The *eXTP* contribution to the study of Rotation-Powered Pulsars

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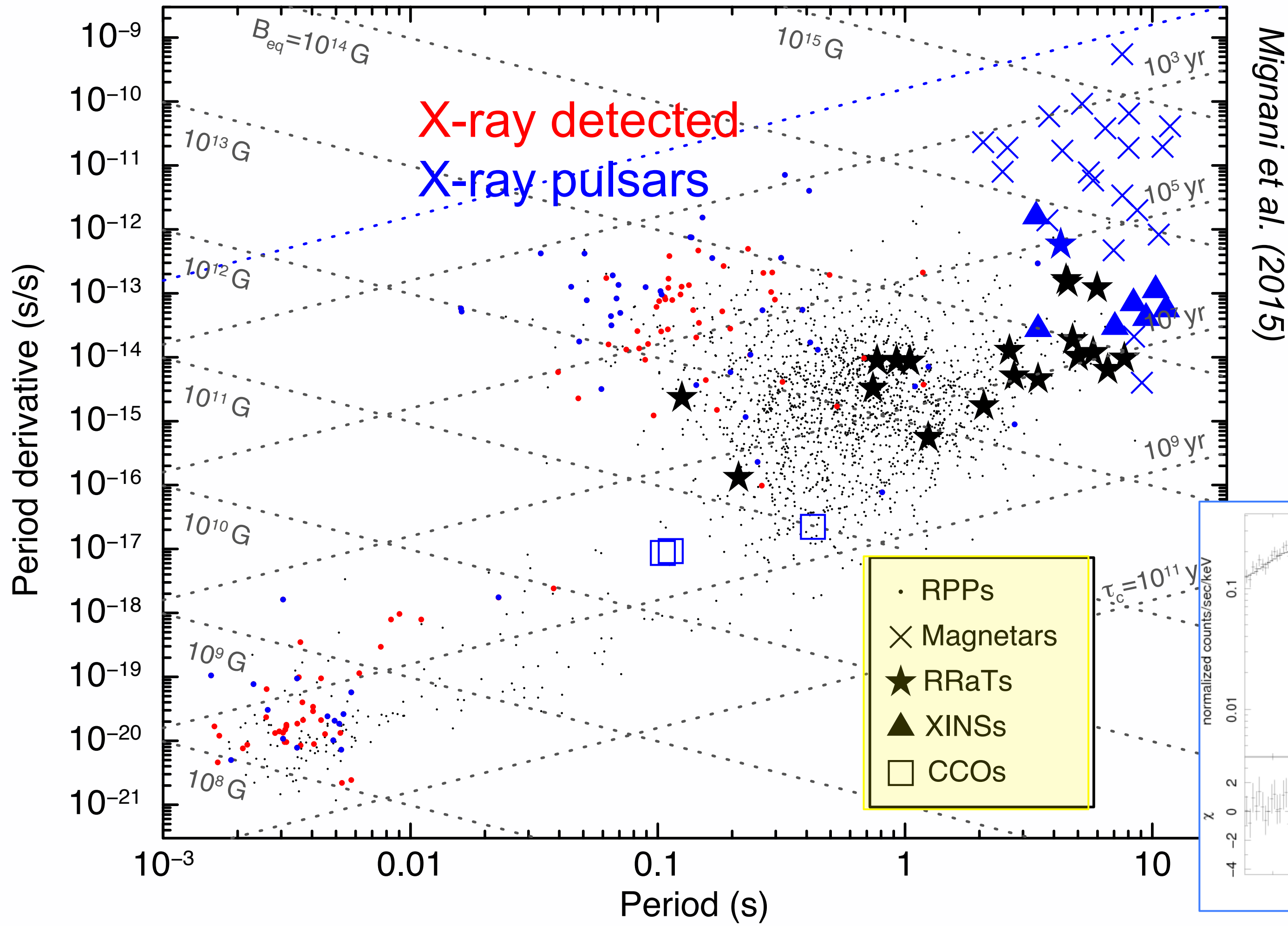
With

A. Shearer (NUIG), M. Marelli (INAF, IASF), E. Massaro (U. Rome), A. Slowikowska (UZG) et al.

High-throughput X-ray Astronomy in the eXTP era, Rome, February 6-8, 2017

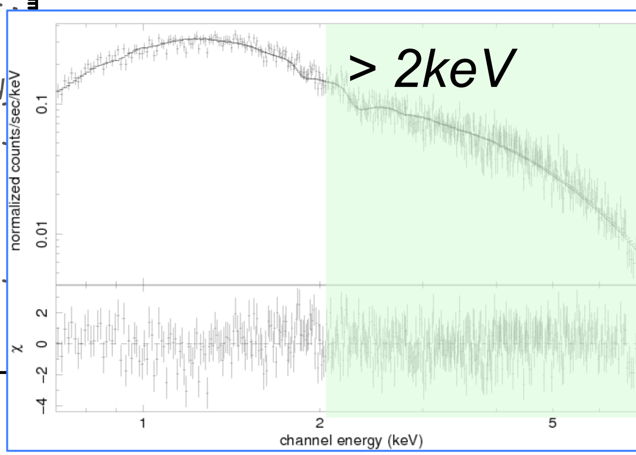
Isolated Neutron Stars in X-rays

Since *Einstein*, Isolated Neutron Stars are major targets for X-ray observatories



Harding 2013
For a review on INS zoology

PSR B0540-69



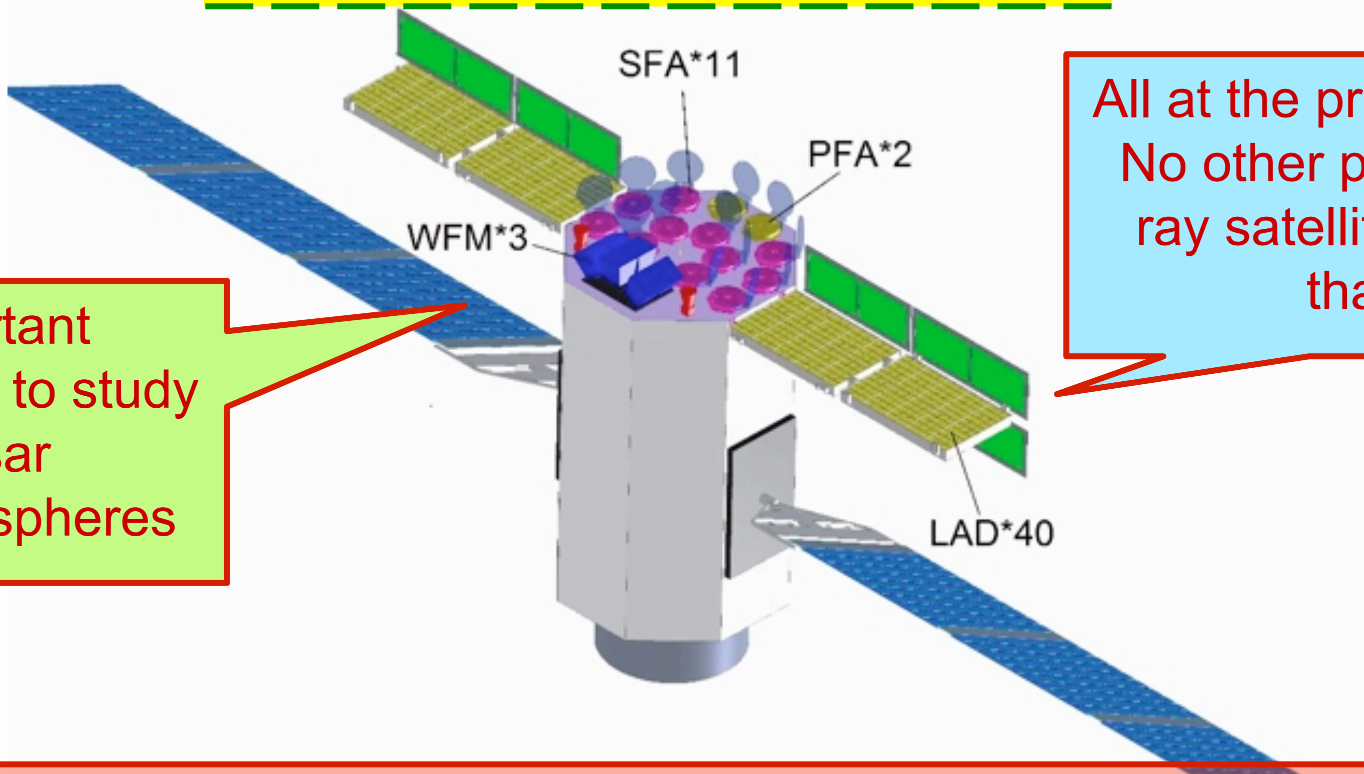
eXTP potentials for some INS classes **are limited** (or null) by the source **soft X-ray** spectra (e.g. **XINSs**, **CCOs**), *unless extending response to ~1 keV*
Rotation-Powered Pulsars (**RPPs**) –and **magnetars**- are the best targets

