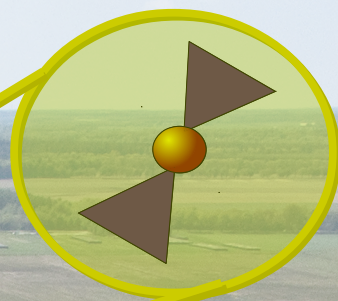
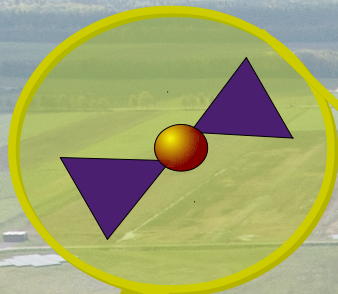
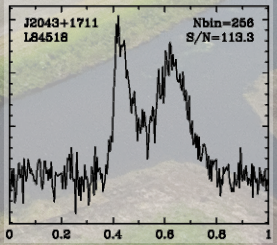
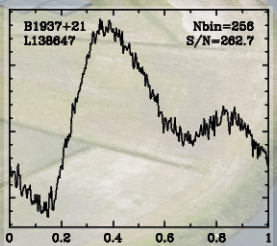
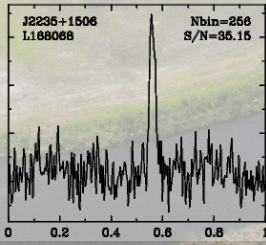
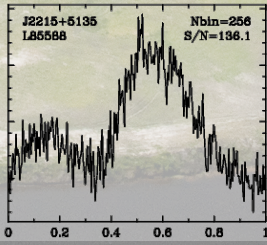
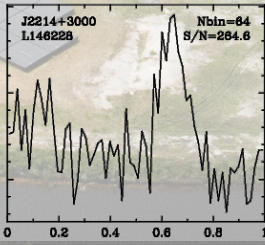
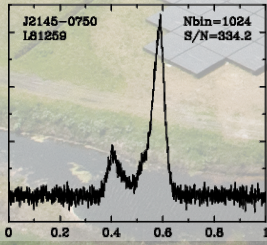
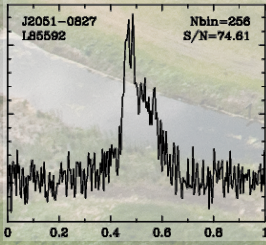
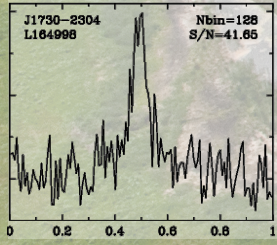
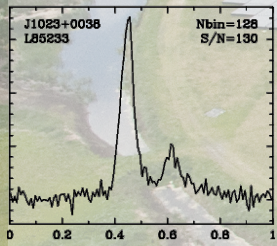
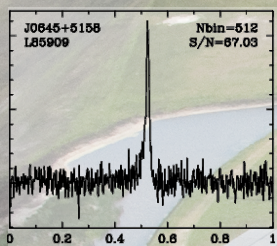


Vlad Kondratiev (ASTRON)



and
Jason Hessels
Joris Verbiest, Ben Stappers
and LOFAR Pulsar Working Group

Millisecond pulsars at low frequencies with LOFAR



LOFAR Pulsar Working Group



LOFAR

Jason Hessels (co-lead)

Ben Stappers (co-lead)

Anya Bilous

Thijs Coenen

Sally Cooper

Heino Falcke

Jean-Mathias Grießmeier

Aris Karastergiou

Evan Keane

Vlad Kondratiev

Michael Kramer

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Aris Noutsos

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Maura Pilia

Maciej Serylak

Charlotte Sobey

Sander ter Veen

Joris Verbiest

Patrick Weltevrede

Kimon Zagkouris

ASTRON/Universiteit van Amsterdam

University of Manchester

Radboud Universiteit Nijmegen

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LPC2E/CNRS/Université d'Orléans

University of Oxford

Swinburne University of Technology

ASTRON

MPI für Radioastronomie

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Universität Bielefeld

ASTRON

University of Oxford

ASTRON

Radboud Universiteit Nijmegen

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University of Manchester

University of Oxford

MSPs: why low freqs?

- Almost unexplored regime for MSPs
- Spectra of most MSPs do not turn over
- Profile and polarization evolution with frequency
- Time variability of DM, RM and SMs from the ISM
→ Improve high-frequency timing

MSPs: why low freqs?

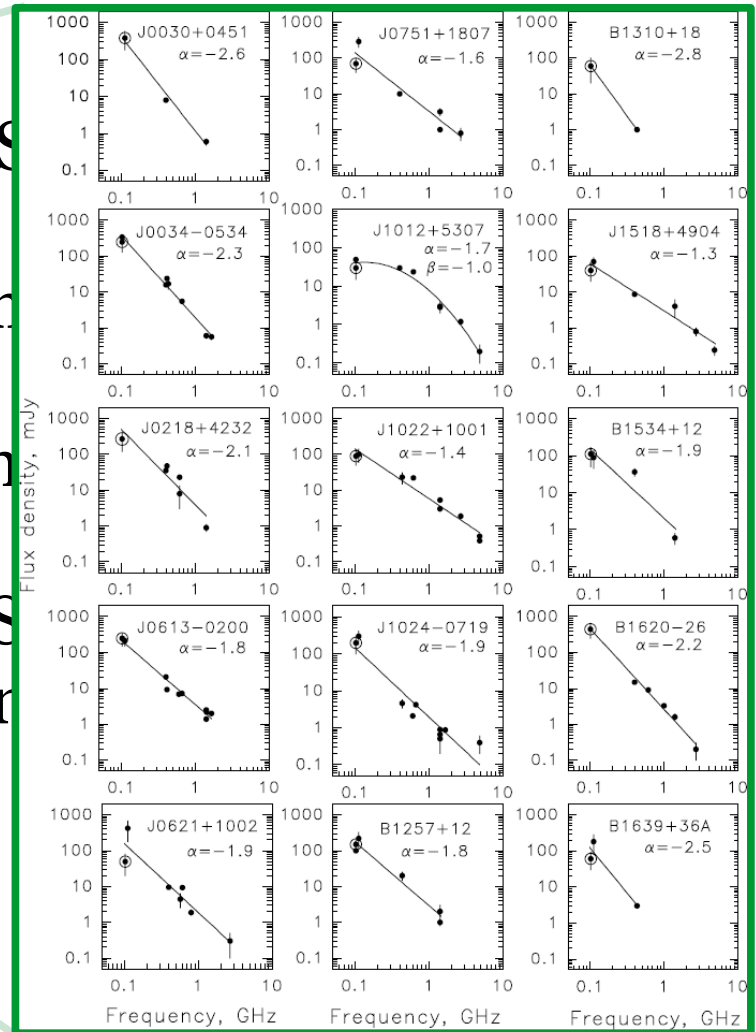
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- Time variability of DM, RM and
→ Improve high-frequency timing

Past Observations

- ✓ B1855+09
Kuzmin et al. (1990)
- ✓ J2145–0750, profile evolution
Kuzmin & Losovskii (1996)
- ✓ Spectra
Kuzmin & Losovskii (1999, 2001)
- ✓ WSRT @150 MHz
Stappers et al. (2008)
- ✓ GMRT @240 MHz
Joshi & Kramer (2009)
- ✓ J2145–0750 @37–81 MHz (LWA)
Dowell et al. (2013)

