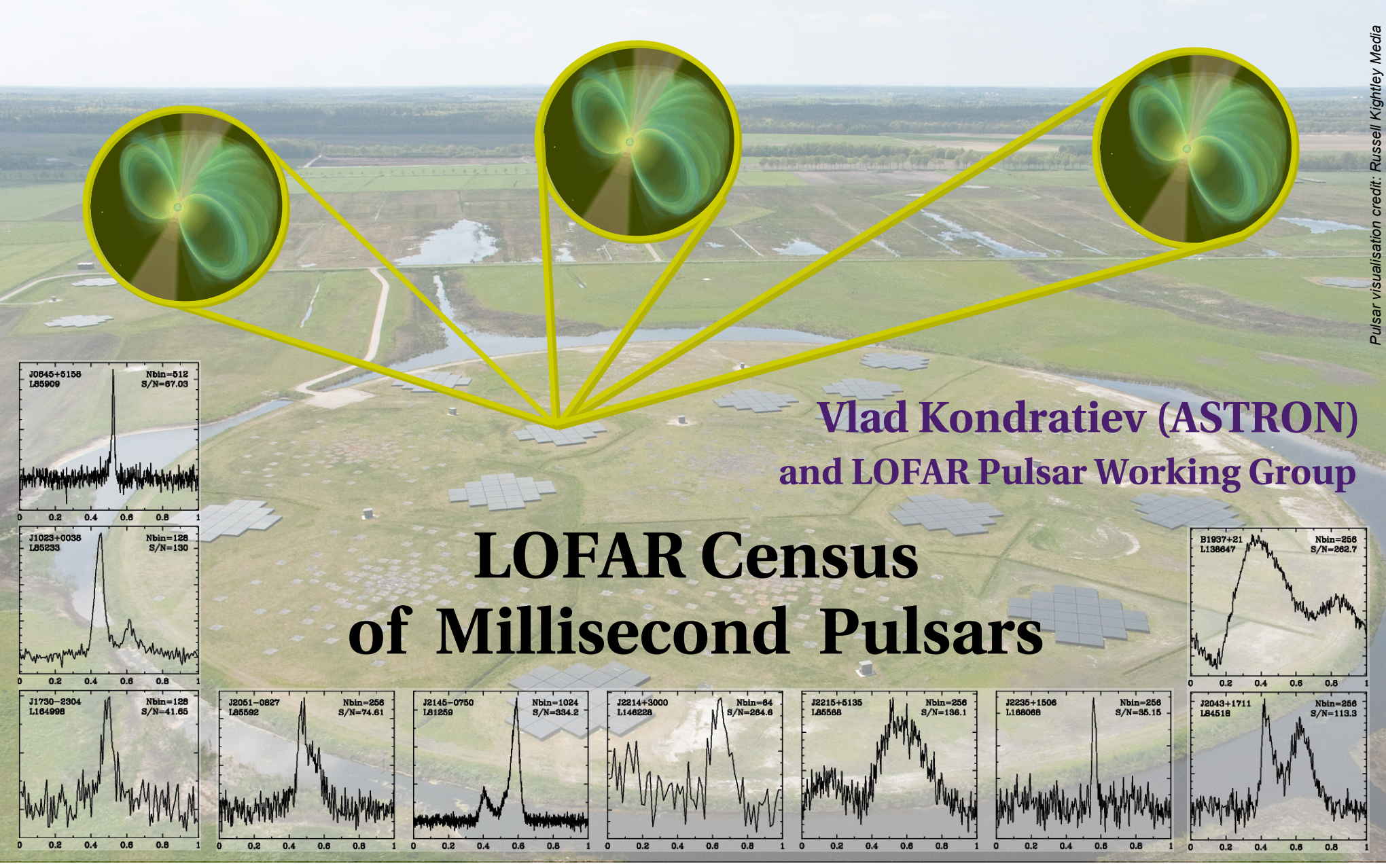


Vlad Kondratiev (ASTRON)
and LOFAR Pulsar Working Group

LOFAR Census of Millisecond Pulsars

MSPs: why low freqs?

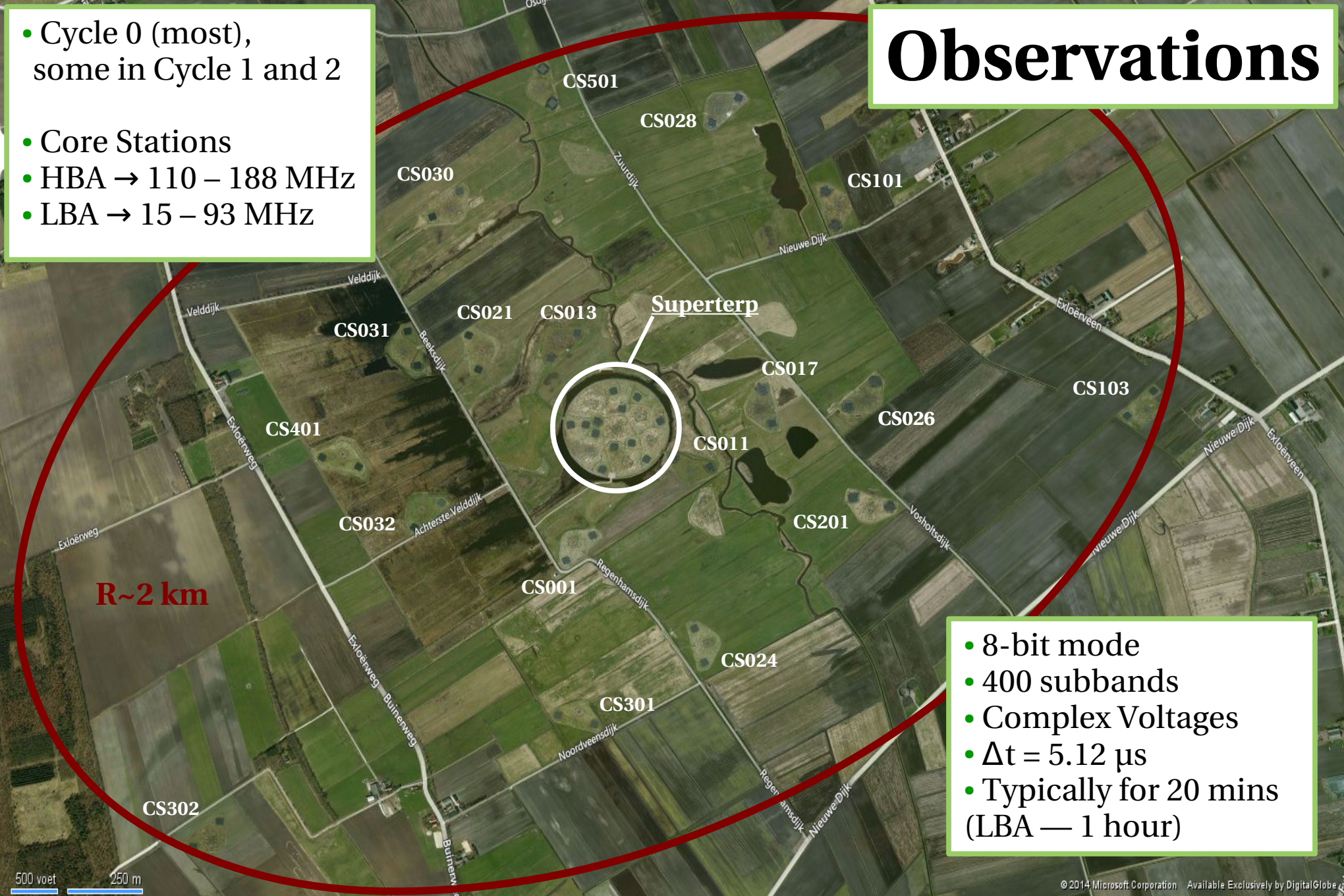
- Almost unexplored regime for MSPs
- Profile and polarization evolution with frequency
- Spectra of MSPs, do they turn over?
- Time variability of DM, RM and Scattering from the ISM

