X-ray Polarimetry

by
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IAPS Rome –INAF

Future of Polarimetry

COSTA Action MP1104
Brussels 21 - 23 September 2015

Measurements in 53 years of 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)

The status

A vast theoretical literature, started from the very beginning of X-ry Astronomy, predicts a wealth of results from Polarimetry

In 43 years only one positive detection of X-ray Polarization: the Crab (Novick et al. 1972, Weisskopf et al.1976, Weisskopf et al. 1978) $P = 19.2 \pm 1.0$ %; $\theta = 156.4^{o} \pm 1.4^{o}$

Plus a fistful of upper limits, most of marginal significance

A window not yet disclosed in 2011

THE TECHNIQUES ARE THE LIMIT!

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

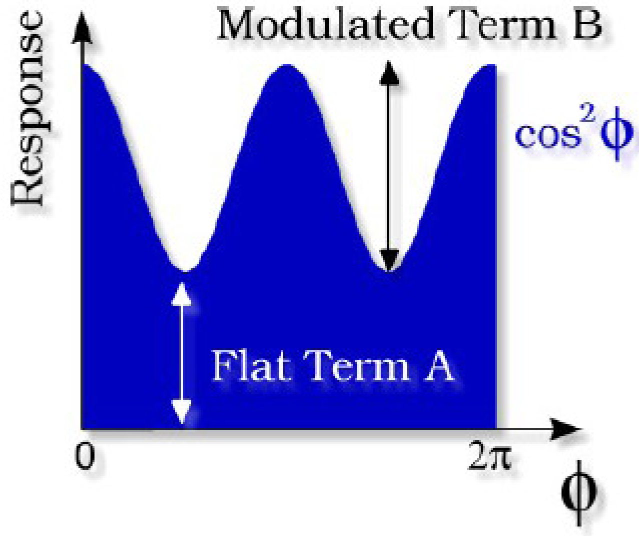
The window is still undisclosed in 2015

But New technical solutions are now ready

The attitude of Agencies is cleary changed

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

Stokes Parameters

$$I = A + \frac{B}{2}$$

$$Q = \frac{A}{2}\cos(2\varphi_0)$$

$$U = \frac{A}{2}\sin(2\varphi_0)$$

The measurement of circular polarization is so far unfeasible

X-Ray Astronomers rarely use StokesParameters. The formalism is correctly assessed in the chapter 2 (X-Ray Polarimetry) of the book resulting from this COST Action by F.Muleri and G.Matt.

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

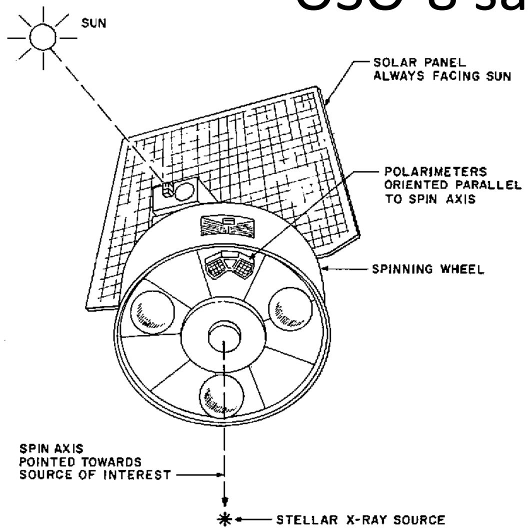
If background is negligible: $$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N_{ph}}}$$

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

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.

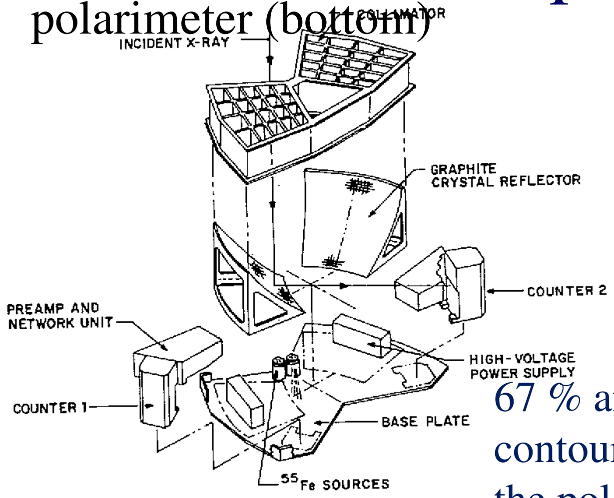
Mosaic spread of 0.8° Band-pass = 40 eV (2.62 keV)
Bragg angles allowed between 40° and 50°
Overall band-pass 400 eV (2.62 keV) $\mu = 0.94$
Projected crystal Area = 2 x 140 cm^2 ; Detector area = 2 x 5 cm^2 ;
FOV= 2° B = 2 x 3 10^{-2} counts/s in each order (pulse shape analysis + anti-coincidence)

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

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

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

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



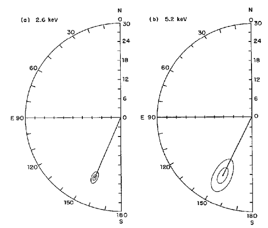
67 % and 99 % confidence contour. The radial scale is the polarization in percent

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	53.13 ± 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.



.—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.

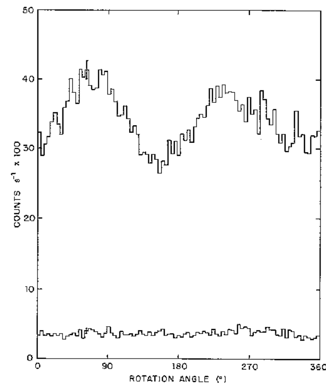
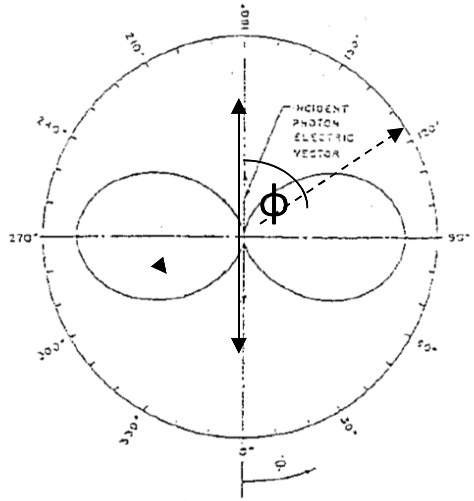
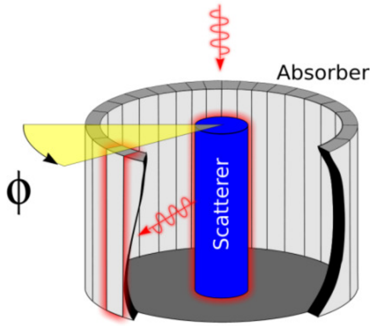


FIG. 2.—Average modulation curves obtained with both detectors at 2.6 keV during (*upper curve*) observations of the Crab Nebula and during (*lower curve*) observations of the Earth-occulted instrumental background.

At higher energies (>10 keV) 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.

But this is another story

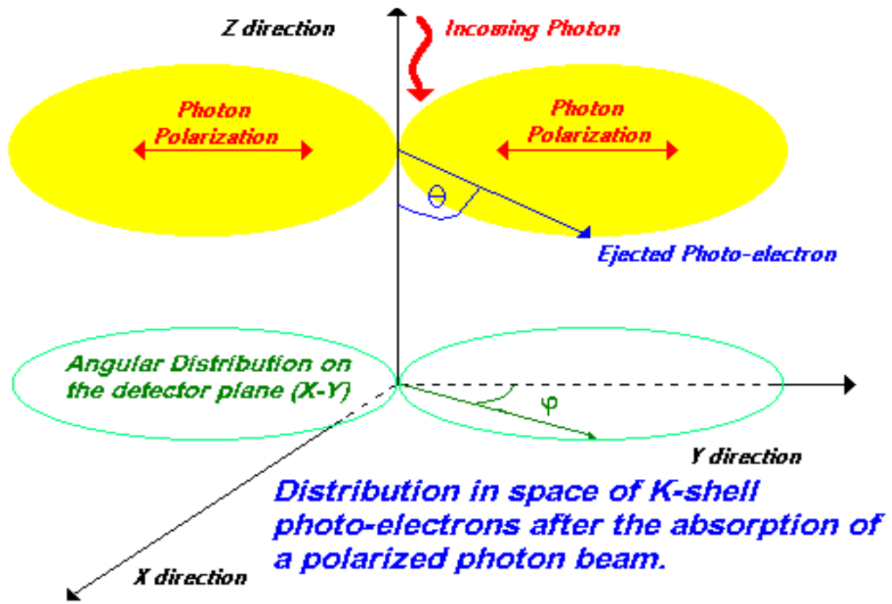
At 90° of angle of scattering (θ) the modulation factor is 100 % since there are not photons diffused along the electric field.

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. **A 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 in the focus of X-ray telescopes.

Modern polarimeters dedicated to X-ray Astronomy exploit the photoelectric effect resolving most of the problems connected with Thomson/Bragg polarimeter.



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

Costa, Bellazzini
Nature, 2001

$\beta = v/c$

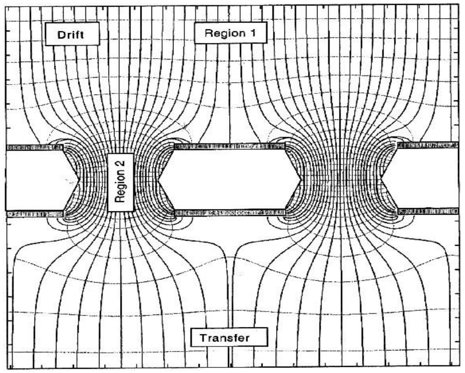
$$\frac{\partial\sigma}{\partial\Omega} = r_o^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$

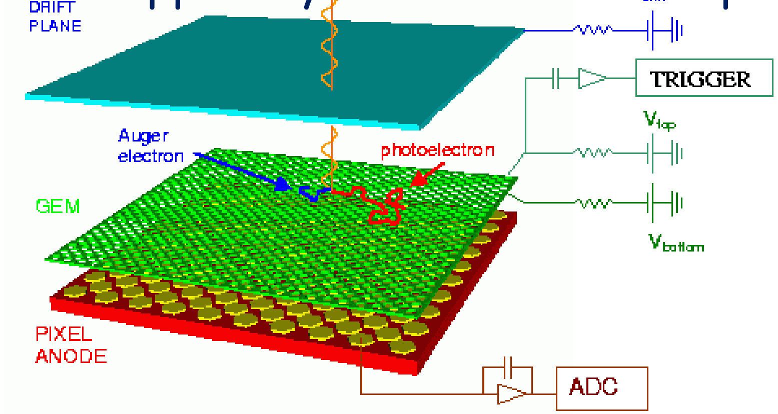
Heitler W.,The Quantum Theory of Radiation

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.

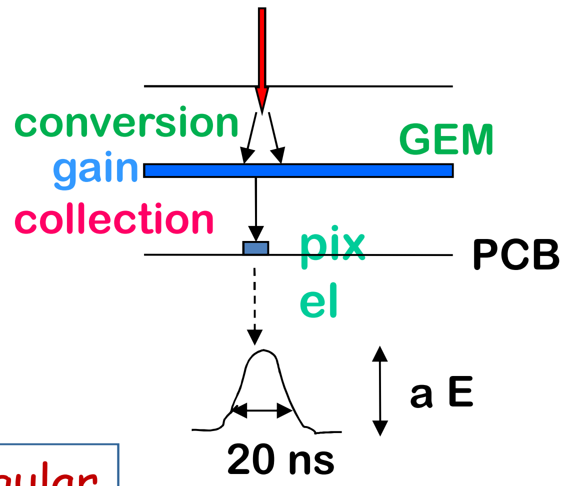
A photon cross a Beryllium window and it is absorbed in the gas gap, the photoelectron produces a track. The track drifts toward the multiplication stage that is the GEM (Gas Electron Multiplier) which is a kapton foil metallized on both side and perforated by microscopic holes (30 um diameter, 50 um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

