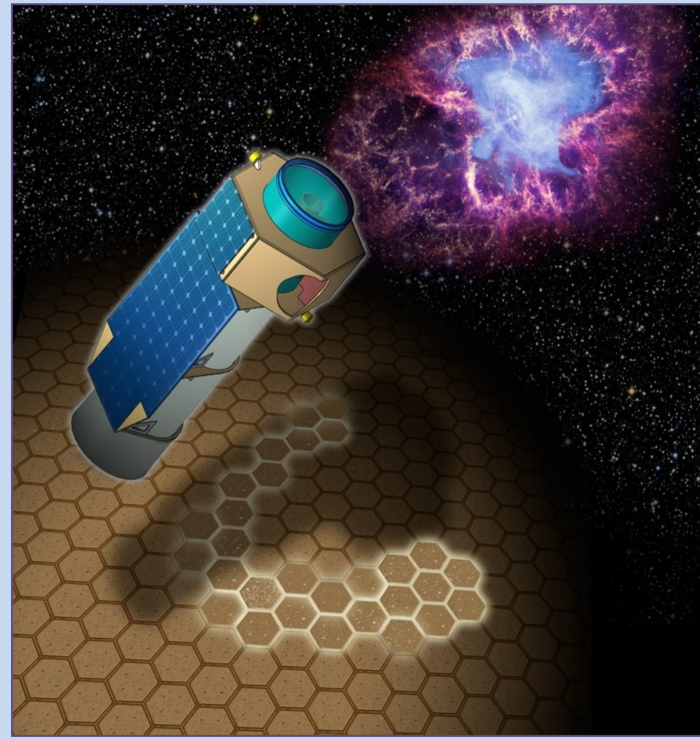
The X-ray Imaging Polarimeter Explorer

Giorgio Matt
Univ. Roma Tre, Italy

on behalf of the XIPE Study Science Team

Picking the right direction
Xipe



Selected by ESA for Phase A study in the M4 program

Why X-ray polarimetry?

Introduction

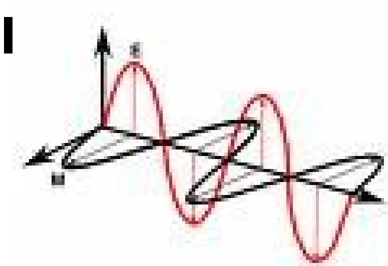
Information on celestial (extra-solar) sources are mostly provided by electromagnetic radiation.

They can be obtained by studying the spatial, spectral, timing and *polarization* properties of the observed radiation.

In particular, the 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.

Our knowledge of the emission from a celestial source in a certain energy band is therefore incomplete without polarimetry.

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



Why X-ray polarimetry?

Introduction

Polarimetry has proved very important in radio, IR and optical bands (eg. jet emission in blazars, Unification Model of AGN, ...).

In X-rays, where non-thermal emission processes and aspherical geometries are likely to be more common than at lower energies, polarimetry is expected to be vital to fully understand emitting sources.

However, 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.

The lack, for many decades, of significant technical improvements implied that no polarimeters were put on board of X-ray satellites.

Why X-ray polarimetry?

Why XIPE?

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!

Time is ripe for a X-ray polarimetric mission !

Indeed, a X-ray polarimeter was part of the focal plane suite of detectors of XEUS/IXO, but it did not survive the severe descooping towards Athena.

A X-ray polarimetric mission, GEMS, was approved by NASA as a SMEX but later cancelled for programmatic reasons.

And finally, XIPE has been selected for a phase A study in ESA M4 (together with Ariel, devoted to exoplanets, and Thor, a solar magnetosphere mission; final down-selection in Spring 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?

XIPE goals

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**

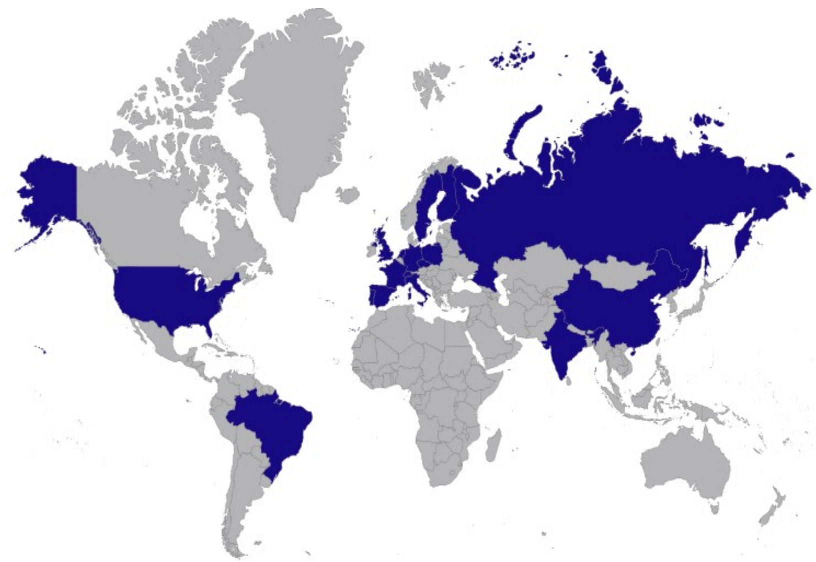
XIPE will observe **almost all classes of X-ray sources**

A large community involved (as for the proposal):

17 countries

146 scientists

68 institutes around the world



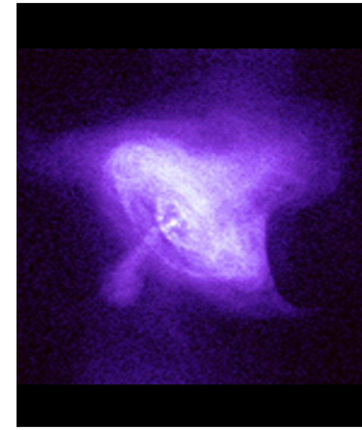
XIPE scientific goals

Astrophysics: Acceleration: PWN

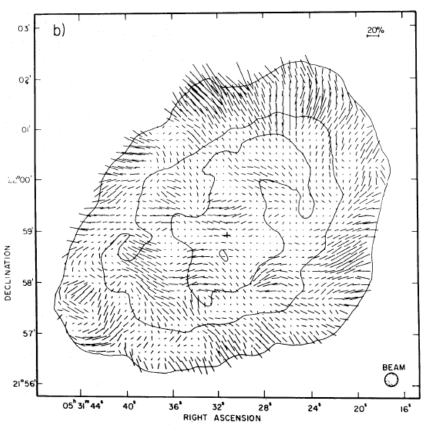
Radio (VLA)

Infrared (Keck)

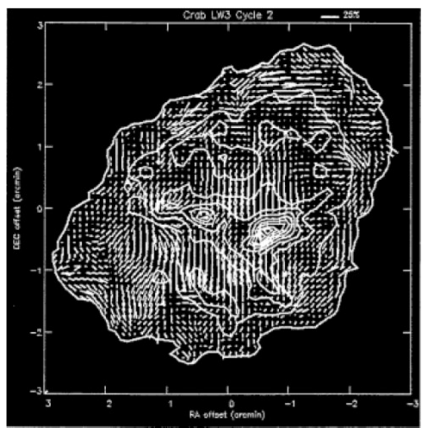
Optical (Palomar)



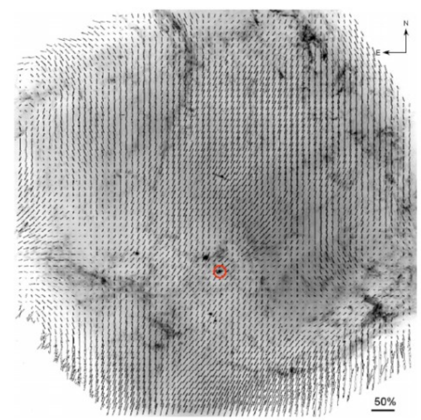
X-rays (Chandra)



Radio polarisation



IR polarisation



Optical polarisation

?

