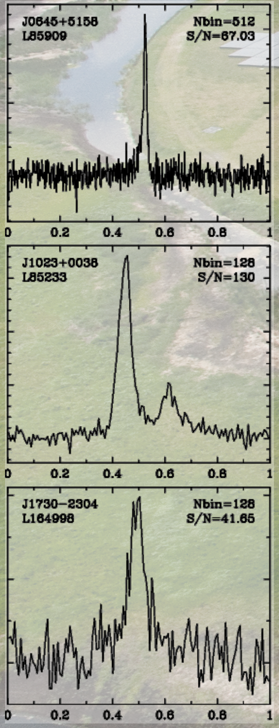
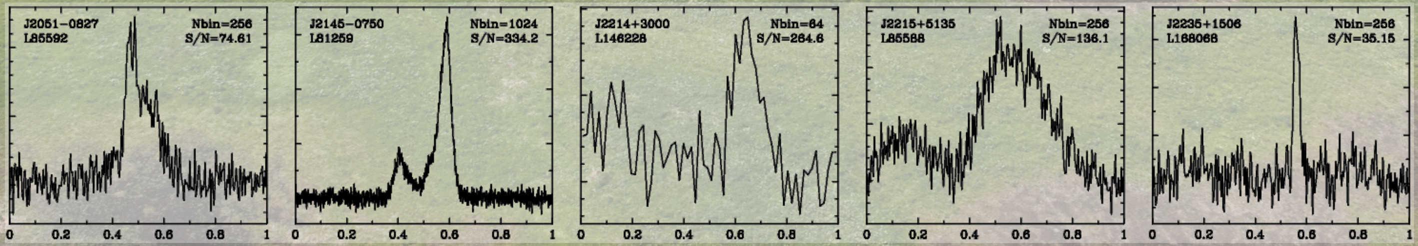
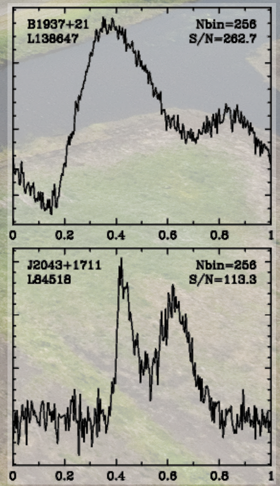
Vlad Kondratiev (ASTRON)

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

Millisecond pulsars at low frequencies with LOFAR







LOFAR

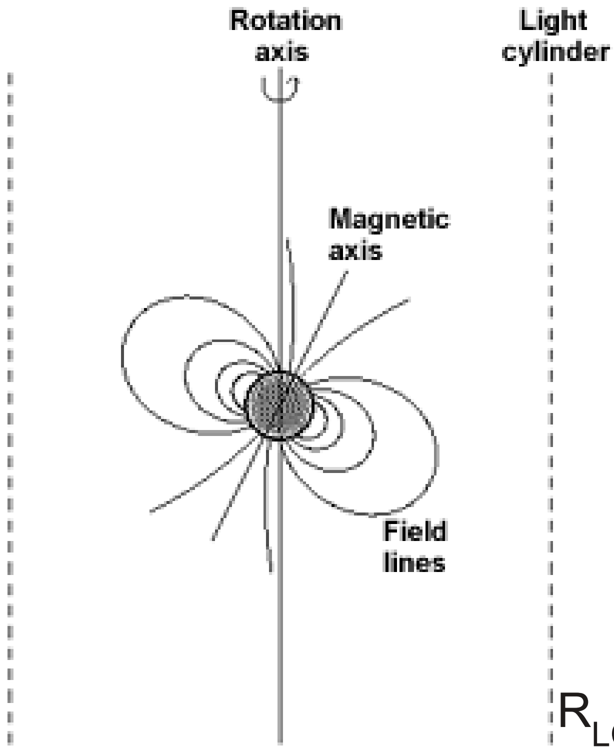
LOFAR Science 2014, Amsterdam — Apr 8, 2014

ASTRON

LOFAR Pulsar Working Group

Jason Hessels (co-lead)	*ASTRON/Universiteit van Amsterdam*
Ben Stappers (co-lead)	*University of Manchester*
Anya Bilous	*Radboud Universiteit Nijmegen*
Thijs Coenen	*Universiteit van Amsterdam*
Sally Cooper	*University of Manchester*
Heino Falcke	*Radboud Universiteit Nijmegen*
Jean-Mathias Grießmeier	*LPC2E/CNRS/Université d'Orléans*
Tom Hassall	*University of Southampton*
Aris Karastergiou	*University of Oxford*
Evan Keane	*Swinburne University of Technology*
Vlad Kondratiev	*ASTRON*
Michael Kramer	*MPI fűr Radioastronomie*
Masaya Kuniyoshi	*MPI fűr Radioastronomie*
Joeri van Leeuwen	*ASTRON/Universiteit van Amsterdam*
Aris Noutsos	*MPI fűr Radioastronomie*
Maura Pilia	*ASTRON*
Maciej Serylak	*University of Oxford*
Charlotte Sobey	*ASTRON*
Sander ter Veen	*Radboud Universiteit Nijmegen*
Joris Verbiest	*Universität Bielefeld*
Patrick Weltevrede	*University of Manchester*
Kimon Zagkouris	*University of Oxford*

MSPs vs. PSRs



$R_{LC} = cP/2\pi$

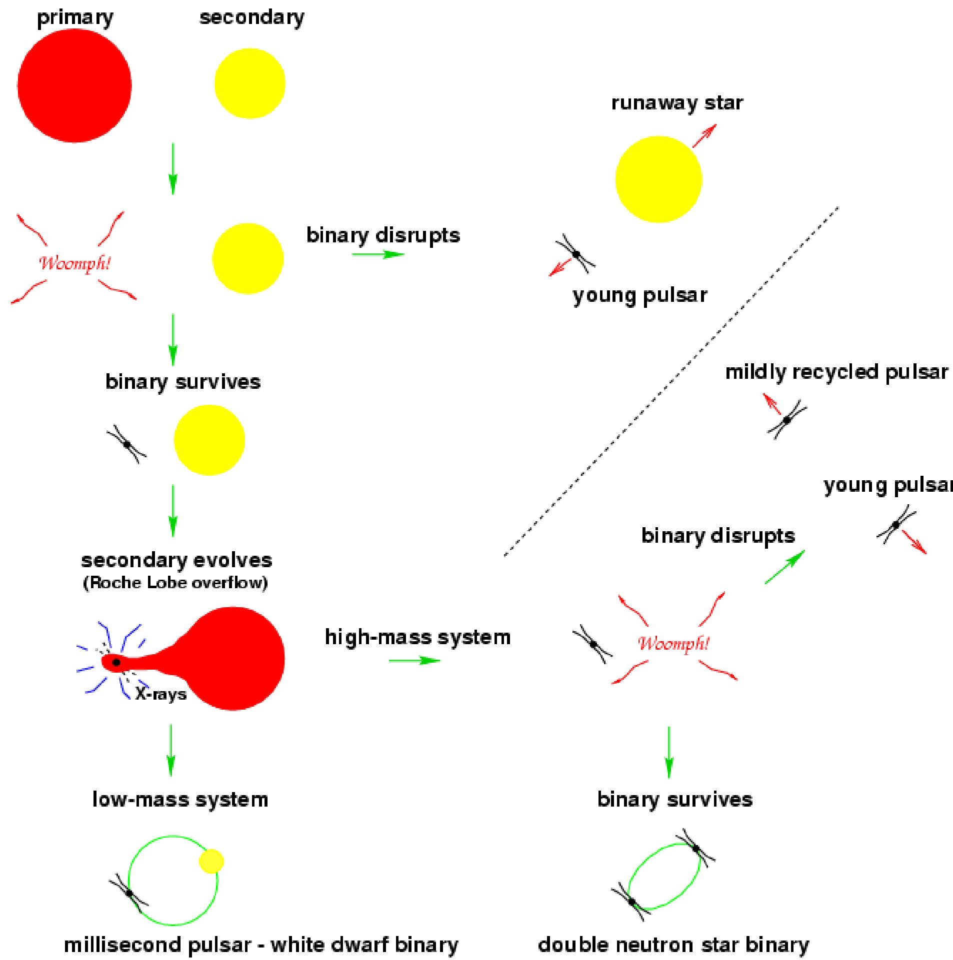
$\sim 10^2 - 10^3$ km

P ~ 1-10 ms

Pdot ~ 10^{-19} s/s

B ~ $10^8 - 10^9$ G

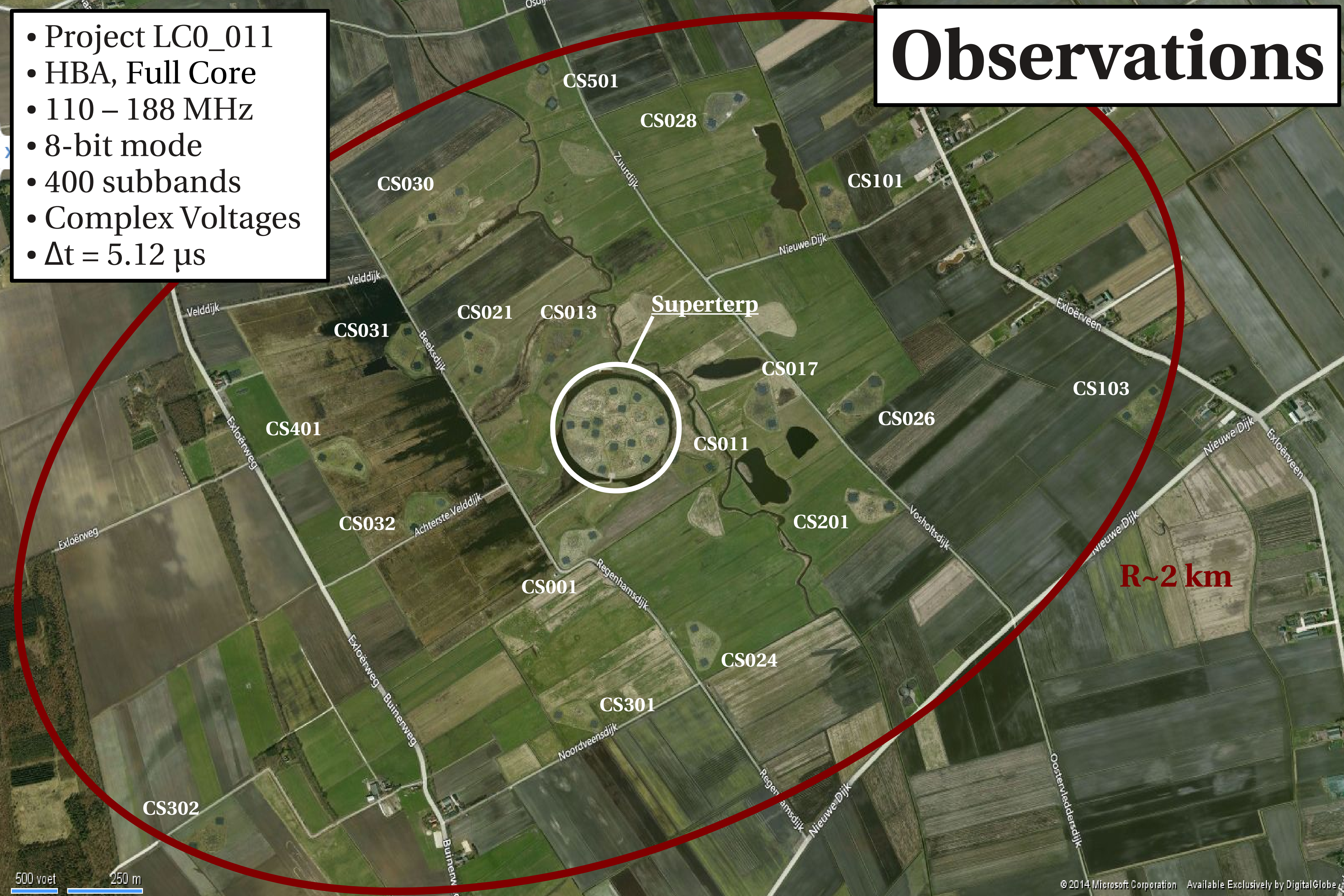
MSPs formation



D. Lorimer (2005)

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


• Project LC0_011
• HBA, Full Core
• 110 – 188 MHz
• 8-bit mode
• 400 subbands
• Complex Voltages
• Δt = 5.12 μs
Observations
CS501
CS028
CS030
CS101
Zuurdijk
Nieuwe Dijk
Velddijk
Velddijk
CS031
CS021
CS013
Superterp
Beekstdijk
CS017
CS103
CS026
CS401
CS011
Exloërveen
Exloërveen
Nieuwe Dijk
Exloërweg
CS032
Achterste Velddijk
CS201
Vosholtsdijk
Exloërweg
Nieuwe Dijk
CS001
Regenhamsdijk
R~2 km
CS024
Exloërweg
Buinerweg
CS301
Noordveensdijk
CS302
Regenhamsdijk
Nieuwe Dijk
Oostervleddersdijk
500 voet
250 m
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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	

