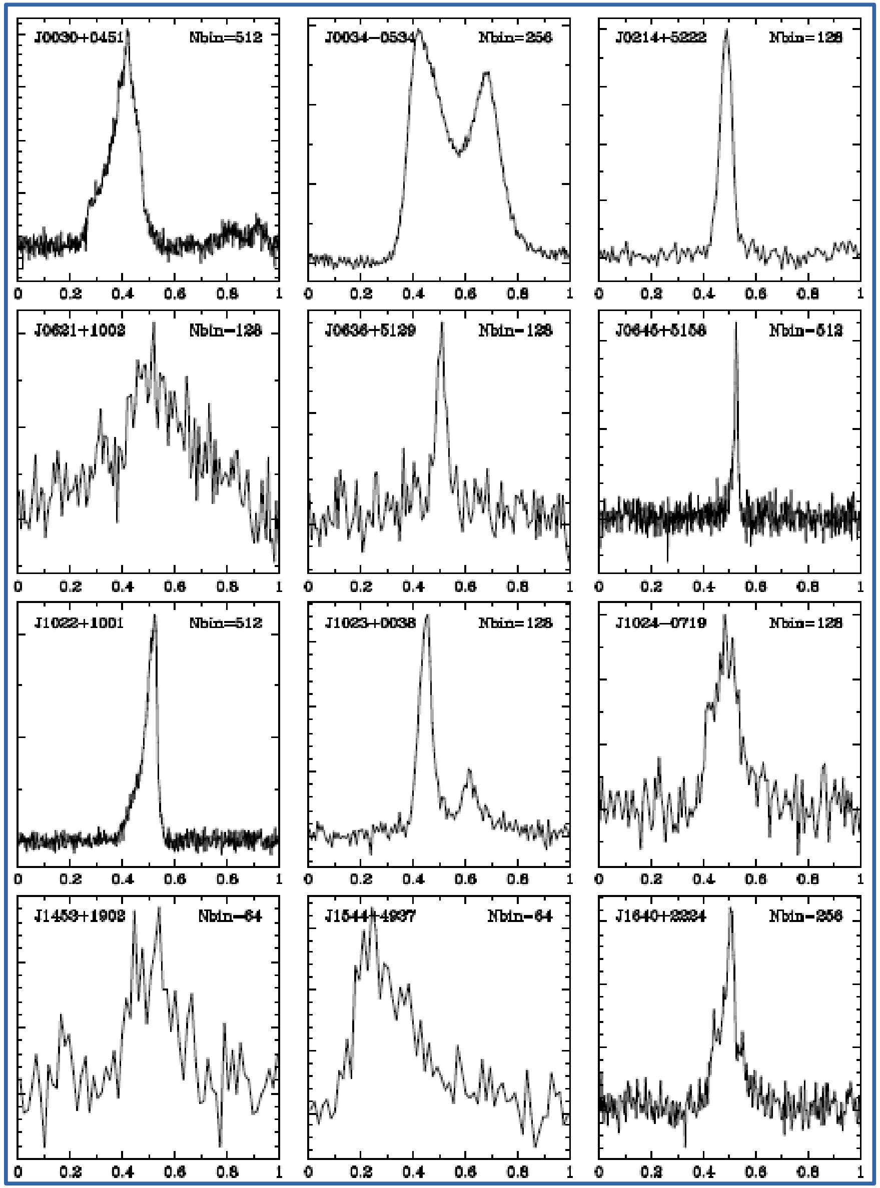


Millisecond pulsar

LOFAR MSP population. Pulsar flux calibration

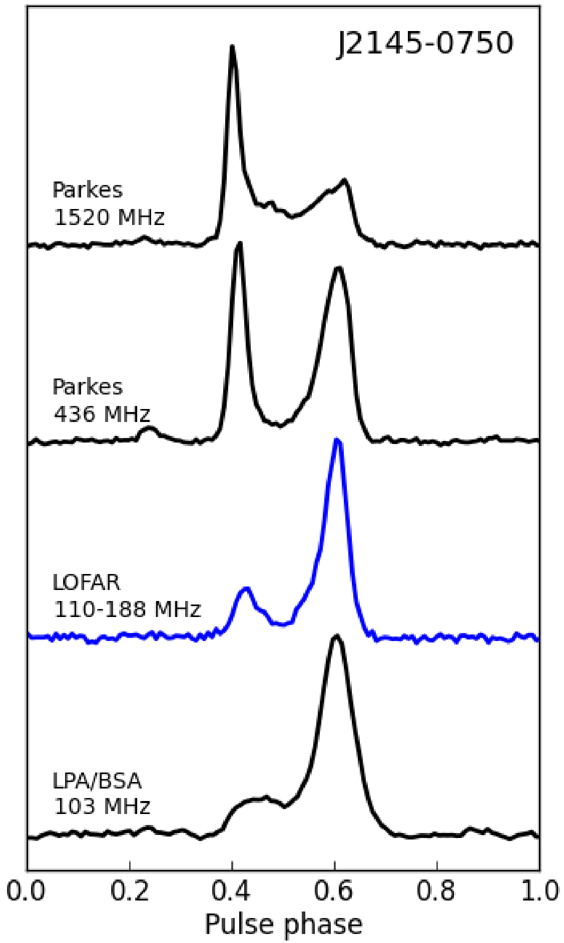
Vlad Kondratiev (ASTRON)

and

Joris Verbiest, Jason Hessels

and LOFAR Pulsar Working Group

MSPs: why LOFAR?

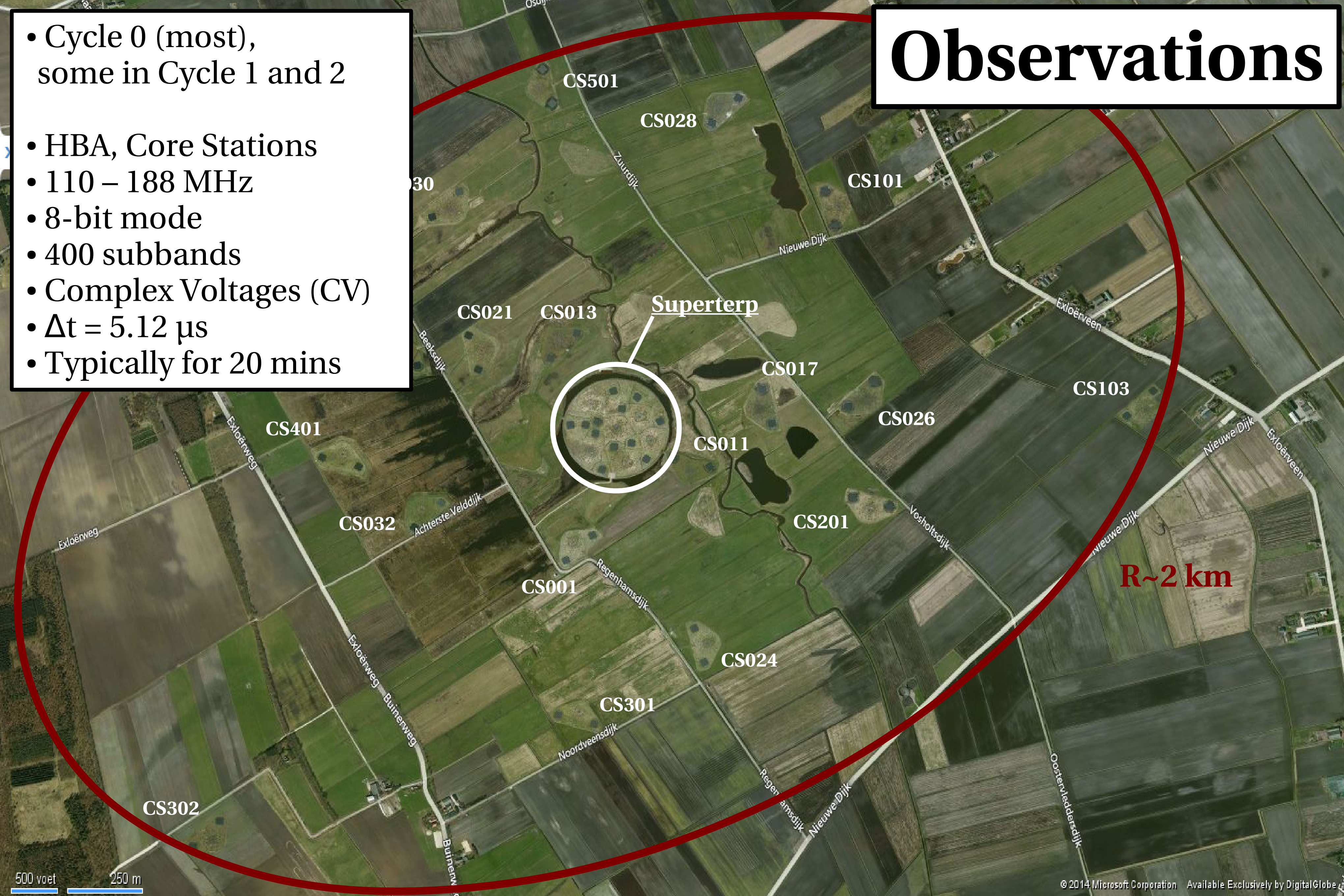


- Almost unexplored regime for MSPs
- Spectra: turn over or not?
- Profile and polarization evolution with frequency
- Time variability of DM, RM and SMs from the ISM
  → Improve high-frequency timing

Observations

- Cycle 0 (most), some in Cycle 1 and 2

- HBA, Core Stations
- 110 – 188 MHz
- 8-bit mode
- 400 subbands
- Complex Voltages (CV)
- $\Delta t = 5.12\ \mu s$
- Typically for 20 mins