GEM electric field





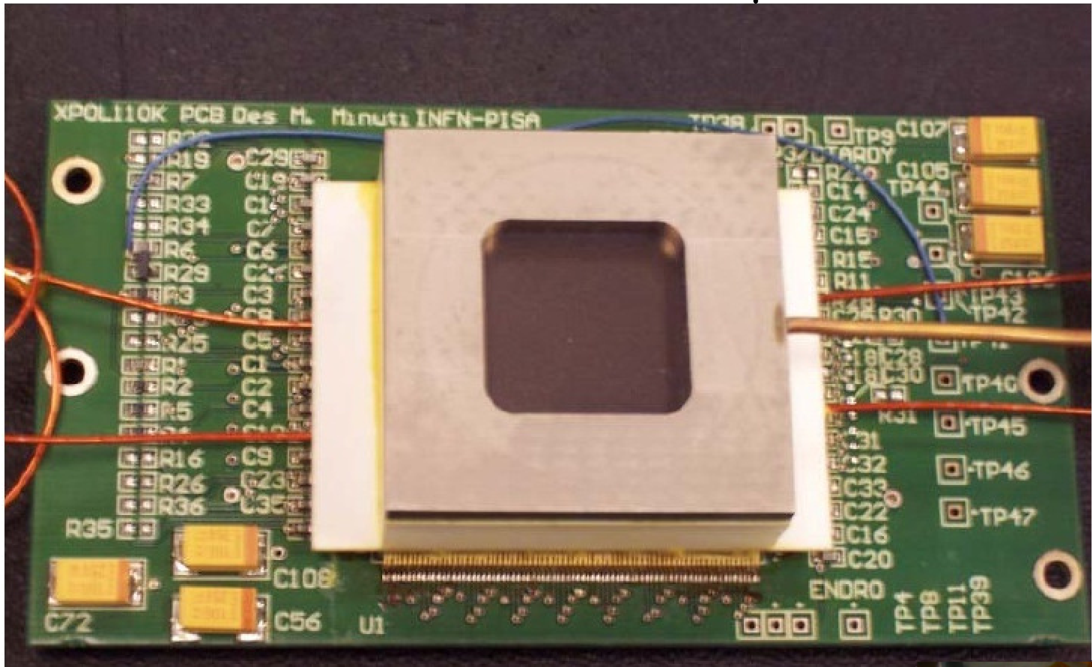
Costa et al., 2001, Bellazzini et al.2006, 2007

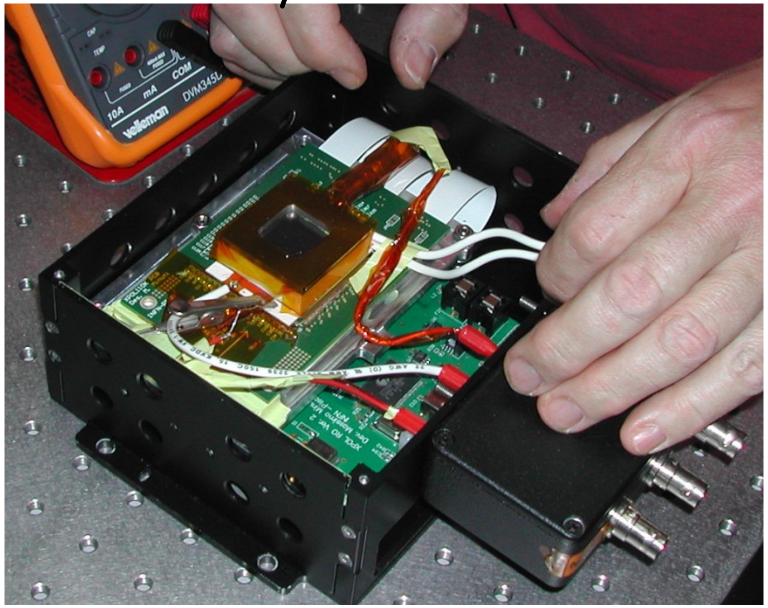


Polarization information is derived from the angular distribution of the emission direction of the tracks produced by the photoelectrons. The detector has a very good imaging capability.

The real implementation of a working GPD prototype

A sealed polarimeter has been built by the INFN-Pisa team (R.Bellazzini) with the contribution of INAF-IAPS team, since more than 10 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.



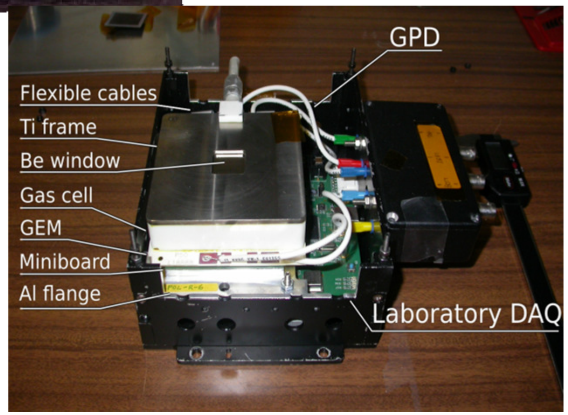


The GPDs under test was filled with
1) 20-80 He-DME 1 bar, 1cm.

2) pure DME 0.8 bar, 1 cm.

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

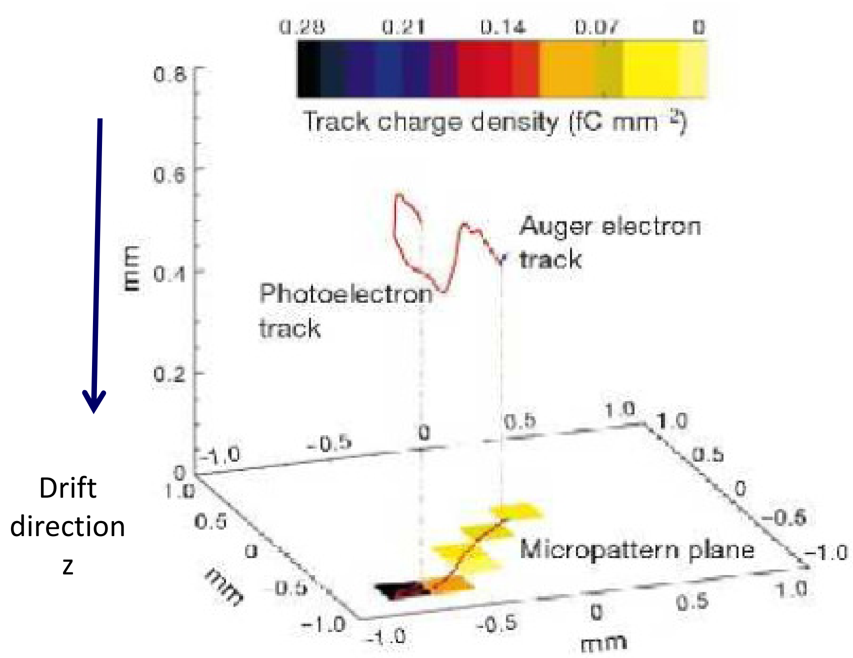
60 μm/$\sqrt{}$cm diffusion

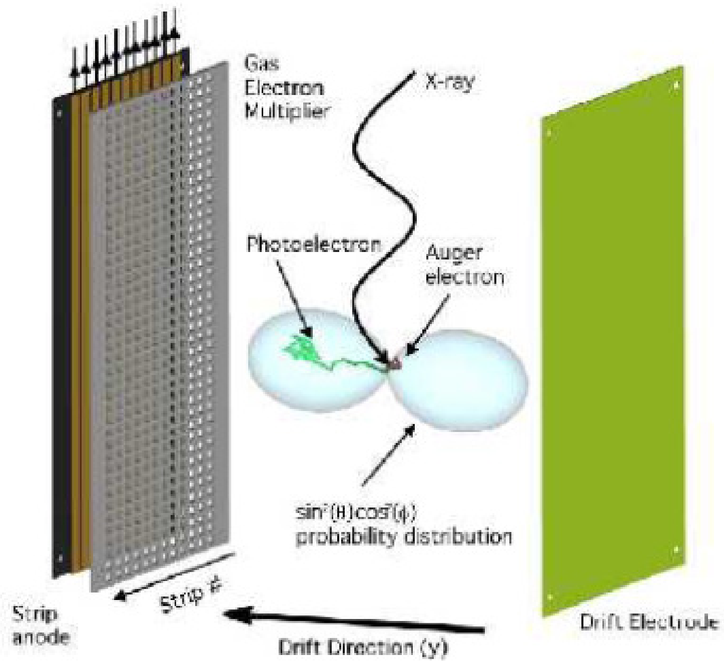


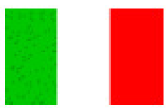
New prototypes with a btter control of electric Field

Two approaches

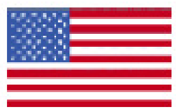
Two different instrumental approaches:







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.

The first attempts

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 ambitious project of ESA with a telescope of 6m^2 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+** , without a polarimeter, was selected as ESA L2 mission.

POLARIX was one ofthe two missions selected as italian small missions, but the whole program was later dropped.

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**.
- 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 phase A 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 phase A 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.

Synergy with observations in other wavelengths may be very supportive. In particular for some topics (e.g. blazars, pulsars) the comparison with polarimetry in other wavelength may be very meaningful.

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

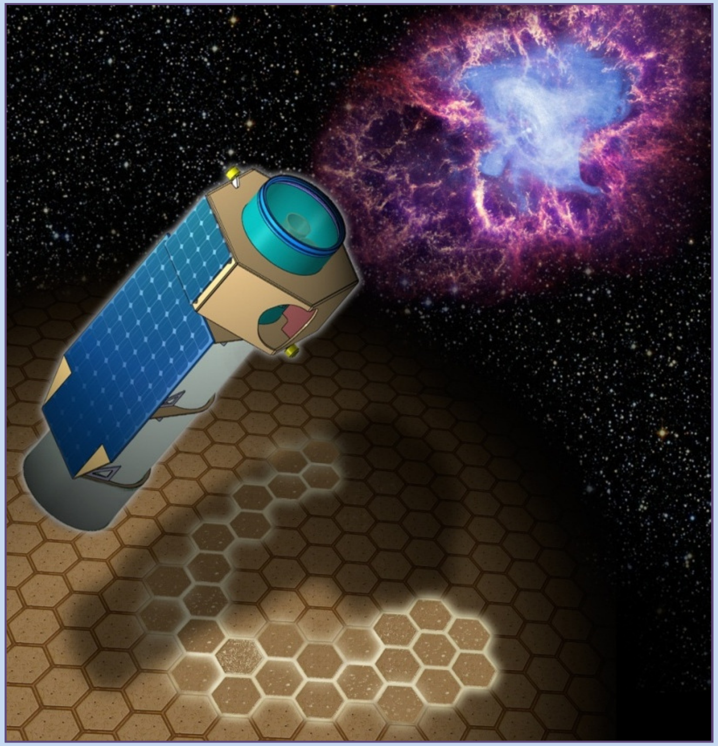
Paolo Soffitta, Ronaldo Bellazzini, Enrico Bozzo, Vadim Burwitz, Alberto J. Castro-Tirado, Enrico Costa, Thierry J-L. Courvoisier, Hua Feng, Szymon Gburek, René Goosmann, Vladimir Karas, Giorgio Matt, Fabio Muleri, Kirpal Nandra, Mark Pearce, Juri Poutanen, Victor Reglero, Maria Dolores Sabau, Andrea Santangelo, Gianpiero Tagliaferri, Christoph Tenzer, Martin C. Weisskopf, Silvia Zane

XIPE Science Team

Agudo, Ivan; Aloisio, Roberto; Amato, Elena; Antonelli, Angelo; Atteia, Jean-Luc; Axelsson, Magnus; Bandiera, Rino; Barcons, Xavier; Bianchi, Stefano; Blasi, Pasquale; Boër, Michel; Bozzo, Enrico; Braga, Joao; Bucciantini, Niccolo'; Burderi, Luciano; Bykov, Andrey; Campana, Sergio; Campana, Riccardo; Cappi, Massimo; Cardillo, Martina; Casella, Piergiorgio; Castro-Tirado, Alberto J.; Chen, Yang; Churazov, Eugene; Connell, Paul; Courvoisier, Thierry; Covino, Stefano; Cui, Wei; Cusumano, Giancarlo; Dadina, Mauro; De Rosa, Alessandra; Del Zanna, Luca; Di Salvo, Tiziana; Donnarumma, Immacolata; Dovciak, Michal; Elsner, Ronald; Eyles, Chris; Fabiani, Sergio; Fan, Yizhong; Feng, Hua; Ghisellini, Gabriele; Goosmann, René W.; Gou, Lijun; Grandi, Paola; Grosso, Nicolas; Hernanz, Margarita; Ho, Luis; Hu, Jian; Huovelin, Juhani; Iaria, Rosario; Jackson, Miranda; Ji, Li; Jorstad, Svetlana; Kaaret, Philip; Karas, Vladimir; Lai, Dong; Larsson, Josefin; Li, Li-Xin; Li, Tipei; Malzac, Julien; Marin, Frédéric; Marscher, Alan; Massaro, Francesco; Matt, Giorgio; Mineo, Teresa; Miniutti, Giovanni; Morlino, Giovanni; Mundell, Carole; Nandra, Kirpal; O'Dell, Steve; Olmi, Barbara; Pacciani, Luigi; Paul, Biswajit; Perna, Rosalba; Petrucci, Pierre-Olivier; Pili, Antonio Graziano; Porquet, Delphine; Poutanen, Juri; Ramsey, Brian; Razzano, Massimiliano; Rea, Nanda; Reglero, Victor; Rosswog, Stephan; Rozanska, Agata; Ryde, Felix; Sabau, Maria Dolores; Salvati, Marco; Silver, Eric; Sunyaev, Rashid; Tamborra, Francesco; Tavecchio, Fabrizio; Taverna, Roberto; Tong, Hao; Turolla, Roberto; Vink, Jacco; Wang, Chen; Weisskopf, Martin C.; Wu, Kinwah; Wu, Xuefeng; Xu, Renxin; Yu, Wenfei; Yuan, Feng; Zane, Silvia; Zdziarski, Andrzej A.; Zhang, Shuangnan; Zhang, Shu.

