X-ray Polarimetry in Astrophysics with Gas Pixel Detectors

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on behalf of a larger team:

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Outline

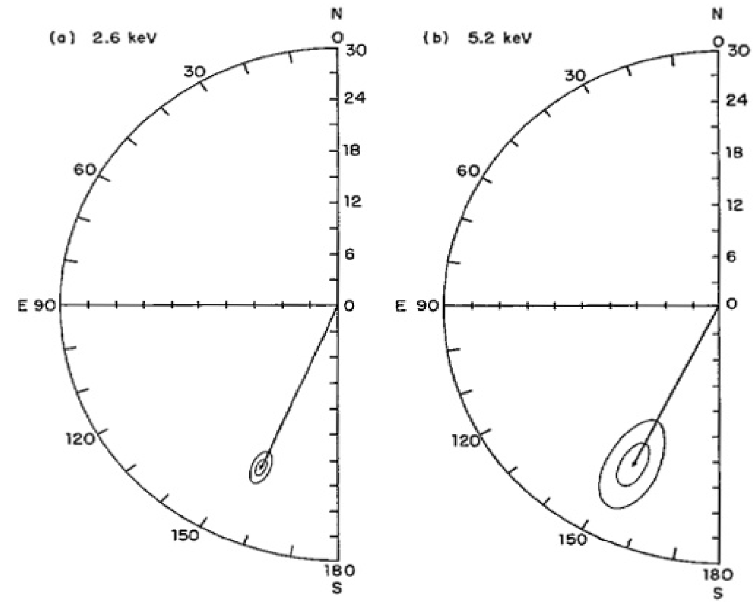
- X-ray polarimetry in Astrophysics today
- The Gas Pixel Detector
- The X-ray facility @ IASF-Rm
- Measurements
- Future missions
- Conclusions

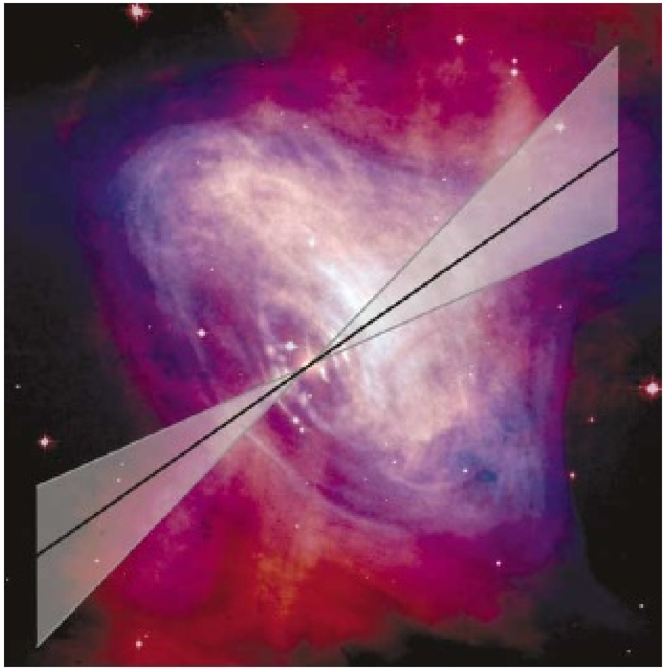
X-ray polarimetry today, i.e. the Crab Nebula

ROCKET 1709 (Novick et al., 1972), P=(15.4 +- 5.2)%, angle 156°+-10°

OSO 8 (Weisskopf et al, 1978): P=(19.22 +- 0.92)%, angle 155°.8 +- 1°.4

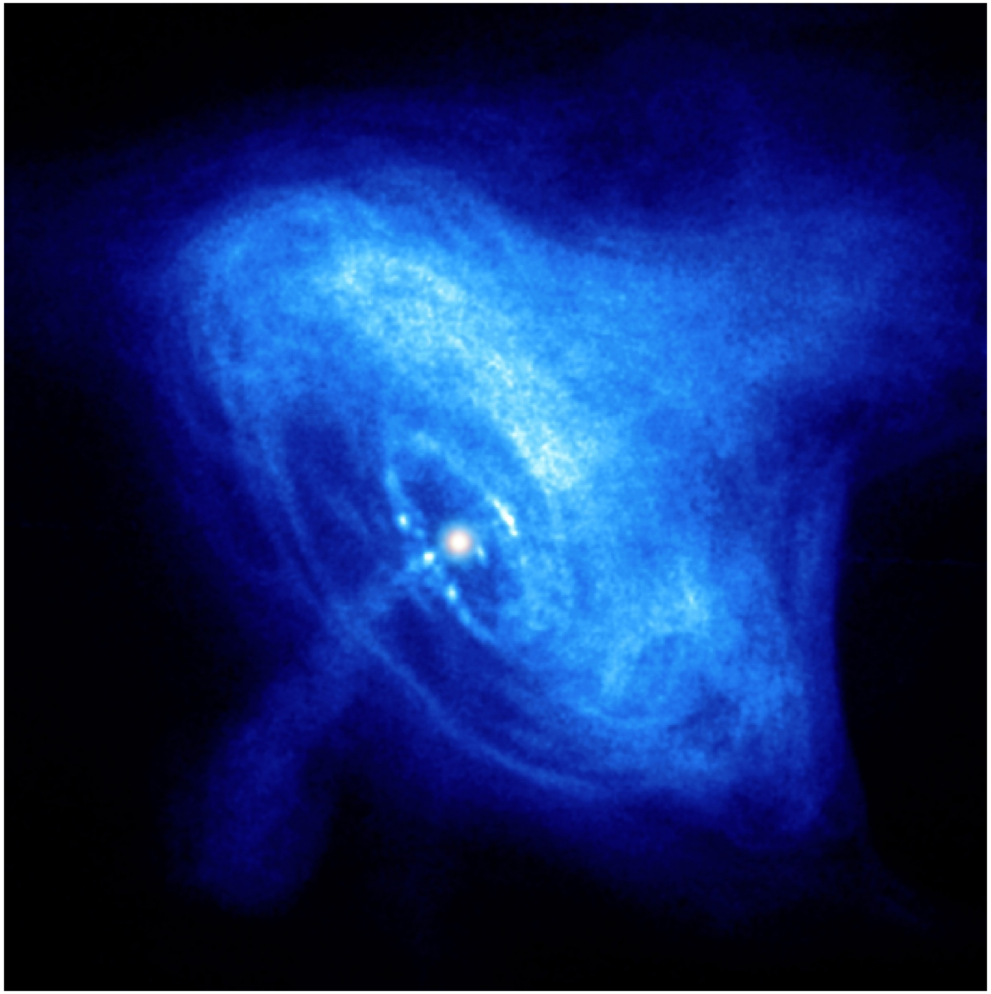
INTEGRAL (Dean et al. 2008): P=(46+-10)%, 123° +-11° between 0.1-1 MeV, confirmed by IBIS (Forot et al., 2008)





X-ray polarimetry today, i.e. the Crab Nebula

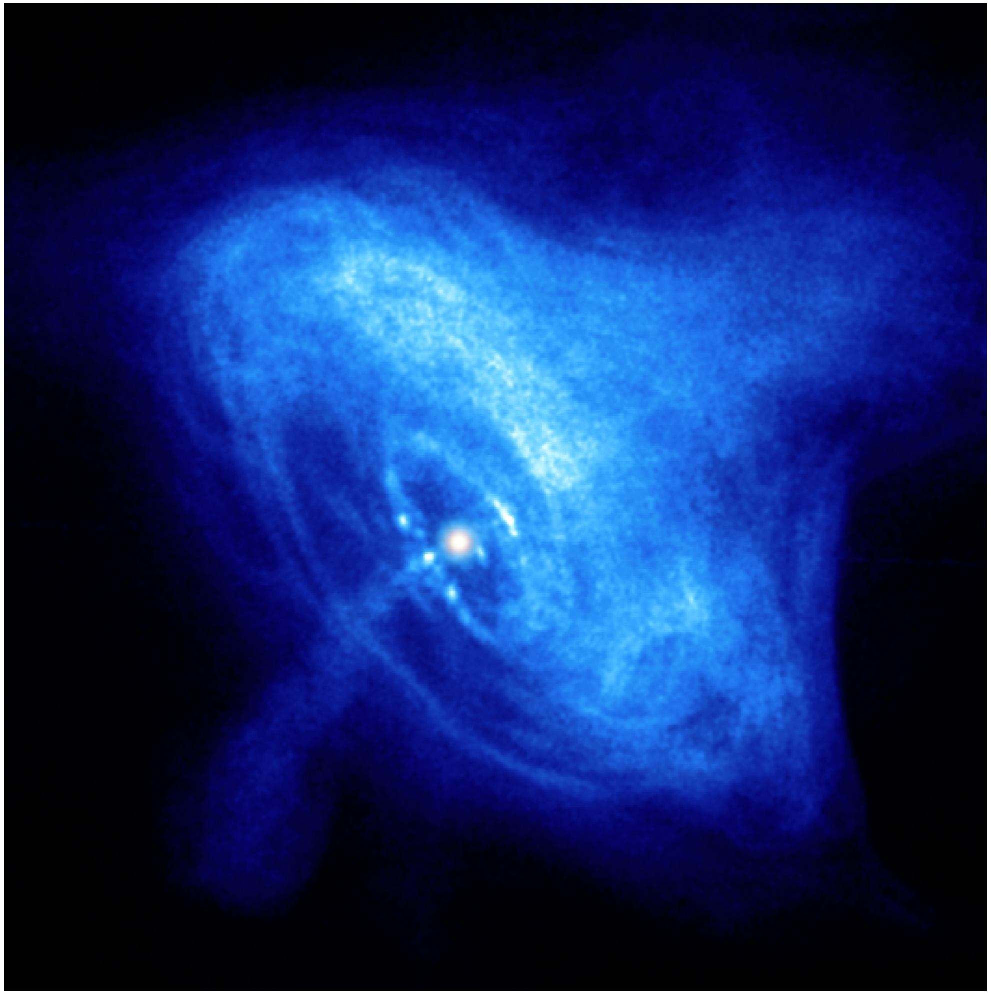
1. Synchrotron emission



X-ray polarimetry today, i.e. the Crab Nebula

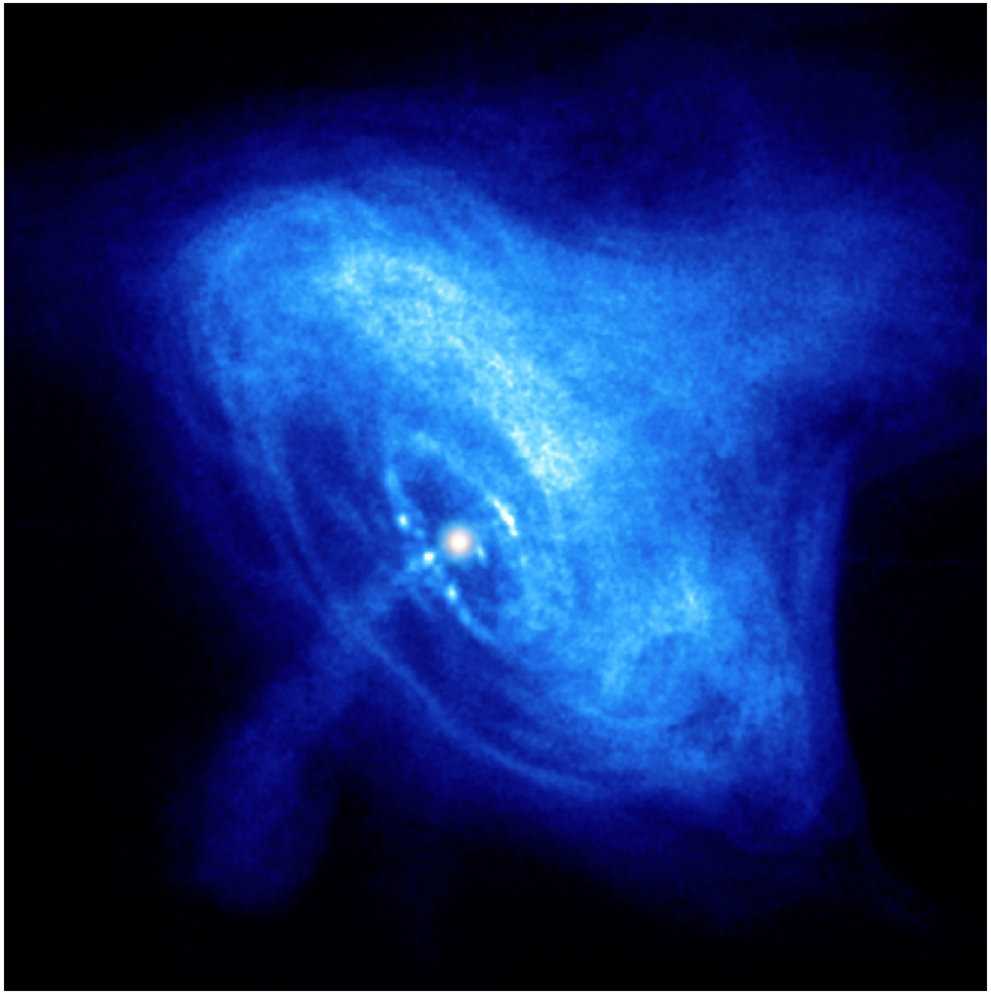
1. Synchrotron emission

2. Flow in the nebula



X-ray polarimetry today, i.e. the Crab Nebula

1. Synchrotron emission
2. Flow in the nebula
3. Acceleration mechanism



Quantum gravity with X-ray polarimetry

Gambini e Pullin (1999): within Loop Quantum Gravity, birefringence increasing with energy:

$$v_{\pm} = c\left[1 \pm \chi\left(\frac{E}{E_{QG}}\right)^n\right]$$

$$\Delta\phi(E) \simeq \chi\frac{D_{ly}}{hc}\frac{E^2}{E_{QG}} \simeq \chi E^2_{keV} D_{ly}$$

- Kaaret (2004): $|\chi| < 10^{-4}$ ($\Delta\phi < 0.3°$);
- Yi-Zhong Fan (2007): $|\chi| < 10^{-7}$ (polarization of the optical afterglow of GRB 020813 and GRB 021004);
- Maccione et al. (2008): $|\chi| < 10^{-9}$ (high energy polarization of the Crab Nebula);
- Mitrofanov (2003): $|\chi| < 10^{-14}$ (X-ray polarization of GRB 021206, ?).

Why X-ray polarimetry?

X-ray polarization can be obtain by means of:

- Emission Processes: accretion (non spherical scattering, reflection), synchrotron emission, etc.

