

LOFAR Tied Array All-sky Survey (LOTAAS) for Pulsars and Fast Transients

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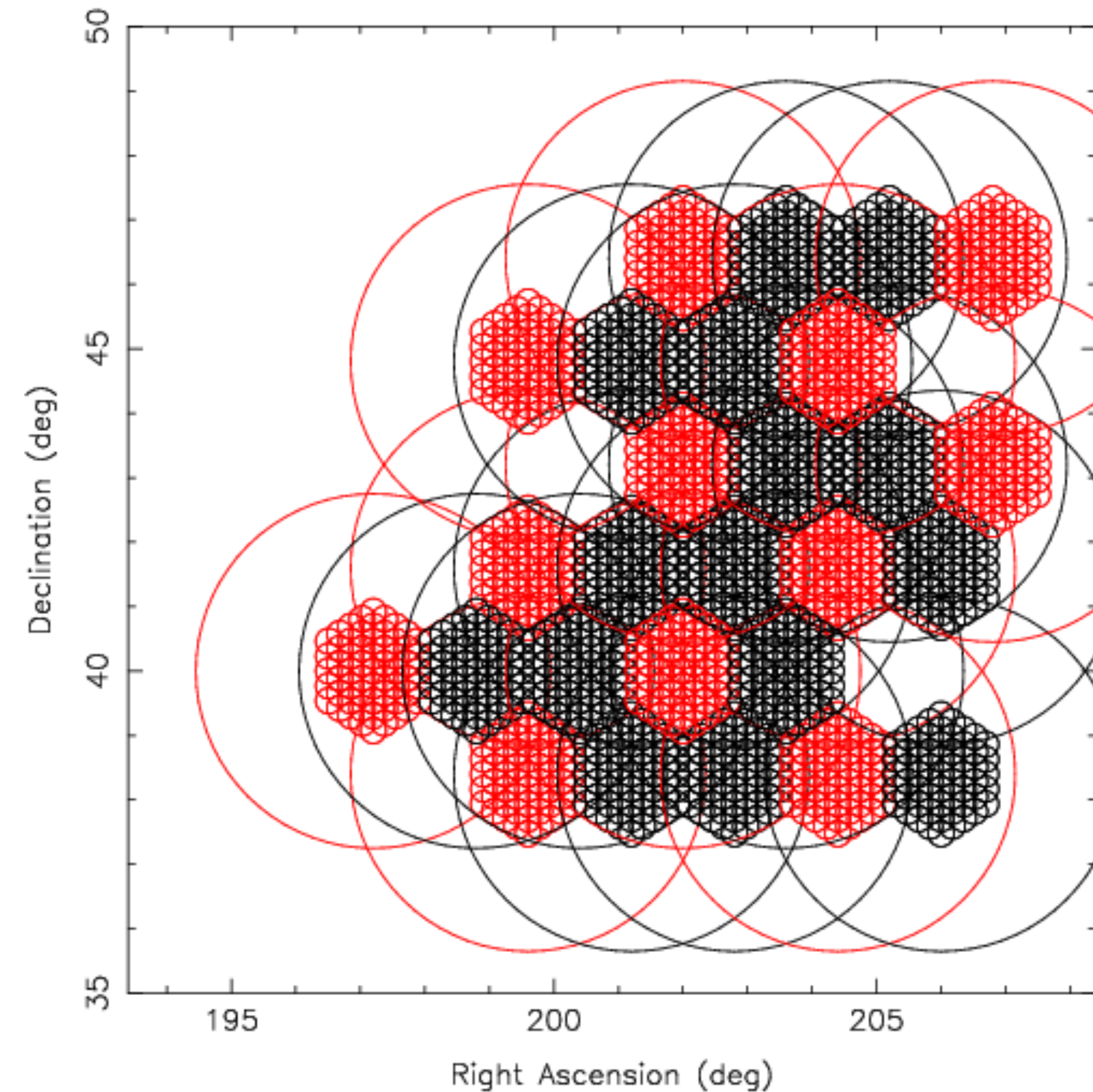
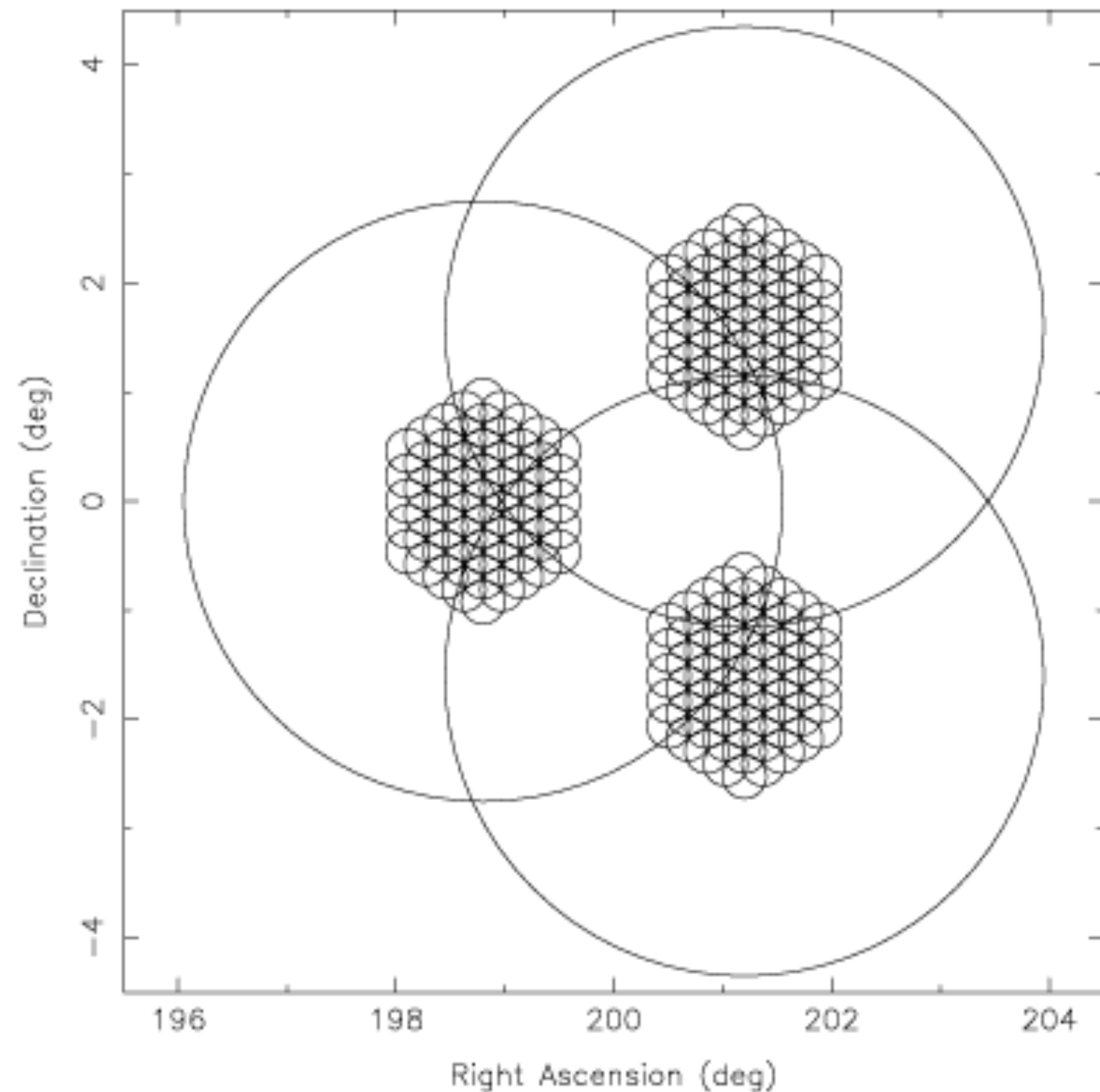
Robert Lyon University of Manchester

