X-ray Polarimetry: a new diagnstic tool for γ-ray emitters?

by

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Measurements in X-ray Astronomy

Timing: (Geiger, Proportional Counters, MCA, in the future Silicon Drift Chambers)
Rockets, UHURU, Einstein, EXOSAT, ASCA, SAX, XMM, Chandra, …, LOFT(?).

Imaging: Pseudo-imaging (modulation collimators, grazing incidence optics + Proportional Counters, MCA, CCD in the future DepFET)
Rockets, SAS-3, Einstein, EXOSAT, ROSAT, ASCA, SAX, Chandra, XMM, INTEGRAL, SWIFT, Suzaku, NUSTAR, …….., ATHENA.

Spectroscopy: Non dispersive (Proportional Counters, Si/Ge and CCD, Bolometers in the future Tranition Edge Spectrometers)
Dispersive: Bragg, Gratings.
Rockets, Einstein, EXOSAT, HEAO-3, ASCA, SAX, XMM, Chandra, XMM, INTEGRAL, Suzaku, ……….., ATHENA.

Polarimetry: (Bragg, Thomson/Compton, in the future photoelectric and subdivided compton)
Rockets, Ariel-5, OSO-8, ……………., XIPE(?) or other (IXPE, Praxys, XTP)

What can 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
- Quantum gravity effects
- Axions

Big Hopes Meager Results

A vast theoretical literature predicts a wealth of results from X-ray Polarimetry

Polarimetry would add to energy and time two further observable quantities (the amount and the angle of polarization) constraining any model and interpretation: a theoretical/observational break-through (Mészáros, P. et al. 1988).

The swing on the polarization vector of photon trajectories near a black hole was long ago suggested (Connors, Piran & Stark,1980) as another diagnostic; but this is still not feasible because X-ray polarimeters are far from capable of detecting the few percent polarization expected (Rees, 2001).

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) $P = 19.2 \pm 1.0\,\%$; $\theta = 156.4^{o} \pm 1.4^{o}$

A window not yet disclosed

THE TECHNIQUES ARE THE LIMIT!

Conventional X-ray polarimeters are cumbersome and have low sensitivity, completely mismatchedwith sensitivity in other topics

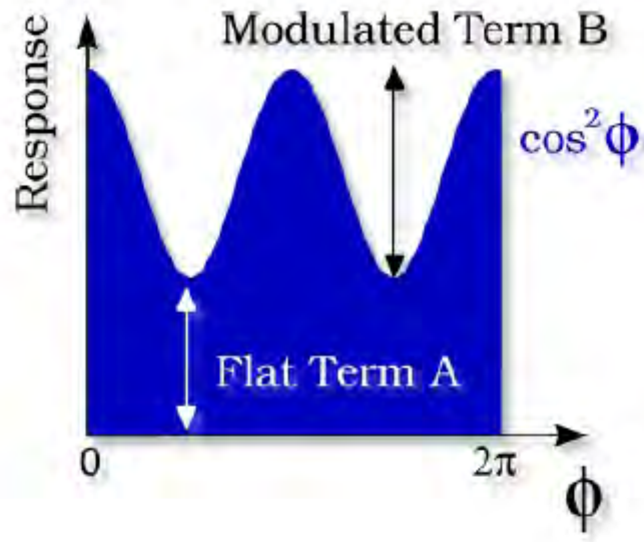
New technical solutions are now ready

The same year of the pessimistic statement by Martin Rees a new instrument was developed with the potentiality of a dramatic improvement in both sensitivity and control of systematics.

A new Era for X-ray Polarimetry is about to come (maybe….)

The conventional formalism

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



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

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

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

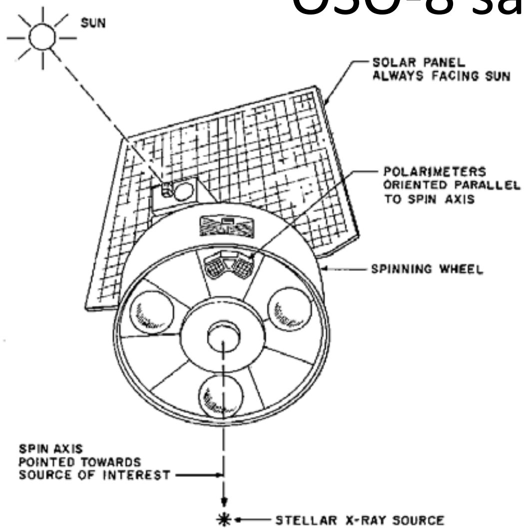
If background is negligible: $$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N_{ph}}}$$

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

OSO-8 satellite with a dedicated Bragg polarimeter



468 graphite mosaic crystals were mounted to the two sector of parabolic surface of revolution. Mosaic spread of 0.8° Band-pass = 40 eV (2.62 keV) Bragg angles allowed between 40° and 50° Overall band-pass 400 eV (2.62 keV) μ = 0.94

Projected crystal Area = 2 x 140 cm^2 ; Detector area = 2 x 5 cm^2 ; FOV= 2°

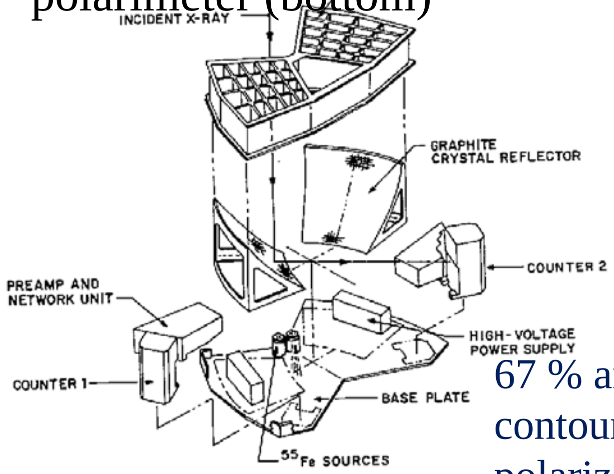
B = 2 x 3 10^{-2} counts/s in each order (pulse shape analysis + anti-coincidence)

Precision measurement: of X-ray polarization of the Crab Nebula without pulsar contamination (by lunar occultation, Weisskopf et al.,1978).

$$P = 19.2 \pm 1.0\ \%;\quad \theta = 156.4^\circ \pm 1.4^\circ\ (2.6\ \text{keV})$$

$$P = 19.5 \pm 2.8\ \%;\ 152.6^\circ \pm 4.0^\circ\ (5.2\ \text{keV})$$

OSO-8 satellite (top) and polarimeter (bottom)



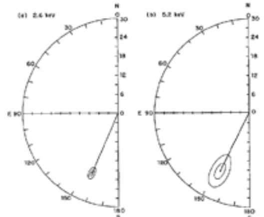
67 % and 99 % confidence contour. The radial scale is the polarization in percent

TABLE 3

POLARIZATION RESULTS FOR TIME-AVERAGED 1976 AND 1977 OBSERVATIONS WITH AVERAGE EARTH-OCCULTED AND OFF-SOURCE BACKGROUNDS

Parameter*	First Order (2.6 keV)	Second Order (5.2 keV)
$\bar{R}$ (Counts $s^{-1} \times 10^3$)	302.32 ± 1.29	53.33 ± 0.65
Q (%)	13.02 ± 0.65	11.24 ± 1.86
U (%)	−14.10 ± 0.65	−15.94 ± 1.86
P (%)	19.19 ± 0.97	19.50 ± 2.77
φ (degrees)	156.36 ± 1.44	152.59 ± 4.04

*See footnote to Table 2.



3.—The polarization vectors for the Crab Nebula at (a) 2.6 keV and (b) 5.2 keV. Surrounding the vectors in order of increasing the 67% and 99% confidence contours. The radial scale is the polarization in percent.

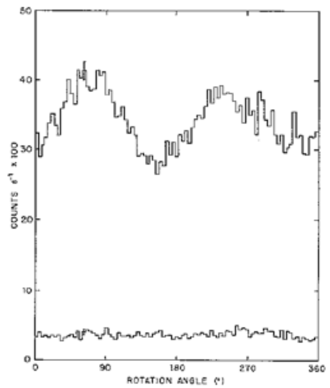
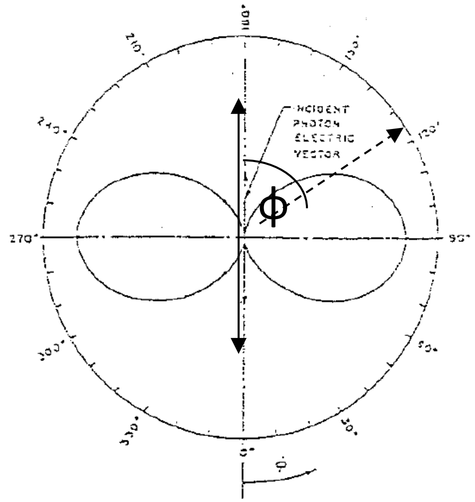
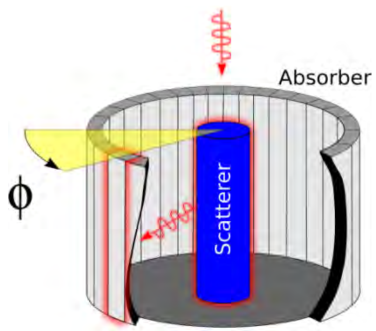


FIG. 2.—Average modulation curves obtained with both detectors at 2.6 keV during (upper curve) observations of the Crab Nebula and during (lower curve) observations of the Earth-occulted instrumental background.

X-ray polarimetry with Thomson scattering





$$\frac{d\sigma}{d\Omega} = \left(\frac{e^2}{m_e c^2}\right)^2 (1 - \sin^2(\theta) cos^2(\varphi))$$

θ is the angle of scattering.

φ is the azimuthal angle, the angle of the scattered photon with respect to the electric vector of the incident photon.

At 90° of angle of scattering (θ) the modulation factor is 100 % since there are not photons diffused along the electric field.

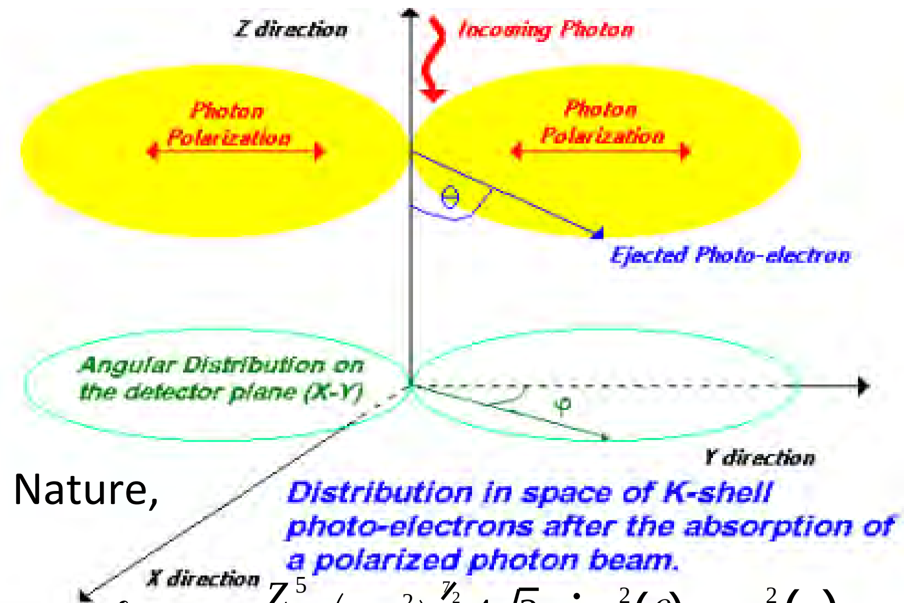
From Bragg/Thomson to Photoelectric

The turning point of X-Ray Astronomy was the launch of Einstein satellite that first introduced the X-ray Optics.
The dramatic increase in sensitivity for the detection of faint sources and the capability to resolve extended source with imaging detectors in the focus of grazing incidence telescopes, that do not require rotation, made the mismatching in the sensitivity of polarimeters, and on the requirements to the payload (rotation) unsustainable. Polarimeter was disembaked from Einsten and Chandra and not accepted on XMM.
The only big mission that included a polarimeter was Spectrum-X-Gamma with SXRP. SRG was never launched and SXRP concludes the era of traditional polarimeters.

The new Era is based on photoelectric polarimeters and finely subdivided scattering polarimeters.

Modern polarimeters dedicated to X-ray Astronomy exploit the photoelectric effect resolving most of the problems connected with Thomson/Bragg polarimeter. The exploitation of the photoelectric effect was attempted very long ago, but only since 2001 it was possible to devise photoelectric polarimeters mature for a space mission.

Heitler W.,The Quantum Theory of Radiation



Costa, Nature, 2001

$\beta = v/c$

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

By measuring the angular distribution of the ejected photelectrons (the modulation curve) it is possible to derive the X-ray polarization.

An X-ray photon directed along the Z axis with the electric vector along the Y axis, is absorbed by an atom.

The photoelectron is ejected at an angle θ (the polar angle) with respect the incident photon direction and at an azimuthal angle φ with respect to the electric vector.

If the ejected electron is in ‘s’ state (as for the K–shell) the differential cross section depends on $\cos^2(\varphi)$, therefore it is preferentially emitted in the direction of the electric field. It is an ideal analyzer of the polarization.

Being the cross section always null for $\varphi = 90^o$ the modulation factor μ equals 1 for any polar angle.

The very beginning: Pierre Auger 1926

With a cloud chamber PierreAuger could visualize tracks of photoelectrons andmeasure the angles of ejection.

We need something like that

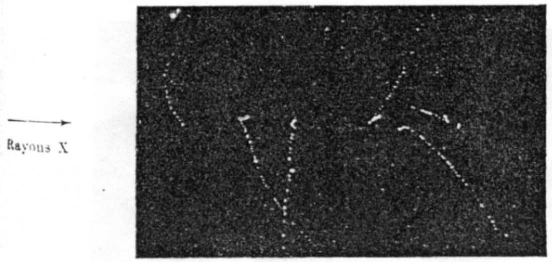
JOURNAL DE PHYSIQUE

Les points blancs aux origines des rayons β secondaires manifestent l'existence d'un rayonnement mou.
(*Tous ces clichés sont grossis environ 2 fois*).

Cliché 1.
Atmosphère d'argon.
Rayons X de 30 kilovolts.

Les points sont plus petits dans ce cas.

Cliché 2.
Atmosphère d'hydrogène à 10 p. 100 d'azote.
Rayons X de 30 kilovolts.



On voit ici nettement les trajectoires des rayons tertiaires (1 mm).

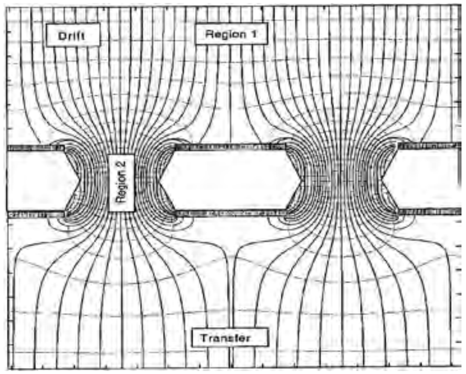
Cliché 3.
Atmosphère d'hydrogène à 5 p. 100 d'argon
Rayons X de 45 kilovolts.

