Multi-wavelength Polarisation studies of Pulsars

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With

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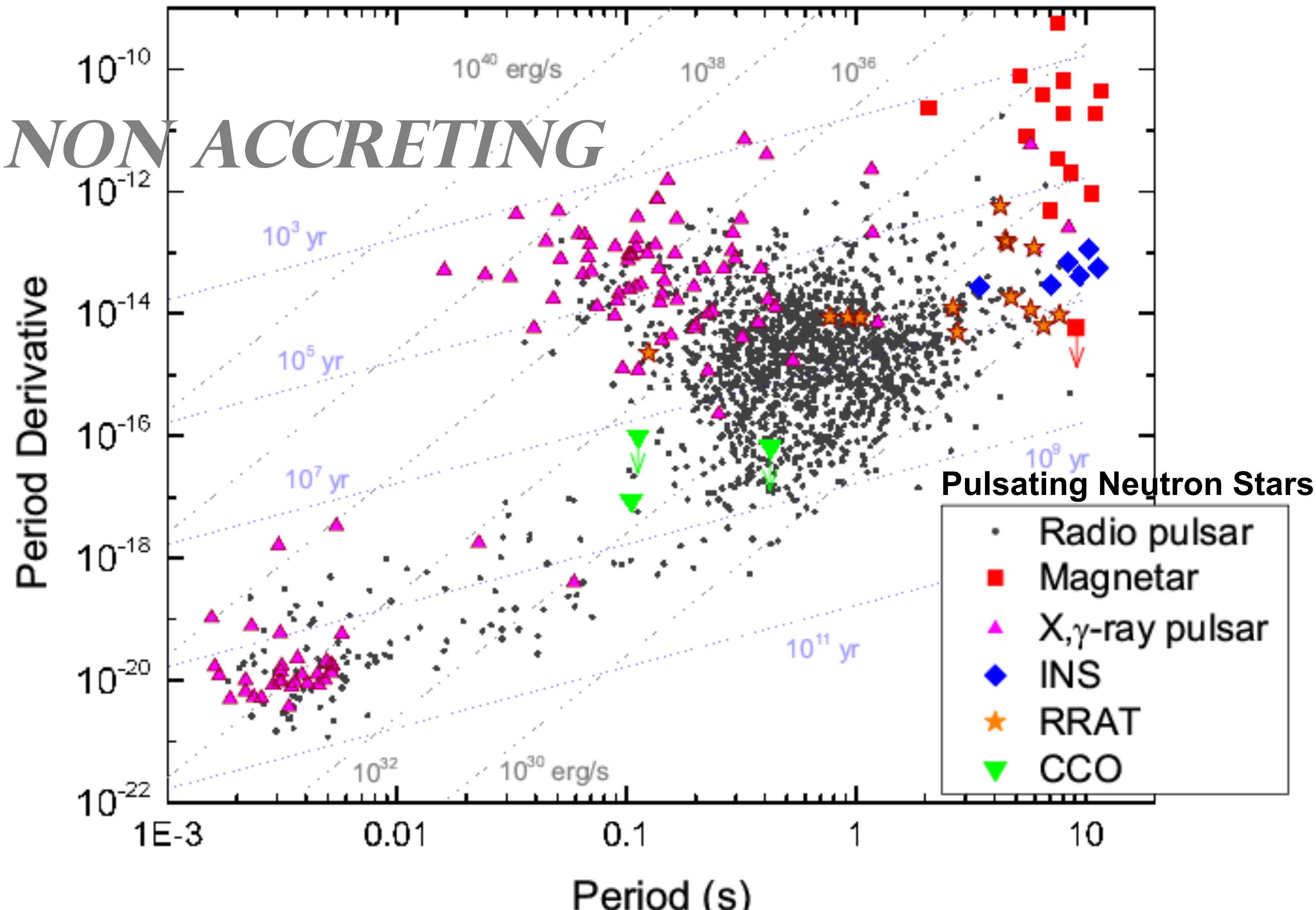
eASTROGAM Workshop: The Extreme Universe, Padua, February 28-March 2, 2017

pulsar = Rotation-Powered Pulsar



Alice Harding, ***The neutron star zoo***, 2013, Frontiers of Physics, Vol. 8, Issue 6, p.679

Why pulsars?

i. The most numerous class of isolated neutron stars (INSs) – ample choice of targets

ii. The only INS class discovered/detected up to the e-ASTROGAM energy range (and beyond)

iii. The only INS class emitting across the whole spectrum: (radio), infrared, optical, X, gamma-rays - multi-wavelength polarisation studies

iv. The only INS class with at least a case of multi-wavelength polarisation measurements

v. The only INS class with polarisation measurements obtained for multiple objects

Pulsar Polarimetry, why?

- Polarisation measurements (phase-res & phase-avg) offer unique insights into pulsars' highly-magnetised relativistic environments and are a primary test for neutron star magnetosphere models and theory of radiation emission processes.

L. C.

P.A.

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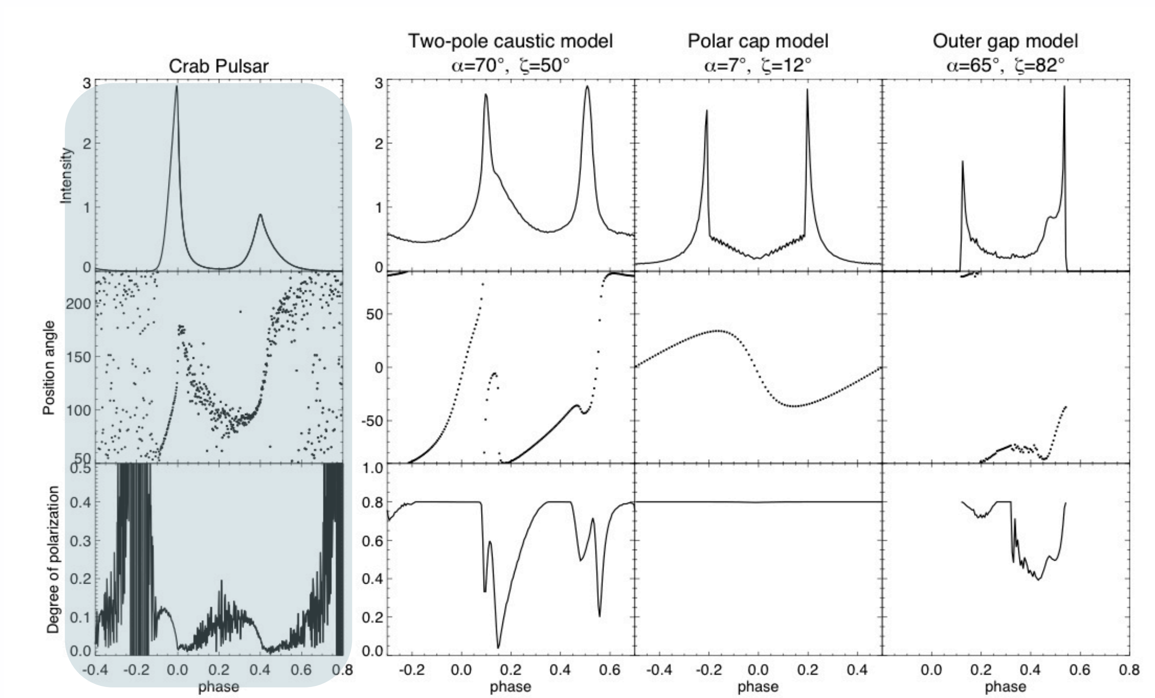
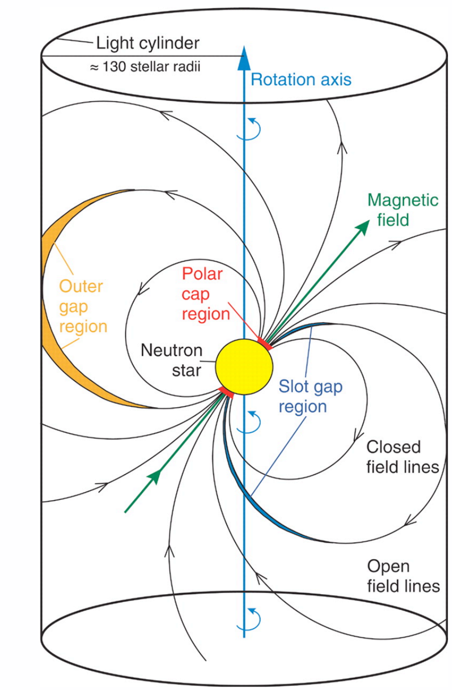