Major advances from eXTP

High time resolution X-ray timing (LAD; <10μs), not possible with *ATHENA*

X-ray polarimetry (PFA), sensitivity ~better than *IXPE* and comparable to *XIPE*

Phase-res X-ray spectroscopy (LAD+SFA; <10μs) <250 eV,180 eV



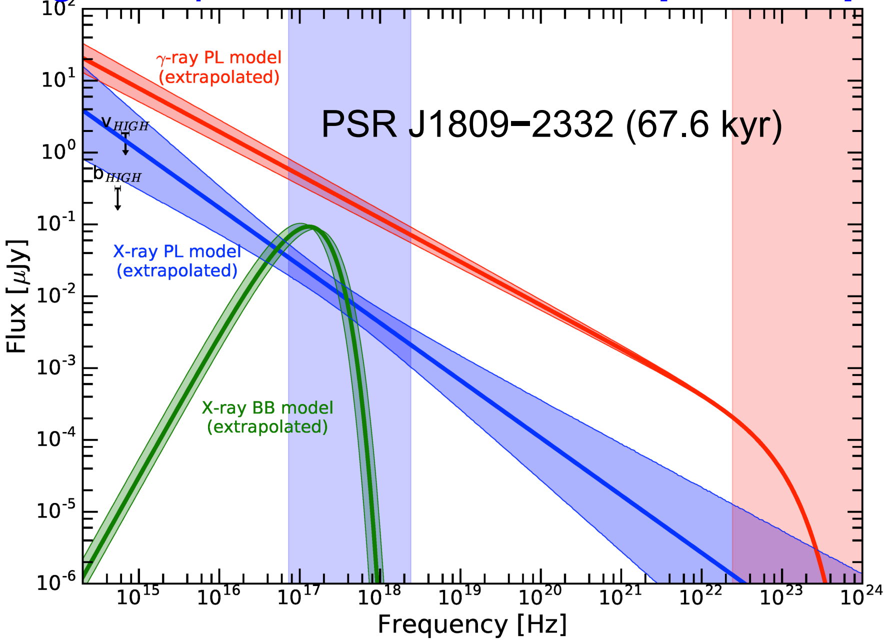
Important diagnostic to study pulsar magnetospheres

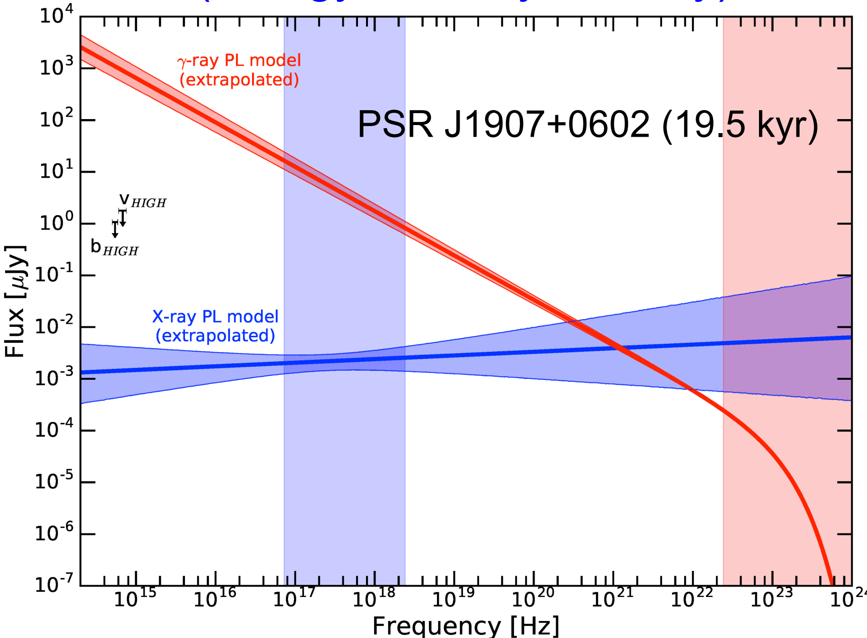
All at the price of one ! No other planned X-ray satellite can do that!

Smaller **effecive area** wrt to *LOFT* and *XIPE* compensated by synergy between LAD & PFA

Pulsar Magnetospheres

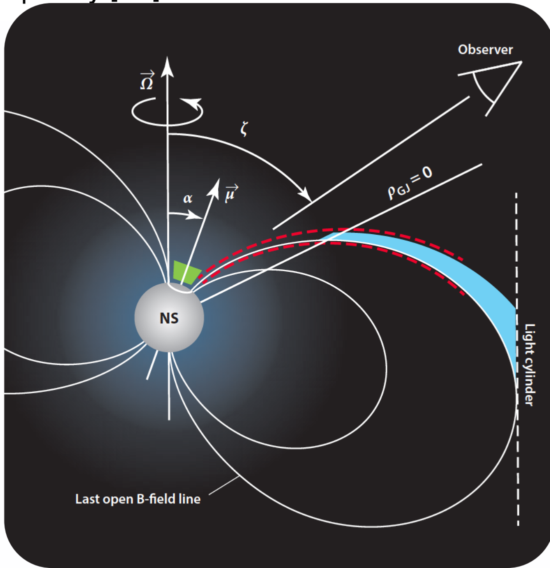
Is the emission produced at **different regions and altitudes** in the pulsar magnetosphere, from **different particle populations** (energy, velocity, density)?





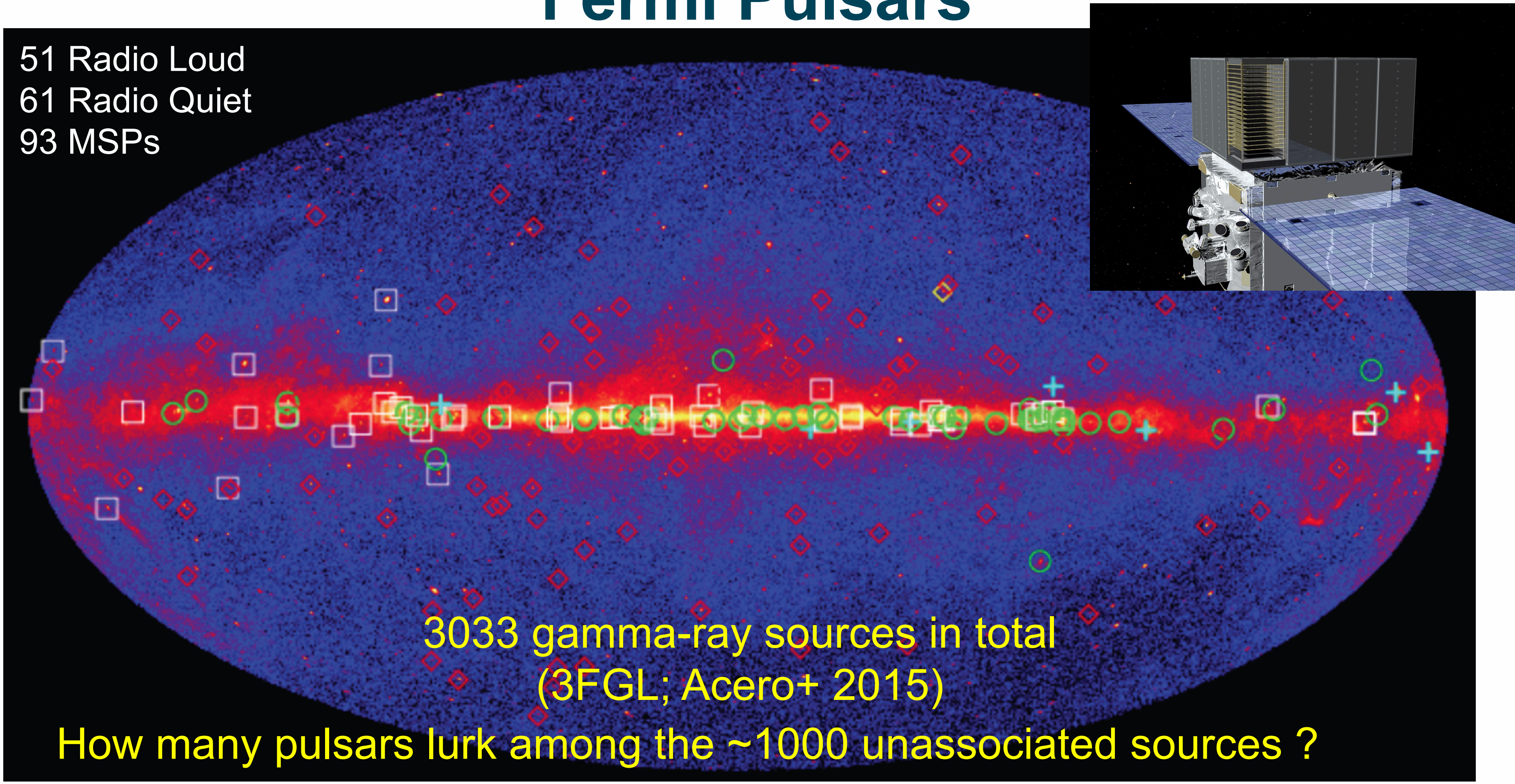
Mignani et al. (2016)

