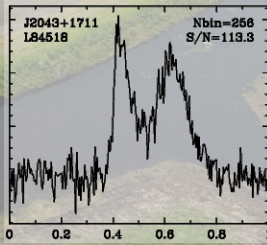
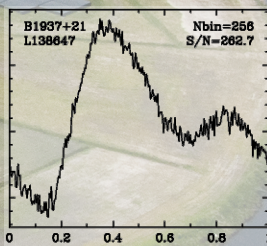
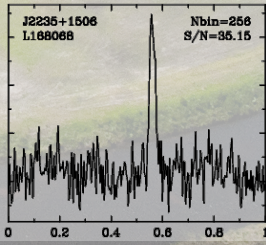
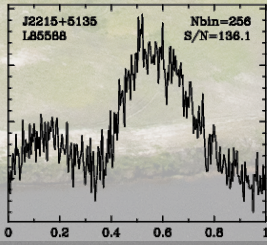
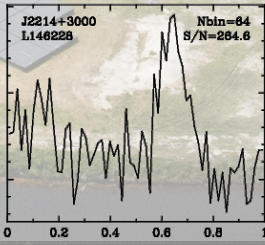
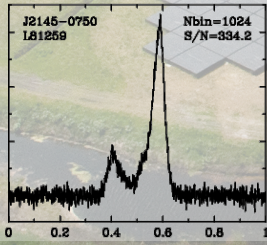
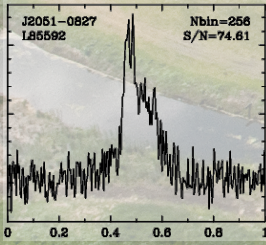
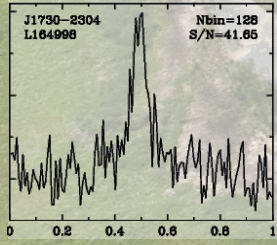
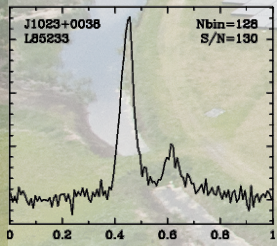
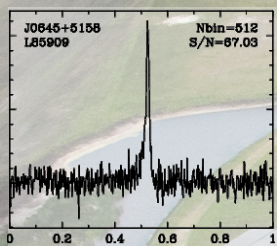




Vlad Kondratiev (ASTRON)  
and LOFAR Pulsar Working Group

# LOFAR Census of Millisecond Pulsars



# MSPs: why low freqs?

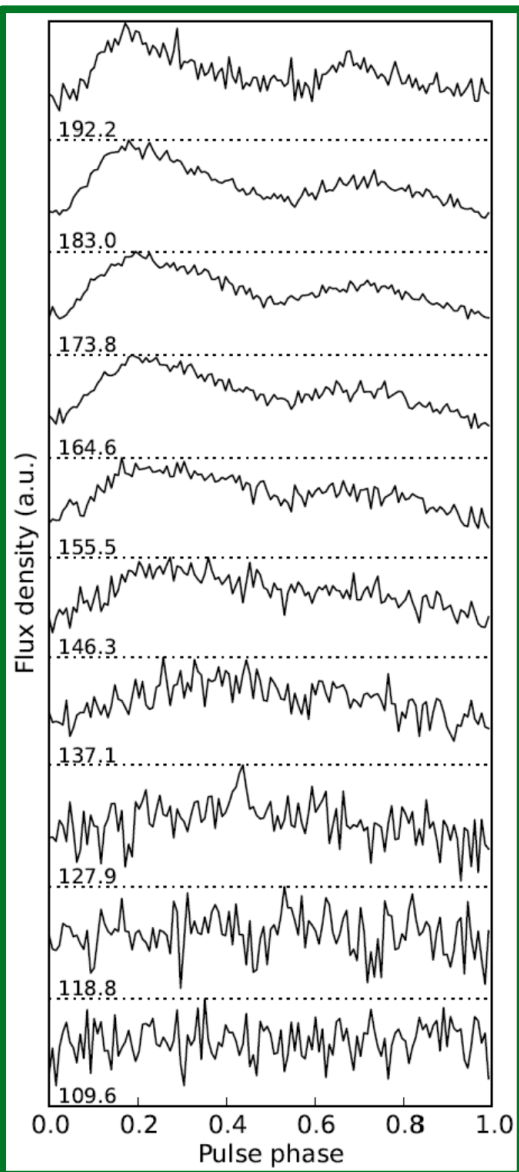
- Almost unexplored regime for MSPs
- Profile and polarization evolution with frequency
- Spectra of MSPs, do they turn over?
- Time variability of DM, RM and Scattering from the ISM  
→ Improve high-frequency timing



# PSR B1937+21

$P = 1.56$  ms  
 $DM = 71$  pc/cc

LOFAR HBA



192 MHz

2 ms (1.3 P)

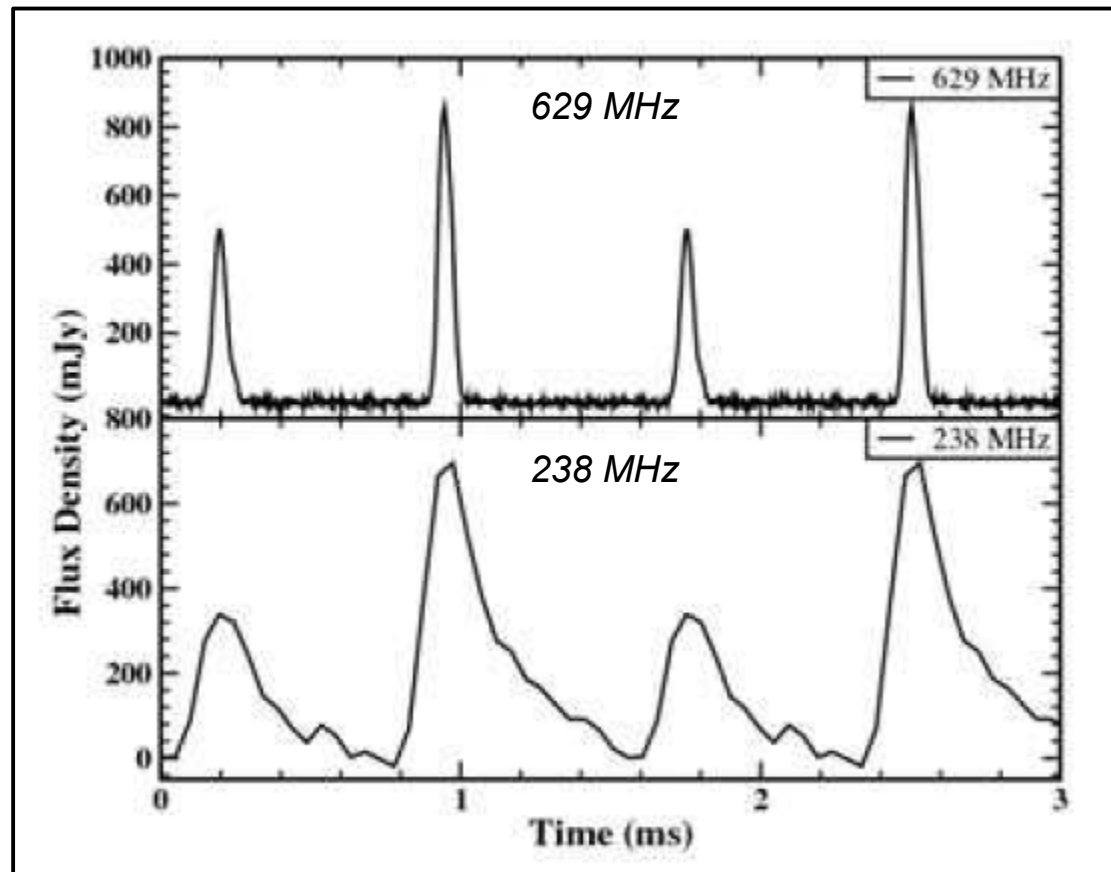
scattering  
time

18 ms (12 P)

110 MHz

GMRT

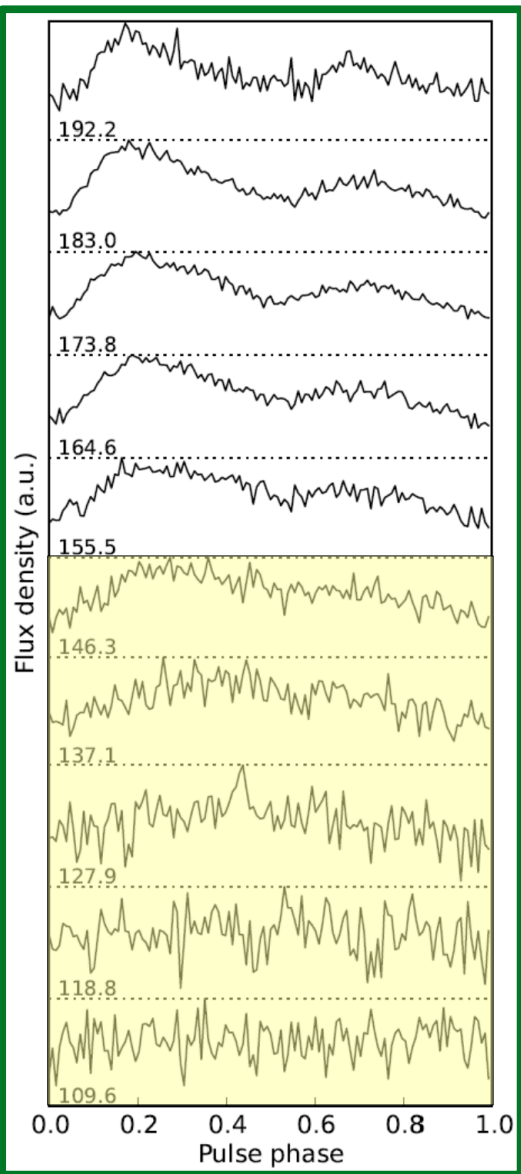
Joshi & Kramer 2009



# PSR B1937+21

$P = 1.56$  ms  
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LOFAR HBA



192 MHz

2 ms (1.3 P)

