X-Ray Imaging Light Polarimetry Explorer

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On behalf of a large collaboration

Big hopes. Meager results

Polarimetry is an [almost] undisclosed domain of X-ray Astronomy. It can be performed, with a wealth of guaranteed results and with a large discovery space.

In 50 years of X-ray Astronomy only one positive detection of X-ray Polarization: the Crab (Novick et al. 1972, Weisskopf et al.1976, Weisskopf et al. 1978):

$$P = 19.2 \pm 1.0\ \%; \quad \varphi = 156.4^{o} \pm 1.4^{o}$$

The only dedicated instrument, OSO-8 gave this result plus a fistful of upper limits of moderate significancy. Spectrum-X-Gamma mission, including a polarimeter was approved but never flown.

The technique have been the limit

After 2001 new, much more sensitive, techniques based on photoelectric effect in gas are available. One mission, GEMS, was approved by NASA but cancelled later due to programmatic reasons.

A blank blackboard

- After the suppression of IXO and GEMS no experiment of X-ray polarimetry is approved
- Only one instrument of γ-ray polarimetry is approved (ASTRO-H)
- In the future possibly Timing and Polarimetry X-ray Mission (XTP)

Competing techniques for which proposals have been submitted in past years:
1) photoelectric polarimetry with focal plane TPC (GSFC)/Tsinghua Un.
More sensitive than GPD (~2)
Not imaging
Needs rotation
2) Diffractive polarimeter MIT (multilayer + CCD), LAMP (Tsinghua Un./Tonji Univ./IAPS/INFN
Low energy ~200 eV
3) Focal Plane Scattering Polarimetry, Washington University Saint Louis, balloon.
3) Byproduct polarimetry (CosX, NUSTAR, CCD,…)
Sensitivity: very low Control of Systematics: not discussed but likely very poor.

The XILPE Concept

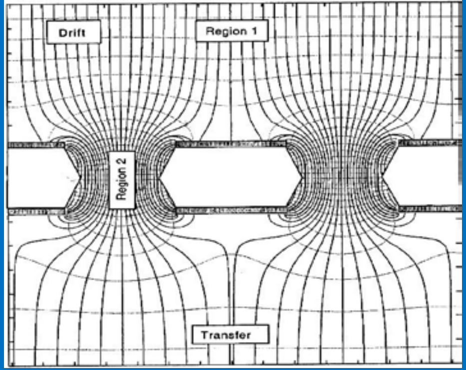
To open the window of X-ray polarimetry by:

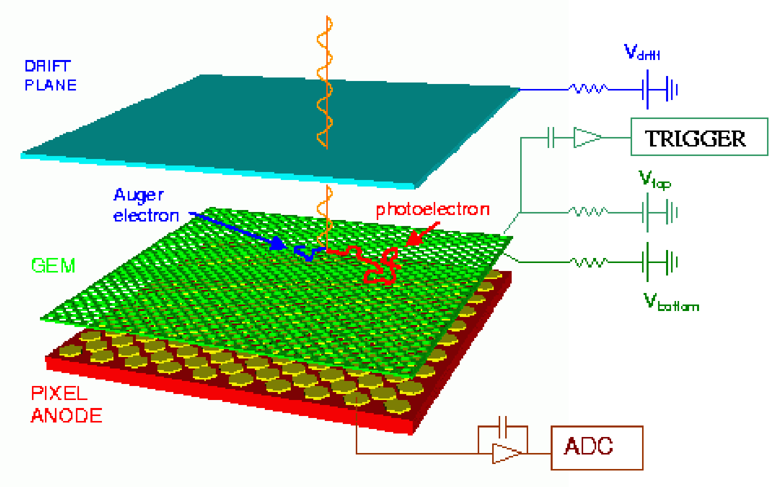
- Exploiting the capability of Gas Pixel Detectors, an all european technology, primarly developed by Pisa INFN, now jointly studied with IAPS-Rome and Tsinghua University-Beijing, to perform polarimetry, imaging, timing and spectroscopy of X-sources, with unprecedented sensitivity, when used as a focal plane device.
- Benefiting of the existing telescopes developed by OAB for the JET-X program and already tested in flight with SWIFT. The exstence of mandrels could allow (NtH) for the manufacture of two more telescopes.
- By a wise use of already available items and, in any case, of high TRL technology, we want to make a break-through mission in the tight programmatic and finacial limits defined by the announcement (2+4 years; 50×2 M€).

X-ray polarimetry with a Gas Pixel Detector

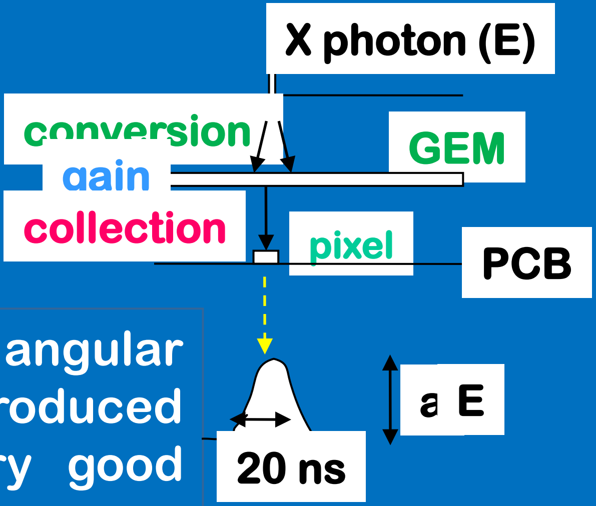
A photon cross a Beryllium window and it is absorbed in the gas gap, the photoelectron produces a track. The track drifts toward the multiplication stage that is the GEM (Gas Electron Multiplier) which is a kapton foil metallized on both side and perforated by microscopic holes (30 um diameter, 50 um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

GEM electric field



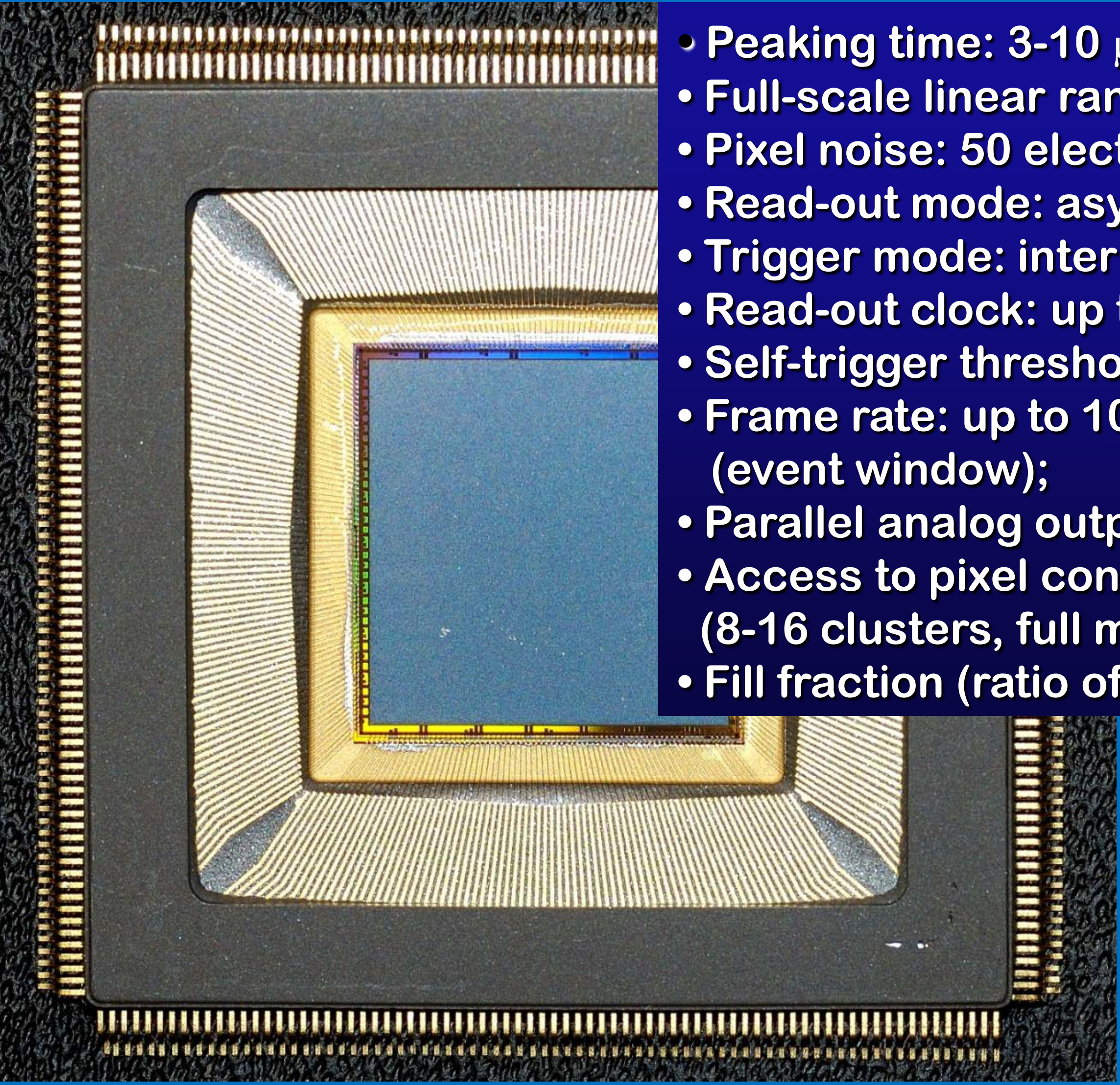


Costa et al., 2001, Bellazzini et al.2006, 2007



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.

ASIC features 105600 pixels 50 µm pitch

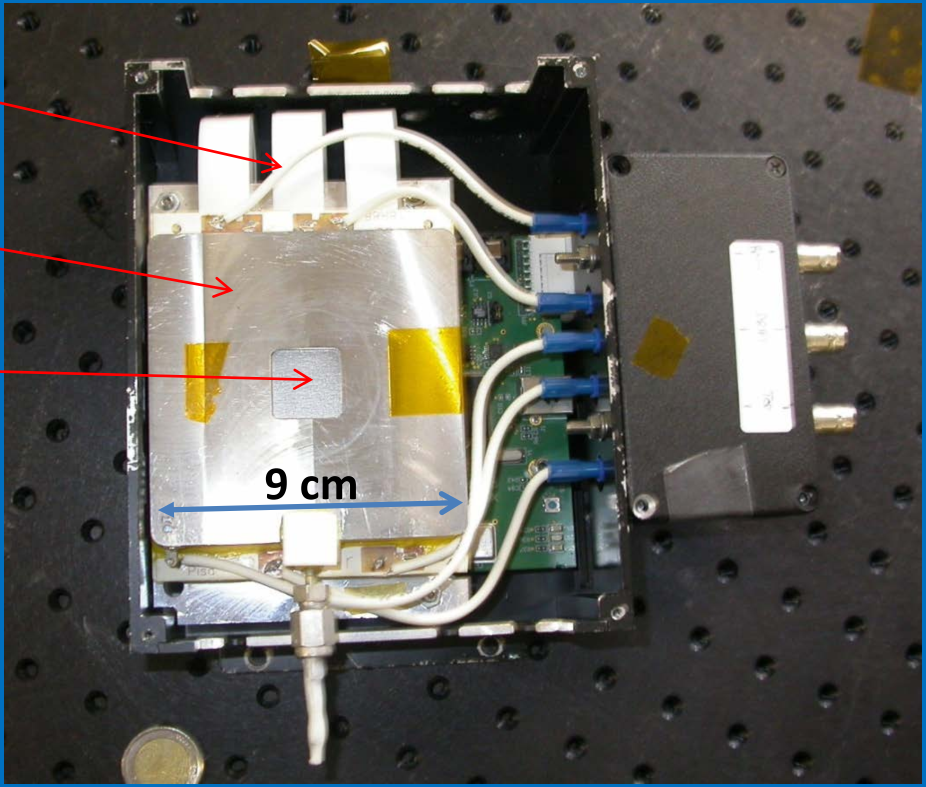


- Peaking time: 3-10 µs, externally adjustable;
- Full-scale linear range: 30000 electrons;
- Pixel noise: 50 electrons ENC;
- Read-out mode: asynchronous or synchronous;
- Trigger mode: internal, external or self-trigger;
- Read-out clock: up to 10MHz;
- Self-trigger threshold: 2200 electrons (10% FS);
- Frame rate: up to 10 kHz in self-trigger mode (event window);
- Parallel analog output buffers: 1, 8 or 16;
- Access to pixel content: direct (single pixel) or serial (8-16 clusters, full matrix, region of interest);
- Fill fraction (ratio of metal area to active area): 92%)

The chip is self-triggered and low noise. It is not necessary to readout the entire chip since it is capable to define the sub-frame that surround the track. The dead time downloading an average of 1000 pixels is 100 time lower with respect to a download of 10^5 pixel.