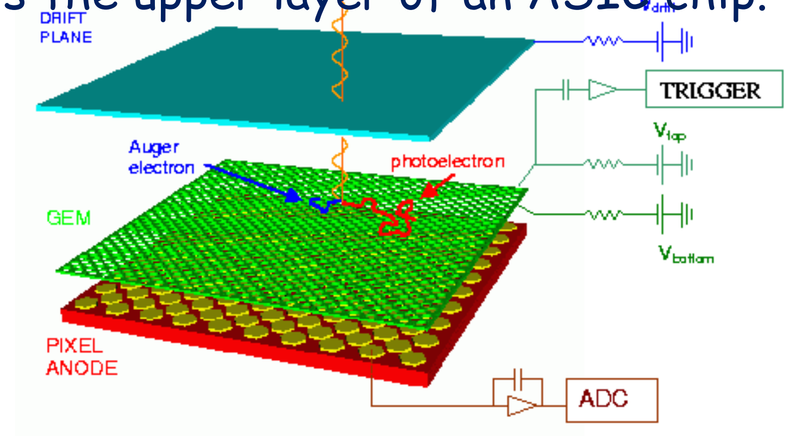
PLANCHE I

To efficiently image the track at energies typical of conventional telescopes INFN-Pisa and IASF-Rome developed the **Gas Pixel Detector**. The tracks are imaged by preserving the charge.

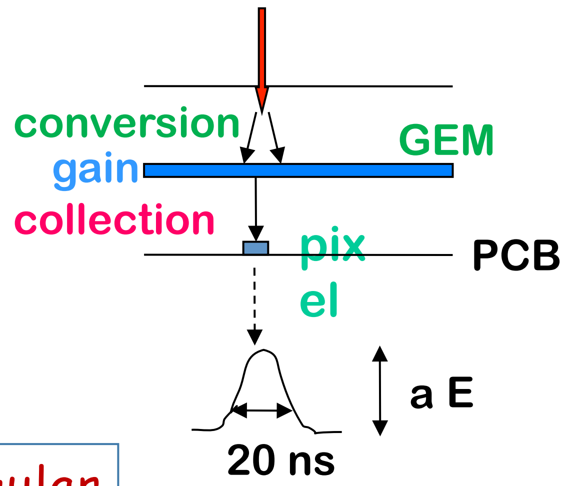
A photon cross a Beryllium window and it is absorbed in the gas gap, the photoelectron produces a track. The track drifts toward the multiplication stage that is the GEM (Gas Electron Multiplier) which is a kapton foil metallized on both side and perforated by microscopic holes (30 um diameter, 50 um pitch) and it is then collected by the pixellated anode plane that is the upper layer of an ASIC chip.

GEM electric field





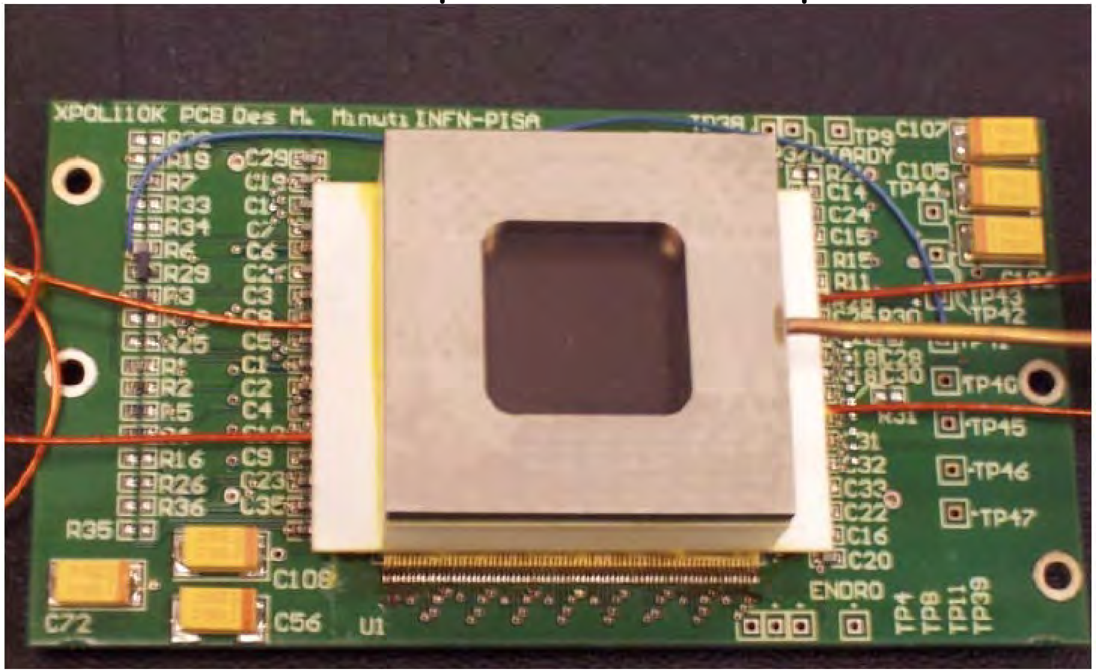
Costa et al., 2001, Bellazzini et al.2006, 2007

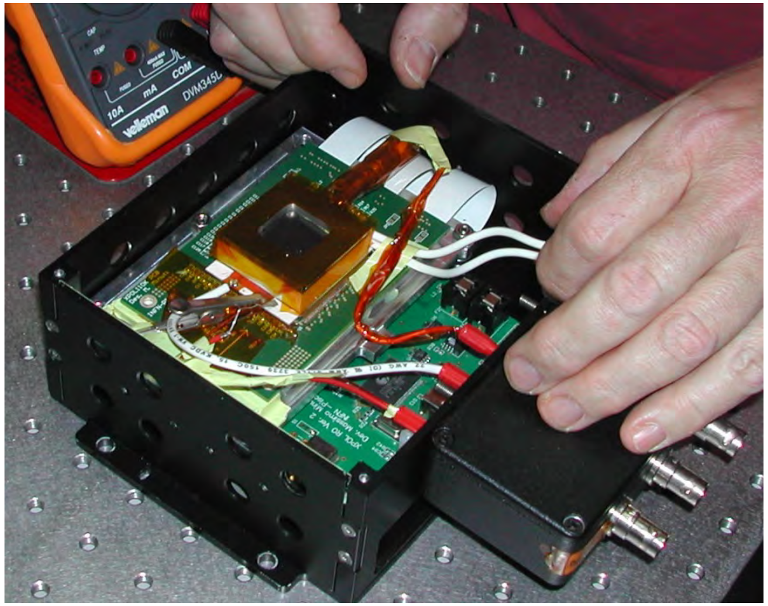


Polarization information is derived from the angular distribution of the emission direction of the tracks produced by the photoelectrons. The detector has a very good imaging capability.

The real implementation of a working GPD prototype

A sealed polarimeter has been built since some years and has been extensively tested, with thermal-vacuum cycles, it has been vibrated, irradiated with Fe ions and calibrated with polarized and unpolarized X-rays.



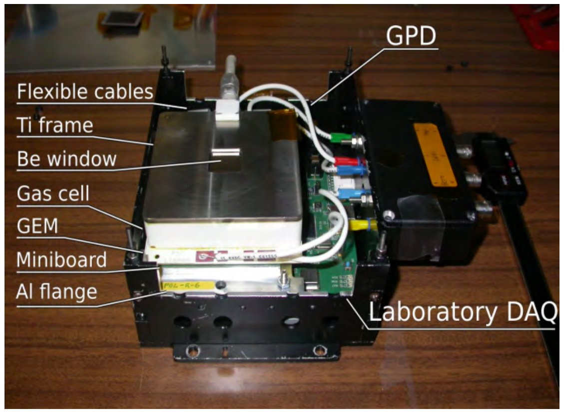


The GPDs under test was filled with
1) 20-80 He-DME 1 bar, 1cm.

2) pure DME 0.8 bar, 1 cm.

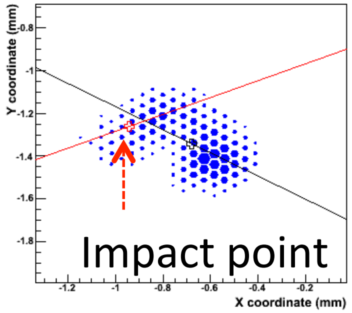
3) Ar DME 60-4E = $(CH3)_2O$

60 μm/√cm diffusion

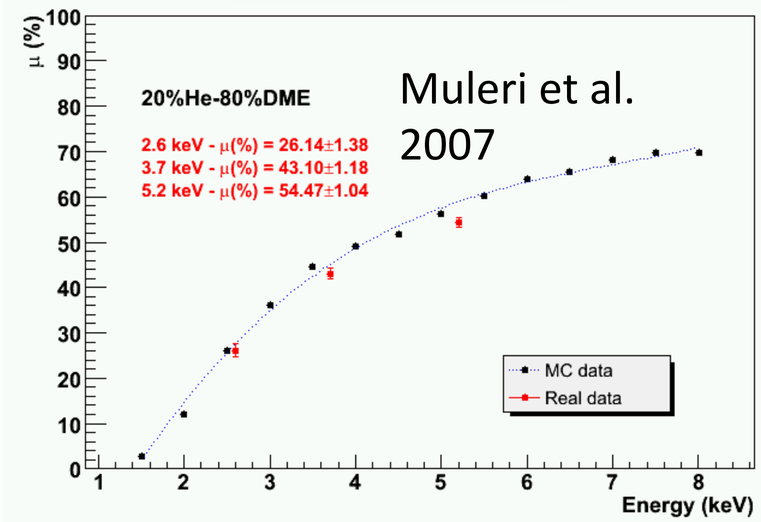


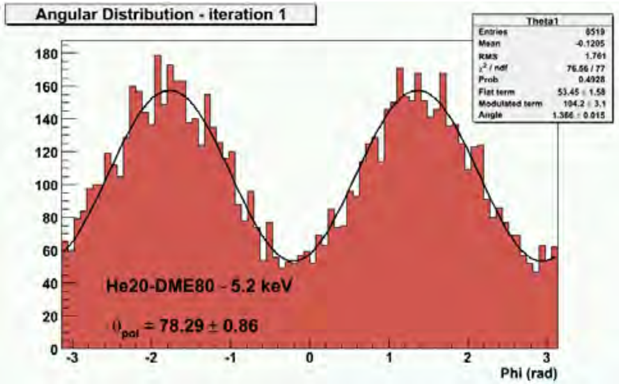
New prototypes with a btter control of electric Field

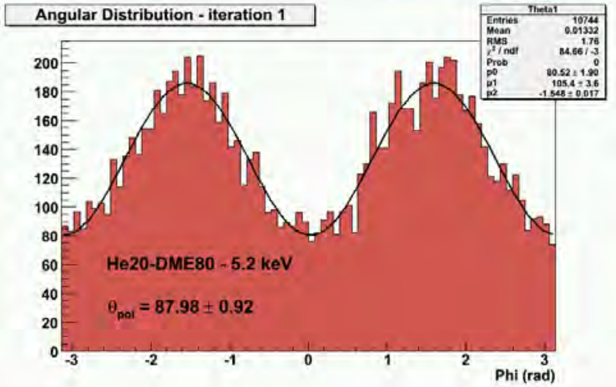
Each photon produces a track. From the track the impact point and the emission angle of the photoelectron is derived. The distribution of the emission angle is the modulation curve.



Not only MonteCarlo: Our predictions are based on data

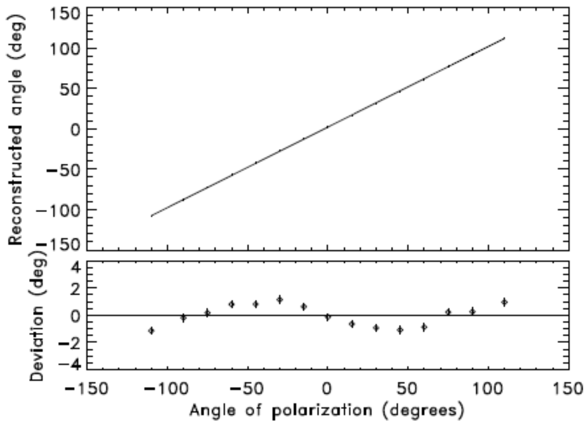




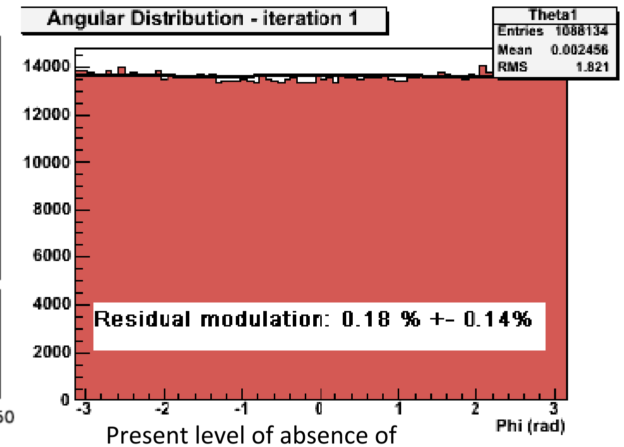


By rotating the polarization vector the capability to measure the polarization angle is shown by the shift of the modulation curve.

The modulation factor measured 2.6 keV, 3.7 keV and 5.2 keV has been compared with the Monte Carlo previsions. The agreement is very satisfying.



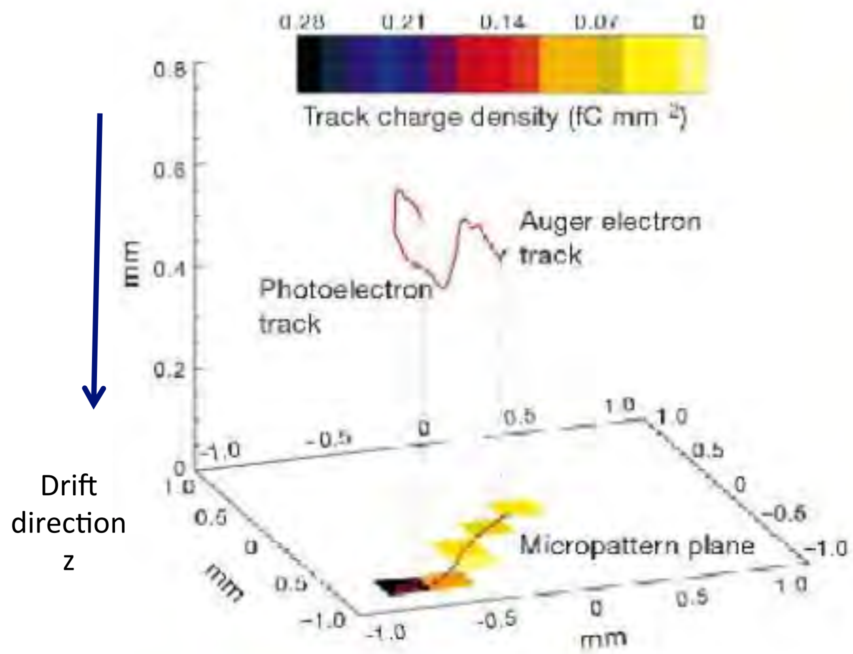
Soffitta et al., 2010

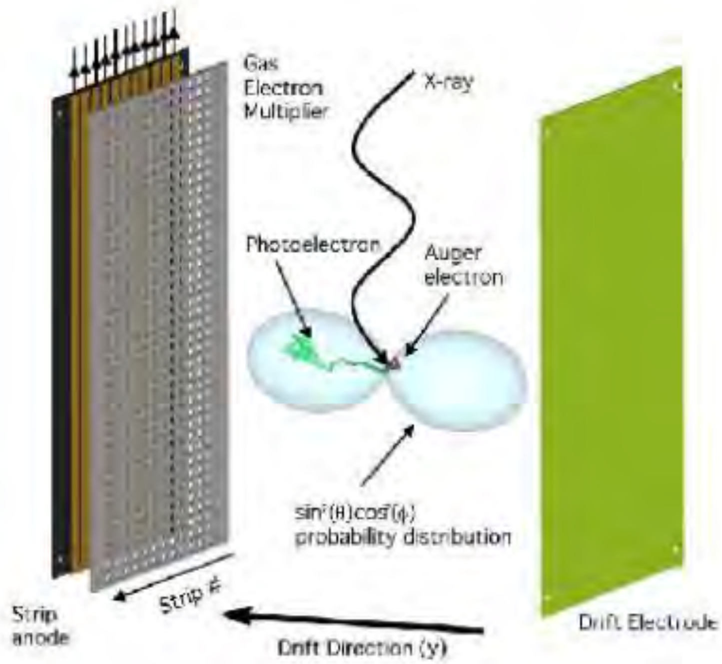


Present level of absence of systematic effects (5.9 keV). Bellazzini 2010

Two approaches

Two different instrumental approaches:





Gas Pixel Detector
Costa et al. 2001
Bellazzini et al. 2006, 2007

Time Projection Chamber
Black et al. 2007

The photons enters perpendicularly with respect to the readout plane.