Detected MSPs

Kondratiev et al. 2015,
to be submitted

75 MSPs observed

PSR	Period (ms)	DM (pc cm^{-3})	Binary?	WSRT detected?	BSA detected?	LOFAR ObsID	Epoch (MJD)	T_{obs} (min)	S/N	Peak* S/N	LBA detected?	Ref
J0030+0451	4.865	4.333	Isolated	...	y	L83021	56304.694	20	251	31	y	1
J0034−0534	1.877	13.765	He WD	y	y	L81272	56286.738	20	543	63	y	1
J0214+5222	24.575	22.037	He WD/sdB?	...	...	L196378	56646.791	20†	116†	41†		4
J0218+4232	2.323	61.252	He WD	n	y	L155442	56473.304	20	126	19		1
J0337+1715	2.733	21.316	He WD+He WD	...	...	L167133	56512.229	60	31	6		2
J0407+1607	25.702	35.65	He WD	...	...	L227494	56790.515	20	194	30		20
J0621+1002	28.854	36.601	CO WD	n	y	L81270	56289.023	20	47	9		3
J0636+5129	2.869	11.107	UL/BW?	...	...	L196371	56648.046	10†	30†	10†		4
J0645+5158	8.853	18.247	Isolated	...	...	L85909	56322.009	20	59	19		4
J0737−3039A	22.699	48.920	PSR	...	...	L85911	56321.940	60	25	6		5
J0751+1807	3.479	30.249	He WD	...	y	L81051	56280.049	20	24	7		1
J1012+5307	5.256	9.023	He WD	y	y	L81268	56289.149	20	183	32	n	1
J1022+1001	16.453	10.252	CO WD	y	y	L81254	56296.126	20	274	49	n	6
J1023+0038	1.688	14.325	He WD/Redback	y	...	L85233	56315.163	20	105	30		7
J1024−0719	5.162	6.485	Isolated	n	y	L81049	56280.168	20	40	10	n	1
J1038+0032	28.852	26.59	Isolated	...	...	L227490	56782.804	20	39	8		21
J1231−1411	3.684	8.090	He WD	...	...	L227492	56789.862	20	27	7		17
B1257+12	6.219	10.166	Planets	y	y	L81253	56296.230	20	313	44	n	8
J1453+1902	5.792	14.049	Isolated	...	...	L227293	56779.988	20	18	6		22
J1544+4937	2.159	23.226	BW	...	...	L227294	56780.003	20	89	23		23
J1640+2224	3.163	18.426	He WD	...	y	L81266	56289.368	20	66	15		1
J1709+2313	4.631	25.347	He WD	...	...	L249810	56964.533	20	14	5		24
J1713+0747	4.570	15.992	He WD	n	y	L149156	56465.941	60	30	8		1
J1730−2304	8.123	9.617	Isolated	...	y	L164998	56490.889	30	32	9		1
J1738+0333	5.850	33.778	He WD	...	...	L124889	56399.183	20	21	6		1
J1744−1134	4.075	3.139	Isolated	y	y	L81264	56293.440	20	37	15		1
J1810+1744	1.663	39.7	BW	...	...	L81263	56293.456	20	861	65	n	9
J1816+4510	3.193	38.887	He? WD/sdB?	...	...	L212736	56737.245	20†	888†	159†		4, 25
J1853+1303	4.092	30.570	He WD	...	...	L84523	56311.438	20	24	7		10
B1855+09	5.362	13.300	He WD	...	y	L131365	56417.151	20	23	5		1
J1905+0400	3.784	25.692	Isolated	...	...	L249826	56964.657	20	18	7		10
J1911−1114	3.626	30.975	He WD	y	y	L81277	56286.527	20	25	8		11
J1918−0642	7.646	26.554	He WD	...	...	L81276	56286.543	20	28	7		1
J1923+2515	3.788	18.858	Isolated	...	...	L85594	56318.472	20	58	12		12
B1937+21	1.558	71.040	Isolated	...	...	L138647	56434.134	30	275	25		1
J1944+0907	5.185	24.34	Isolated	...	...	L84521	56311.472	20	103	12		13
B1953+29	6.133	104.501	He WD	...	...	L84522	56311.456	20	44	6		10
B1957+20	1.607	29.117	BW	y	...	L81275	56286.559	20	230	24		14
J2019+2425	3.935	17.203	He WD	...	y	L146225	56457.103	20	18	6		1
J2043+1711	2.380	20.710	He WD	...	...	L84518	56311.522	20	96	14		15
J2051−0827	4.509	20.745	BW	n	y	L85592	56318.504	20	65	12		16
J2145−0750	16.052	8.998	CO WD	y	y	L81259	56293.607	20	324	37	y	1
J2214+3000	3.119	22.557	BW	...	...	L146228	56457.159	20	27	7		17
J2215+5135	2.610	69.2	He WD/Redback	...	...	L85588	56318.567	20	114	13		9
J2235+1506	59.767	18.09	Isolated	...	y	L168068	56521.018	30	25	9		18
J2302+4442	5.192	13.762	He(?) WD	...	...	L84516	56311.603	20	40	10		19
J2317+1439	3.445	21.907	He WD	...	y	L83022	56304.635	20	176	40	n	1
J2322+2057	4.808	13.372	Isolated	...	y	L146234	56460.218	20	14	9		1

Detected MSPs

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75 MSPs observed

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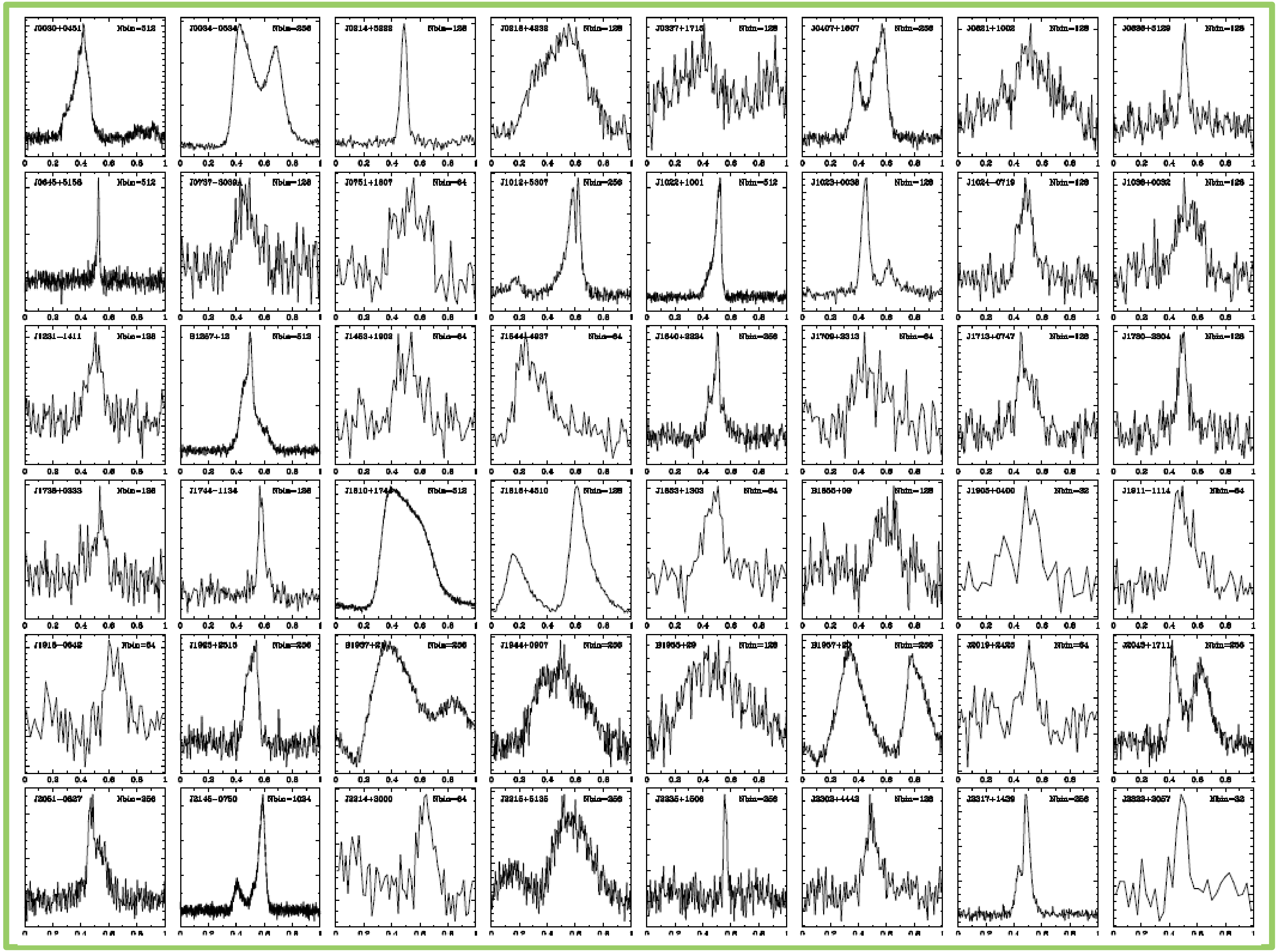
64% of observed MSPs Detected!