→ Improve high-frequency timing

Observations

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

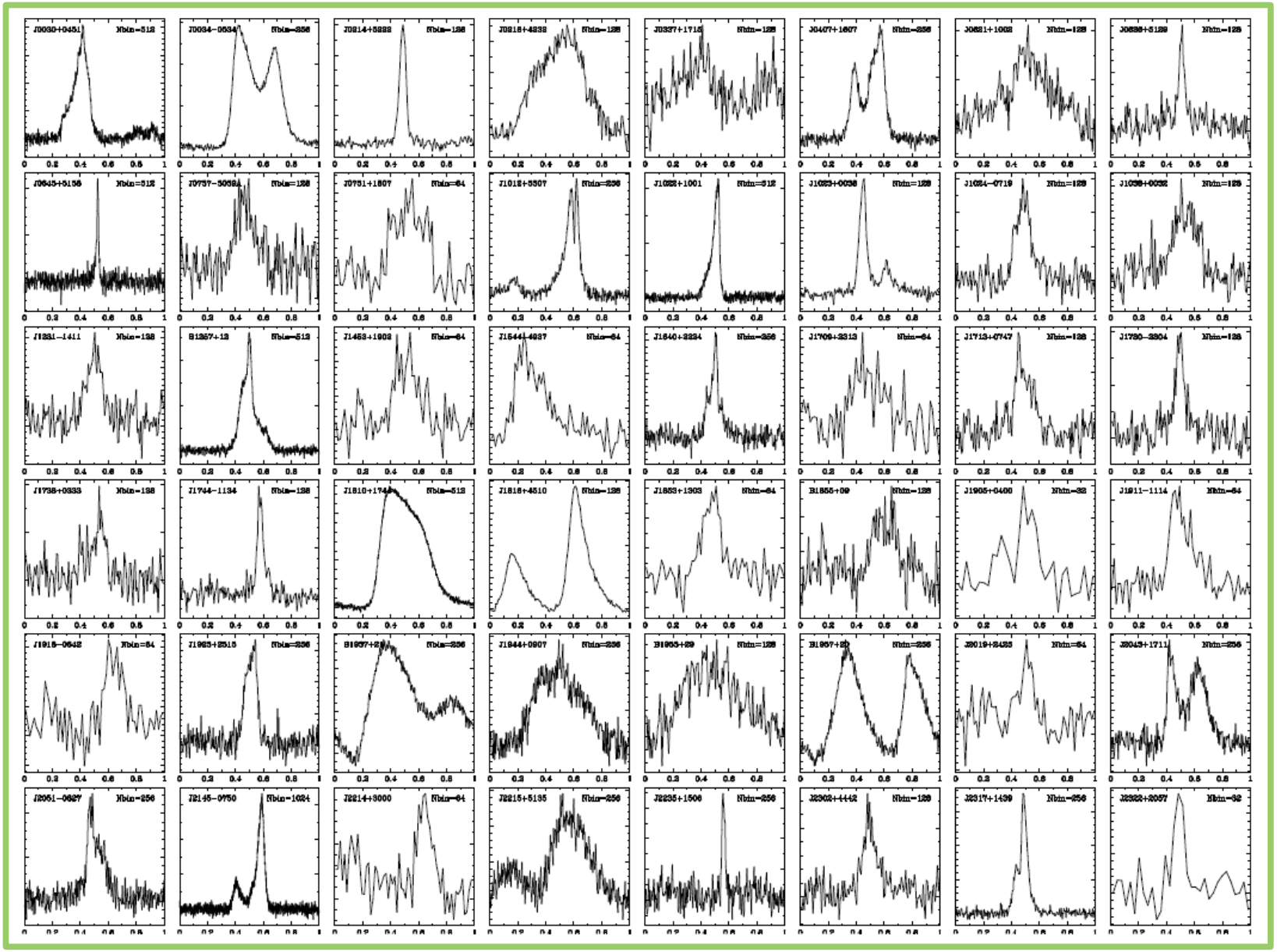
- Core Stations
- HBA → 110 – 188 MHz
- LBA → 15 – 93 MHz



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

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,
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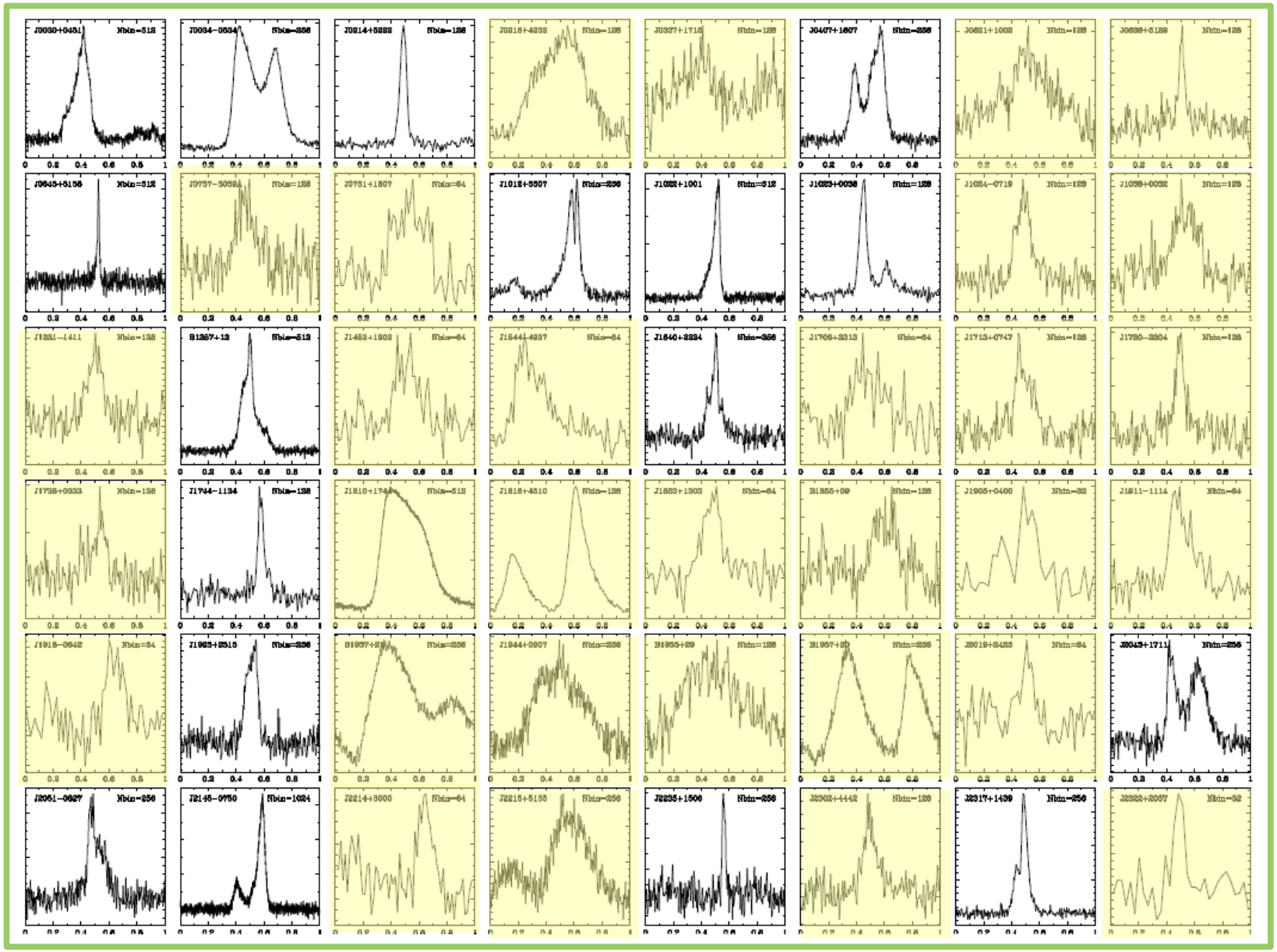


75 MSPs observed

48 detected (64%)

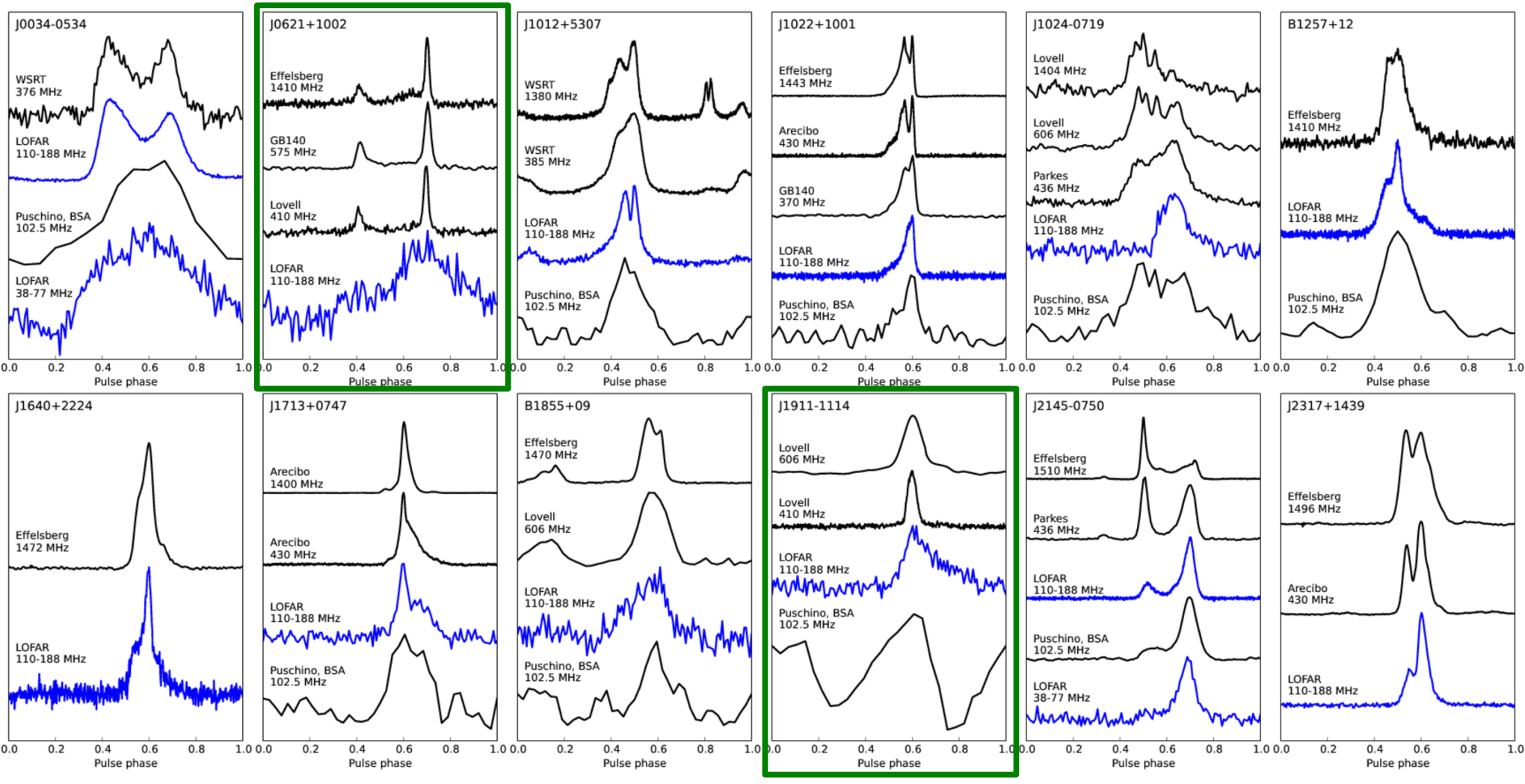
~25% scattered
~40% weak
~35% strong, narrow(-ish) profile

