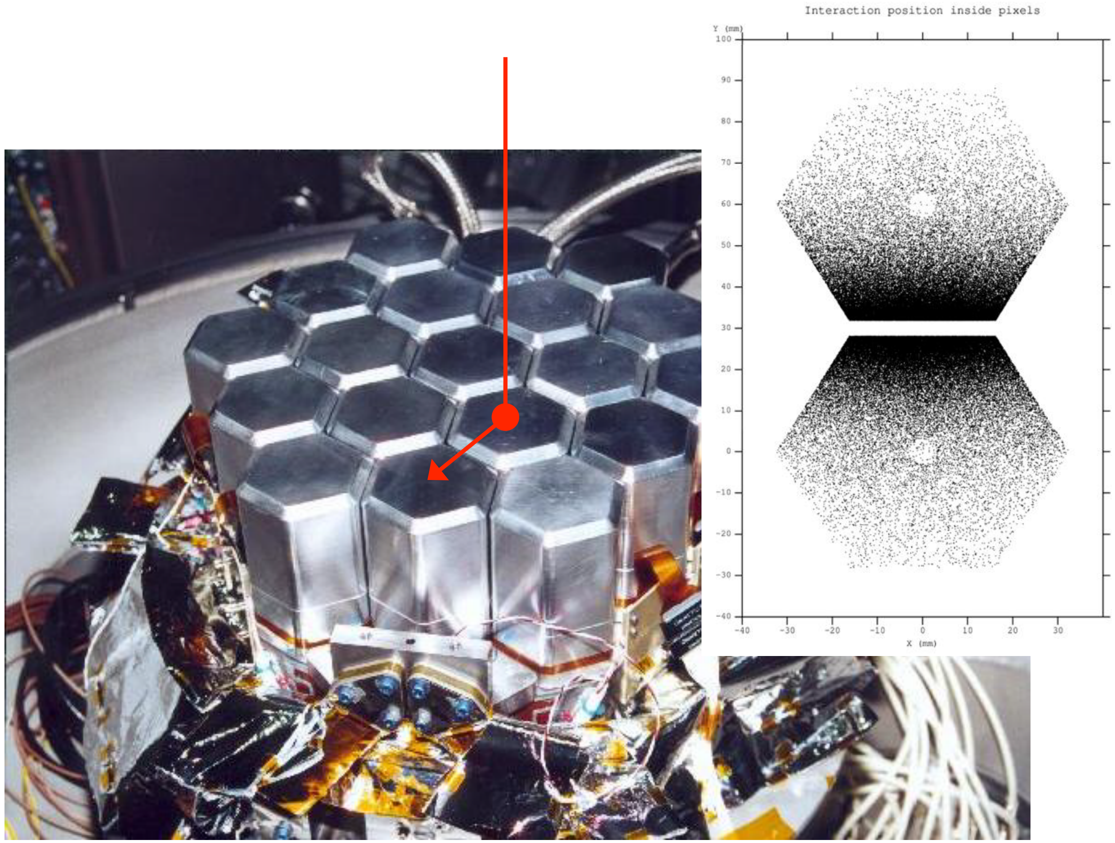
Detecting Gamma-ray Polarisation Using SPI

JP ROQUES

SPI as a Polarimeter

- No positional information available within the detectors
- Scatter angles determined by the centre to centre line
- 90% multiples events occur in adjacent pixels