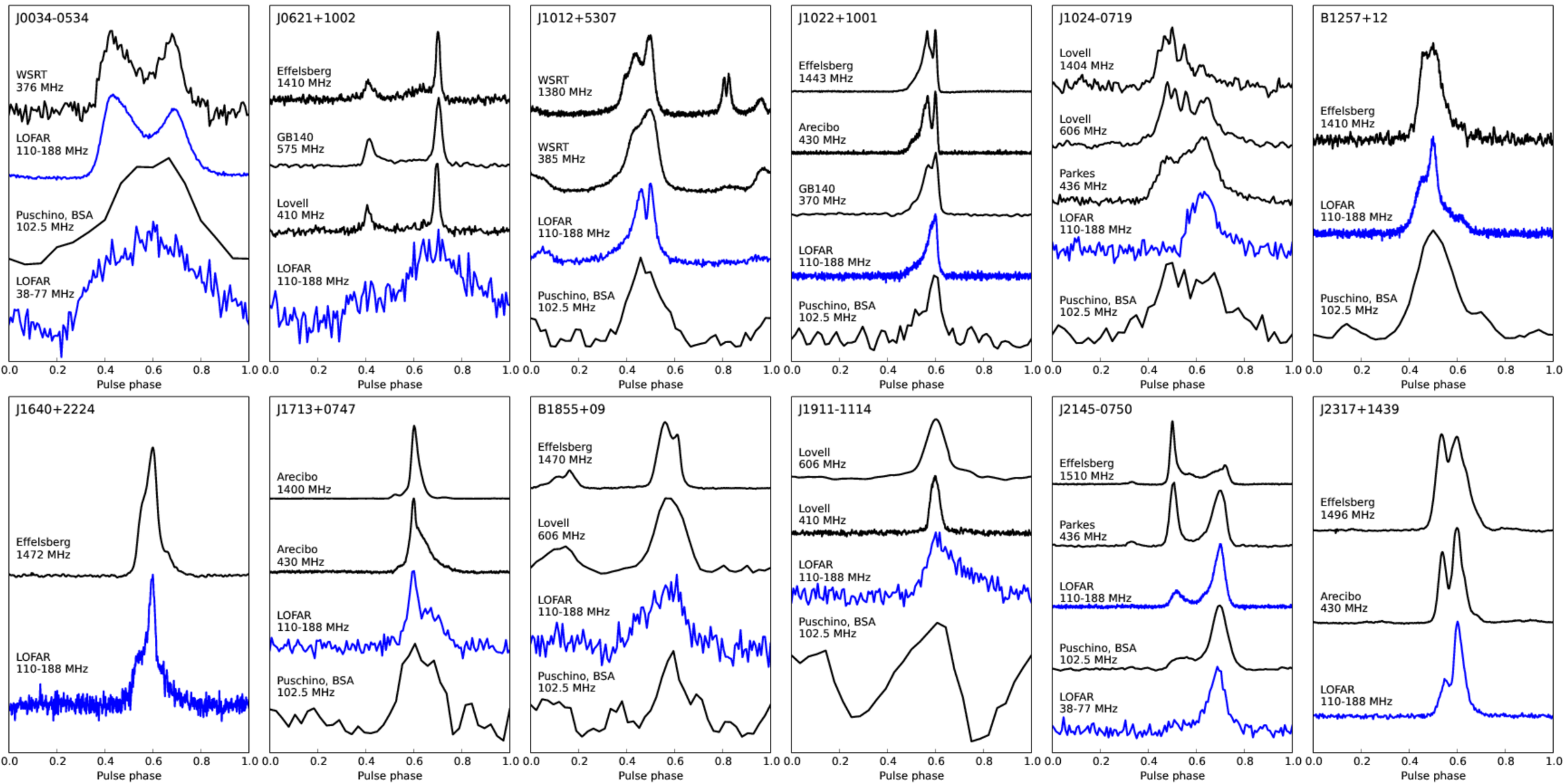
48 — Detections, 27— non-Detections

Detected MSPs

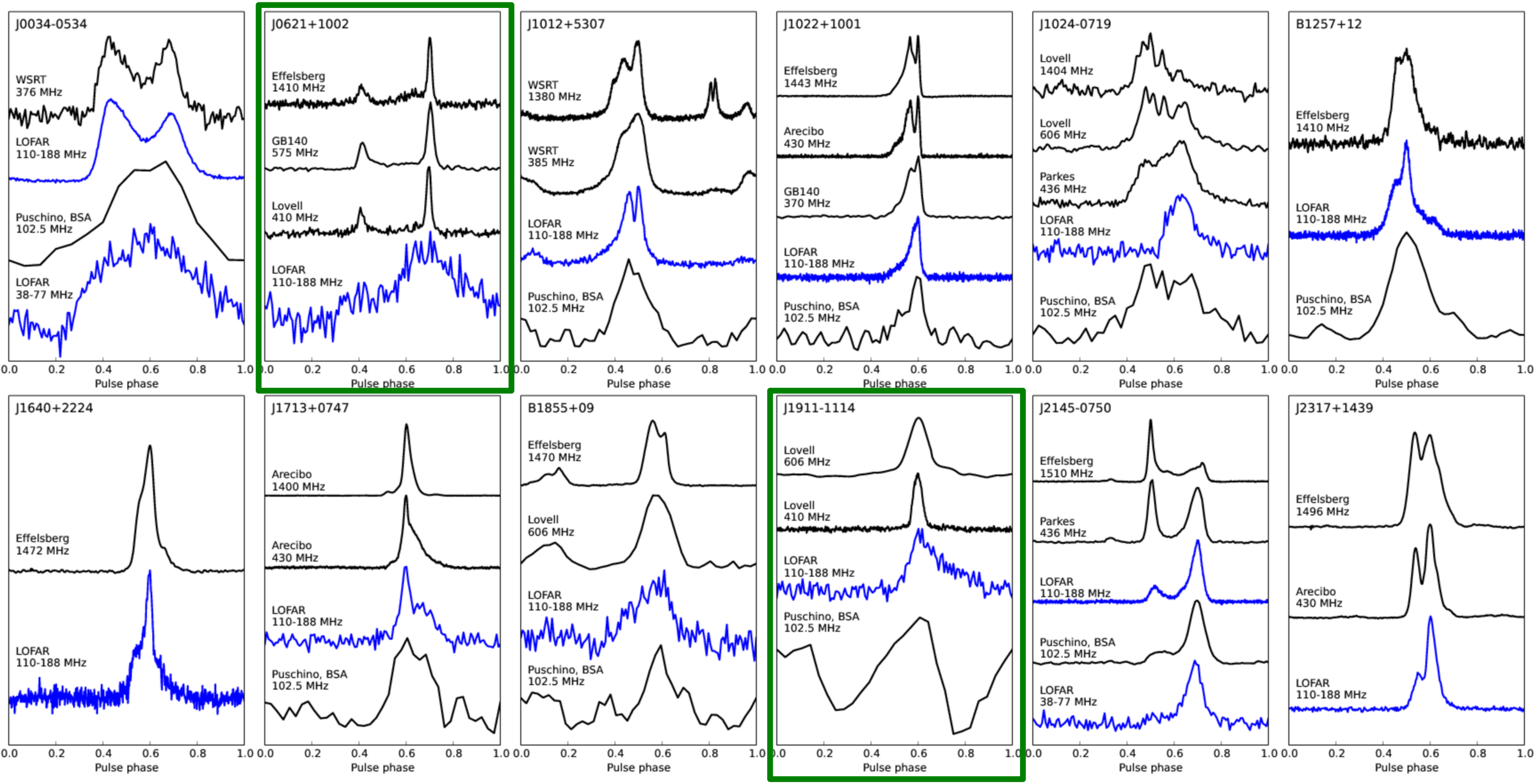


Best
20-min
profiles
(for most)