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B1953+29	6.133	104.501	BT	...	...	L84522	56311.45	20	61	7	
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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	
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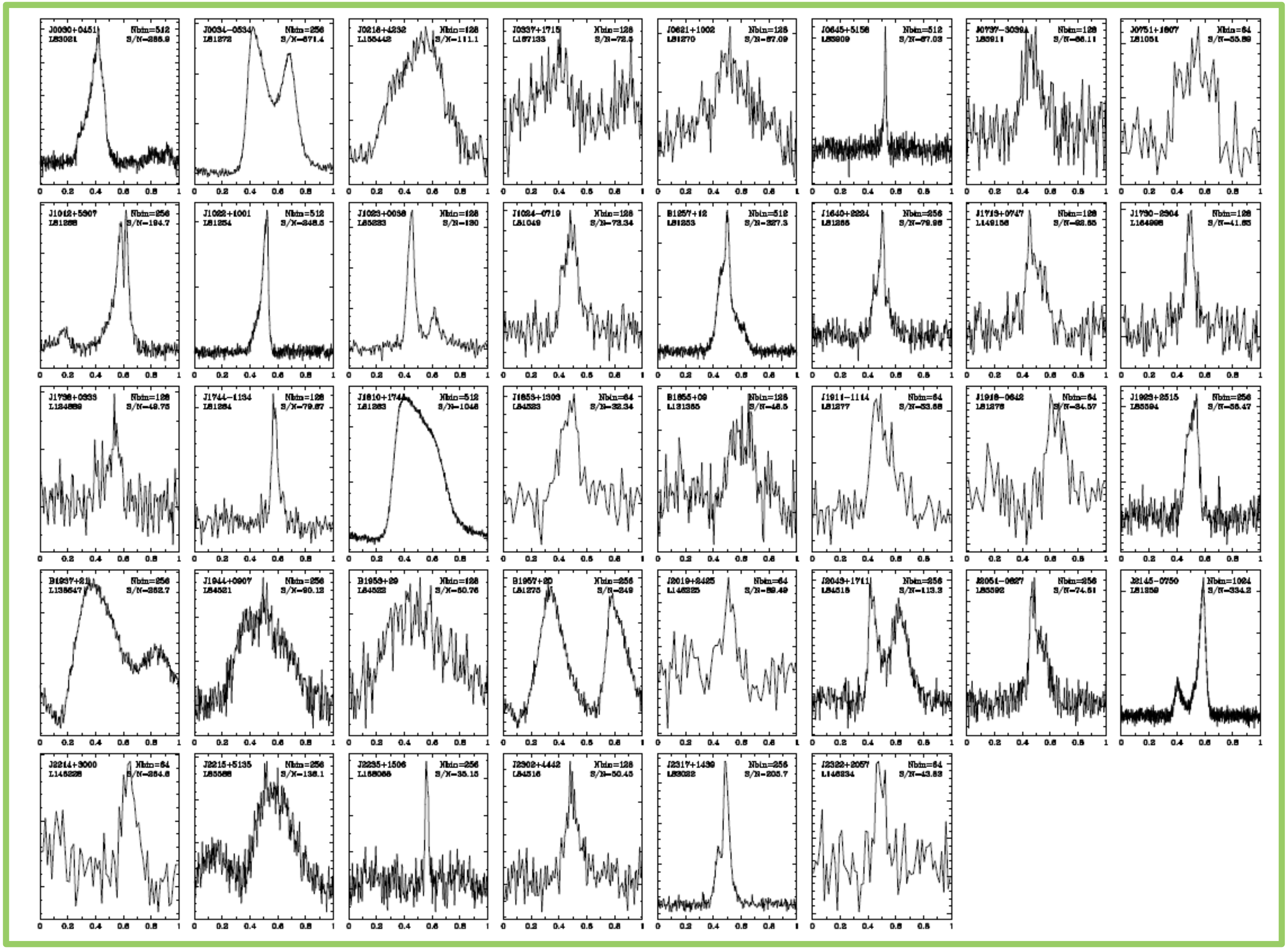
J2317+1439	3.445	21.907	BT	...	y	L83022	56304.63	20	206	47	n
J2322+2057	4.808	13.372	Isolated	...	y	L146234	56460.21	20	44	8	

69% of observed MSPs Detected!