XIPE Instrument Team

Baldini, Luca; Basso, Stefano; Bellazzini, Ronaldo; Bozzo, Enrico; Brez, Alessandro; Burwitz, Vadim; Costa, Enrico; Cui, Wei; de Ruvo, Luca; Del Monte, Ettore; Di Cosimo, Sergio; Di Persio, Giuseppe; Dias, Teresa H. V. T.; Escada, Jose; Evangelista, Yuri; Eyles, Chris; Feng, Hua; Gburek, Szymon; Kiss, Mózsi; Korpela, Seppo; Kowaliski, Miroslaw; Kuss, Michael; Latronico, Luca; Li, Hong; Maia, Jorge; Minuti, Massimo; Muleri, Fabio; Nenonen, Seppo; Omodei, Nicola; Pareschi, Giovanni; Pearce, Mark; Pesce-Rollins, Melissa; Pinchera, Michele; Reglero, Victor; Rubini, Alda; Sabau, Maria Dolores; Santangelo, Andrea; Sgrò, Carmelo; Silva, Rui; Soffitta, Paolo; Spandre, Gloria; Spiga, Daniele; Tagliaferri, Gianpiero; Tenzer, Christoph; Wang, Zhanshan; Winter, Berend; Zane, Silvia.



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.

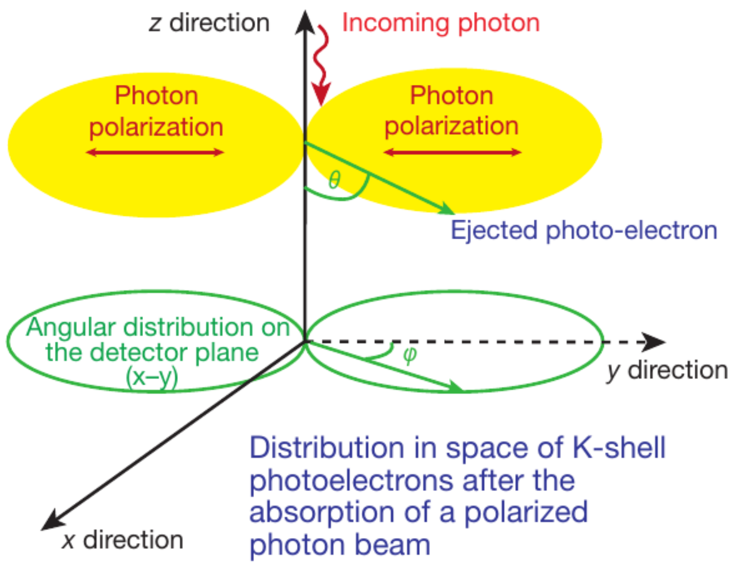
XIPE is going to exploit the complete information contained in X-rays.

The Gas Pixel Detector

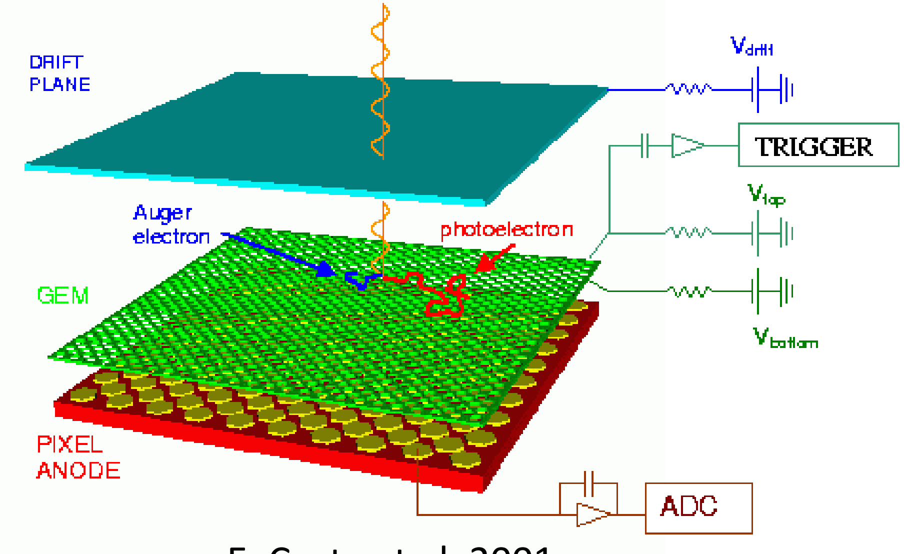
We developed at this aim a polarization-sensitive instrument capable of imaging, timing and spectroscopy

The photoelectric effect

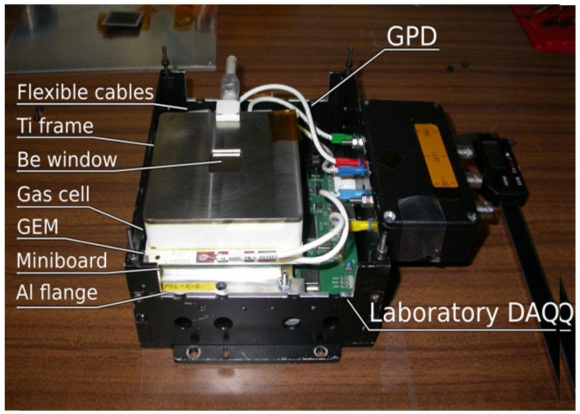
$$\frac{\partial \sigma}{\partial \Omega} = r_0^2 \frac{Z^5}{137^4} \left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$



The Gas Pixel Detector



E. Costa et al. 2001



Why this is now possible

The Gas Pixel Detector

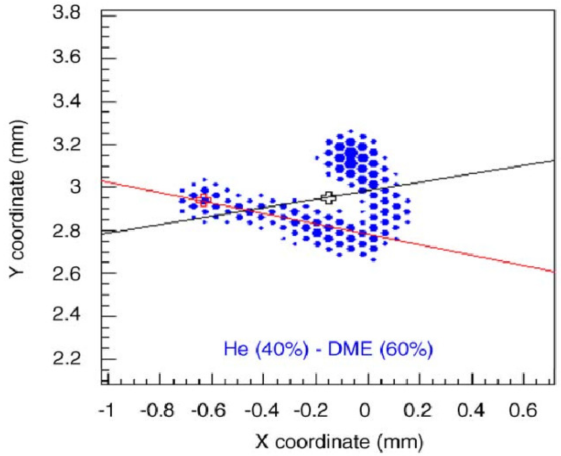
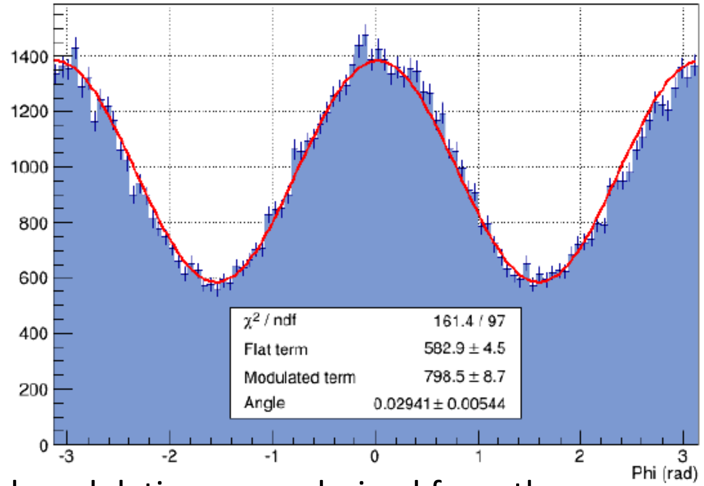
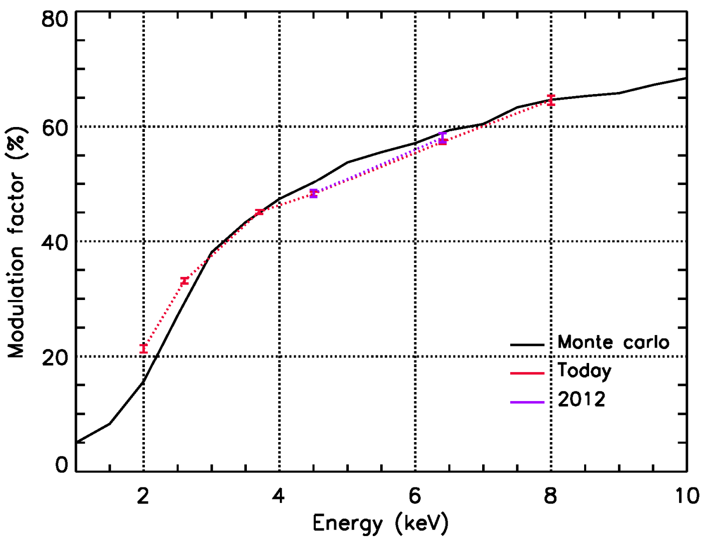


Image of a real photoelectron track. The use of the gas allows to resolve tracks in the X-ray energy band.

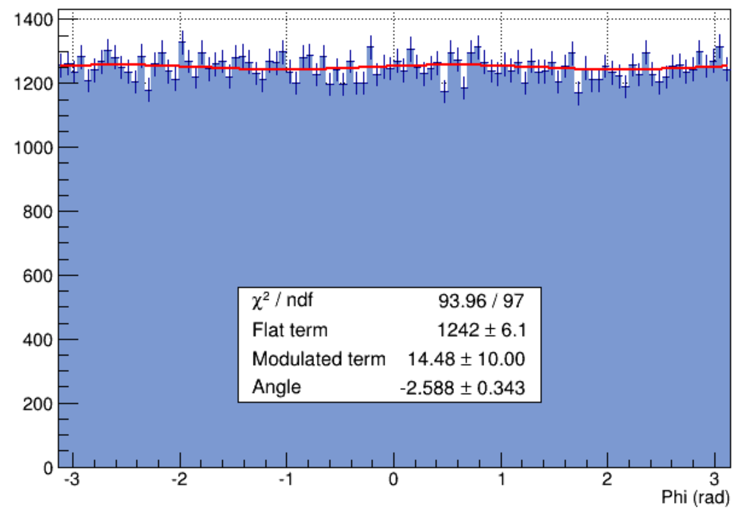


Real modulation curve derived from the measurement of the emission direction of the photoelectron.



Muleri et al. 2008,2010

Modulation factor as a function of energy.

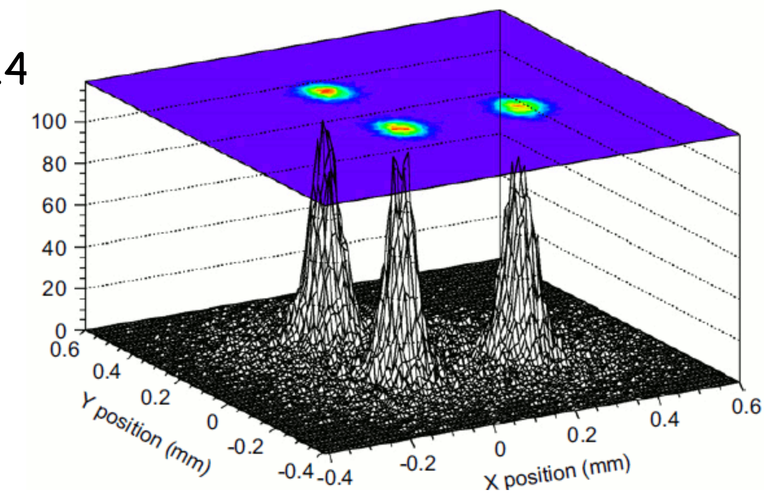


Bellazzini et al. 2012

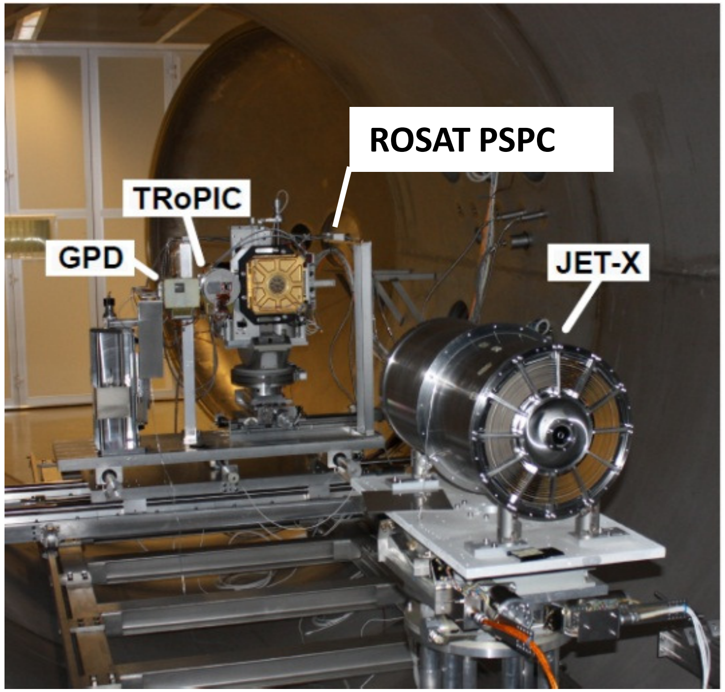
Residual modulation for unpolarised photons.

