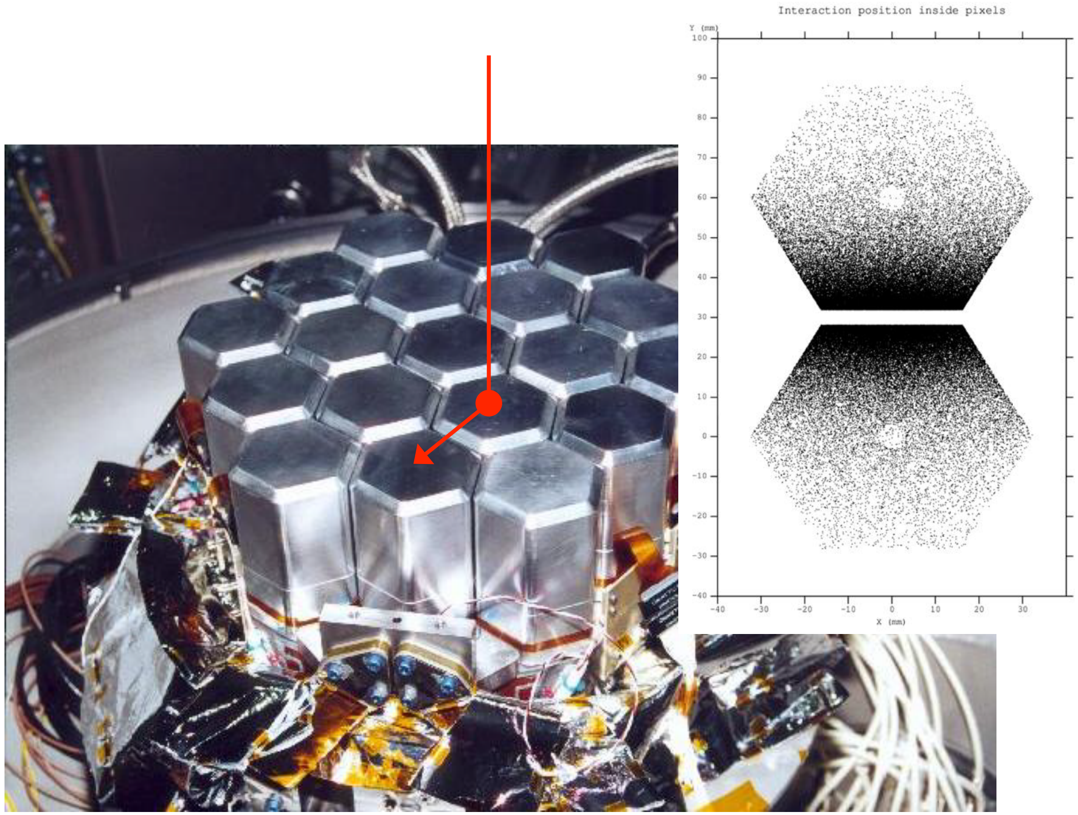
Detecting Gamma-ray Polarisation Using SPI