- **How this affects** the multi-wavelength spectra?
- What is producing the **difference seen** even in seemingly similar pulsars?
- Are **different spectra** associated with a **different emission** or **viewing geometry**?



- A large multi-wavelength data base extending from the γ-rays to the optical is crucial to address these points

Fermi Pulsars

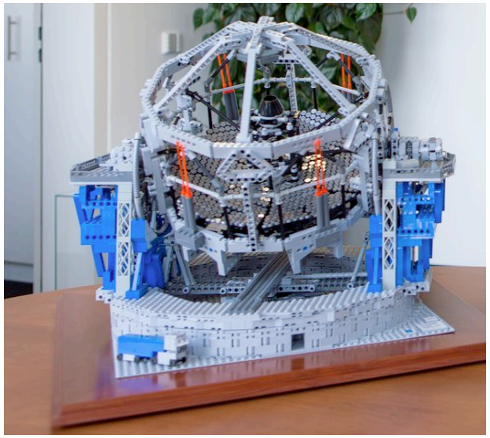


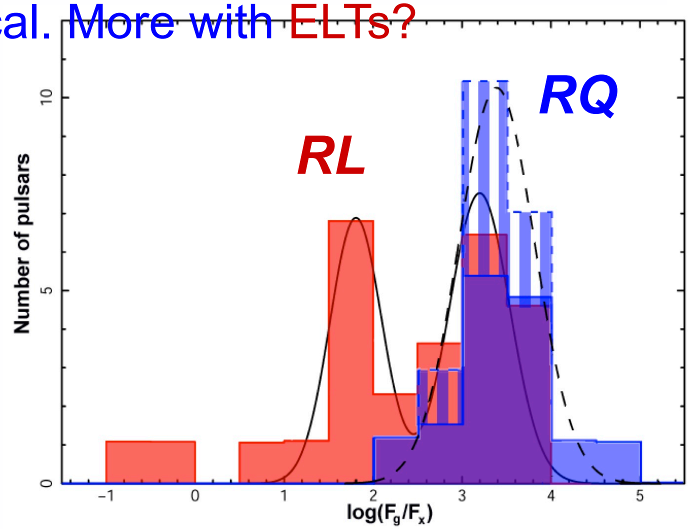
- Only **7** gamma-ray pulsars known before the launch of *Fermi* (June 2008)
- **117** pulsars in 2nd *Pulsar Gamma-ray Catalogue* (2PC); Abdo+ 2013, ApJS, 208, 17
- **205** As of May 2016[1], and counting … 3PC is coming ……
- Reference for multi-wavelength follow-ups (Marelli+ 2015; Mignani+ 2016)

[1] *https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars*

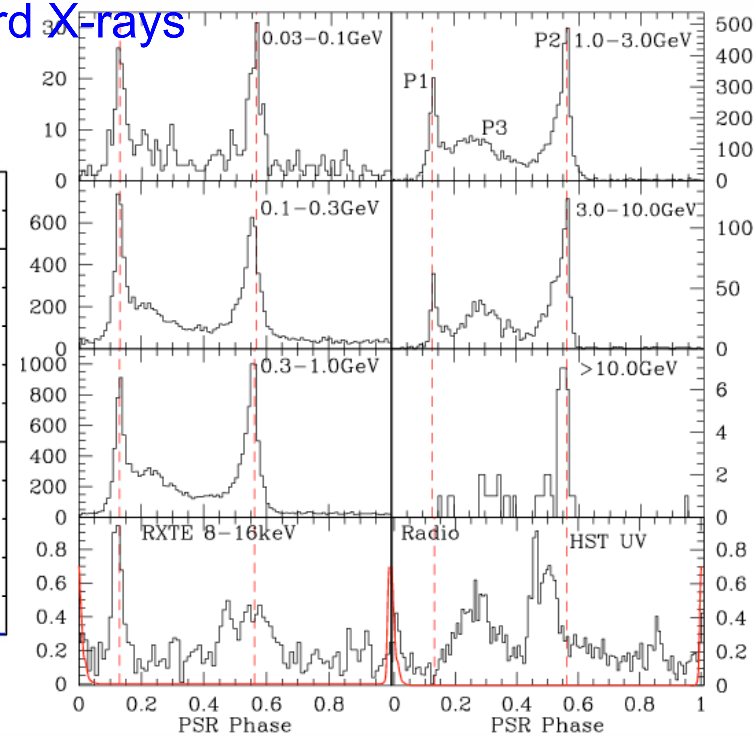
Pulsar Timing

- MWL timing is crucial to map different emission regions
- All pulsars detected in γ-rays are γ-ray pulsars by definition !
- **28**/39 RQ + **30**/42 RL LAT pulsars detected in the X-rays (Marelli+ 2015) BUT Only **7** RQ+**15** RL pulsate in X rays. Need **good quality** X-ray light curves, like Vela
- Is the emission geometry producing the bi-modal F_γ/F_X distribution ?
- LAD can measure X-ray light curves >2keV* down to F_X~3 10^{-13} erg cm^{-2} s^{-1}→ **~20** of the *LAT* pulsars detected in X-rays
- Double the number of pulsar seen to pulsate in hard X-rays
- Optical needed to set the picture. **5** LAT pulsars pulsate in the optical. More with ELTs?