→ **Double Events**

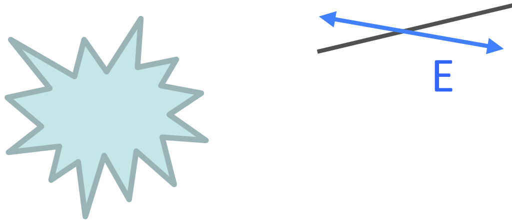


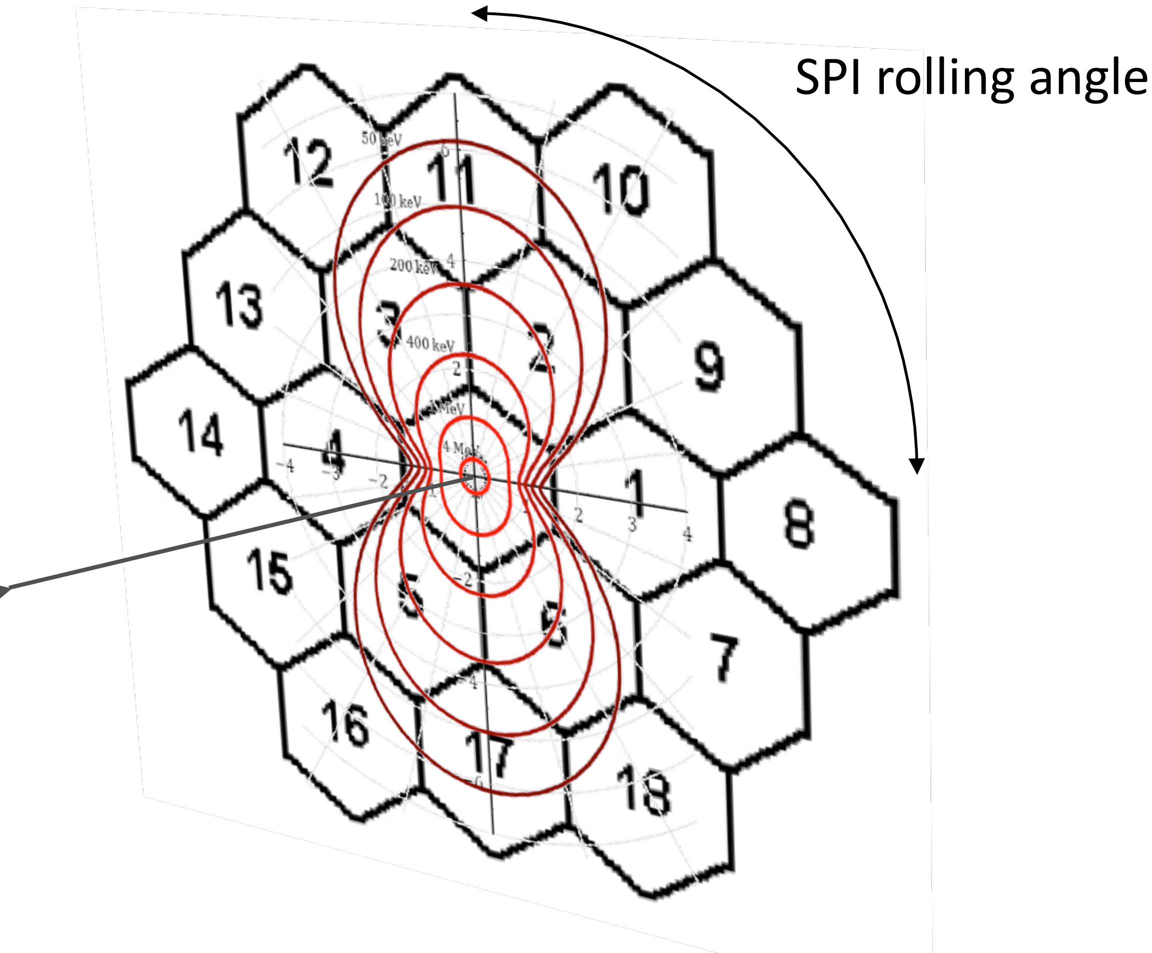
SPI as a Polarimeter

$$Q = \frac{N_{\perp} - N_{\parallel}}{N_{\perp} + N_{\parallel}}$$

From 100keV to 1MeV

- Q-factor ~25%



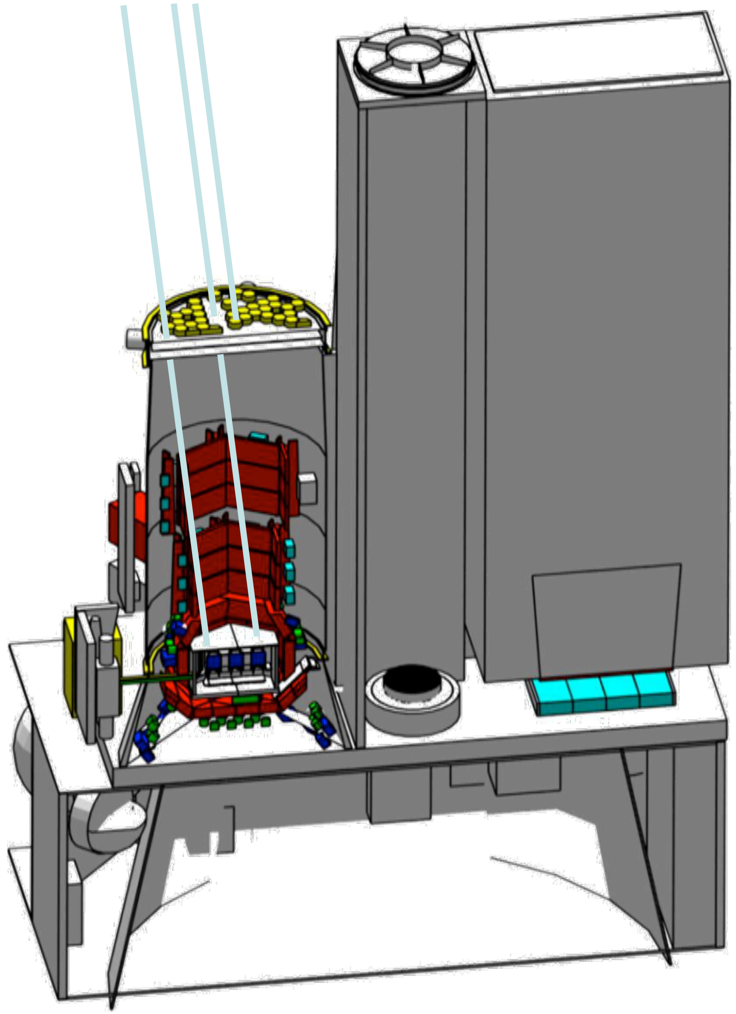


Pb: mask shadow, rolling angle, dead detectors, anticoincidence, background

→We need simulations

The GEANT4 Model

- Based on the TIMM Model
- Originally designed to calculate SPI line background
- Current Model Includes SPI, JEM-X, limited IBIS models



The GEANT4 Model

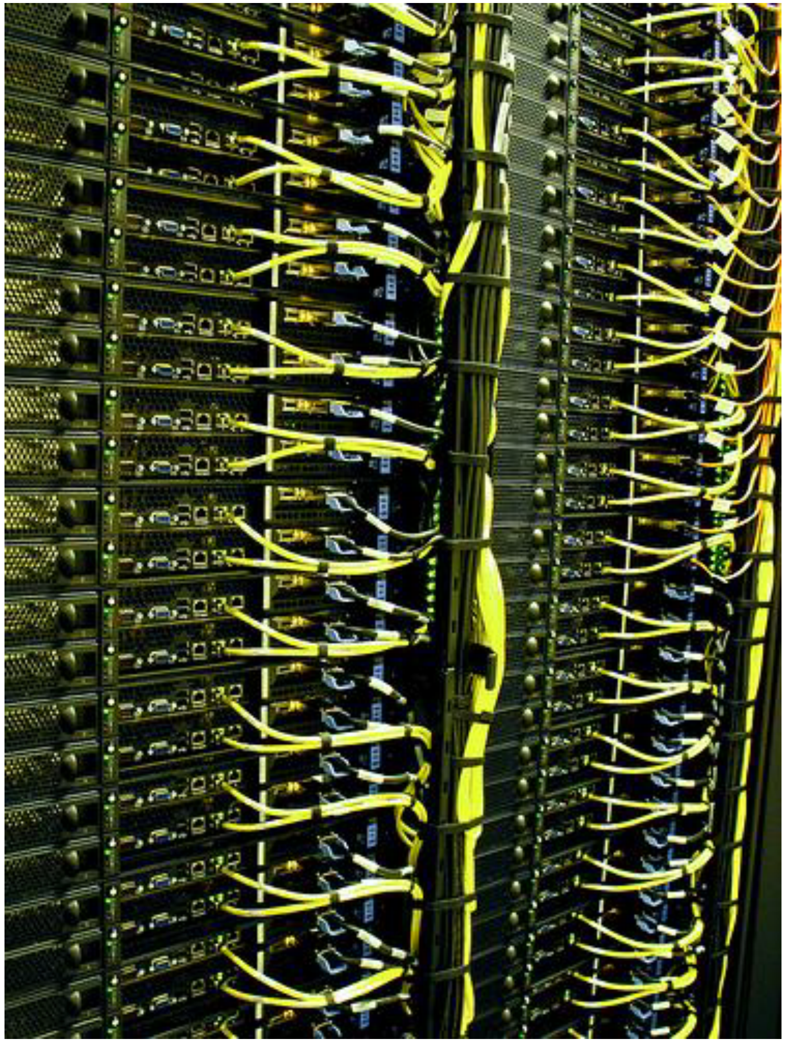
Each simulation

- 50 million photons
- Equivalent of ~6hrs of real SPI data
- Takes ~6hrs to run on a single processor
- 19 simulations for a pointing
- 18 for 0° - 170° in 10° steps
  + 1 unpolarised

For Cygnus X-1 (2000 scw):
$6\text{h}\times19\times2000=228000\text{h} =9500\text{days!}$

Integral-13 Cluster

- 32 10-core compute nodes (Intel Xeon 2.26 GHz)
- Completes 144 simulations in ~3hrs
- Completes Cygnus X-1 in 33 days