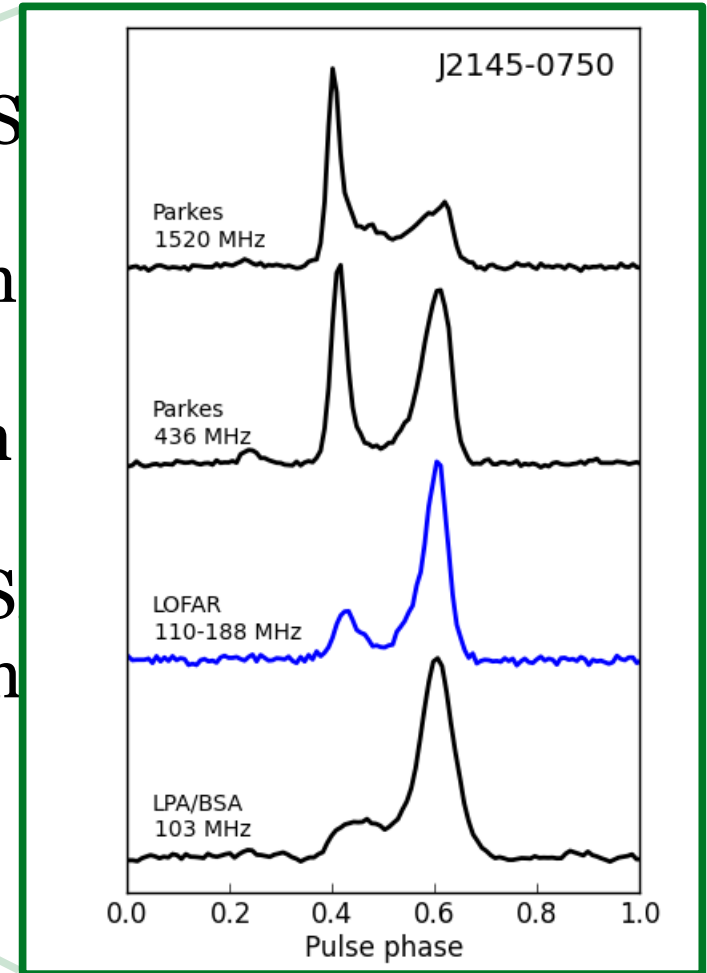
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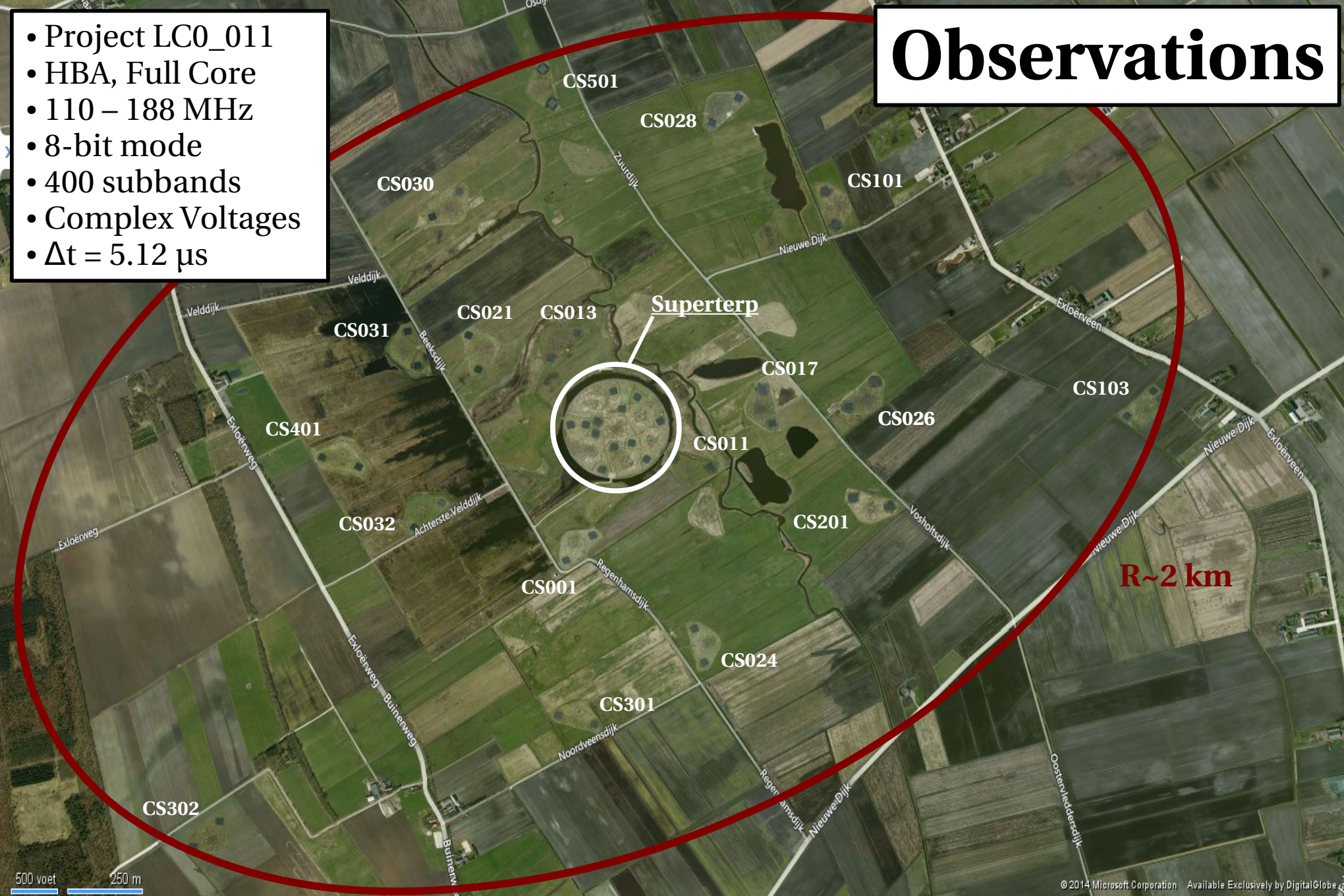


MSPs: why low freqs?

- Almost unexplored regime for MSPs
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Observations

- Project LC0_011
- HBA, Full Core
- 110 – 188 MHz
- 8-bit mode
- 400 subbands
- Complex Voltages
- $\Delta t = 5.12 \mu s$



500 voet 250 m

Detected MSPs

Kondratiev et al. 2014,
nearly submitted

PSR	Period (ms)	DM (pc cm ⁻³)	Type	WSRT detected?	BSA detected?	LOFAR ObsID	Epoch (MJD)	T _{obs} (min)	S/N	Peak S/N	LBA detected?
J0030+0451	4.865	4.333	Isolated	...	y	L83021	56304.69	20	293	34	y
J0034-0534	1.877	13.765	ELL1	y	y	L81272	56286.73	20	653	75	y
J0218+4232	2.323	61.252	ELL1	n	y	L155442	56473.30	20	111	16	
J0337+1715	2.733	21.316	BT1P	...	...	L167133	56512.21	60	72	6	
J0621+1002	28.854	36.601	BT	n	y	L81270	56289.02	20	67	7	
J0645+5158	8.853	18.247	Isolated	...	...	L85909	56322.00	20	67	18	
J0737-3039A	22.699	48.920	DDS	...	...	L85911	56321.92	60	66	9	
J0751+1807	3.479	30.249	ELL1	...	y	L81051	56280.04	20	56	13	
J1012+5307	5.256	9.023	BT	y	y	L81268	56289.14	20	191	32	n
J1022+1001	16.453	10.252	T2	y	y	L81254	56296.12	20	248	44	n
J1023+0038	1.688	14.325	ELL1	y	...	L85233	56315.16	20	130	35	
J1024-0719	5.162	6.485	Isolated	n	y	L81049	56280.16	20	73	17	n
B1257+12	6.219	10.166	BT2P	y	y	L81253	56296.22	20	327	45	n
J1640+2224	3.163	18.426	DD	...	y	L81266	56289.36	20	80	16	
J1713+0747	4.570	15.992	DD	n	y	L149156	56465.92	60	93	24	
J1730-2304	8.123	9.617	Isolated	...	y	L164998	56490.88	30	42	9	
J1738+0333	5.850	33.778	ELL1	...	...	L124889	56399.18	20	50	10	
J1744-1134	4.075	3.139	Isolated	y	y	L81264	56293.43	20	80	20	
J1810+1744	1.663	39.7	BT	...	...	L81263	56293.45	20	1048	78	n
J1853+1303	4.092	30.570	BT	...	...	L84523	56311.43	20	32	13	
B1855+09	5.362	13.300	T2	...	y	L131365	56417.14	20	58	14	
J1911-1114	3.626	30.975	ELL1	y	y	L81277	56286.52	20	54	12	
J1918-0642	7.646	26.554	ELL1	...	...	L81276	56286.54	20	24	8	
J1923+2515	3.788	18.858	Isolated	...	...	L85594	56318.46	20	56	11	
B1937+21	1.558	71.040	Isolated	...	...	L138647	56434.12	30	269	25	
J1944+0907	5.185	24.34	Isolated	...	...	L84521	56311.47	20	90	10	
B1953+29	6.133	104.501	BT	...	...	L84522	56311.45	20	61	7	
B1957+20	1.607	29.117	BT	y	...	L81275	56286.55	20	319	33	
J2019+2425	3.935	17.203	BT	...	y	L146225	56457.10	20	90	20	
J2043+1711	2.380	20.710	ELL1H	...	...	L84518	56311.52	20	121	16	
J2051-0827	4.509	20.745	BT	n	y	L85592	56318.50	20	75	13	
J2145-0750	16.052	8.998	T2	y	y	L81259	56293.60	20	334	37	y
J2214+3000	3.119	22.557	ELL1	...	...	L146228	56457.15	20	95	19	
J2215+5135	2.610	69.2	BT	...	...	L85588	56318.56	20	130	12	
J2235+1506	59.767	18.09	Isolated	...	y	L168068	56521.01	30	35	10	
J2302+4442	5.192	13.762	ELL1	...	...	L84516	56311.60	20	50	11	
J2317+1439	3.445	21.907	BT	...	y	L83022	56304.63	20	206	47	n
J2322+2057	4.808	13.372	Isolated	...	y	L146234	56460.21	20	44	8	