The photons enter parallel with respect to the readout plane.

X-ray polarimetry with a Time Projection Chamber

High efficiency Not an imager

Black 2007

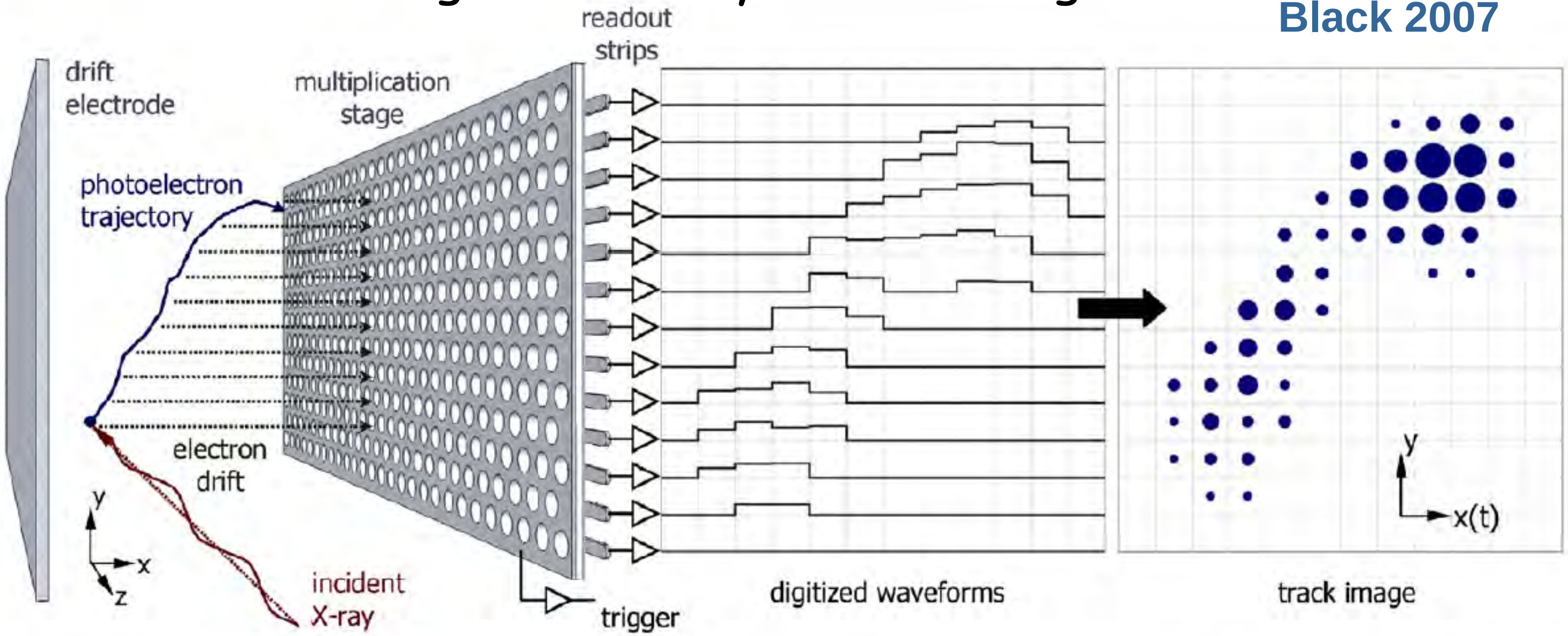


Fig. 1. Photoelectron track imaging with a micropattern TPC. The digitized waveforms are represented as an image in which the areas of the circles are proportional to the charge deposited. The pixels are on a 130 µm spacing, while the waveforms are sampled with a 40 ns period.

The photons enter along Z, the readout strips run also along Z. The GEM multiply the charge. The charge is then collected by the 1-d strip detector. The signal in each strip is connected to a waveform digitizer and by using its timing characteristics the information the other coordinate is derived.

This method allows for decoupling the drift length that blurs the image and decreases the modulation factor from the absorption depth that controls the efficiency. Since the origin of the time is not known the TPC is not an astronomical imager because the event is not referred to an angular direction.

The first attempts

Since the first achievements with GPD technique from 2002 to 2008 missions based on photoelectric polarimetry or including polarimeters have been proposed to NASA, ESA, ASI, JAXA and CNSA.

•A GPD X-ray Polarimeter was included in the baseline design of XEUS a very anbitious project of ESA with a telescope of 6m2 and a focal of 50m. XEUS was merged with NASA mission Constellation X into the combined ESA/NASA/JAXA mission IXO still includinga polarimeter. IXO was not approved by the USA Decadal Survey. ESA came back to an all-european propsal ATHENA, that did not include any more the polarimeter. ATHENA was not selected as L1 mission of Cosmic Vision. Subsequently ATHENA+ was selected as ESA L2 mission.

• POLARIX an all italian mission was submitted to ASI in response to an AOO for small scientific missions. POLARIX was one ofthe two missions selected but the whole project of Small Missions was dropped.

•Also the mission NHXM, proposed to the ESA AOO for M3 mission included polarimeters but was not selected

GEMS close to the goal but .....

- In response to an AOO for Small Explorers in 2007, 2 missions of X-ray polarimetry have been proposed. One based on GPD and one based on TPC.
- GEMS was selected by NASA on May 2008 to fly on 2014. GEMS was based on detectors with TPC concept. GEMS was expected to restart the field of X-ray polarimetry 35 years after OSO-8.
- At the end of May 2012 NASA, while confirming the scientific validity of this mission, has decided to stop GEMS for programmatic and budgetary reasons.
- When the news arrived an AOO for a small scientific mission, issued by ESA, was still open.
- In about two weeks XIPE a proposal based on GPD was set-up and submitted. XIPE was not selected.
- Papers published in 2013-2014 showed that GEMS detectors were not ready to flight.

What next? A mission of polarimetry? And with which concept?

ESA

In 2014 ESA issued an AOO for the 4th Scientific Mission of Medium Size (M4) with a budget of 450 M€ (+ national contributions).

3 missions have been selected on 2015 for advanced study:

1)XIPE: and X-ray Imaging Polarimeter based on GPD

2)ARIEL: a mission for the spectroscopy of Exoplanets

3)Thor: a mission to study turbolence on Solar Wind

On 2017 one of these 3 missions will be selected for flight

NASA

In 2014 NASA issued an AOO for a Small Explorer Mission (budget of ~ 150 M$)

On july 30 NASA selected 3 missions for advanced study

1)IXPE: a Mission of X-ray Polarimetry based on GPD

2)Praxys: a Mission of X-ray Polarimetry based on TPC

3)SPHEREx: a Mission of All Sky Survey of NearIR spectroscopy

On end of 2016 NASA will select one of the 3 missions to flight

CNSA

CNSA is defining its planning and XTP, a very large mission of X-ray astronomy, including some polarimeters, is a strong candidate.

Close to an approved polarimetry mission

Three out of 6 missions under study are of X-ray Polarimetry.
No question X-ray Polarimetry is acknowledged as a “fashonable” topic.
Maybe this is the right time.

But nothing is sure!

We are working very hard to have at least one GPD mission approved

Beside the work to improve the performance (and the credibility) of hardware it is important to enrich and better focus the science case. Theory is always fed by data. Compared with the tiotal lack of data literature on predictions of X-ray polarimetry measurement is Huge, but unavoidably uncomplete.

Synergy with observations in other wavelengths may be very supportive. VHE γ-ray astrophysics and CR physics is a good candidate because observations in many cases refer to the same objects and to extreme physical context.

Let us focus on XIPE

XIPE is the most performing of the 3 missions under study.

I use it as a reference of what X-Ray Polarimetry can do in the next future.

X-ray Imaging Polarimetry Explorer

Proposed by

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XIPE Science Team

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XIPE Instrument Team

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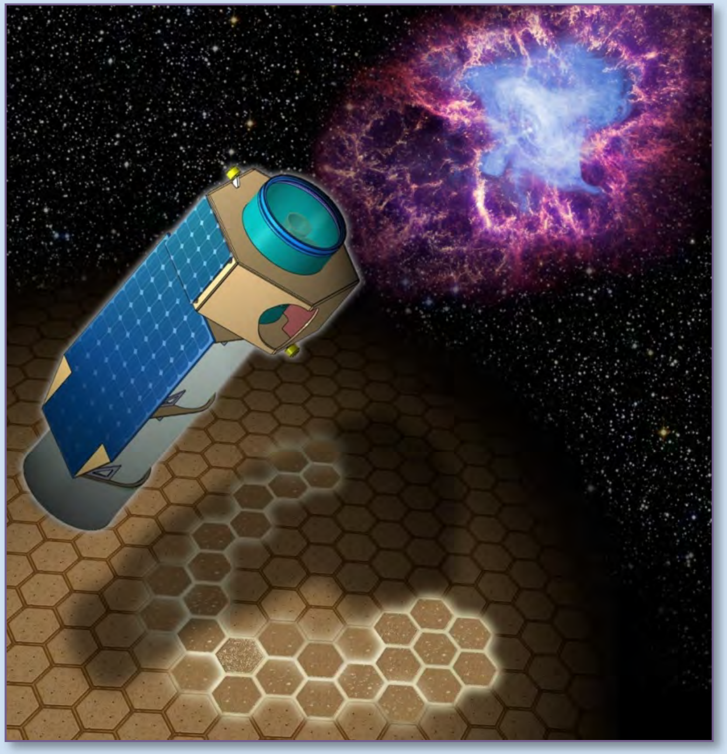


XIPE participating Institutions

BR: INPE; **CH**: ISDC - Univ. of Geneva; **CN**: IHEP, NAOC, NJU, PKU, PMO, Purdue Univ., SHAO, Tongji Univ, Tsinghua Univ., XAO; **CZ**: Astron. Institute of the CAS; **DE**: IAAT Uni Tübingen, MPA, MPE; **ES**: CSIC, CSIC-IAA, CSIC-IEEC, CSIC-INTA, IFCA (CSIC-UC), INTA, Univ. de Valencia; **FI**: Oxford Instruments Analytical Oy, Univ. of Helsinki, Univ. of Turku; **FR**: CNRS/ARTEMIS, IPAG-Univ. of Grenoble/ CNRS, IRAP, Obs. Astron. de Strasbourg, **IN**: Raman Research Institute, Bangalore; **IT**: Gran Sasso Science Institute, L'Aquila, INAF/IAPS, INAF/IASF-Bo, INAF/IASF-Pa, INAF-OAA, INAF-OABr, INAF-OAR, INFN-Pi, INFN-Torino, INFN-Ts, Univ of Pisa, Univ. Cagliari, Univ. of Florence, Univ. of Padova, Univ. of Palermo, Univ. Roma Tre, Univ. Torino; **NL**: JIVE, Univ. of Amsterdam; **PL**:CopernicusAstr. Ctr., SRC-PAS; **PT**: LIP/Univ. of Beira-Interior, LIP/Univ. of Coimbra; **RU**: Ioffe Institute, St.Petersburg: **SE**: KTH Royal Institute of Technology. Stockholm Univ.: **UK**: Cardiff Univ., UCL-MSSL, Univ. of Bath; **US**: CFA, Cornell Univ., NASA-MSFC, Stony Brook Univ., Univ. of Iowa, Boston Univ., Institute for Astrophysical Research, Boston Univ., Stanford Univ./KIPAC.

XIPE is devoted to **observation of celestial sources in X-rays**

XIPE uniqueness:

- Time-, spectrally-, spatially-resolved **X-ray polarimetry** as a breakthrough in high energy astrophysics and fundamental physics

- It will explore this observational window after 40 years from the last positive measurement, with a dramatic improvement in sensitivity: **from one to hundred sources**

In the violent X-ray sky, polarimetry is expected to have a **much greater** impact than in most other wavelengths.

XIPE is going to exploit the complete information contained in X-rays.

A **large** number of scientific topics and observable sources:

Astrophysics

Acceleration phenomena

Pulsar wind nebulae

SNRs

Jets

Emission in strong magnetic fields

Magnetic cataclysmic variables

Accreting millisecond pulsars

Accreting X-ray pulsars

Magnetar

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

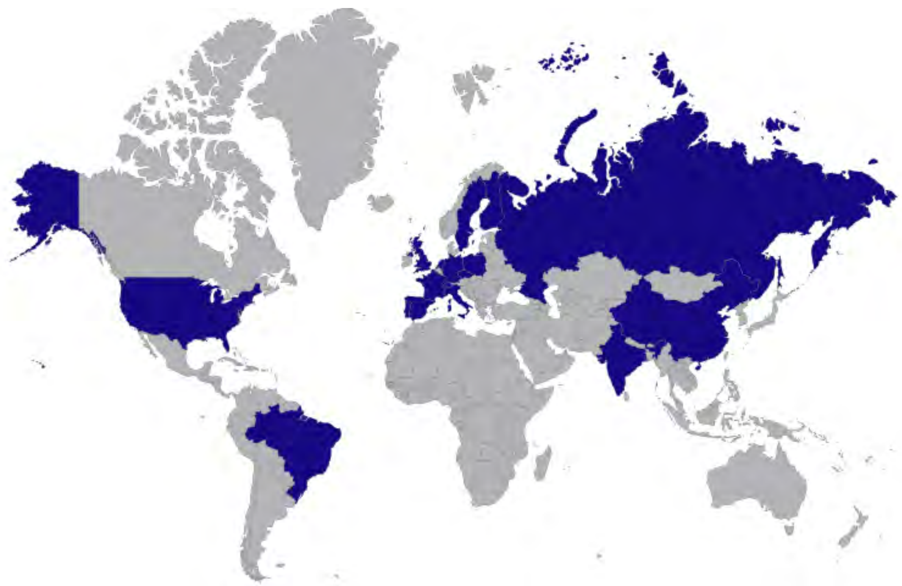
Galactic black hole system & AGNs

Quantum Gravity

Search for axion-like particles

A **large** community involved:

