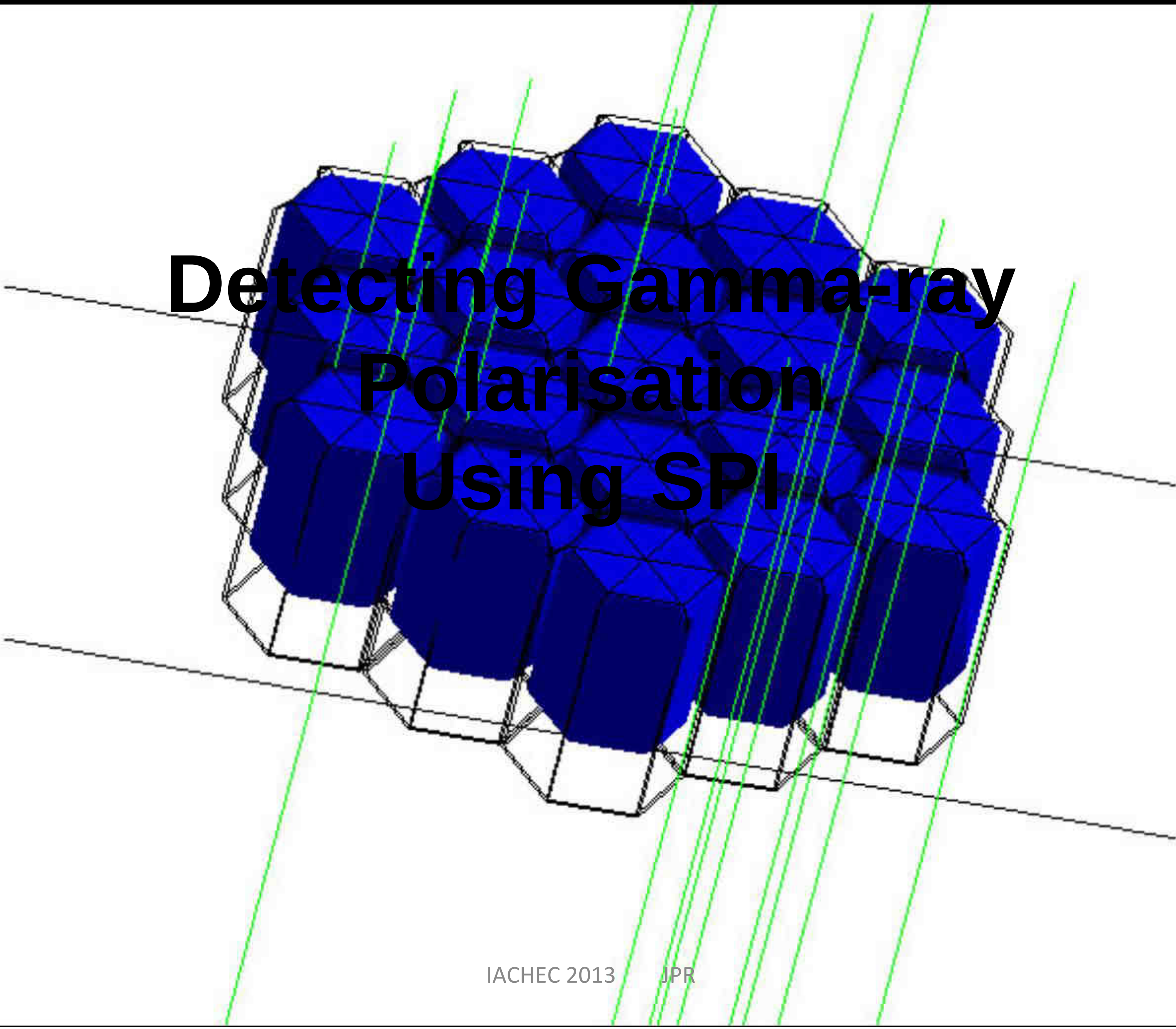
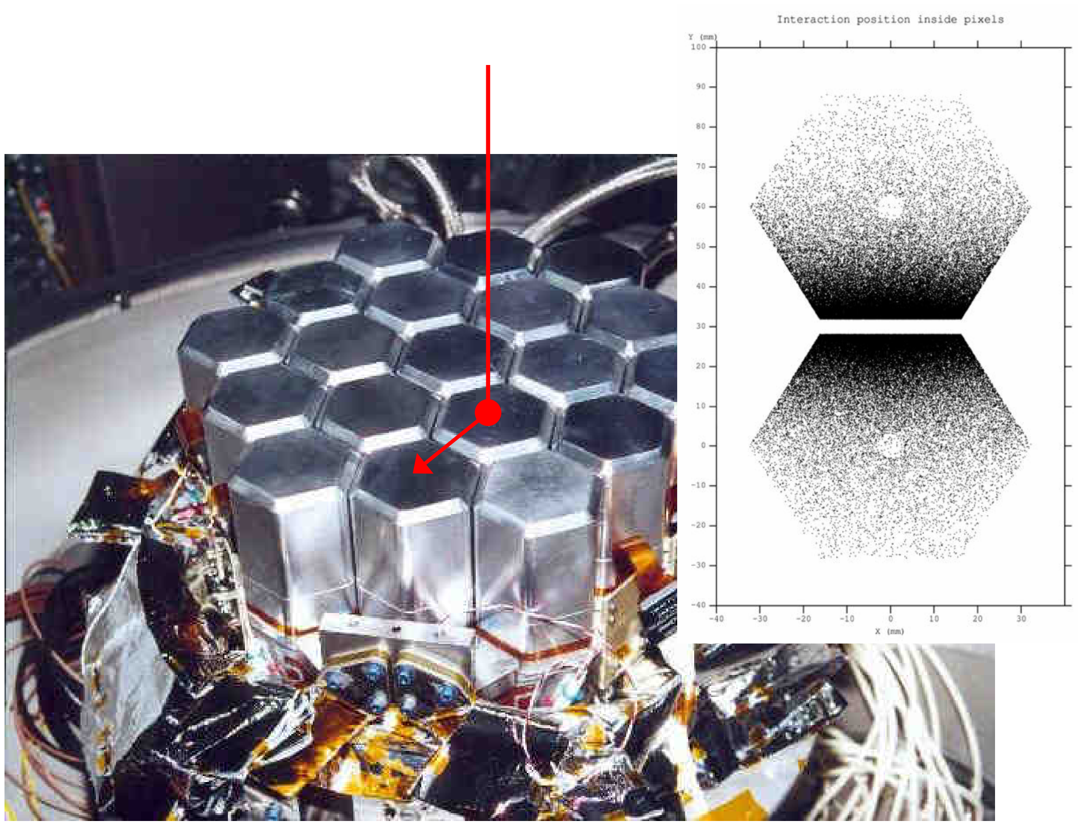
Detecting Gamma-ray Polarisation Using SPI



