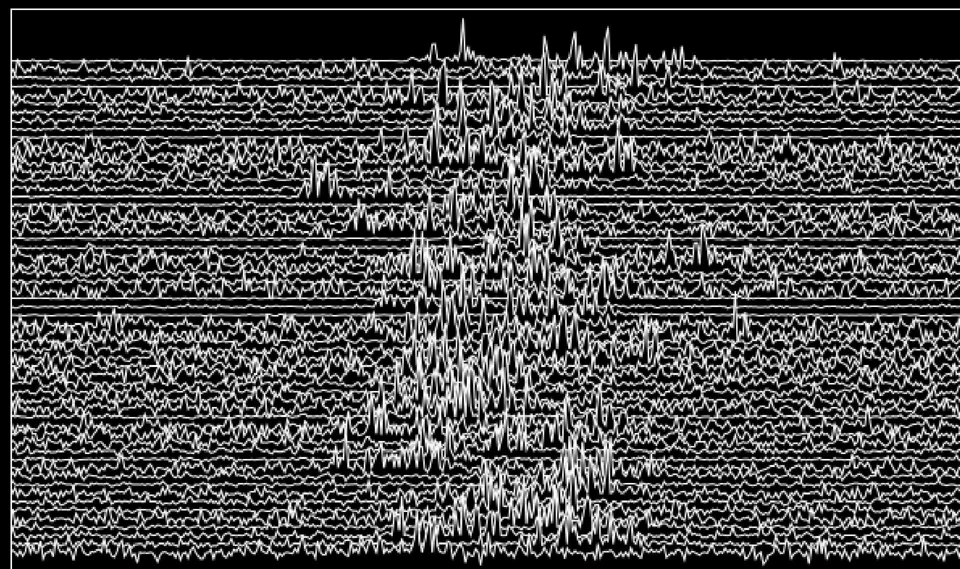
Giant Pulses from PSR B1937+21 using the Large European Array for Pulsars



Bonn Neutron Star Workshop

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In collaboration with B. Stappers, C. Bassa, S. Chen, I. Cognard, M. Gaikwad, G. Janssen, R. Karuppusamy, M. Kramer, K. Lee, K. Liu, D. Perrodin, S. Sanidas R. Smits, L. Wang, W. Zhu

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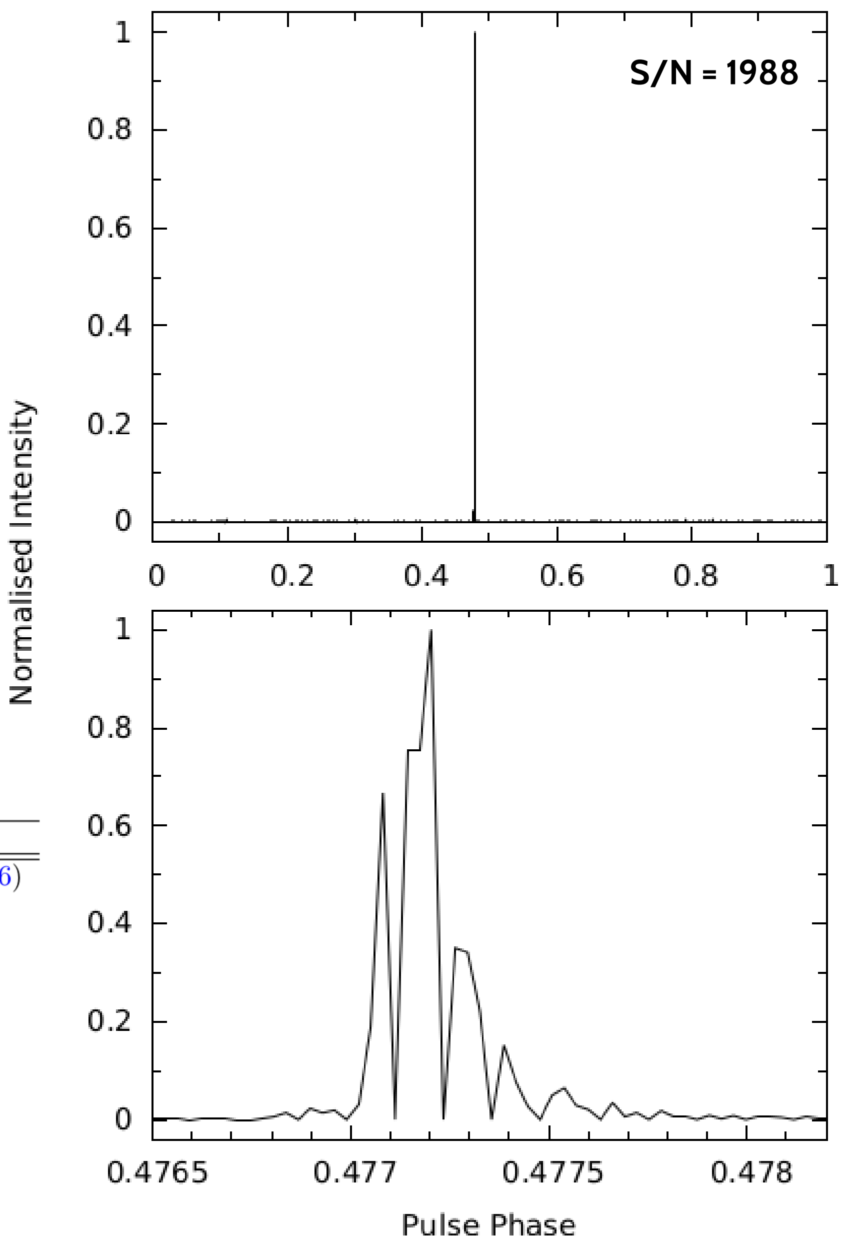
Introduction

- Detected 4265 giant pulses (GPs) from B1937+21 in 21 observations with the Large European Array for Pulsars (LEAP)
- Obtained pulse energy distributions
- Estimated emission rates of detectable GPs from cosmological distances and the Galactic Centre
- Measured the phase-dependent intensity modulation of GPs
- Measured scattering and DM variations, polarisation properties
- Explored the prospects of using GPs to time the pulsar

Giant Pulses - Description

- Occasional single pulses with flux densities greatly exceeding that of the single-pulse average
- Detected in only 14 pulsars to date (see table)
- Generated by a different emission mechanism to the regular emission
  - Originally thought to be linked to magnetic field strength at the light cylinder, B_{LC} (Cognard et al. 1996)
- Pulse width of GPs much narrower than regular single pulses
  - Unresolved durations as short as 2 ns in the case of the Crab Pulsar (Hankins et al. 2003)
- Pulse energy distributions usually well-modelled as a power law
- GP emission occurs in a narrow phase window, often offset from the regular radio components, but aligned with the high-energy emission (Cusumano et al. 2004)

Name	B_{LC} (G)	Rank	Reference
B1937+21 (J1939+2134)	1.0×10^6	2	Wolszczan et al. (1984), Cognard et al. (1996)
B0531+21 (J0534+2200)	9.6×10^5	3	Staelin & Reifenstein (1968)
B1821−24A (J1824−2452A)	7.4×10^5	4	Romani & Johnston (2001)
B1957+20 (J1959+2048)	3.8×10^5	6	Joshi et al. (2004)
B0540−69 (J0540−6916)	3.6×10^5	7	Johnston & Romani (2003)
J0218+4232	3.2×10^5	9	Joshi et al. (2004)
B1820−30A (J1823−3021A)	2.5×10^5	16	Knight et al. (2005)
B0656+14 (J0659+1414)	770	437	Kuzmin & Ershov (2006)
B0950+09 (J0953+0755)	140	790	Singal (2001), Smirnova (2012)
J1752+2359	71	1007	Ershov & Kuzmin (2005)
B0529−66 (J0529−6652)	39	1183	Crawford et al. (2013)
B0031−07 (J0034−0534)	7.0	1694	Kuzmin et al. (2004)
B1112+50 (J1115+5030)	4.2	1832	Ershov & Kuzmin (2003)
B1237+25 (J1239+2453)	4.1	1843	Kazantsev & Potapov (2017)



