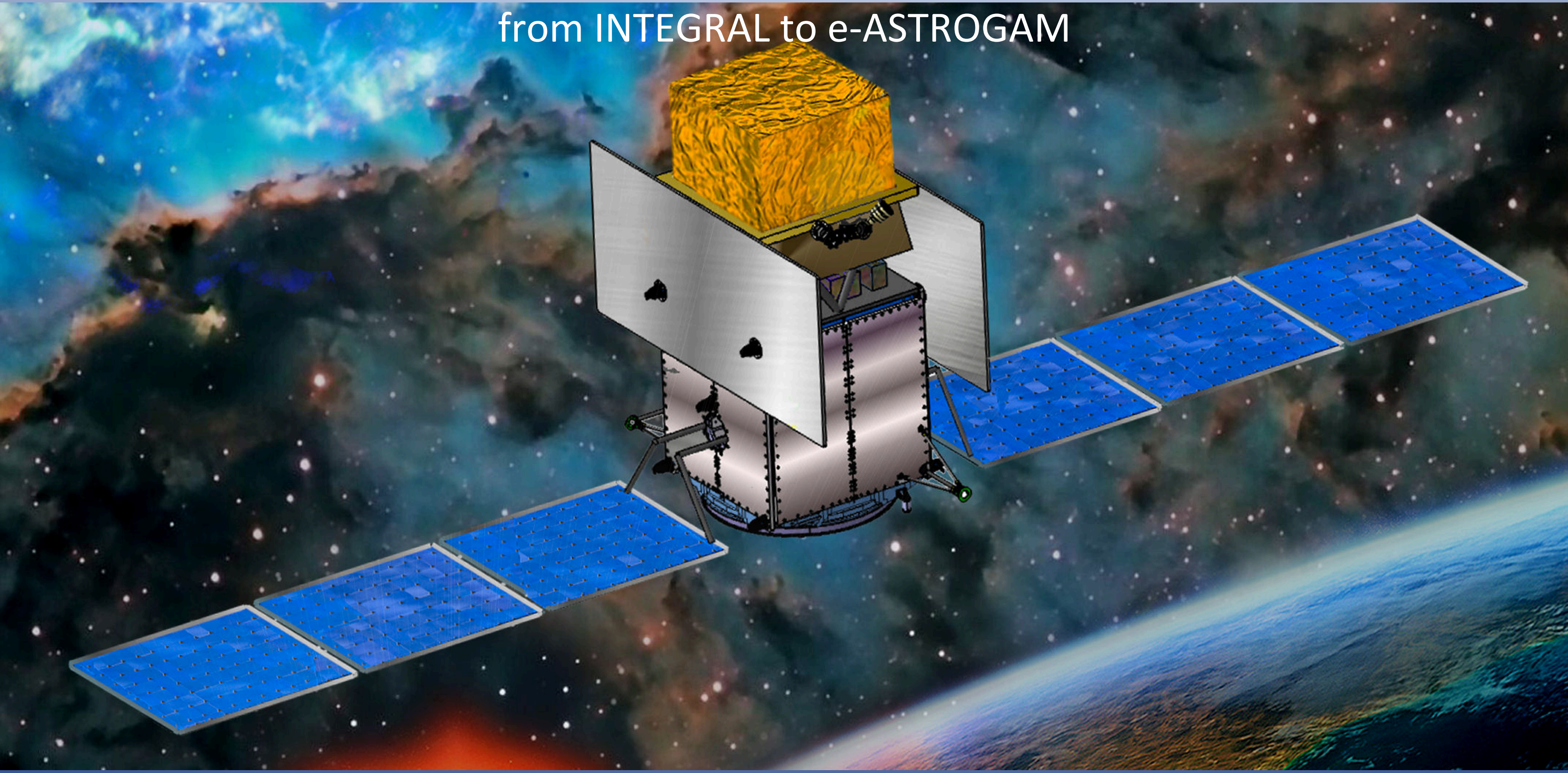
Hard X-ray/Gamma-ray polarization

from INTEGRAL to e-ASTROGAM



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2) *CSNSM (CNRS/IN2P3 et Université Paris Sud)*
3) *SLAC/KIPAC*

e-ASTROGAM workshop : The extreme Universe

Padova, 2017 February 28 – March 2

Gamma-ray polarization :
Provide complementary information's to imaging, spectroscopy and timing tools

Measuring gamma-ray polarization gives access to :

- Geometry of the source
- Constraints on magnetic field structure
- Nature of gamma-ray processes
- Discriminate between leptonic/hadronic models ?
- Constraints on fondamental physics for cosmological sources

Polarization potentially present in various classes of high energy sources

⟺

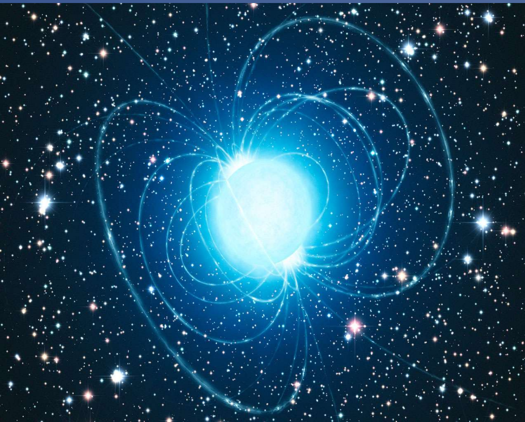
e-ASTROGAM science program

Galactic sources :

- Neutron stars : pulsars, magnetars
- Pulsar nebulae wind (PWN)
- X-rays binaries

Extragalactic sources :

- GRB
- AGN




Polarization mature in radio and optical but
nascent in the high energy domain
for technical and programmatic reasons

Panorama is changing with the emergence of several missions
(I)X(I)PE (see Sergio Fabiano's talk), COSI (see Andreas Zoglauer's talk)

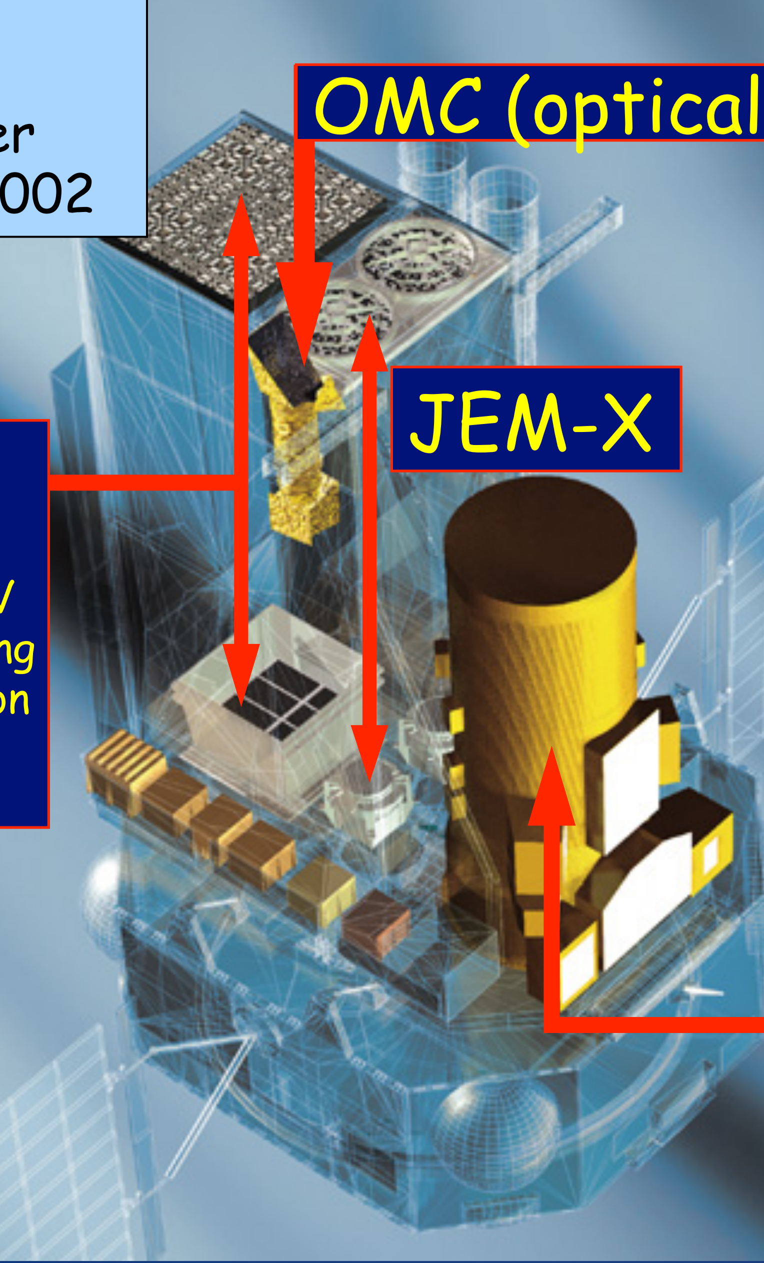
In the hard X-rays/gamma-ray band, polarimetry measurement is based on Compton polarimetry principles

INTEGRAL/IBIS experience and prospects with e-ASTROGAM

(For polarimetry at higher energy, see Denis Bernard's talk)

INTEGRAL Scientific payload

Satellite
4.1 tons
5 m height
3.7 m diameter
Launched in 2002



OMC (optical)

IBIS

15 keV – 10 MeV
12′ FWHM imaging
<1′ source location
19°x19° FOV

JEM-X

SPI

20 keV – 8 MeV
2 keV FWHM
26° Ø FOV

ISDC

IBIS (Imager on Board the INTEGRAL Satellite)

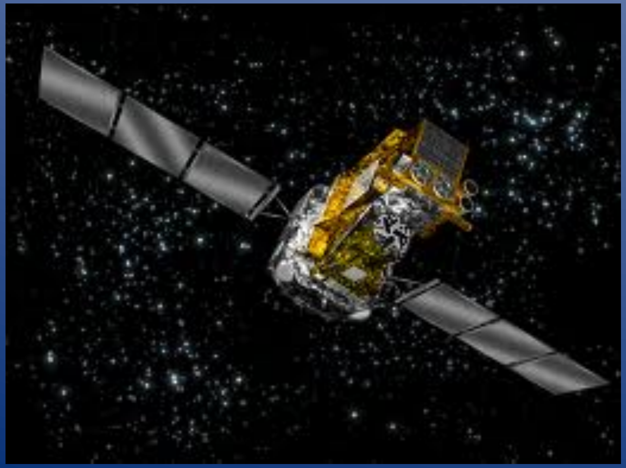
- Gamma-ray imager with two detector layers:

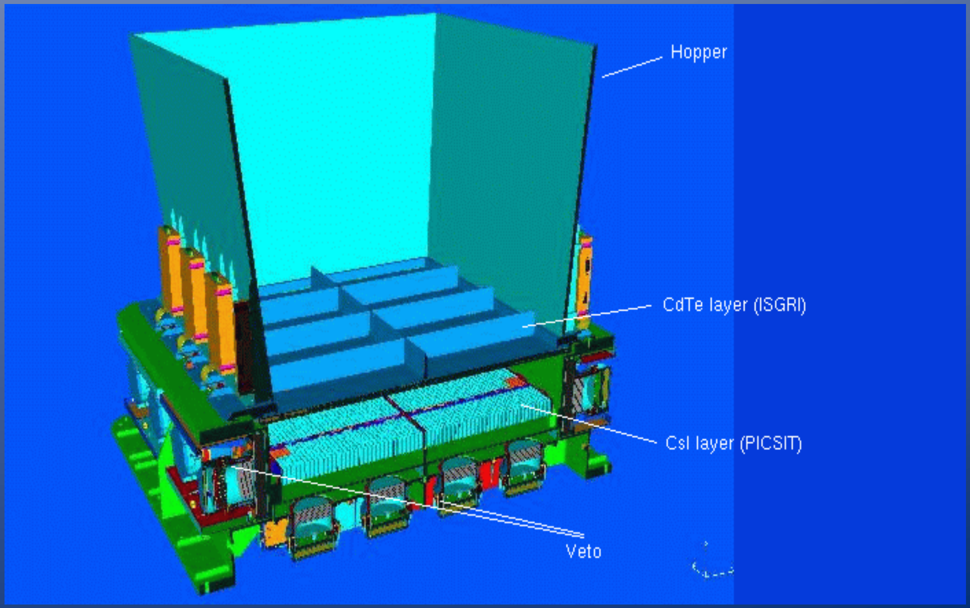
  ISGRI (Integral Soft Gamma-Ray Imager)
  - semi-conductor, CdTe, 2600 cm² (18 Kev – 1 MeV)

  PICsIT (PIxellated Ceasium Iodide Telescope)
  - crystal scintillator, CsI, 3000 cm² (175 Kev – 10 Mev)