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**



Multiple events

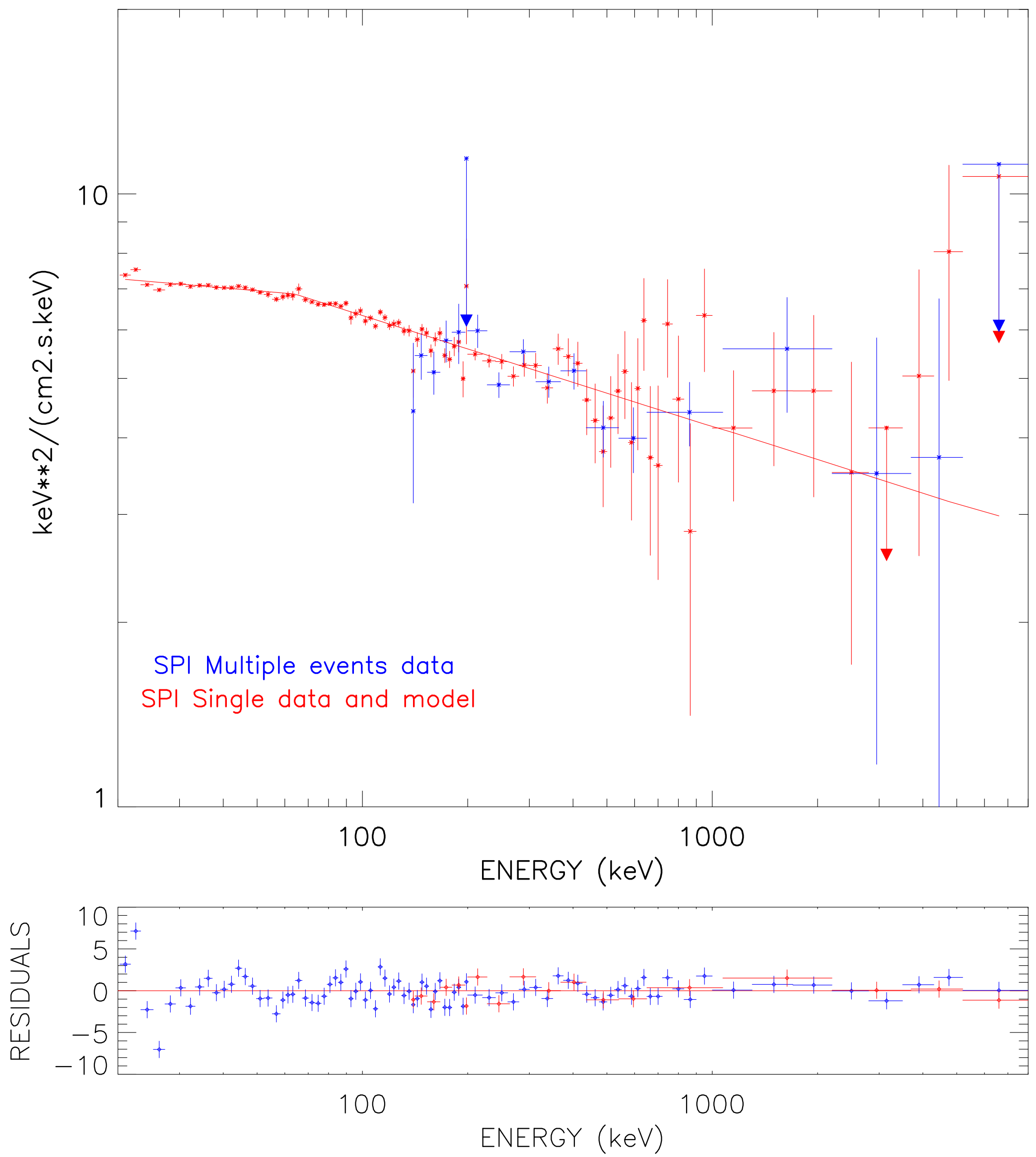
When the energy deposit concerns 2 or more detectors, we have to:

- Reconstruct the total energy, attributed to a « pseudo-detector » i.e detector pair
- 42 for double events
- Use the corresponding responses

Interest:

- very low background
- Increase the SPI sensitivity at high energy
- Polarisation studies

