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IAPS/INAF

XIPE (X-Ray Imaging Polarimetry Explorer)

28th Texas Symposium on Relativistic Astrophysics
13 December 2015 – 18 December 2015
International Conference Center Geneva

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 Transition 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-ray Astronomy, predicts a wealth of results from Polarimetry.

In 43 years only one positive detection of X-ray Polarization: the Crab nebula (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 them of marginal significance

THE TECHNIQUES HAVE BEEN 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

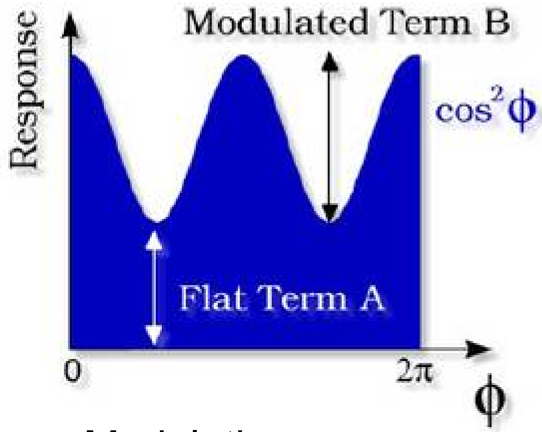
But new technical solutions are now ready

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 curve

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

Or by Using Stokes Parameters

$$S(\phi) = I + Q\sin(2\phi) + U\cos(2\phi)\,,$$

$$I = (A + B/2),\ Q = (B/2)\sin(2\phi_0),\ \text{and}\ U = (B/2)\cos(2\phi_0),$$

No V $\rightarrow$ no circular polarization with present techniques

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

Minimum Detectable Polarization (MDP)

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

R_S is the Source rate, R_B is the Background rate, T is the observing time
μ is the modulation factor: the response of the polarimeter to a 100% polarized beam (spanning from 0 or no sensitivity, to 1 or maximum sensitivity)

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

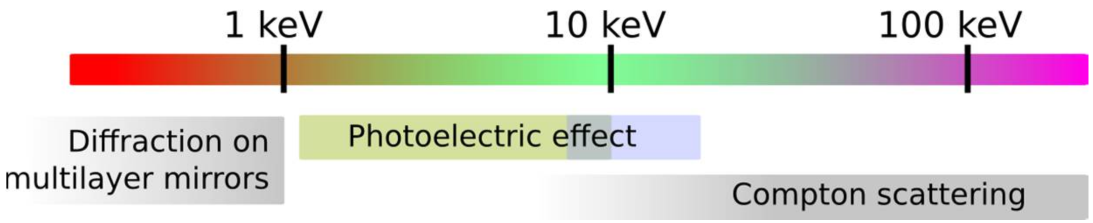
To reach MDP=1% with μ=0.5: $$N_{ph} = \left(\frac{4.29}{\mu\,\mathrm{MDP}}\right)^2$$ = 736 10^3 ph

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

Caution: the MDP describes the capability of rejecting the null hypothesis (no polarization) at 99% confidence. For a 3-sigma meaurement an observing time 2.2 times longer is needed while the 1-sigma error scales like : $28^o.5$/S/N

The XIPE energy band

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

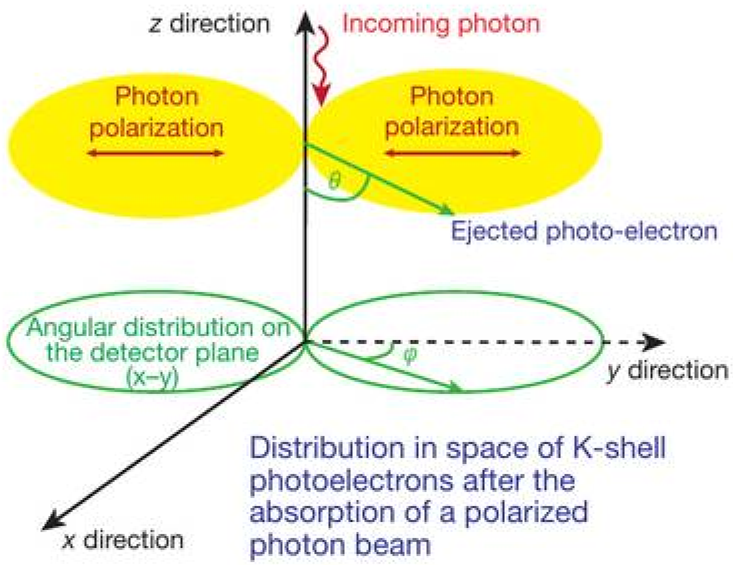


The Gas Pixel Detector

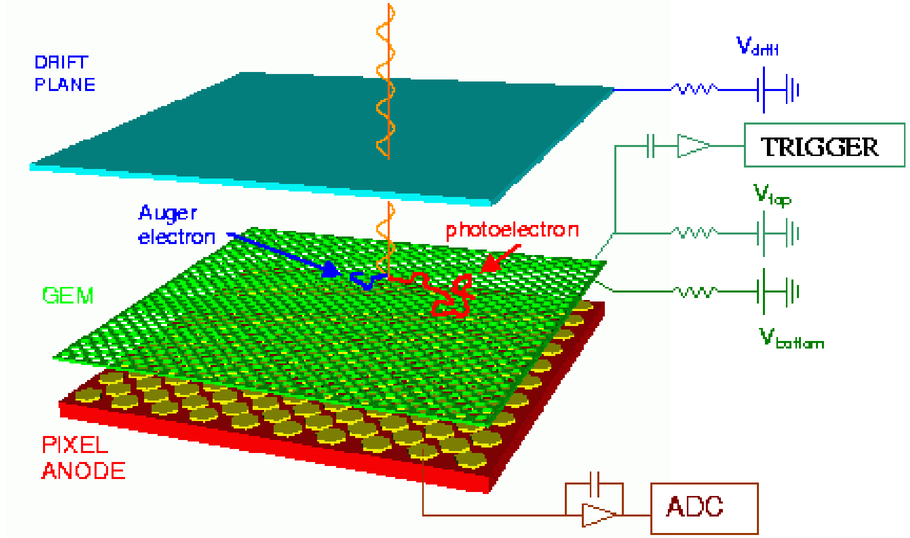
We developed at this aim a polarization-sensitive instrument capable of imaging, timing and spectroscopy

The photoelectric effect

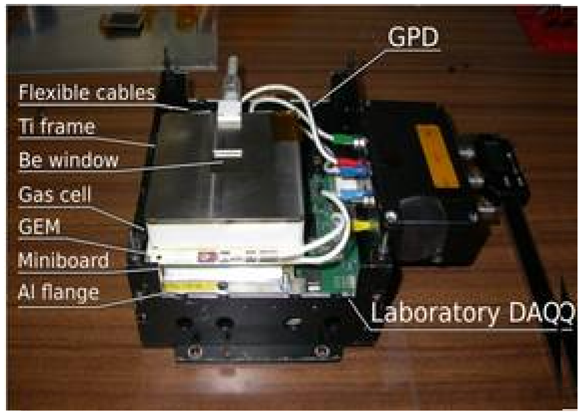
$$\frac{\partial\sigma}{\partial\Omega} = r_0^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$



The Gas Pixel Detector



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



Why this is now possible

The Gas Pixel Detector

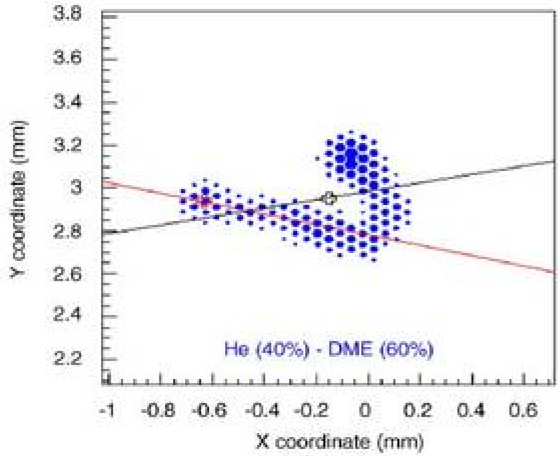
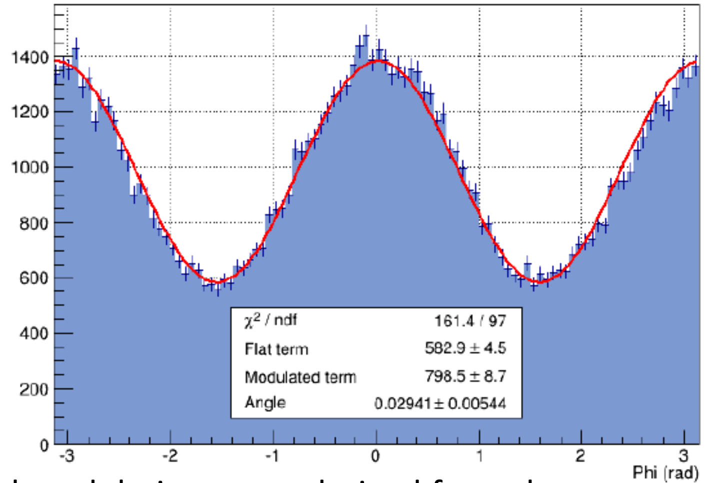
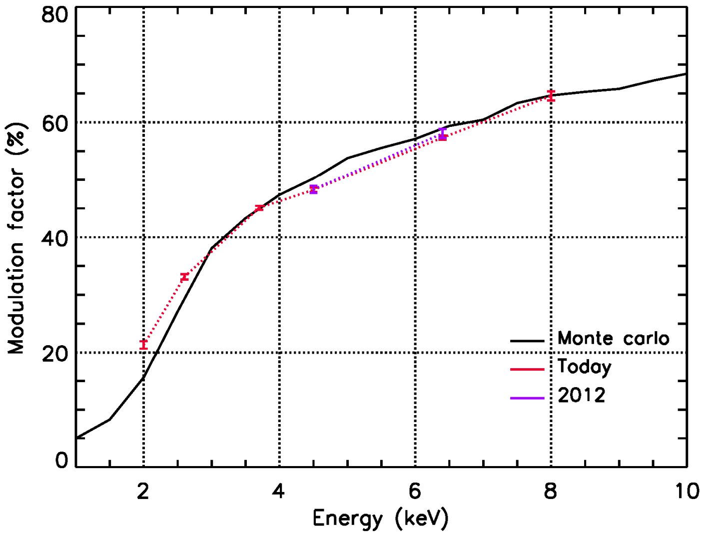


Image of a real photoelectron track. The use of the gas allows to resolve tracks in the X-ray energy band.

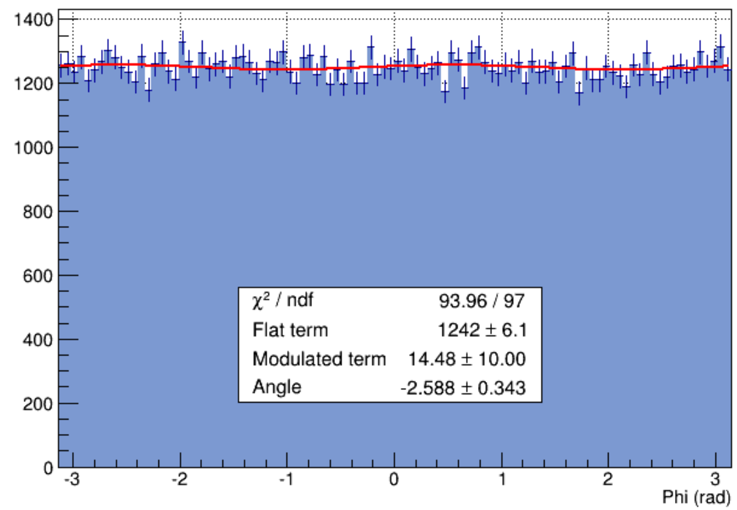


Real modulation curve derived from the measurement of the emission direction of the photoelectron.



Muleri et al. 2008,2010

Modulation factor as a function of energy.