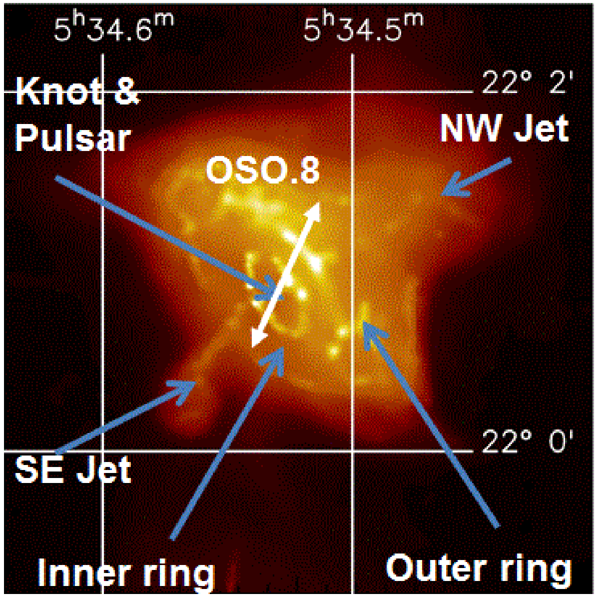
P=19% integrated over the entire nebula (Weisskopf et al. 1978)

X-ray polarisation

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

XIPE scientific goals

Astrophysics: Acceleration: PWN



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

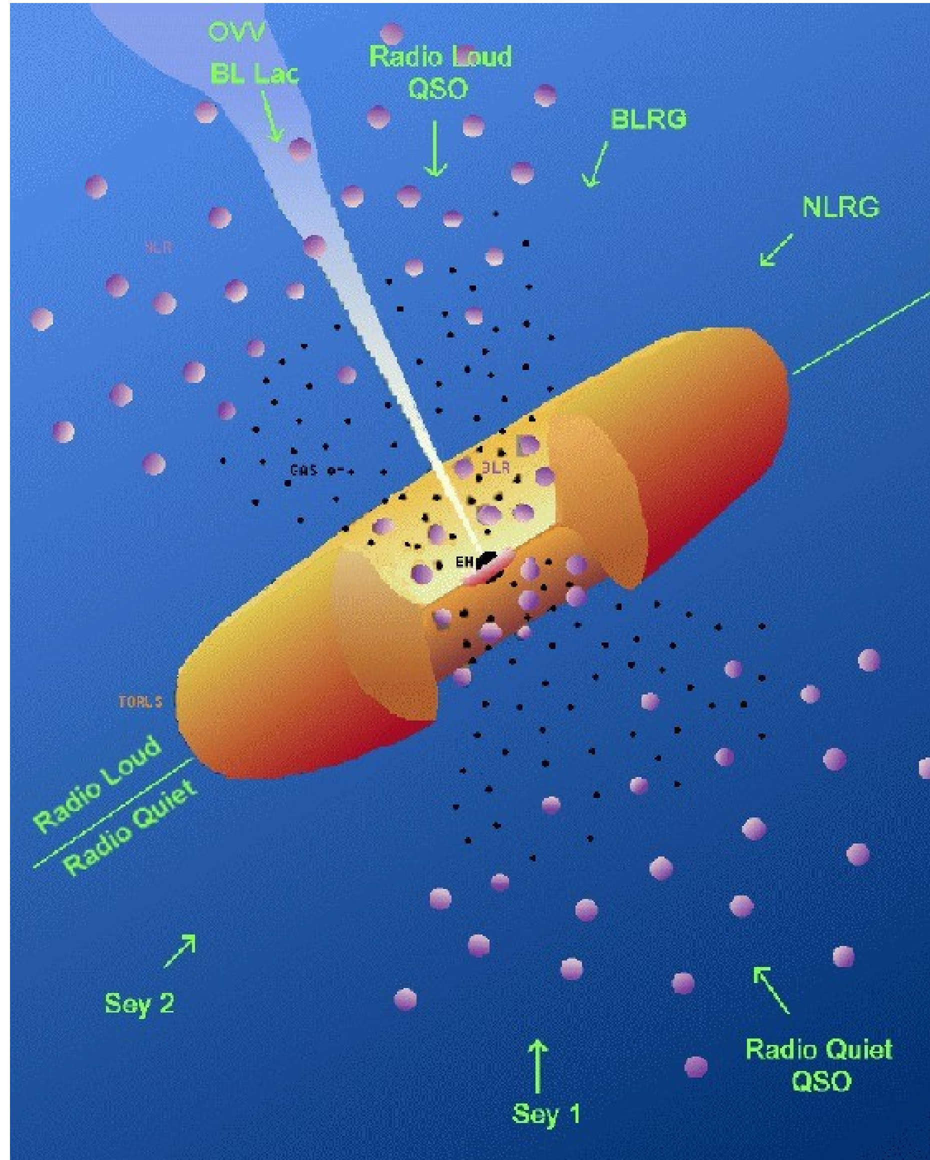
- The OSO-8 observation, integrated over the entire nebula, measured a position angle that is tilted with respect to the jets and torus axes.
- What is the role of the magnetic field (turbulent or not?) in accelerating particles and forming structures?
- XIPE imaging capabilities will allow us to measure 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

Astrophysics: Acceleration: Unresolved Jets in Blazars

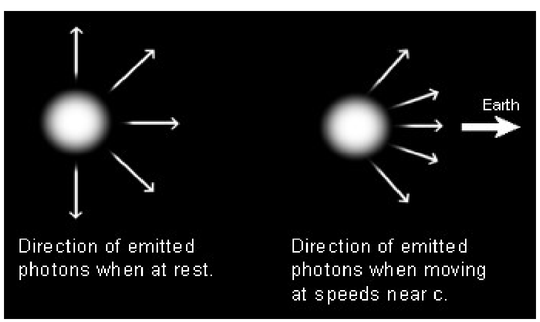
Schematic view of an AGN

➡



Blazars are those AGN which not only have a jet (like all radiogalaxies), but it is directed towards us.

Due to a Special Relativity effect (aberration), the jet emission dominates over other emission components



XIPE scientific goals

Astrophysics: Acceleration: Unresolved Jets in Blazars

Blazars are extreme accelerators in the Universe, but the emission mechanism is far from being understood.