Crab rev 43-45 - single vs double events



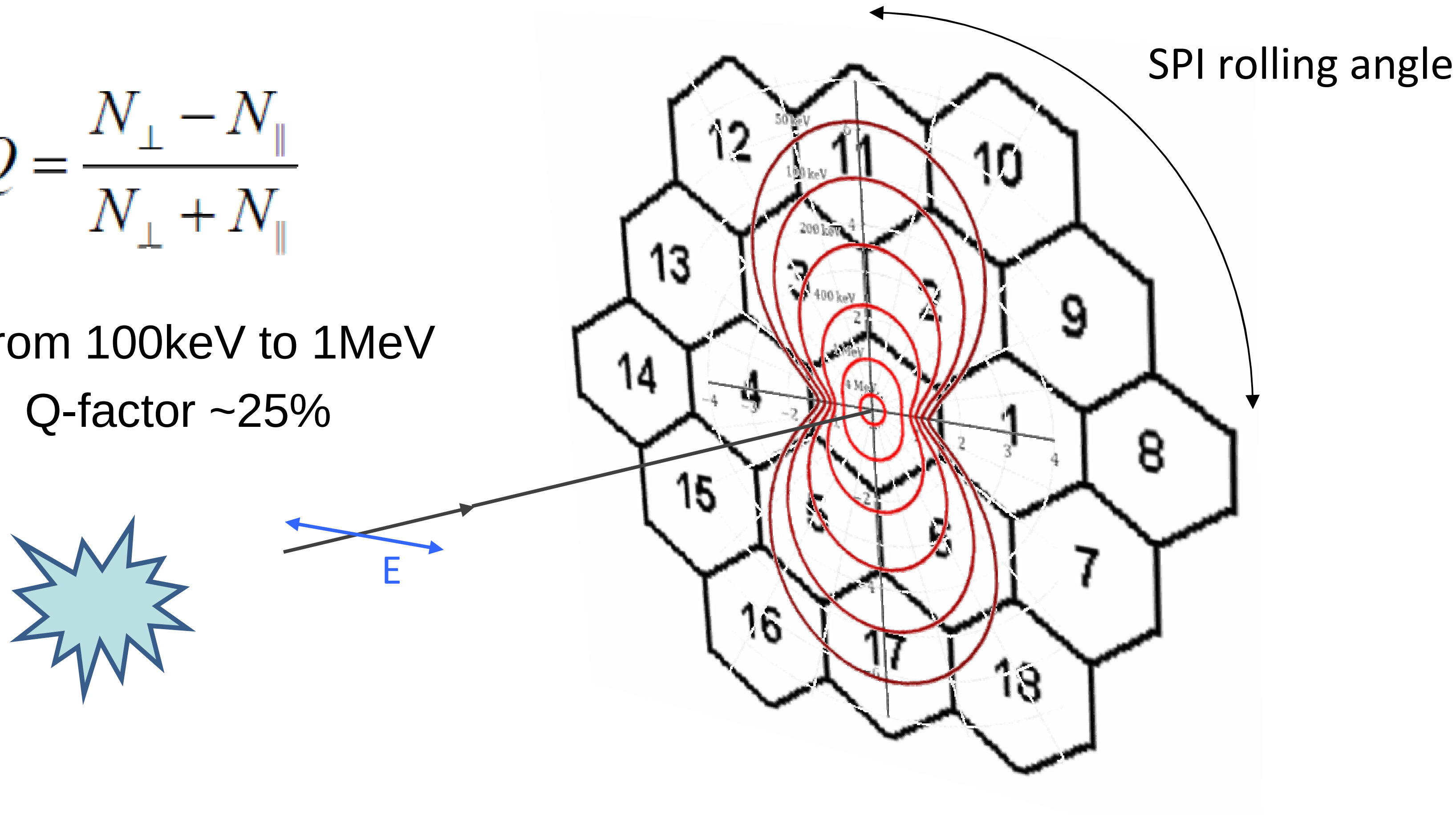
Good agreement
from 130-160 keV

SPI as a Polarimeter

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

From 100keV to 1MeV

- Q-factor ~25%

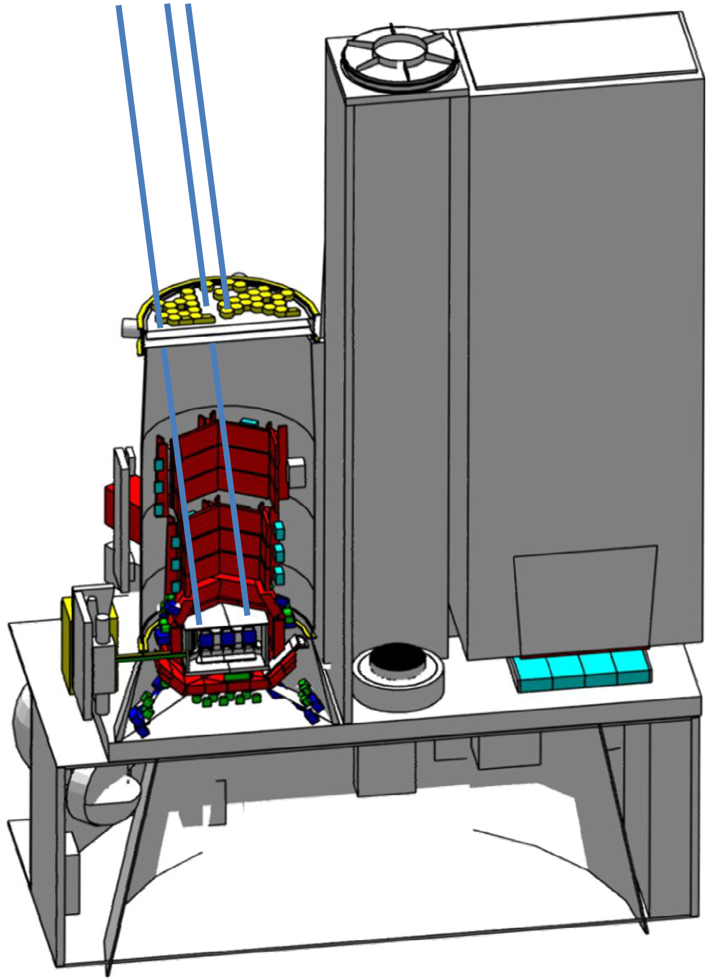


Pb: mask shadow, rolling angle, dead detectors, anticoincidence, background

→**We need simulations**

The GEANT4 Model

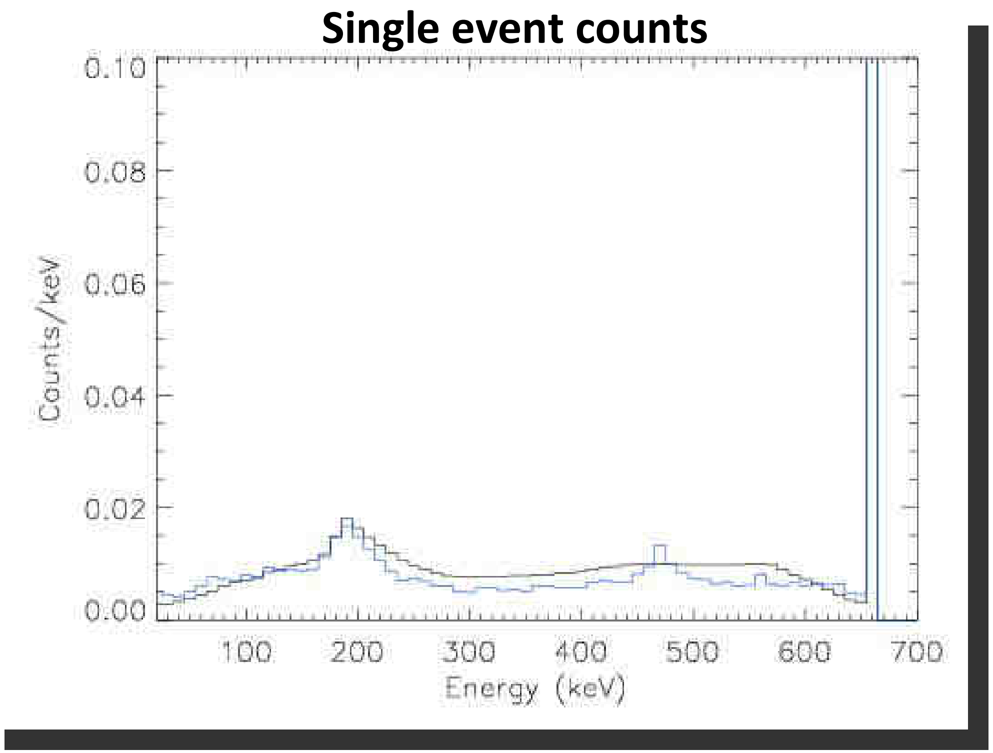
- Based on the TIMM Model
- Originally designed to calculate SPI line background
- Current Model Includes SPI, JEM-X, limited IBIS models



The GEANT4 Model

Model improvements:

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

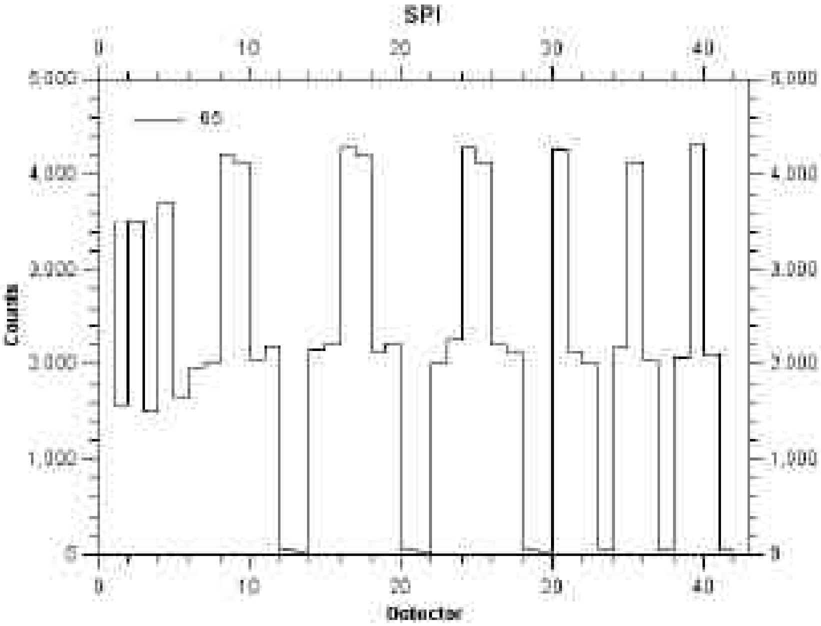


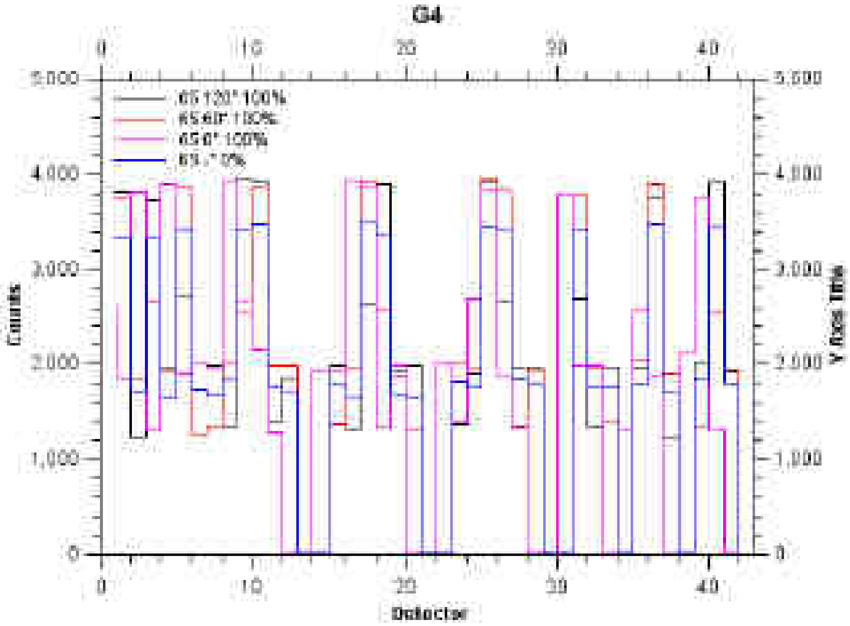
SPI IRF (black) and G4model (blue) differs by only 8%

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

Validation with the Long Distance Calibration Source

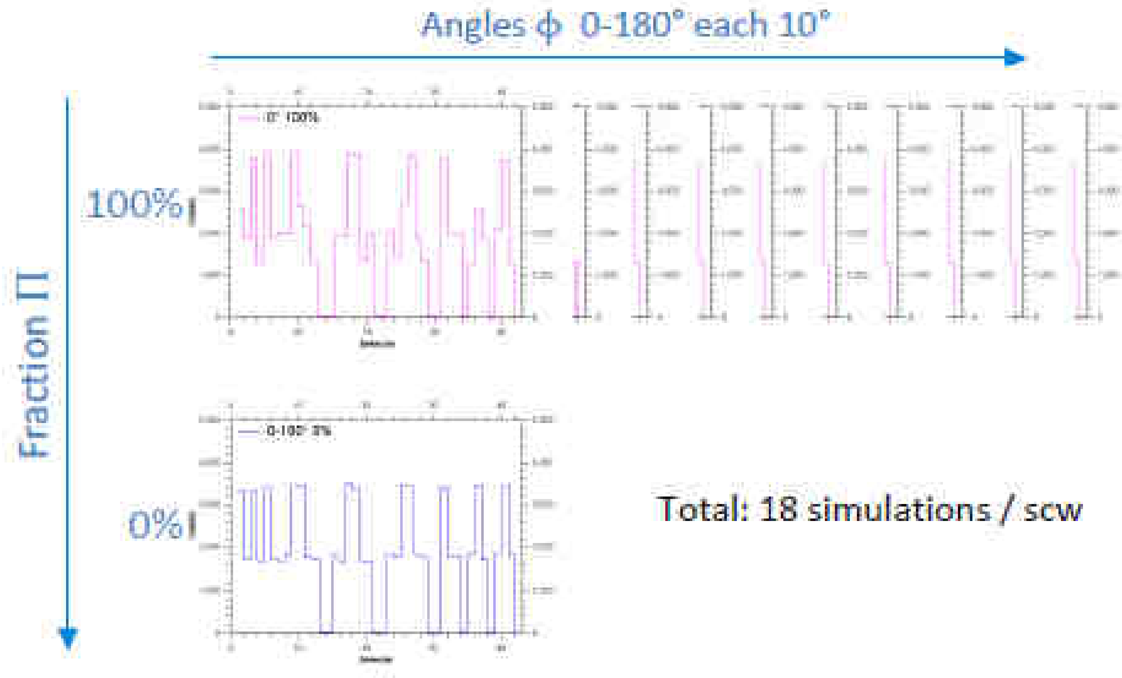
Run 65 ^{137}Cs (661 keV)