Best 20-min profiles (for most)

Multi-Frequency Profiles

scattered

LOFAR

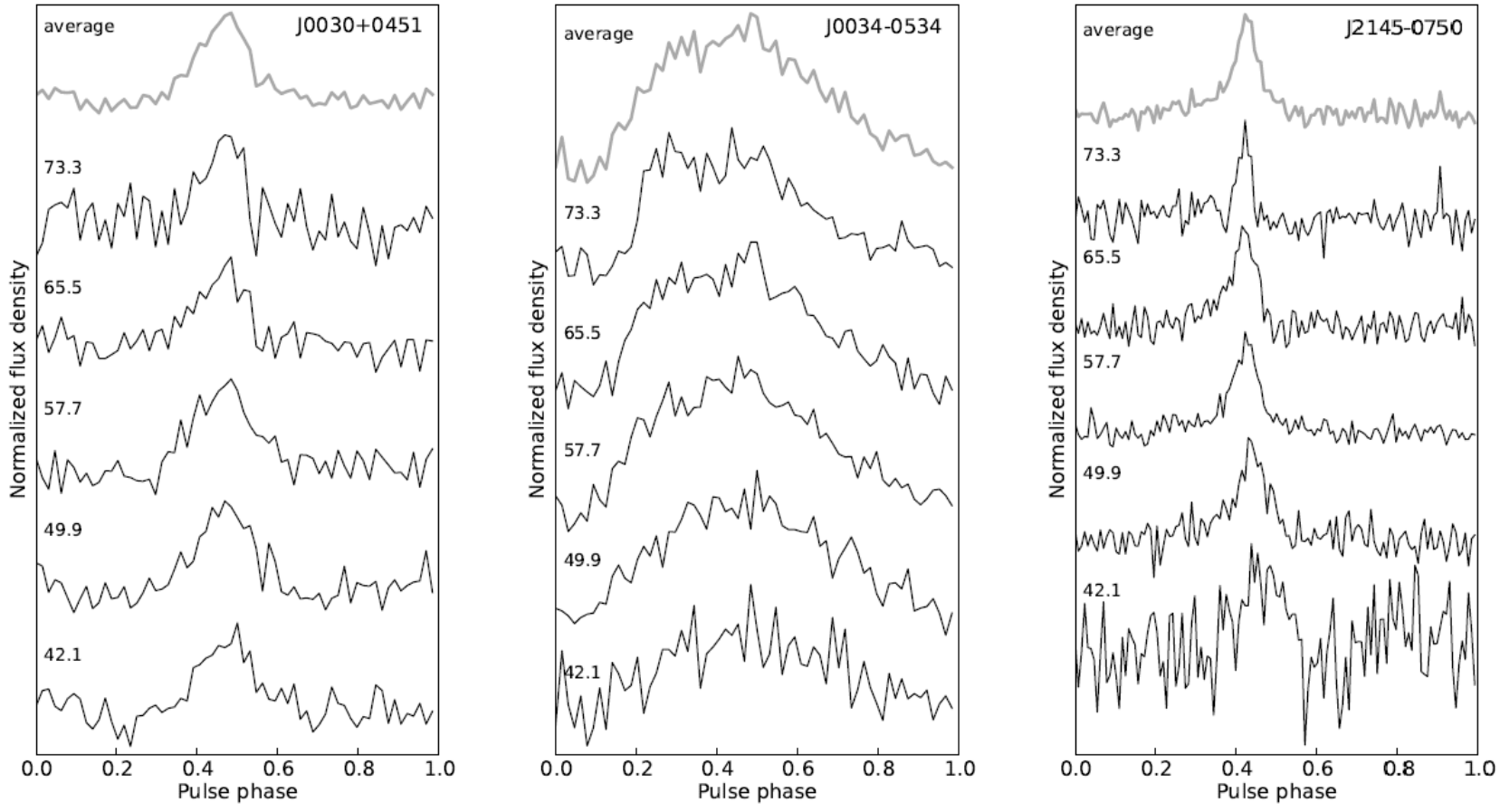


~25% - scattered, ~40% - weak, ~35% - strong, narrow(-ish) profile

LBA detections

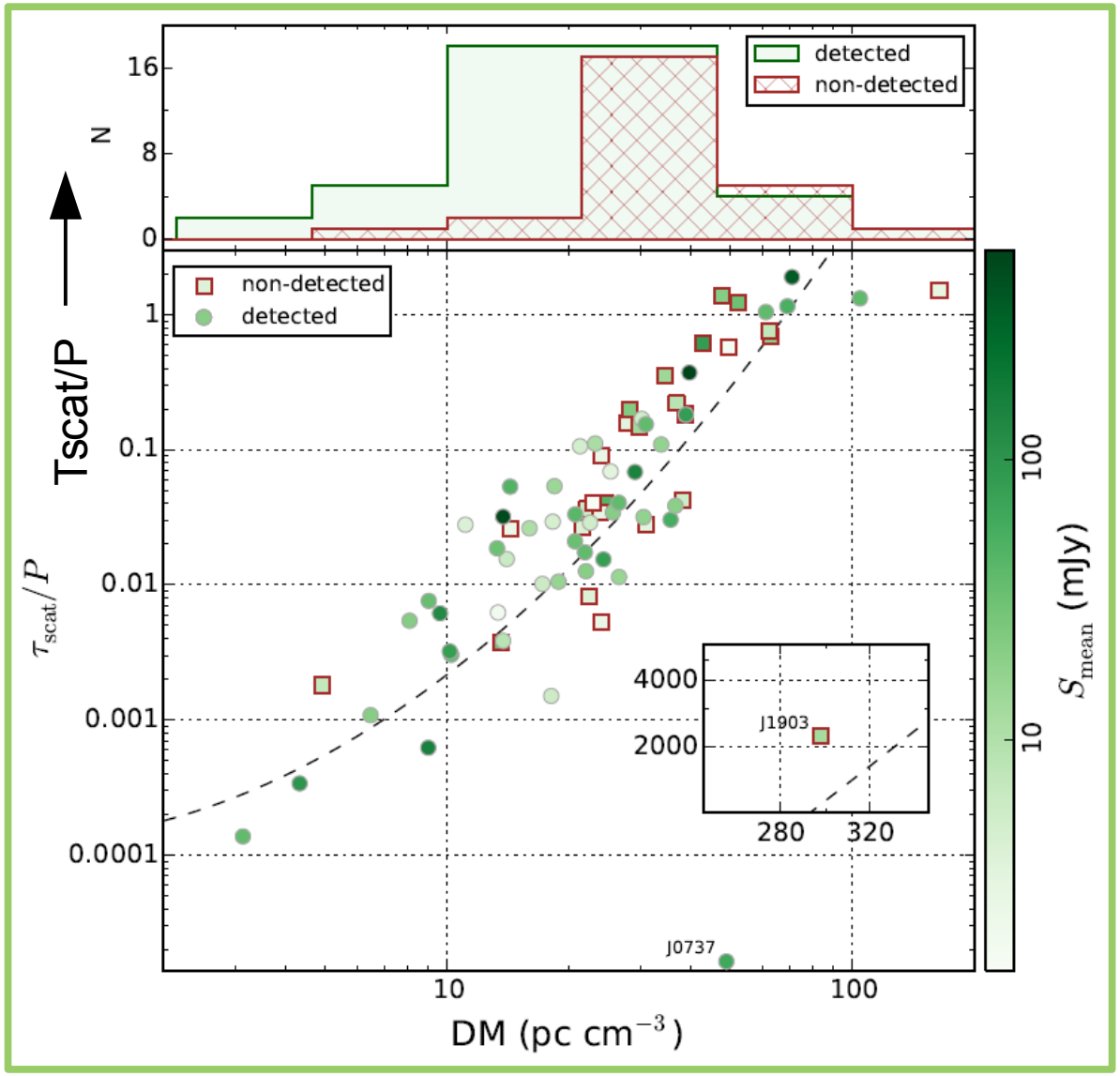
38–77 MHz

J0030+0451 **J0034–0534** **J2145–0750**



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

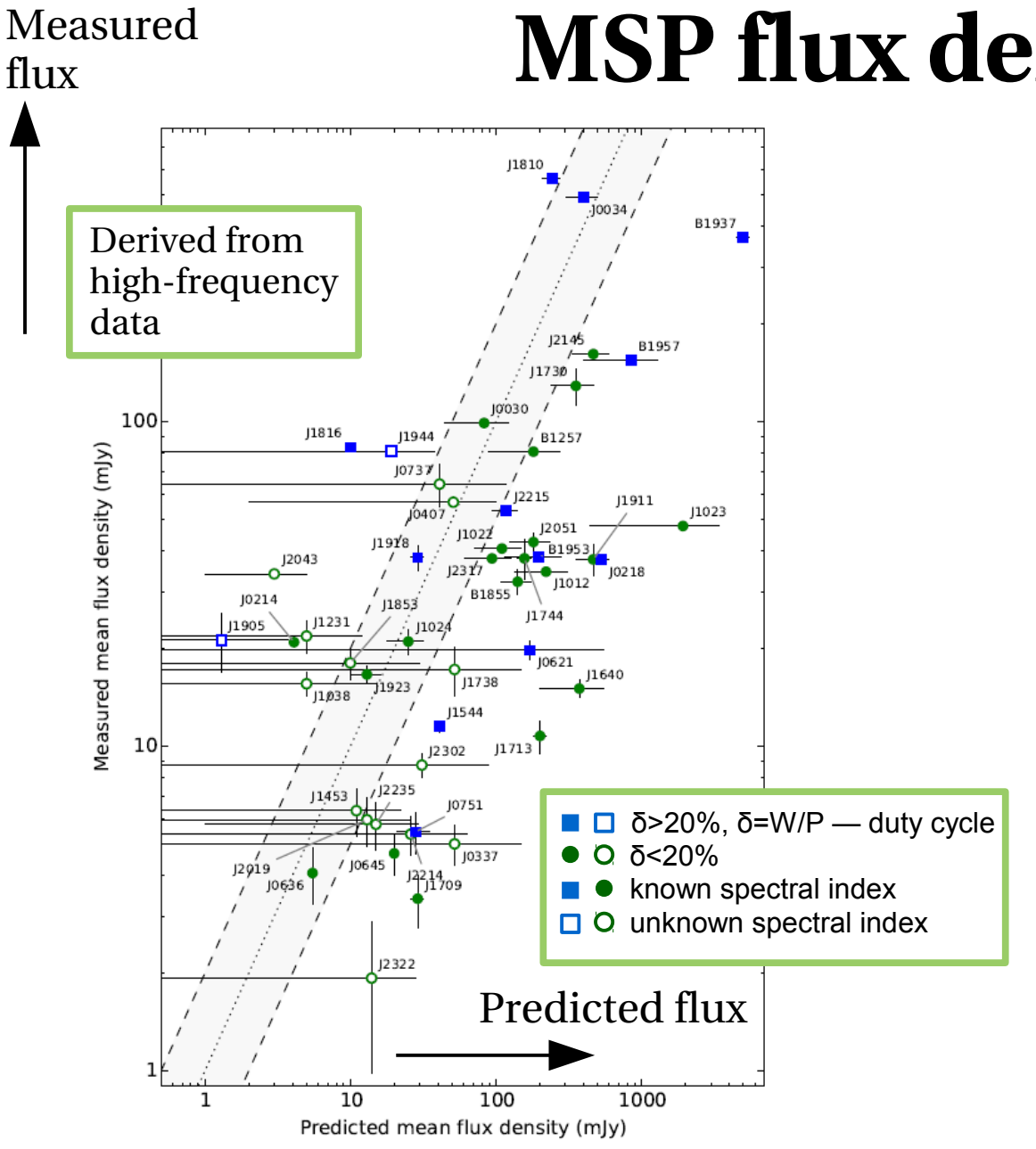
MSP detectability