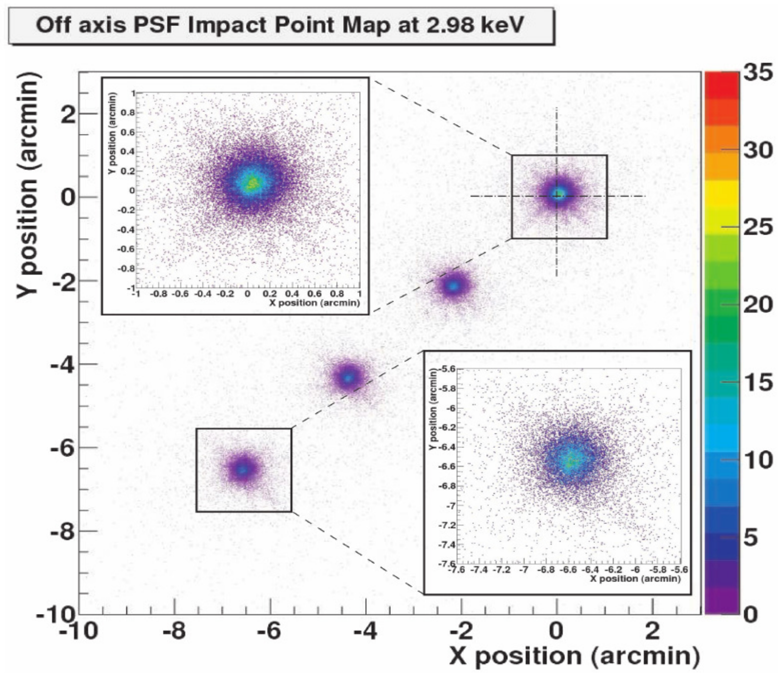
Imaging capabilities of GPD tested at PANTER

STSM acknowledged in the paper by Fabiani et al.2014

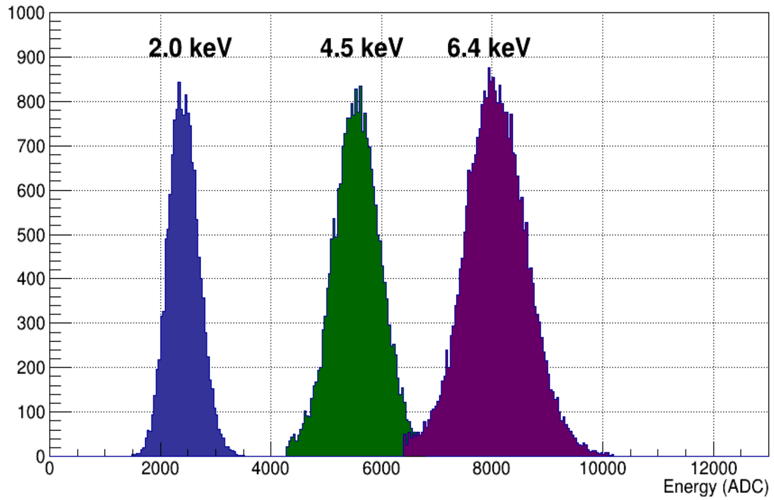


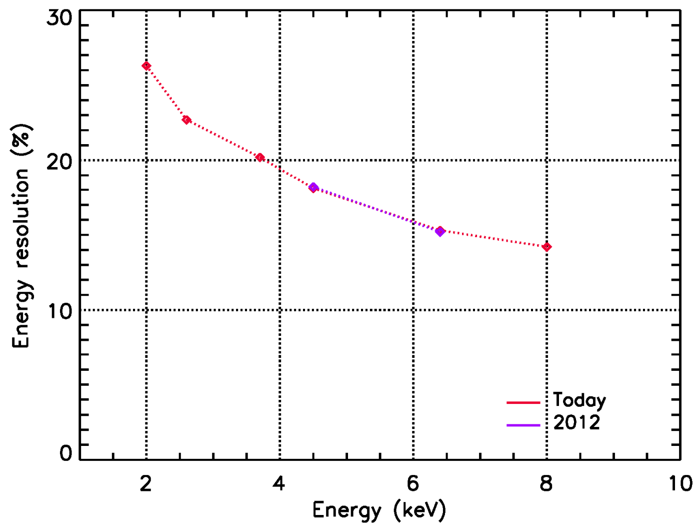
- Good spatial resolution: 90 μm Half Energy Width
- Imaging capabilities on- and off-axis measured at PANTER with a JET-X telescope (Fabiani et al. 2014)
- Angular resolution for XIPE: <26 arcsec



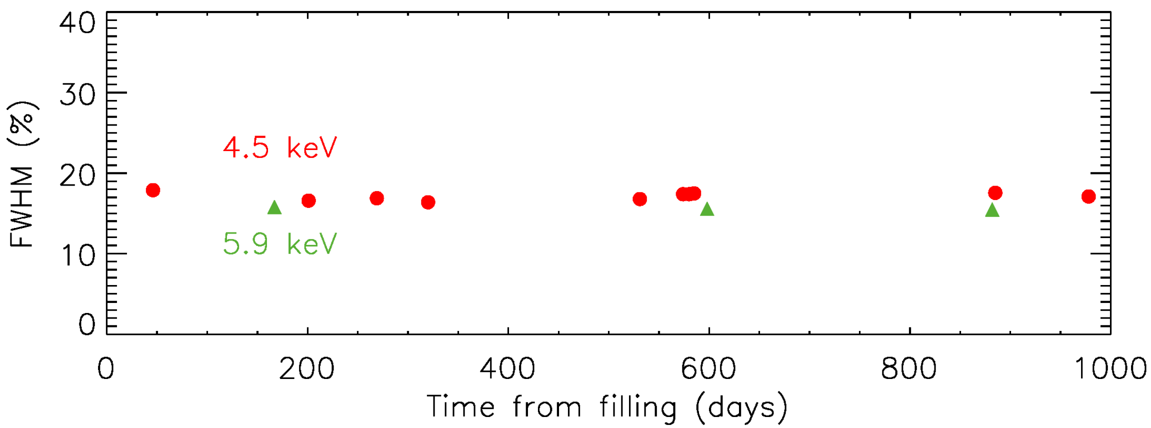


Spectroscopic capabilities





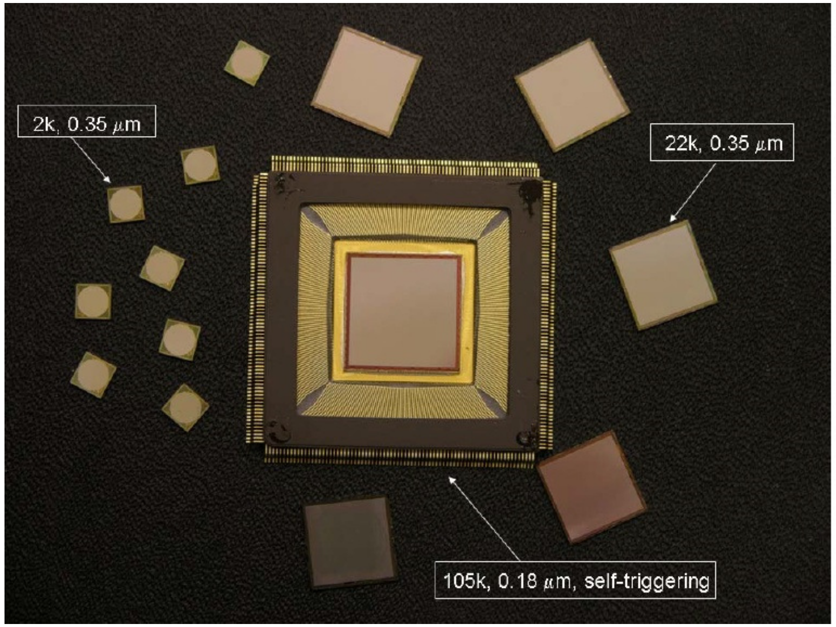
- Adequate spectrometer for continuum emission (16 % at 6 keV, Muleri et al. 2010).
- Stable operation over 3 years

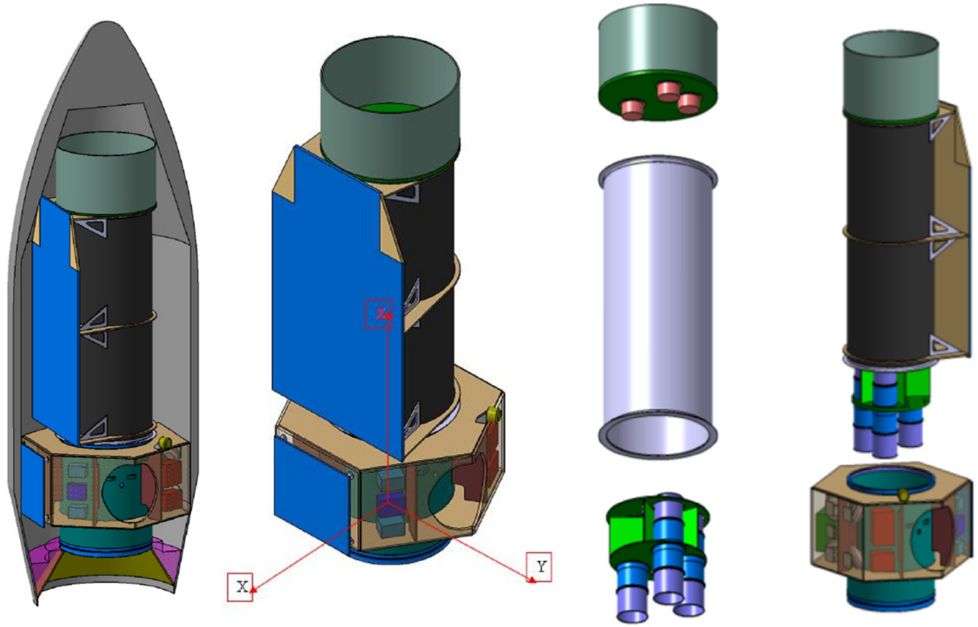


XIPE design guidelines

A light and simple mission

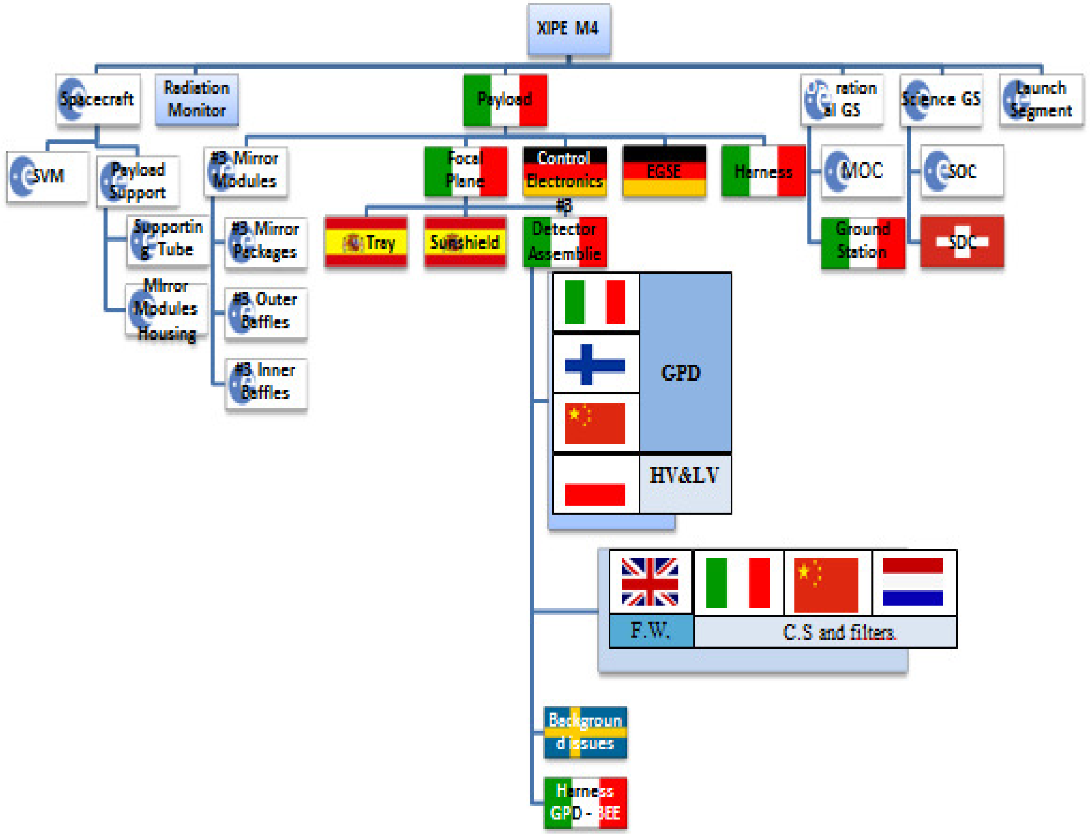
- Three telescopes with 3.5 m (possibly 4m) focal length to fit within the Vega fairing.
  Long heritage: SAX → XMM → Swift → eROSITA → XIPE
- Detectors: conventional proportional counter but with a revolutionary readout.
- Mild mission requirements: 1 mm alignment, 1 arcmin pointing.
- Fixed solar panel. 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