Fitting The Data

- Each adjacent detector pairs considered (Pseudo detectors: 42 later reduced to 22 after failure of four Ge pixels)
- **Recorded data modelled as**:

$$D_{is} = x \times G4_{is}(\%, \Pi) + y \times B_{is}$$

i: pseudo detector, s: scw

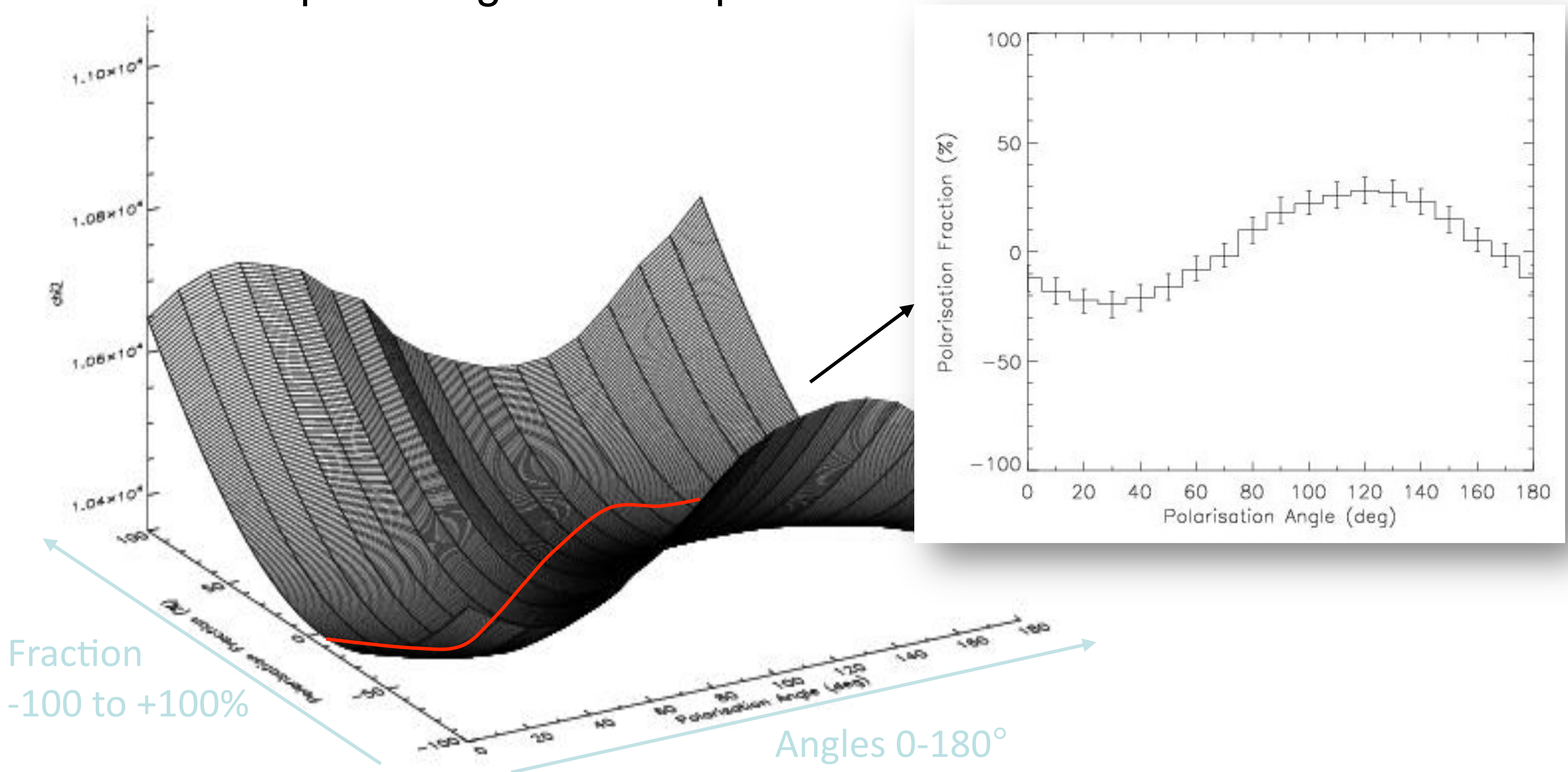
- $G4_{is}(\%,\Pi)$ is the counts from the Geant4 simulation, as a function of polarisation **fraction** % and **angle** Π. Values weighted by livetime

- B_{is} is taken from a Flat Field

- **Data fitted** on a Science window by Science window and pseudo detector by pseudo detector basis resulting in a **Chi²**

Fitting The Data

- **Chi²** is calculated looping over the **polarisation angles** and **fraction** producing a Chi² map:



Crab Pulsar

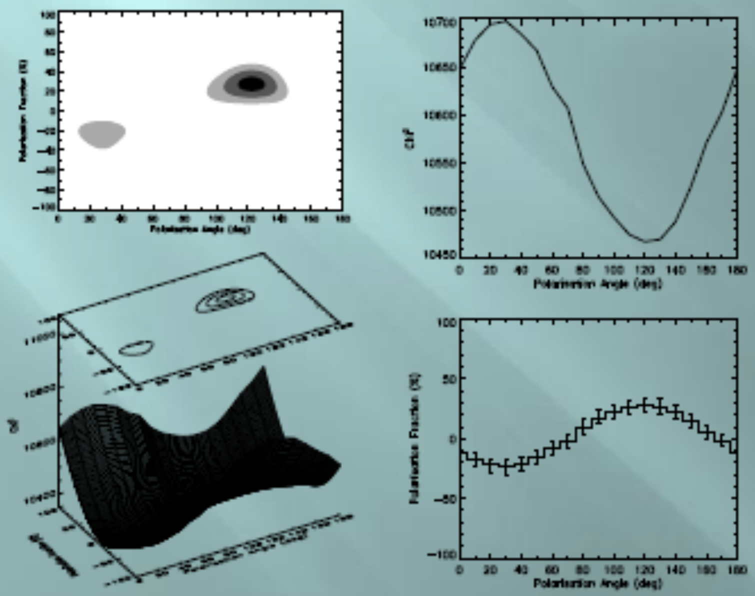
Emission mechanism = synchrotron radiation

Polarisation seen at all wavelengths even in X-rays

→ wind geometry and B,

Acceleration processes

INTEGRAL results : highest energy particles



For the total emission (Psr + nebula)

