Change in hard X-rays and optical polarization of the Crab nebula and pulsar

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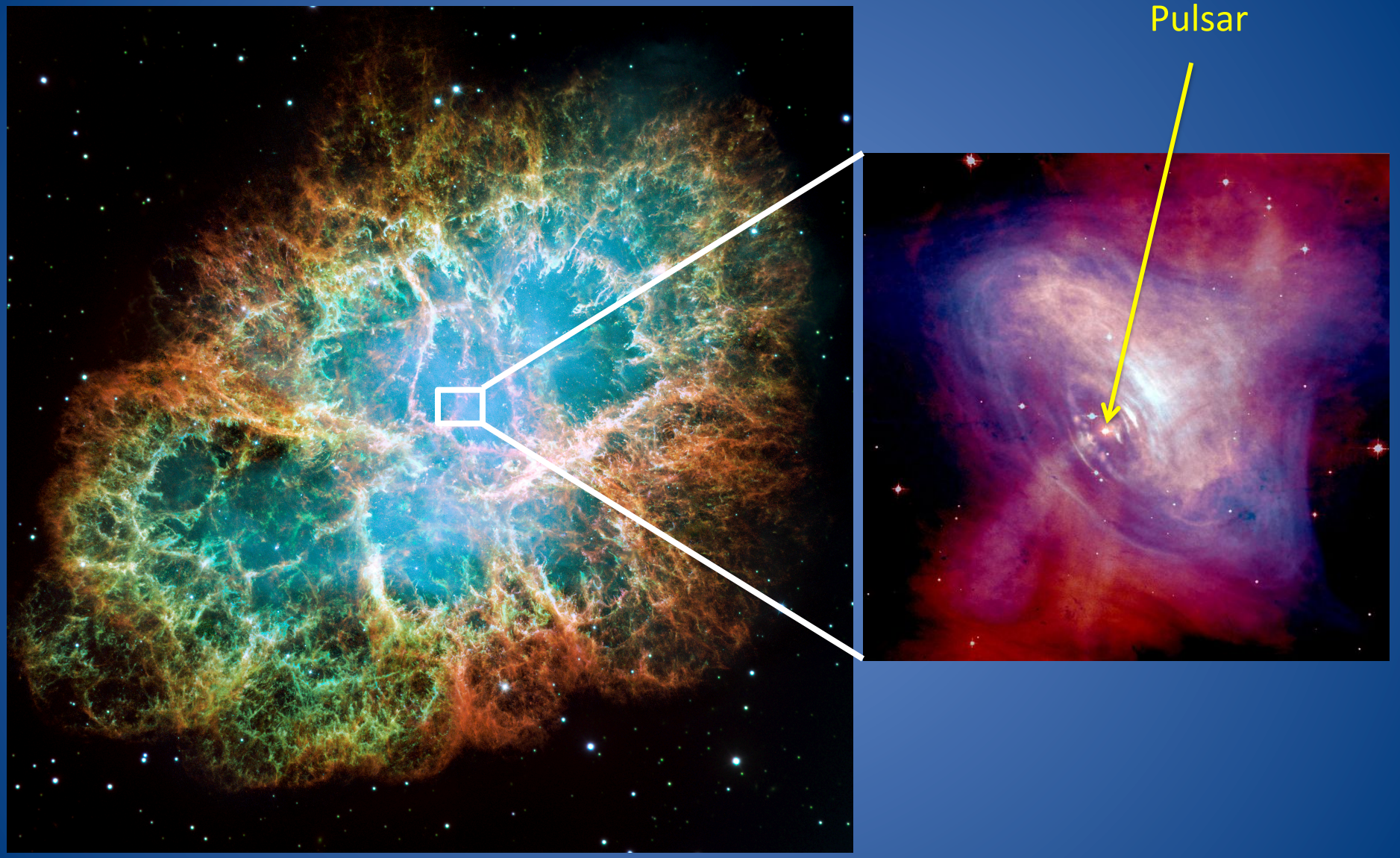
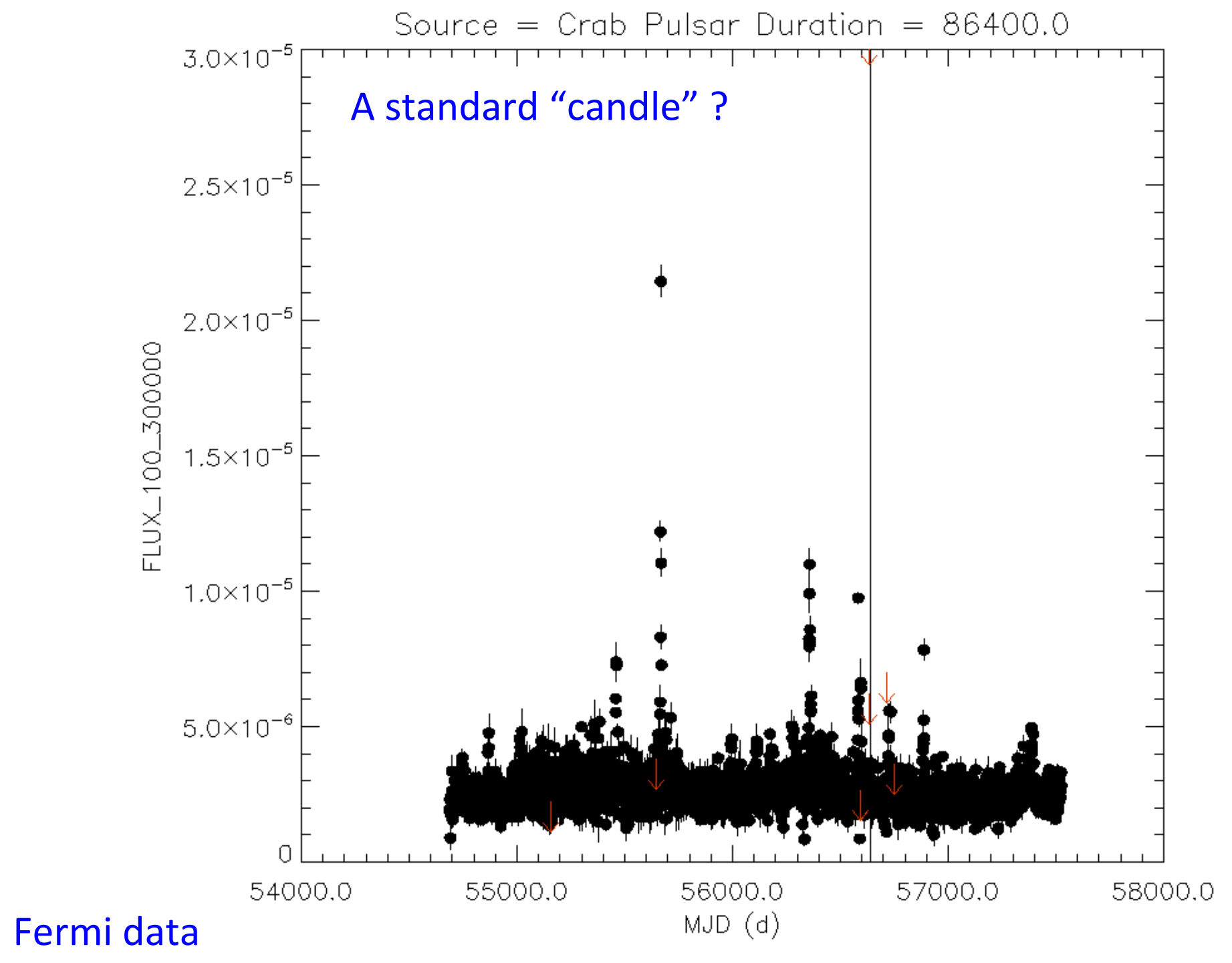
The Crab Nebula and Pulsar



Useful number : at distance = 2kpc, 1”= 0.009 pc = 2000 au = 3 10^{16} cm


Source = Crab Pulsar Duration = 86400.0
A standard “candle” ?
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

Polarimetry

a powerful tool after imaging, spectroscopy and timing

- related to many radiation processes (synchrotron, curvature, etc)

- can provide extra information to discriminate among different models

  - Solar flares
  - GRBs (prompt emission, afterglow)
  - X-ray binaries (disc, corona, jets)
  - AGNs
  - Cosmic background radiation
  - FRBs (fast radio burst)

  - Pulsars : information of the magnetic environment, radiation emission processes, models) (see G. Voisin's talk yesterday : no polarization from curvature radiation with quantum-electrodynamics treatments, yes otherwise).

Recent window in the high energy domain when mature in radio and optical

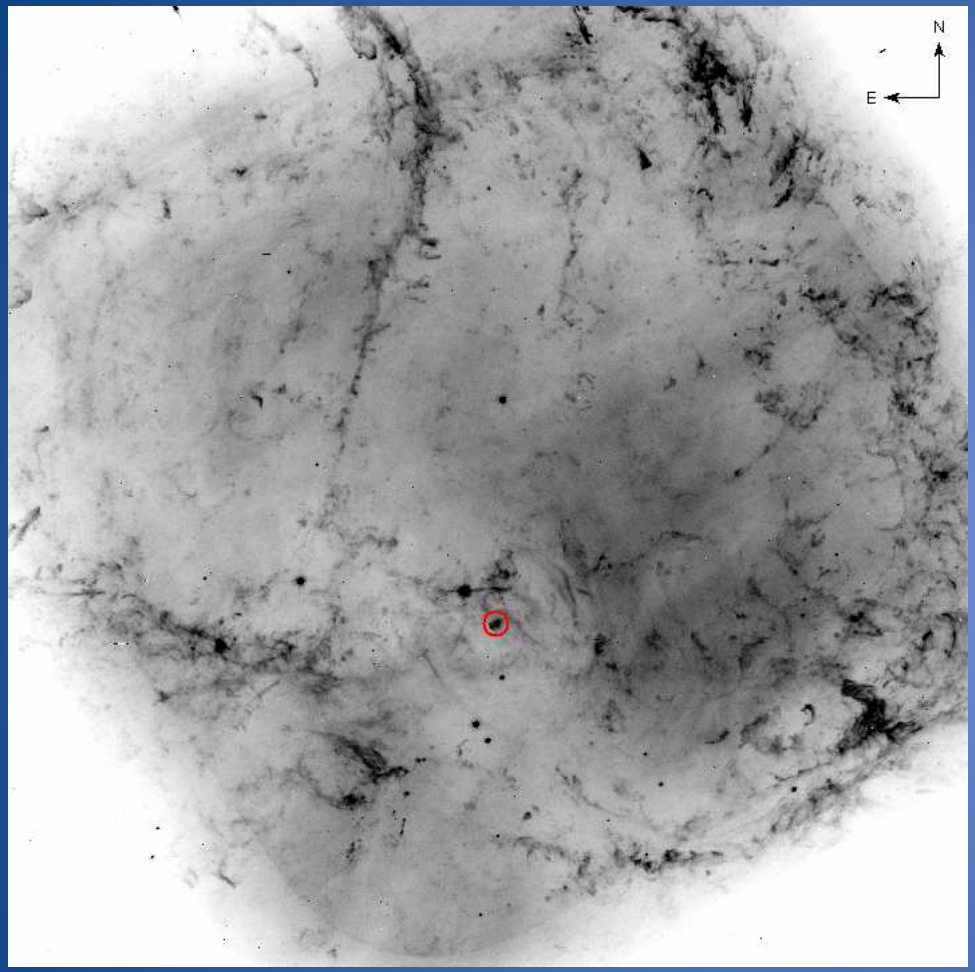
Polarization of the Crab nebula/pulsar system