- Radiative Transfer: matter in strong gravitational/magnetic field.

Why X-ray polarimetry?

X-ray polarization can be obtain by means of:

- Emission Processes: accretion (non spherical scattering, reflection), synchrotron emission, etc.

- Radiative Transfer: matter in strong gravitational/magnetic field.

- PWN, PSR: Crab;
- INS: XDINS, CCO, AXP, SGR
- binary system with BH, HMXB, LMXB
- RN: Sgr B2
- AGN, Blazar
- μQSO
- CV
- GRB?
- ...

Why not?

Polarimetry requires **good** performances and **tens of thousands** of photons

Classical techniques (Bragg diffraction and Thompson/Compton scattering) can provide "good" performances but with very low efficiency.

Photoelectric polarimeters

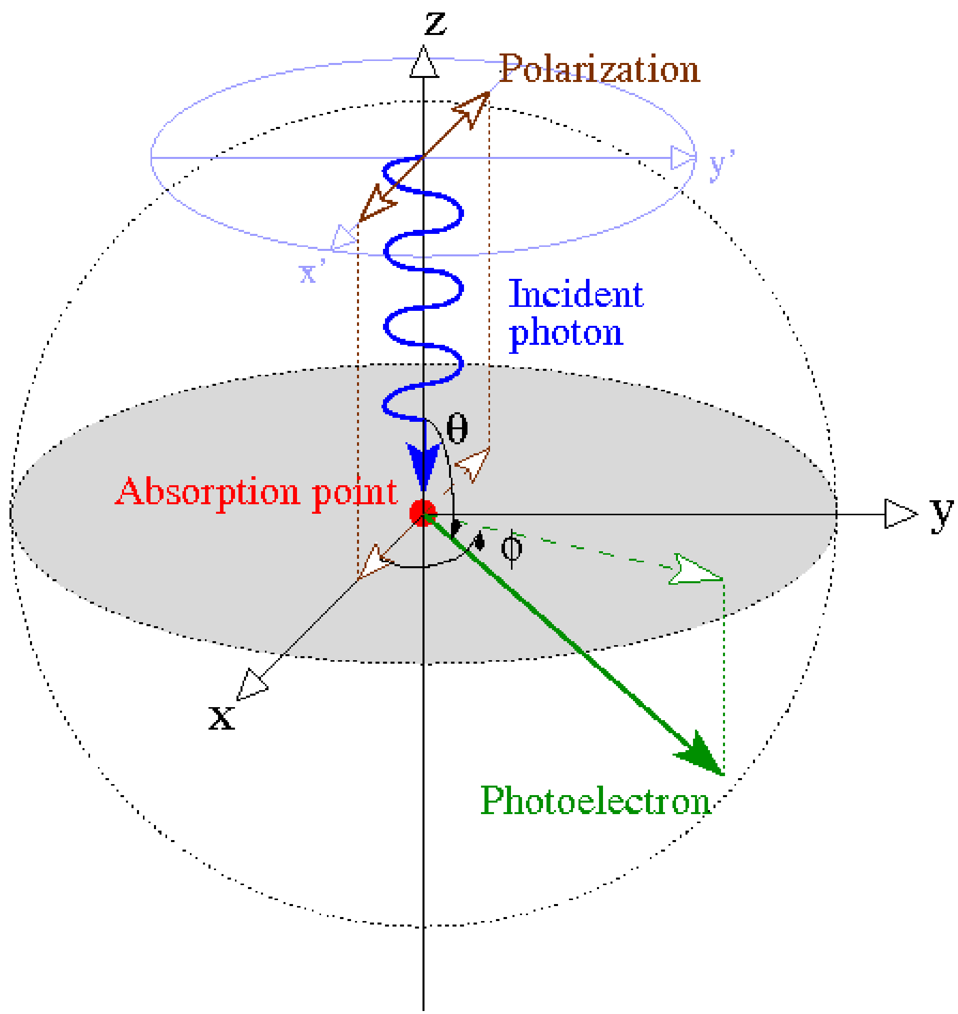
In case of spherical symmetric shells:

$$\frac{d\sigma}{d\Omega} \propto \cos^2\phi \quad \sin^2\theta \quad \frac{1}{(1+\beta\cos\theta)^4}$$

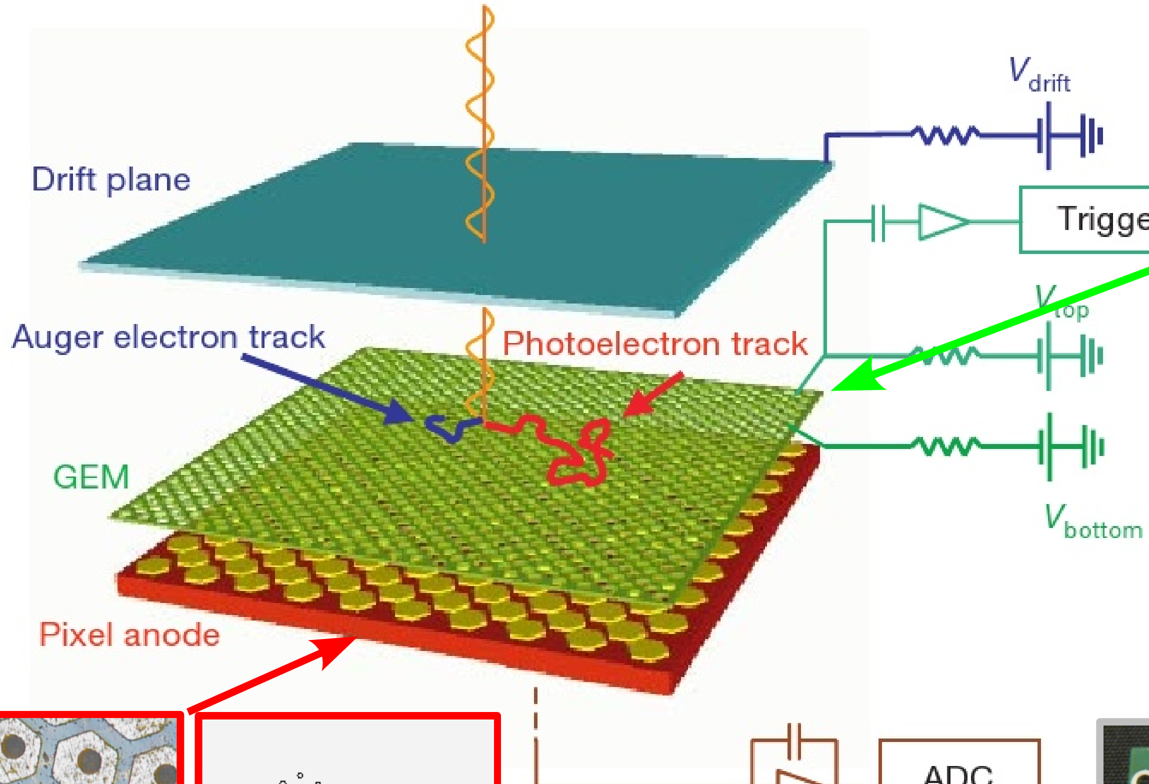
azimuthal dependency

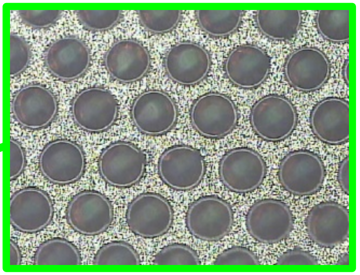
latitudinal dependency

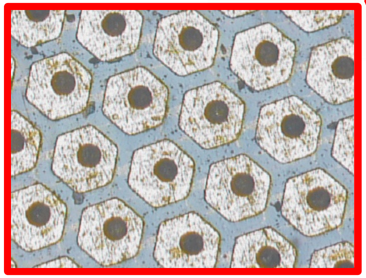
"relativistic correction" to the latitudinal dependency

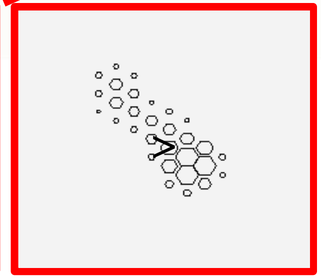


The Gas Pixel Detector







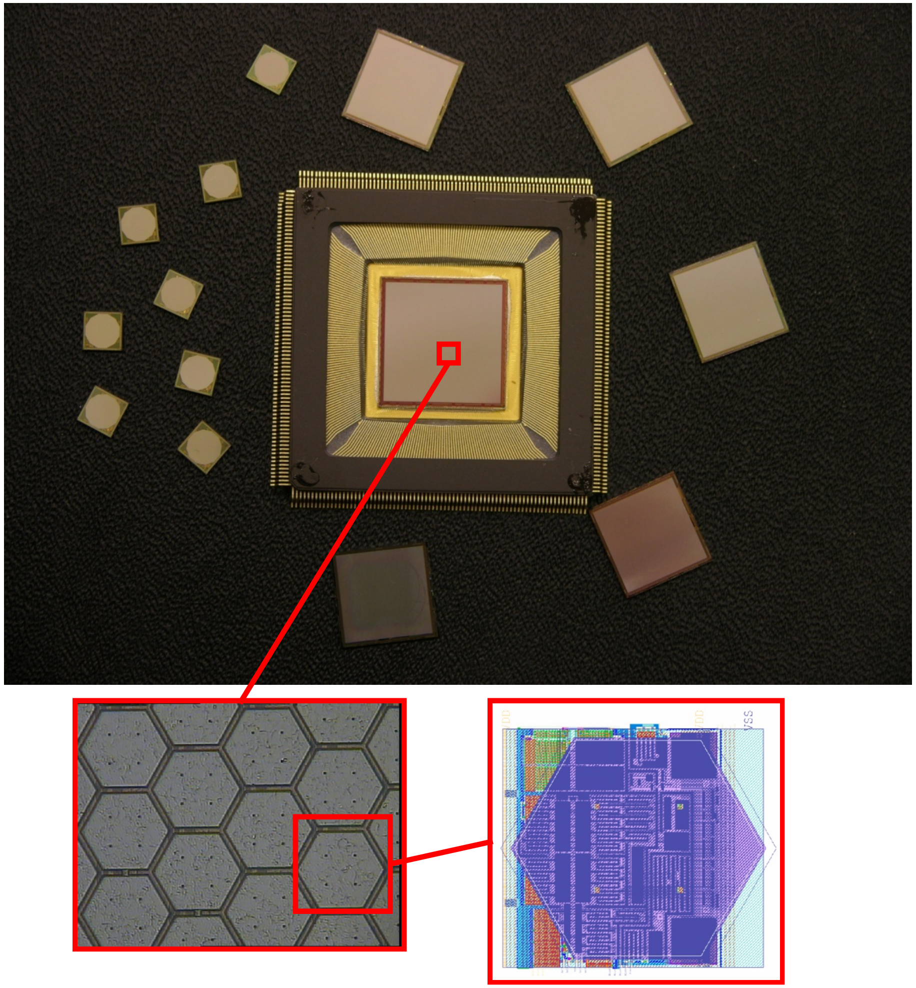


Costa et al. 2001, Bellazzini et al. 2006, 2007

Weight: only **50**g !

The current prototype

The chip integrates more than 16.5 million transistors and has a 15 mm x 15 mm active area. It is composed of 105600 pixels organized in a honeycomb matrix with 50 µm pitch.