MSP Multi-Frequency Profiles



MSP Multi-Frequency Profiles

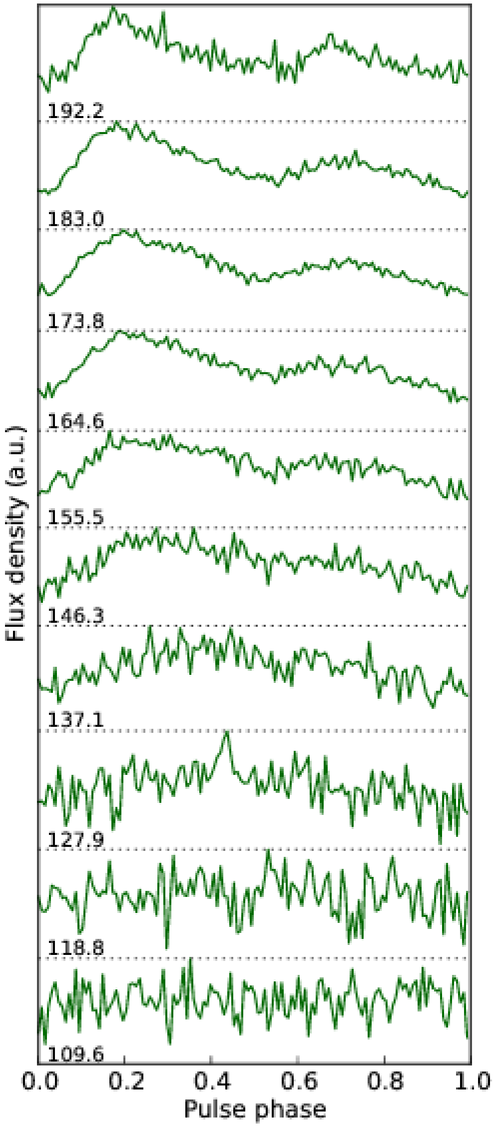


~25% - scattered, ~40% - weak, ~35% - strong, narrow profile

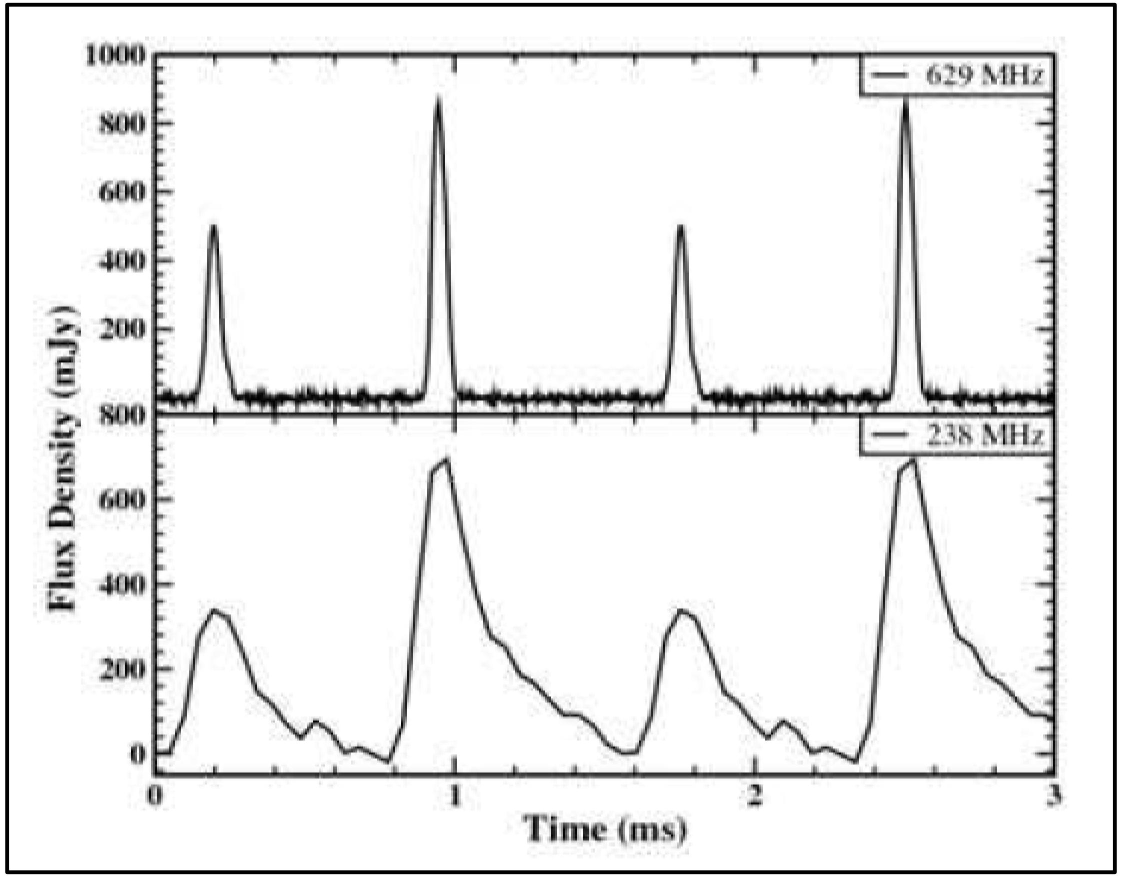
Original MSP B1937+21

P = 1.56 ms
DM = 71 pc/cc

τ_{scat} =
2 — 18 ms
(1.3 — 12 P)

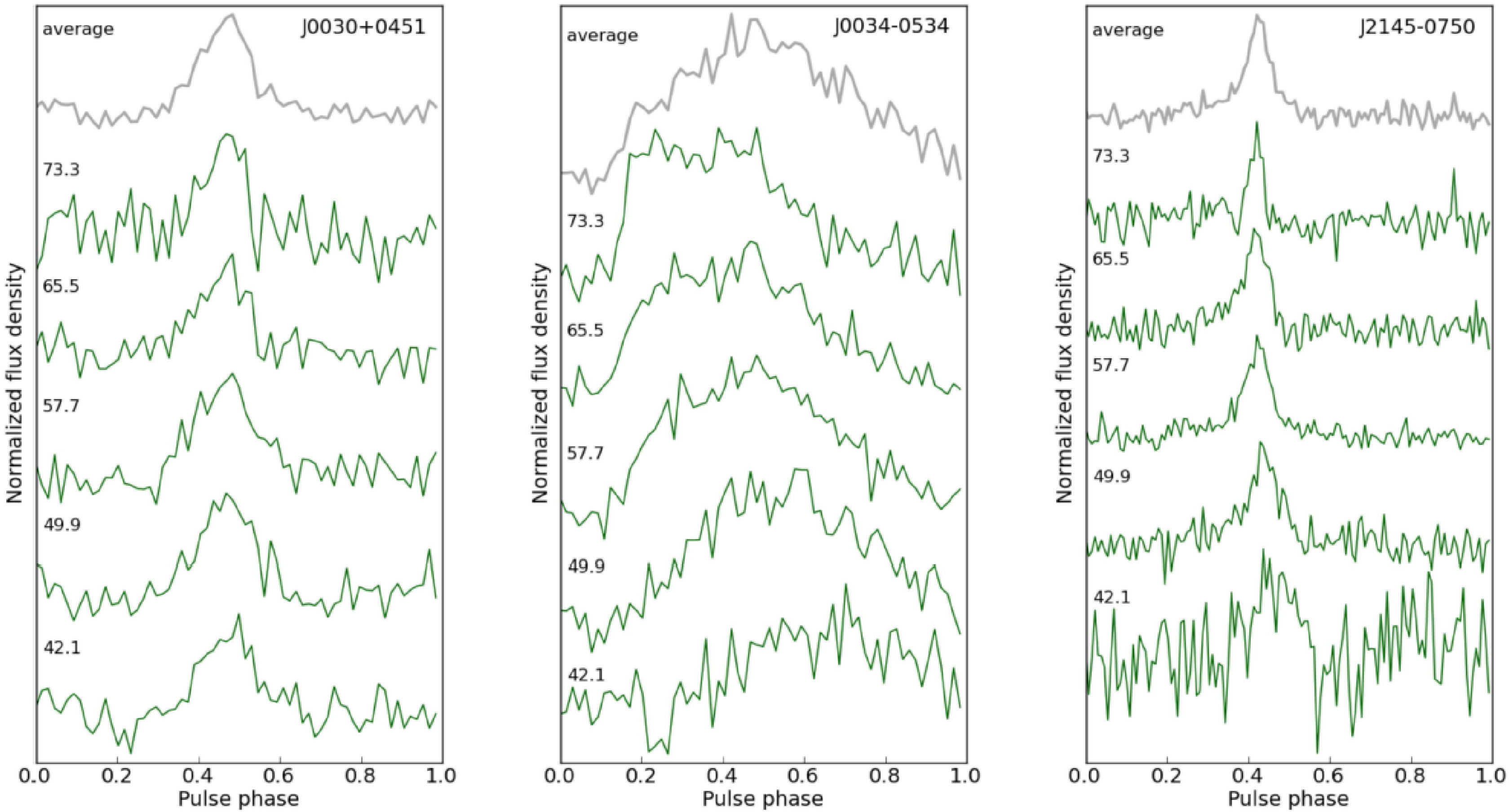


Joshi & Kramer 2009



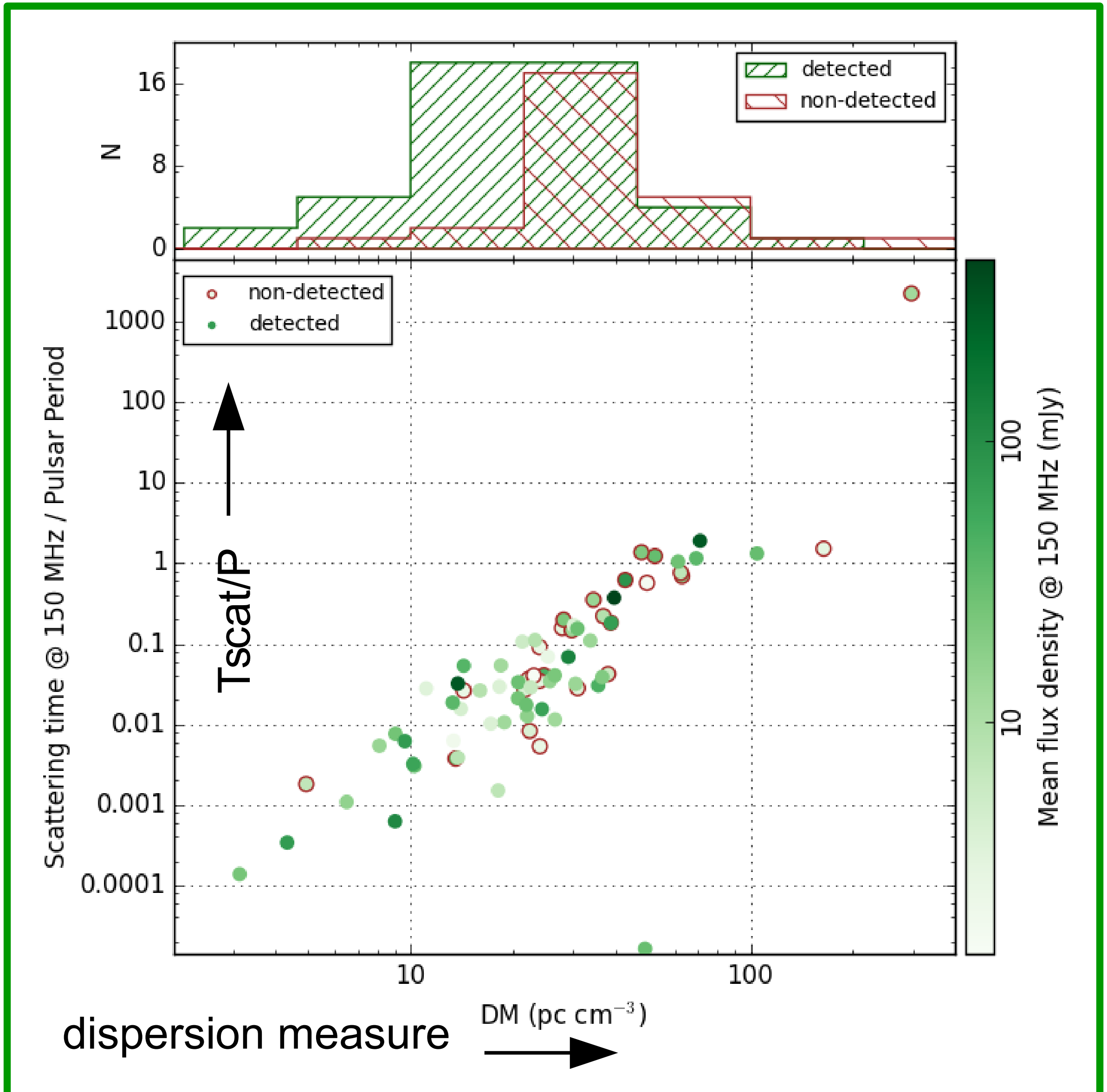
MSP LBA detections

38–77 MHz



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

MSP detectability



- ✔ DM < 20:
  detected 25 out of 28
- ✔ DM = 20-100: (50/50)
  22 detected
  23 not detected
- ✔ DM > 100:
  1 detected (DM = 104.5)
  2 not detected (DMs: 164, 297)