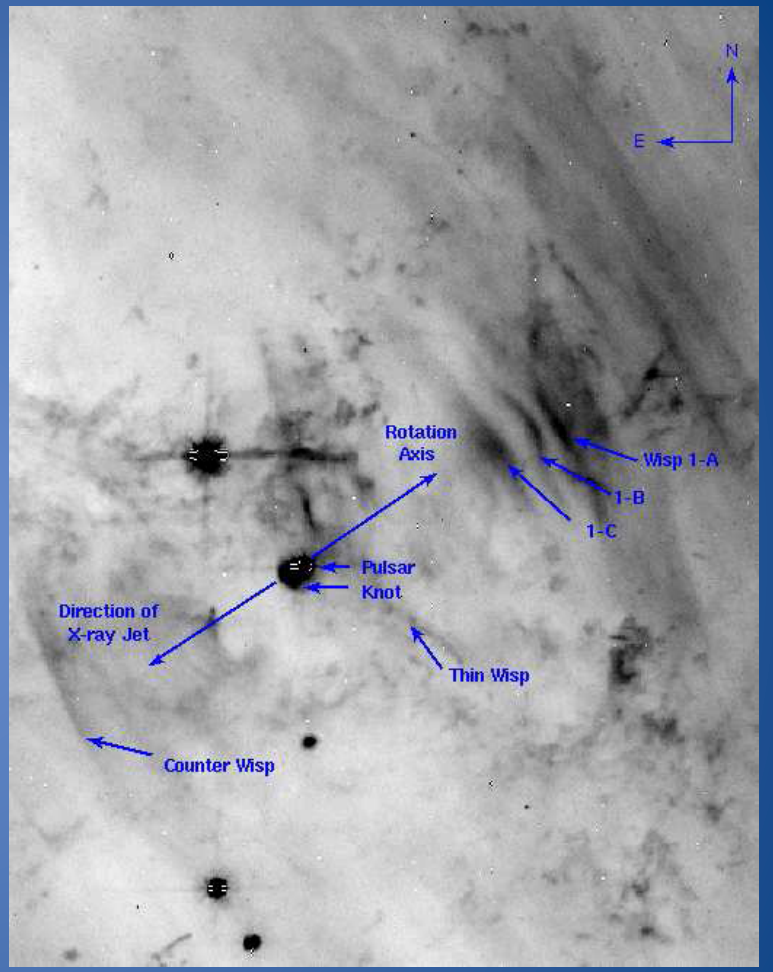
1/ Optical view : HST and GASP

2/ Hard X-rays view : INTEGRAL

3/ On-going work and perspectives

Optical Polarimetry of the Crab Nebula & Pulsar : HST data





- Observations of nebula with HST/ACS (0, 60 & 120^0) September – December 2005
- Why Polarisation? Constrain emission models

Moran et al, 2013

Optical Polarimetry of the Crab Nebula & Pulsar

- Measured the degree of linear polarisation (%) and position angle (°) of the pulsar, knot, and wisps
- Used IMPOL software (Walsh 1999) to map polarisation of inner nebula
- Aperture photometry for count rates of targets in each polariser: r (0), r (60), r (120)
- Count rates ⇒ Stokes parameters ⇒ Polarisation

$$I = \frac{2}{3}\,[r(0) + r(60) + r(120)]$$

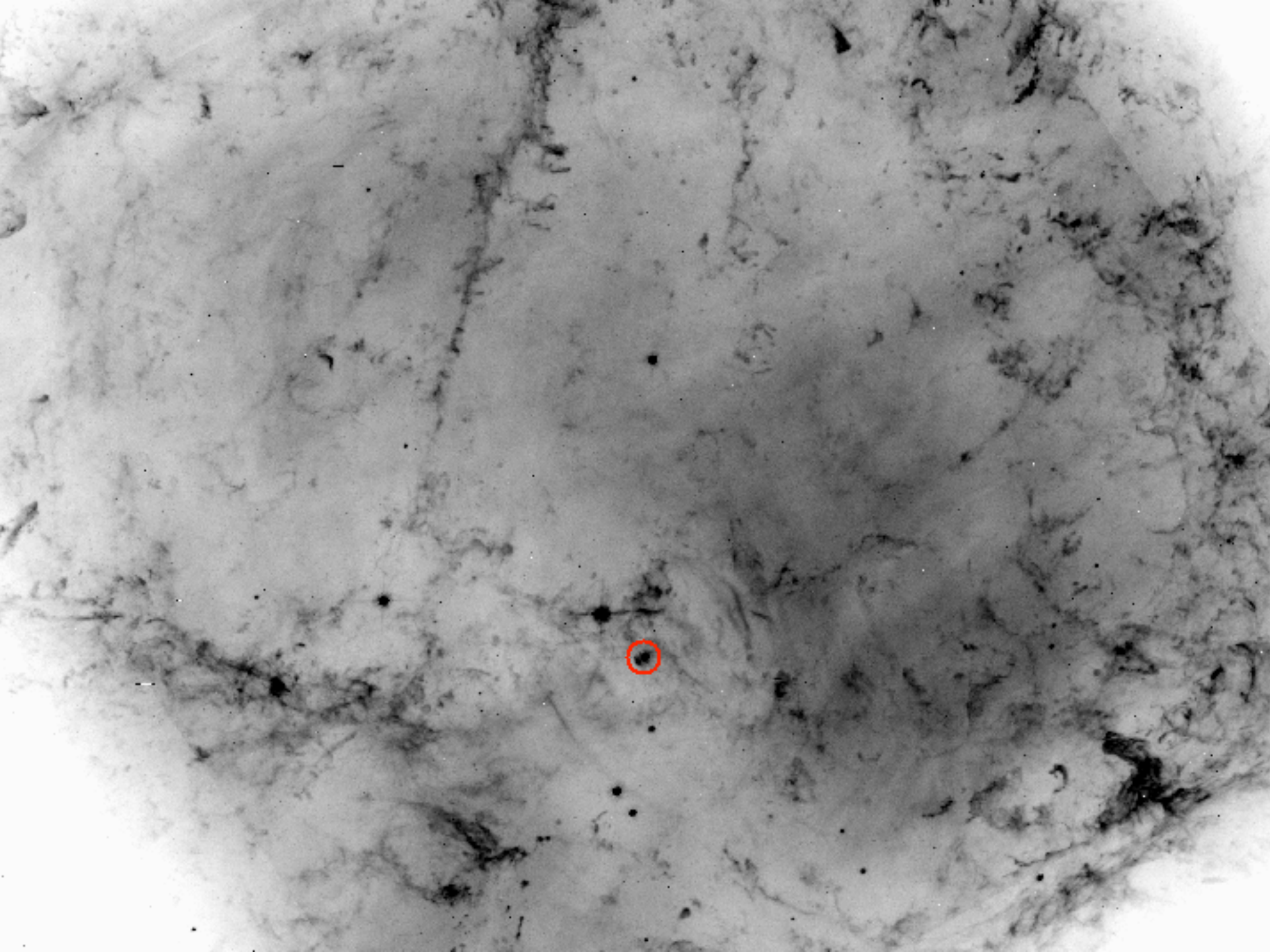
$$Q = \frac{2}{3}\,[2r(0) - r(60) - r(120)]$$

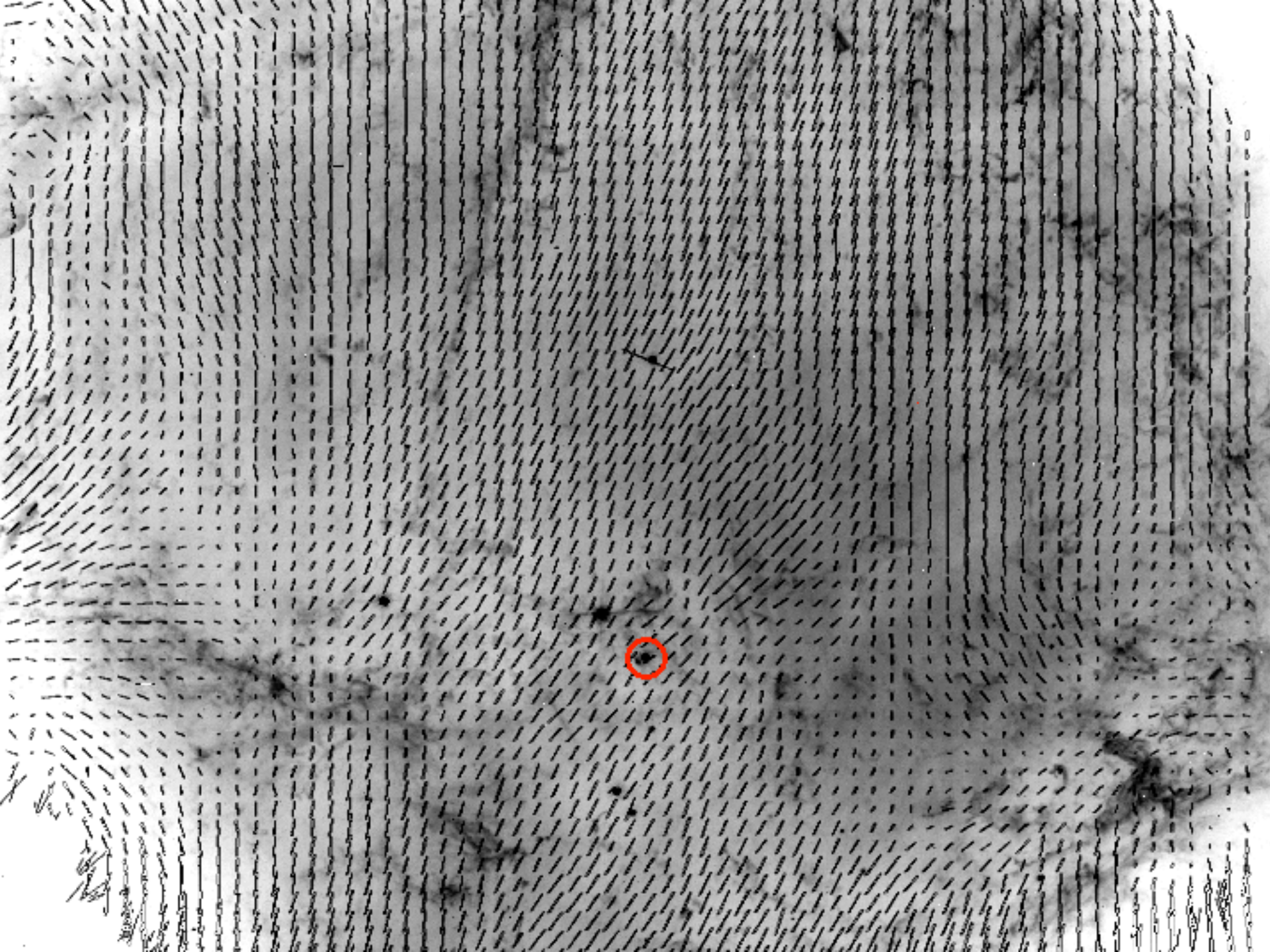
$$U = \frac{2}{\sqrt{3}}\,[r(60) - r(120)]$$