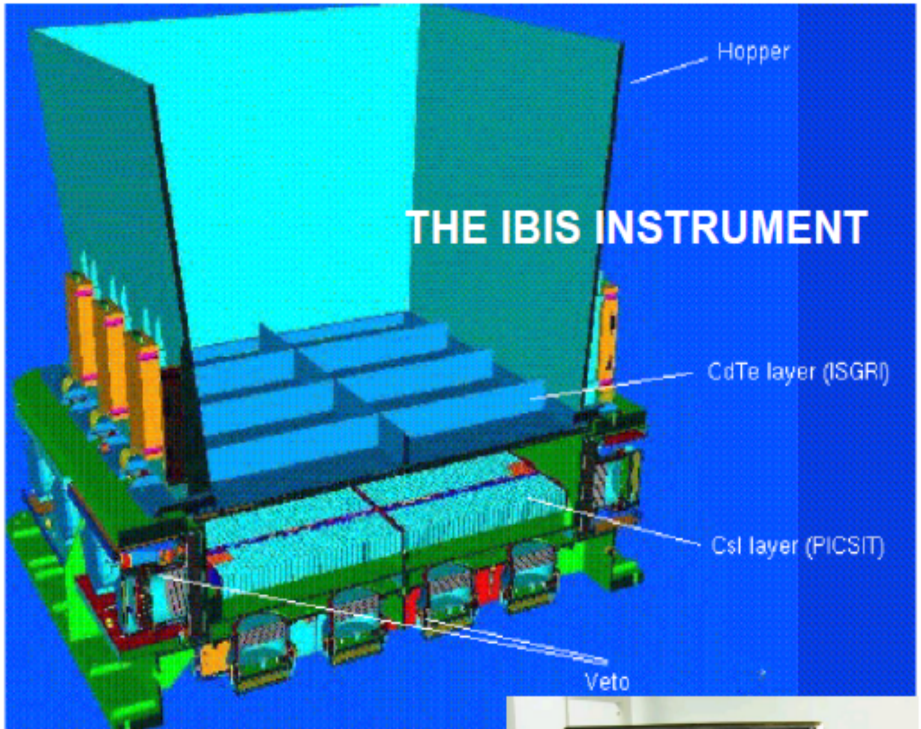
- Energy resolution (FWHM) = 8% @ 100 keV

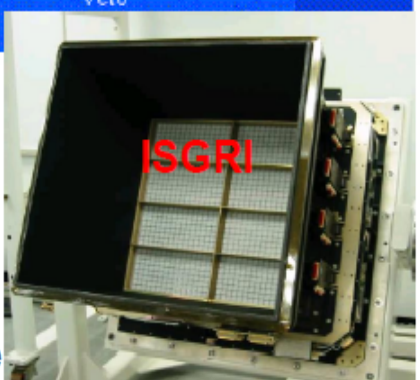
- Angular resolution (FWHM) = 12'





The INTEGRAL Imager : the IBIS telescope





IBIS detector assembly:

two stacked detection planes, lateral and bottom veto anticoincidence, passive tungsten shield

Collection area ~ 3000 cm^2

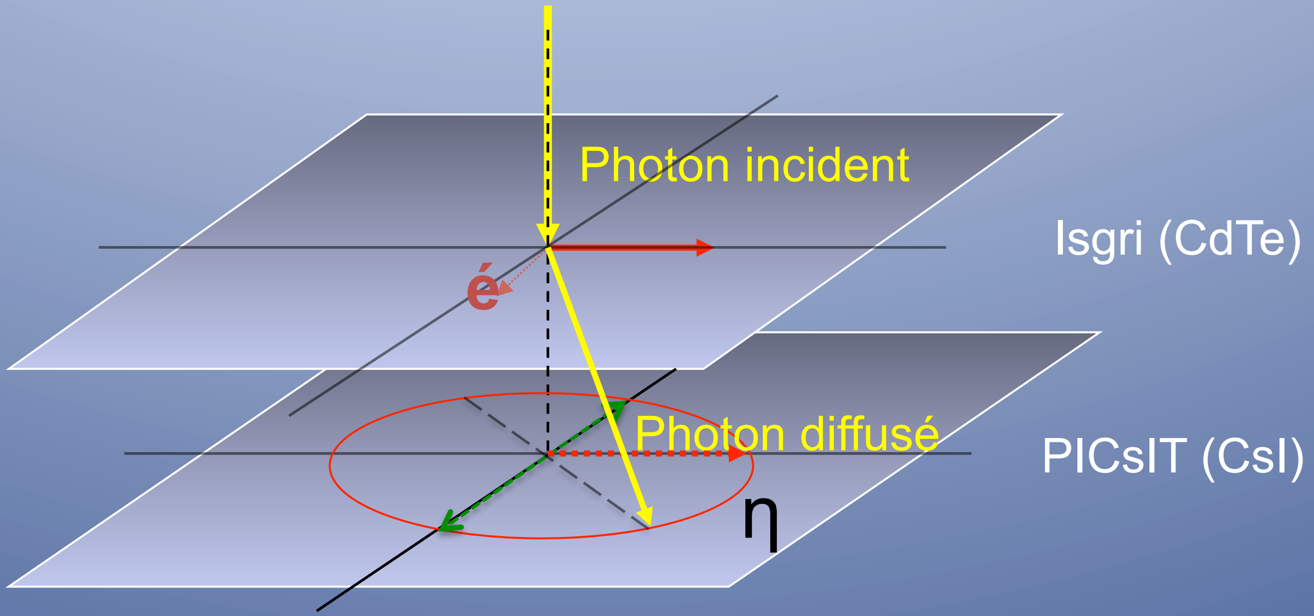
Two-Layers detector:

1) 2mm thick CdTe (ISGRI)

2) 30mm thick CsI (PICsIT)

Field-of-view: ±14.5°FWZR (± 4.5°fully coded)

INTEGRAL :The IBIS/Compton telescope



• The IBIS telescope is a coded mask telescope which could be used as a Compton telescope.

• The Compton mode events are ISGRI and PICSIT events in temporal coincidence, within a window $\tau_W \approx 3.8\ \mu s$.

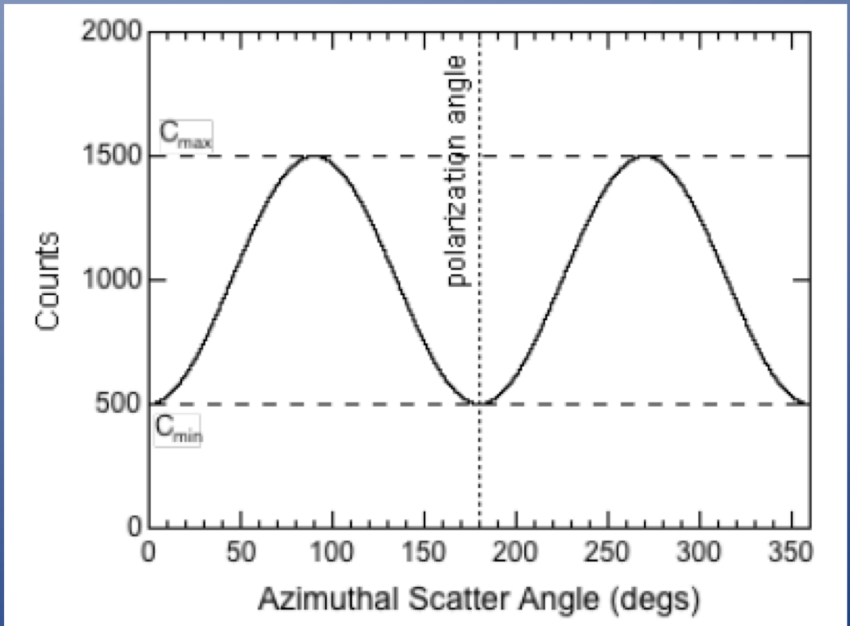
• Within this window, chance coincidence, called hereafter “spurious events”, may also occur.

Compton polarimetry principles

- Compton scattering cross section is maximum for photons scattered at right angle to the direction of the incident electric vector ⇒ asymmetry in the azimuthal profile S of scattered events.

$$S = \overline{S}\left[1 + a.\cos(2(\varphi - \varphi_0))\right]$$

- modulation
  - a = modulation factor
  - polar. fraction = PF = a/a_{100}
  - a_{100} = modulation for a 100 % polarized source.
  - polar. angle = PA = $\varphi_0 - \pi/2 + n\pi$



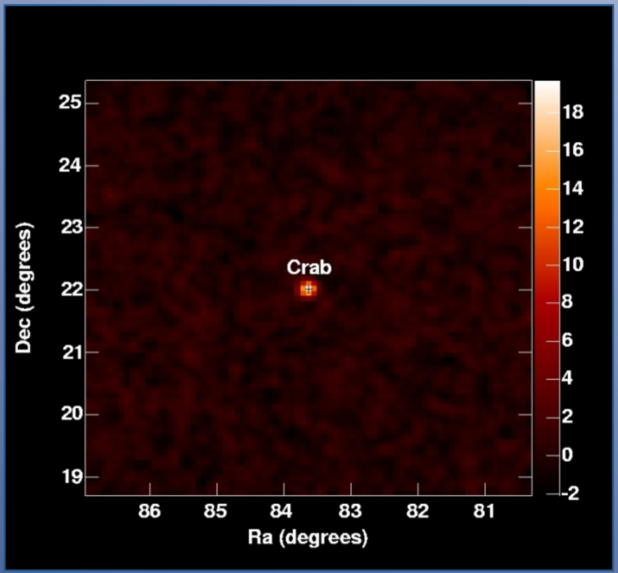
Minimum Detectable Polarization (MDP)

$$MDP = \frac{4.29}{\mu_{100} S}\sqrt{\frac{S+B}{T}}$$

S = Source counting rate c/s
B = Background counting rate c/s
T = Exposure time
μ_{100} = modulation factor for a 100% polarization source

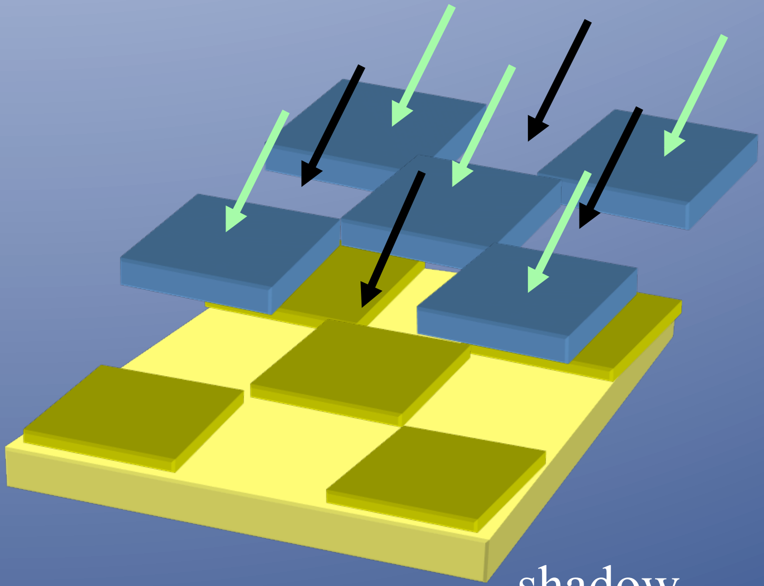
By this definition, the "minimum detectable polarization" is the degree of polarization corresponding to the amplitude of modulation that has only a 1% probability of being detected by chance. (Weisskofp et al., 2010)

Image deconvolution



200-800 keV T=300 ks

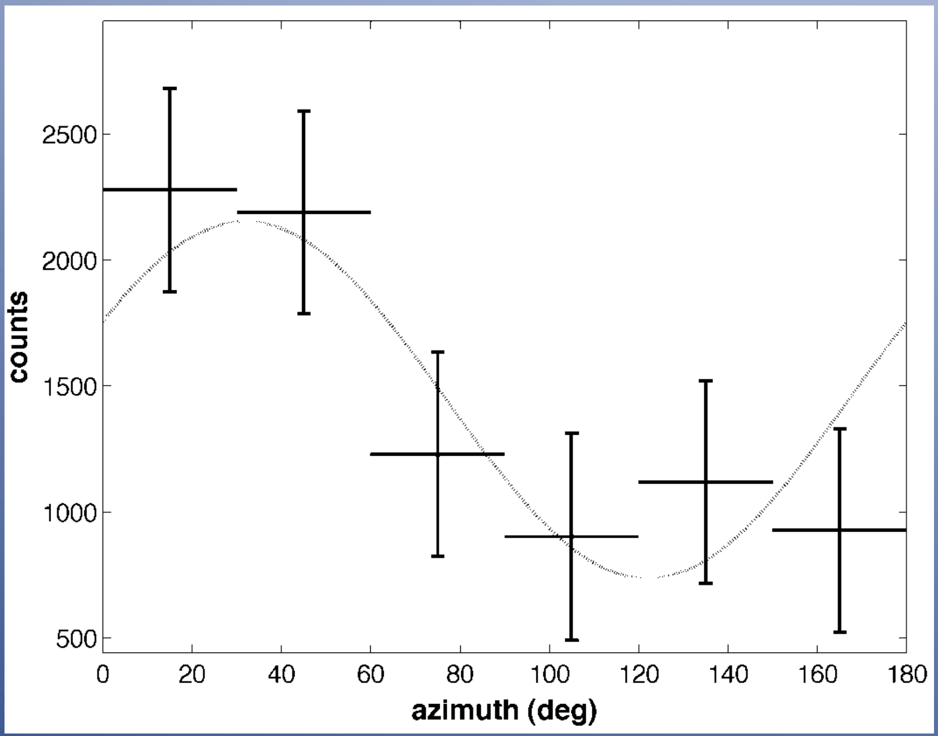
Shadowgram deconvolution



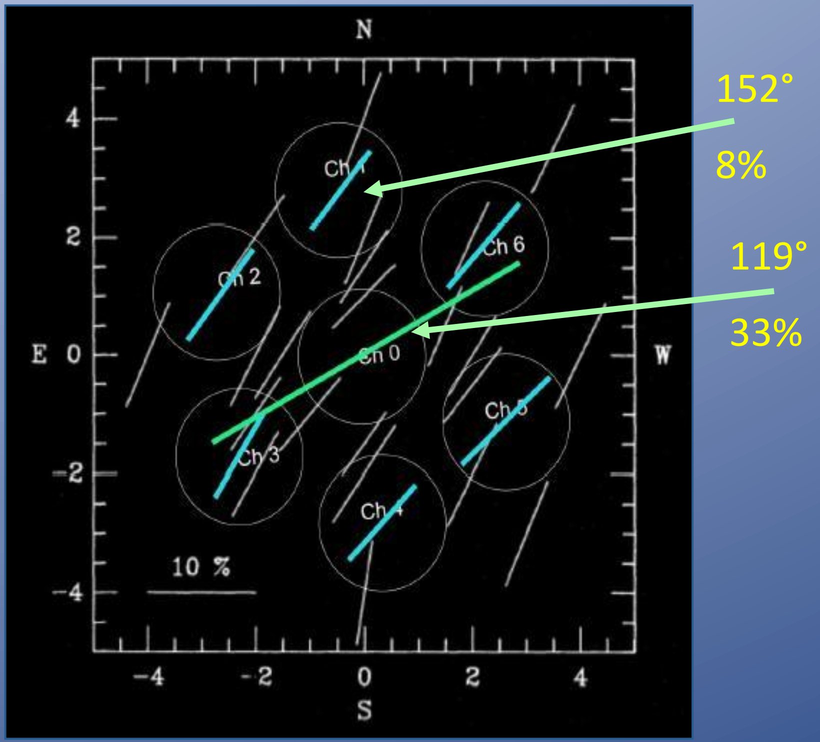
shadow

⇒ SOURCE DIRECTION

Crab polarimetry



Forot et al. 2008



Slowikowska et al. 06, Smith et al. '88, Weisskopf et al. '78

polarization angles

- INTEGRAL off-pulse: PA = 120.6° ± 8.5°
- projected rotation axis: 124.0° ± 0.1°
- optical r < 0.01 pc: PA = 119°
- X-ray: PA = 152°