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**

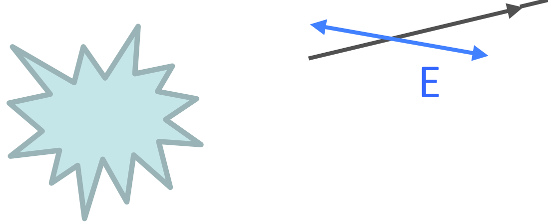


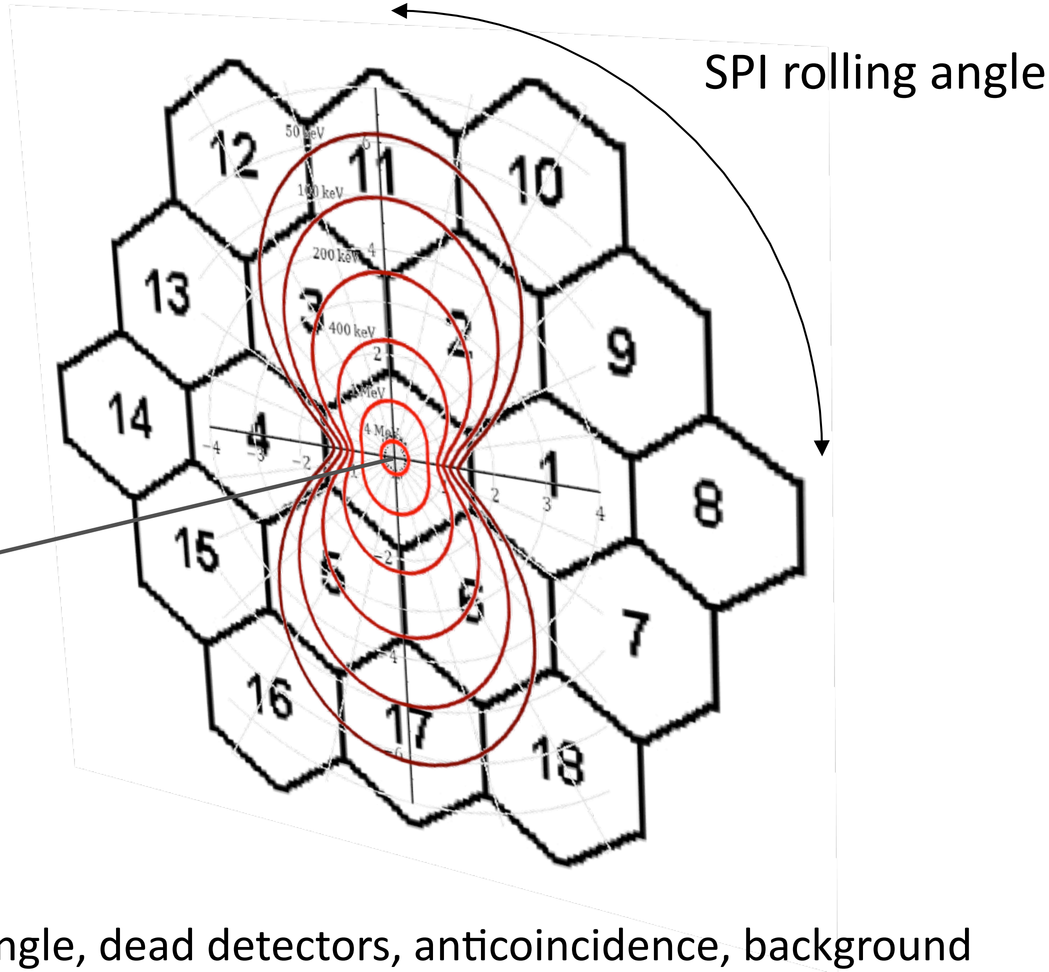
SPI as a Polarimeter

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

From 100keV to 1MeV

- Q-factor ~25%



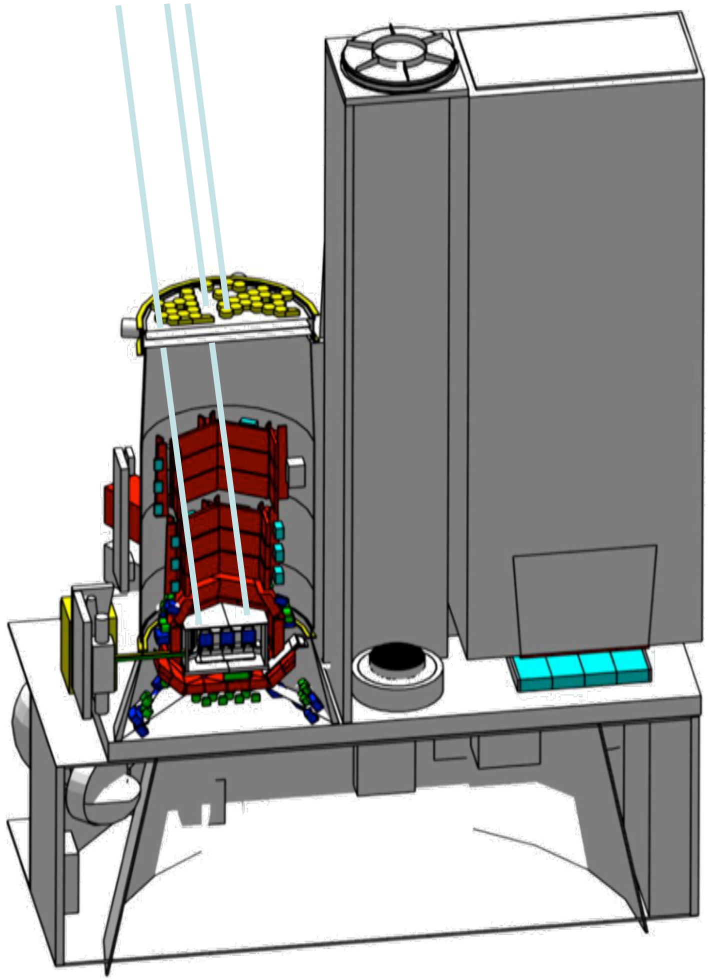


Pb: mask shadow, rolling angle, dead detectors, anticoincidence, background

→**We need simulations**

The GEANT4 Model

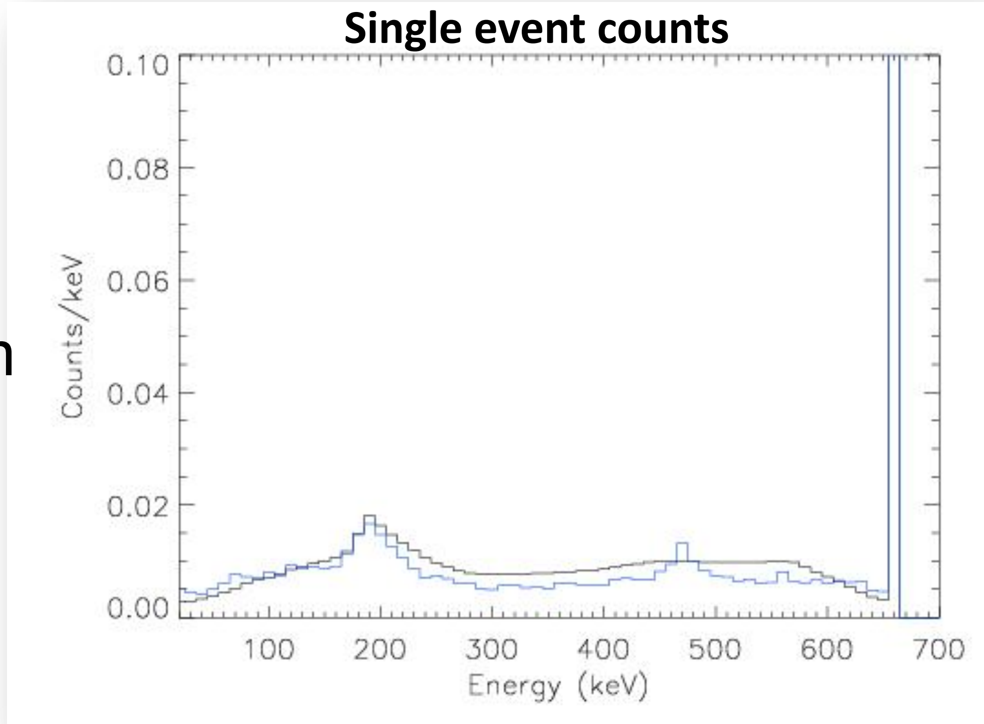
- Based on the TIMM Model
- Originally designed to calculate SPI line background