~ 400 ks

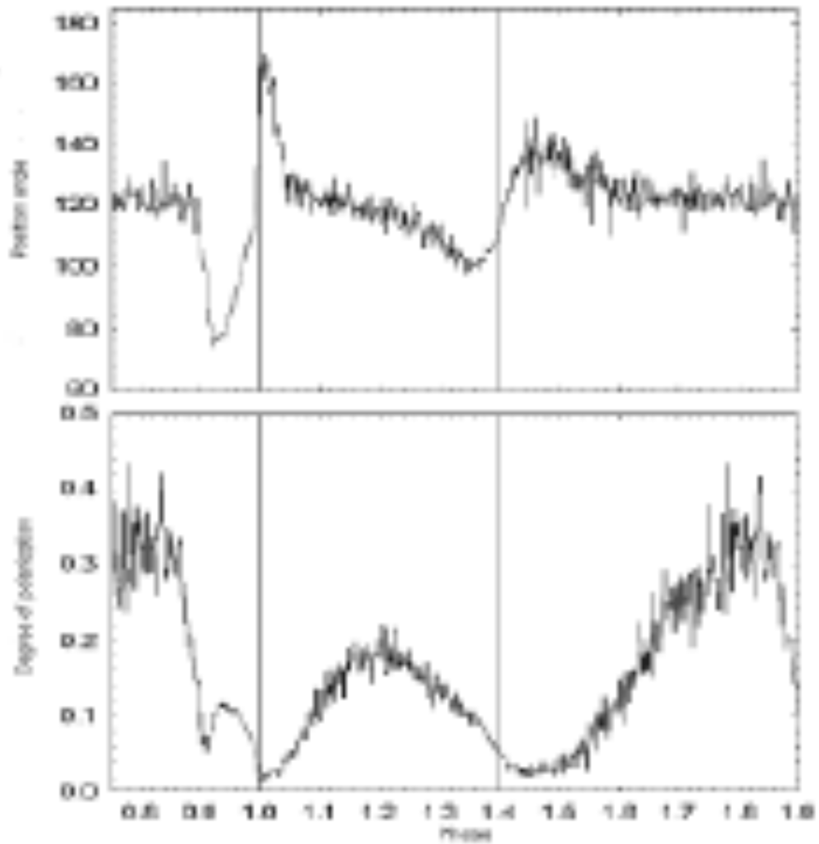
Angle = 122° ±7°

aligned with rotation axis

Fraction = 28% ±6%

CRAB PULSAR : next steps

- Evolution during phase:
  - Dean et al,2008 : nothing in the pulsed emission (PF radio and optical < 10 %)



- Much more data to analyse (~2.5 Ms)
- Precision increase
- Stability investigation
- Preliminary results are consistant with those ones
- Aim : produce a Crab polarized spectrum for future reference and calibration
- More to be presented at Annapolis (15-19 /09)

Optical : Kanbach et al.,2005

Cygnus X-1 polarisation

Data set and Field of view

Mainly based on the data set analysed in Jourdain et al. 2012

Angle selection : 13°
More than ~20 scw in the revolution

42 parts of revolutions

Total duration : **4 Ms**

From June 2003 to December 2009

Log of the *INTEGRAL* SPI Observations of Cyg X-1 Used in This Paper

Revolution Number	Start	End	Useful Duration (ks)
79–80 (5 × 5)	2003 Jun 7 00:59	2003 Jun 12 03:35	293
210–214 (A)	2004 Jul 3 00:01	2004 Jul 17 00:25	709
251–252 (A)	2004 Nov 3 14:23	2004 Nov 7 16:26	176
259 and 261 (H)	2004 Nov 26 12:28	2004 Dec 3 15:43	143
470 (EXO, H)	2006 Aug 19 09:19	2006 Aug 21 16:02	159
486 (EXO, H)	2006 Oct 6 00:11	2006 Oct 8 07:55	160
498–505 (GP)	2006 Nov 11 19:31	2006 Dec 4 06:20	535
628–631 (A)	2007 Dec 4 19:05	2007 Dec 15 21:08	388
673 (A)	2008 Apr 18 17:41	2008 Apr 19 22:09	54
682–684 (A)	2008 May 14 08:13	2008 May 22 19:54	304
739–746 (A)	2008 Nov 1 02:14	2008 Nov 24 05:25	551
803–806 (A)	2009 May 11 08:27	2009 May 22 11:32	371
875(H*) and 877(H)	2009 Dec 12 16:18	2009 Dec 19 20:57	160

The differences

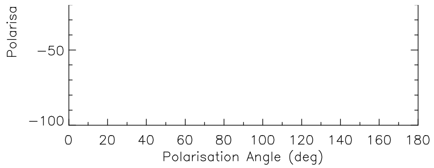
Sky Model : Cyg X-1
Cyg X-3
EXO 2030+375
GRS 1915

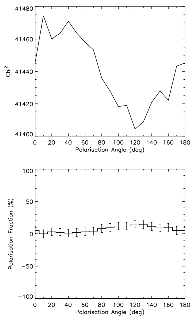
Rev 470-505 removed (complex sky model)
Rev 739-746 removed : more tests needed

=> Total duration ~ 2.6 Ms

RESULTS SUMMARY

100-230 keV

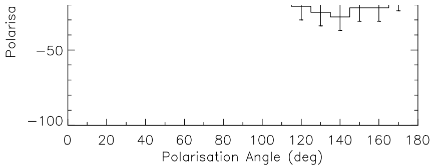


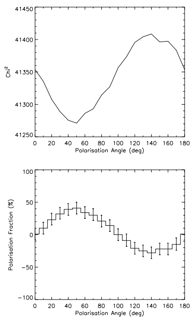


Not significant

122° +/- 6°
15 % +/- 6 %

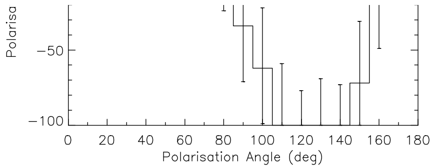
230-370 keV

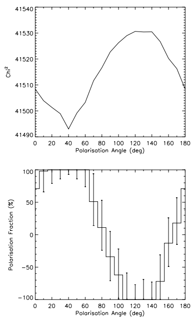




47° +/- 4°
41 % +/- 10 %

370-850 keV





39° +/- 3°
100 % ; > 75 % (2 σ)

Cygnus X-1: High Energy Polarization at 40degrees

- Cygnus X-1 analysis
- Summary of Cygnus X-1 polarization
  - Polarization angle: 42° ±3°
  - Polarization fraction:

130keV – 230keV: non polarised

230keV – 370keV: 41% ±10%

370keV – 850keV: > 75%

- Electric vector ~60° away from the jet Structure

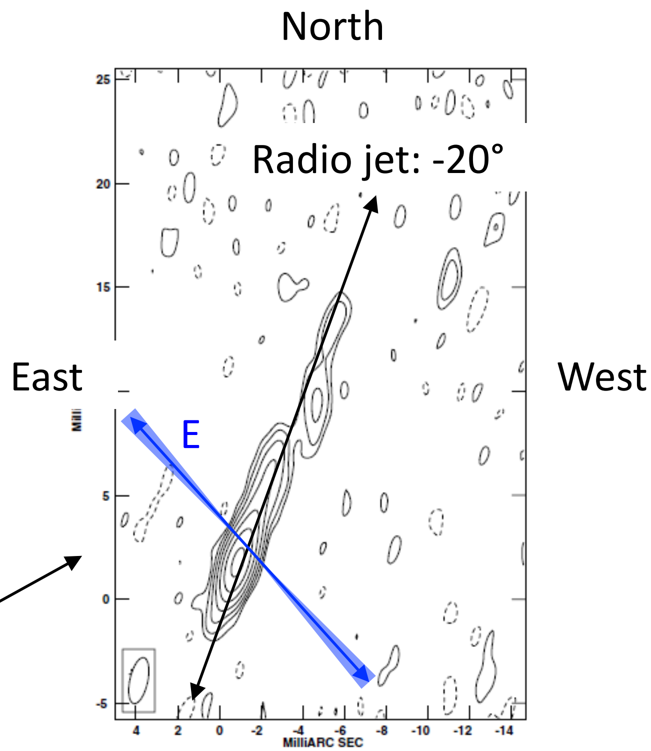


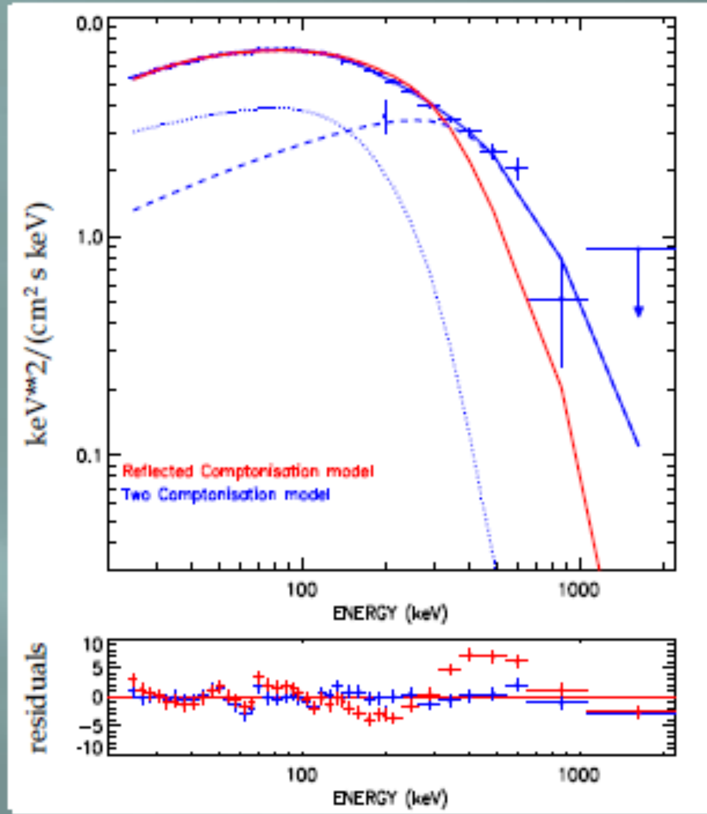
Figure 3. A high-resolution (robust 0) image of Cygnus X-1 at 8.4 GHz; lowest contour 0.157 mJy beam^{-1}, convolved with a Gaussian beam 2.25 × 0.86 mas^2 in PA −12°.4.

Stirling et al. 2001

CYG X-1

Link with the spectral results

High Energy spectral shape more complex than a single Comptonisation emission: Requires at least 2 components



CYG X-1

Link with the spectral results

High Energy spectral shape more complex than a single Comptonisation emission: Requires at least 2 components

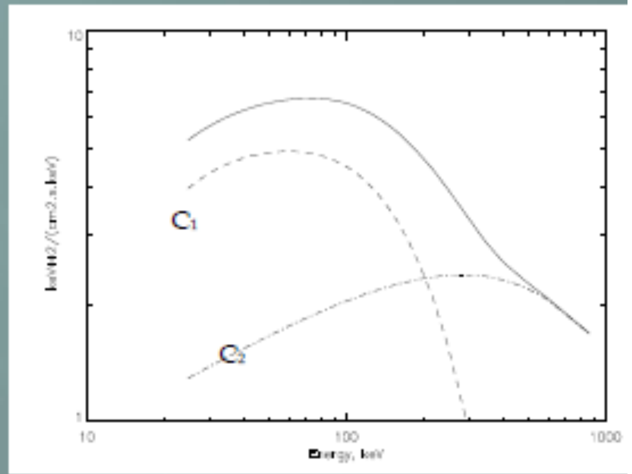
- Identification of the second component with the polarised signal

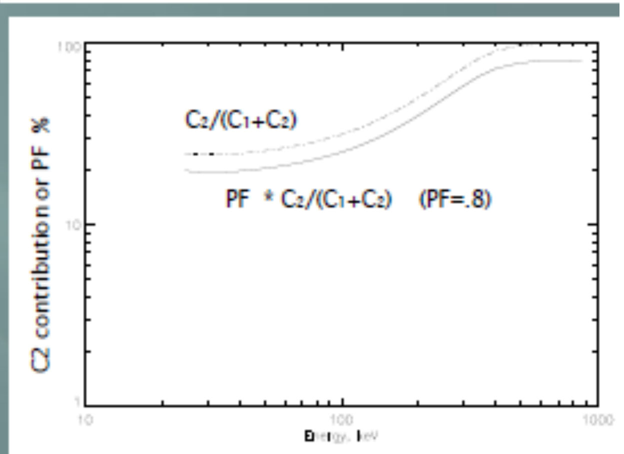
→ The evolution of the polarisation fraction with E can be explained by **two emission components**, one non polarised at low energy and the second strongly polarised and harder

$$PF_T = PF_2 * C_2 / (C_1 + C_2)$$

→ Synchrotron radiation in a **very ordered magnetic field**

→ Reciprocally: PF(E) determination allows to separate the two contributions to the hard X-ray emission : access to the corona and jet components parameters





CYGNUS X-1

- Since a long time, High energy excess above the comptonisation law has been reported – HEAO – SIGMA – OSSE – SPI…..
- Thanks to polarisation this component can be isolated and identified.
- Significant impact on our view of X-ray binaries
- Jet structure plays a major role in the high energy emission

- More data on Cygnus X-1 are welcome… but since a few years Cyg X1 is in low state: polarisation in undetectable. (Jourdain et al, 2013)

Prospects for Crab and other Pulsar

Currently, INTEGRAL polarimetry studies start at E > 100 keV
With a MDP ~50 mCrab (for 0.5 Ms)

With a polarimeter :

- Working down to 40-50 keV
- With a MDP of ~1 % in 100 ks (10 x better than INTEGRAL)

→ Detailed evolution of the polarisation along the phase (Crab)
→ Polarisation measurements for other pulsars
→ Information from PF and PA
→ Comparison with model predictions

- a spatial resolution ~20''

→ Determination of parameters evolution inside the nebula
localisation of the acceleration site

CYG X-1 and other XRB

Polarisation measurements in the hard X-ray domain crucial for

- Identification of the mechanism at work for the second component observed in several objects (role of the jet)

  GX 339-4, GRS1915, H1743-322, Sco X-1, 1E, GRS 1758, GS 1826….