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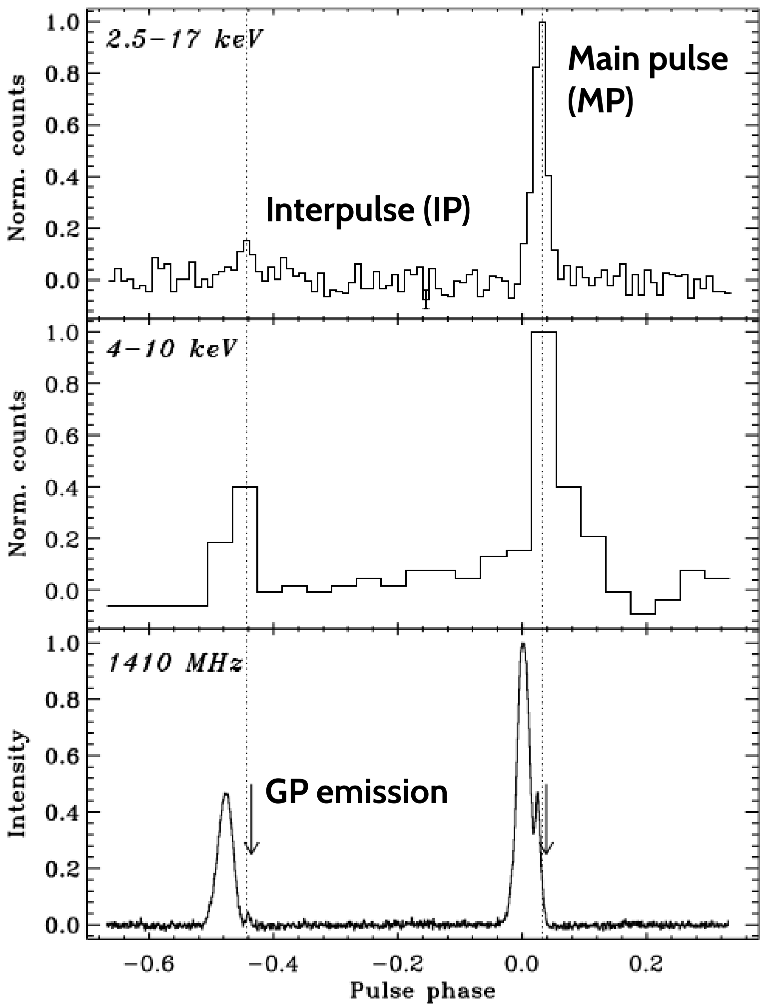
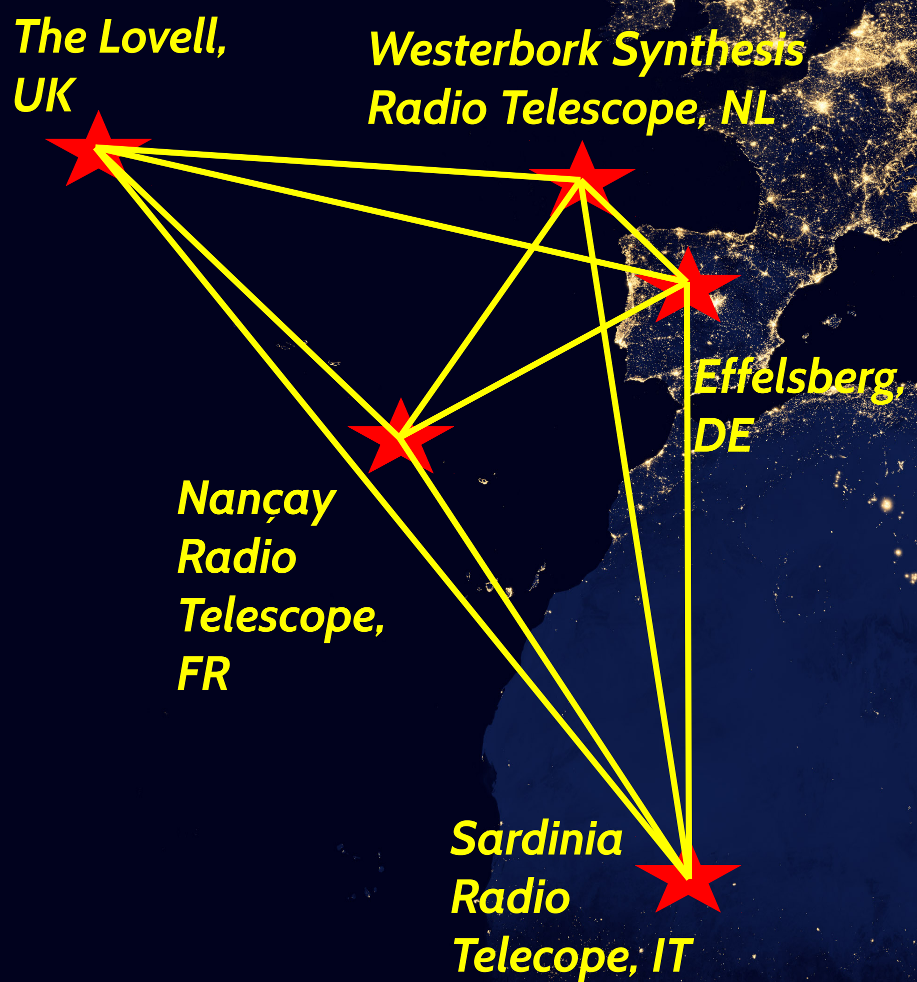


Figure from Cusumano et al. (2003)

LEAP: The Large European Array for Pulsars



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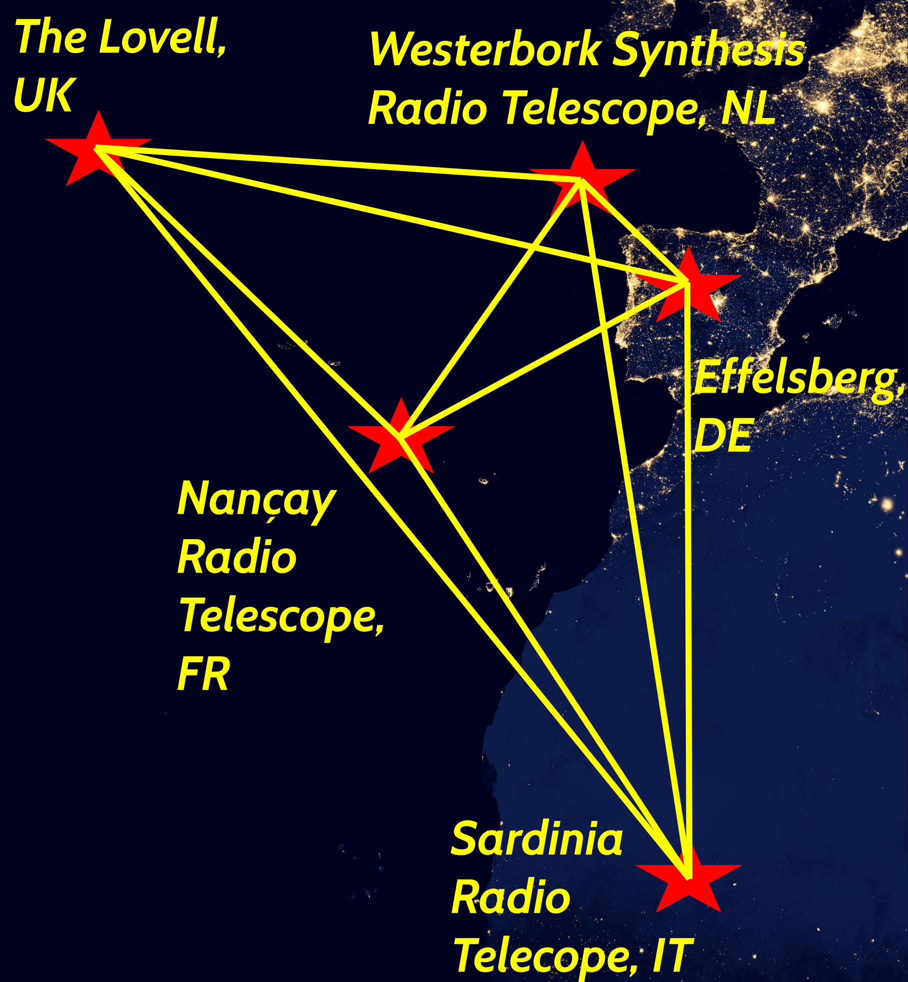
LEAP: The Large European Array for Pulsars



