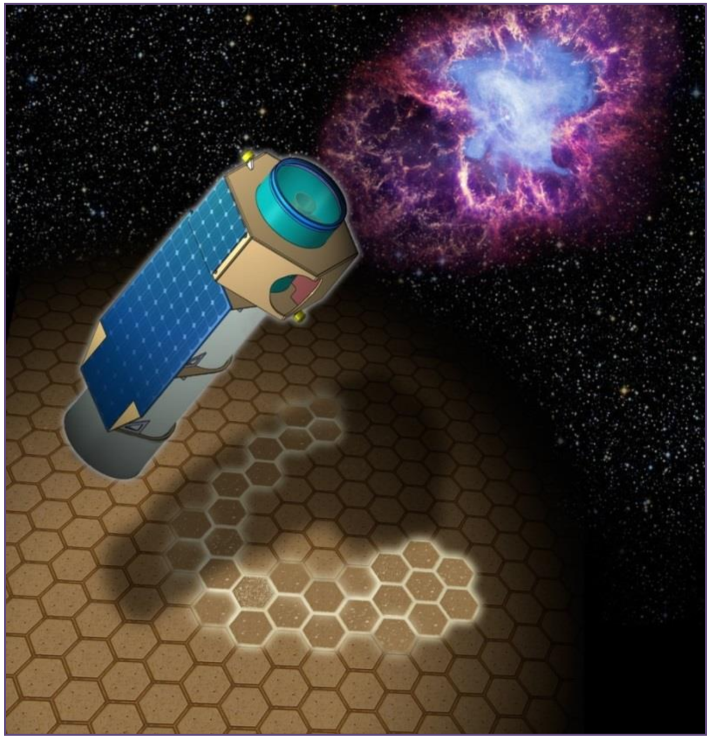
XIPE:
The X-ray Imaging Polarimeter Explorer

Silvia Zane

MSSL, University College London

on behalf of the
XIPE Study Science Team
and XIPE Consortium



BH Accretion and Jets, October 2016,
Kathmandu, Nepal

www.isdc.unige.ch/xipe

Picking the right direction

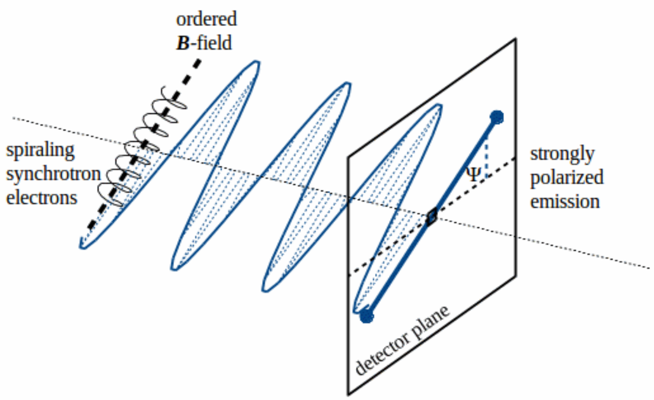
Xipe

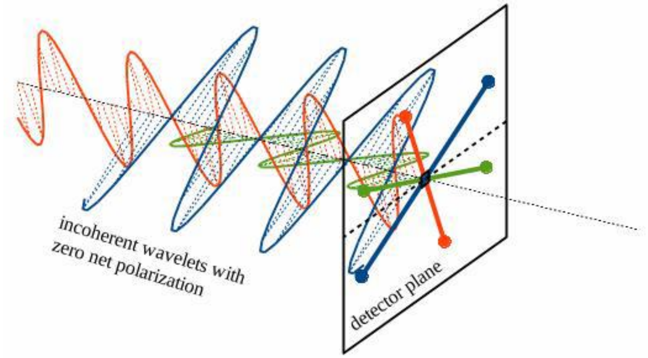
What is polarimetry?

Linear polarization quantifies to which extent the time-averaged electric field vector, ***E***, of electromagnetic radiation oscillates along a preferred direction.

For a maximum polarization fraction of *P* = 1, the ***E***-vector would have a fixed direction with respect to the reference axis of the detector plane. Its angle with the ***E***-vector defines the polarization position angle Y.

The case of *P* = 1 would only occur for the case of perfectly coherent light, whereas astronomical light is always incoherent. Still, the conditions to measure astronomical polarization are particularly favourable in the X-ray band





Why X-ray polarimetry?

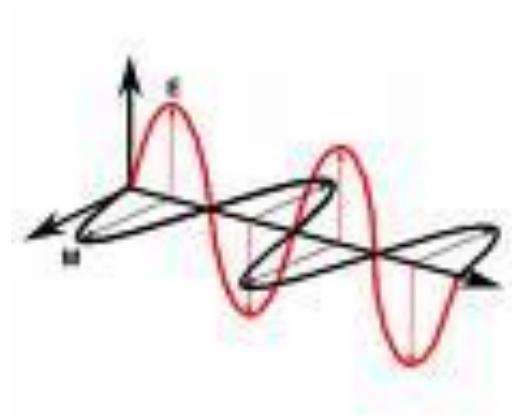
Celestial (extra-solar) sources ⇒ electromagnetic radiation.

Information from spatial, spectral, timing and *polarization* properties of the observed radiation.

Polarization properties give us information on *geometry* (in a broad sense:geometry of the emitting matter but also of magnetic and gravitational fields, of space-time, etc.): the polarization degree depends on the level and type of symmetry of the system, the polarization angle indicates its orientation.

Important results from Polarimetry in radio, IR and optical (eg. jet emission in blazars, Unification Model of AGN, ...).

However, polarimetric informations of astrophysical sources are basically missing the X-ray band !



Why X-ray polarimetry?

Only one measurement (P=19% for the Crab Nebula, indicating synchrotron emission) has been obtained so far, together with a tight upper limit to Sco X-1.

These measurements have been obtained in the 70s, for the two brightest sources in the X-ray sky.

Lack, for many decades, of significant technical improvements ⇒ no polarimeters were put on board of X-ray satellites.

The situation has changed dramatically with the advent of polarimeters based on the photoelectric effect. Such detectors, on the focal plane of a X-ray telescope, may provide astrophysically interesting measurements for hundreds of sources (remember that polarimetry is a photon hungry technique...). The brightest specimens of all major classes of X-ray sources are now accessible!

XIPE has been selected for a phase A study in ESA M4 (3 missions selected ; final down-selection in Summer 2017).
XIPE will perform spectrally-, spatially- and time-resolved polarimetry of hundreds of celestial sources to provide a breakthrough in astrophysics and fundamental physics

Why X-ray polarimetry?

Astrophysics

- **Acceleration phenomena**
  - Pulsar wind nebulae
  - SNRs
  - Jets
- **Emission in strong magnetic fields**
  - Magnetic cataclysmic variables
  - Accreting millisecond pulsars
  - Accreting X-ray pulsars
  - Magnetars
- **Scattering in aspherical situations**
  - X-ray binaries
  - Radio-quiet AGN
  - X-ray reflection nebulae

Fundamental Physics

- **Matter in Extreme Magnetic Fields:**
  - **QED effects**
- **Matter in Extreme Gravitational Fields: GR effects**
  - Galactic black hole system & AGNs
- **Quantum Gravity**
- **Search for axion-like particles**

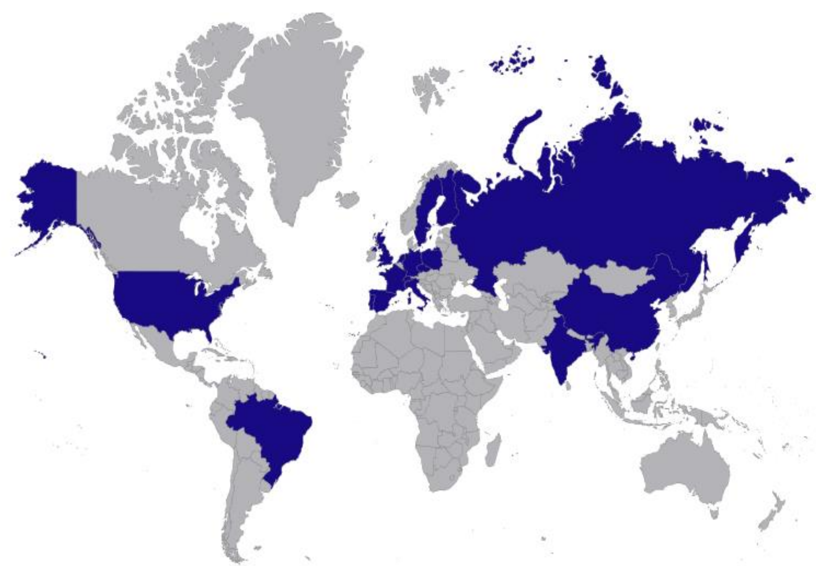
XIPE will observe **almost all classes of X-ray sources**

A large community involved (as for the proposal):