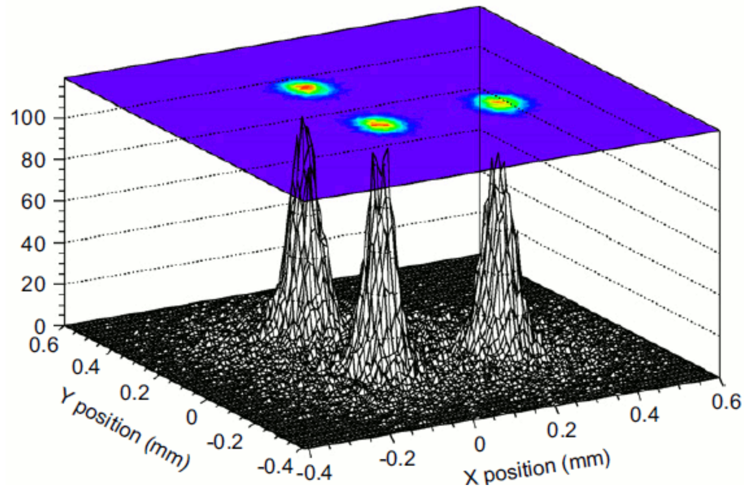


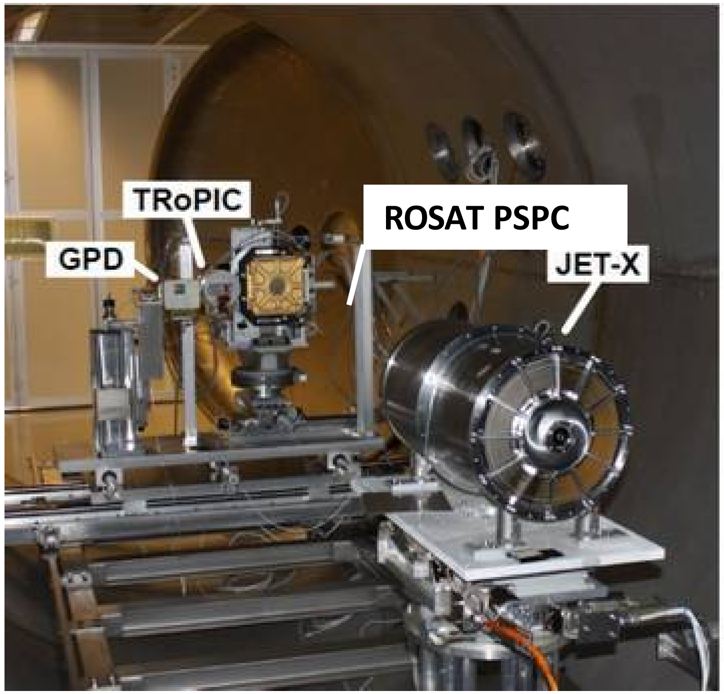
Bellazzini et al. 2012

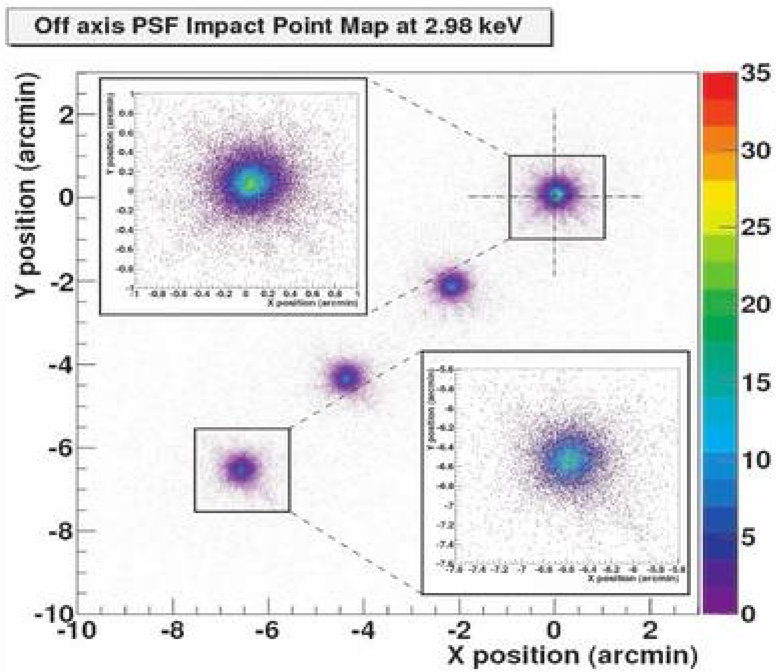
Residual modulation for unpolarised photons.

Imaging capabilities of GPD tested at PANTER

- 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

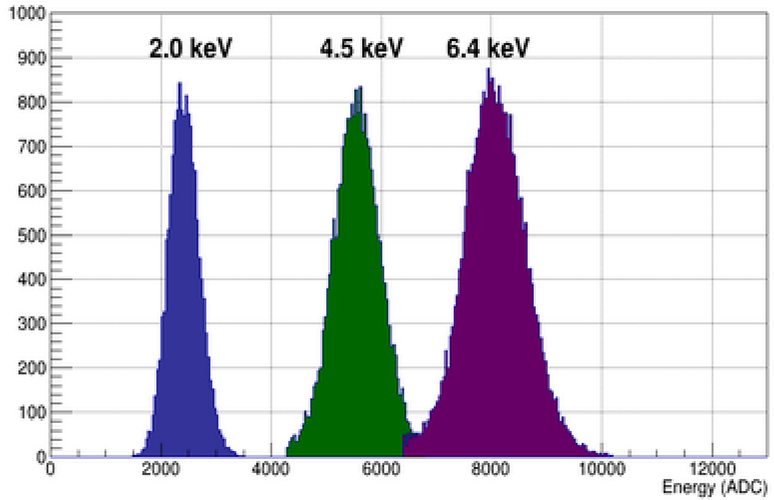


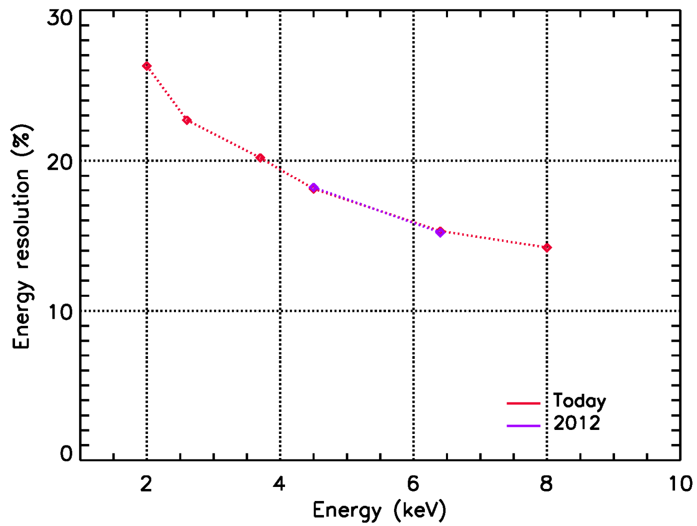




The Gas Pixel Detector

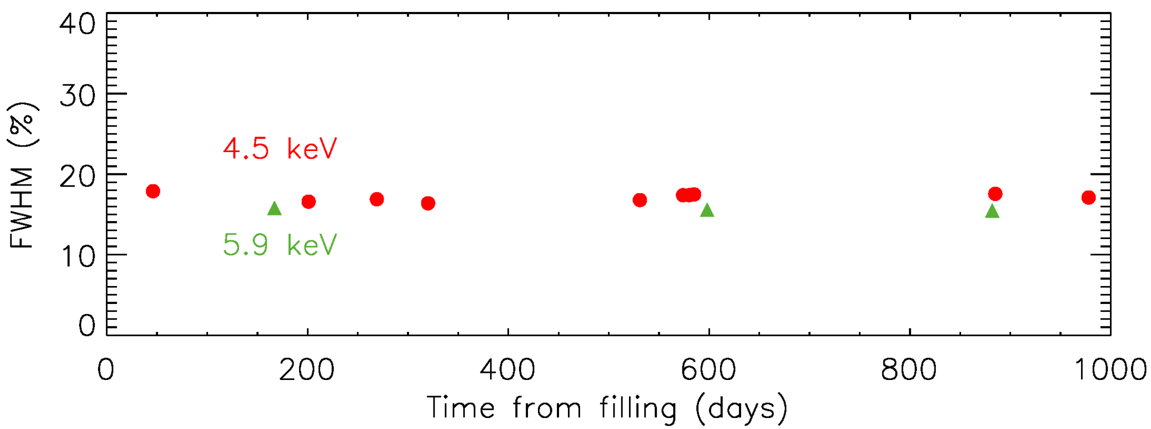
Spectroscopic capabilities





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

- Stable operation over 3 years



What’s next ?

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 May/June 2017 one of these 3 missions will be selected for flight

Launch in 2026

NASA

In 2014 **NASA** issued an AOO for a Small Explorer Mission (budget of ~ 175 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

Launch in 2020

Three out of 6 missions under study are of X-ray Polarimetry

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

X-ray Imaging Polarimetry Explorer

Proposed by

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XIPE Science Team

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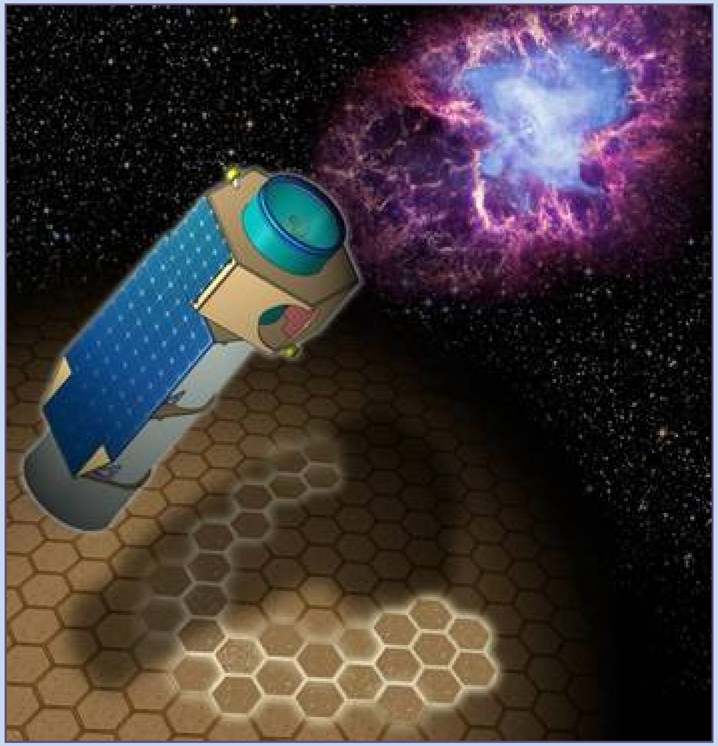
XIPE Instrument Team

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.

<u>XIPE uniqueness</u>: Time-, spectrally-, spatially-resolved **X-ray polarimetry** as a breakthrough in high energy astrophysics and fundamental physics



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.

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

Astrophysics

Acceleration phenomena

Pulsar wind nebulae
SNRs
Jets Blazars

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

Magnetars

Matter in Extreme Gravitational Fields: GR effects

Galactic black hole system & AGNs

Quantum Gravity

Search for axion-like particles

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

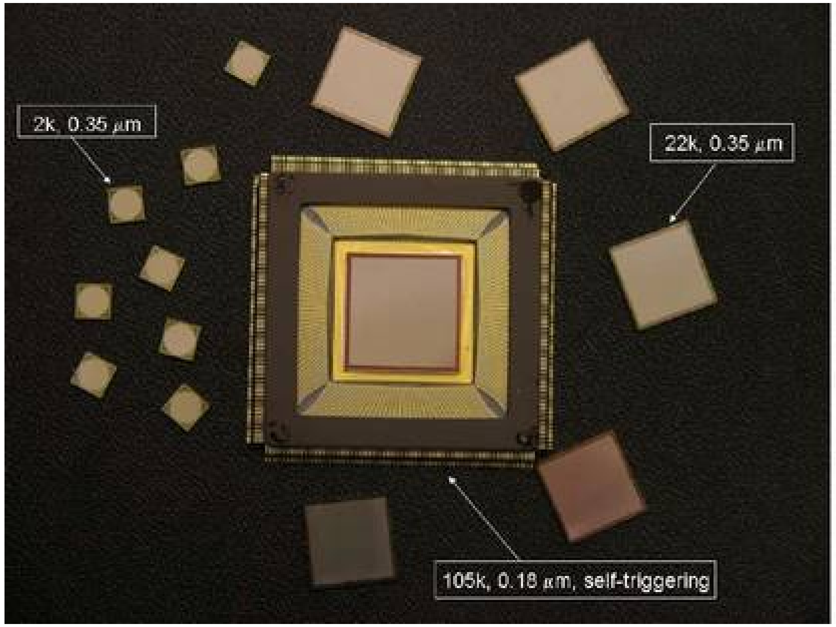
A **large** community involved:

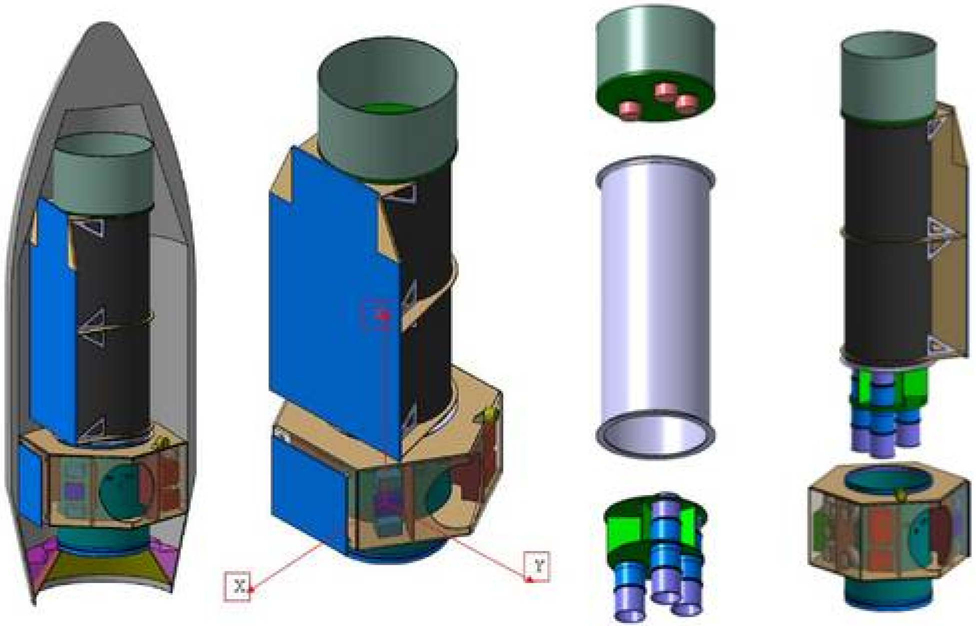
- **17 countries**
- **146 scientists**
- **68 institutes around the world**

XIPE design guidelines

A light and simple mission

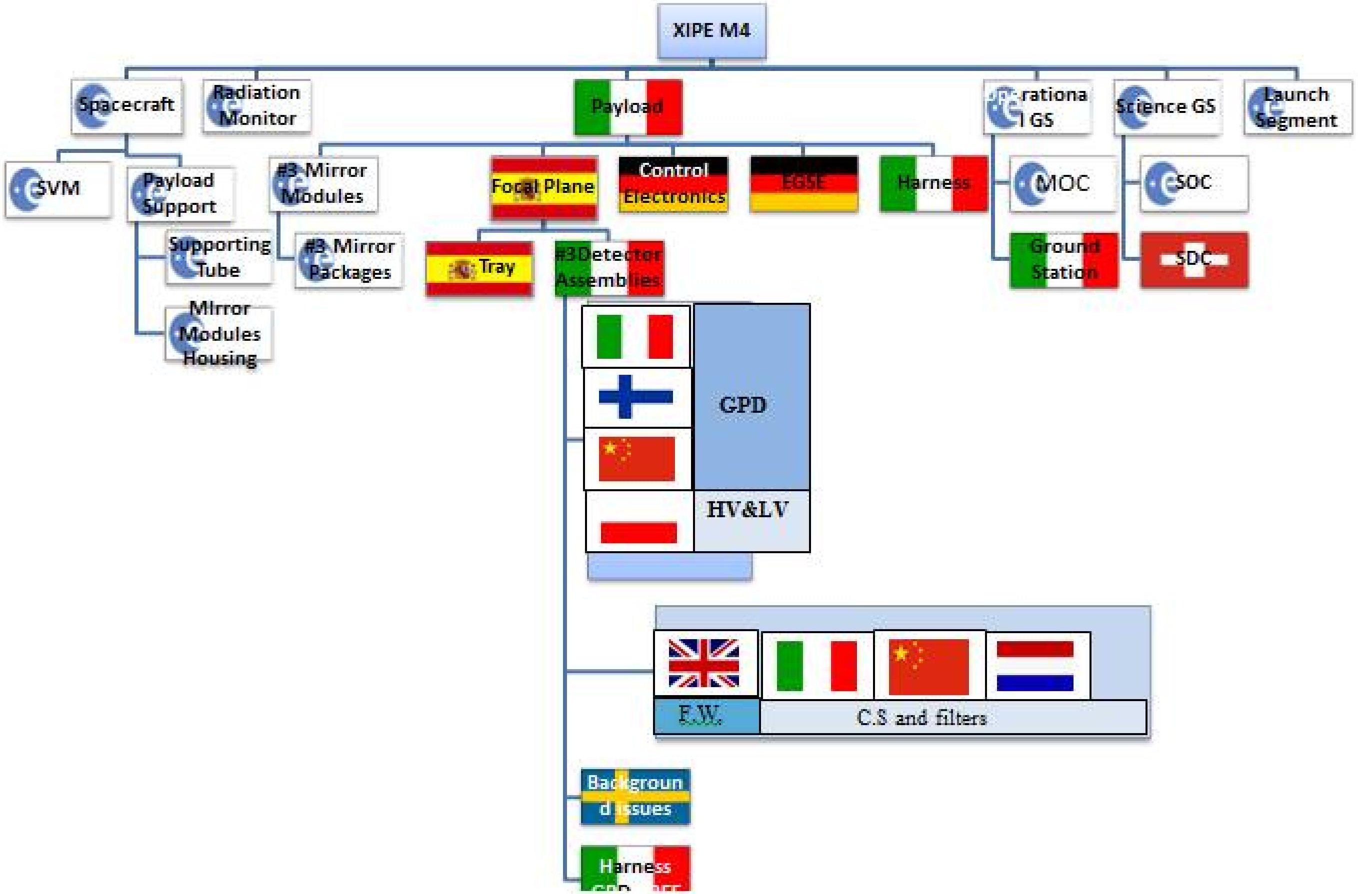
- Three telescopes with 3.5 m (possibly 4m) focal length to fit within the Vega fairing.
  Long heritage: SAX → XMM → Swift → eROSITA → XIPE
- Detectors: conventional proportional counter but with a revolutionary readout.
- Mild mission requirements: 1 mm alignment, 1 arcmin pointing.
- Fixed solar panel.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

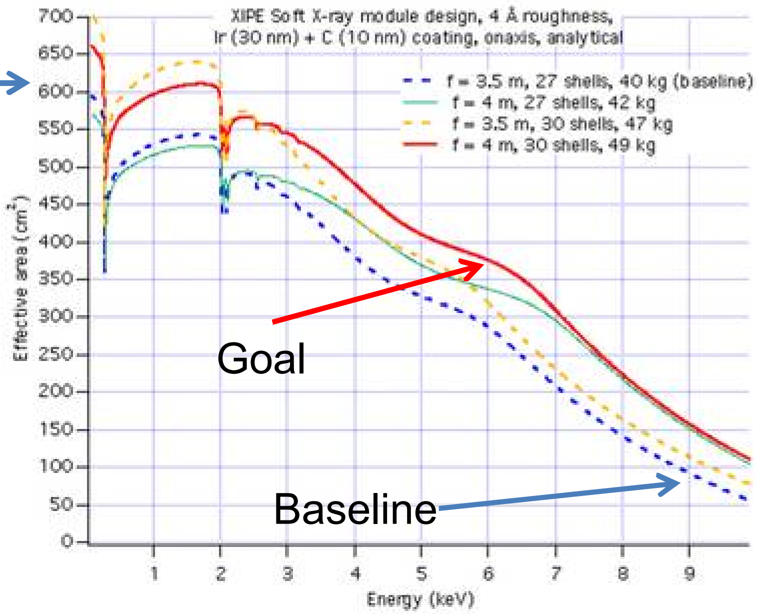


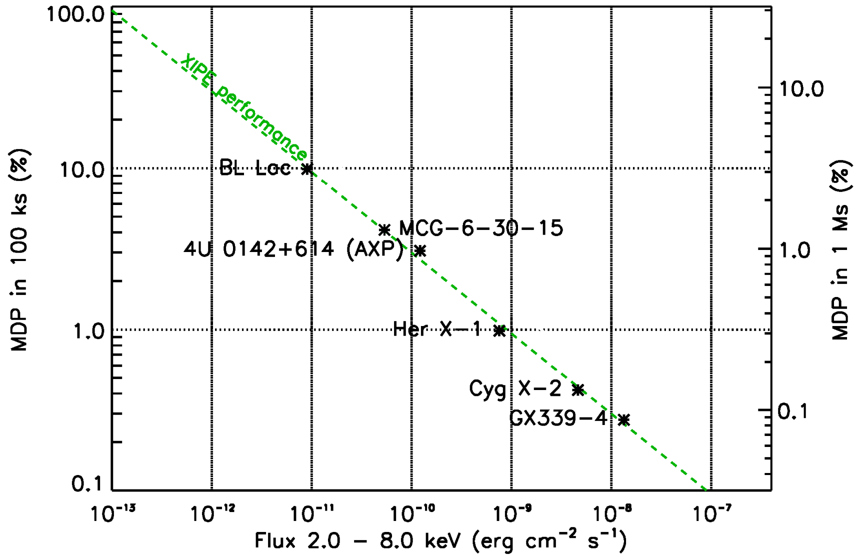
The distribution of activities

XIPE facts

3 of these optics

Polarisation sensitivity	1.2% MDP for 2×10^{-10} erg/s cm^2 (10 mCrab) in 300 ks
Spurious polarization	<0.5 % (goal: <0.1%)
Angular resolution	<26 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	2×10^{-6} c/s or 4 nCrab





A world-wide open European observatory

CP: Core Program (25%):

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

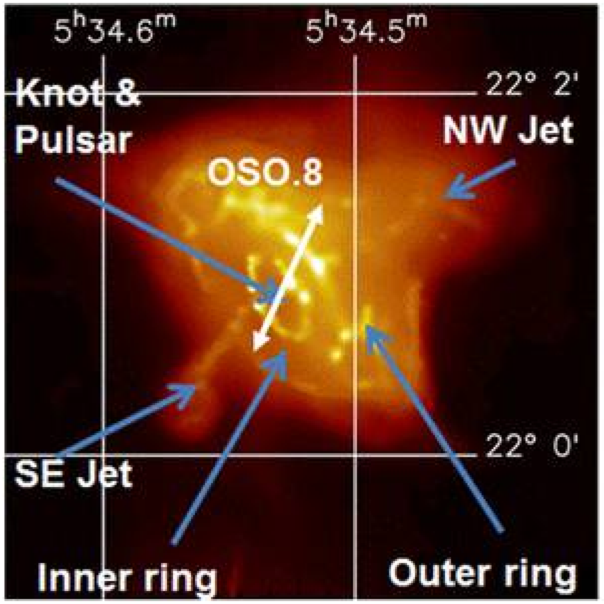
GO: Guest Observer program on competitive base (75%):

- 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.

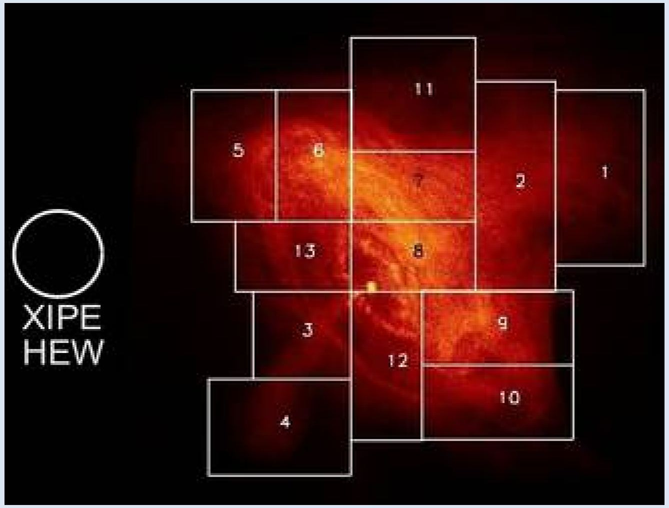
In organising the GO, a fair time for each class will be assigned. This will ensure "population studies" in the different science topics of X-ray polarimetry.

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. It was not possible to measure the polarization of PSR0531+21 because the contribution to the total counts was around 4% and the nebula was acting as a huge background.

- XIPE has a resolution which is not imaging capabilities will allow to measure the pulsar polarisation by separating from the much brighter nebula emission.