Extensively tested, with thermal-vacuum cycles, it has been vibrated, irradiated with Fe ions and calibrated with polarized and unpolarized X-rays..

The real implementation of a working GPD prototype.

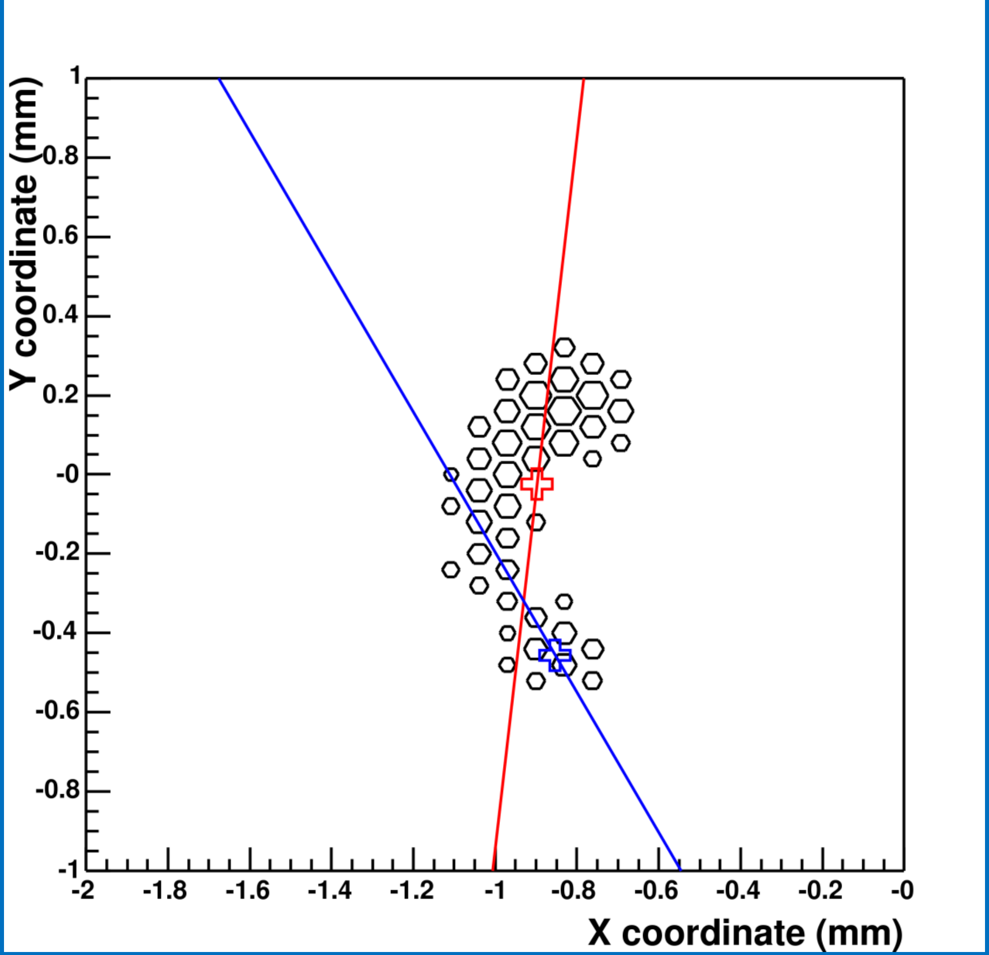


DME = $\mathrm{(CH3)_2O}$

60 μm/$\sqrt{\text{cm}}$ diffusion

Weight of the Detector (including FEE) is 400g
Power Consumption of the Detector 2W

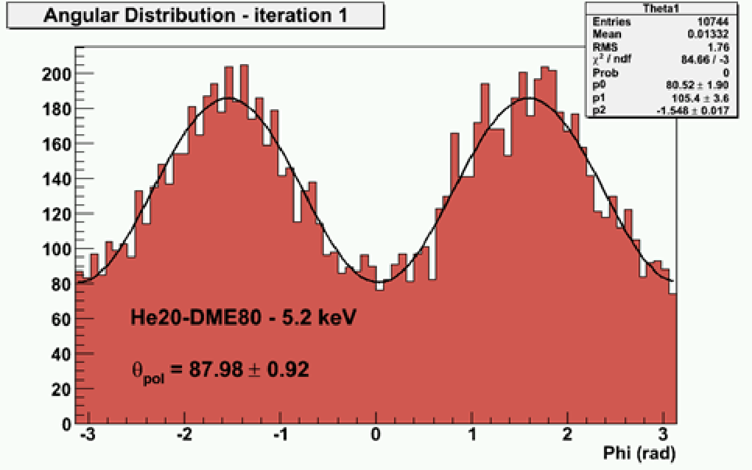
Tracks analysis



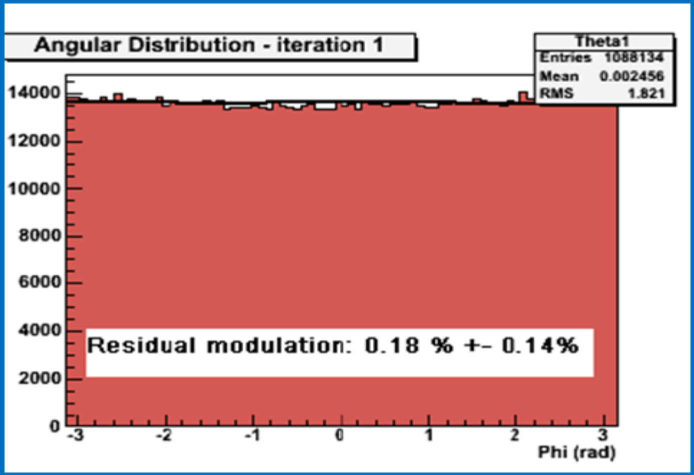
From the analysis of the track we reconstruct the original direction of the photoelectron (blue line) and the impact point (blue cross).

The hystogram of direction gives the polarization

polarized beam



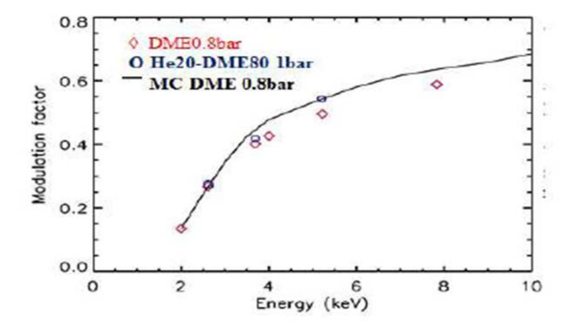
unpolarized beam



The system is axis-symmetric and rotation is not needed. For each photon we measure the location, the time, the energy and the angle of polarization.

The Minimum Detectable Polarization (99%) depends on the modulation factor μ and on the number of detected photons

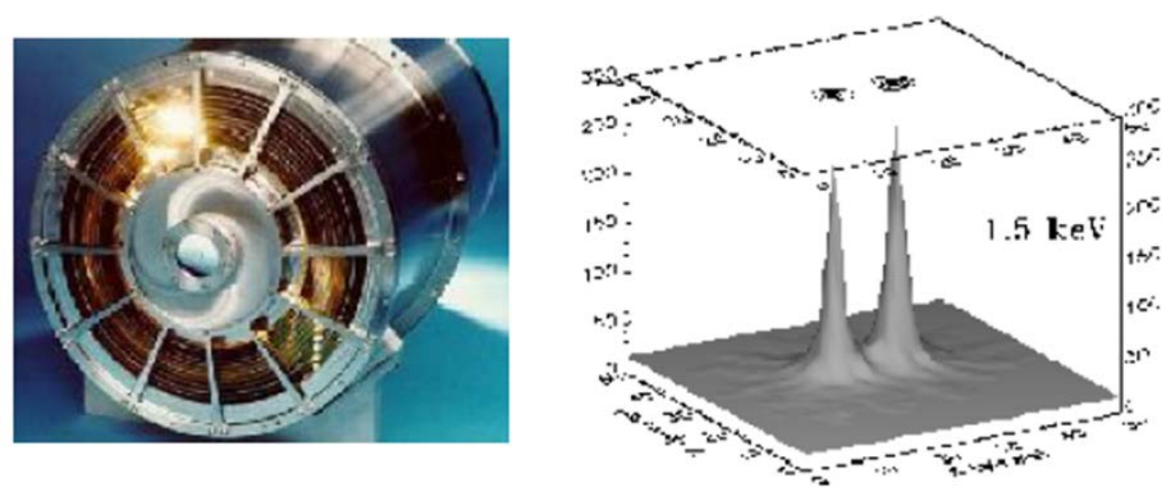
$$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N_{ph}}}$$