- ✔ 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)

Kondratiev et al. (2015)

MSP flux densities



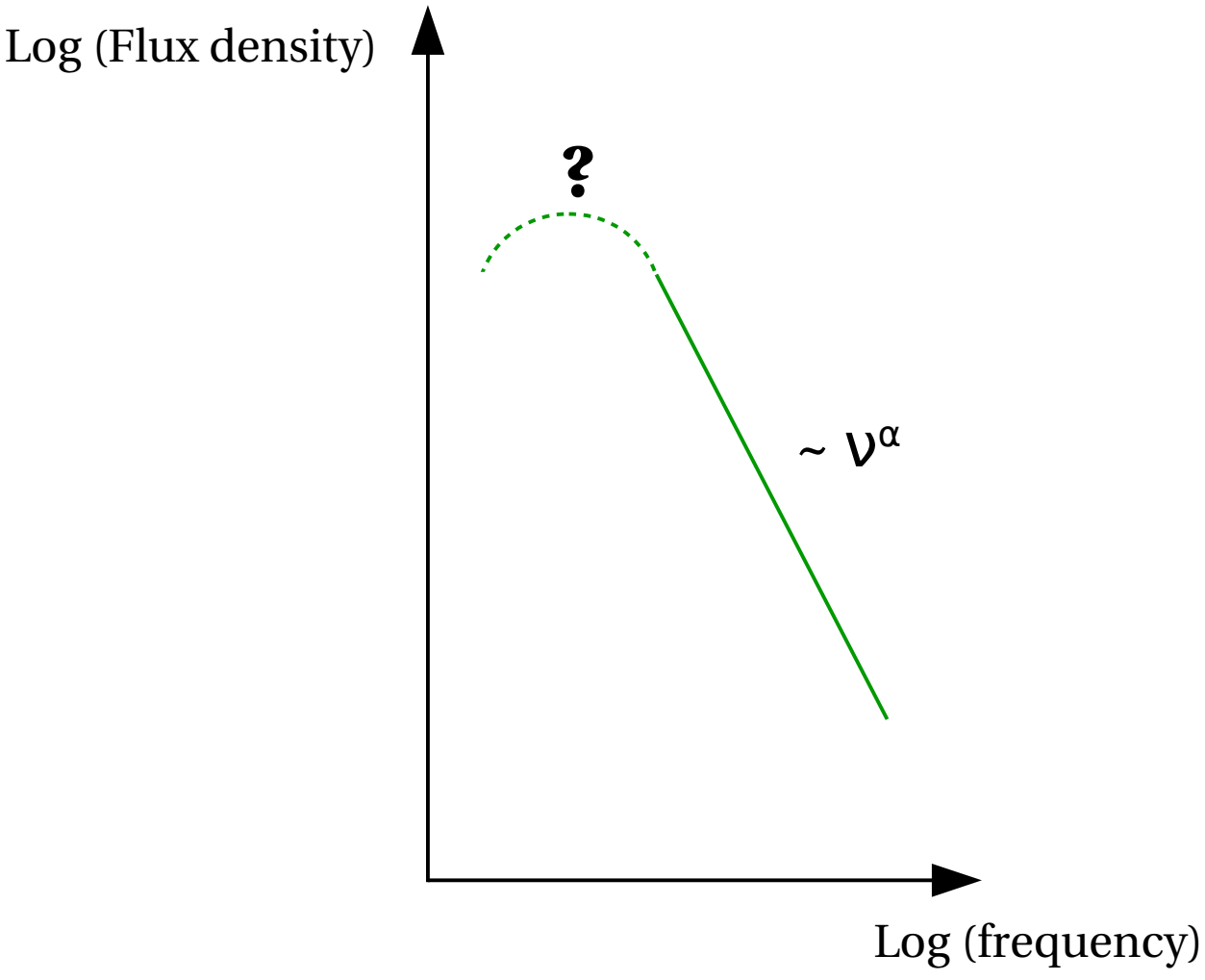
ours

- Scattering → hard to get S/N, thus flux is underestimated
- Refractive scintillation
- Beam jitter by the ionosphere (up to ~2 arcmin)
- Variation of Tsys 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)

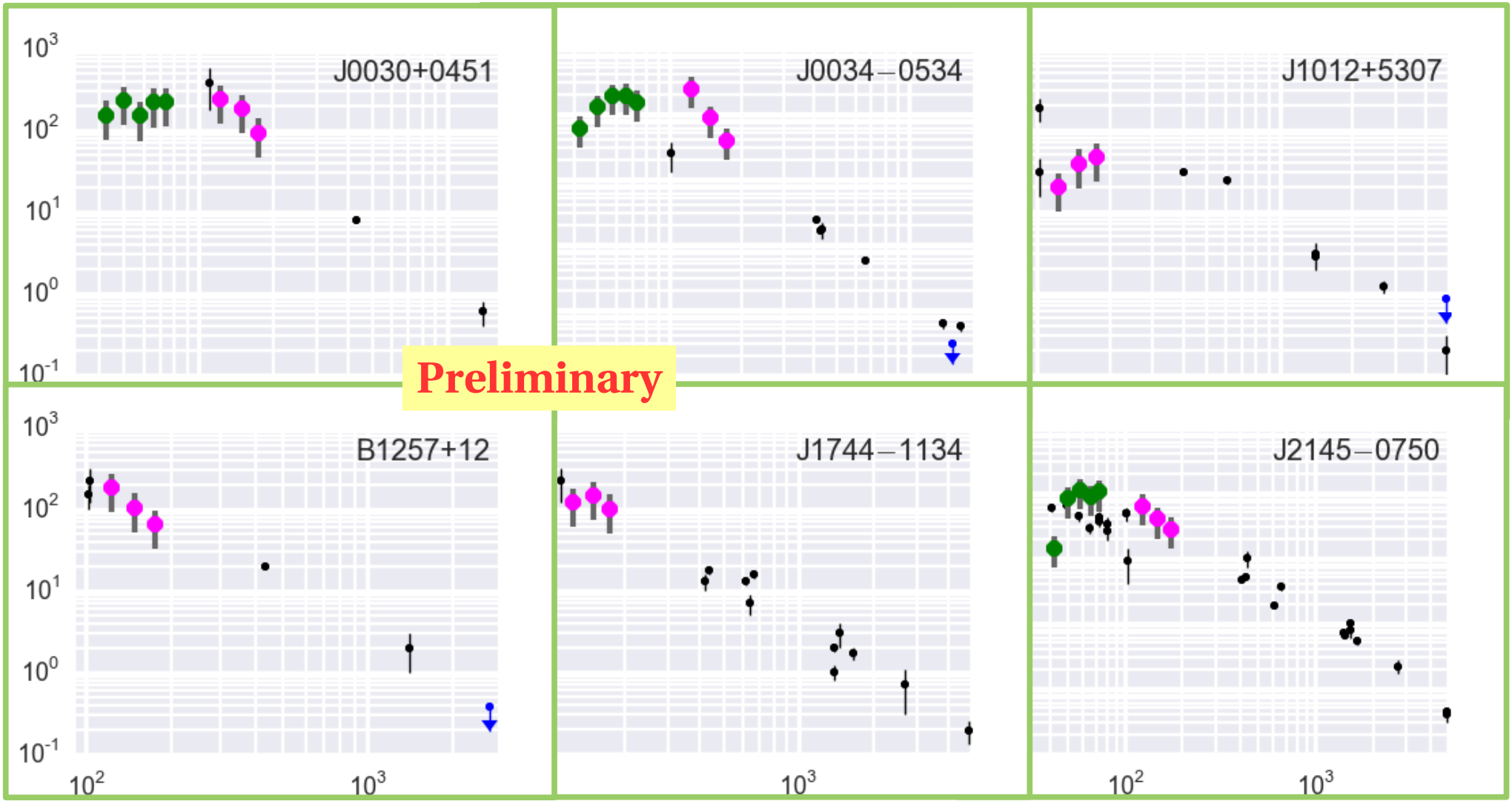
MSP spectra



Flux density (mJy)