Detected MSPs

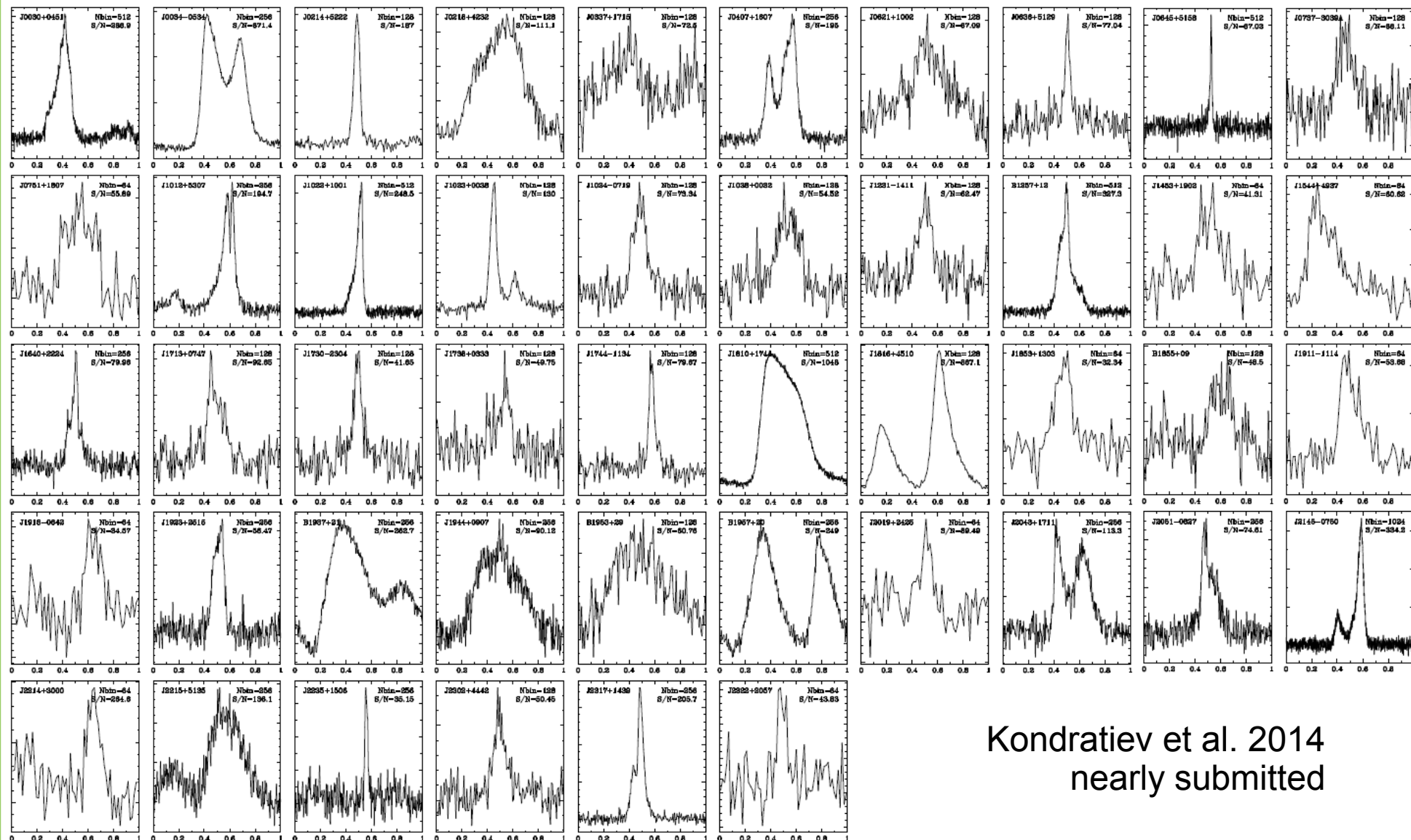
Kondratiev et al. 2014,
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J1022+1001	16.453	10.252	T2	y	y	L81254	56296.12	20	248	44	n
J1023+0038	1.688	14.325	ELL1	y	...	L85233	56315.16	20	130	35	

71% of observed MSPs Detected!
46 — Detections, 19 — non-Detections

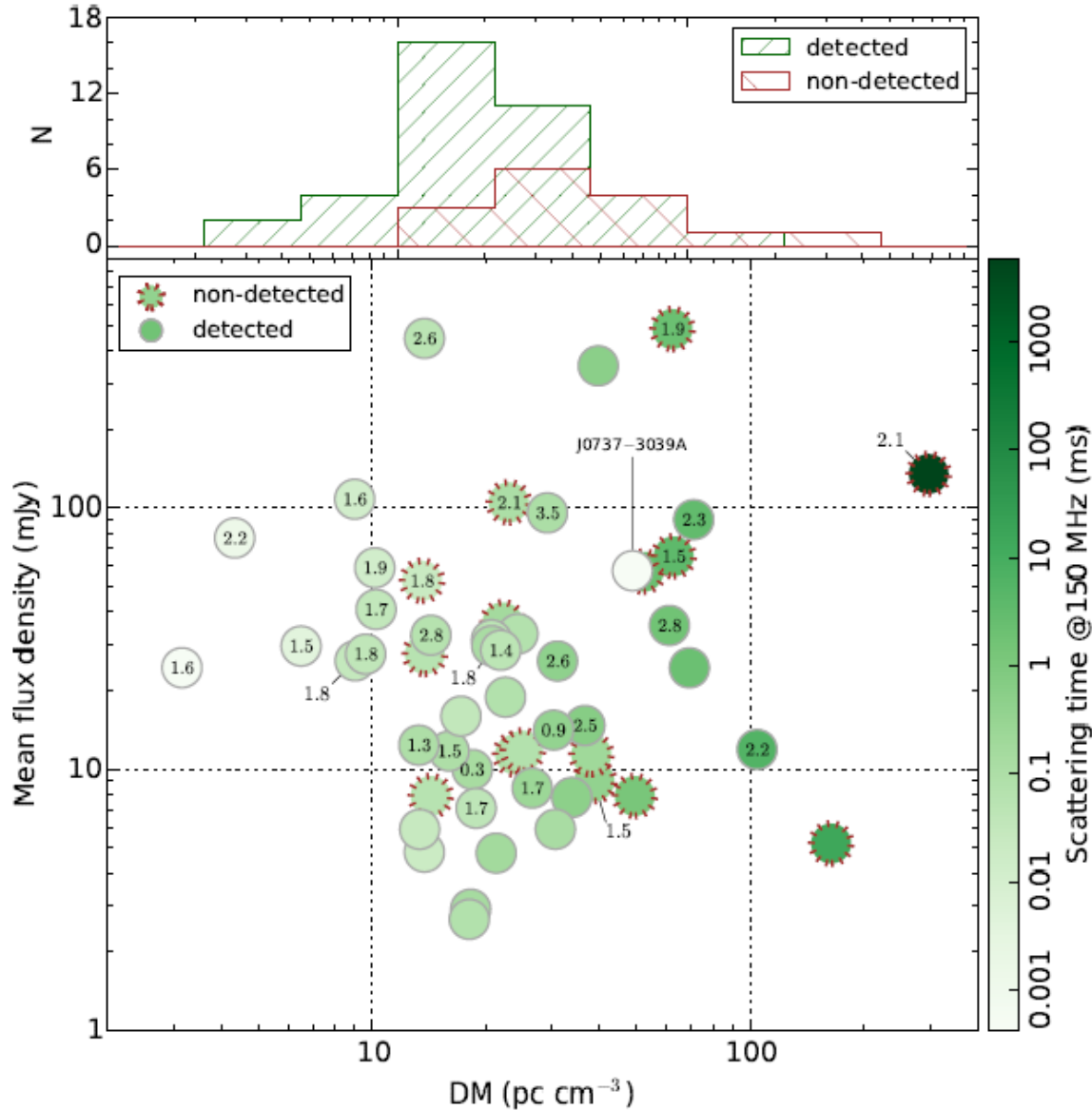
B1937+21	1.558	71.040	Isolated	L138647	56434.12	30	269	25	
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Detected MSPs