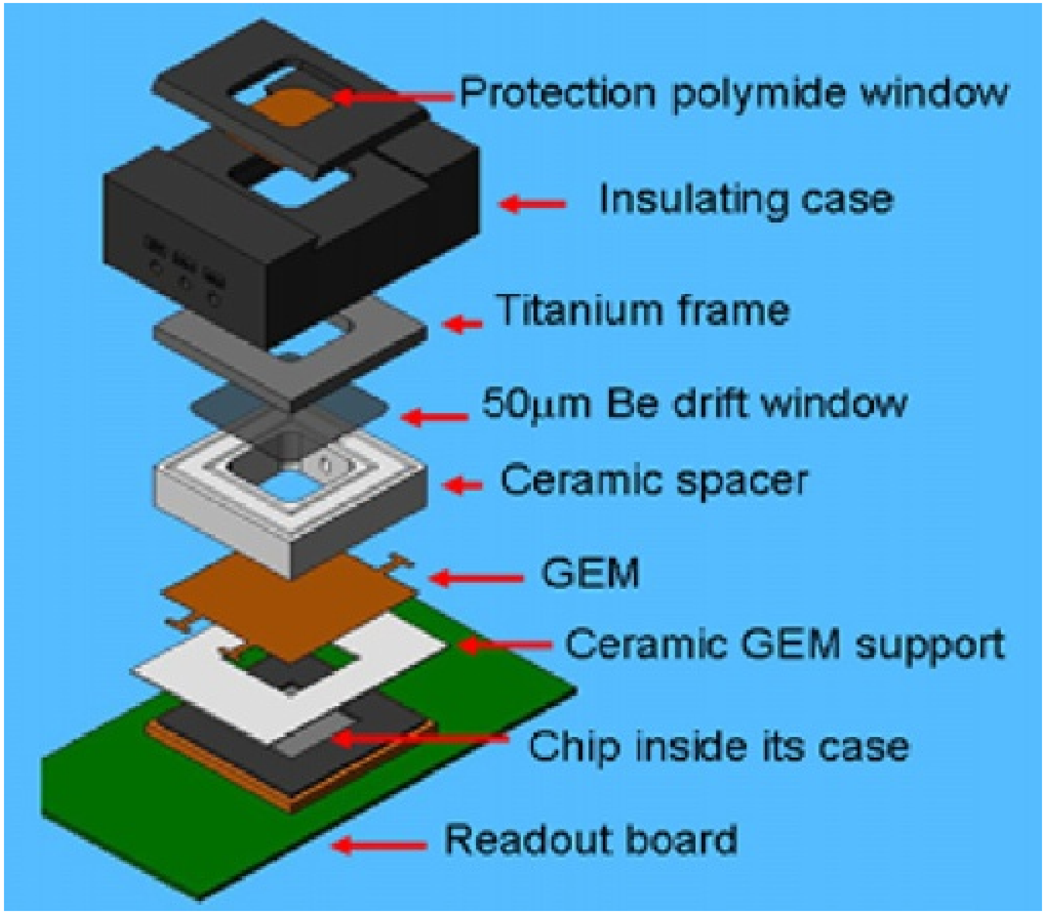


Bellazzini et al. 2006

The current prototype - Characteristics

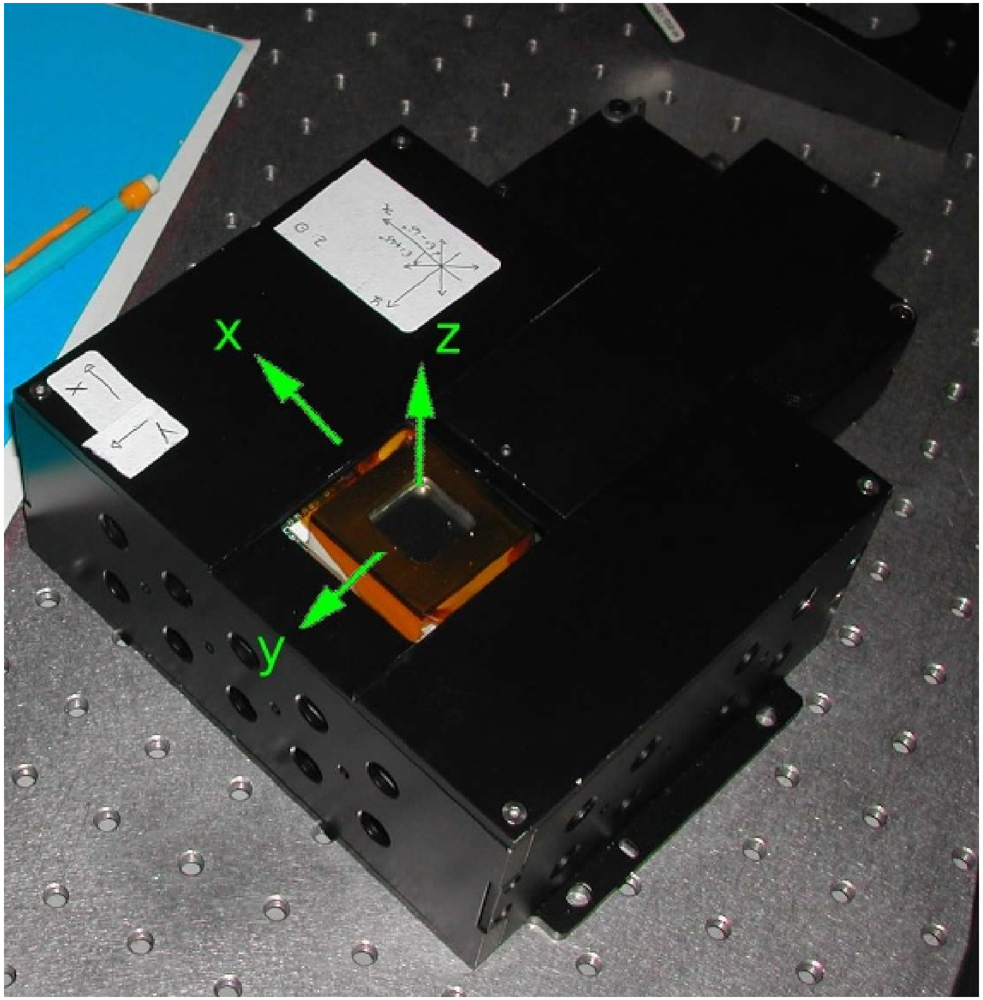
Area:	15×15 mm^2
Active area fill fraction:	92%
Window:	50 μm, beryllium
Mixture:	He 20% + DME 80%, 1 atm
Cell thickness:	1 cm
GEM material:	gold-coated kapton
GEM pitch:	50 μm
GEM holes diameters:	30 μm
GEM thickness	50 μm
Gain:	~500
Pixels:	300×352, hexagonal pattern
Pixel noise:	50 electrons ENC
Full-scale linear range:	30000 electrons
Peaking time:	3-10 μs, externally adjustable
Trigger mode:	internal, external or self-trigger
Self-trigger threshold:	3000 electrons (10% FS)
Pixel trigger mask:	individual
Read-out mode:	asynchronous or synchronous
Read-out clock:	up to 10 MHz
Frame rate:	up to 10 kHz in self-trigger mode
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)