Slowikowska et al. (2009)

- Besides the radio band, optical observations have been most successful for polarimetry studies [**special case, RQ pulsars**], exploiting a mature technology

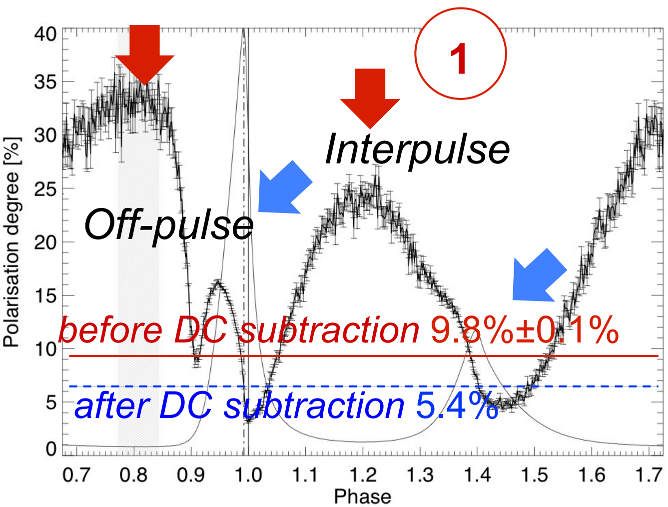
I. Pulsar Optical Polarisation

- Optical polarization of the Crab pulsar was discovered (Wampler et al. 1969), soon after the discovery of its counterpart (Cocke et al. 1969).
- Being the brightest (V=16.5) optical pulsar the Crab is the only one with both phase-resolved and averaged polarization measurements (linear and circular)

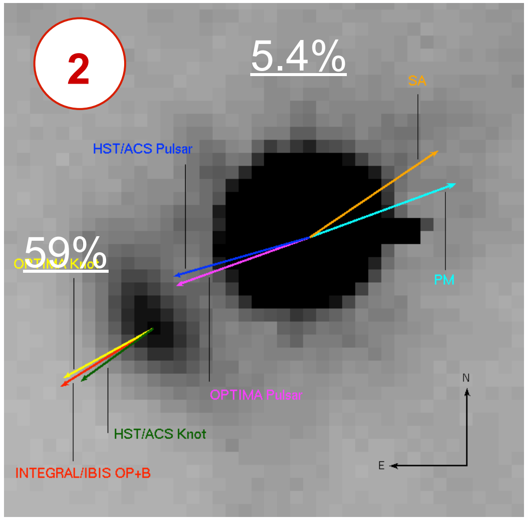
① Higher time resolution (phase dependence)

② Higher spatial resolution polarisation maps (structures)

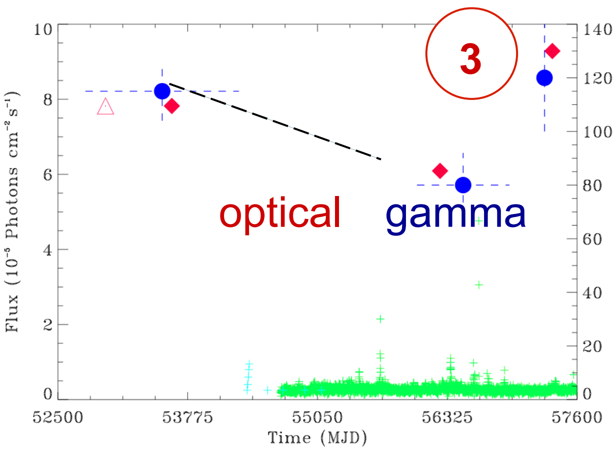
③ Secular changes in the pulsar polarisation (flares)



Slowikowska et al. (2009)



Moran et al. (2013)



Moran et al. (2016)

Pulsar optical polarisation, summary

Pulsar	τ (10^3 yr)	P_s (s)	$\dot{P}_s$ (10^{-13} s s^{-1})	$\dot{E}$ (10^{38} erg cm^{-2} s^{-1})	B_S (10^{12} G)	B_{LC} (10^5 G)	P.D. (%)	References
B0531+21	1.24	0.033	4.22	4.6	3.78	9.80	5.2±0.3	(1)
							5.5±0.1	(2)
B0540−69	1.67	0.050	4.79	1.5	4.98	3.62	5.0±2.0	(3)
							16.0±4.0	(4)
							≈5.0	(5)
B1509−58	1.56	0.151	15.3	0.17	15.40	0.42	10.4	(5)
B0833−45	11.3	0.089	1.25	0.069	3.38	0.44	8.1±0.7	(6)
							9.4±4	(7)
							8.5±0.8	(5)
B0656+14	111	0.384	0.55	0.00038	4.66	0.007	11.9±5.5	this work

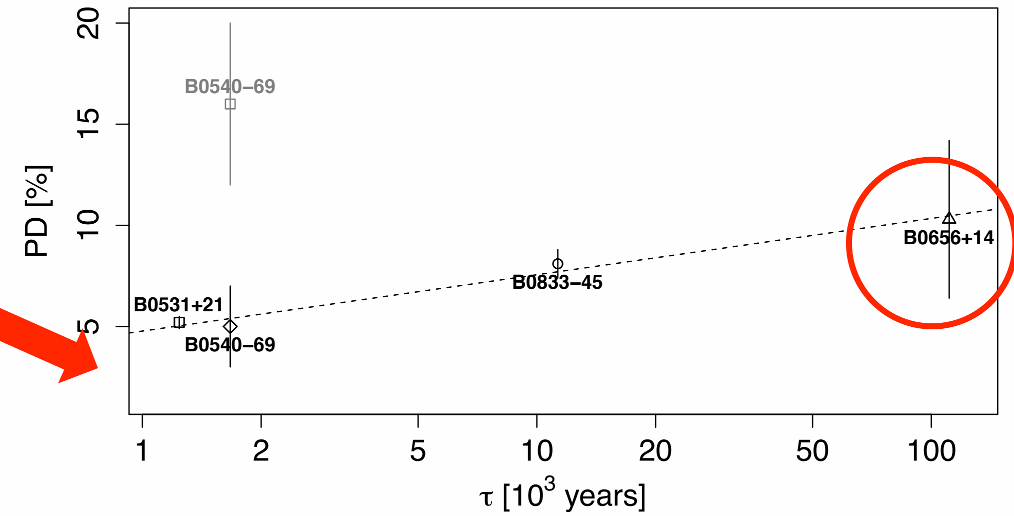
Phase resolved

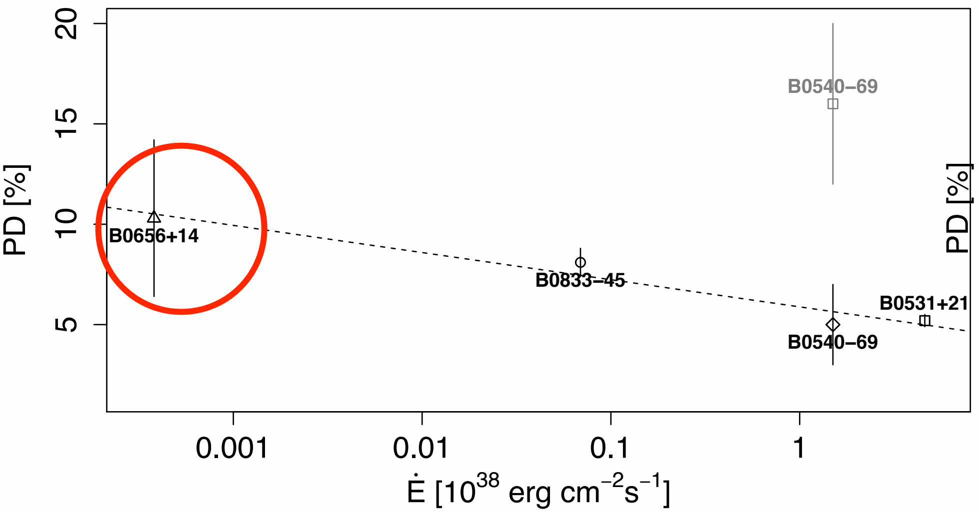
(1) Moran et al. (2013); (2) Słowikowska et al. (2012); (3) Lundqvist et al. (2011); (4) Mignani et al. (2010); (5) Wagner & Seifert (2000); (6) Moran et al. (2014); (7) Mignani et al. (2007)