Kondratiev et al. 2014
nearly submitted

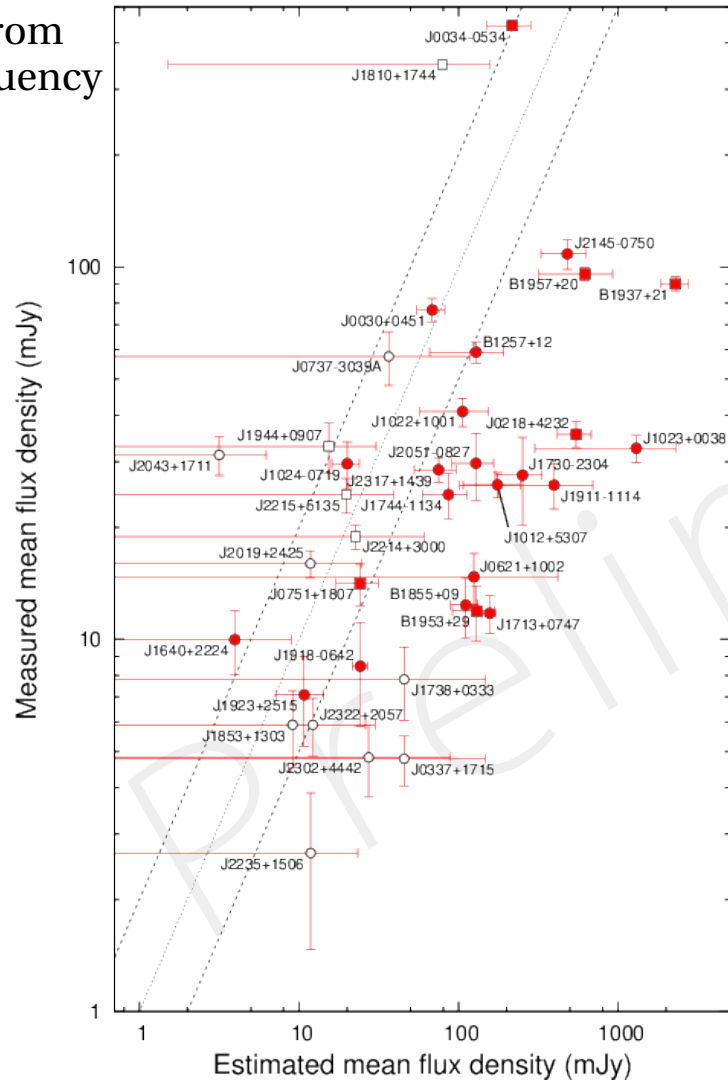
MSP detectability



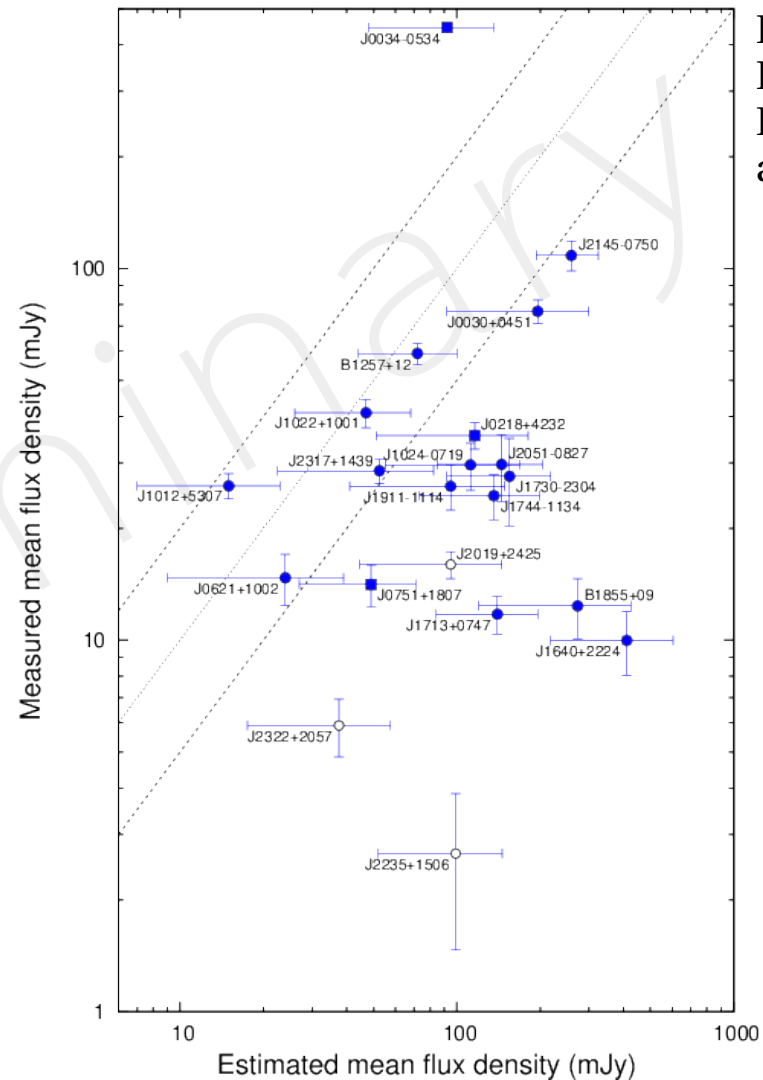
- ✓ detected: all 8 with $\text{DM} < 10$
- ✓ not detected: $\text{DM} > 105$
- ✓ $\text{DM} = 10-100$:
 - 32 MSPs detected
 - 13 MSPs not detected
- ✓ On average spectral indices are larger at higher DMs for detected MSPs

MSP flux densities @ 150 MHz

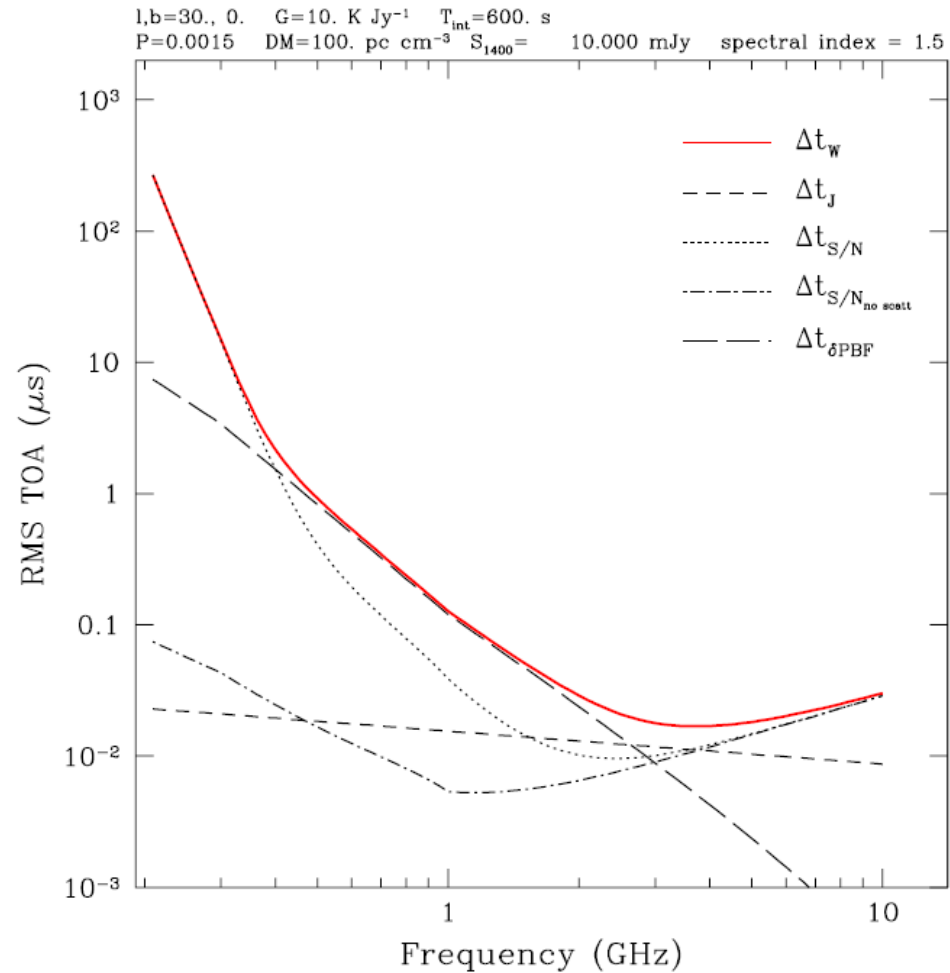
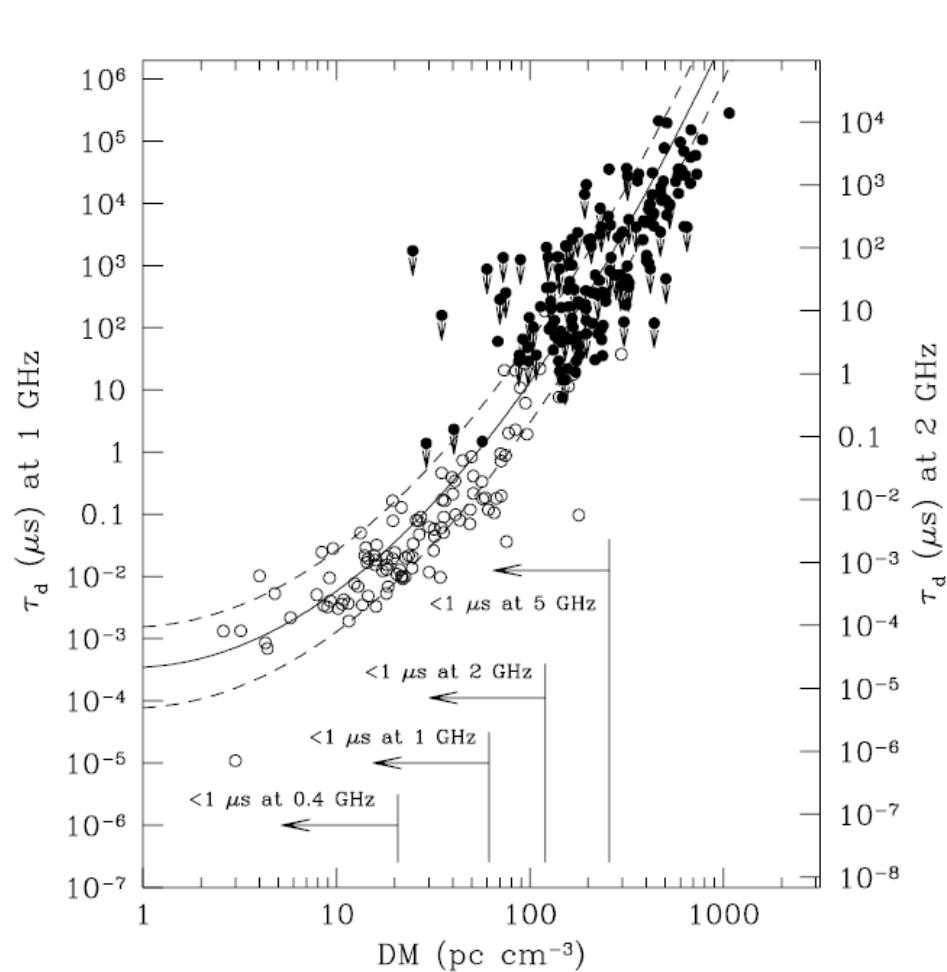
Derived from
high-frequency
data



Derived from
Kuzmin &
Losovsky (2001)
at 102 MHz

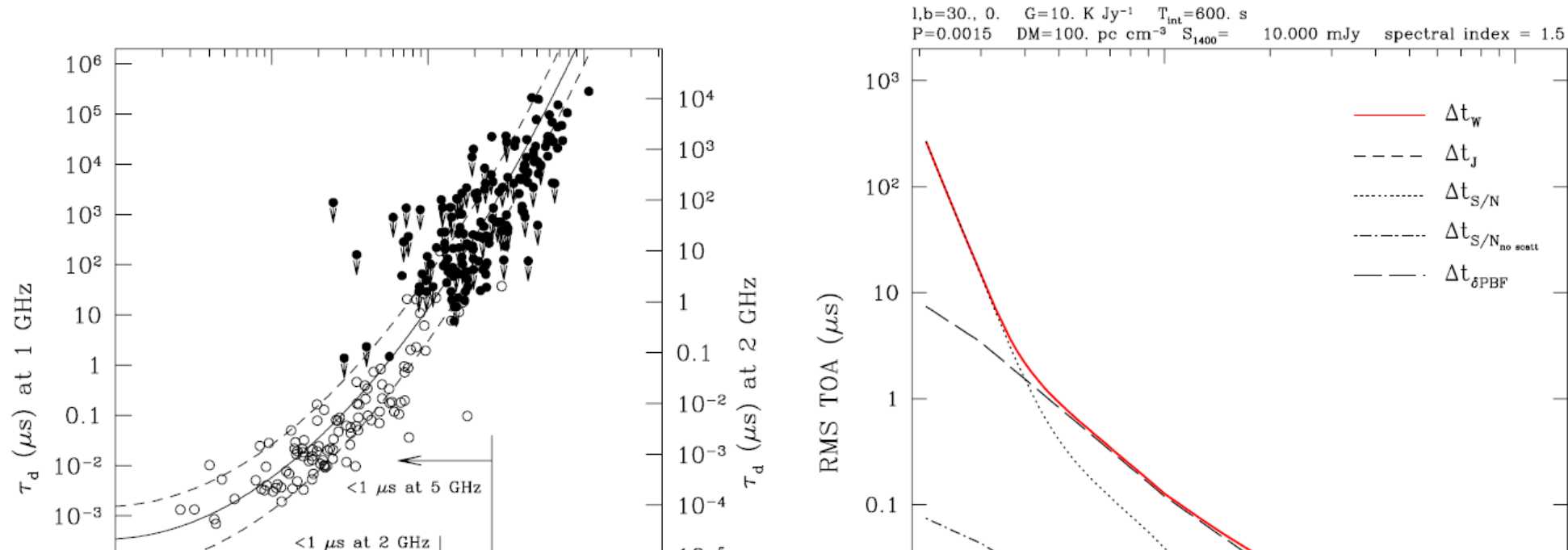


Timing with LOFAR?