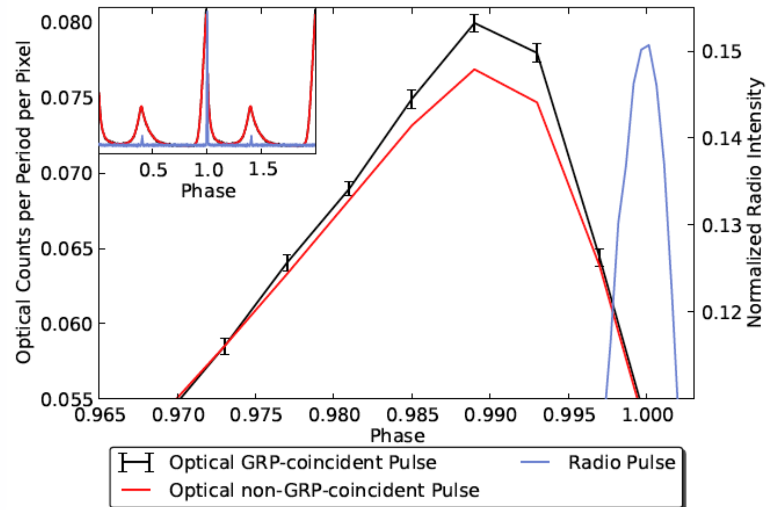
Vela pulsar

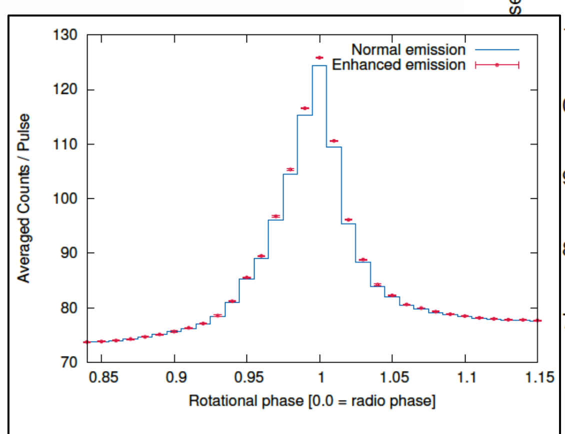


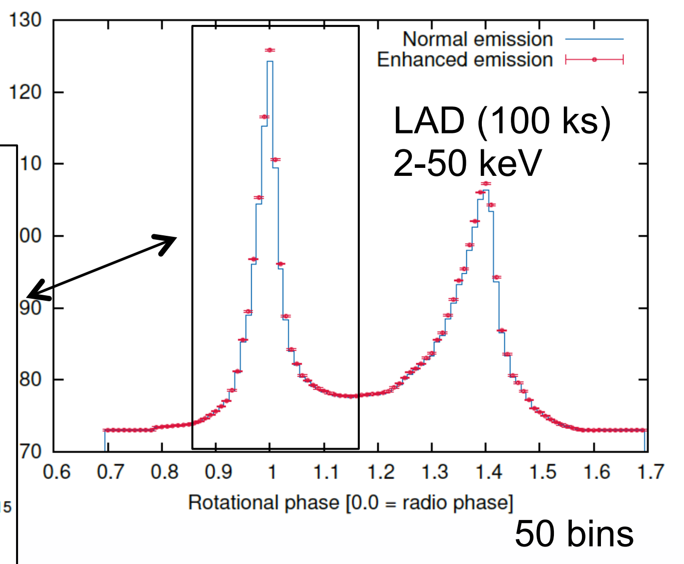
**Assuming a 50% PF and a 0.1 FWHM (T=30 Ks)*

A special case: Giant pulses in radio pulsars

- Giant Radio Pulses (GRPs) are erratic variation of the peak-to-peak single pulse intensity (few %)
- GP also seen in the optical (GOPs) in the Crab pulsar (Shearer+ 2003; Collins+ 2012; Strader+ 2013)
- GOPs occur in time with GRPs (coherent vs. incoherent radiation)
- Not yet observed in X (Bilous+ 2012) and γ-rays (Lewandowska+ 2011).
- We estimated the LAD sensitivity to Crab GP through single-pulse analysis on 303000 Monte Carlo simulated light curves
- For $\Delta P/P_{opt} \sim \Delta P/P_X$ LAD will detect ~0.3% GXPs in the Crab MP
- Not possible with any other existing/planned X-ray mission

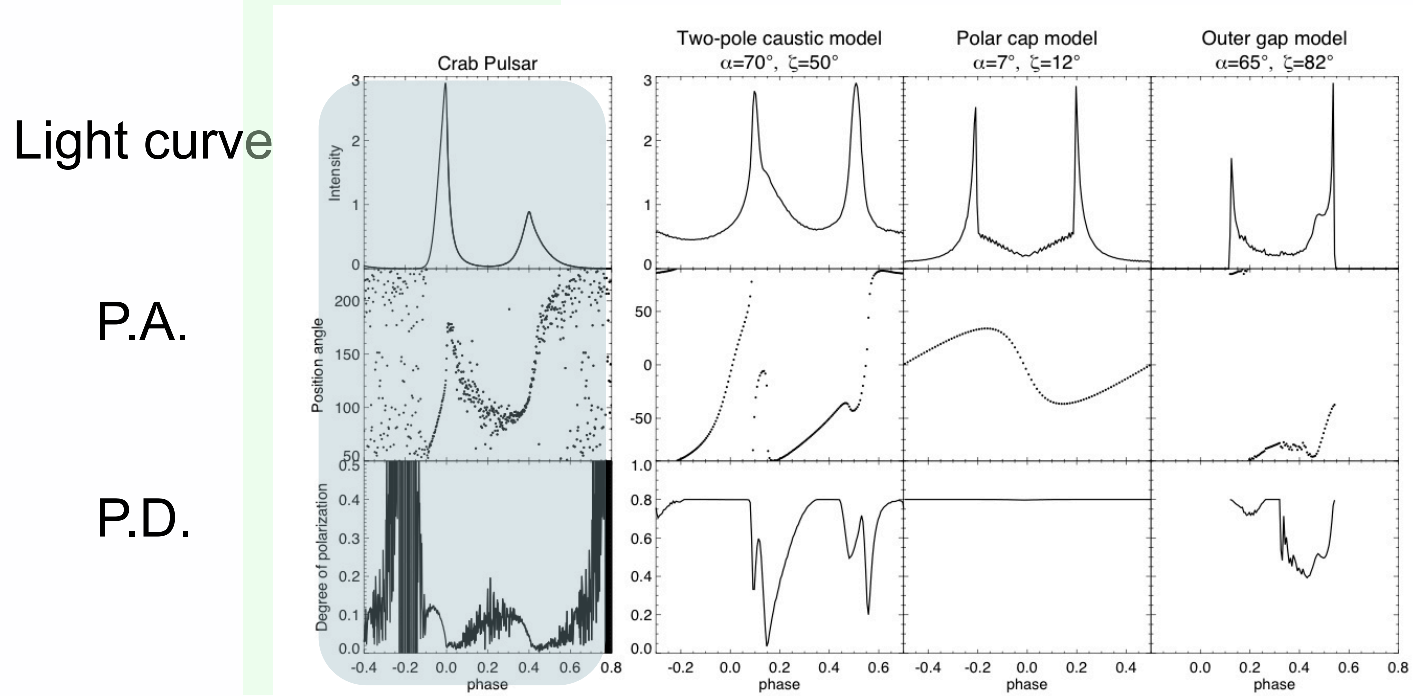






Pulsar Polarimetry

- 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.



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

- X-ray polarimetry will open a new channel – **optical observations are a reference**

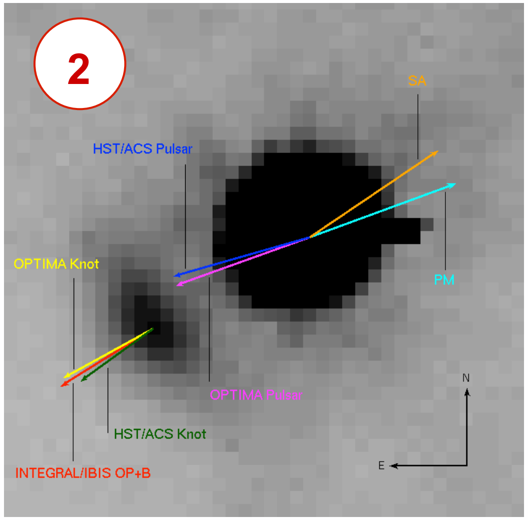
Pulsar Optical Polarisation

- 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)

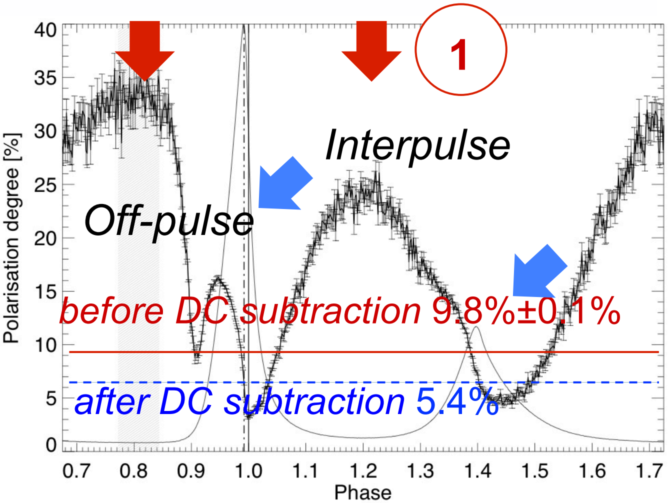
② Higher spatial resolution polarisation maps (structures)