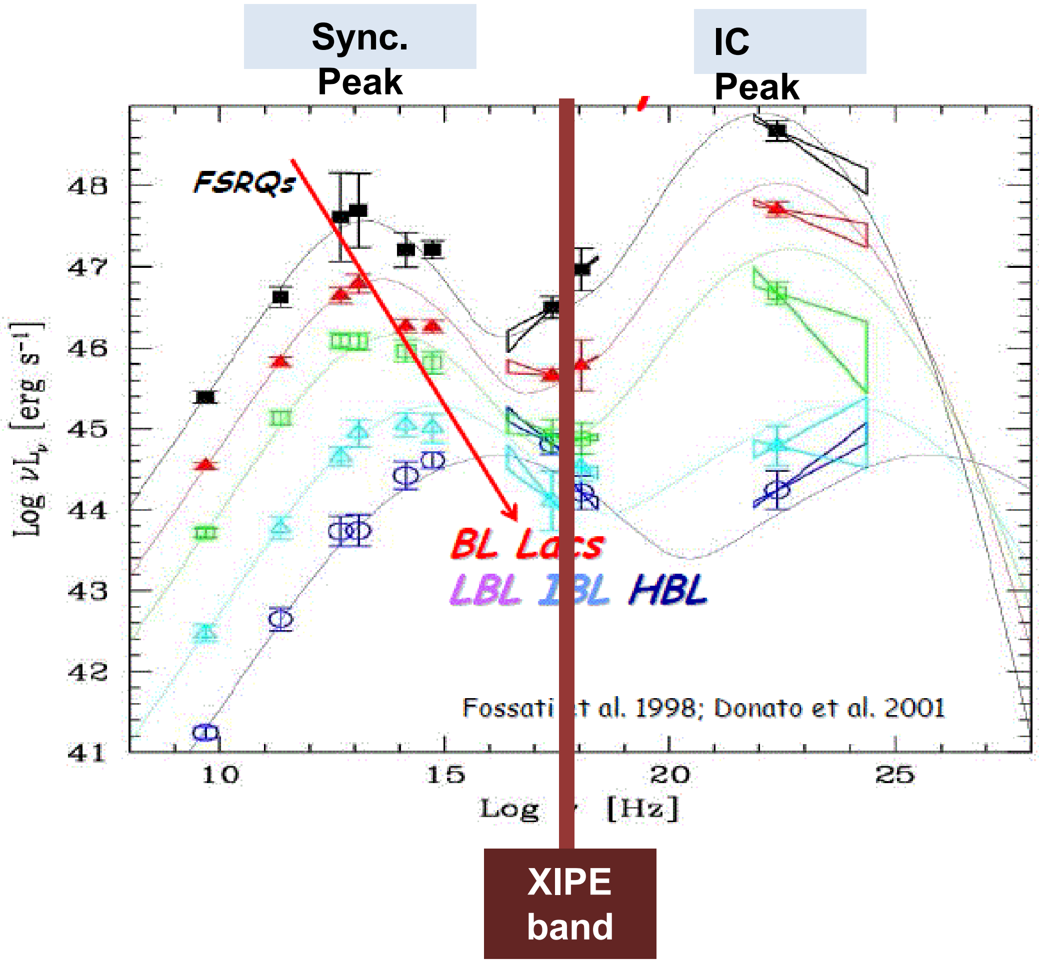
Acceleration phenomena: Unresolved jets

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

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

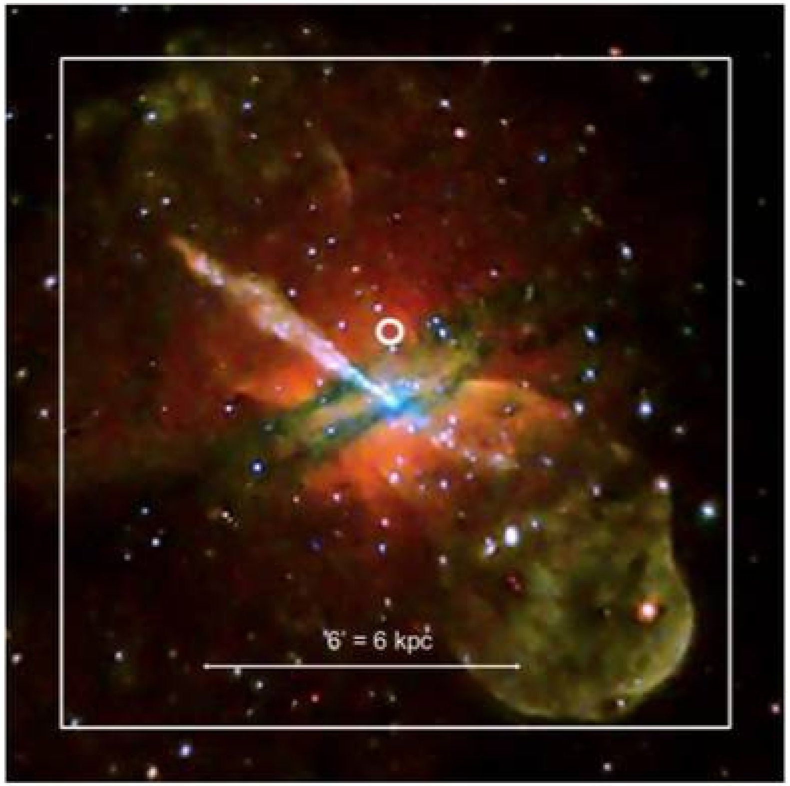
- Synchrotron-Self Compton (**SSC**) ?
The polarization angle is the same as for the synchrotron peak.

- External Compton (**EC**) ?
The polarization angle may be different. The polarization degree determines the electron temperature in the jet.



XIPE can, map the X-ray polarisation and thus the magnetic field of resolved X-ray emitting jets.

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



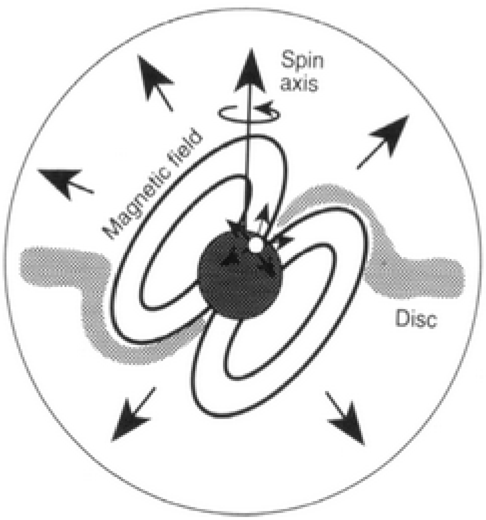
The extended (4') radio jet in Cen A.

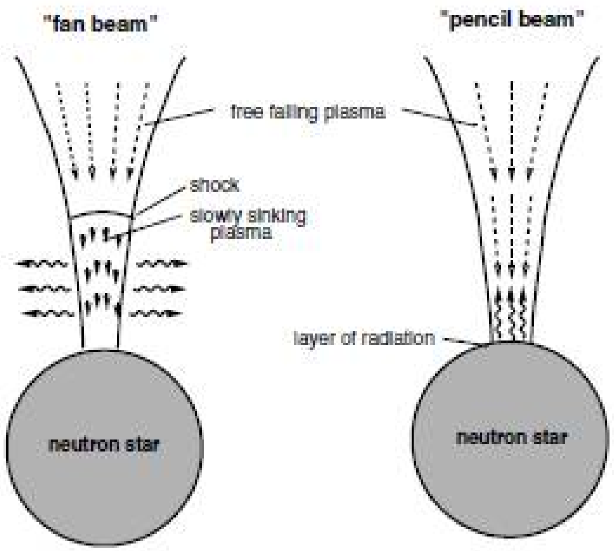
Emission in strong magnetic field: X-ray pulsars

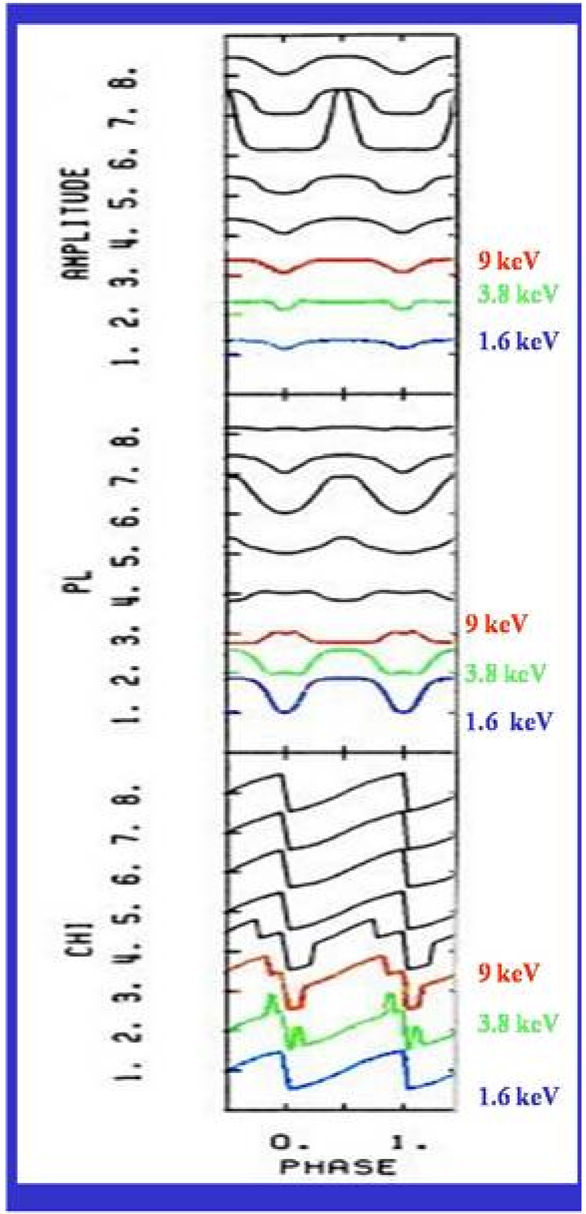
Disentangling geometric parameters from physical ones

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

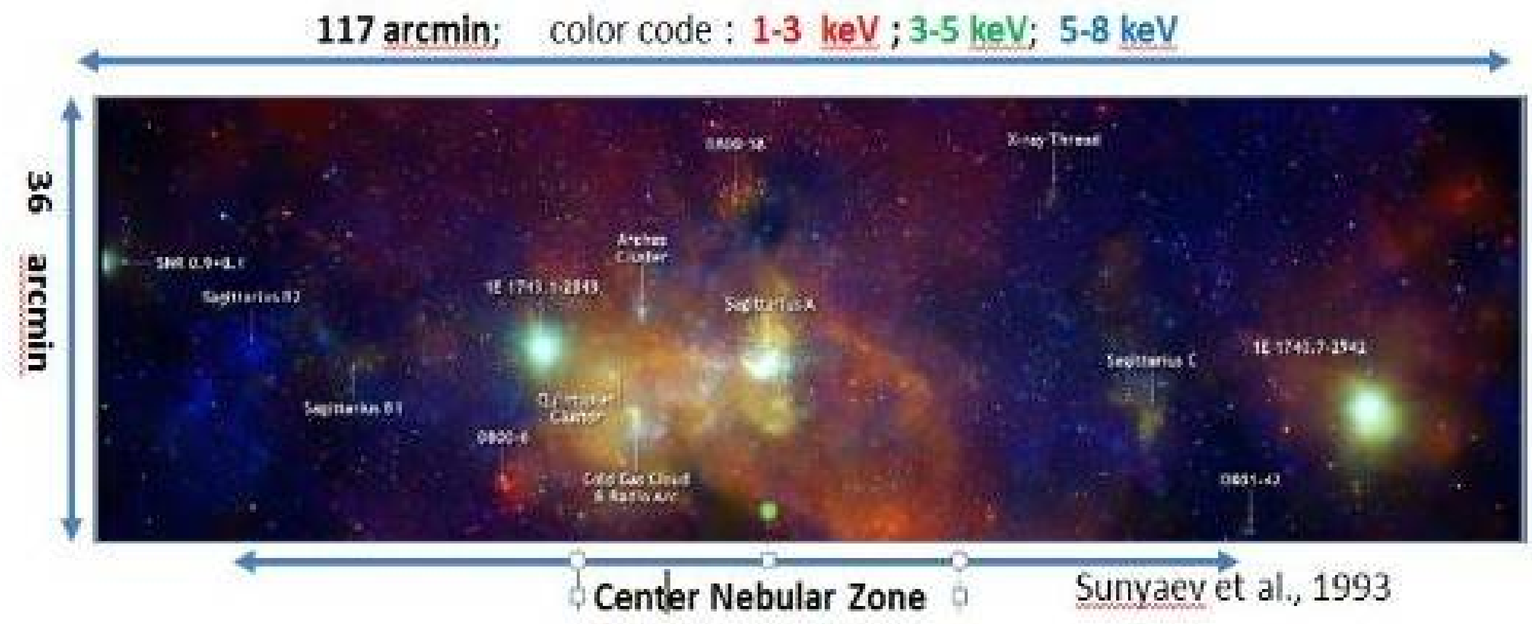
For the best class of XIPE candidates we use a paper 27 y old!

Scattering: X-ray reflection nebulae in the GC

Was in the past the galactic center a faint AGN ?