17 countries

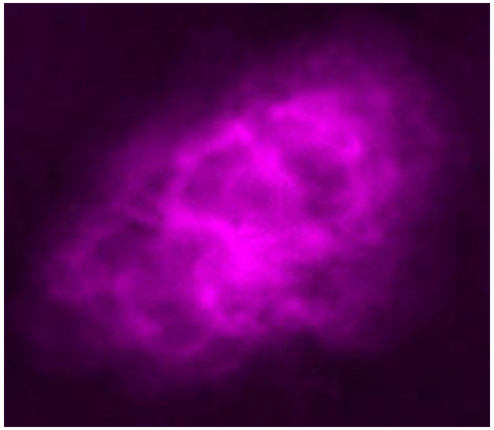
146 scientists

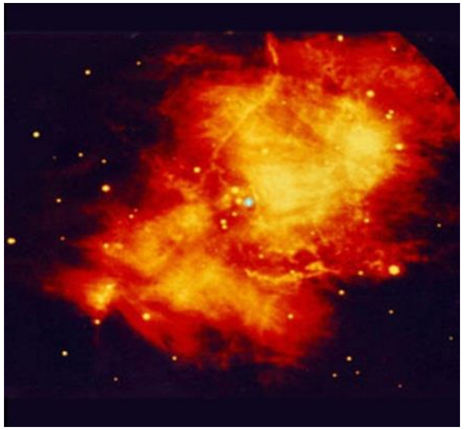
68 institutes around the world

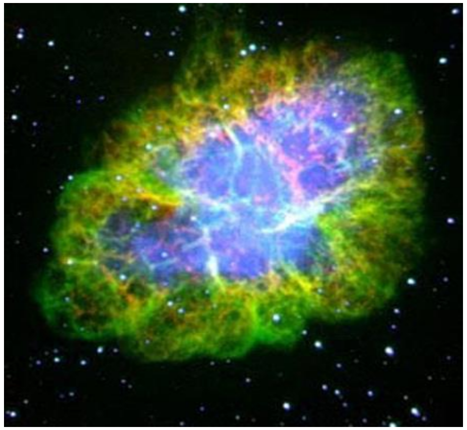


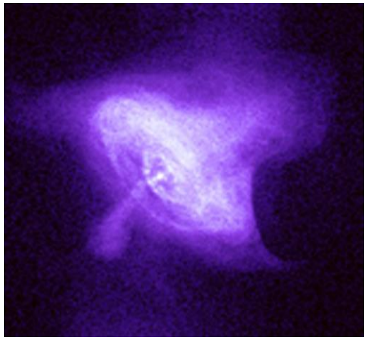
Xipe

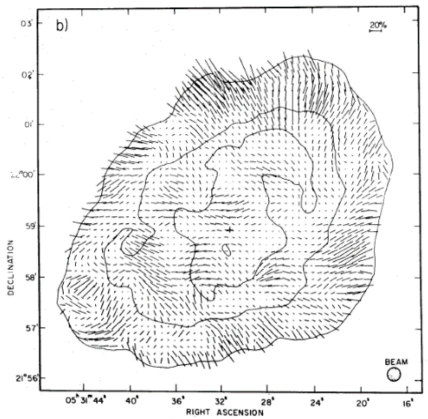
XIPE scientific goals. 1) Crab Nebula


Radio (VLA)

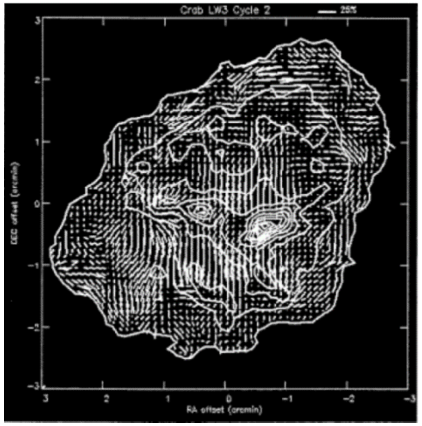

Infrared (Keck)


Optical (Palomar)

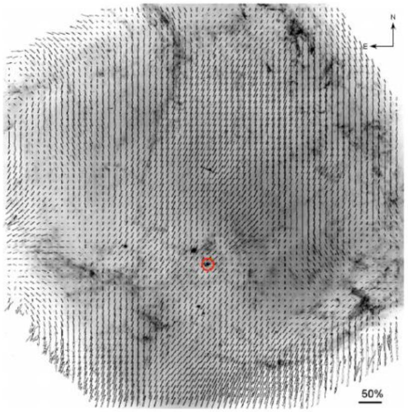

X-rays (Chandra)



Radio polarisation



IR polarisation



Optical polarisation

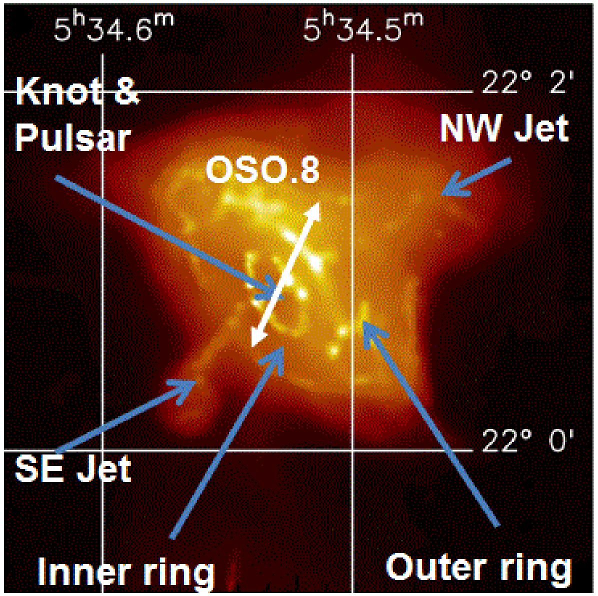
?

P=19% integrated over the entire nebula (Weisskopf et al. 1978)

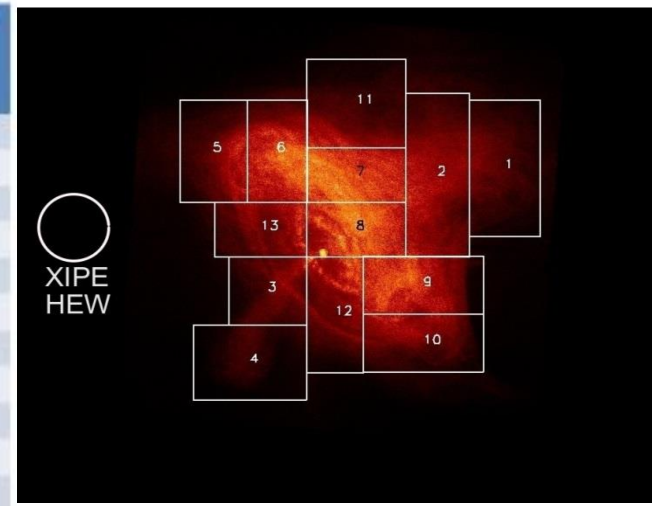
X-ray polarisation

X-rays probe **freshly accelerated** electrons and their acceleration site.

XIPE scientific goals. 1) Crab Nebula



Region	σdegree (%)	σangle (deg)	MDP (%)
1	±0.60	±0.96	1.90
2	±0.41	±0.65	1.30
3	±0.68	±1.10	2.17
4	±0.86	±1.39	2.76
5	±0.61	±0.97	1.93
6	±0.46	±0.75	1.48
7	±0.44	±0.70	1.40
8	±0.44	±0.71	1.41
9	±0.46	±0.74	1.47
10	±0.60	±0.97	1.92
11	±0.52	±0.83	1.65
12	±0.53	±0.85	1.69
13	±0.59	±0.95	1.89



20 ks with XIPE

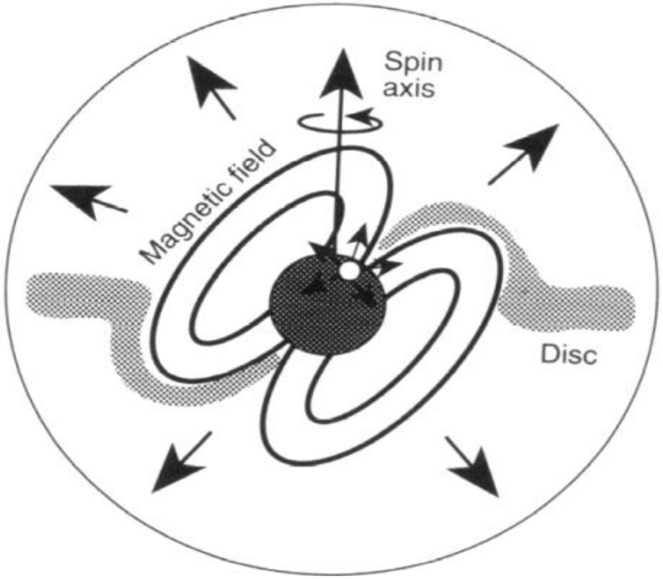
- The OSO-8 observation, integrated over the entire nebula, measured a position angle that is tilted with respect to the jets and torus axes.
- What is the role of the magnetic field (turbulent or not?) in accelerating particles and forming structures?
- XIPE imaging capabilities will allow us to measure the pulsar polarisation by separating it from the much brighter nebula emission.
- Other PWN, up to 5 or 6, are accessible for larger exposure times (e.g. Vela or the “Hand of God”).