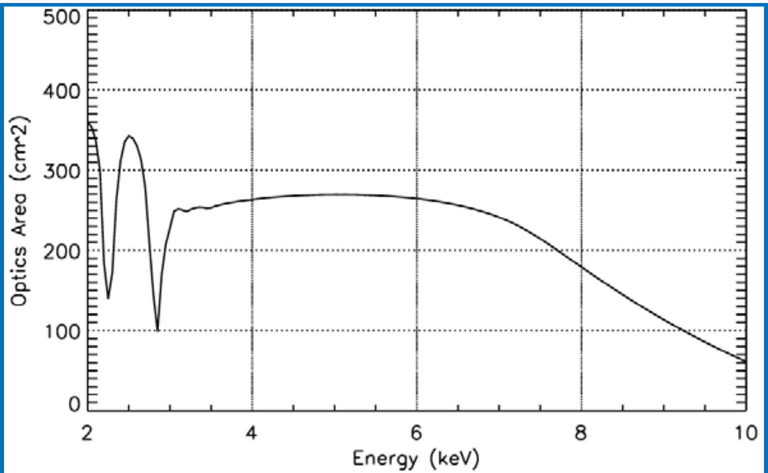


μ

The Parent Proposal: XIPE proposed as ESA SM1 AOO

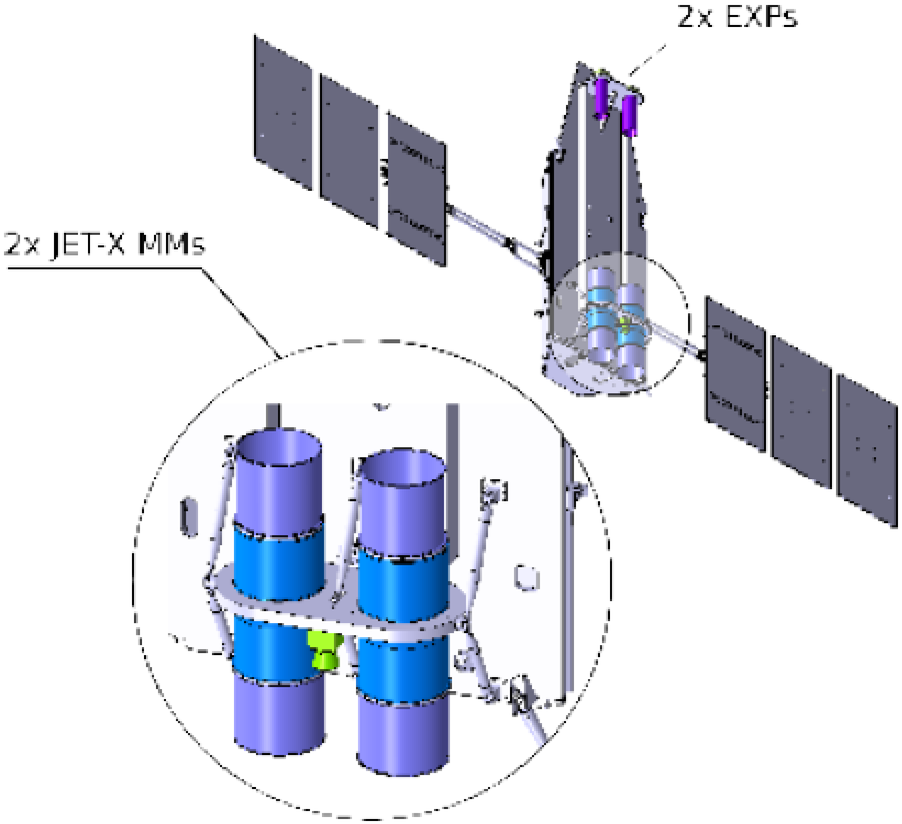
- 2 X-ray Telescopes From the JET-X Program
- GPD detectors already sudied for XEUS and IXO Program
- The sandard bus of IRIDIUM Program

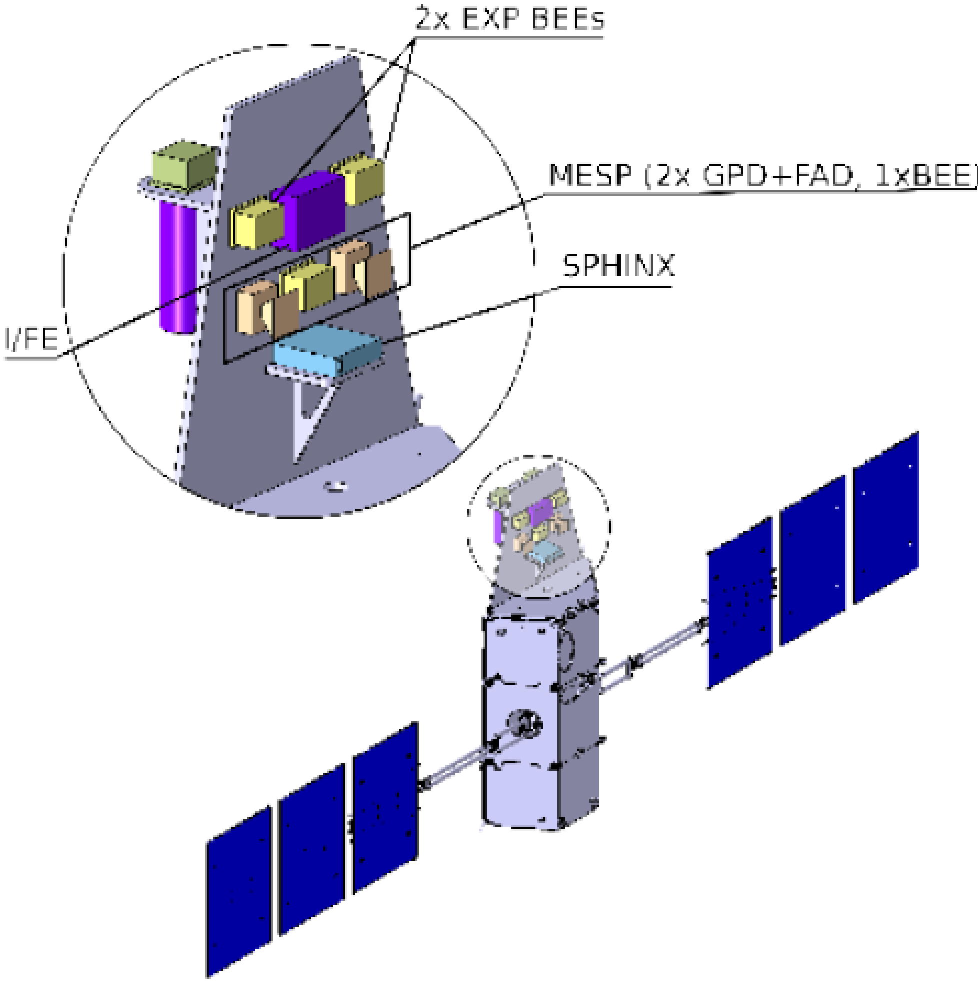




The XIPE mission

Proposed to ESA small mission call for a launch in 2017.
- 2 Jet-X optics
- 2 + 2 GPDs
- Solar photometer
- commercial bus





XILPE after XIPE not selected

XIPE was submitted at the first AOO for an ESA small mission

Good evaluation by ESA from the feasibility and readiness. Weak only from the budget point of view.

CHEOPS (exoplanets photometry) was selected

From the debriefing following the selection we derive major guidelines both related to remove the criticalities and mitigate the complexity of XIPE and the related costs:

1) The total mass should have more margin to the bus capability
2) The solar polarimeters are more suitable for a solar mission. In fact they will be proposed within the solar mission SEEPE.
3) One telescope is sufficient for a pathfinder small mission

In response to the ESA-CAS announcement we propose XILPE: a Ligth (=descooped) version of XIPE.

No solar polarimeters. One telescope only.

We hope to fit the (very tight) boundaries fixed by the announcement?

JET-X telescopes are existing, integrated and calibrated. One of them is flying aboard SWIFT (=TRL 8). The long term stability of one of them has been already tested at PANTER facility.

Yet a single telescope and the structure to fix it has a mass of 70kg and is by itself out of the mass boundaries. We can image 3 strategies:

1) ESA and CAS relax the boundary on the mass given that the item that exceeds these boundaries is already existing and TRL=8.
2) We manufacture a new telescope starting from the same mandrels. With nowadays technology a telescope with thinner shells (0.2 mm) could have similar performance with a total mass of the order of 20 kg.
3) We build a completely new telescope based on thin shells, with a larger number of shells and, possibly, a shorter focal length, to reduce the requirements to the bus in terms of thermal stabilization and of AOCS.

The 3 stategies have increasing costs. The strategy 3) would also significantly improve the performance in terms of sensitivity (with some trade-off on angular resolution).

An example of optimized optics

A single telescope with a focal length of 2100 mm composed by 30 shell with diameter ranging from 90 to 270 mm. Iridium and Carbon coating is foreseen for the 22 outer shells.

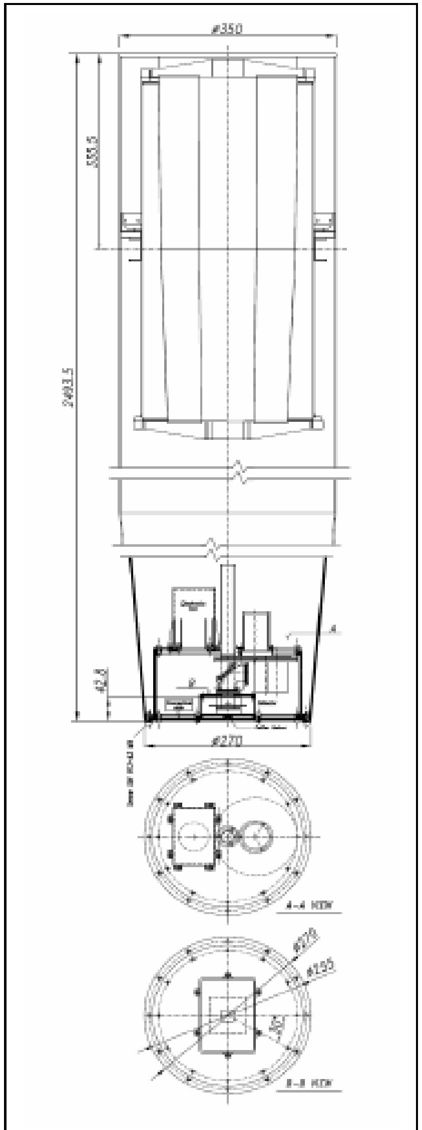
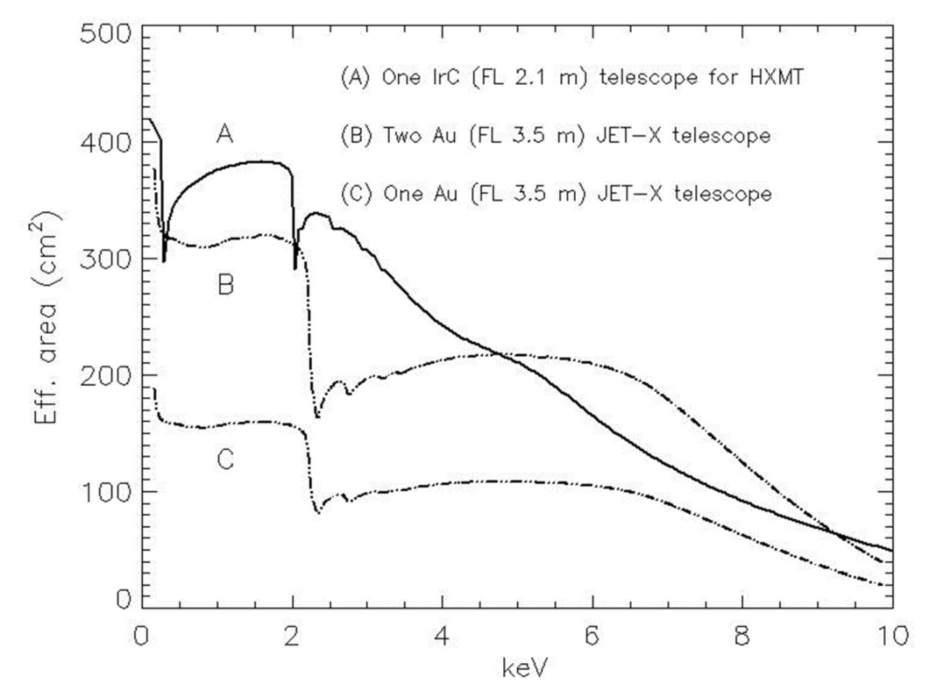


Fig. 8 The unit composed by the



1) The effective are of one telescope is larger than that of two JET-X telecopes.
2) Because of the shorter focal length some of the ingredients of the PSF would increas. The HEW could move from 23 to ~ 35 arcseconds.

An example of optimized optics

Such a telescope would have a mass of about 30 kg. Also e considerable reduction of mass is expected from the shorter focal length (2.1 m instead of 3.5 m) that would also reduce the requirements on thermal stabilization, given that both the telescope and the focal plane will be within the shadow of the bus. In any case the design of a new optics could be less ambitious and be assessed on a lower mass, while, in any case, be an improvement with respect to a single JET-X optics.

