucial for blazars.

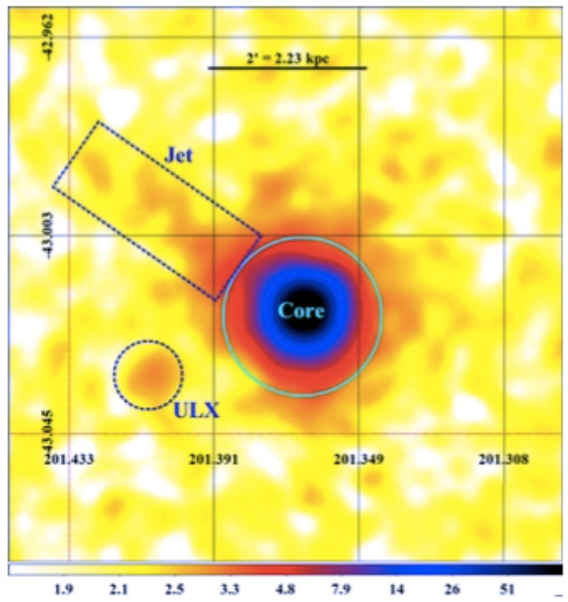
Such campaigns (including polarimetry) are routinely organised and it will be easy for XIPE to join them.



Slide written before the lsunch

The extragalactic sky with IXPE

The situation is less brilliant than hoped. Some observation last less than and we have upper limits of doubtful meaning. Contemporary observations with NUSTAR or Swift have been possible. Less with ground based.



CenA was observed (Ehlert et al 2022) for 100 ks.
An upper limit was found of 6.5%. But this is all from the core. The jet (for which the expected polarization could be much higher) is only marginally detected.
The low polarization suggest that fields are disordered.

Blazars

More interesting results have been achieved with LBL blazars.

MK501 and MK 421 show a significant degree of polarization, including time variability (compatible with a minimum needed integration time).

But the results and their meaning are still object of debate within the team and I am not allowed to say anything here.

BL Lac (for sure of high interest for the VHE community) was observed twice and found in a very low state so that the significance of the u.l. is null.

The future of X-Ray Polarimetry

IXPE performance is constant in the first 6 months. Optimistically we can hope to have IXPE operative for ≥ 5 years.

The Enhanced X-Ray Timing and Polarimetry Mission (eXTP) is in a state of advanced study by CAS and CNSA. It should include a set of polarimetry telescopes similar to IXPE with a collecting surface 4 to 8 times larger. Simultanously it shoud do timing and spectroscopy of the same source with highly performing instrumentation.

In the last surveys in USA (Krawczynski H. 2019) and Europe (Soffitta 2020) future X-ray Polarization Probes were proposed (P) which could offer a sensitivity improvement by a factor of 3-10 over IXPE, an energy bandpass broadened from 2-8 keV to 0.1-60 keV, and an angular resolution improvement from 30" to 5" half power diameter.

In the hard X-ray/soft γ-Ray range ITOMI was apparenty well performing. The new satellite will not include the polarimeter. In the 100 keV – 100 MeV range Compton Telescopes are also Polarimeters..