In inverse Compton dominated Blazars, a XIPE observation can determine the origin of the seed photons:

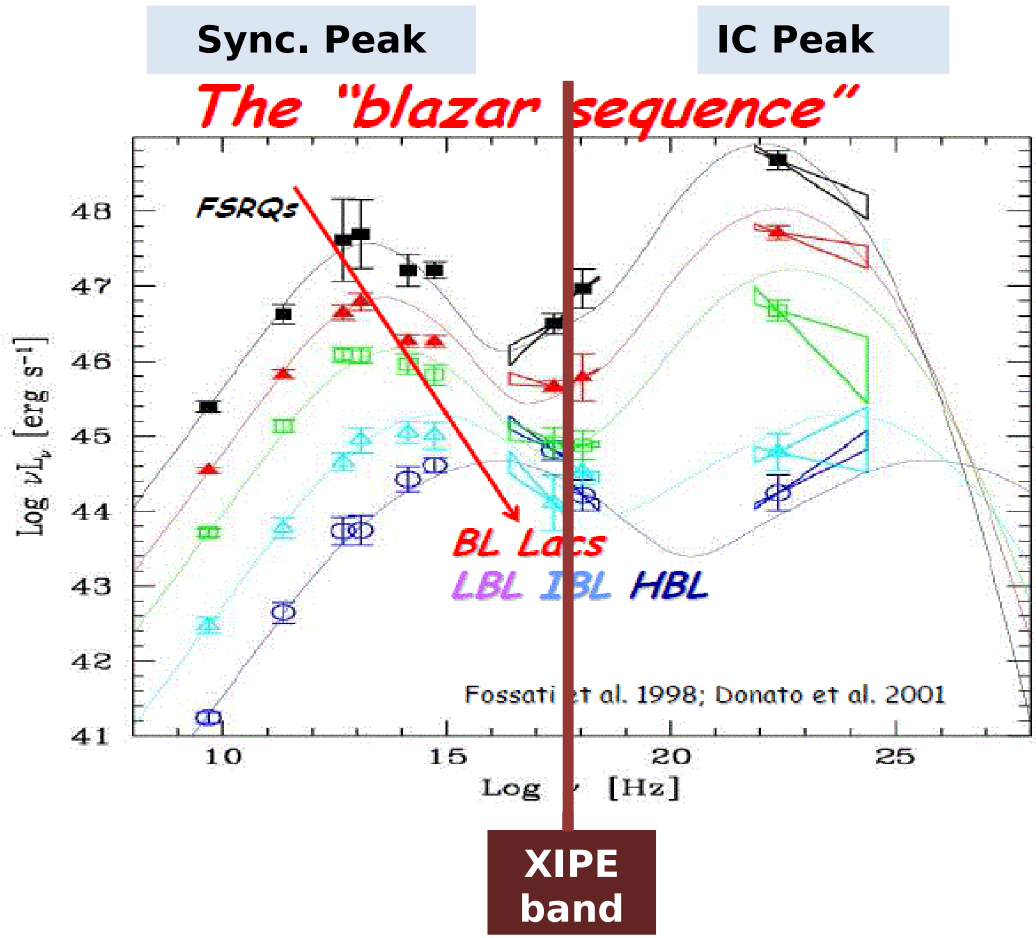
- Synchrotron-Self Compton (**SSC**) ?

The polarization angle is the same as for the synchrotron peak.

- External Compton (**EC**) ?

The polarization angle may be different.

The polarization degree determines the electron temperature in the jet.



XIPE scientific goals

Astrophysics: Acceleration: Unresolved Jets in Blazars

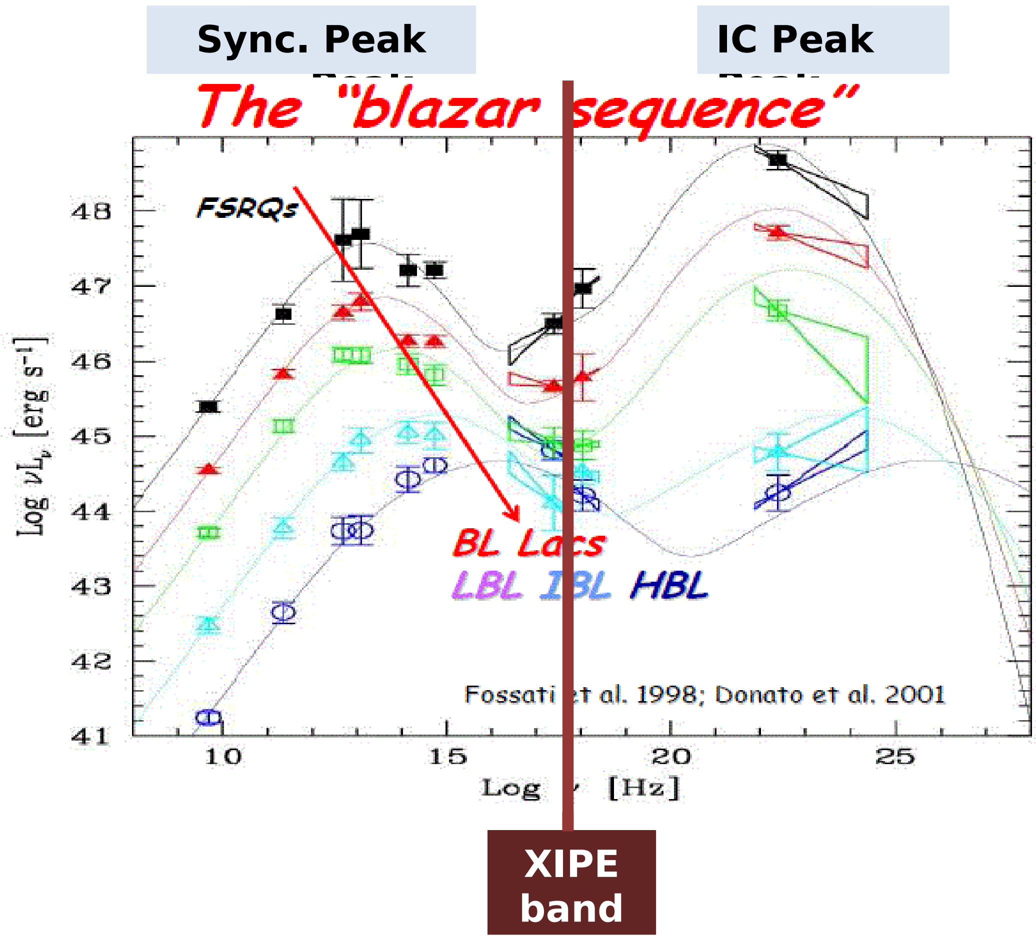
Blazars are extreme accelerators in the Universe, but the emission mechanism is far from being understood.