LOTAAS

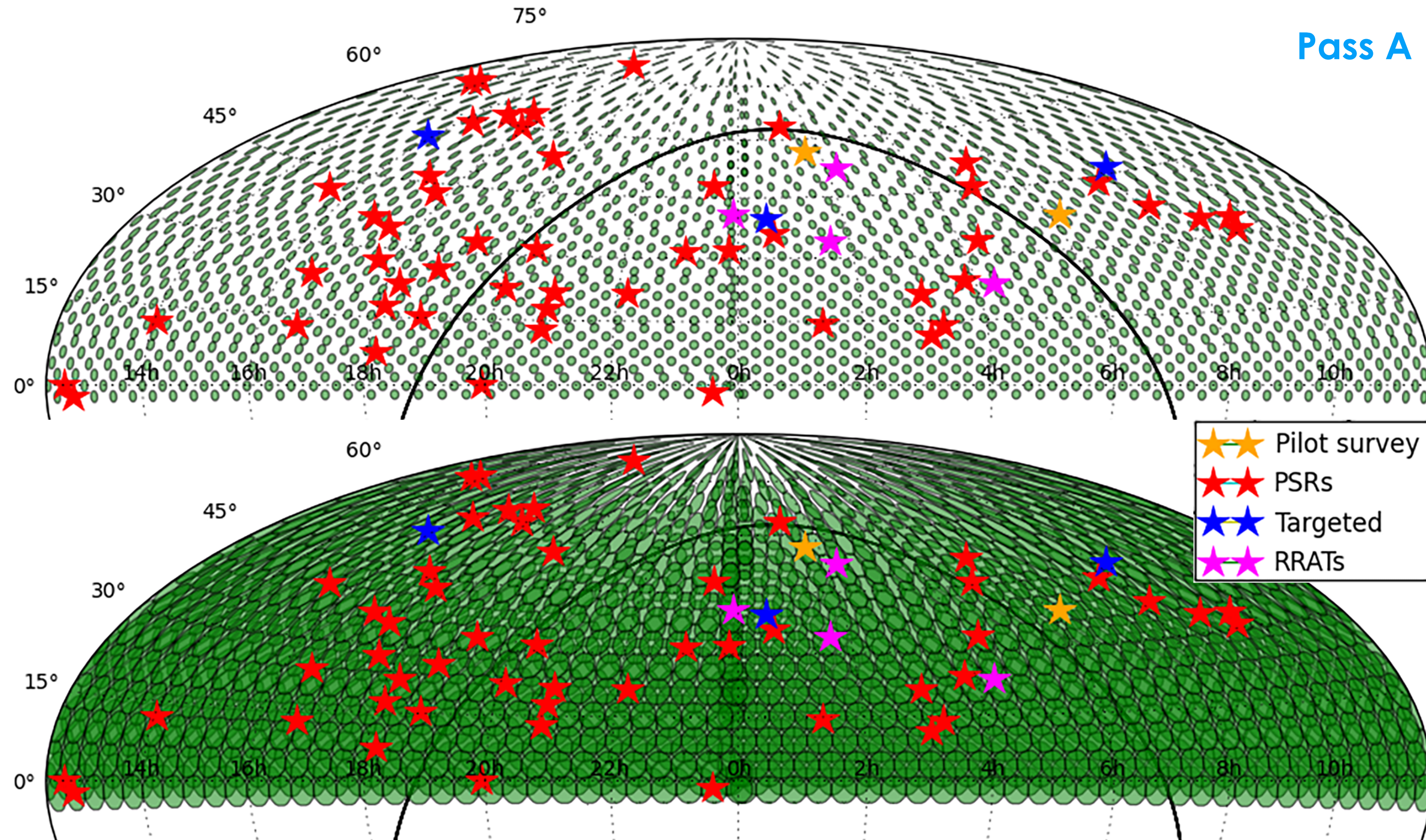
- All northern sky survey for pulsars, RRATs and fast transients.
- 12 HBA sub-stations of superterp
- Observing band 119-151 MHz, 12 kHz channels.
- Sampling time 492 μ s.
- 1 hour dwell time.

Field of View (FoV)

- 222 beams per pointing — First SKA-like pulsar survey
 - ▶ 3 sub-array pointings (SAP), incoherent beams (IB), 30 deg² FoV
 - ▶ 183 tied-array beams (TAB), 61 per SAP, 9 deg² FoV
 - ▶ 12 free TAB per SAP, known sources within SAP or “random”



Sky Coverage



- 3 passes of 651 pointings required to cover the northern sky with TABs
- Pass A completed (survey area covered by IBs)
- 648/651 pointings completed in Pass B
- 60 pointings into Pass C