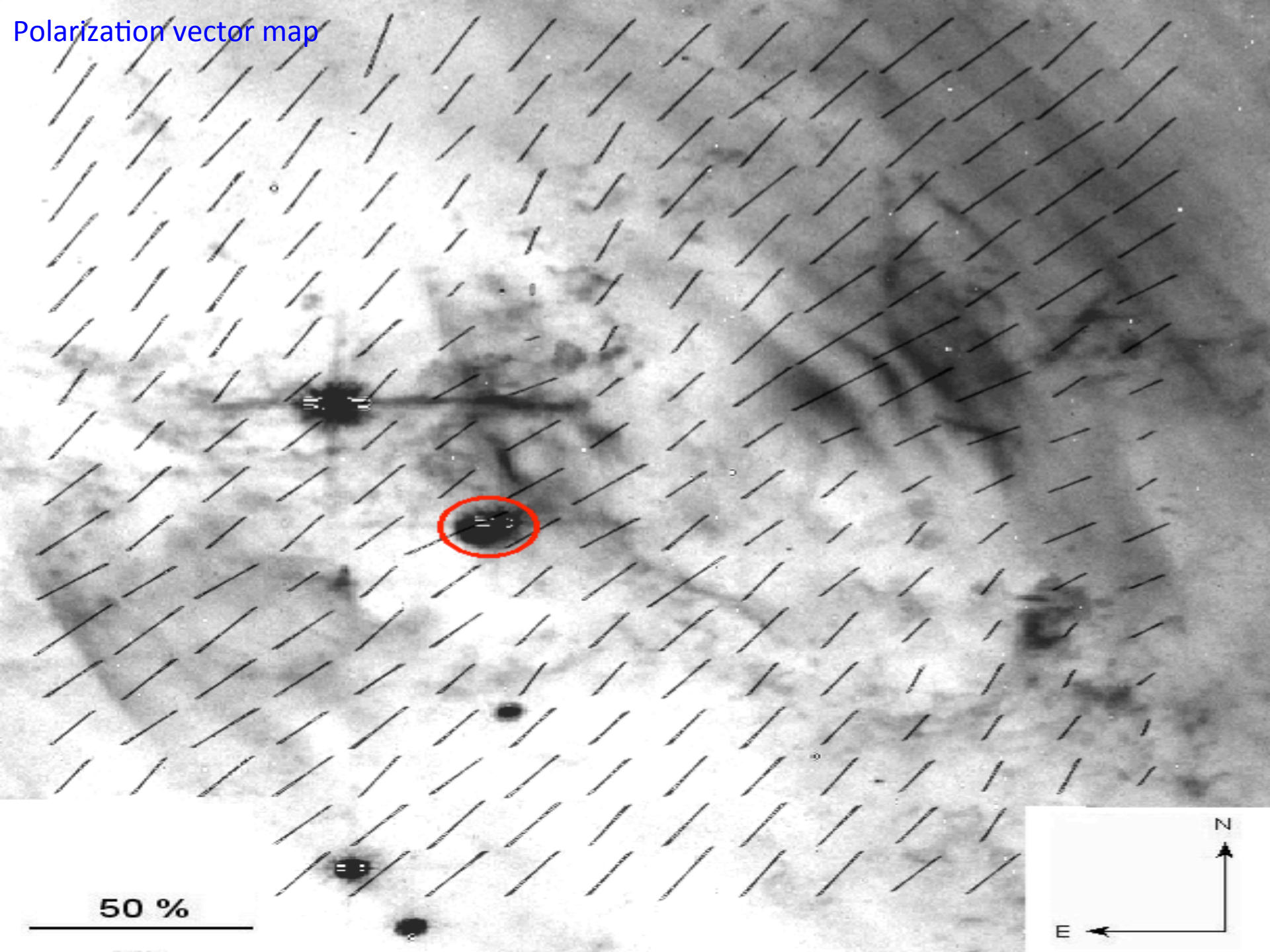
$$\mathrm{P.D.} = \frac{\sqrt{Q^2 + U^2}}{I}\,\frac{T_{par} + T_{perp}}{T_{par} - T_{perp}} \times 100$$

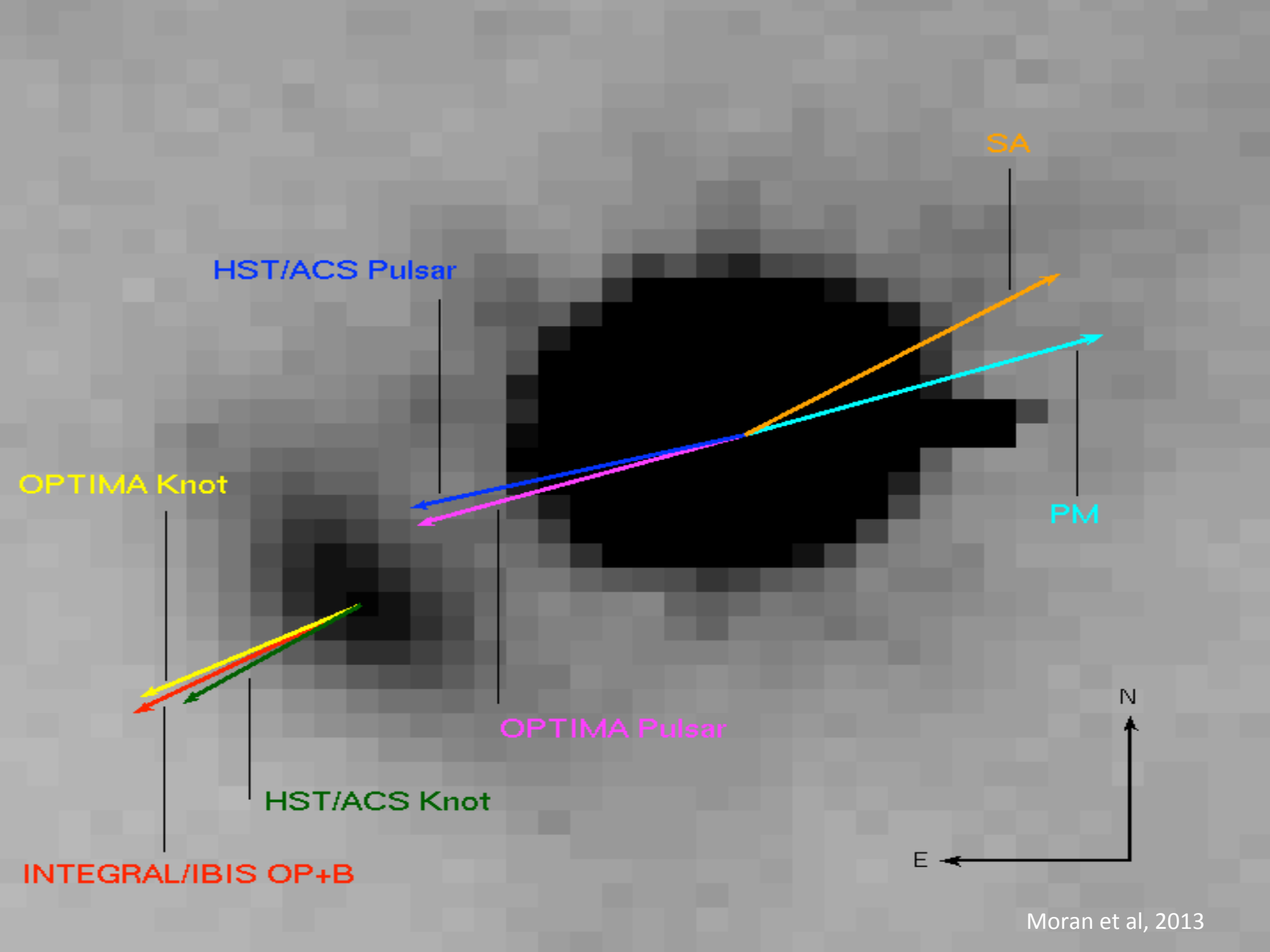
$$\mathrm{P.A.} = \frac{1}{2}\,\tan^{-1}\left(\frac{U}{Q}\right) + \mathrm{PA\_V3} + \chi$$