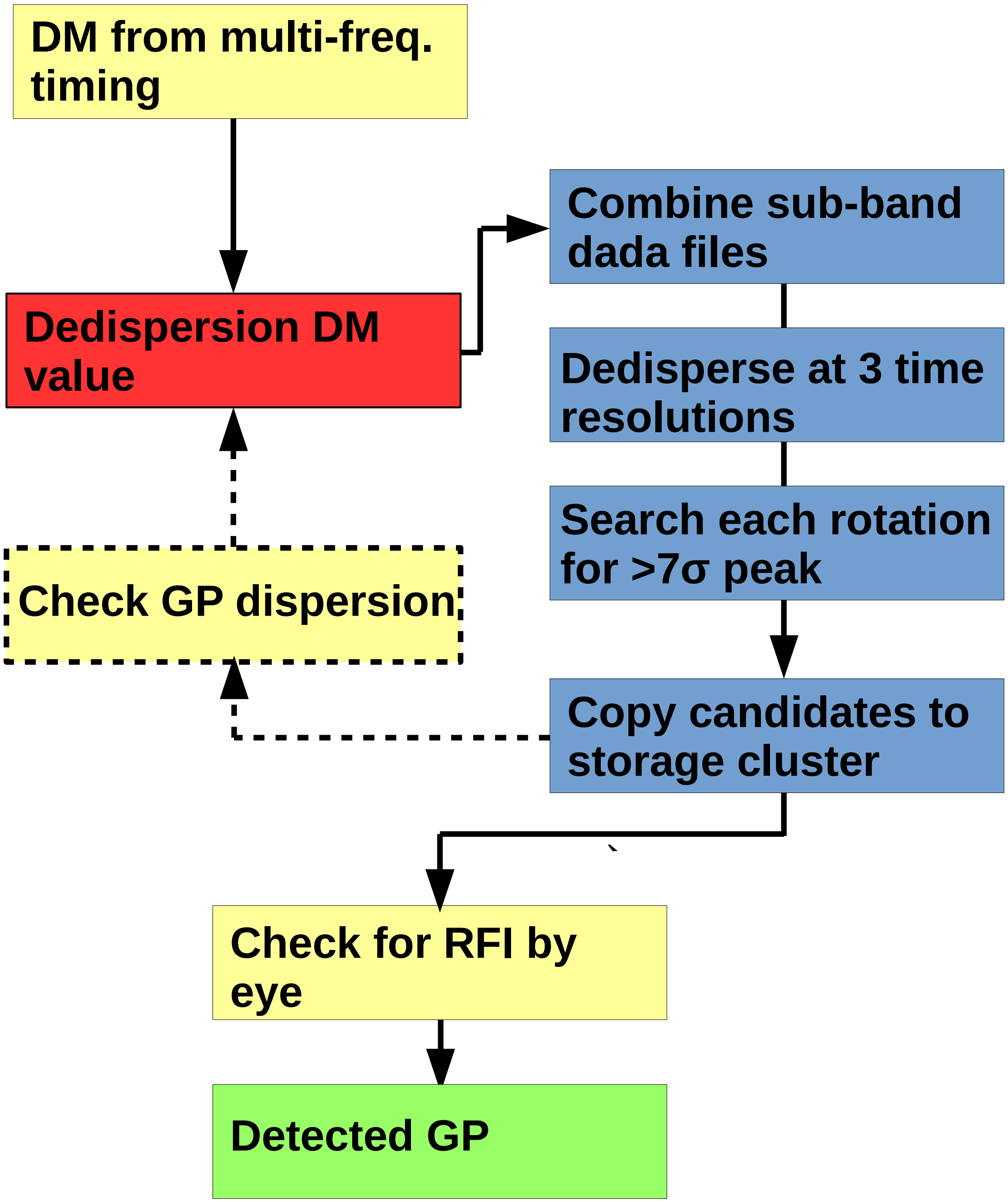
- Tied-array consisting of combinations of Effelsberg Telescope (DE), The Lovell (UK), Nançay Radio Telescope (FR), Sardinia Radio Telescope (IT), Westerbork Synthesis Radio Telescope (NL)
- Equivalent dish size (all 5 telescopes): 195-m
- Monthly observations of MSPs (from 2012 until present)
- Phase up initially on nearby calibrator, then later on the pulsar itself
- Centre Freq. 1396 MHz
- Bandwidth: 128 MHz
- Polarisation calibrated
- Baseband data recorded, shipped to Jodrell Bank for offline processing
- Coherent addition of baseband data
- Combined baseband data saved to tape for future scientific use

Experiment overview: Bassa et al. (2016)

Software correlator overview: Smits et al. (2017)

Giant Pulses Search

- LEAP is ideal for single-pulse studies of pulsars (Liu et al. 2016)
- Searched for GPs in 21 observations of PSR B1937+21 with LEAP
- GP search performed on each rotation individually
- DM calibrated by searching for high-S/N GPs and minimising their pulse width
- Apply the DM from these to the coherently dedisperse and search the full observation for GPs
- Select all candidates greater than 7σ at 3 different time resolutions (48 ns, 95 ns, 190 ns)



Search Summary

Date	Telescopes	f_c (MHz)	BW (MHz)	T_{obs} (sec)	$S/N_{profile}$	N_{MGP}	N_{IGP}	N_{GP}
20120923 (1)	EJW	1412	64	1240	719	125	77	202
20120923 (2)	EJW	1412	64	1020	808	124	74	198
20130727	EJW	1404	112	1800	525	138	106	244
20130825	EW	1364	64	2700	1065	278	154	432
20140522	ESW	1396	128	2760	904	168	83	251
20140707	EW	1420	80	2770	435	172	84	256
20140727	EW	1380	96	2760	492	31	22	53
20140824	EJNW	1396	128	2490	852	155	75	230
20141015	EJNW	1380	64	1470	587	139	76	215
20150225	EJNW	1396	128	2120	715	145	94	239
20150326	EJNSW	1396	128	2510	1232	171	87	258
20150417	EJNSW	1396	128	2510	1202	137	52	189
20150620	EJW	1396	128	2230	598	112	63	175
20150719	EJS	1412	96	2790	458	112	92	204
20150918	EJN	1404	112	2520	429	90	32	122
20151010	EJ	1412	96	2790	543	112	52	164
20151107	EJS	1396	128	2790	729	81	55	136
20151212	EJNS	1396	128	2520	755	138	55	193
20160109	EJNS	1396	128	2520	1122	154	99	253
20160205	EJNS	1404	112	2390	629	97	49	146
20160407	EJNS	1388	80	2380	924	110	48	158
Mean	-	-	-	2337	709	133	70	203
Total	-	-	-	49080	-	2789	1476	4265

- MGP:IGP ratio = 65:35
- Average detection rate:
  - MGP: 205 hr^{-1}
  - IGP: 108 hr^{-1}
  - Total: 313 hr^{-1}