Cordes & Shannon (2010)

Timing with LOFAR?

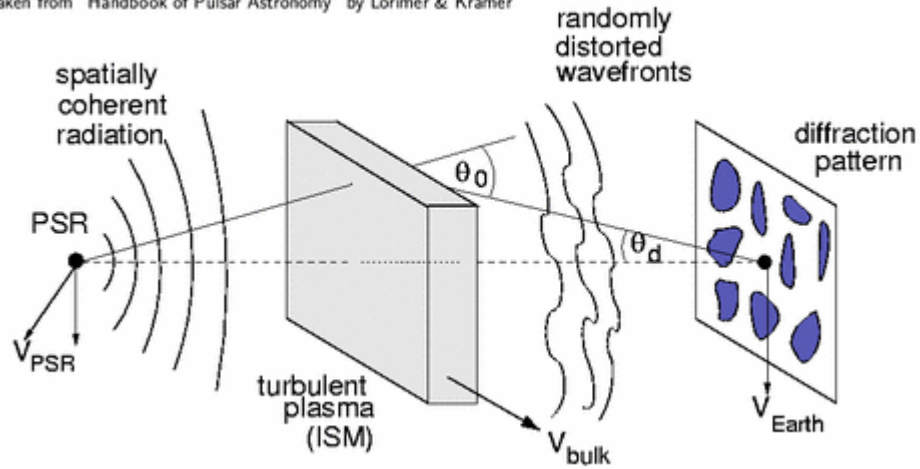


✓ 1 μs scatt. at 1400 MHz is 10 ms scatt. at 140 MHz

✓ 1 ms scatt. at 140 MHz is 100 ns scatt. at 1400 MHz

Dispersion measure (DM) variations

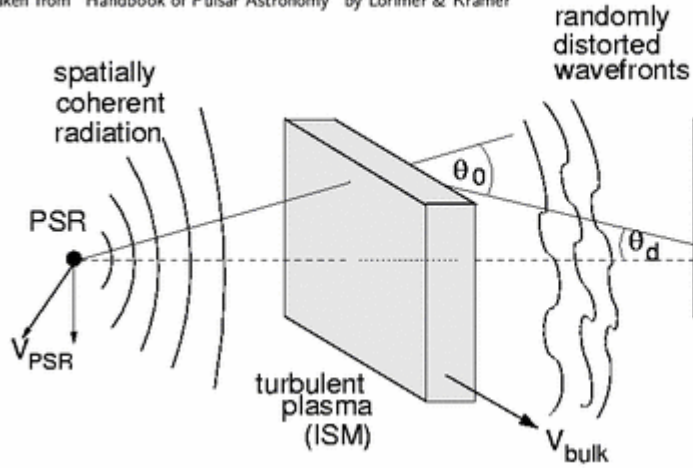
Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer



$$\left. \begin{array}{l} V_{\text{plasma}} \neq 0 \\ V_{\text{PSR}} \neq 0 \end{array} \right\} \text{DM} = \text{DM}(t)$$