Moran et al, 2013





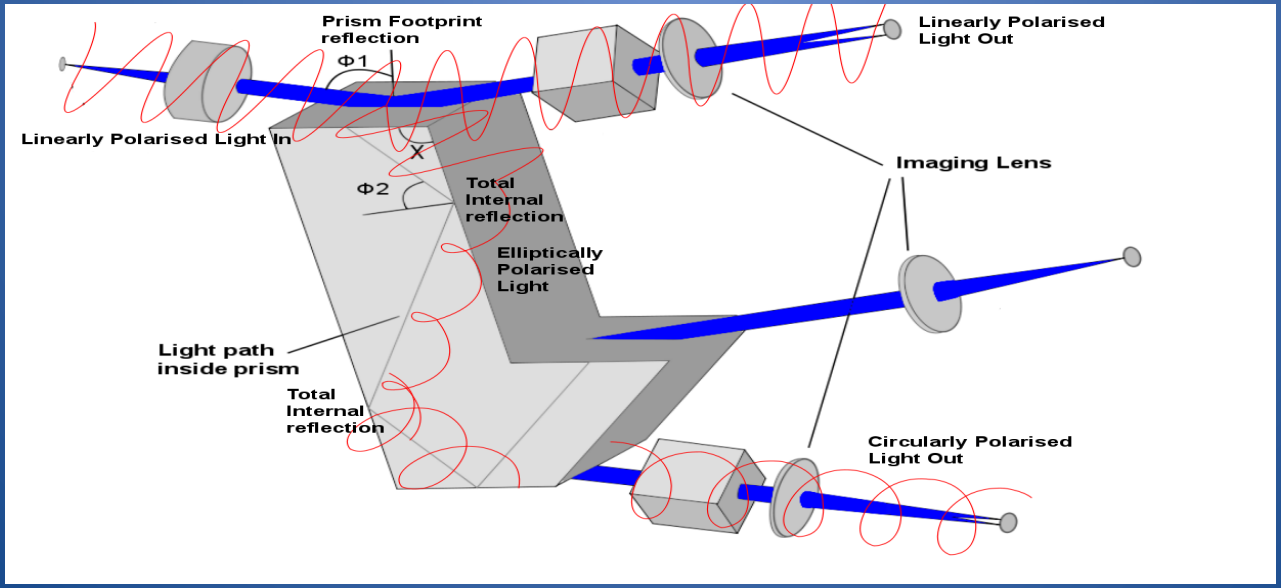

Polarization vector map
50 %
N
E



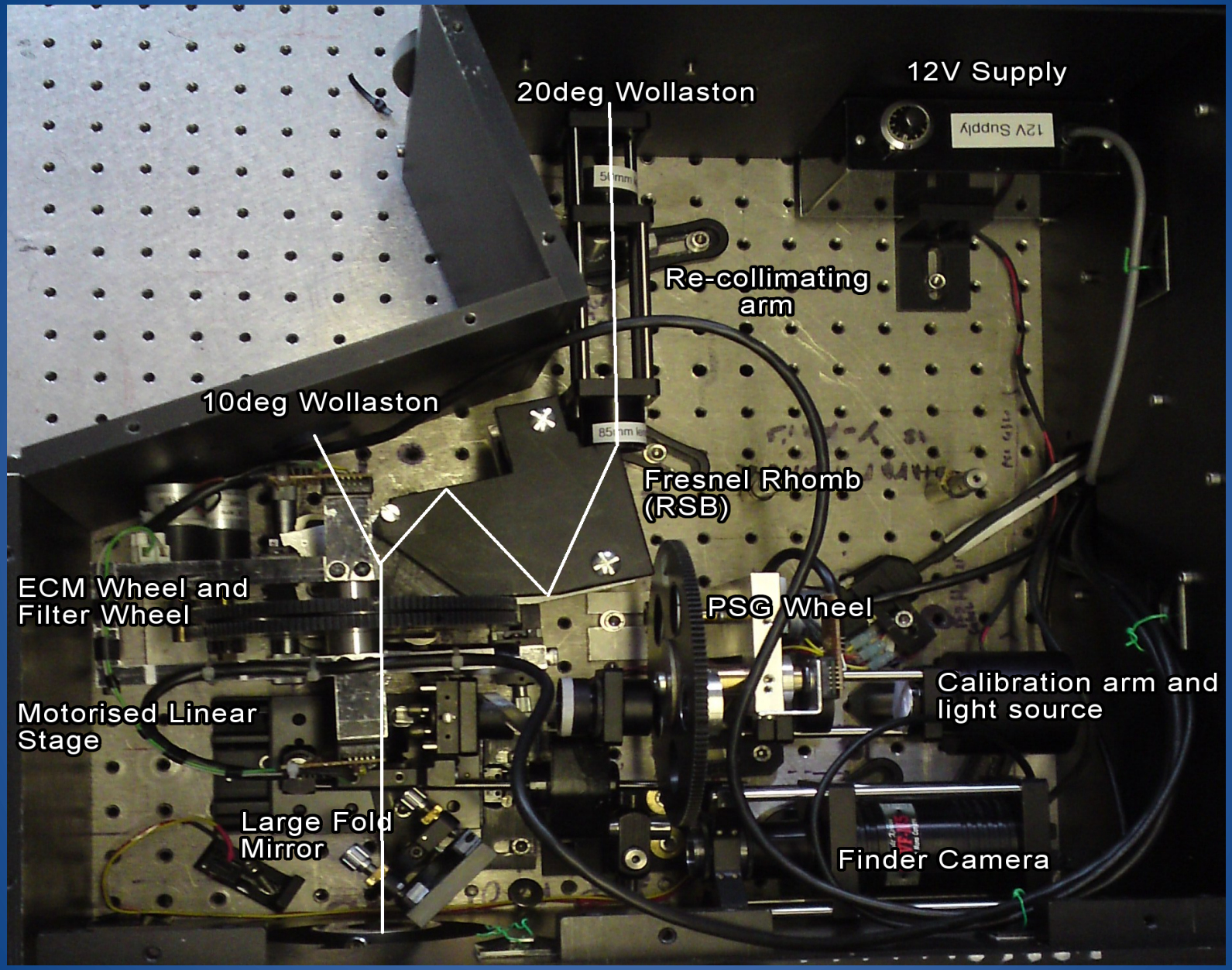
Moran et al, 2013

Optical Polarisation with the Galway Astronomical Stokes Polarimeter (GASP)

- 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)



GASP Instrument and system

Palomar, 5 meter telescope

GASP observation in 2012, November

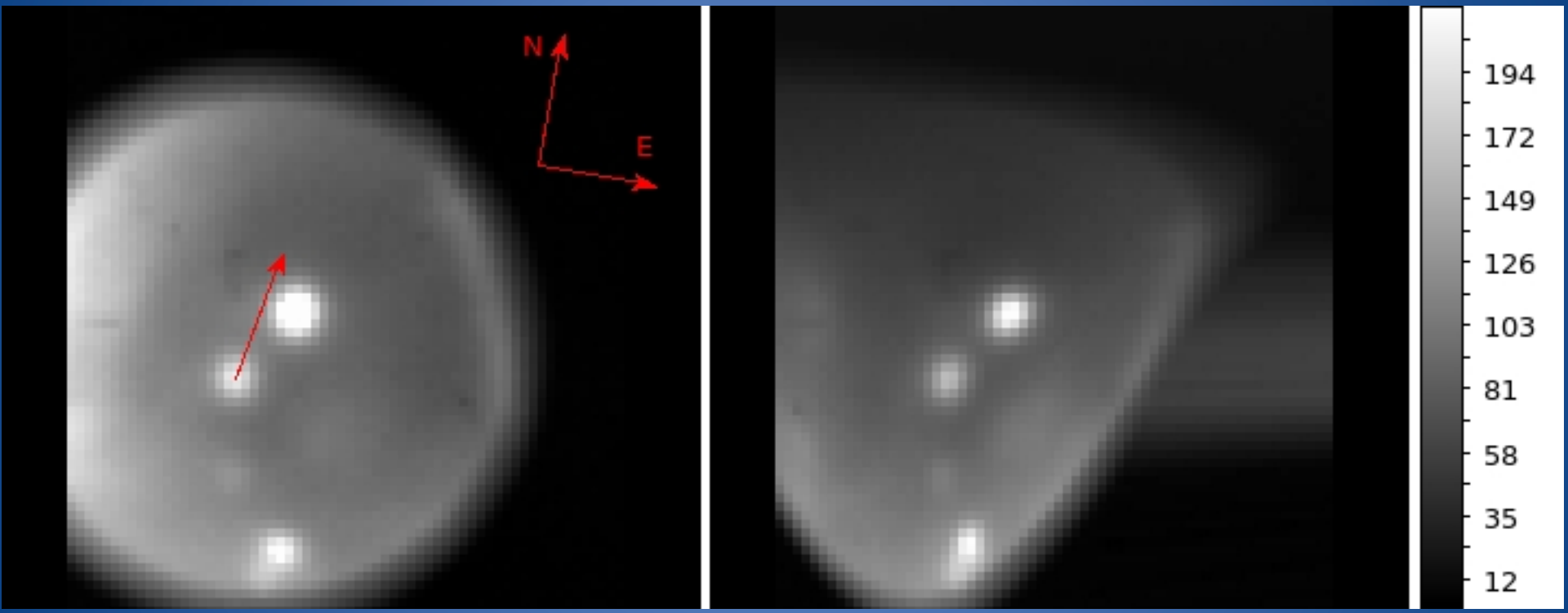

N
E
194
172
149
126
103
81
58
35
12

Table 2. Summary of the multi-wavelength polarimetry of the Crab nebula and pulsar.

Waveband	Instrument	Observation Year	Component	Polarization (%)	Position Angle (°)	Reference
γ-ray	Integral/IBIS	2003-07	Phase-avg[a] 300-450 keV	96±34	115±11	[1]
γ-ray	Integral/IBIS	2012-14	Phase-avg 300-450 keV	98±37	80±12	[1]
Optical	RGO-PP/INT	1988	Phase-avg	9.8	117	[2]
Optical	HST/ACS	2005	Pulsar	5.2±0.3	105.1±1.6	[3]
Optical	HST/ACS	2005	Knot	59.0±1.9	124.7±1.0	[3]
Optical	HST/ACS	2005	Pulsar+Knot	7.7±0.1	109.5±0.7	[1]
Optical	GASP/Hale 200″	2012	Pulsar+Knot	9.6±0.5	85.3±1.4	[1]
Optical	GASP/Hale 200″	2012	Pulsar+Knot (circular pol.)	-1.2 ±0.4	-	[1]

[a] The phase-avg refers to the average polarization over many pulsar rotations

Reference: [1] This work, [2] Smith et al. (1988), [3] Moran et al. (2013)

Table 3. Optical polarimetry of the Crab pulsar and knot field of view. The F606W filter corresponds to $\lambda = 590.70$ nm and $\Delta\lambda = 250.00$ nm.

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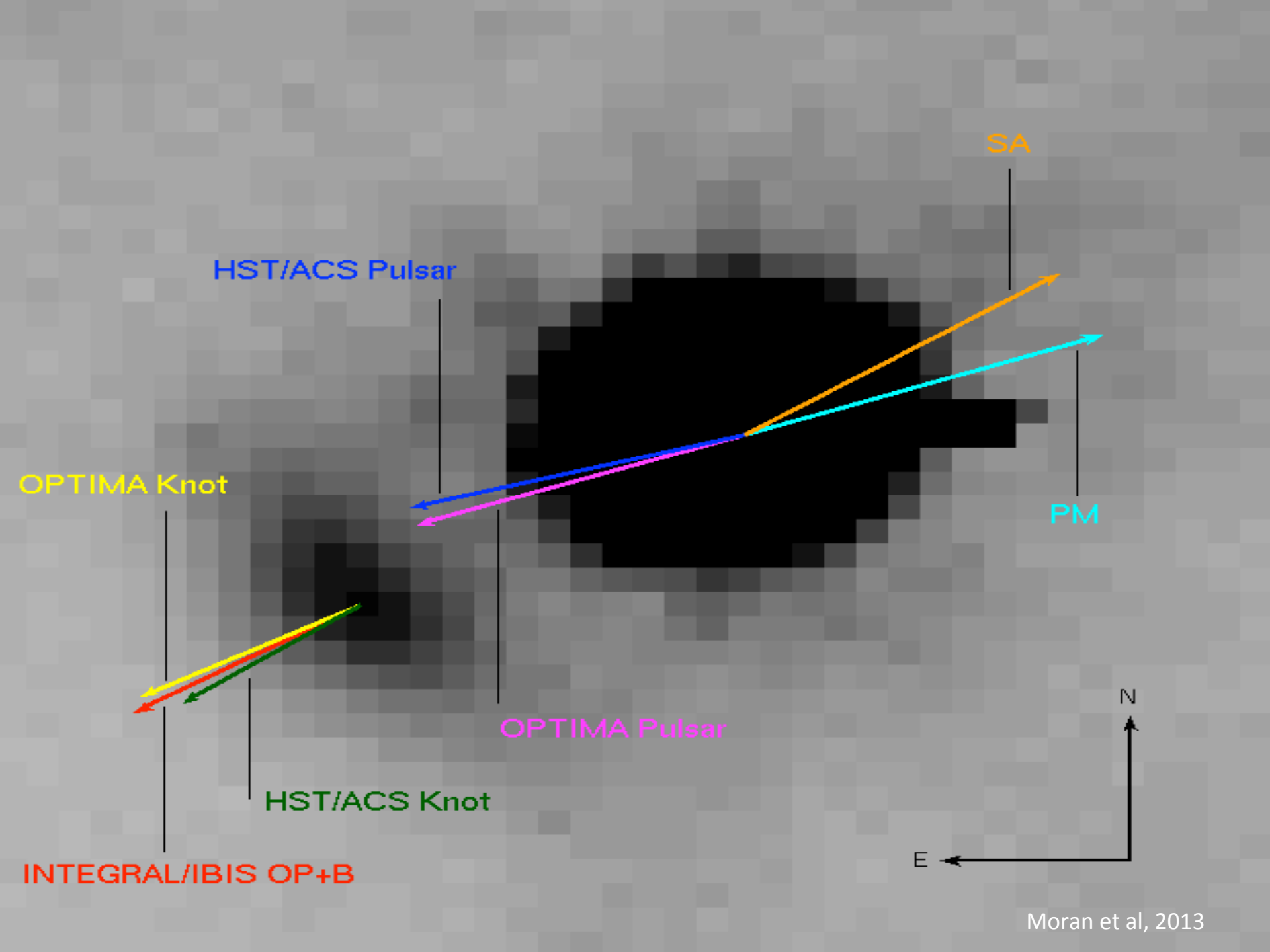
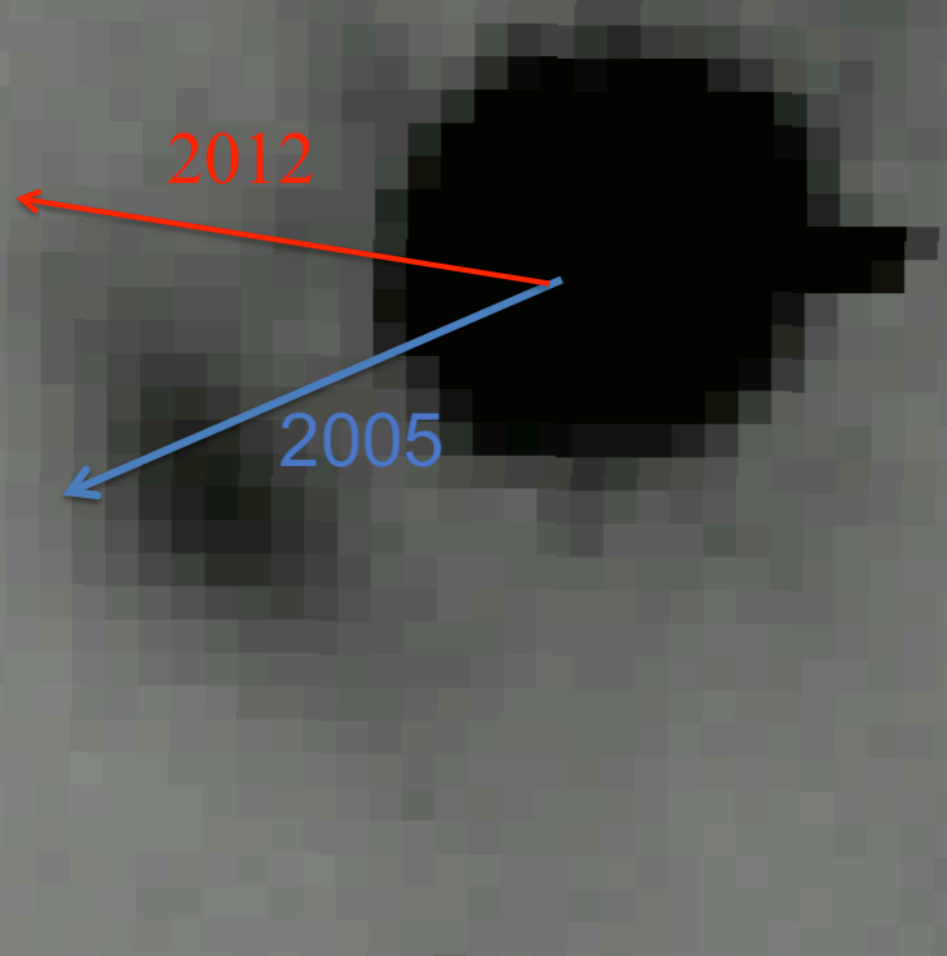
Trimble 28	GASP/Hale 200″	2012	R	6.5±0.3	60.9±2.7	This work