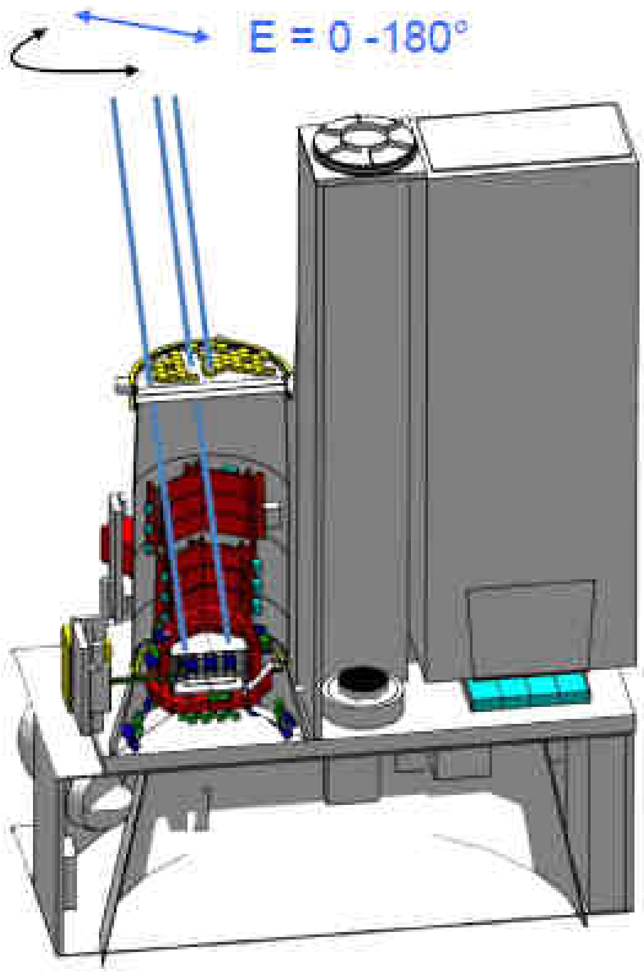
Geant 4 simulations

- The Geant4 Data Production
  - For each science window



Total: 18 simulations / scw

For fraction 1 – 99%: $G4(\Pi,\phi) = \frac{\Pi \times G4(\phi)}{100} + \frac{(100-\Pi) \times G4(U)}{100}$



The GEANT4 Model

Each simulation

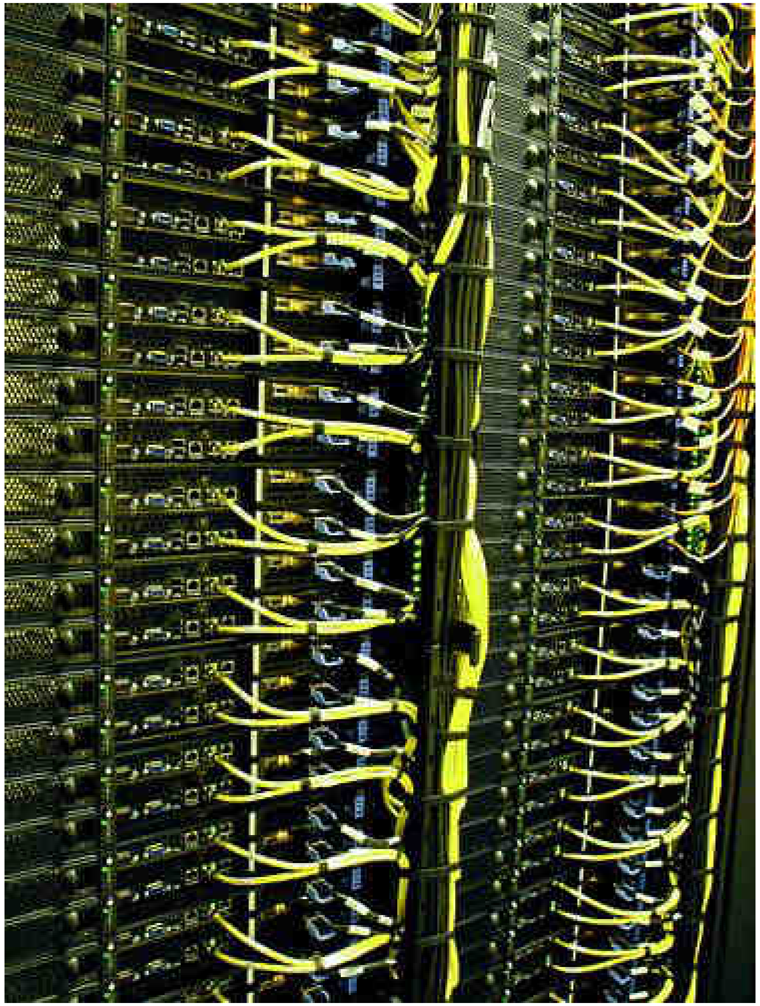
- 50 million photons
- Equivalent of ~6hrs of real SPI data
- Takes ~6hrs to run on a single processor
- 19 simulations for a pointing
- 18 for 0° - 170° in 10° steps
  + 1 unpolarised

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

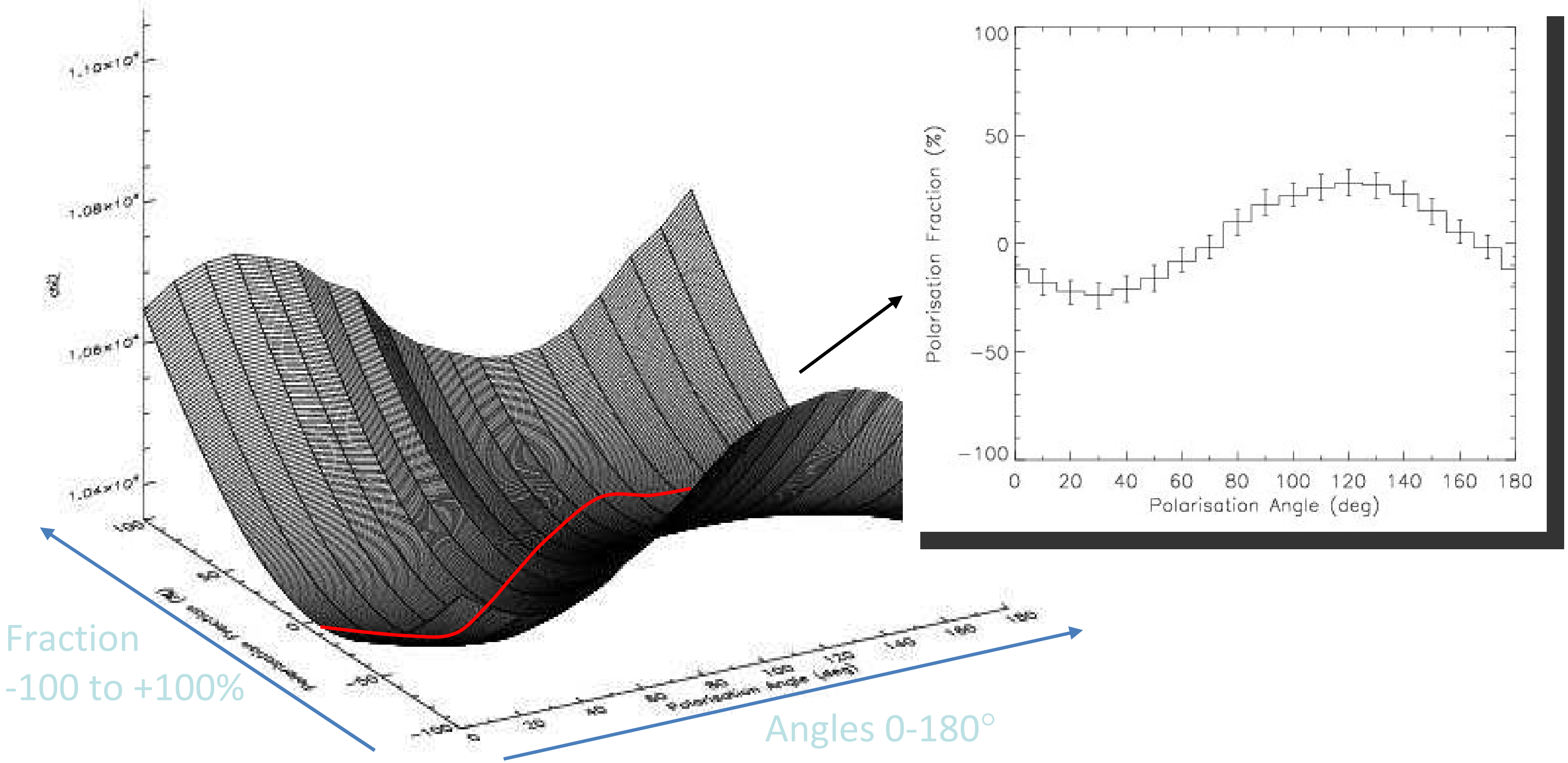
- $G4_{is}$(%,Π) is the counts from the Geant4 simulation, as a function of polarisation **fraction** % and **angle** Π. Values weighted by livetime