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

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

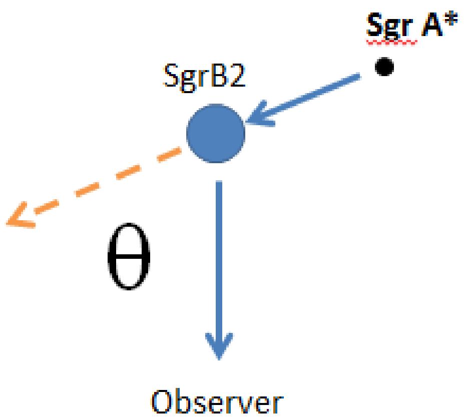


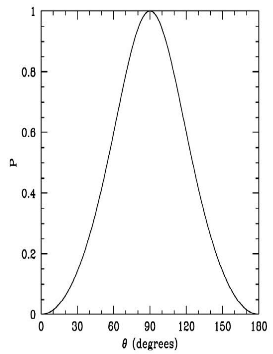
XIPE scientific goals

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

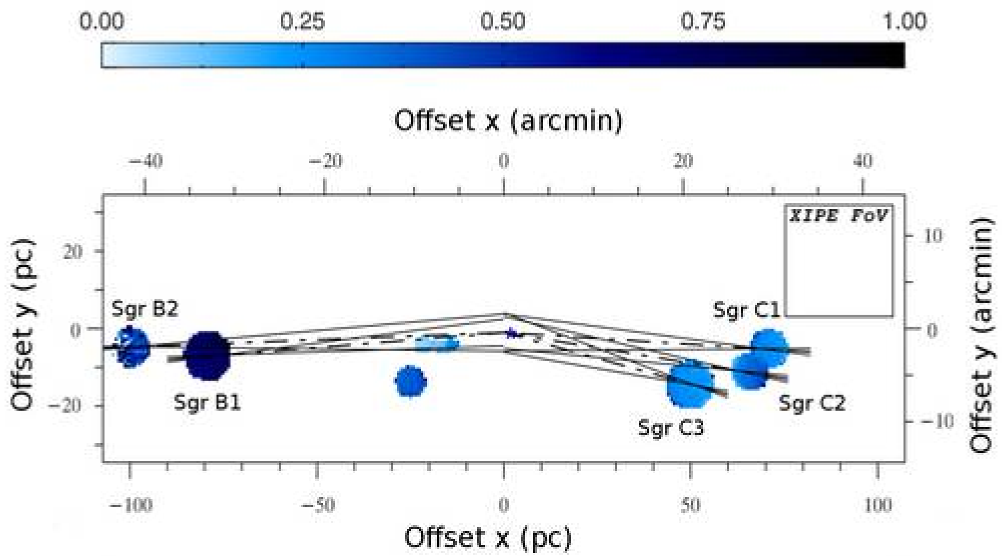
Polarization by scattering from Sgr B complex, Sgr C complex

- 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



Fundamental Physics: 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).

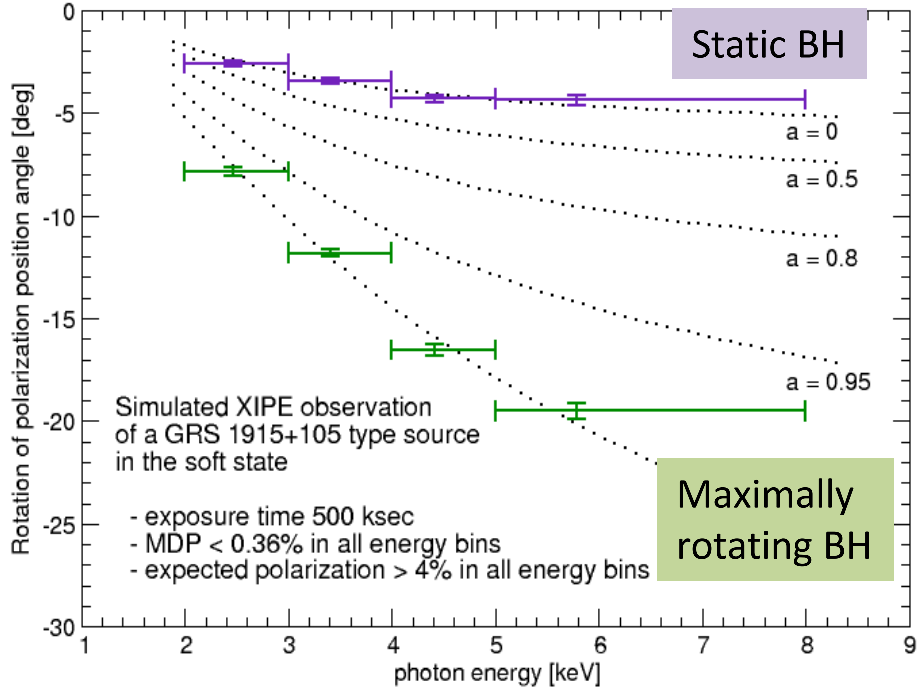
Problem: for a number of XRBs, the methods do not agree!

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, …



Many sources in each class available for XIPE

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.

Working groups set : about 300 scientists signed for participation.

WG1. Acceleration mechanisms: Giampiero Taglaferri(1), Jacco Vink(2)
(1) Osservatorio Astronomico di Brera INAF, Italy, (2) Astronomical Institute Anton Pannekoek, The Netherlands

WG1.1 **Pulsar Wind Nebulae**: Emma de Ona Wilhelmi , ICE, Spain
WG1.2 **Supernova Remnants**: **Andrei Bykov,** Ioffe Physical-Technical Institute, Russia
WG1.3 **Blazars: Ivan Agudo, Instituto** de Astrofísica de Andalucía, Spain
WG1.4 **Micro-QSO**s: **Elena Gallo**, University of California, Santa Barbara, USA
WG1.5 **Gamma Ray** Bursts: **Carol Mundell**, University of Bath, UK
WG1.6 **Tidal Disruption** Events: **Immacolata Donnarumma**, IAPS/INAF, Italy
WG1.7 **Active Stars**: **Nicholas Grosso**, Astronomical Observatory in Strasbourg, France
WG1.8 **Clusters of Galaxy**: **Sergey Sazonov**, Space Research Institute, Russian Academy of Sciences, Russia

WG2. Magnetic Fields in compact objects: Andrea Santangelo (1), Silvia Zane (2)
(1) Institut für Astronomie und Astrophysik Tuebingen, (2) University College London/MSSL, UK

WG2.1 **Magnetic Cataclismic Variables**: **Domitilla De Martino**, Osservatorio di Capodimonte, taly
WG2.2 **Accreting Millisecond Pulsars**: **Juri Poutanen**, Finland Tuorla Observatory, U. of Turku,Finland
WG2.3 **Accreting X-ray Pulsars**: **Victor Doroshenko**, IAAT, Germany
WG2.4 **Magnetars**: **Roberto Turolla**, University of Padua, Italy

WG3. Scattering in aspherical geometries and accretion Physics: Eugene. Churazov (1), Rene‘ Goosmann(2)
(1)Max-Planck-Institut für Astrophysik, Germany (2) Astronomical Observatory in Strasbourg, France

WG3.1 **X-ray binaries and QPOs**: **Julien Malzac**, CESR/CNRS, France
WG3.2 **AGNs**: **Pierre Olivier Petrucci**, Institut de Planétologie et d'Astrophysique de Grenoble, France
WG3.3 **Molecular Clouds & SgrA***: **Frédéric Marin**, Astronomical Institute of the Academy of Sciences, Czech Republic
WG3.4 **Ultra Luminous X-ray sources**: **Hua Feng**, Tsinghua University, Beijing, China

WG4. Fundamental Physics: Enrico Costa (1), Giorgio Matt (2)
(1) INAF/IAPS, Italy (2) Universita' Roma Tre, Italy

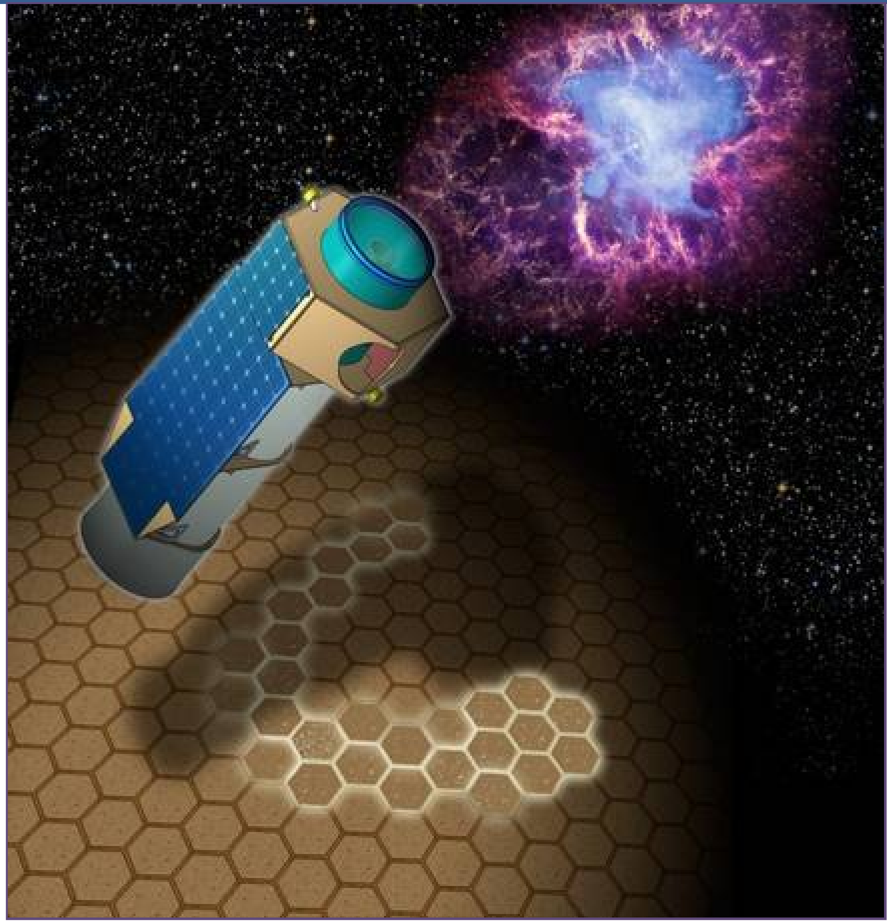
WG4.1 **QED and X-ray polarimetry**: **Rosalba Perna**, Stony Brook University, USA
WG4.2 **Strong Gravity: Jiří Svoboda**, Astronomical Institute of the Academy of Sciences, Czech Republic
WG4.3 **Quantum Gravity**: **Philip E. Kaaret**, Iowa University, USA
WG4.4 **Axion-like particles**: **Marco Roncadelli**, University of Pavia , Italy

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.

Coverage of theoretical work on different topics is unevenly covered. This is natural, given the absence of data. But to plan the observations is not very good. Predictions on some of the most straightforward targets for XIPE, such as bright binaries with NS are based on a few old papers.



We hope that a larger community will start to think to polarization as an observable. The probability to have observation in the future is high.

More about XIPE

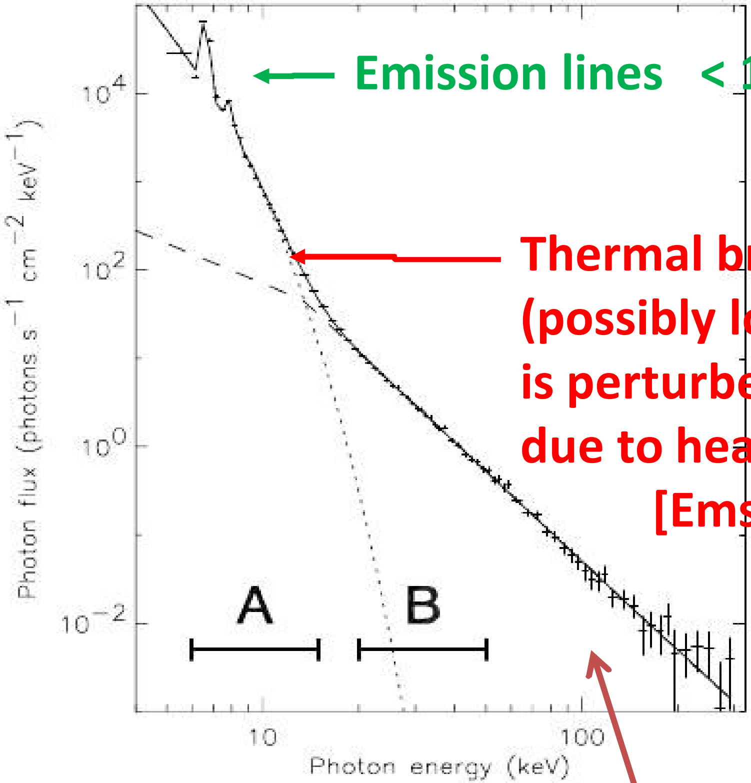
http://www.isdc.unige.ch/xipe/

The site also includes sciece working groups just set up

The site includes a (very preliminary) calculator of sensitivity of XIPE for a given source and for a given observing time