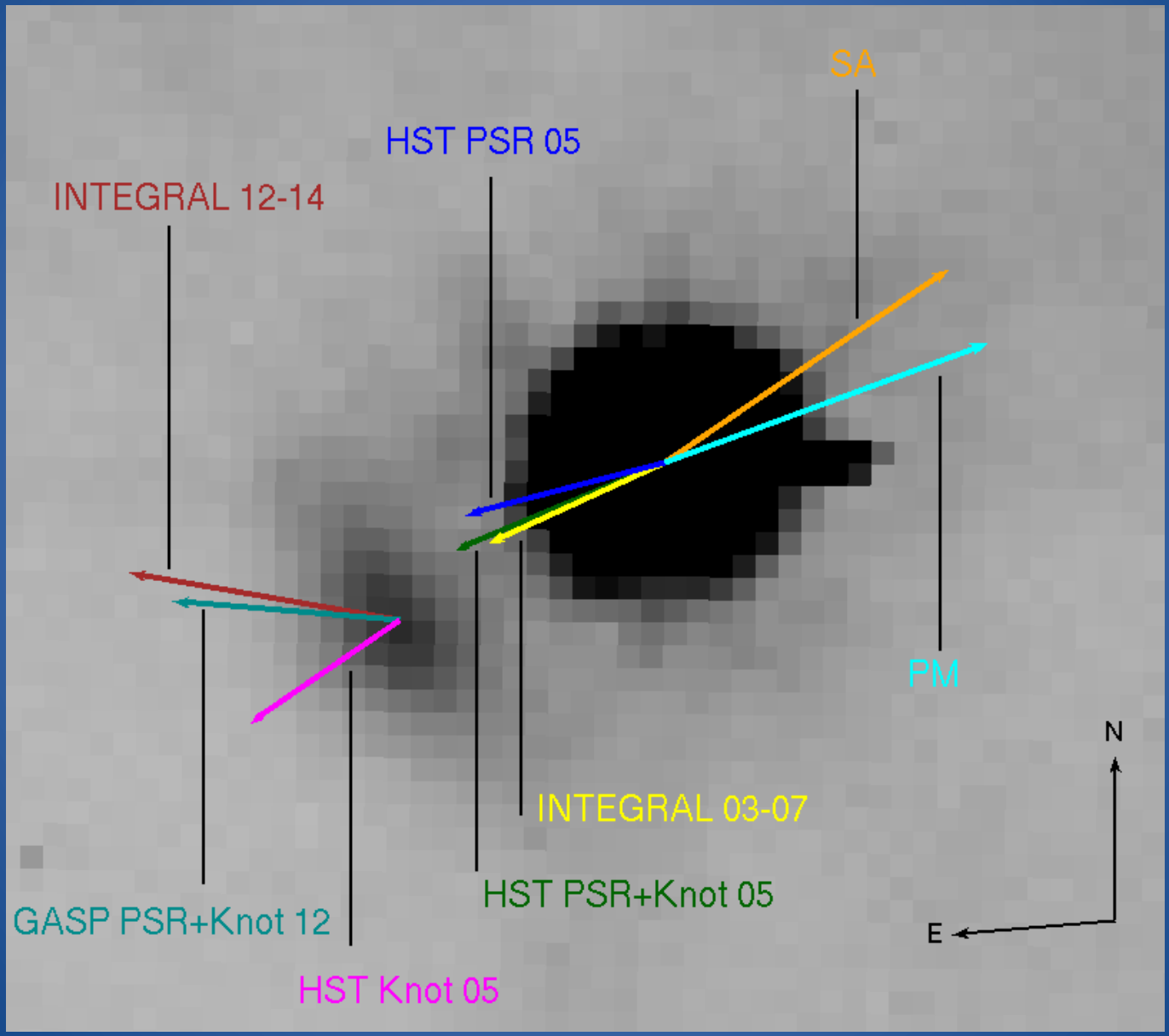


Moran et al, 2013

Result (Optical)



Optical + Hard X-rays



INTEGRAL (International Gamma-ray Astrophysics Laboratory)

- Launched 17th October 2002

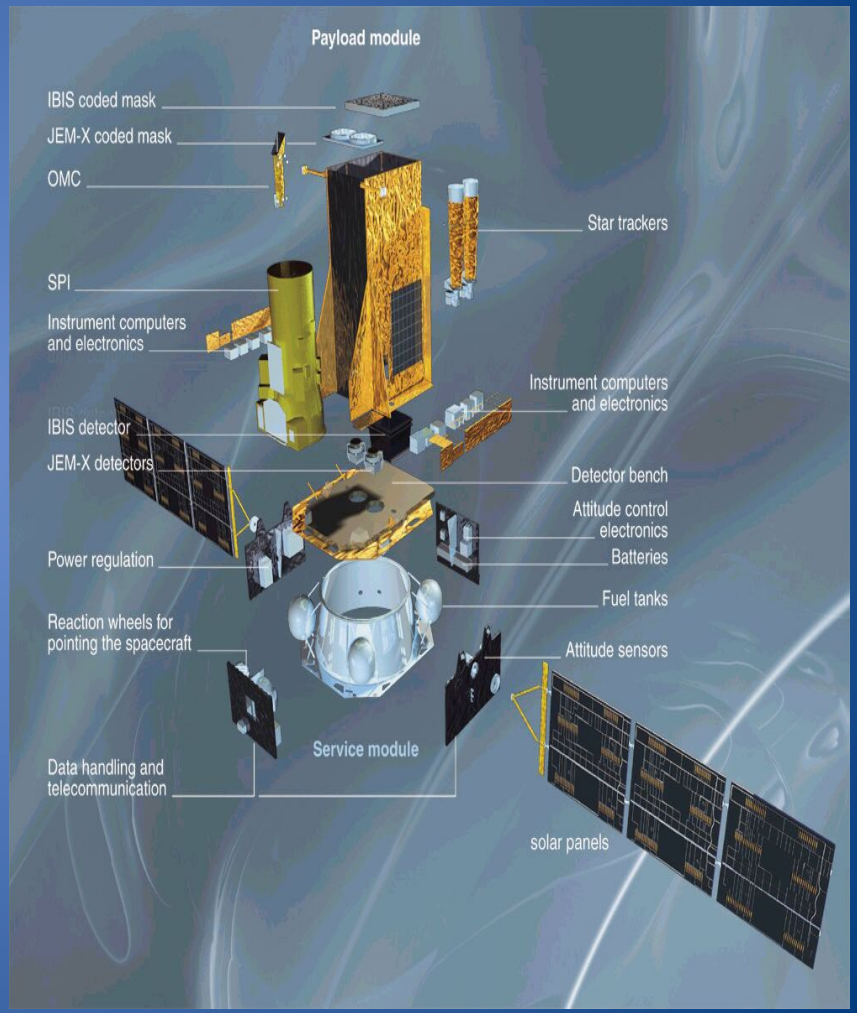
- Operational lifetime: 10+ years
  (at least December 2016)

- 4 Science Instruments:

  - SPI (Spectrometer on Integral)
  - IBIS (Imager onboard Integral Satellite)
  - JEM-X (Joint European X-ray Monitor)
  - OMC (Optical Monitoring Camera)

- Scientific Cases:

  - AGN & Black Holes
  - X-ray Binaries
  - Neutron Stars
  - Gamma-ray Bursts
  - Galactic Centre & Nucleosynthesis



IBIS (Imager on Board the INTEGRAL Satellite)

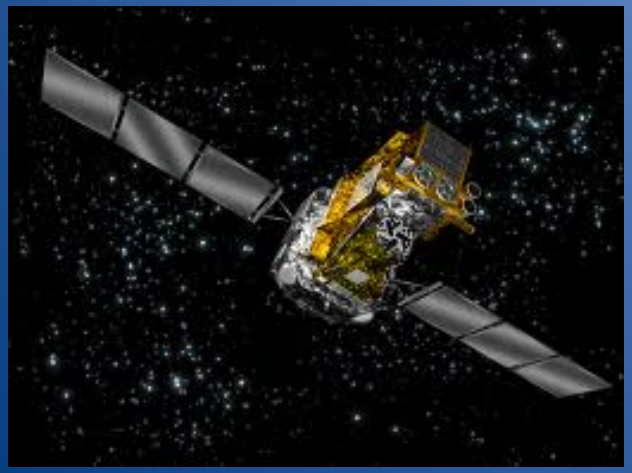
- Gamma-ray imager with two detector layers:

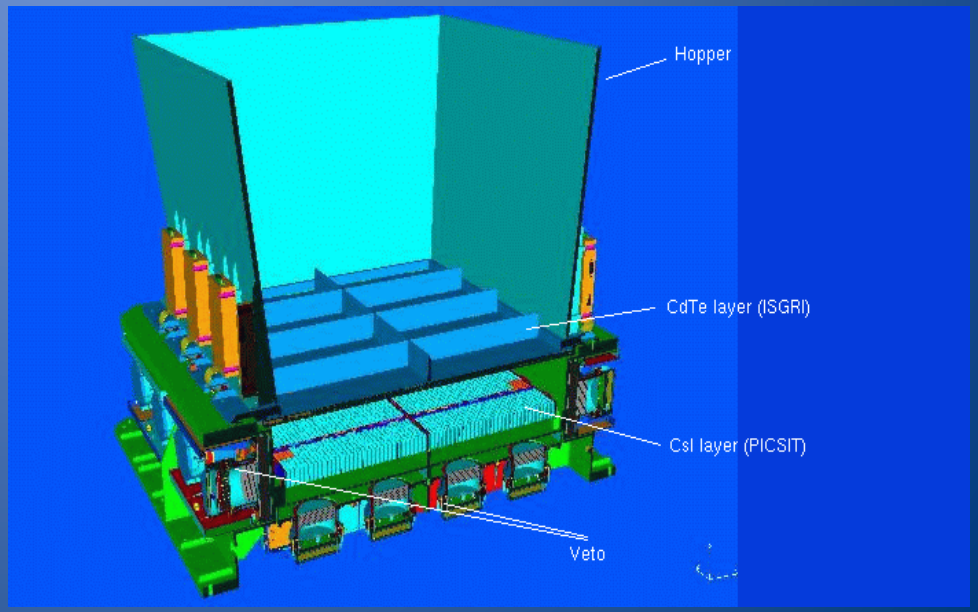
  ISGRI (Integral Soft Gamma-Ray Imager)
  - semi-conductor, CdTe, 2600 cm² (18 Kev – 1 MeV)