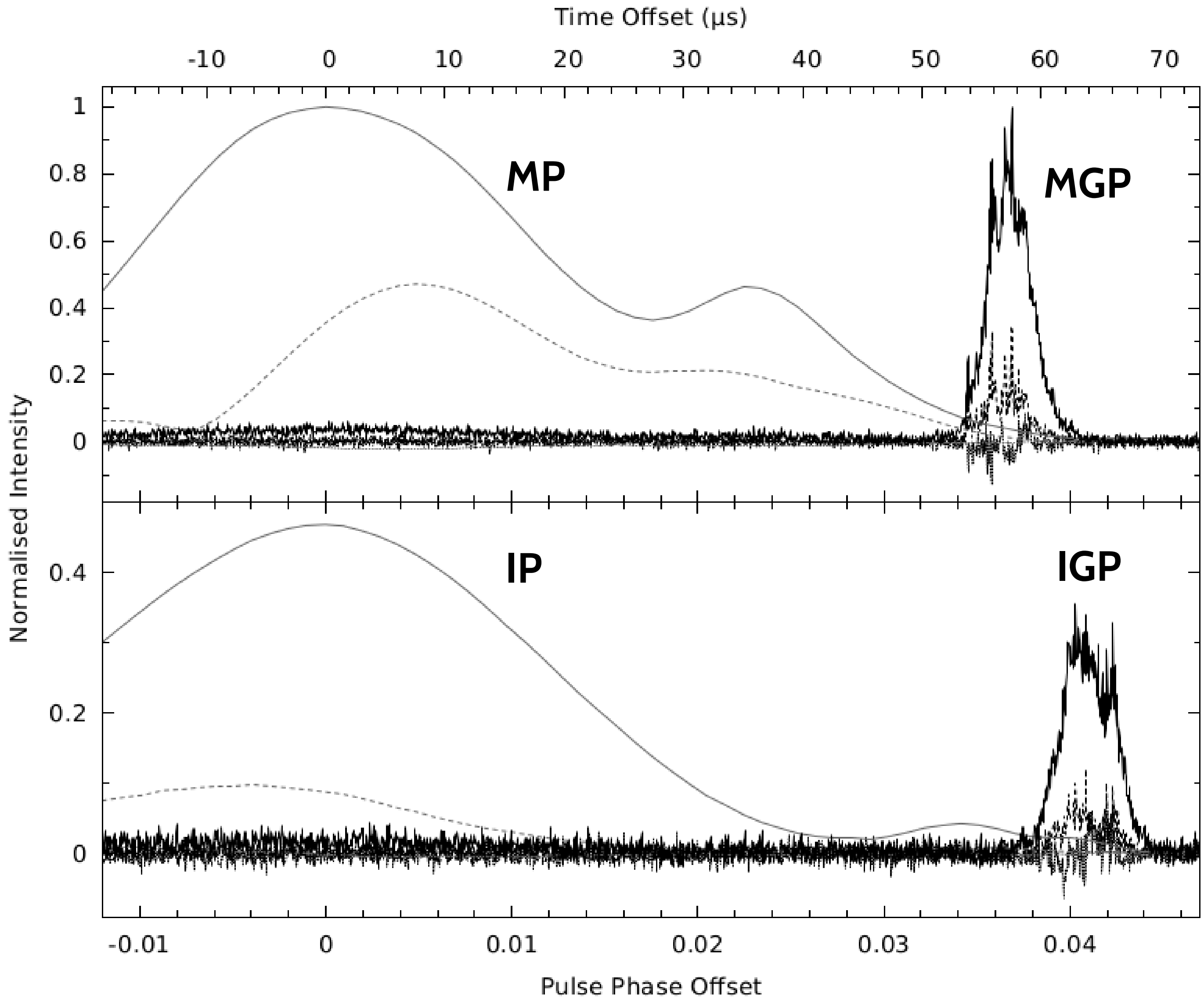
3.1×10^7 rotations

Largest GP sample ever obtained for this pulsar`

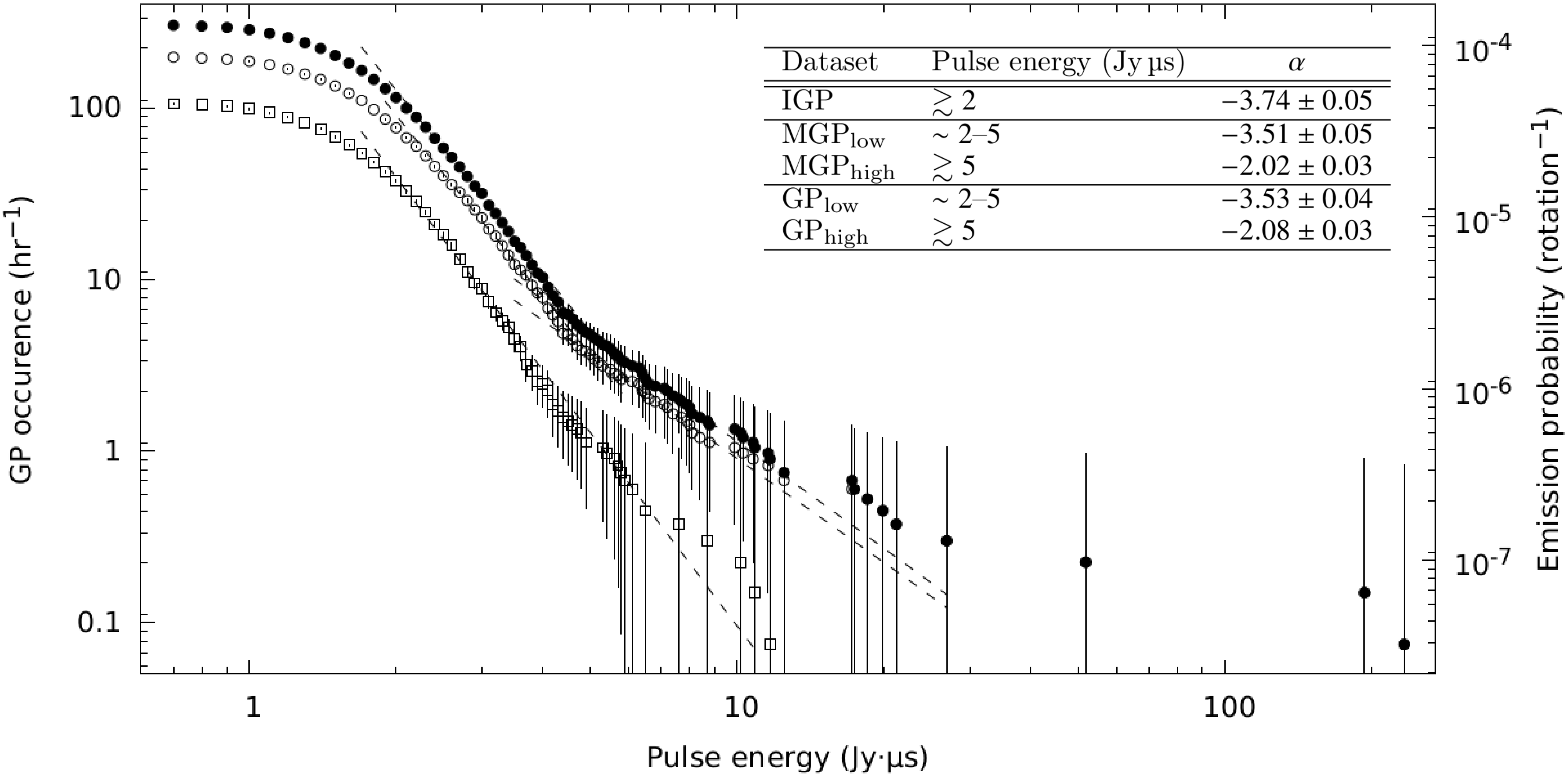
Phase Location

- GPs occur in a narrow phase window (Kinkhabwala & Thorsett 2000)
  - Peak of MGP distribution trails peak of regular emission by 58 µs
  - IGP trails regular emission by 64 µs
- Emission at the phase of the regular profile occurs during GP emission
  - GP emission and regular emission can occur simultaneously

Solid:	Total intensity (I)
Dashed:	Total linear (L)
Dotted:	Total circular (V)

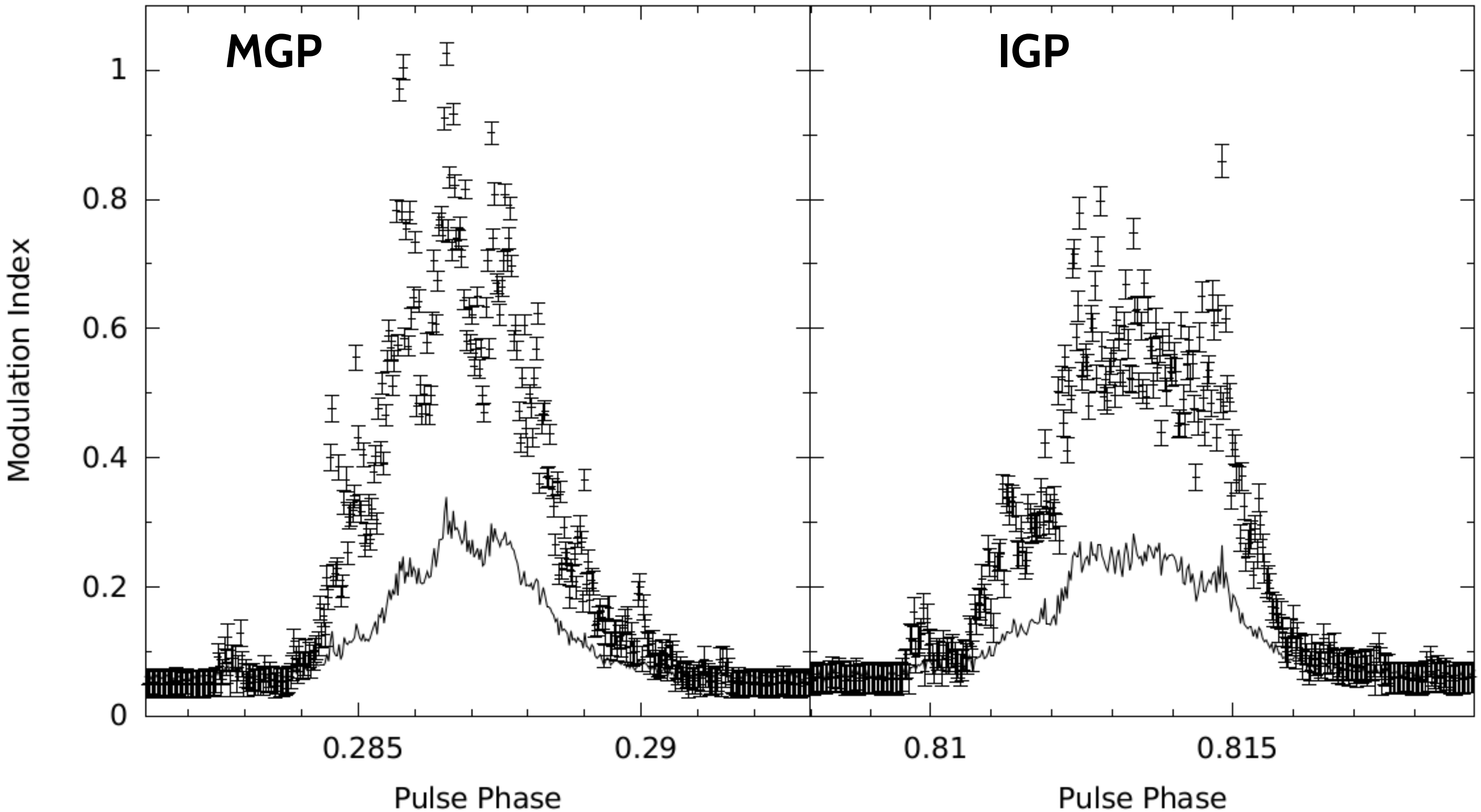


Energy Distribution



- FRBs proposed to be 'super giant pulses' (e.g. Meyers et al. 2017)
- Occurrence rate for FRBs at 1400 MHz with energies of 130-1500 Jy µs = 7000 sky^{-1} day^{-1} (Champion et al. 2016)
- Wait time for a 130 Jy µs GP (0.5 Gpc): 5.6×10^{19} years
- Undiscovered population of pulsars thought to exist at the Galactic Centre (distance ~8.3 kpc)
  - ~10^4 detectable from the Earth (Rajwade et al. 2017)
- Wait time for a 130 Jy µs GP from a single pulsar: 6661 hrs
  - If fraction of GP emitters is the same as the known pulsars, wait time for GP from one: 133 hrs

Intensity Modulation



Phase-resolved modulation index:

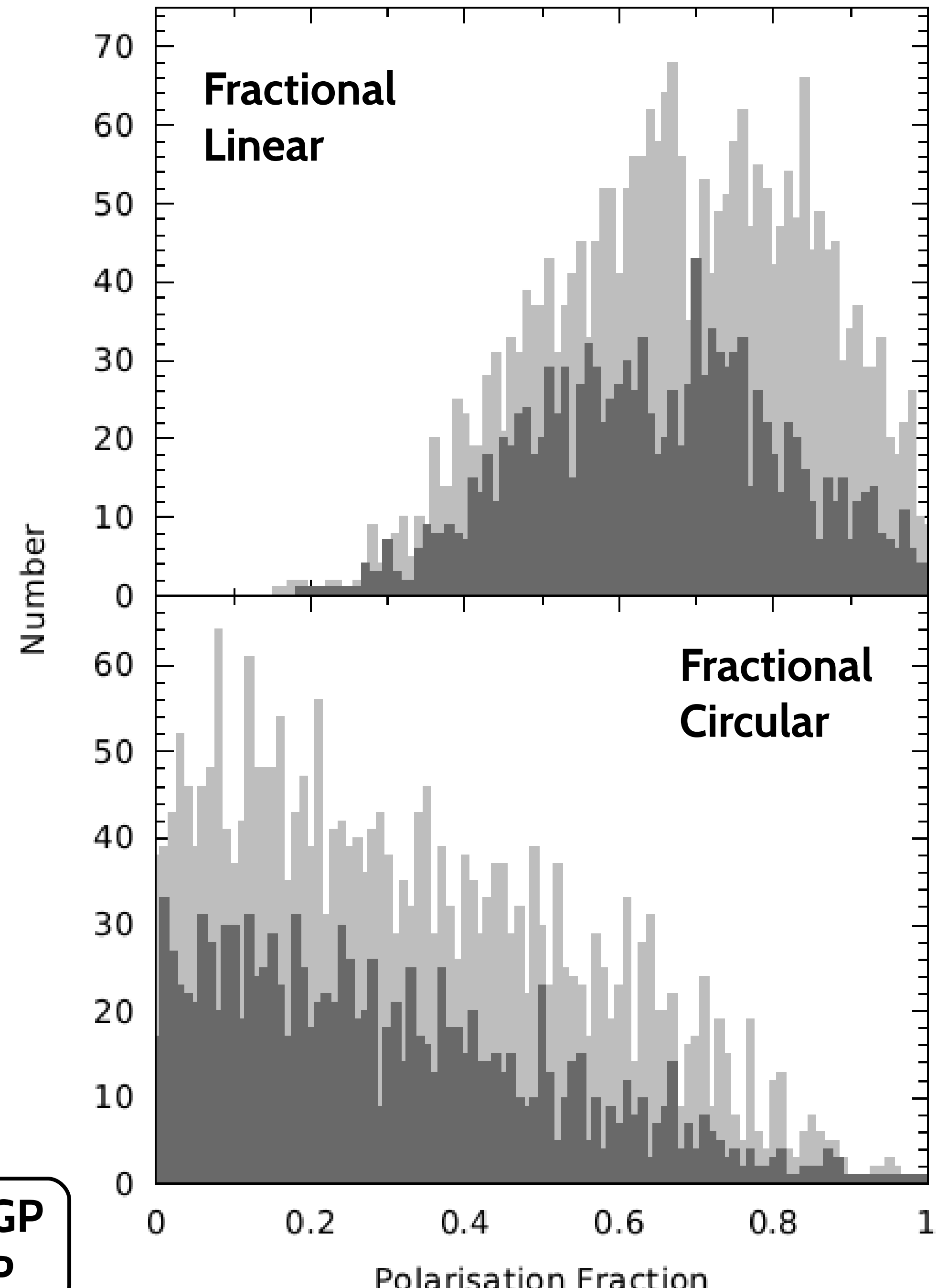
$$m(\phi) = \frac{\sqrt{\langle I(\phi)^2 \rangle - \langle I(\phi) \rangle^2}}{\langle I(\phi) \rangle}$$

- Intensity fluctuations between individual pulses quantified by the phase-resolved modulation index (Jenet & Gil 2004, Weltevrede et al. 2006)
- Pulse stacks generated for each observation
  - Modulation index computed for MGP and IGP separately using PSRSALSA† (Weltevrede 2016)
- Distributions are approximately Gaussian
  - Vary by ~50% around the peak
  - Very little variation about the edges (in contrast to normal pulsar emission e.g. Crawford et al. 2013)
- Apparent modulation at the edge of the regular emission
  - In contrast to Jenet et al. (2001)?

† https://github.com/weltevrede/psrsalsa/

Polarisation

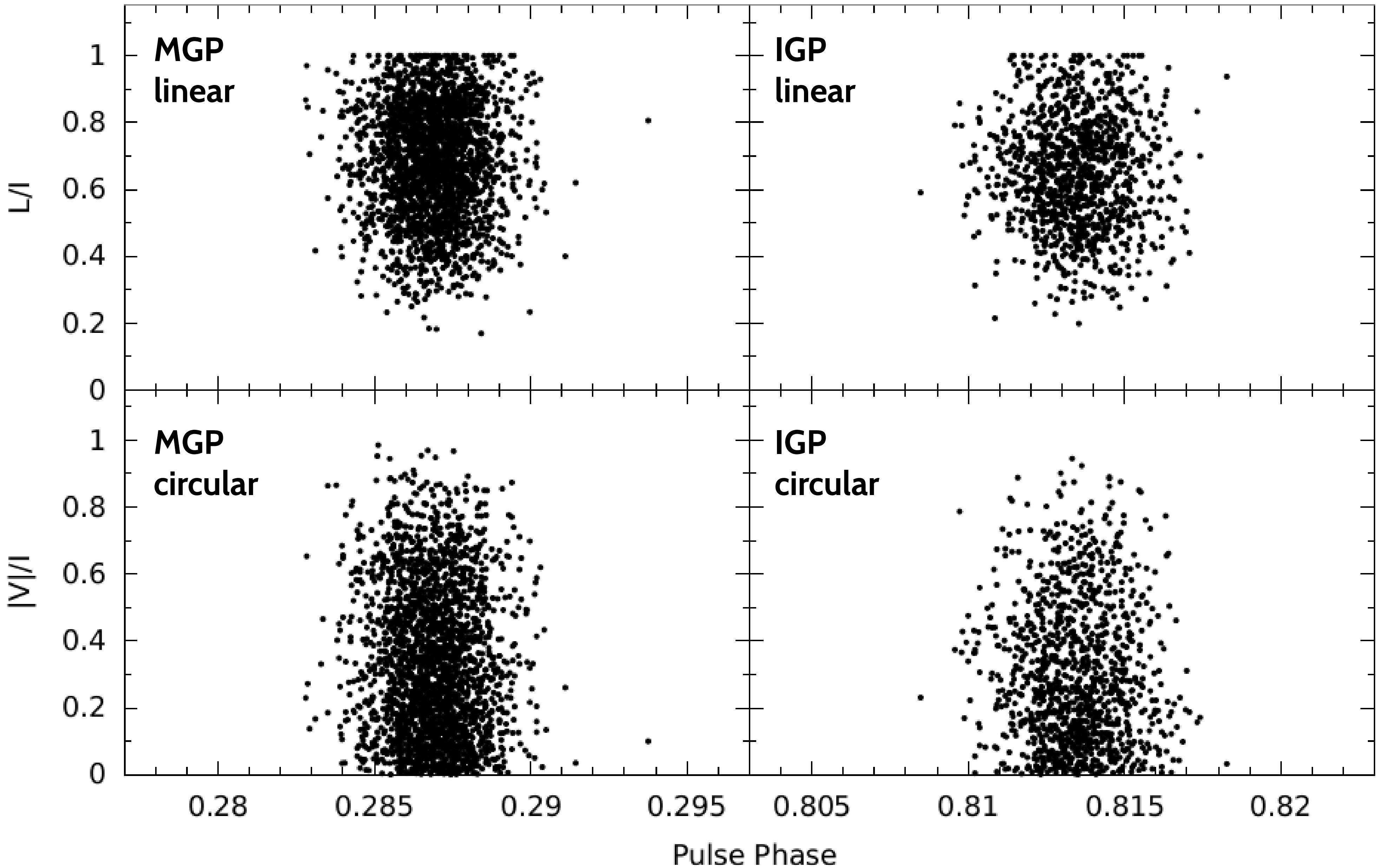
- Our data are polarisation calibrated
  - Calibrate LEAP data using PSR B1933+16 and/or PSR J1022+1001 with their EPN polarisation profiles† (Stairs et al. 1999)
- GPs are found to be highly polarised
  - B1937+21 GPs upto 100% circular polarisation (Cognard et al. 1996, Soglasnov et al. 2004)
    - At sampling rates close to the Nyquist rate or the scattering time scale, unresolved emission can appear to be 100% polarised (Cordes 1976, van Straten 2009)
- GPs in our sample:
  - Not RM calibrated
    - Effect is small, max. error of ~0.007 rad across our bandwidth
  - Tend to be highly linearly polarised (minimum = 17%)
  - ~100% polarisation is rare
    - <1% of sample is >90% circularly polarised
    - <10% of sample is >90% linearly polarised
- No evidence for phase-dependent polarised emission