- Determination of its relative contribution

  → more precise knowledge of the Comptonisation part

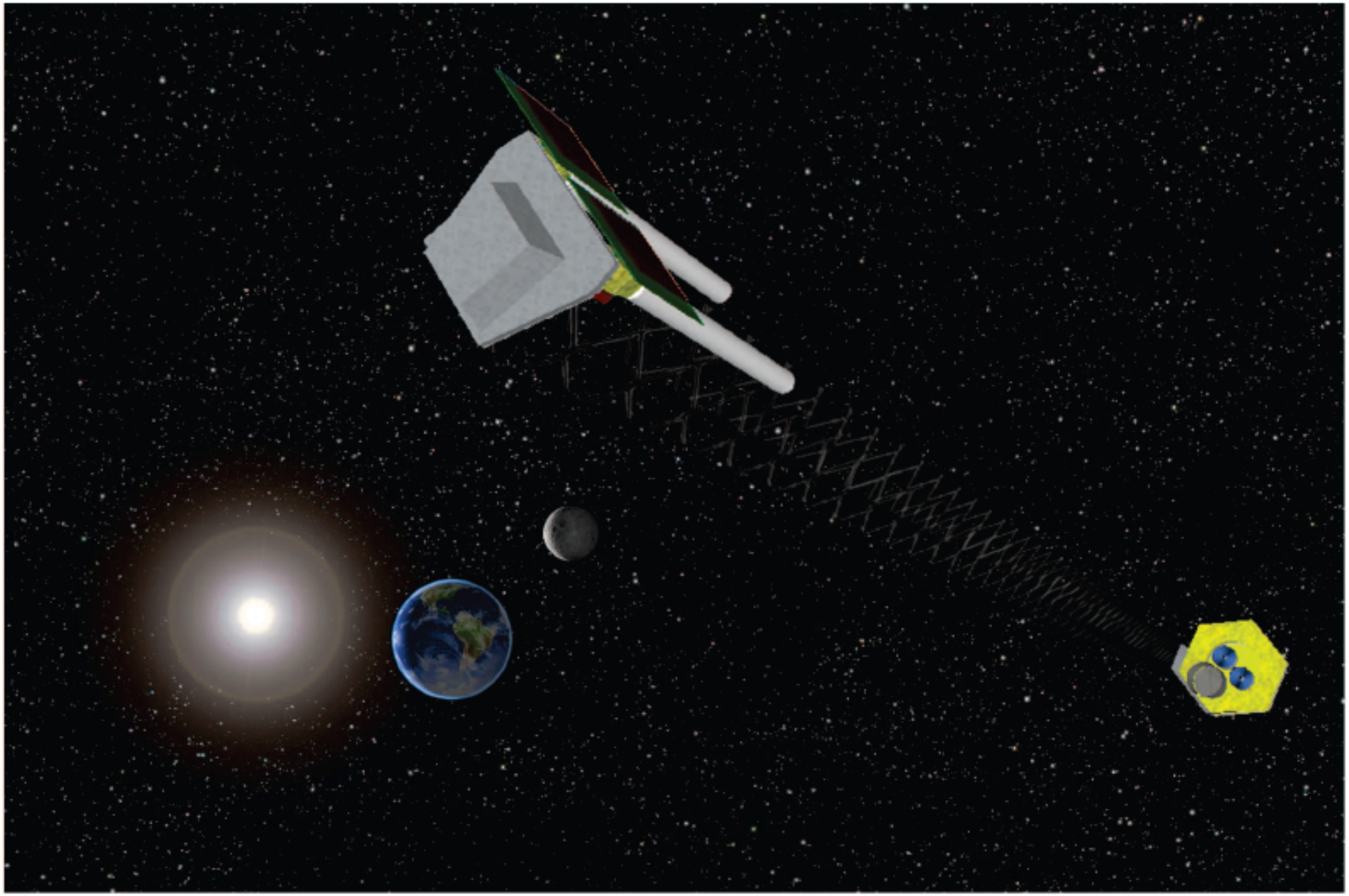
- Potential studies of the reflection component

  (PF ~10 % predicted in some models)

NEXT STEPS

PheniX – M4

A NEW VISION OF THE HARD X-RAY SKY

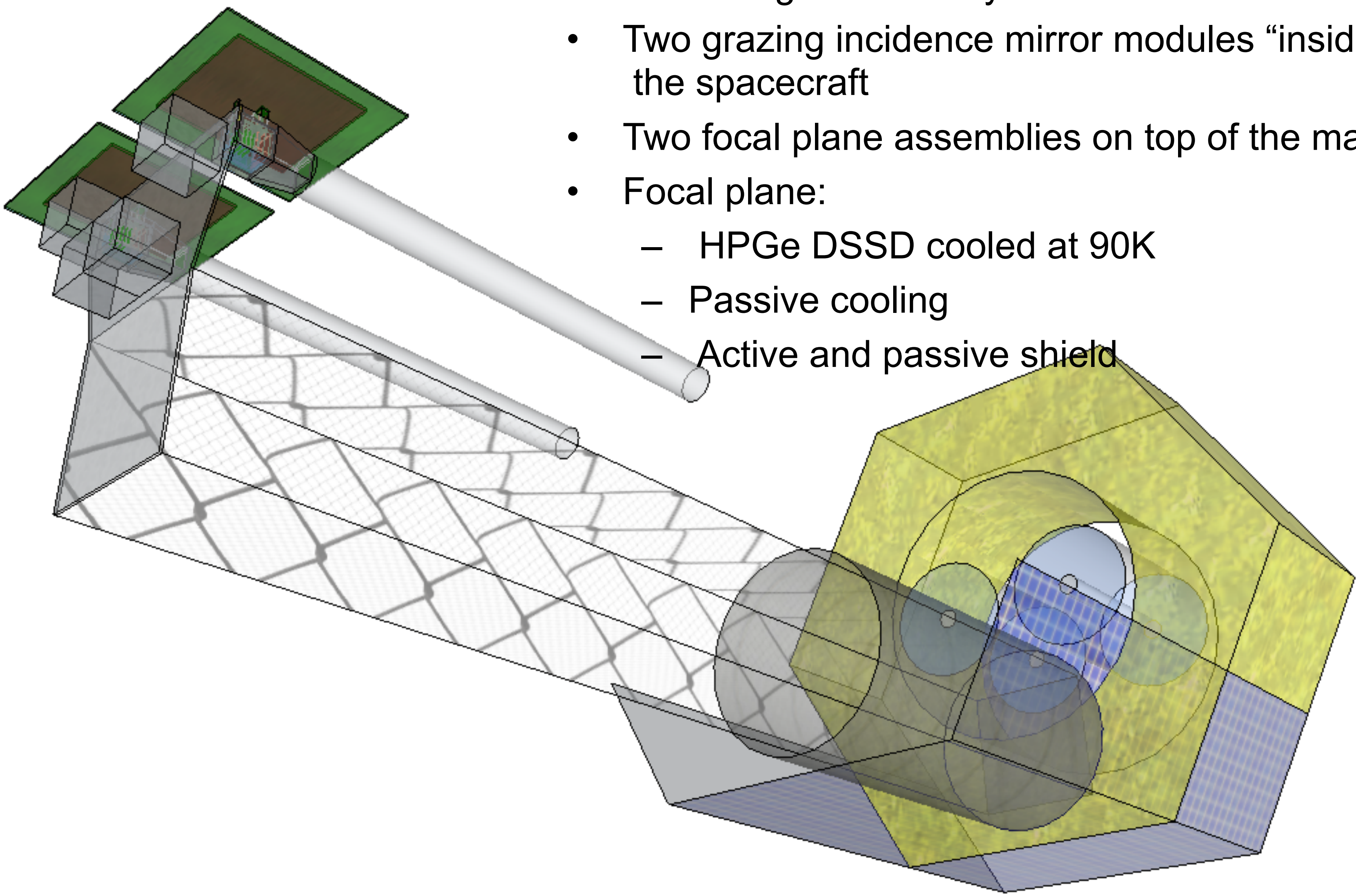


PheniX

- Unique instrument covering the ~3-400 keV range
- High sensitivity: > x5-10 Nustar and >x50-100 Integral
- High energy resolution and high counting rate
- Polarimetry capability