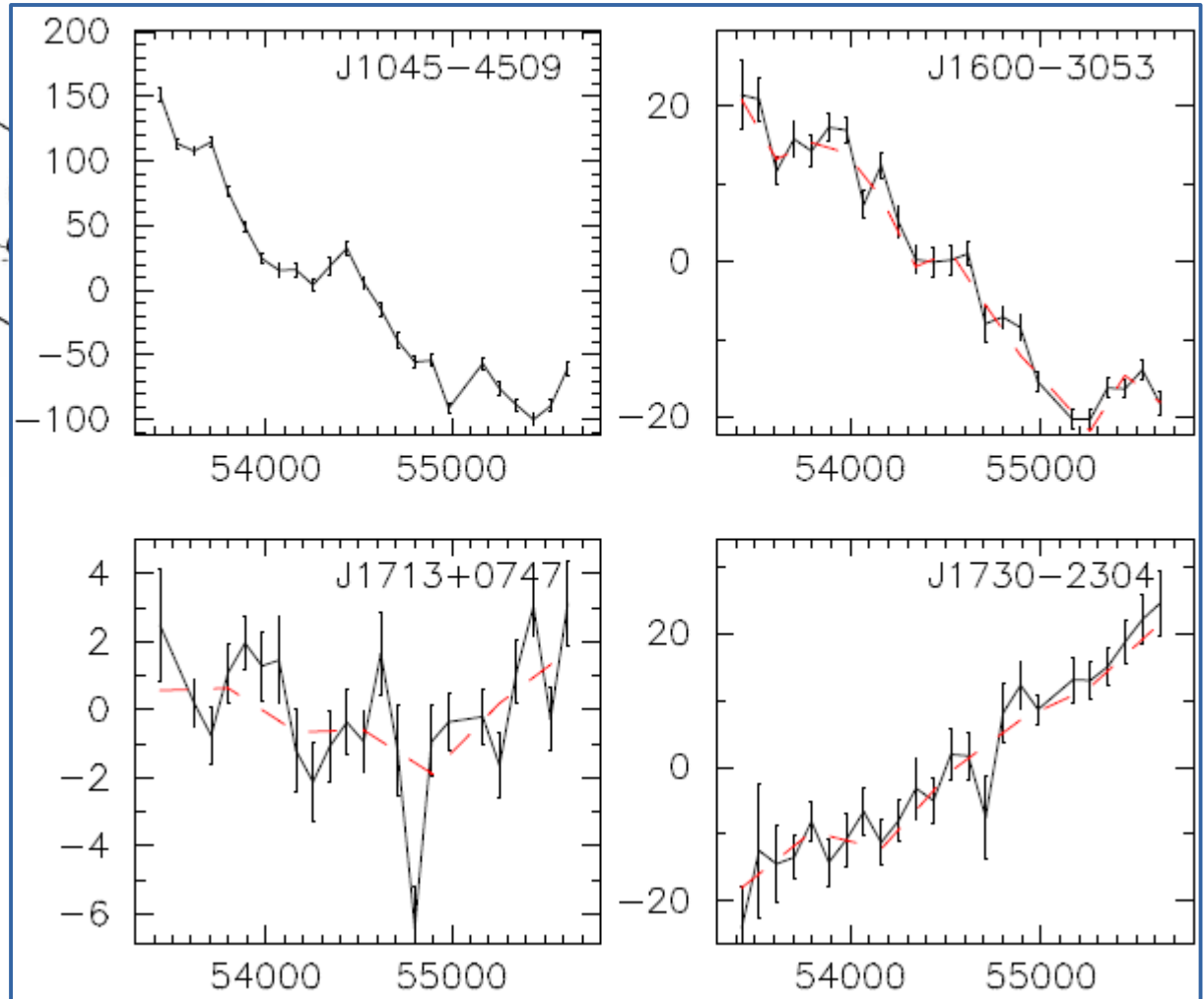
DM variations

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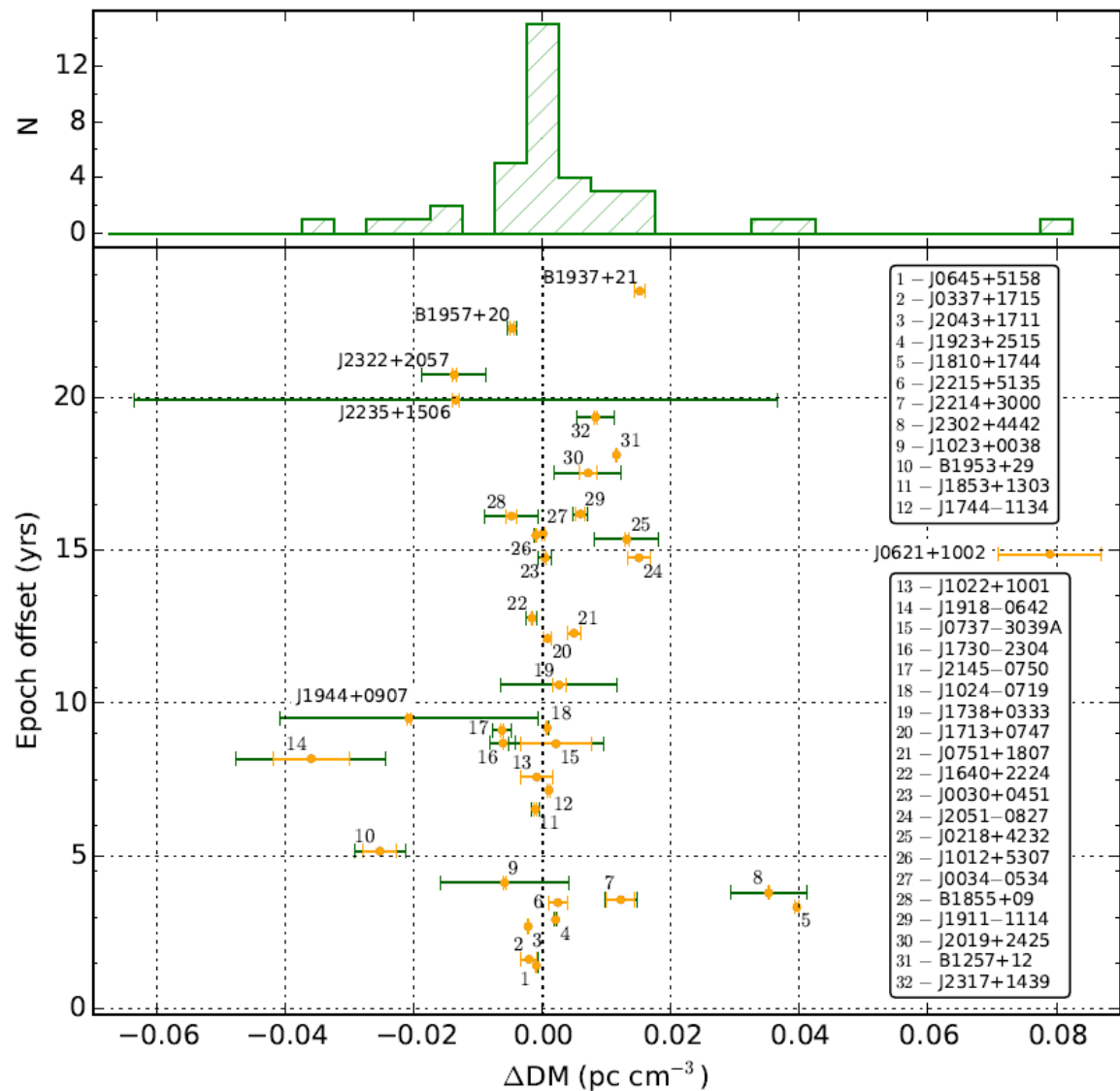
DM offset ($10^{-4} \text{ pc cm}^{-3}$)



Keith et al. 2013

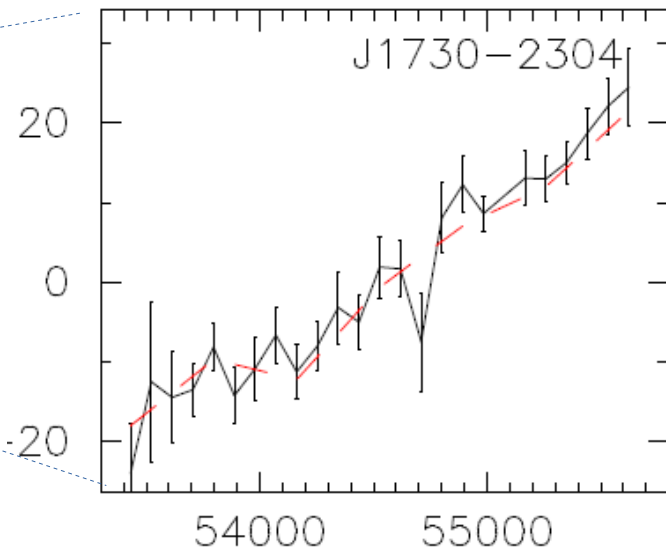
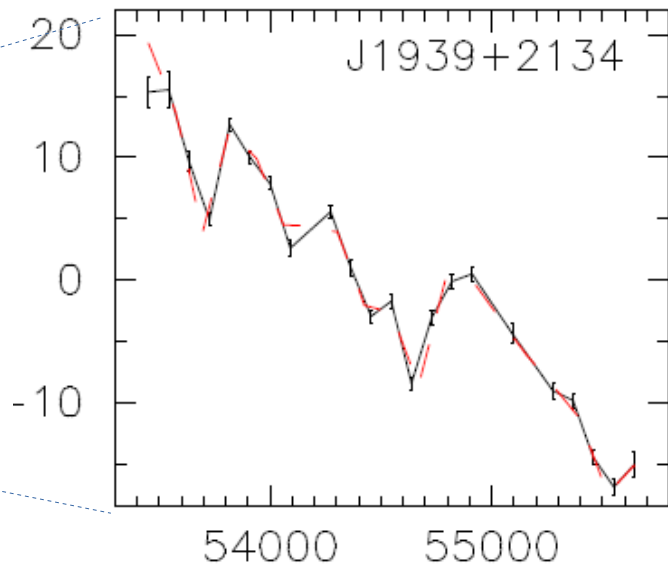
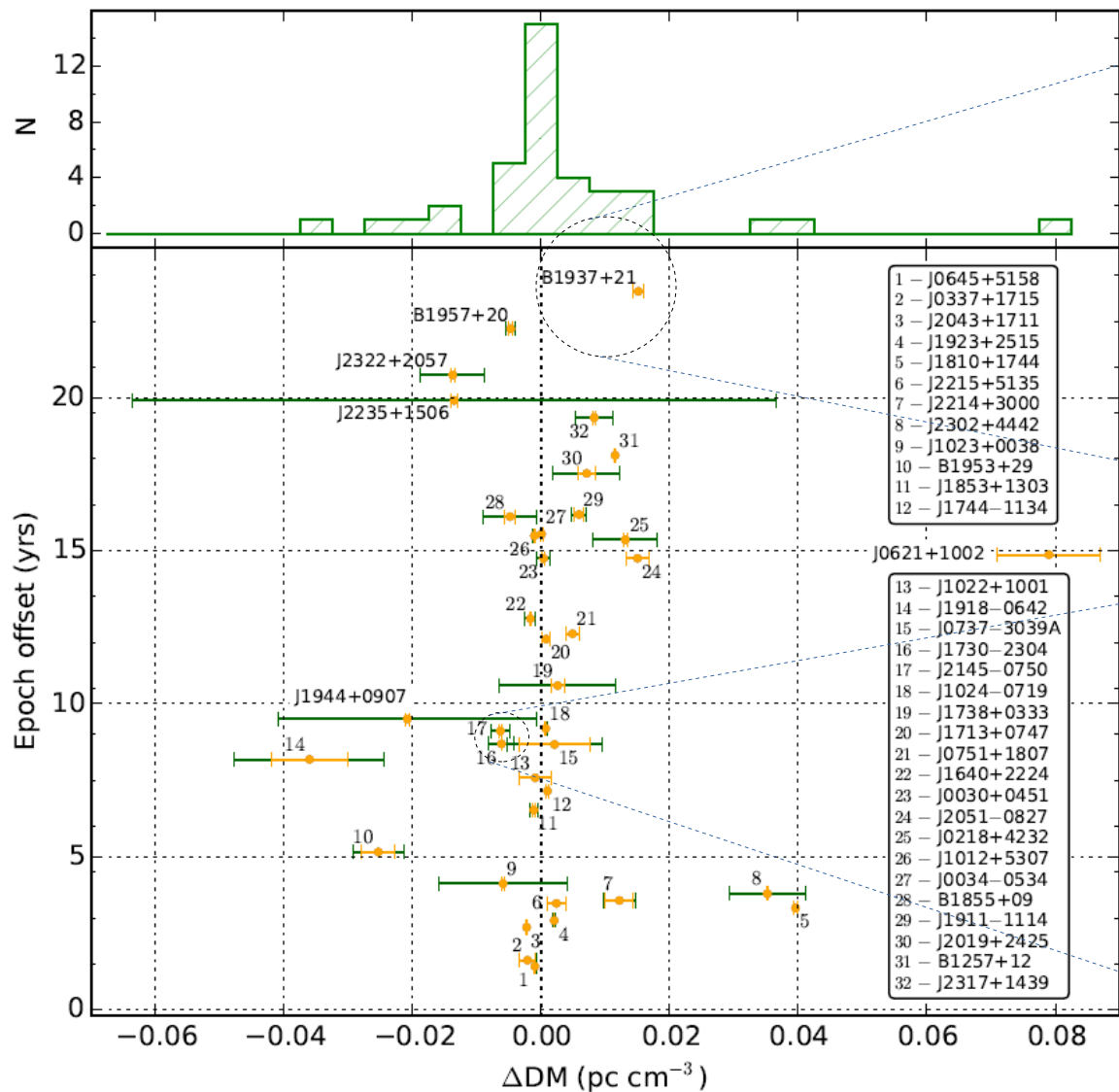
time (MJD)