MSP spectra

Kondratiev et al., in prep

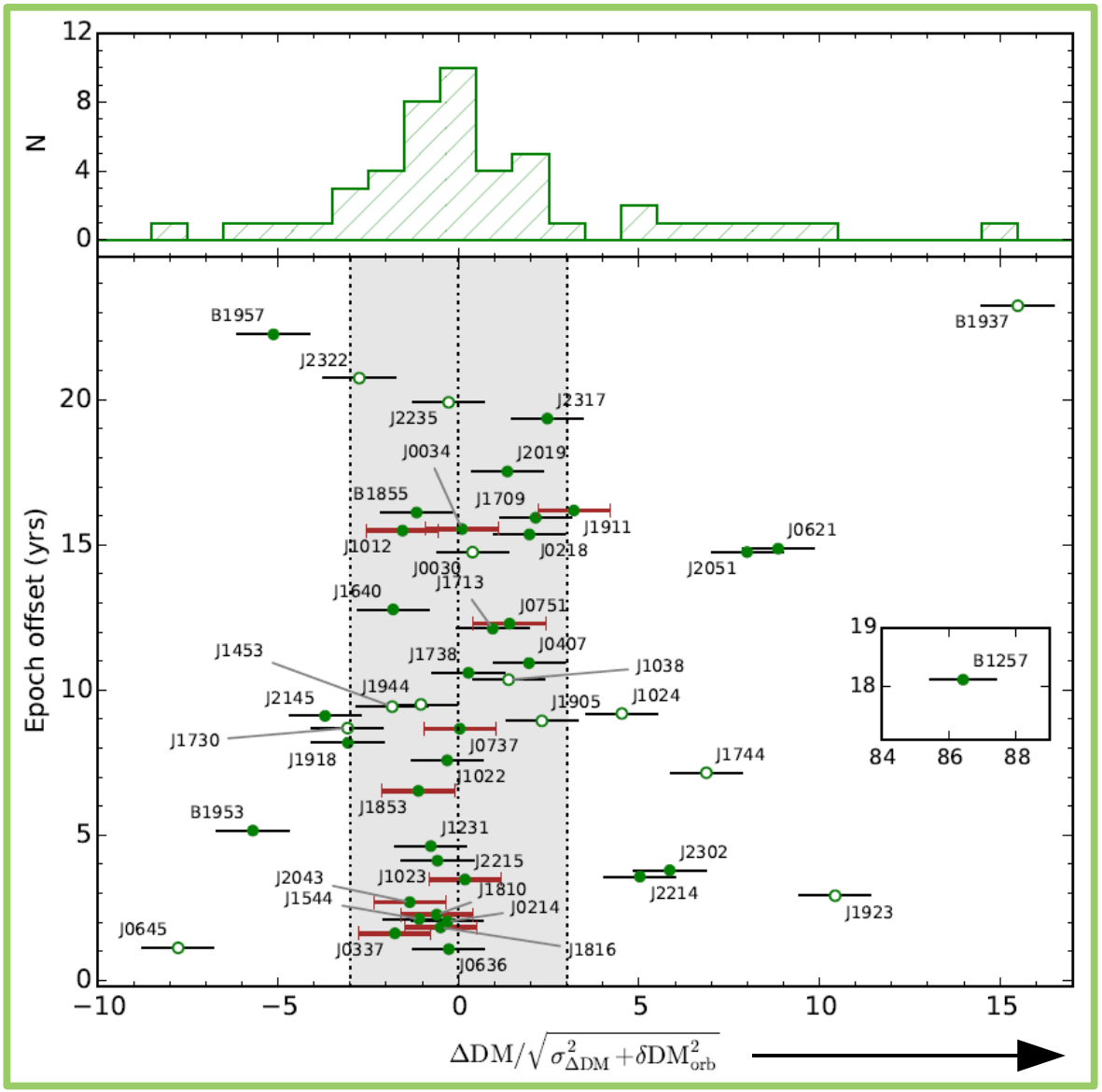


Frequency (MHz)

DM variations

Kondratiev et al. (2015)

Years since catalog DM measurement

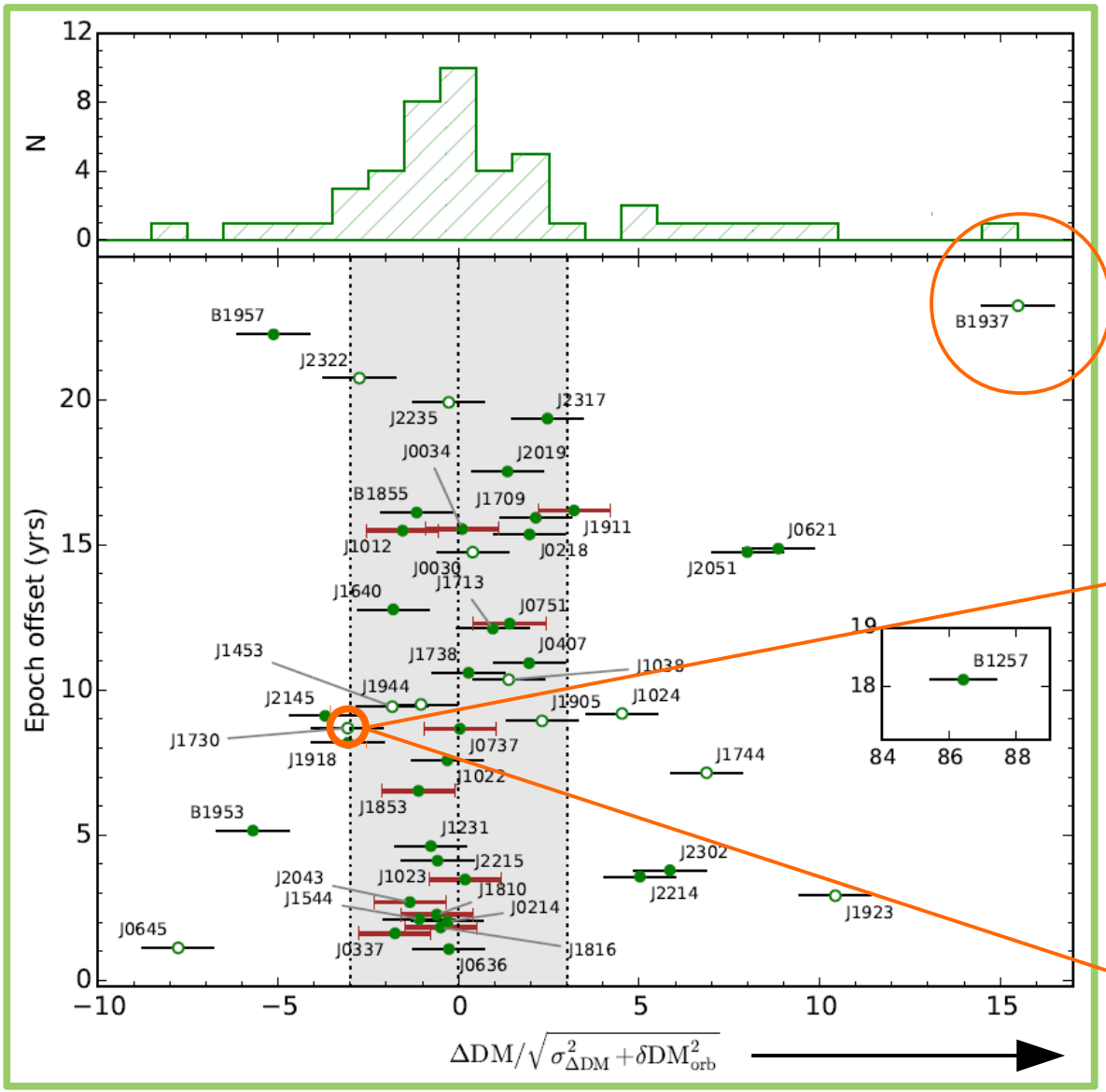


$V_{plasma} \neq 0$
$V_{PSR} \neq 0$
} DM = DM(t)