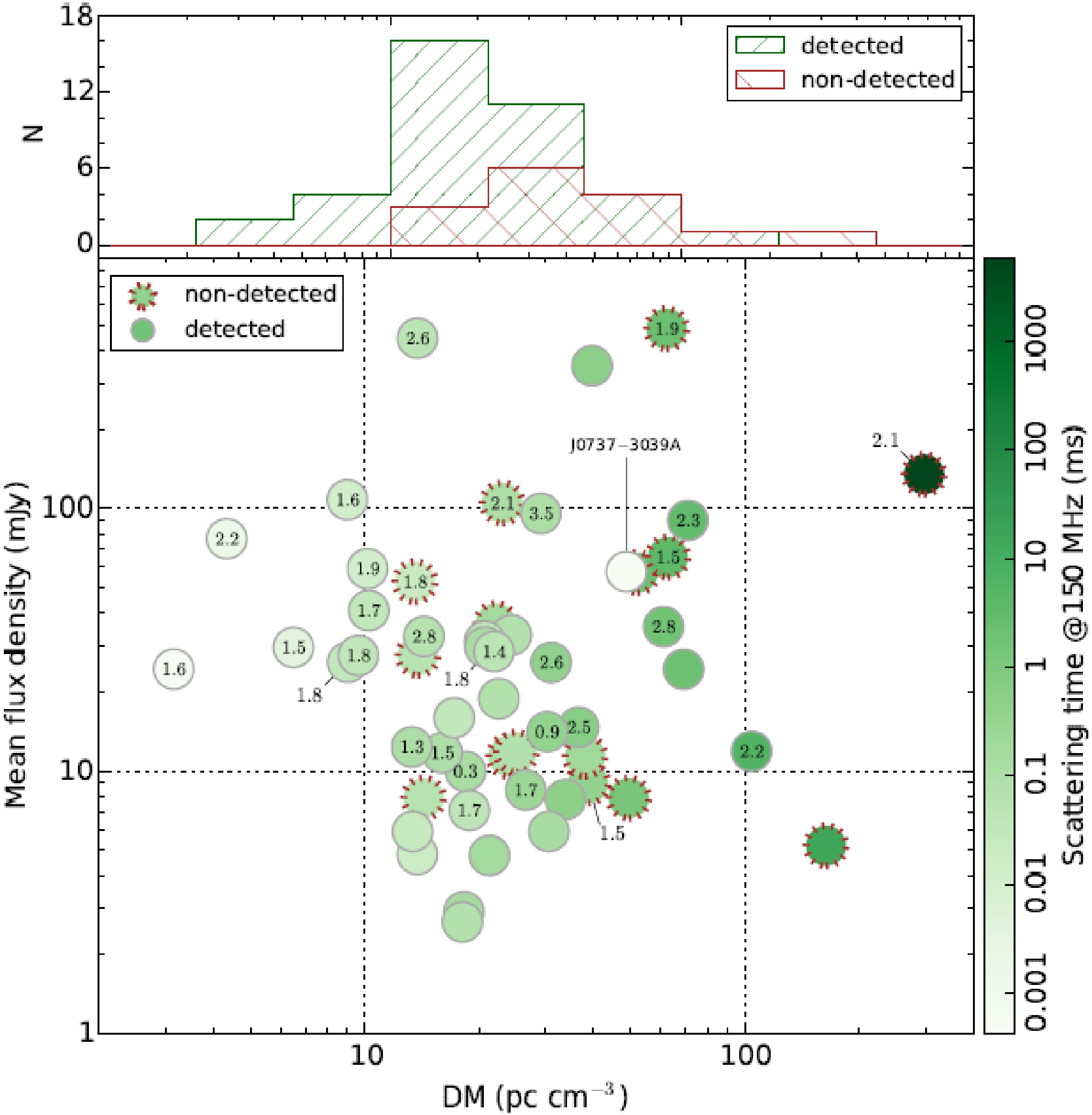
38 — Detections, 17 — non-Detections

Detected MSPs

Kondratiev et al. 2014, nearly submitted



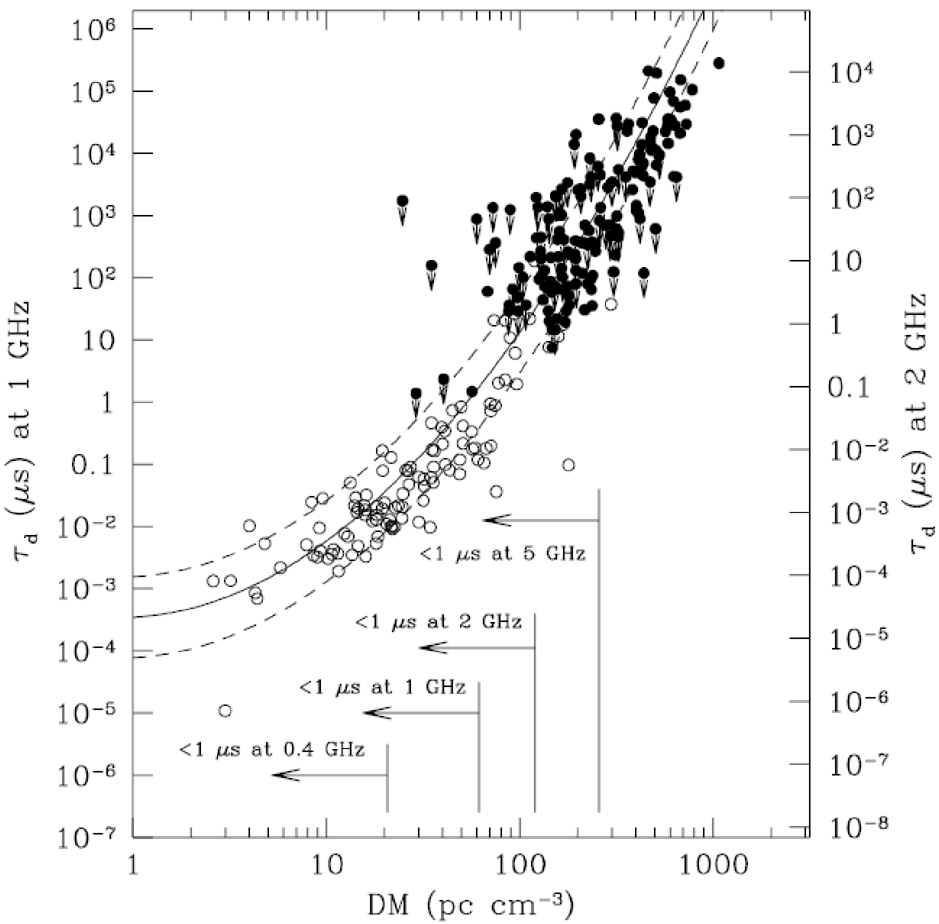
MSP detectability

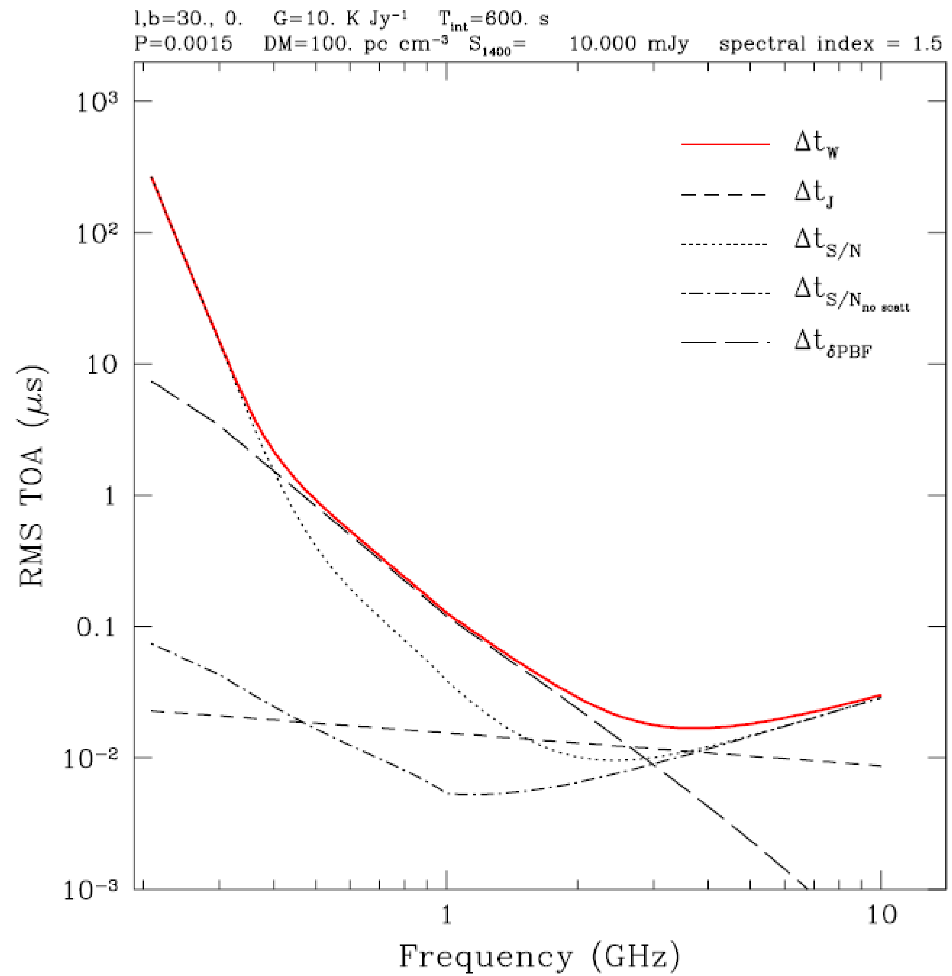


- ✔ detected: all 8 with DM < 10
- ✔ not detected: DM > 105
- ✔ DM = 10-100:
  - 32 MSPs detected
  - 13 MSPs not detected

✔ On average spectral indices are larger at higher DMs for detected MSPs

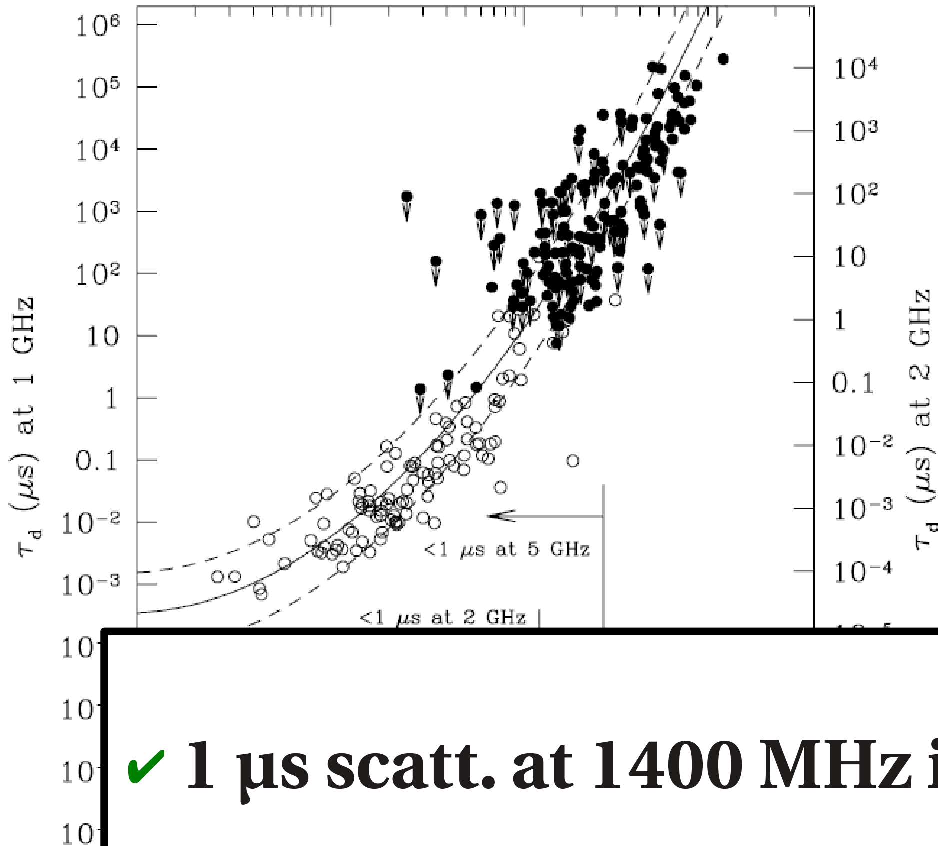
Timing with LOFAR?

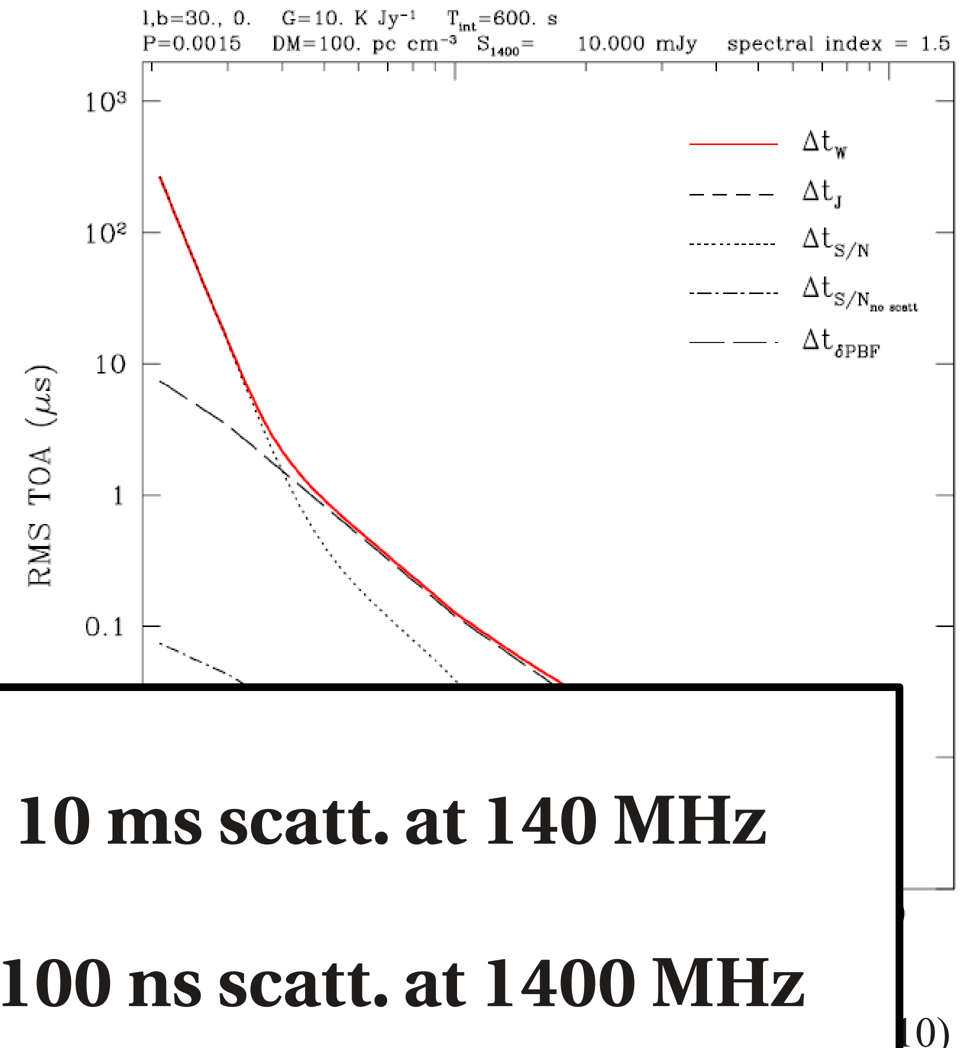




Cordes & Shannon (2010)

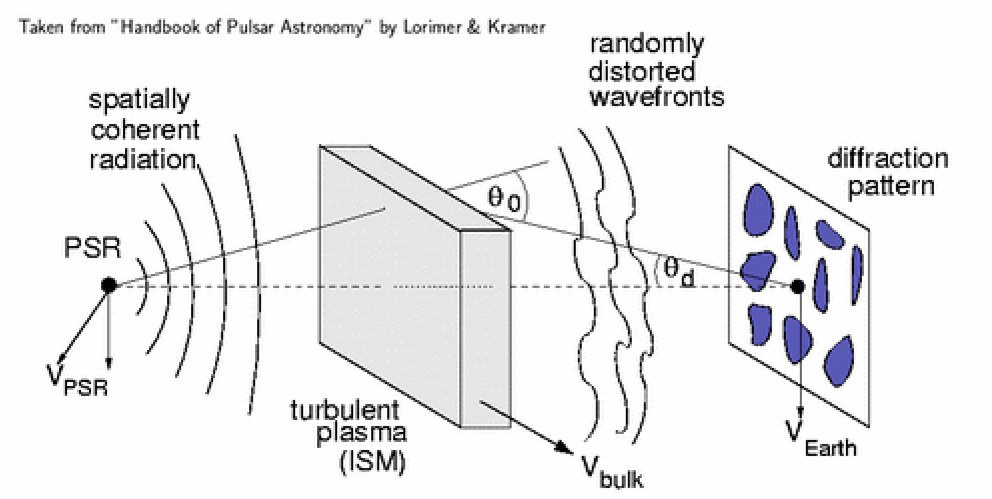
Timing with LOFAR?





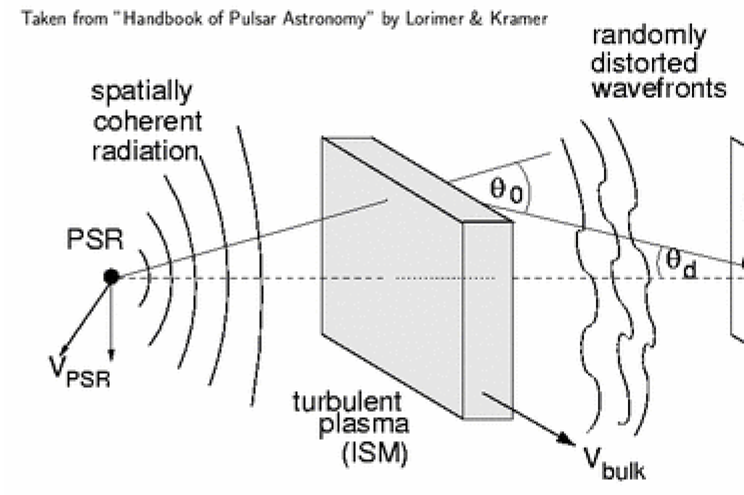
- ✔ 1 μs scatt. at 1400 MHz is 10 ms scatt. at 140 MHz
- ✔ 1 ms scatt. at 140 MHz is 100 ns scatt. at 1400 MHz