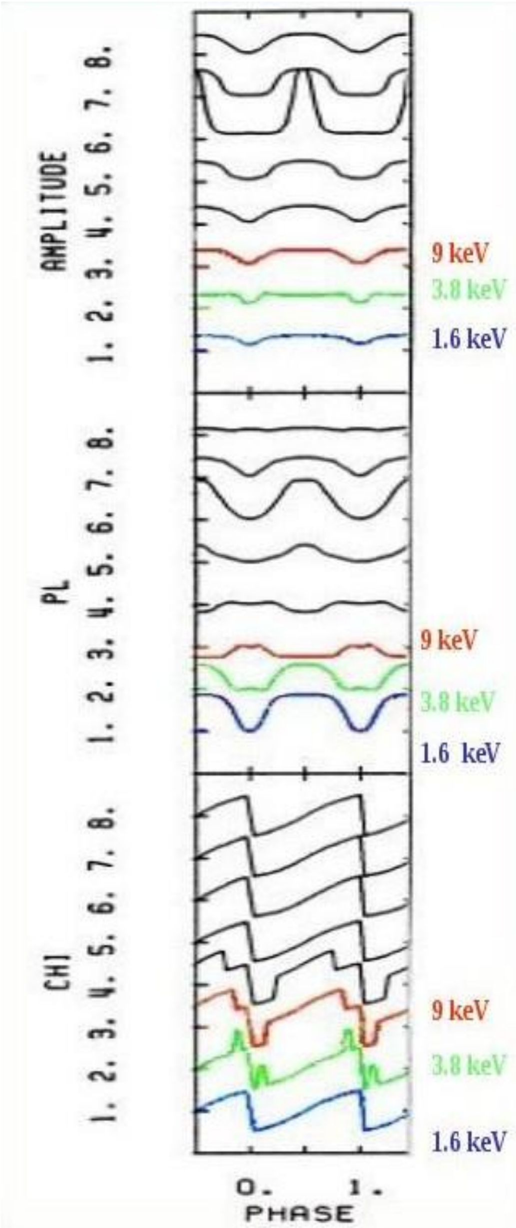
XIPE scientific goals. 2) Accreting MSPs

Opacity in highly magnetized plasma

⇒ $k_\perp \neq k_\parallel$

⇒ Phase-dependent linear polarization





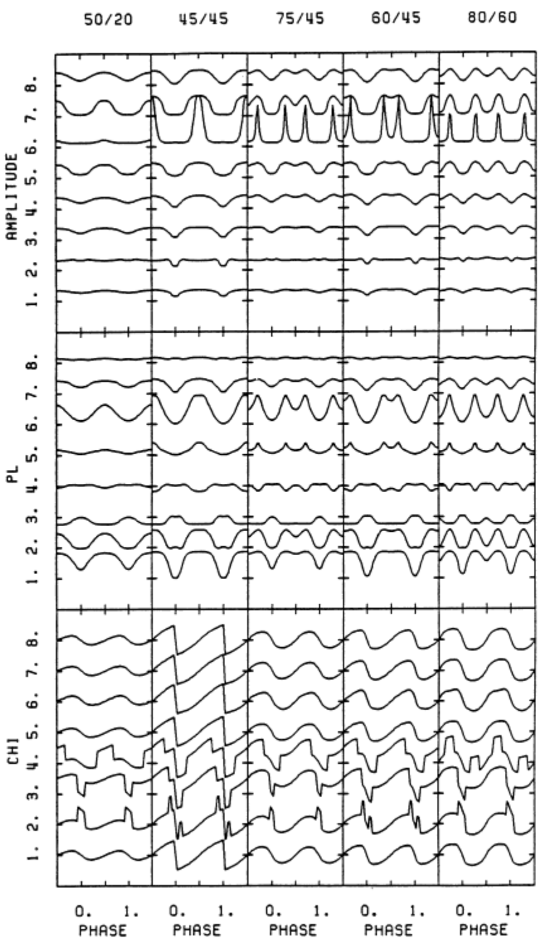
From the (phase-resolved) swing of the polarisation angle :

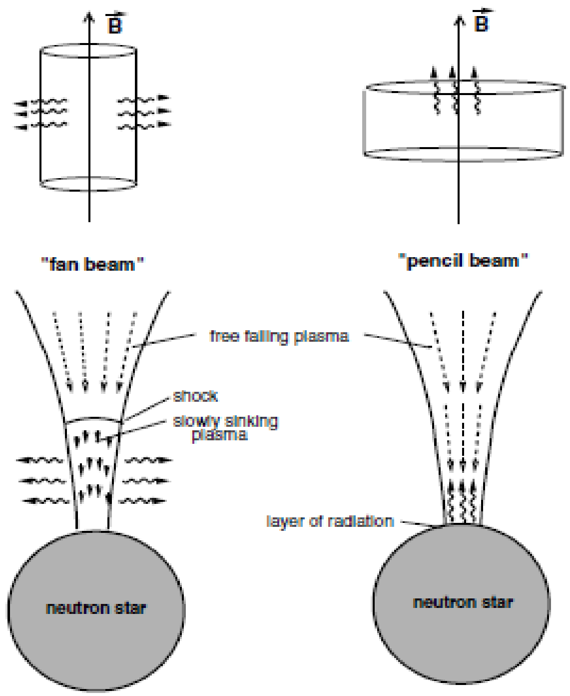
Orientation of the rotation axis and inclination of the magnetic field (required for many purposes, e.g. measure of mass/radius relation ⇒ EOS!)

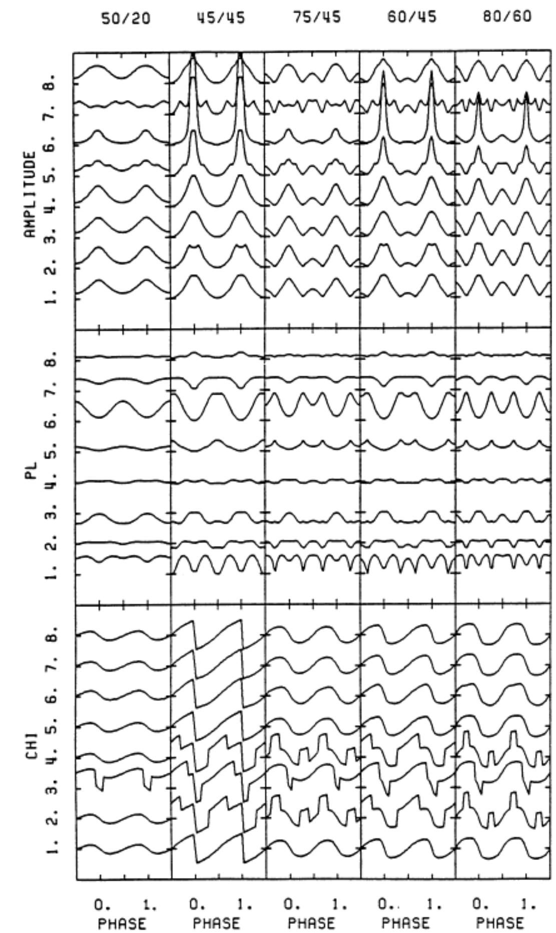
Meszaros et al. 1988
Viironen & Poutanen 2004

XIPE scientific goals: 3) Accreting Binaries

“Fan” vs. “Pencil” beam







Meszaros et al. 1988

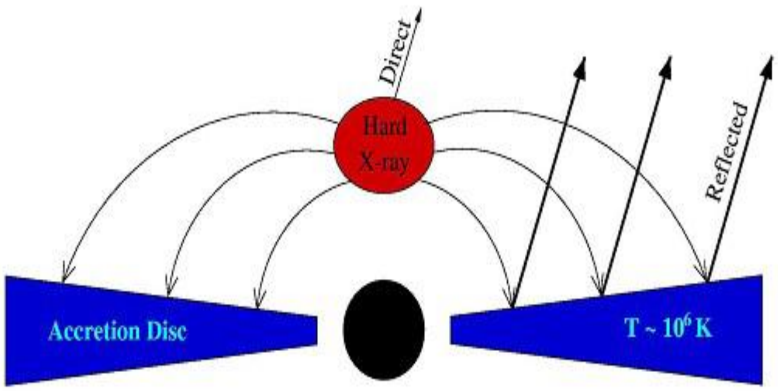
XIPE scientific goals: 4) AGNs

A) The geometry of the hot corona, considered to be responsible for the X-ray emission in binaries and AGN, is largely unconstrained.

The geometry is related to the corona origin:

- Slab – high polarisation (up to more than 10%): disc instabilities?
- Sphere – very low polarisation: aborted jet?

(Schnittman et al. 2011)



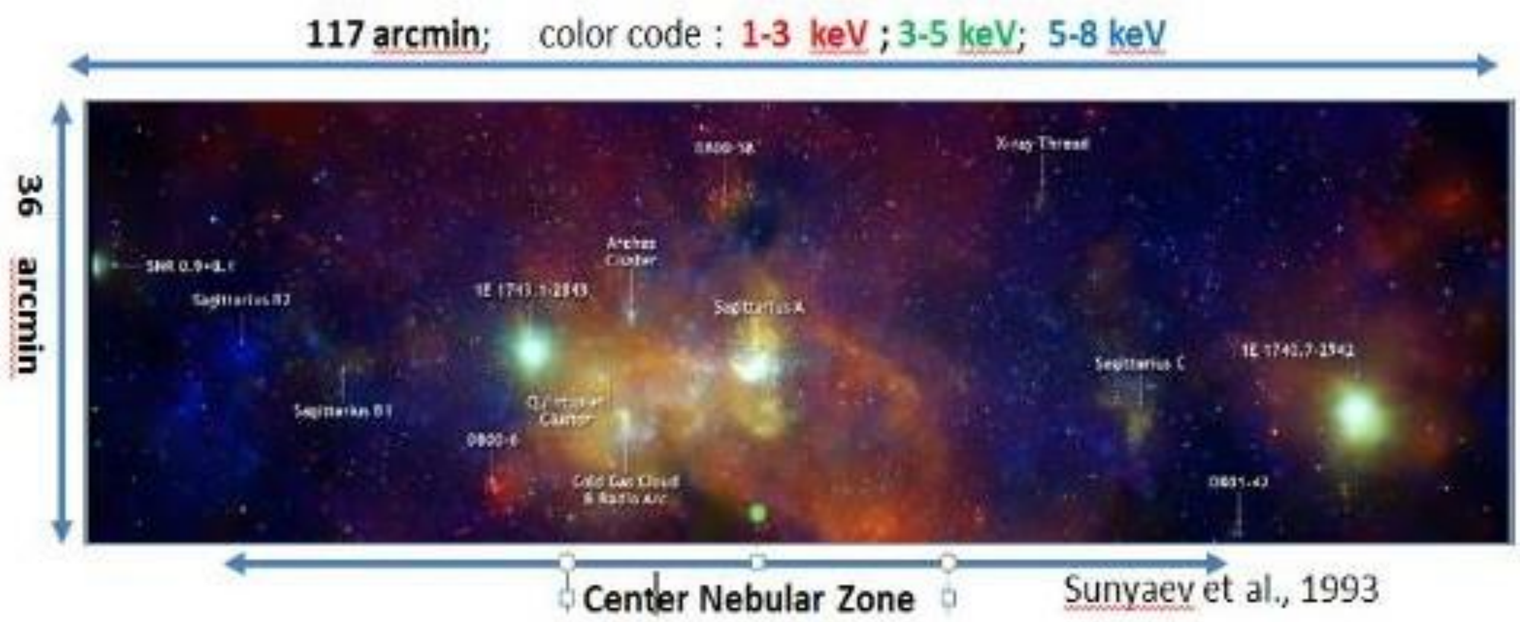
B) Jets: hadronic or leptonic?