- B_{is} is taken from a Flat Field

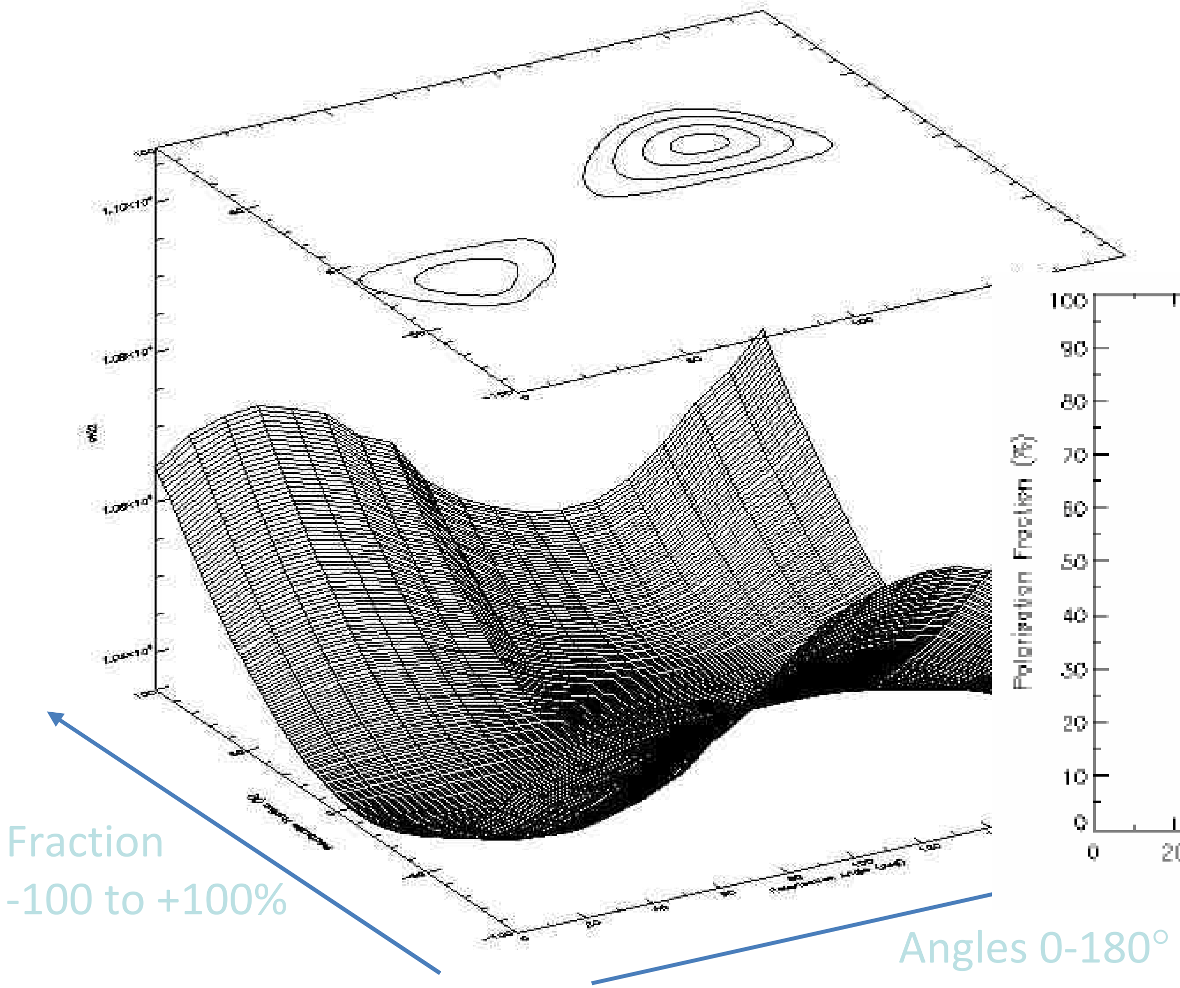
- **Data fitted** on a Science window by Science window and pseudo detector by pseudo detector basis resulting in a **Chi²**

Fitting The Data

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

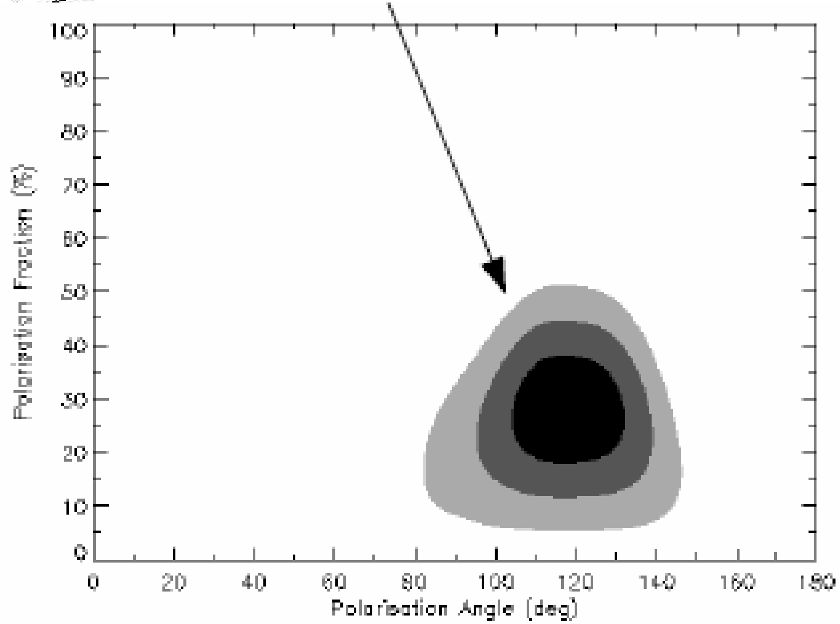


Fitting The Data



Contour map

Chi^2_{min}+2.3 (1 sigma)
Chi^2_{min}+6.18 (2 sigma)
Chi^2_{min}+11.8 (3 sigma)