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

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



XIPE scientific goals

Astrophysics: Strong Magnetic Fields: Accreting X-ray Pulsars

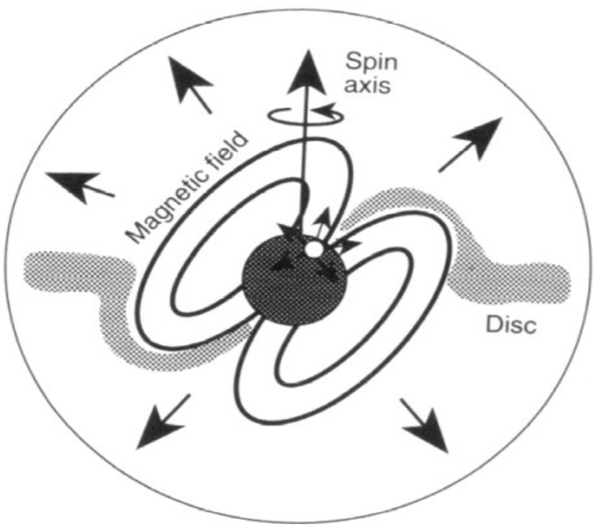
Opacity in highly magnetized plasma

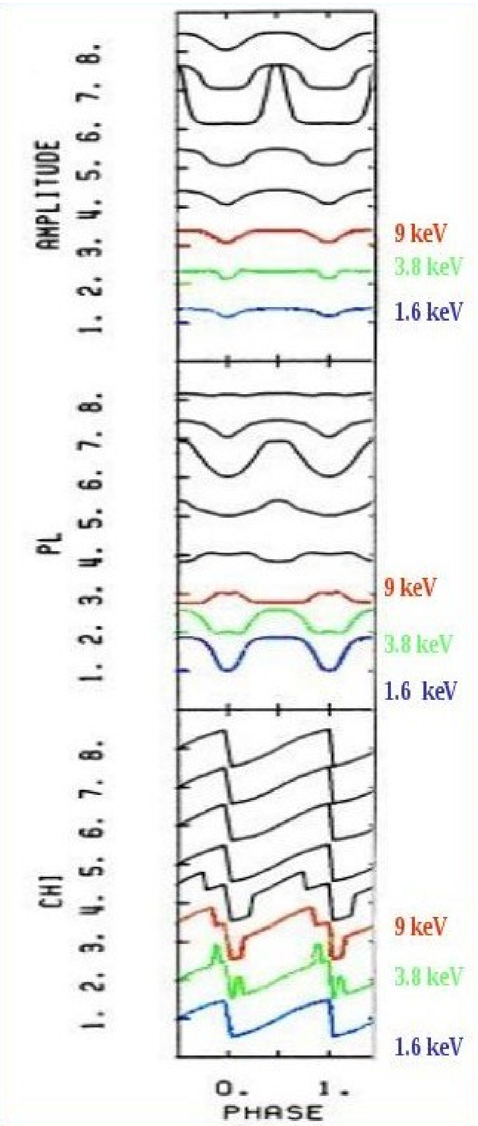
$$\Rightarrow \quad k_{\perp} \neq k_{\parallel}$$