(Celotti & Matt 1993, McNamara et al. 2009; Begelman & Sikora 1987)

XIPE scientific goals: 5) Probing the Galactic Center Past Activity

Cold molecular clouds around Sgr A* (i.e. the supermassive black hole at the centre of our own Galaxy) show a neutral iron line and a Compton bump → Reflection from an external source!?!

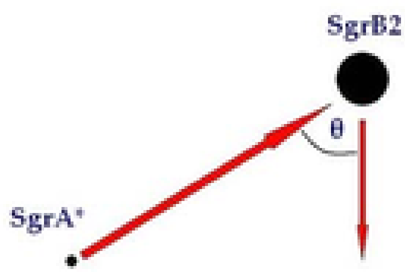
No bright enough sources are in the surroundings. Are they reflecting X-rays from Sgr A*? so, was it one million times brighter a few hundreds years ago? Polarimetry can tell!

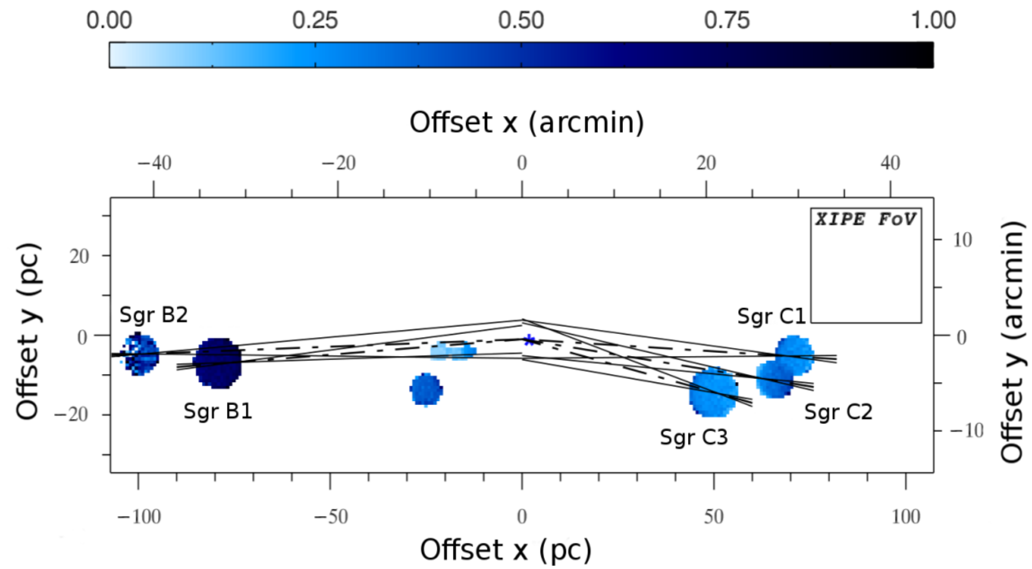


XIPE scientific goals. 5) Probing the Galactic Center Past Activity

Polarization by scattering from Sgr B complex, Sgr C complex

- The angle of polarisation pinpoints the source of X-rays
- The degree of polarization measures the scattering angle and determines the true distance of the clouds from Sgr A*.

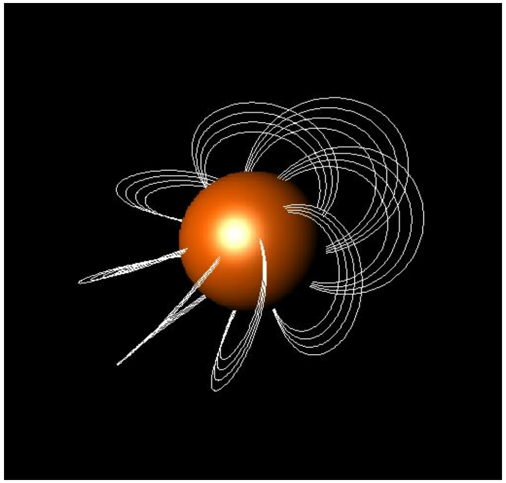




Marin et al. 2014

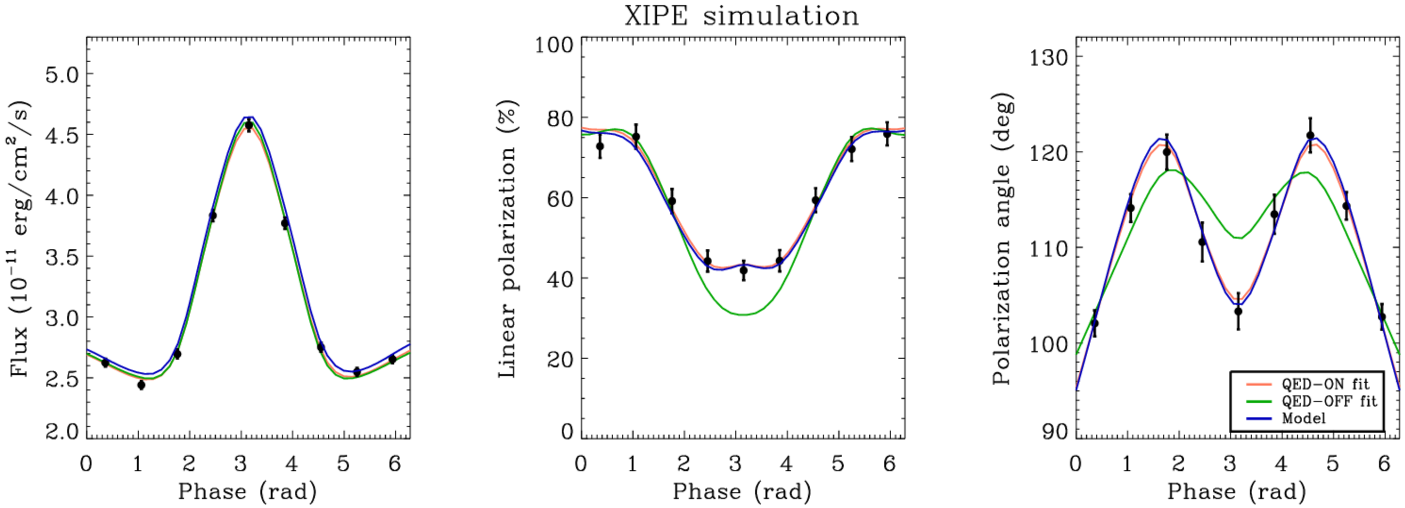
XIPE scientific goals. 6) Probing QED through NSs and Magnetars Observations

Magnetars are isolated neutron stars with likely a huge magnetic field (B up to 10^{15} Gauss).
Energy dissipation from B-field onto the star crust can explain why the X-ray luminosity largely exceeds the spin down energy loss.



QED foresees vacuum birefringence:
- predicted 80 years ago (Eisenberg & Euler 1936),
- expected in such a strong magnetic field,
- and never detected yet !

Light curve **Polarisation degree** **Polarisation angle**



Such an effect is **only** visible in the phase dependent polarization degree and angle.

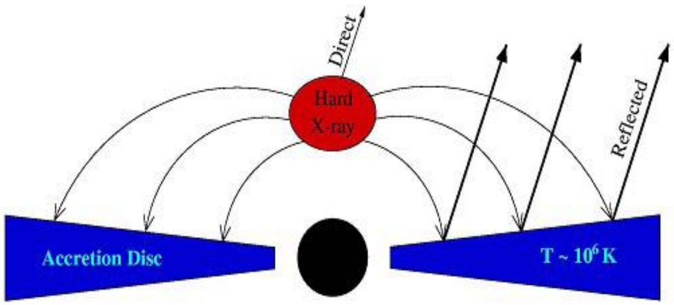
Taverna et al. 2014

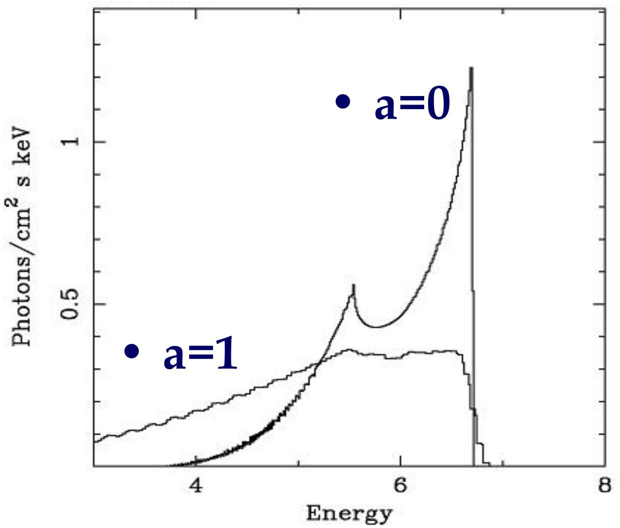
XIPE scientific goals. 7) Black Holes Spin

Knowledge of the spin tells us about the BH birth (in Galactic black holes) or the BH growth (in galaxies).