Optical and hard-X rays polarimetry study of the Crab system (Nebula+pulsar)

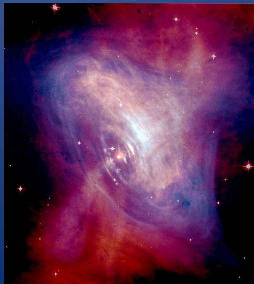
Observations with the GASP polarimeter and the INTEGRAL/IBIS telescope

1/ Optical observations :

- 2005 (HST), 2012 (GASP at Palomar)
- 2015 (GASP at WHT)

2/ Hard X-rays view : INTEGRAL/IBIS

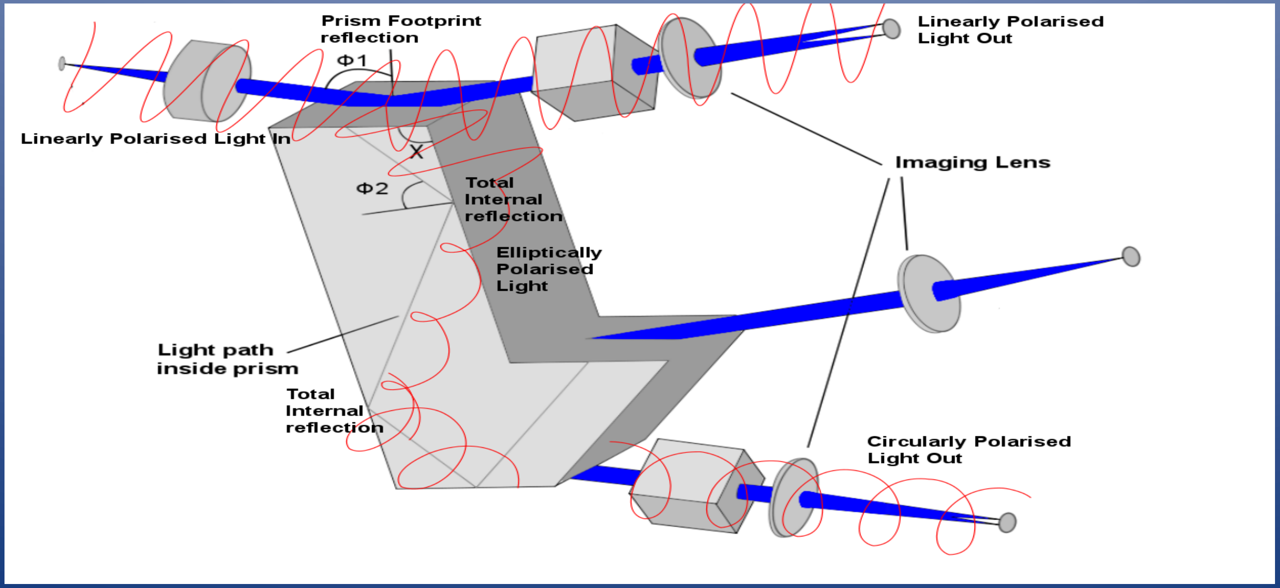
- calibration and regular monitoring of Crab with INTEGRAL



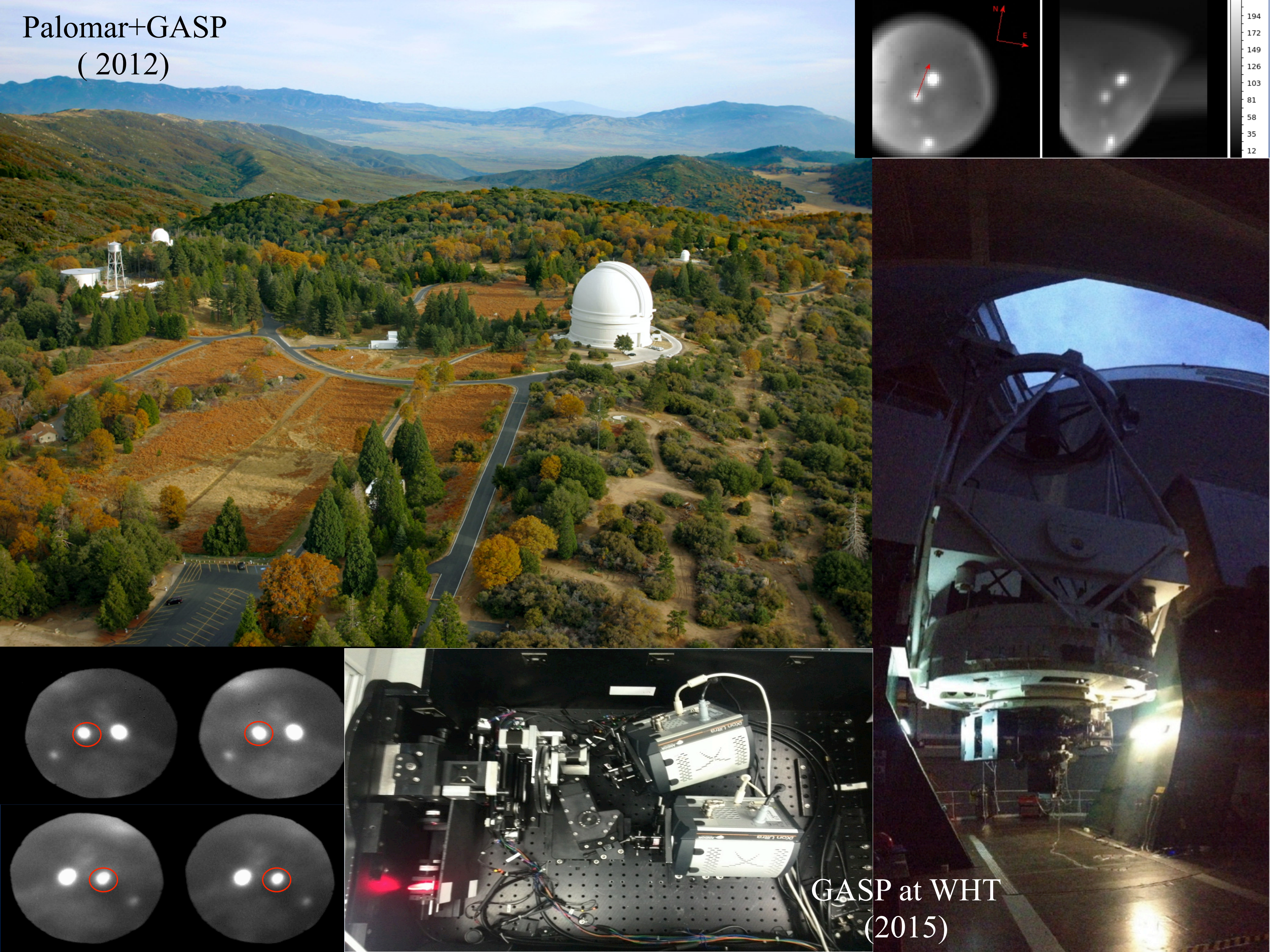
Optical Polarisation with the Galway Astronomical Stokes Polarimeter (GASP)

(See Andy Shearer's talk)

- Ultra-high speed, Full Stokes, Astronomical Imaging Polarimeter
- Division of Amplitude Polarimeter (DOAP)
- Linear & Circular polarisation
- Studies(~ms) variations in optical pulsars and magnetic CVs



Optical Layout of GASP: light path through DOAP from telescope focus to detectors (Kyne et al. 2012)



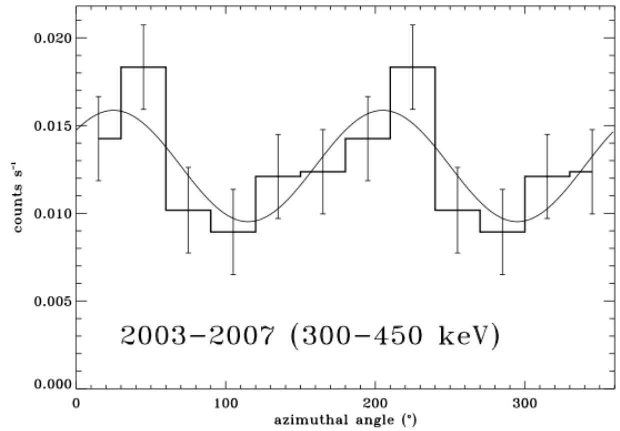
Palomar+GASP
(2012)
N
E
194
172
149
126
103
81
58
35
12
GASP at WHT
(2015)

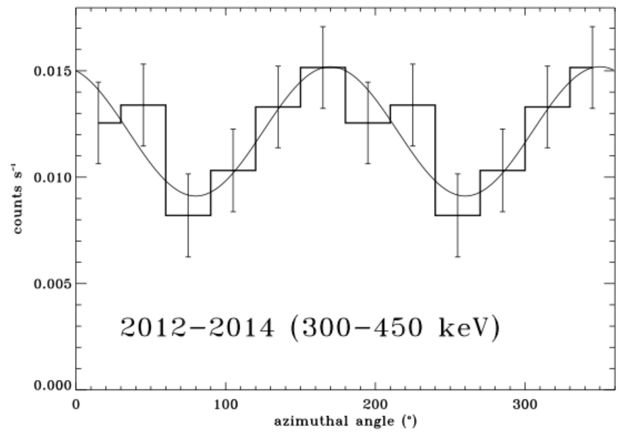
INTEGRAL

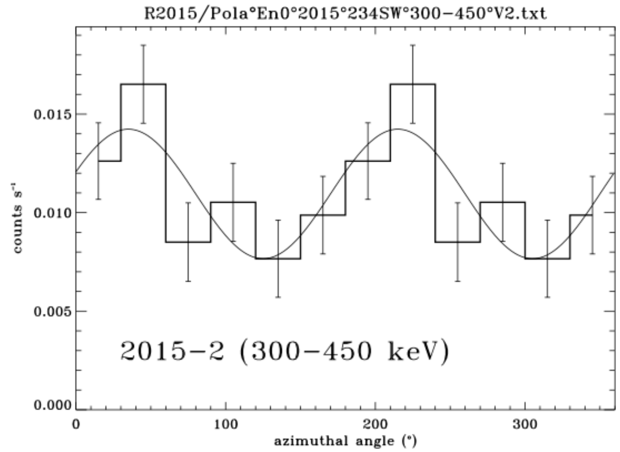
2003 – 2007 data
Θ = 115 ± 11°
PF = 96 ± 34 %