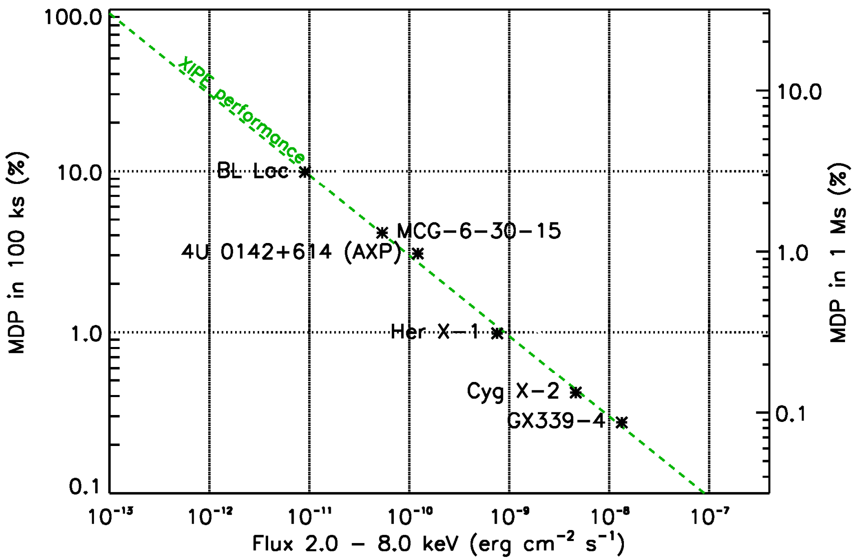
All Europe and more



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.

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.

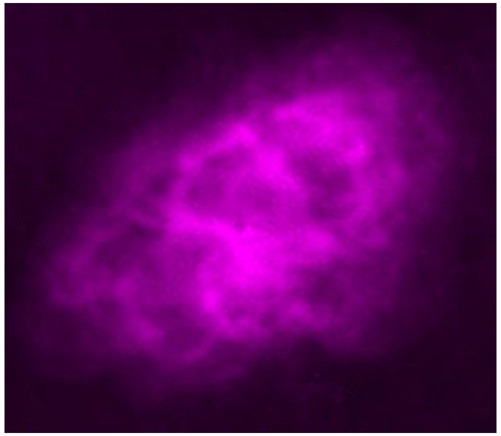
Timing & spectroscopy may provide rather ambiguous and model dependent information.

What XIPE can do:

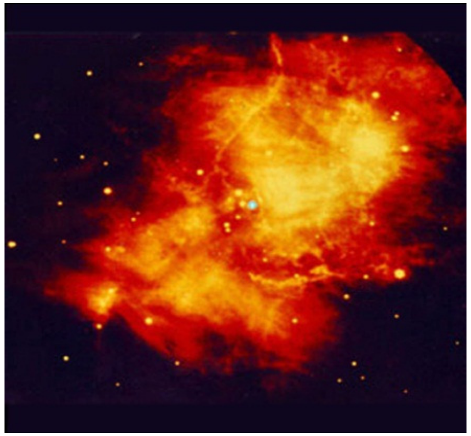
- **Resolved sources**: Emission mechanisms and mapping of the magnetic field: PWNs, SNR and extragalactic jet
- **Unresolved sources**: Geometrical parameter of inner part of compact sources: X-ray pulsars, Coronae in XRB and AGNs.

Acceleration phenomena: The Crab Nebula

X-rays vs other wavelengths: a pictorial explication

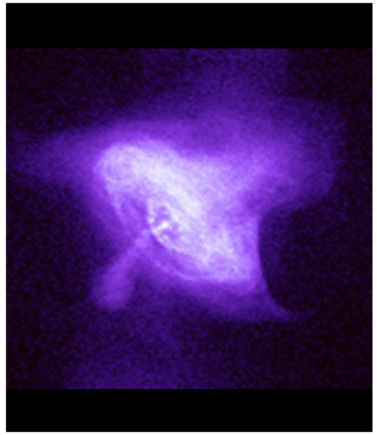


Radio (VLA)

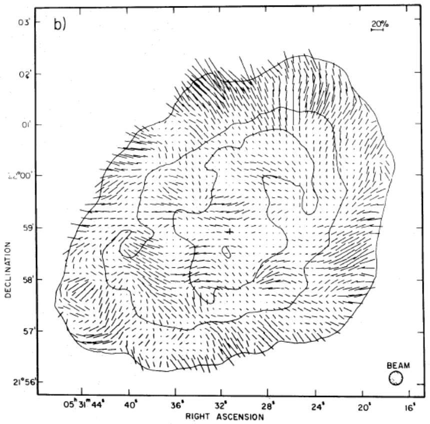


Infrared (Keck)

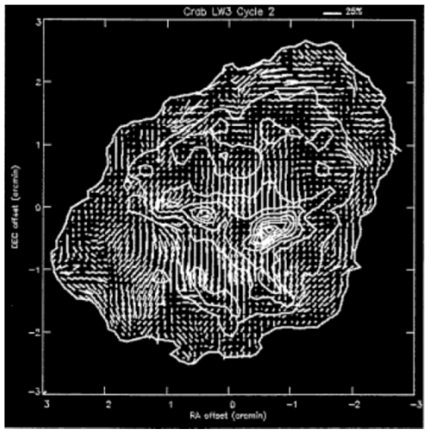
Optical (Palomar)



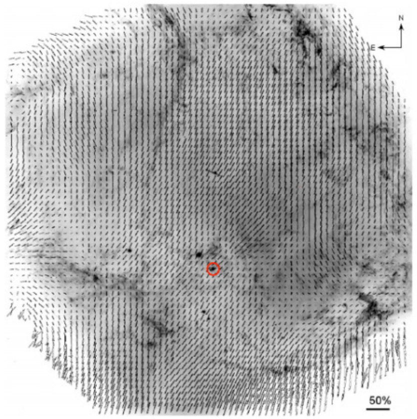
X-rays (Chandra)



Radio polarisation



IR polarisation



Optical polarisation

?

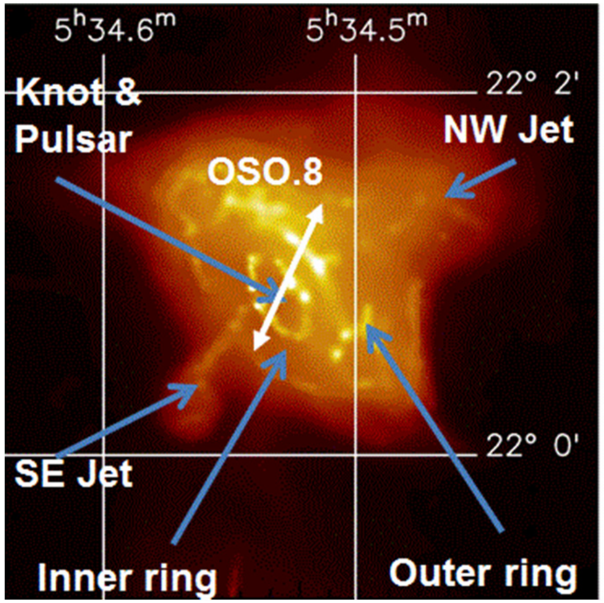
P=19% for the whole nebula (Weisskopf et al. 1978)

X-ray polarisation

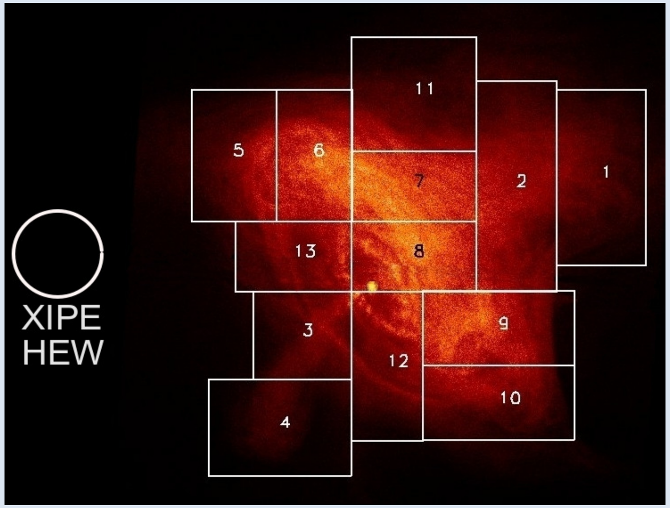
X-rays probe **freshly accelerated** electrons and the site of acceleration.

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.

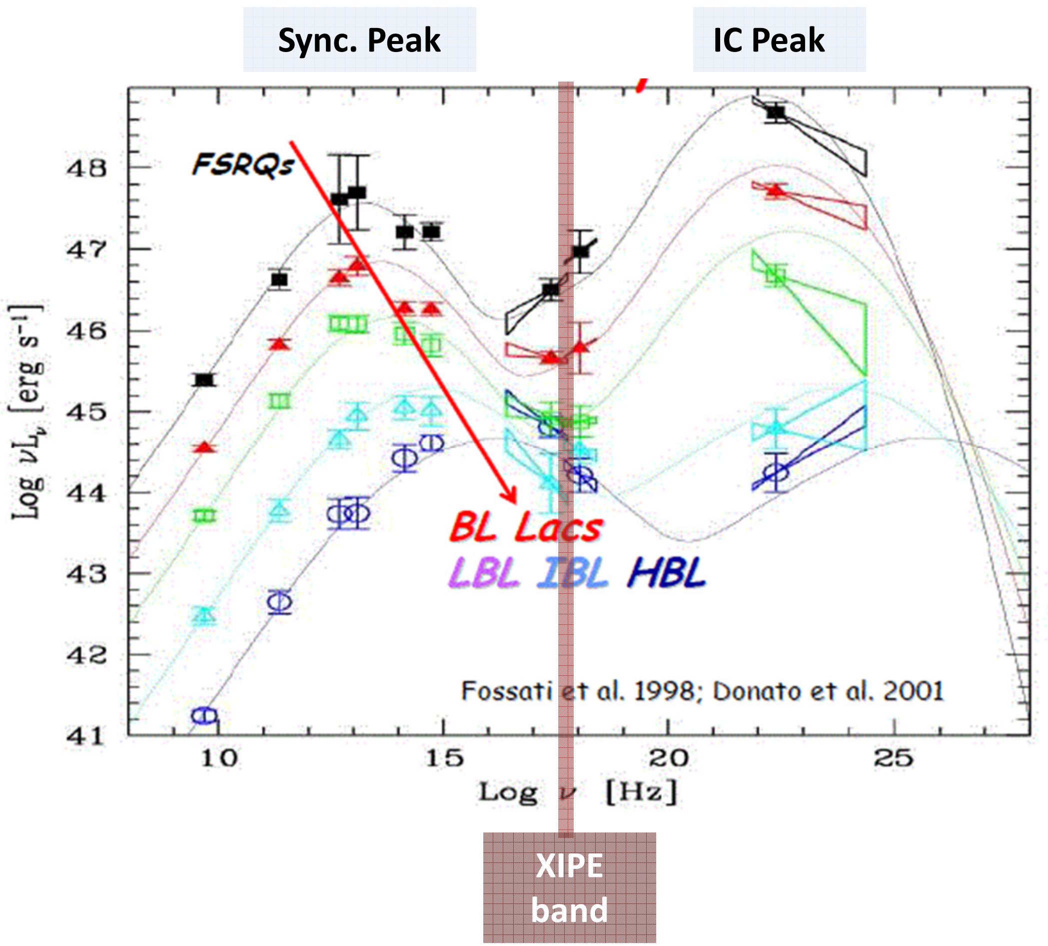
Is the Inverse Compton peak of Blazars due to:

- 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.