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

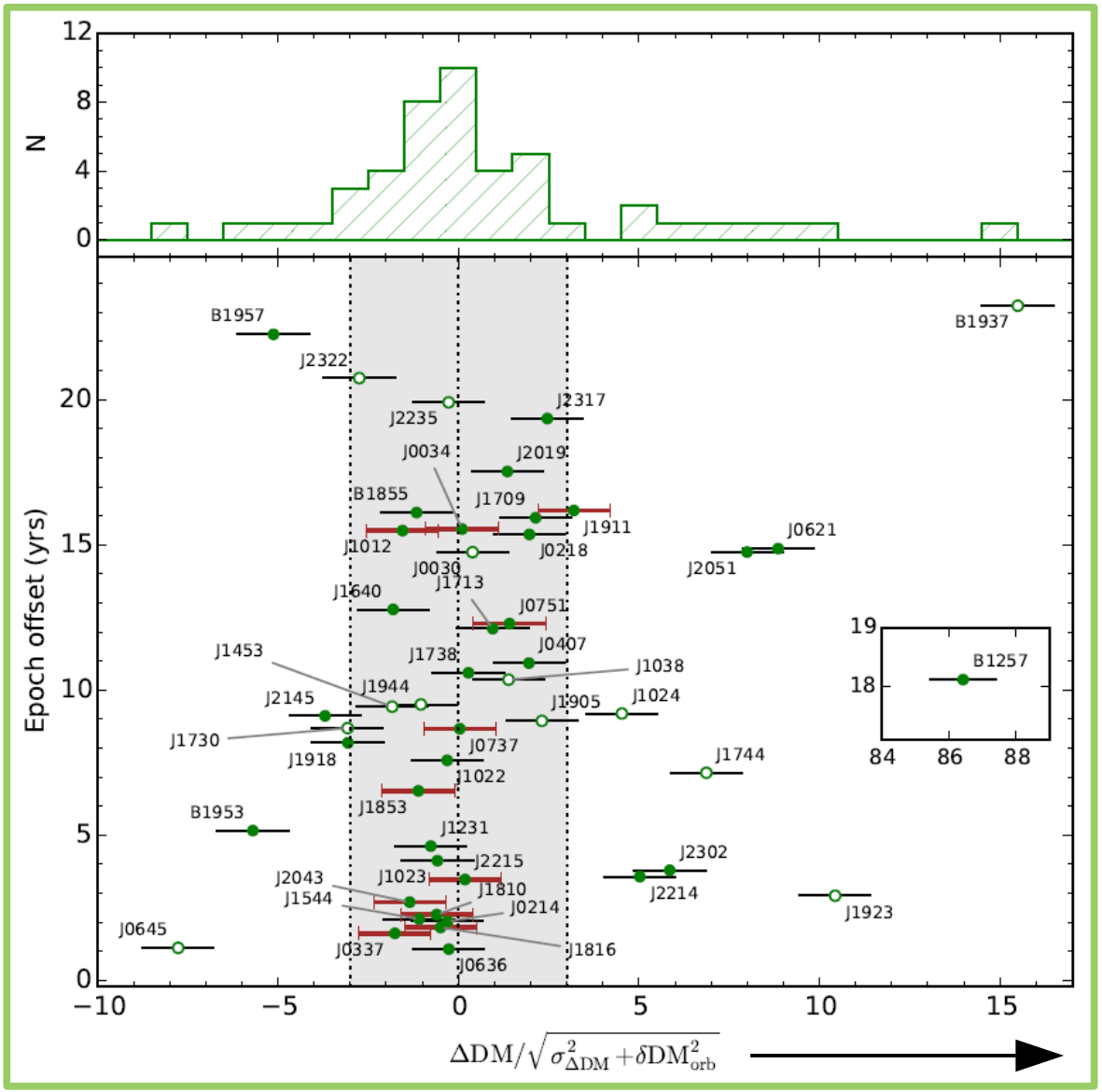
DM variations

Kondratiev et al. (2015)



DM variations

Years since catalog DM measurement



- 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**

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

Summary:

- First large sample of high-quality MSP profiles below 200 MHz. 48 MSPs detected out of 75 observed. Three MSPs detected in the LBA range. Low-frequency profiles, DM and flux density measurements.

- Developed pulsar flux calibration (presented at the previous LSM on Oct 14, 2015), first MSP flux 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 third 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 ~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 ~2-3 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.

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)

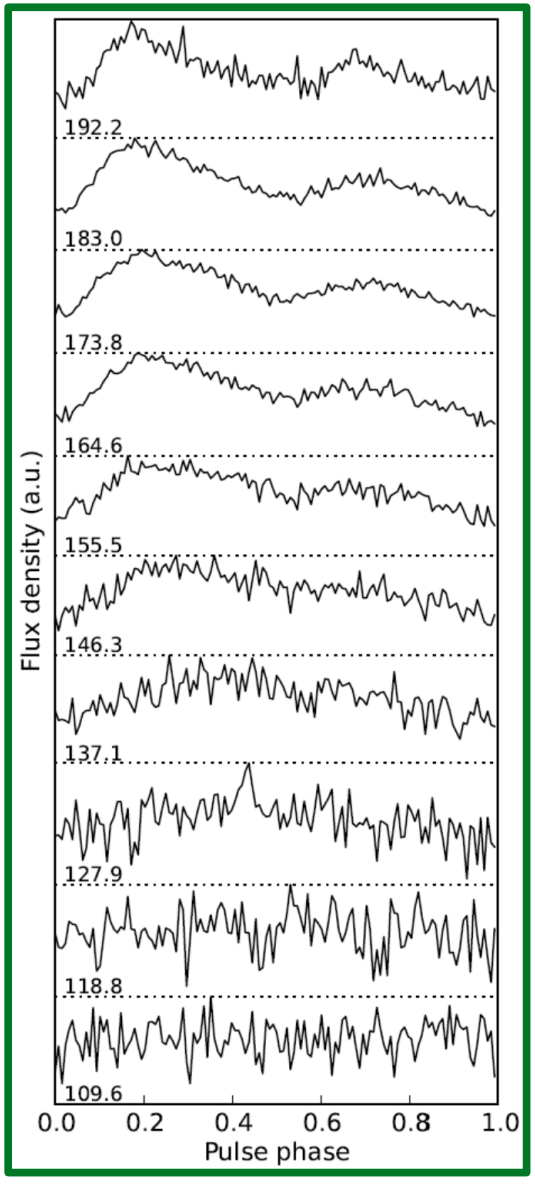
WSRT & 150 MHz → Stappers et al. (2008)
GMRT & 240 MHz → Joshi & Kramer (2009)
LWA & 37-81 MHz (J2145) → Dowell et al. (2013)

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

PSR B1937+21

P = 1.56 ms
DM = 71 pc/cc

LOFAR HBA



192 MHz

2 ms (1.3 P)

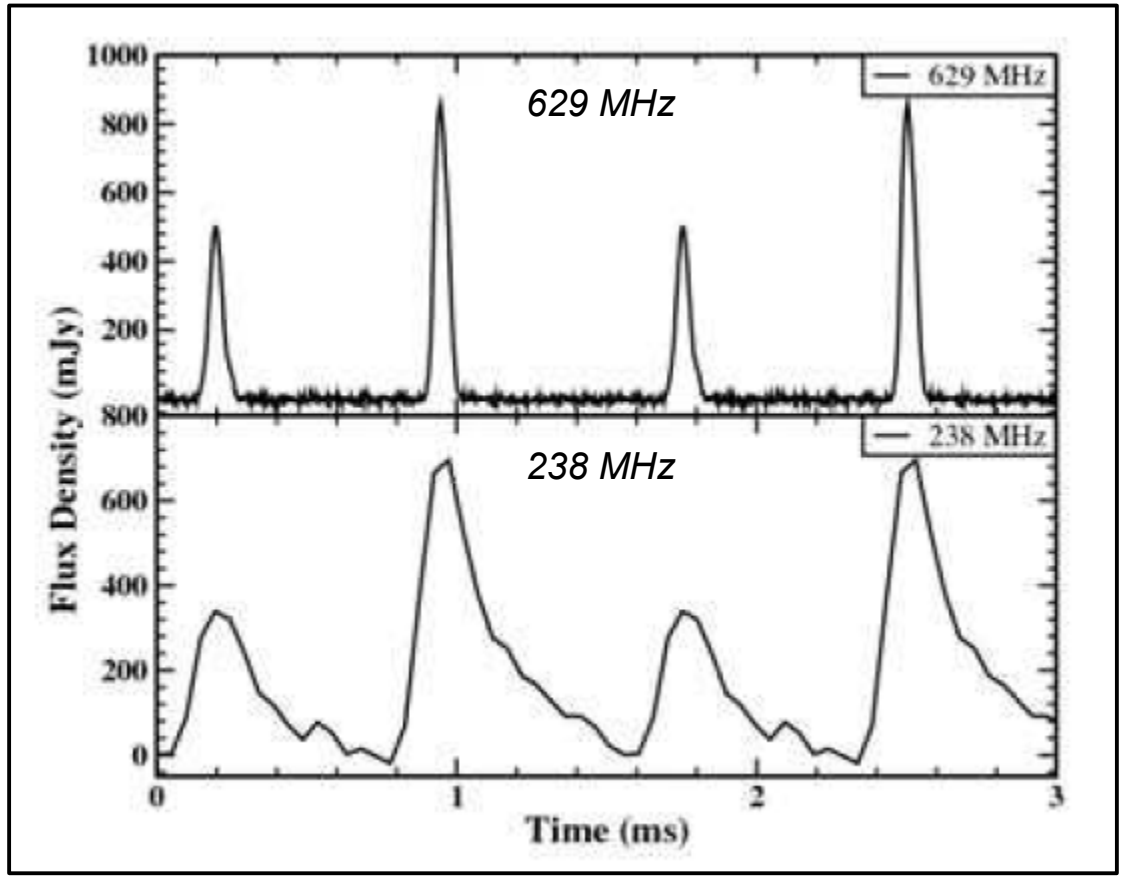
scattering time

18 ms (12 P)