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

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

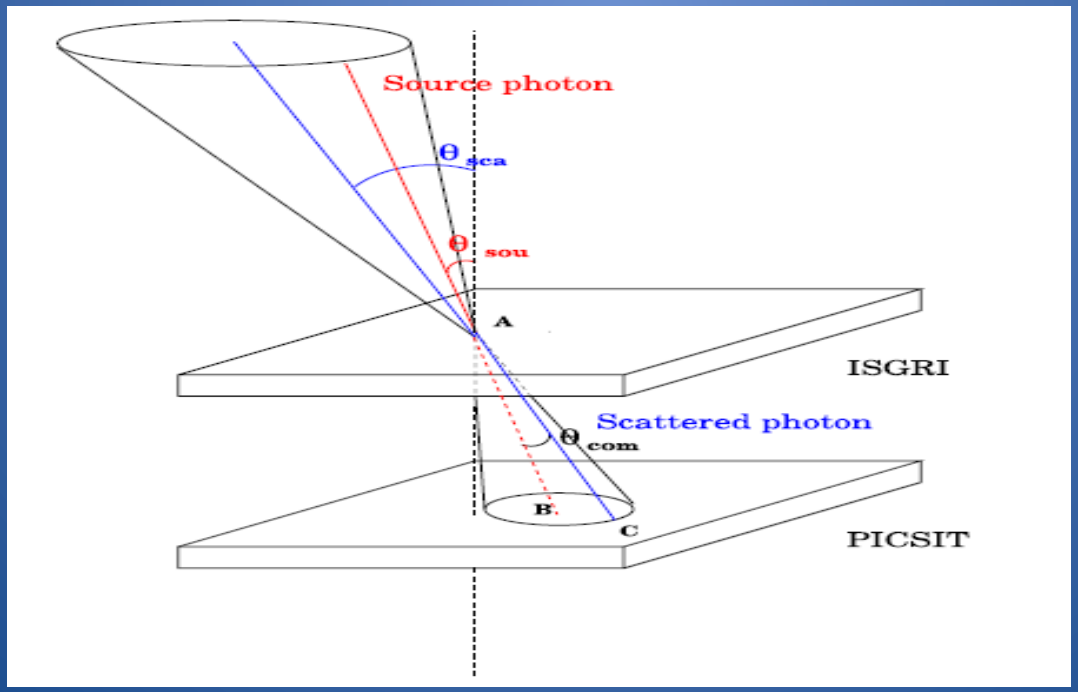
- Angular resolution (FWHM) = 12'



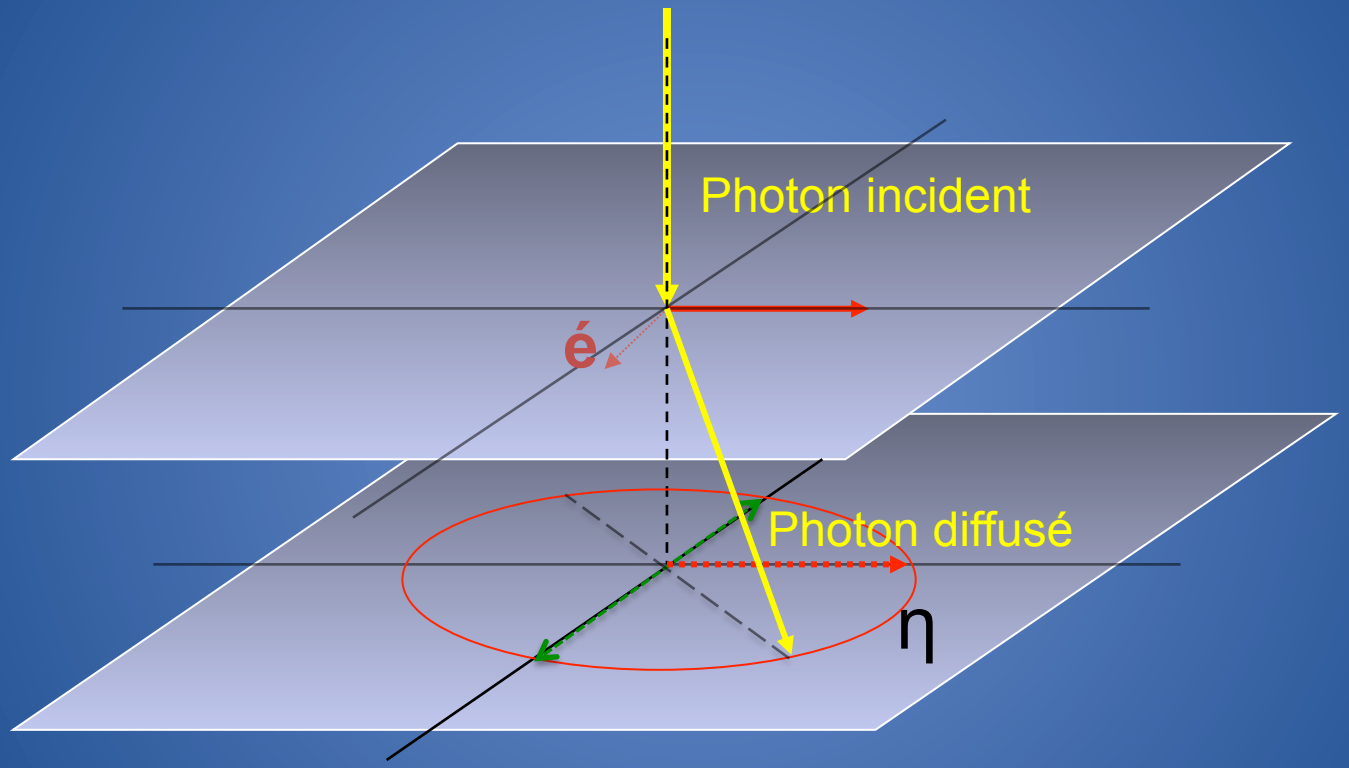


Polarimetry: IBIS Compton mode

- Compton Scattering of photons between ISGRI & PICsIT:
  - "*Compton Events*" temporal coincidences within 3.8 µs
  - "Spurious Events" chance coincidences within this window
  - Events: Background 92%, Spurious 6%, Source 2%
  - Polarimetry inferred from Scattering azimuth



The IBIS/Compton telescope



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

IBIS Compton mode advantages

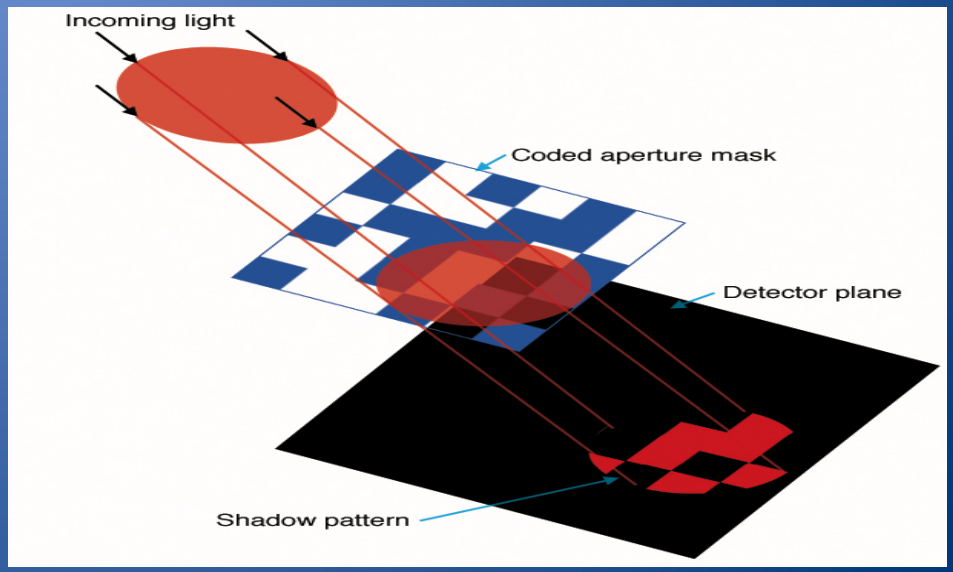
- Utilises abilities of both a coded mask and Compton telescope:

  - Reconstructs sky images

  - High angular resolution

  - Very low background (~ 90 count/s)

  - Use Compton kinetics to further reduce background, by selecting events coming only from coded mask FOV



Data: Observations & Analysis

- Continuation of work done by Forot et al. 2008, Moran et al. 2013 (Integral conference).
- Use Jodrell Bank ephemeris for pulsar phase-folding
- Event selection (energy range, pulse phase)
- Spurious events correction
- Uniformity correction
- Coded mask deconvolution

Compton polarimetry principles

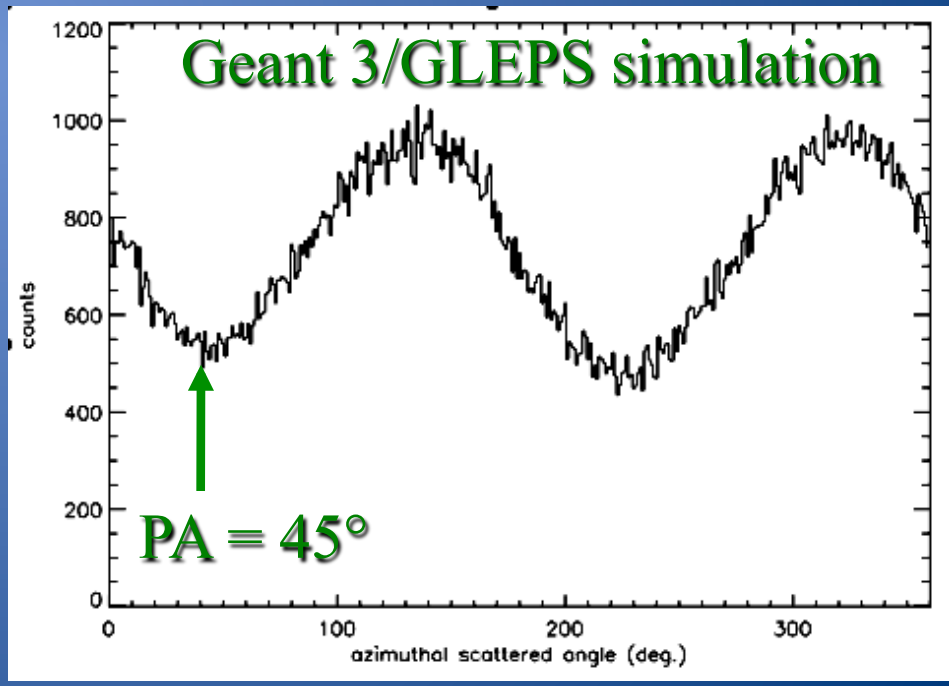
Compton scattering cross section max for photons scattered at right angle to direction of incident electric vector