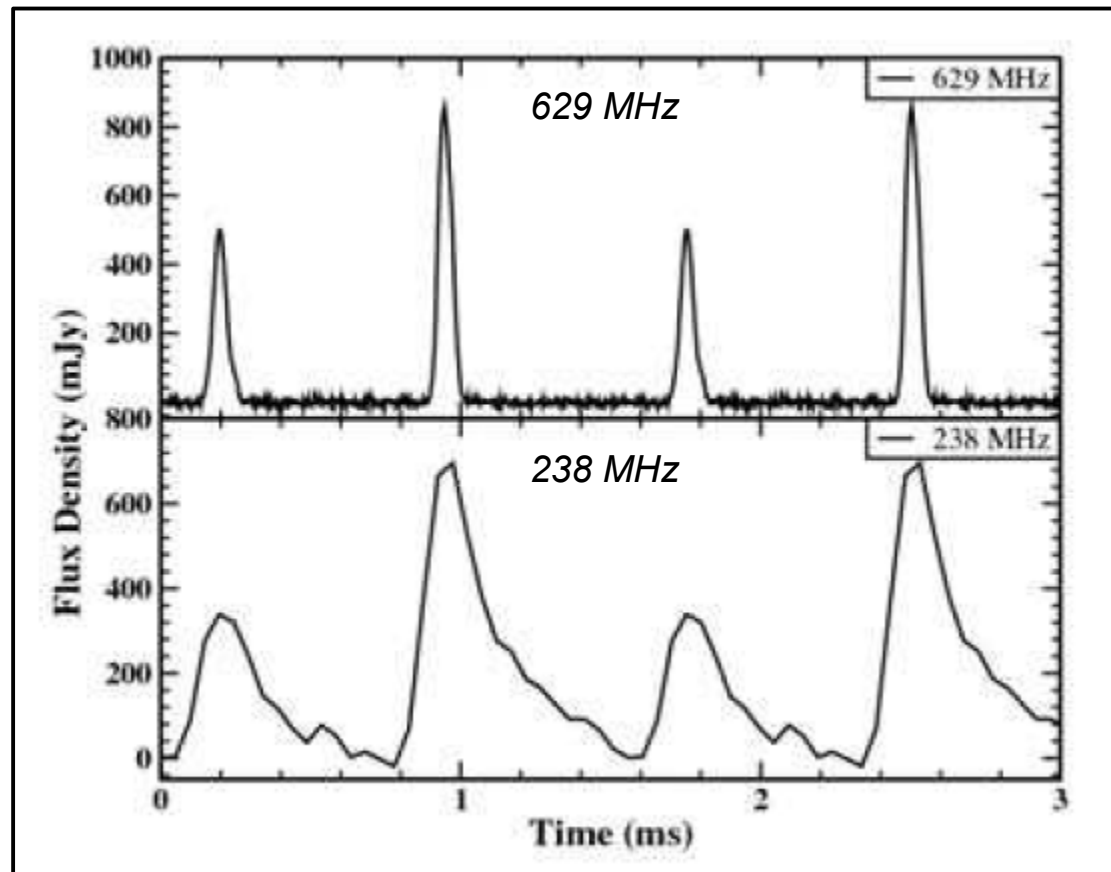
scattering  
time

18 ms (12 P)

110 MHz

GMRT

Joshi & Kramer 2009





# MSPs: why low freqs?

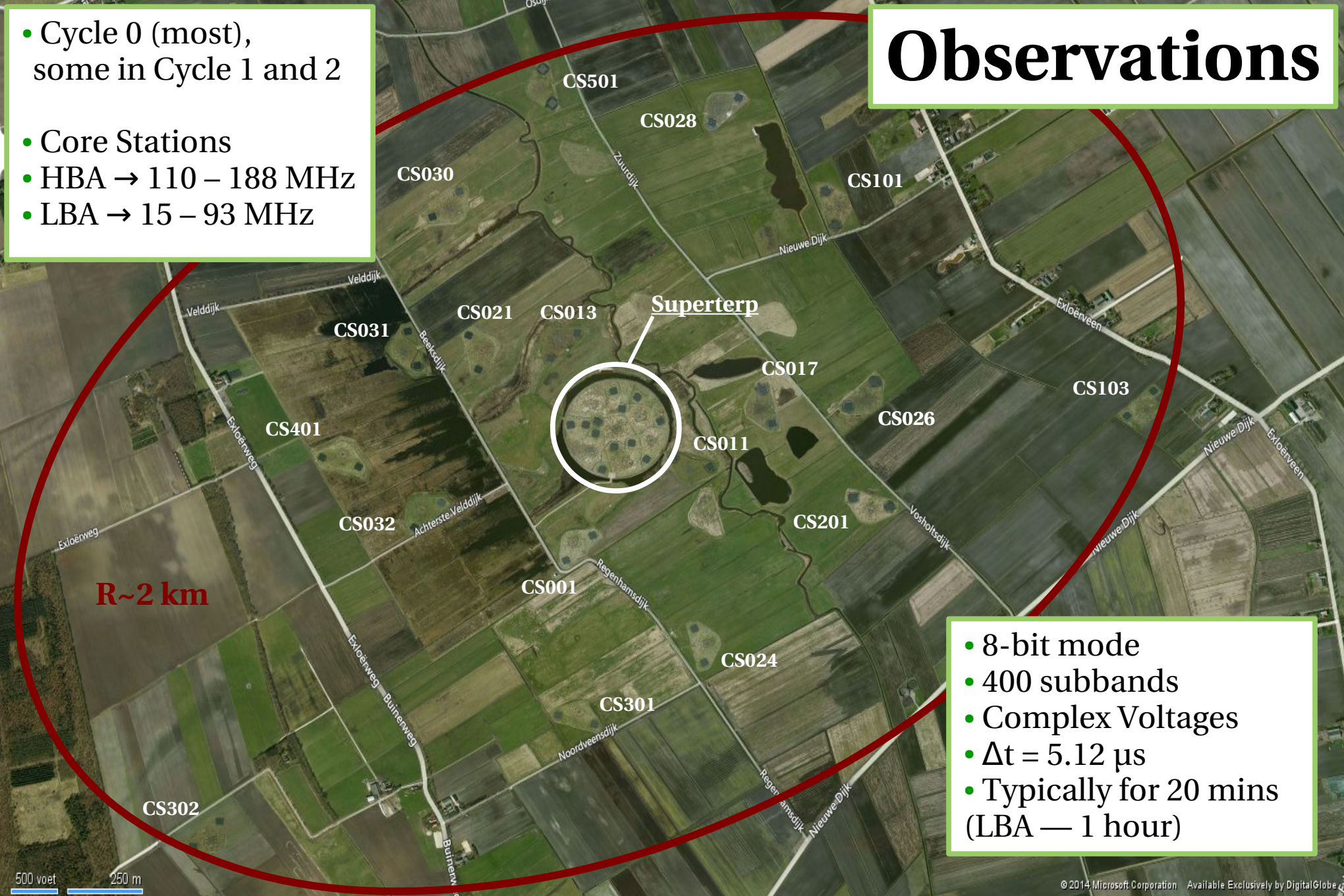
- Almost unexplored regime for MSPs
- Profile and polarization evolution with frequency
- Spectra of MSPs, do they turn over?
- Time variability of DM, RM and Scattering from the ISM  
→ Improve high-frequency timing

# Observations

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

## • Core Stations

- HBA → 110 – 188 MHz
- LBA → 15 – 93 MHz

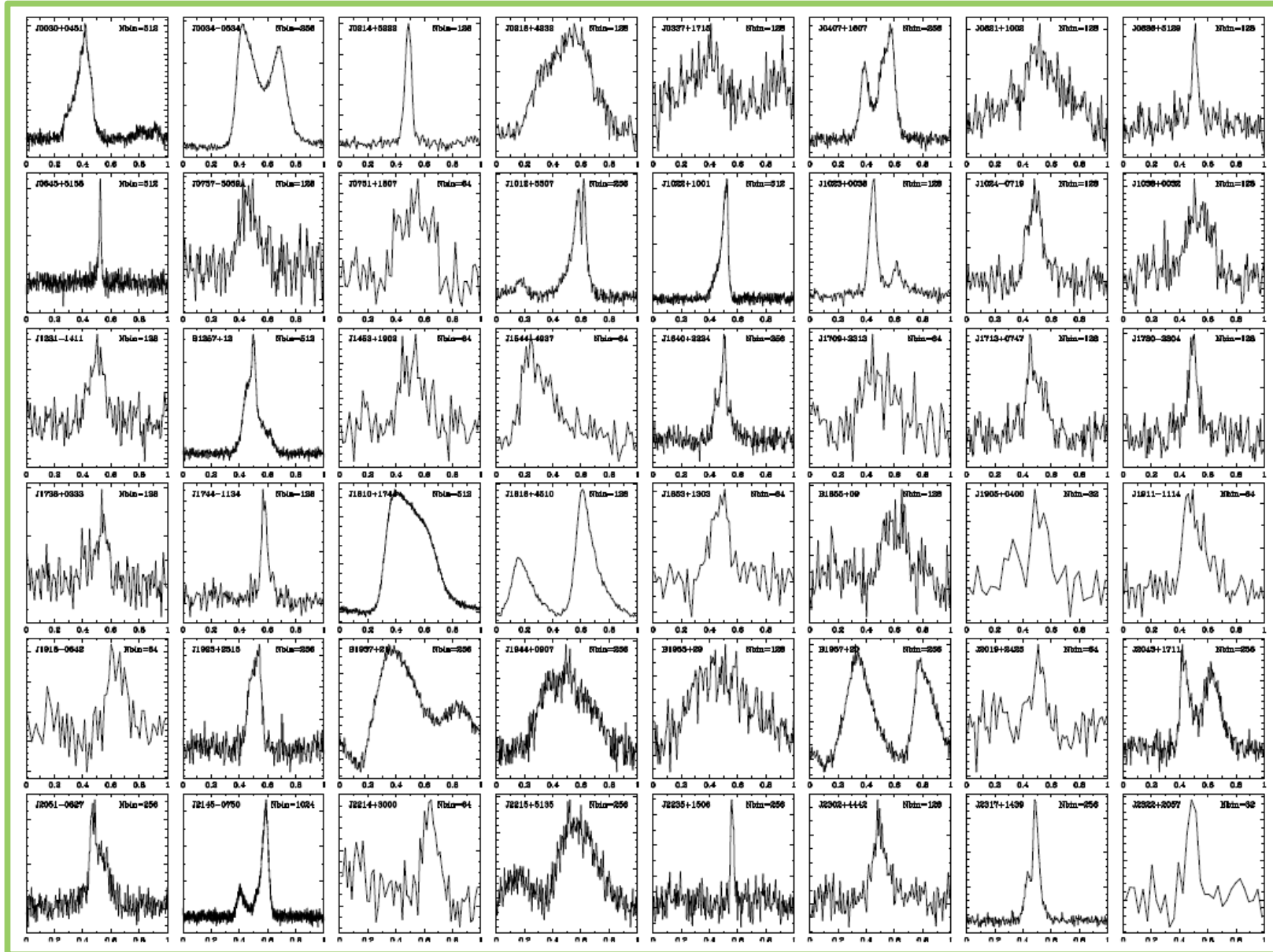


- 8-bit mode
- 400 subbands
- Complex Voltages
- $\Delta t = 5.12 \mu s$
- Typically for 20 mins (LBA — 1 hour)