PheniX: model payload

- Two co-aligned telescopes working in parallel
- Focal length of 40m by extensible mast
- Two grazing incidence mirror modules “inside” the spacecraft
- Two focal plane assemblies on top of the mast
- Focal plane:
  - HPGe DSSD cooled at 90K
  - Passive cooling
  - Active and passive shield

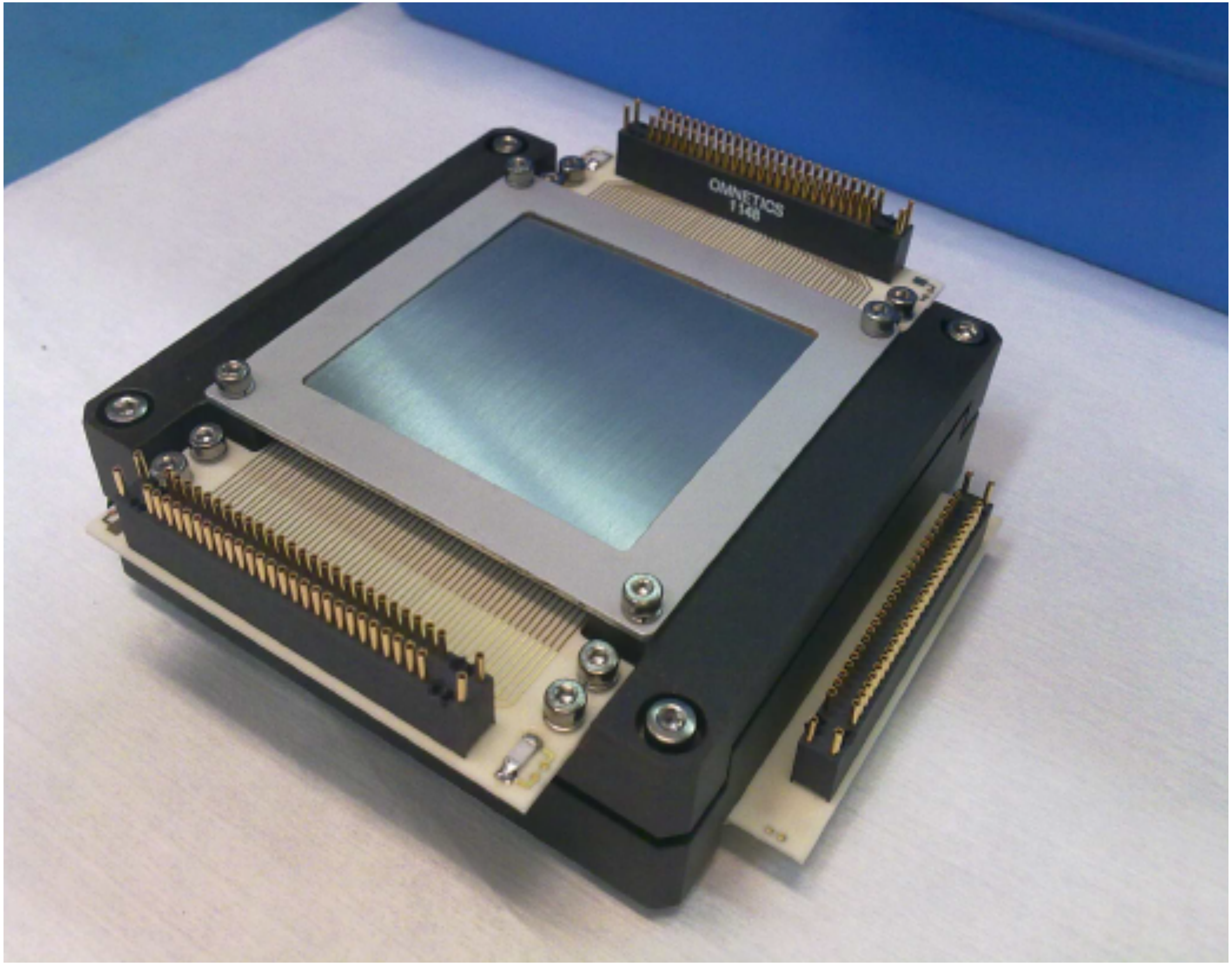


PheniX: 3 DIMENSIONS Ge DETECTOR

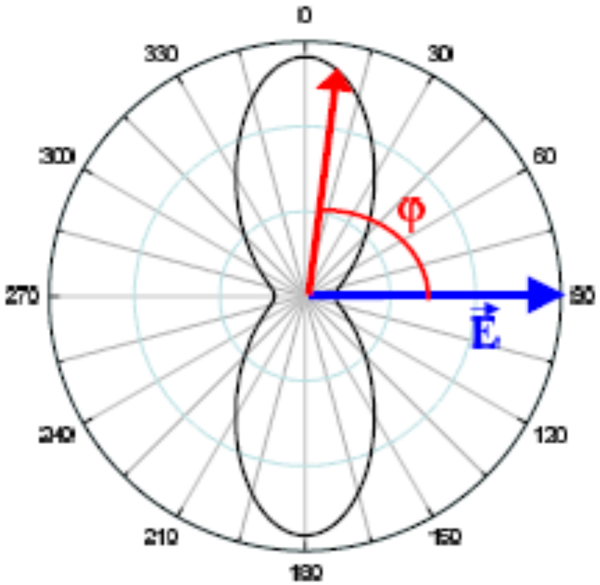
New generation detector for the focal plane of Hard X-ray telescope

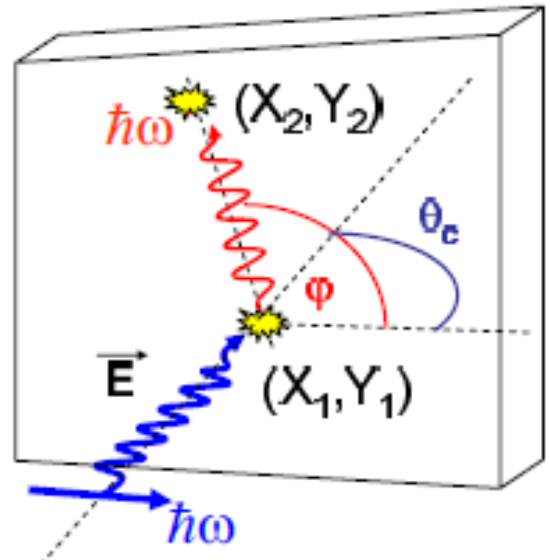
- Double sided stripped Germanium detector:
  - Size: around 8 x 8 x 1.5 cm cooled at 80 K
  - Strip pitch 0.5 mm
  - Depth of interaction (1-2 mm) : Background reduction
    Energy resolution 0.13 keV @ 5 kev, <0.5 kev @100 keV
  - Energy range : 1 -400 keV
  - Low number of electronic chains: 2x SQRT(Npix)
- Intensive use of digital electronics for position and energy reconstruction.
- Annealing capabilities
- Multiple events reconstruction capability
- Polarization measurements