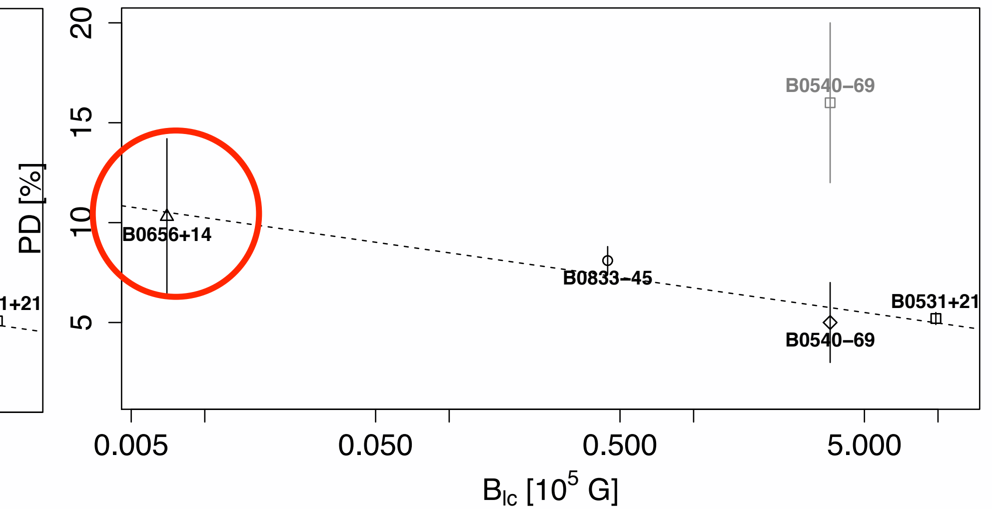
- **PD values ~5%-10%**, below model predictions ! And much less than radio.
- Alignment between pulsar polarisation and proper motion PA (Crab, Vela, B0656+14)
- Must do:
- ➢ Expand the sample and revisit uncertain cases (**PSR B1509-58**)
- ➢ Phase-resolved polarimetry of **PSR B0540-69** (possibly of **Vela**, as well)
- ➢ Phase-average polarisation of **Geminga** (V~25.5)
- ➢ Phase-resolved polarimetry of the **Crab** continuing

Pulsar optical polarisation, emerging picture

PD seems to be higher for older and less energetic pulsars



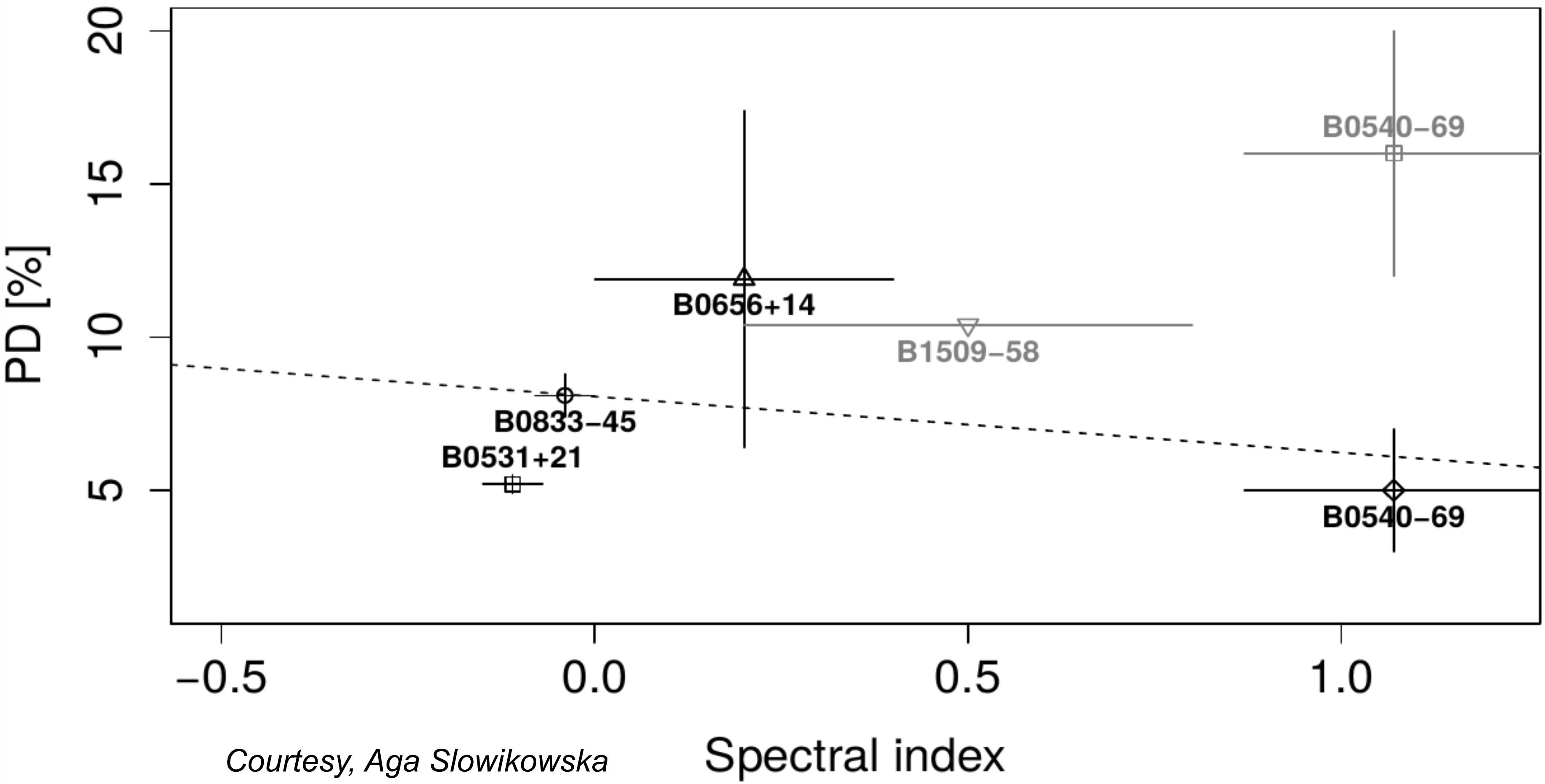




Trends biased by B0656+14 !
Measurement for Geminga crucial

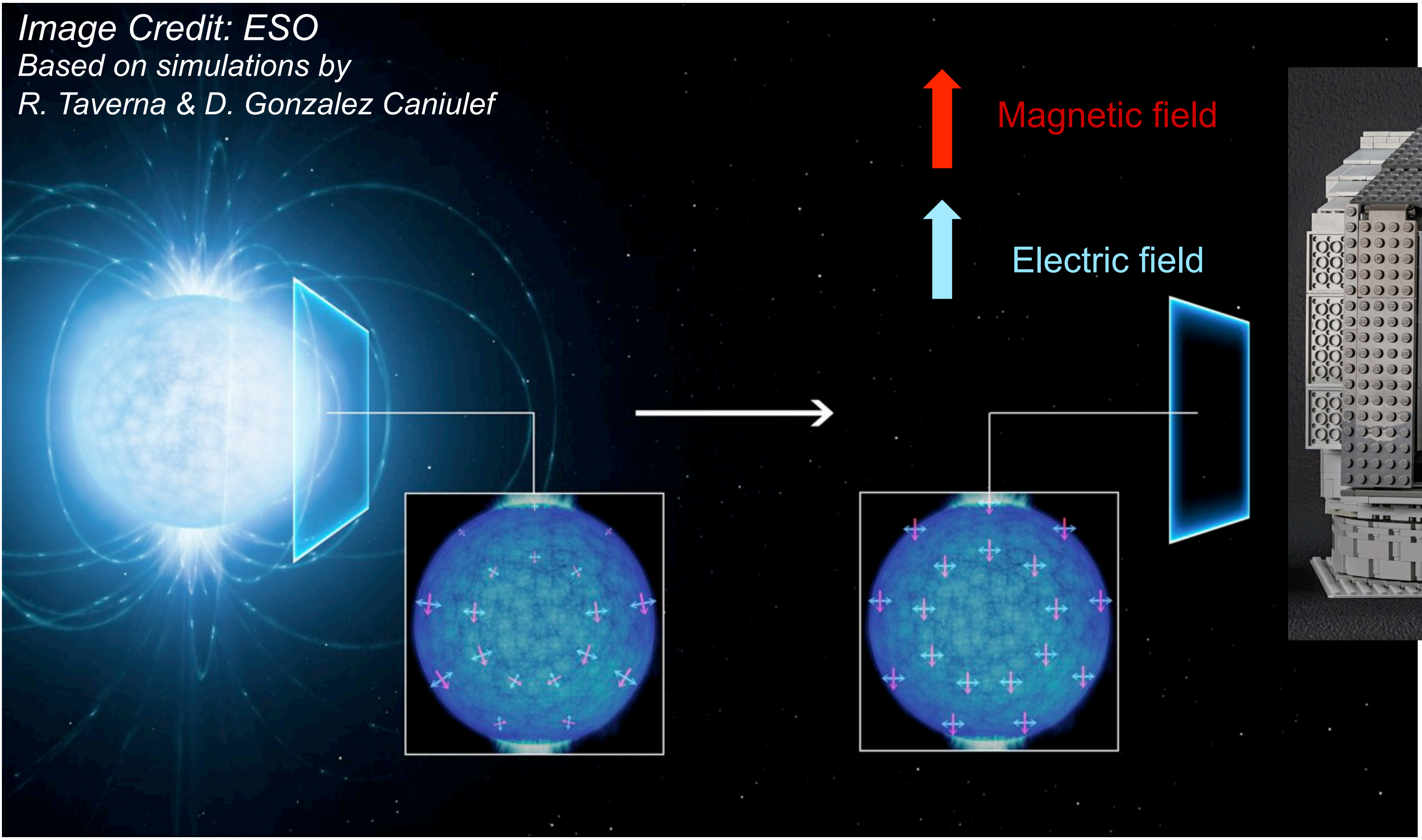
Possible anti-correlation between PD and B_{LC} but not with the surface magnetic field B_S (nearly constant)