So far, three methods have been used to measure the BH spin in XRBs:

1. Relativistic reflection (still debated, requires accurate spectral decomposition);
2. Continuum fitting (requires knowledge of the BH mass, distance and inclination);
3. QPOs (three QPOs required to completely determine the parameters, so far applied only to two sources).



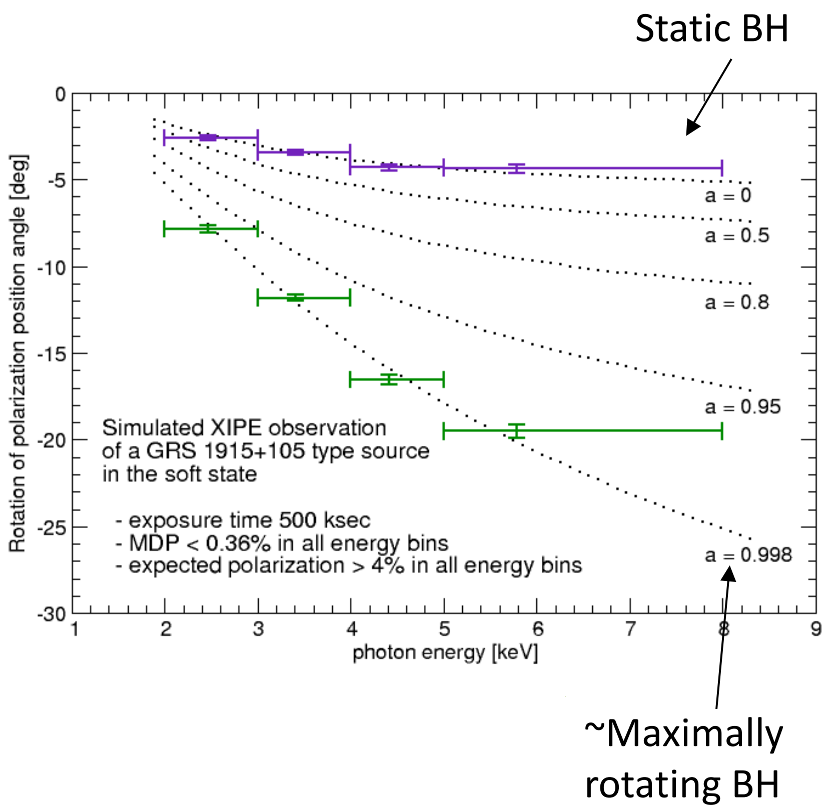


XIPE scientific goals. 7) Black Holes Spin

For a number of XRBs, the three methods do not agree!

Example: J1655-40:

QPO:	a = J/Jmax = 0.290±0.003
Continuum:	a = J/Jmax = 0.7±0.1
Iron line:	a = J/Jmax > 0.95



Energy dependent rotation of the X-ray polarisation plane expected in the high/soft state of stellar mass black holes

- Two observables: polarisation degree & angle
- Two parameters: disc inclination & black hole spin

(Stark and Connors 1977; Connors et al. 1980; Matt et al. 1993; Li et al. 2008; Dovčiak et al. 2008,2011; Schnittman & Krolik 2009, 2010).

XIPE scientific goals. 8) Testing Quantum Gravity and Dark Matter particle candidates

Search for energy-dependent birefringence effects on distant polarized sources (e.g. Blazars) may put tighter constraint on QG theories.

Variation of polarization angle and degree on radiation from sources in the background of large regions with significant magnetic field (eg clusters of galaxies) may indicate the presence of Axion-like particles, a candidate to be one of the dark matter main ingredients.

→ **Very challenging measurements, but potentially very rewarding!!**

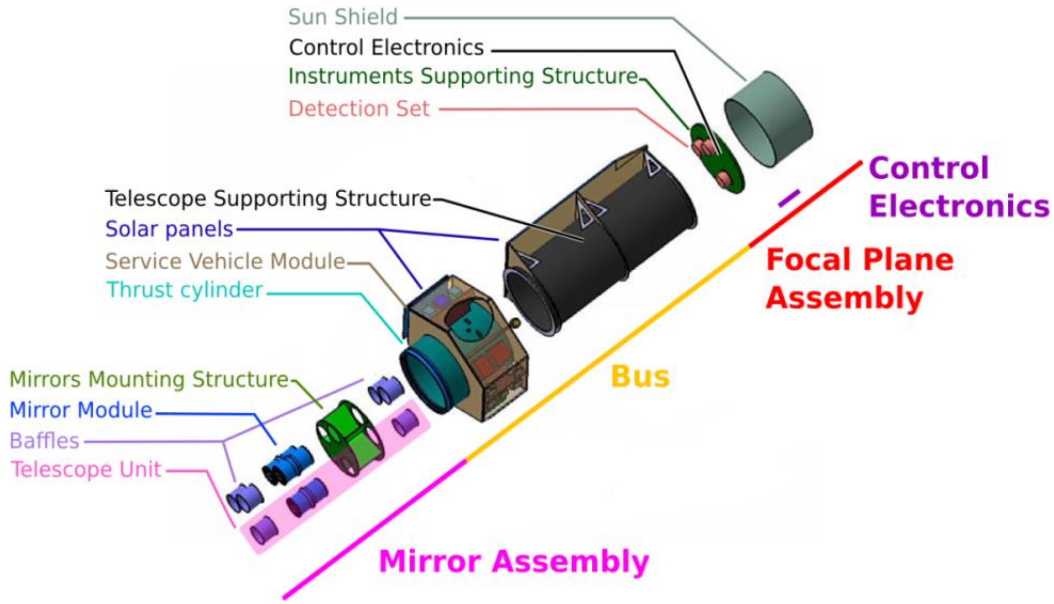
XIPE Observing Plan

Target Class	Ttot (days)	Tobs/ source (Ms)	MDP (%)	Number in 3 years	Number available
AGN	219	0.3	< 5	73	127
XRBs (low+high mass)	91	0.1	< 3	91	160
SNRe	80	1.0	< 15 % (10 regions)	8	8
PWN	30	0.5	<10 % (more than 5 regions)	6	6
Magnetars	50	0.5	< 10 % (in more than 5 bins)	10	10
Molecular clouds	30	1-2	< 10 %	2 complexes or 5 clouds	2 complexes or 5 clouds
Total	**500**			**193**	**316**

XIPE Design

- Three telescopes with 4m focal length to fit within the Vega fairing:
  Long heritage: SAX → XMM → Swift → eROSITA → XIPE
- Pioneering, yet mature detectors: conventional proportional counter but with a revolutionary readout, already studied by ESA during XEUS/IXO.
- Mild mission requirements: 1 mm alignment, 1 arcmin pointing.

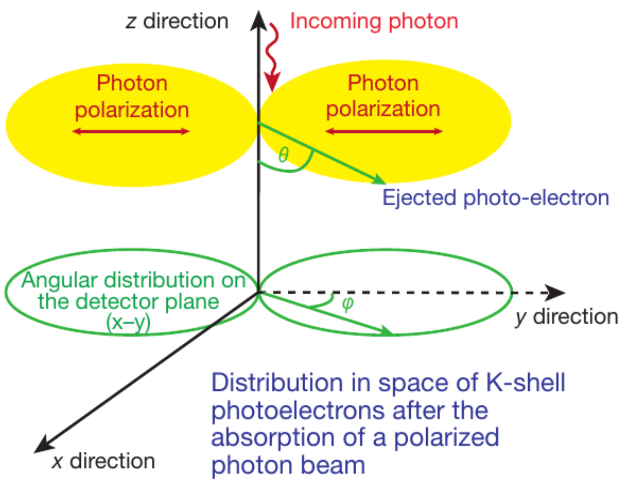
- Fixed solar panel. No deployable structure. No cryogenics. No movable part except for the filter wheels.
- Three years of nominal operation. No consumables.
- Optics designed by the XIPE consortium and procured by ESA; Focal Plane Assembly and Control Electronics procured by the XIPE consortium.