Dispersion measure (DM) variations



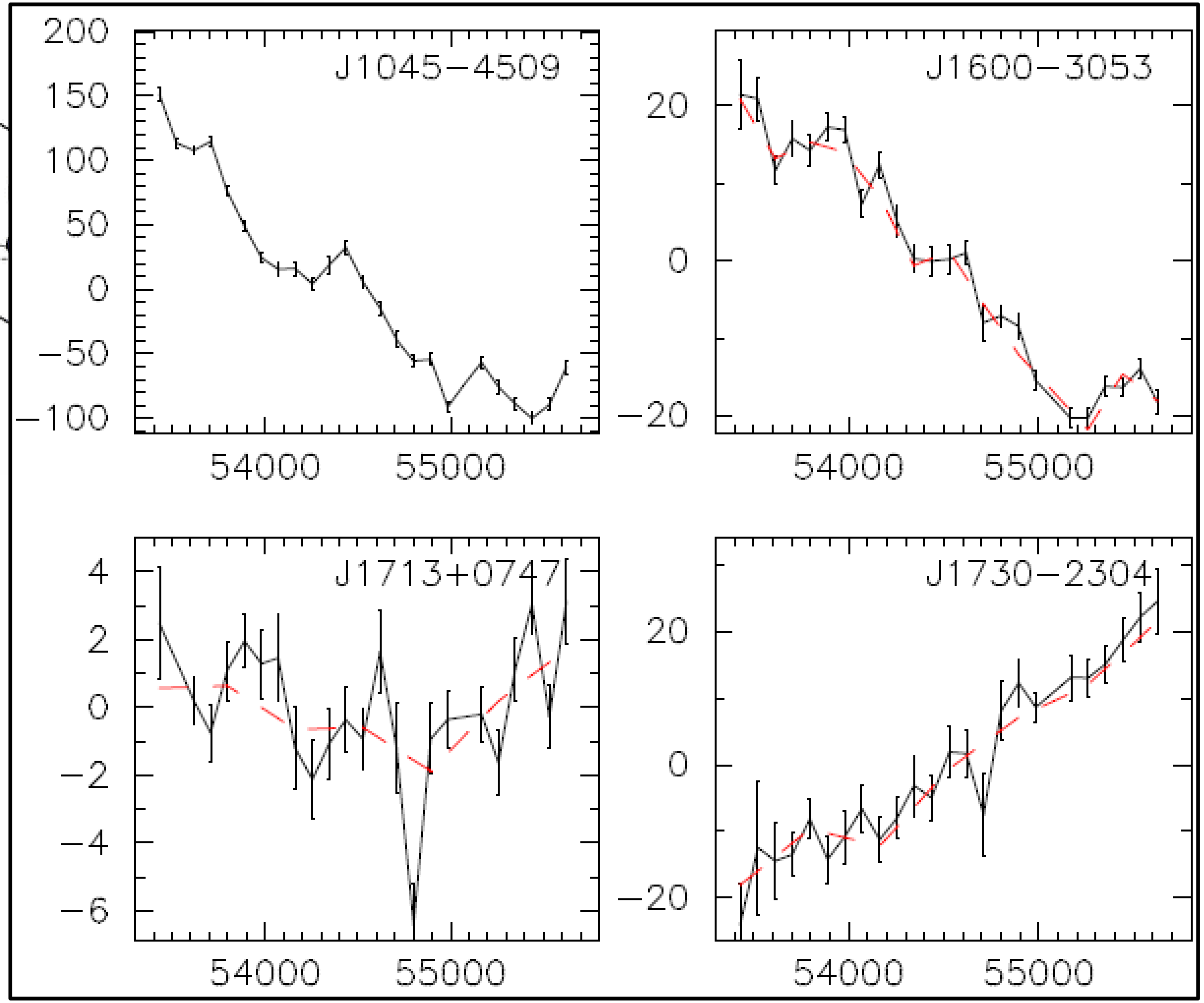
$$\left.\begin{array}{l} V_{plasma} \neq 0 \\ V_{PSR} \neq 0 \end{array}\right\} \quad DM = DM(t)$$

DM variations



$V_{plasma} \neq 0$
$V_{PSR} \neq 0$ } DM = DM(t)

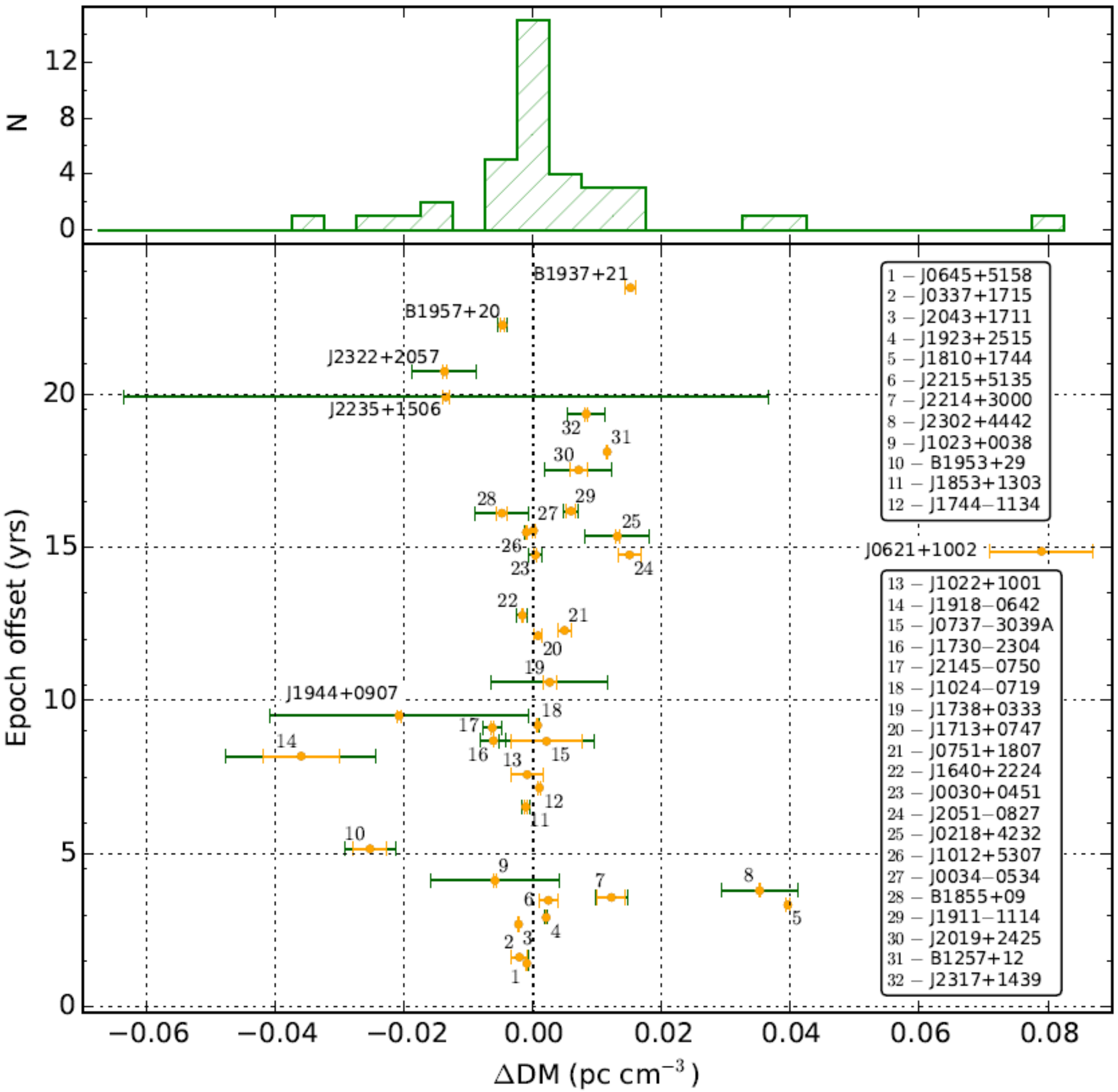
DM offset (10^{-4} pc cm^{-3})



time (MJD)