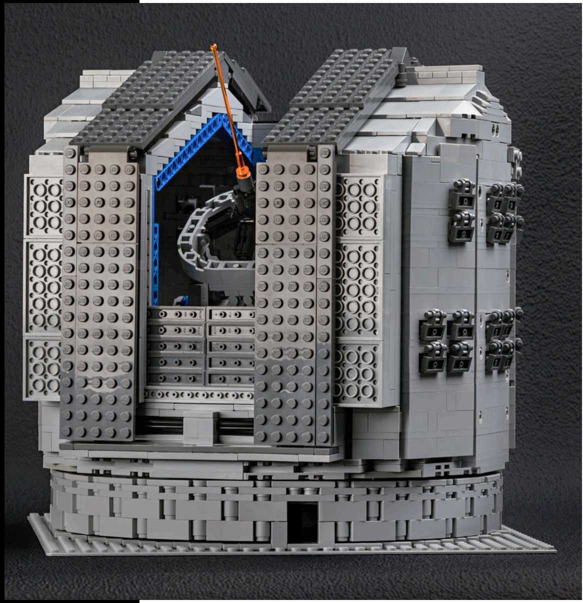
The picture not emerging, yet



Courtesy, Aga Slowikowska

Vacuum Birefringence in Neutron Stars

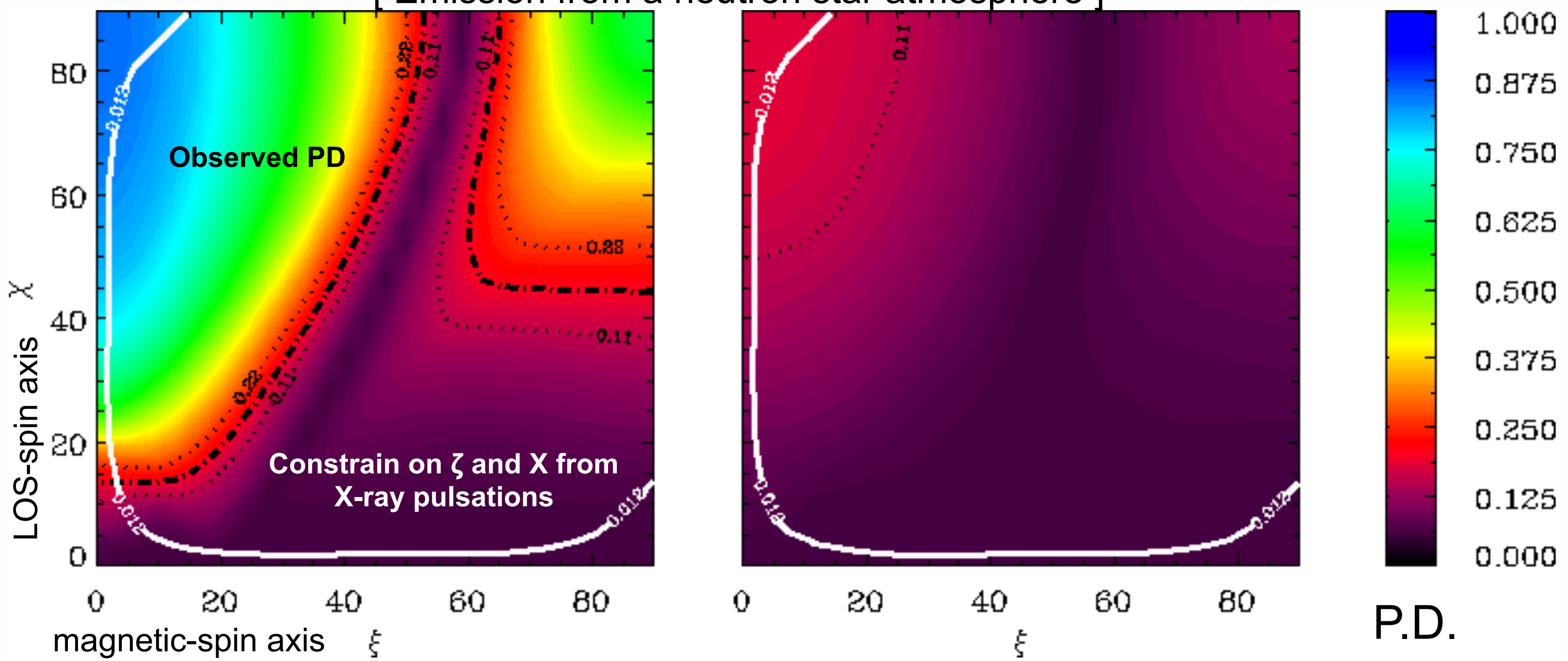




- Optical polarisation measurement for RX J1856.5-3754 (Mignani+ 2017), obtained with the VLT; PD=16.43%±5.26%.
- **First polarisation measurement for an INS (V=25.5) other than a pulsar**
- Follow-up VLT observations in progress

Vacuum Birefringence in Neutron Stars

[Emission from a neutron star atmosphere]



QED ON **QED OFF**

- For any considered emission model, **measurement not explained without introducing QED vacuum birefringence effects.**
- First observational evidence. To be searched for in X-rays, too
- RX J1856.5-3754 is a major target for future soft X-ray polarimetry missions

Gonzalez Caniulef D., Zane S., Taverna R., Turolla R., & Wu K.,2016, MNRAS, 459, 3585

II. Pulsar/PWN X-ray polarisation

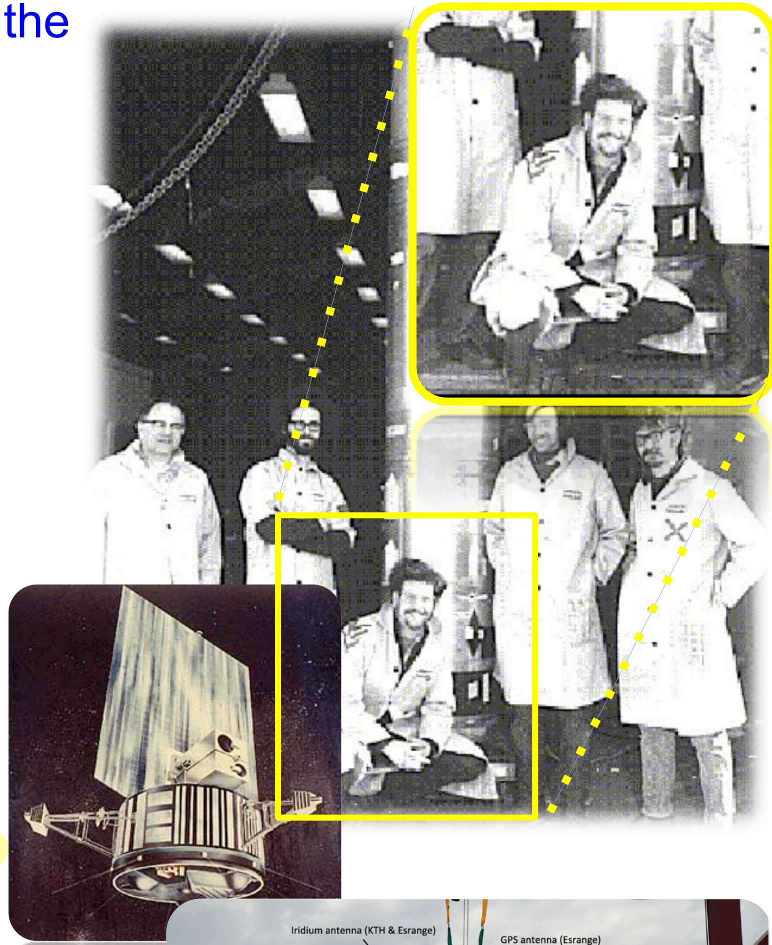
- First attempt to measure the X-ray polarisation of the **Crab Nebula** back in 1969 with sounding rockets
  – PD<36% (Wolff et al. 1970)