- Current Model Includes SPI, JEM-X, limited IBIS models



The GEANT4 Model

Model improvements:

- Central hub mask
- SPI Pointing error
- Detector geometry
- Anti-coincidence system (low veto activated + threshold at 100 keV)



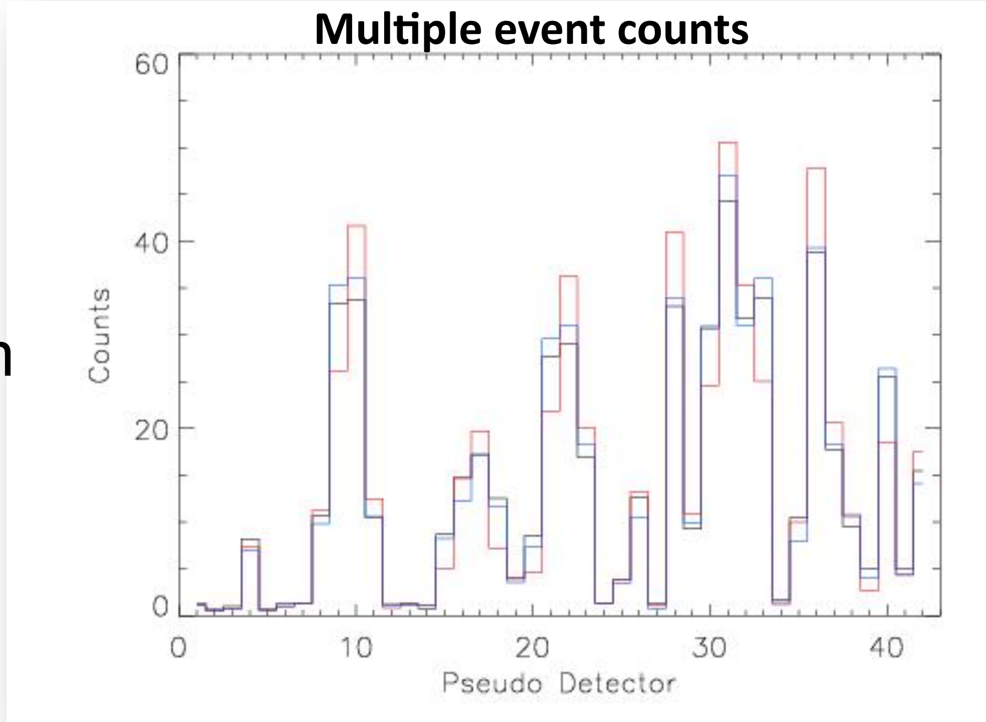
SPI IRF (black) and G4model (blue) differs by only 8%

The ratio photopeak/total is 0.65% for IRF and 0.67% for G4model

The GEANT4 Model

Model improvements:

- Central hub mask
- SPI Pointing error
- Detector geometry
- Anti-coincidence system (low veto activated + threshold at 100 keV)