Phase-dependent linear polarization

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

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

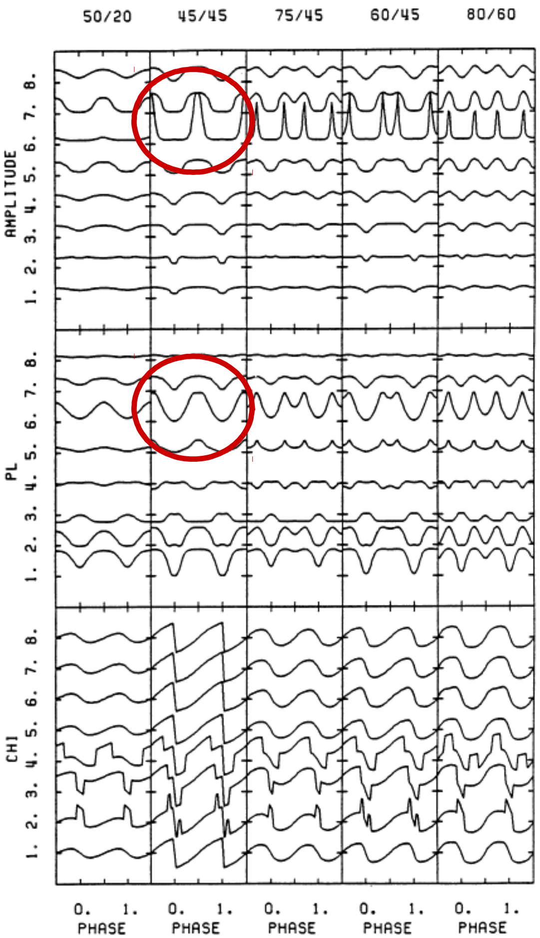




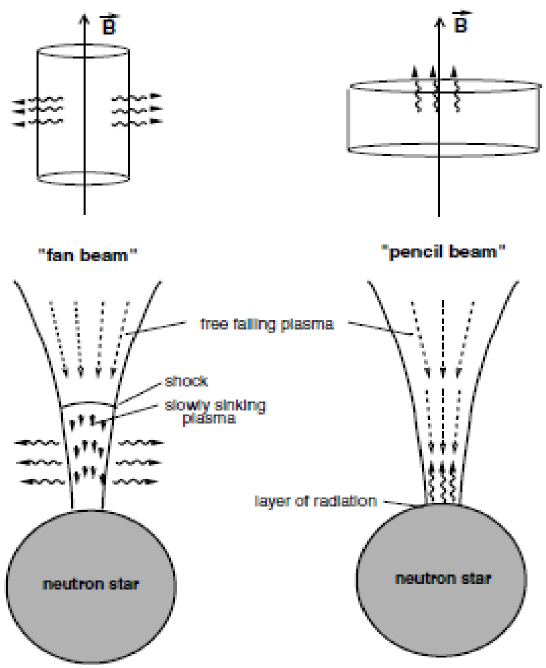
Meszaros et al. 1988

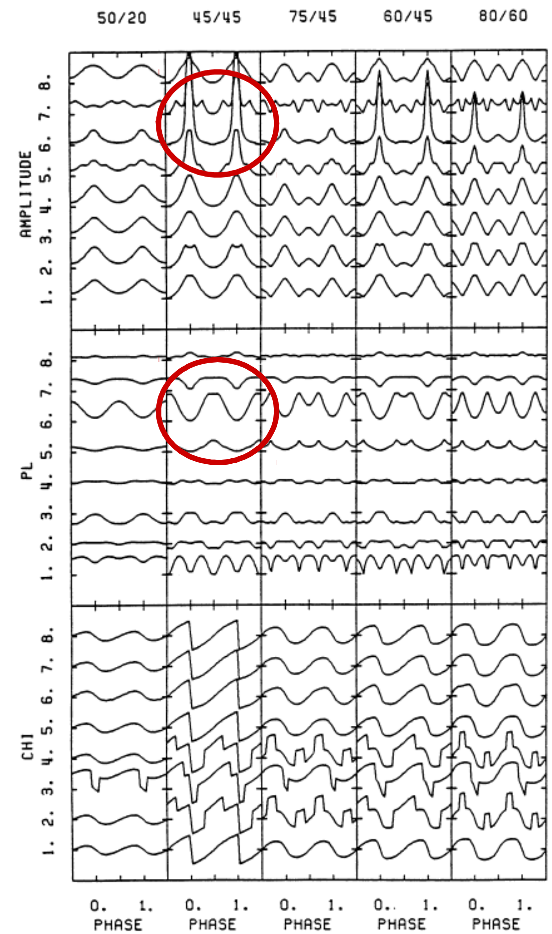
XIPE scientific goals

Astrophysics: Strong Magnetic Fields: Accreting X-ray Pulsars



“Fan” vs. “Pencil” beam





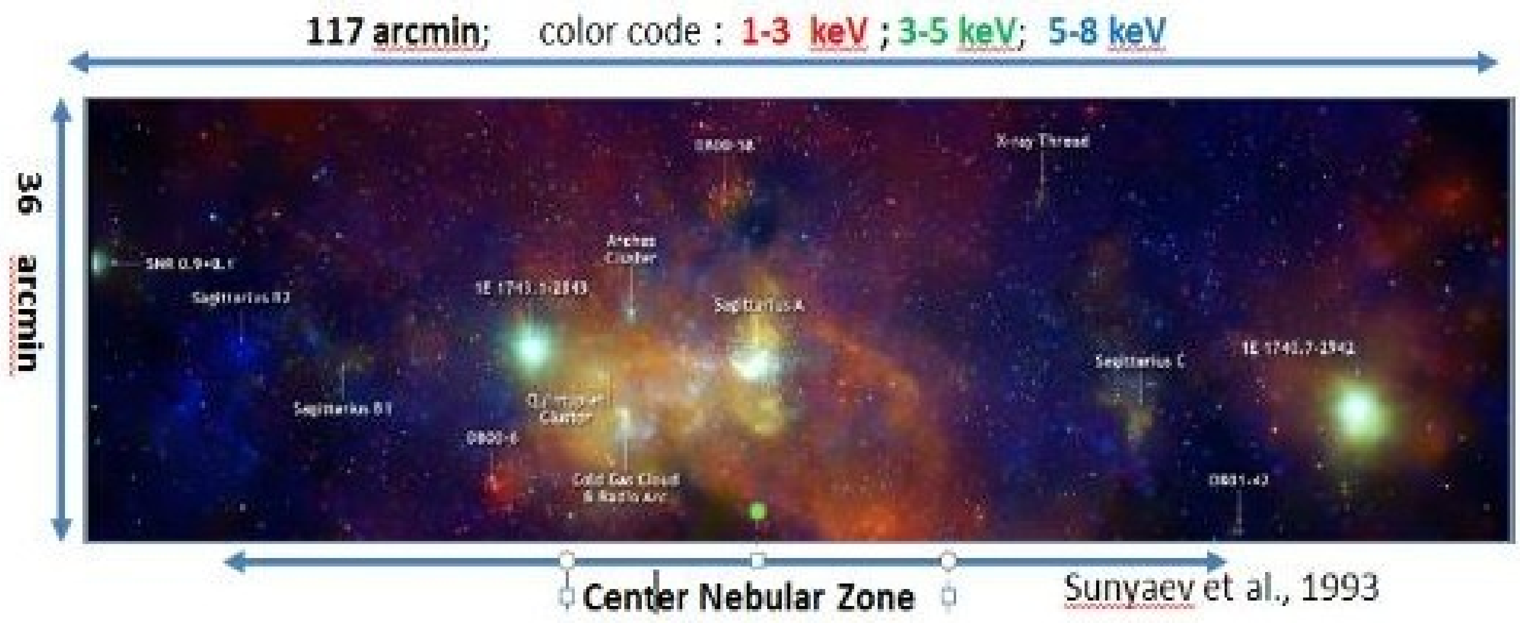
Meszaros et al. 1988

XIPE scientific goals

Astrophysics: Scattering: X-ray reflection nebulae in the GC

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!?!

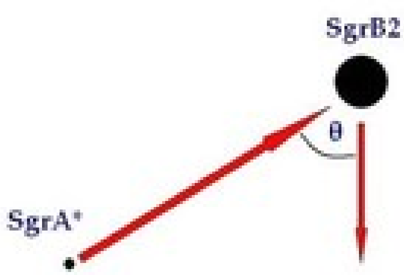
No bright enough sources are in the surroundings. Are they reflecting X-rays from Sgr A*? so, was it one million times brighter a few hundreds years ago? Polarimetry can tell!

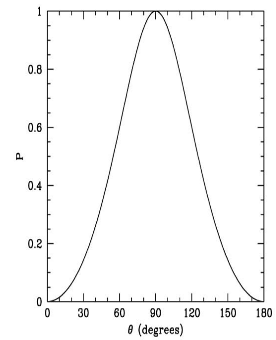


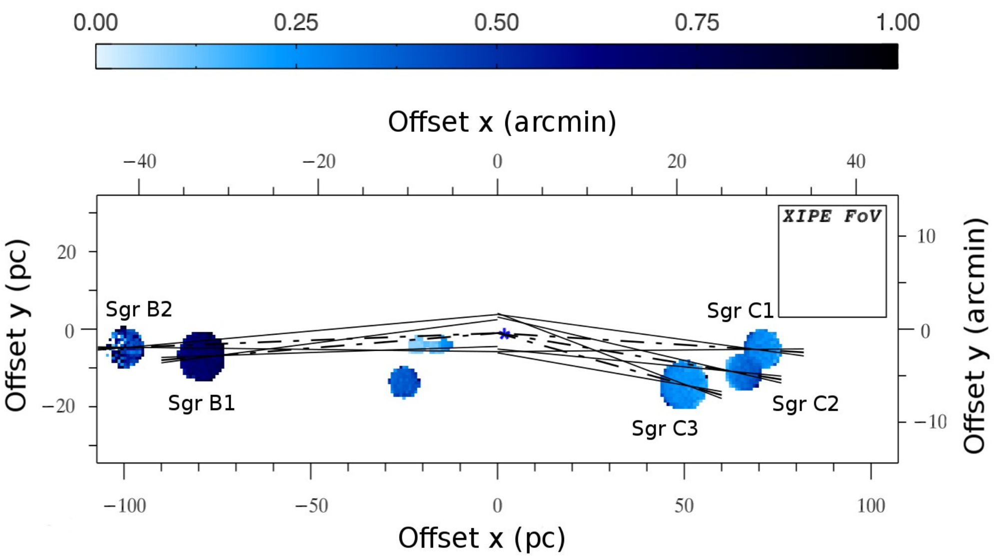
Polarization by scattering from Sgr B complex, Sgr C complex

- 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







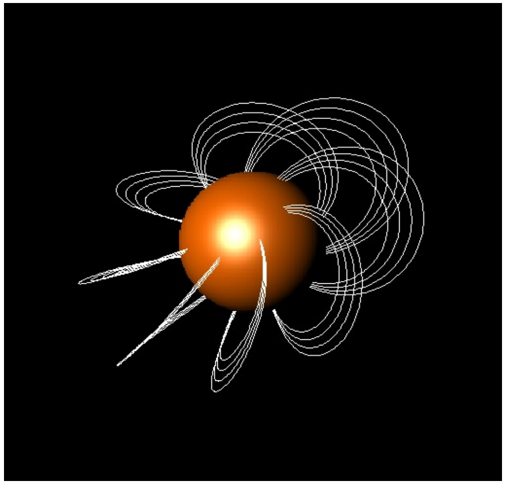
XIPE scientific goals

Fundamental Physics: Matter in extreme magnetic fields: QED effects

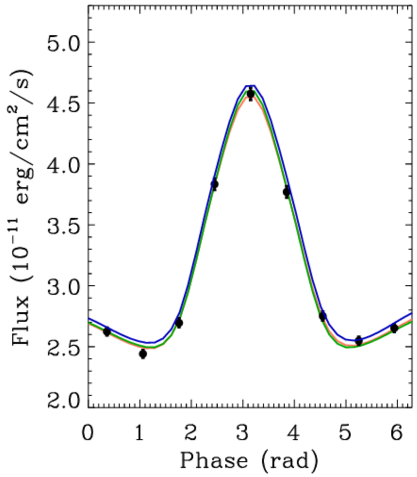
Magnetars are isolated neutron stars with likely a huge magnetic field (B up to 10^{15} Gauss).