To resume we will work on a design that could fit within the boundaries of the call while providing a sensitivity spanning from that of XIPE and that of ½ XIPE.

I will show that this is still sufficient to be an enormous improvement with respect to the present situation and a break-through in High Energy Astrophysics.

Readiness

GPD detectors have been extensively tested, also under the control of ESA, for XEUS and IXO studies.

JET-X telescops have been tested and calibrated one unit has been calibrated again on december 2012 at PANTER facility. The performance is basically the same it was at beginning. One unit of the lot is part of SWIFT XRT.

In case we go to hypothesis 2) or 3) the technique of producing and mounting thin shells has been also extensively tested and can be considered very robust.

In fact even though the telescope is not there as the JET-X one are we can state that there is nothing new in what we are proposing.

Media Lario's "replication by electroforming" technology has enabled almost all X-ray observatory missions of the last 20 years with high-precision nickel mirrors

1993

Beppo SAX (ASI)

- 4 mirror modules
- 30 mirrors/module
- Thickness: 0.4-2 mm
- HEW@1,5keV: 60 "

1995

JET-X → SWIFT (NASA-ASI)

- 1 mirror module
- 12 mirrors/module
- Thickness: 0.4-1.5 mm
- HEW@1,5keV: 15 "

1999

XMM (ESA)

The most powerful X-ray telescope ever built

- 3 mirror modules
- 58 mirrors/module
- Thickness: 0.5-1 mm
- HEW@1,5keV: 13"

2010

ASI-sponsored technology development for NHXM

- New mandrel manufacturing technology
- Aperiodic multilayer for hard-X ray reflection

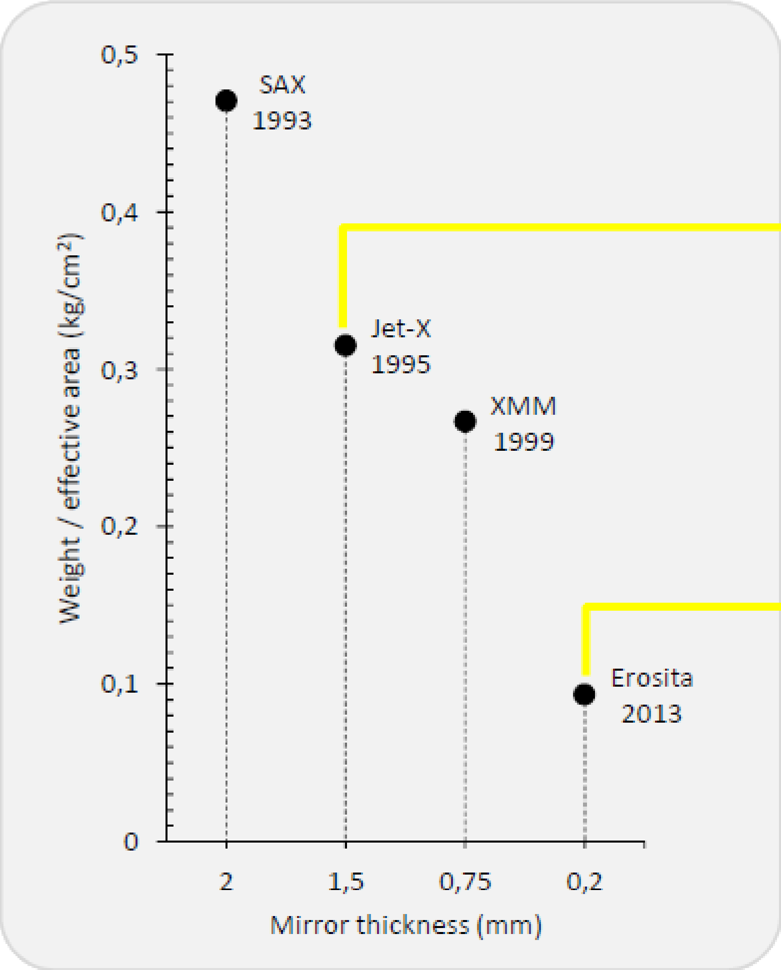
2013

EROSITA (MPE)

- 7 mirror modules
- 54 mirrors/module
- Thickness: 0.2-0.5 mm
- HEW@1,5keV: 14"

In 20 years, Media Lario has reduced mirror thickness by 10 times, enabling 60% weight reduction of the mirrors

Weight/effective area versus mirror thickness



	20 years ago	Today
Year	1995	2014
Mirror modules	3	1
Mirrors per module	12	12
Mirror thickness	1-2 mm	0.2-0.5 mm
Average mirror weight	3 kg	1.2 kg (-60%)

Year		2013
Mirror modules		7
Mirrors per module		54
Mirror thickness		0.2-0.5 mm
Average mirror weight		0.5 kg

The chinese contribution

To define the chinese contribution.
A collaboration with Tsinghua University is already active on GPD detectors.

Optics could be another area of interest.

Although ASI is in a transition phase we can expect that Italy, beside detectors and optics could privide the Malindi Base and the ASI Scientific Data Center, that could start from the strong heritage of the activities performed for SAX, SWIFT and NUSTAR.

A.o.b. is on the table.

XILPE

Polarization sensitivity	**19.8% @ 1mCrab T= 10^5 s**
Imaging capability	23.2’’ (HEW); 14’.7 x 14’.7 (FOV)
Spectral resolution	20 % @ 6 keV
Timing	2 μs (Accuracy) 10 μs (Dead Time)
Gas Mixture	20 % He-80% DME 1-atm 1-cm
Energy range	2-10 keV
Crab rate	47.6 counts/s
Background rate	1.0 10^{-6} c/s (21 nCrab)

Why Polarimetry? Digging in literature

Astrophysics

Acceleration phenomena:

- Pulsar wind nebulae
- µQSO
- Blazar and radiogalaxy
- Solar Flares

Emission in magnetic fields:

- Emission in strong magnetic fields: magnetic cataclysmic variables
- Emission in strong magnetic fields: accreting millisecond pulsars
- Emission in very strong magnetic fields: accreting X-ray pulsars

Scattering in aspherical situations

- X-ray binaries
- Radio-quiet AGN
- X-ray reflection nebulae

Fundamental Physics

Matter in Extreme Magnetic Fields: QED effects

Matter in Extreme Gravitational Fields: GR effects

Quantum Gravity

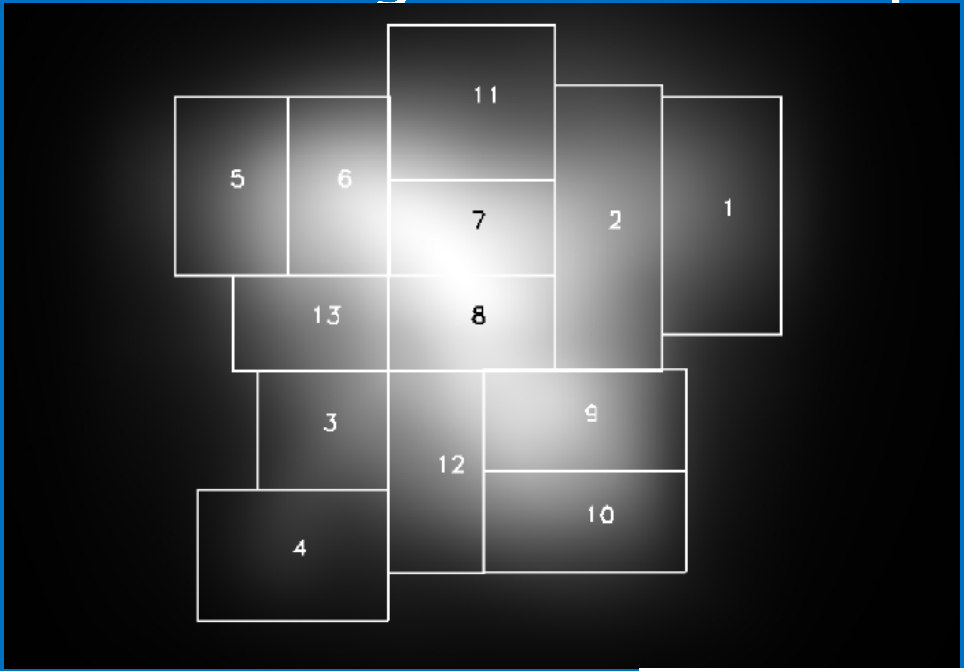
Search for axion-like particles

Which Science with XILPE? A few examples

XILPE can perform significant measurements useful to disentingle geometric parameters from physical ones and to remove degeneracy from models complementing the data from spectroscopy, timing and imaging, for a certain number of sources belonging to the previous list of topics. See the paper on XIPE by Soffitta et al. Experimental Astronomy, Vol.36, pp.523, 2013.

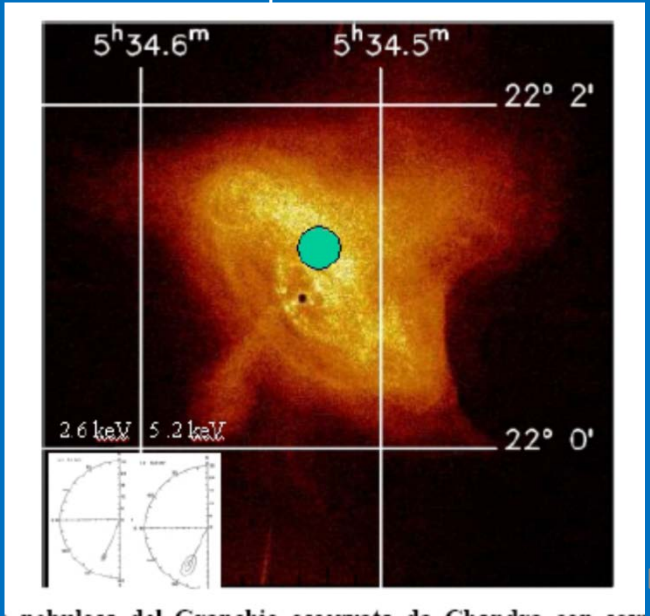
In the following we only give a few examples:

Angular resolved polarimetry of Crab



We simulated a long observation of Crab with XIPE. We blurred the Chandra image to account for the limited resolution of XIPE. The major features are still visible. We computed the sensitivity to the amount and angle of polarization for different selected regions of the nebula.

Fabiani et al. ApJ under review.