SPI IRF (black) and G4model (blue) differs by only 6%

It reach 20% between IRF and 20° polarised simulation from G4

The GEANT4 Model

Each simulation

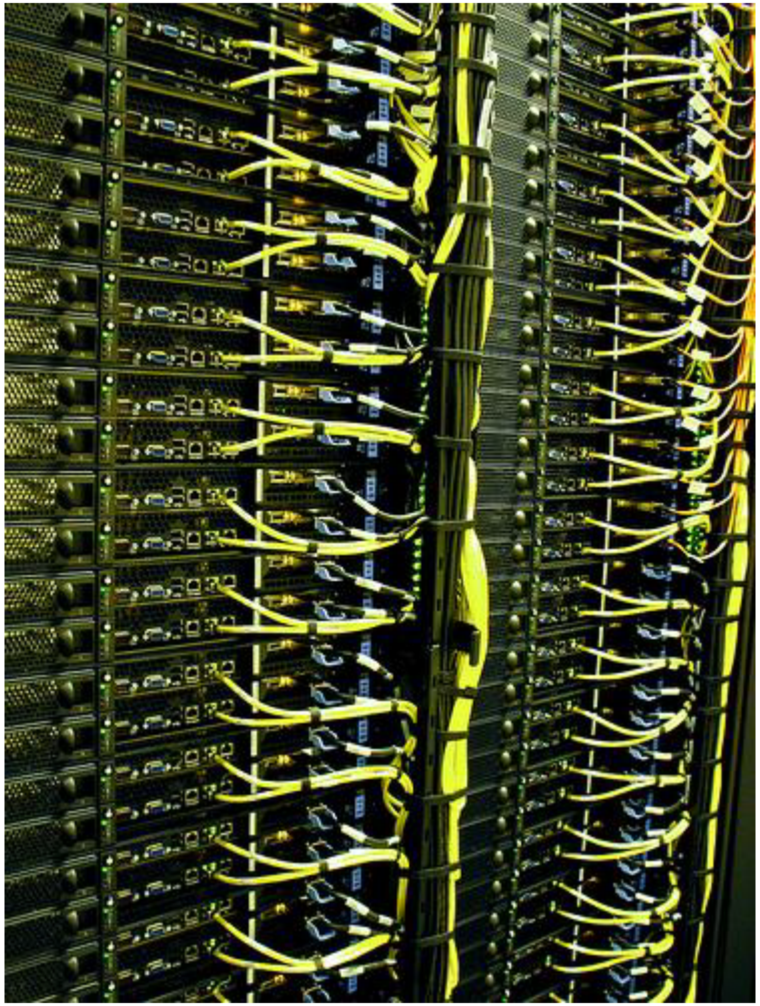
- 50 million photons
- Equivalent of ~6hrs of real SPI data
- Takes ~6hrs to run on a single processor
- 19 simulations for a pointing
- 18 for 0° - 170° in 10° steps
  + 1 unpolarised

For Cygnus X-1 (2000 scw):

$6h \times 19 \times 2000 = 228000h = 9500$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

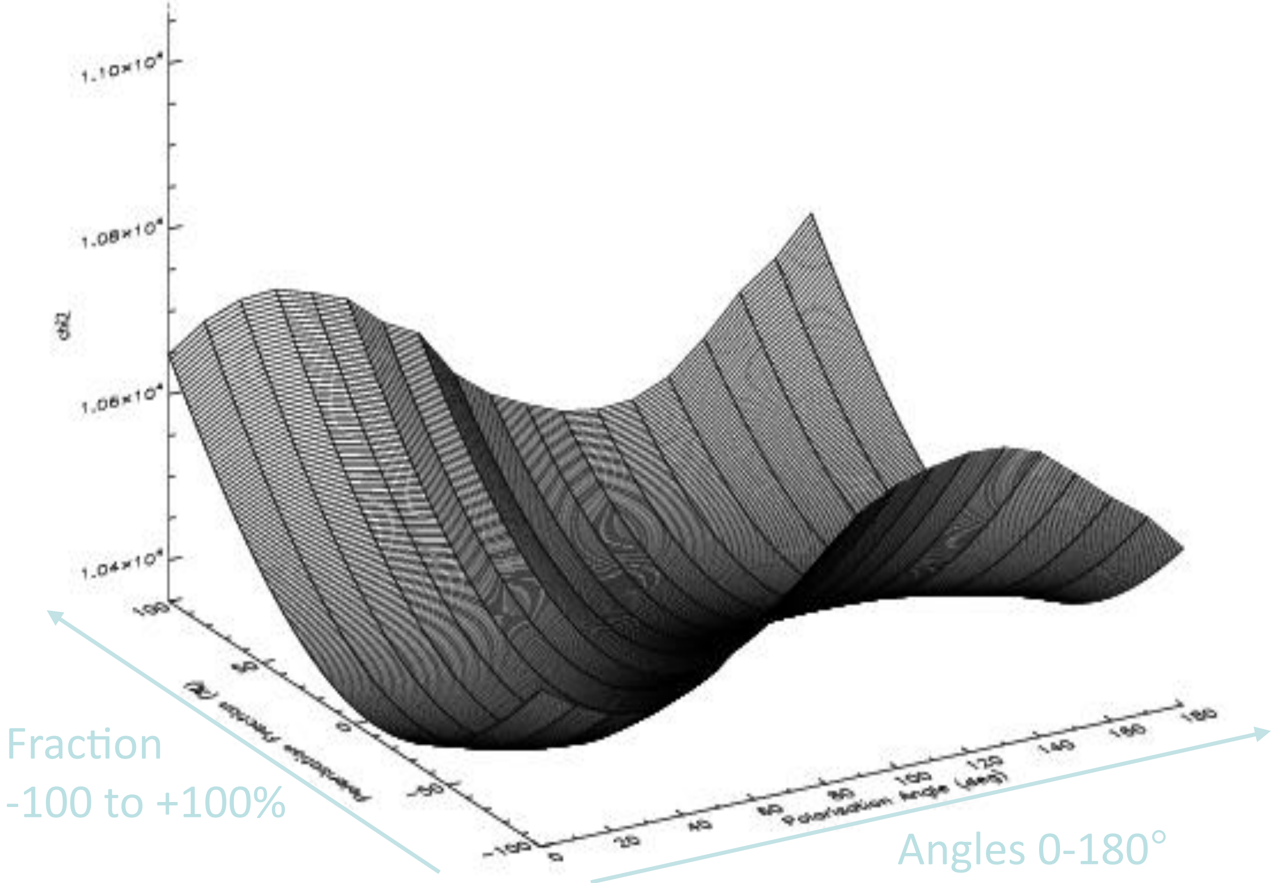
- $G4_{is}(\%,\Pi)$ is the counts from the Geant4 simulation, as a function of polarisation **fraction** % and **angle** Π. Values weighted by livetime