XIPE Design

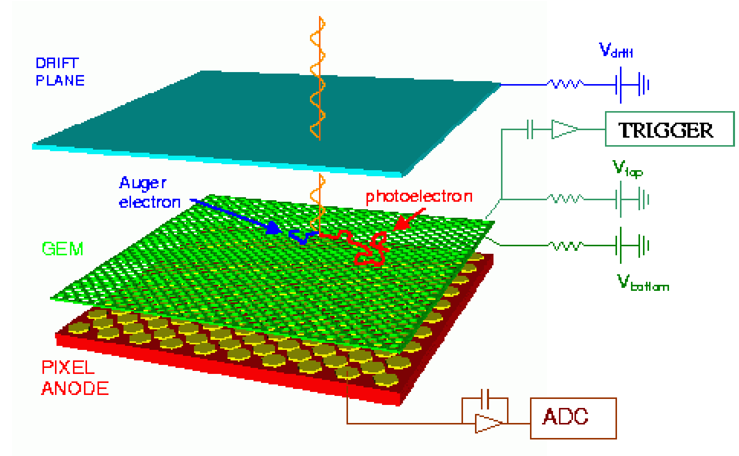
The Gas Pixel Detector (Costa et al. 2001, Bellazzini et al. 2006, 2007) is a polarization-sensitive instrument capable of imaging, timing and spectroscopy

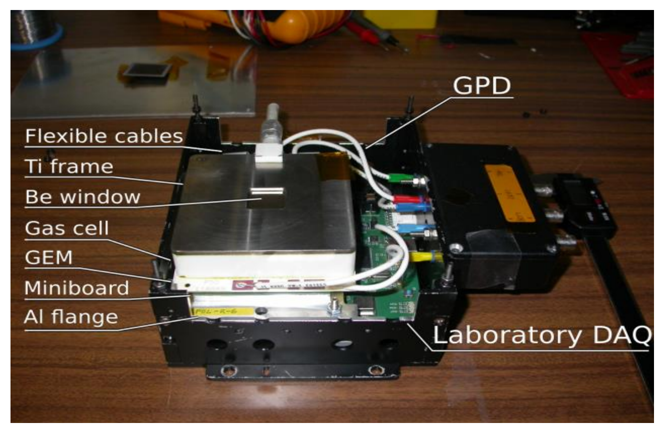
$$\frac{\partial \sigma}{\partial \Omega} = r_0^2 \frac{Z^5}{137^4} \left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$



The direction of the ejected photoelectron is **statistically** related to the polarisation of the absorbed photon.

The Gas Pixel Detector





XIPE Design

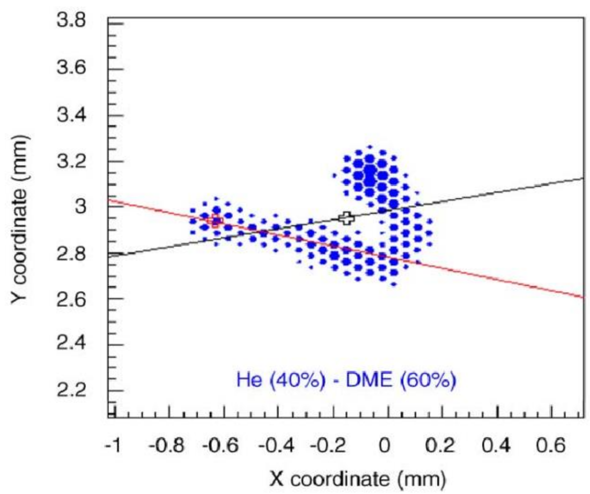
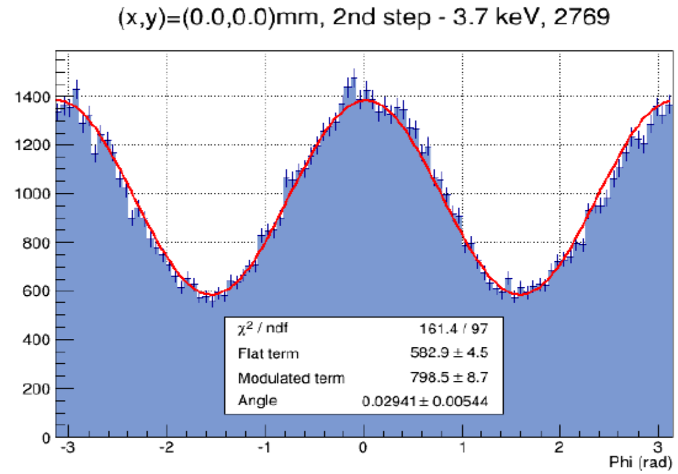
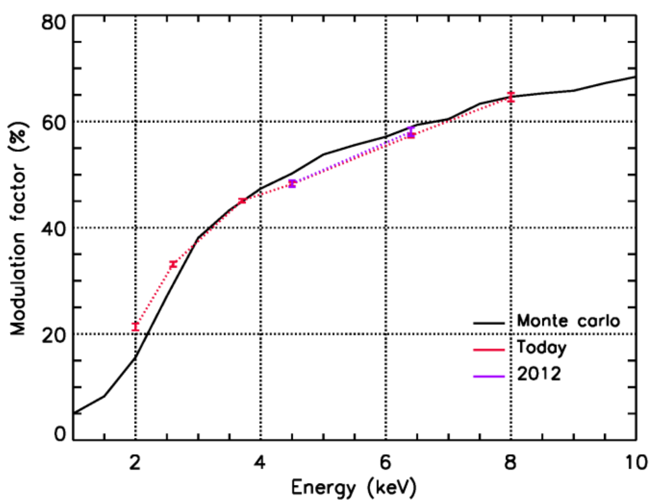


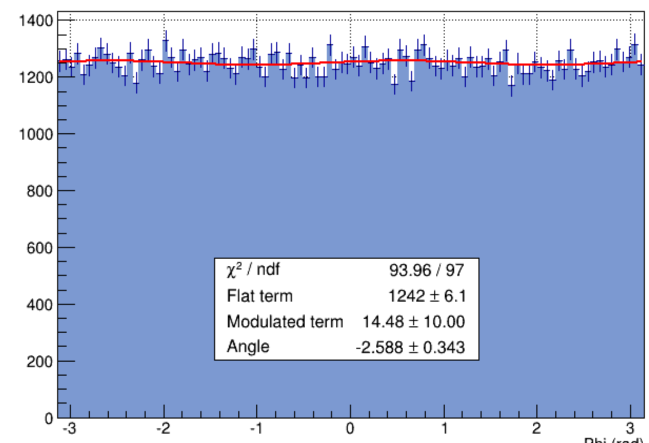
Image of a real photoelectron track. The use of the gas allows to resolve tracks in the X-ray energy band.



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



Modulation factor as a function of energy.

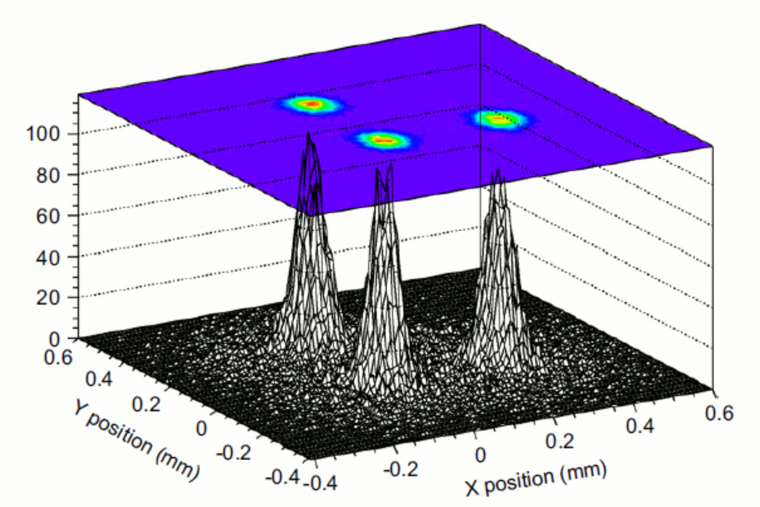


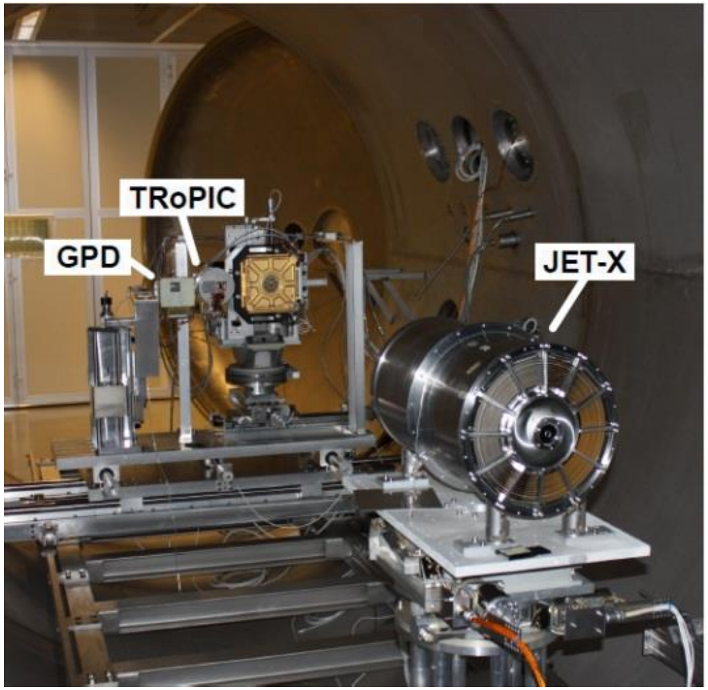
Residual modulation for unpolarized photons.