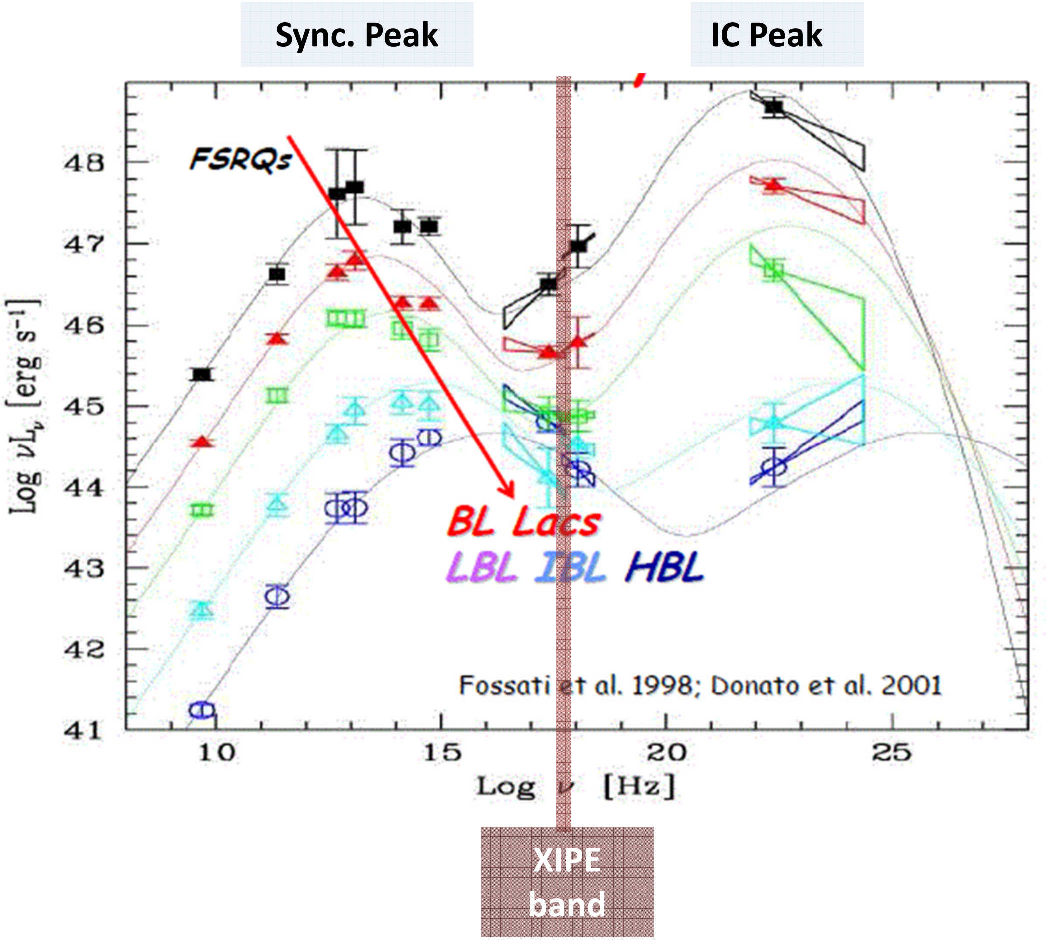


In synchrotron-dominated X-ray blazars, multi-wavelength polarimetry probes the structure of the magnetic field along the jet.

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

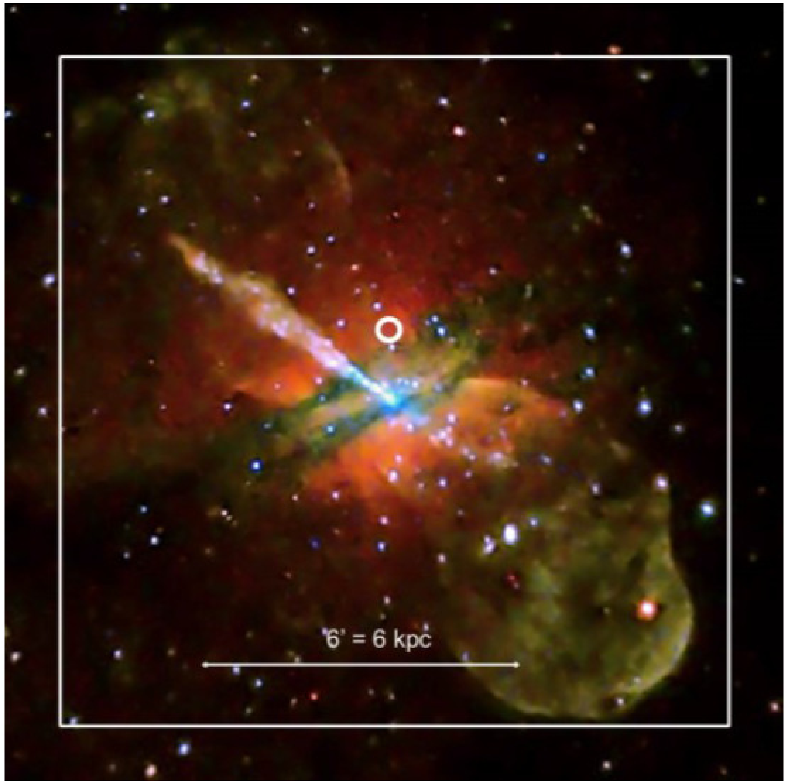
Coordinated multi-wavelength campaigns are crucial for blazars.

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



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

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

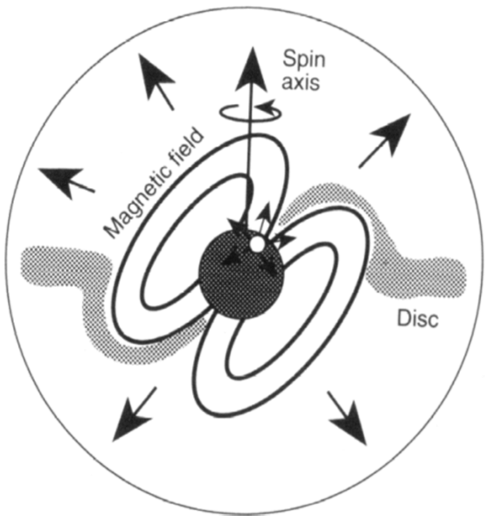


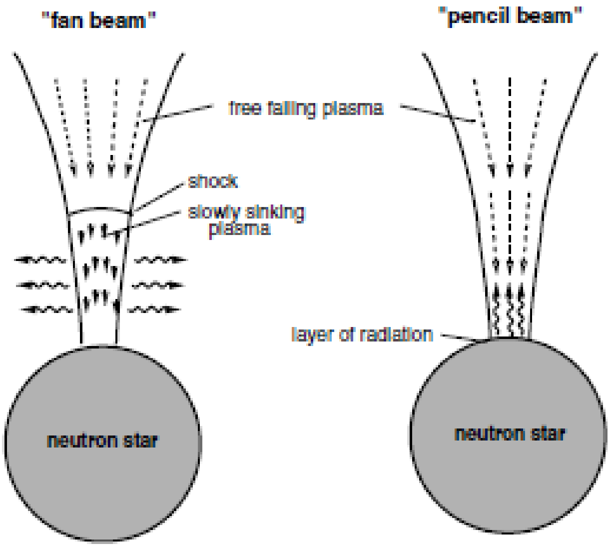
The extended (4’) radio jet in Cen A.

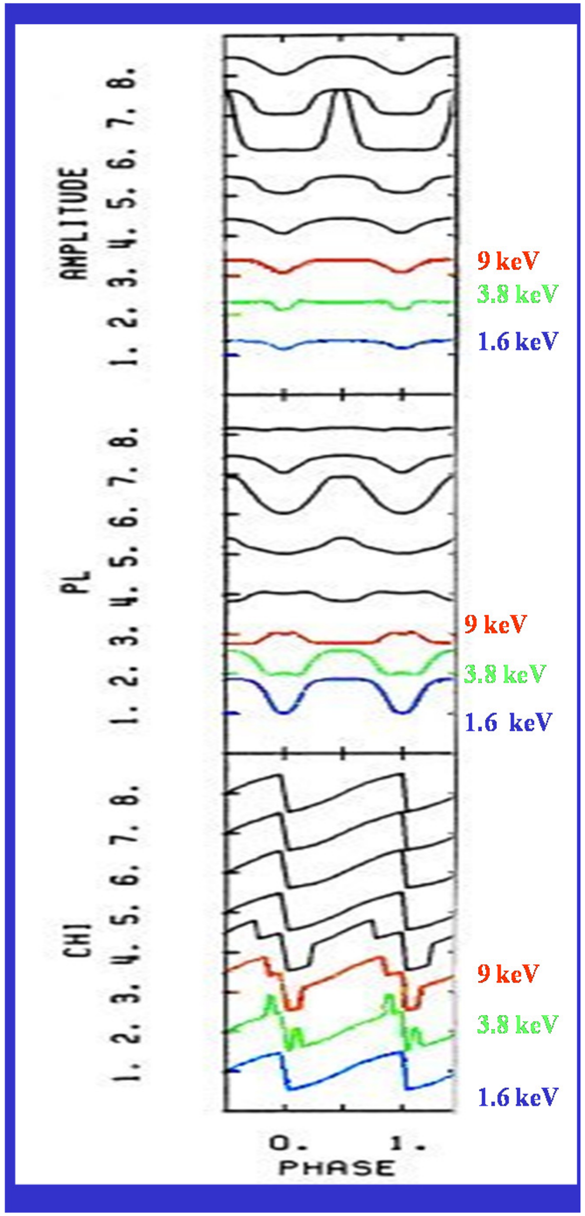
Disentangling geometric parameters from physical ones

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

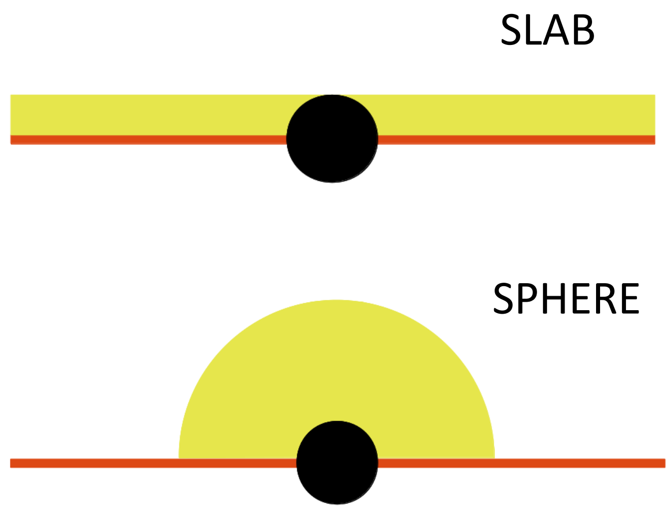
Constraining components of X-ray emission from AGNs

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?

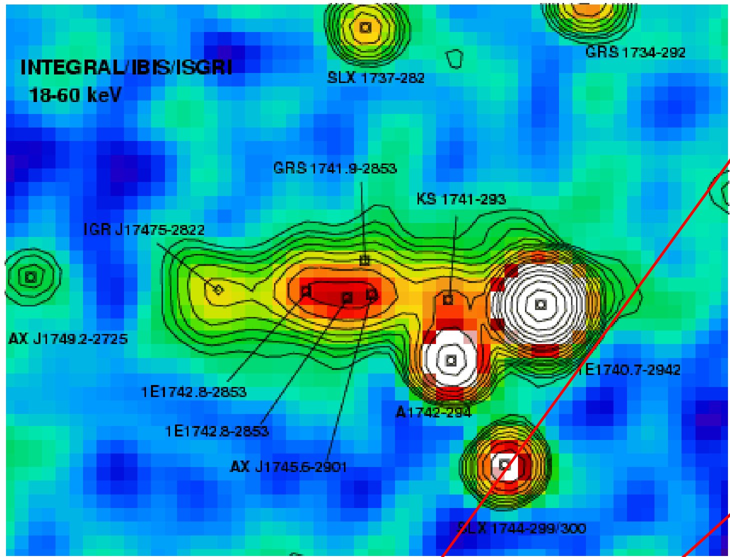
The sensitivity of XIPE will allow to detect the polarisation of the corona in a large sample of binaries and AGN.