- 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**

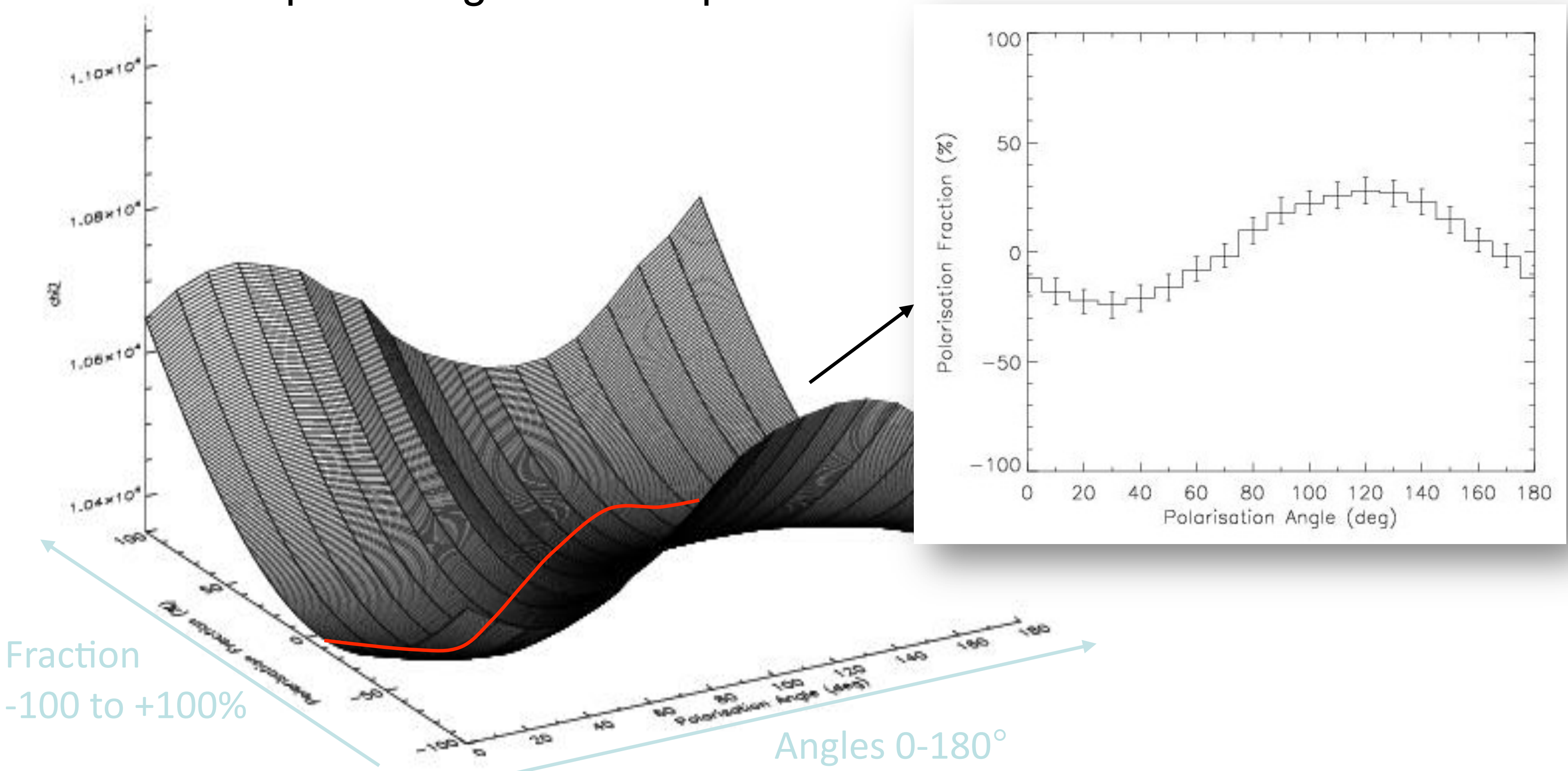
Fitting The Data

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



Fitting The Data

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



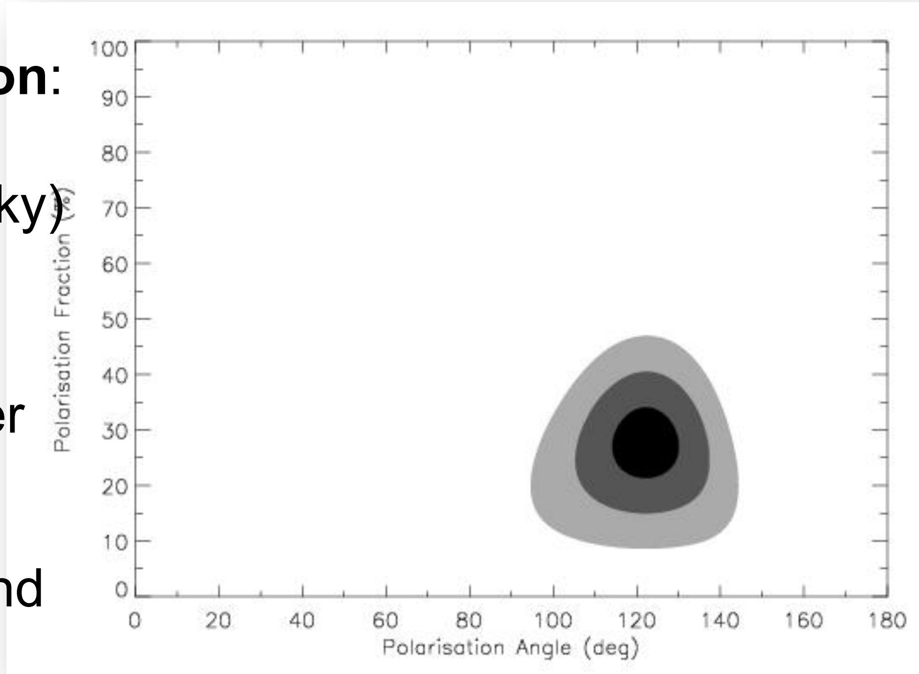
Fitting The Data: The Crab analysis

- Data set: revolution 43, 44 and 45
- Simulation spectrum: Power law, alpha=2.2