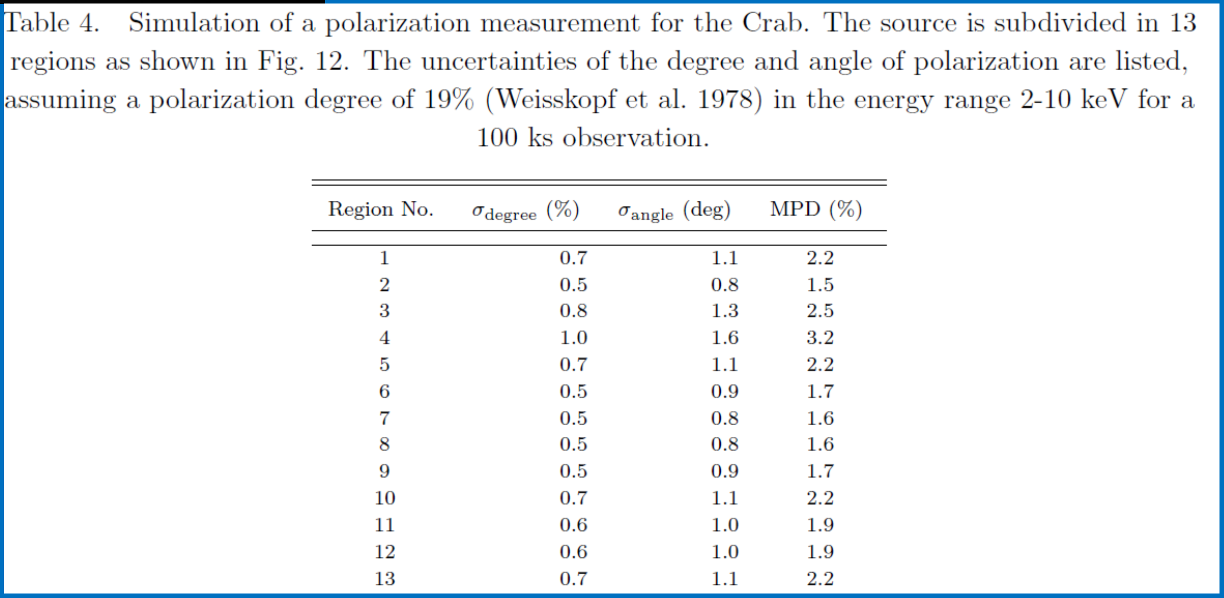


Table 4. Simulation of a polarization measurement for the Crab. The source is subdivided in 13 regions as shown in Fig. 12. The uncertainties of the degree and angle of polarization are listed, assuming a polarization degree of 19% (Weisskopf et al. 1978) in the energy range 2-10 keV for a 100 ks observation.

Region No.	$\sigma_{\rm degree}$ (%)	$\sigma_{\rm angle}$ (deg)	MPD (%)
1	0.7	1.1	2.2
2	0.5	0.8	1.5
3	0.8	1.3	2.5
4	1.0	1.6	3.2
5	0.7	1.1	2.2
6	0.5	0.9	1.7
7	0.5	0.8	1.6
8	0.5	0.8	1.6
9	0.5	0.9	1.7
10	0.7	1.1	2.2
11	0.6	1.0	1.9
12	0.6	1.0	1.9
13	0.7	1.1	2.2

Acceleration: SNR

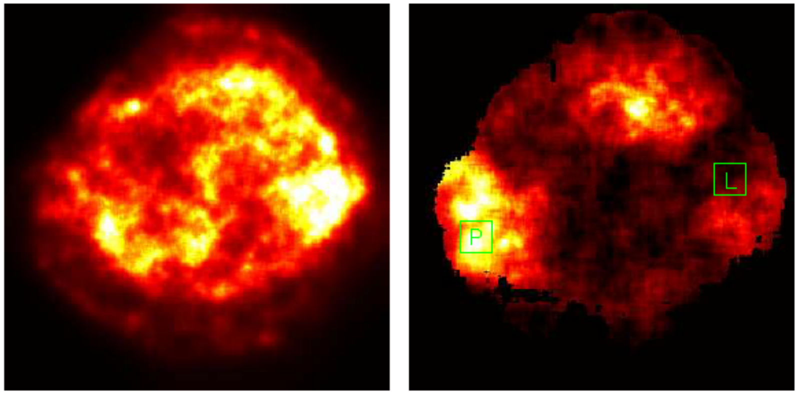
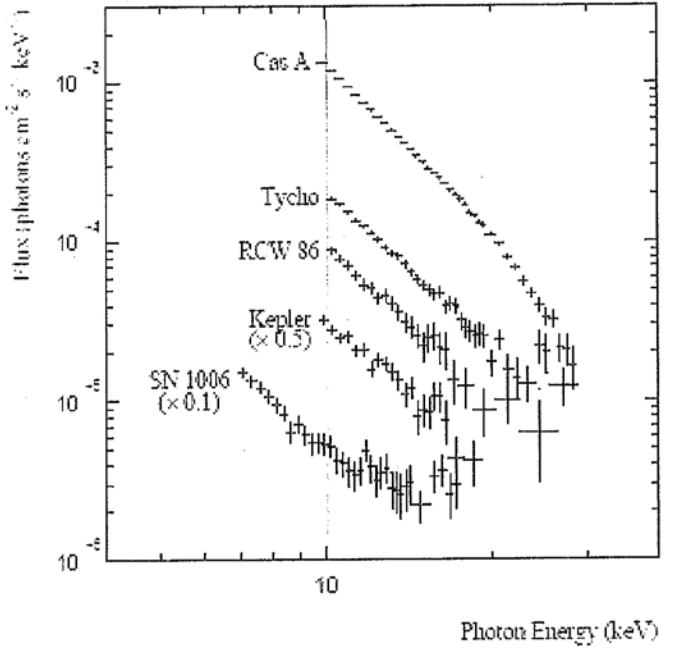
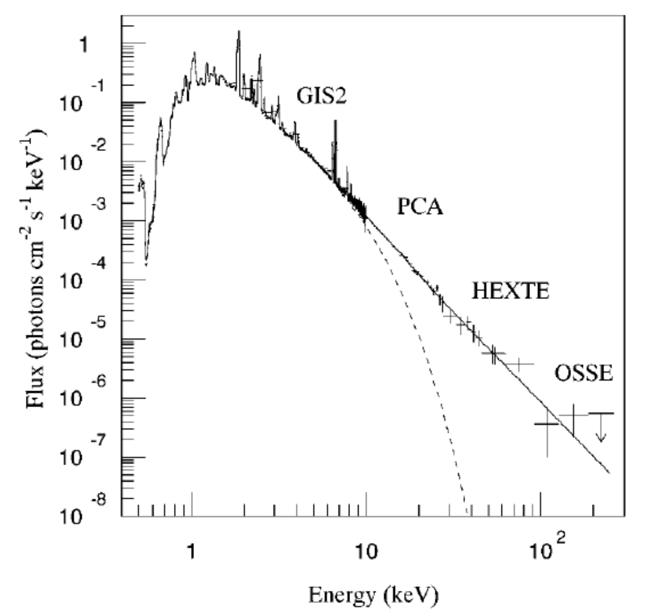


Fig. 2. Continuum 4.06–6.07 keV (left) and Fe K equivalent width (right) black 0 keV to white 4 keV and above.





It is well established that SN are one of the sites of acceleration of CR. The X-ray emission is dominated by the thermalemission from the heathed ISM. In SNR the high energy tails show a non thermal emission, in the front regions of the shock. This could also be singed out by polarimetry, depending on how mch the magnetic fields are ordered.

When Our Galaxy was an AGN

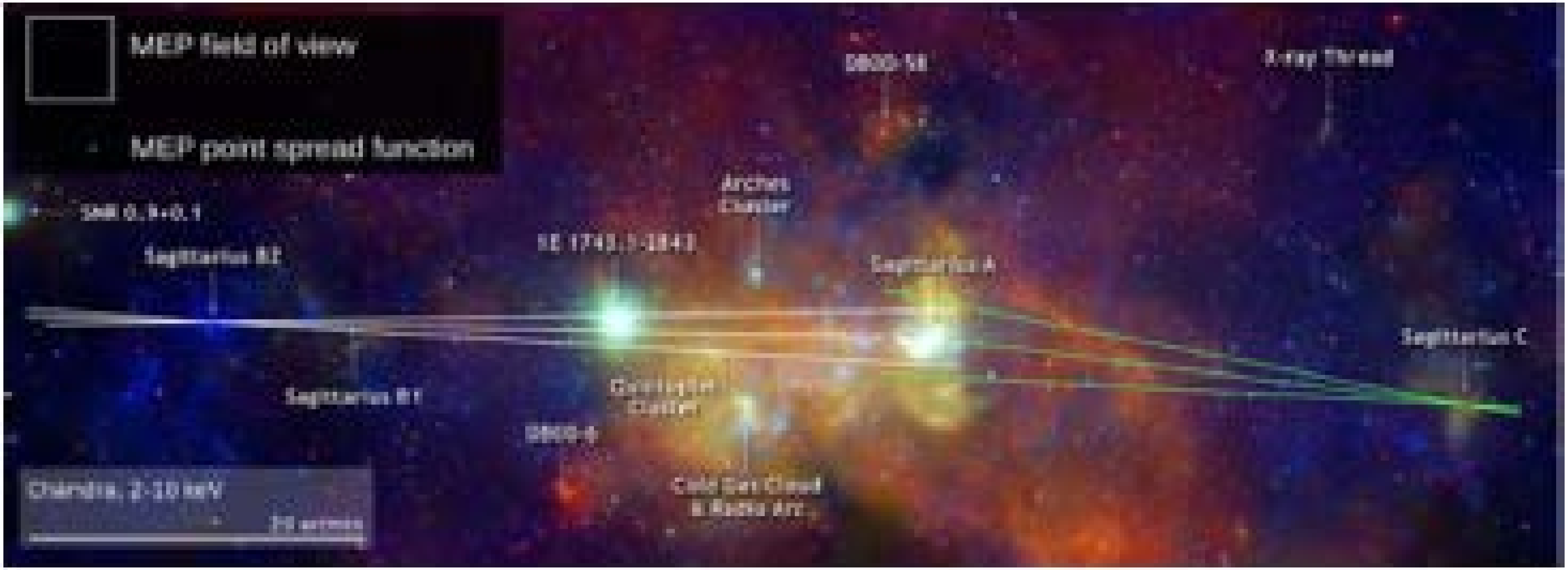
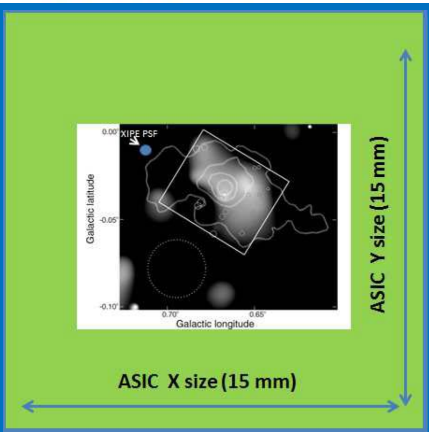
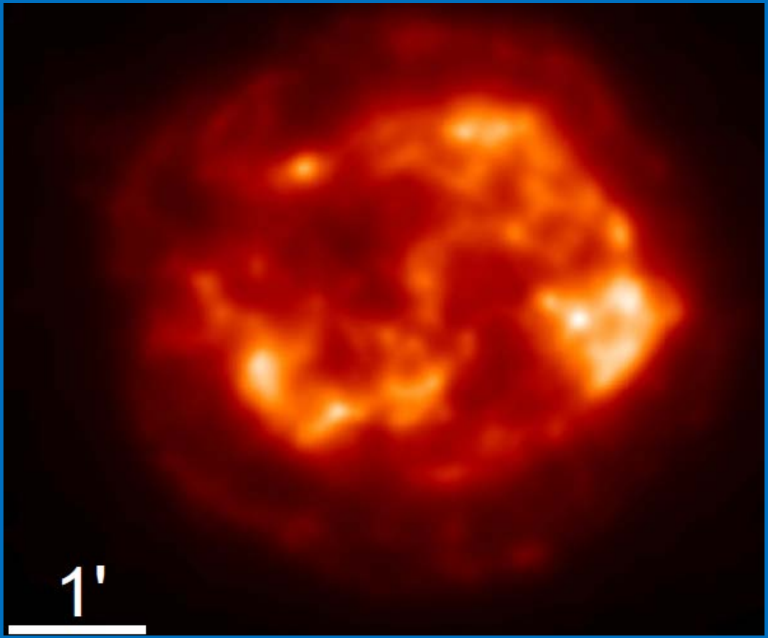