500 voet 250 m

# Detected MSPs

Kondratiev et al. 2015,  
A&A, accepted



75 MSPs  
observed

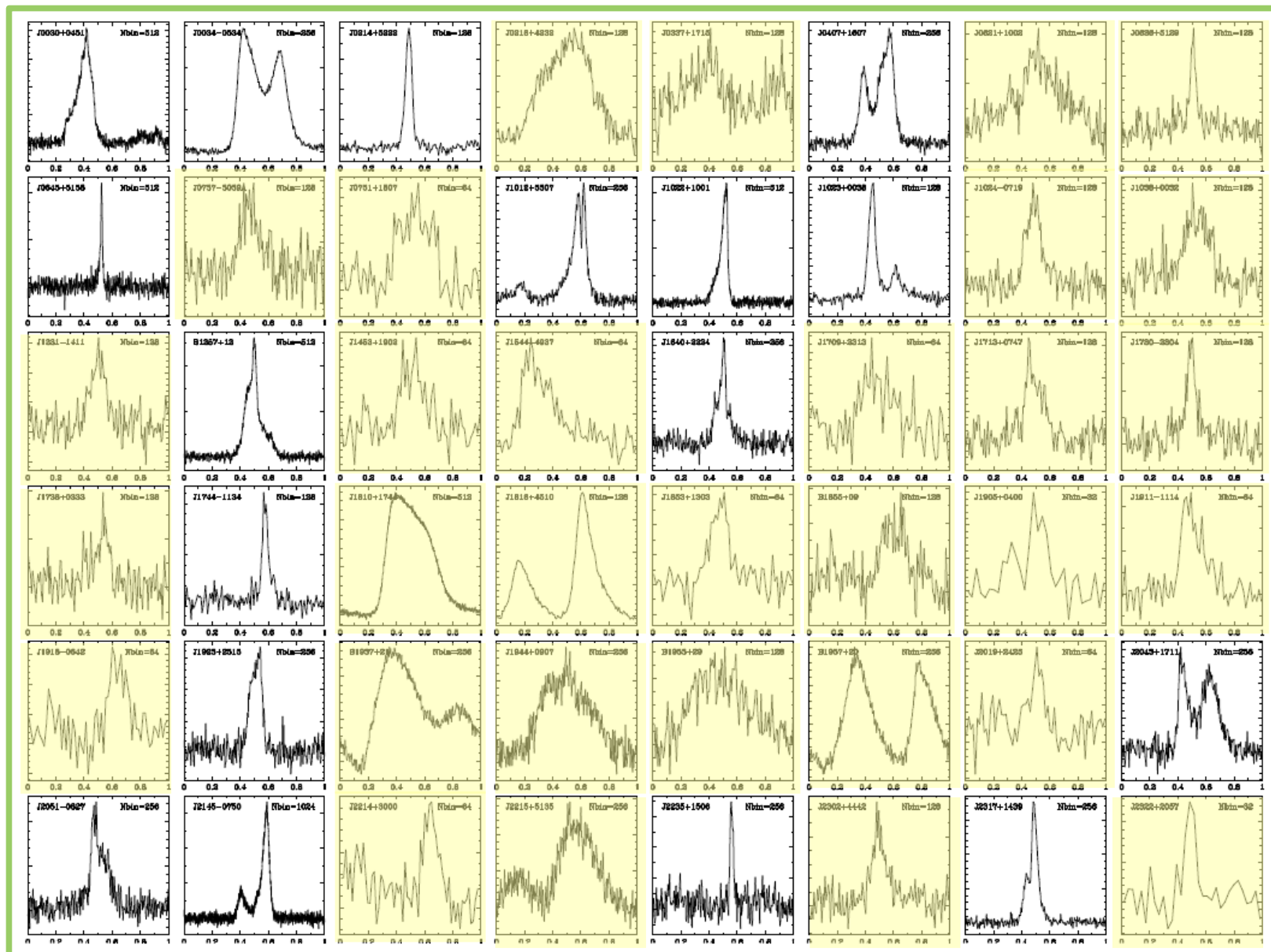
48 detected  
(64%)

Best  
20-min  
profiles  
(for most)



# Detected MSPs

Kondratiev et al. 2015,  
A&A, accepted



**75 MSPs  
observed**

**48 detected  
(64%)**

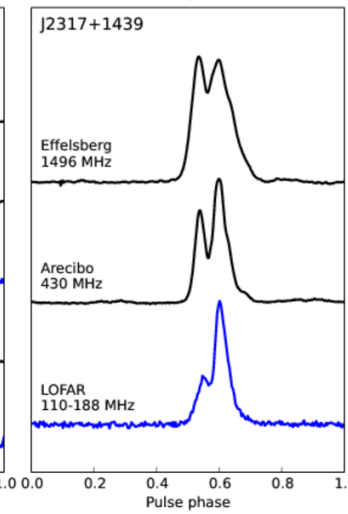
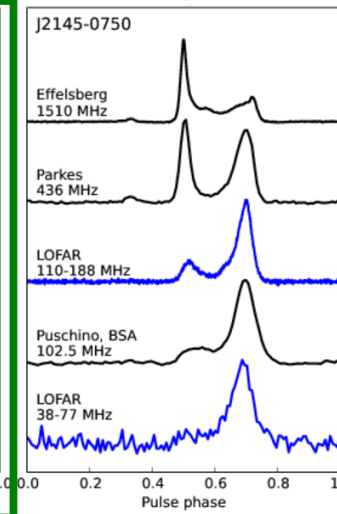
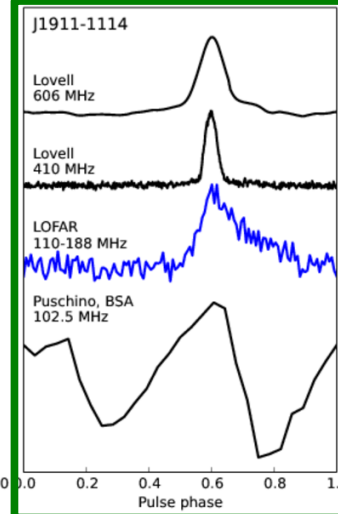
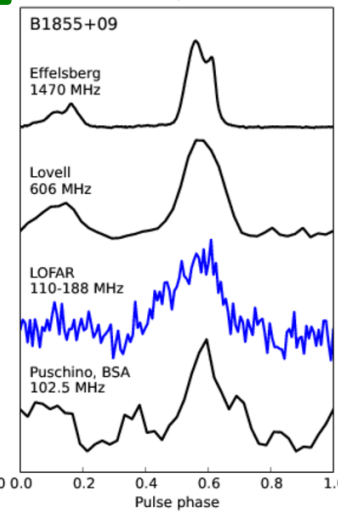
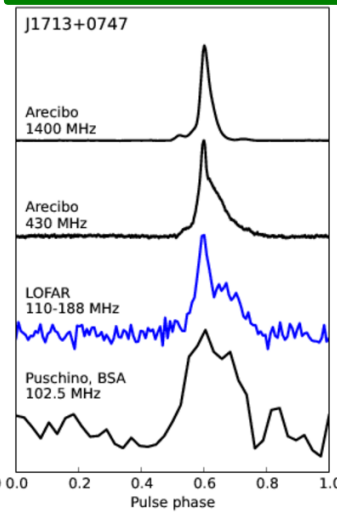
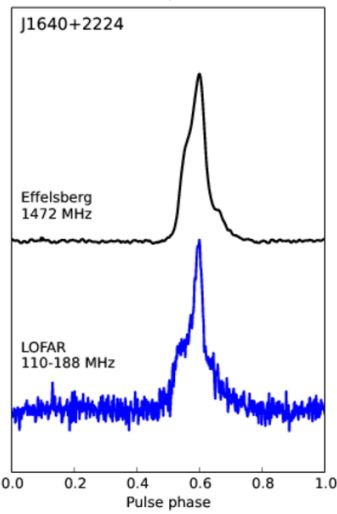
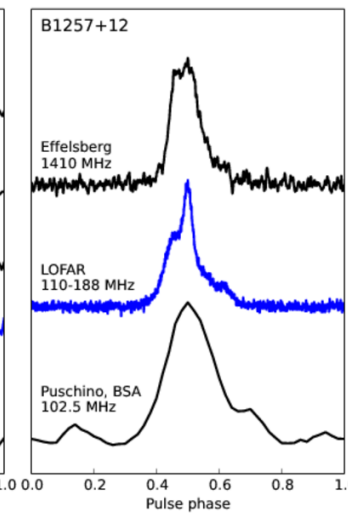
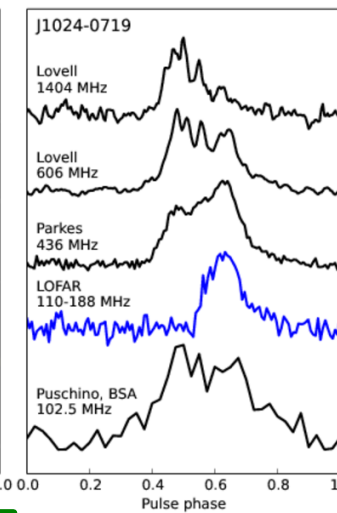
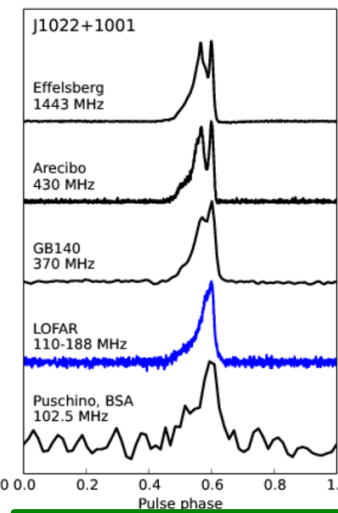
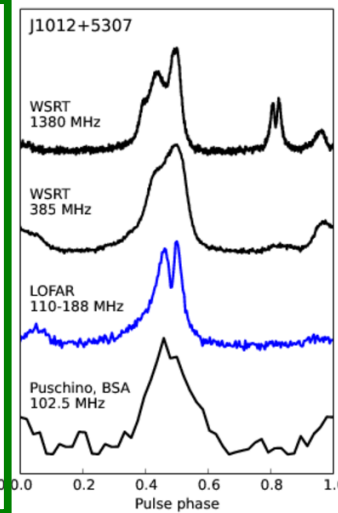
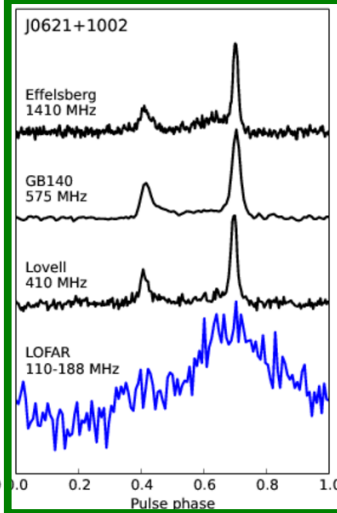
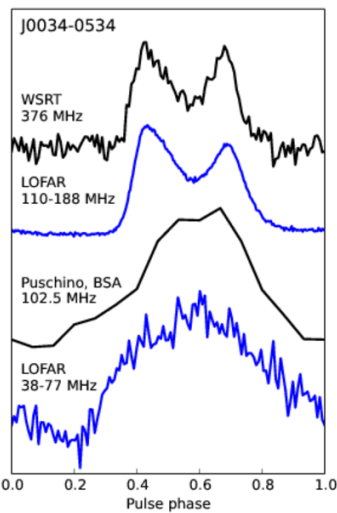
~25% scattered  
~40% weak  
~35% strong,  
narrow(-ish)  
profile