- **17 countries**
- **146 scientists**
- **68 institutes around the world**

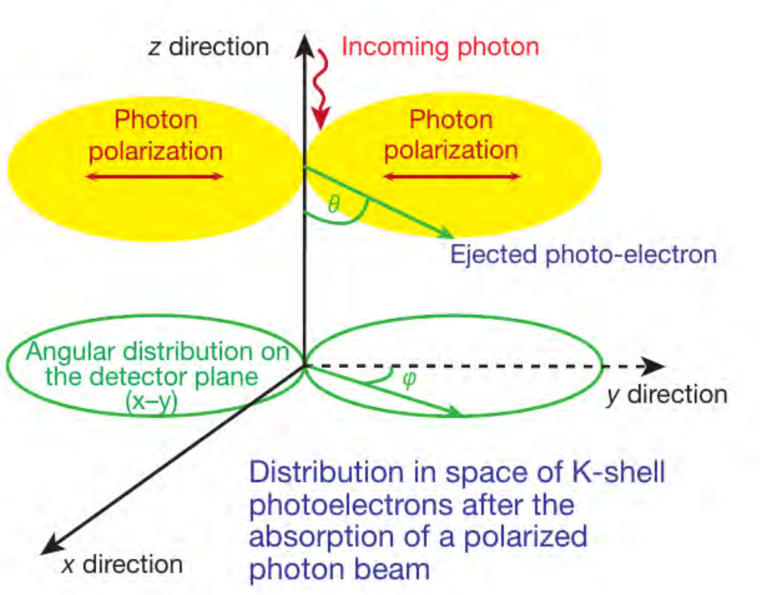


The Gas Pixel Detector

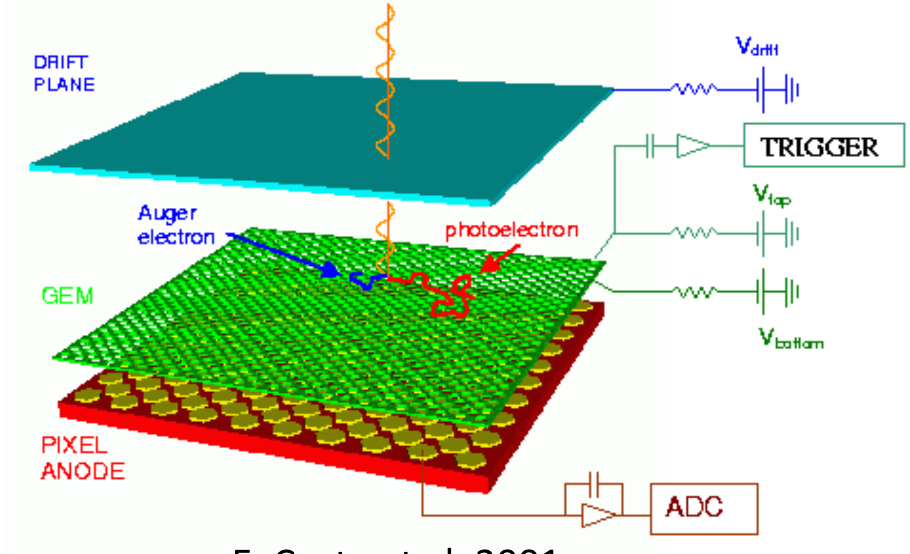
We developed at this aim a polarization-sensitive instrument capable of imaging, timing and spectroscopy

The photoelectric effect

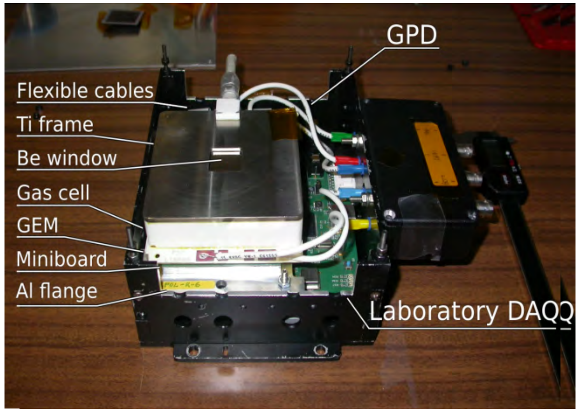
$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2}\frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$



The Gas Pixel Detector



E. Costa et al. 2001



Why this is now possible

The Gas Pixel Detector

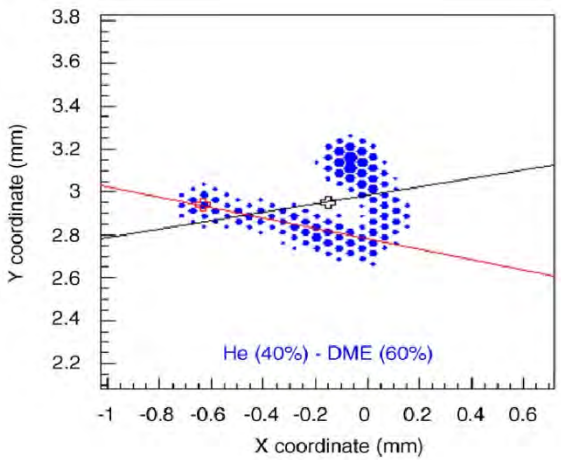
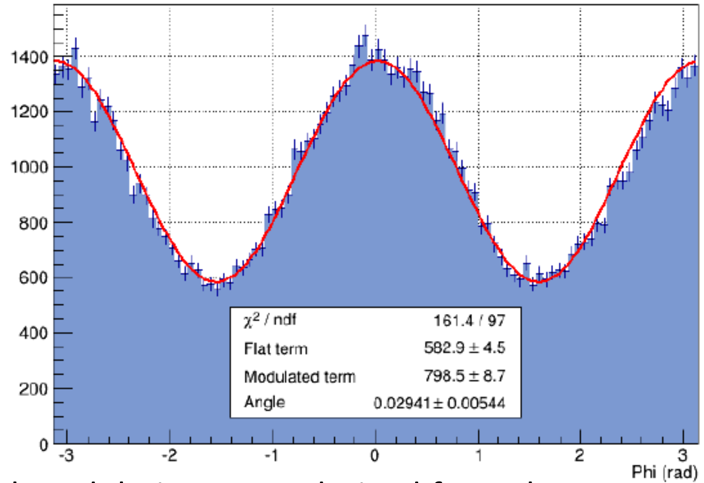
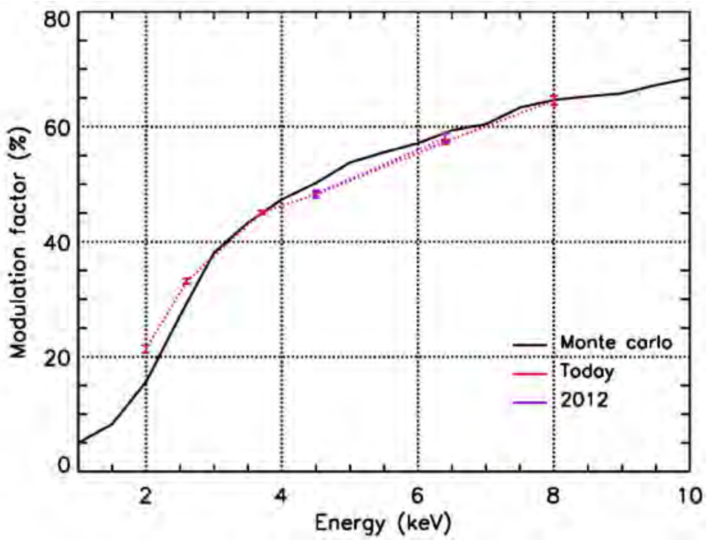


Image of a real photoelectron track. The use of the gas allows to resolve tracks in the X-ray energy band.

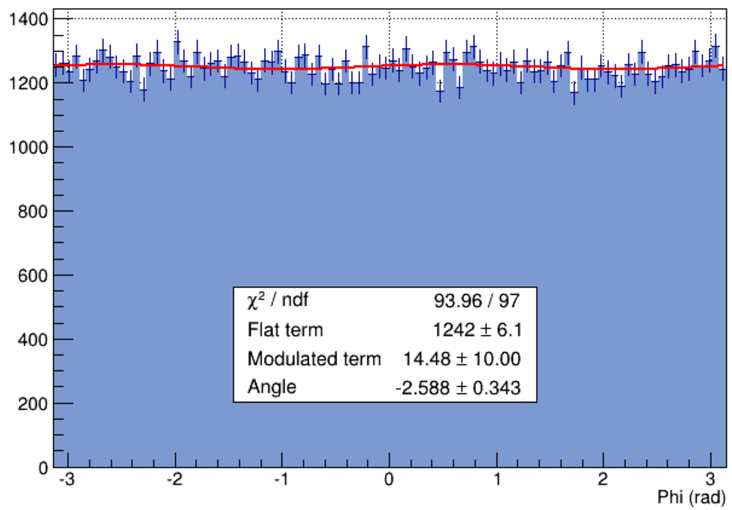


Real modulation curve derived from the measurement of the emission direction of the photoelectron.



Muleri et al. 2008,2010

Modulation factor as a function of energy.

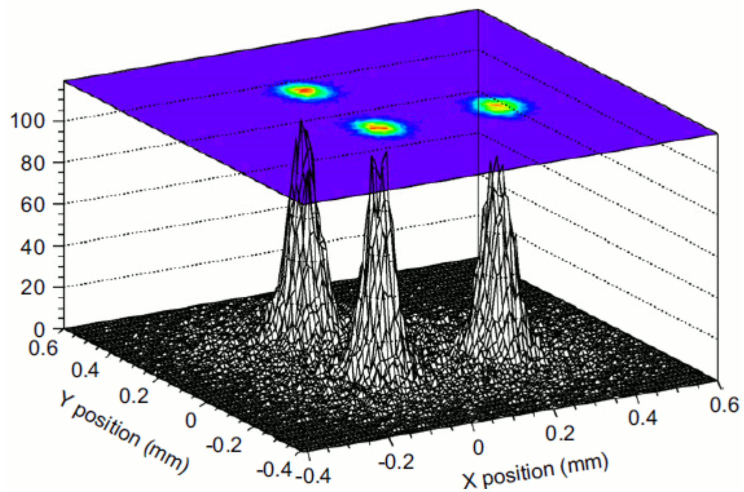


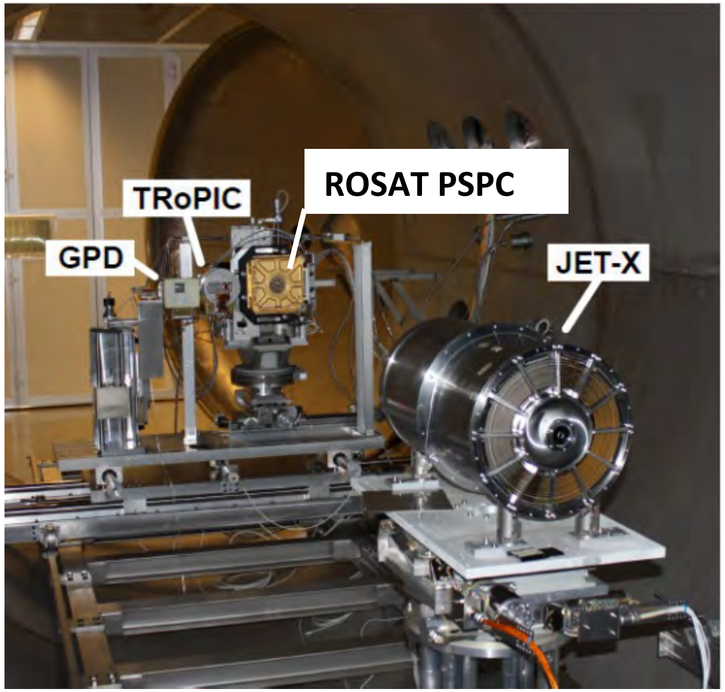
Bellazzini et al. 2012

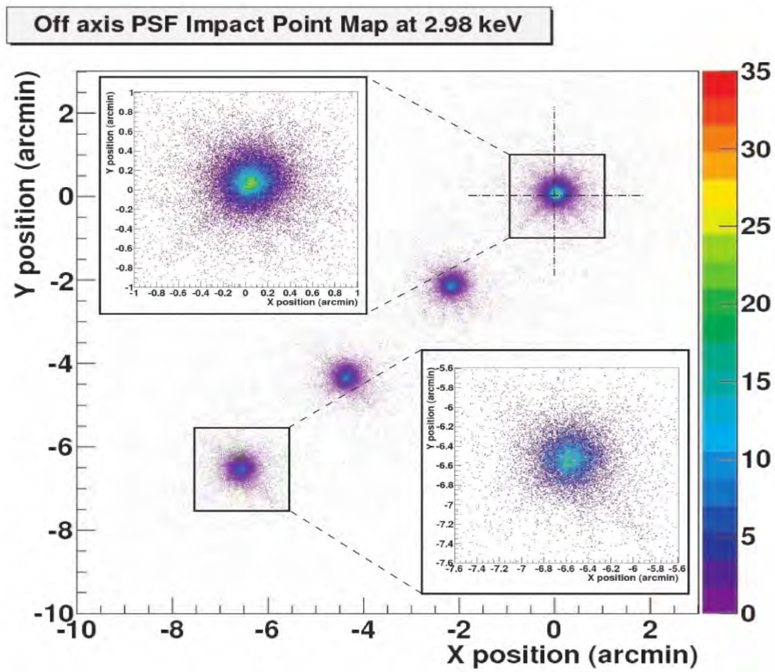
Residual modulation for unpolarised photons.

Imaging capabilities

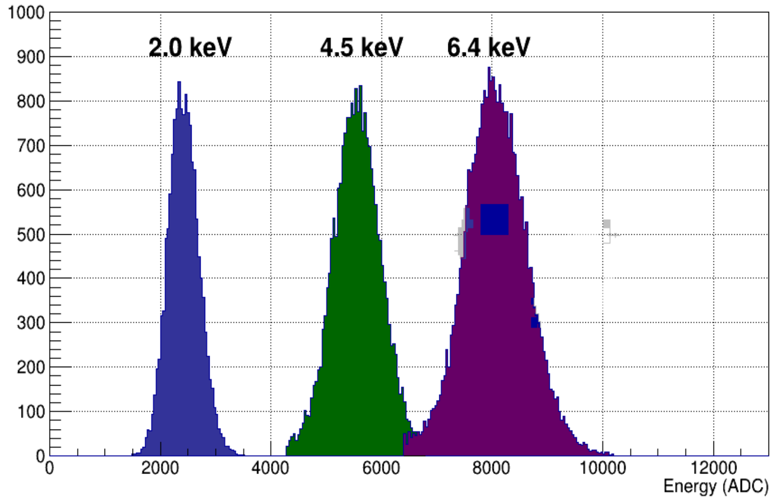
- Good spatial resolution: 90 µm Half Energy Width
- Imaging capabilities on- and off-axis measured at PANTER with a JET-X telescope (Fabiani et al. 2014)
- Angular resolution for XIPE: <26 arcsec

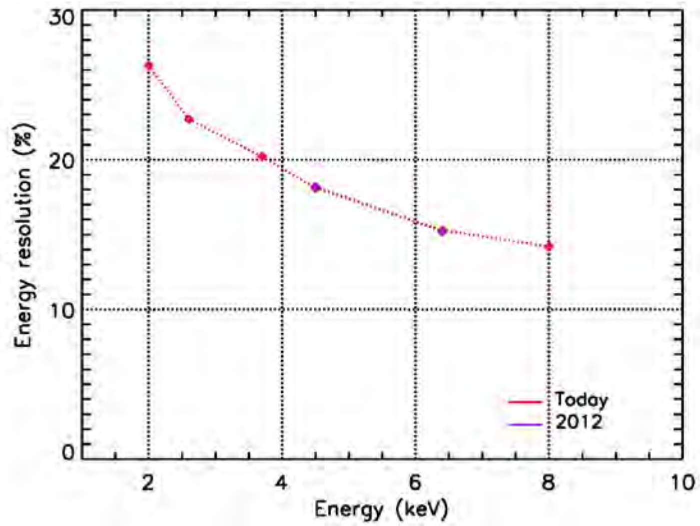






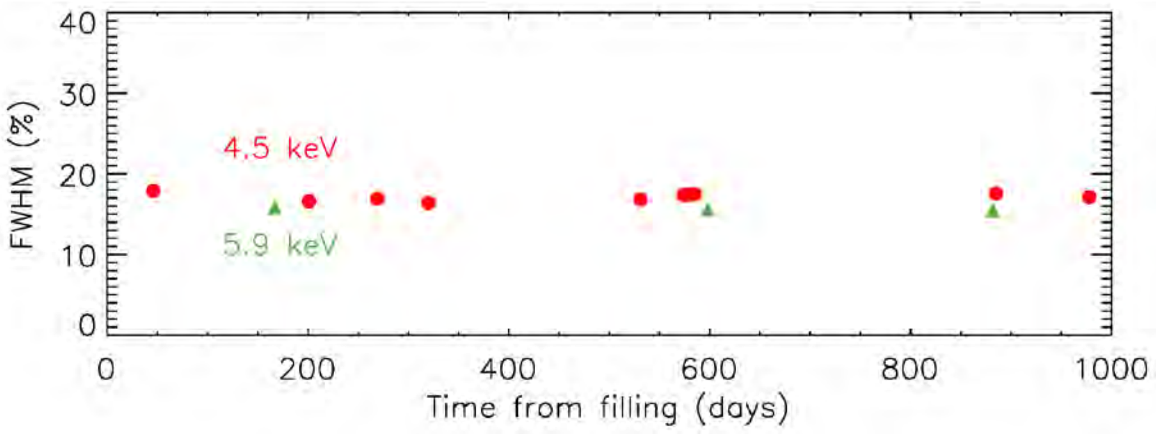
Spectroscopic capabilities





- Adequate spectrometer for continuum emission (16 % at 6 keV, Muleri et al. 2010).