2012 – 2014 data
Θ = 80 ± 12°
PF = 98 ± 37 %

Fall 2015 data
Θ = 125 ± 15°
PF = 89 ± 28 %







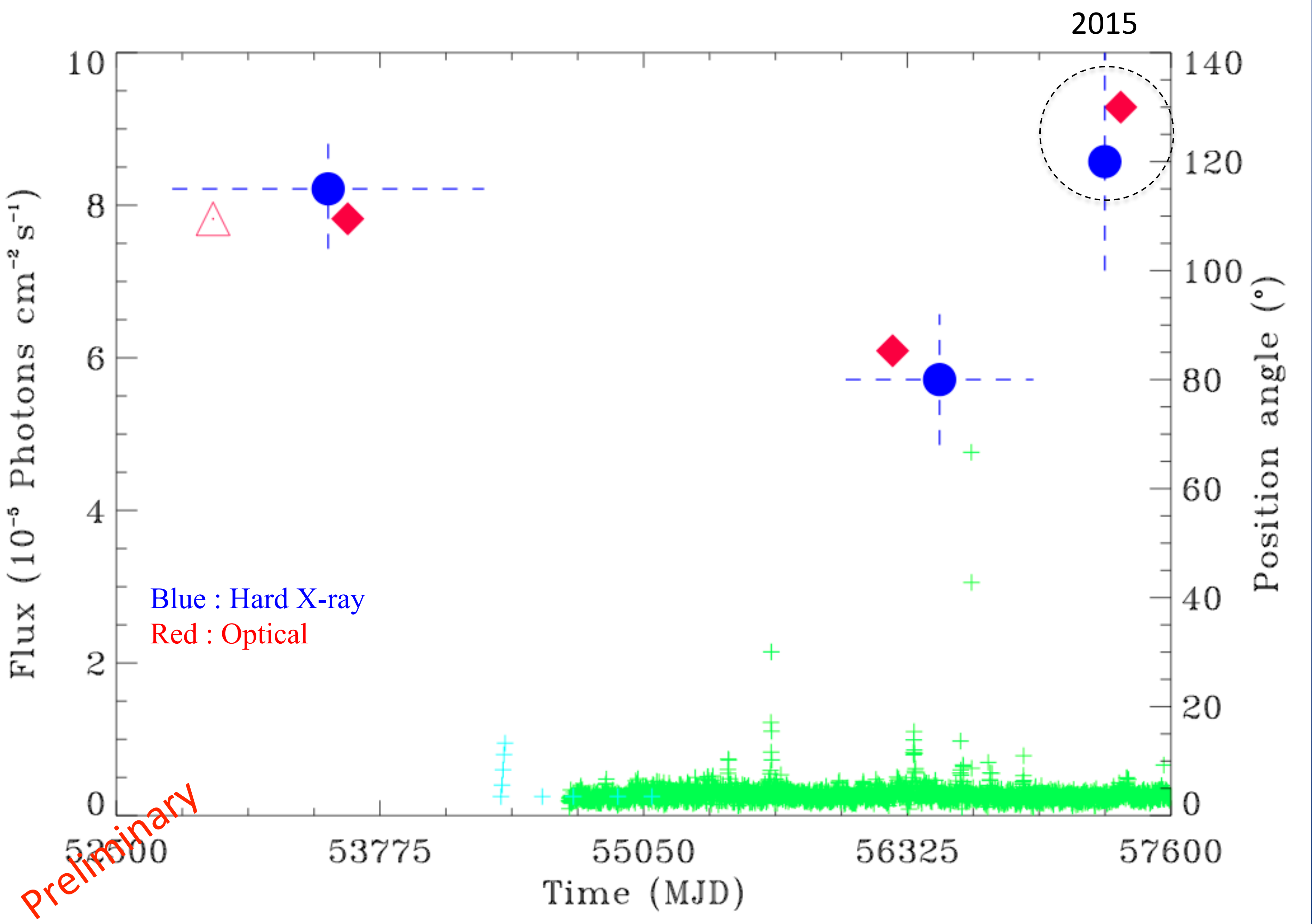
Optical values

2005 HST data
Θ = 109.5 ± 0.7°
PF = 7.7 ± 0.1 %

2012 GASP data
Θ = 85.3 ± 1.4°
PF = 9.6 ± 0.5 %

2015 GASP data
Θ = 130°
(analysis in progress)

Moran et al, 2013, 2016



Astrosat measurement in October 2015 in good agreement with INTEGRAL result

Change in polarization seen with GASP in optical and Integral in hard X-rays

Which origin ?

- Magnetic reconnection ?
- Time scale of the change (hours, days, week, year ?)
- What are the links with high energy flares ?
- Where the observed change come from (knot?)

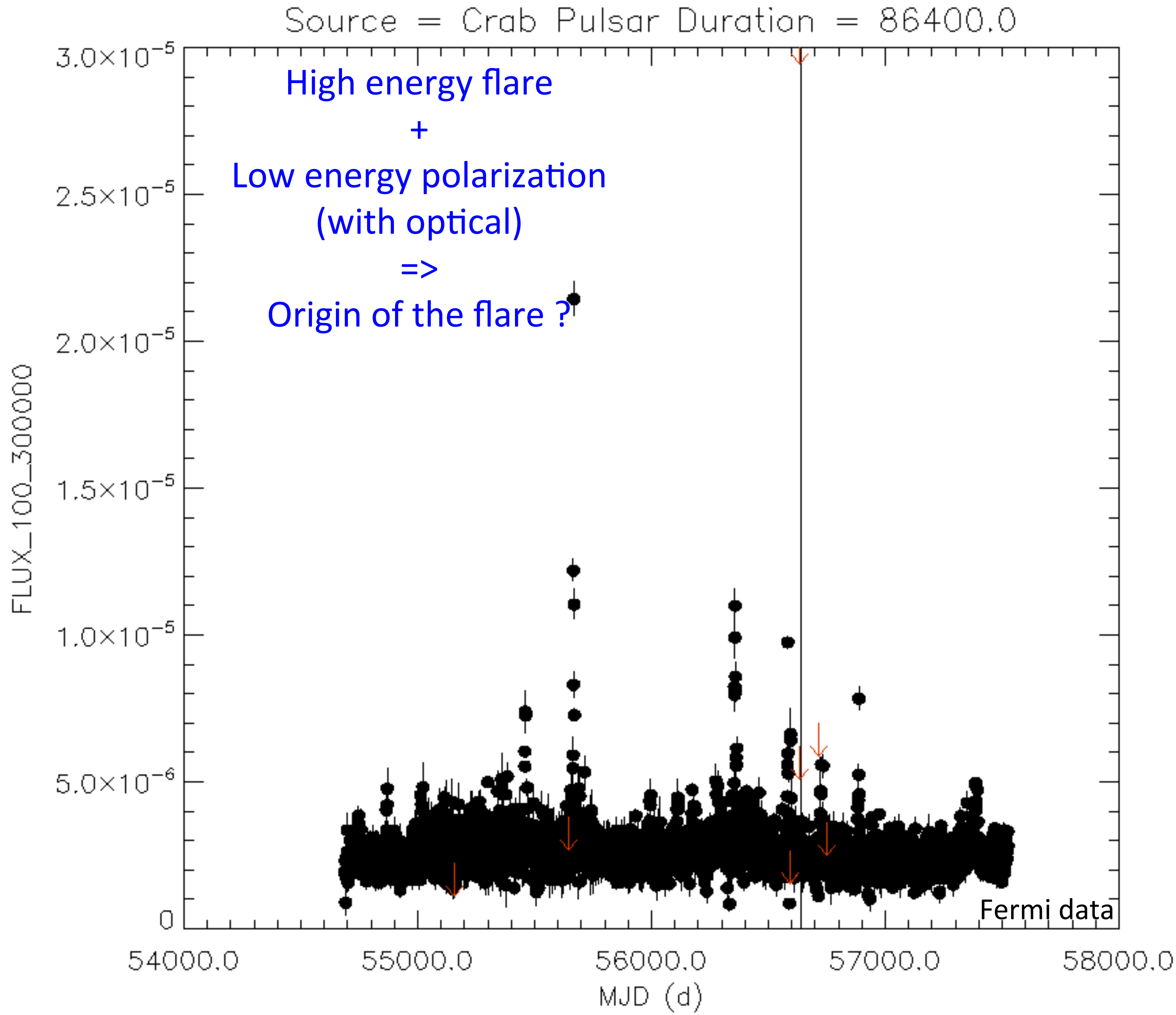
Works on-going with more observations and phase resolved analysis

Note : Astrosat and Hitomi/SGD have on-going works !

- A similar study will greatly benefit of e-ASTROGAM sensitivity (better timescale, spectral coverage, spectral resolution)

Towards a phase resolved multiwavelength polarimetric spectrum of a pulsar/ PWN?

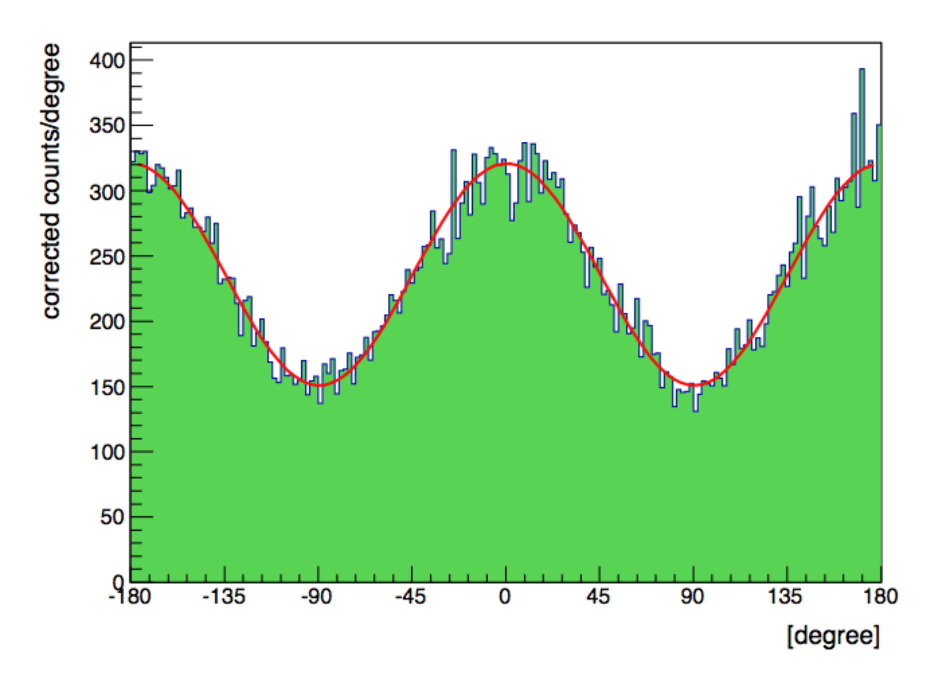
- Collaboration/contacts with other groups in particular in optical for joint observations crucial



Source = Crab Pulsar Duration = 86400.0
High energy flare
+
Low energy polarization
(with optical)
=>
Origin of the flare ?
FLUX_100_300000
3.0×10^-5
2.5×10^-5
2.0×10^-5
1.5×10^-5
1.0×10^-5
5.0×10^-6
0
54000.0
55000.0
56000.0
57000.0
58000.0
MJD (d)
Fermi data

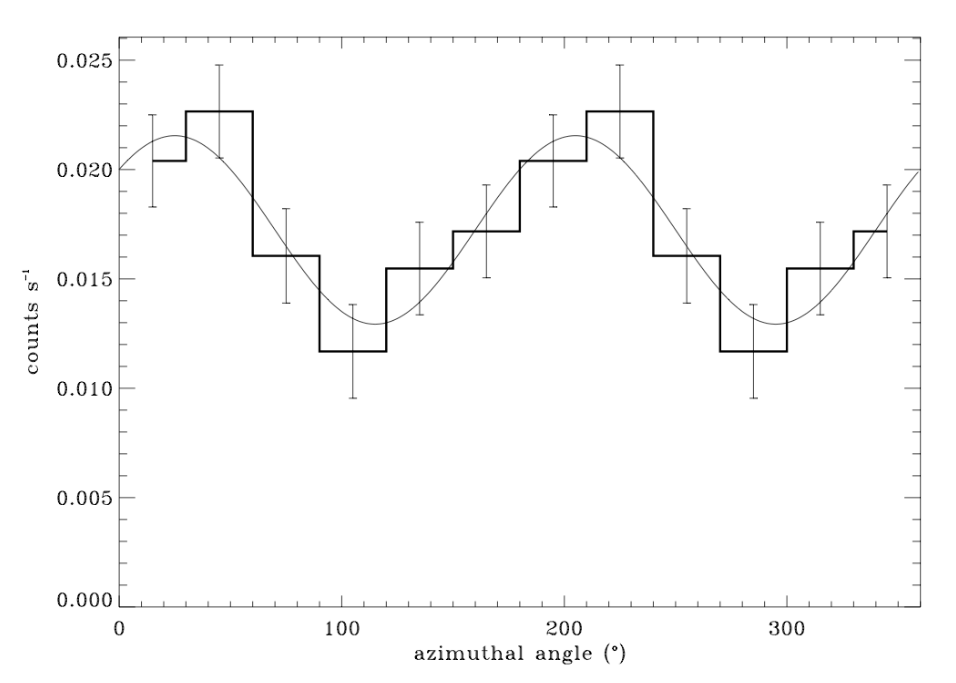
From INTEGRAL to e-ASTROGAM

e-ASTROGAM polarization response



E=0.2-2 MeV, 100% pol., 10mCrab, T=10^6sec

Crab INTEGRAL/IBIS polarization curve

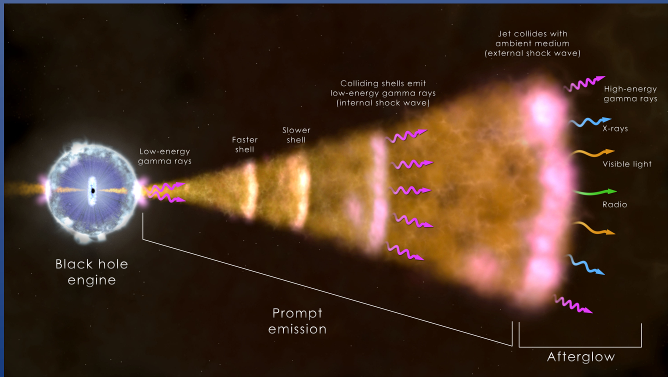


E=300-800 keV, T = 10^6sec (data 2015)