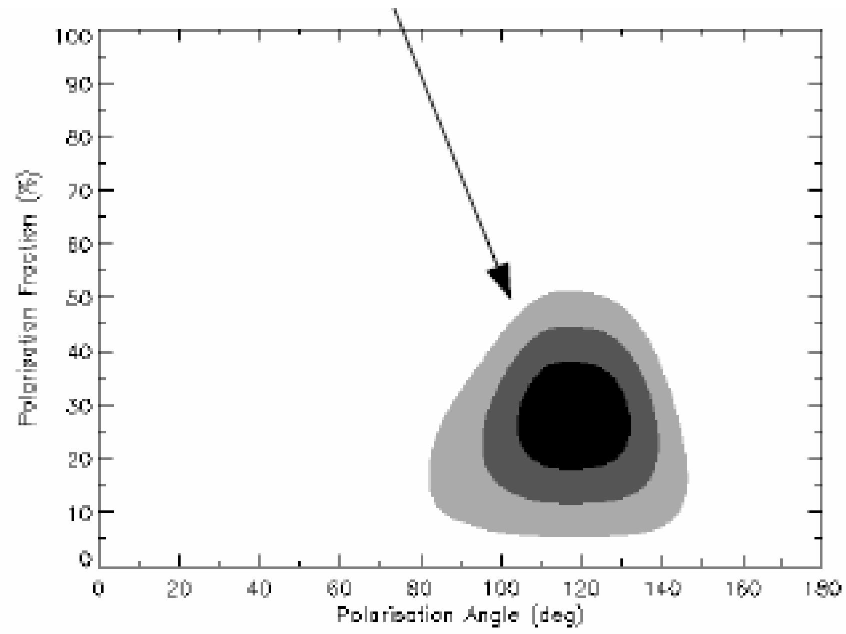
Fitting The Data: The Crab analysis

- 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°)



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 data analysis is the same than the standard one: the response is more complex…
- The analysis of the crab with only 3 revolutions (43-45) gives more constraint results than previous attempts

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

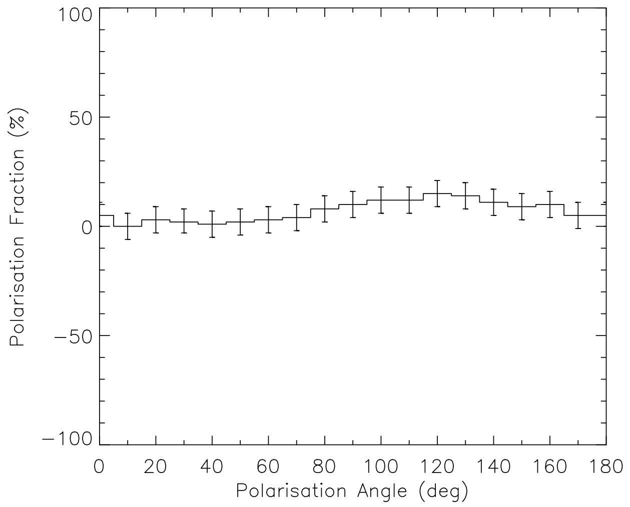
Sky Model : Cyg X-1
Cyg X-3
EXO 2023+375
GRS 1915

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

=> Total duration ~ 2.6 Ms

RESULTS SUMMARY

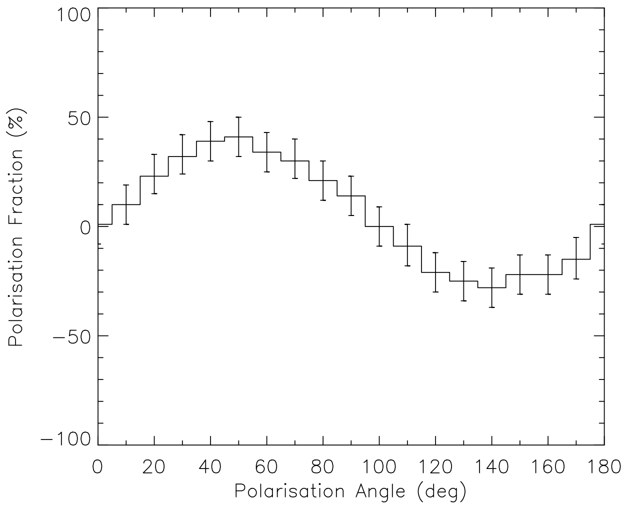
100-230 keV



Not significant

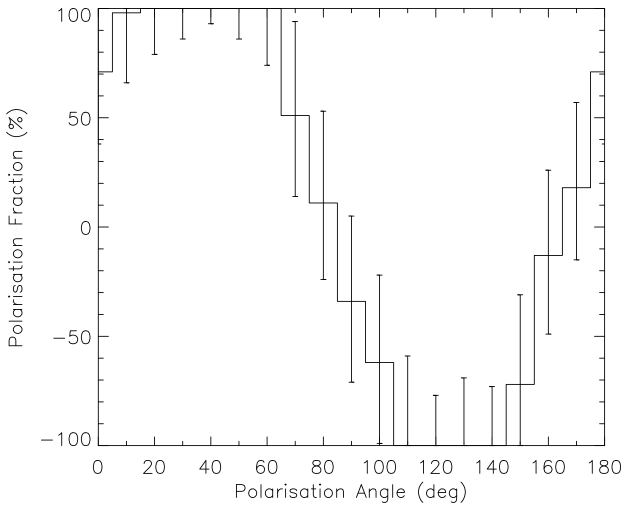
122° +/- 6°
15 % +/- 6 %

230-370 keV



47° +/- 4°
41 % +/- 10 %

370-850 keV



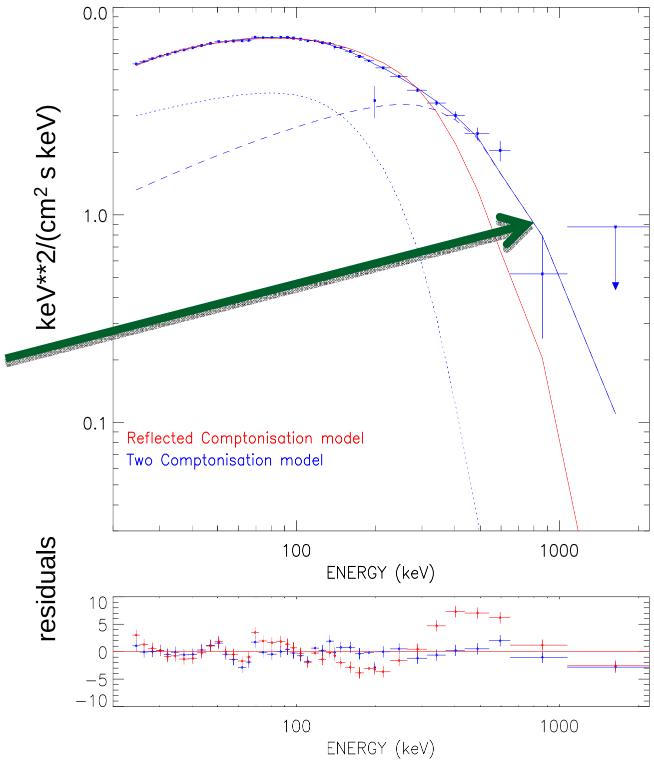
39° +/- 3°
100 % ; > 75 % (2 σ)