Best  
20-min  
profiles  
(for most)

# Multi-Frequency Profiles

LOFAR

scattered



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

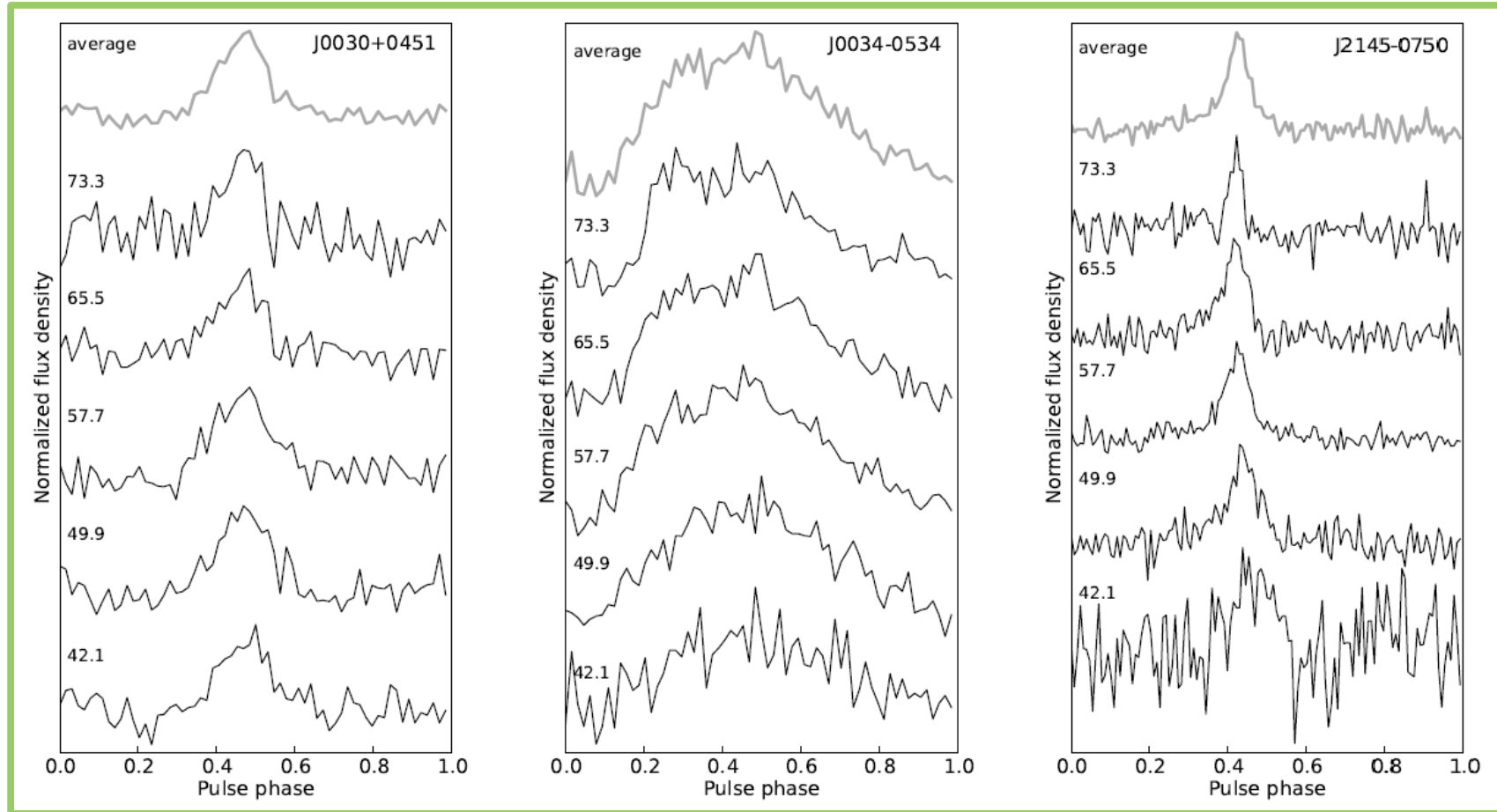
# LBA detections

38–77 MHz

**J0030+0451**

**J0034–0534**

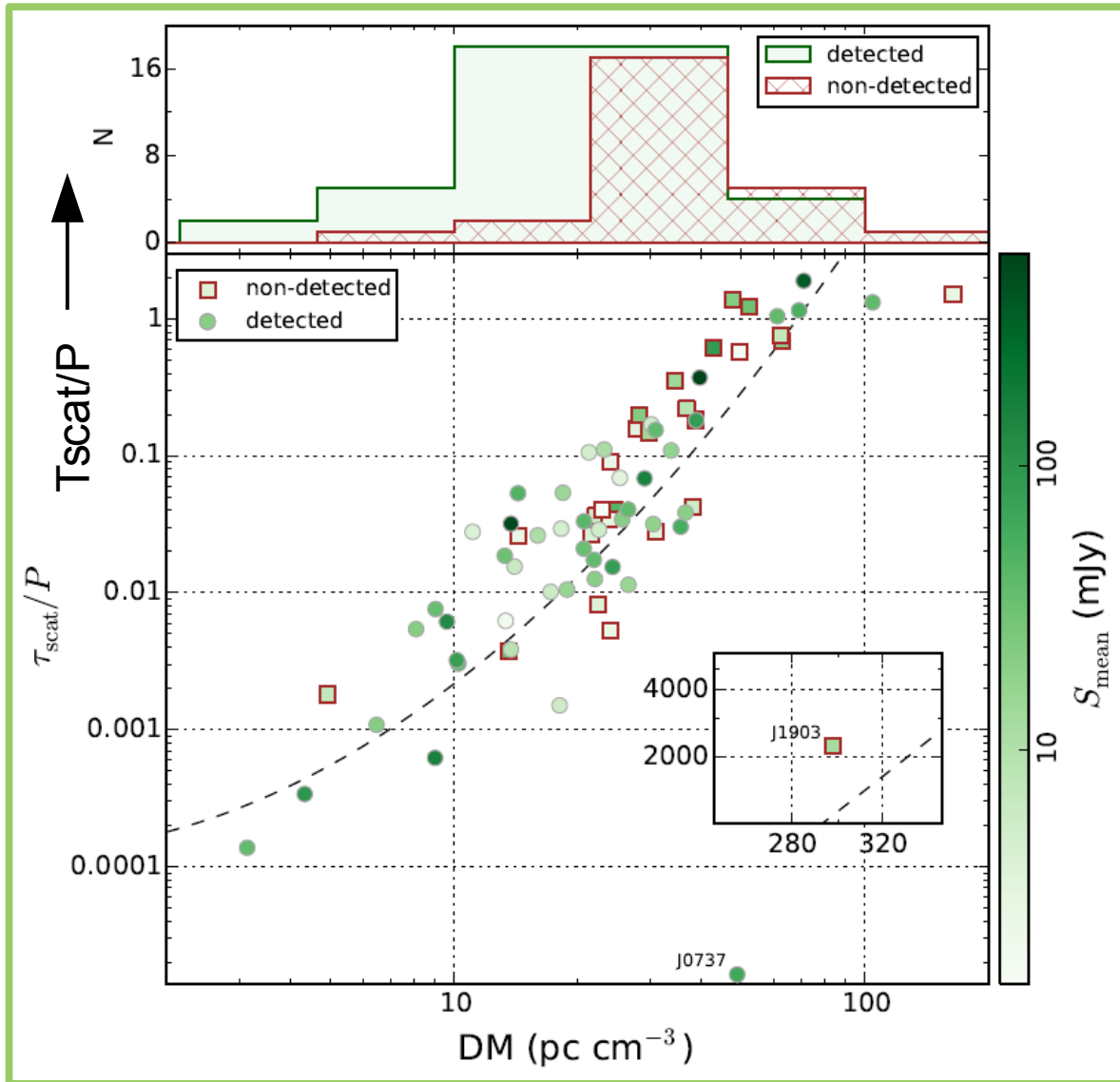
**J2145–0750**



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



# MSP detectability

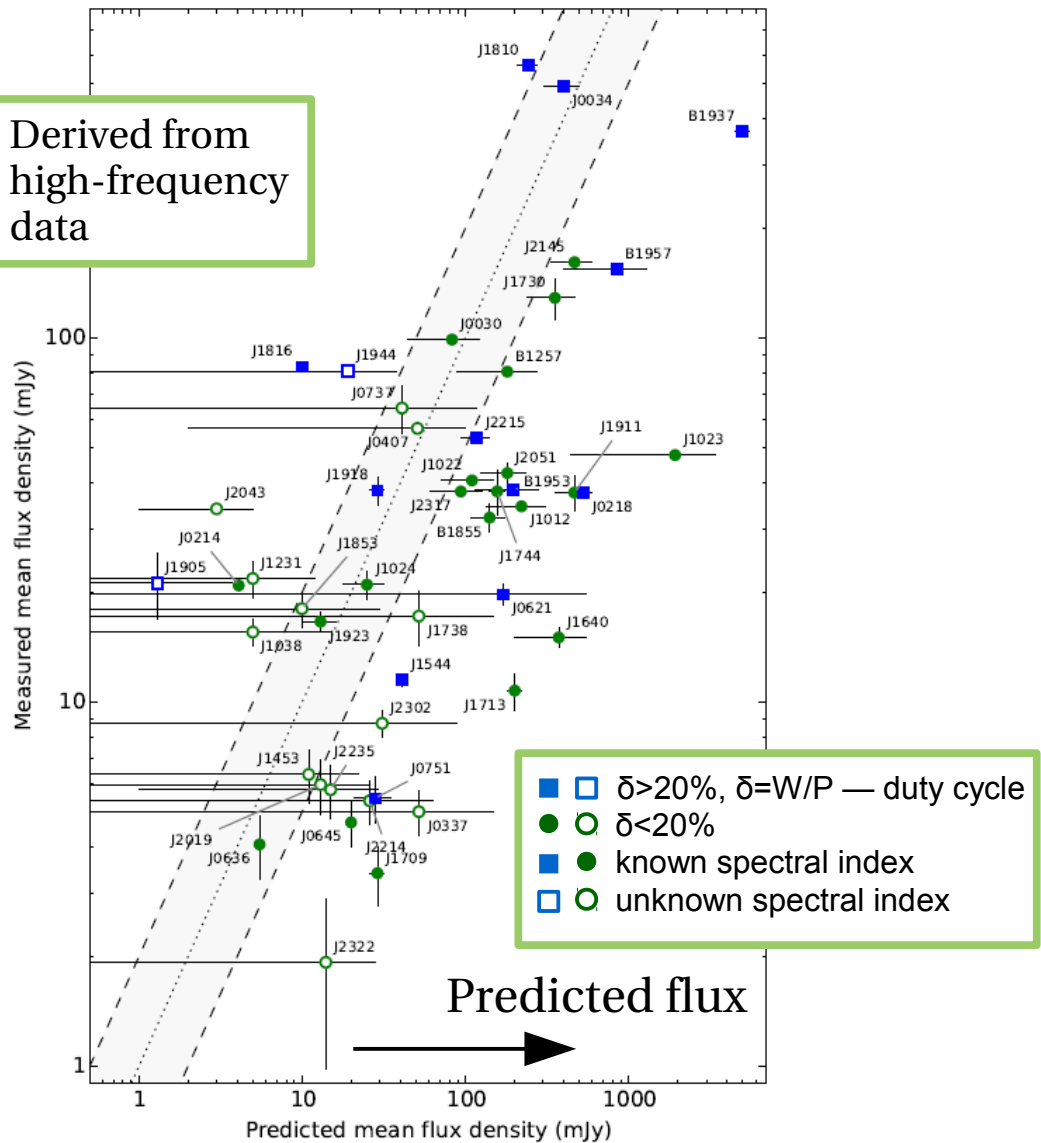


- ✓ DM < 20:  
detected 25 out of 28
- ✓ DM = 20-100: (50/50)  
22 detected  
23 not detected
- ✓ DM > 100:  
1 detected (DM = 104.5)  
2 not detected (DMs: 164, 297)

dispersion measure (DM) →

# MSP flux densities

Measured flux