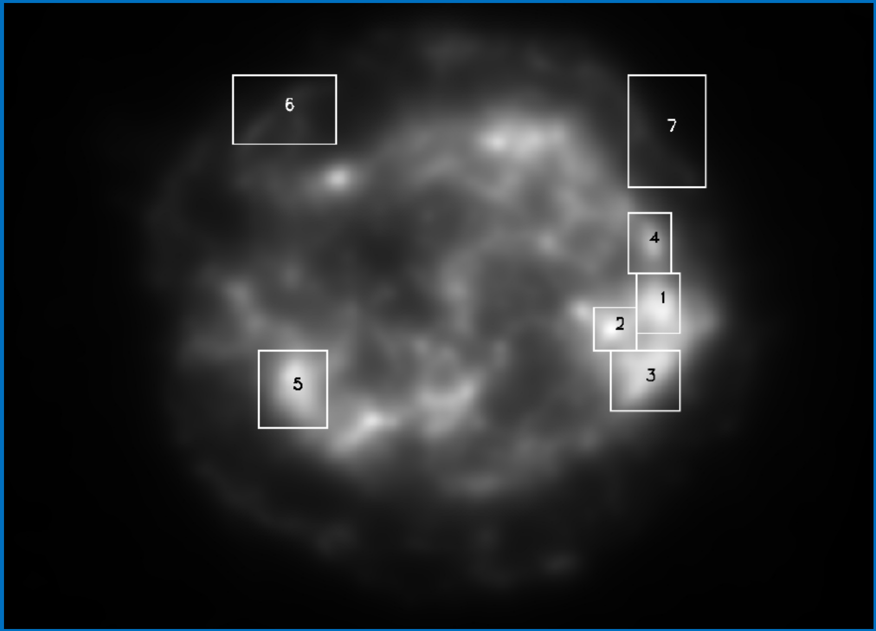
Fig. 3 SgrA*, SgrB2, SgrB1 and SgrC region as seen by Chandra. Overlaid are the angular constraints on the source illuminating Sgr B2 and Sgr C, that can be derived with an observation of the Medium Energy Polarimetric camera (see payload section)

Definitely imaging is needed
also in this case



Angular resolved polarimetry of CAS-A





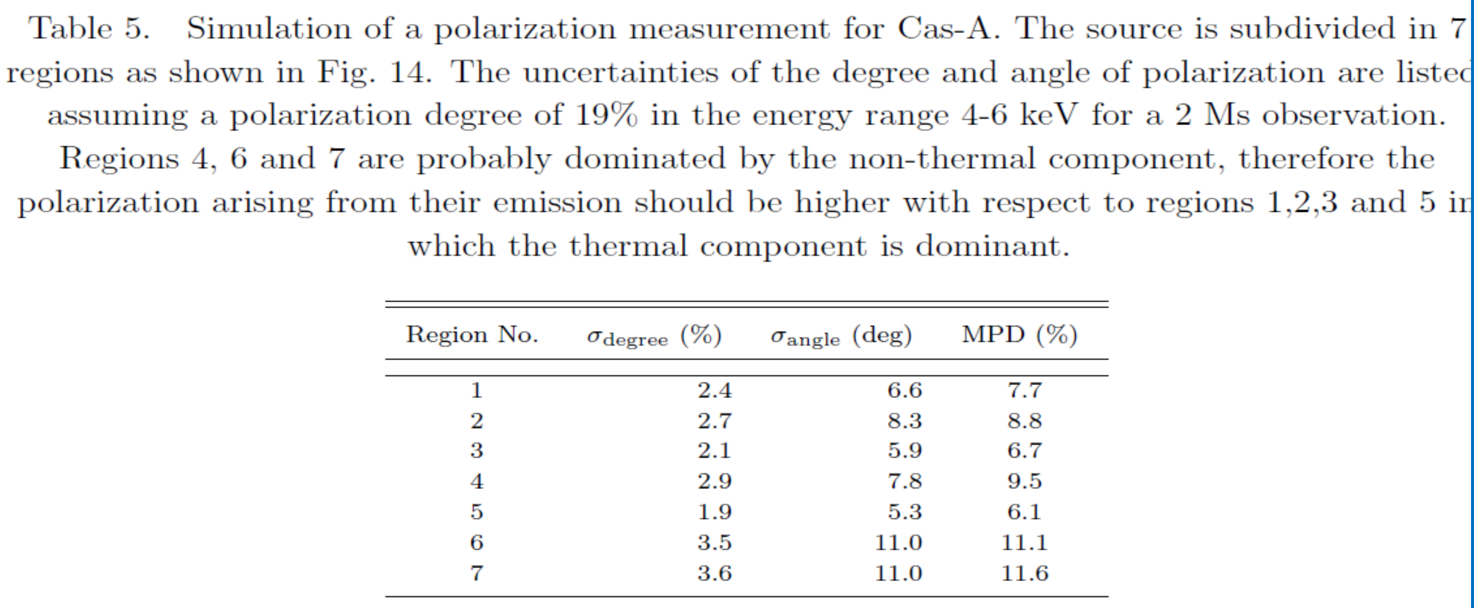


Table 5. Simulation of a polarization measurement for Cas-A. The source is subdivided in 7 regions as shown in Fig. 14. The uncertainties of the degree and angle of polarization are liste assuming a polarization degree of 19% in the energy range 4-6 keV for a 2 Ms observation. Regions 4, 6 and 7 are probably dominated by the non-thermal component, therefore the polarization arising from their emission should be higher with respect to regions 1,2,3 and 5 i which the thermal component is dominant.

Region No.	σ_{degree} (%)	σ_{angle} (deg)	MPD (%)
1	2.4	6.6	7.7
2	2.7	8.3	8.8
3	2.1	5.9	6.7
4	2.9	7.8	9.5
5	1.9	5.3	6.1
6	3.5	11.0	11.1
7	3.6	11.0	11.6

Blazars: acceleration processes and more …

While the polarization angles of synchrotron and SSC emission are expected to be the same, and perpendicular to the magnetic field (Celotti & Matt 1994), in the external photons model the IC polarization is related to the jet axis (Begelman & Sikora 1987), and the polarization angle in the two peaks needs no longer to be the same. In both models, the polarization degree (see Figure 2) is expected to be very high, up to 50% or more unless the electrons responsible for the IC emission are hot (see also Poutanen 1994).

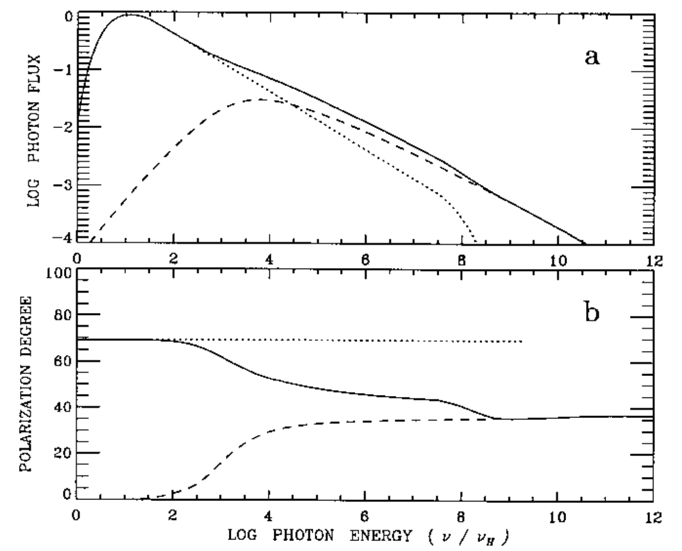
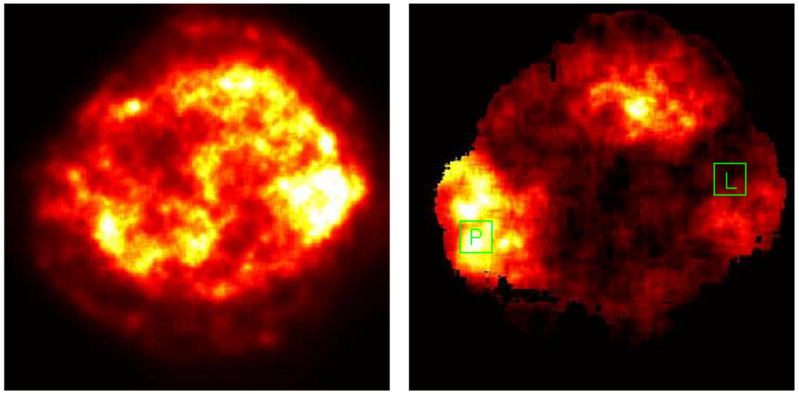


FIG. 1.—(*a*) Intensity and (*b*) polarization of synchrotron self-Compton radiation. *Dotted lines*—initial synchrotron radiation; *dashed lines*—inverse Compton scattered radiation; *solid lines*—intensity and polarization of the total radiation. Here $\tau = 0.1$, $\alpha = 0.5$, $\sin \zeta = 1$, and $\gamma_{\rm min} = 10$.

Blazars in synchrotron regime can also provide a «ladder» to test theories of Loop Quantum Gravity that predict that the polarization angle rotates with the distance and with the square of the energy. With XILPE we can arrive with an observation of 2×10^6s, values of η down to 3×10^{-10} can be measured with XIPE using e.g. the known Blazar 1ES1101+232, at z=0.186, with clear synchrotron spectrum and high optical polarization, assuming it has a 10% polarization degree in the X-ray band.