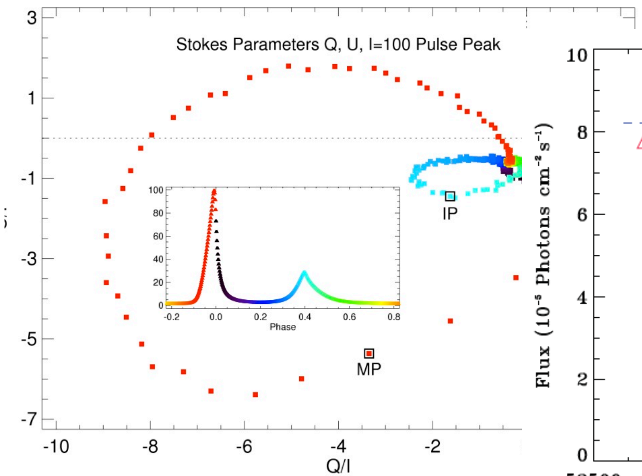
③ Secular changes in the pulsar polarisation (flares)



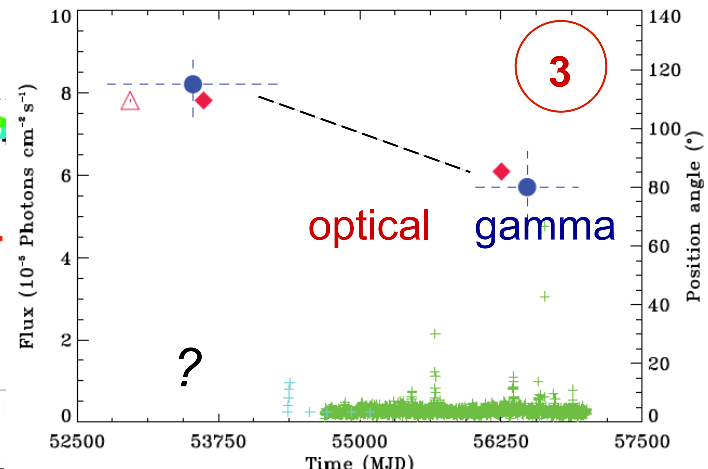
Moran et al. (2013)

Slowikowska et al. 2009





Slowikowska et al. (2009)



Moran et al. (2016)

✓ Alignment between pulsar polarisation and proper motion PA

Andy's talk

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

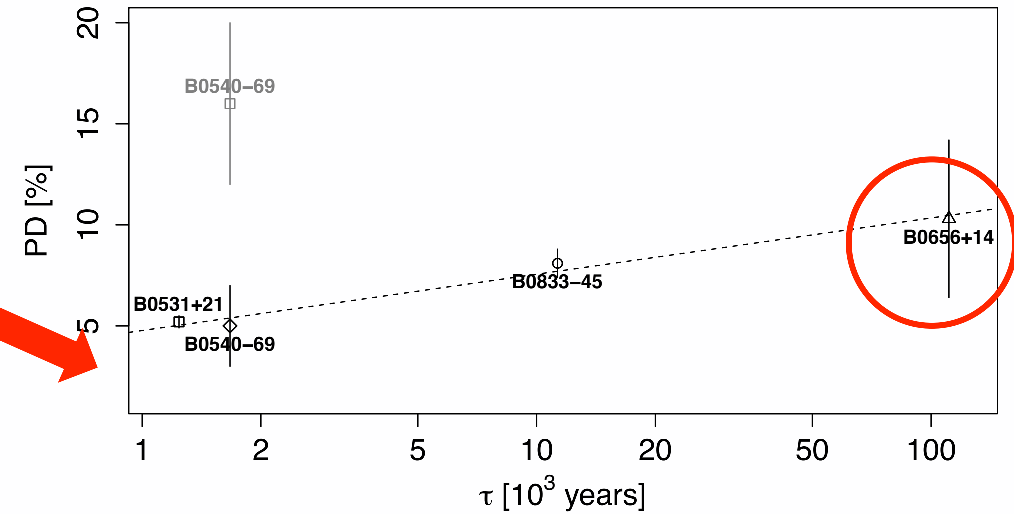
(1) Moran et al. (2013); (2) Słowikowska et al. (2012); (3) Lundqvist et al. (2011); (4) Mignani et al. (2010); (5) Wagner & Seifert (2000); (6) Moran et al. (2014); (7) Mignani et al. (2007)

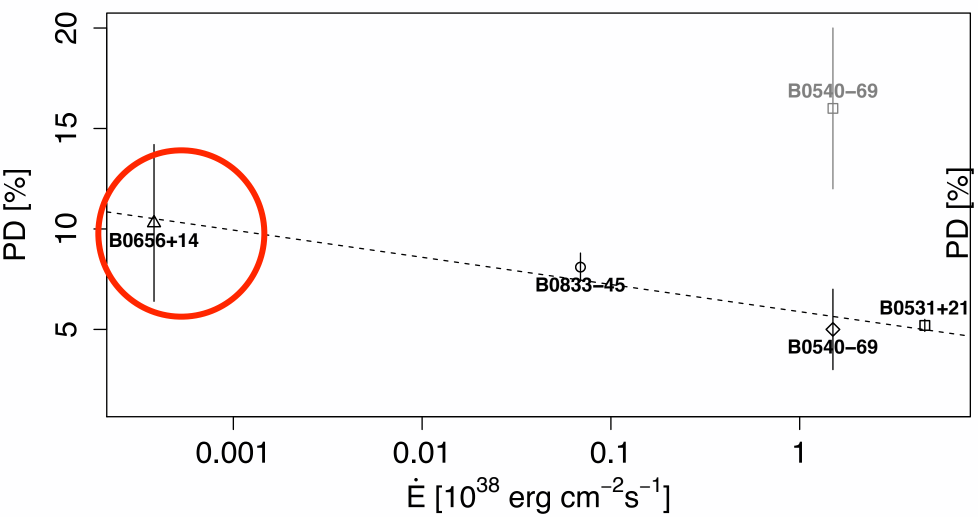
- **PD values ~5%-10%**, below model predictions ! And much less than radio.

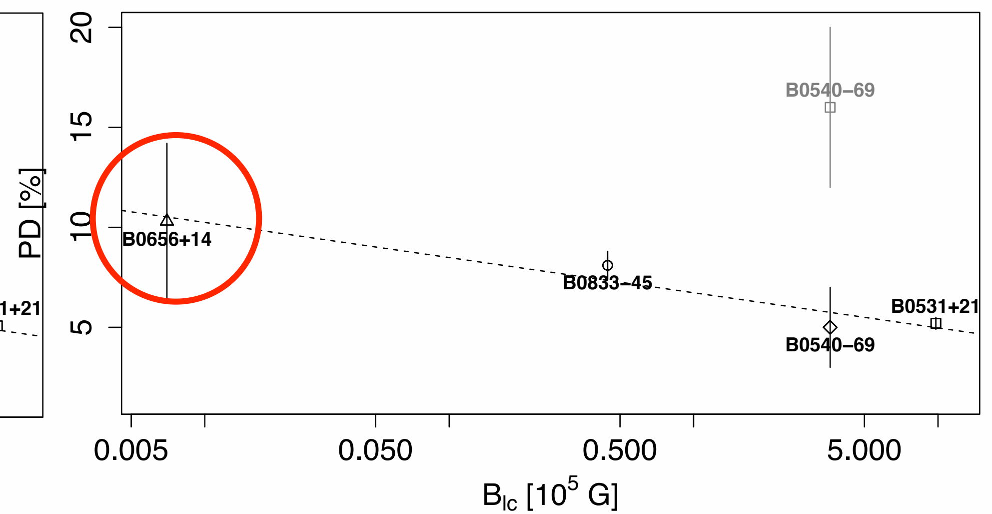
- Expand the sample and revisit uncertain cases (**PSR B1509-58**):
- Phase-resolved polarimetry of **PSR B0540-69** (possibly of **Vela**, as well) – only possible with guest instruments (e.g. GASP) !
- Phase-average polarisation of **Geminga** (V~25.5)
- Phase-resolved polarimetry of the **Crab** continuing – Giant Pulse polarimetry