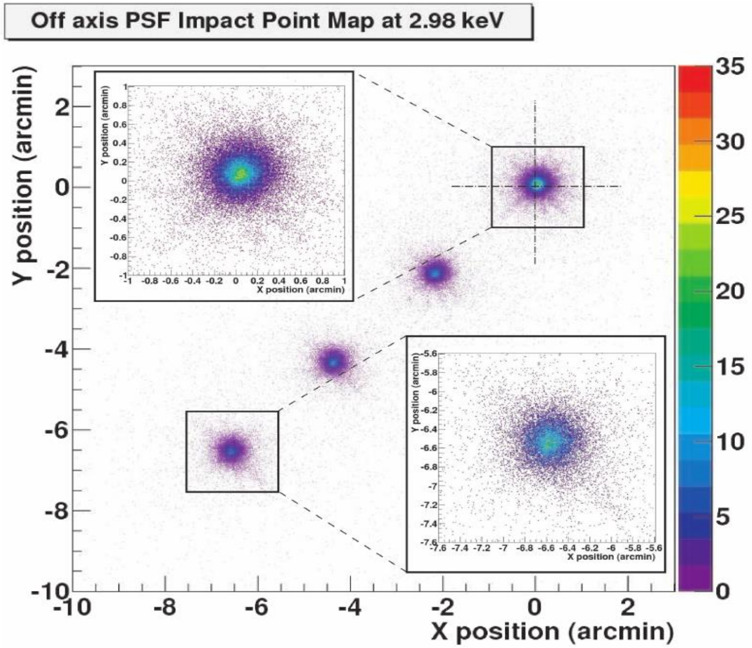
Muleri et al. 2008, 2010 Bellazzini et al. 2012

XIPE Design

- Good spatial resolution: 90 µm HEW
- Imaging capabilities on- and off-axis measured at the PANTER X-ray testing facility of the MPE with a JET-X telescope (Fabiani et al. 2014)
- Angular resolution for XIPE: <26 arcsec



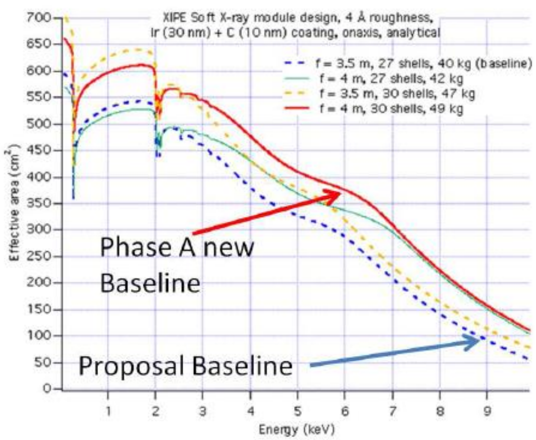


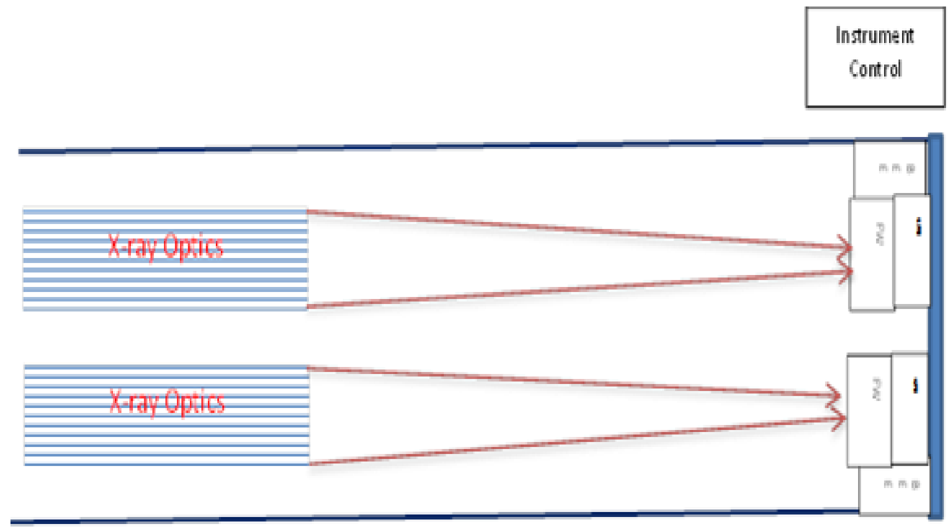


Mirrors and sensitivity

- 3 GPD located at the focus of 3 telescopes.
- Each of the 3 XIPE Mirror Units made of 30 mirror shells
- Diameters from 407mm to 181mm.
- Based on a double-cone approximation of the Wolter-1 profile
- 4m focal length (maximum within Vega launcher)

⇒ **total area larger than a single XMM mirror, good angular resolution (≤25 arcseconds) and a small mass.**



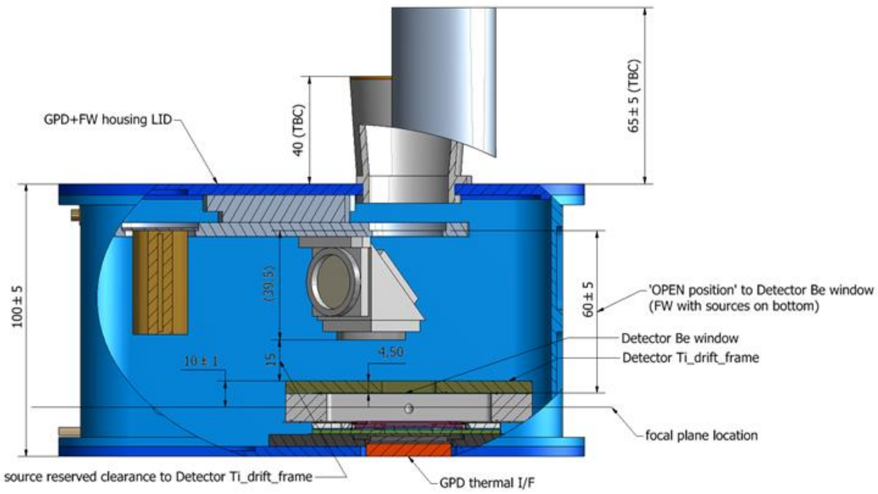


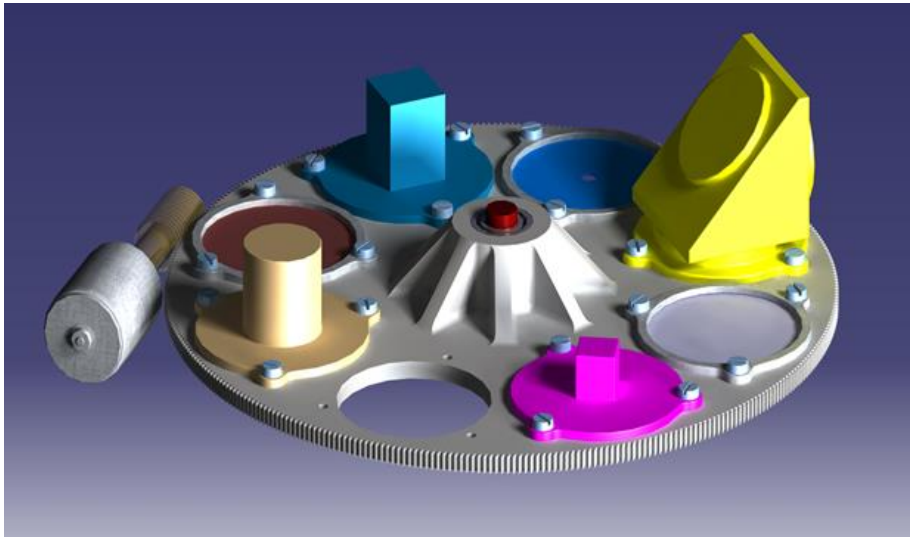
Left: performances of a single XIPE mirror units for different configurations.
Right: Schematic of the telescope. Two out of the three X-ray telescopes are shown with the optics on the left, illuminating the detector unit (DU), which contains the filter wheel and the Gas Pixel Detector (GPD) . Next to the DU there is the back end electronics (BEE) unit.

Filter and Calibration Wheel

- A set of filter and calibration wheels (FCWs) allows to position on board calibration sources and filters in front of the detector.
- FCWs are controlled by the Instrument Control Unit to select one out of eight positions: different calibration sources and different observing modes

The overarching characteristic of the XIPE FCW is that it has to hold polarised light sources for the GPD, in addition to attenuation filters and non-polarised sources.
The FCW is driven using a stepper motor. The polarised source requires angular repeatability ~ few arcmin, never achieved before on previous space missions.