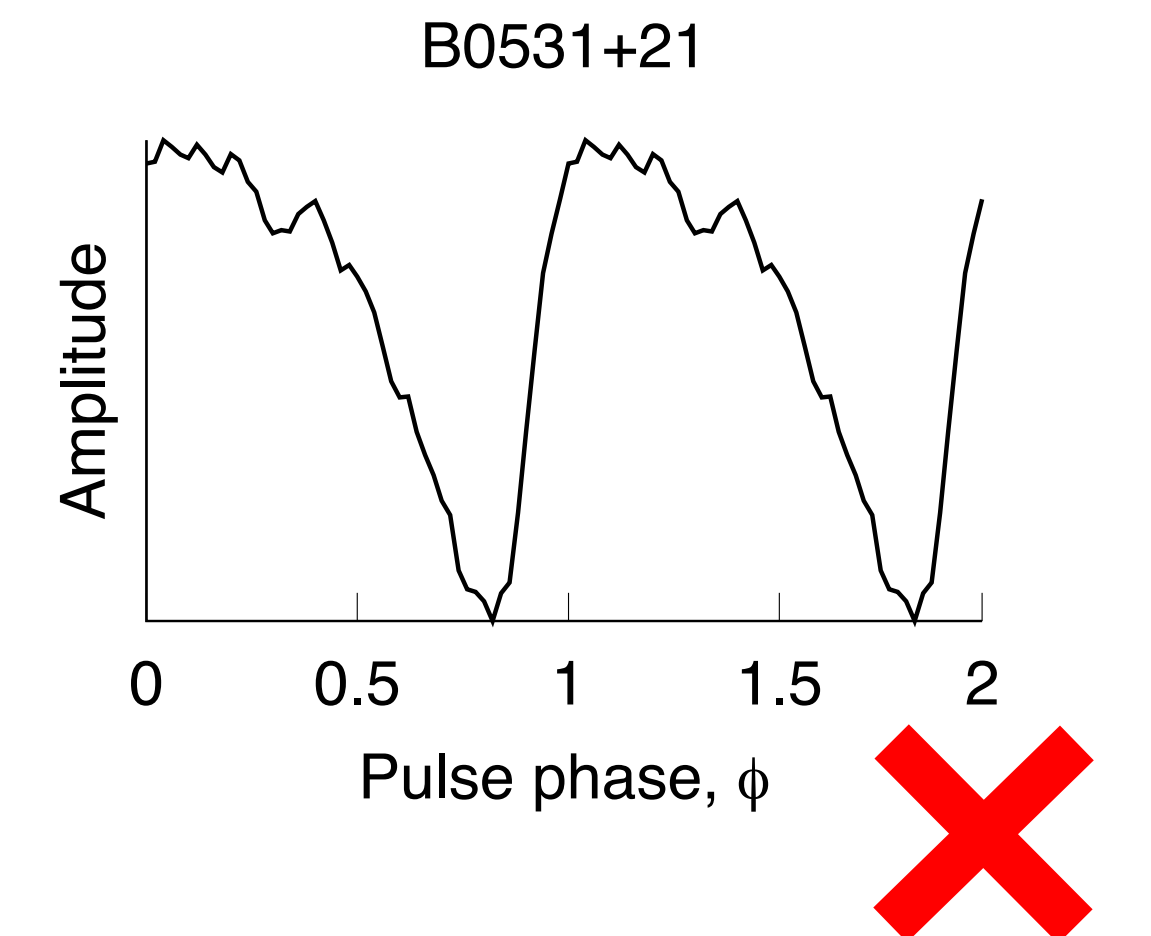
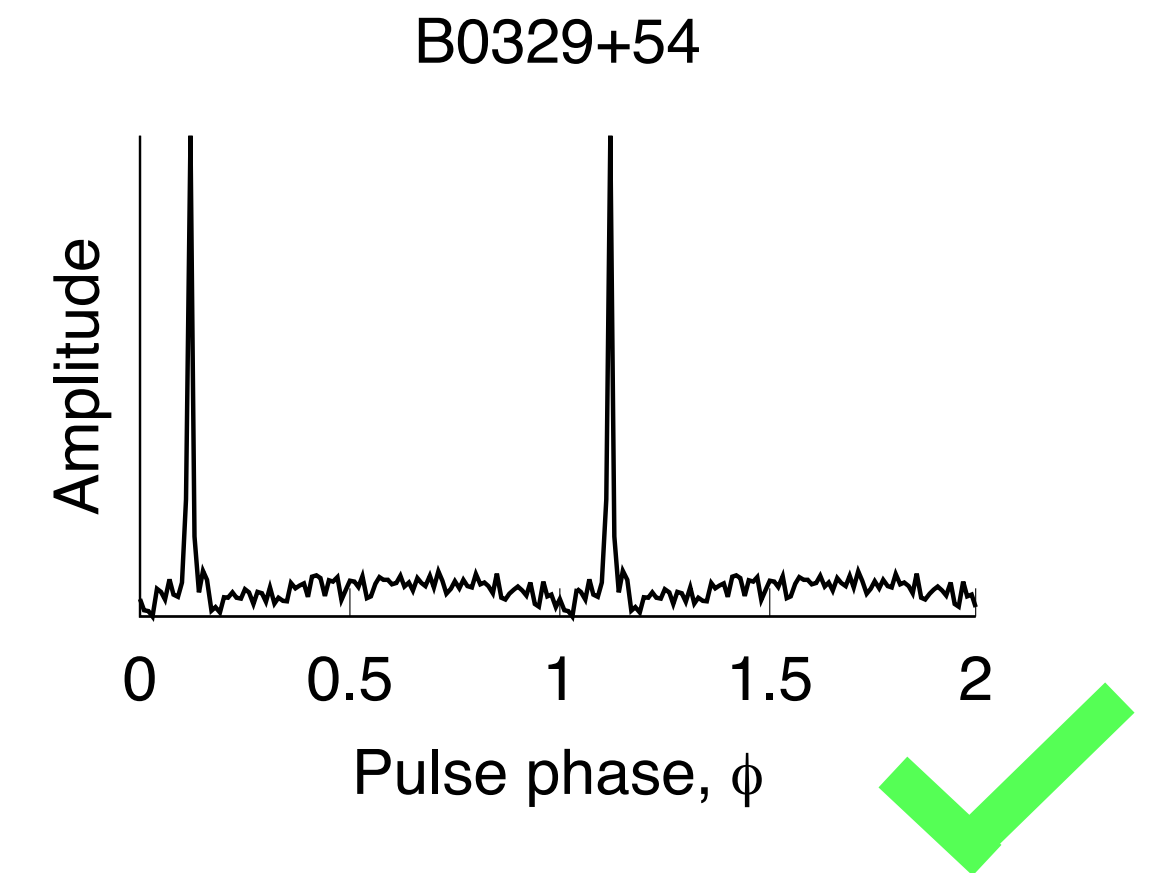
Data Processing



- Cartesius (SURFsara) — 1500 nodes (24 cores, 64 GB RAM)
- Dedispersion of DM 0-500 pc cm⁻³
- Fourier-based periodicity searches with presto — no acceleration searches yet
- Single pulse searches
- ~3 hours processing time/beam/node

Periodicity Candidates

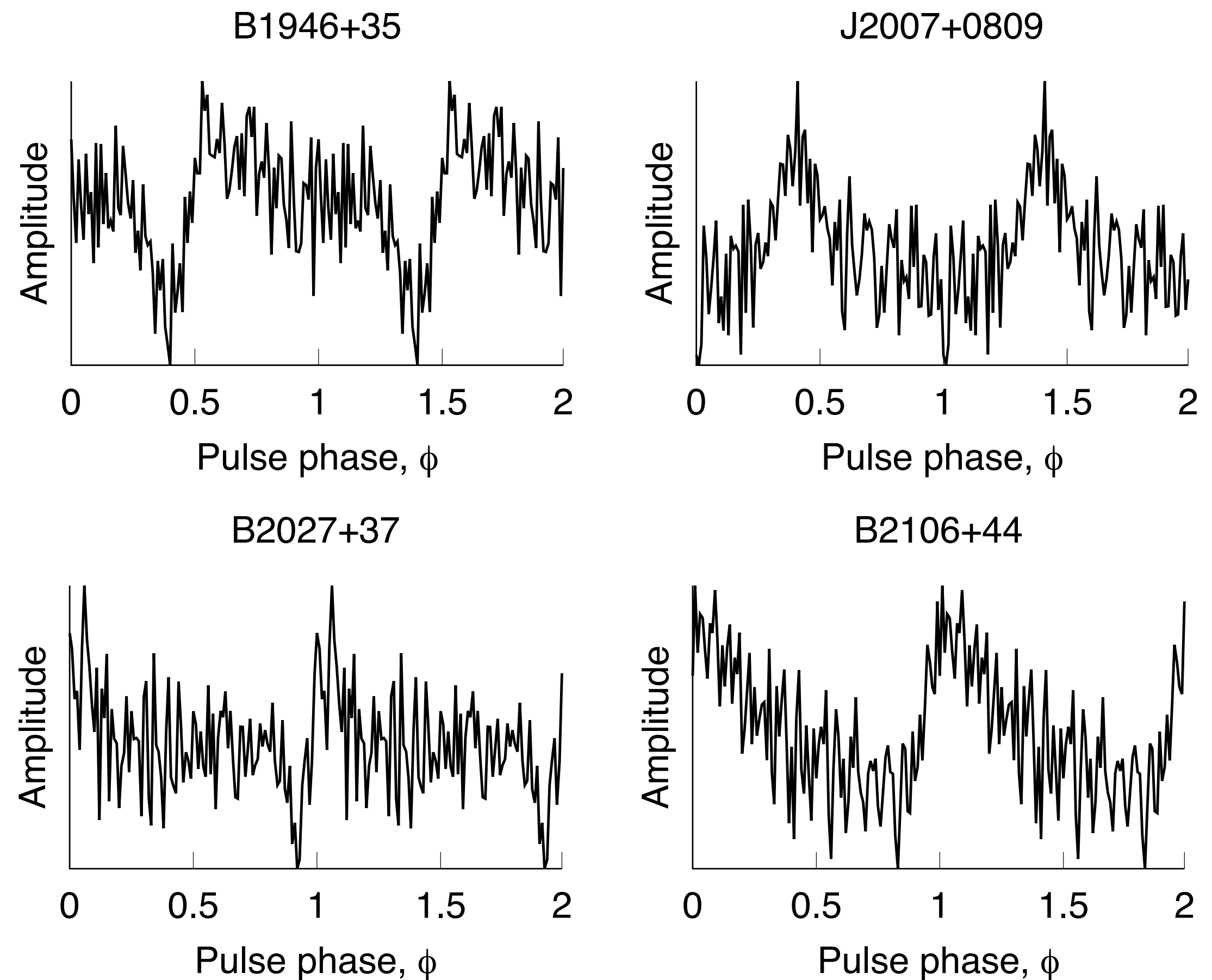
- ~20,000 periodicity candidates per pointing — expecting 40 million candidates for the whole survey
- Machine Learning (ML) classifier to choose the best candidate
- First ML classifier
 - ▶ 8 features from pulse profile & DM curve
 - ▶ Very Fast Decision Tree (VFDT) binary classifier
 - ▶ ~500 candidates per pointing
- **Less effective with pulsars with wide pulse profile**