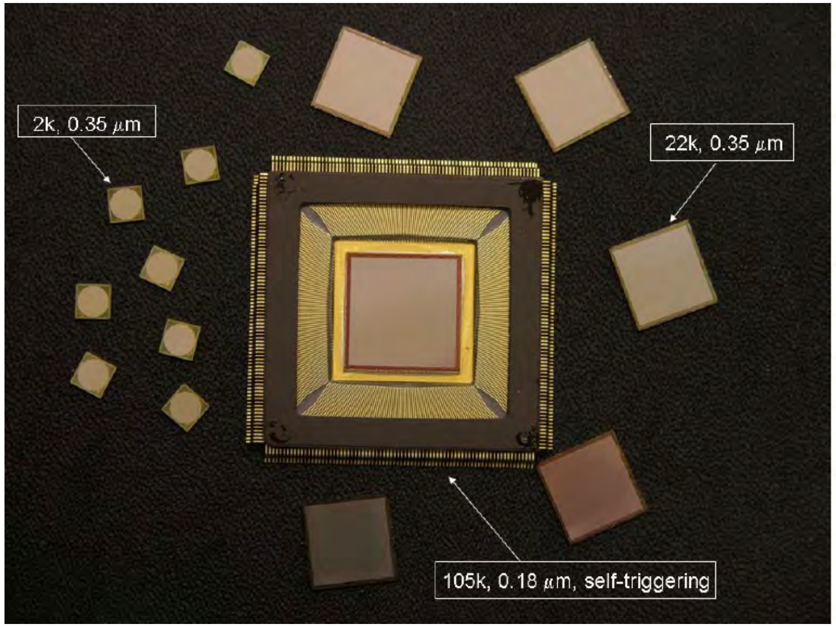
- Stable operation over 3 years

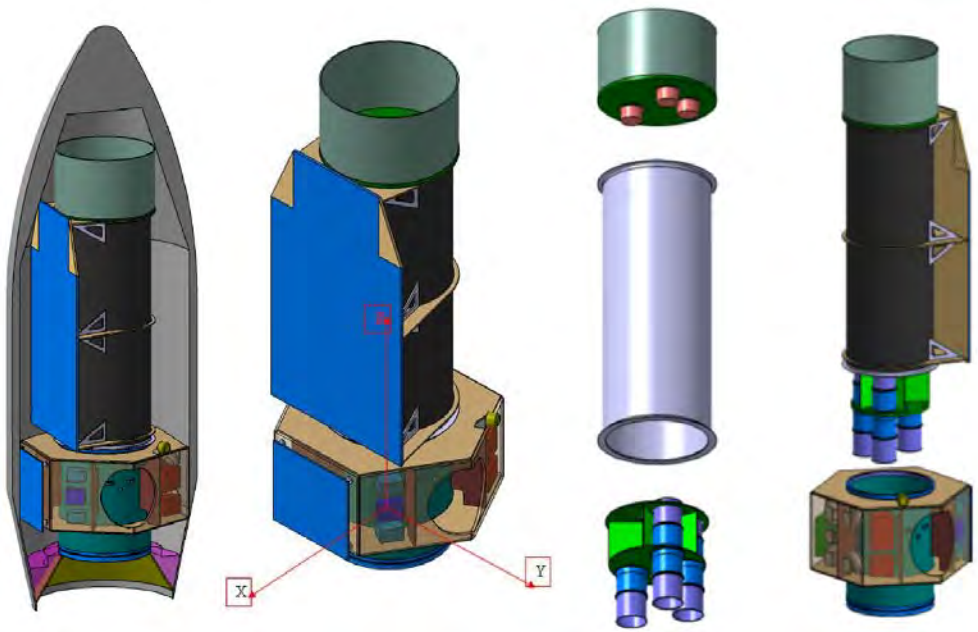


XIPE design guidelines

A light and simple mission

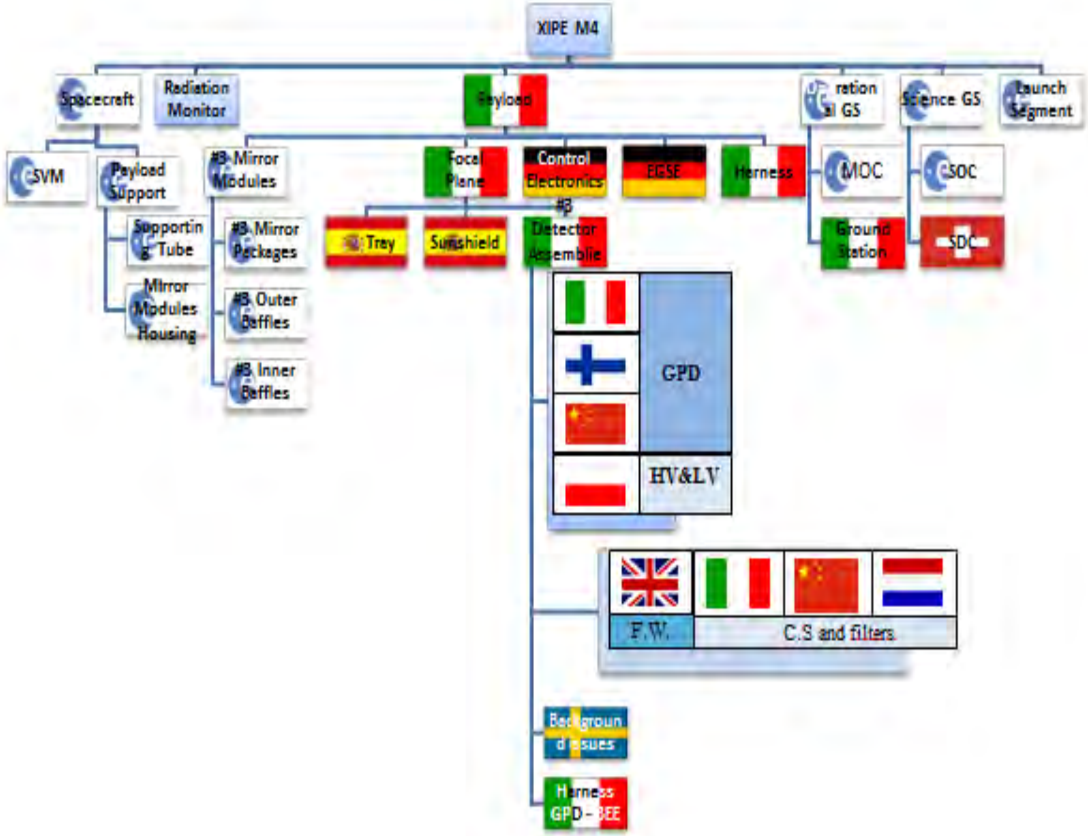
- Three telescopes with 3.5 m focal length to fit within the Vega fairing.
  Long heritage: SAX → XMM → Swift → eROSITA → XIPE
- Detectors: conventional proportional counter but with a revolutionary readout.
- Mild mission requirements: 1 mm alignment, 1 arcmin pointing.
- Fixed solar panel. No deployable structure. No cryogenics. No movable part except for the filter wheels.
- Low payload mass: 265 kg with margins. Low power consumption: 129 W with margins.
- Three years nominal operation life. No consumables.
- Low Earth equatorial orbit.





Bellazzini et al. 2006, 2007

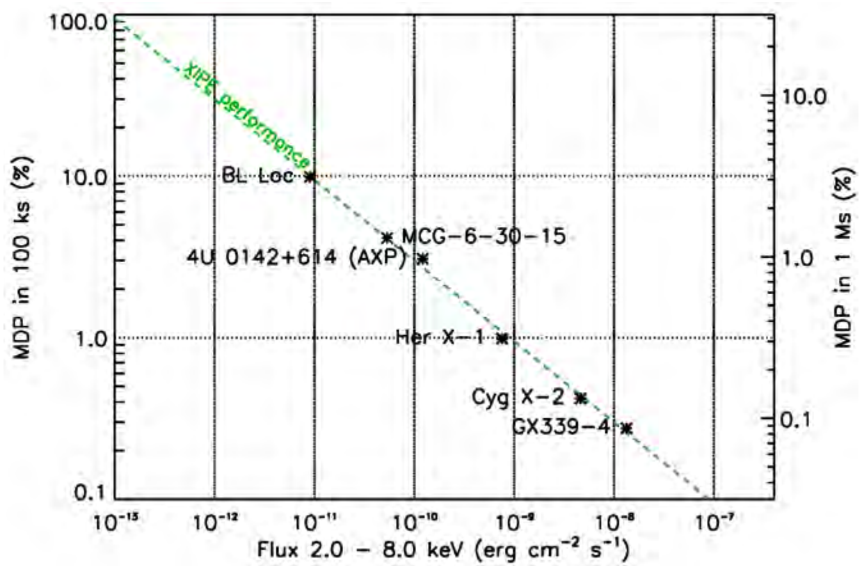
All Europe and more



The distribution of activities

XIPE facts

Polarisation sensitivity	1.2% MDP for $2x10^{-10}$ erg/s cm^2 (10 mCrab) in 300 ks
Spurious polarization	<0.5 % (goal: <0.1%)
Angular resolution	<26 arcsec (goal: <24 arcsec)
Field of View	15x15 $arcmin^2$
Spectral resolution	16% @ 5.9 keV
Timing	Resolution <8 μs
	Dead time 60 μs
Stability	>3 yr
Energy range	2-8 keV
Background	$2x10^{-6}$ c/s or 4 nCrab



CP: Core Program (25%):

- To ensure that the key scientific goals are reached by observing a set of representative candidates for each class.

GO: Guest Observer program on competitive base (75%):

- To complete the CP with a fair sample of sources for each class;
- To explore the discovery space and allow for new ideas;
- To engage a community as wide as possible.

In organising the GO, a fair time for each class will be assigned. This will ensure "population studies" in the different science topics of X-ray polarimetry.

Unique contributions (Question I & Q1)

In X-ray sources it is more common that in other wavelengths to find:

- Aspherical emission/scattering geometries (disk, blobs and columns, coronae);
- Non-thermal processes (synchrotron, cyclotron and non-thermal bremsstrahlung).

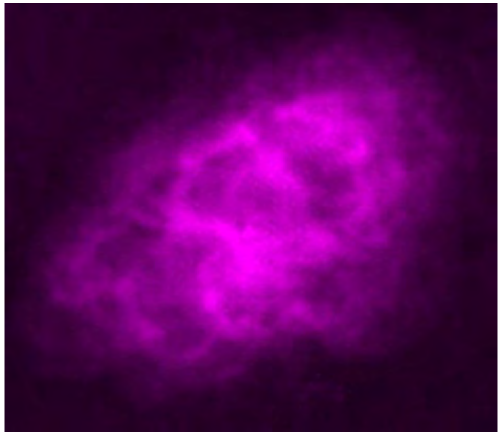
Furthermore, fundamental physics effects like, e.g., QED birefringence in strong magnetic fields, can be studied by X-ray polarimetry.

Timing & spectroscopy may provide rather ambiguous and model dependent information.

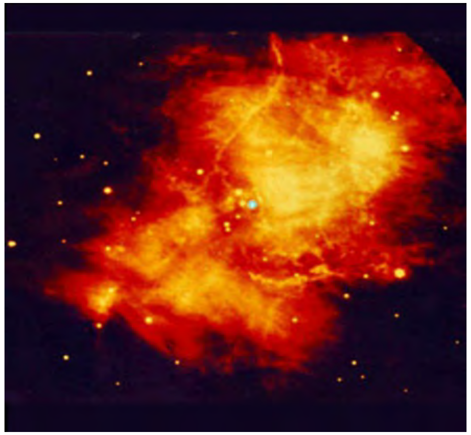
What XIPE can do:

- **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.

X-rays vs other wavelengths: a pictorial explication

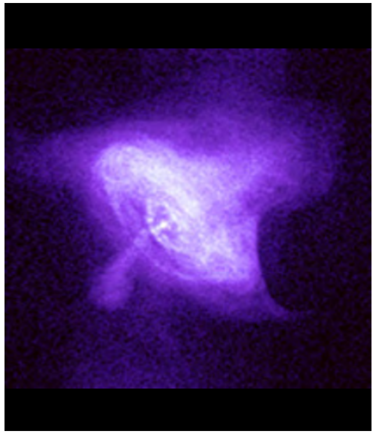


Radio (VLA)

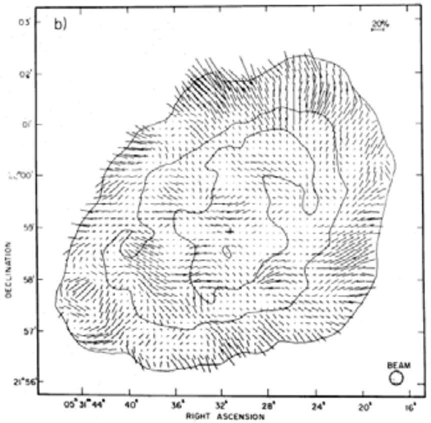


Infrared (Keck)

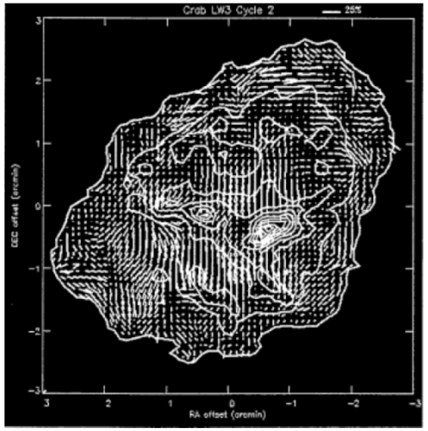
Optical (Palomar)



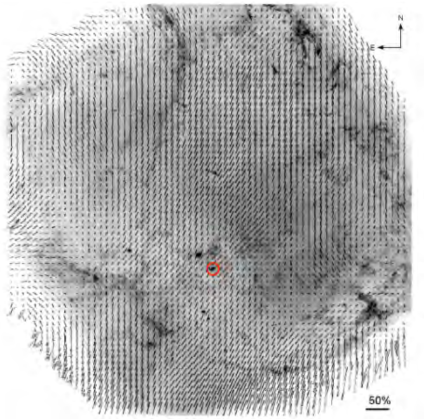
X-rays (Chandra)



Radio polarisation



IR polarisation



Optical polarisation

?