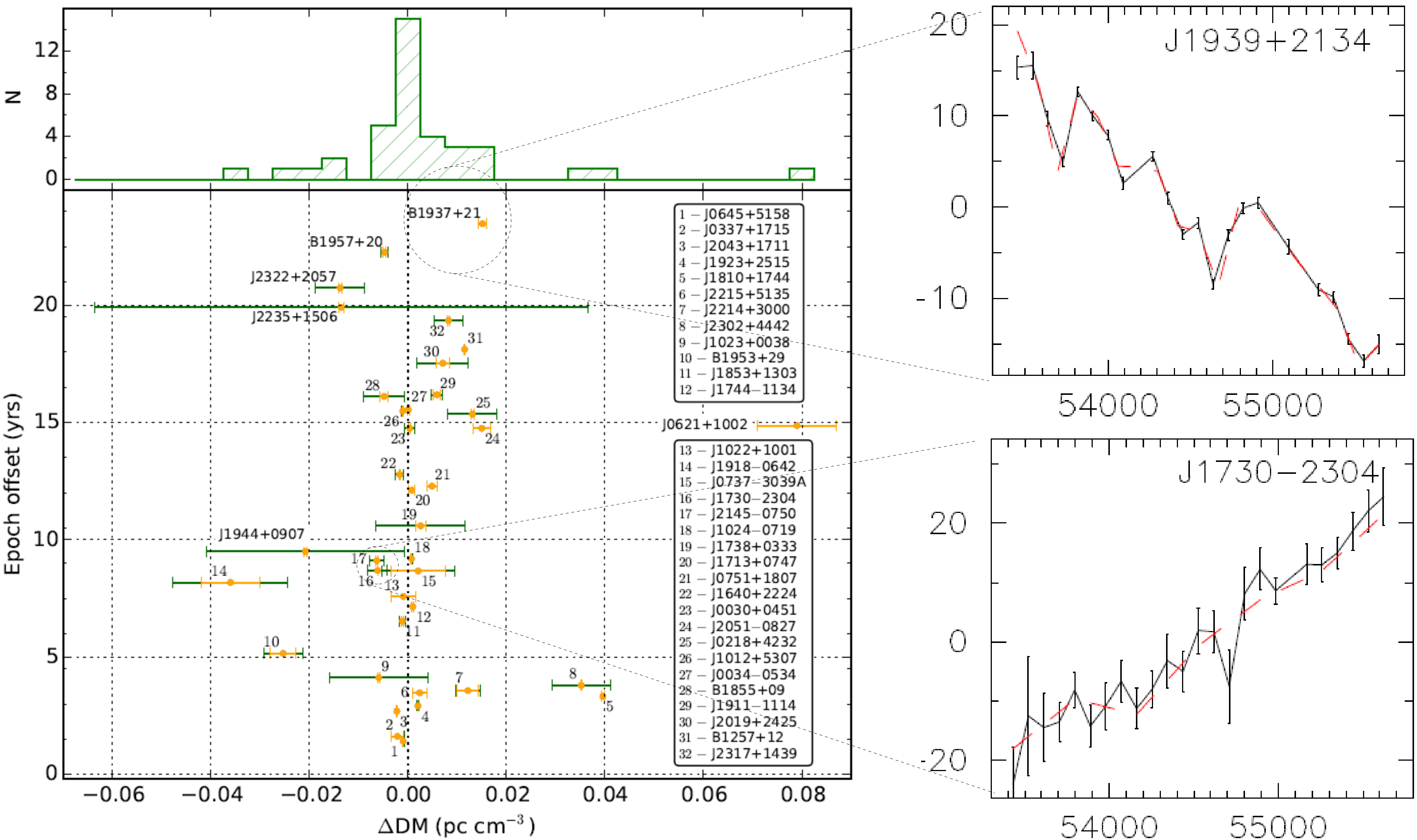
Keith et al. 2013

DM variations

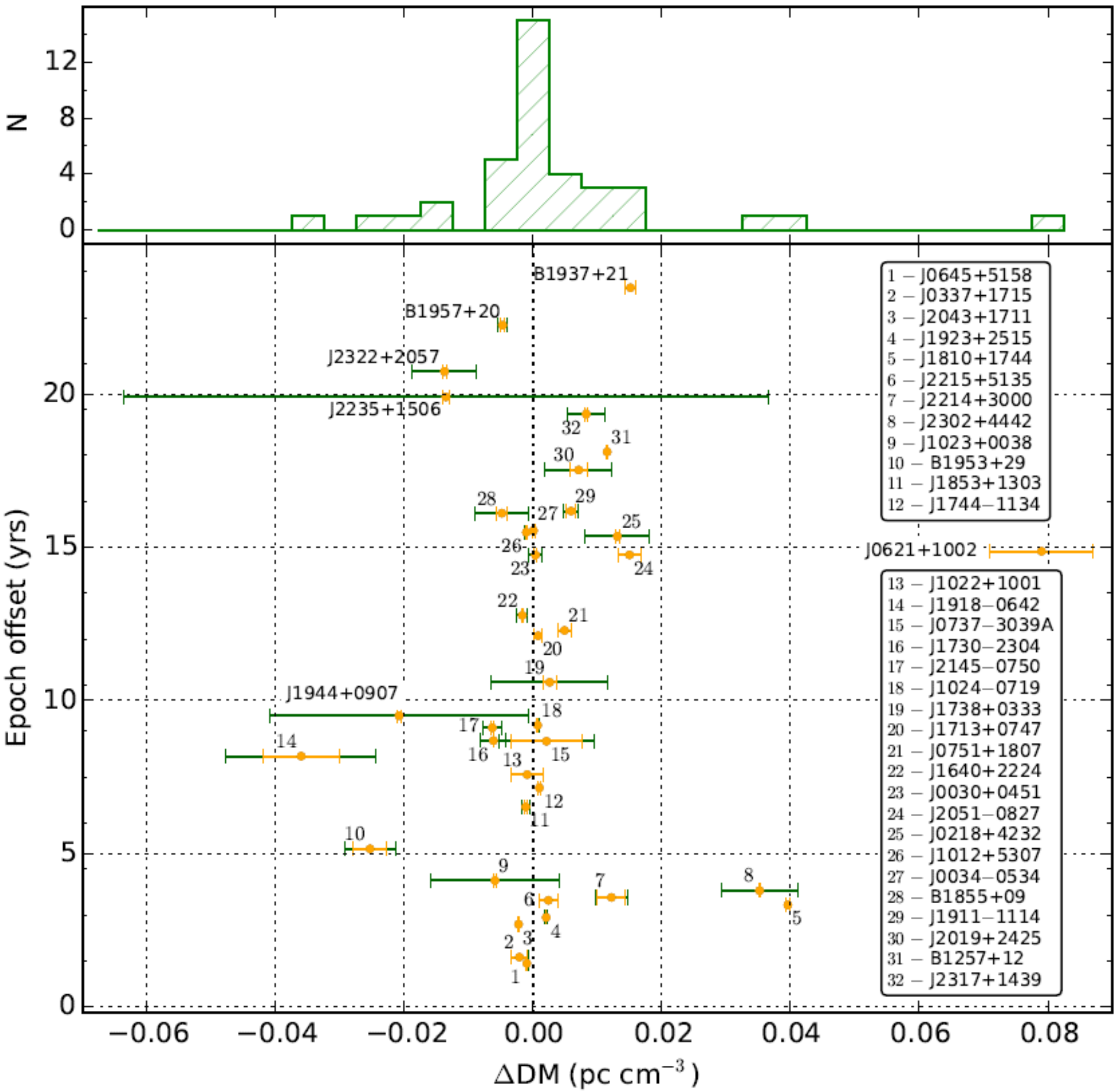


DM variations

Keith et al. 2013

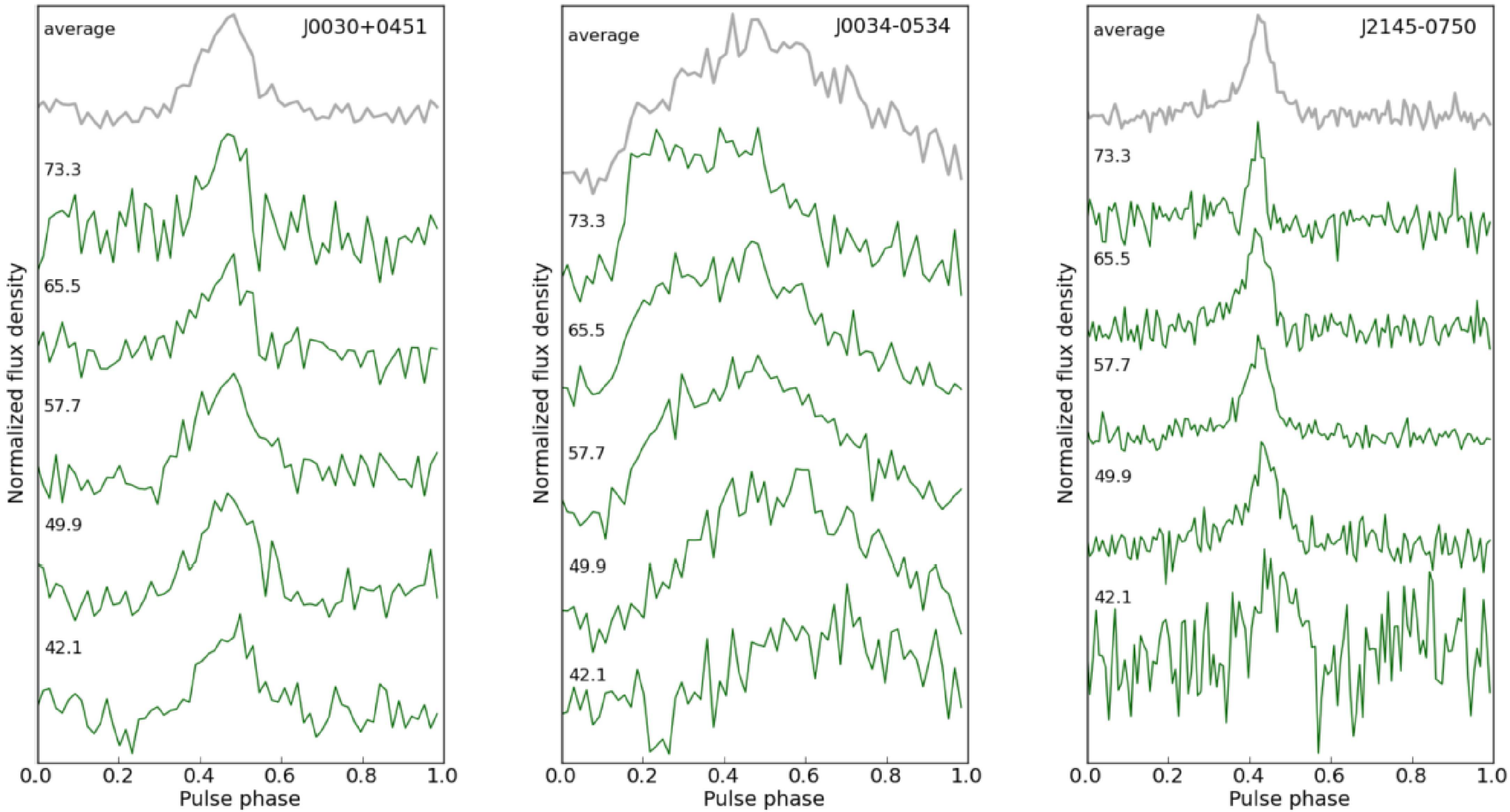


DMvariations



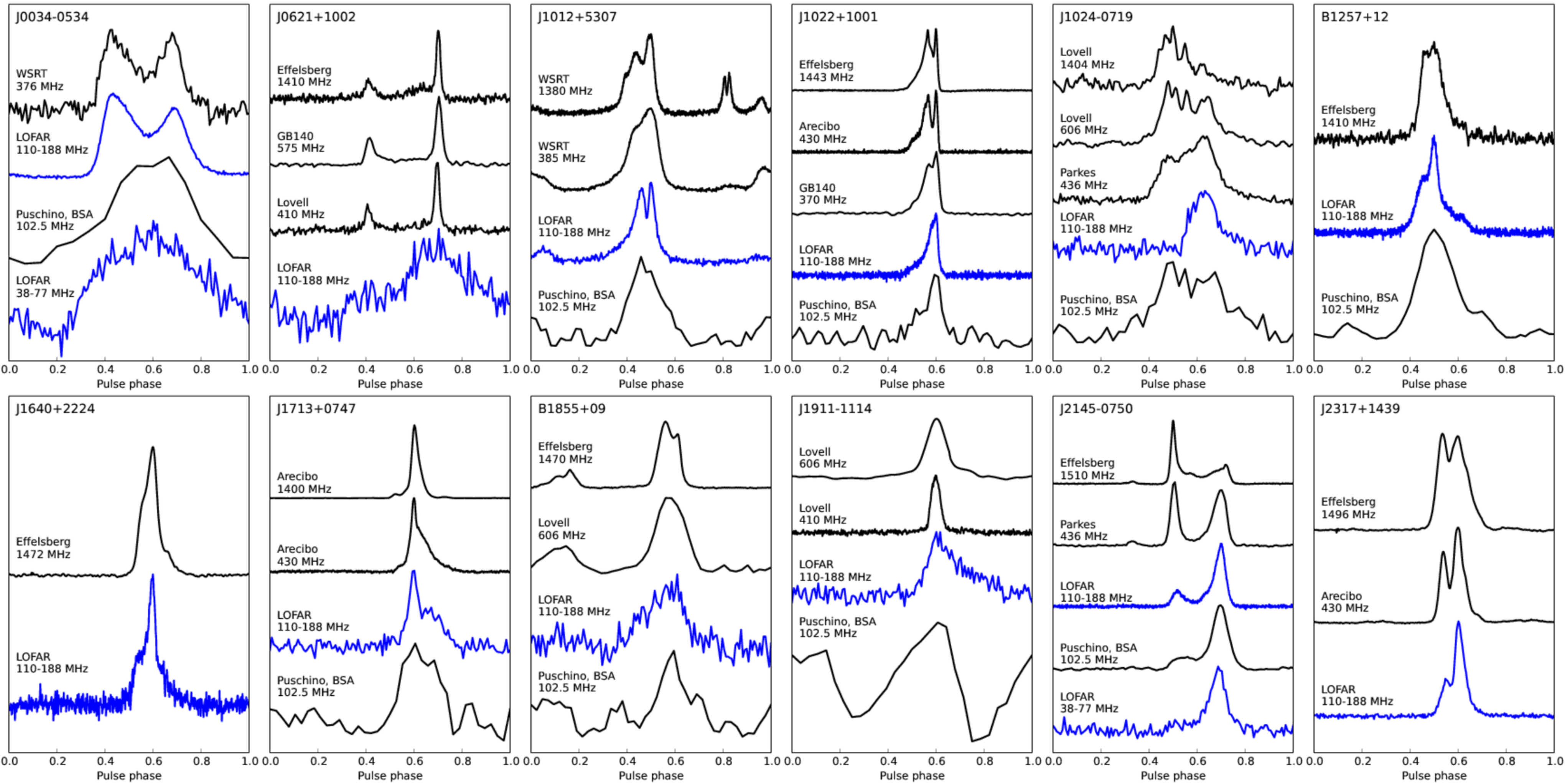
- Provide LOFAR "ISM Weather" report (on shorter time scales from single observation)
- Independent DMs to compare with high frequencies

MSP LBA detections

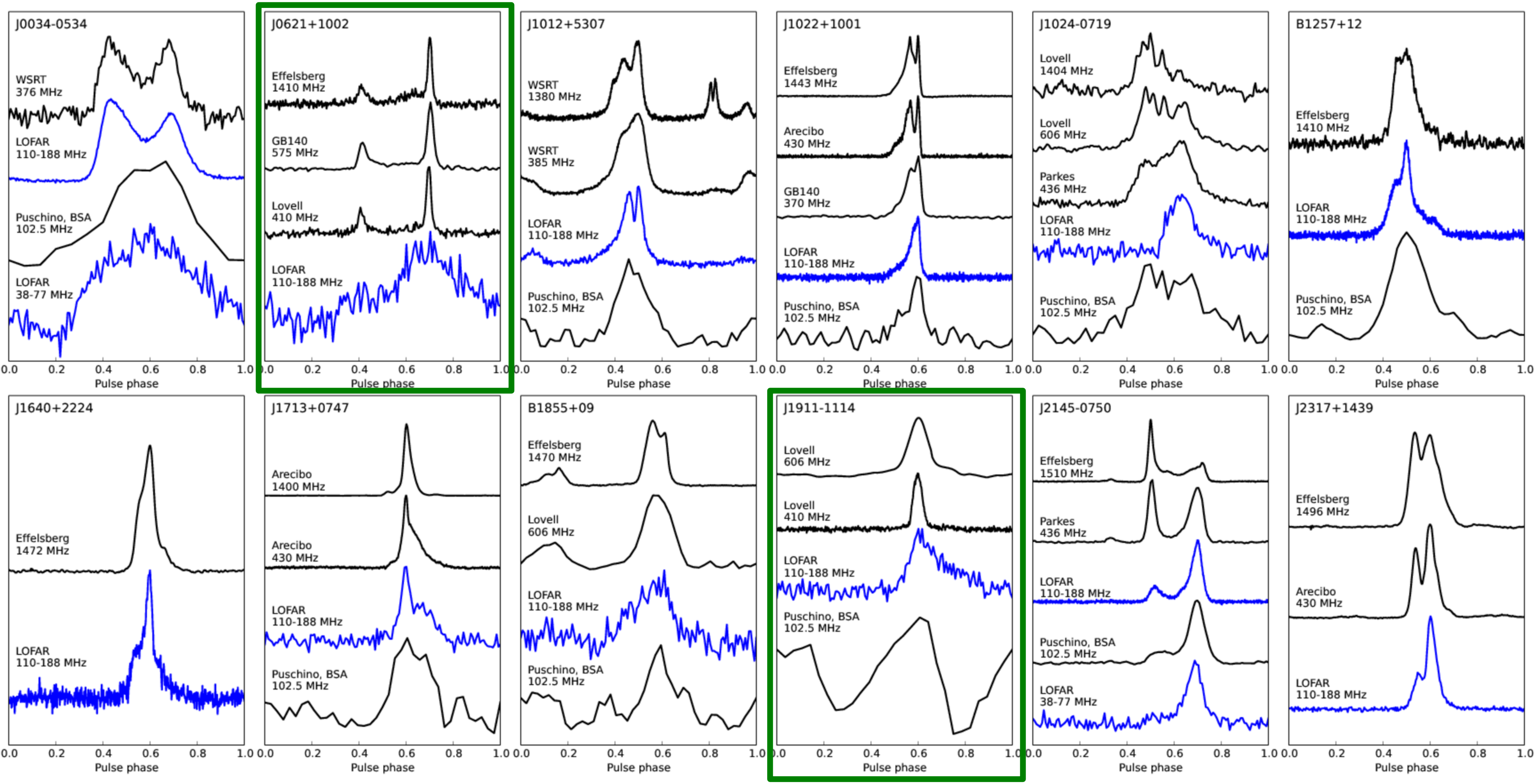


LBA non-detections: J1012+5307, J1022+1001, J1024-0719
B1257+12, J1810+1744, J2317+1439

MSP Multi-Frequency Profiles



MSP Multi-Frequency Profiles



Mostly unscattered

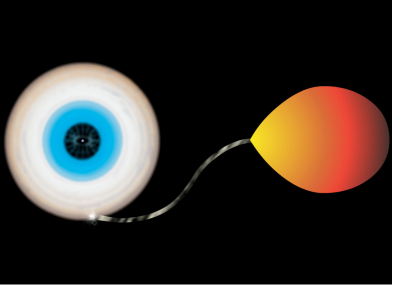
Summary:

- Great start with MSP detections with LOFAR – 38 out of 55 observed). First large sample of "high-quality" MSP profiles below 200 MHz (Kondratiev et al. 2014, nearly submitted, flux calibration to be addressed first).