Pulsar optical polarisation, emerging picture

PD seems to be higher for older and less energetic pulsars



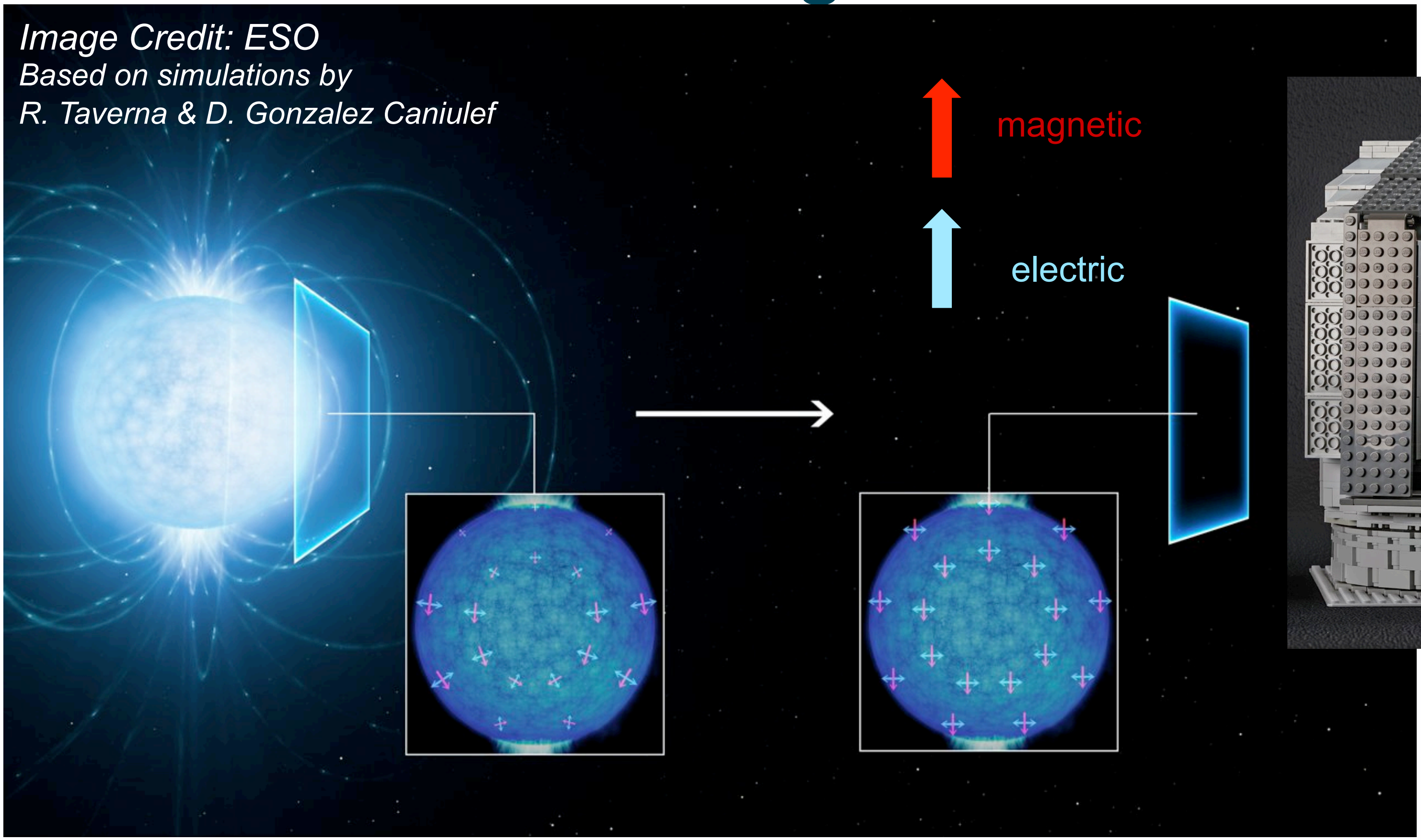


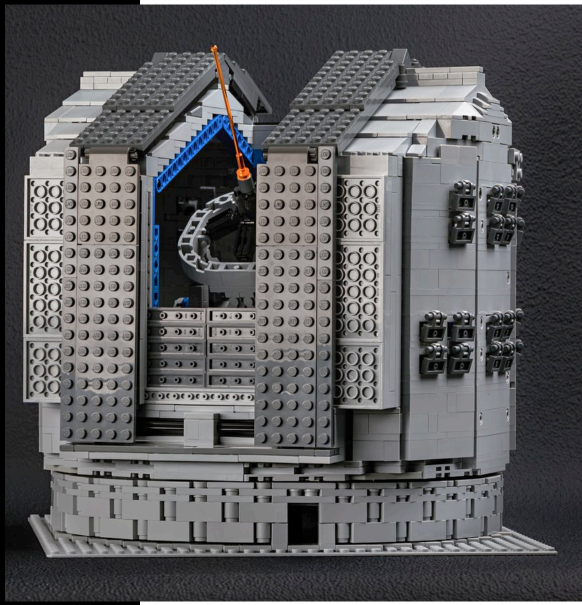


Trends biased by B0656+14 !
Measurement for Geminga crucial

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

Vacuum Birefringence in Neutron Stars





Jeremy's talk

- Optical polarisation measurement for RX J1856.5-3754 (Mignani+ 2017), obtained with the VLT; PD=16.43%±5.26%. → Follow-up VLT observations in progress
- Measurement not explained without introducing vacuum birefringence effects. First observational evidence. To be searched for in X-rays too (Gonzalez Caniulef talk).
- Spectrum not hard enough for *eXTP* but a major target for future soft X-ray polarimetry missions (Marshall's talk)

Pulsar/PWN X-ray polarisation

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

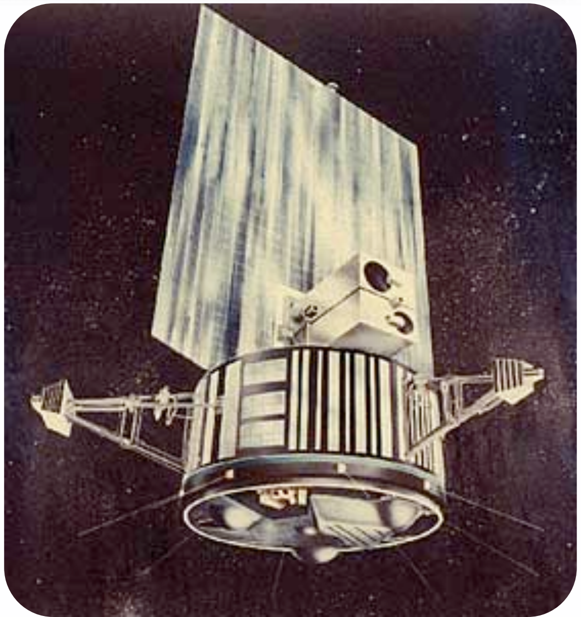
See Hua Feng's talk

- 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)

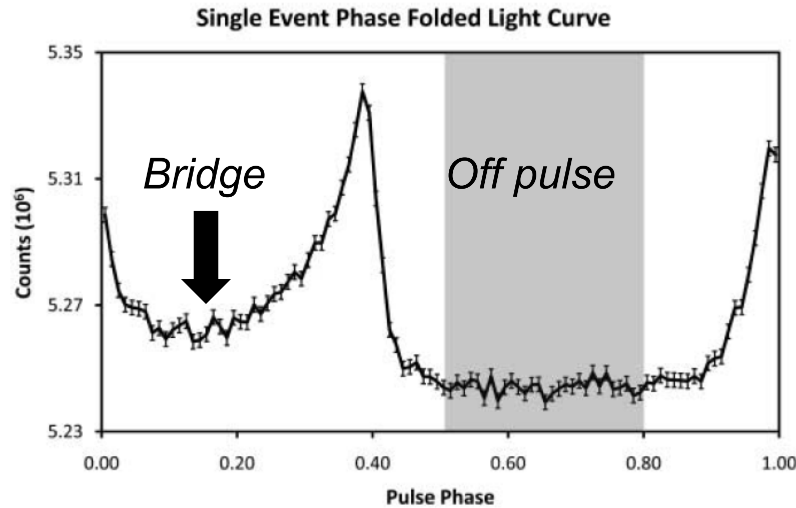
- After **Pulsar subtraction** (Weisskopf et al. 1978):
  PD=19.2%±1.0%, PA=156.4°±1.4° @2.6 keV
  PD=19.5%±2.8%, PA=152.6°±4.0° @5.2 keV