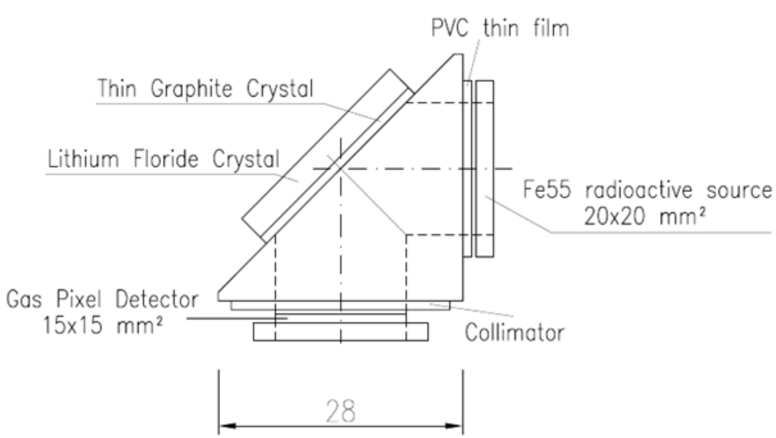


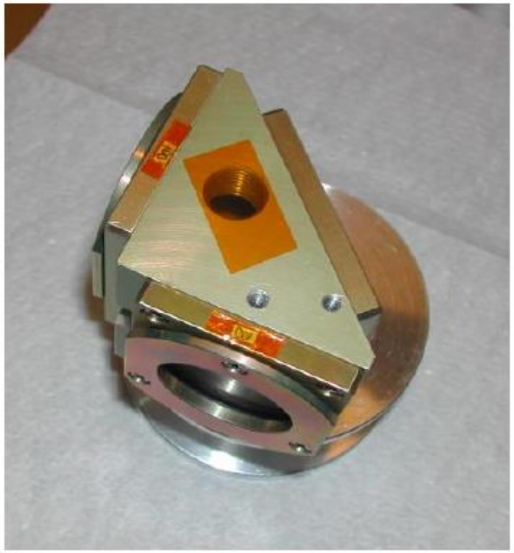


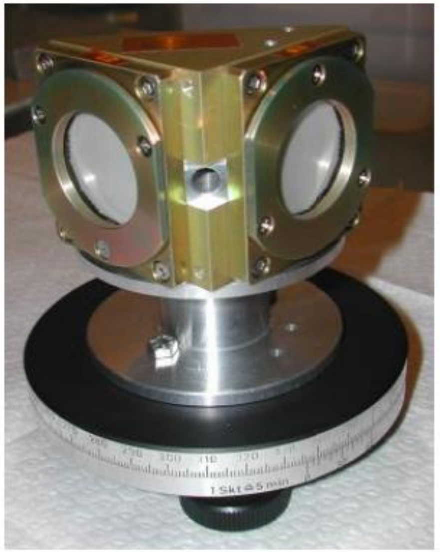
The XIPE FW design

Filter and Calibration Wheel – 8 Positions

- **Open position**. No filter is put in front of the detector (standard observations).
- **Close position**. A black (opaque) filter is placed in front of the detector. Tungsten disk, 0.5 mm thick, with a multilayer coating.
- **Grey filter**. A partially opaque filter to observe bright sources. Beryllium disk, 0.25 mm thick.
- **Diaphragm**. A tungsten diaphragm placed in front of the GPD to reduce source confusion in crowded fields.
- **Calibration source A** . A source of polarized photons with a ^{55}Fe radioactive source
- **Calibration source B, C, D:** 1 collimated and 2 isotropic unpolarized sources, based on ^{55}Fe and ^{109}C radioactive sources.



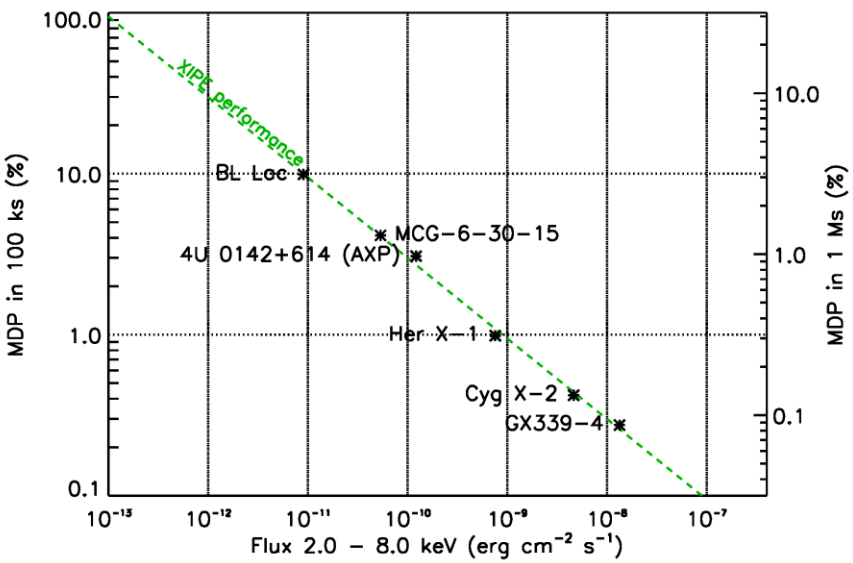




Preliminary drawing of Calibration source A and a larger laboratory version made of aluminium

XIPE in a nutshell

Polarisation sensitivity	1.2% MDP for 2x10-10 erg/s/cm2 (10 mCrab) in 300 ks **or** 6.7% MDP for 2x10-11 erg/s/cm2 (1 mCrab) in 100 ks
Energy range	2-8 keV
Angular resolution	<26 arcsec (goal: 20 arcsec)
Field of View	15x15 arcmin^2
Spectral resolution	16% @ 5.9 keV
Timing	Resolution <8 µs Dead time 200 µs
Stability	>3 yr
Spurious polarization	<0.5 % (goal: <0.1%)
Background	2x10^{-6} c/s or 4 nCrab



MDP = minimum detectable polarisation at the 99% confidence level:

$$MDP = \frac{4.29}{\mu\sqrt{S}}\frac{1}{\sqrt{T}}$$

μ: modulation factor
S: collecting area
T: observing time

XIPE/ESA Science Study Team

Soffitta Paolo (Lead Scientist) (INAF-IAPS, I)
Bellazzini Ronaldo (INFN-Pi, I)
Courvoisier Thierry (University of Geneva, CH)
Goosmann Rene (Obs. Astron. de Strasbourg, F)
Matt Giorgio (Univ. Roma Tre, I)
Reglero Victor (Univ. of Valencia, E)
Santangelo Andrea (IAAT, D)
Tagliaferri Gianpiero (INAF-OA Brera, I)
Vink Jacco (Univ. of Amsterdam, NL)
Zane Silvia (MSSL-UCL, UK)

Andrea Santovincenzo (ESA/ESTEC, NL)
Jonan Larranga (ESA/ESTEC, NL)
Ivo Ferreira (ESA/ESTEC, NL)
Tim Oosterbroek (ESA/ESTEC, NL)
David Lumb (ESA/ESTEC, NL)
Jan-Uwe Ness (ESA/ESTEC, Spain)

M4 Timeline

Activity	Date
Phase 0 kick-off	Jun-2015
Phase 0 completed (ARIEL, THOR, XIPE)	Oct-Nov 2015
ITT for Phase A industrial studies	Nov-2015
Phase A kick-off	Mar-2016
Preliminary Requirement Review completed	Apr-2017
Down-selection recommendation for M4 mission	May-2017
SPC selection of M4 mission	Jun-2017
Phase B1 kick-off for the selected M4 mission	Jul-2017
Phase B1 completed	Sep-2018
SPC adoption of M4 mission	Nov-2018
Phase B2/C/D kick-off	2019
Launch	2026

Table 1: Tentative timeline for M4 activities

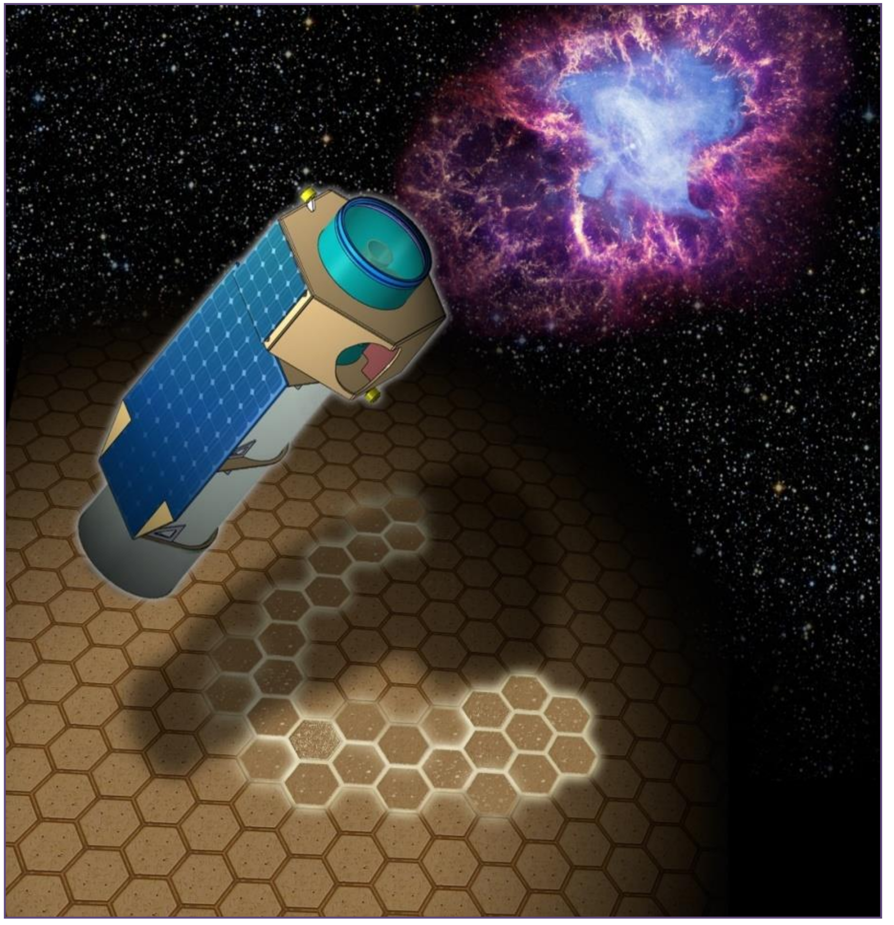
Summary

XIPE will open a new observational window, adding the two missing observables in X-rays.

Many X-ray sources are aspherical and/or non-thermal emitters, so radiation must be highly polarised.

XIPE is simple and ready, using pioneering, yet mature, technology.

www.isdc.unige.ch/xipe



+ see Poster by SZ et al