- DM variations for 2 MSPs with secular DM drift from high-freqiency observations with Parkes (from Keith et al. 2013) agree with LOFAR DM measurements.

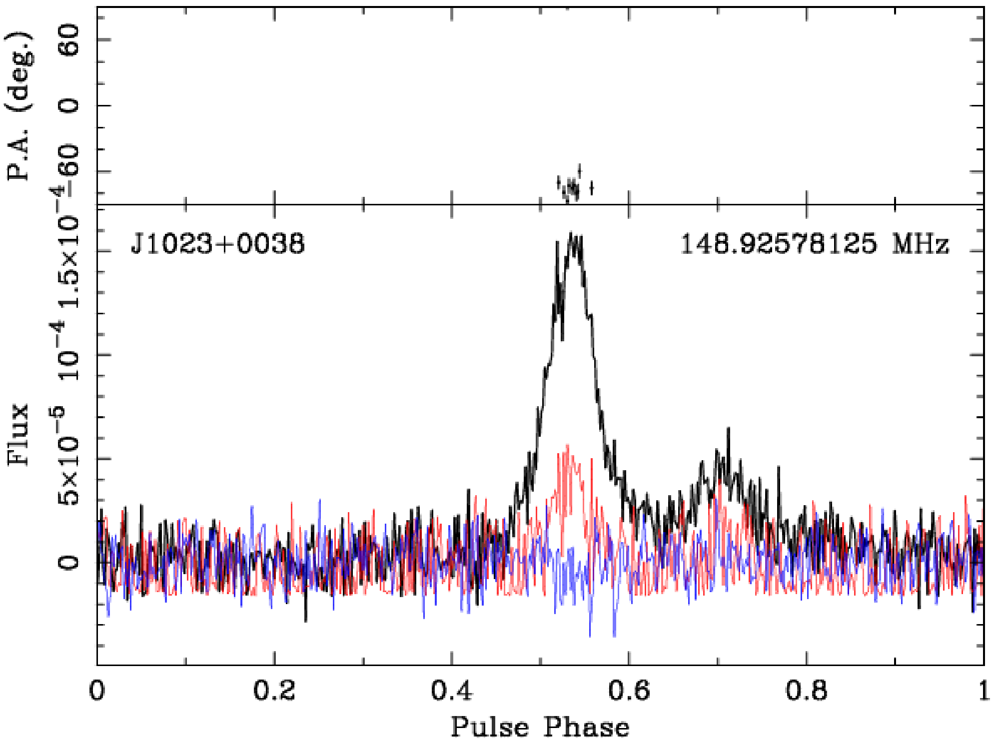
- Continued timing will measure high-precision DMs, RMs, and scattering and their long-term variations. We will make these data publicly available.

LMXB/MSP "Missing Link" J1023+0038

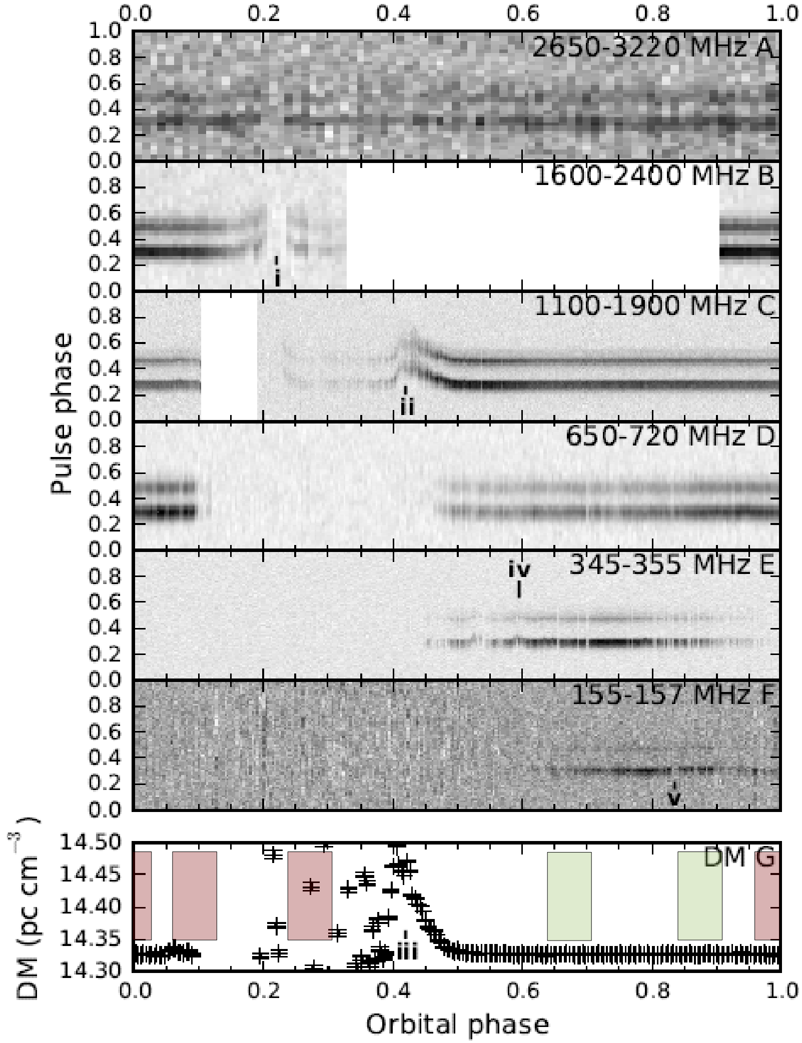


Credit: Bill Saxton (NRAO)

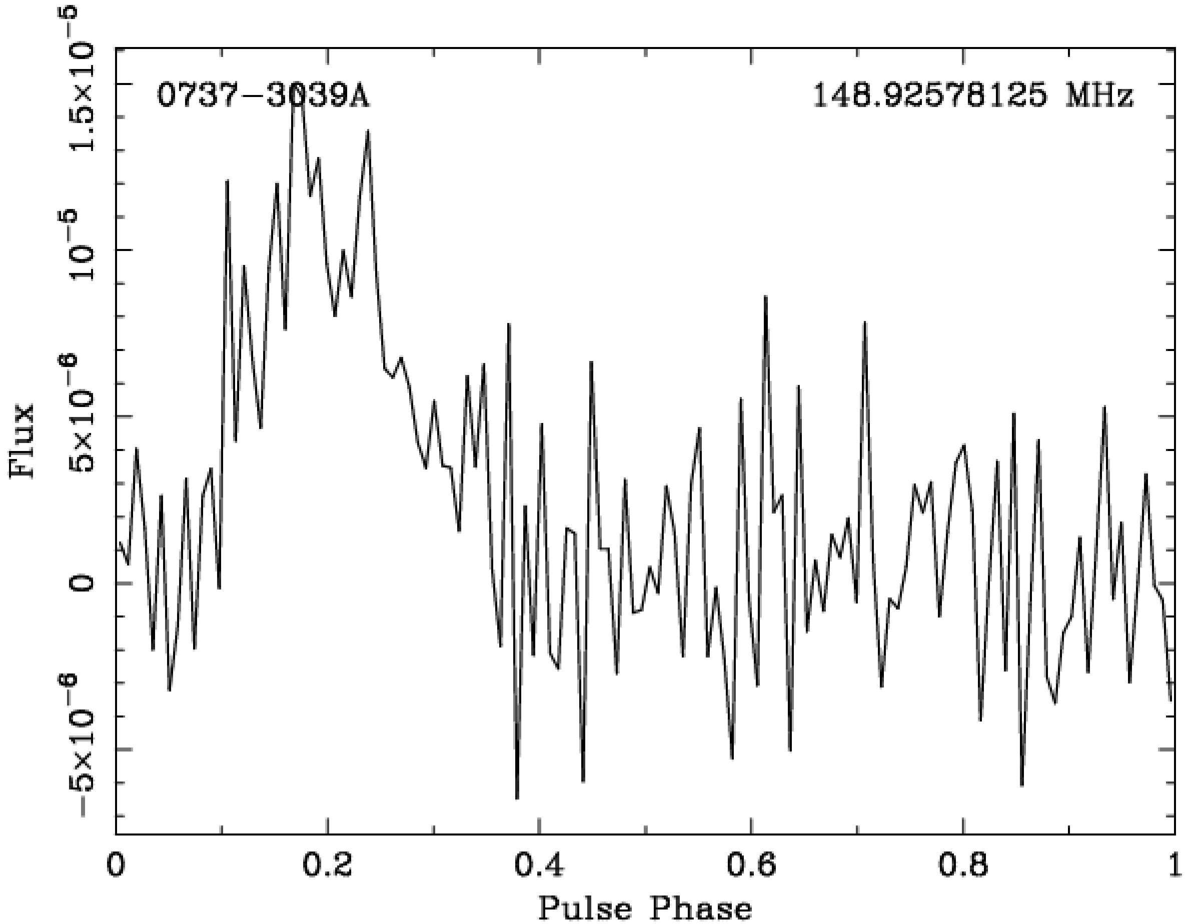
P = 1.69 ms
Porb = 0.198 d
d ~ 1.3 kpc



Archibald et al., 2009



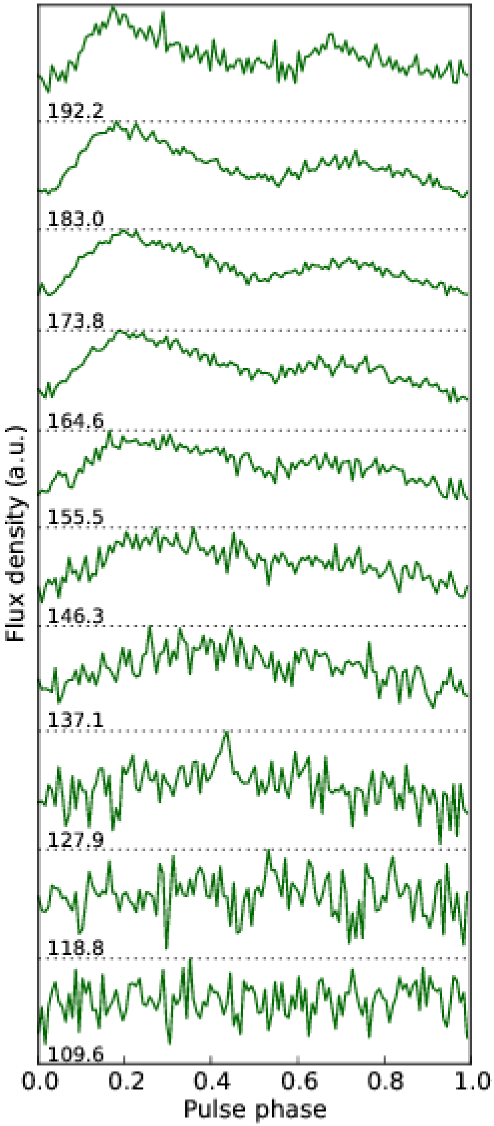
"A"-pulsar in the double pulsar system J0737–3039



Elevation was only 6 deg at transit!