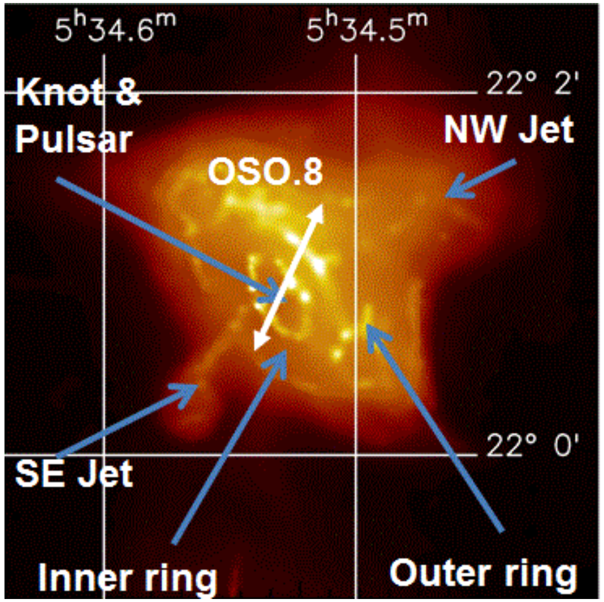
P=19% for the whole nebula (Weisskopf et al. 1978)

X-ray polarisation

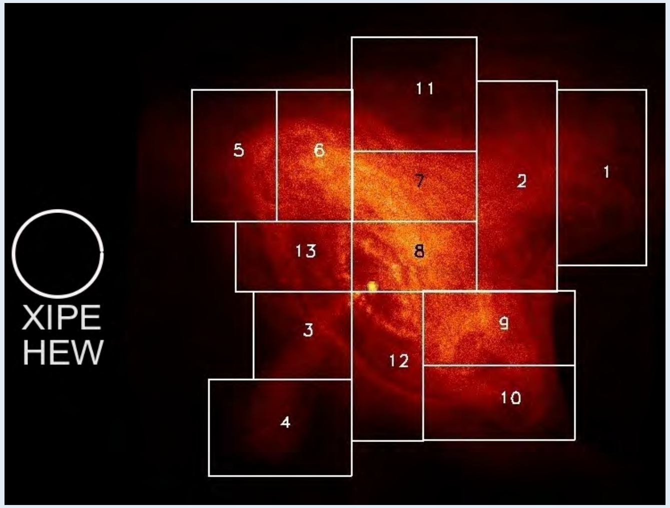
X-rays probe **freshly accelerated** electrons and the site of acceleration.

Acceleration phenomena: The Crab Nebula

OSO-8 measured the polarization of the Crab Neula+pulsar as a whole. But after Chandra image ...



Region	σ_{degree} (%)	σ_{angle} (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 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?
- XIPE imaging capabilities will allow to measure the pulsar polarisation by separating from the much brighter nebula emission.

Acceleration phenomena: Unresolved jets

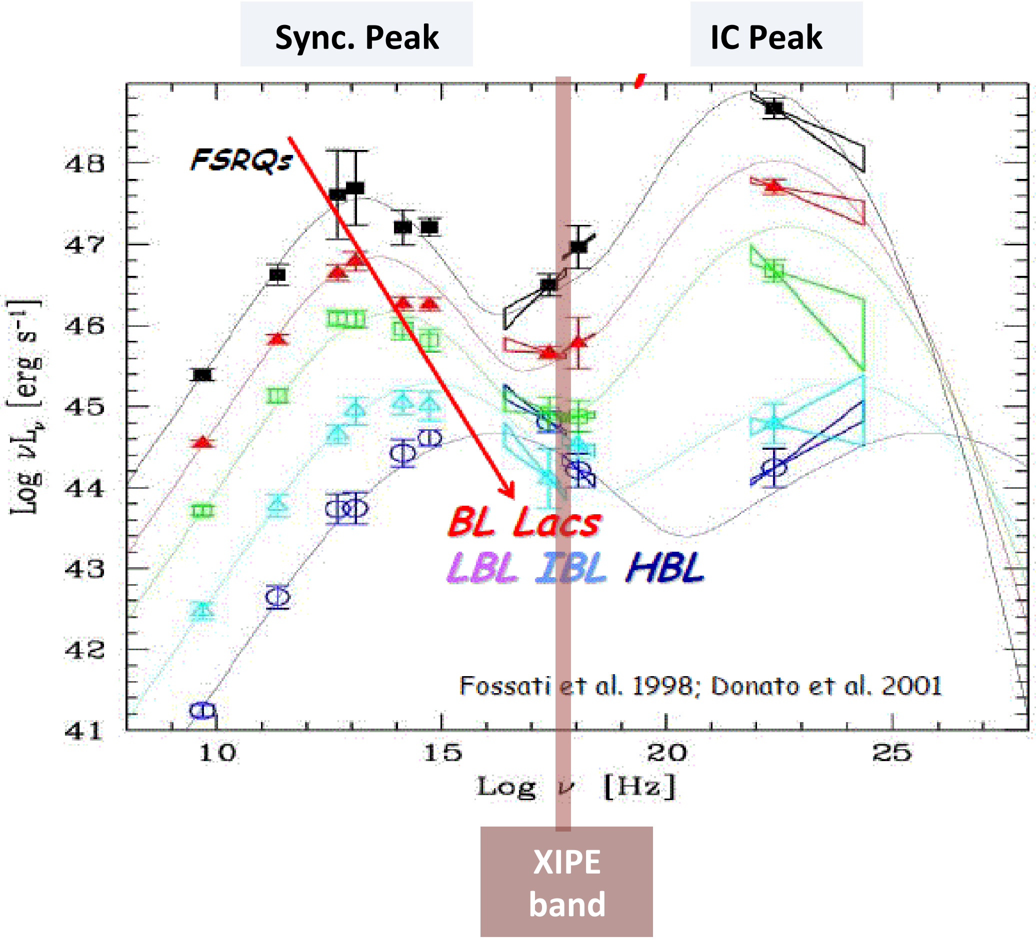
Is the Inverse Compton peak of Blazars due to:

- Synchrotron-Self Compton (SSC) ?
- External Compton (EC) ?

SSC: polarization angle is the same of the synchrotron peak.

EC: the angle may be different.

Polarization degree determines the temperature of electrons in the jet.

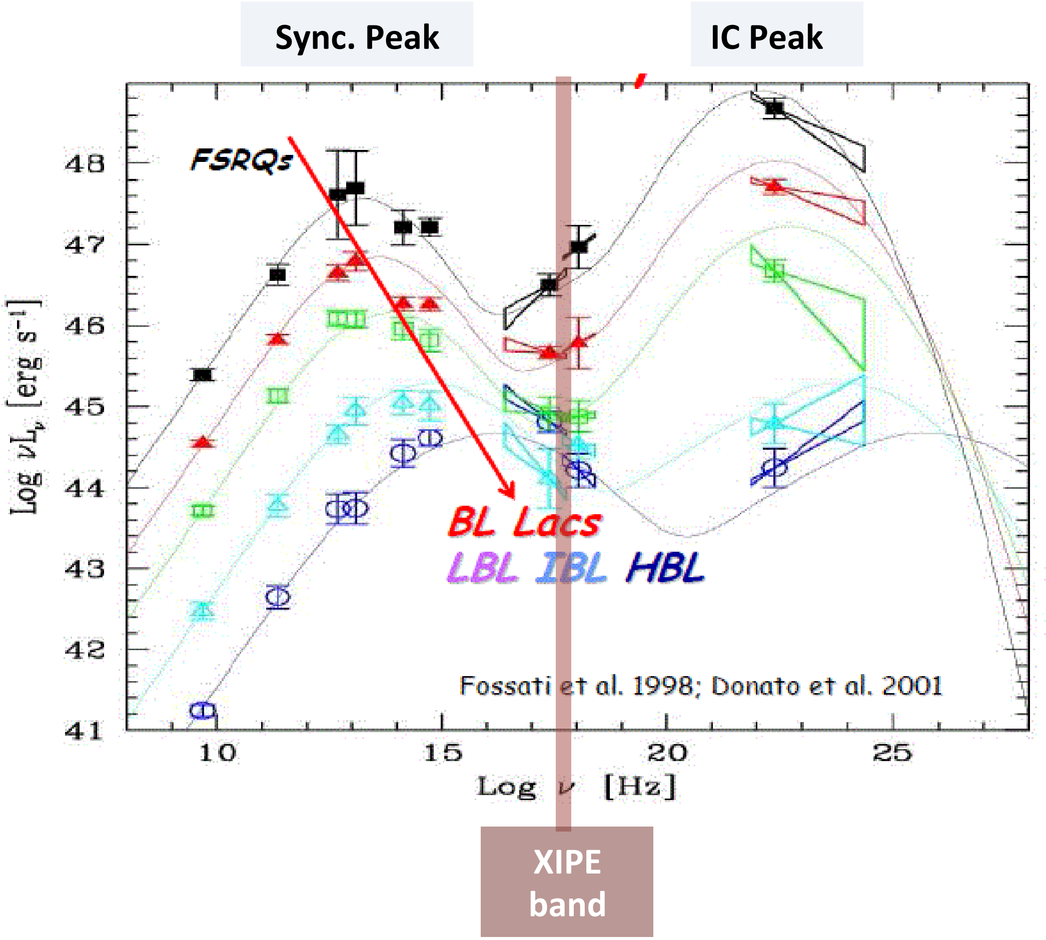


In synchrotron-dominated X-ray blazars, multi-wavelength polarimetry probes the structure of the magnetic field along the jet.

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

Coordinated multi-wavelength campaigns are crucial for blazars.

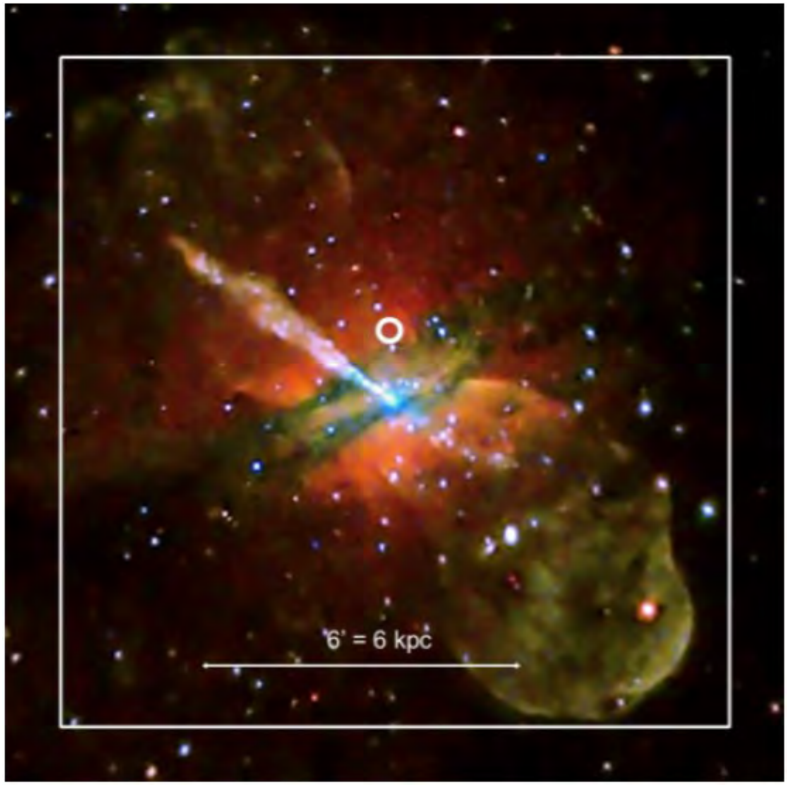
Such campaigns (including polarimetry) are routinely organised and it will be easy for XIPE to join them.



Acceleration phenomena: Resolved jets

Map of the magnetic field of the resolved X-ray emitting jet

MDP for the jet is 5% in 1 Ms in 5 regions.



The extended (4') radio jet in Cen A.

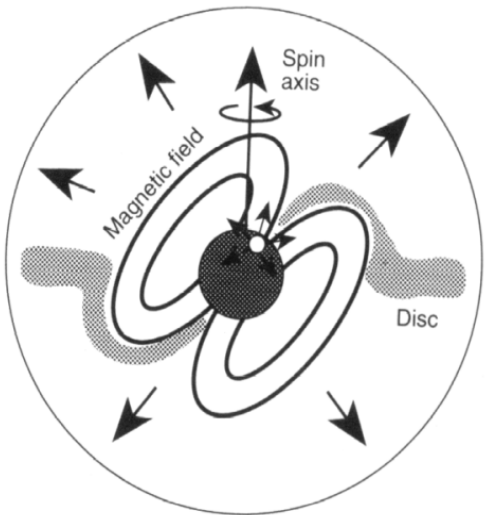
Disentangling geometric parameters from physical ones

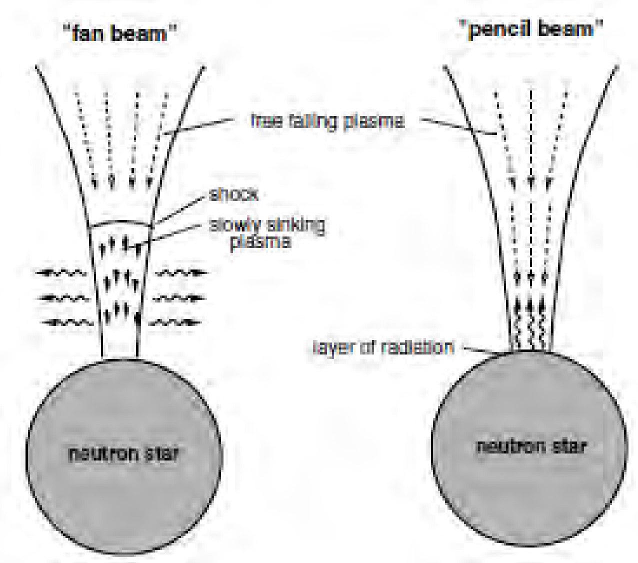
Emission process:

- cyclotron
- opacity on highly magnetised plasma: $k_{\perp} < k_{\parallel}$

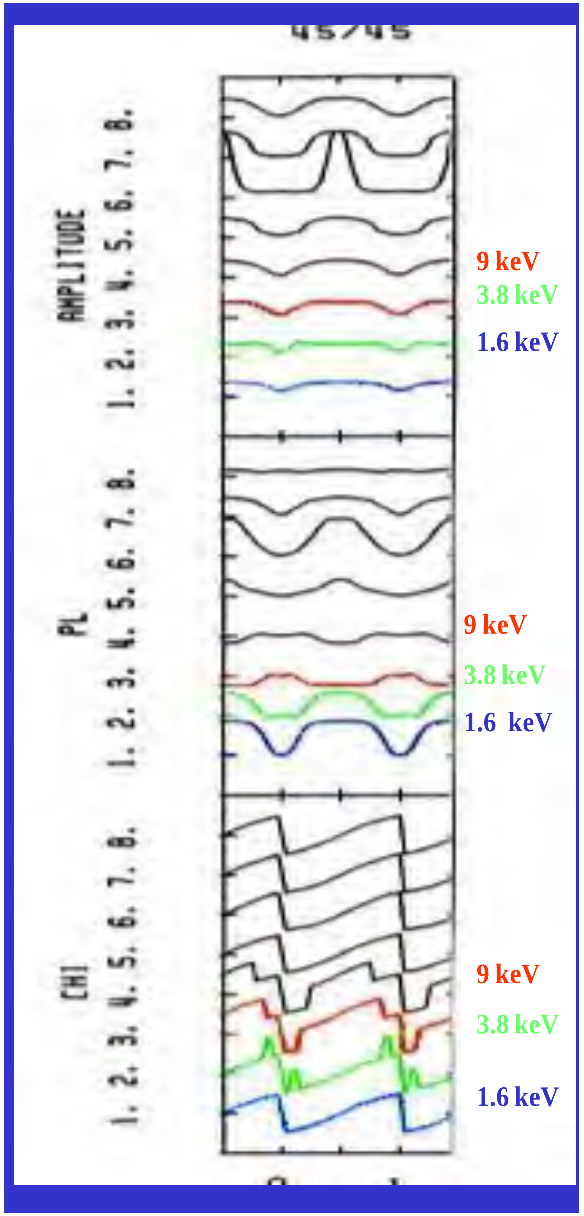
From the swing of the polarisation angle:

- Orientation of the rotation axis
- Inclination of the magnetic field
- Geometry of the accretion column: “fan” beam vs “pencil” beam





Meszaros et al. 1988



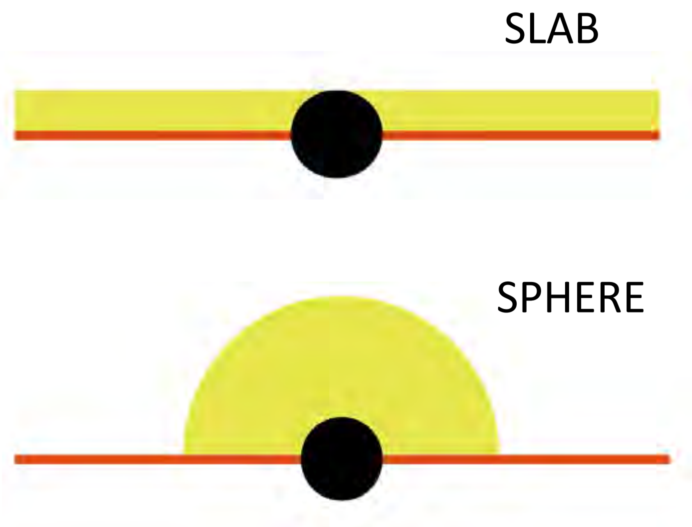
Constraining components of X-ray emission from AGNs

The geometry of the hot corona of electrons, considered to be responsible for the (non-disc) 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?