A sealed detector

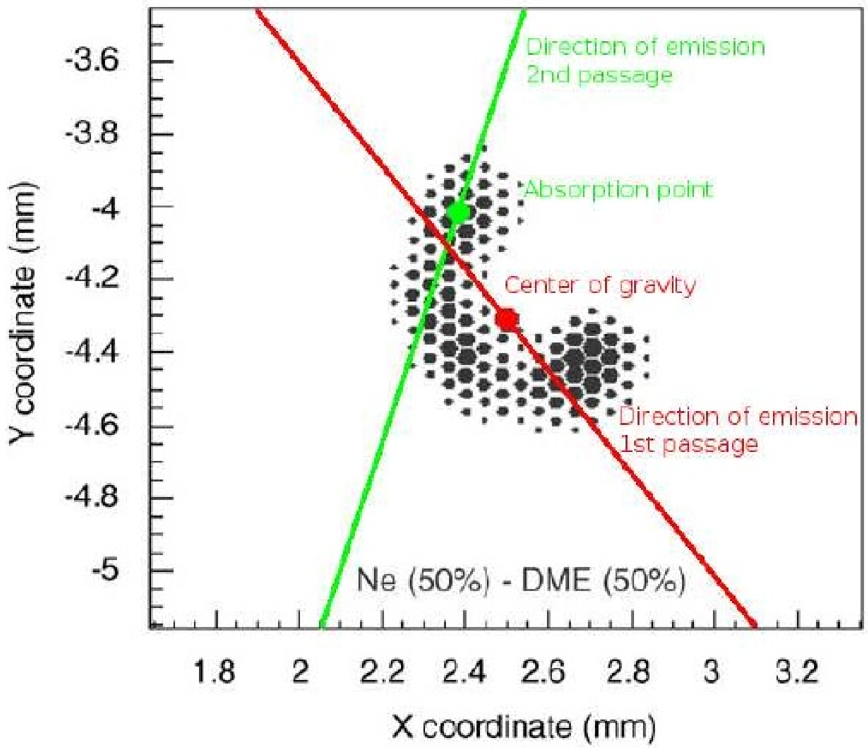


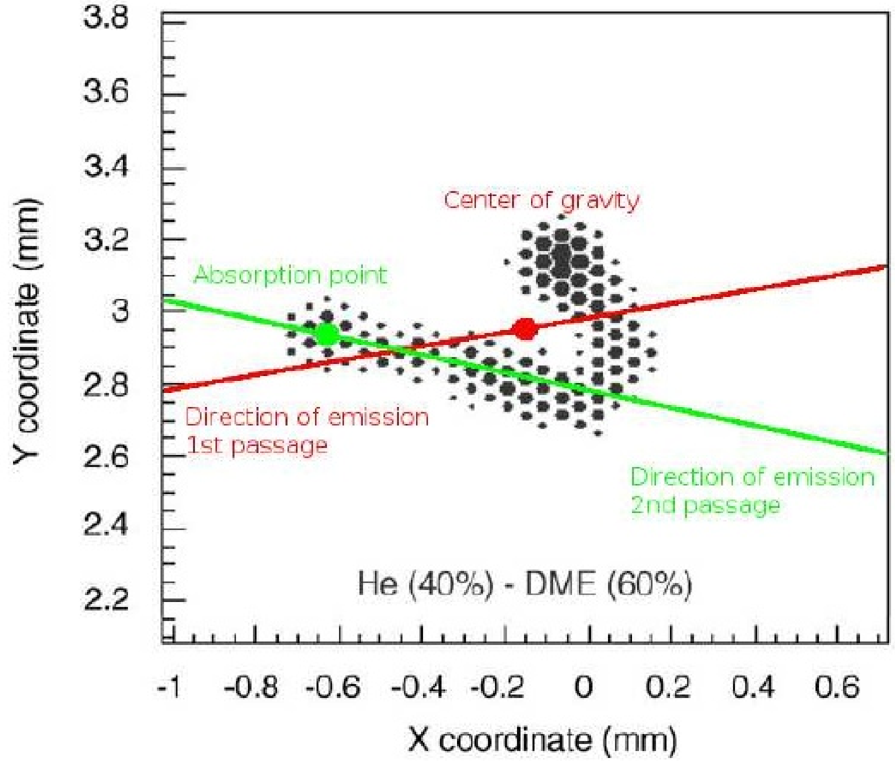
Bellazzini et al. 2007

Chip + read-out electronics



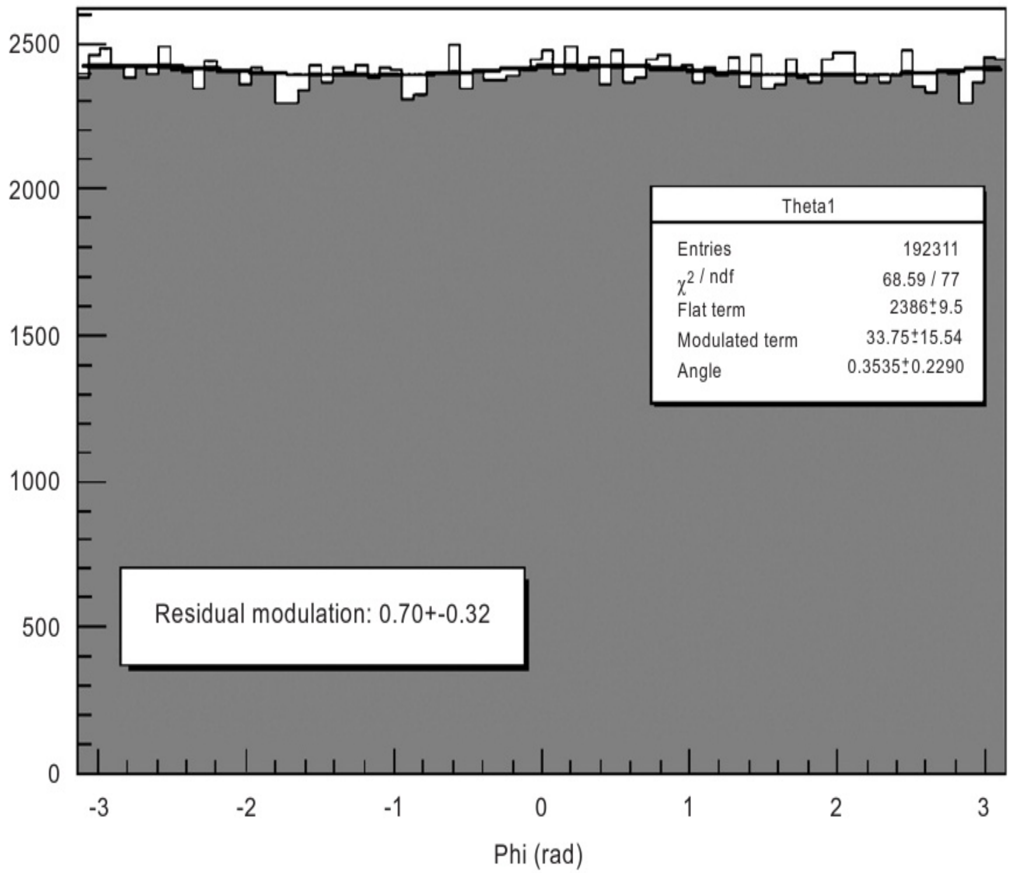
Performances - Real tracks



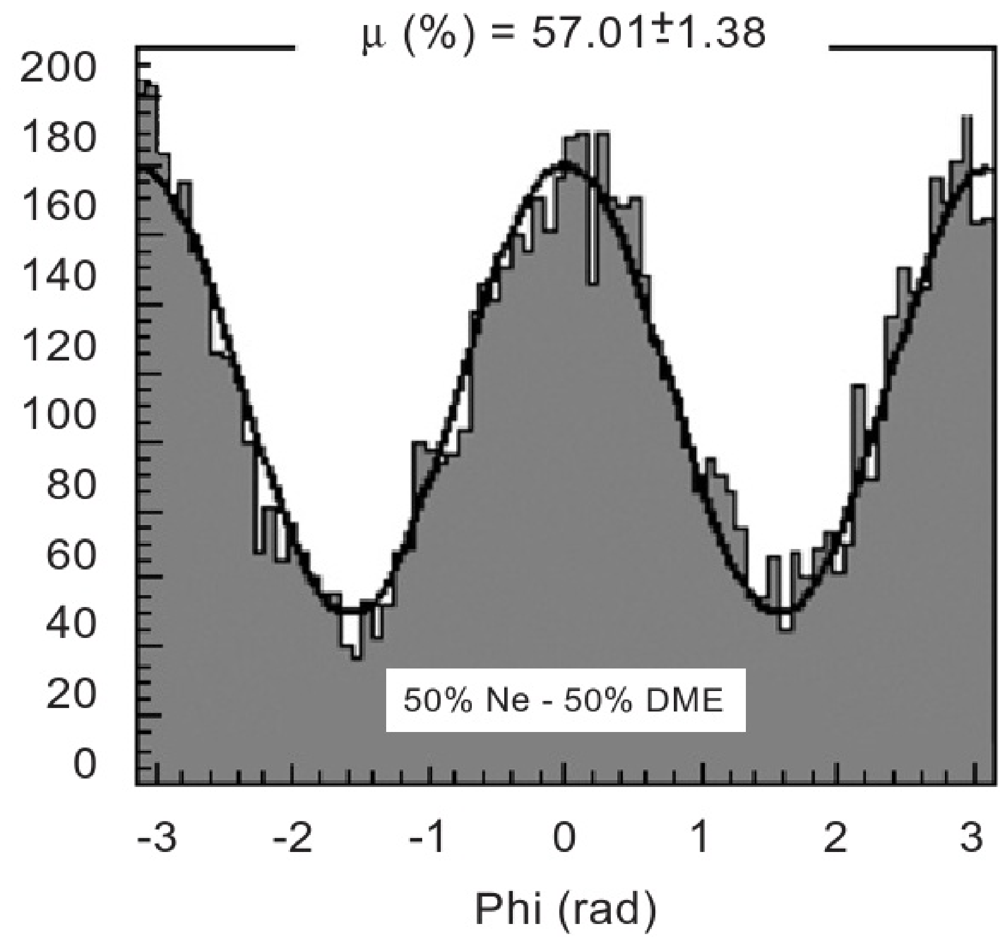


5.41 keV, He-DME mixture at 1 atm

Modulation curve

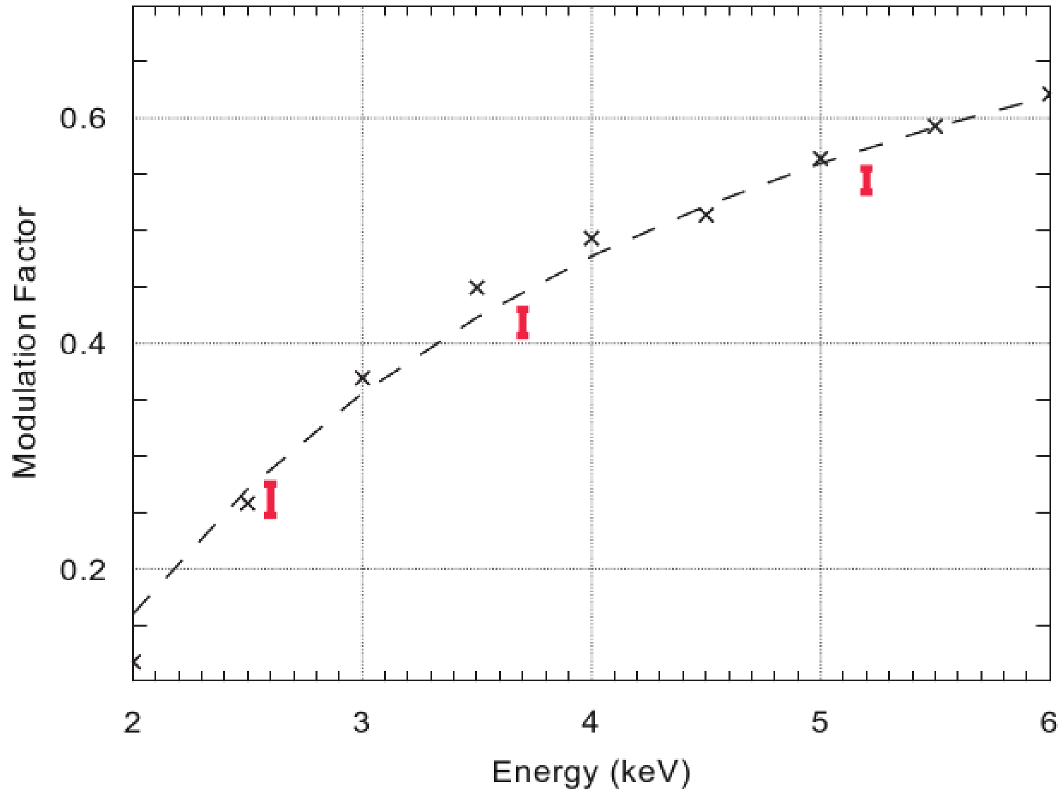


5.9 keV



6.4 keV

Modulation factor

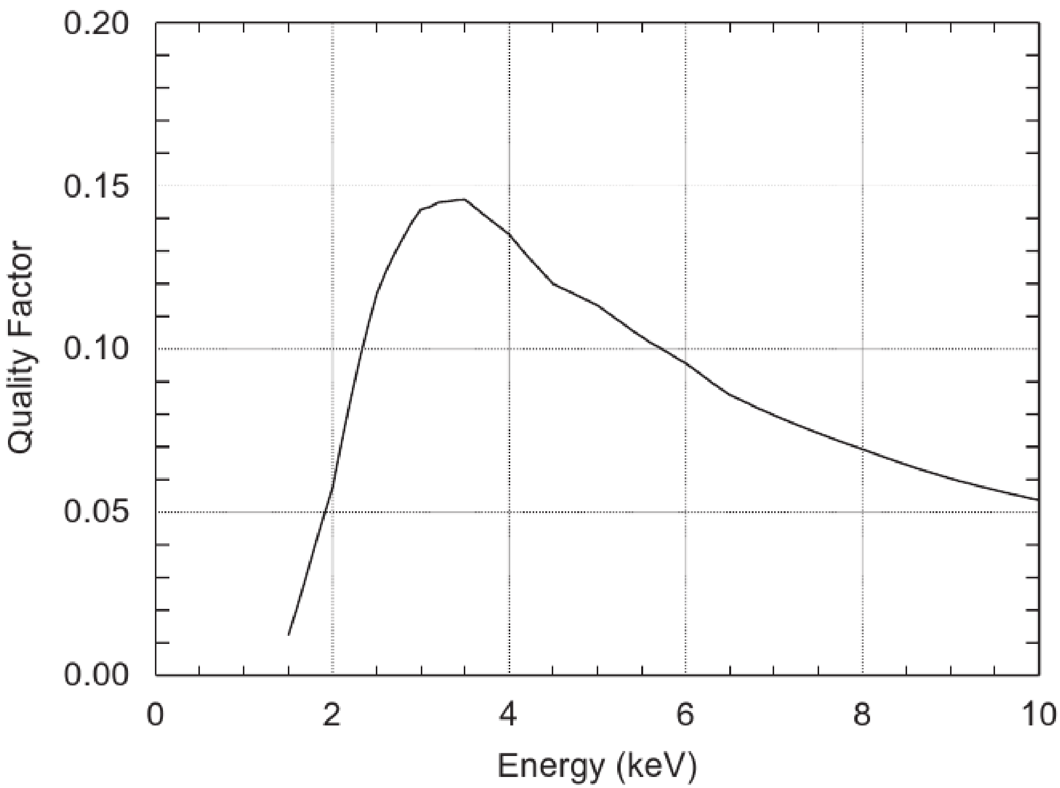


Muleri et al. 2008

The instrument provides the polarimetric information together with imaging, spectral and timing capabilities.

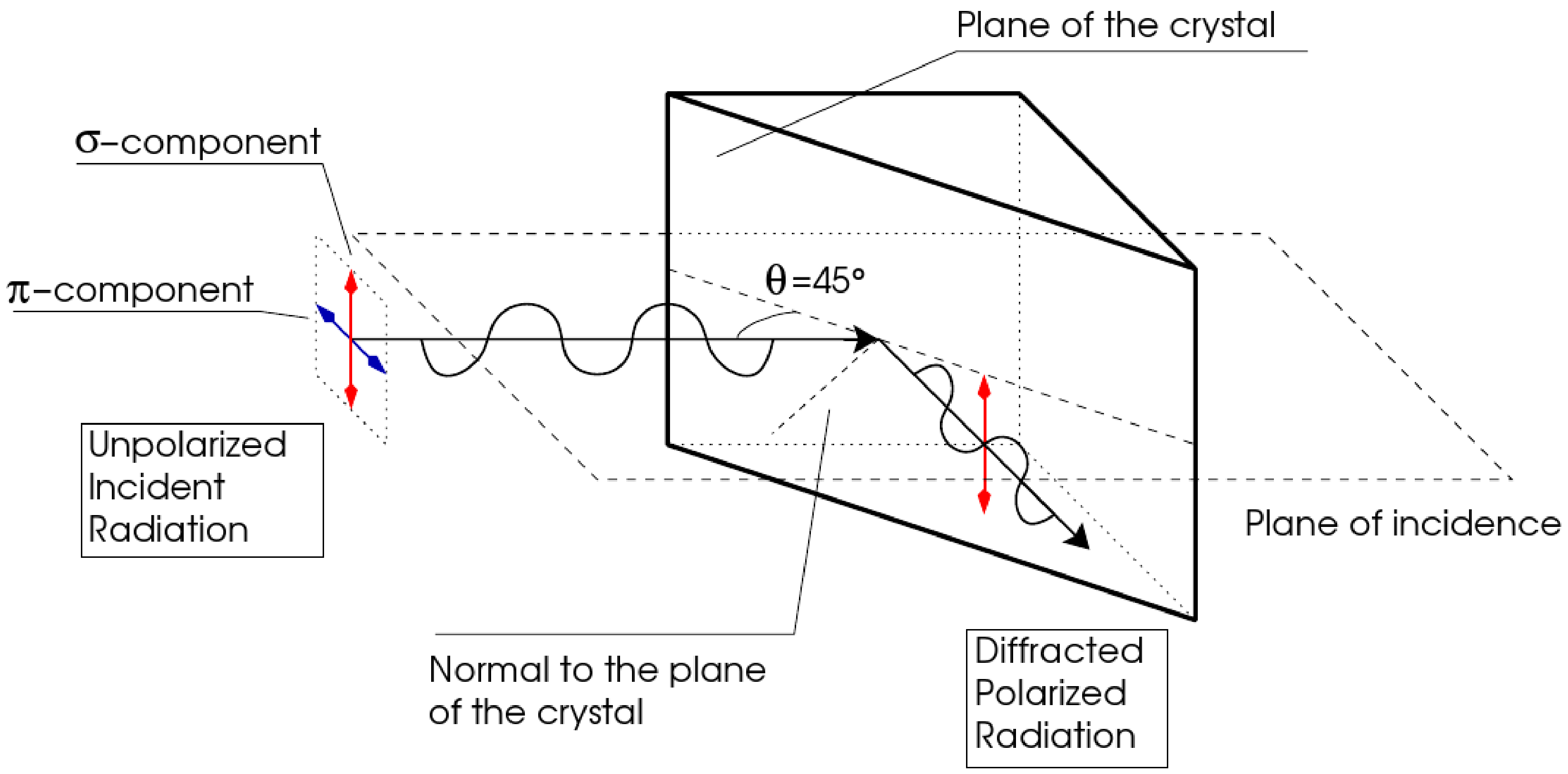
The X-ray facility @ IASF-Rm

Energy response of GPD



- Thomson Scattering source: continuum background, energy higher than ~ 5 keV.
- Bragg diffraction source: narrow line (FWHM~10 eV), high polarization, relatively high flux if line emission in accordance with the diffracting crystal is employed.

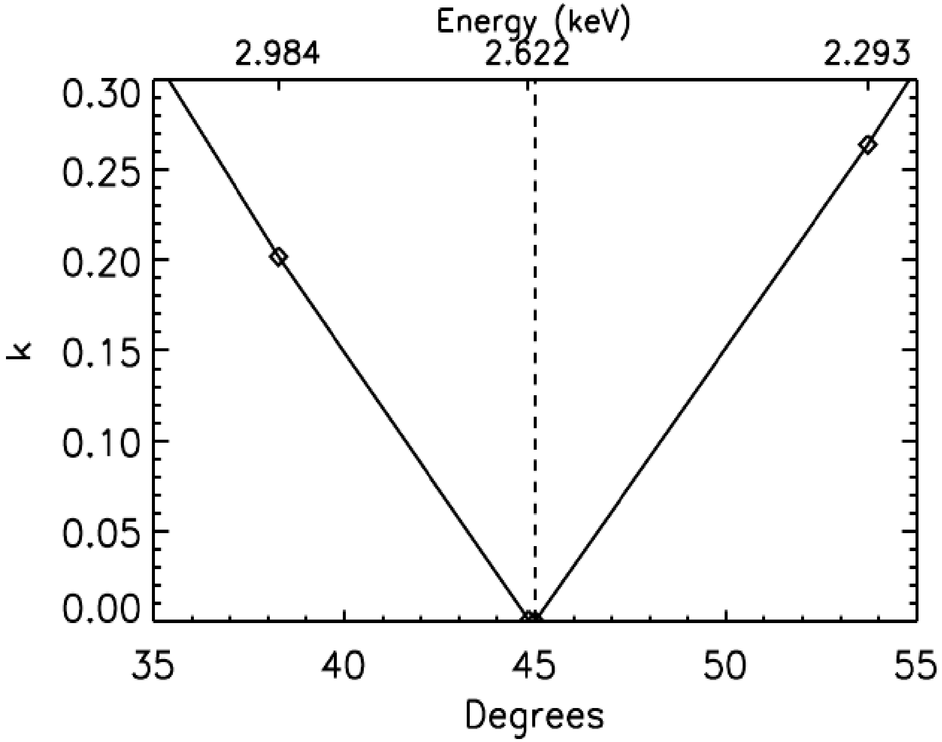
Bragg diffraction @ 45°

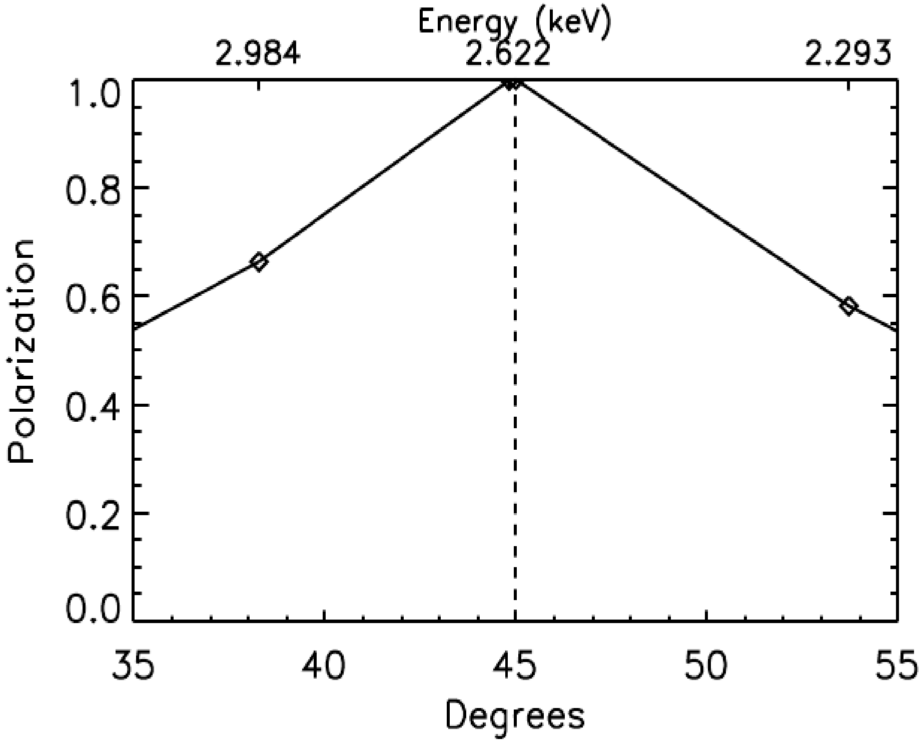


Bragg diffraction @ 45°

Different "efficiency" of diffraction for different polarization:

$$k = R_E^{\pi} / R_E^{\sigma} \qquad \mathcal{P} = \frac{1-k}{1+k} \qquad E = \frac{nhc}{2d \sin\theta}$$