- Energy range: 100keV – 430keV

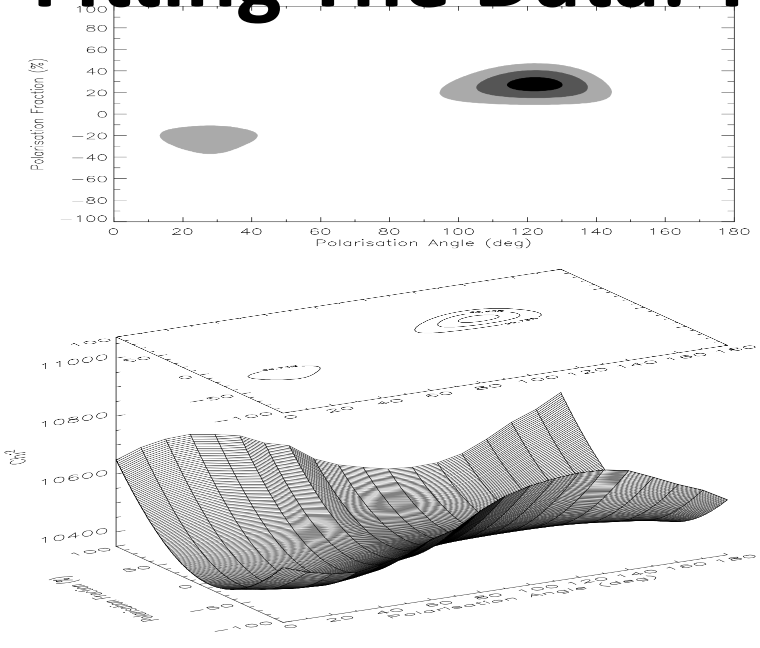
Best Fit for the **Crab total emission**:

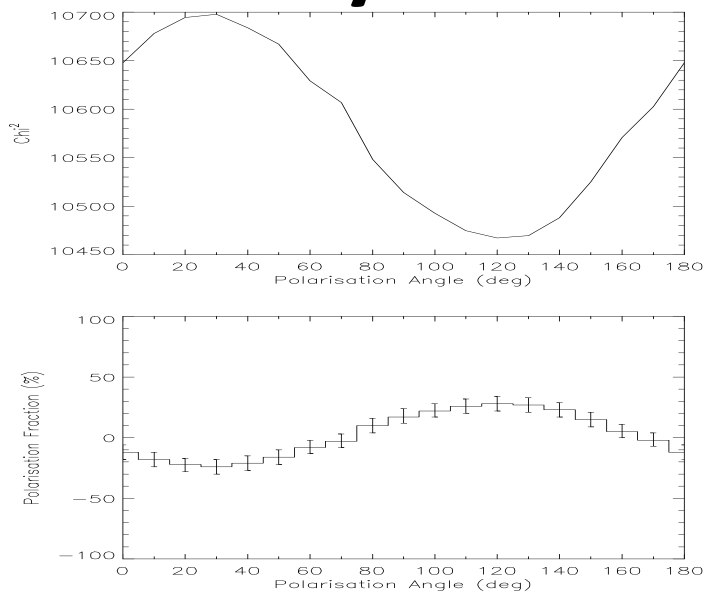
- **Angle = 122° ±7°**
  (from North, anticlockwise on sky)
- **Fraction = 28% ±6%**

→ Electric vector aligned with inner jet Structure in agreement with Ng et al. 2004 (124° ±0.1°), Dean et al. 2008 (123° ±11°) and Forot et al. 2008 (122° ±7.7°)