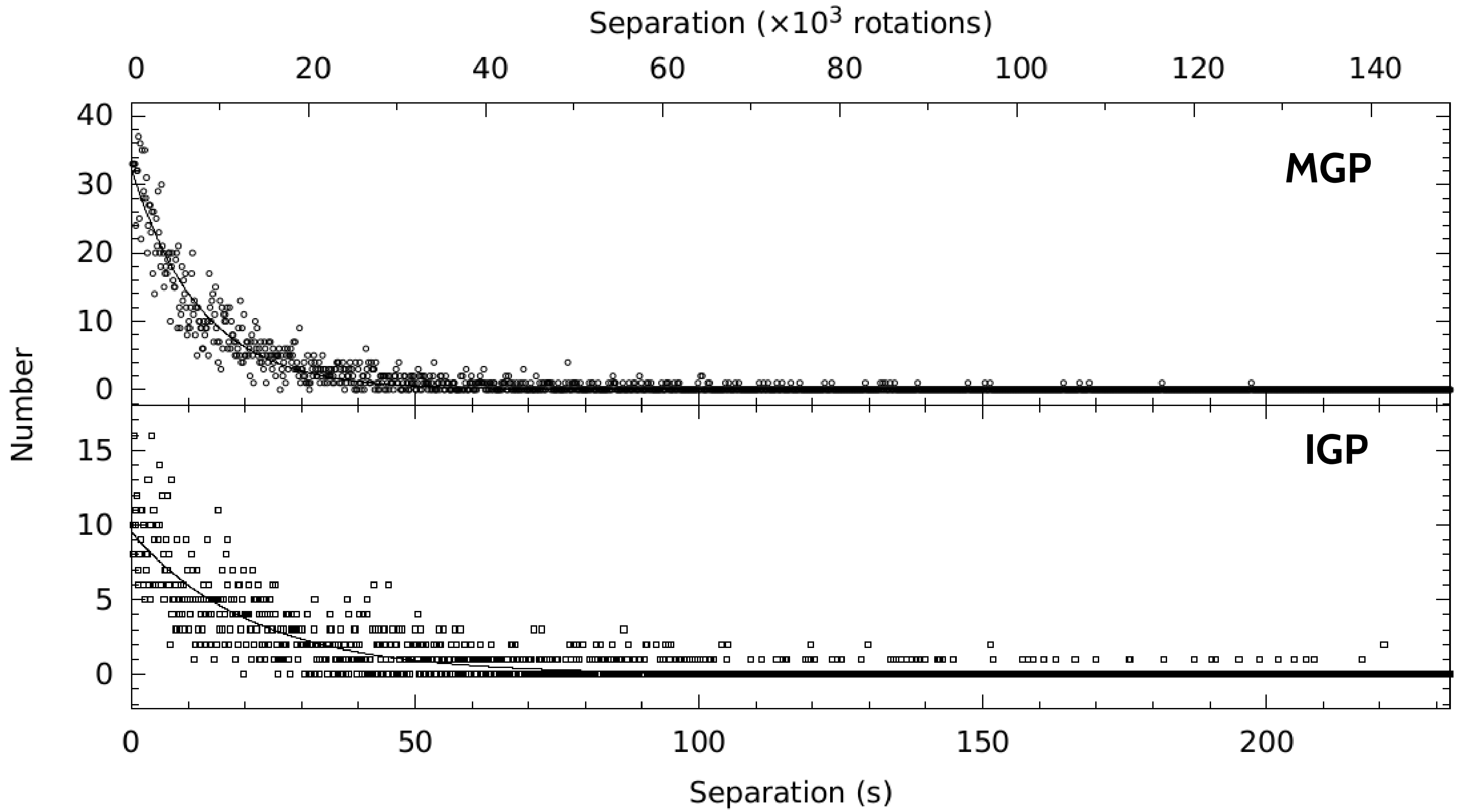
Light grey: MGP
Dark grey: IGP

† http://www.epta.eu.org/epndb/

Polarisation



Occurrence Rates



- Proposed (Cairns et al. 2004, Melatos et al. 2008) that GPs arise from a self-organised criticality process (Bak et al. 1988)
- Distribution of time intervals between GPs should follow a Poisson distribution (Lundgren et al. 1995)
  - Exponentially-decreasing time from most likely separation
- Exponential decay function fits our sample very well