DM variations

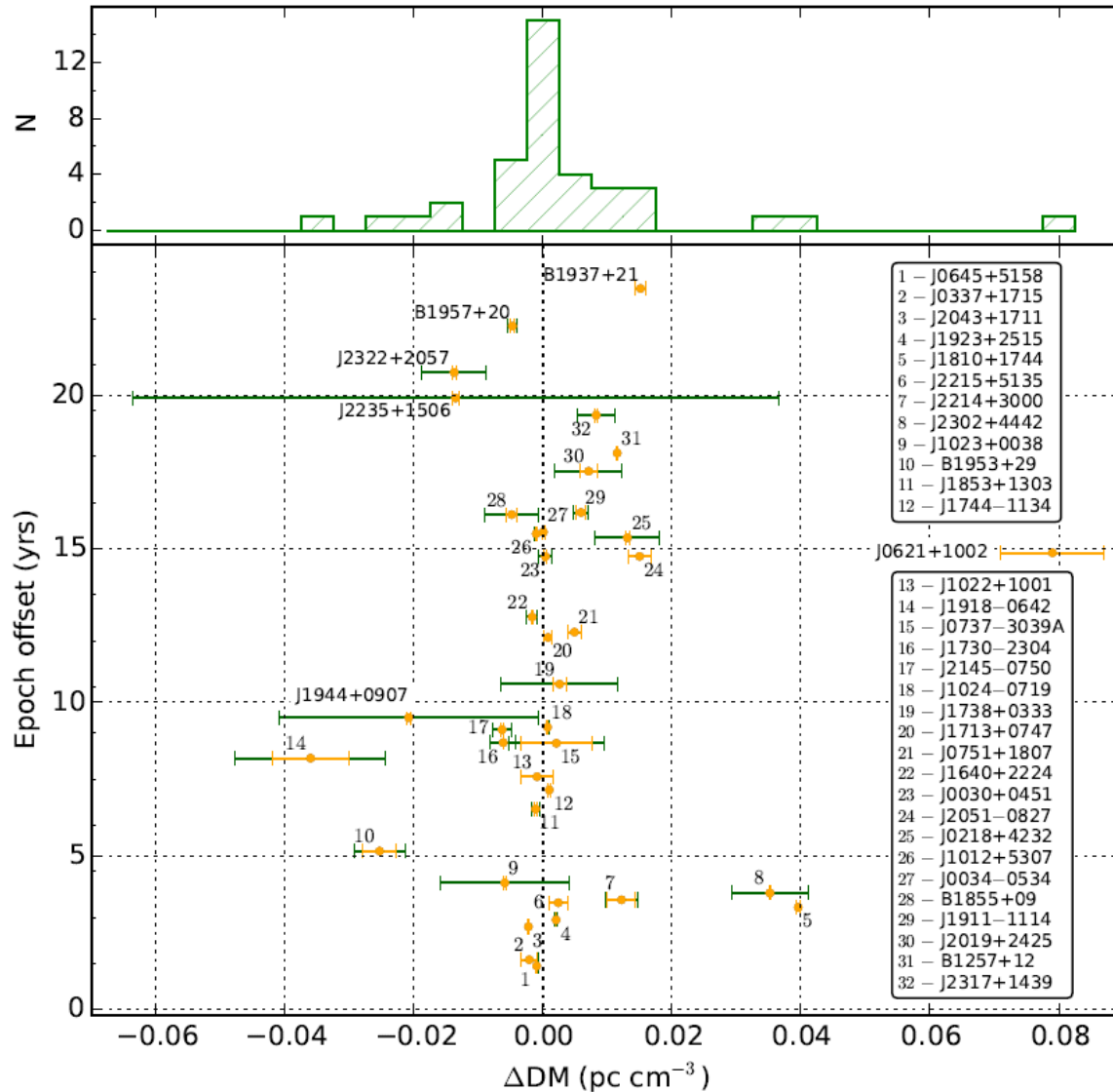


DM variations

Keith et al. 2013



DM variations

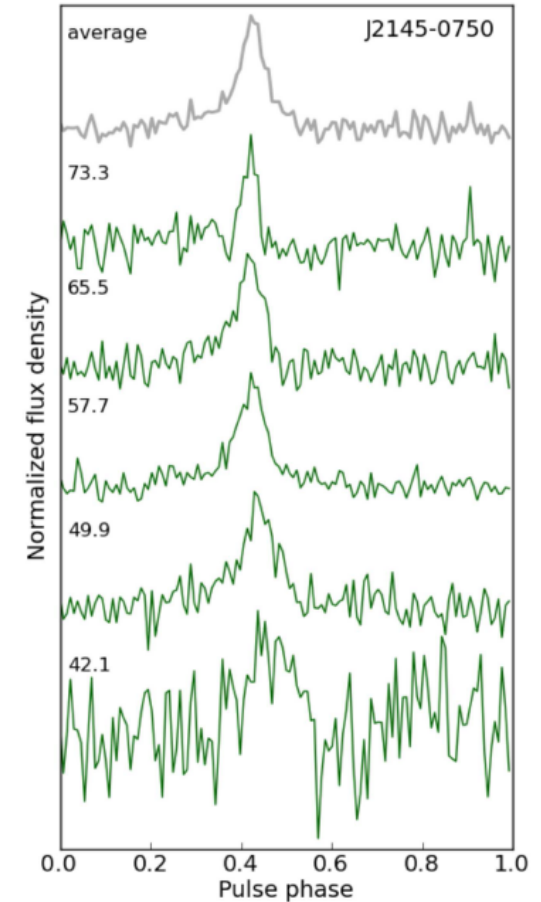
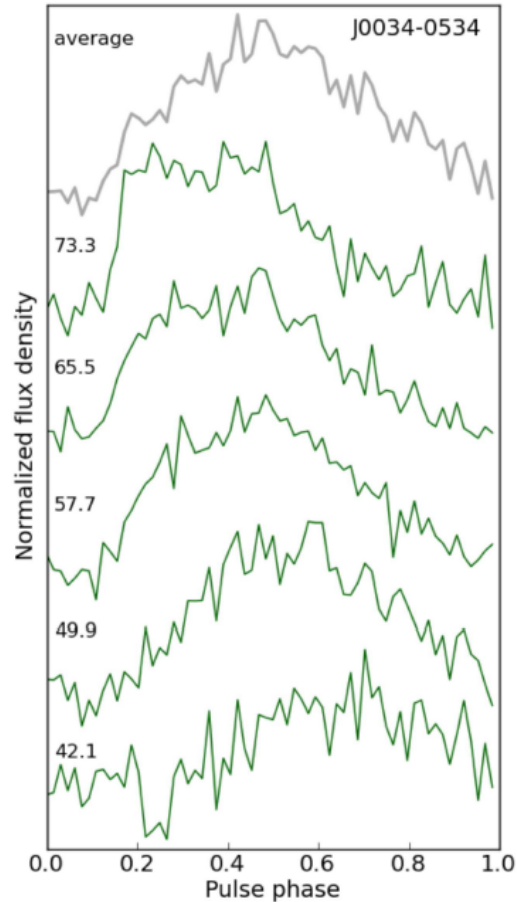
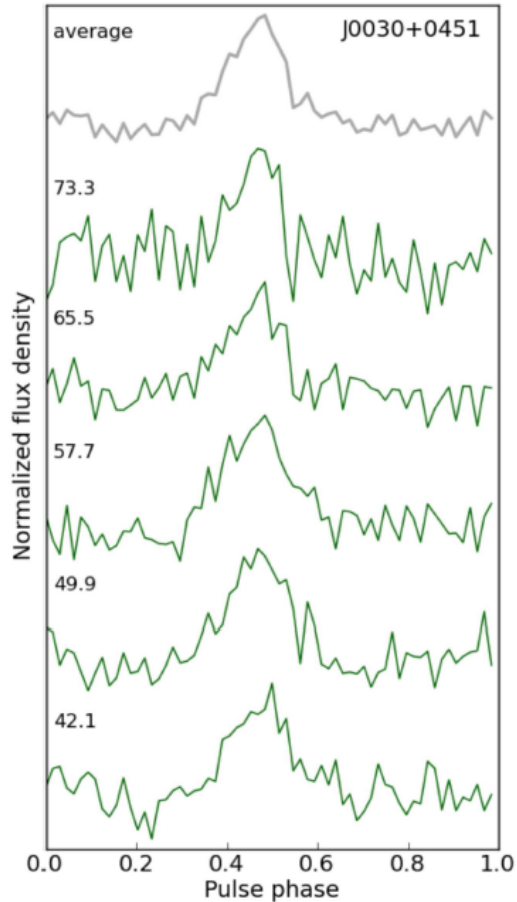


- Provide LOFAR "ISM Weather" report (on shorter time scales from single observation)