It heats the star crust and explains why the X-ray luminosity largely exceeds the spin down energy loss.

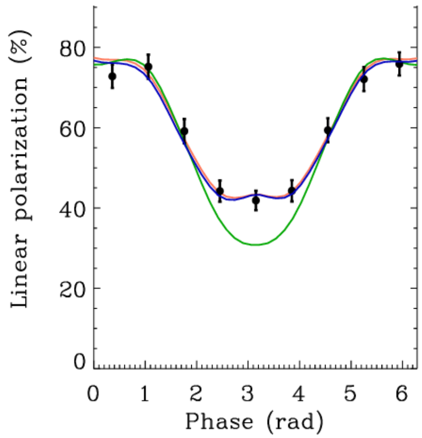
QED foresees vacuum birefringence, an effect predicted 80 years ago (Eisenberg & Euler 1936), expected in such a strong magnetic field and never detected yet.



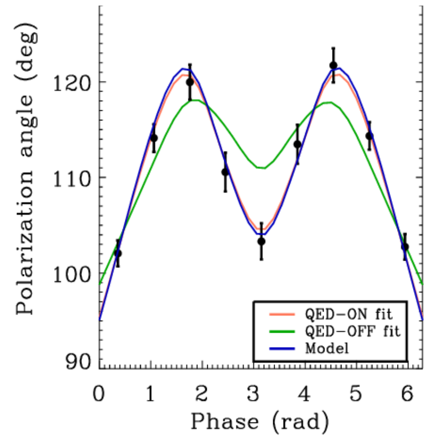
Light curve



Polarisation degree



Polarisation angle



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

XIPE scientific goals

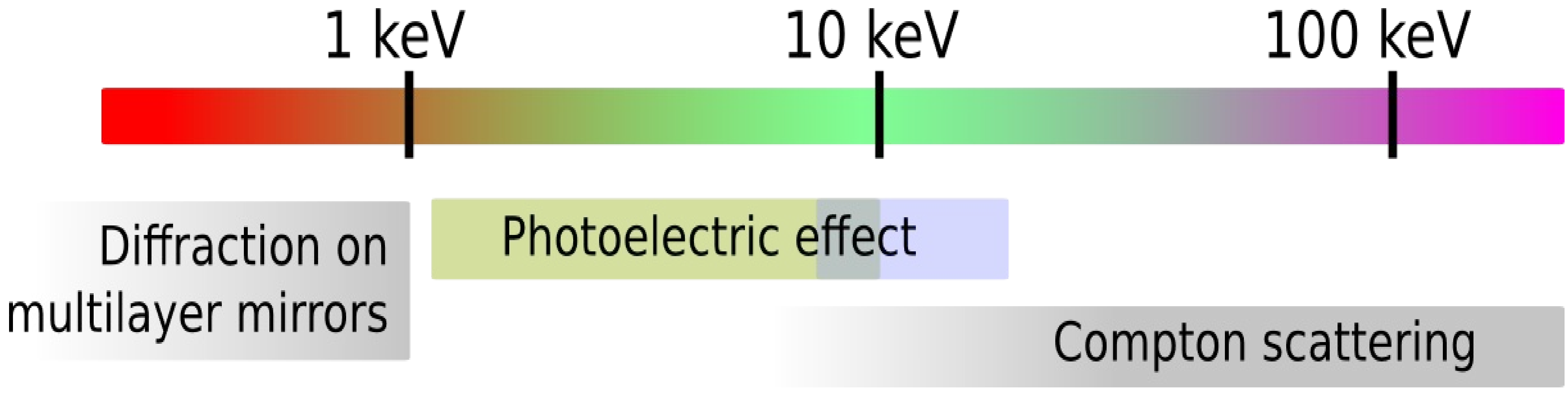
Fundamental Physics: Loop QG and search for Axion-like particles

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!!

The energy band



XIPE Science Requirements

The energy band

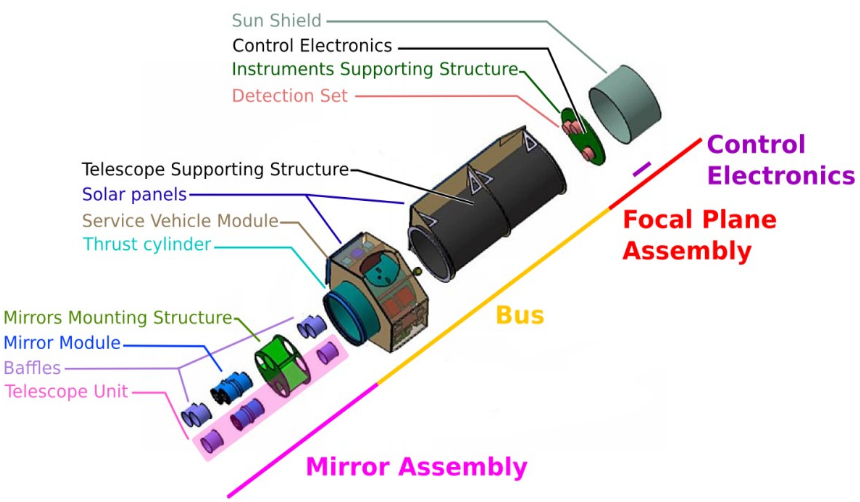
Scientific goal	Sources	< 1keV	1-10	> 10 keV
Acceleration phenomena	PWN	yes (but absorption)	yes	yes
	SNR	no	yes	yes
	Jet (Microquasars)	yes (but absorption)	yes	yes
	Jet (Blazars)	yes	yes	yes
Emission in strong magnetic fields	WD	yes (but absorption)	yes	difficult
	AMS	no	yes	yes
	X-ray pulsator	difficult	yes (no cyclotron)	yes
	Magnetar	yes (better)	yes	no
Scattering in aspherical geometries	Corona in XRB & AGNs	difficult	yes	yes (difficult)
	X-ray reflection nebulae	no	yes (long exposure)	yes
Fundamental Physics	QED (magnetar)	yes (better)	yes	no
	GR (BH)	no	yes	no
	QG (Blazars)	difficult	yes	yes
	Axions (Blazars, Clusters)	yes ?	yes	difficult

XIPE Design

Overview

- **Three telescopes with 3.5 m 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.**