- ✓ e-ASTROGAM at least 100 times more sensitive than INTEGRAL
- ✓ From simulation MEGAlib : MDP at 99% confidence level of 0.7% for a Crab-like source in 1 Ms (or MDP_{99} of 10%, 10 mCrab, 1 year)

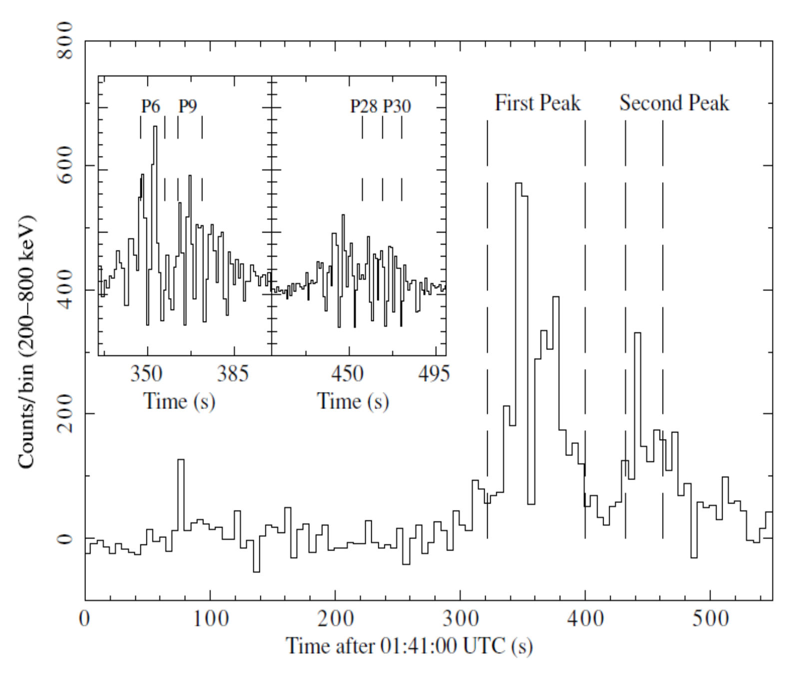
Gamma-ray Burst

Polarization measurements might help to solve some points on GRB modelling for prompt and afterglow emission (jet composition, jet geometry, etc)

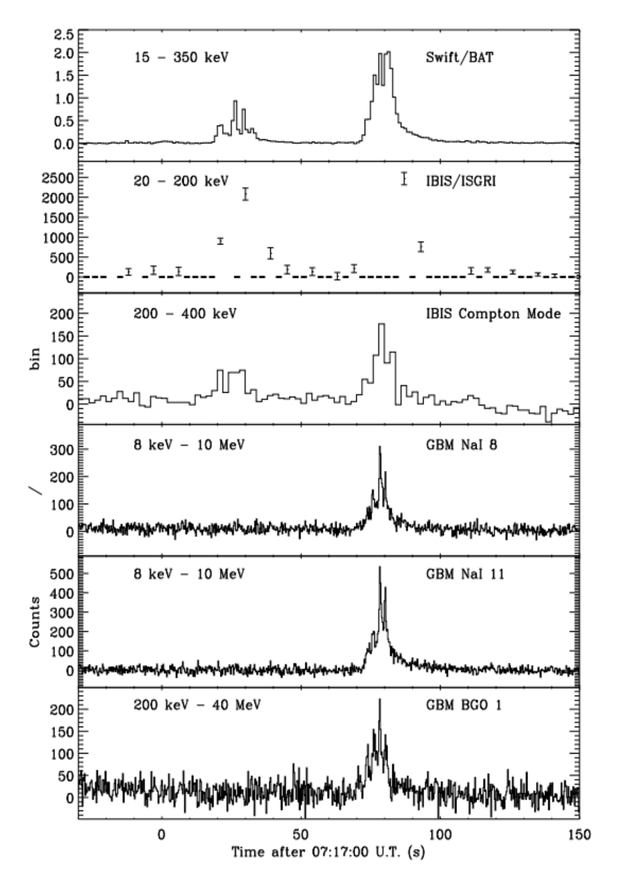


INTEGRAL studies of GRBs with two examples: GRB 041219A and GRB 140206A

GRB 041219A is the longest and brightest GRB detected so far in the Integral FOV



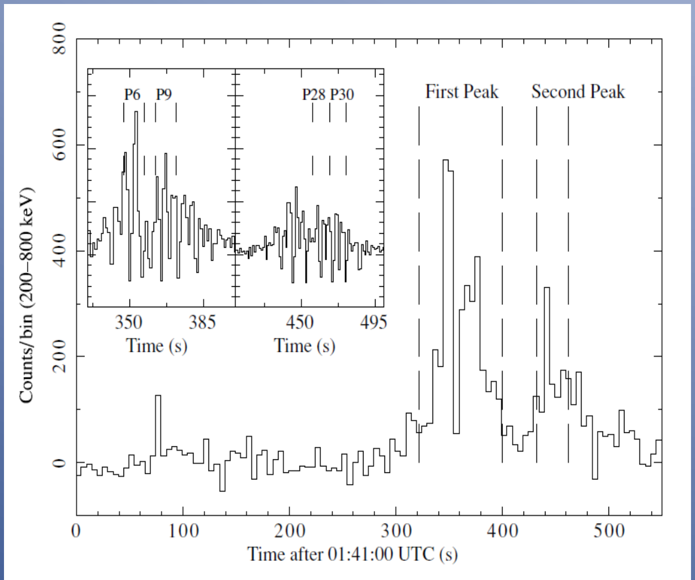
Compton mode light curve, 5 s bins
The brightness of the source allows for time resolved analysis (10 s bins)



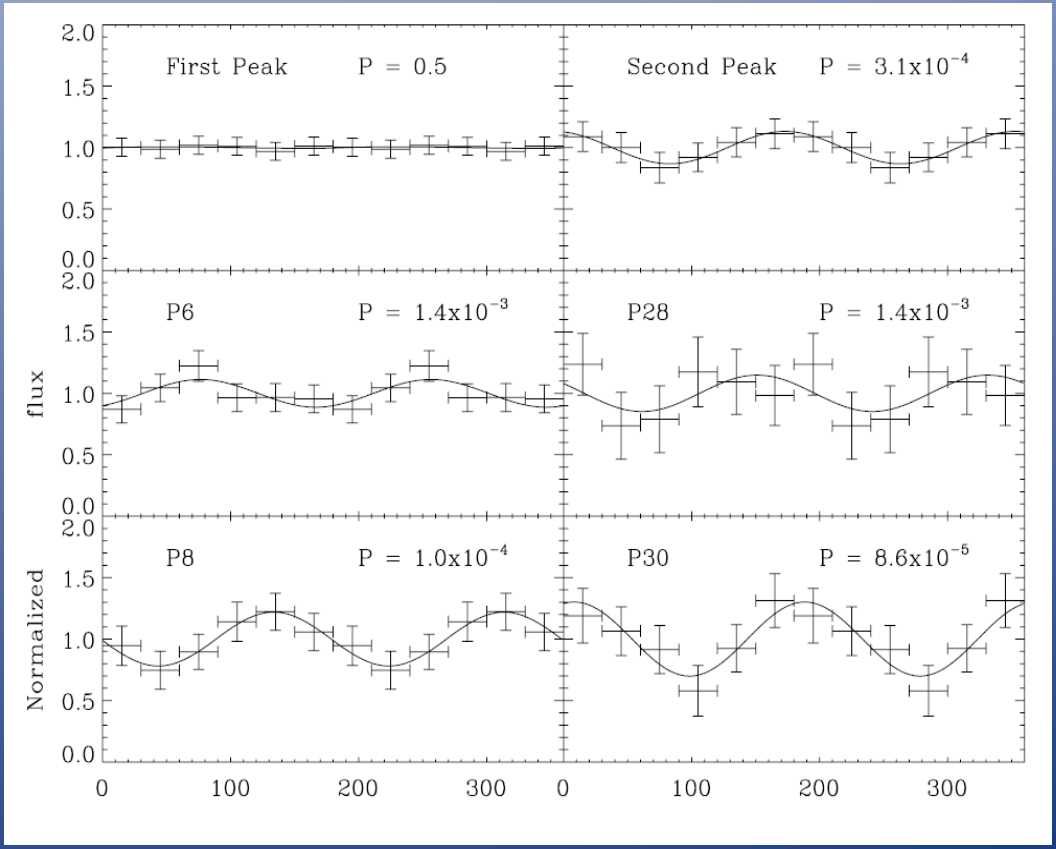
GRB 140206A is the most distant polarized GRB we observed with INTEGRAL.

Götz et al, 2014

GRB 041219A polarization temporal evolution



Light curve of GRB041219A divided in 10 s time bins to measure the polarization evolution.



Götz et al, 2014

GRB 041219A polarization temporal variability

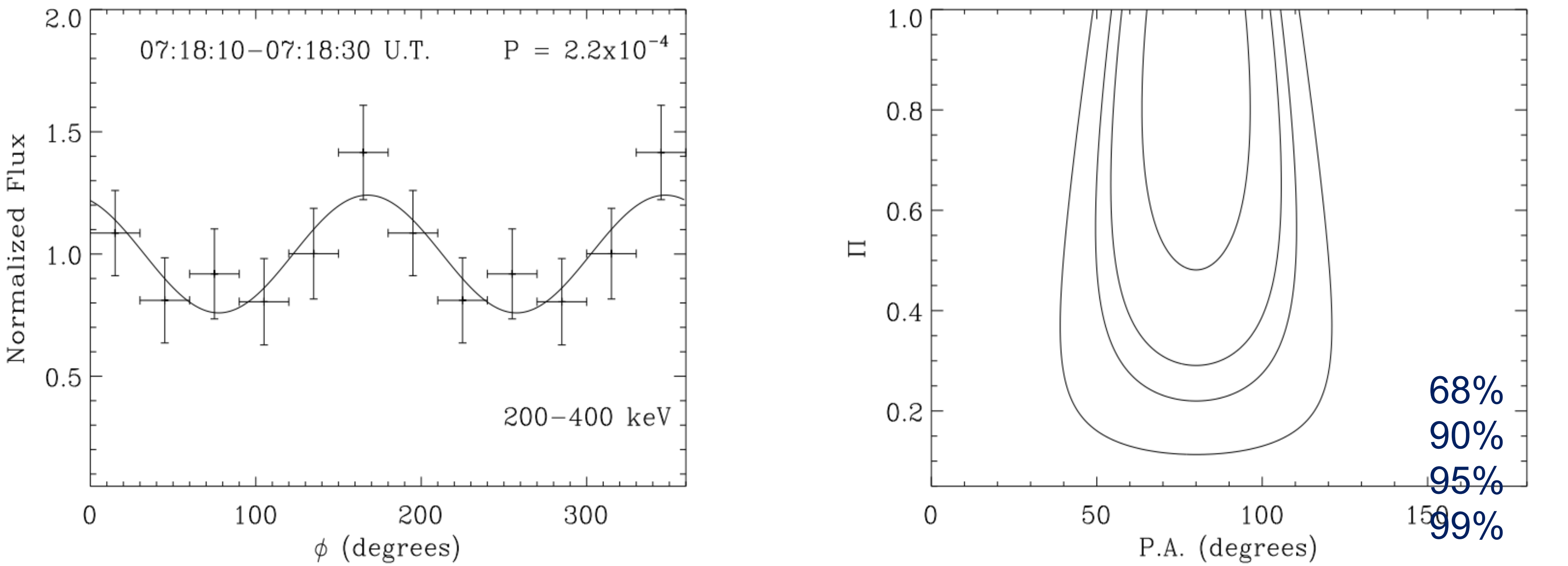
Polarization Results for the Different Time Intervals

Name	$T_{\rm start}$ (UT)	$T_{\rm stop}$ (UT)	Π %	P.A. (deg)	Image (SNR)
First peak	01:46:22	01:47:40	<4	...	32.0
Second peak	01:48:12	01:48:52	43 ± 25	38 ± 16	20.0
P6	01:46:47	01:46:57	22 ± 13	121 ± 17	21.5
P8	01:46:57	01:27:07	65 ± 26	88 ± 12	15.9
P9	01:47:02	01:47:12	61 ± 25	105 ± 18	18.2
P28	01:48:37	01:48:47	42 ± 42	106 ± 37	9.9
P30	01:48:47	01:48:57	90 ± 36	54 ± 11	11.8

Notes. Errors are given at 1σ c.l. for one parameter of interest.