DMs are in units of pc/cm^3

Flux calibration

In general (see e.g. Lorimer & Kramer 2005):

$$\Delta S_{\rm sys} = \frac{T_{\rm sys}}{G\sqrt{n_{\rm p} t_{\rm obs} \Delta f}} = C\sigma_{\rm p},$$

C = SEFD

For high-frequency observations
with generic single-dish telescopes:

- Δf / f << 1
- Beam shape(AZ, EL, f) ~ const
- Gain(f) ~ const
- Tsys (f) ~ const

Flux calibration

In general (see e.g. Lorimer & Kramer 2005):

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For high-frequency observations with generic single-dish telescopes:

- Δf / f << 1
- Beam shape(AZ, EL, f) ~ const
- Gain(f) ~ const
- Tsys (f) ~ const

LOFAR

- Δf / f ~ 0.5
- Beam shape has strong dependence on AZ, EL, and frequency, and thus the gain, G
- Gain(f) ≠ const
- Tsys = Tsky + Tinst
- Tsky(f) ~ $f^{-2.55}$
- Tinst(f) ≠ const
- Tsrc(f) ≠ const

Beam model

«AKW» model by Arts M., Kant G., & Wijnholds S. (2013)

- 1st verson of the improved Hamaker model (2006) → BBS
- Provides full EM sumulations of a 48-tile HBA station,
  including edge effects and grating lobes
  (Hamaker's model is based on an infinite array of elements)
- Flux values with both models agree with a factor of ~1.5 for most of the MSPs

AKW model → Aeff for a given frequency range, AZ, and EL

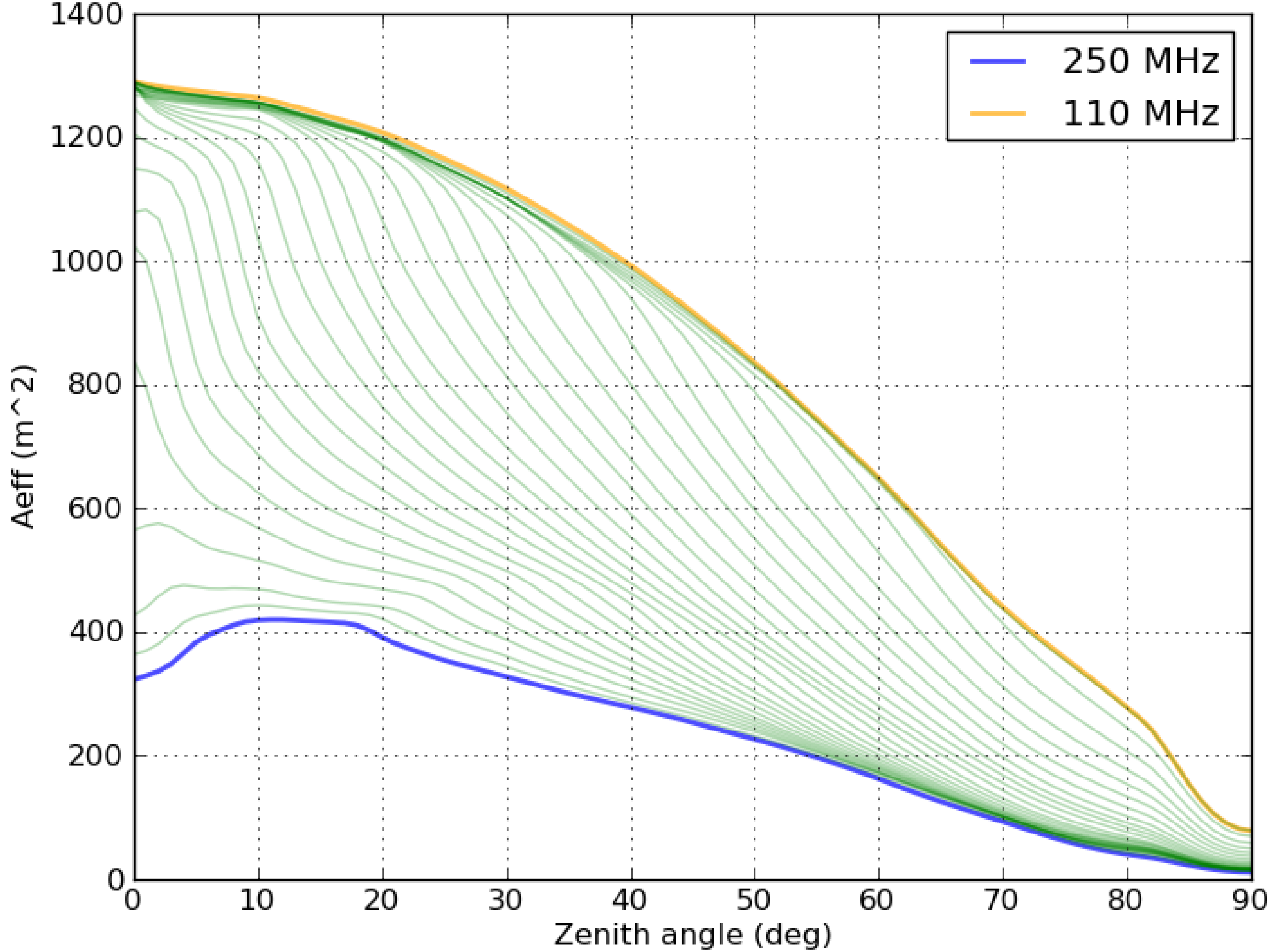
In practice →

Table of 91 ELs * 361 AZs * 29 frequencies

- AZ, 0 — 360 deg, 1-deg step
- EL, 0 — 90 deg, 1-deg step
- Frequency, 110 — 250 MHz, 5-MHz step

Note! When calibrating, for a given EL Aeff is averaged over all azimuths, as the stations are randomly rotated.