110 MHz

GMRT

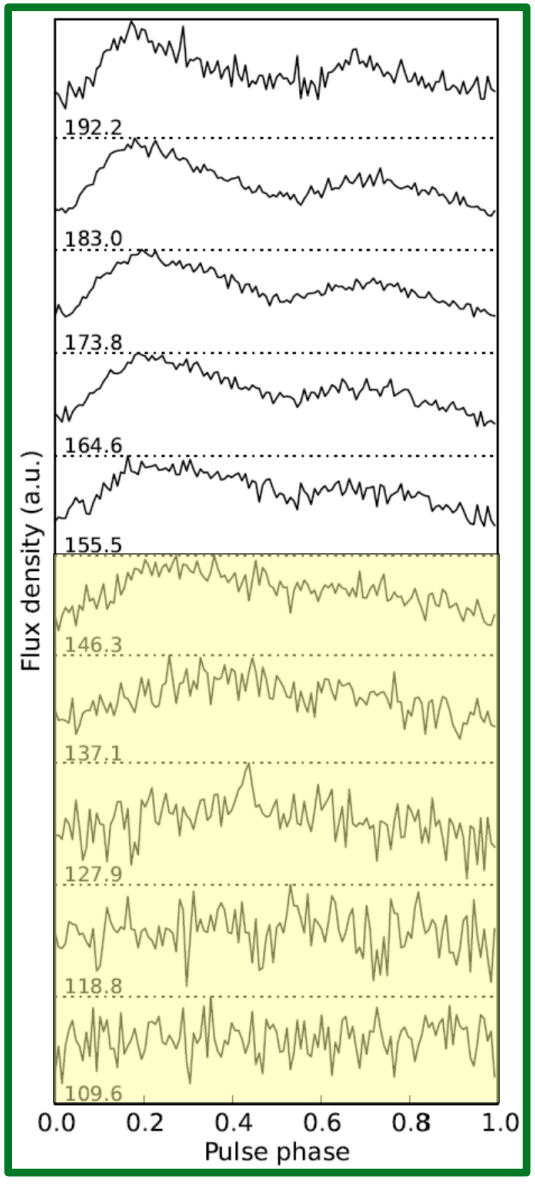
Joshi & Kramer 2009



PSR B1937+21

P = 1.56 ms
DM = 71 pc/cc

LOFAR HBA



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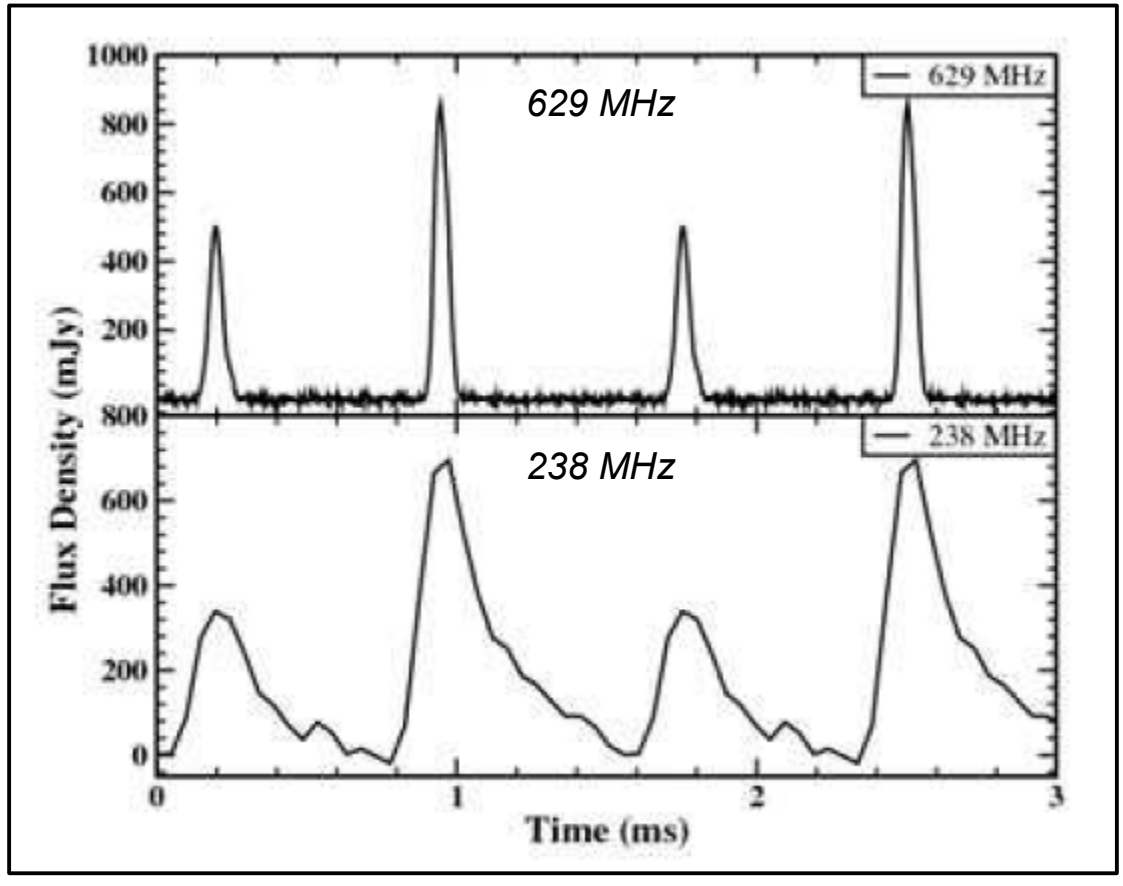
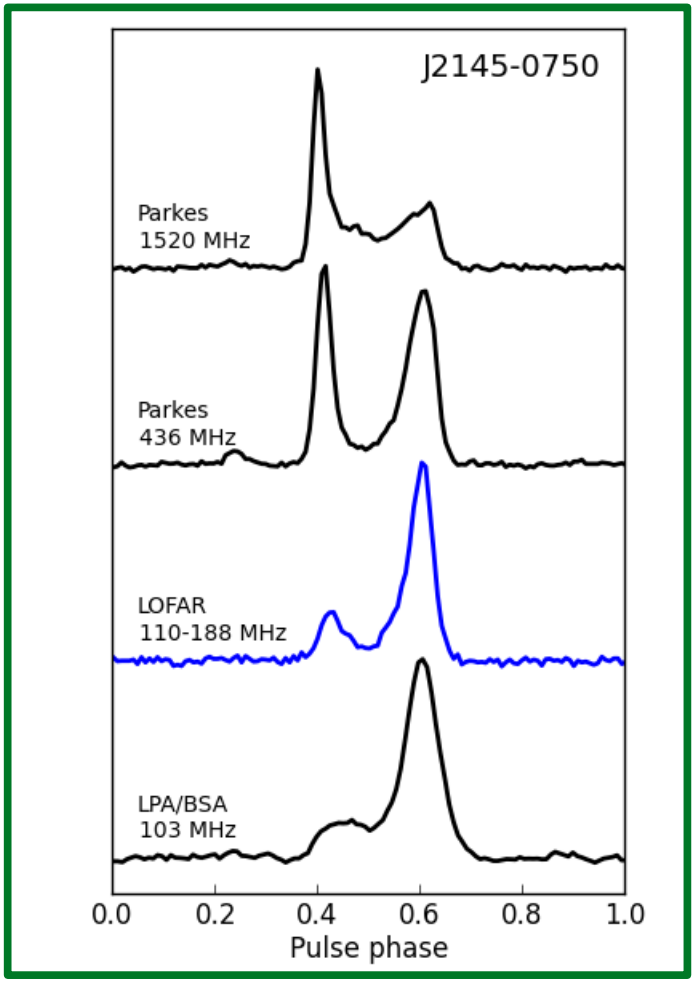
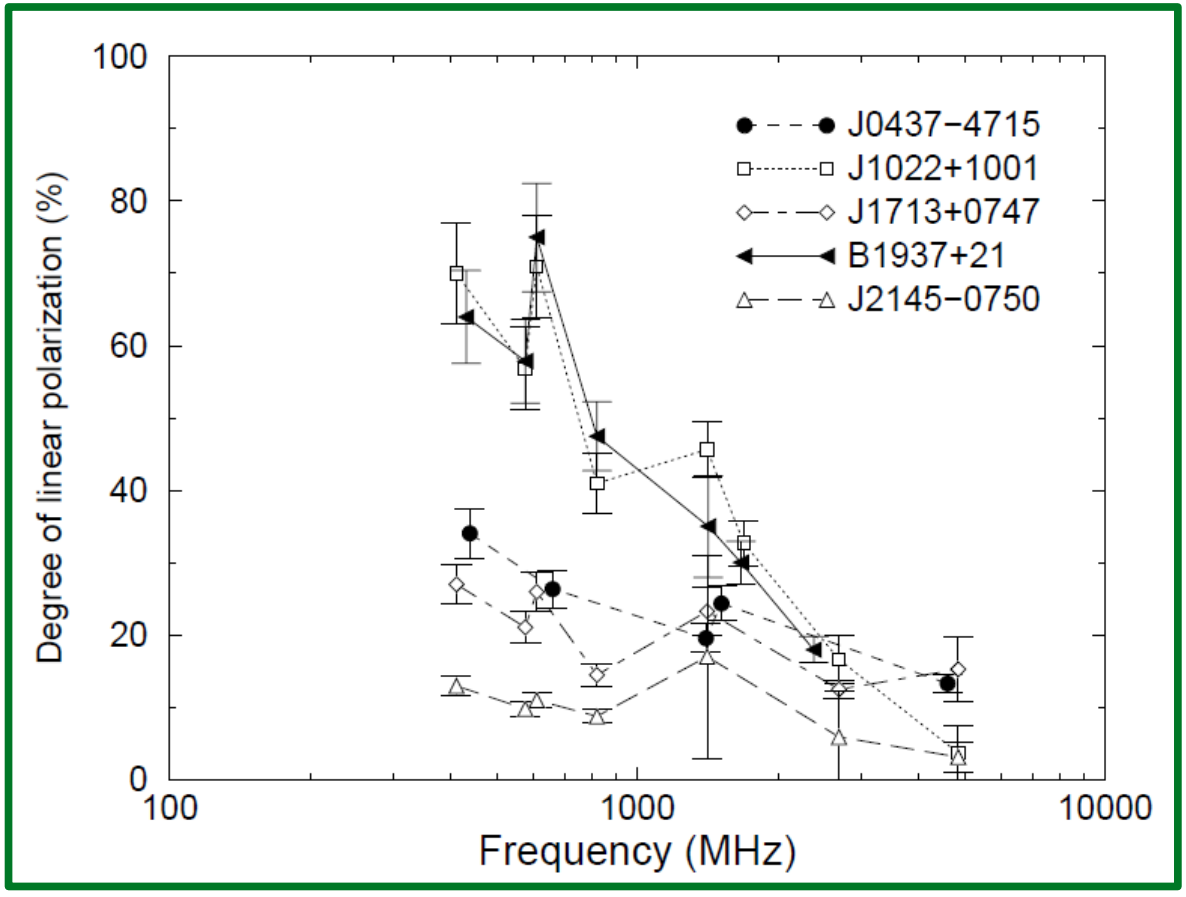
Joshi & Kramer 2009