Götz et al, 2014

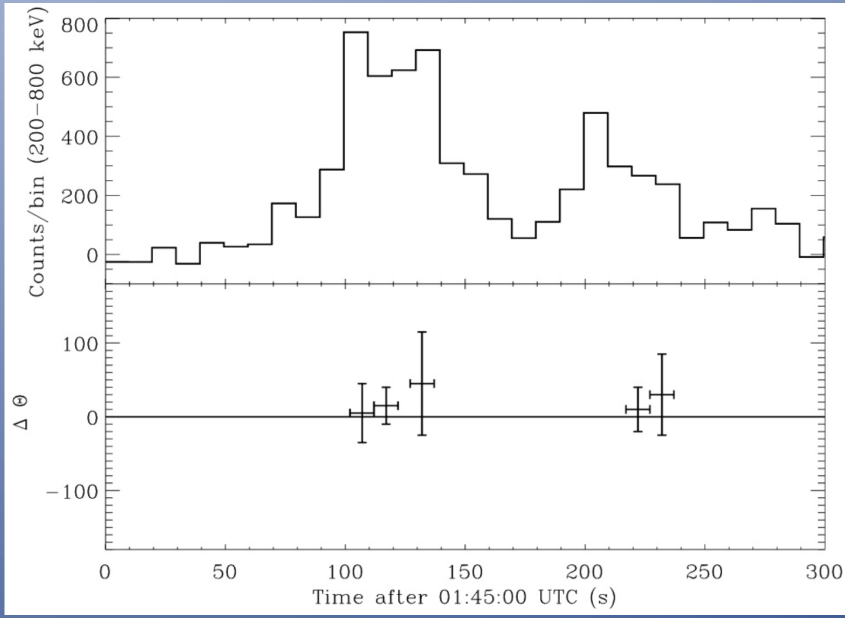
GRB 140206A polarimetry
(z=2.74)



20s of data: Θ = 80 ± 15° PF > 48 %

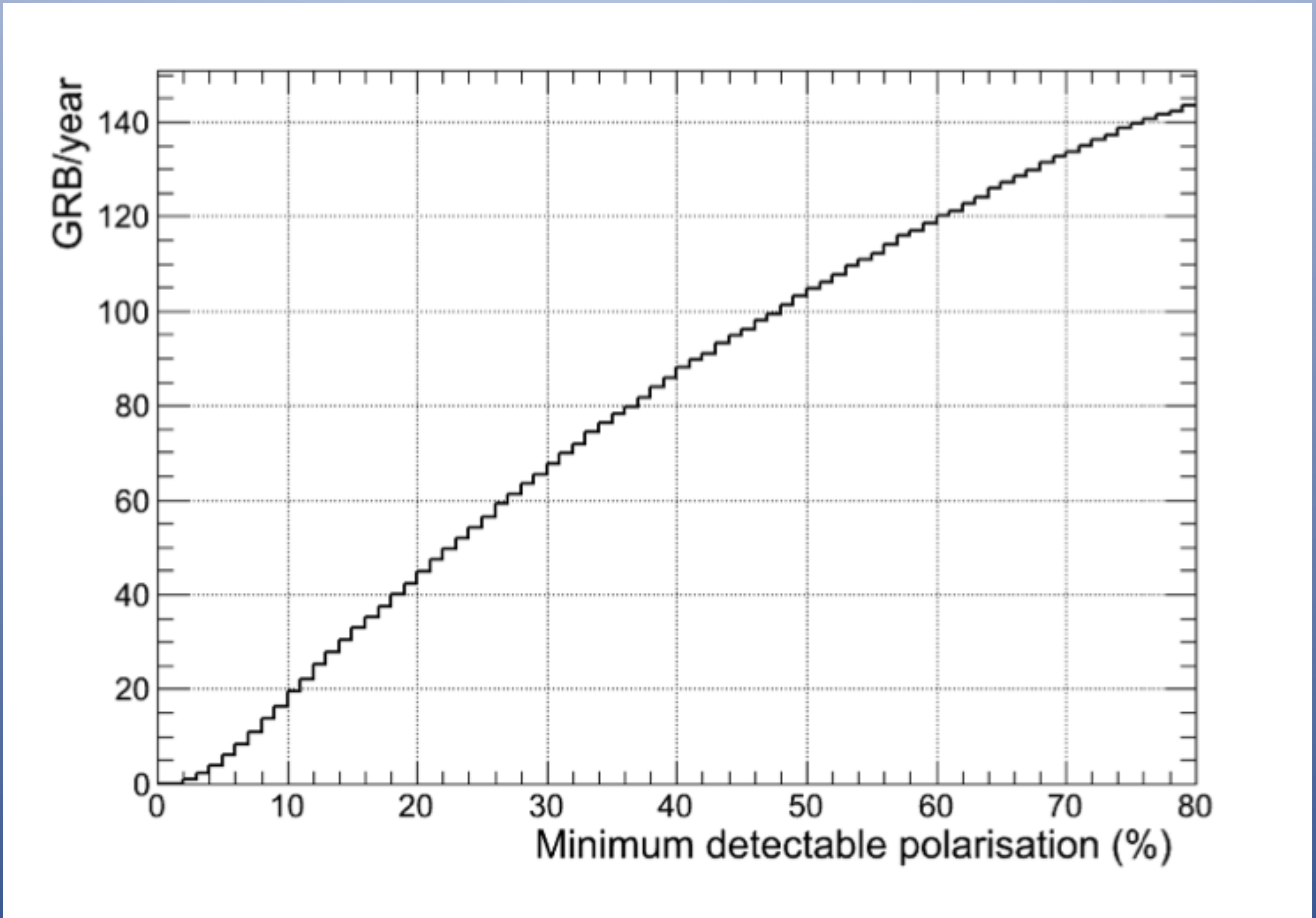
GRB 140206A: constraints on Lorentz Invariance Violation (LIV)

- LIV => differential rotation of the polarization angle.
- The further away is the source, the better is the constraint.



$\Longrightarrow$ Strong limit on vacuum birefringence ($\xi < 10^{-16}$)

e-ASTROGAM (simulation)



Cumulative number of GRBs to be detected by e-ASTROGAM as a function of the minimum detectable polarization at the 99% confidence level

- a polarization fraction of 20% in about 42 GRBs per year
- a polarization fraction of 10% in 16 GRBs per year

From INTEGRAL to e-ASTROGAM

- Better modeling with level of polarization and angle : synchrotron vs inverse compton emission
- Instrumental performances => measurements of many GRB => constraints on possible anisotropy of LIV (predicted by theoretical models)

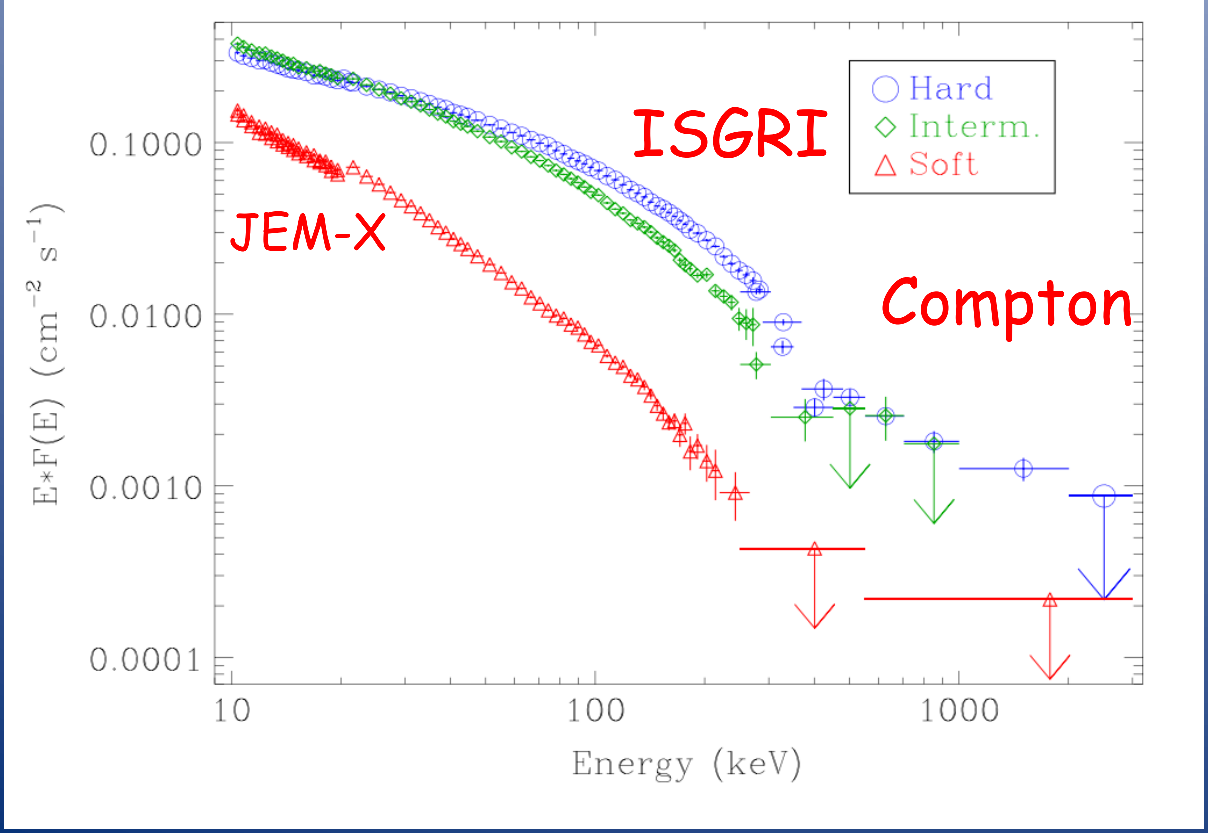
Polarization of X-rays binaries

Cygnus X-1 high energy spectrum

Selection of the data according to the spectral state of the source:

- Soft state (HSS) : emission dominated by a warm (1keV) accretion disk, variability low, power law, little or no radio emission (absence of a jet)

- Hard state (LHS) : disk colder (<0.5keV), power law up to hundreds of keV, rapid variability, compact jet detected from radio to IR.



Two spectral components:

20-400 keV
Thermal Comptonisation
kT = 53 ± 2 keV
tau = 1.15 ± 0.04

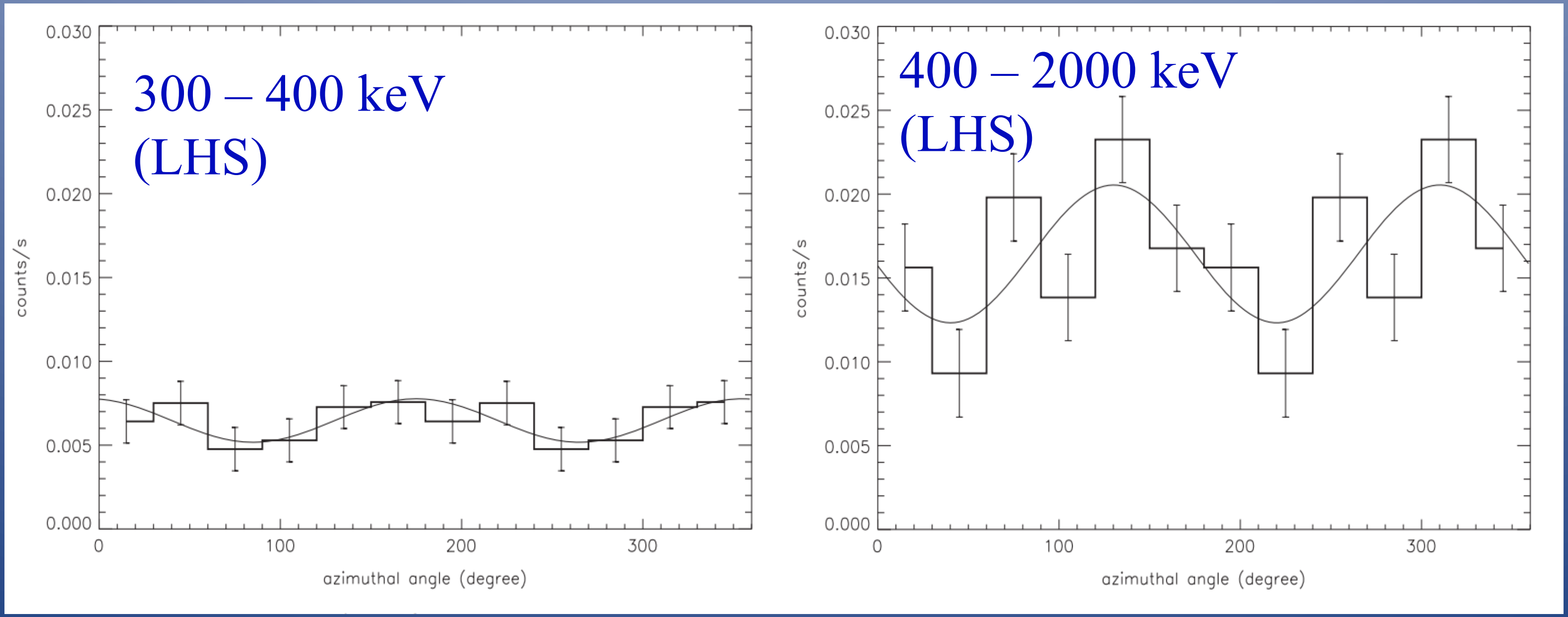
400 -2000 keV
Power-law : index = 1.4 ± 0.3

Break around 2 MeV ?
=> e-ASTROGAM

Laurent et al., 2011, Rodriguez et al., 2015

Cygnus X-1 polarization
(400 - 2000 keV)