Periodicity Candidates

New ML classifier :

- 8 new features from time & sub-band vs phase plots + 4 new features from DM curve
- Third class for known RFI instances
- Ensemble of 5 VFDT classifiers
 - trained with 5 separate training set
 - pulsar if +ve in 3+ classifiers
- Improved performance
 - Pulsar recall rate from **96.2% to 98.7%**
 - False positive rate from **2.5% to 1.1%**

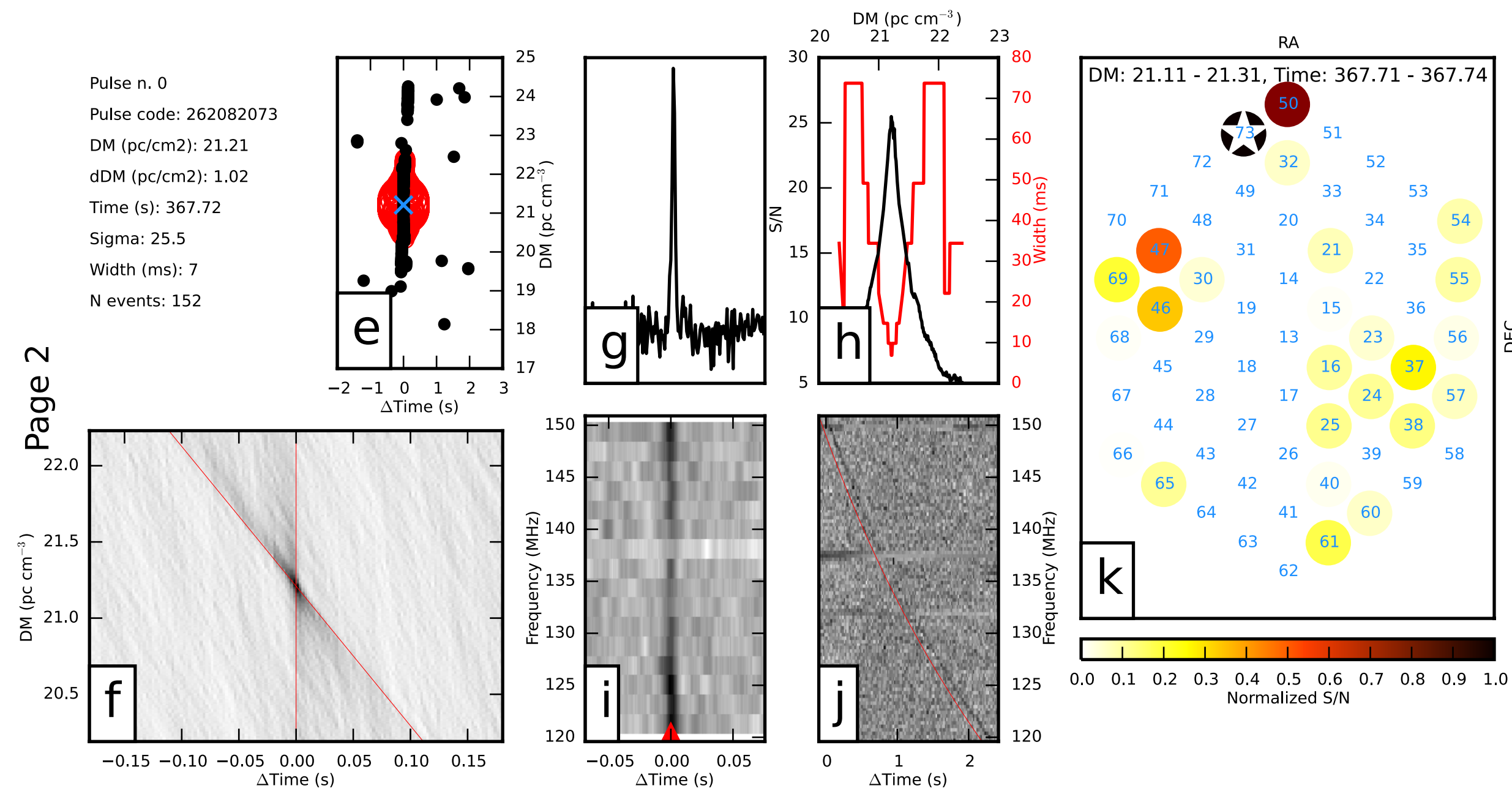
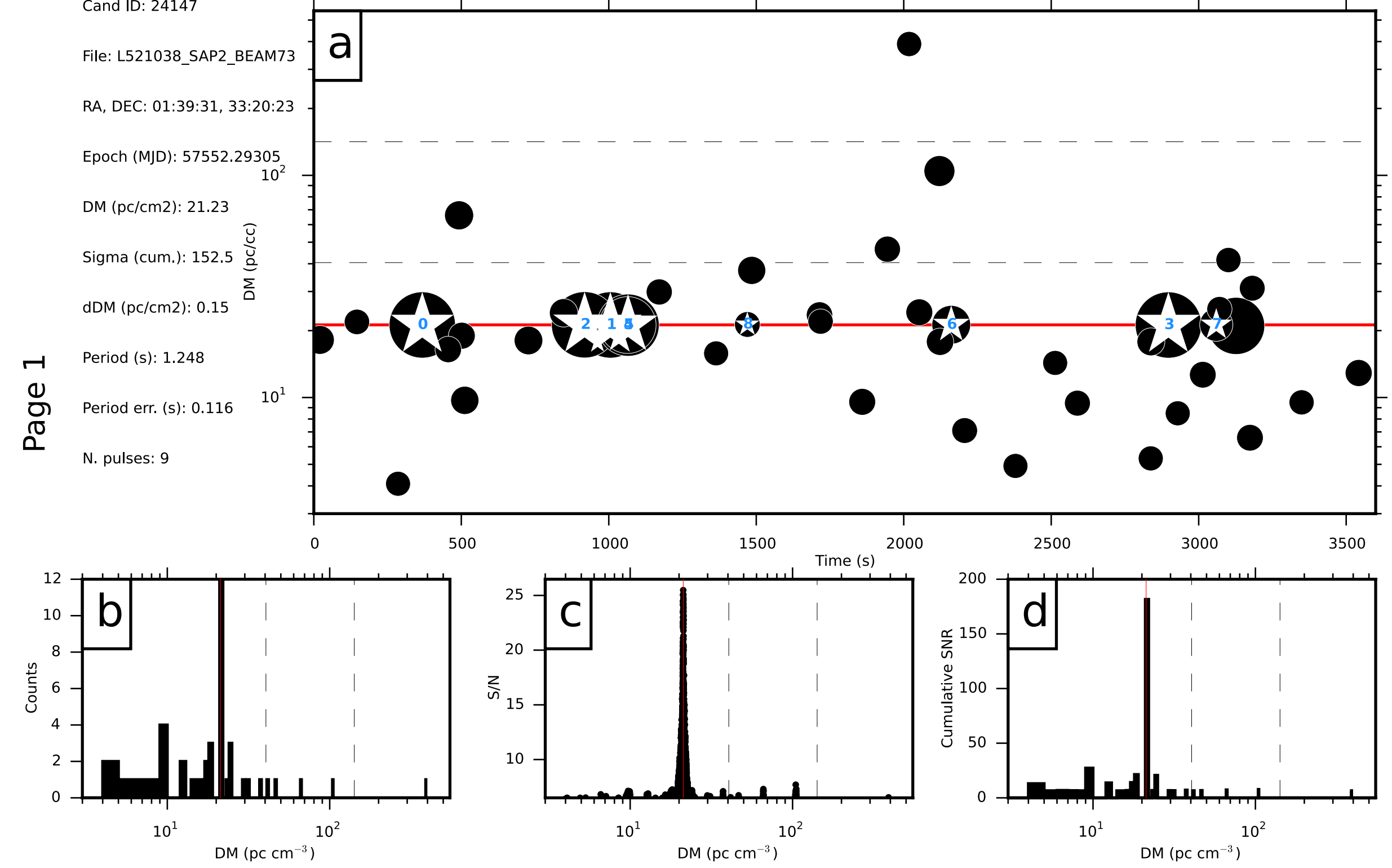