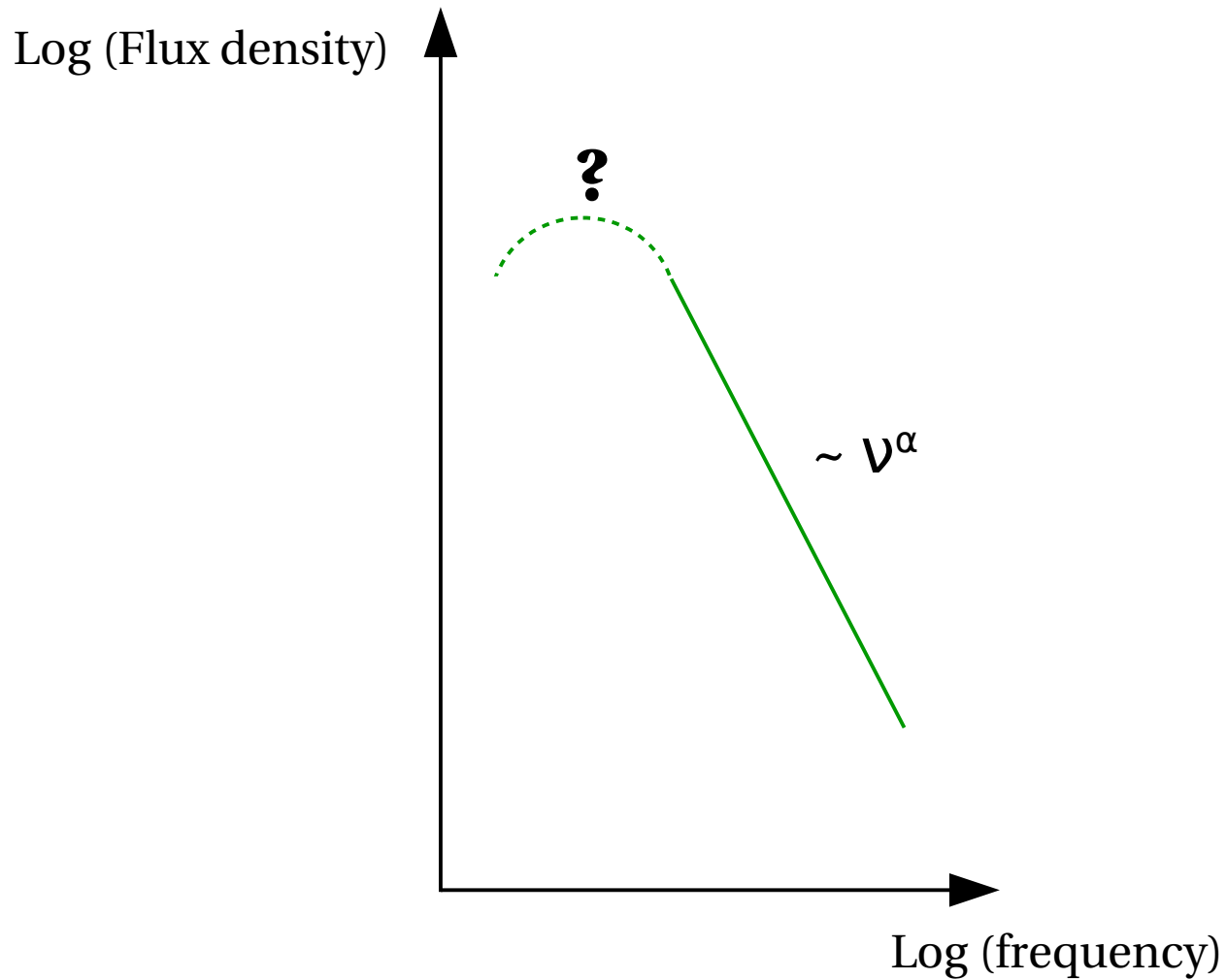


- Scattering → hard to get S/N, thus flux is underestimated
- Refractive scintillation
- Beam jitter by the ionosphere (up to ~2 arcmin)
- Variation of  $T_{\text{sys}}$  with time due to rise/set of the Galactic plane (up to 30-40%)
- Spectral turn-over?
- Beam model – need better knowledge. Tried three different approaches, the Hamaker-Carozzi currently gives the best result

literature

- main uncertainty – poor knowledge of spectral indices
- published data could be over- or underestimated due to scintillation (refractive)

# MSP spectra

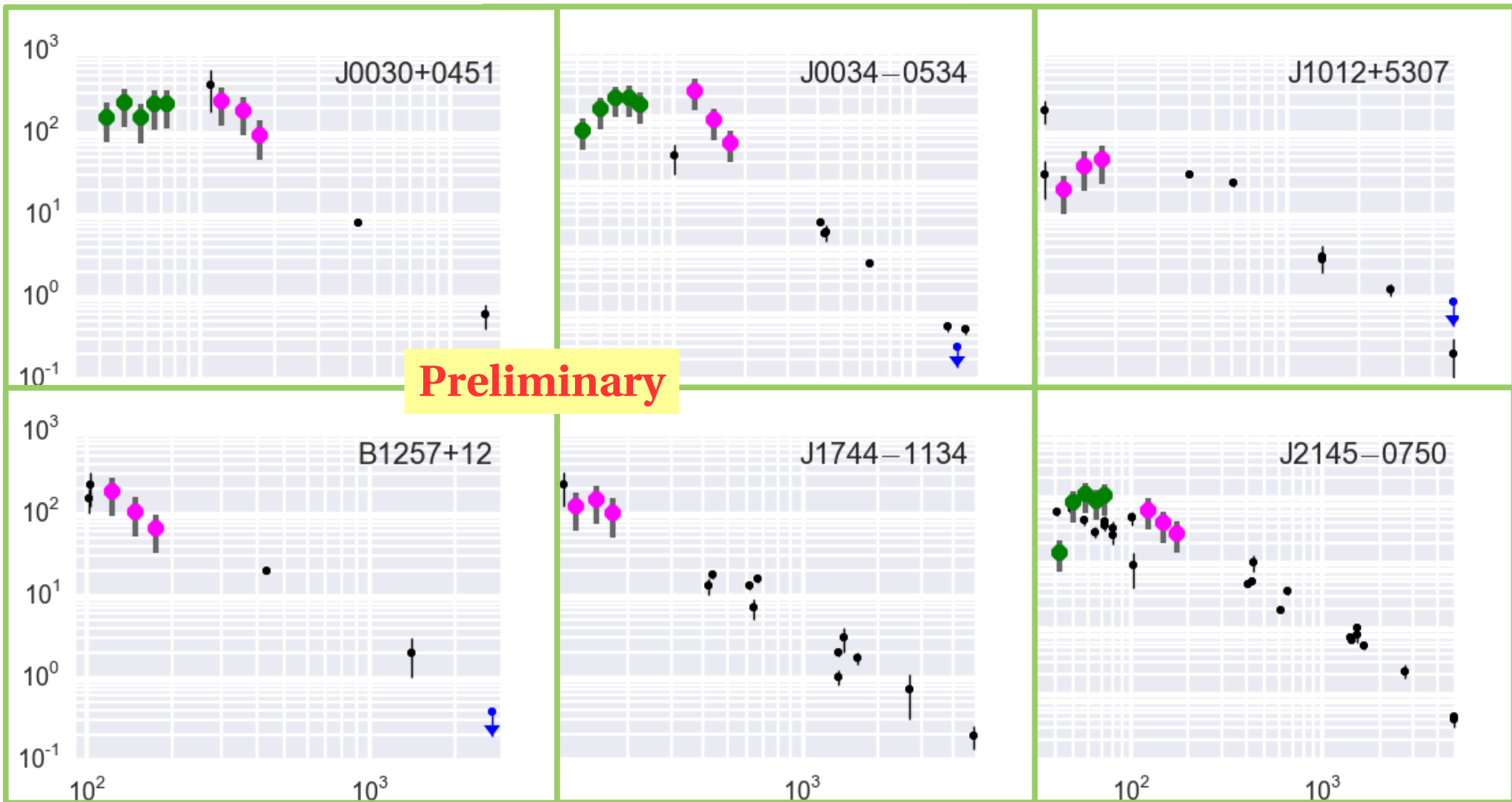




Flux density  
(mJy)