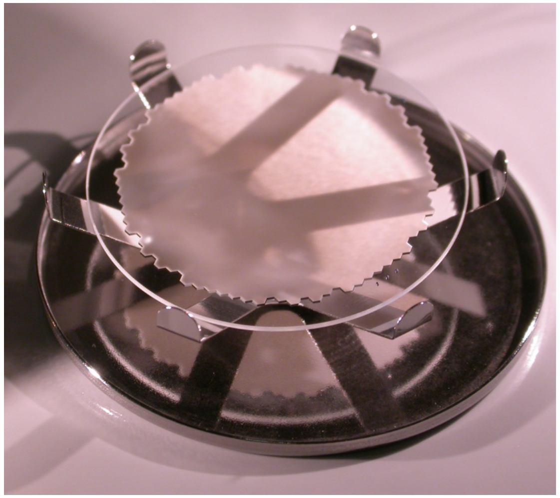


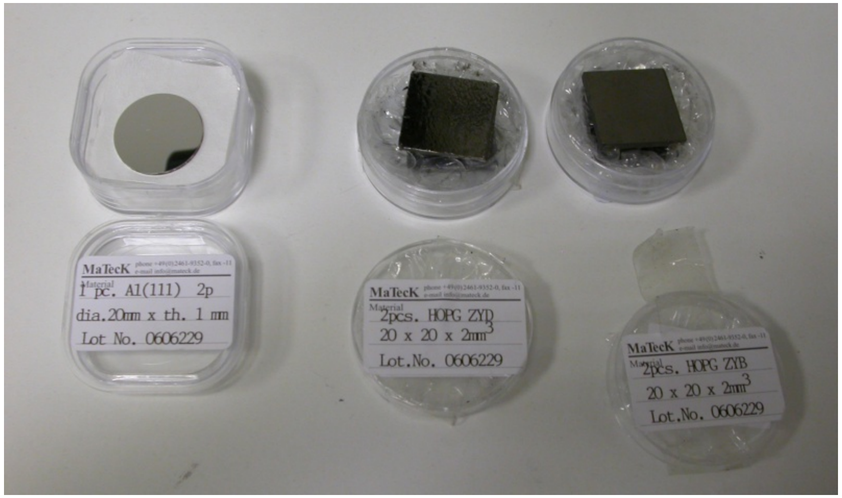


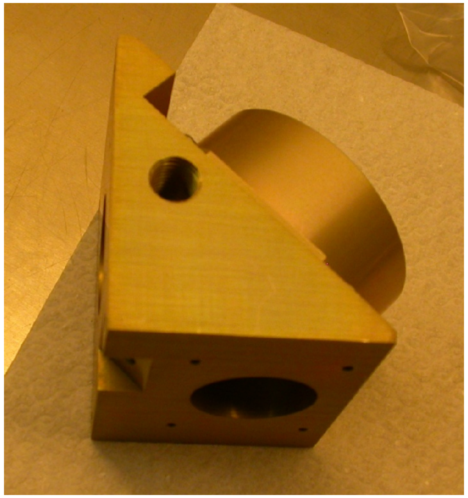
data from Henke et al., Atomic Data and Nuclear Data Tables 54, 181 1993

The components of the polarizer

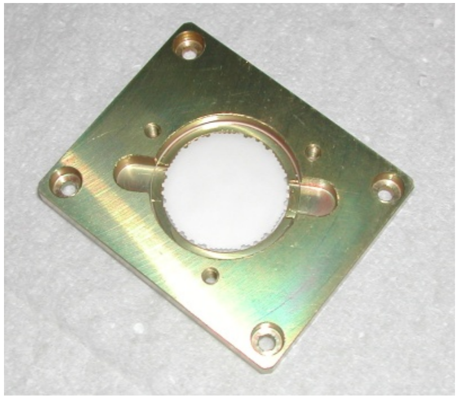
- capillary plates with 10μm holes, thickness 0.4mm or 1.0mm: high collimation with limited size;
- The crystal;
- A central body on which the parts are mounted

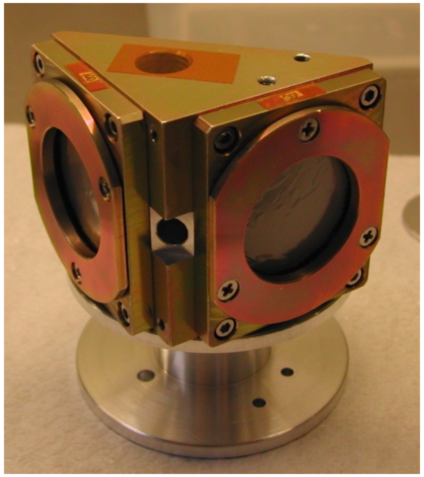


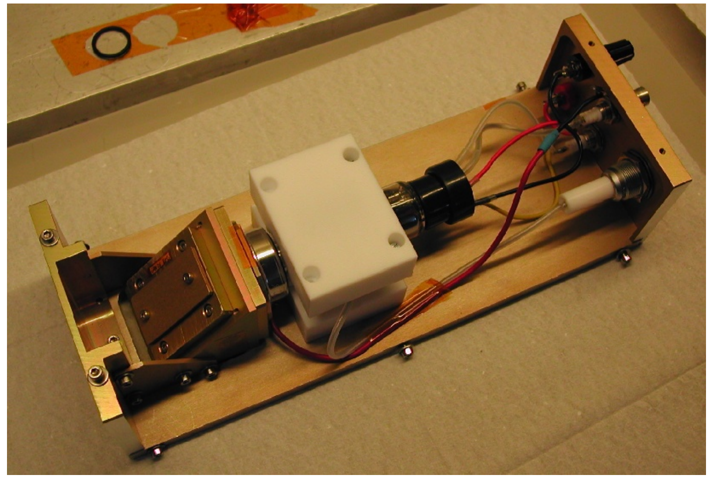


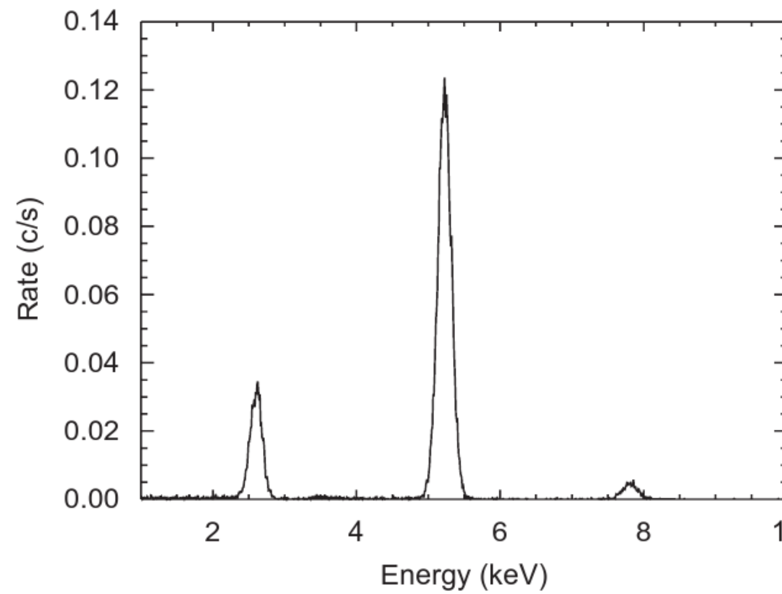


Each crystal and capillary plate is mounted in an aluminium holder.







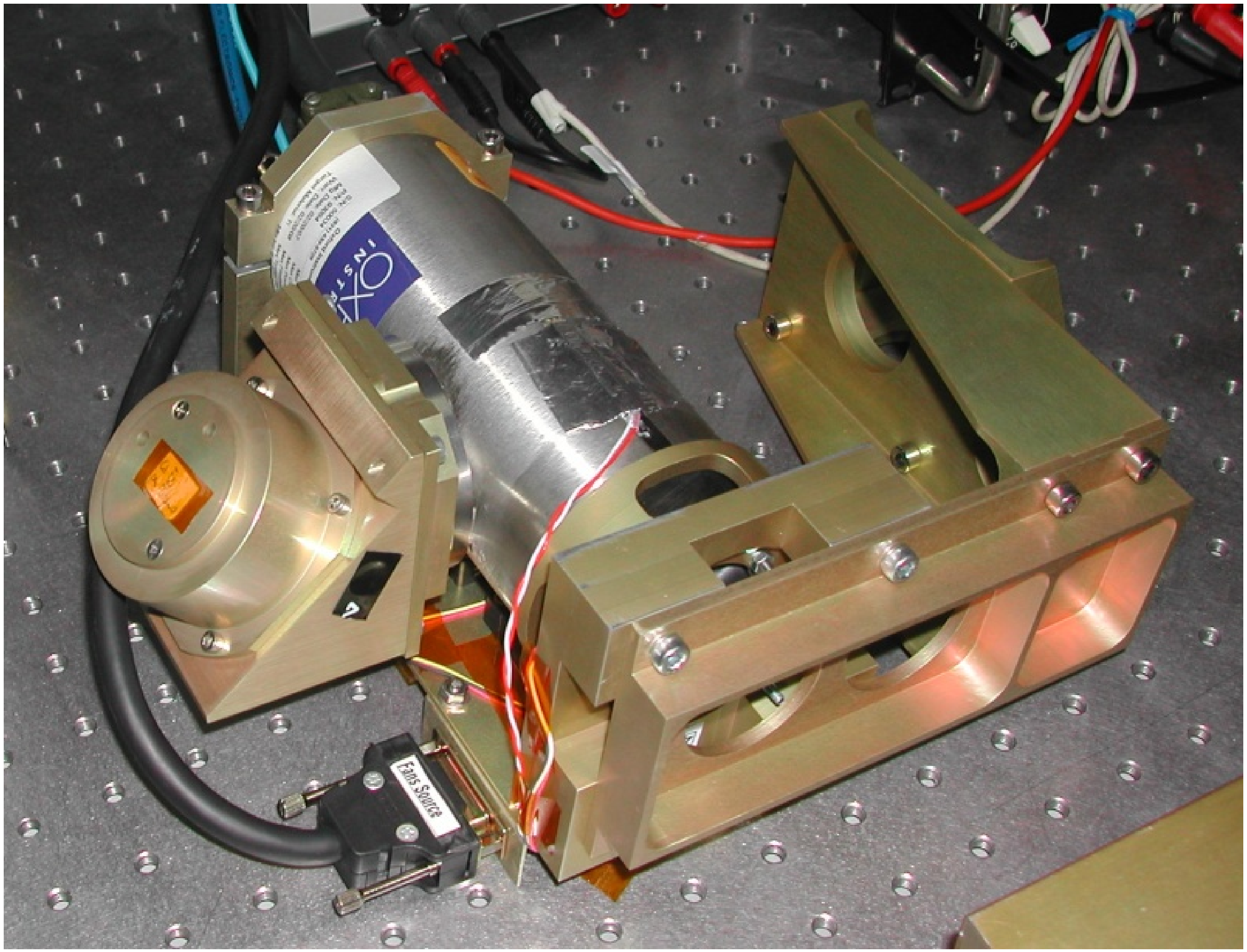


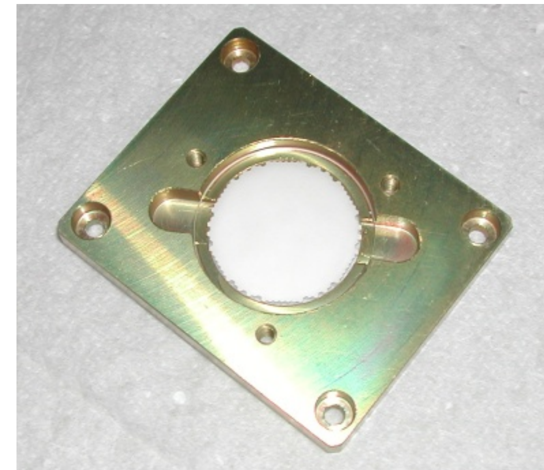
Good performances with a low power X-ray tube (200 mW):

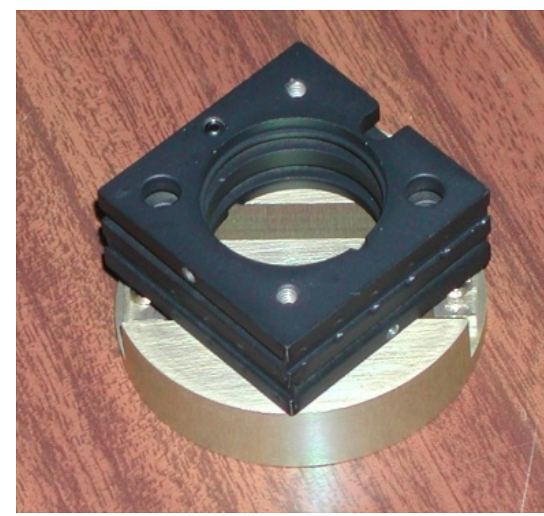
Diffraction	Incident radiation	E (keV)	FWHM (eV)	χ^2	θ_{Bragg} (deg)	$\mathscr{P}$	Rate (c/s)
Incoming and output $\frac{1}{40}$ collimators							
Graphite, I order	Continuum	2.6105 ± 0.0020	193.6 ± 3.2	0.849	45.07	~ 0.98	0.66
Graphite, II order	Continuum	5.2261 ± 0.0018	220.1 ± 1.6	1.101	45.02	>0.96	2.8
Output $\frac{1}{40}$ collimator							
Graphite, I order	Continuum	2.6109 ± 0.0036	198.6 ± 4.7	1.096	45.07	>0.95	3.5
Graphite, II order	Continuum	5.2269 ± 0.0037	248.2 ± 2.6	0.926	45.01	>0.94	16.8
Aluminum, I order	Calcium Kα line	3.6889 ± 0.0024	200.1 ± 0.2	1.396	45.93	0.9938	140.1