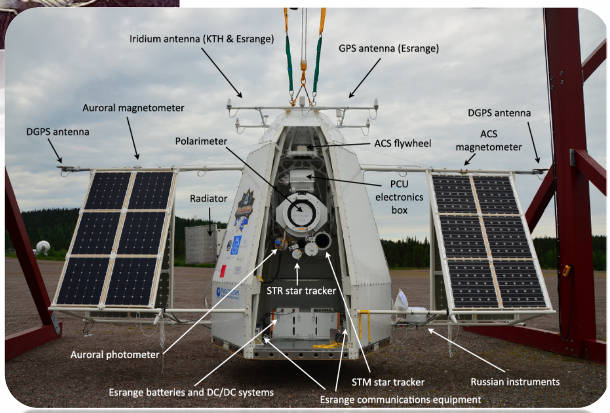
- First X-ray **nebula** polarisation measurement:
  PD=15.4%±5.2%, PA=156°±10° (5-20 keV)
  (Novick et al. 1972)

- New **nebula** polarisation by OSO-8 with:
  PD=15.7%±1.5%, PA=161.1°±2.8° @2.6 keV
  PD=18.3%±4.2%, PA=155.5°±6.6° @5.2 keV
  (Weisskopf et al. 1976)

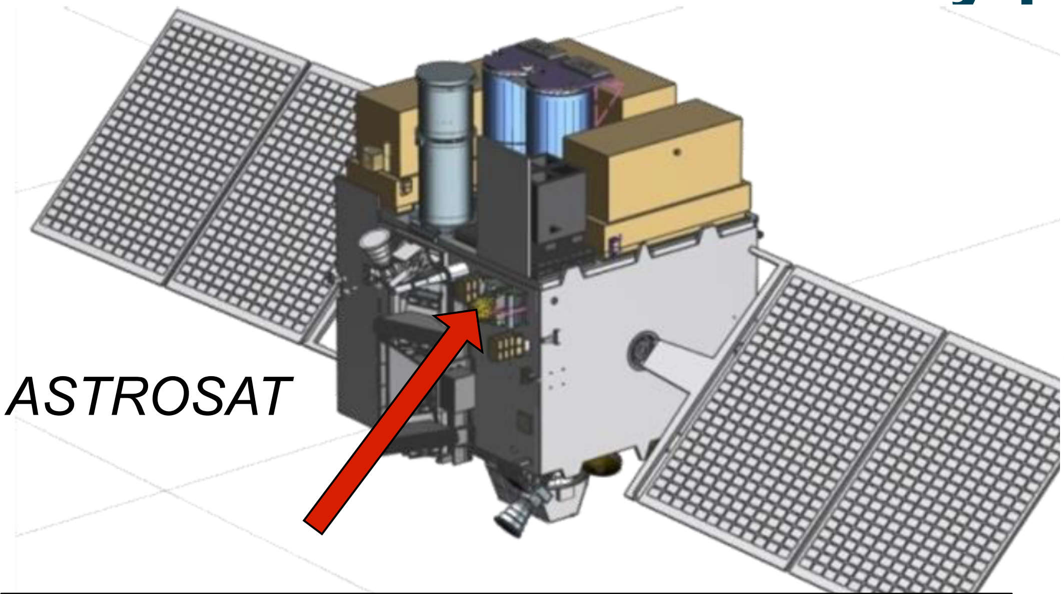
- After **Pulsar subtraction** (Weisskopf et al. 1978):
  PD=19.2%±1.0%, PA=156.4°±1.4° @2.6 keV
  PD=19.5%±2.8%, PA=152.6°±4.0° @5.2 keV

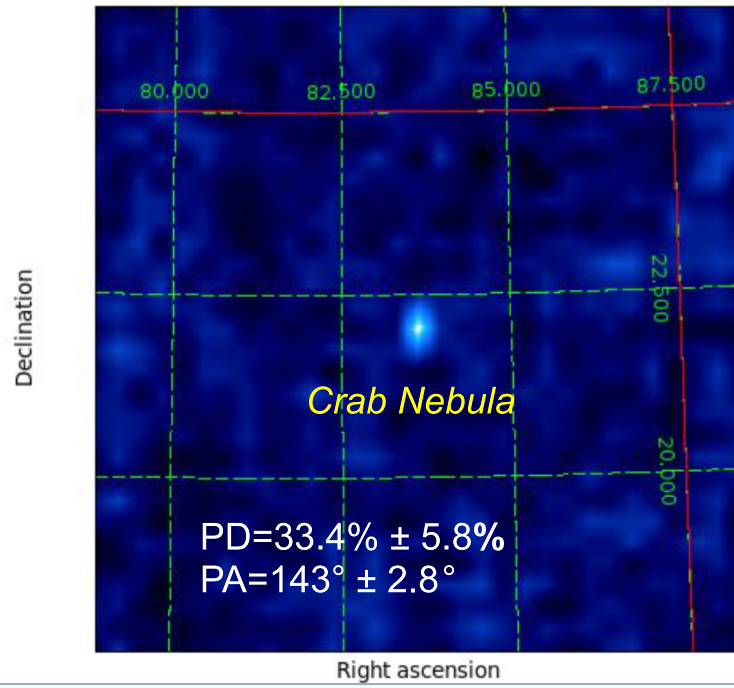
- Attempts to measure the **pulsar** polarisation @ 2.6 and 5.2 keV with OSO-8 (Silver et al. 1978) and at 20-120 keV with PogoLIte (Chauvin et al. 2016) - PD<42.2%





Pulsar/PWN X-ray polarisation





Cadmium Zinc Telluride Imager (CZTI)	
Launched:	2015
Duration:	> 5 yrs
Angular resolution:	8 arcmin
FoV:	6x6 deg^2
Energy Range:	10-100 keV
Effective Area:	1000 cm^2
Energy Resolution:	5% @ 100 keV
Time Resolution:	1 ms

See, Sudip Battacharya in

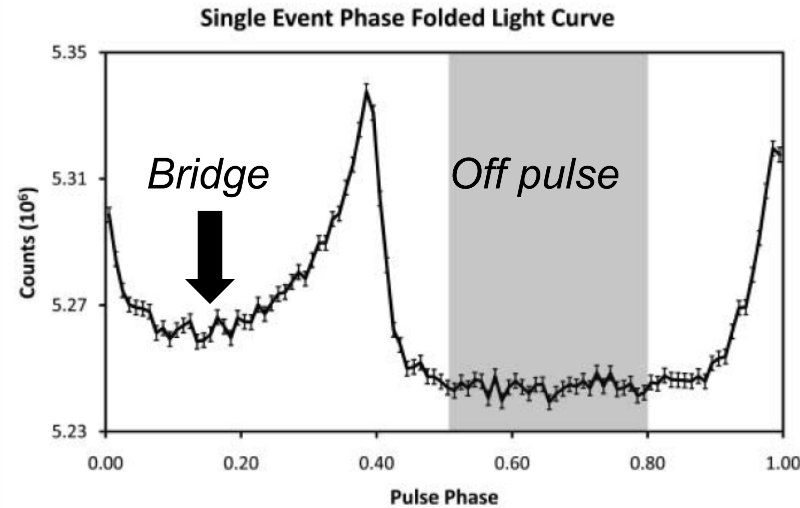
High Throughput X-ray Astronomy in the eXTP Era
http://www.isdc.unige.ch/extp/home.html

Measurement of the Hard X-ray polarisation of The Crab Nebula
Vadawale et al., in prep.