Single Pulse Candidates

- $\sim 10^8$ events detected per pointing
- Single pulse classifier that uses :
 - a. “Classical” techniques — event grouping in DM-time space, removal of low-DM events, comparison between TABs etc.
 - b. ML approach with 5 features to analyse grouped events
- ~ 20 candidates per pointing produced, diagnostic plots generated for inspection
- 8 new sources + ~ 80 known pulsars identified by classified

Single Pulse Candidates

Diagnostic Plot of J0139+33

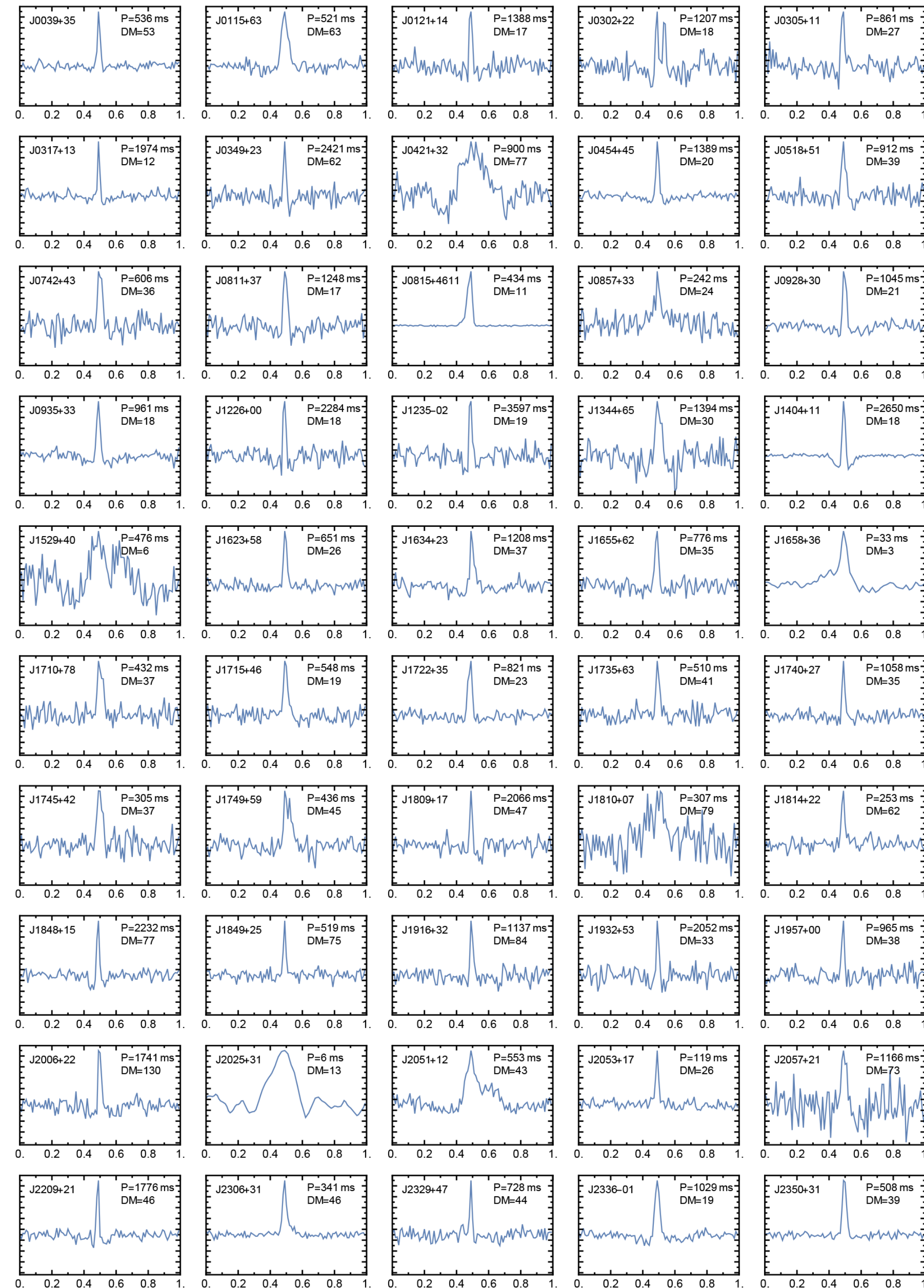


LOTAAS Discoveries

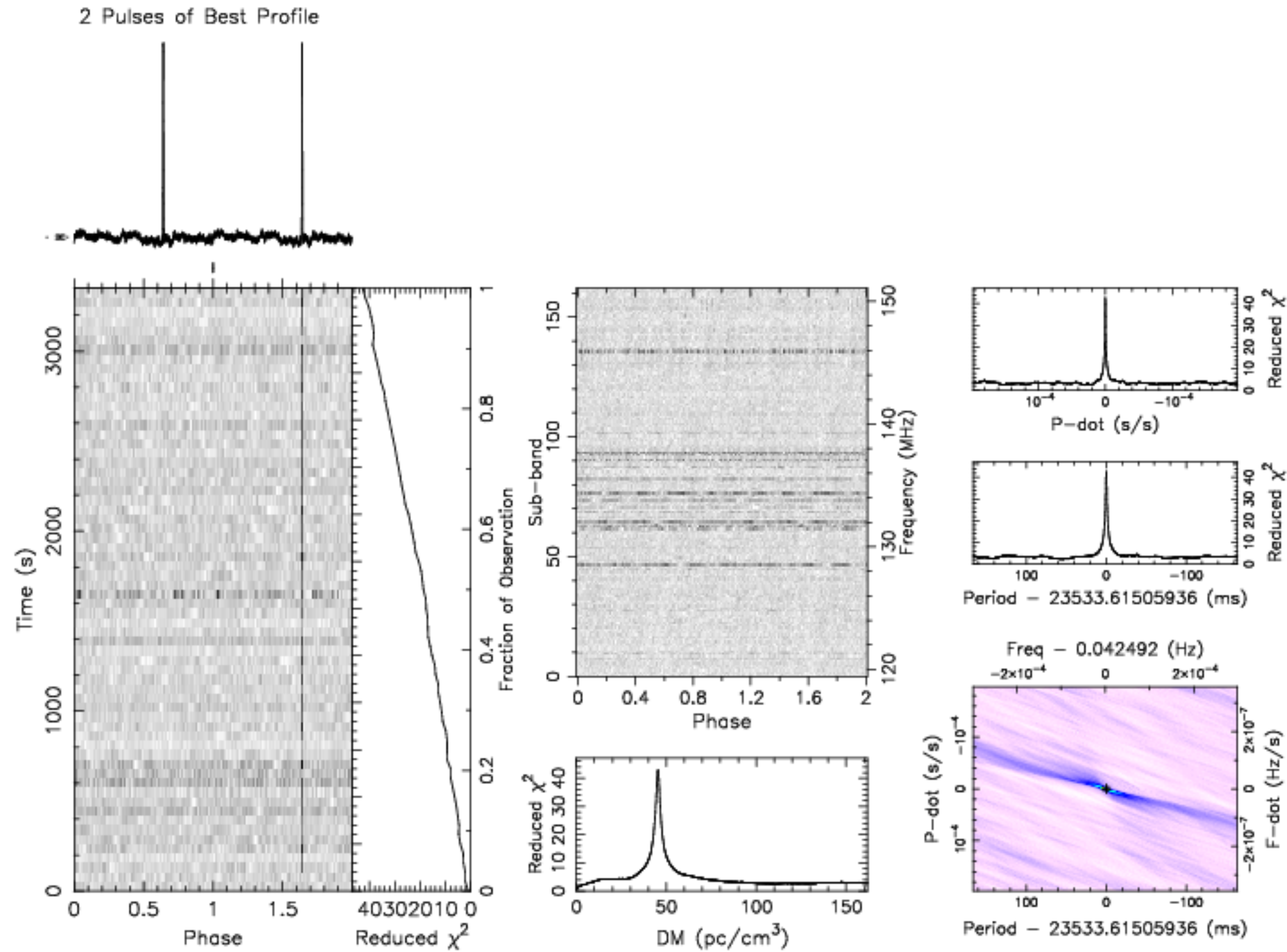
- >60 pulsars discovered via periodicity searches
- 5 RRATs from single pulse searches (Michilli)
- Timing of new pulsars by LOFAR
- Only ~half detected & timed by Lovell (1.4 GHz)
— steep spectrum
- Discoveries are on

<http://www.astron.nl/lotaas>

LOTAAS Overview Paper +
50 first discoveries
Sanidas et al. 2017, in prep.



LOTAAS Discoveries — J0250+58



- 23.5 s period — longest ever
- DM $\sim 45 \text{ pc cm}^{-3}$ — Small duty cycle $\sim 0.4\%$