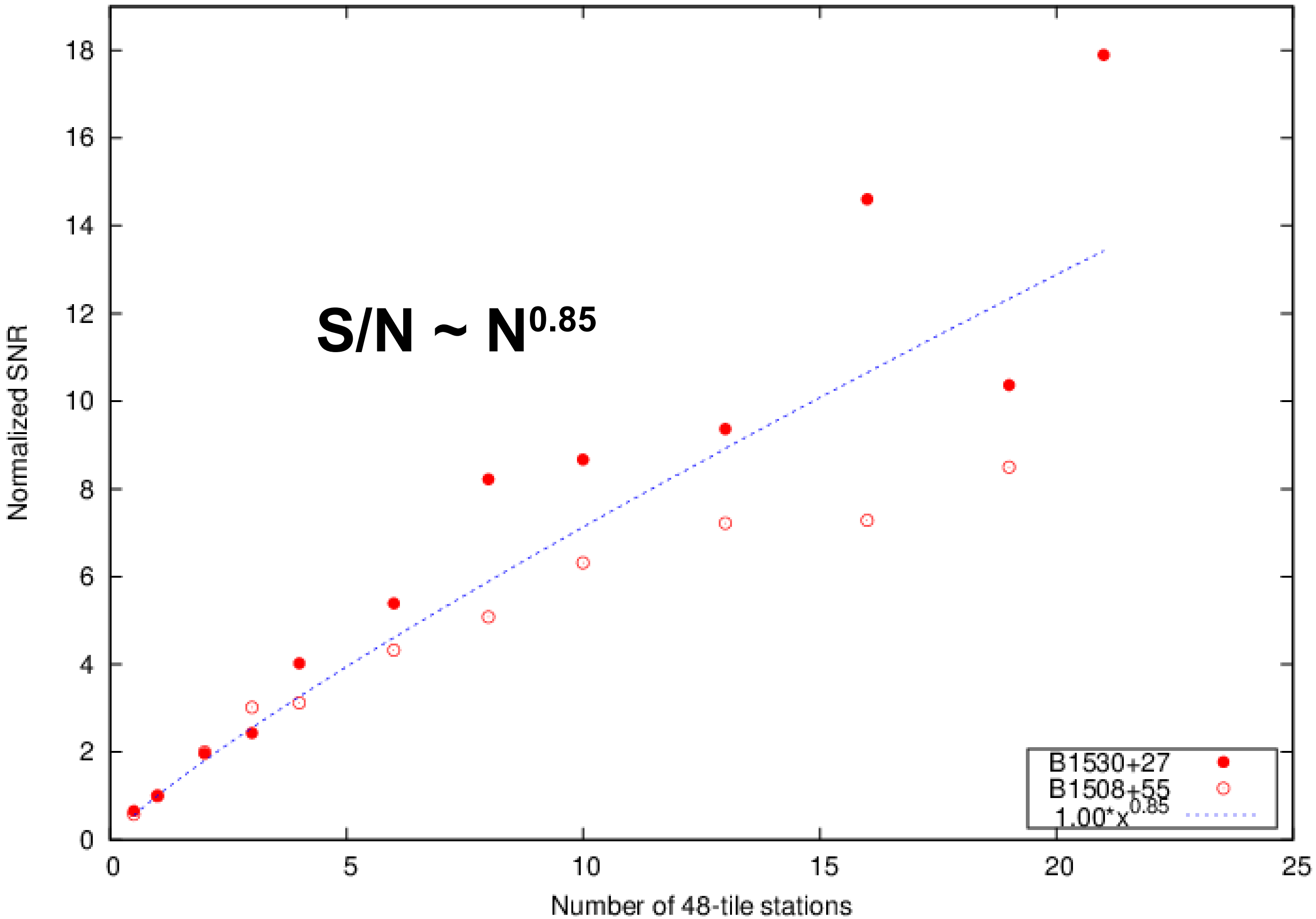
Aeff vs. ZA



one 48-tile station

Coherence scaling

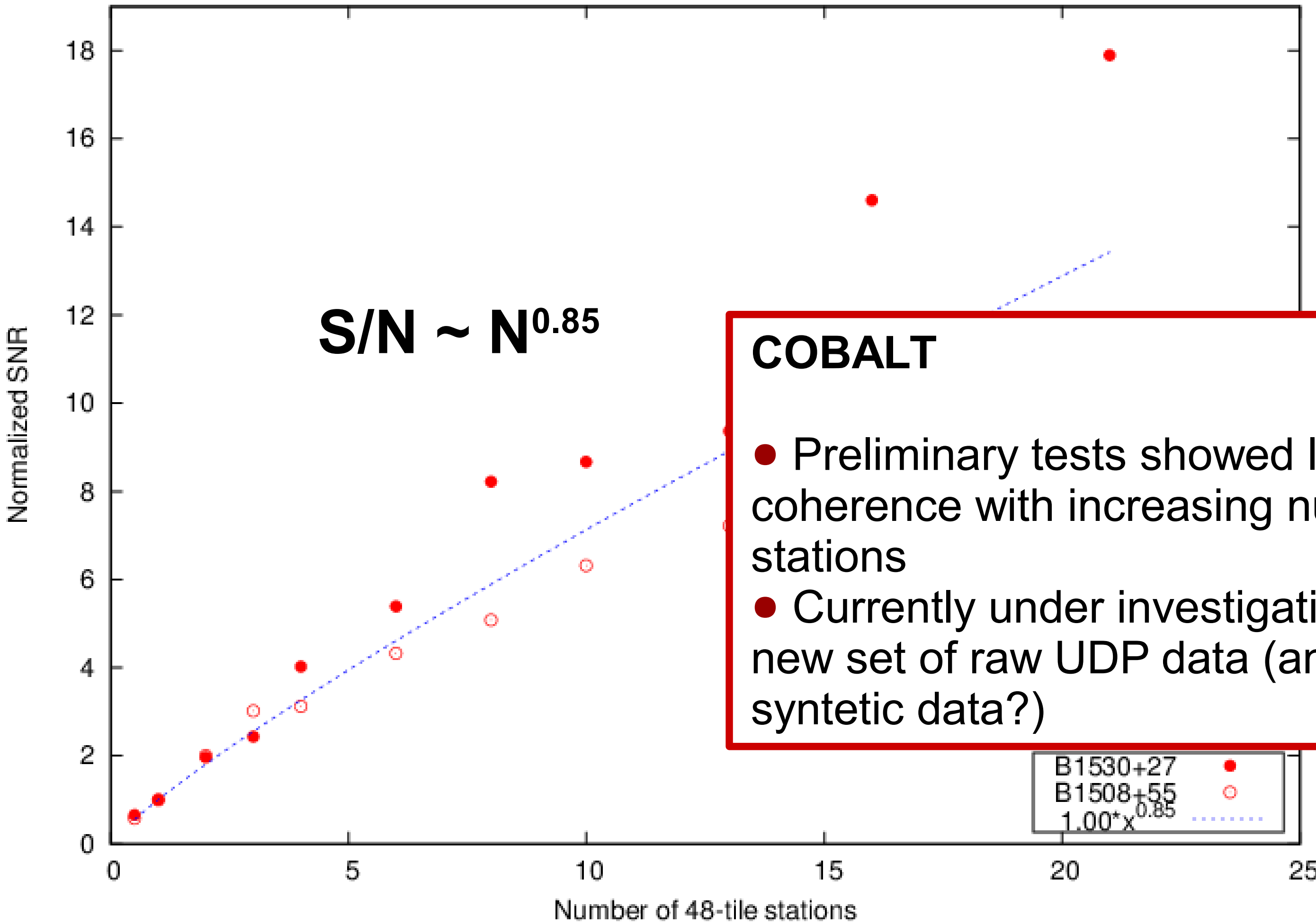
BG/P data



N – number of 48-tile stations

Coherence scaling

BG/P data



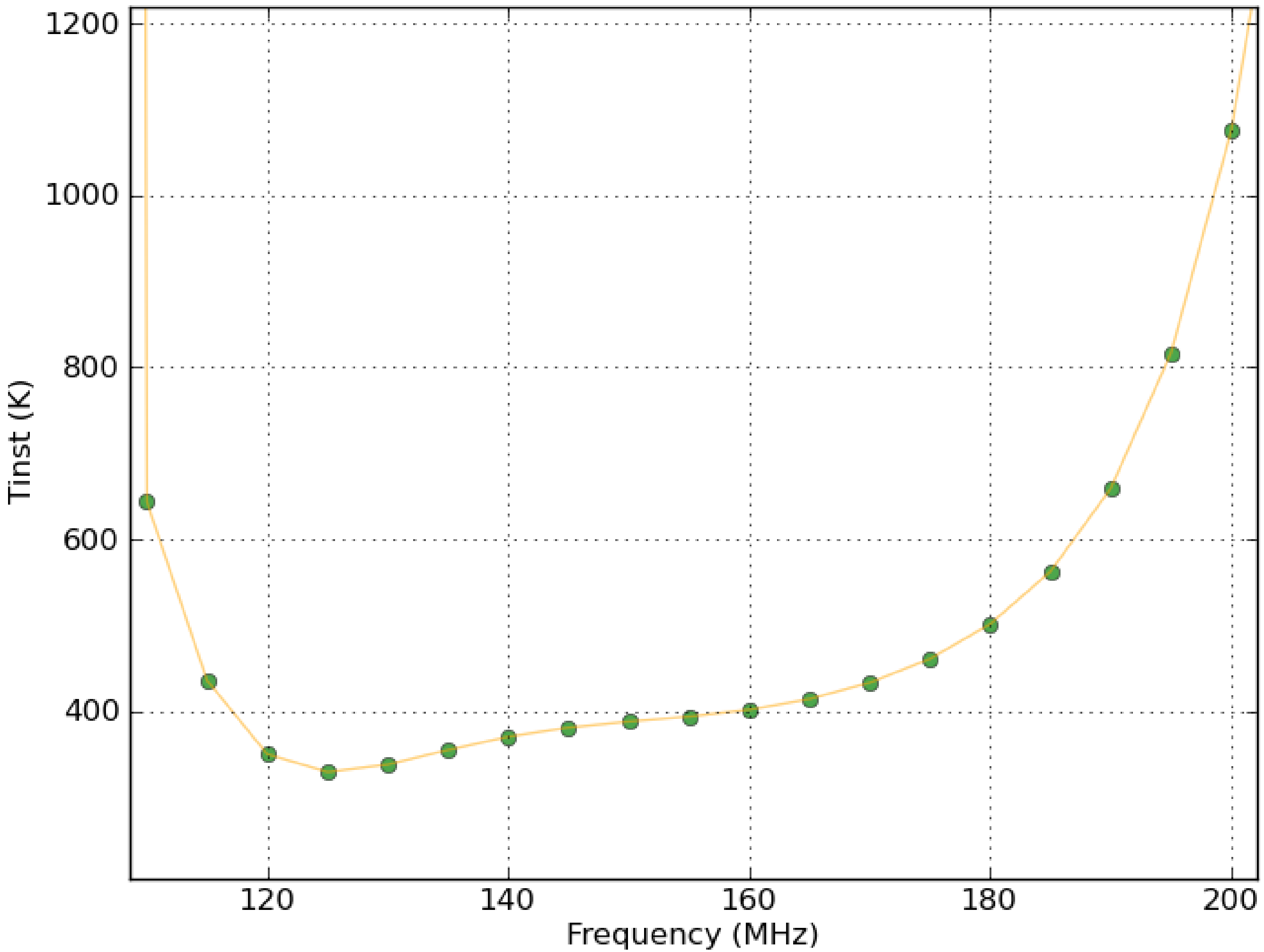
S/N ~ $N^{0.85}$

COBALT

- Preliminary tests showed larger de-coherence with increasing number of stations
- Currently under investigation using new set of raw UDP data (and also syntetic data?)