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

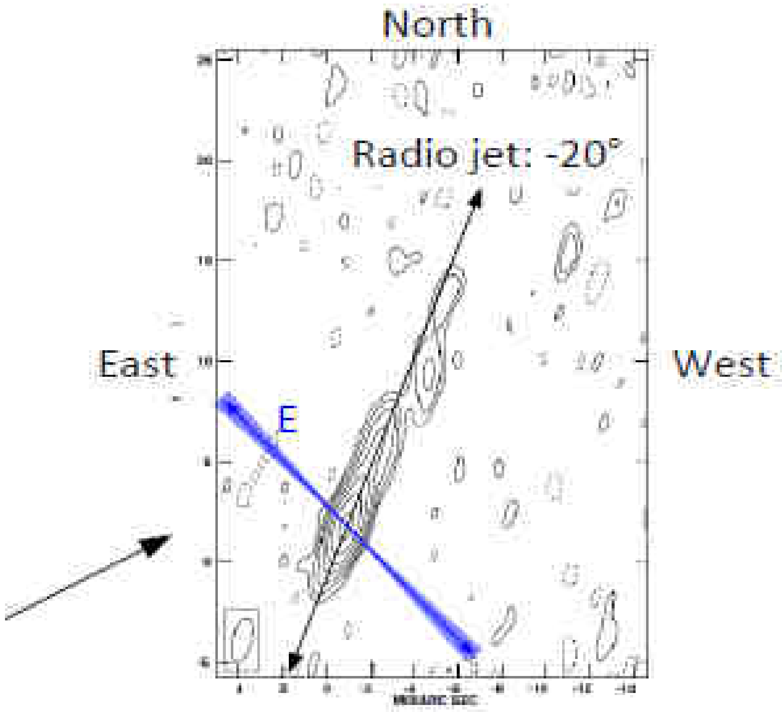
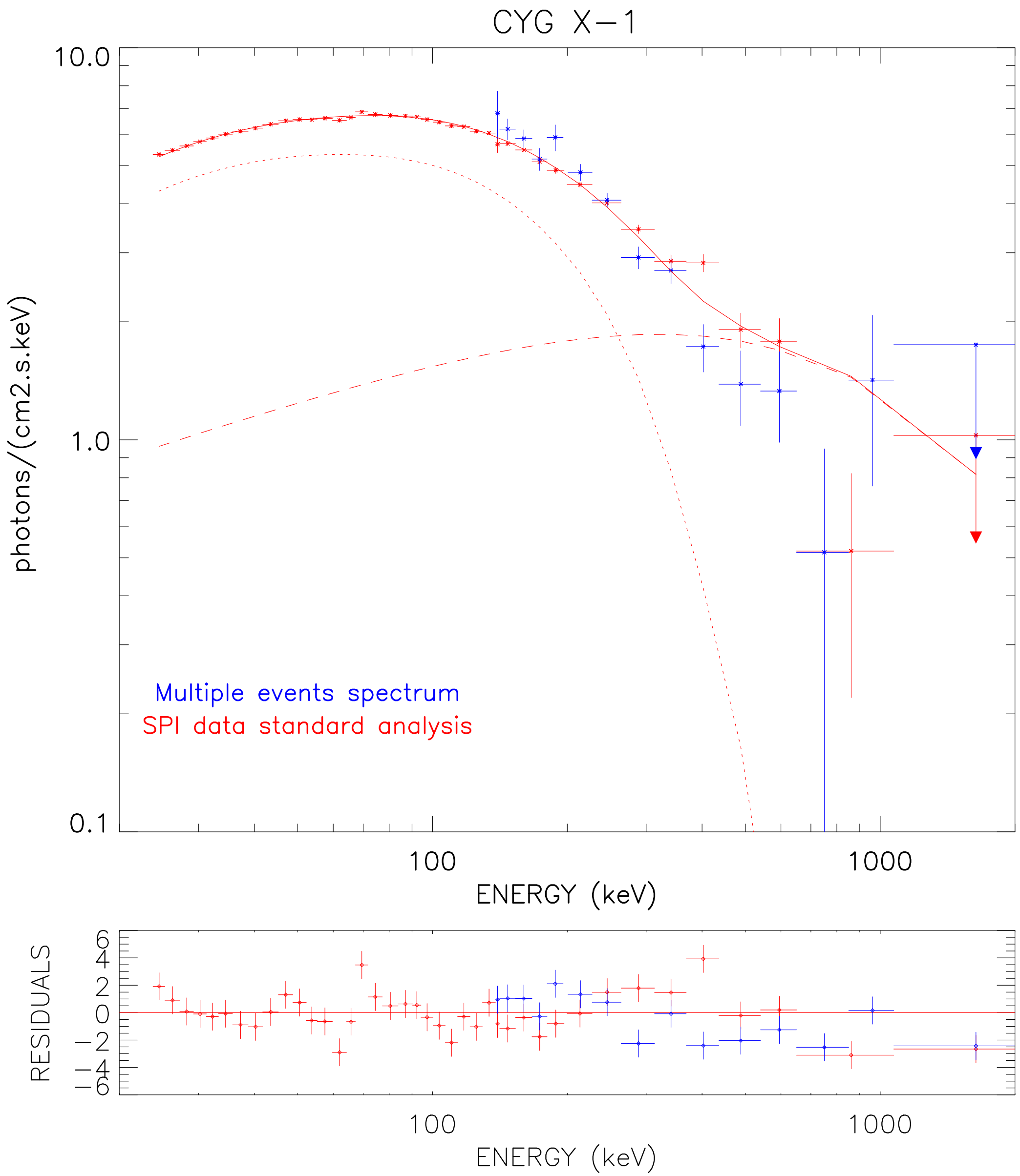


Figure 3. A high-resolution (robust 0) image of Cygnus X-1 at 8.4 GHz; lowest contour 0.157 mJy beam^{-1}, convolved with a Gaussian beam 2.25 × 0.86 mas^2 in PA −12.4.

Stirling et al. 2001



- 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

- Polarimetry data analysis involves a significant effort to derive the instrument response:
  - One more dimension polarization angle !
- How to do in-flight calibration ?
- How to make « good » ground calibration:
  - Synchrotron facility ?
- Should we rely only on simulations ?

HOW TO MAKE AN ABSOLUTE CALIBRATION OF POLARISATION ?