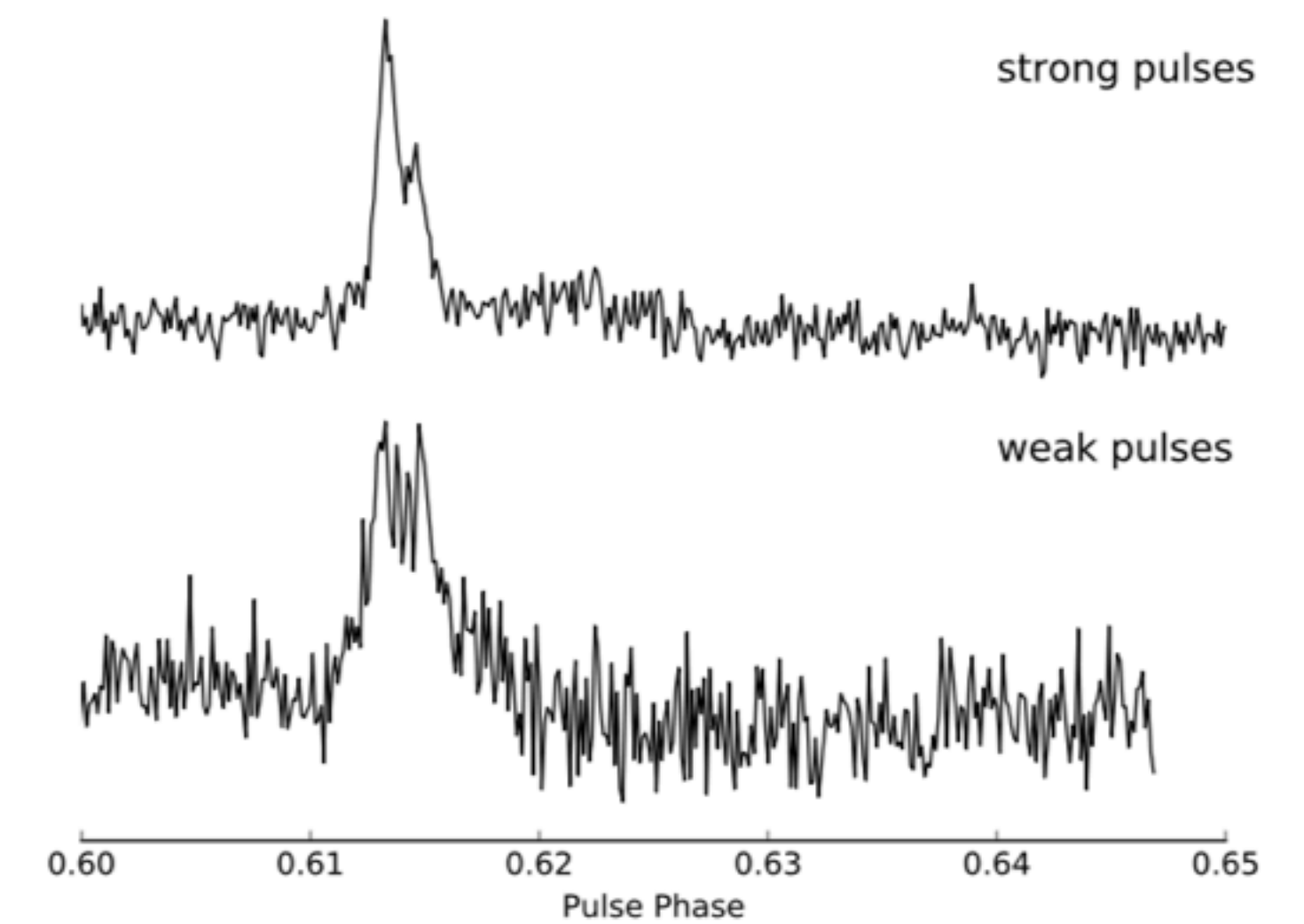
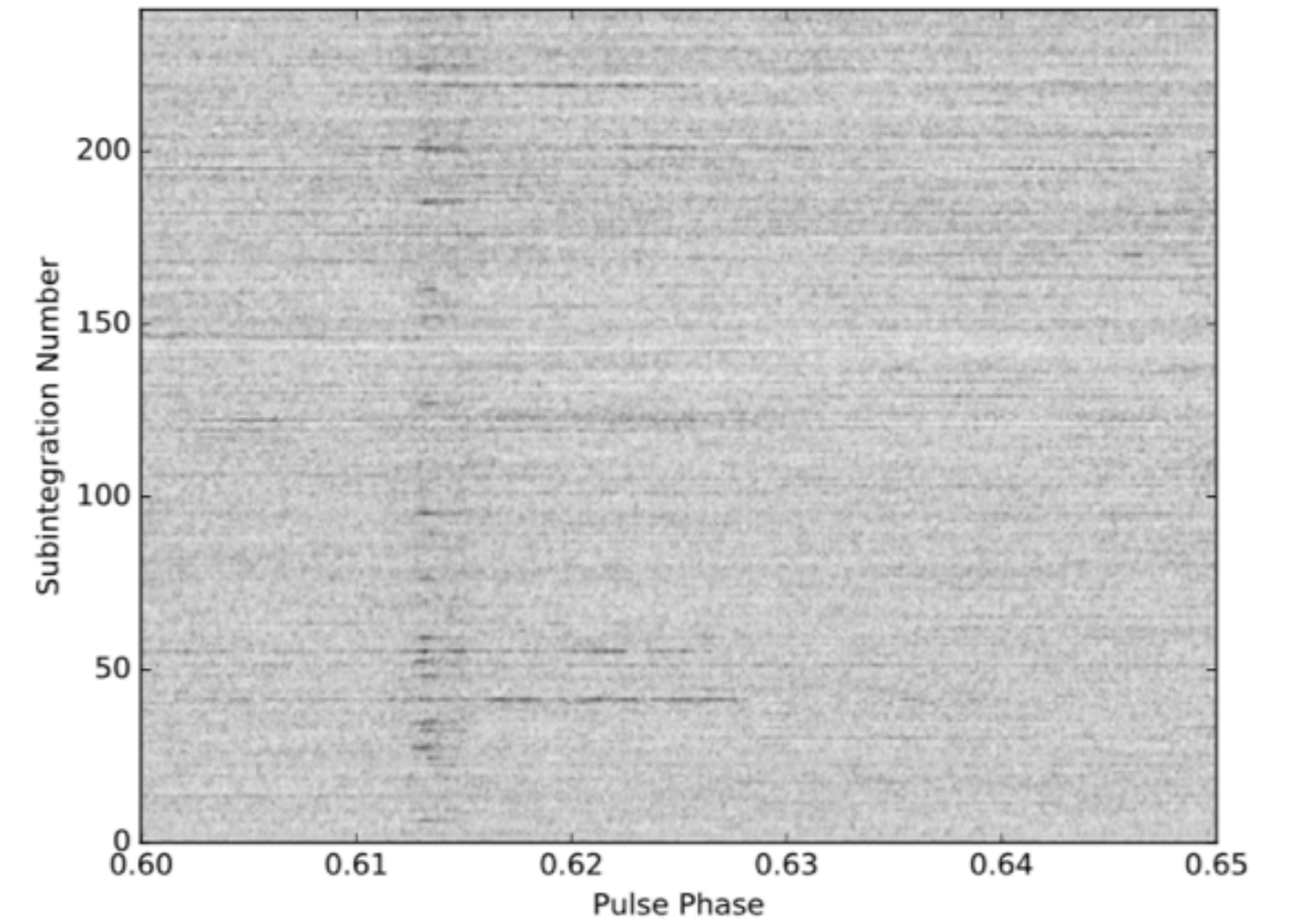