$S = S[1 + a_0 \cos(2(\phi - \phi_0))]$

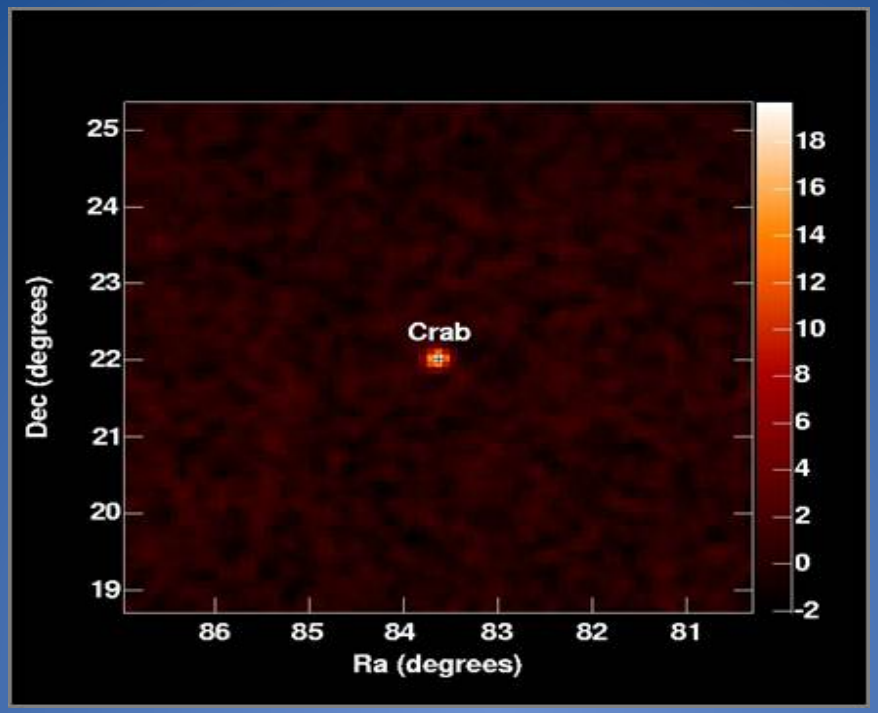
$\Rightarrow$ asymmetry in azimuthal profile S of scattered events

Modulation:

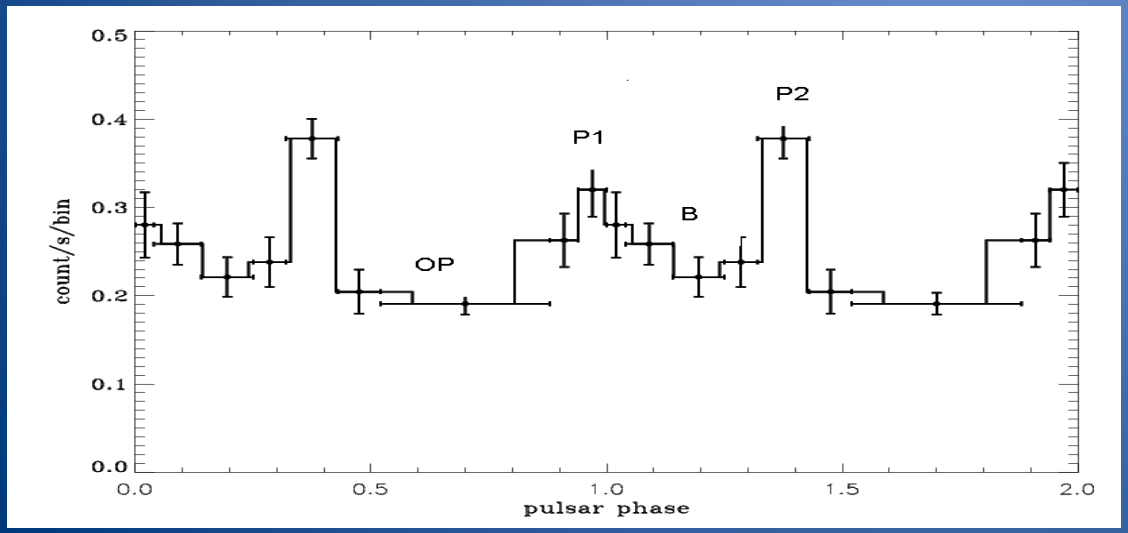
- a = modulation factor
- a_{100} = modulation for 100% polarised source
- pol. frac. = PF = a/a_{100}
- pol. angle = PA = $\varphi_0 - \pi/2 + n\pi$
- a_{100} estimate: GEANT3/GLEPS simulation for 100% linearly polarised source
- **a_{100} = 0.304 ± 0.003 for Crab-like spectrum**

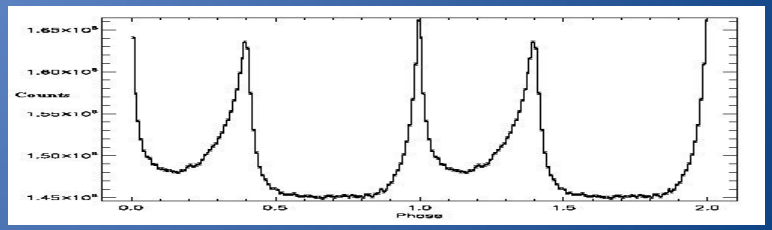


Results



Deconvolved significance map of Crab pulsar (Compton mode, 200-800 keV, 1 Ms)

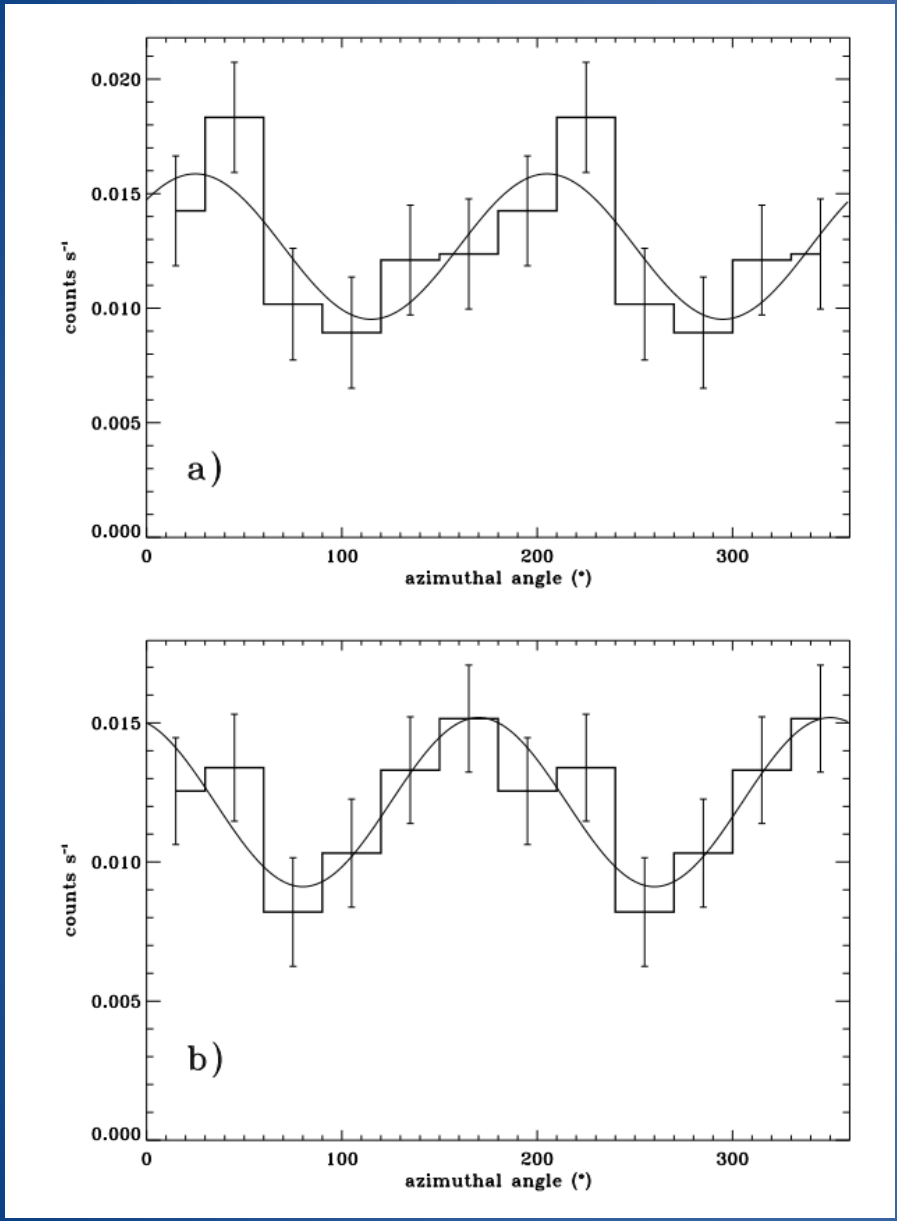




INTEGRAL/ISGRI lightcurve of the Crab pulsar, 20-120 Kev, 300 Ks, 100 bins.

INTEGRAL/Compton lightcurve of the Crab pulsar, 200-600 keV, 2.6 Ms.

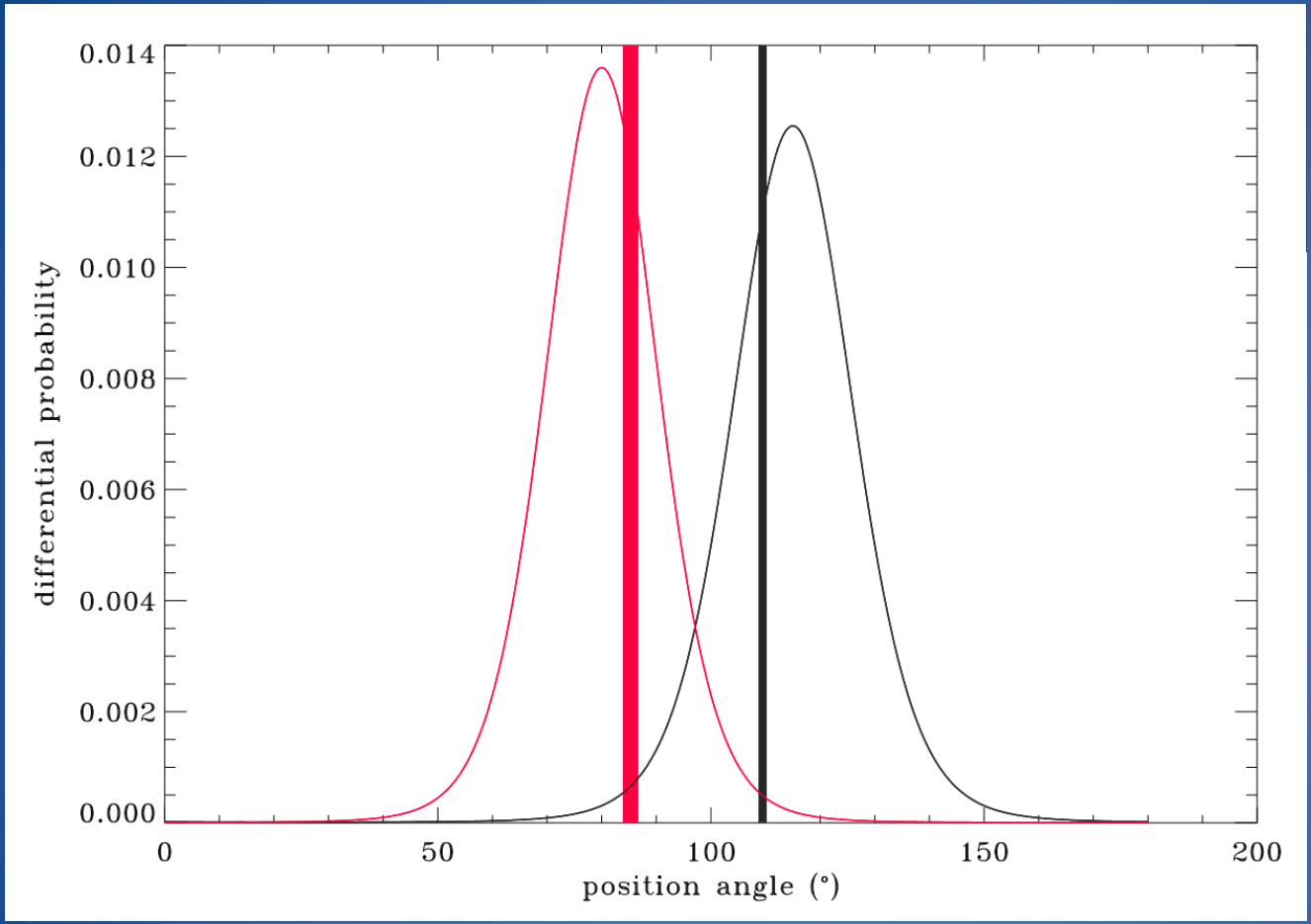
Results : azimuthal Profiles (300 – 450 keV)



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

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

True change of polarization angle ?