Diode Ge 100X-100Y



POLARIMETRY





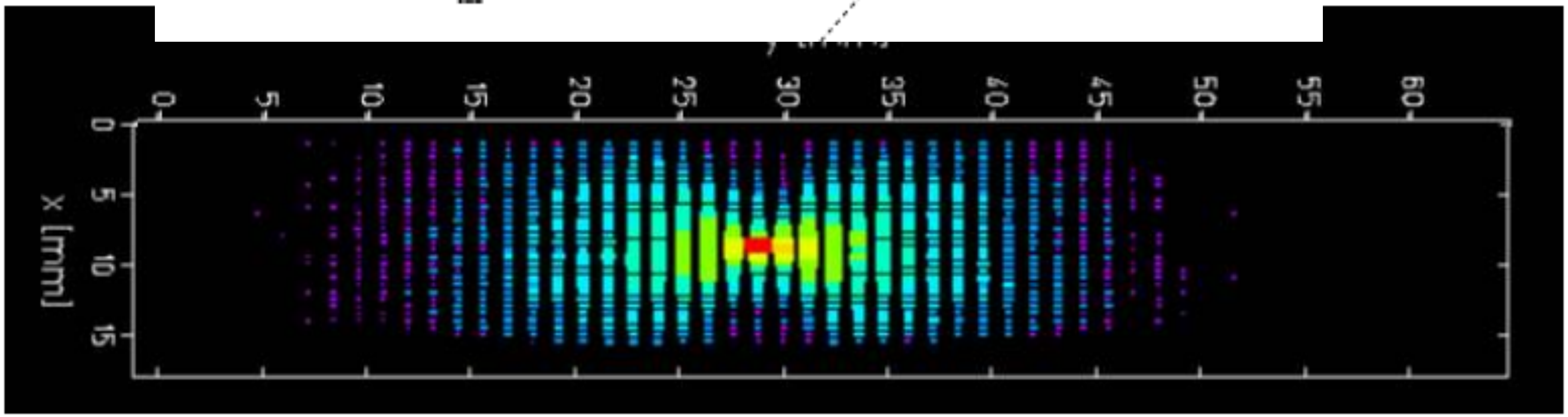


Figure 2. 2D image for Compton scattering of almost 98% linearly polarized x-rays (210 keV) (preliminary result). The image displays the spatial distribution of Compton scattered photons which exhibit an energy of 149 keV corresponding to a scattering angle of $\theta = 90°$. The image was recorded during a detector performance test at the ESRF synchrotron facility.

PHENIX-POLARIZATION

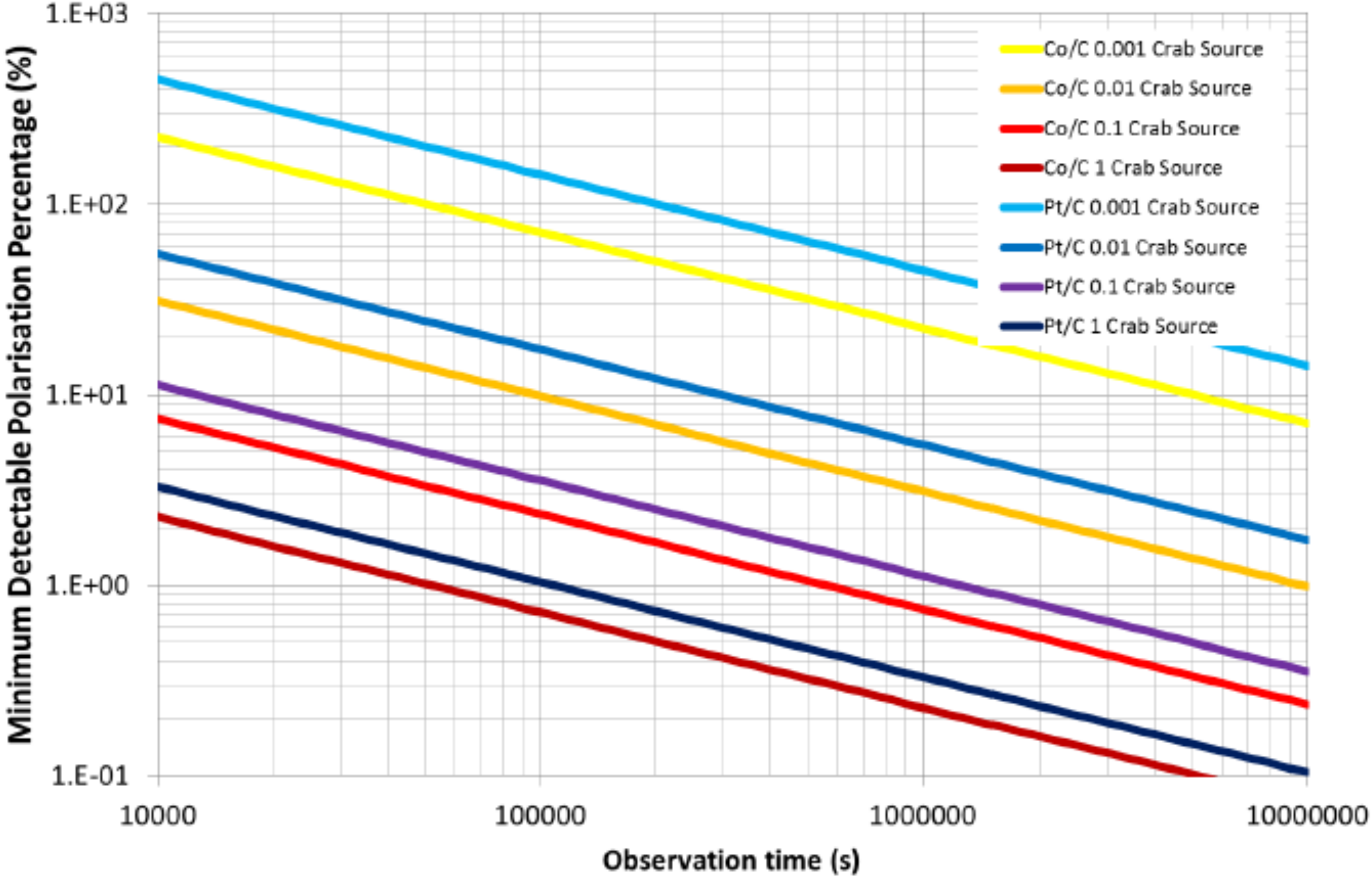


Figure 5: The minimum detectable polarisation (50-200 keV) for PheniX vs observation duration for different source strengths and mirror coatings.