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



Pulsar Gamma-ray polarisation

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

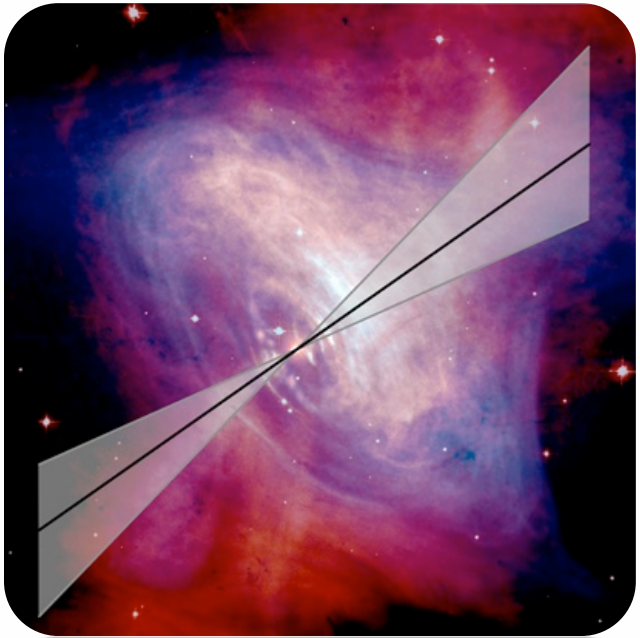


- Off-pulse events only (0.1-1 MeV) → **nebula** (pulsar localisation within ± 20")

- Off pulse: PD=46%±10%, PA=123°±11°

- **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**

Crab Multi-wavelength polarisation

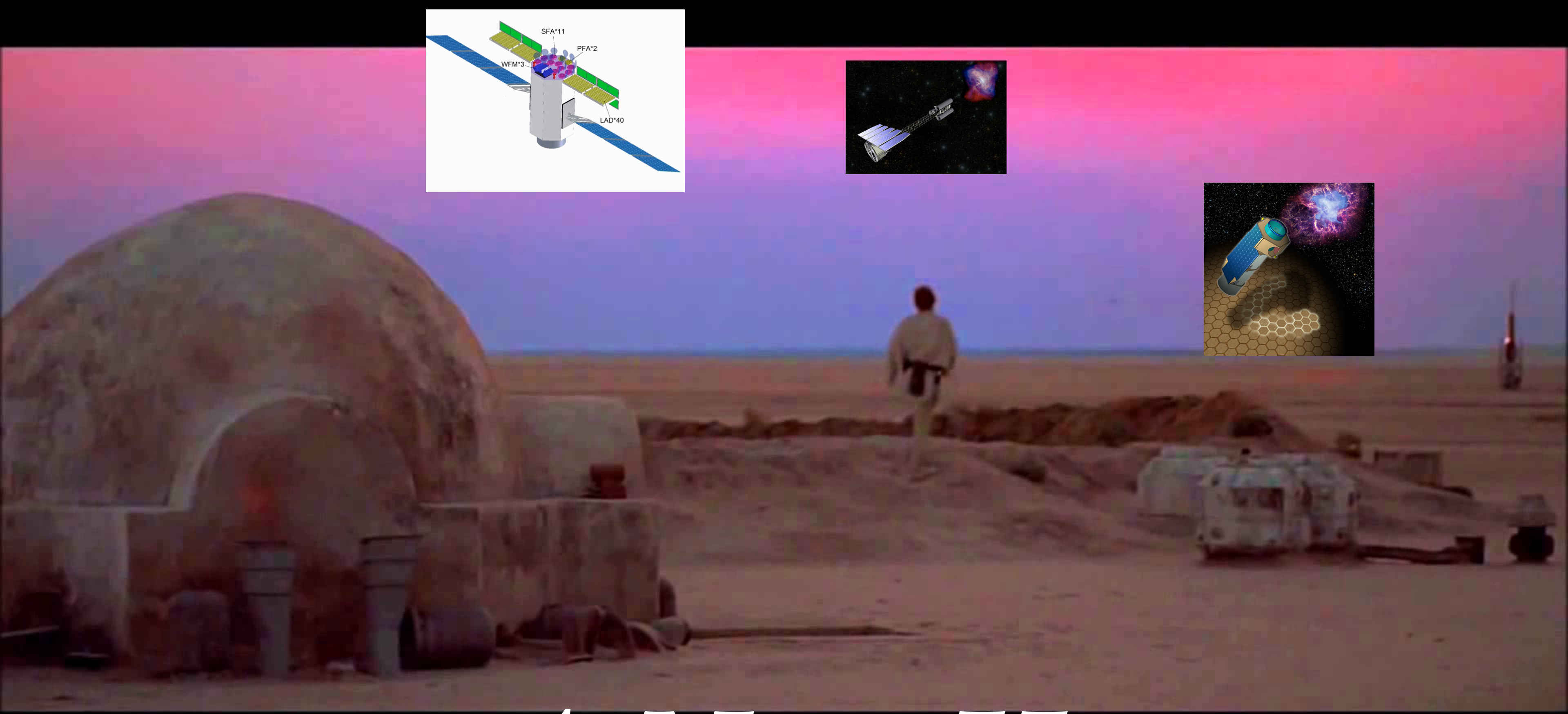
	Polarisation (%)	Position Angle (°)
[1] γ-ray (0.1-1 MeV) OP *nebula*	46 ± 10	123 ± 11
[2] γ-ray (0.2-0.8 MeV) OP *nebula*	> 72	120.6 ± 8.5
[2] γ-ray (0.2-0.8 MeV) OP+B *nebula*	> 88	122.0 ± 7.7
[2] γ-ray (0.2-0.8 MeV) $P_1 + P_2$ *pulsar*	$42 \pm^{30}_{16}$	70 ± 20
[3] *X-ray (20-120 keV)* *pulsar*	<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 multi-wavelength PD and PA difficult.**

- Different phase intervals (off-pulse, phase-averaged, pulsed)
- Different spatial regions (different contibution from the PWN and SNR)
- Different energies – PD seems to decrease with energy – need to investigate against a wider sample



A New Hope

eXTP Potential Targets

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

Many bright PSRs are embedded in PWNe

PWN contamination problem - eXTP/GPD resolution <30” (goal<15”)

Selected PSRs with PWN flux ~0.1PSR flux within a 30”radius (exception Crab and Vela) **~20 possible targets**

Caveat: **faint PWN does not mean little 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	9.18	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