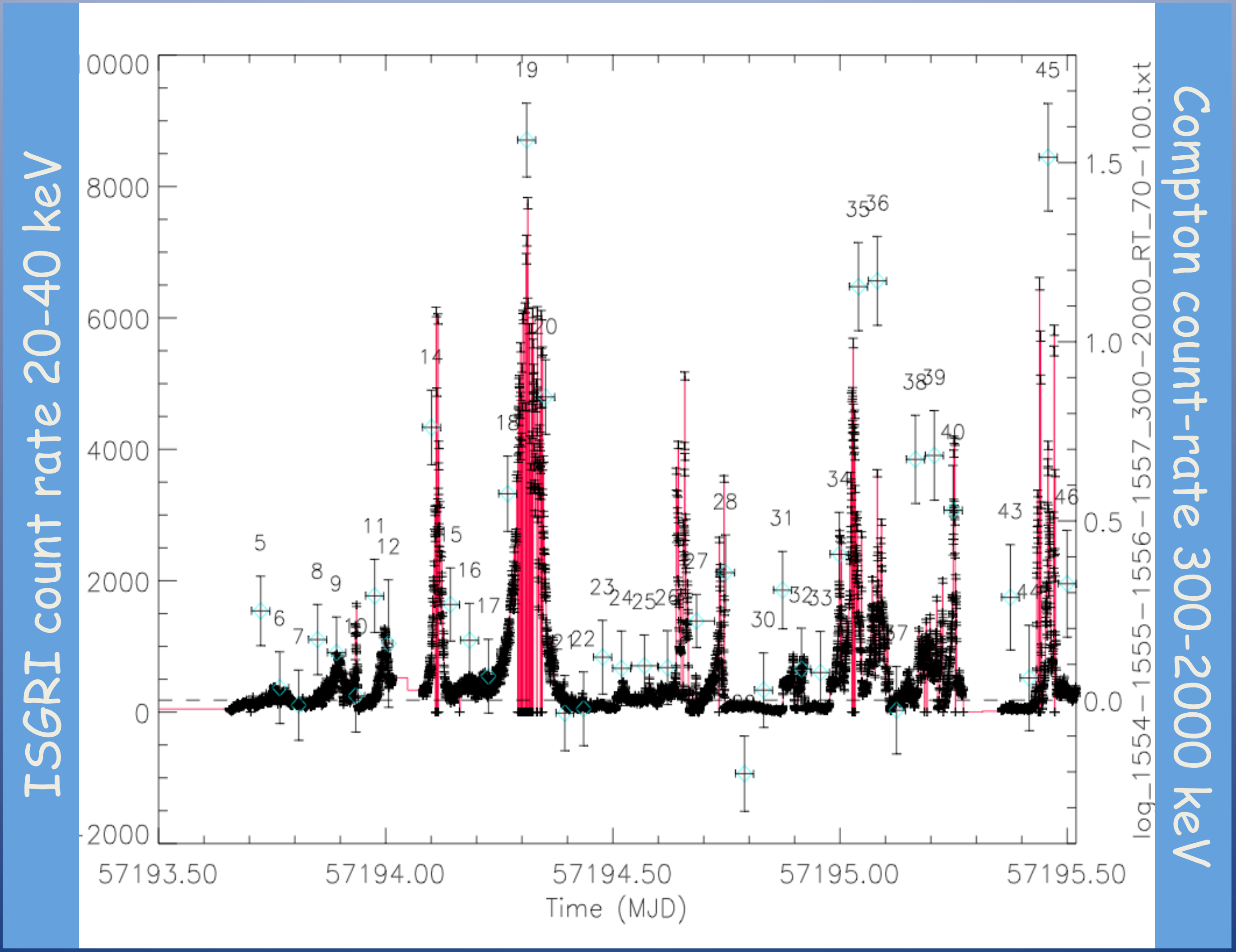
- No detection in HSS with 1.2Msec, PF < 70 %
- In LHS (2 Msec) polarization detected Θ = 40 ± 15° , PF = 67 ± 30 %



Strong polarization at MeV energy => signature of a jet, coronal effect ?

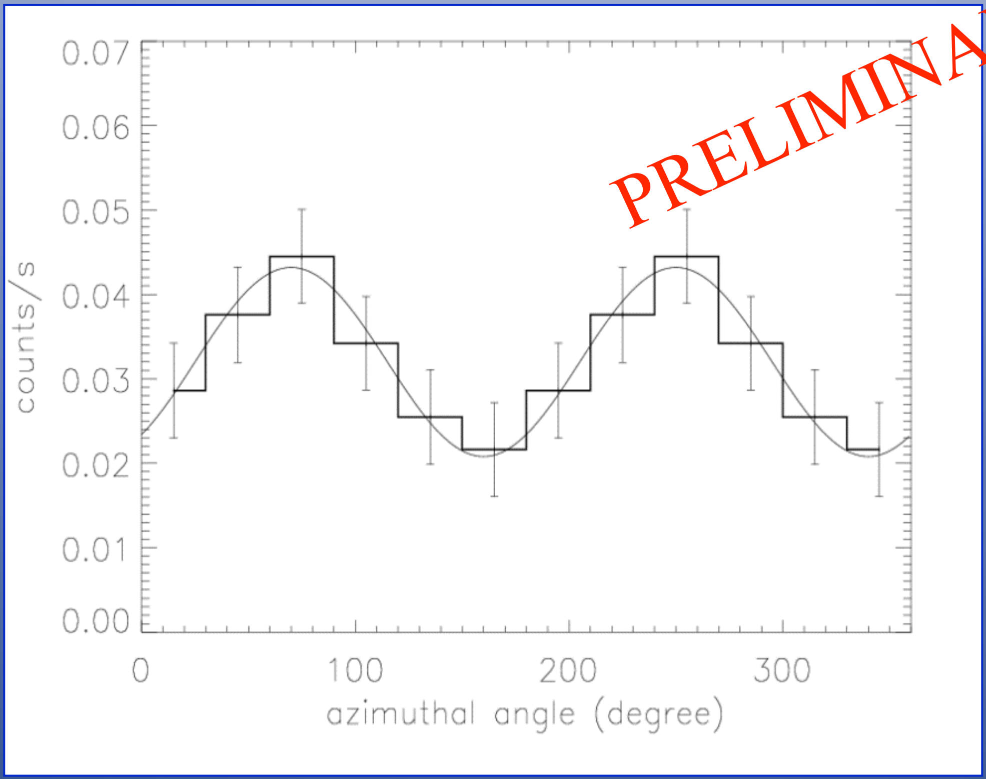
Laurent et al., 2011, Rodriguez et al., 2015

V404 Cygni Compton light curves (32s; rev. 1555)

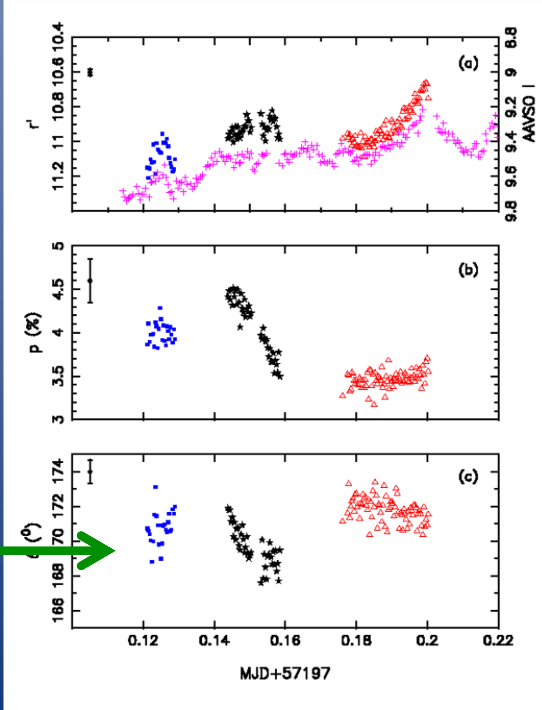


V 404 Cygni polarisation (450 - 2000 keV)

June 2015
149 ks of data:
Θ = 160 ± 15°
PF = 95 ± 35 %



Θ = 171°
NIR (Shahbaz et al. 2016)



=> Coordinated observations in radio, optical, NIR

From INTEGRAL to e-ASTROGAM

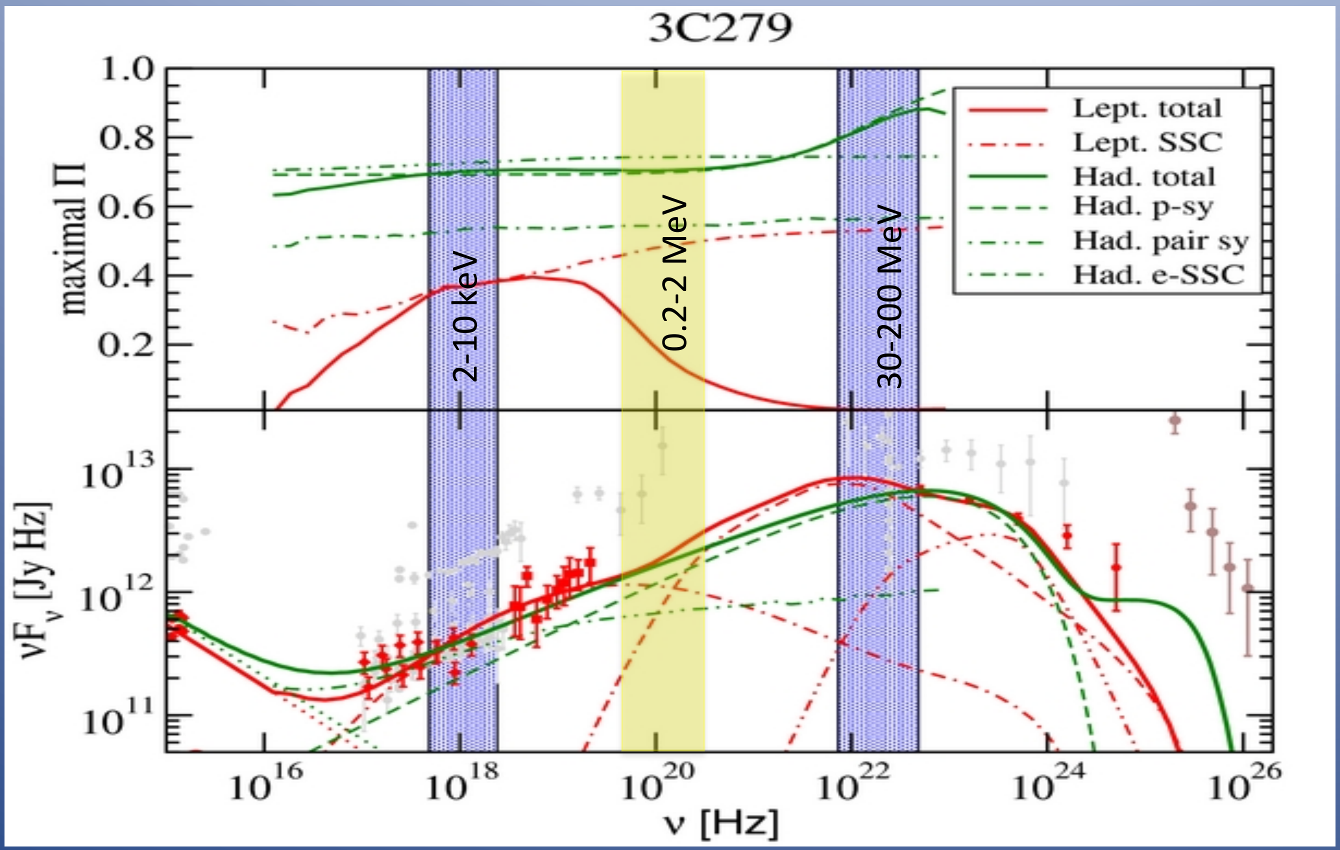
- Study of the hard component, energy of the break
- Study of the jet component in particular on a short time base : precession of the jet ?
- Joint multi-wavelength programs crucial to better understand the physics : need good coordination with radio, infrared, optical and X-rays telescopes

AGN

~~From INTEGRAL to~~ e-ASTROGAM

Polarization

A key observation to distinguish between leptonic and hadronic jet models of Blazars

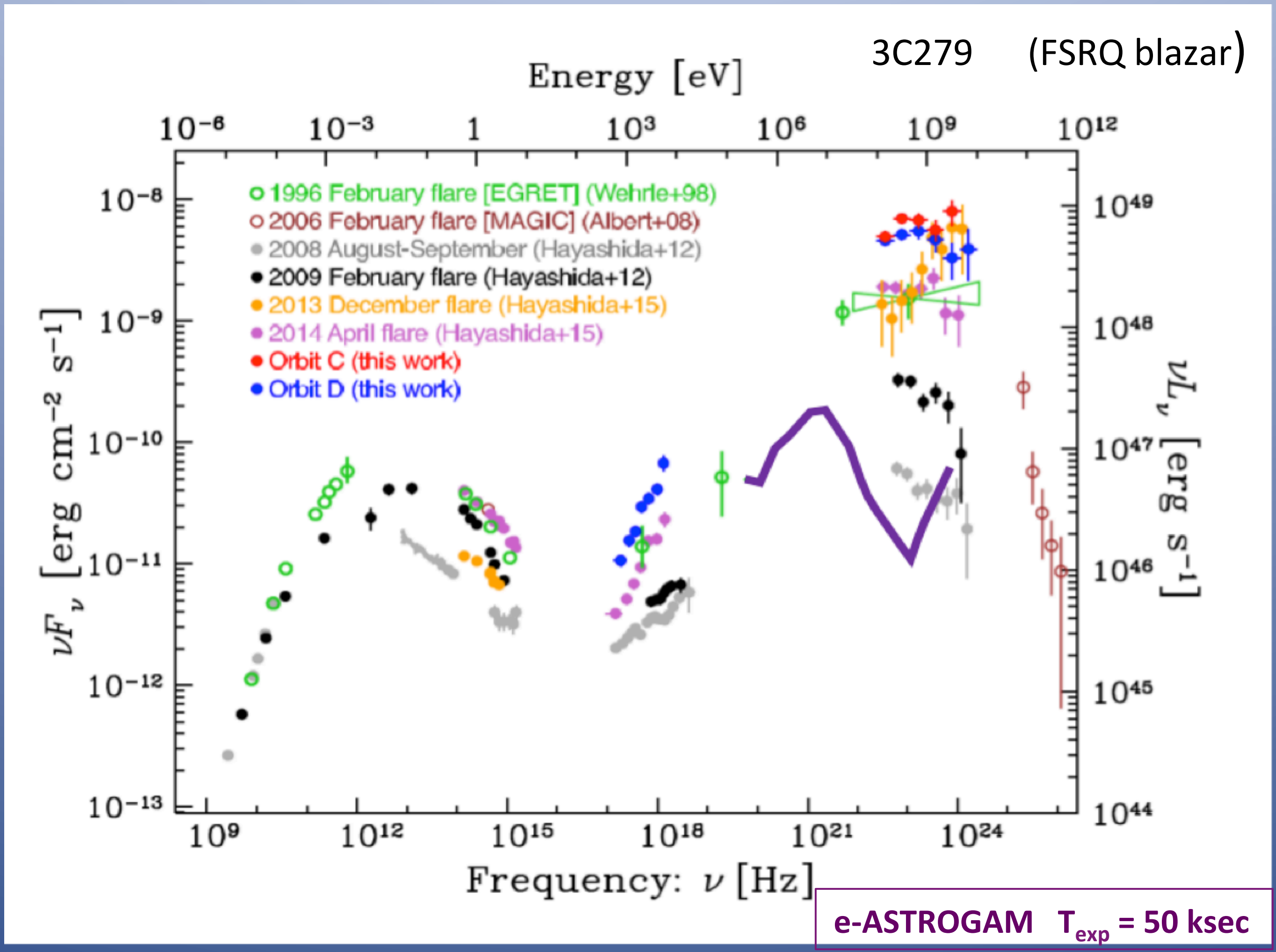


<u>Leptonic model</u> :
X-rays SSC dominated
-> Π~20-40%
γ-rays EC(accretion disk, broad-line clouds) dominated, ->
Low polarization