Probability densities for the two sets of observations (red : 2012 – 2014; black : 2003 – 2007). Vertical bars are optical measurements. There is a 11% probability that the true polarization is > 100° in 2012 – 2014 (red).

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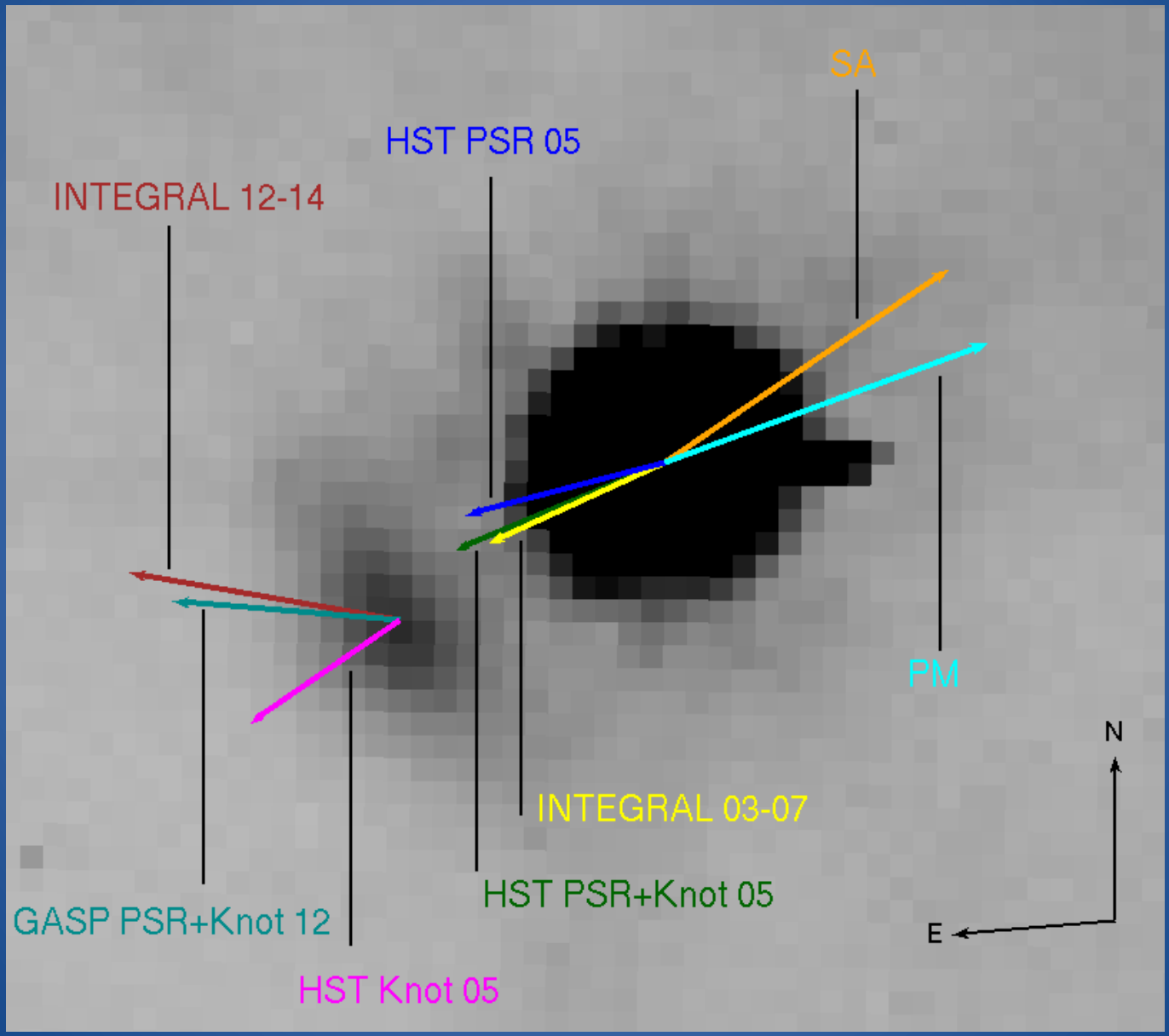
Optical + Hard X-rays

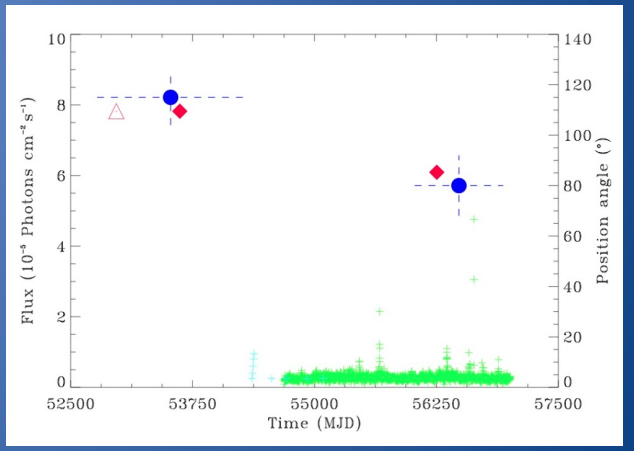


Questions and Conclusions

- Origine of the change in optical and hard X-rays polarisation : Magnetic reconnection ?
- Time scale of the change (hours, days, week, year ?)
- What are the links with high energy flares ?
- Where come from the observed change (knot, near-by pulsar?)

In a perfect world : phase resolved spectro-imaging-polarimetry with sub–arc second resolution with coordinnated observations during flaring activities

- The Crab nebula is not a polarimetric standard !
- It is also not standard in the high energy gamma-ray domain (Fermi, Agile flares).



Moran et al, 2016

⇒ Useful source to understand high energy sources variability (GRB, AGN, …) where reconnection processes have been suggested.

⇒ Illustrate the power of polarimetric measurements.

Conclusions - bis

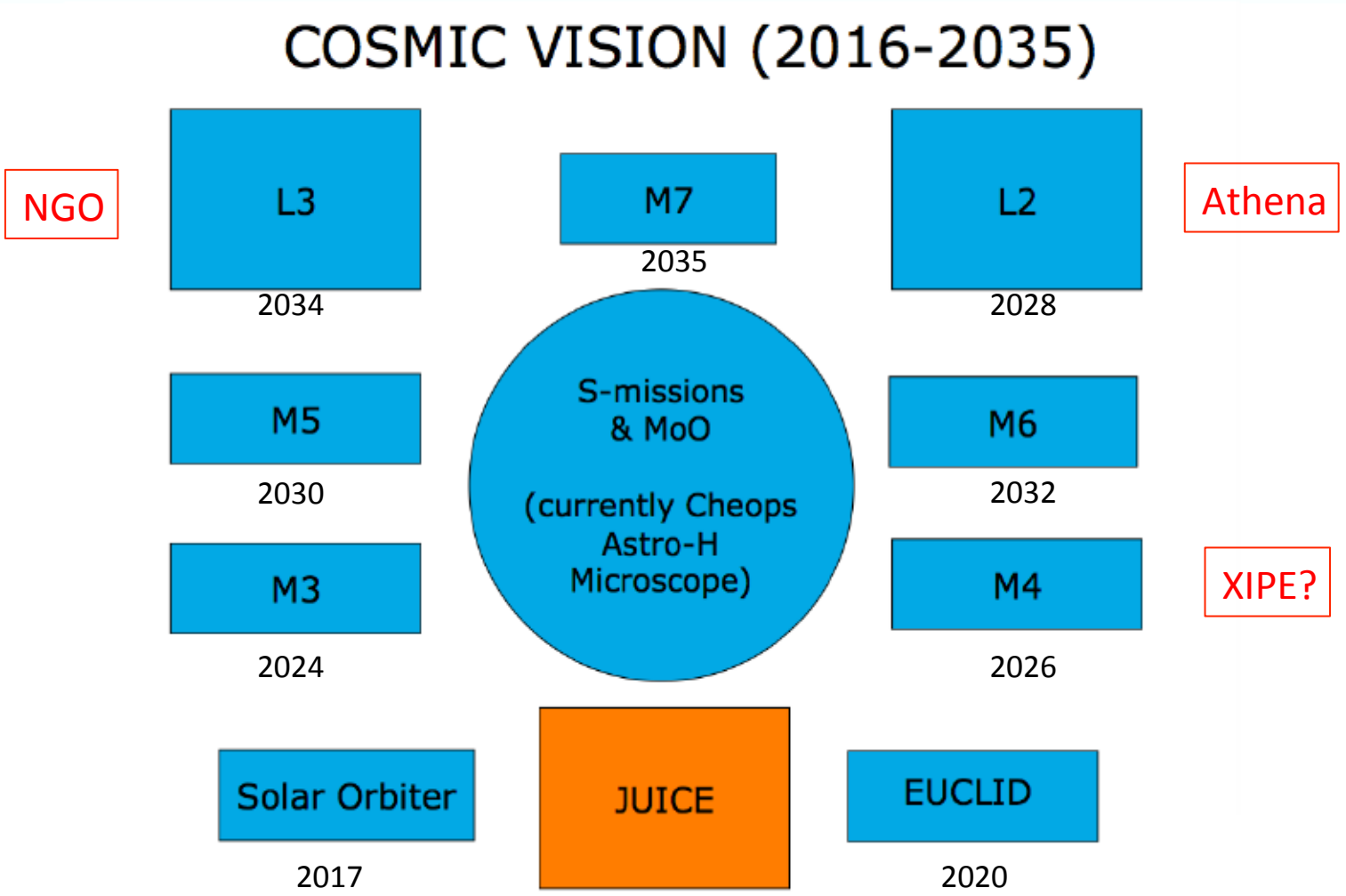
- Polarimetry provides an unique insight to pulsar emission geometries & constrains theoretical models of emission
- First multi-wavelength & multi-epoch study of polarisation of inner Crab Nebula and pulsar
- Optical & Gamma-ray comparisons ongoing + Radio (in particular with GRP studies)
- Mapped optical polarisation of the inner nebula
- Off-pulse emission (DC) highly polarised due to Knot
- PA of E-vector of NS, spin-axis, and proper-motion aligned
- More multi-wavelength polarisation studies of pulsars needed

On-going work

- new observations in 2015 (in optical at WHT and in hard X-rays with Integral)
- Phase resolved polarimetric studies
- Simultaneous optical + radio data (Nançay/NRT) : GRP's connection

News at MODE 2017

COSMIC VISION (2016-2035)



INTEGRAL is for the next decade the only ESA hard X-ray/low gamma-ray mission (with in particular a polarimetric mode) !