Precise DM measurements will allow for more stringent GR tests

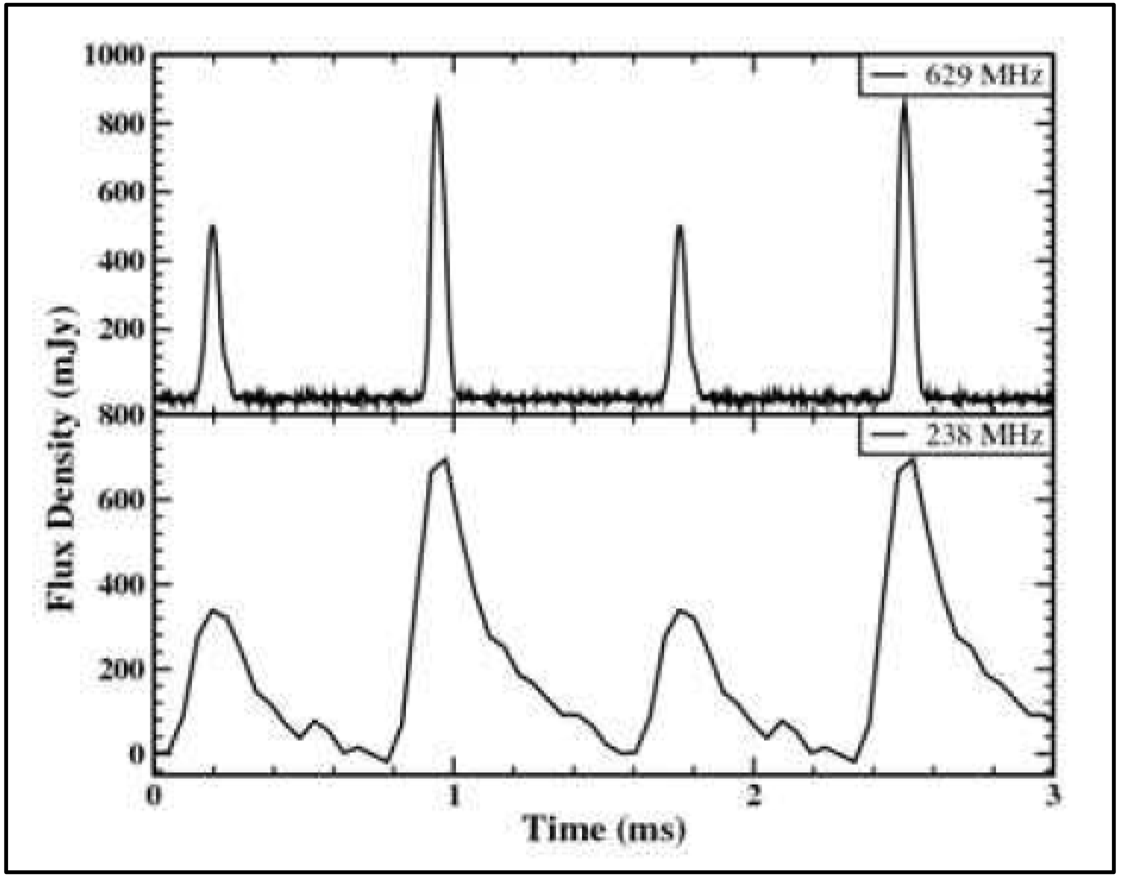
Original MSP B1937+21



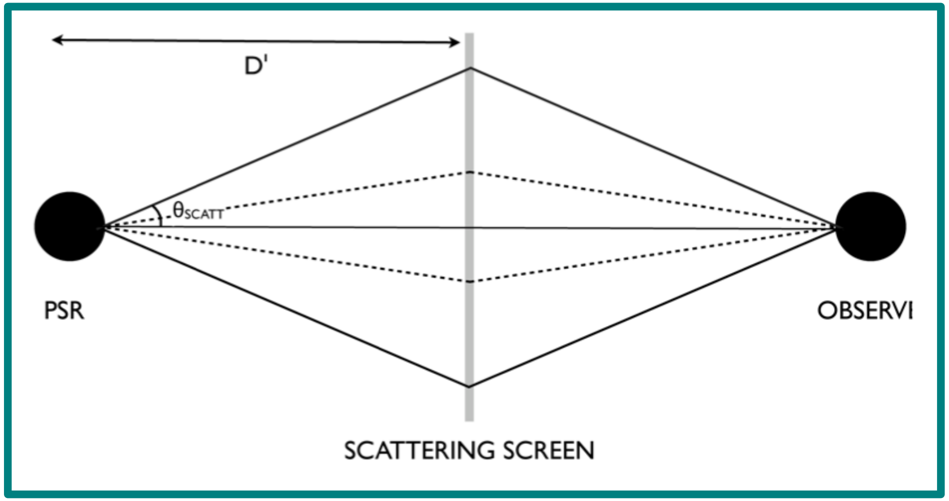
P = 1.56 ms
DM = 71 pc/cc

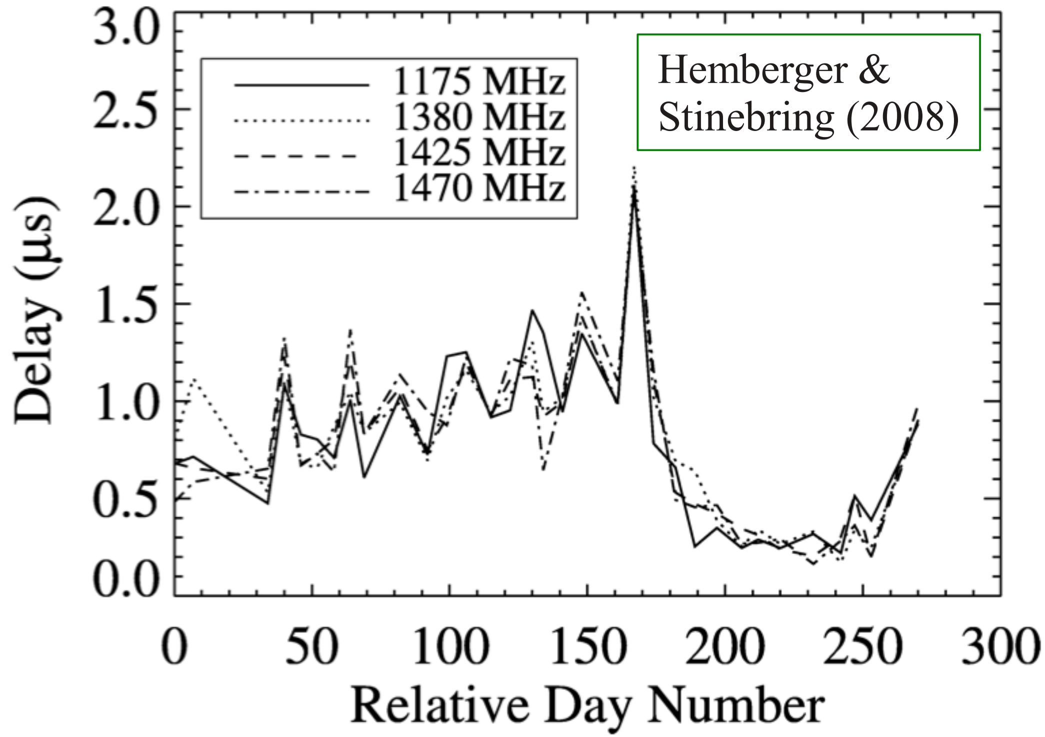
t_{scat} =
2 — 18 ms
(1.3 — 12 P)