End of presentation

SOLAR FLARES X-RAY POLARIMETRY

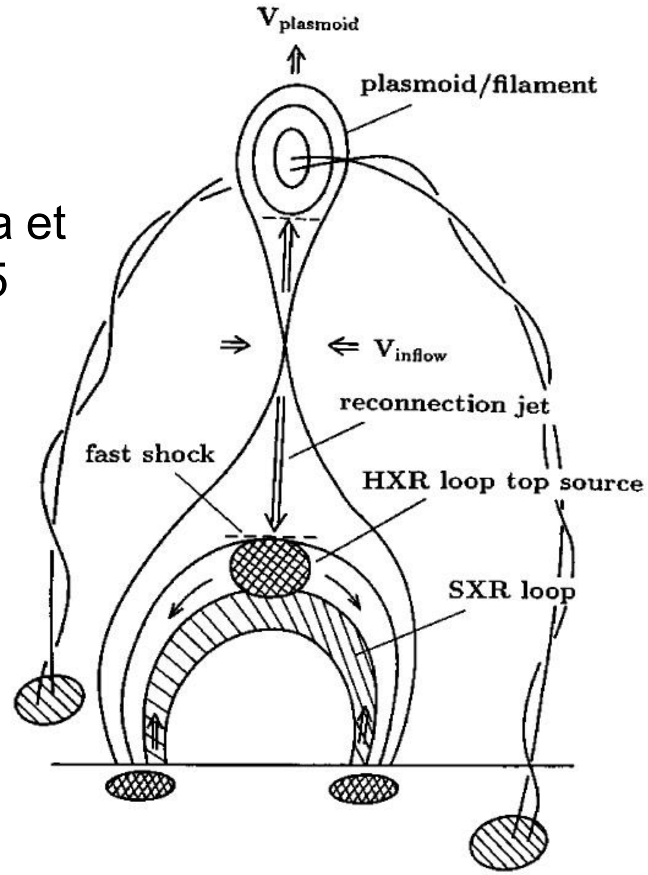


Emission lines < 10 keV [Doschek 2002]

Thermal bremsstrahlung up to 20 keV
(possibly low polarized if Maxwellian distribution of velocity is perturbed by plasma expansion along magnetic field lines due to heat propagation)
[Emslie & Brown 1980]

Non-thermal bremsstrahlung >20 keV
(highly polarized up to 40%)
[Zharkova et al. 2010]

Shibata et al.1995

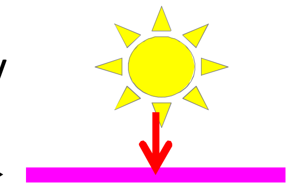


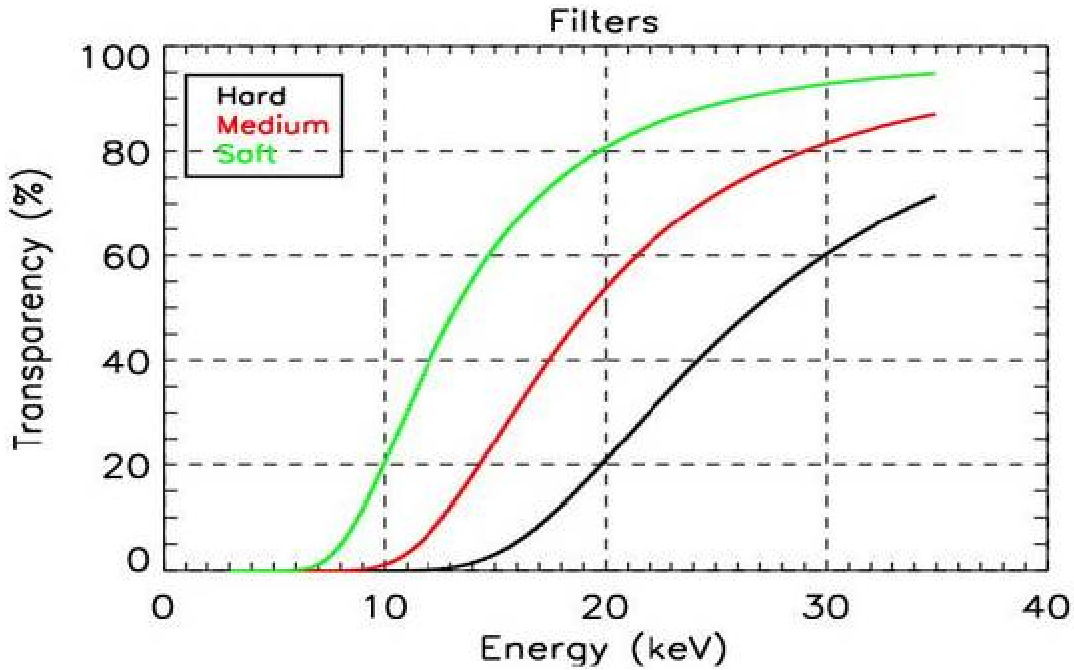
Moreover:
Scattering of radiation… therefore still polarization

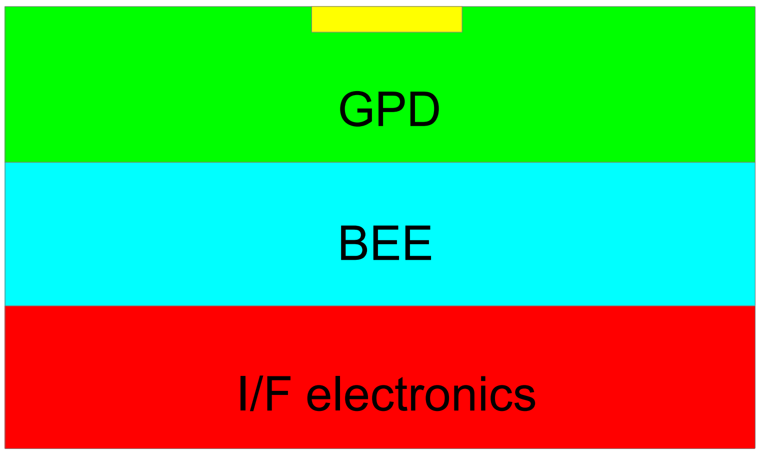
THE POLARIMETRIC PAYLOAD LAYOUT

2 GPD (MEP): Ar70%, DME30%,
3 atm, 3 cm, 2.25 cm^2
10-35 keV

Metallic low energy
radiation shield







Height (boards+GPD+HV)	< 10 cm
Total Weight	500 g
Total Power	< 5 W

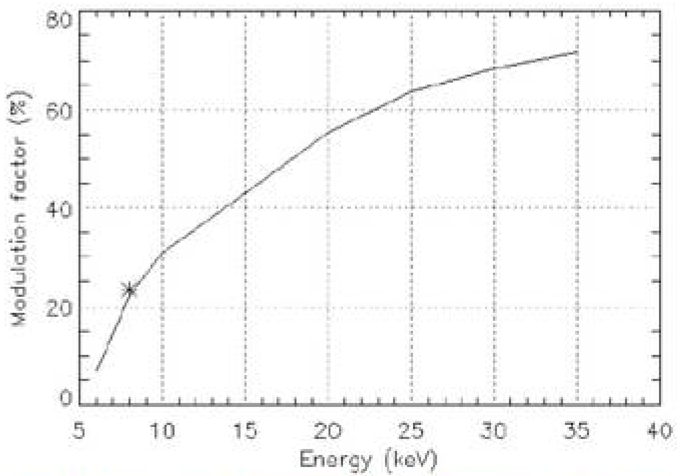
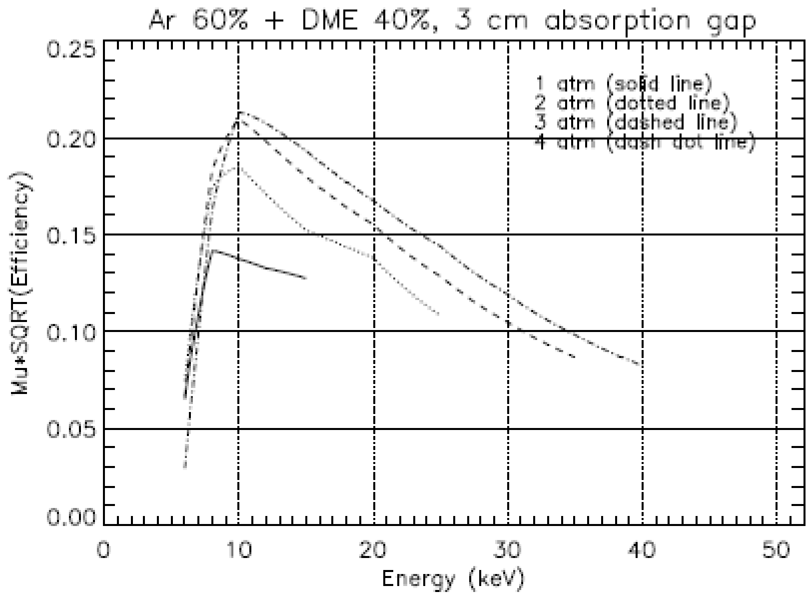
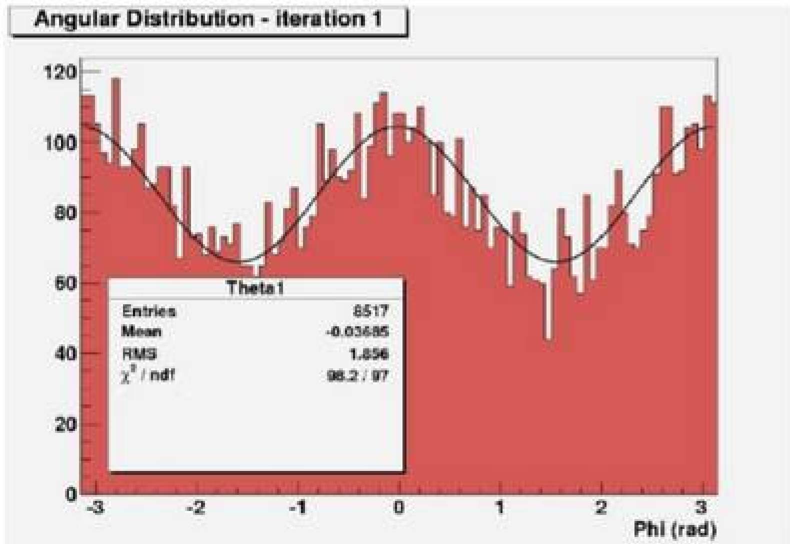


Figure 18 Modulation factor for a MEP prototype. The point is a real measurement at 8.0 keV (Muleri et. 2006).





Simulated observation from a sun-flare

Flare Class	Rate (cts/s) [2GPDs]	Filter type	Energy cuts (keV)	Pol. degree non-thermal comp. (%)	Integr. time (s)	Measured pol. degree (%)	Measured pol. degree 1-σ error (%)	Measured pol. angle 1-σ error (deg)	MDP (%)	Notes
X10	**$5.0x10^3$**	**Hard**	**15 – 35**		**180**				**0.9**	Single peak flare SOL20031029T19:49
				40		5.7	0.3	1.4		
				30		4.2	0.3	1.8		
				20		2.7	0.3	2.7		
				10		1.9	0.3	5.5		
X5	**$0.6x10^3$**	**Hard**	**15 – 35**		**110**				**3.2**	Single peak flare SOL20140225T00:46
				40		8.2	1	3.5		
				30		6.8	1	4.9		
				20		4.1	1	7.5		
				10		5	1	18.3		
X1.2	**$1.0x10^3$**	**Med.**	**14 – 35**		**300**				**1.7**	Single peak flare SOL20030529T00:25
				40		7.8	0.5	2.2		
				30		5.4	0.6	3.0		
				20		3.2	0.6	4.6		
				10		2.1	0.6	9.1		
M3.7	**$0.3x10^3$**	**Med.**	**13 – 35**		**120**				**5.4**	Forth peak of SOL20020415T00:15
				40		23.5	1.6	2.2		
				30		16.6	1.7	2.9		
				20		11.7	1.7	4.5		
				10		6.1	1.7	9.6		
M2	**$0.2x10^3$**	**Soft**	**12 – 35**		**80**				**8.0**	Single peak flare SOL20121120T12:39
				40		17.4	2.5	3.8		
				30		11.6	2.5	4.8		
				20		10.7	2.5	7.6		
				10		6.2	2.6	14.5		

2-GPDS

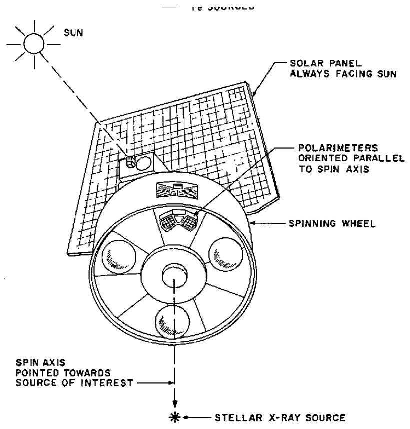
XIPE scientific goals

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

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

Very challenging measurements, but potentially very rewarding!!

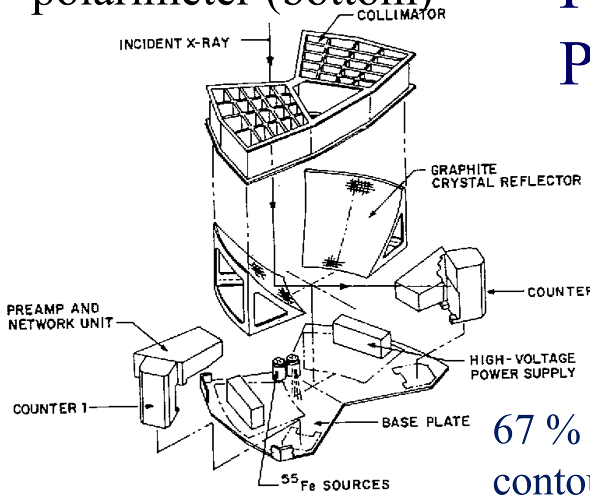
OSO-8 satellite with a dedicated Bragg polarimeter



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)

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



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

P = 19.2 ± 1.0 %; θ = 156.4° ± 1.4° (2.6 keV)

P = 19.5 ± 2.8 %; 152.6° ± 4.0° (5.2 keV)

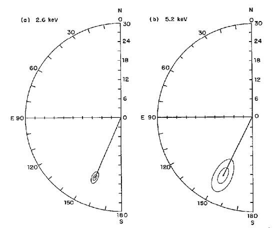
TABLE 3

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.