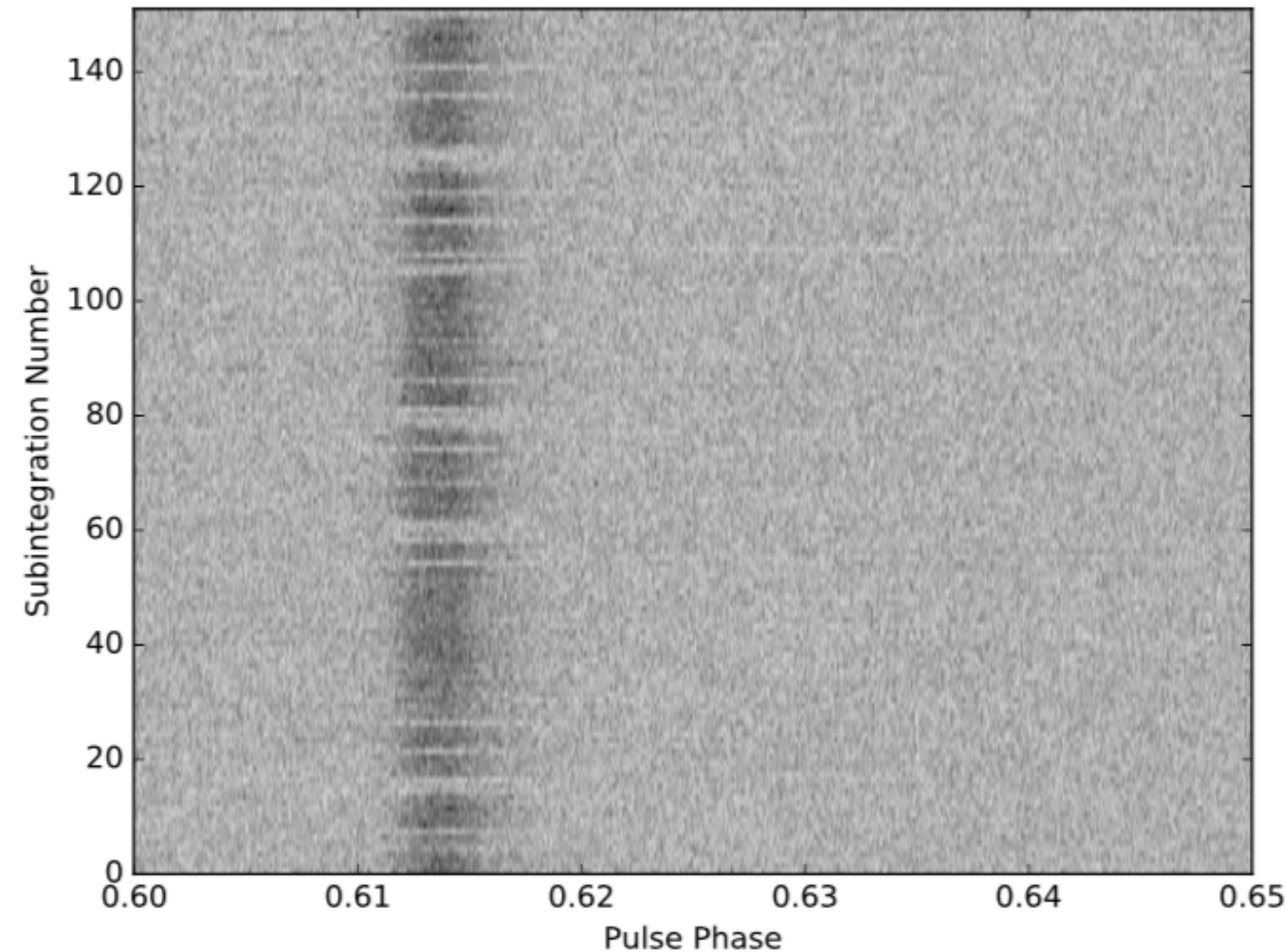
LOTAAS Discoveries — J0250+58