The sensitivity of XIPE will allow to detect the polarisation of the corona in a large sample of binaries and AGN.



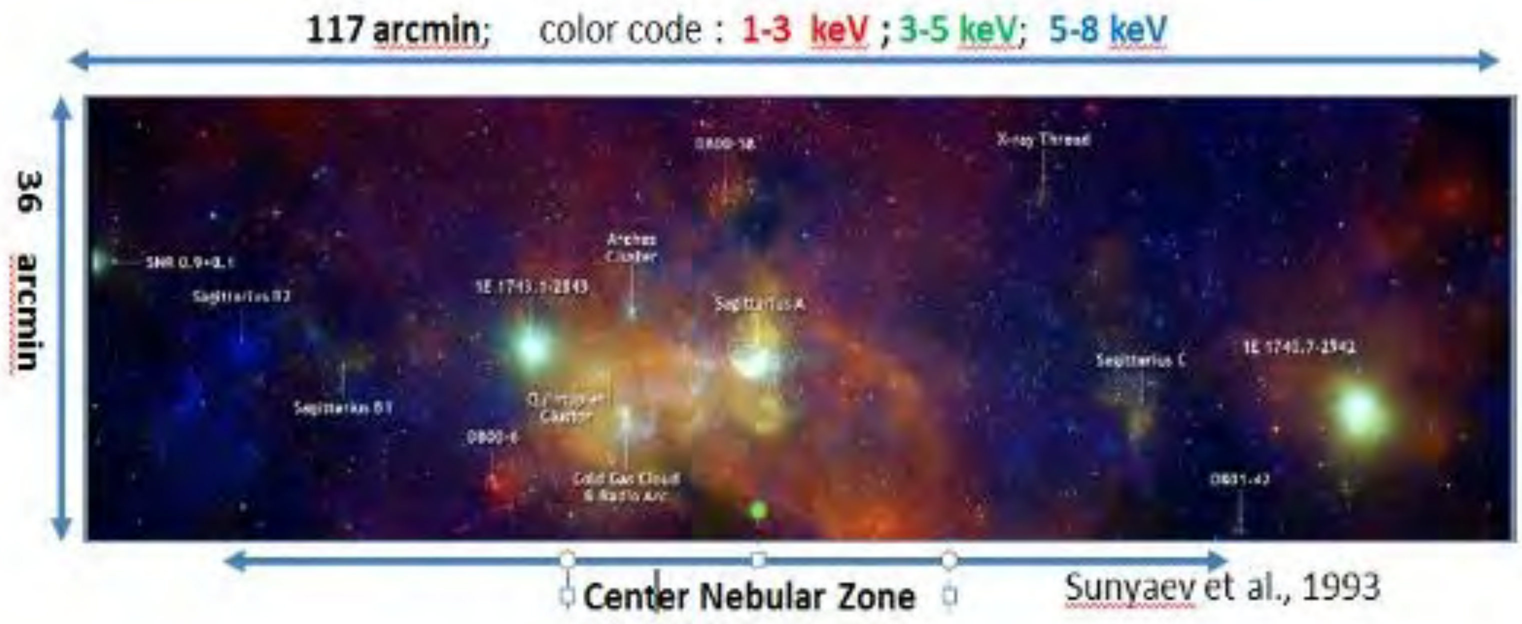
Marin & Tamborra 2014

Even larger (more than 20%) polarisation is expected if the X-ray emission of galactic black hole candidates in hard states is due to jet.

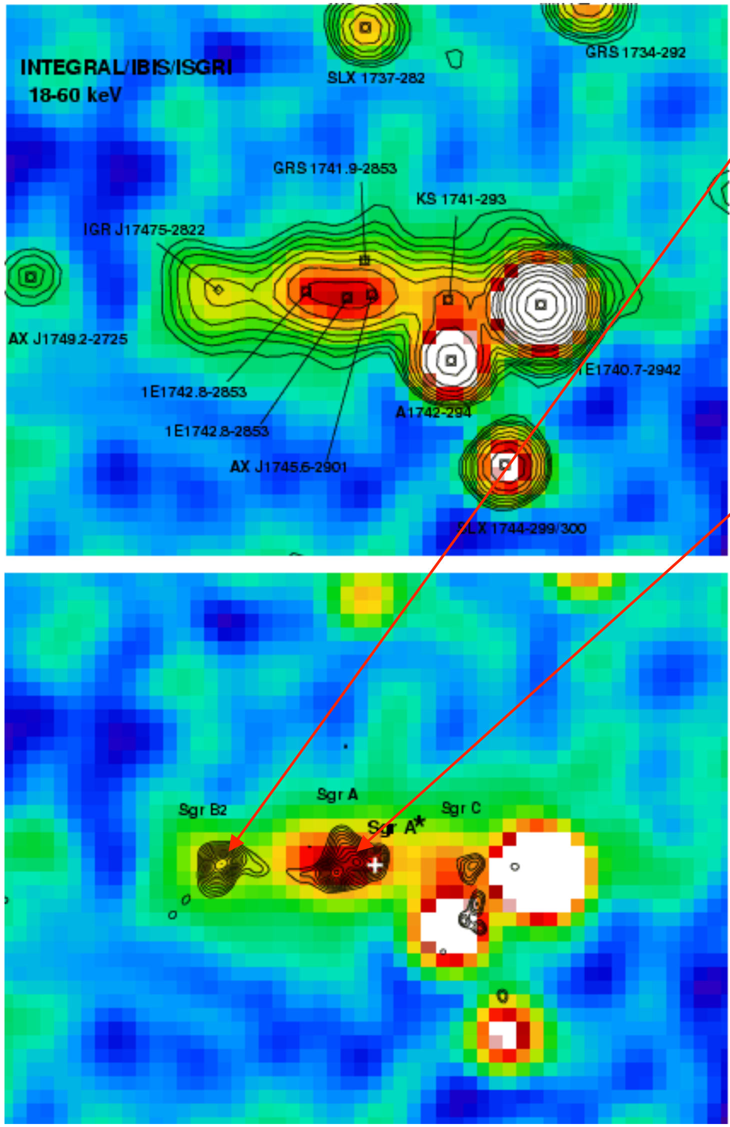
XIPE scientific goals

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!



The strange case of Sgr B2

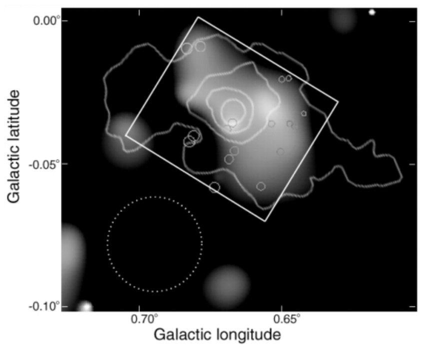


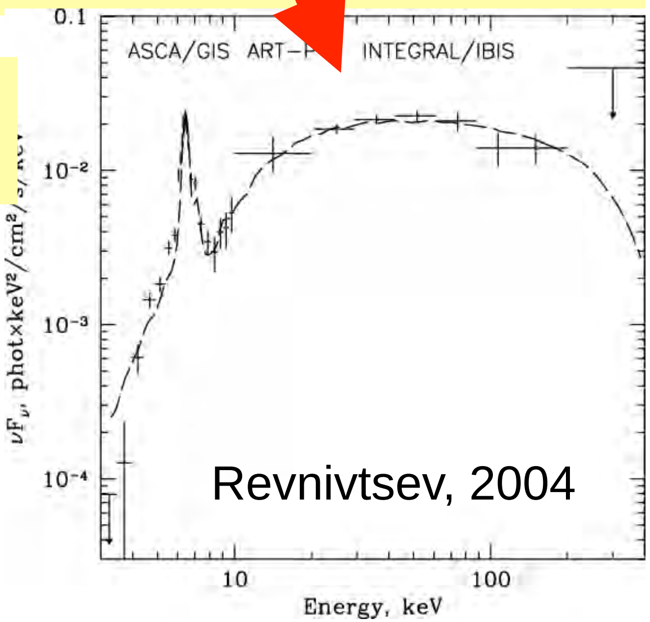
INTEGRAL Image of GC (Revnivtsev 2004)

SgrB2 is a giant molecular cloud at ~100pc projected distance from the Black Hole

The spectrum of SgrB2 is a pure reflection spectrum (Sunyaev et al. 1993)

But no bright enough source is there !!!





The emission from SgrB2 is extended and brighter in the direction of the BH (Murakami 2001). It is also varying in time (Inui et al. 2008).

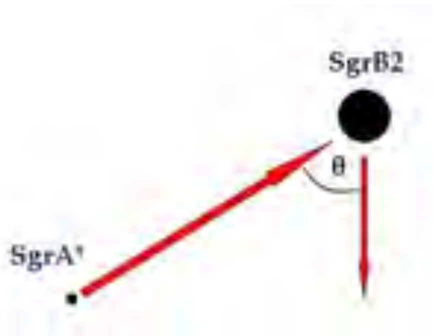
Is SgrB2 echoing past emission from the BH, which was therefore one million time more active (i.e. a LLAGN) ~300 years ago ??? (e.g. Koyama et al. 1996)

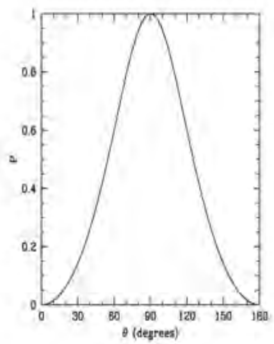
XIPE scientific goals

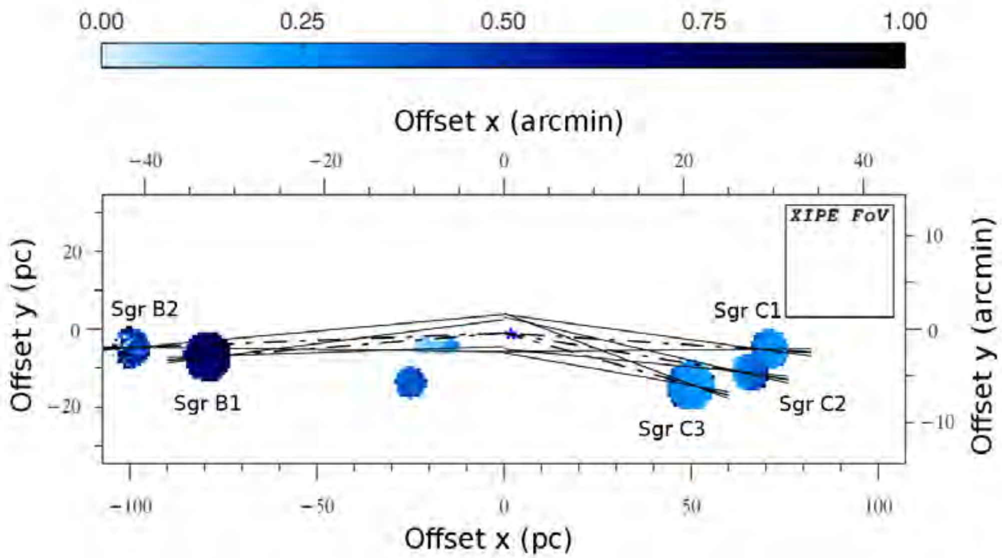
Polarization by scattering from Sgr B complex, Sgr C complex

- 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







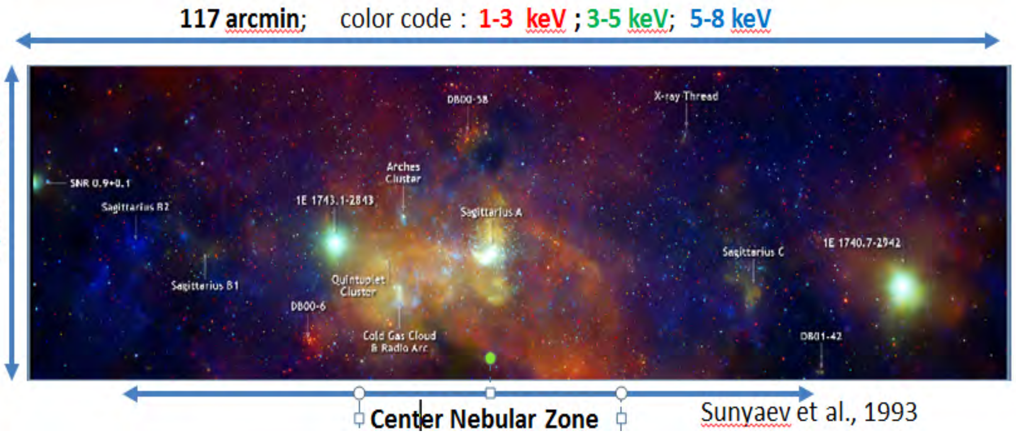
A unique contributions from Polarimetry

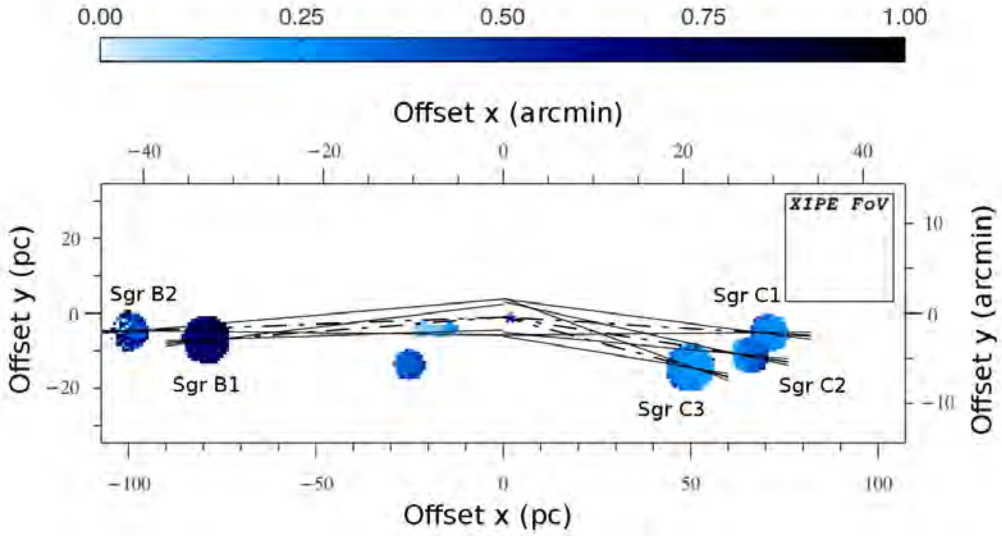
Cold molecular clouds around Sgr A* show neutral iron line and a Compton bump → Reflection from an external source!?!