- Independent DMs to compare with high frequencies

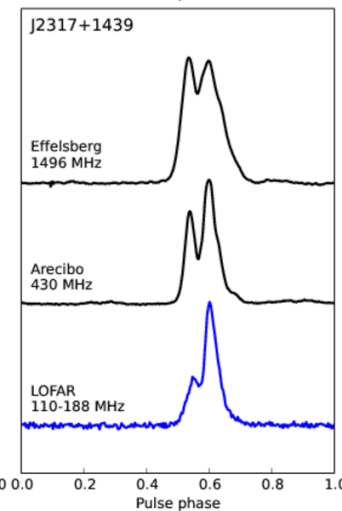
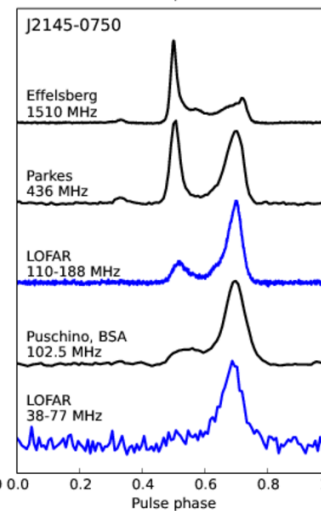
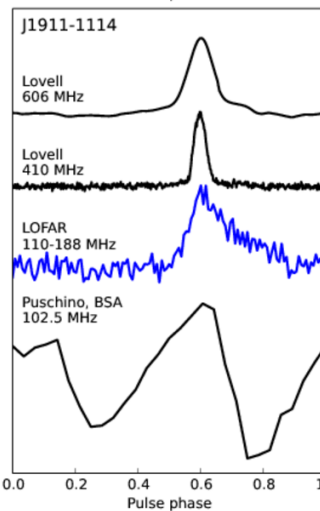
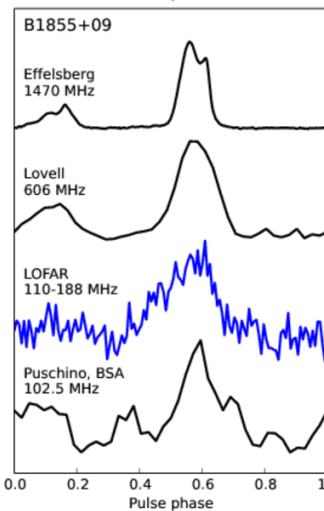
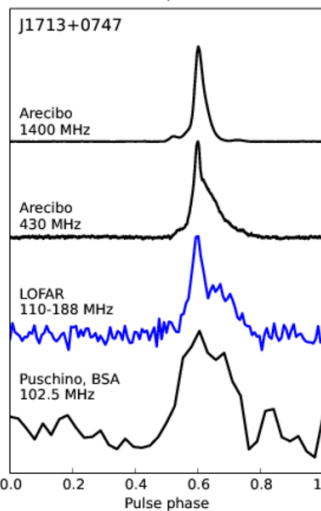
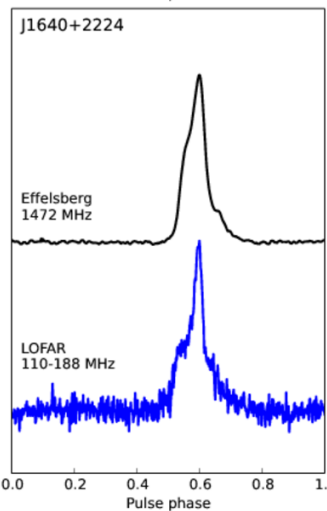
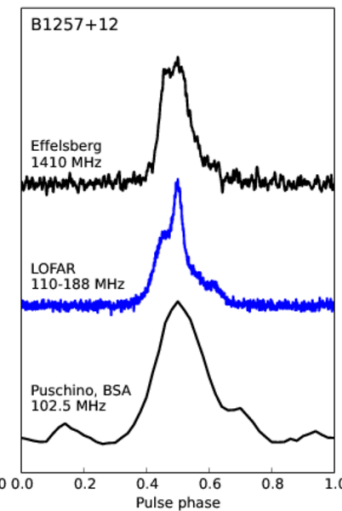
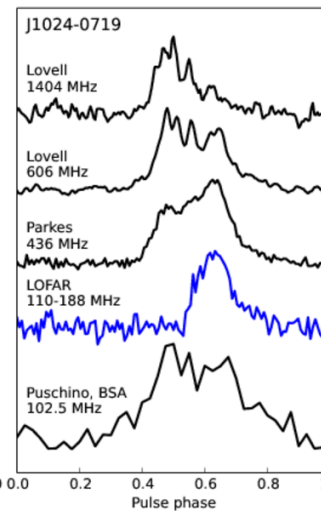
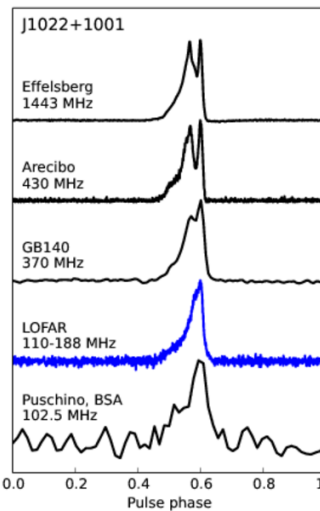
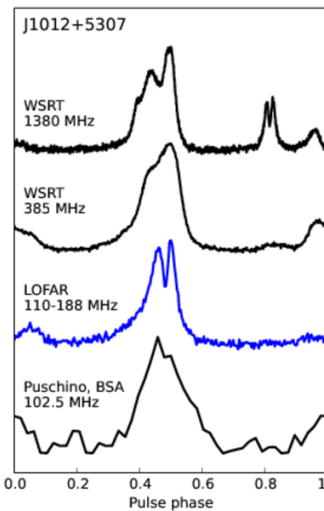
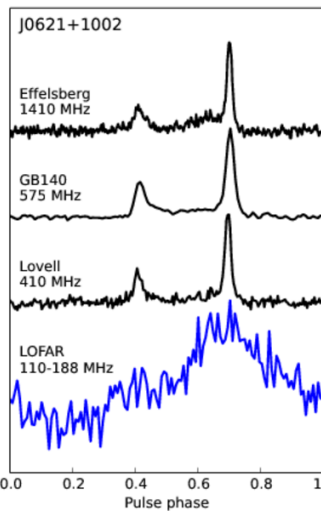
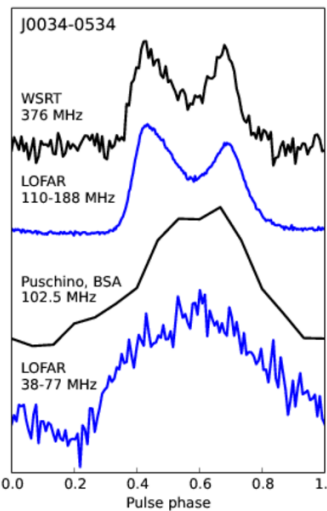
MSP LBA detections

38–77 MHz

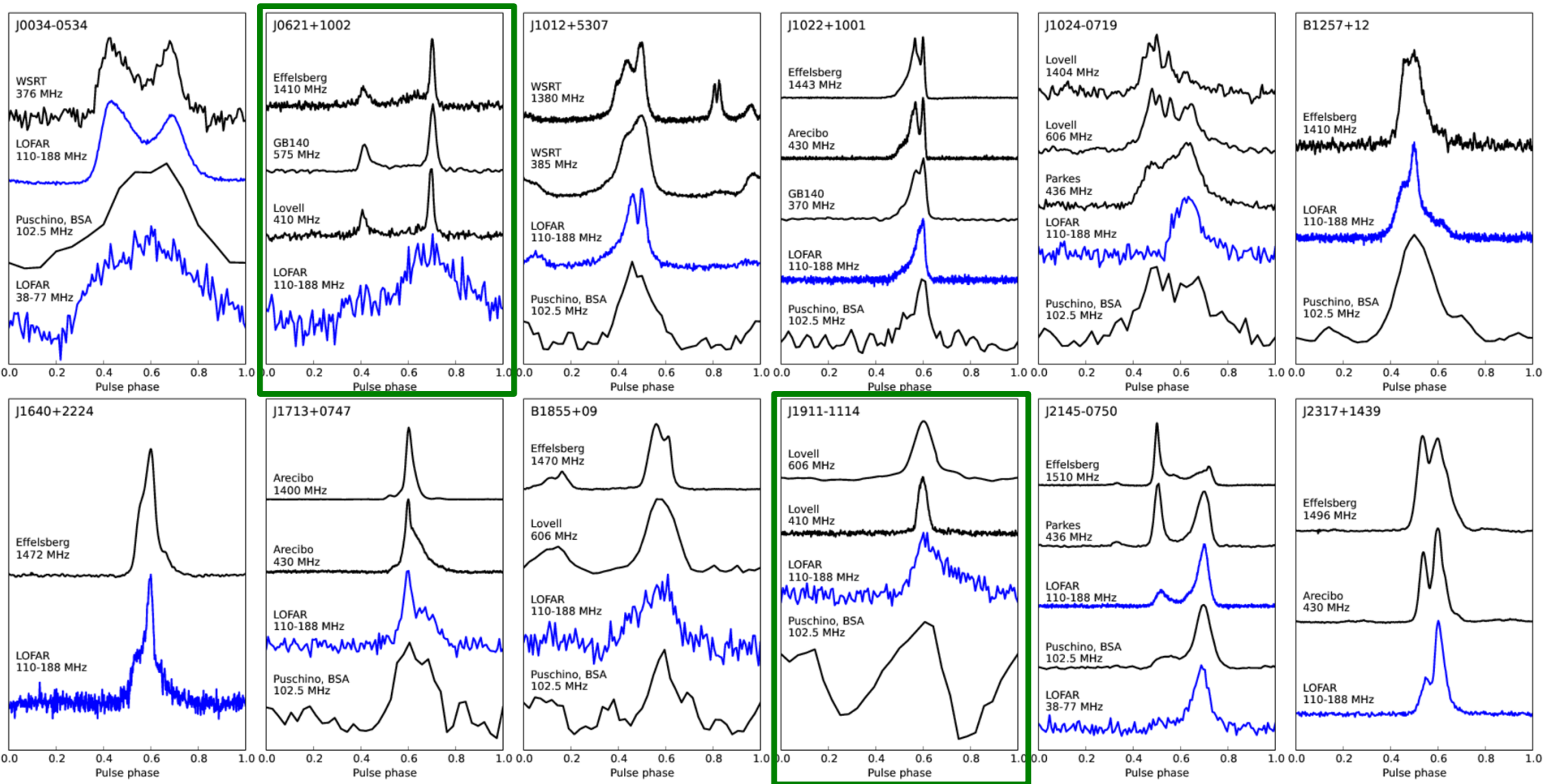


LBA non-detections: J1012+5307, J1022+1001, J1024-0719
B1257+12, J1810+1744, J2317+1439

MSP Multi-Frequency Profiles



MSP Multi-Frequency Profiles



Mostly unscattered

Summary:

- Great start with MSP detections with LOFAR – 46 out of 65 observed). First large sample of "high-quality" MSP profiles below 200 MHz (Kondratiev et al. 2014, nearly submitted).
- DM variations for 2 MSPs with secular DM drift from high-frequency observations with Parkes (from Keith et al. 2013) agree with LOFAR DM measurements.
- Continued timing will measure high-precision DMs, RMs, and scattering and their long-term variations. We will make these data publicly available.