Muleri et al. 2007

The improved source







Muleri et. al. 2008

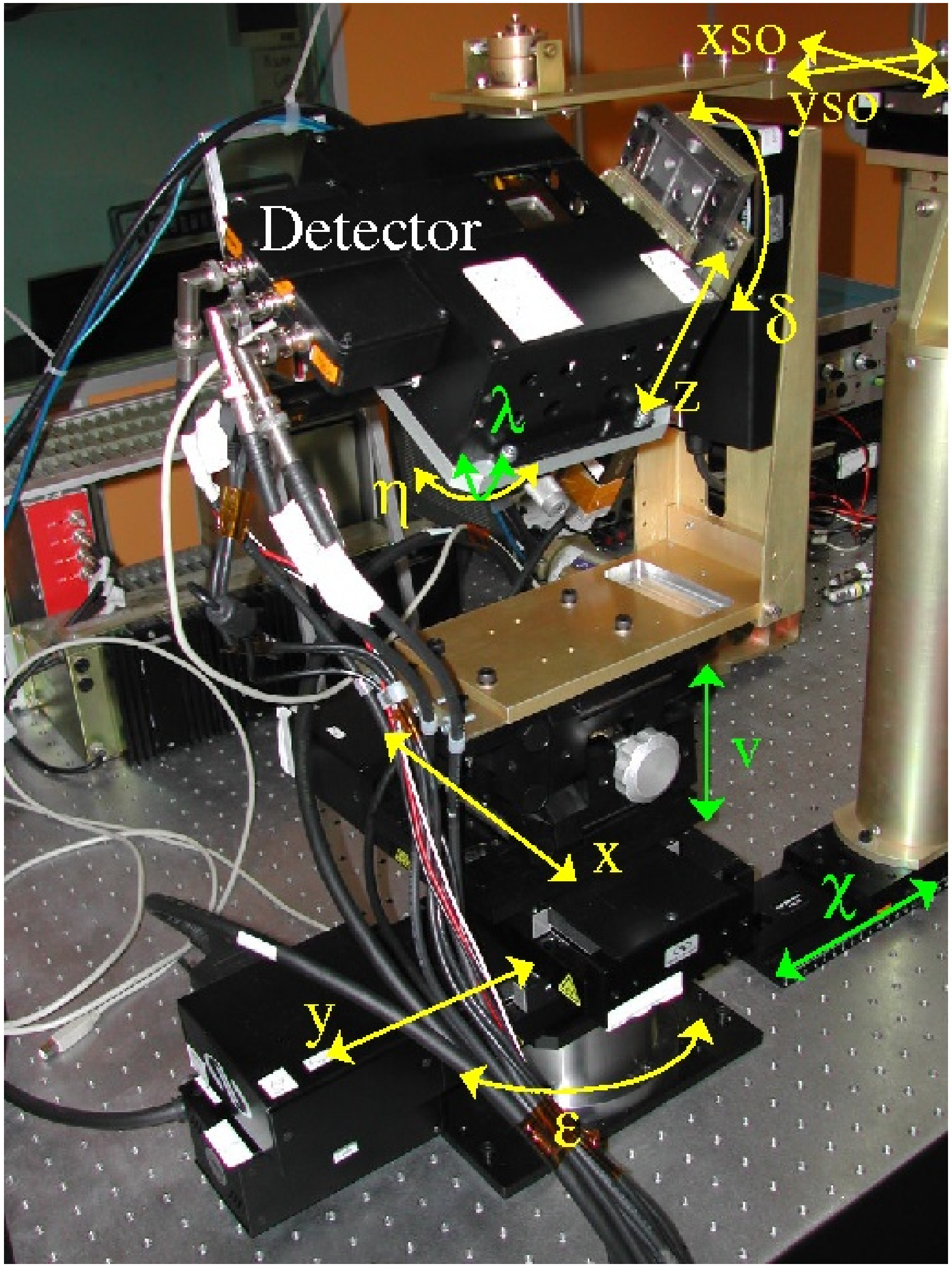
Incident radiation (X-ray tube)	E (keV)	Crystal	θ	$\mathcal{P}$
Polarized radiation				
Continuum	1.65	ADP ($NH_4H_2PO_4$, 101)	45°	$\sim$1.0
Continuum	2.04	PET ($C(CH_2OH)_4$, 002)	45°	$\sim$1.0
Lα Molybdenum (50 W)	2.293	Rhodium (001)	45.36°	0.9994
Continuum	2.61	Graphite (002)	45°	$\sim$1.0
Lα Rhodium (50 W)	2.691	Germanium (111)	44.86°	0.9926
Kα Calcium (200 mW)	3.692	Aluminum (111)	45.88°	0.9938
Kα Titanium (50 W)	4.511	Fluorite CaF_2 (220)	45.37°	0.9994
Kα Manganese (Fe^{55} radioactive source, 5mCi in 2008-01)	5.899	Lithium Floride (220)	47.56°	0.8822
Kα Copper (200 mV)	8.048	Germanium (333)	45.06°	0.9849
Unpolarized radiation				
Lα Molybdenum (50 W)	2.293	—	—	$\sim$0
Lα Rhodium (50 W)	2.691	—	—	$\sim$0
Kα Titanium (50 W)	4.511	—	—	$\sim$0
Kα Manganese (Fe^{55} radioactive source, 5mCi in 2008-01)	5.899	—	—	0
Kβ Manganese (Fe^{55} radioactive source, 5mCi in 2008-01)	6.490	—	—	0
Kα Molybdenum (50 W)	17.479	—	—	$\sim$0
Kα Rhodium (50 W)	20.216	—	—	$\sim$0

The X-ray facility

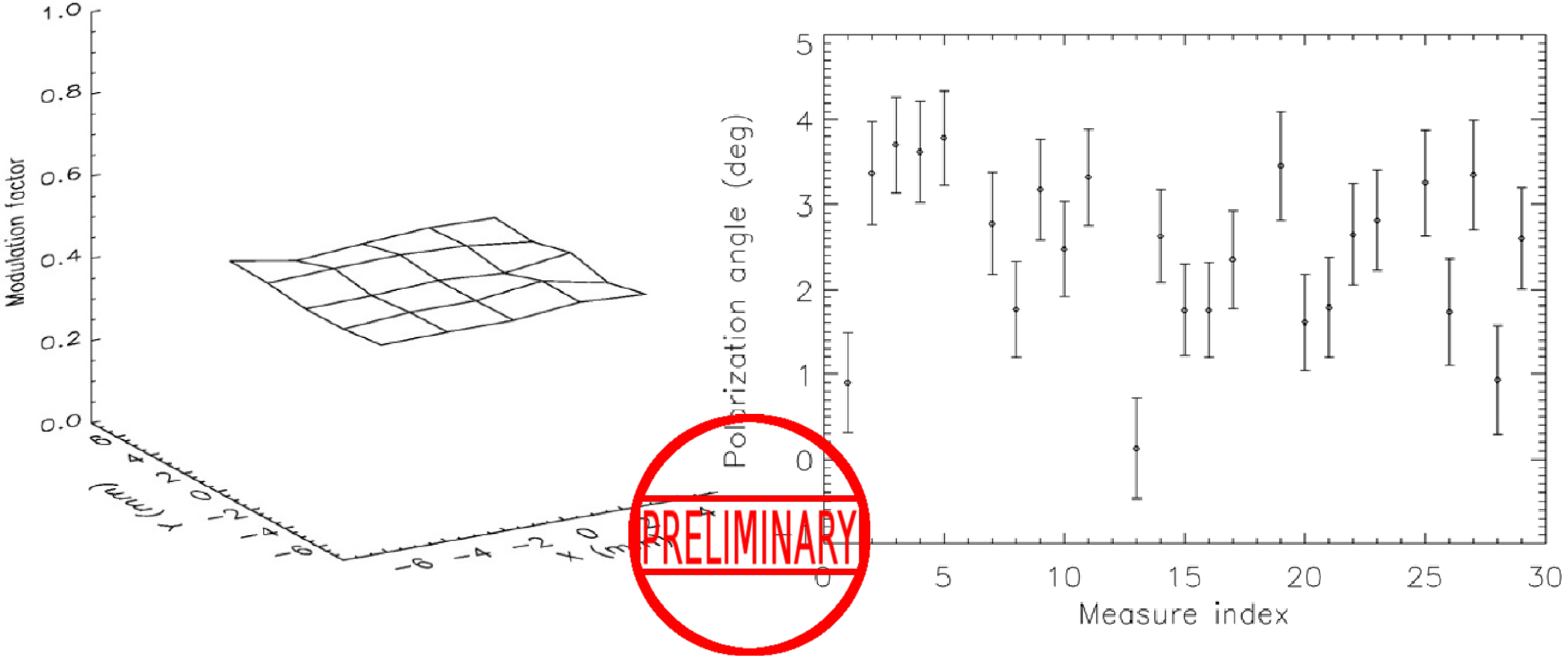
The facility

10 movements (8 motorized + 2 manual)

- XY mapping;
- angular reconstruction;
- inclined beams



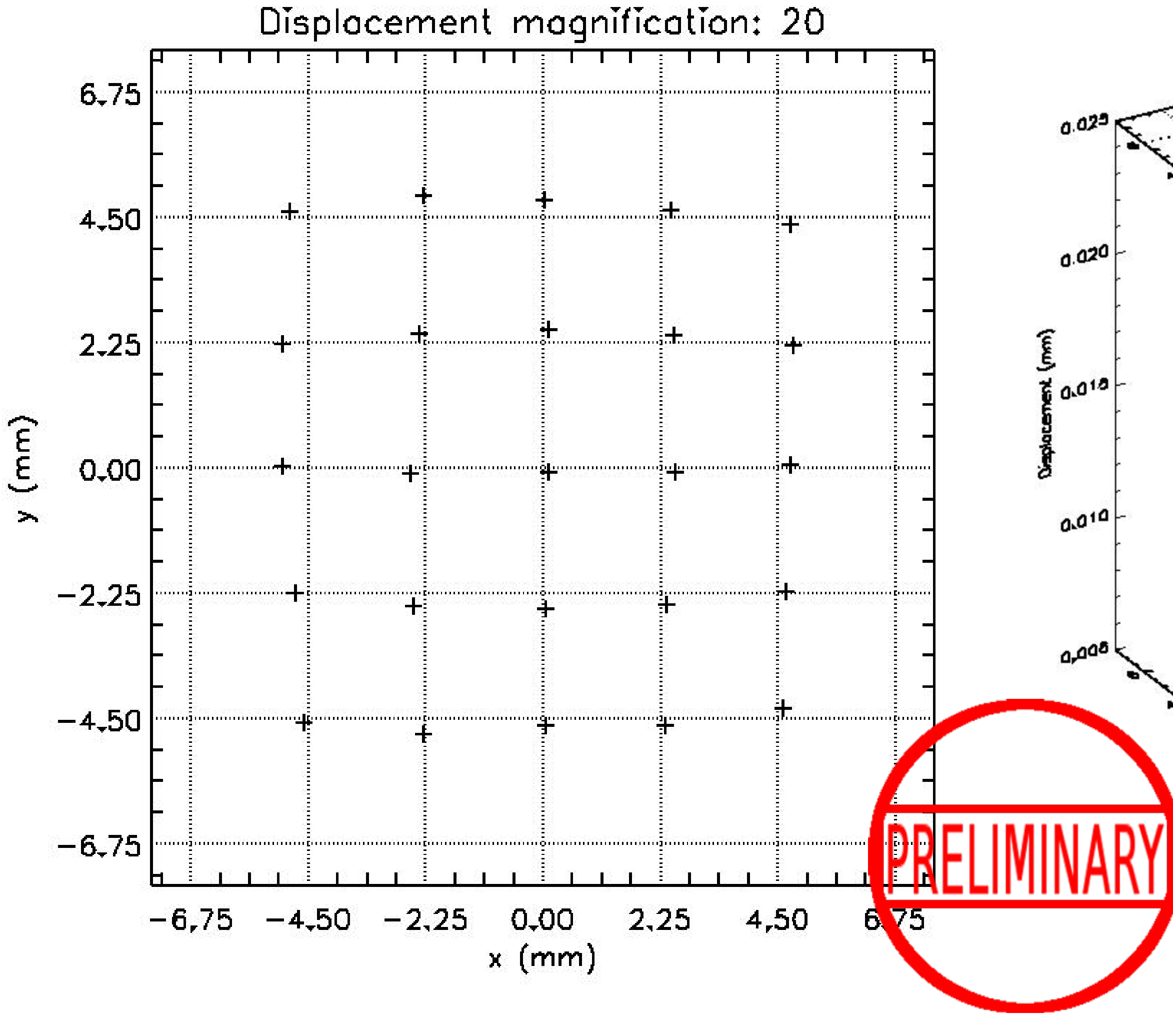
Step 2.25 mm, 5x5 Measurements @ 4.5 keV (Ti X-ray tube and CaF_2 crystal)



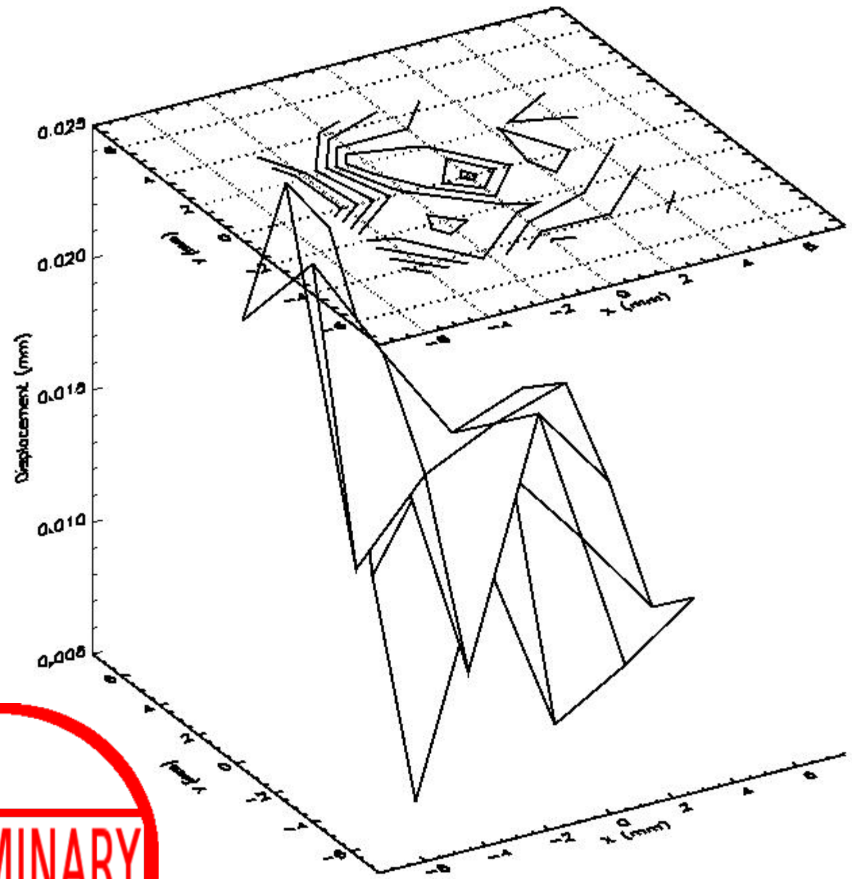
Modulation factor **Angle of polarization**

XY mapping

Step 2.25 mm, 5x5 Measurements @ 4.5 keV (Ti X-ray tube and CaF_2 crystal)