N – number of 48-tile stations

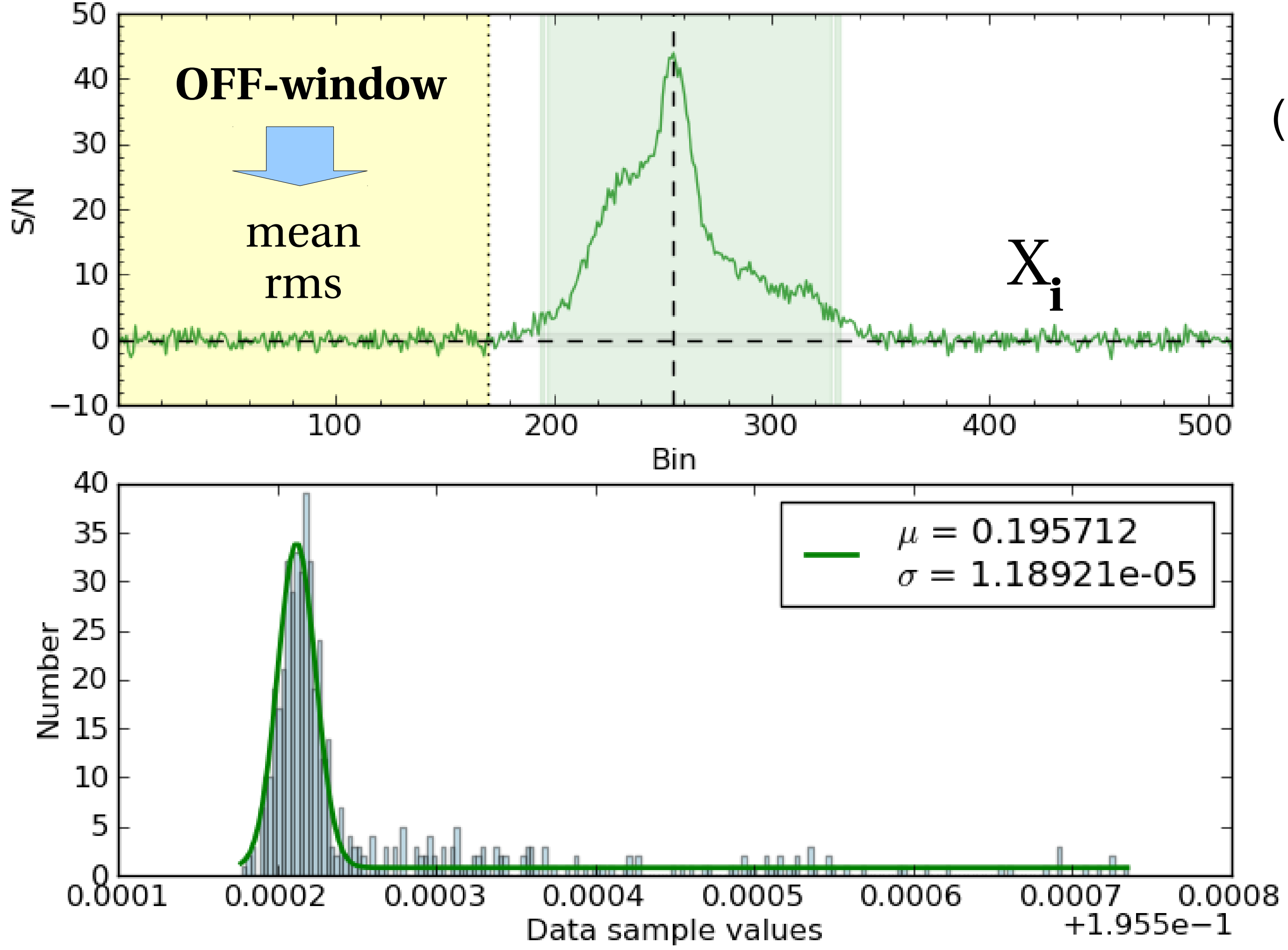
Instrumental temperature, Tinst



5th order polynomial function of the frequency based on CasA measurements

Wijnholds & van Cappellen (2011)

Pulsar profile, S/N



$(S/N)_i = (X_i - \text{mean}) / \text{rms}$

i — profile bin

$\text{Flux}_i = (S/N)_i * \text{SEFD}$

Flux calibration

In general (see e.g. Lorimer & Kramer 2005):

C = SEFD

$$\Delta S_{\rm sys} = \frac{T_{\rm sys}}{G\sqrt{n_{\rm p} t_{\rm obs} \Delta f}} = C\sigma_{\rm p},$$

$$\mathrm{SEFD} = \frac{2\beta k [T_{\rm inst}(f) + T_{\rm sky}(f, \mathrm{GL}, \mathrm{GB})]}{N_{\rm s}^{\gamma} A_{\rm eff}(f, \mathrm{EL})[1-\xi]\sqrt{n_{\rm p}[1-\zeta(f)](\frac{\mathrm{T_{obs}}}{\mathrm{nbins}})\Delta f}}$$

β — digitization factor = 1
GL, GB — Galactic longitude and latitude
γ — coherence factor ≈ 0.85
N_s — number of stations used
n_p — number of polarizations (2)
A_{eff} — effective area of a 48-tile station

ξ — average fraction of bad/flagged dipoles/tiles
ζ — RFI fraction
nbins — number of bins in the profile
T_{obs} — observation length (s)
Δf — frequency channel width (Hz)

Flux software

use -h option to get help

- tsky.py – Tsky (GL, GB, freq) or (RA, DEC, freq)

- lofar_tinst.py – T of the instrument (both HBA and LBA)
  --plot – Tinst-vs-Freq diagnostic plot

- lofar_gain.py – Aeff (freq, EL) for a 48-tile station (HBA only)
  --plot - diagnostic plots

- snr.py – calculate S/N using different methods (Q-Q probability plot, Off-pulse range, Polynomial to the baseline), so one can choose proper method and/or other parameters (fscrunching/bscrunching, off-pulse window) for flux calculation

Functions available to return values for the list of frequencies when one imports module in Python, e.g. import tsky

Flux software (cont.)

use -h option to get help

- lofar_psrflux.py – to calculate flux density in mJy for a given
  PSRFITS file (ar-file). First tscrunching all observation (so, good only for not very long ones)
  --plot – diagnostic plots
  --spectrum #NCHAN – to produce calibrated spectrum for N <u>output</u> channels, and plot

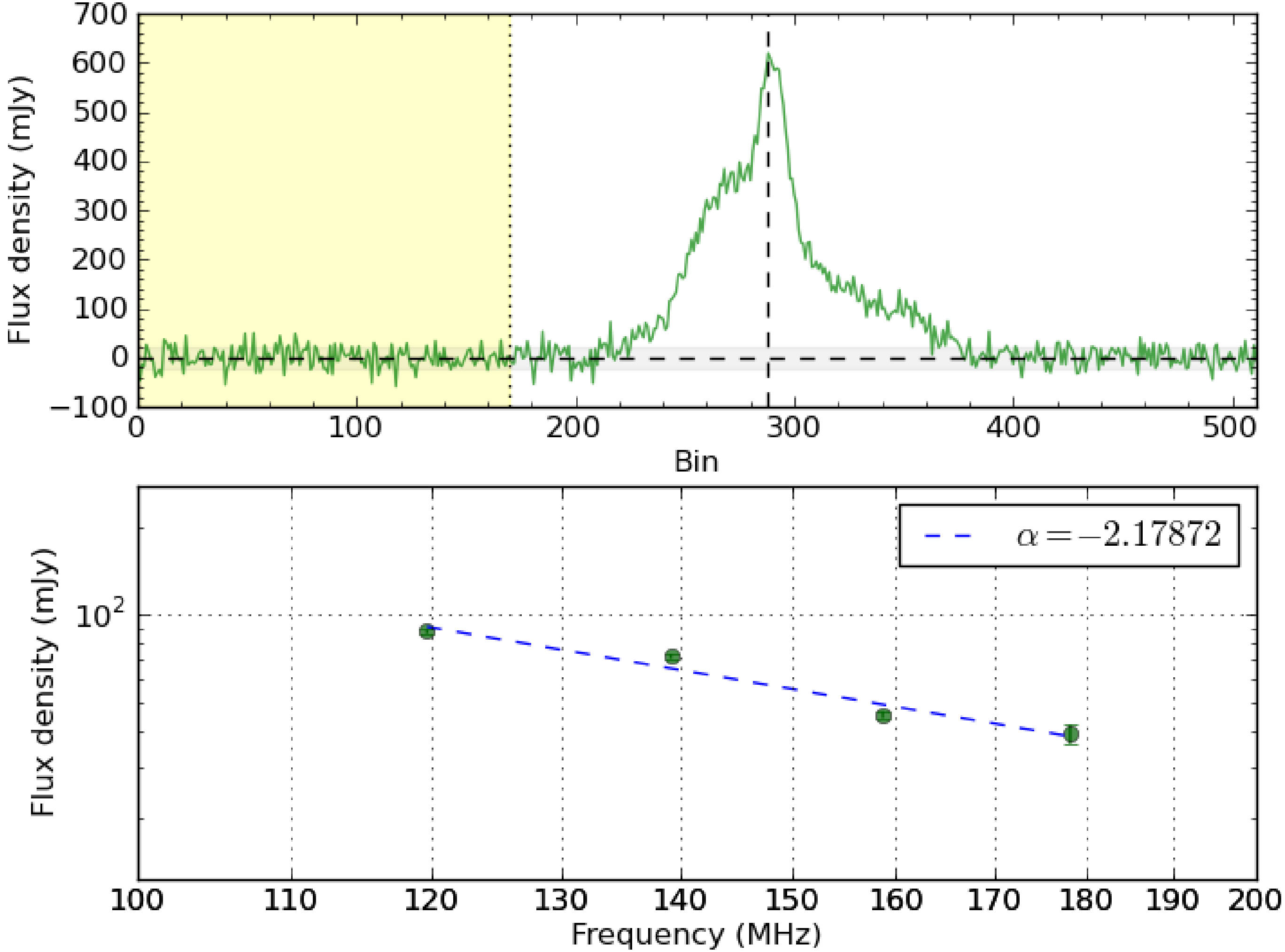
- lofar_fluxcal.py – to calibrate the samples in mJy in the PSRFITS file (or writes out new file). Calibrates separately individual sub-integrations.