# MSP spectra

Kondratiev et al., in prep



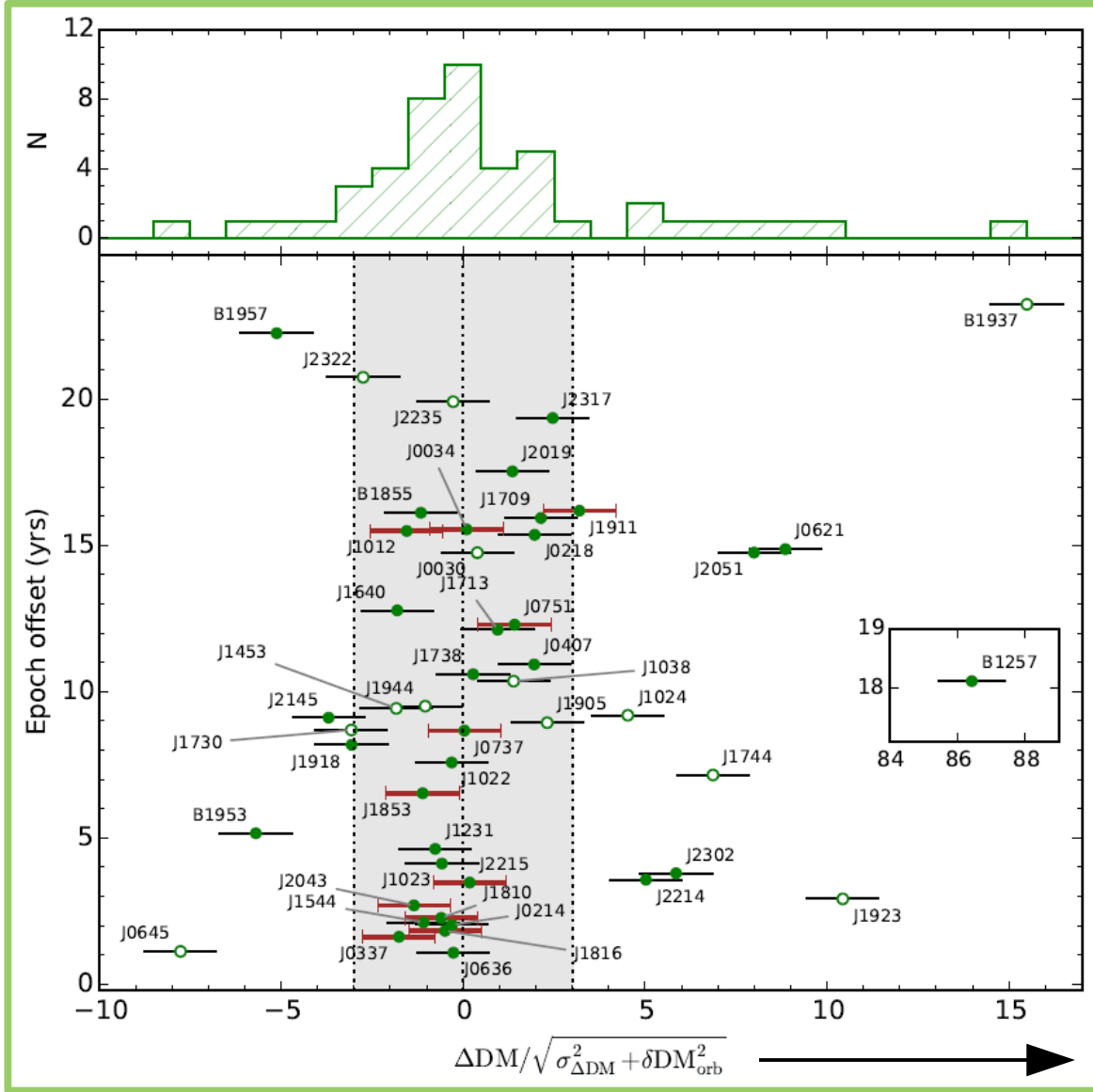
Preliminary

Frequency (MHz)

Years since catalog  
DM measurement

# DM variations

Kondratiev et al. (2015)



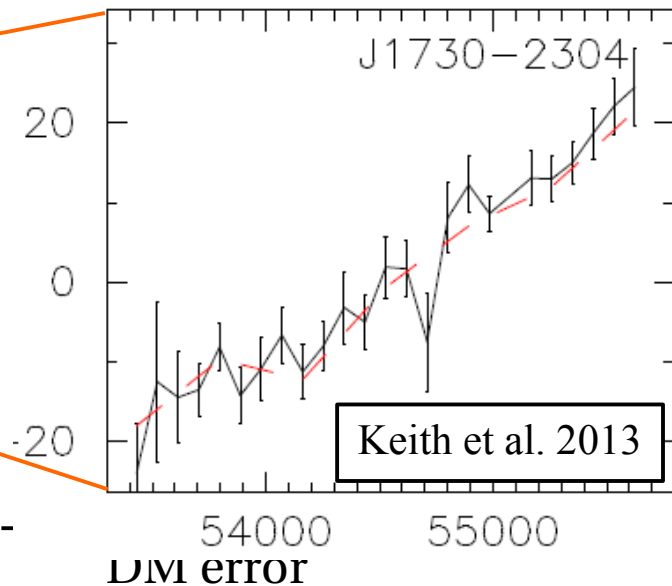
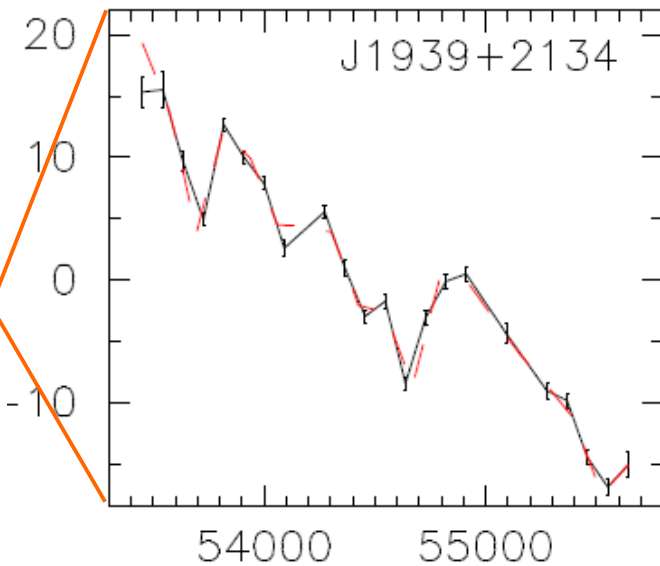
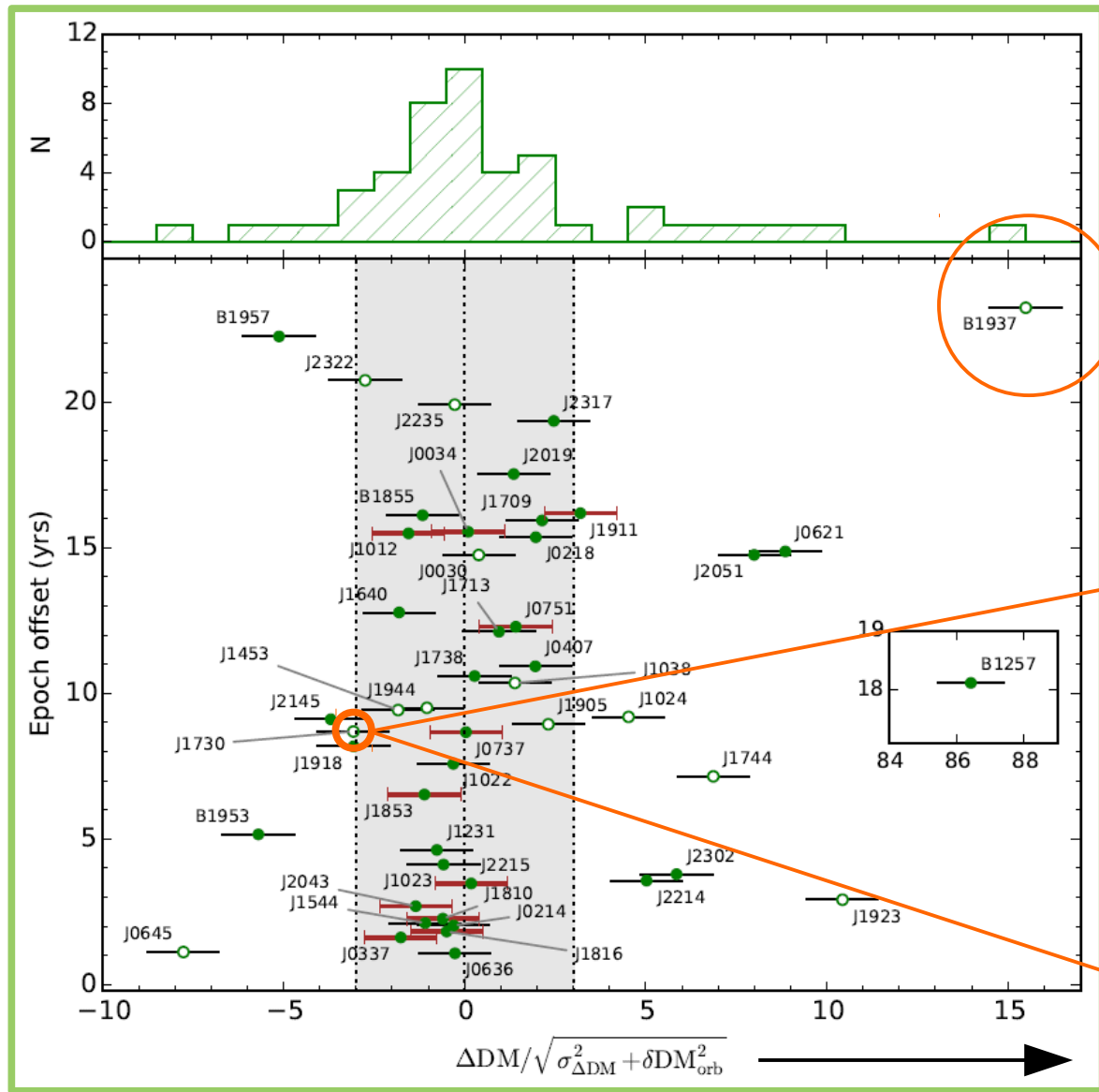
$$\left. \begin{array}{l} V_{\text{plasma}} \neq 0 \\ V_{\text{PSR}} \neq 0 \end{array} \right\} DM = DM(t)$$