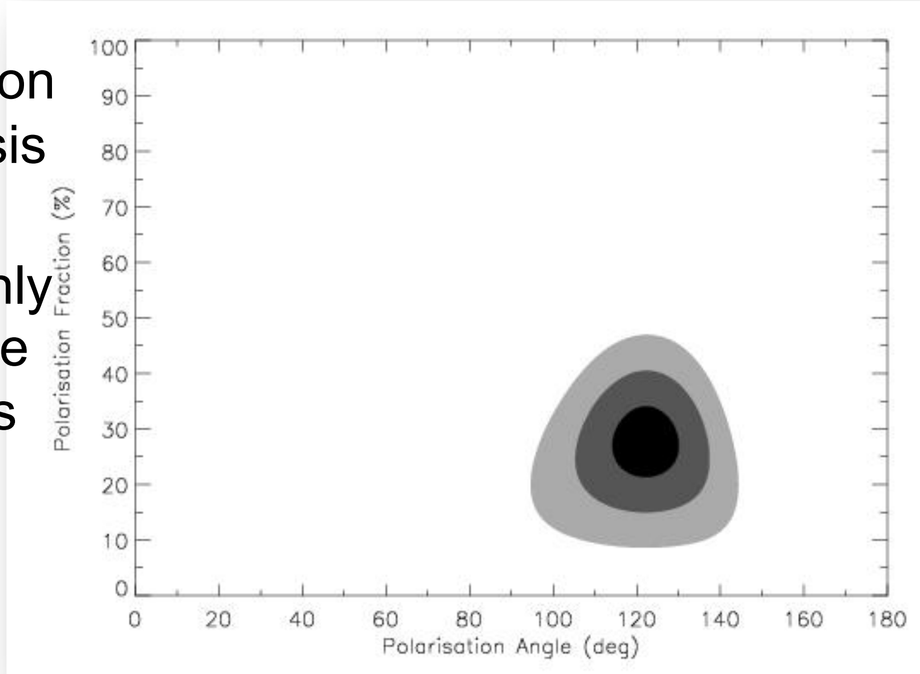
Fitting The Data: The Crab analysis





Conclusion

- Improvements have been made in the model of SPI reducing the systematic errors in the analysis
- This improved model has been fully tested and compared with SPI calibrations
- The analysis now use information from Flat Fields allowing analysis of any kind of source
- The analysis of the crab with only 3 revolutions (43-45) gives more constraint results than previous attempts



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SEPARATION OF TWO CONTRIBUTIONS TO THE HIGH ENERGY EMISSION OF CYGNUS X-1: POLARIZATION MEASUREMENTS WITH *INTEGRAL* SPI*

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ABSTRACT

Operational since 2002 on board the *INTEGRAL* observatory, the SPI spectrometer can be used to perform polarization measurements in the hard X-ray/softγ-ray domain ($\sim$130 keV–8 MeV). However, this phenomenon is complex to measure at high energy and requires high fluxes. Cyg X-1 appears to be the best candidate amongst the X-ray binaries since it is one of the brightest persistent sources in this energy domain. Furthermore, a polarized component has recently been reported above 400 keV from IBIS data. We have therefore dedicated our efforts to developing the required tools to study the polarization in the *INTEGRAL* SPI data and have first applied them to 2.6 Ms of Cyg X-1 observations, covering 6.5 years of the *INTEGRAL* mission. We have found that the high energy emission of Cyg X-1 is indeed polarized, with a mean polarization fraction of 76% $\pm$ 15% at a position angle estimated to be $42^\circ \pm 3^\circ$, for energies above 230 keV. The polarization fraction clearly increases with energy. In the 130–230 keV band, the polarization fraction is lower than 20%, but exceeds 75% between 370 and 850 keV, with the (total) emission vanishing above this energy. This result strongly suggests that the emission originates from the jet structure known to emit in the radio domain. The same synchrotron process could be responsible for the emission from radio to MeV, implying the presence of high energy electrons. This illustrates why the polarization of the high energy emission in compact objects is an increasingly important observational objective.

Key words: methods: observational – polarization – radiation mechanisms: general – X-rays: binaries – X-rays: individual (Cyg X-1)

Online-only material: color figure

SPI DATA:
Polarisation information in the multiple events

Flux extraction for the multiples : Our standard method

- Background based on flat-field observations
  - 1 pattern per ~ 6 months
  - 1 normalization factor each ~ 10 ks (5 scw)
- All multiple events for E > 100 keV
- Source' flux kept constant per revolution

- Model fitting: choice of all free parameters value through a $\mathcal{X}^2$ minimization

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- Check at the end of the flux extraction that final $\mathcal{X}^2$ values close to 1 (per energy bin and scw).
- Validation of the flux extraction by testing the spectrum with that from the single events

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

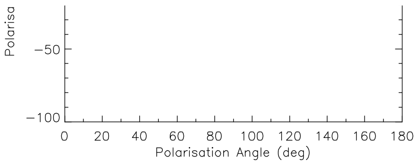
Sky Model : Cyg X-1
Cy X-
EX 23+375
GR 1 5