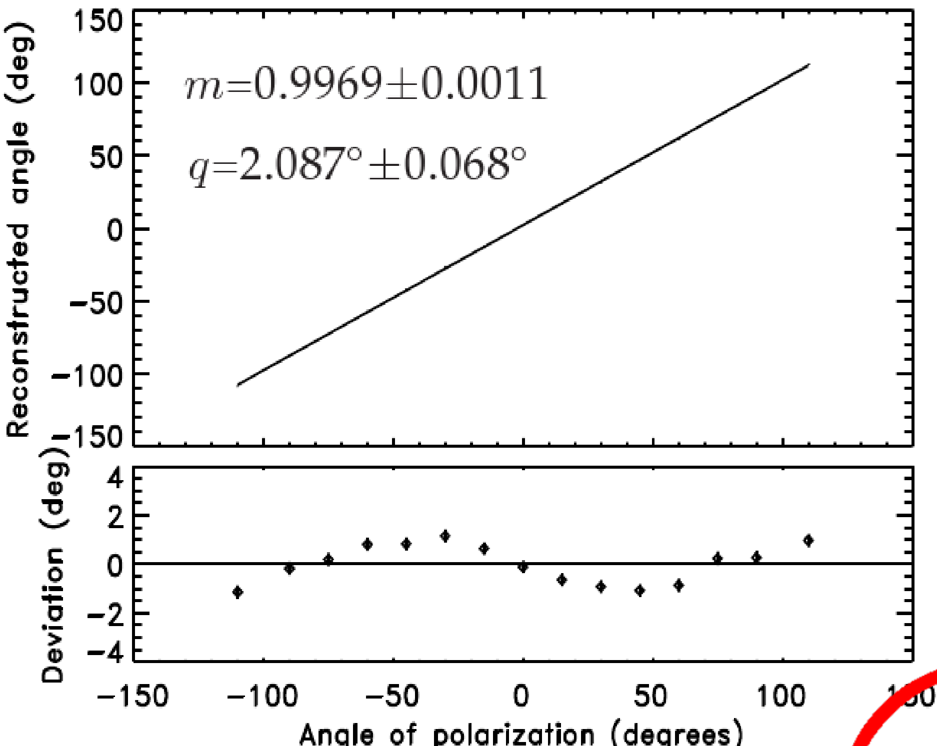


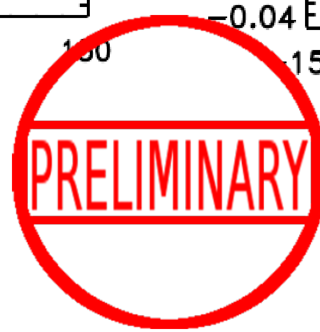
Position of the beam

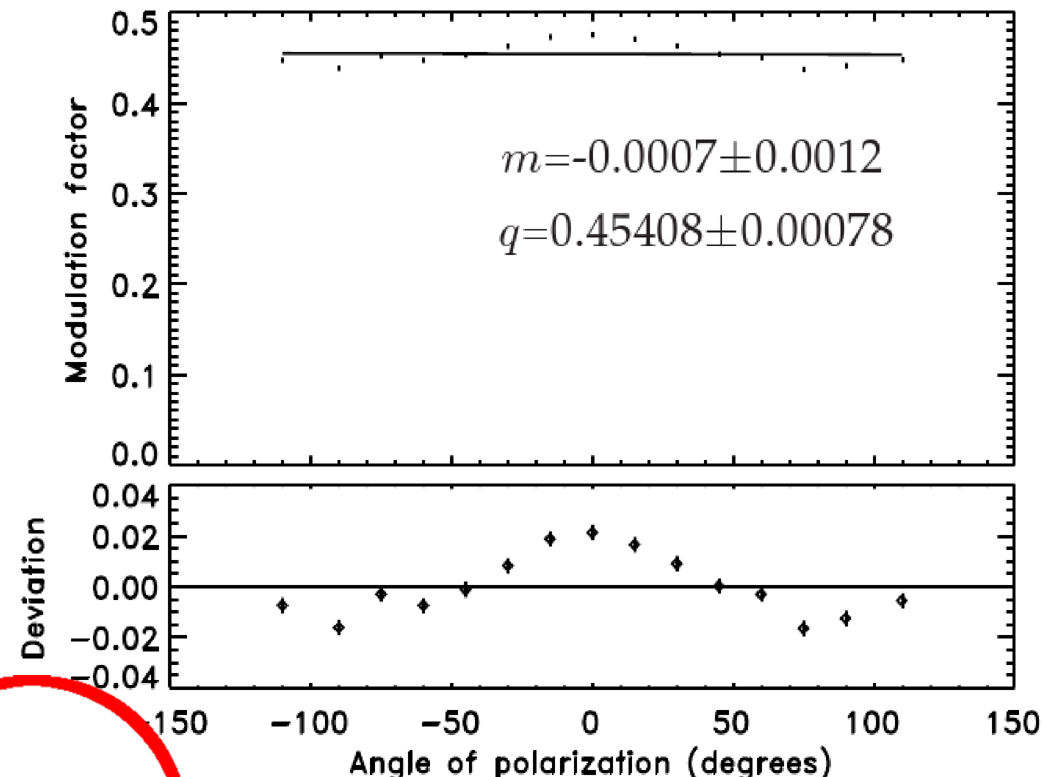


Displacement

Rotation around the center of the detector







Angle of polarization

Modulation factor

Future missions

Future missions

- ✔ ASI approved the inclusion of an X-ray polarimeter, EXP^2, on-board the HXMT satellite;
- ✔ ASI founded the Phase A of POLARIX, a dedicated mission to the X-ray polarimetry;
- ✔ NASA/ESA/JAXA is founding the Phase A of IXO, a multi-purposes observatory which includes in the focal plane an X-ray polarimeter.

The Hard X-ray Modulation Telescope

Devoted to a survey in the Hard X-rays (20 - 250 keV), with only a fraction of time dedicated to pointed observations.

Its launch has been planned in the 2010-2011, but with the inclusion of the X-ray Polarimeter the launch probably will be moved at least to 2012.

Main Detector	NaI(Tl)/CsI(Na) Phoswich
Total Detect Area	~5000 cm2
Energy Range	20-250 keV
Energy Resolution	~19% (@60keV)
Continuum Sensitivity	~3.0×10-7 ph cm-2 s-1 keV-1 ,or 0.5 mCrab (3σ@100keV,10^5s)
Field of View	5.7°x 5.7° （FWHM ）
Source Location	≤1 arcmin
Angular Resolution	≤5 arcmin
Mass	~2500 kg (payload ~1100 kg)
Dimension	2.0×2.0×2.8 m3 (L×W×H)
Nominal Mission lifetime	2 — 3 years
Orbit	Altitude 550km, Inclination 43°
Attitude	Three-axis stabilized

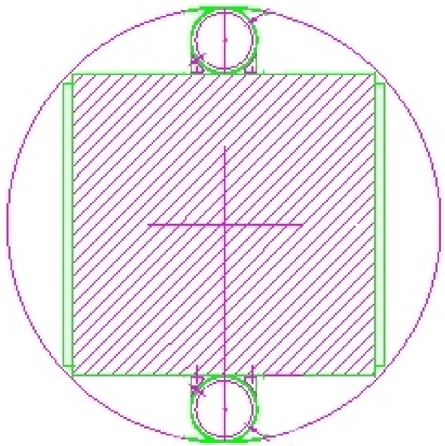
EXP^2: an Efficient X-ray Photoelectric Polarimeter for the HXMT mission

The Institutes currently involved are:

- IASF/INAF Rome;
- INFN Pisa;
- OAB/INAF – Brera
- Università di Roma Tre

The polarimeter is designed to fit the specification of the HXMT launcher and bus:

- Two short focal length optics;
- Total mass: ~110 kg;
- Total power: ~40 W.



Soffitta et al. 2008

PolariX: An italian polarimetry mission

PolariX is one of the five missions selected by ASI within the small mission announcement of October 2007 with a budget of **50 M€** for the bus and the payload.

Phase A started in April and will end in December, when there will be a downselection to two missions to be launched between 2012 and 2014.

To reduce costs, developments and risks, the heritage of past missions will be employed in various aspects of the mission.

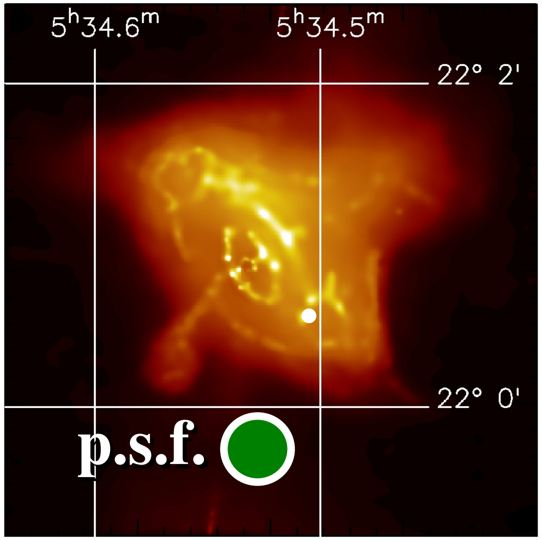
Costa et al. 2008

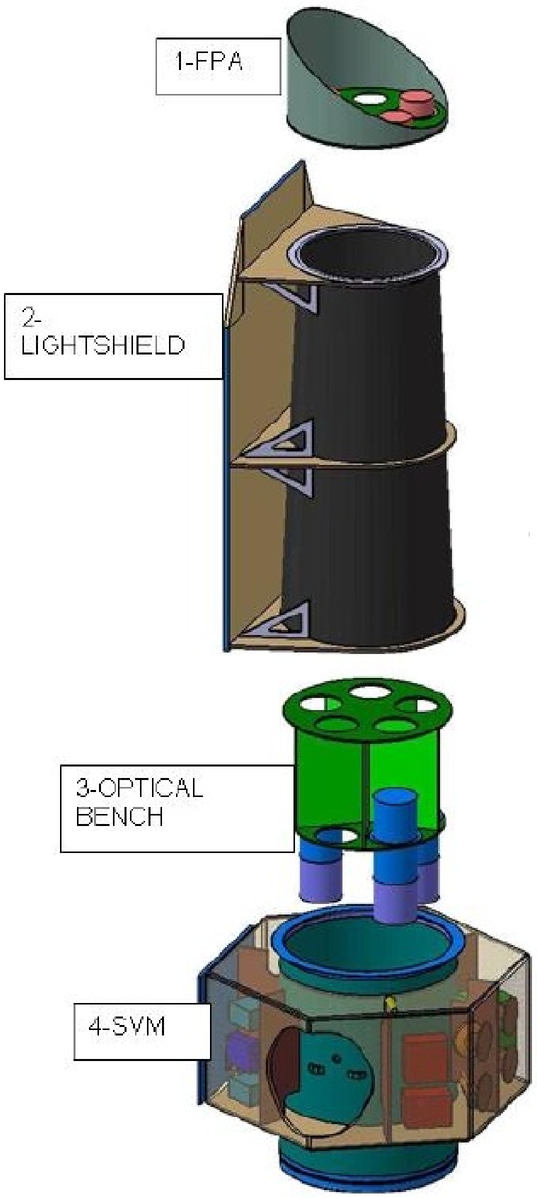
PolariX: An italian polarimetry mission

Three optics are already built and calibrated for the Jet-X mission which has never flown (same optics as XRT on board SWIFT):

- very low cost but high mass
- mandrels can be exploited to produce further low cost and low mass optics

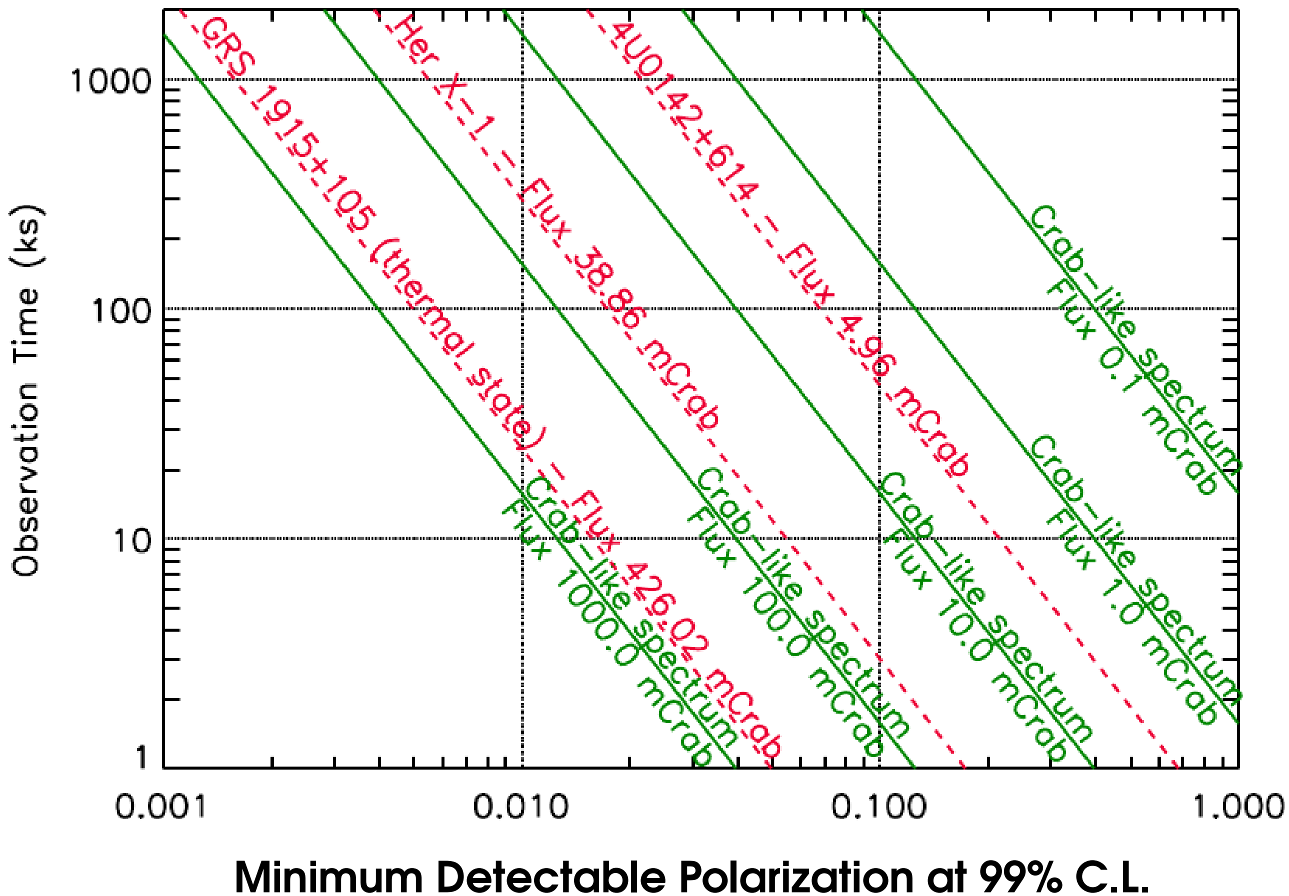
Good (measured) performances: HEW=15 arcsec