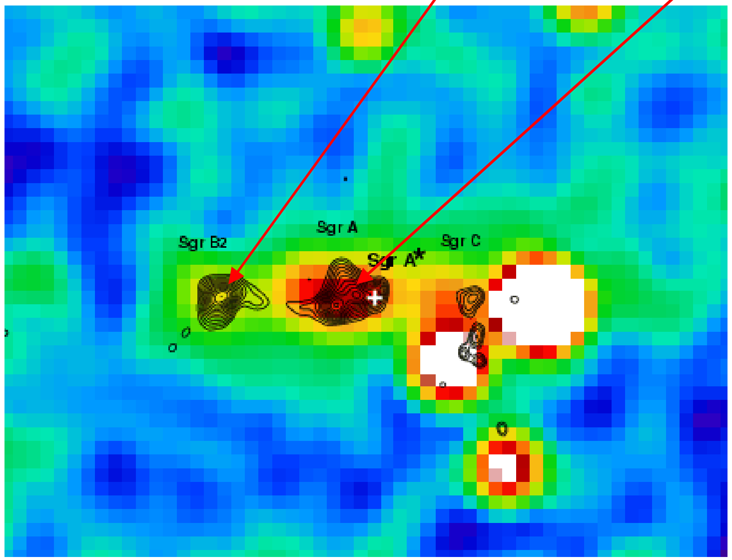


Marin & Tamborra 2014

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.

The strange case of Sgr B2



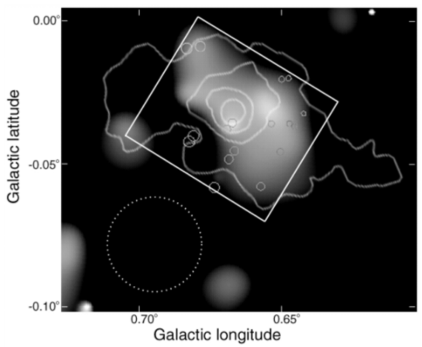


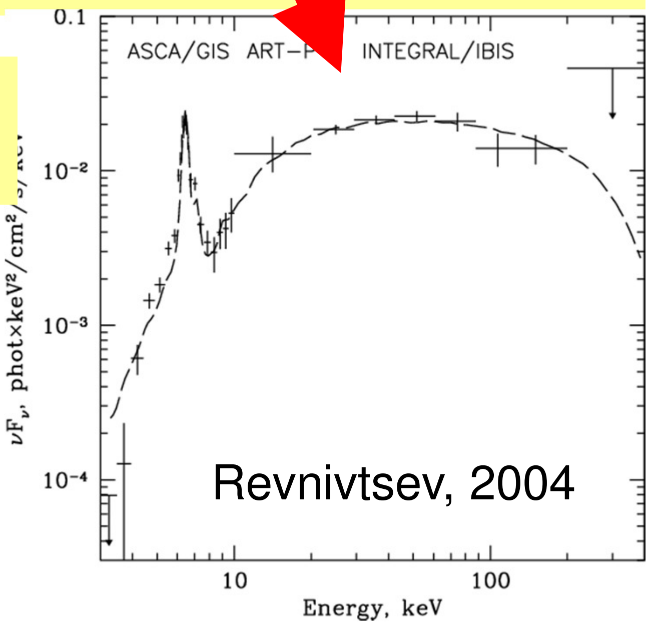
INTEGRAL Image of GC (Revnivtsev 2004)

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 !!!





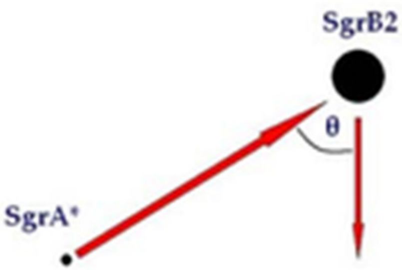
The emission from SgrB2 is extended and brighter in the direction of the BH (Murakami 2001). It is also varying in time (Inui et al. 2008).

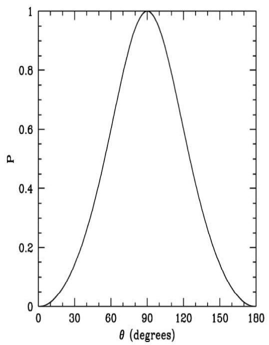
Is SgrB2 echoing past emission from the BH, which was therefore one million time more active (i.e. a LLAGN) ~300 years ago ??? (e.g. Koyama et al. 1996)

XIPE scientific goals

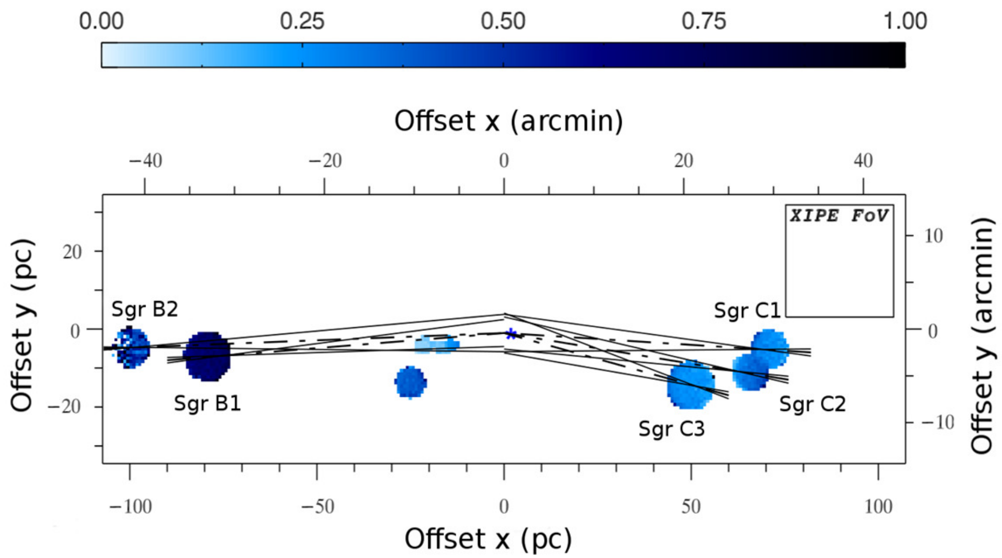
Polarization by scattering from Sgr B complex, Sgr C complex

- 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



Was Sgr A* a faint AGN in the past?

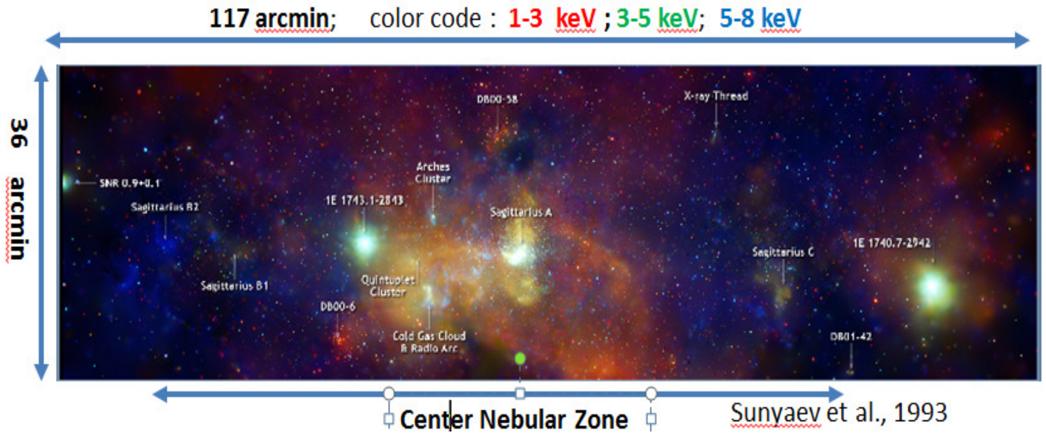
A unique contributions from Polarimetry

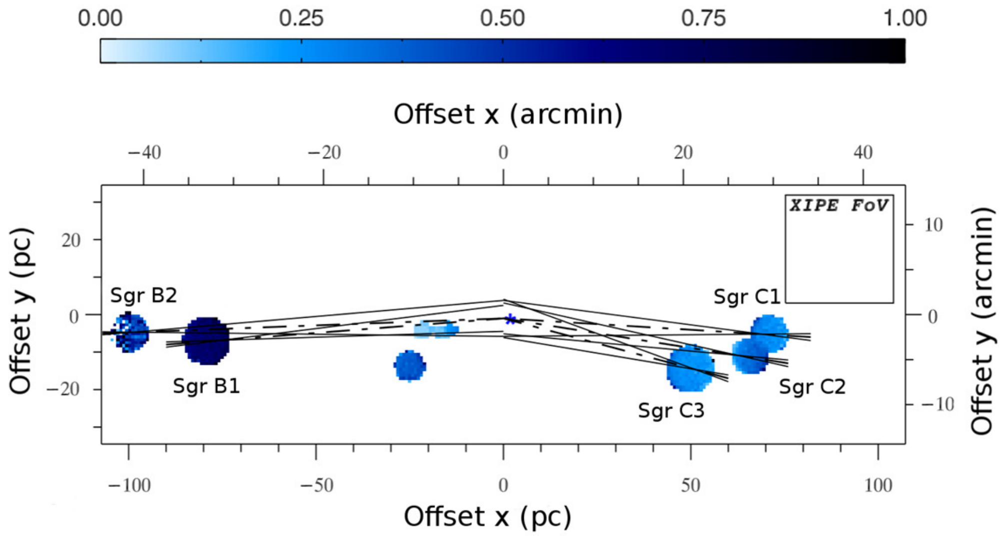
Cold molecular clouds around Sgr A* show neutral iron line and a Compton bump → Reflection from an external source!?!

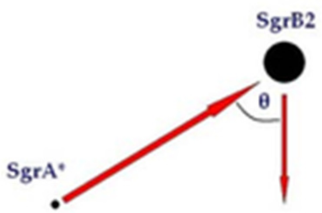
No bright source is there. Are they reflecting X-rays from Sgr A* when it was 10^6 times brighter?

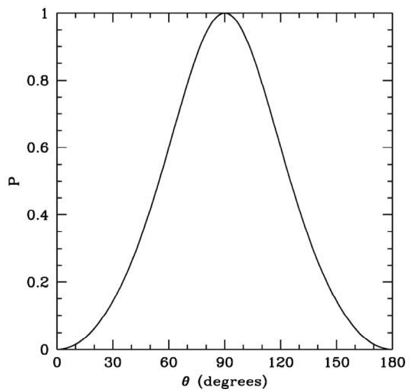
Polarization by scattering from Sgr B complex, Sgr C complex

- 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.

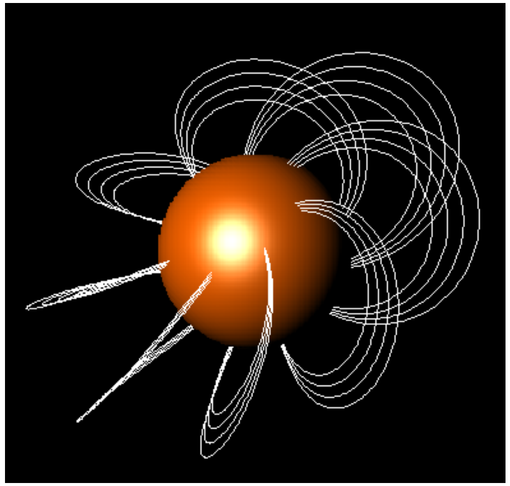
Birefringence in the magnetosphere of magnetars

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

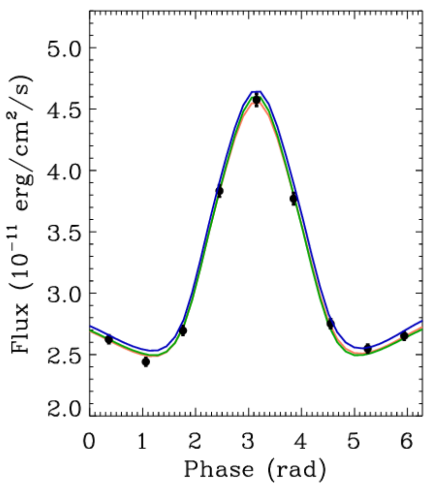
It heats the star crust and explains why the X-ray luminosity largely exceeds the spin down energy loss.

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

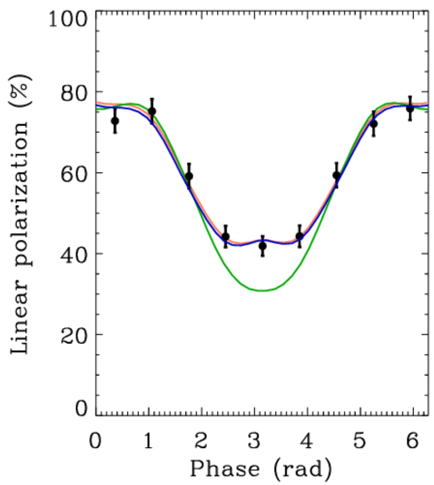
A twisted magnetic field.