Profile and polarization evolution

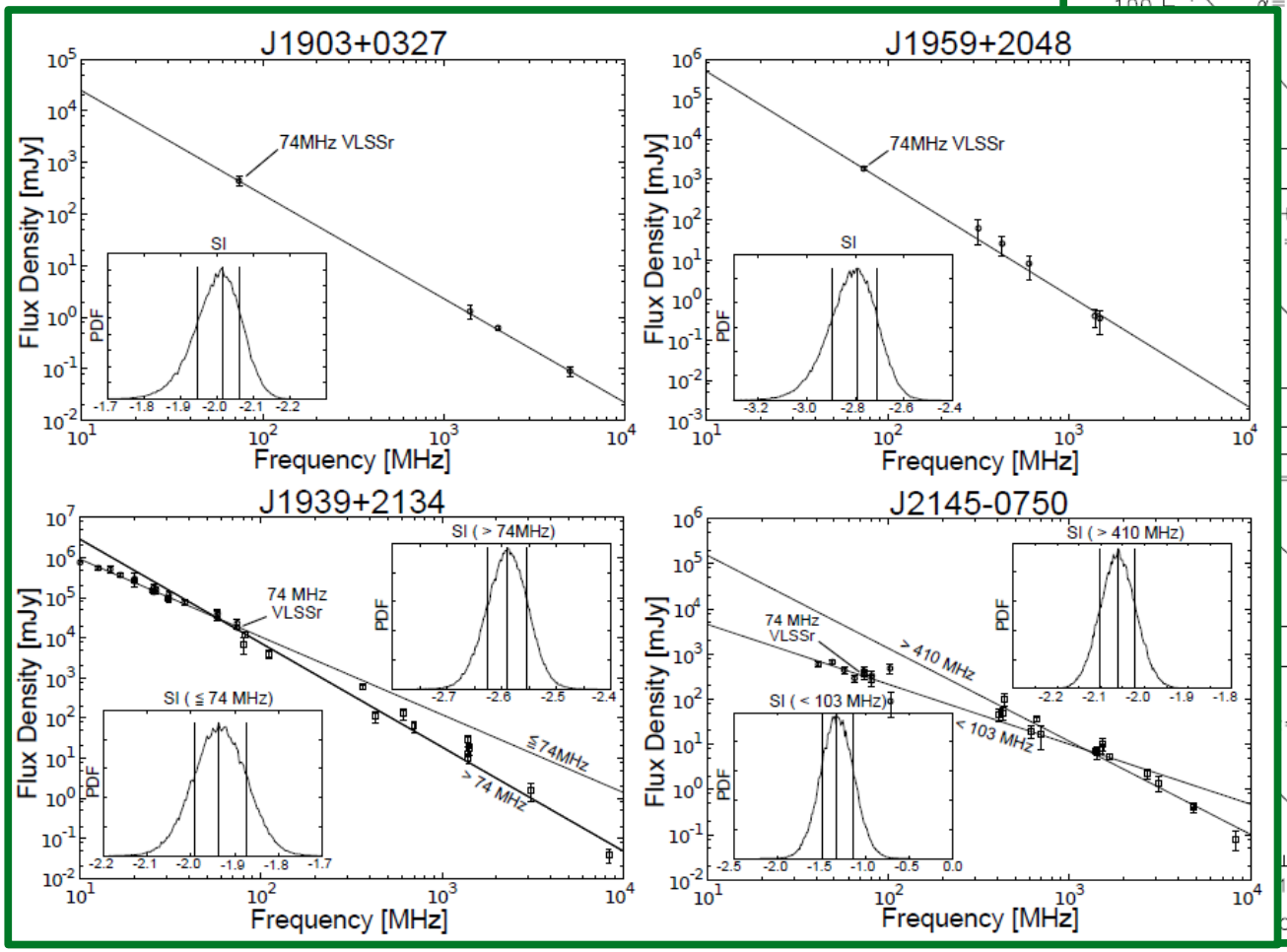


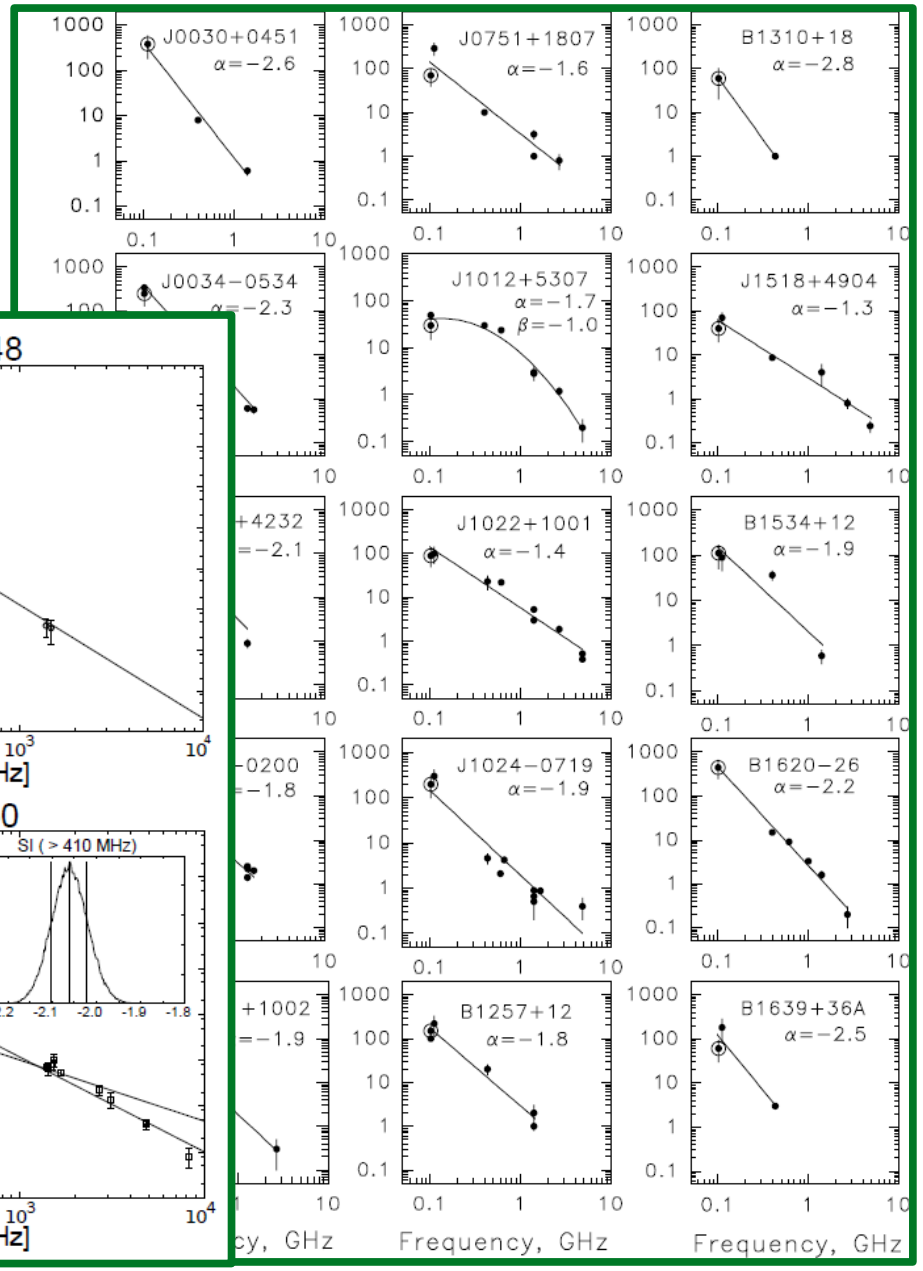
Kramer et al. (1999)



Spectra of MSPs

Kuniyoshi et al. (2015)





Kuzmin & Losovskii (2001)