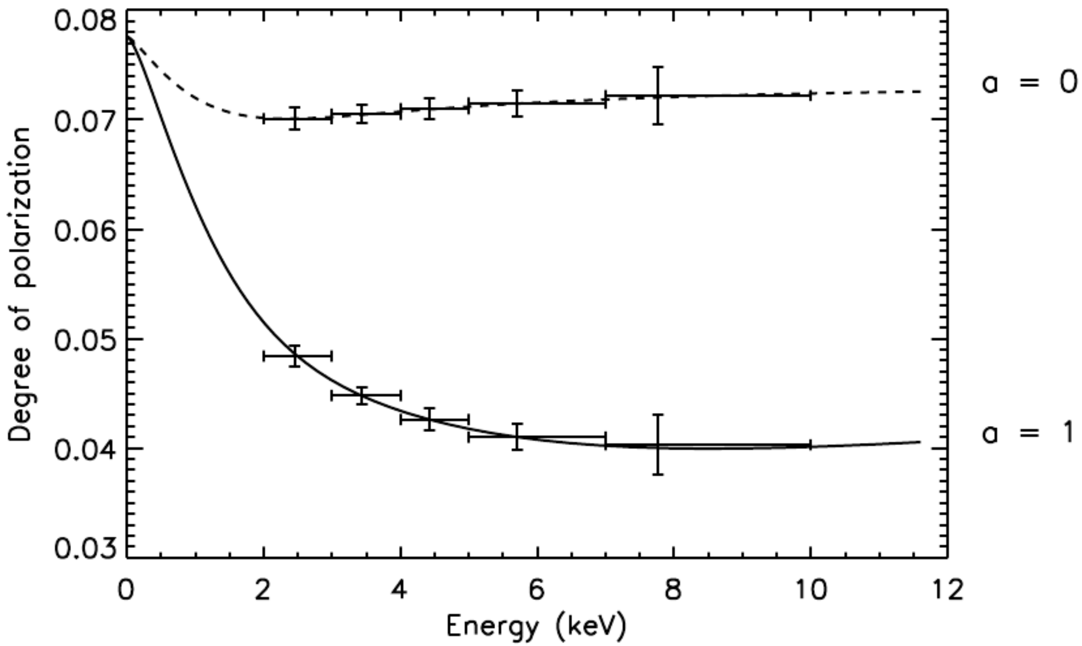
Pathfinder missions: Main Characteristics

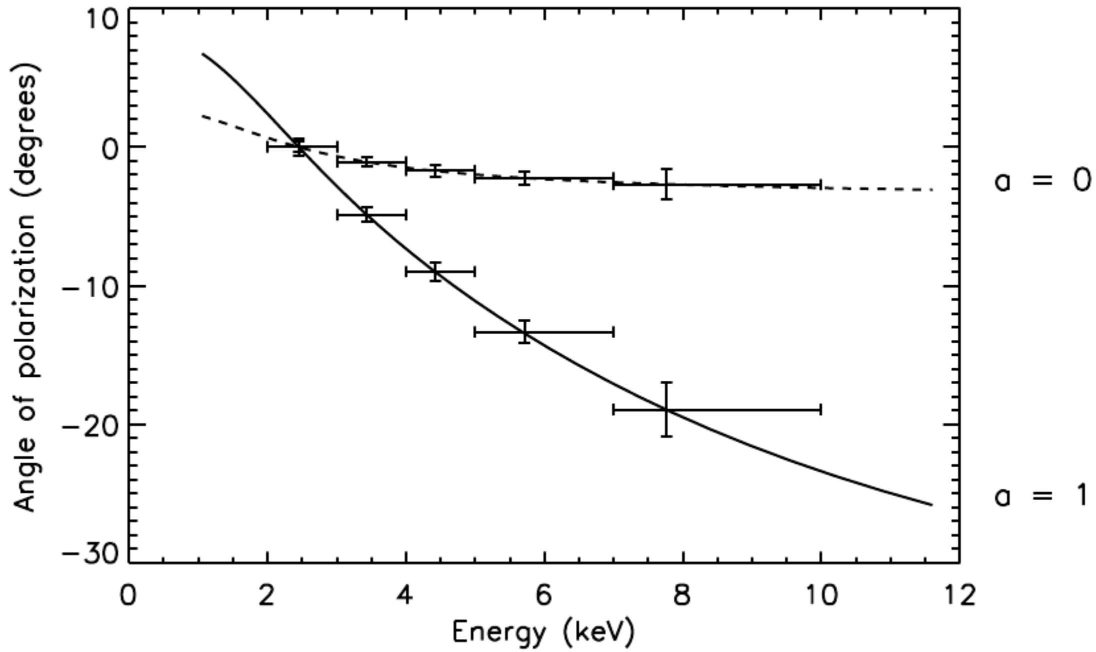
- **Polarimetry**: MDP~1% for 100ks of observation for 100 mCrab sources (1 Crab, 2.0 10^{-8} erg/s cm^2, 2-10 keV)
- **Imaging**: angular resolution <1', f.o.v. 22'x22'
- **Spectral capability**: $\frac{\Delta E}{E}=0.2\sqrt{\frac{6}{E}}$, energy band: 2 - 10 keV (but depends on gas mixture)
- **Timing**: 10 μs



Relativistic effects on black hole emission

Dovciak, et al. (2008): standard thin disk (multitemperature BB) + Thomson scattering atmosphere (no absorption).





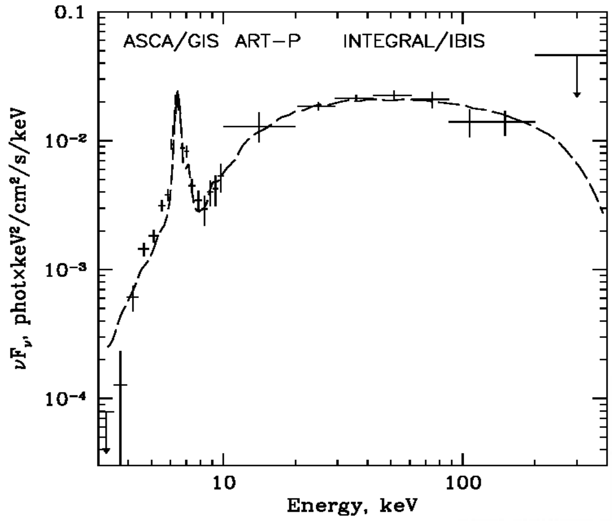
Reflection Nebulae: the case of Sgr B2

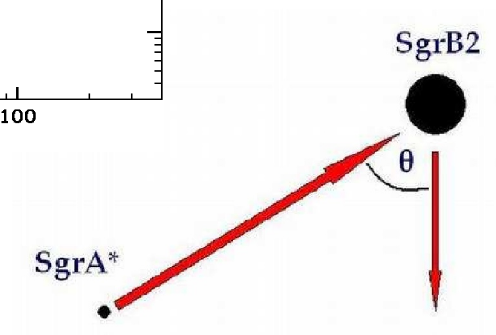
<u>Koyama et al (1996), Revnivtsev et al (2004)</u>:

- Kα del Fe neutro;
- Hard emissin

Reflection nebula: **outburst** from Sgr A*?

- $\tau \sim 1$, $\theta \sim 80^\circ$, $\Gamma \sim 1.8$;
- $L_{Sgr\,A^*}$ (2-10 keV) ~ 5 10^{38}erg/s (LLAGN)

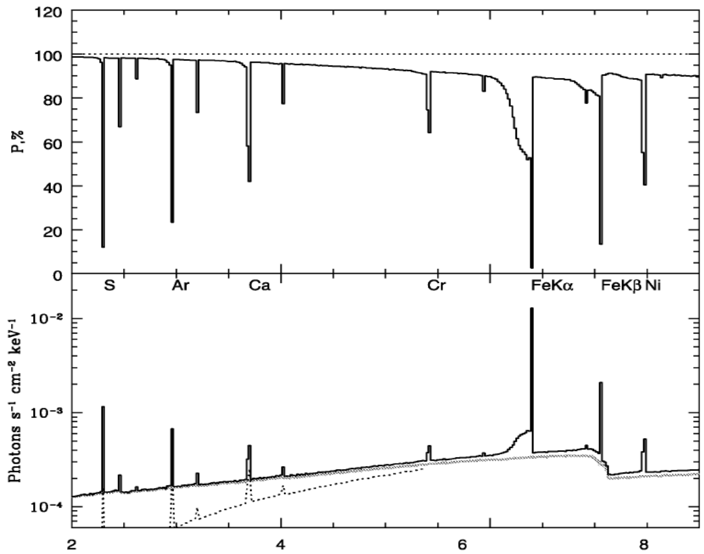


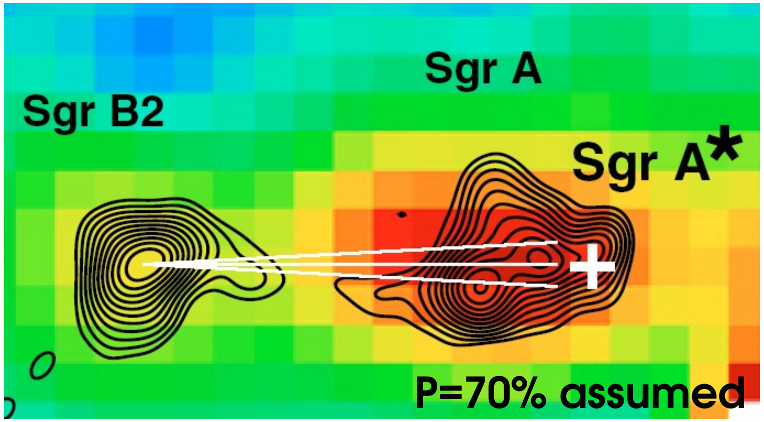


Thomson scattering: $P = \frac{1-\cos^2\theta}{1+\cos^2\theta}$

<u>Churazov et al (2002)</u>:

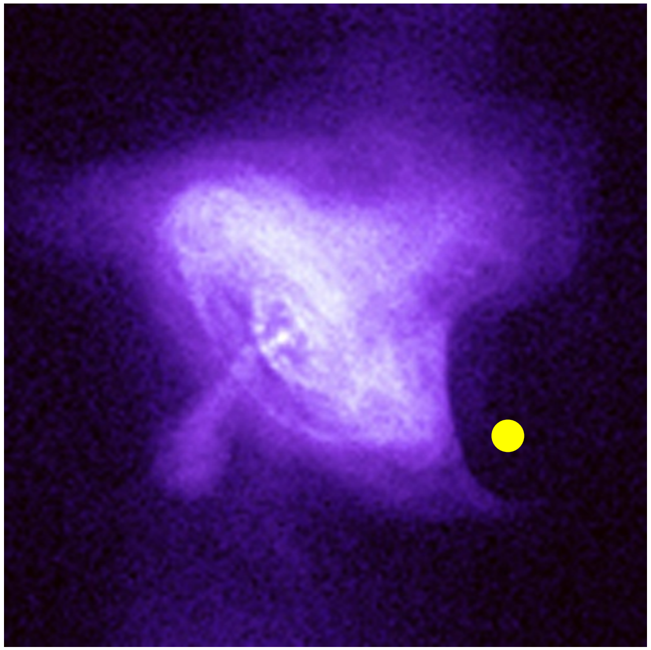
- Strongly polarized contiuum emission
- Unpolarized fluorescence lines.



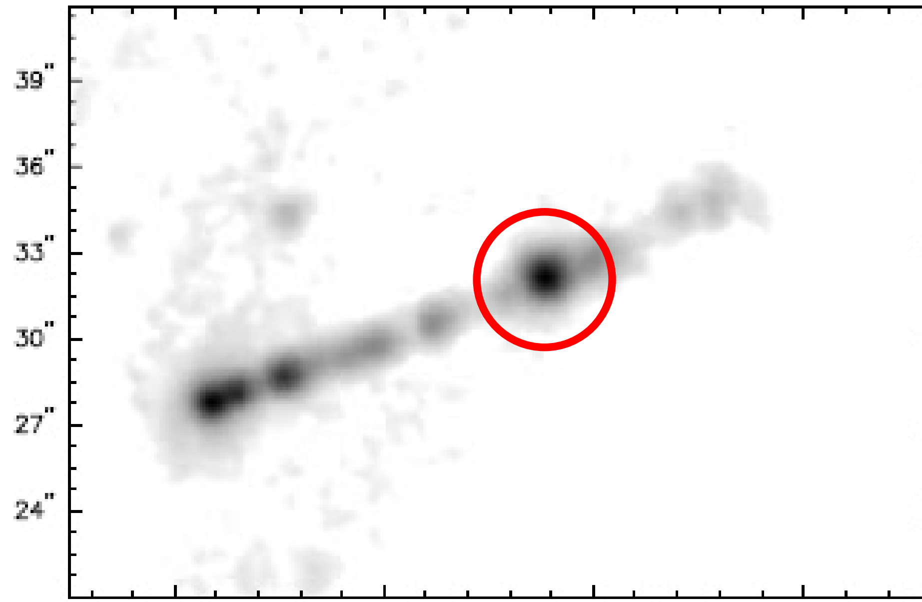


Why other X-ray polarimeters beyond pathfinder?

IXO: an X-ray polarimeter in the focal plane with ~10% of dedicated time, very large optics ~14000(?) cm^2 @ 3 keV, f = 2000 cm, resolution ~5 arcsec



PSF



M87 Knot A: MDP~7% for T=200ks

Performances: 1% @ 1 mCrab and 100 ks (goal, current: 2%)

Conclusions

X-ray polarimetry is becoming real thanks to photoelectric devices, such as Gas Pixel Detector.

We developed a facility which allows its complete characterization with polarized and unpolarized photons.

Calibrations are on-going.

Pathfinders in a **few** years.

Polarimetry of galactic and extragalactic sources with pathfinders.

MDP~1% for F=100 mCrab and T=100 ks

With IXO accessible even faint extragalactic sources.

MDP~1% for F=1 mCrab and T=100 ks