- **Fixed solar panels. 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.**

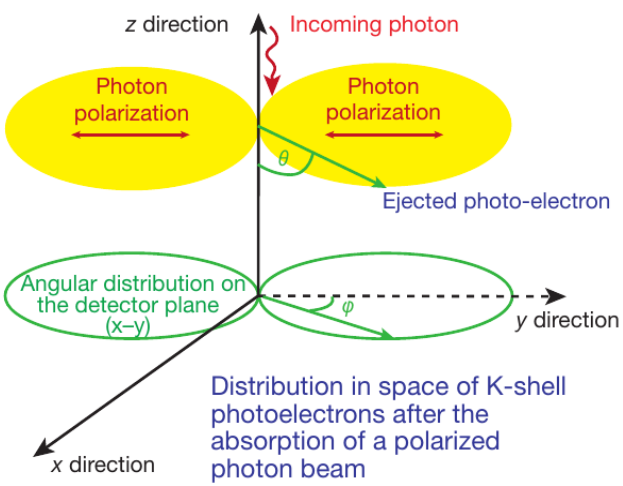


XIPE Design

The Gax Pixel Detector

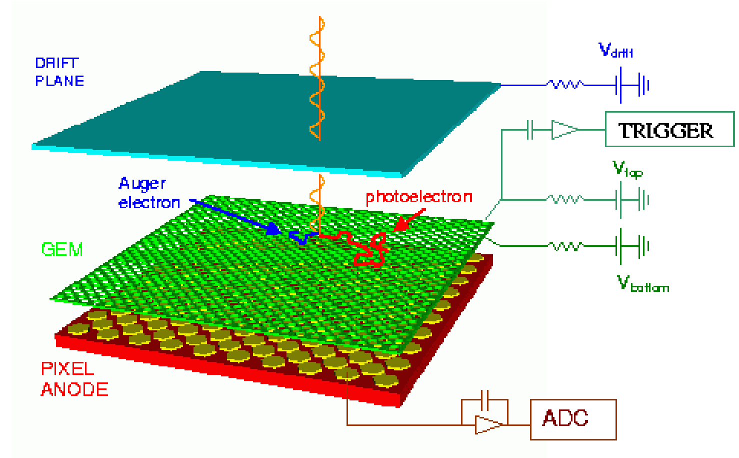
The Gas Pixel Detector (Costa et al. 2001, Bellazzini et al. 2006, 2007) is a polarization-sensitive instrument capable of imaging, timing and spectroscopy

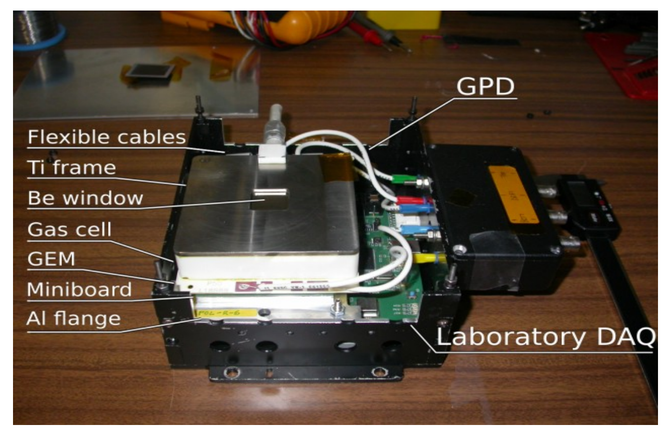
$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4} \left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$



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

The Gas Pixel Detector





XIPE Design

The Gax Pixel Detector

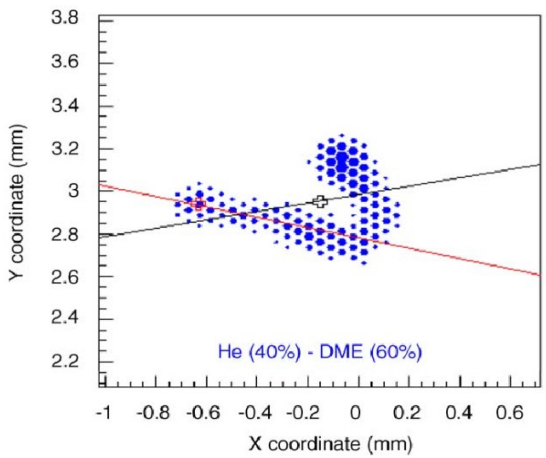
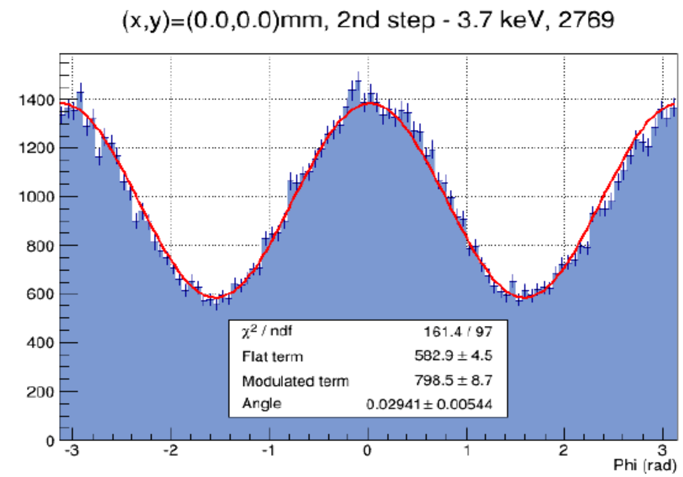
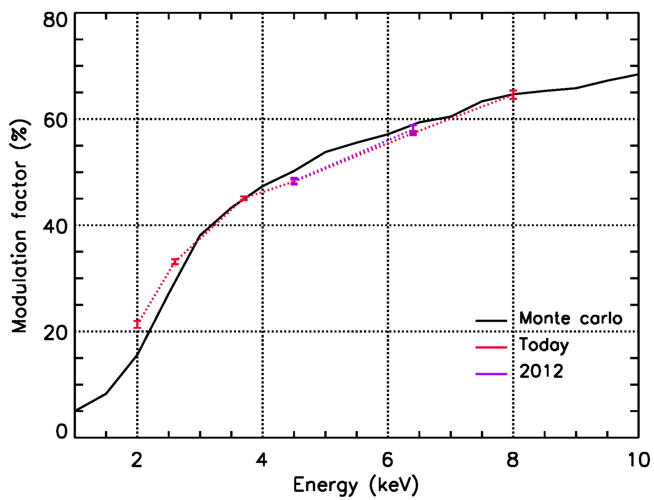


Image of a real photoelectron track. The use of the gas allows to resolve tracks in the X-ray energy band.

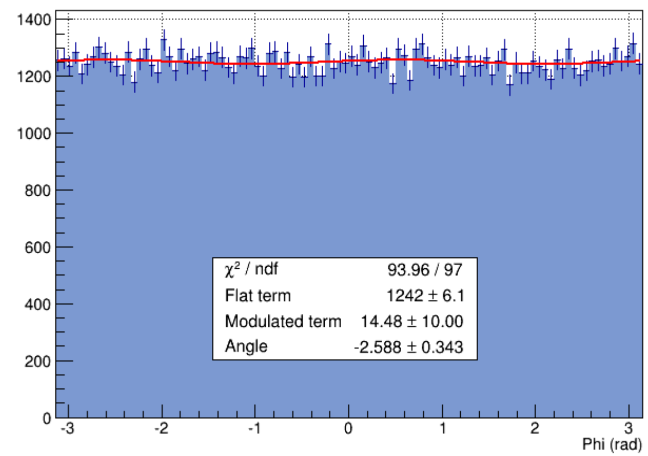


Real modulation curve derived from the measurement of the emission direction of the photoelectron.