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

=> Total duration ~ 2.6 Ms

RESULTS SUMMARY

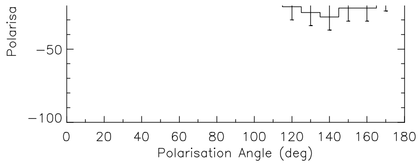
100-230 keV



Not significant

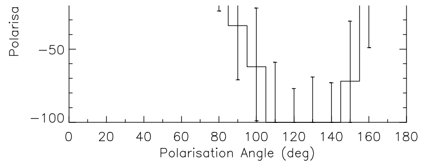
122° +/- 6°
15 % +/- 6 %

230-370 keV



47° +/- 4°
41 % +/- 10 %

370-850 keV



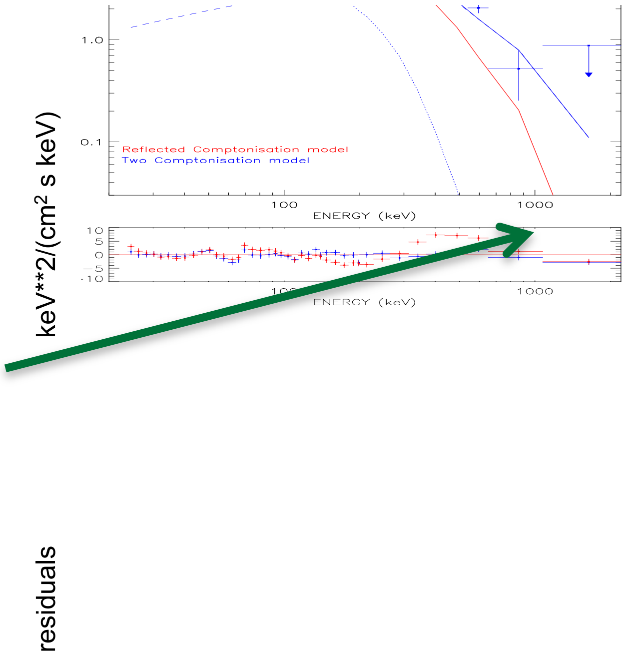
39° +/- 3°
100 % ; > 75 % (2 σ)

Physical Interpretation

1) 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.

Obvious link with the spectral results

→ Idendification of the second spectral components, with the polarised one.



2) Polarisation ⇔ synchrotron

in a very ordered magnetic field (jet)

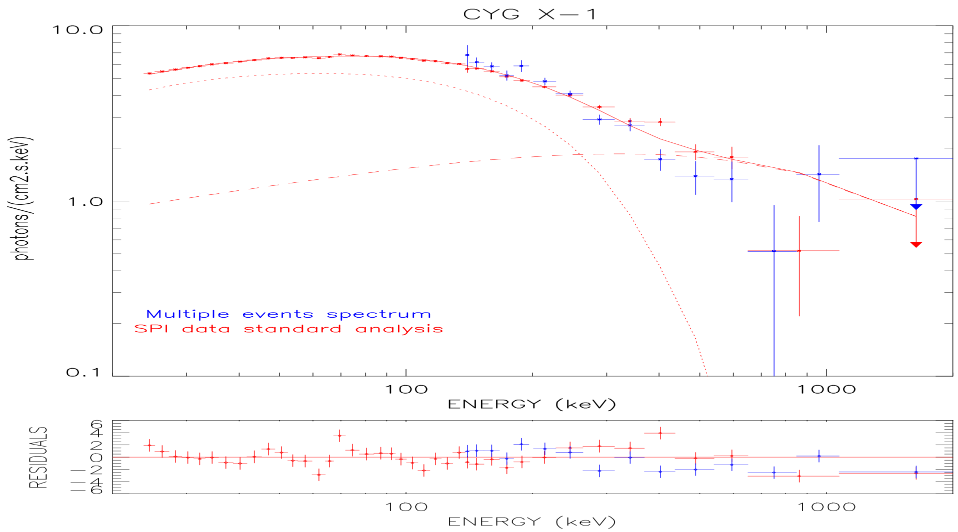
Conclusion : The jet, mainly observed in radio, contributes to the HE emission

A lot of information contained in the data :

Spectral shape Position angle	⇔	electron distribution (slope, Emax) pitch angle distribution

Physical Interpretation

- Comptonisation + reflection
- Cutoff power law:
  - Index ~1.6
  - Ecut ~700 keV



CONCLUSIONS

- 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

CONCLUSIONS

- No enough time spent to observe the high energy emission:
  - Cyg X-1 has been mainly observed on the edge of the FOV or in « strange » modes.
- Integral is a unique observatory for these observations

SPI vs IBIS
Issues solved and discrepancies

IBIS Cyg X-1 polarisation angle is now compatible with SPI:

Error in conversion from IBIS coordinates to sky coordinates

GRB 041219a polarisation angle 70 deg. McGlynn et al. is in instrument coordinate system. We confirm Mc Glynn results.

Spectral discrepancy problem between IBIS Compton mode and SPI is pending.

SPI events spectrum versus multiple events spectrum are compatible within the accuracy of the calibration.

HOW TO MAKE AN ABSOLUTE CALIBRATION OF POLARISATION ?