$$\frac{DM_{\text{catalog}} - DM_{\text{LOFAR}}}{DM \text{ error}}$$

Years since catalog  
DM measurement

# DM variations

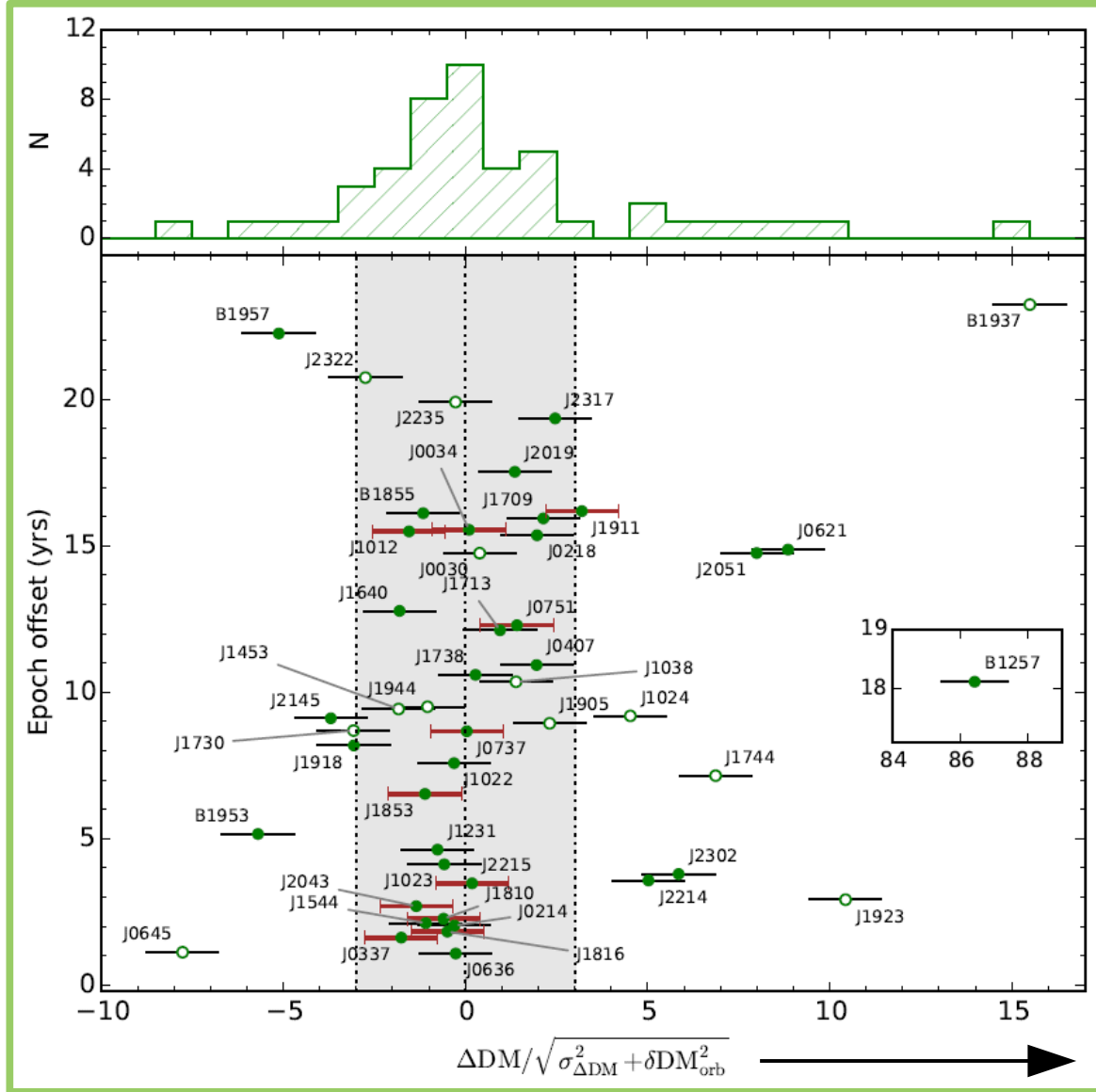
Kondratiev et al. (2015)





Years since catalog  
DM measurement

# DM variations



- About 25% of MSPs have noticeable DM offset from the catalog value

- Multifrequency simultaneous observations are needed to compare low- and high-frequency DM measurements

- LOFAR can provide precise DM measurements from a single observation on shorter time scales (2–4 weeks) → **input to higher-frequency pulsar timing**

$$\frac{DM_{\text{catalog}} - DM_{\text{LOFAR}}}{DM \text{ error}}$$

# Summary:

- First large sample of high-quality MSP profiles below 200 MHz. 48 MSPs detected out of 75 observed (**49 now!**). Three MSPs detected in the LBA range. Low-frequency profiles, DM and flux density measurements.
- Preliminary MSP spectra seem to be no different from those of slow pulsars: some show turn-over, some do not. Fluxes below 100 MHz are needed in most of the cases to probe spectral shape → hard (if not possible at all) due to scattering with beamformed observations → imaging...
- LOFAR DM values have noticeable offset from the catalog values for a 25% of detected MSPs.



# Factors affecting flux measurements

- Beam model — better knowledge is needed
- Scattering → hard to get S/N, it is underestimated
- Refractive scintillations.  
Can change pulsar flux by a factor of  $\sim 1.5$ . Need long-term monitoring program  
Diffractive scintillations is not a factor → averaged out,  $\Delta v_d < 0.2$  MHz
- Beam jitter by the ionosphere.  
Can be up to  $\sim 2-3$  arcmins, i.e. half the Full-Core HBA TA beam (at half maximum)
- Variation of  $T_{\text{sys}}$  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.



# MSPs: why low freqs?

- **Almost unexplored regime for MSPs**

BSA & 102, 111 MHz →

Kuzmin et al. (1990), Kuzmin & Losovskii (1996, 1999, 2001), ...

Kramer et al. (1998, 1999), Xilouris et al. (1998)

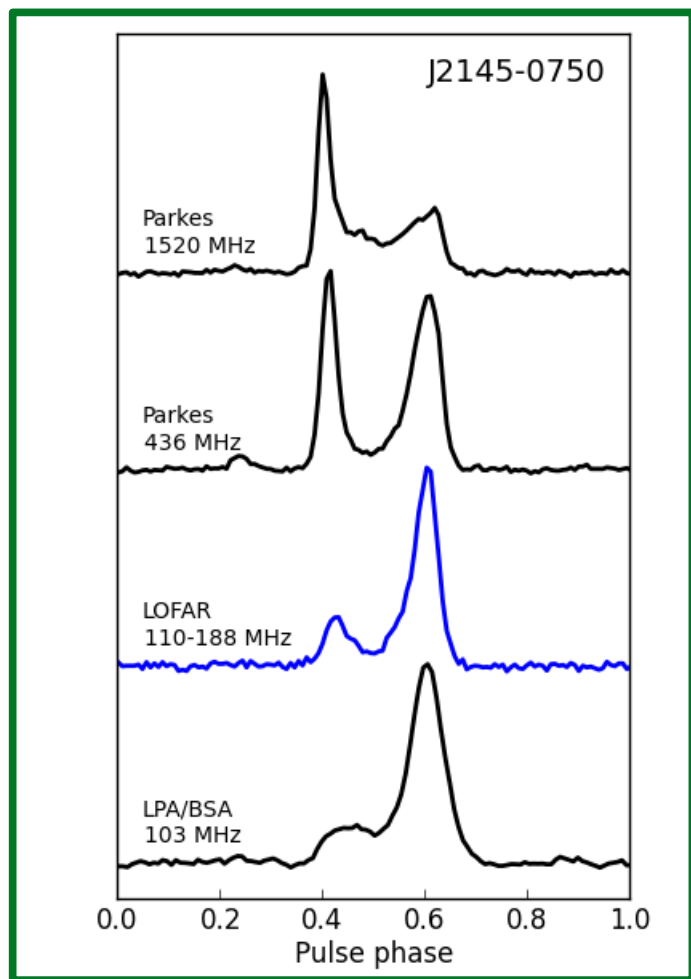
WSRT & 150 MHz → Stappers et al. (2008)

GMRT & 240 MHz → Joshi & Kramer (2009)