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



—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.

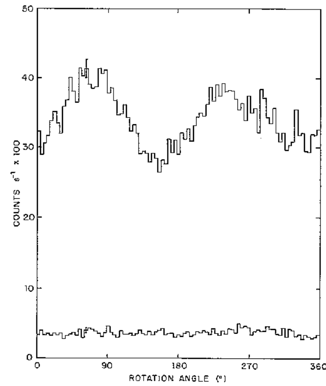


FIG. 2.—Average modulation curves obtained with both detectors at 2.6 keV during (*upper curve*) observations of the Crab Nebula and during (*lower curve*) observations of the Earth-occulted instrumental background.

From Bragg 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.

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.

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!

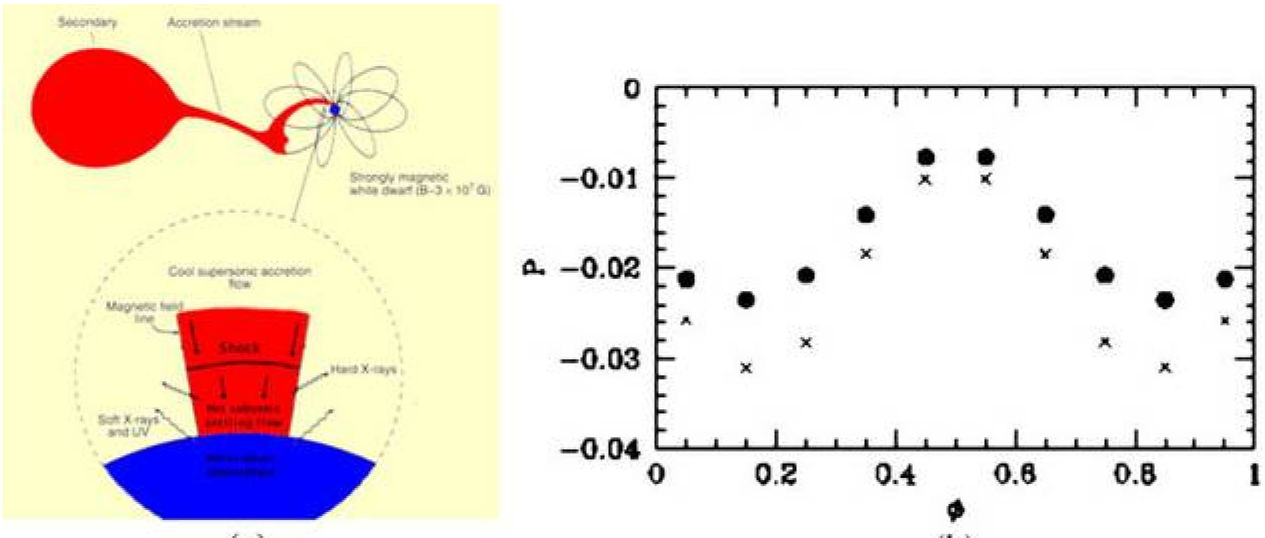
We are working very hard to have at least one GPD mission approved

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.

Shock near the WD surface. The post-shock material is cooled by emitting optical-IR cyclotron radiation and bremsstrahlung in X-rays. The X-rays are in part scattered and reflected by the WD surface, the disk (if present) and the magnetosphere. Scattering opacity in the accretion column need not be negligible for high accretion rates, and the emission may be polarized. The polarization depends on the viewing inclination of the accreting column and it is sensitive to the system configuration. The polarization signal is therefore periodic, with an amplitude reaching 4–8% (Matt 2004; McNamara et al. 2008). Reflection from the WD surface, which is relevant above a few keV, is also expected to be significantly polarized, providing a characteristic energy dependence of the polarization properties (Matt 2004). X-ray polarimetry can therefore help testing accretion models and determining model parameters.

Several bright intermediate polars, and certainly the brightest polar, AM Her, when in high state, can be searched for phase-dependent polarization. In the latter case, an MDP of 2.6% can be reached in 10 phase bins with 1Ms observation.



(a) (b)

Birefringence in the magnetosphere of magnetars

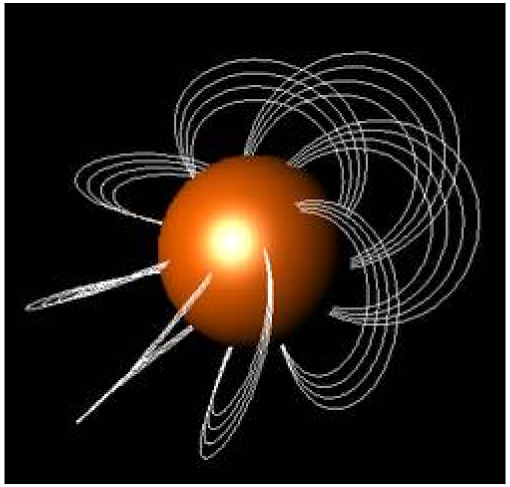
More papers on isolated neutron stars

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

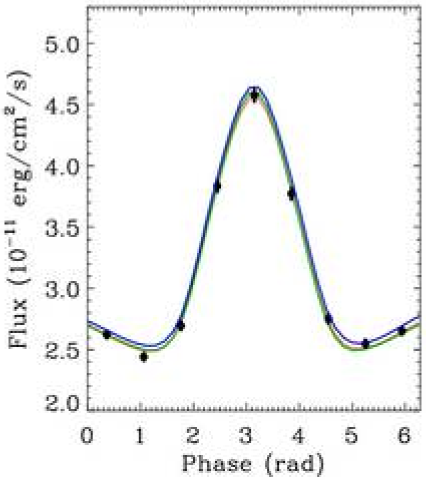
It heats the star crust and explains why the X-ray luminosity largely exceeds the spin down energy loss.

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

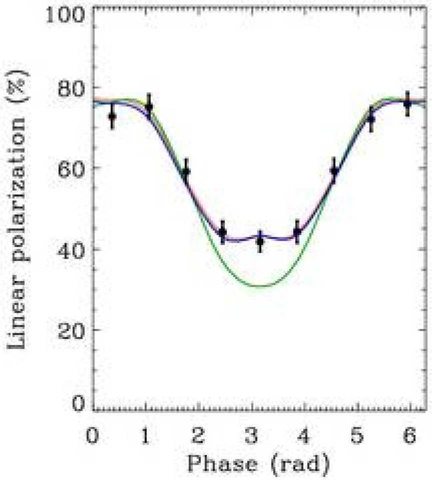
A twisted magnetic field.



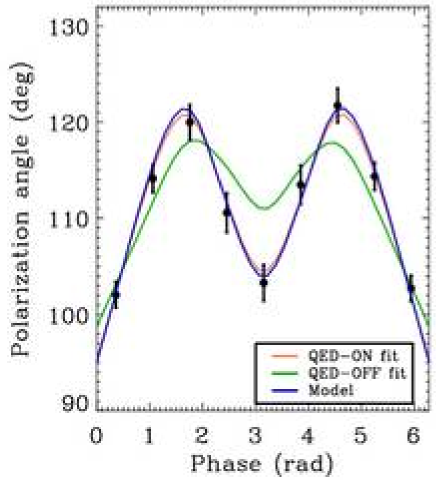
Light curve



Polarisation degree



Polarisation angle

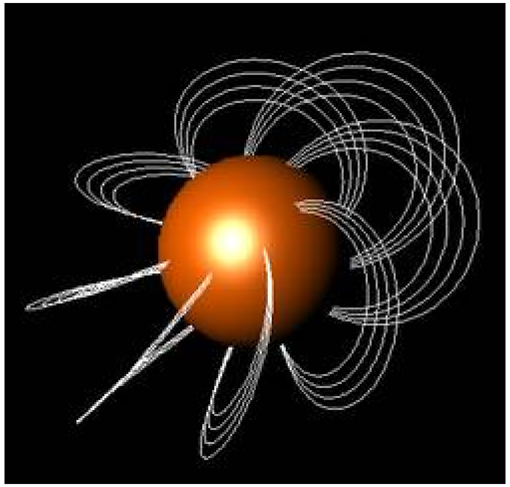


Such an effect is **only** visible in the phase dependent polarization degree and angle.

Fundamental Physics: Birefringence in the magnetosphere of magnetars

More papers on isolated neutron stars

A twisted magnetic field.



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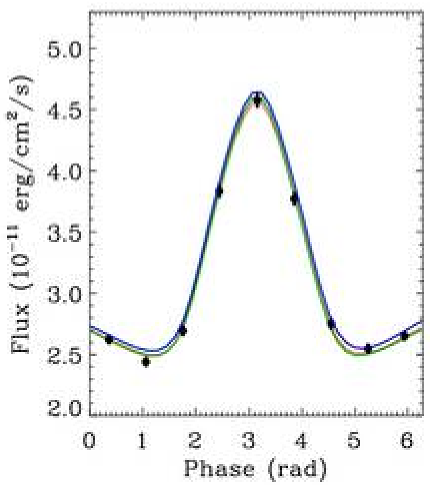
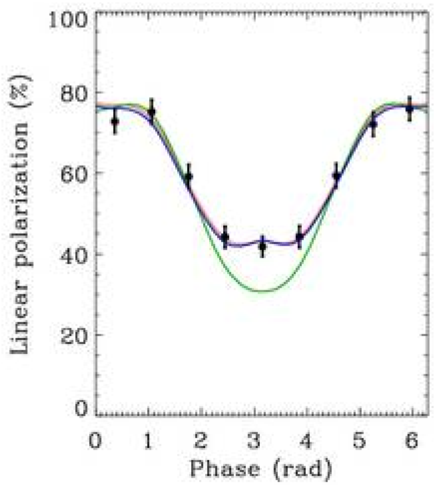
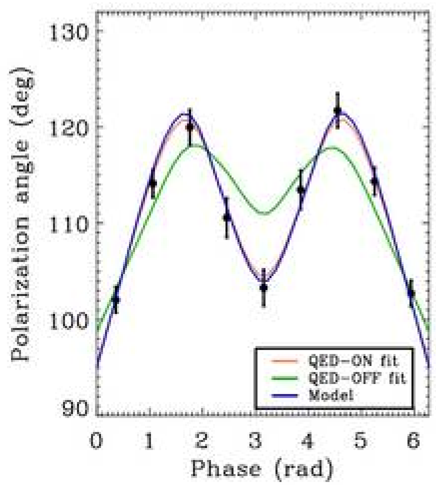
Light curve



Polarisation degree



Polarisation angle



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

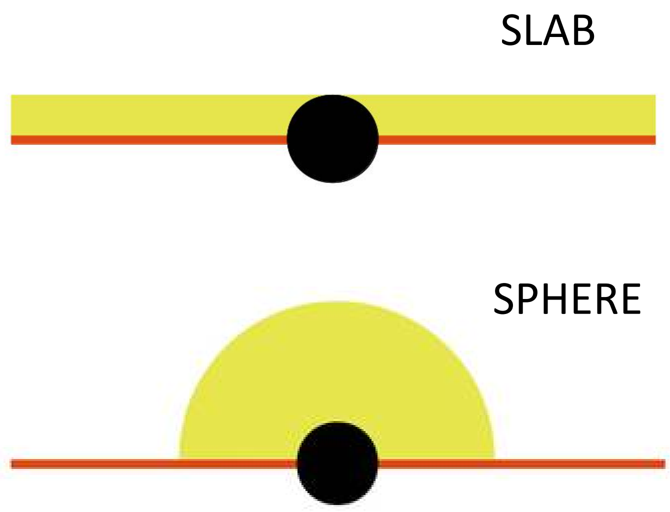
Constraining components of X-ray emission from AGNs

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.

Why do we need 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.

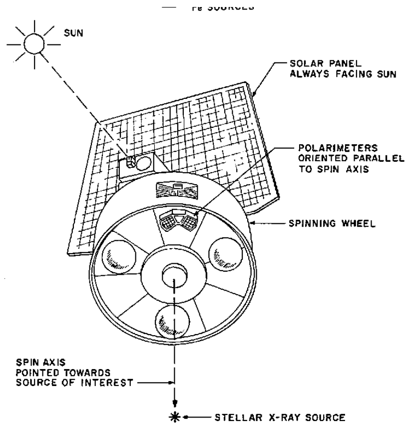
Of course let us focus on unresolved galactic sources

But is imaging useless for compact sources?