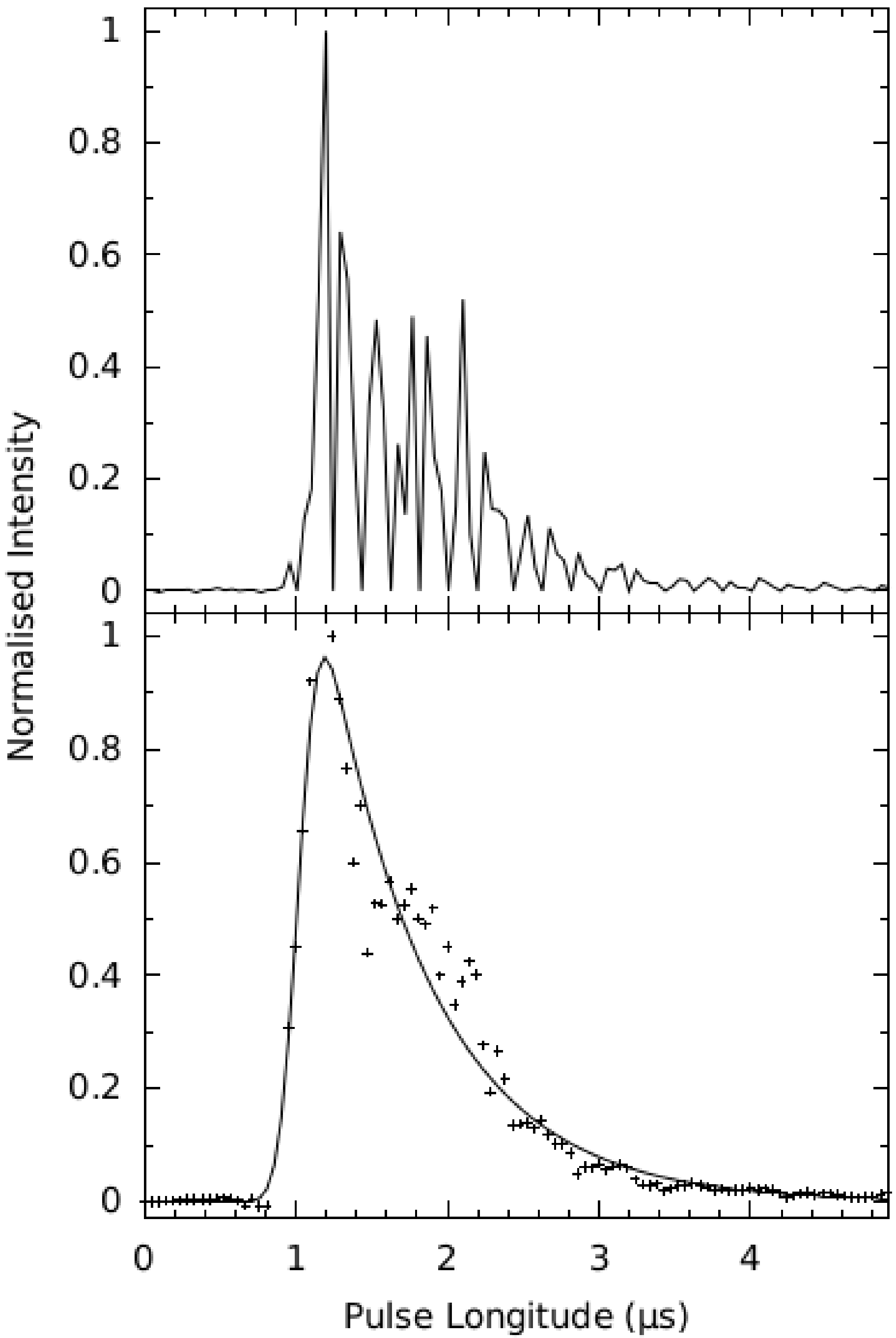
$$N(t) = N_0 \exp(-\lambda t)$$

$$\lambda_{\rm MGP} = 1.28 \pm 0.01 \times 10^{-4}$$

$$\lambda_{\rm IGP} = 7.3 \pm 0.1 \times 10^{-5}$$

Scattering Variations

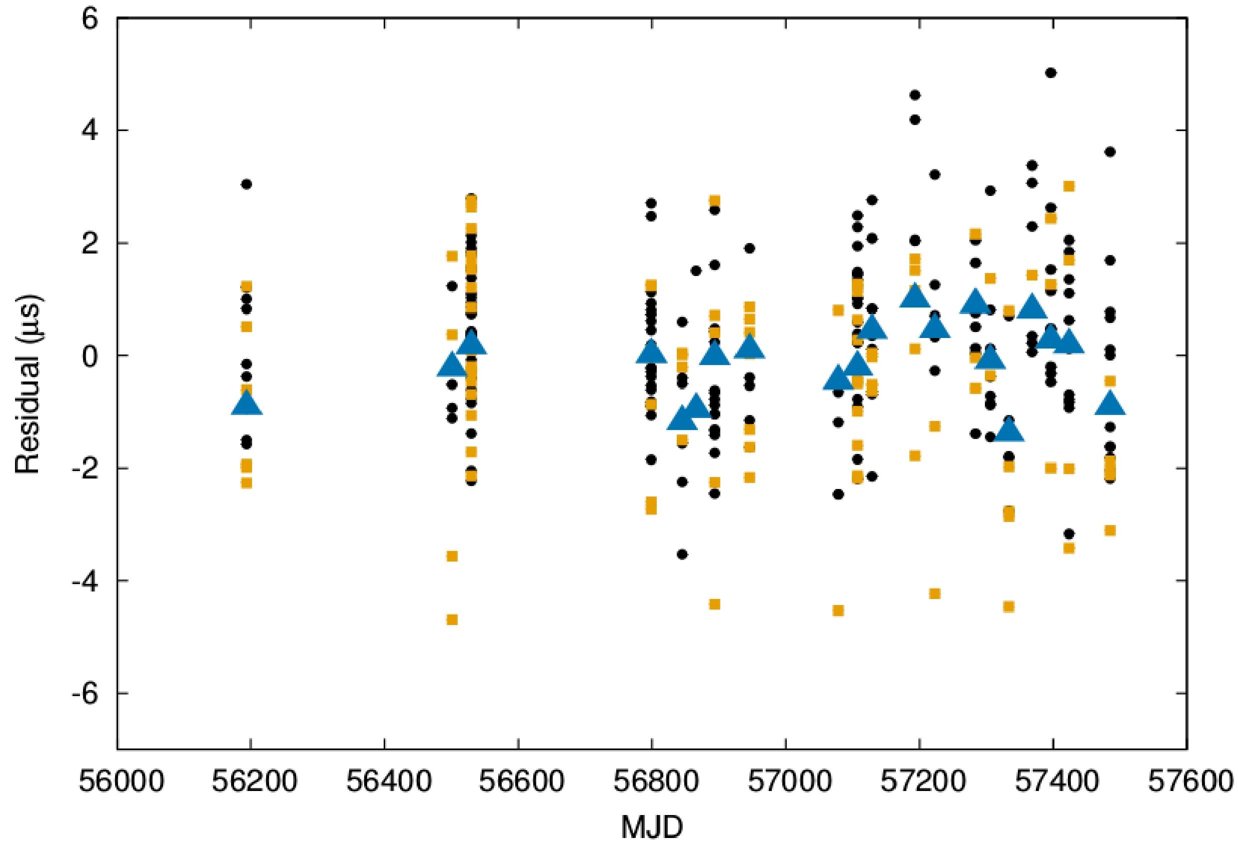
- Suggestion that scatter-broadening is the only cause of pulse-shape variations (Jenet et al. 2001)
- We observe a wide distribution of GP widths
  - Similar to the Crab GPs (Karuppusamy et al. 2010)
- Scattering measurements:
  - Smoothed with Savitzky-Golay filter (Savitzky & Golay 1964)
  - Fit exponentially-modified Gaussian (Lyne et al. 2017, McKee et al. 2018, submitted)
  - Fit to MGP and IGP separately



GP Timing

- GPs have very small duty cycle
  - δ ~ 0.001
- Small duty cycle related to TOA precision
  - Measure TOAs with much higher precision many times per observation
- Timing using GPs
  - Generated from polarisation- and frequency-scrunched profiles
  - Used a delta-pulse as a template
    - GP max. as fiducial point
  - Restricted analysis to σ_{TOA} < 1 ns
    - 45% of our sample
  - Timing precision not improved, compared to using the average profile
    - Phase jitter

$$\sigma_{\rm TOA} \propto \delta^{3/2}$$



Yellow:	MGP
Black:	IGP
Blue:	regular profile

Regular profile RMS:	0.7 µs
IGP RMS:	1.8 µs
MGP RMS:	1.5 µs

Conclusions

- Searched for GPs using 13.4 hrs of observations with LEAP
- Found 4265 GPs, the largest-ever sample for this pulsar
- Estimated GP fluxes and their distributions
- Measured scattering influence on pulse shape
- Found that GPs are generally more polarised than the average profile, no phase dependency of polarised emission
- Timed PSR B1937+21 using GPs, did not offer an improvement
- Paper submitting soon

Thank you!

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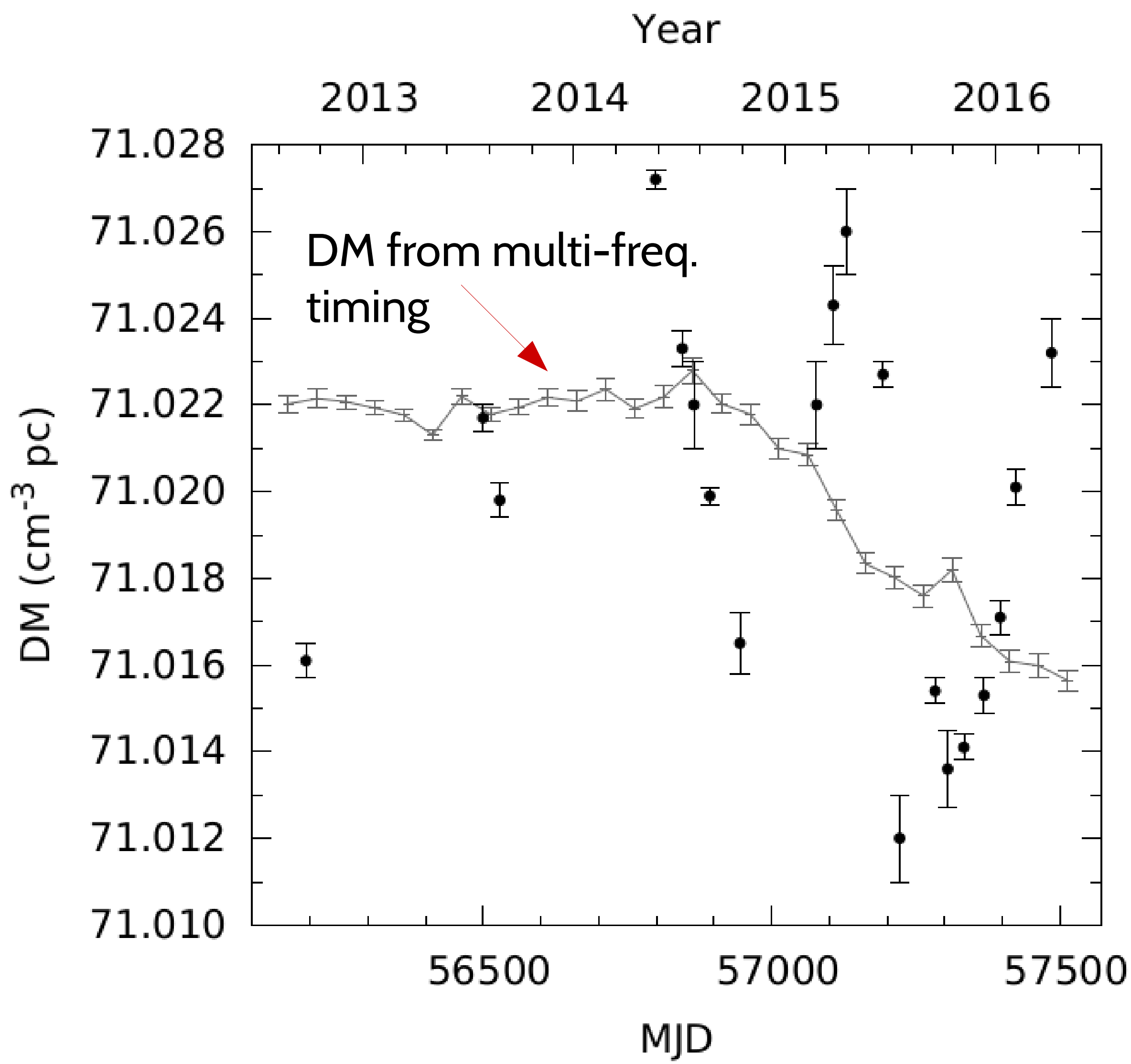
DM Variations

- Dedisperse using DM values that minimise the GP width
- DM from the GP width disagrees with those derived from multi-frequency timing
  - Value that optimises delay over 64-128 MHz band doesn't best-describe the delay between 610-1532 MHz?
  - Variable dispersion of GP by the pulsar magnetosphere?
    - Seen in the Crab Pulsar (Hankins & Eilek 2007)
  - Frequency-evolution of the GP pulse shapes?
- DM consistent with Popov & Stappers (2003) (71.025 cm^{-3} pc)
  - Consistent with that seen in EPTA DR1 dataset (Desvignes et al. 2016)
    - Janssen, McKee et al. (in prep)