Hard X-ray polarimetry with Astrosat-CZTI
Vadawale et al., 2015, A&A, 578, 73

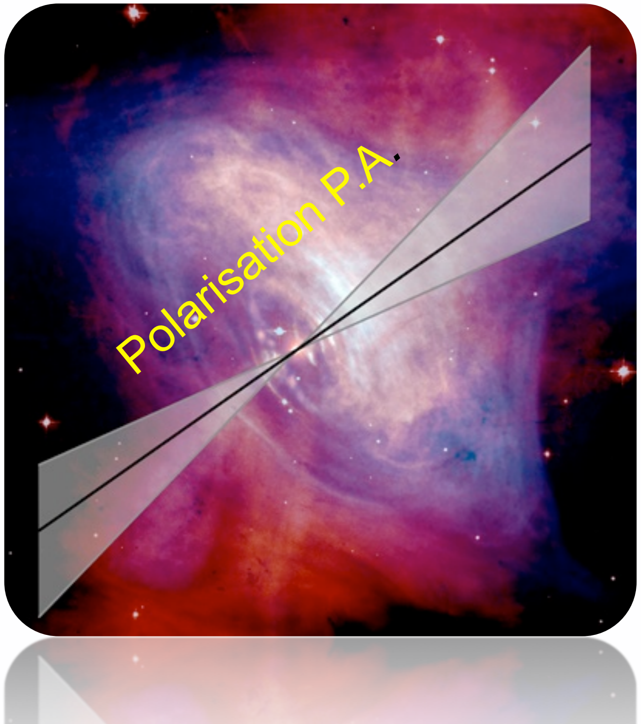
III. Pulsar Gamma-ray polarisation

- First measurement of gamma-ray polarisation of the **Crab nebula** with INTEGRAL/SPI (Dean et al. 2008) – **phase resolved**



- Off-pulse events only (0.1-1 MeV) → **nebula** (pulsar localisation within ± 20")
- Off pulse: PD=46%±10%, PA=123°±11°
- **Polarisation P.A. aligned with the pulsar PM**
- Gamma-ray polarisation measurement of the **Crab pulsar** with INTEGRAL/IBIS (Forot et al. 2008) – **phase resolved**

➢ Peaks: PD=42%$+^{30}_{-16}$, PA=70°±20°
➢ Off pulse: PD>72%, PA=120.6°±8.5°
➢ OP+Bridge: PD>88%, PA=122°±7.7°
➢ Phase-av: PD=47%$+^{19}_{-13}$, PA=100°±11°
0.2-0.8 MeV



- **Like in the optical, peaks are less polarised**

SEARCH FOR LINEAR POLARIZATION IN GAMMA-RAY SOURCES: POSSIBLE EVIDENCE FOR THE VELA PULSAR

P. A. Caraveo, G. F. Bignami, I. Mitrofanov,[1] and G. Vacanti
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Received 1987 May 28; accepted 1987 September 21

ABSTRACT

The azimuthal distribution of planes containing e^+/e^- pairs from high-energy photon materialization is reminiscent, through a quadrupole anisotropy, of the degree and position angle of linear polarization of the incident photons. Data on open pairs in the *COS B* spark chamber are used in a search for such an effect in >50 MeV photons from bright sources, such as Vela, Crab, Geminga, and a reference Galactic plane region in Cygnus. After a description of the method and the related simulations and tests, the analysis of the available data shows no anisotropy for the other sources, but for the Vela pulsar a low chance probability effect is found, apparently implying a high ($\sim$100%) degree of linear polarization for the Vela photons. This is discussed in light of the physics of the production mechanisms as well as of their geometry.

If you never try, you'll never know !

ANALYSIS OF THE *COS B* DATA FOR EVIDENCE OF LINEAR POLARIZATION OF VELA PULSAR GAMMA RAYS

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Received 1989 June 19; accepted 1990 April 25

A. Slowikowska

ABSTRACT

We have analyzed the *COS B* spark chamber telescope observations of the Vela pulsar for gamma-ray polarization. No significant quadrupole moment is found in the azimuthal distribution of the electron-positron pair production planes. However, analysis of the sensitivity indicates that even 100% polarization would not be detected. Therefore, the null result does not constrain the polarization of the Vela pulsar gamma-ray emission. This result contradicts the report of Caraveo *et al.* of possible evidence for polarization of the Vela pulsar gamma rays.

Estimate Of The *Fermi* Large Area Telescope Sensitivity To Gamma-ray Polarization

Matteo Giomi*[1], Rolf Bühler[1], Carmelo Sgrò[2], Francesco Longo[3], W. B. Atwood[4]
and on behalf of the Fermi LAT Collaboration

[1]*Deutsches Elektronen-Synchrotron DESY, D-15738 Zeuthen, Germany*
[2]*INFN-Pisa*
[3]*INFN-Trieste, University of Trieste*
[4]*University of California, Santa Cruz Institute for Particle Physics*

MDP~30%-50% at 5σ for the Crab and Vela pulsar after 10 years of observations

IV. Crab Multi-wavelength polarisation

			Polarisation (%)	Position Angle (°)
[1] γ-ray (0.1-1 MeV)	OP	nebula	46 ± 10	123 ± 11
[2] γ-ray (0.2-0.8 MeV)	OP	nebula	> 72	120.6 ± 8.5
[2] γ-ray (0.2-0.8 MeV)	OP+B	nebula	> 88	122.0 ± 7.7
[2] γ-ray (0.2-0.8 MeV)	$P_1 + P_2$	pulsar	$42 \pm^{30}_{16}$	70 ± 20
[3] X-ray (20-120 keV)		pulsar	<42.2	149.2 ± 16
[4] X-ray (2.6 keV)		nebula	19.2 ± 1.0	156.4 ± 1.4
[5] Optical (HST)		pulsar	5.2 ± 0.3	105.1 ± 1.6

Energy

[1] Dean et al. (2008); [2] Forot et al. (2008); [3] Chauvin e al. (2016); [4] Weisskopf et al. (1978); [5] Moran et al. (2014)

- **Comparison between PDs and PAs is scientifically interesting but difficult.**
  - Different phase intervals (off-pulse, phase-averaged, pulsed)
  - Different spatial regions (different contibution from the PWN and SNR)
  - Different energies – Is PD energy-dependent ?

- **A multi-wavelength analysis requires facilities that we have not (yet)**

V. Future Missions

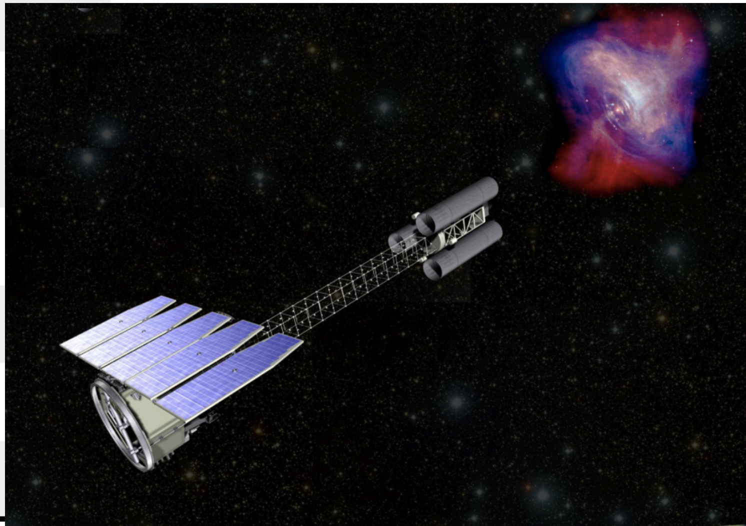
Imaging X-ray Polarimetry Explorer (IXPE)

- NASA SMEX candidate (PI: M. Weisskopf)
- 175 M$
- Pre-selected in 2015 for Phase A study
- Selected as a SMEX mission in January 2017