<u>Hadronic model</u> :
Synchrotron dominated
-> high polarization

⇒ Leptonic models predict much lower degrees (<40%) of polarization than hadronic models (70-75%)

Zhang and Böttcher, 2013



- ✓ At 1 MeV flux variation between 20 and 200 mCrab => Polarization measurement in 10 ksec
- ✓ e-ASTROGAM will be able to measure the polarization of a 100 mCrab source in 10^3 sec i.e. near the shortest time variation scale of 3C279

More recent work on the X-ray and gamma-ray polarization in the synchrotron self-Compton scenario (Zhang and Boettcher 2013)

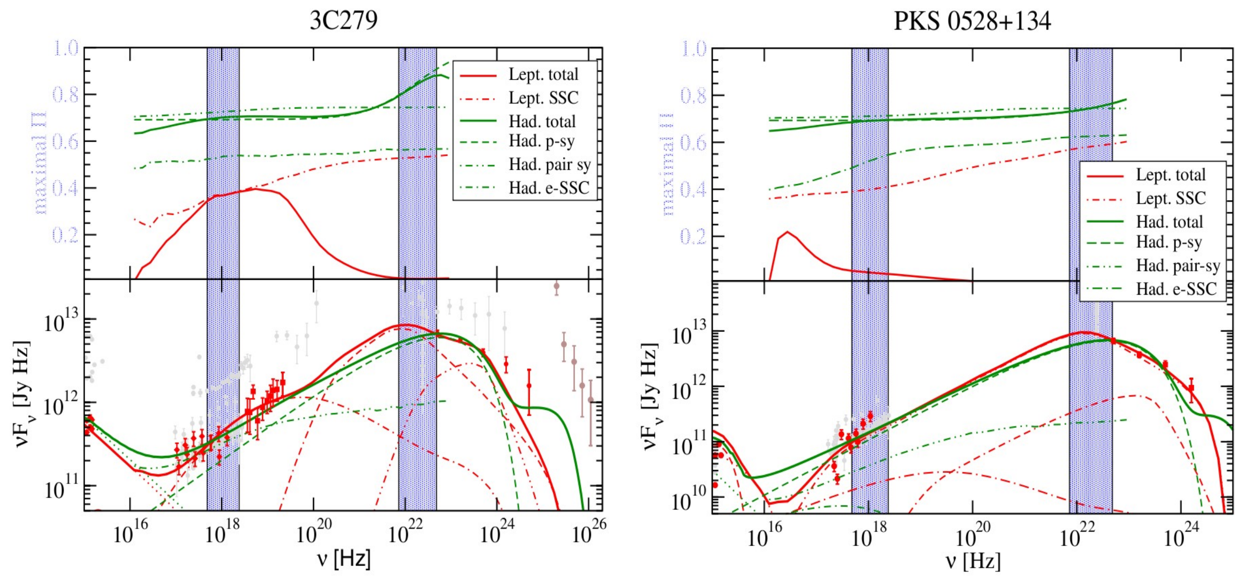


Figure 2. UV through γ-ray SEDs (lower panels) and maximum degree of polarization (upper panels) for the two FSRQs 3C279 (left) and PKS 0528+134 (right). Leptonic model fits are plotted in red and hadronic models in green. Different lines indicate individual radiation components as labeled in the legend. Shaded areas indicate the 2–10 keV X-ray range (X-ray polarimeters) and the 30–200 MeV range in which γ-ray emission may be measurable by *Fermi*-LAT.

(A color version of this figure is available in the online journal.)

- In FSRQs, X-rays and gamma-rays are believed to be generated via inverse Compton process
- Level of polarization depends on the nature of “seed” photons
- If the “seed” photons are polarized – (synchrotron > synchrotron self-Compton) – polarization is preserved, but will be somewhat diluted for a broad range of electron energies comoving in the jet (pointed out by Poutanen 1994)

FSRQ blazars: Synchrotron vs. SSC polarization angles

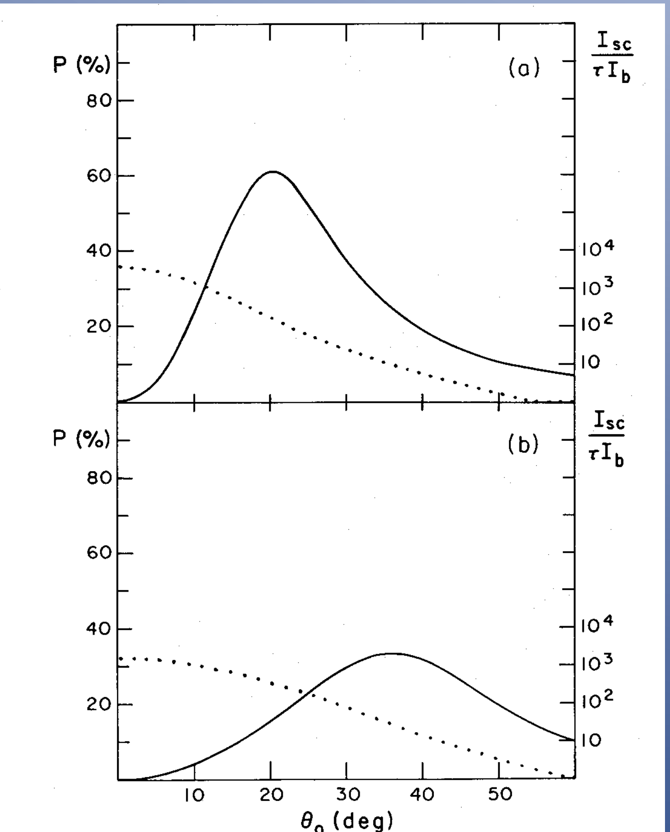
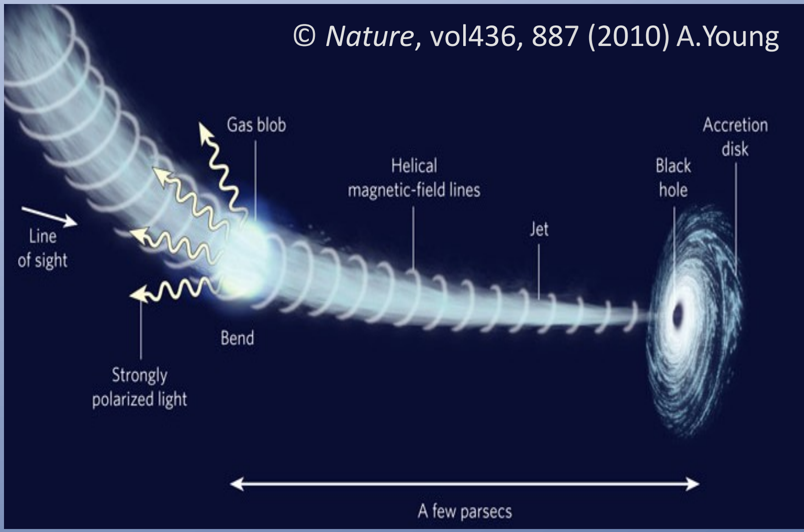


FIG. 4

Polarization angle change as the jet "swings" across the line of sight



- Best scenario has FSRQ X-rays originating via the SSC process

* If the "seed" photons are polarized – (synchrotron > synchrotron self-Compton) – polarization is preserved

- Angle of synchrotron and SSC polarization should be the same

- Angle of polarized synchrotron (optical) and SSC (X-ray) polarization should follow each other (prediction)

* "Swings" should appear in both bands: multi- band, simultaneous observations crucial!

See Madjeski and Sikora, ARAA, 2017

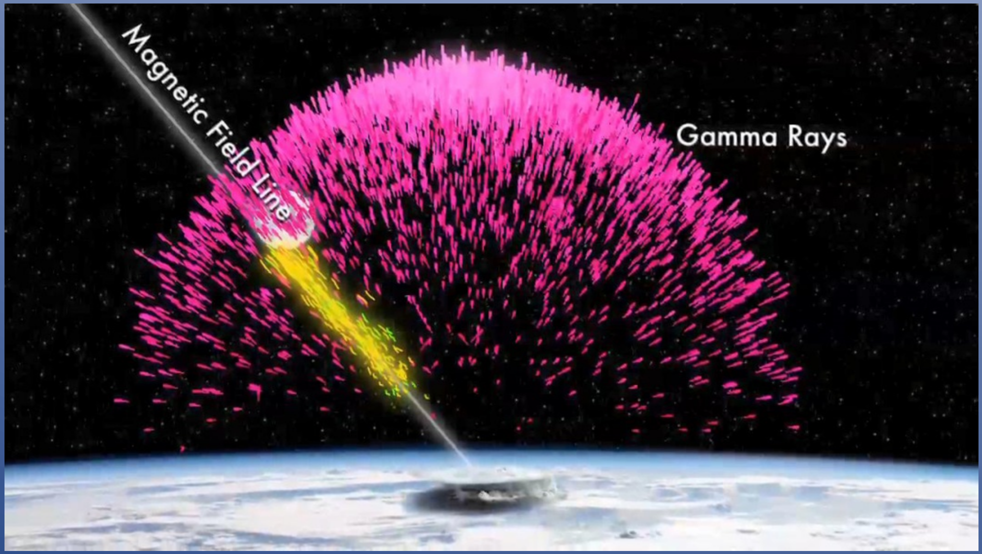
~~From INTEGRAL to~~ e-ASTROGAM

- X-ray / γ-ray polarization <u>predictions</u>: depends on the radiation process
  - ✓ synchrotron: strong polarization, probably same angle as optical (X-rays in HBL-type blazars)
  - ✓ inverse Compton: if seed photons unpolarized – probably no polarization (g-rays in FSRQs)
  - ✓ inverse Compton: if seed photons are polarized – strong polarization, same angle as synchrotron, same swings (X-rays in FSRQs)
- If γ-rays are strongly polarized and pol. angle not related to polarization of synchrotron emission – would point to γ-rays being produced by synchrotron process, much closer to the black hole (suggested for 3C279 flare)
- At 1 MeV flux variation between 20 and 200 mCrab => Polarization measurement in 10 ksec reachable
- e-ASTROGAM will be able to measure the polarization of a 100 mCrab source in 10^3 sec (i.e. near the time variation scale of 3C279 ~ 5min)
- Prove or disprove leptonic/hadronic model

Terrestrial γ-ray flashes (TGFs)

TGFs : millisecond bursts of gamma-rays produced by electrons accelerated upwards to energies of tens of MeV or more.

e-ASTROGAM may discover γ-ray polarization from Terrestrial γ–ray flashes (TGF). γ–ray are thought to be produced from accelerated electrons by Bremsstrahlung. If they are Compton scattered on the atmosphere afterward $\Rightarrow$ polarization



Note: instruments designed specifically to study TGFs are today in flight or in preparation (TARANIS, ASIM, ..) $\Rightarrow$ promising field

Conclusions

- INTEGRAL : gamma-ray polarimetry on bright sources possible with INTEGRAL/IBIS used in Compton mode
  - Results on Crab (possible time variations of polarization)
  - Results on XRBs, GRBs
  - Studies of these classes of objects are going on
  - Collaboration with Astrosat
  - We have settled active collaborations in optical (GASP), radio (Nançay) and in NIR (Subaru in Hawaii)
  - Long term program (IBIS/Compton catalog)

- e-ASTROGAM : good/new polarimetric capabilities in hard X-rays/low gamma-ray/high energy (?)
  - Detailed studies of pulsars, PWN, XRB, GRB, AGN ,SN …
  - Larger spectral coverage, shorter time scale studies
  - SKA, CTA, E-ELT, LSST, GW, Neutrino observatories…
  - Fundamental physics (LIV)
  - Atmospheric physics (TGFs)
  - Catalog of high energy polarized sources (> 45 Comptel sources)