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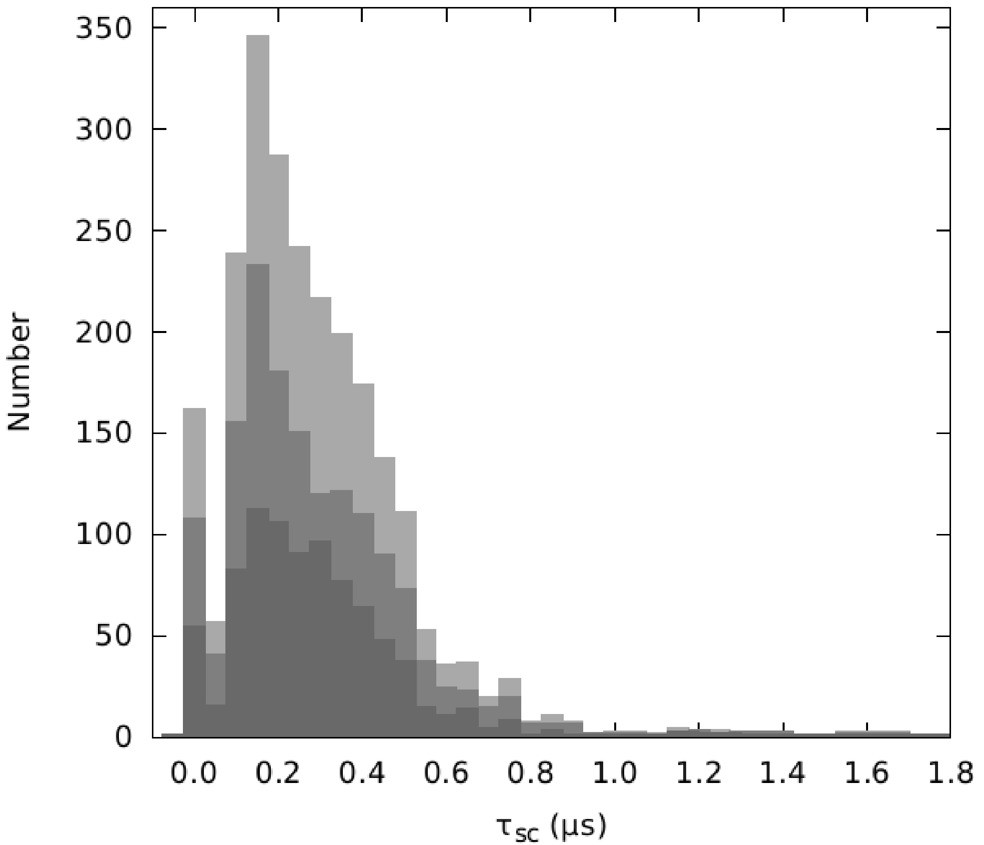
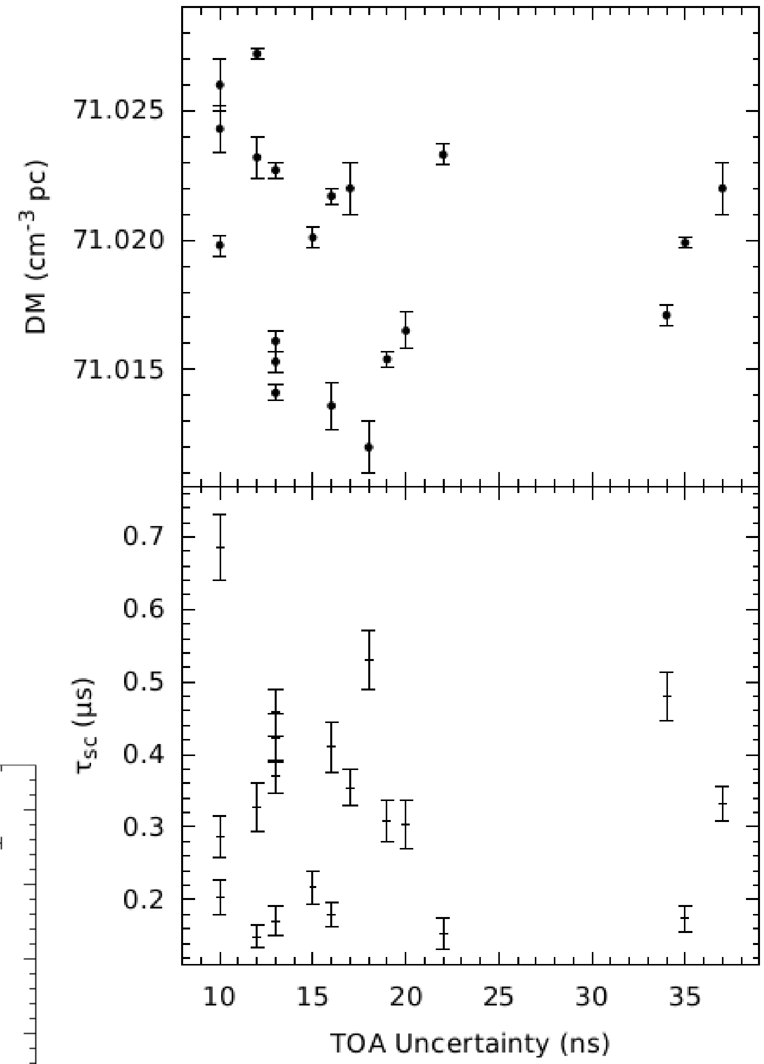
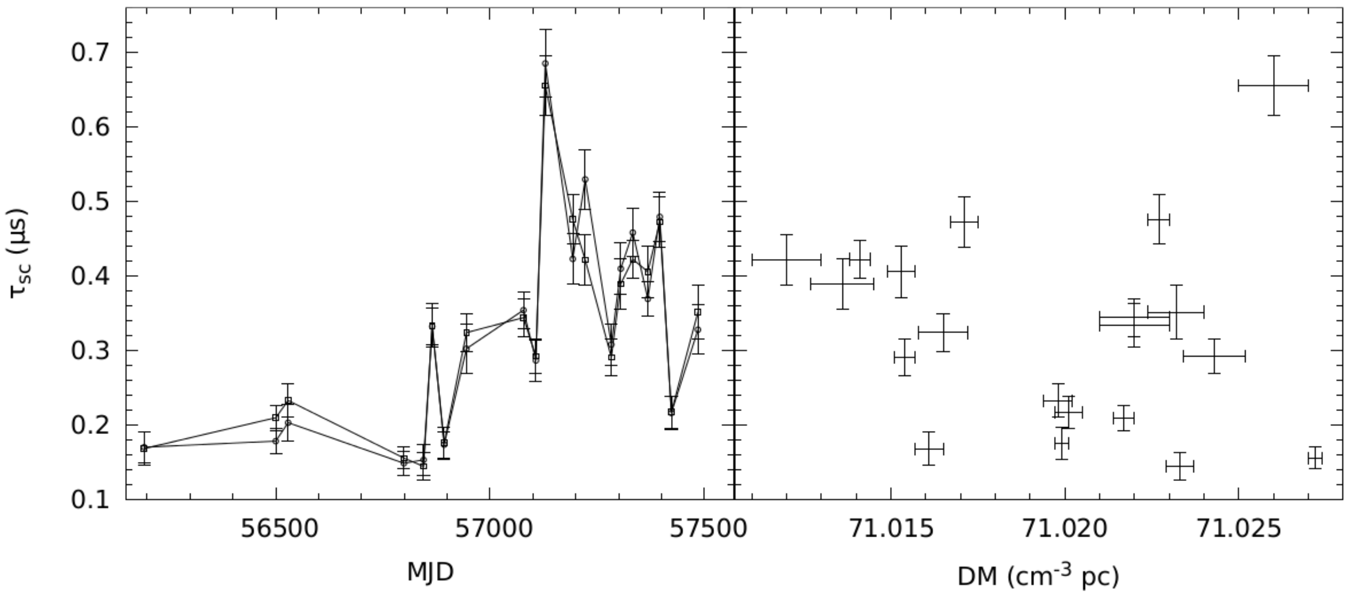


Dark: IGP
Medium: MGP
Light: all GPs

Scattering Variations

- Significant variations
  - Measurements of scattering in MGP and IGP in very close agreement
- No correlation between DM and scattering time scale
  - Scattering variations do not contaminate our optimal DM used for folding?
  - In contrast to strong correlation seen in e.g. the Crab Pulsar (Kuzmin et al. 2008, McKee et al. 2018, submitted)
- No correlation between mean scattering and DM and TOA error from regular pulse profile
  - ISM variations don't limit TOA precession at our frequencies and sensitivity





Occurrence Rates

From our data set of 3.1×10^7 rotations:
$\Pr(\text{IGP}) = 4.7 \times 10^{-5}$ rotation^{-1}
$\Pr(\text{MGP}) = 8.9 \times 10^{-5}$ rotation^{-1}
$\Pr(\text{GP}) = 1.4 \times 10^{-4}$ rotation^{-1}

(assuming GPs are completely independent events)

No GPs detected in consecutive rotations

Probability of *n* GPs occurring within a separation of *m* rotations at some point in a data set of N_r rotations:

$$\Pr(n, m, N_r) = 1 - \left\{1 - \left(\Pr(\text{GP})^n [1 - \Pr(\text{GP})]^{m-n} \frac{m!}{n!(m-n)!}\right)\right\}^{N_r}$$

For our data set: $\Pr(2, 2, 3.1 \times 10^7) = 46\%$

For 95% probability, need $N_r = 1.5 \times 10^8$
4.8× our data set