Sergio Fabiani's Talk

Sensitivity	1.8% MDP ($2x10^{-10}$ erg cm^{-2} s^{-1}) in 300 ks
Spurious polarisation	<0.3%
Telescopes	3
Angular resolution	28”
FoV	12.9x12.9 $arcmin^2$
Effective Area	854 cm^2 @ 3 keV
Spectral Resolution	16% @ 5.9 keV
Time Resolution	<100 μs
Energy Range	2-8 keV
Launch Date	2020
Mission Duration	2+1 yrs

https://wwwastro.msfc.nasa.gov/ixpe/



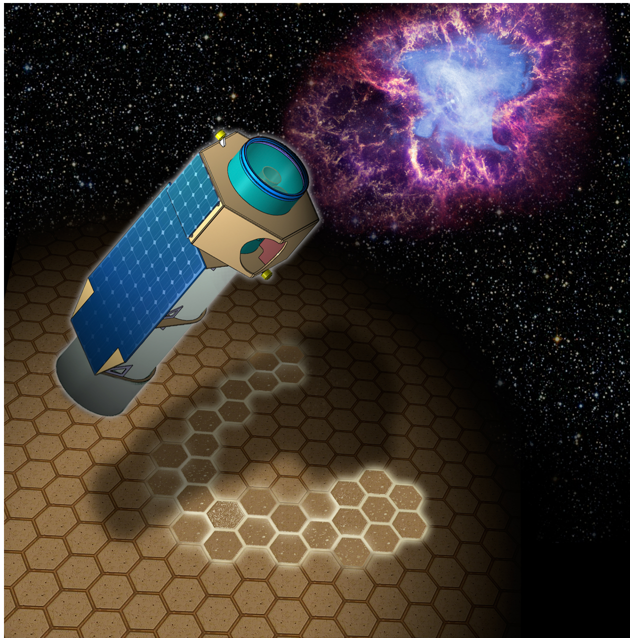
X-ray Imaging Polarimeter Explorer (XIPE)

- ESA M4 candidate (PI: P. Soffitta)
- 450 M€
- Pre-selected in 2015 for Phase A study
- Down selection Spring 2017

Sergio Fabiani's Talk

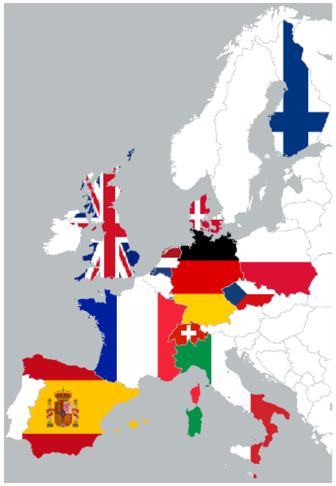
Sensitivity	1.2% MDP ($2x10^{-10}$ erg cm^{-2} s^{-1}) in 300 ks
Spurious polarisation	<0.5% (<0.1%)
Telescopes	3
Angular resolution	22"
FoV	12.9x12.9 $arcmin^2$
Effective Area	1530 cm^2 @ 3 keV
Spectral Resolution	16% @ 5.9 keV
Time Resolution	<8 μs
Energy Range	2-8 keV
Launch date	2025
Mission Duration	3+2 yrs

http://www.isdc.unige.ch/xipe/

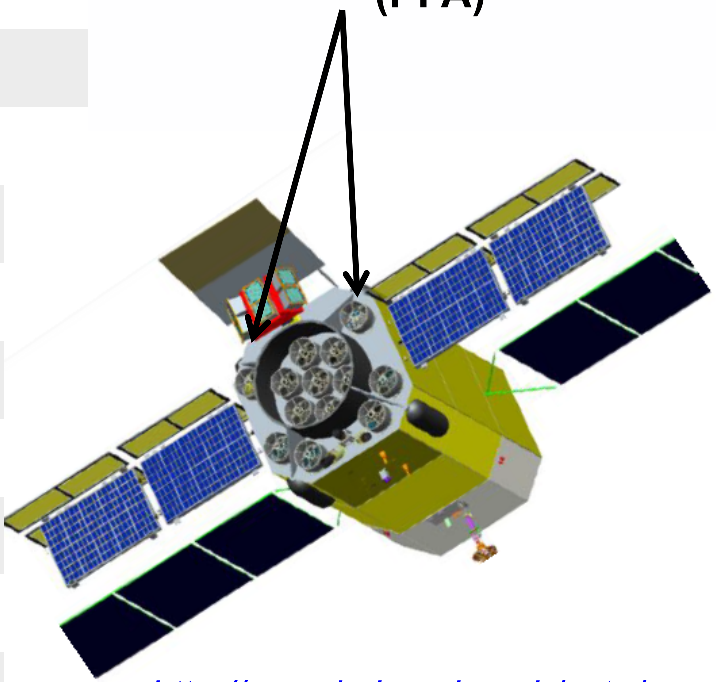


Enhanced X-ray Timing Polarimetry (eXTP) mission

- CAS mission candidate (PI. S. Zhang, M. Feroci)
- China+Europe+ESA
- Selected by CAS in December 2016



Sensitivity	1.2% MDP ($2x10^{-10}$ erg cm^{-2} s^{-1}) in 600 ks
Spurious polarisation	<1%
Telescopes	2
Angular resolution	30” (<15”)
FoV	12x12 $arcmin^2$
Effective Area	1000 cm^2 @ 3 keV
Spectral Resolution	16% @ 6 keV
Time Resolution	500 μs (<100 μs)
Energy Range	2-10 keV
Launch Date	2024
Duration	5 yrs (10)



http://www.isdc.unige.ch/extp/

Potential Targets

MDP=10% (150 ks) down to $F_X \sim 5\ 10^{-13}$ erg cm^{-2} s^{-1}

Many bright PSRs are embedded in PWNe

PWN contamination problem -GPD angular resolution <30”

Workaround: Select PSRs with PWN flux ~0.1PSR flux within a 30”radius

Caveat: **faint PWN does not mean weakly polarised. How do you cope?**

Optical polarisation

NAME	P(s)	d(kpc)	$N_H(10^{21})$	Γ	PWN
J0534+2200	33	2.0	3.45	1.63	Y
J0659+1414	384	0.288	0.43	2.1	N
J0835-4510	89	0.29	0.25	1.64	Y
J1057-5226	197	0.72	0.27	1.7	N
J1420-6048	68	5.6	20.2	0.84	Y
J1513-5908	151	4.2	[illegible].18	2.05	Y
J1617-5055	69	6.5	34.5	1.14	Y
J1747-2809	52	8.5	225.0	1.37	Y
J1747-2958	98	4.8	25.6	1.51	Y
J1801-2451	124	5.2	37.4	1.54	Y
J1811-1925	64	5.0	22.2	0.97	Y
J1813-1246	48	2.5	15.6	0.85	N
J1813-1749	44	4.8	100.0	2.0	Y
J1833-1034	61	4.7	21.0	1.52	Y
J1836+5925	173	0.4	0.07	2.05	N
J1838-0655	70	6.6	67.0	1.0	Y
J1846-0258	326	10.0	39.6	1.88	Y
J1849-0001	38	0.0	43.0	1.1	Y
J1930+1852	136	5.0	16.0	1.35	Y
J2021+3651	103	2.1	6.38	1.68	Y
J2022+3842	24	10.0	16.0	1.0	Y
J2229+6114	51	3.65	3.0	1.01	Y