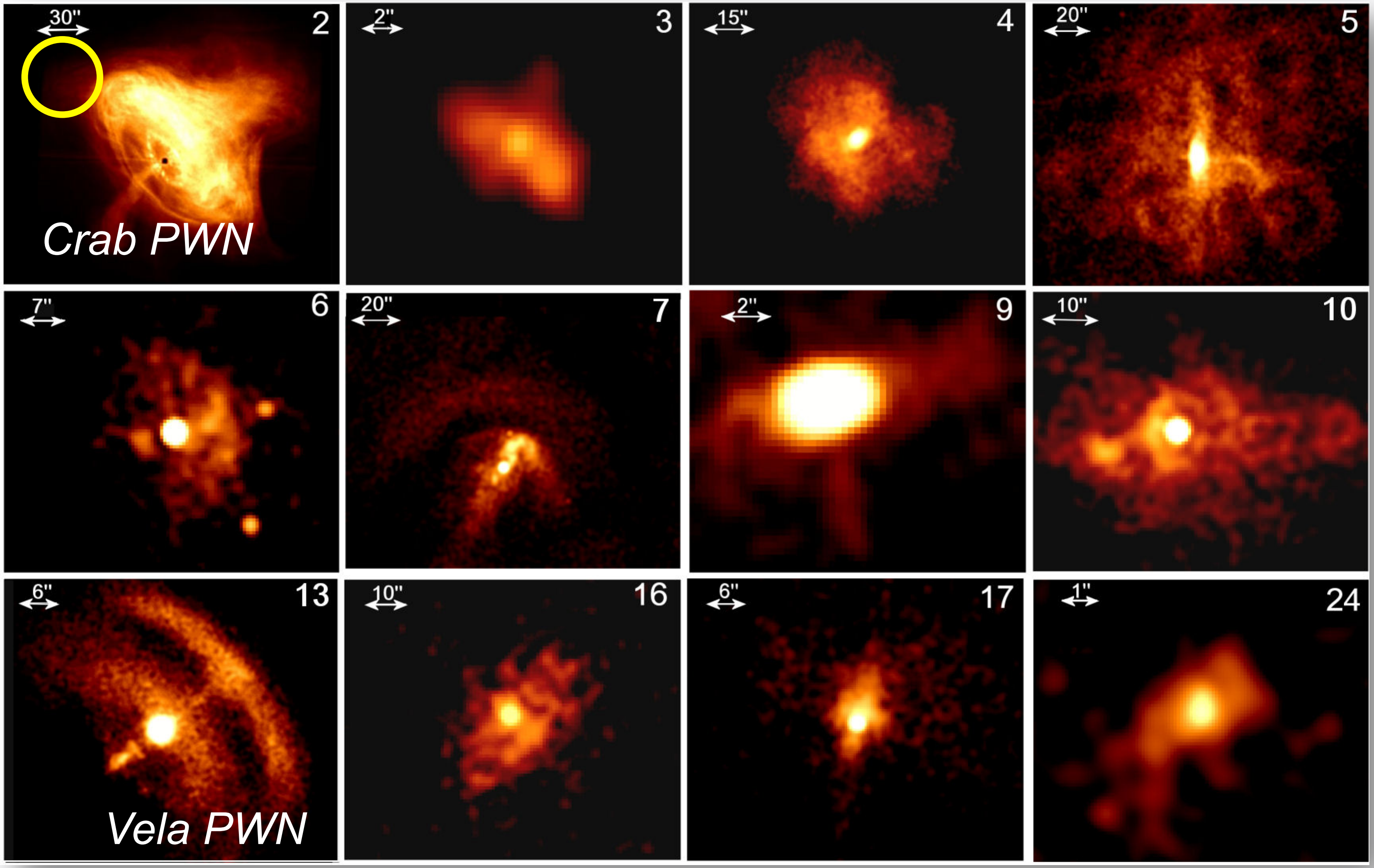


Image Credit: G.G. Pavlov, O. Kargaltsev (PSU)

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)

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]

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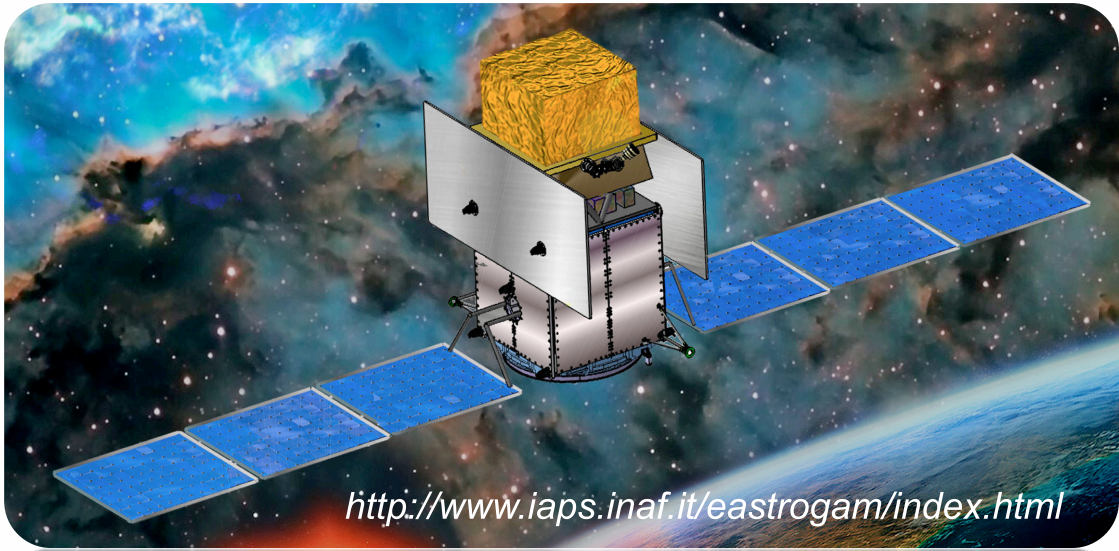
Abstract

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

- Candidate ESA/M5 mission to explore the γ-ray sky in the 0.3 MeV-3 GeV energy range (PI. De Angelis)



- Polarisation measurements possible from pair creation and Compton scattering

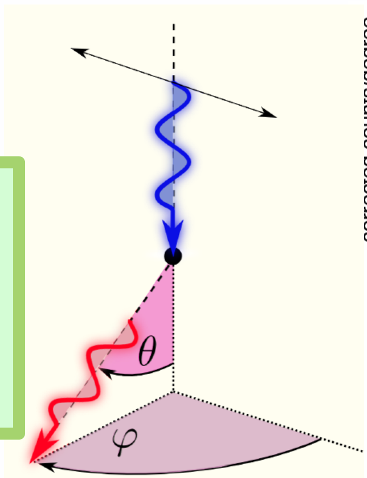
- At low energies (0.2 - 2 MeV), e-ASTROGAM will be achieve an MDP as low as 0.7% for a Crab-like source in 1 Ms

- Monitor changes in polarisation following γ-ray flaring events and verify proposed correlation with optical (Moran et al. 2016)

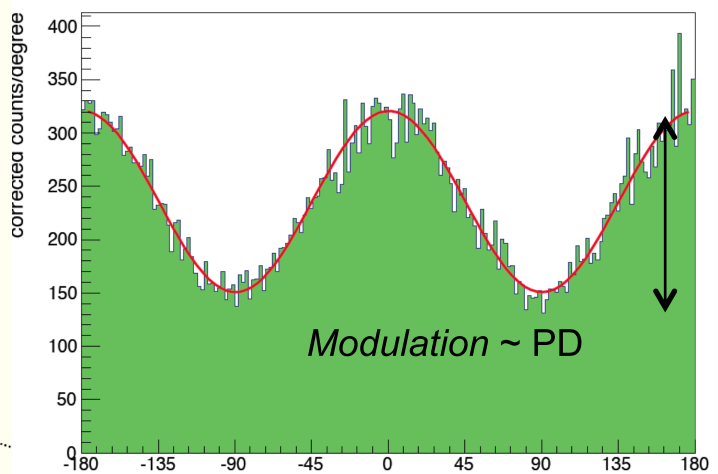
<u>*End of Talk Commercial:*</u>

eASTROGAM the Extreme Universe

February 28th-March 2nd, Padua, Italy



Compton scattering



Azimuth scatter angle distribution

Summary and Conclusions

- Accurate X-ray light curves with *eXTP*/LAD crucial to:
- ***determine the emission geometry in pulsar magnetosphere***
- ***track fast changed by revealing GP in X-rays for the first time***
- ***discover new X-ray pulsars (X-ray ephemeris for γ-ray pulsation search)***

- After the radio band, most pulsar polarisation measurements obtained in the optical
- In the X-rays, polarisation measurements only for the Crab (nebula and pulsar)
- eXTP will make it possible to conduct X-ray polarisation studies on a larger sample

Measurements X-ray polarisation with *eXTP*/PFA will allow to:

- ***Verify dependence of PD vs energy (e.g., optical vs X-ray)***
- ***Verify dependence of PD vs X-ray spectrum (soft/hard vs low/high PD)***
- ***Verify dependence of PD vs. pulsar parameters (age, Edot, ..)***

- ***With eXTP, eASTROGAM, and (hopefully) future optical facilities (ELTs?) will enter the era of multi-wavelength polarimetry***