Acceleration: SNR



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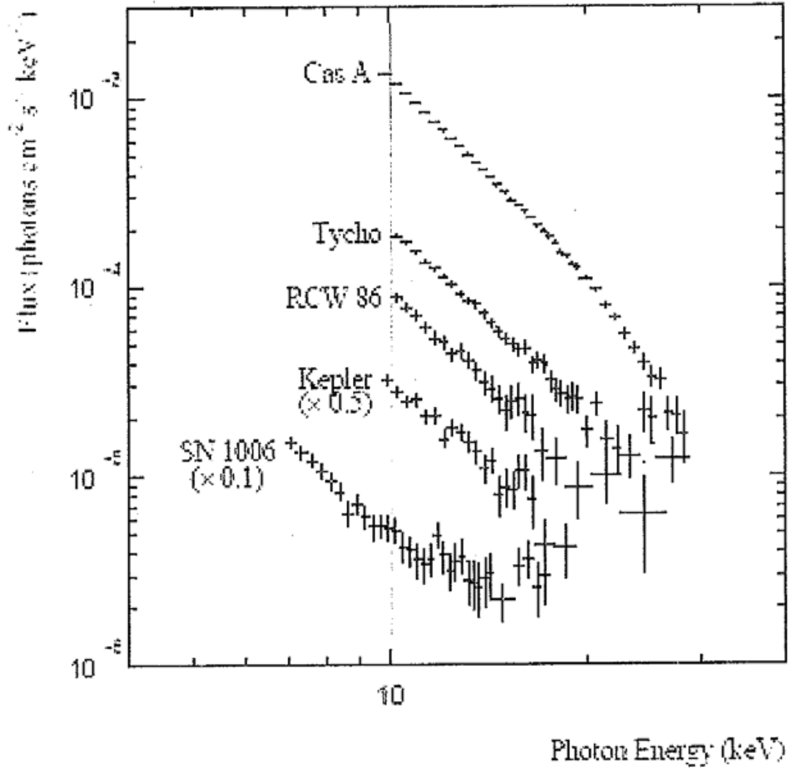
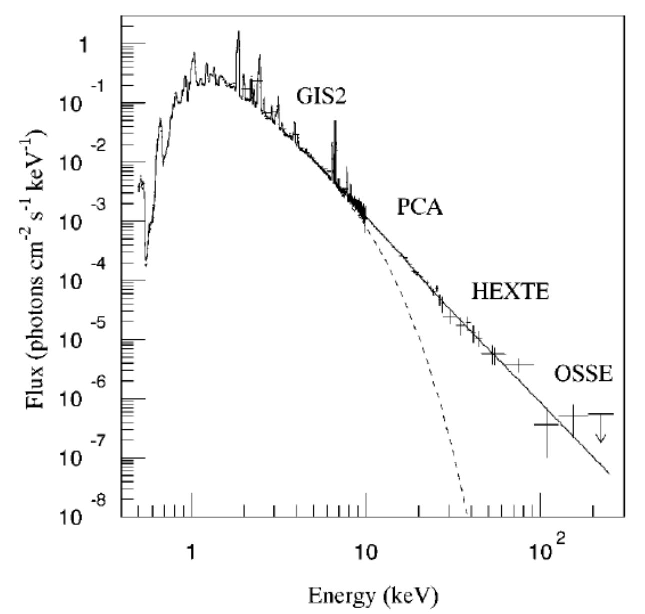
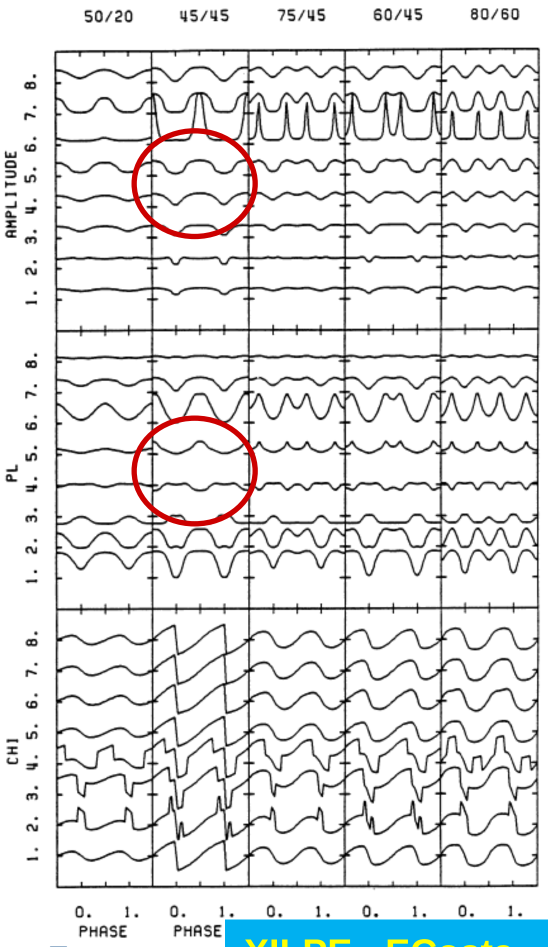


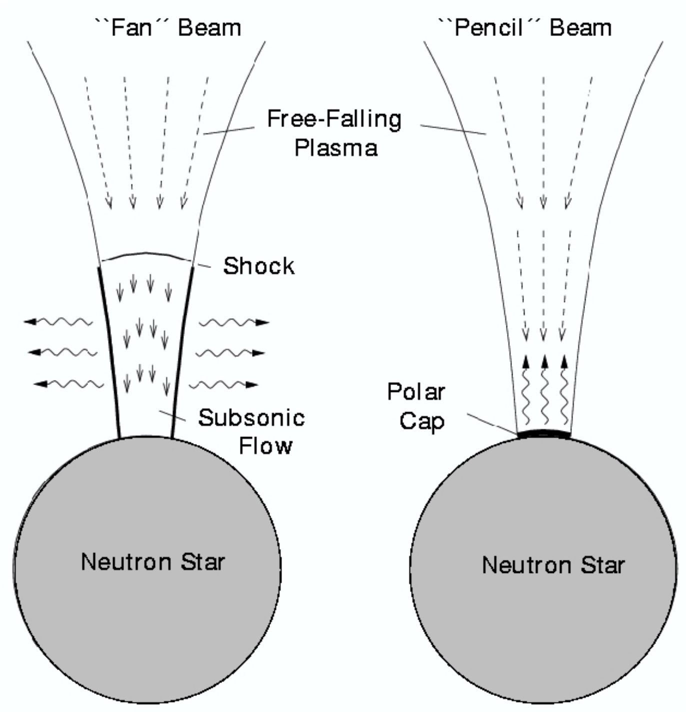


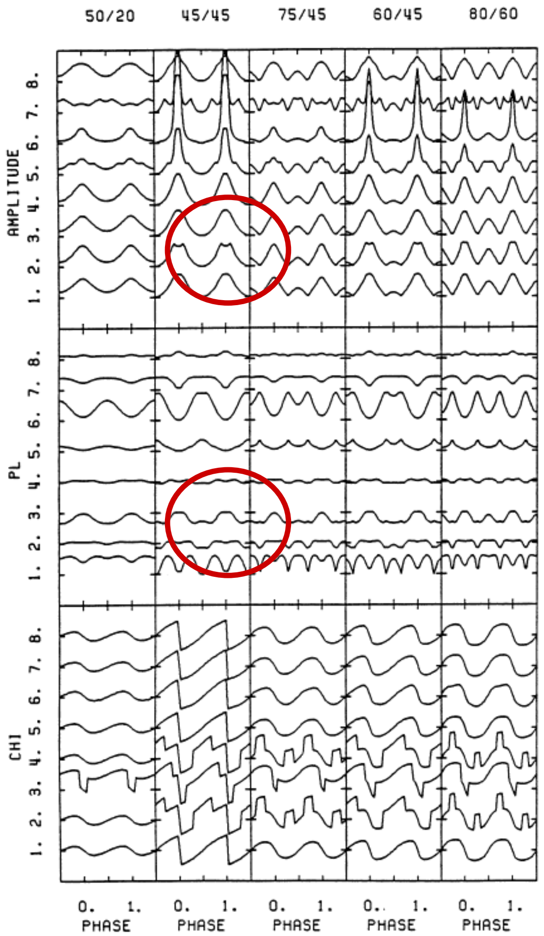
In a shell-like SNR the emssion <10keV is dominated by thermal (not in equilibrium). The polarimetry, as diagnostics oof shocks, can single out the non thermal component <10 keV estimated to be ~ 10%. With Hard X-rays (multilayer optics) the non-thermal component is dominant. In any case imaging is imperative.

Emission in very strong magnetic fields: magnetic NS

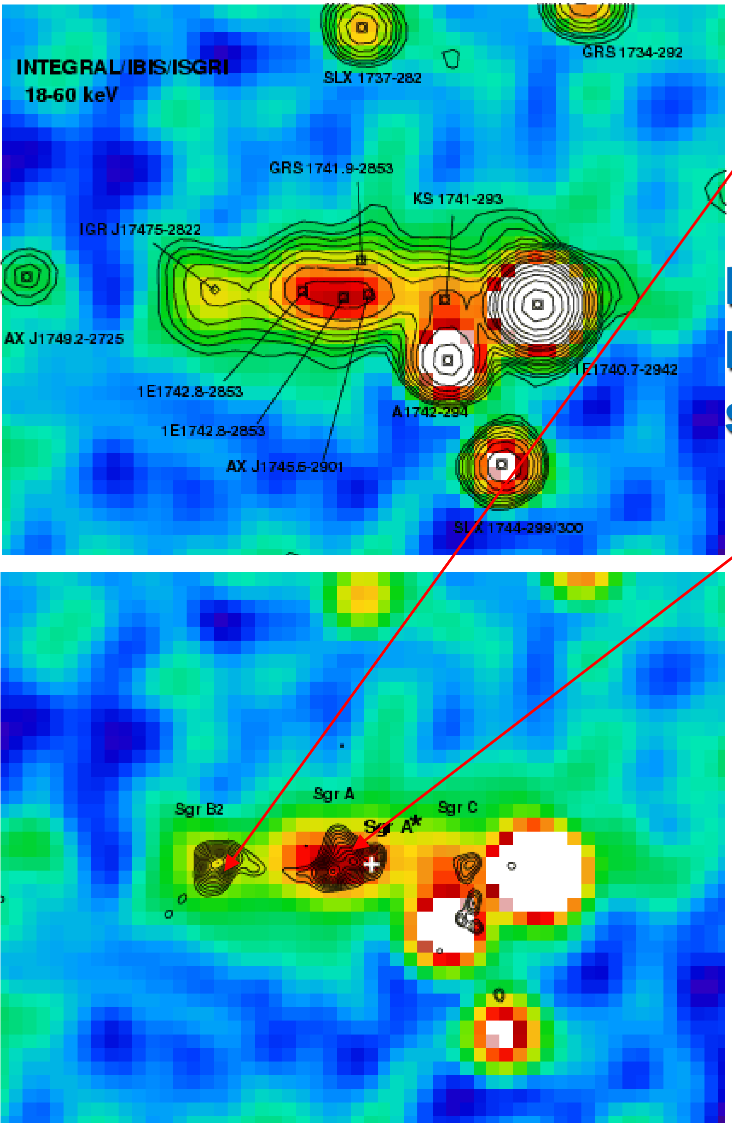
Spectropolarimetry may constraint the accretion geometry. Electron (in strong B) or proton (in extreme B) cyclotron lines may







Scattering in aspherical situations: X-ray reflection nebulae?

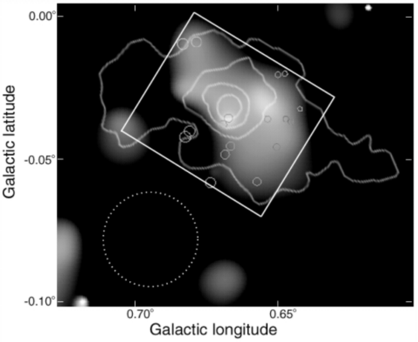


Integral Image of GC, Revnivtsev 2004

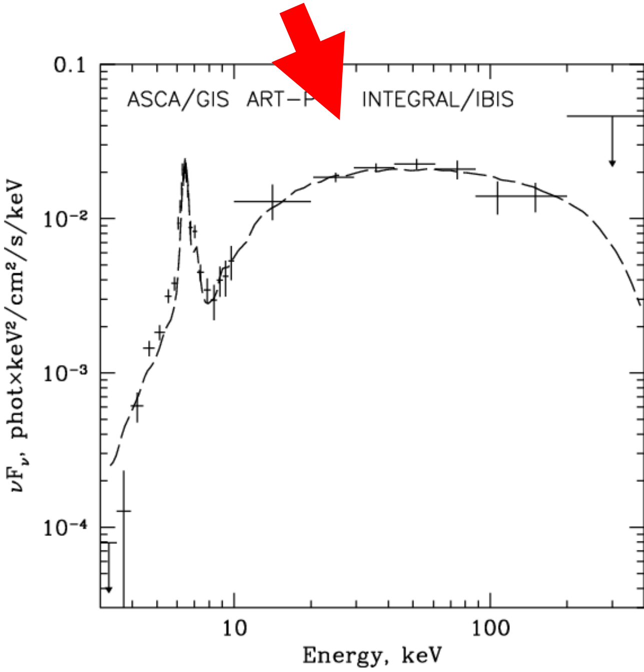
SgrB2 is a giant molecular cloud at 100pc projected distance from SgrA