Subtraction of PWN background through imaging not feasible for small PWNe

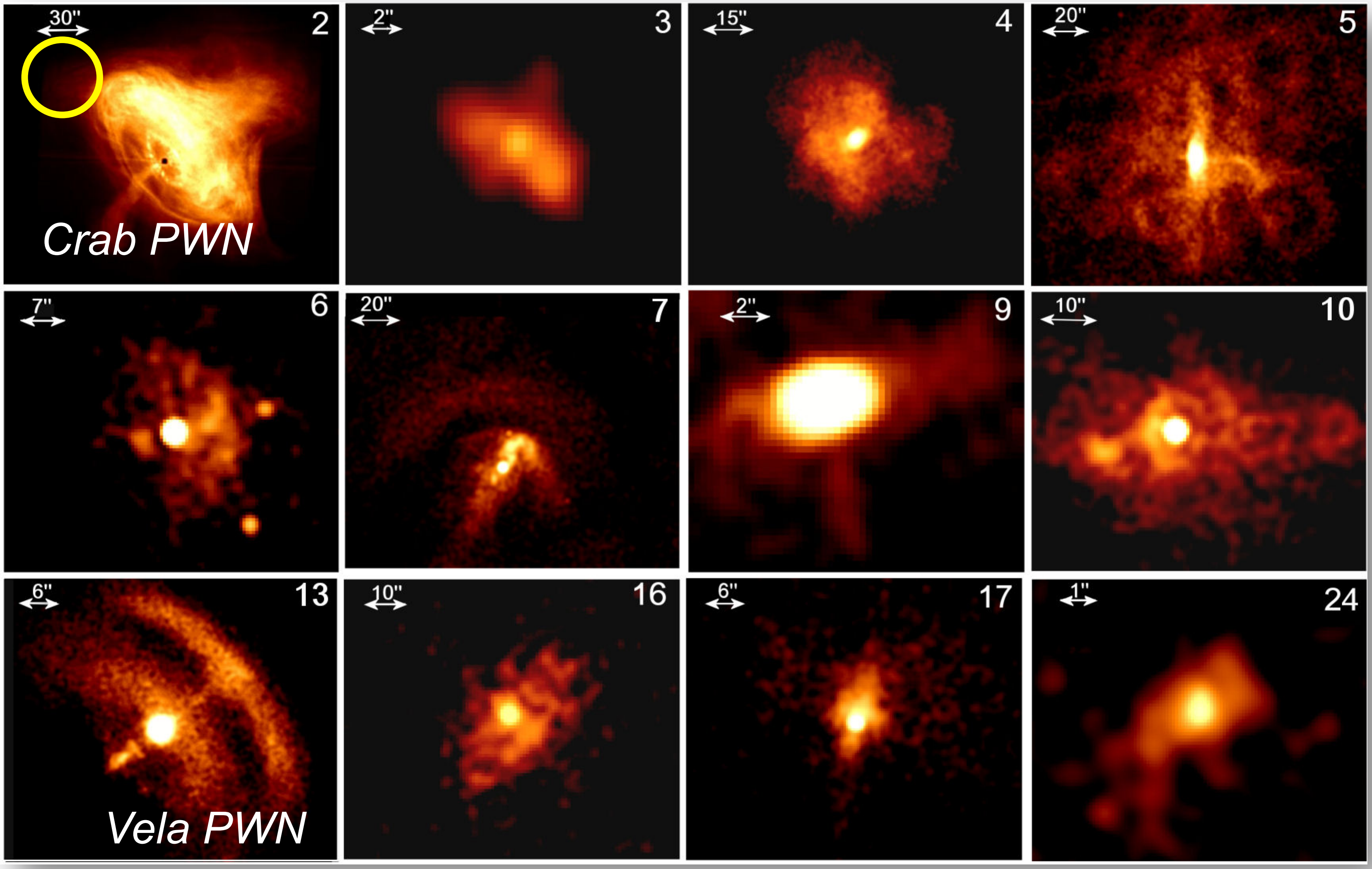


Image Credit: G.G. Pavlov, O. Kargaltsev (PSU)

Phase-resolved X-ray polarisation

All selected targets are X-ray pulsars in the 0.2-12 keV band, important to separate pulsed (PSR) and unpulsed (PWN) components – possible thanks to the GPD time resolution (<100μs *eXTP* and *IXPE*; <8μs *XIPE*)

A MODEL FOR THE X-RAY POLARIZATION OF THE CRAB PULSAR

E. Massaro[1], M. Salvati[2], F. Massa[3], R. Campana[4], R. Turolla[5] *, R. Taverna[5], T. Mineo[6], G. Cusumano[6], E. Del Monte[1], F. Muleri[1], P. Soffitta[1], E. Costa[1]

[1] *INAF-IAPS Roma, In Unam Sapientiam, Roma, Italy* [2] *INAF, Osservatorio di Arcetri, Firenze, Italy* [3] *INFN-Roma1 (retired), Roma, Italy* [4] *INAF-IASF Bologna, Italy* [5] *University of Padova, Italy*
[6] *INAF-IASF Palermo, Italy* (* *Presenter*)

Abstract

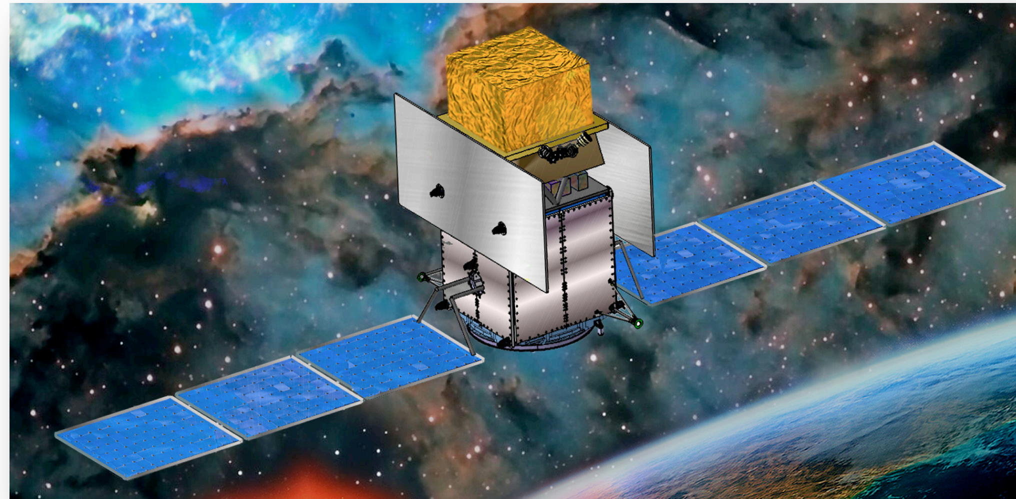
We present preliminary estimates of the expected polarization signal of the Crab Pulsar in the 3-10 keV energy range, based on a multicomponent model reproducing the main broad band features of the pulsed emission (Massaro et al. 2006). We computed the polarization fraction and angle as function of the pulse phase under the assumption that some or all the X ray components have the same polarization properties of the optical components as measured with OPTIMA (Slowikowska et al. 2009), and evaluated the XIPE observing time necessary to reach the statistics sufficient to distinguish the various scenarios.

Narrow down the list of potential targets

e-ASTROGAM

- Polarisation measurements possible from pair creation and Compton scattering

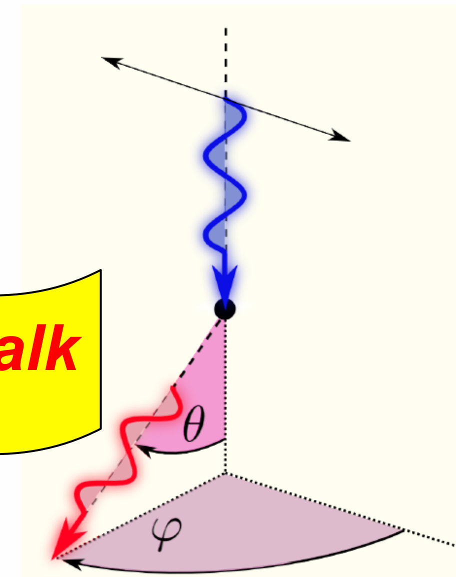
- At low energies (0.2 - 2 MeV), e-ASTROGAM will achieve an MDP as low as 0.7% for a Crab-like source in 1 Ms



- ➢ Monitor changes in polarisation following γ-ray flaring events in the Crab and verify proposed correlation with optical (Moran et al. 2016)
- ➢ Complement the work of IXPE, XIPE, eXTP
- ➢ PWN contamination problem more severe than in X-rays
- ➢ Target selection different from X-rays
- ➢ Phase-resolved polarimetry simulations

C. Gouiffes talk

- **Work for a Pulsar (Polarimetry) Working Group**



Compton scattering

Summary and Conclusions

- After the radio band, pulsar polarisation mostly measured in the optical (**5 pulsars**)
- In the X/γ-rays, polarisation measured **only for the Crab** (nebula and pulsar)

➢ *IXPE* (*eXTP, XIPE*) and *e-ASTROGAM* will make it possible to conduct X and γ-ray polarisation studies on a larger sample of pulsars

- Multi-wavelength polarisation measurements will allow to:

➢ **Study pulsar magnetic field and magnetospheres in different energy regimes**

➢ **Verify dependence of PD vs energy (e.g., optical vs X-rays vs γ-rays)**

➢ **Verify dependence of PD vs X/γ-ray spectrum (soft/hard vs low/high PD)**

➢ **Verify dependence of PD vs. pulsar parameters (age, Edot, ..)**

With IXPE (eXTP, XIPE), e-ASTROGAM, and (hopefully) future optical facilities (ELTs) we will enter the new era of Multi-wavelength Polarimetry, adding a fourth dimension to the multi-wavelength study of Cosmic Sources