Muleri et al. 2008, 2010

Modulation factor as a function of energy.



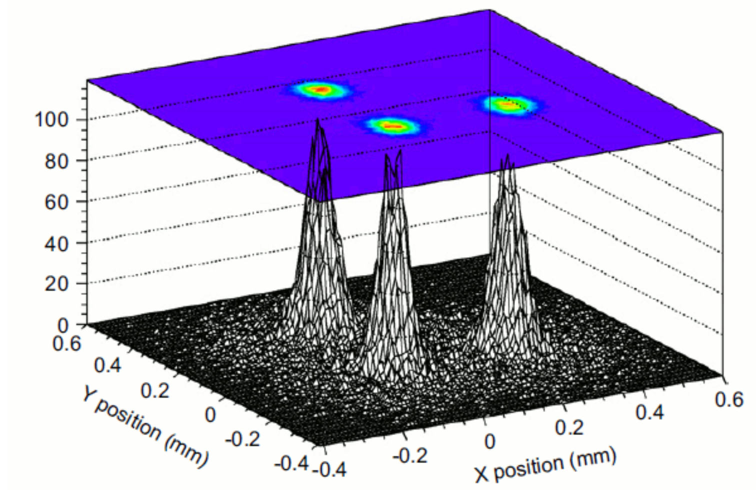
Bellazzini et al. 2012

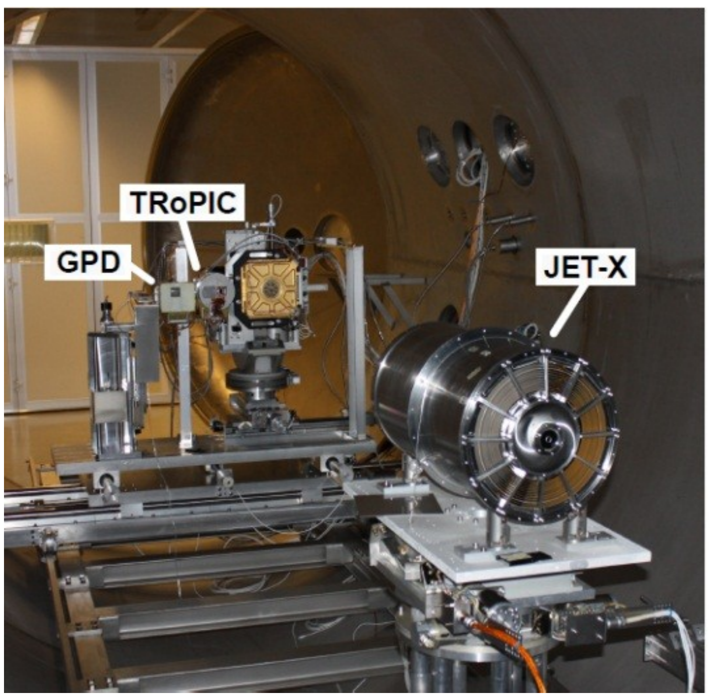
Residual modulation for unpolarized photons.

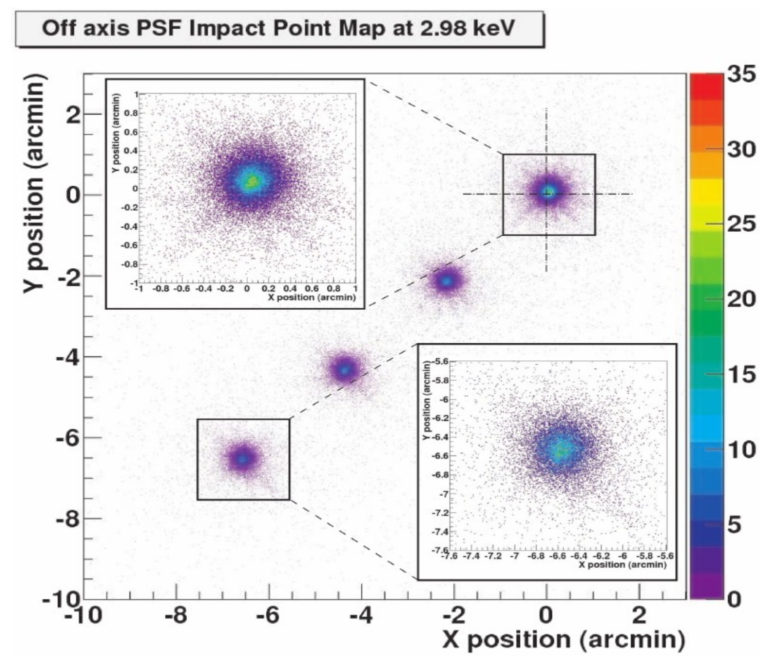
XIPE Design

Imaging capability

- 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

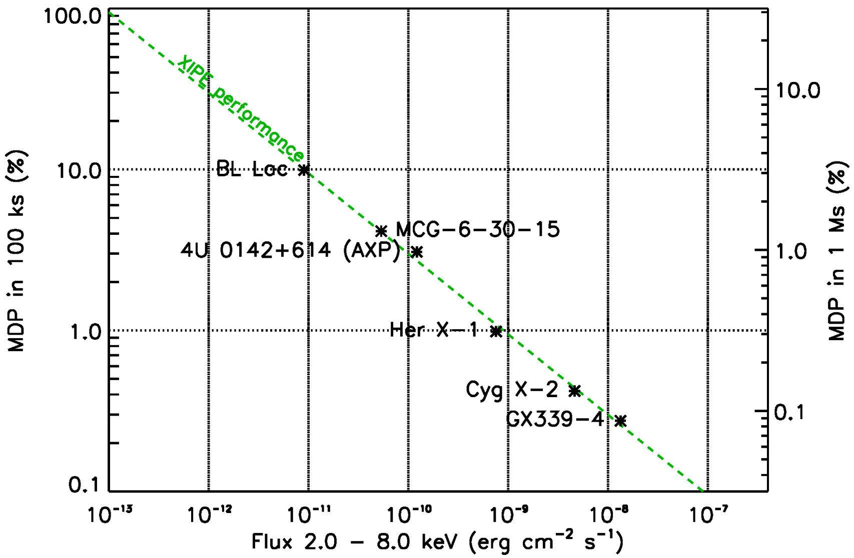






XIPE in a nutshell

Polarisation sensitivity	1.2% MDP for 2×10^{-10} erg/s cm^2 (10 mCrab) in 300 ks **or** 6.7% MDP for 2×10^{-11} erg/s cm^2 (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	2×10^{-6} c/s or 4 nCrab



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

The MDP is the minimum detectable polarisation at the 99% confidence level.

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

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.