Both programs can read .h5 file to get number of stations. Unfortunately, info about the flagged tiles is not yet available for Beamformed data... Currently, this info can be obtained from Science Support (Wilfred) and passed to a program via command-line option --flagged

Next → LBA beam model → calibration

Example of Flux Spectrum (lofar_psrflux.py)

B1257+12



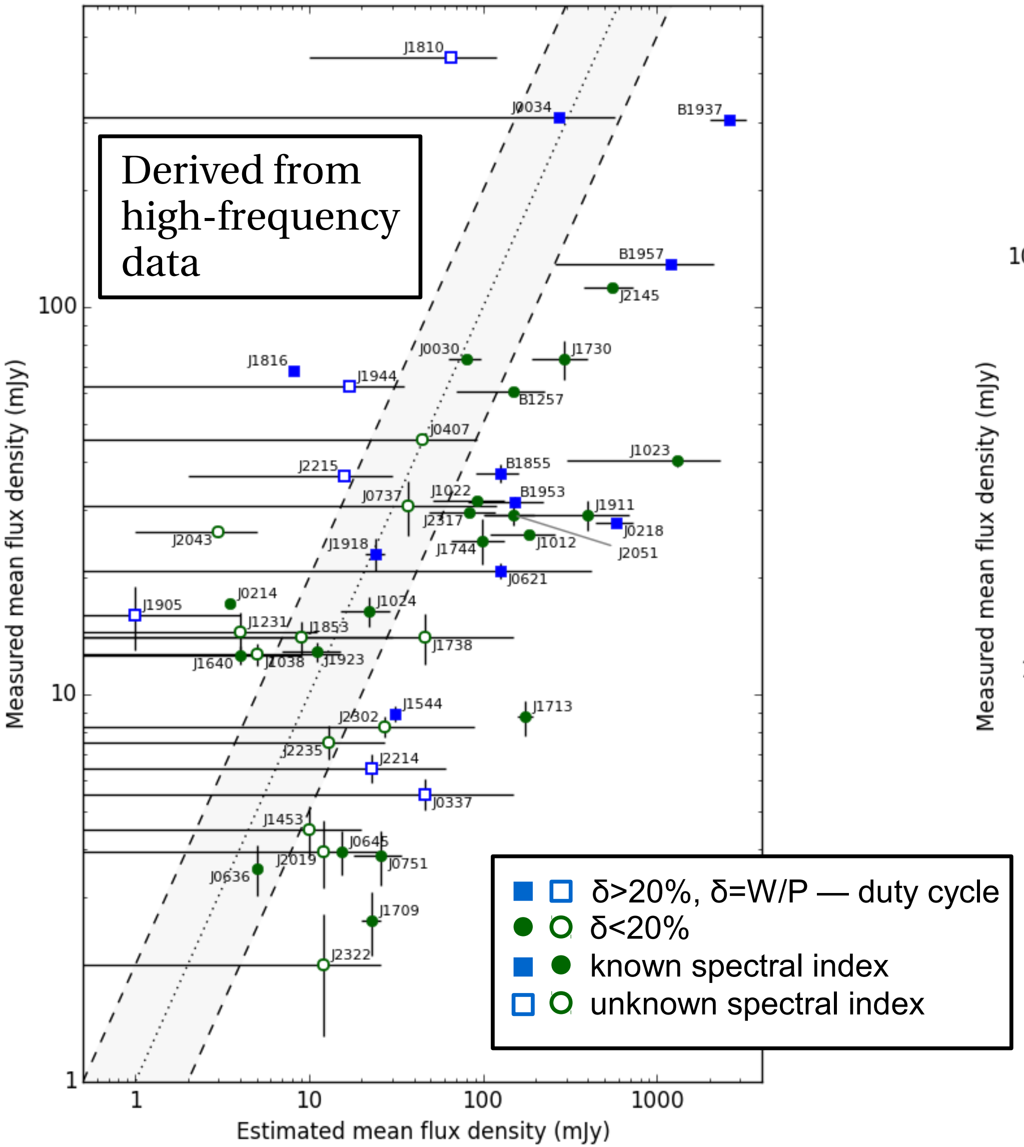
Other factors affecting flux measurements

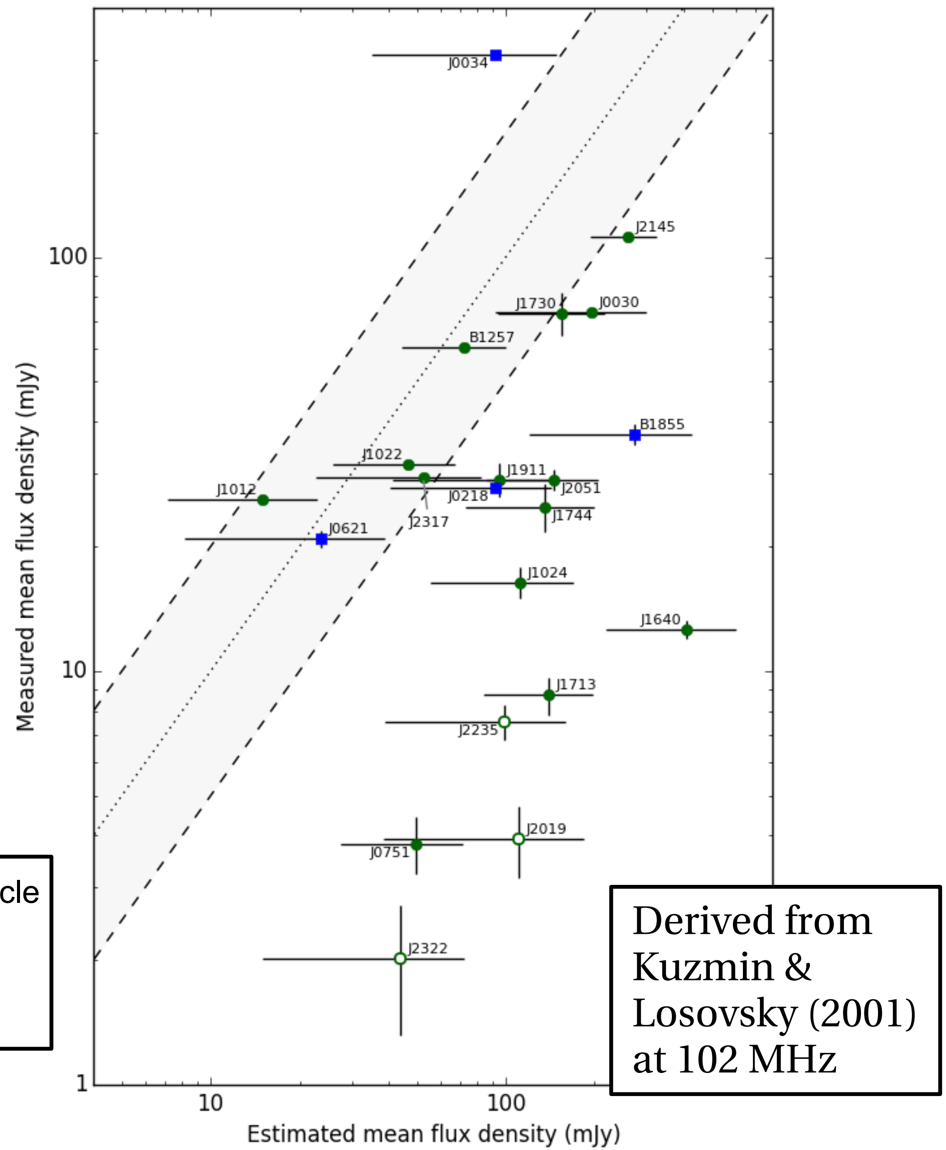
- Scattering → hard to get S/N, it is underestimated
- Refractive scintillations.
  Can change pulsar flux by a factor of ~1.5. Need long-term monitoring program
  Diffractive scintillations is not a factor → averaged out, $\Delta\nu_d < 0.2$ MHz
- Beam jitter by the ionosphere.
  Can be up to ~2 arcmins, i.e. half the Full-Core HBA TA beam (at half maximum)
- Variation of Tsys with time due to rise/set of the Galactic plane (up to 30-40% difference (?) when Galactic plane is in the FoV) and other strong background sources. Also with pointing direction due to noise coupling effects.

Despite these factors:

- We've got ~20% agreement with EOR data for the new LOFAR pulsar J0815+4611
- Preliminary general agreement on a number of pulsars from HBA census
- Currently, our MSP flux measurements are being compared with flux estimates from the MSSS images (Rene Breton)

MSP flux densities @ 150 MHz





Summary:

- First large sample of high-quality MSP profiles below 200 MHz (Kondratiev et al. 2015, to be submitted). 48 MSPs detected out of 75 observed. Currently in the Cycle 3, we are timing 35 of detected MSPs.

- Developed pulsar flux calibration (Python scripts, in the USG repository) based on the AKW beam model for the HBA data.

- Work on LOFAR MSP flux spectra, compare with high-freq data from the literature. Measure spectrum indices. Do MSP spectra turn over?

- and...
  - Cobalt coherence tests (with Alexander, JD, Michiel)
  - LBA beam model (Stefan?) → LBA data calibration
  - Flagged tiles info → HDF5 BF metadata (JD)
  - Further calibration development, e.g. take into account contribution of the Galactic plane and background sources in FoV to Tsys