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.

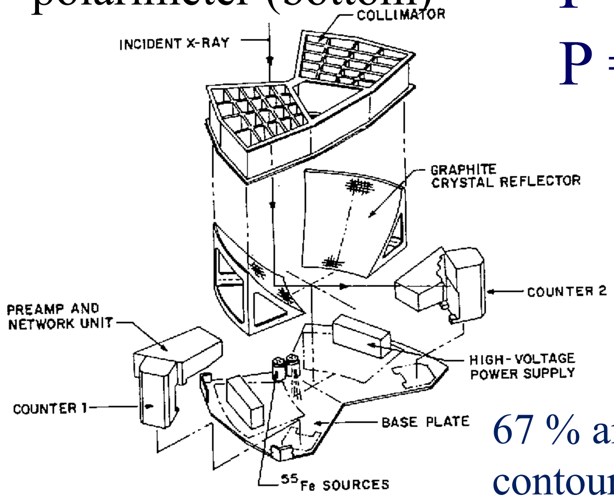
OSO-8 satellite with a dedicated Bragg polarimeter



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)

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



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

P = 19.2 ± 1.0 %; θ = 156.4° ± 1.4° (2.6 keV)

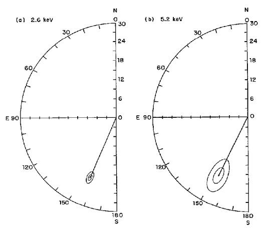
P = 19.5 ± 2.8 %; 152.6° ± 4.0° (5.2 keV)

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.

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



—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.

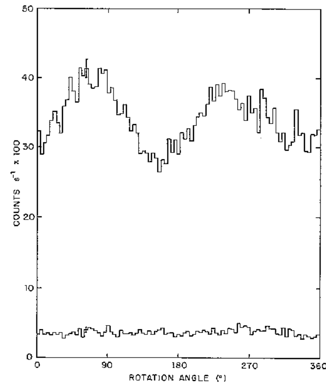
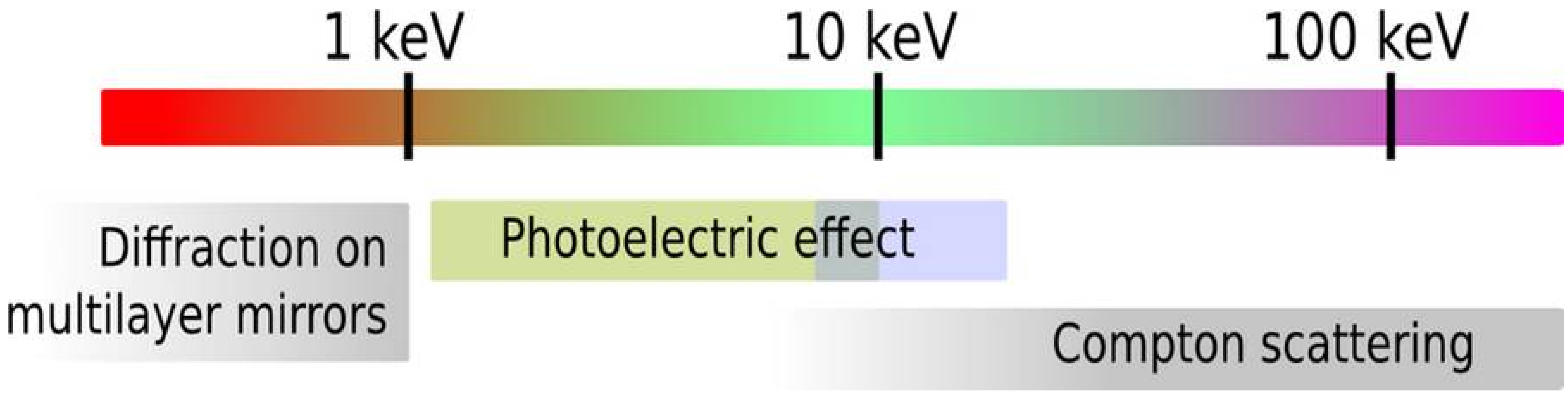


FIG. 2.—Average modulation curves obtained with both detectors at 2.6 keV during (*upper curve*) observations of the Crab Nebula and during (*lower curve*) observations of the Earth-occulted instrumental background.


1 keV
10 keV
100 keV
Diffraction on
multilayer mirrors
Photoelectric effect
Compton scattering

Tsinghua University built and tested a GPD.

INFN-Pi design, assembly procedure & ASIC. Tested @ Tsinghua with INFN-Pi DAQ

Progress at Tsinghua Univerisity (Prof. Hua Feng). A sealed detector 4 cm x 4 cm was built, filled and tested/calibrated with the INFN-Pi design, assembling procedures and ASIC using the Pisa electronics. The results are very good and consistent with those obtained by OXFORD detectors. Tsinghua will help to optimize the gas mixture for XIPE.

(Hong Li et al., accepted on NIM A http://arxiv.org/abs/1509.05595).

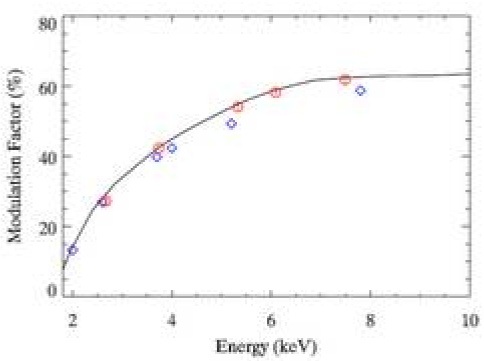


Figure 13: Modulation factor versus energy. The red circles indicate results measured with our detector, while the blue diamonds are results obtained by a previous detector with the same gas mixture [13]. The solid curve is the result obtained using GEANT4/Garfield simulations.

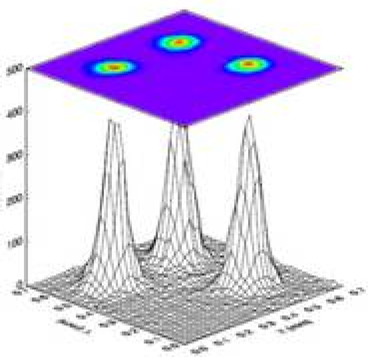


Figure 16: Image of three sources with 300 μm apart in X and Y.

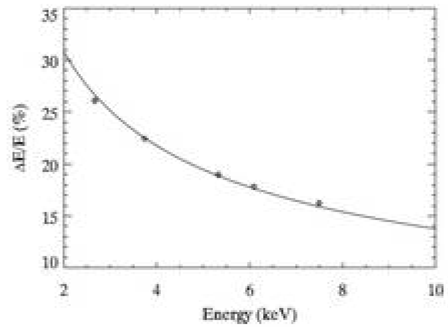


Figure 10: Measured energy resolution (ΔE = FWHM) versus the X-ray energy, along with a best-fit curve in the form of $\Delta E/E \propto 1/\sqrt{E}$.

Many proposed X-ray polarimetry missions triggered by this new technique.

From 2002 to 2008 missions proposed to NASA, ESA, ASI, JAXA and CNSA

A polarimeter was supposed to fly on XEUS/IXO.

Athena without a polarimeter was selected for L2

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

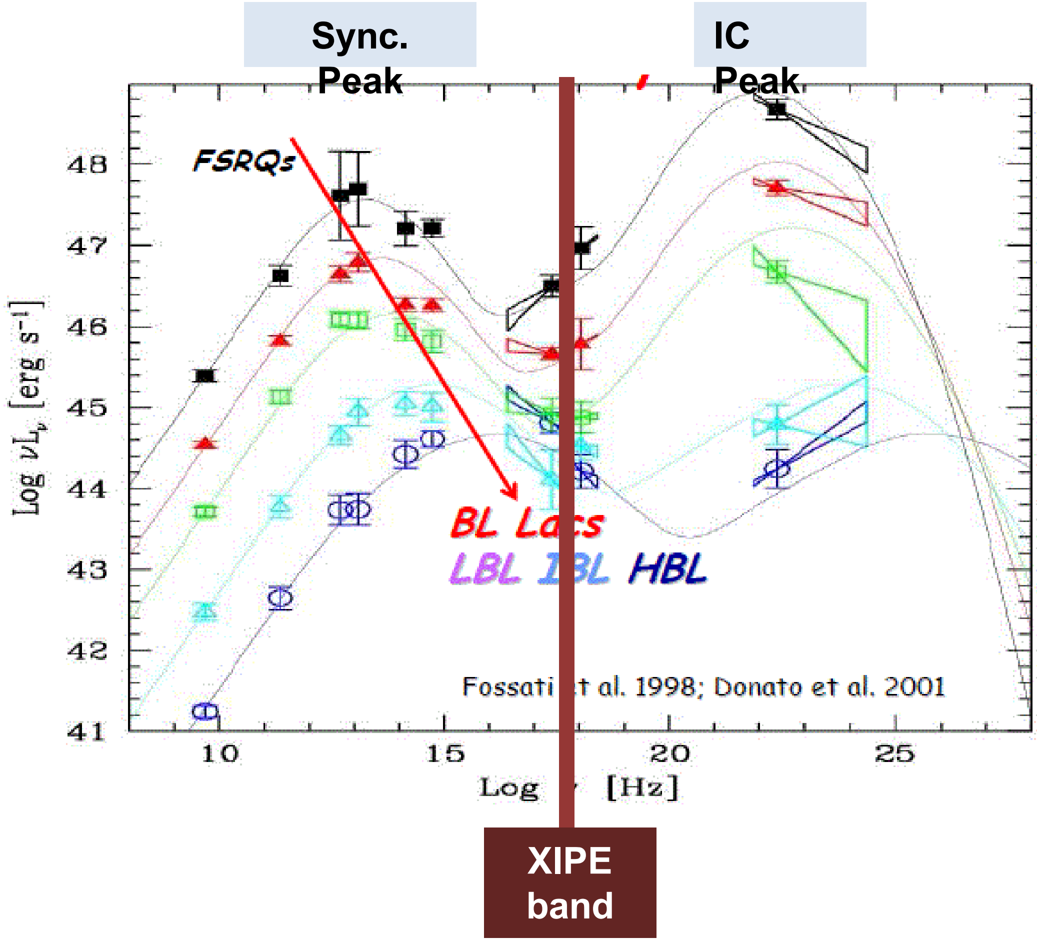
GEMS was selected by NASA on May 2008 to fly on 2014 but stopped in 2012 for programmatic reasons.

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

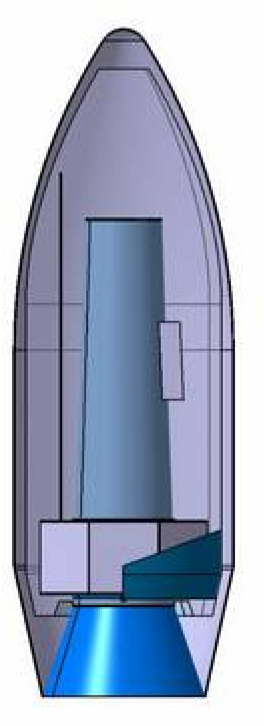
Models predict a larger and more variable polarisation in X-rays than in the optical.

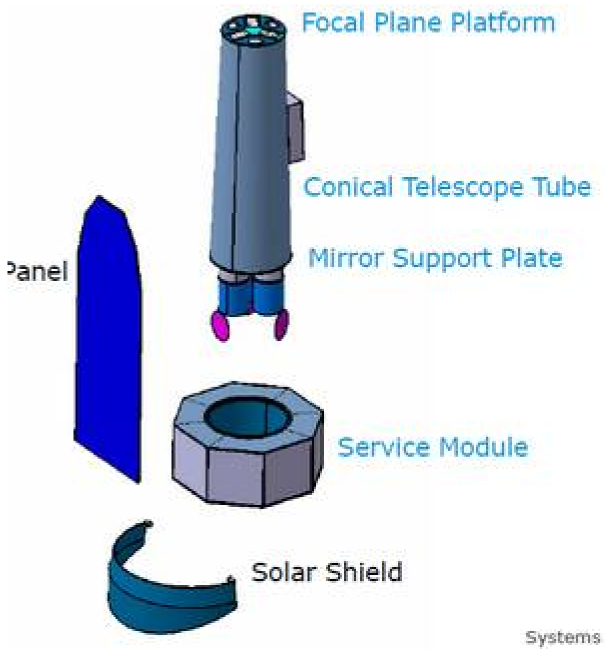
Coordinated multi-wavelength campaigns are crucial for blazars.

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



Out-come of the ESA CDF





- Configuration of the proposal basically confirmed
- Vega Launcher confirmed for 3.5 m focal length. A possible longer focal length will be studied (Goal 4 m)
- Orbit confirmed.
- Efficiency requirement met.
- Power and mass confirmed.
- Estimated cost well within the cap.
- Low risk mission.
- Flight ready for launch before 2026

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.

XIPE Science Requirements

The energy band

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