The spectrumof SgrB2 is pure reflection spectrum

Reflection of what? No bright enough source is there

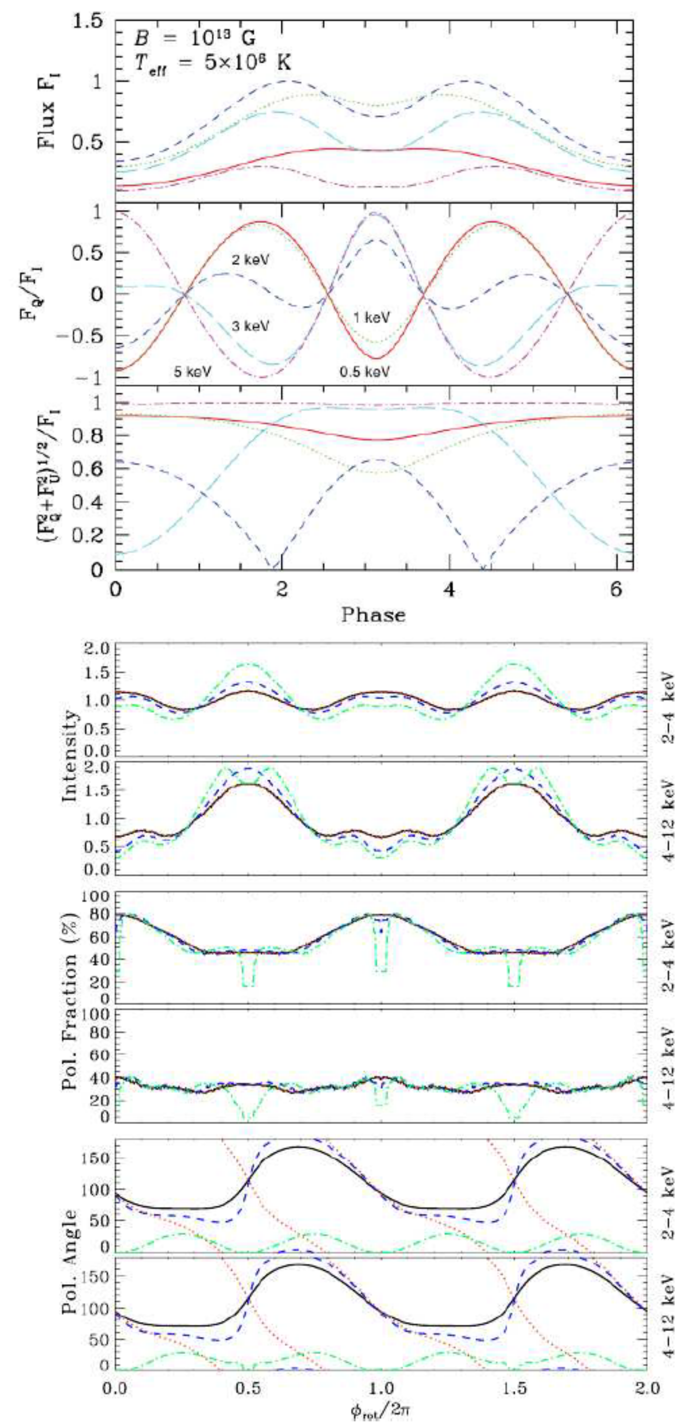


The emission from SgrB2 is extended and brighter in the direction of SgrA,Murakami 2001



Rashid Sunyaev suggested that SgrB2 is reflecting the emission from the Black Hole in SgrA as it was a few hundred years ago.

Matter in Extreme Magnetic Fields: QED effects



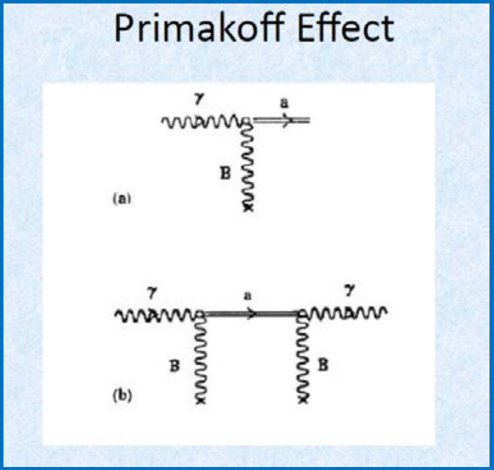
Polarization expected for "normal" pulsars (B=10^{13} G, down) and magnetars (B=10^{14} G, up) as a function of the spin phase for different energy bands. Note that low energy radiation is opposite to high energy radiation in the first case (Adelsberg & Lai 2006; Fernandez & Davis 2011).

Search for axions or axion-like particles

Axion-like particles (ALPs) are spin-zero bosons predicted by many extensions of the Standard Model of particle physics, like four-dimensional models, compactified Kaluza-Klein and superstring theories. Depending on the actual values of their mass and on the $a\gamma\gamma$ photon coupling constant, ALPs can play an important role in cosmology, either as cold dark matter particles responsible for the formation of structures in the Universe or as quintessential dark energy which presumably triggers the present accelerated cosmic expansion (Bassan,Mirizzi,Roncadelli 2010).

So far the search for astrophysical evidence for axions is mainly based on solar mesurements.

Axions are one of the most elusive but of the less exotic candidate for Dark Matter.


Primakoff Effect

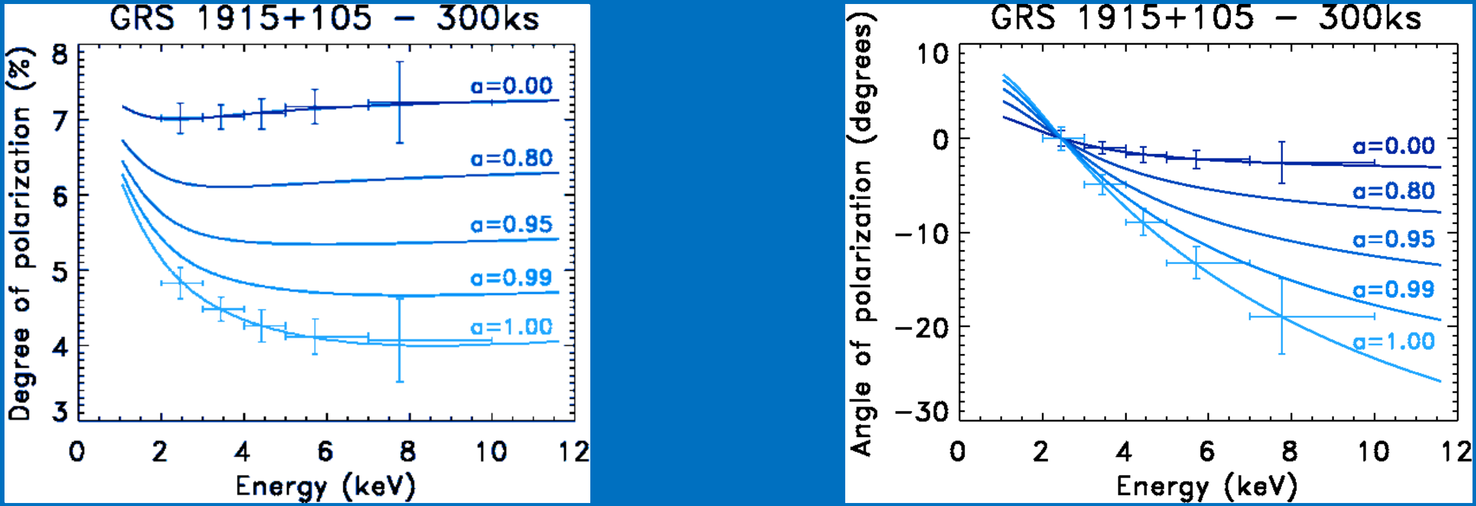
If the magnetic field is oriented the photons will be polarized.
Various papers proposed the search of axions on he basis of measurements of X-ray polarimetry (e.g. Bassan 2010). Unpolarazized photons (e.g. from clusters) could be polarized by IG fields.
Polarized photons could be depolarized.
Quantitative computation for XILPE are missing but the order of magnitude is interesting

Matter in Extreme Gravitational Fields: GR effects

The spin of a Black Hole can be determine by 3 methods:

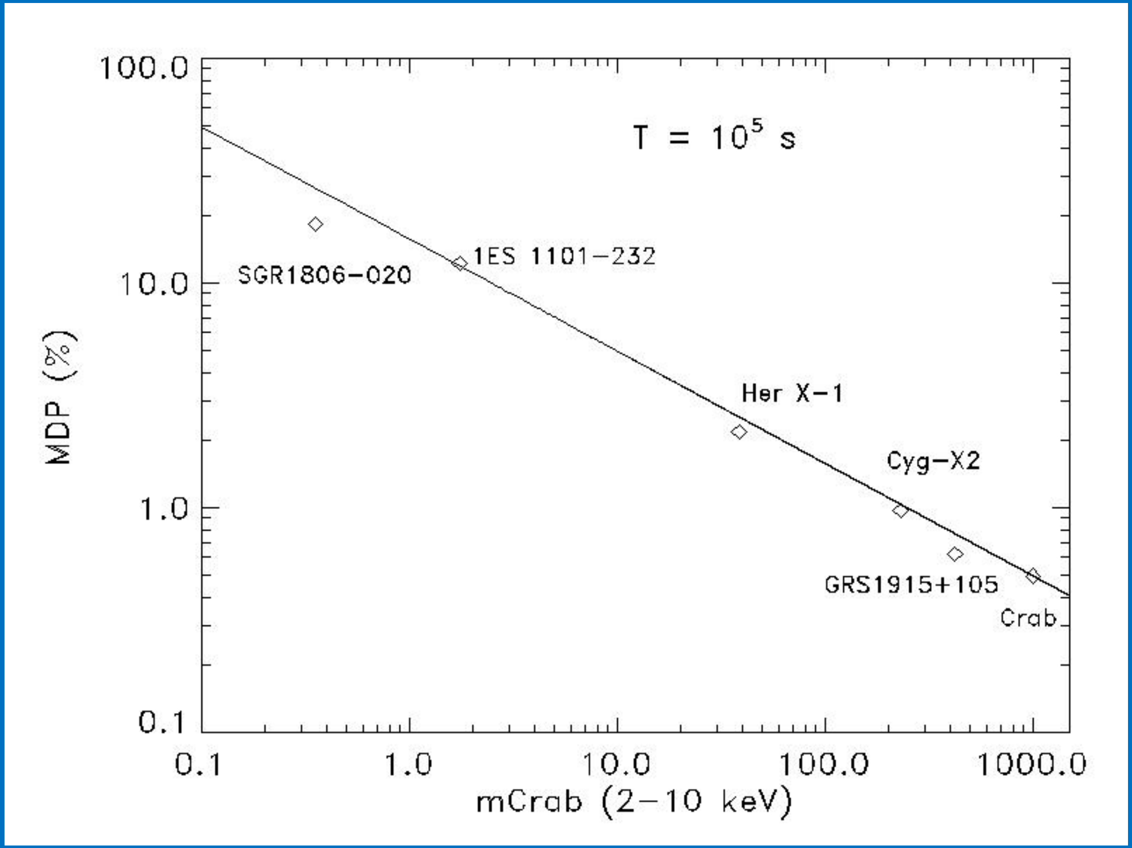
1) Spectroscopy of continuum
2) Spectroscopy of broad relativistic lines
3) Temporal analysis of QPOs

In some case different methods give different values for spin. X-ray polarimetry can provide a 4th mehod. The rotation of the polarization angle with the energy.



The polarization degree (left panel) and angle (right panel) as a function of energy, expected to be measure by XIPE in GRS1915+105 with a 200ks observation (Dovciak et al. 2008).

The Minimum Detectable Polarization



XILPE can perform polarimetry at % level of bright galactic sources and at 10% level of a sample of extragalactic sources and of a few manetars (not in outburst).
Can disclose this window in Astrophysics opening the way to future missions as XTP (20 times larger).