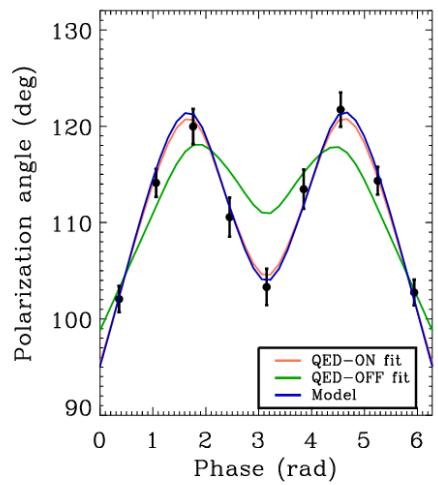
Light curve



Polarisation degree



Polarisation angle



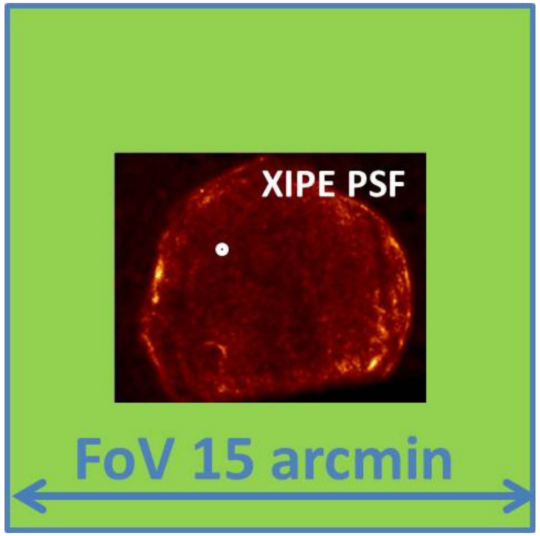
Such an effect is **only** visible in the phase dependent polarization degree and angle.

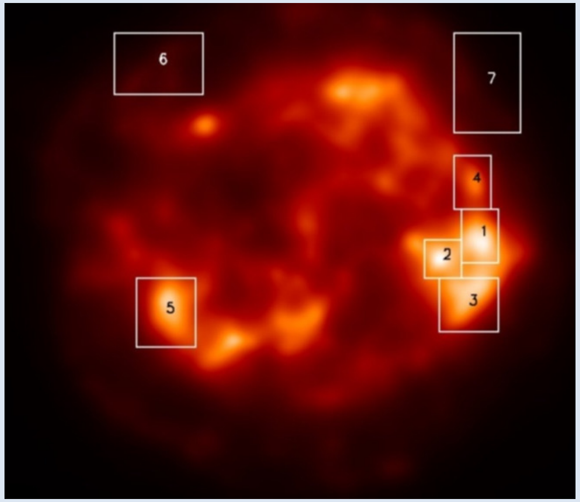
Observation of Supernova Remnants

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.





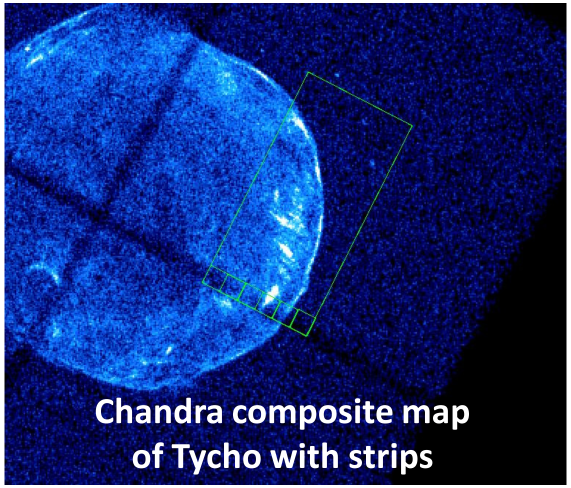
4-6 keV image of Cas A blurred with the PSF of XIPE

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

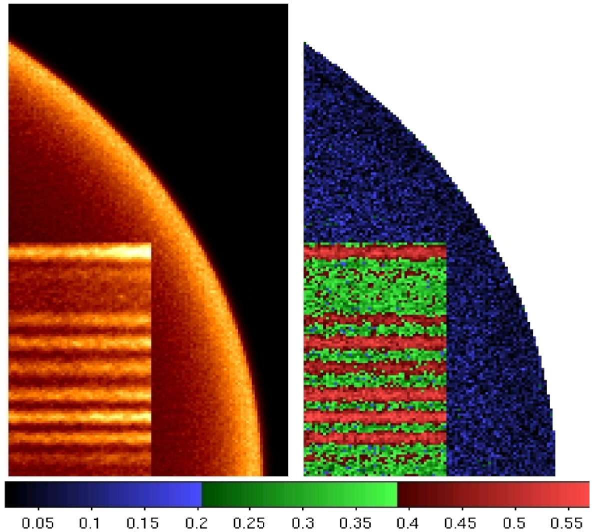
Acceleration phenomena: Tycho stripes

Observation of Supernova Remnants (Question Q6)



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

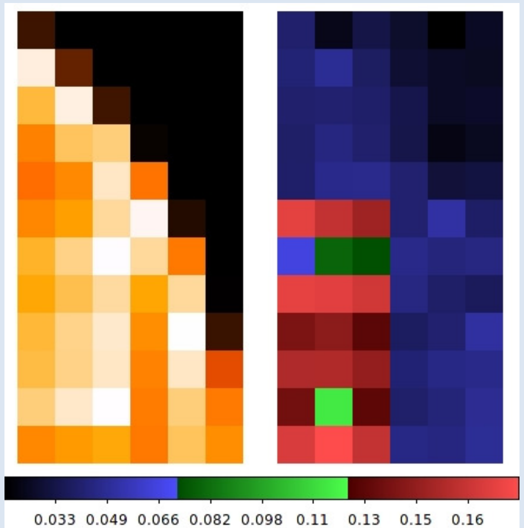


Image of individual stripes is lost, but polarization survives (≈15%).

The same at **XIPE** resolution

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!

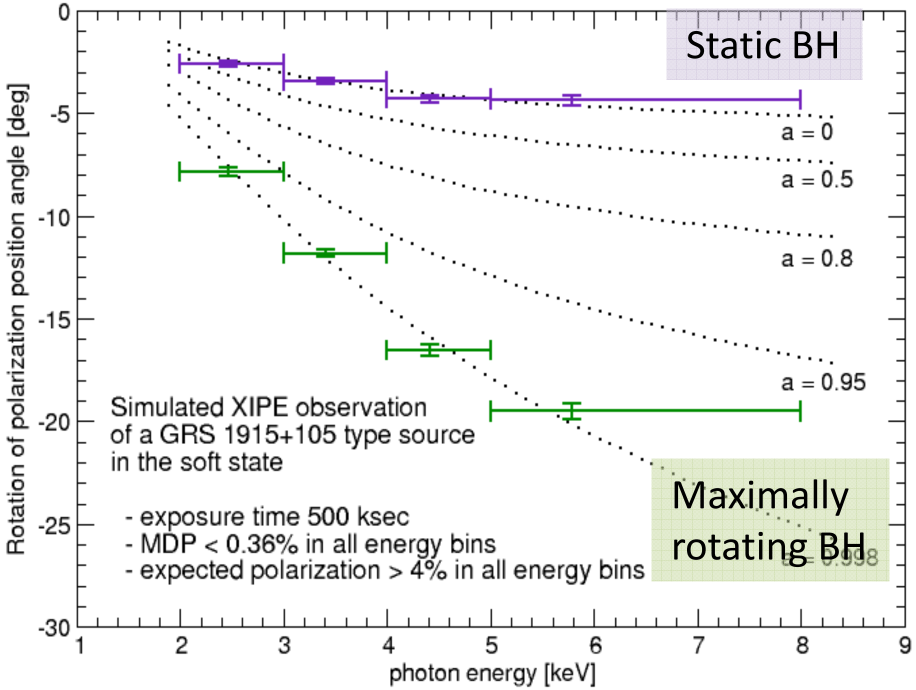
For J1655-40:	QPO:	$a = J/J_{max} = 0.290 \pm 0.003$
	Continuum:	$a = J/J_{max} = 0.7 \pm 0.1$
	Iron line:	$a = J/J_{max} > 0.95$

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: Fundamental Physics

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.

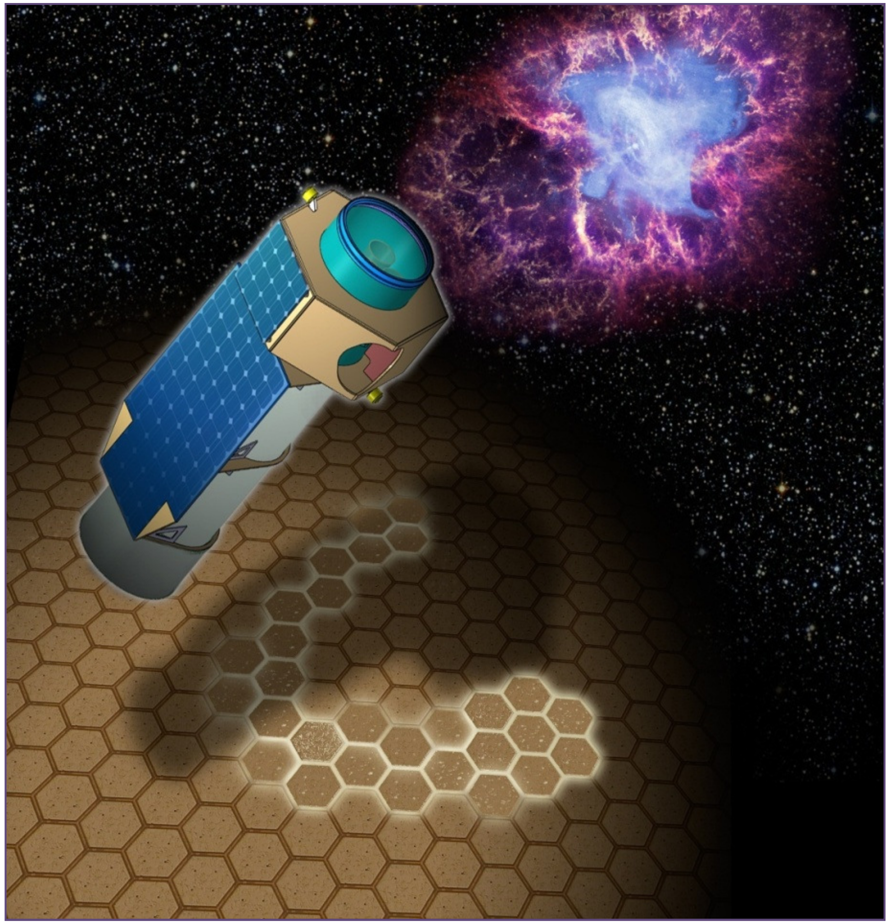
Summary

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.



Has COST contributed to this?

COST action MP1104 has been effective under various aspects:

• It supported directly some relevant activity. The Stockholm Meeting was very succesful and more “operative” than similar initiatives by other institutions. The STSM supported test of GPD polarimeter at the Panter Facility in Munich, was the first such test worldwide. It directly linked polarimetry to the largest european facility for X-ray Astronomy.

• It helped to take **X-ray polarimetry out of a niche**. If polarimetry proposals are succesful in this epoch is also because there is more interest on multifrequency observations and in particular on multiwavelength polarimetry.

•It helped to **extend the new techniques of X-ray polarimetry to the Sun**. The european groups most engaged in stellar X-ray polarimetry met for the first time the group most active in solar X-ray polarimetry at the Warshaw meeting. Also a link with the theoreticians most active in polarimetry of solar flares was completely supported by STSM. The results have been SEEPE, a proposal to the Call for a Small Scientific Mission by ESA and Chinese Academy of Sciences and a CUBESAT study (talk by S.Fabiani).

A new COST proposal by Fabio Muleri

A new COST proposal on high-energy polarimetry

Details
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Dear all,

as you know, this is the last year of our COST Action and we cannot simply ask for a continuation.
But new initiatives based on a sub-group of this network/community are very welcome.

Please find below such an initiative.

The provisional title is **"Polarimetry of high energy processes from the Sun to Gamma Ray Bursts"** and the main aims are to:
(i) explore if and how polarimetry can tackle current scientific questions, and if such questions can be answered more efficiently with a coordinated effort in different fields and wavelengths;
(ii) compare the scientific expectations with the sensitivity of the instruments, to build scientific cases for future missions, drive the development of the instrumentation and support the interpretation of current data.

If you are interested in participating to this COST proposal, please contact Dr. Fabio Muleri at

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Deadline for application of new COST proposals is 24 of March. There will be another call in about 6 months so additional initiatives are welcome.

The time for the decision is now. Let us hope…

The role of COST actions

In a research environment largely dominated by **project oriented budgets** sometime we miss the lubricant sometimes we miss the glue for new projects and new ideas. Sometime you have the perception that nobody is taking care of connecting people of different communities to discover the the exchange can be very fruitful.

Bottom-up initiatives as the one we are now concluding can help a lot and are for sure a good use of european taxpayers money.

But much depends on the coordinator of the initiative that must be gifted of the right combination of competence and patience.

Therefore

Thank You Hervé