Joshi & Kramer 2009



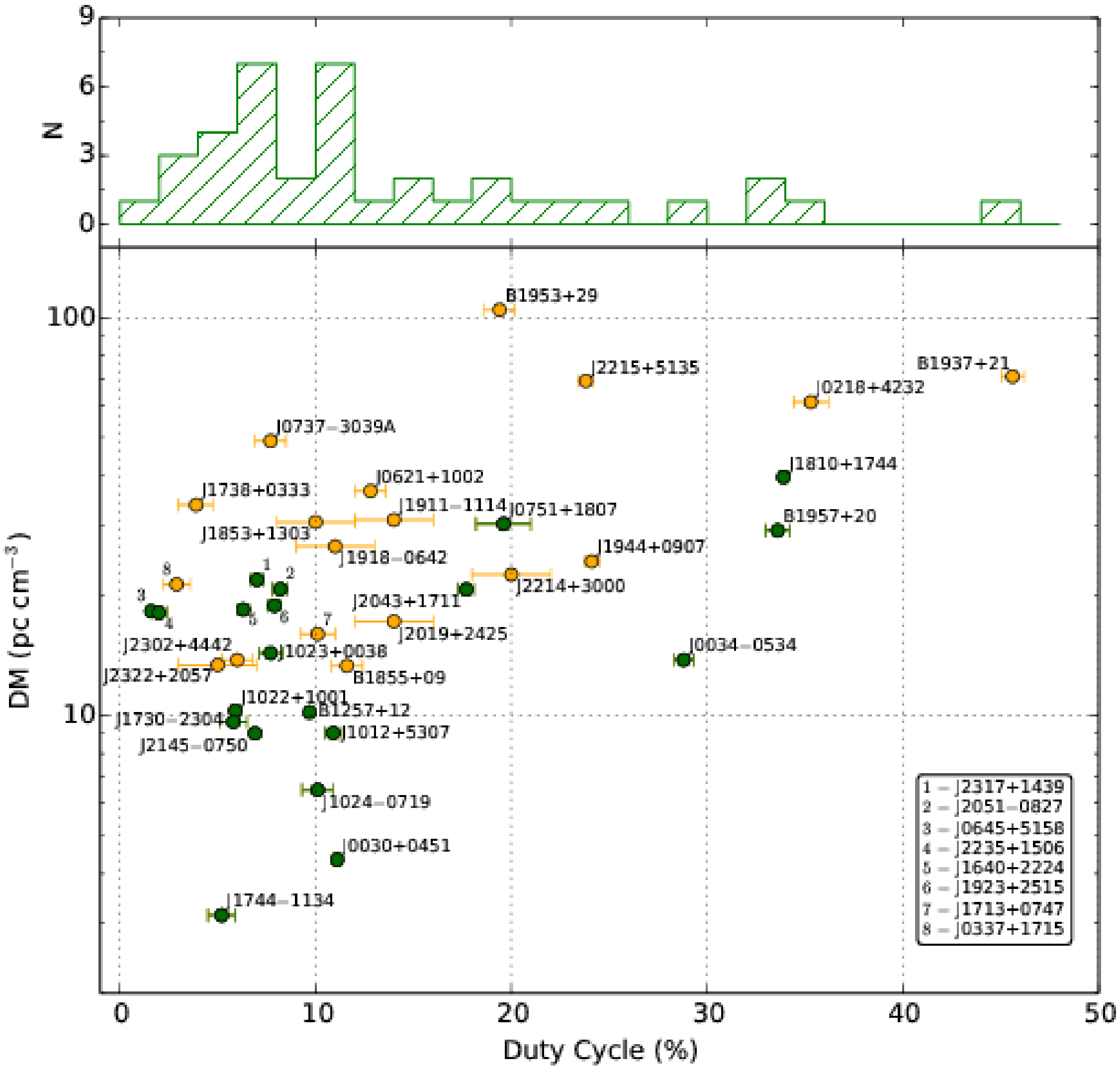
The LOFAR Weather Report





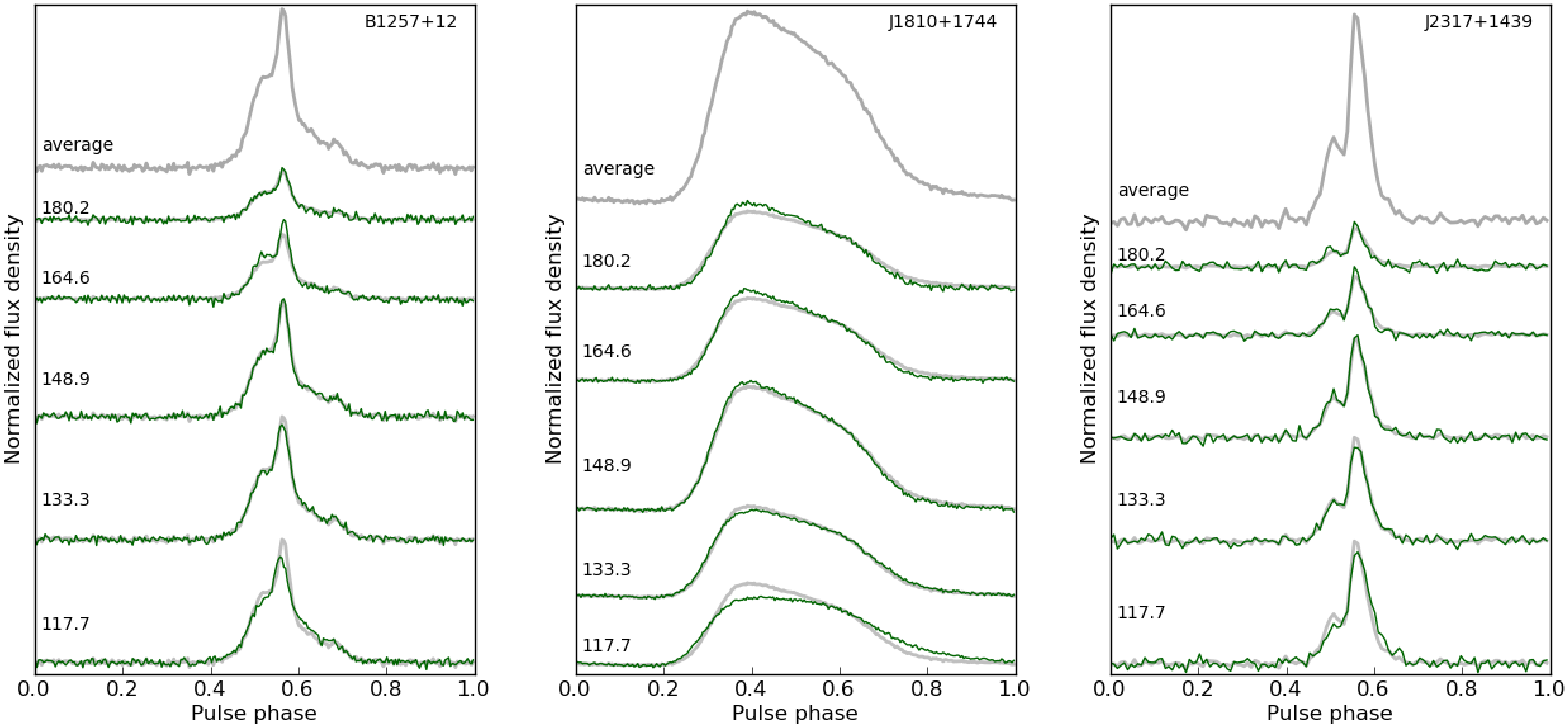
- ✔ 1 μs scatt. at 1400 MHz is 10 ms scatt. at 140 MHz
- ✔ 1 ms scatt. at 140 MHz is 100 ns scatt. at 1400 MHz
- ✔ Do LOFAR DMs/Scatt. agree with those at high-freq?

Profile widths

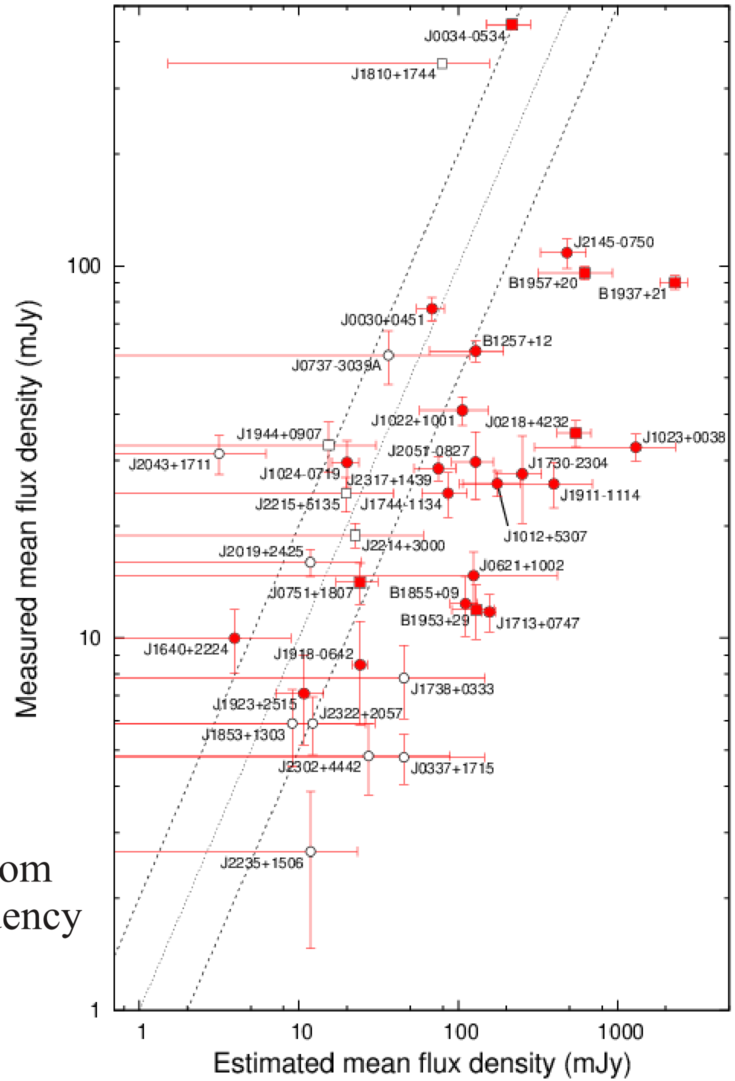


profile is affected by scattering, or weak, or both

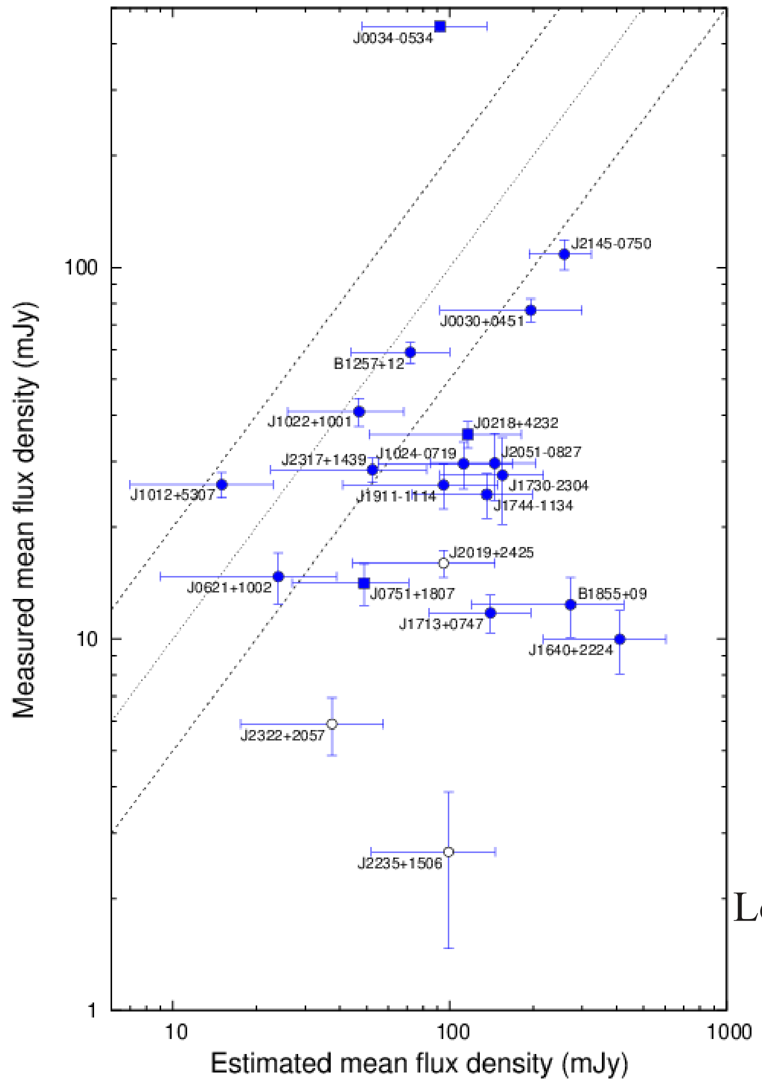
Profile variations



MSP flux densities @ 150 MHz



Derived from high-frequency data



Derived from Kuzmin & Losovsky (2001) at 102 MHz

MSP Timing Campaign

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?
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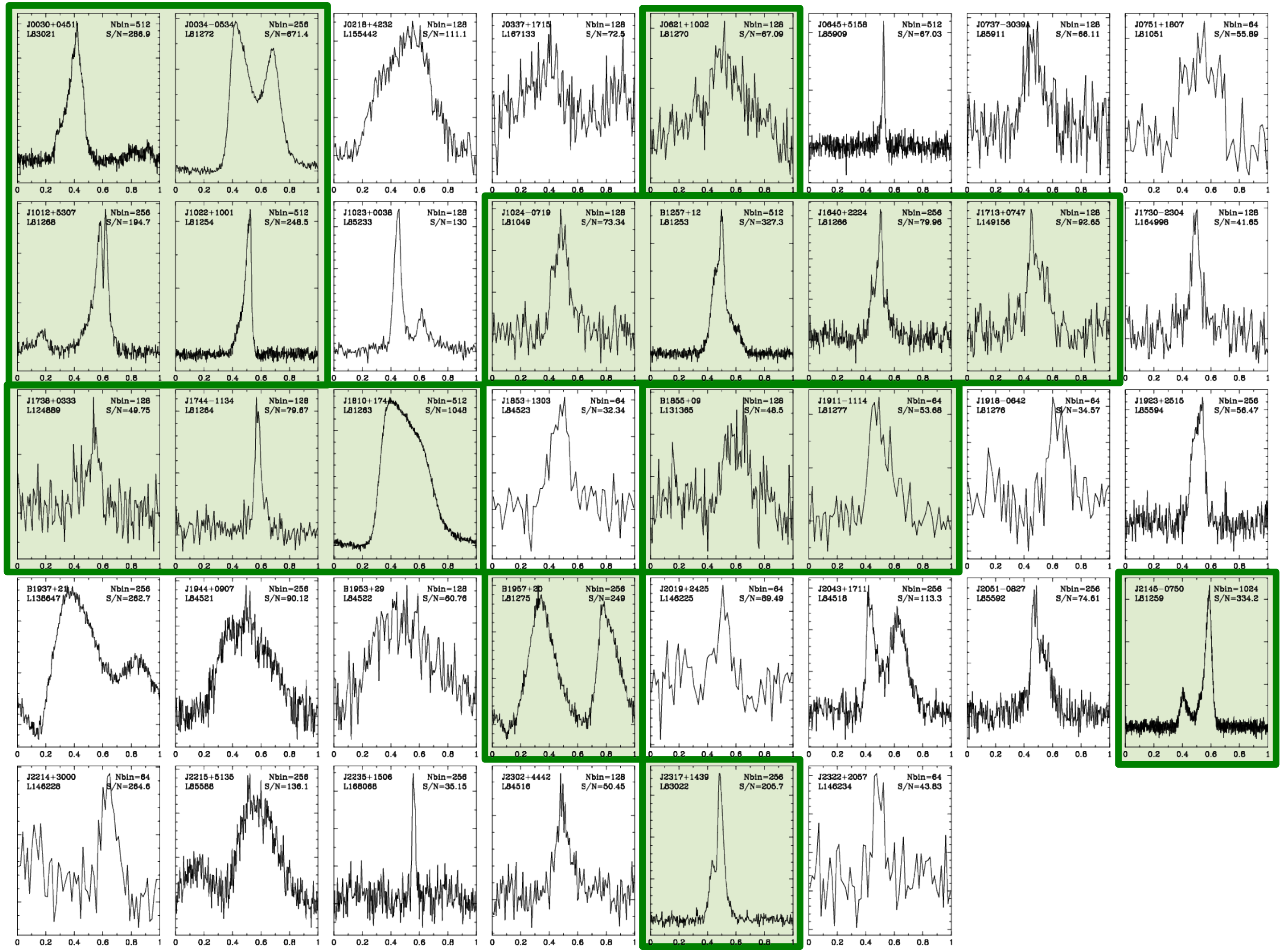
J0621+1002	28.854	36.601	BT	n	y	L81270	56289.02	20	67	7	
J0645+5158	8.853	18.247	Isolated	...	...	L85909	56322.00	20	67	18	
J0737−3039A	22.699	48.920	DDS	...	...	L85911	56321.92	60	66	9	
J0751+1807	3.479	30.249	ELL1	...	y	L81051	56280.04	20	56	13	
J1012+5307	5.256	9.023	BT	y	y	L81268	56289.14	20	191	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	

Cycle0:
17 MSPs

Cycle1:
34 MSPs
38 slow psrs

MSP Exploration and Timing Campaign



MSPs: why low freqs?

- Almost unexplored regime for MS
- Spectra of most MSPs do not turn
- Profile and polarization evolution
- Time variability of DM, RM and S
  → Improve high-frequency timin