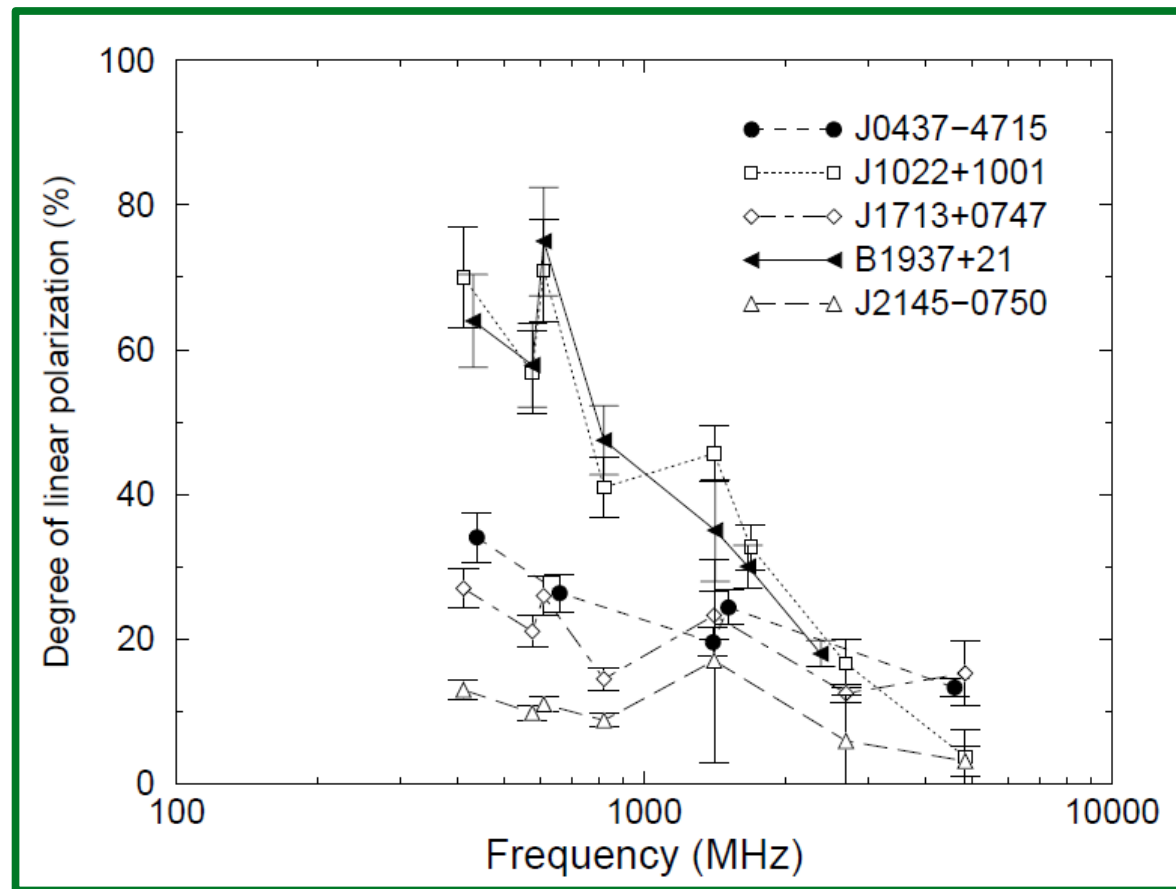
LWA & 37-81 MHz (J2145) → Dowell et al. (2013)

archive imaging data: VLSSr & 74 MHz, WENSS & 325 MHz,  
NVSS & 1.4 GHz → Kuniyoshi et al. (2015)

# Profile and polarization evolution

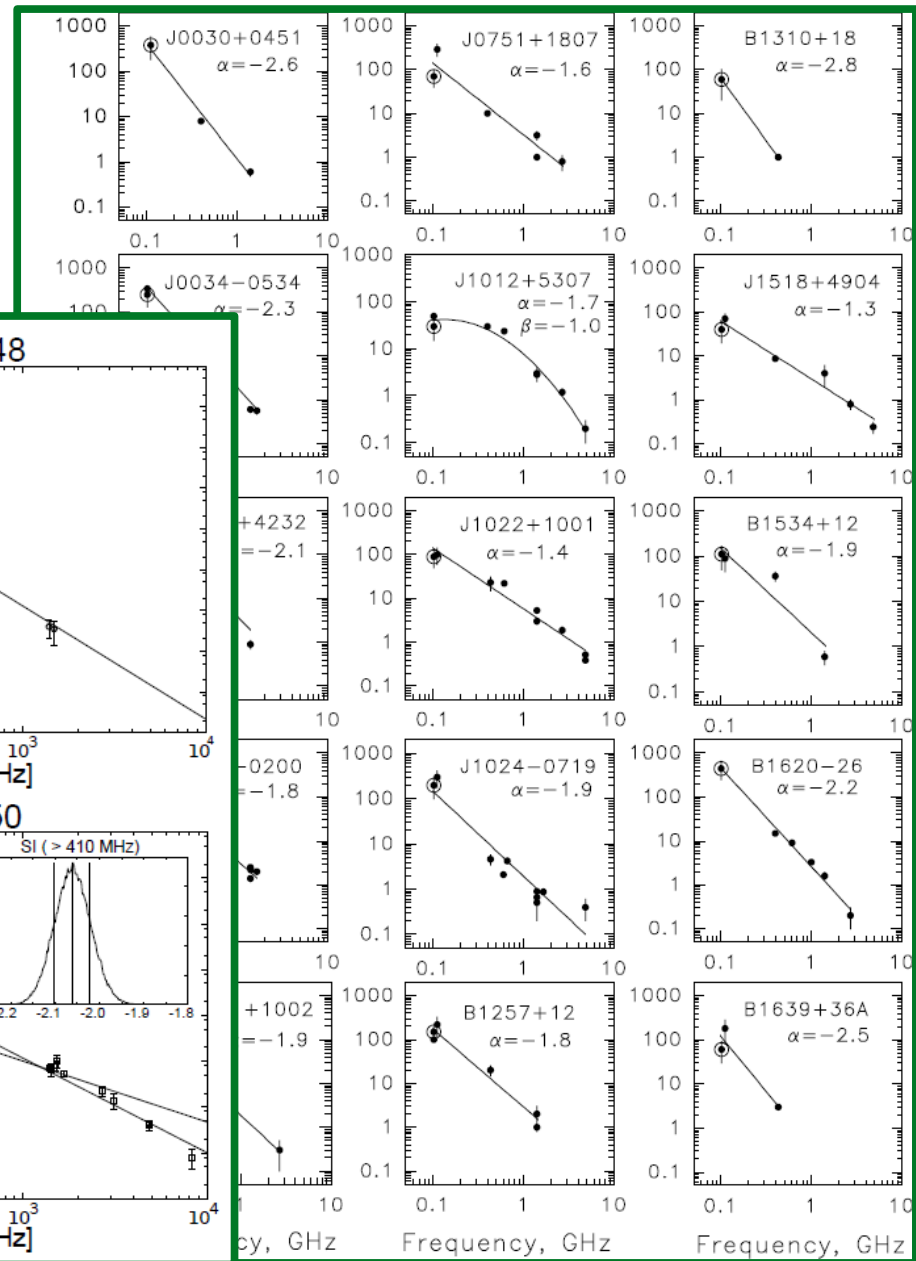
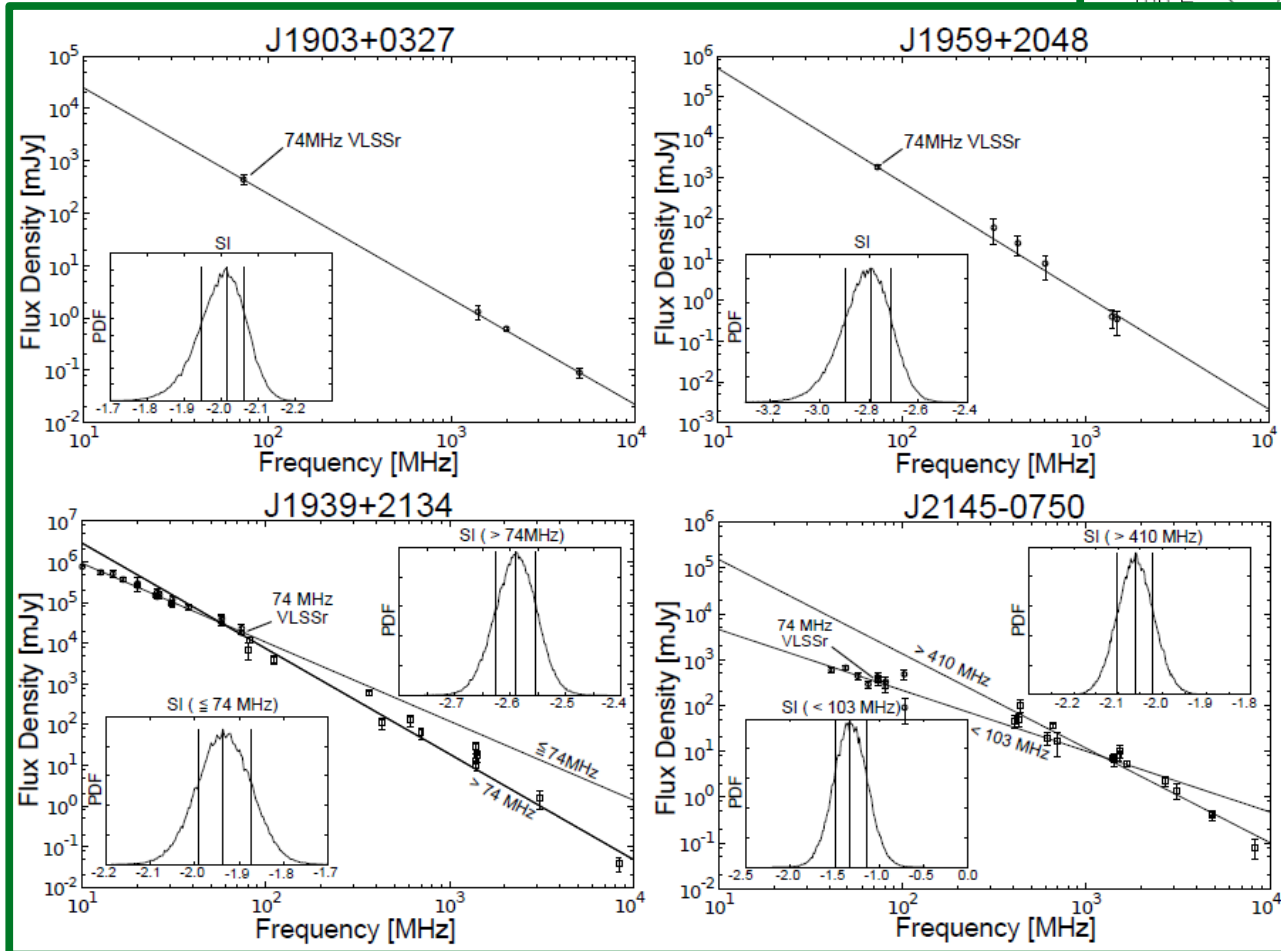


Kramer et al. (1999)



# Spectra of MSPs

Kuniyoshi et al. (2015)



Kuzmin & Losovskii (2001)