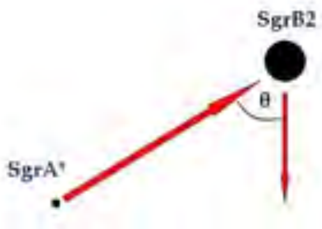
No bright source is there. Are they reflecting X-rays from Sgr A* when it was 10^6 times brighter?

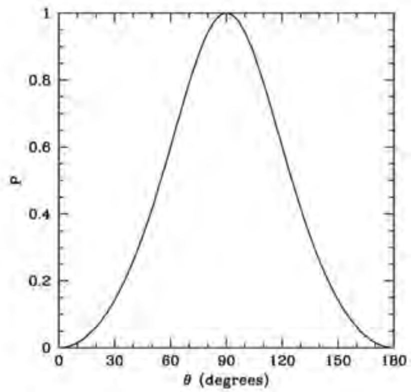
Polarization by scattering from Sgr B complex, Sgr C complex

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









This is the favorite approach but not the only one

F. Yusef-Zadeh1, J.W. Hewitt2, M. Wardle3, V. Tatischeff4, D. A. Roberts1, W. Cotton5, H. Uchiyama6, M. Nobukawa6, T. G. Tsuru6, C. Heinke7 & M. Royster; "Interacting Cosmic Rays with Molecular Clouds: A Bremsstrahlung Origin of Diffuse High Energy Emission from the Inner 2◦×1◦ of the Galactic Center" ApJ 762, article id. 33, 22 pp. (2013)

"We show that the emission detected by Fermi is primarily due to non thermal bremsstrahlung produced by the population of synchrotron emitting electrons in the GeV energy range interacting with neutral gas. The extrapolation of the electron population measured from radio data to low and high energies can also explain the origin of FeI 6.4 keV line and diffuse TeV emission, as observed with Suzaku, XMM-Newton, Chandra and the H.E.S.S. observatories."

The inferences of both models are of the highest interest both for Astrophysics and Cosmic Ray Physics

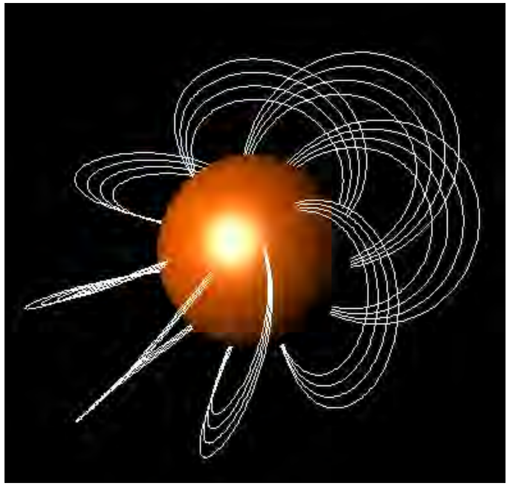
The mesurement of XIPE can disclaim or confirm with extreme robustness the hypothesis of reflection of a past flare of the SMBH.

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

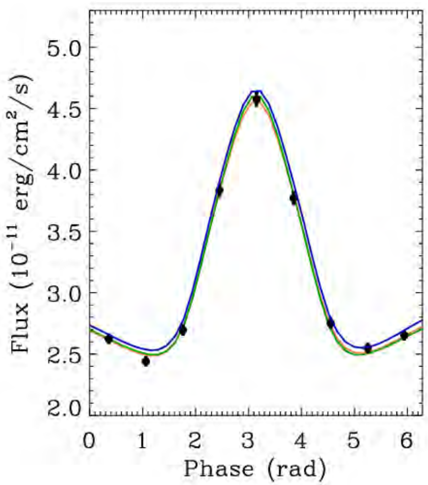
It heats the star crust and explains why the X-ray luminosity largely exceeds the spin down energy loss.

QED foresees vacuum birefringence, an effect predicted 80 years ago, expected in such a strong magnetic field and never detected yet.

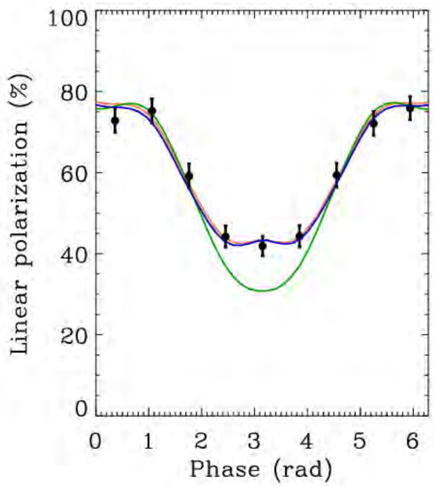
A twisted magnetic field.



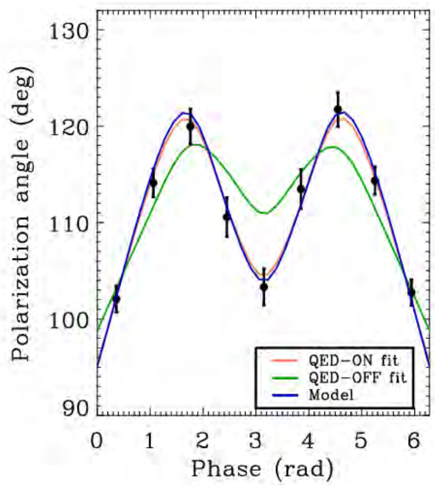
Light curve



Polarisation degree



Polarisation angle



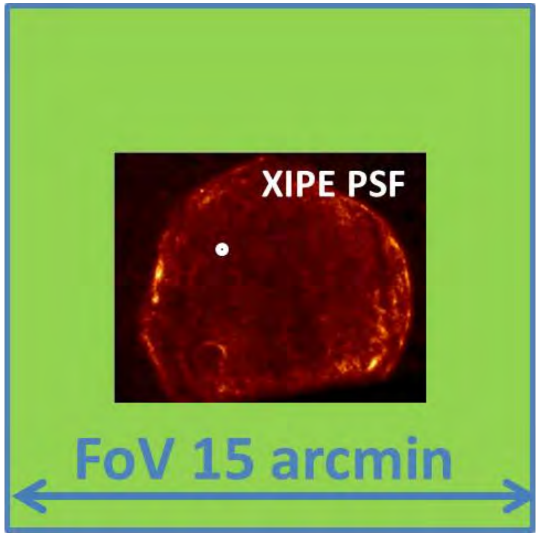
Such an effect is **only** visible in the phase dependent polarization degree and angle.

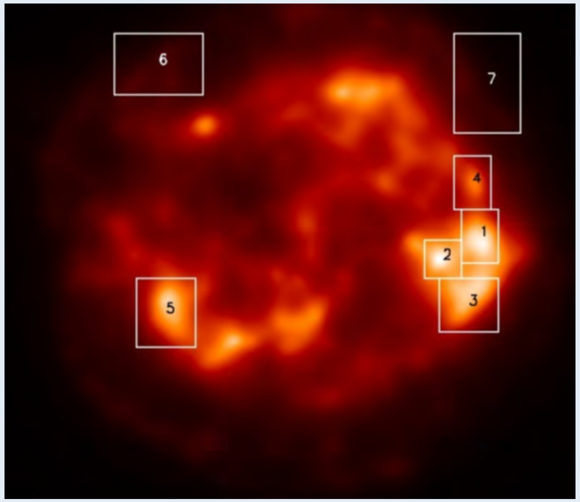
Observation of Supernova Remnants

Map of the magnetic field

Spectral imaging allows to separate the thermalised plasma from the regions where the shocks accelerate the particles.

What is the orientation of the magnetic field? How ordered is it? The spectrum cannot say.





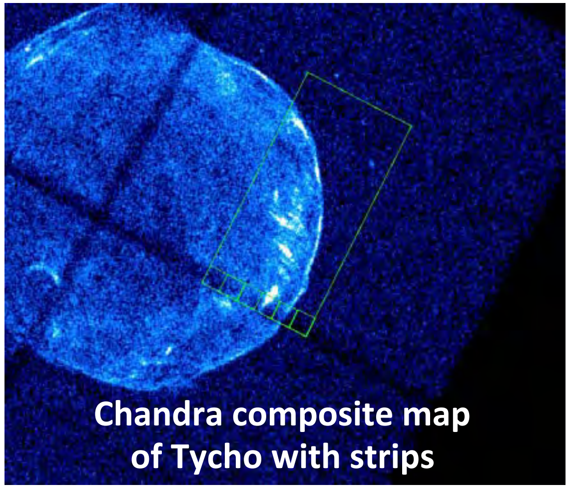
4-6 keV image of Cas A blurred with the PSF of XIPE

Region	MDP (%)	σ_{degree} (%)	σ_{angle} (deg)
		if P=11%	
1	3.7	±1.2	±3.2
2	4.3	±1.3	±3.7
3	3.2	±1.0	±2.8
4	4.6	±1.4	±4.1
5	3.0	±0.9	±2.6
6	5.3	±1.7	±4.5
7	5.4	±1.7	±4.9

2 Ms observation with XIPE

Acceleration phenomena: Tycho stripes

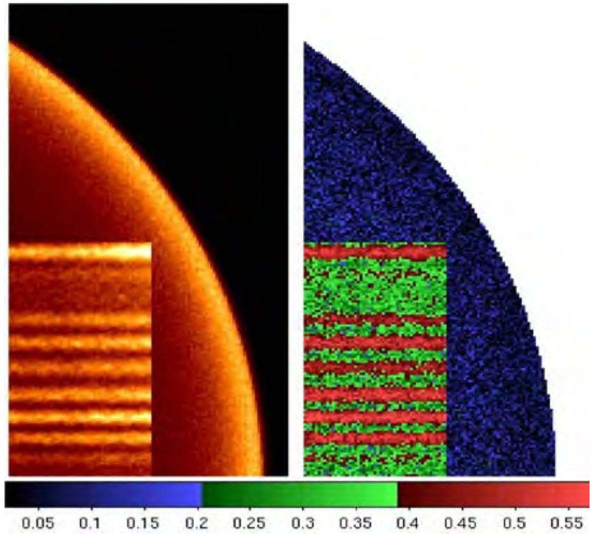
Observation of Supernova Remnants (Question Q6)



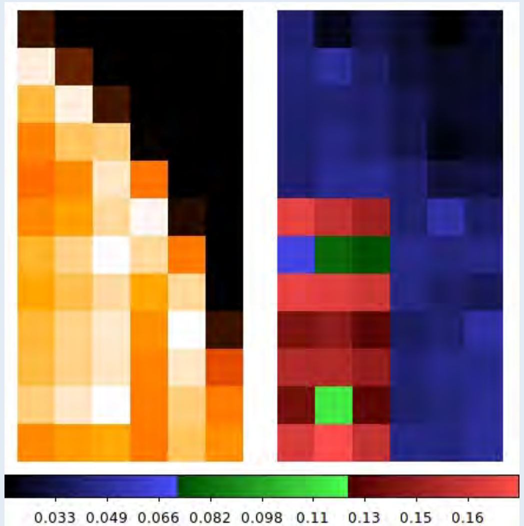
Chandra composite map of Tycho with strips

Polarisation is needed to reveal the zones of predicted ordered magnetic field.

(Bykov et al. 2011)



Intensity (left) and polarisation map (right) at **Chandra** resolution



The same at **XIPE** resolution

Image of individual stripes is lost, but polarization survives (≈15%).

Constraining black hole spin with XIPE

An overdetermined problem: let us increase the confusion

So far, three methods have been used to measure the BH spin in XRBs:
1. Relativistic reflection (still debated, required accurate spectral decomposition);
2. Continuum fitting (required knowledge of the mass, distance and inclination);
3. QPOs (three QPOs needed for completely determining the parameters, so far applied only to two sources).

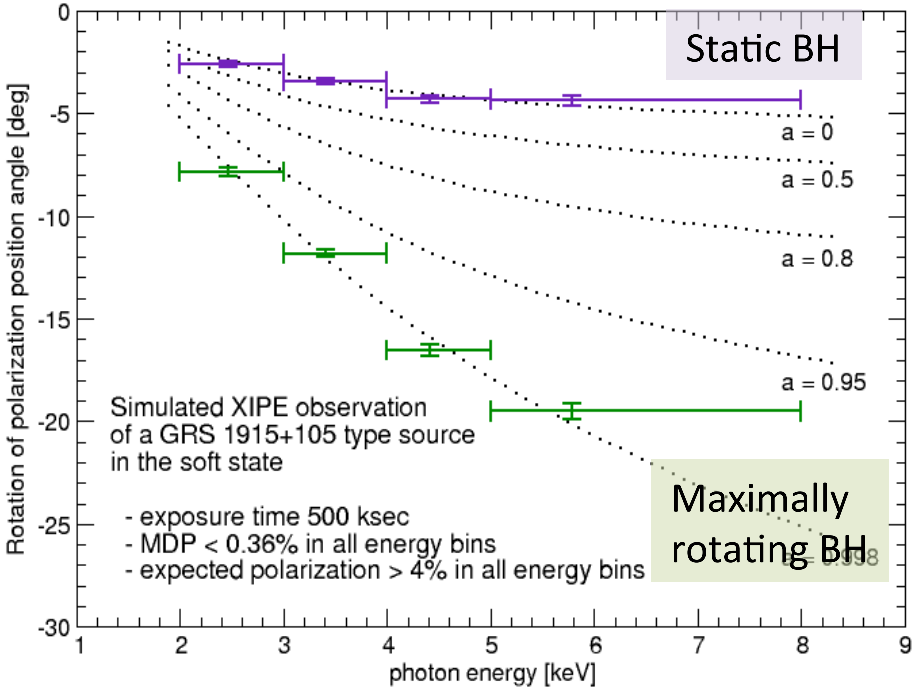
Problem: for a number of XRBs, the methods do not agree!

For J1655-40:	QPO:	$a = J/J_{max} = 0.290 \pm 0.003$
	Continuum:	$a = J/J_{max} = 0.7 \pm 0.1$
	Iron line:	$a = J/J_{max} > 0.95$

A fourth method (to increase the mess...!?)
Energy dependent rotation of the X-ray polarisation plane

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

GRO J1655-40, GX 339-4, Cyg X-1, GRS 1915+105, XTE J1550-564, …



XIPE scientific goals

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

Variation of polarization angle and degree on radiation from sources in the background of large region 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 ingredient.

Very challenging measurements, but potentially very rewarding!!

Many sources in each class available for XIPE

Answer to Question II, Q4 & Q5

100 – 150 quoted in the proposal:

- 500 days of net exposure time in 3 years;
- average observing time of 3 days;
- re-visiting for some of those.

What number for each class?

Target Class	T_{tot} (days)	T_{obs}/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**

From catalogues: Liu et al. 2006, 2007 for X-ray binaries; and XMM slew survey 1.6 for AGNs.

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.

We foresee an interesting overlap of some topics for X-ray Polarimetry and VHE Astronomy, but the ideas are very preliminary.