GBT — 350 MHz

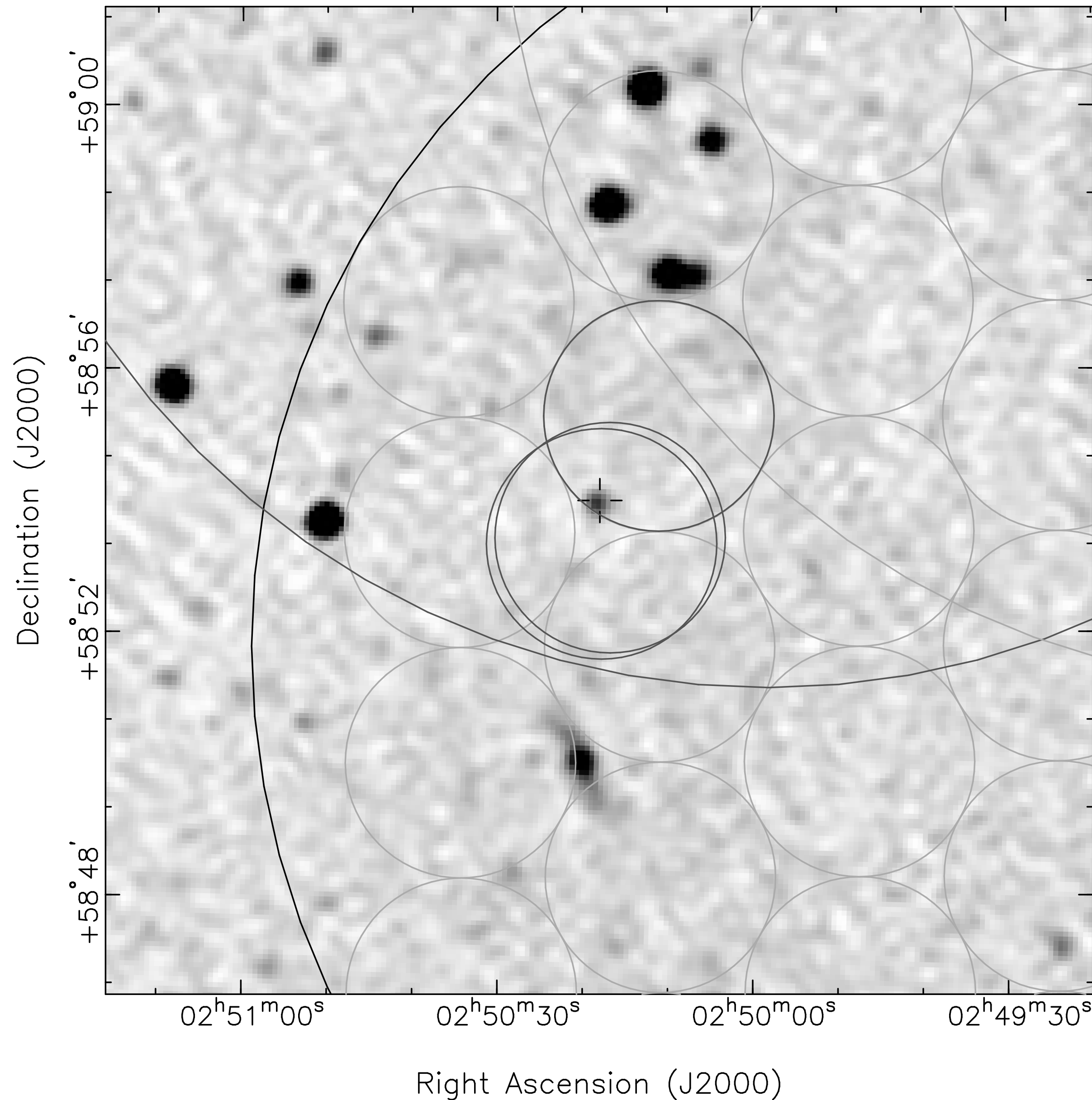
- highly variable in nature
- weak and strong pulses

LOFAR — 150 MHz

- nulls
- little variation in pulse shape



LOTAAS Discoveries — J0250+58



- LOFAR Two-metre Sky Survey (LoTSS; [Shimwell et al. 2017](#)) observed the location of PSRJ0250+58
- Images every 1 second so can effectively “fold” the images at the pulse period
- Accurate position
- Can get \dot{P} without waiting for a year

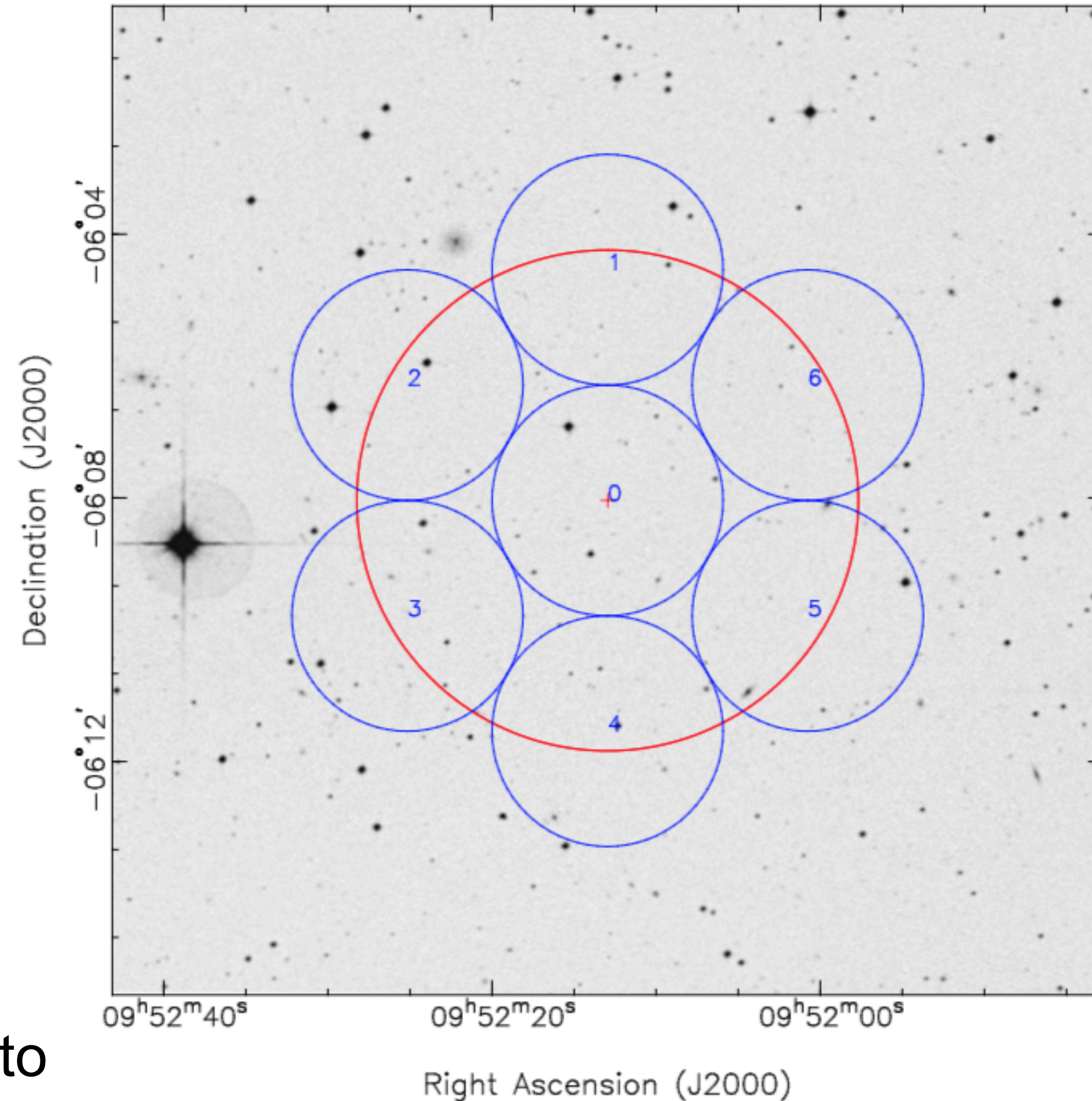
LOFAR MSP survey of Fermi γ -ray sources

Observational setup:

- complex voltage data
- 7 tied-array beams
- 21 HBA core stations
- 115 to 155 MHz (200 subbands)
- target MSP-like γ -ray sources
- 2×20min per target

Processing:

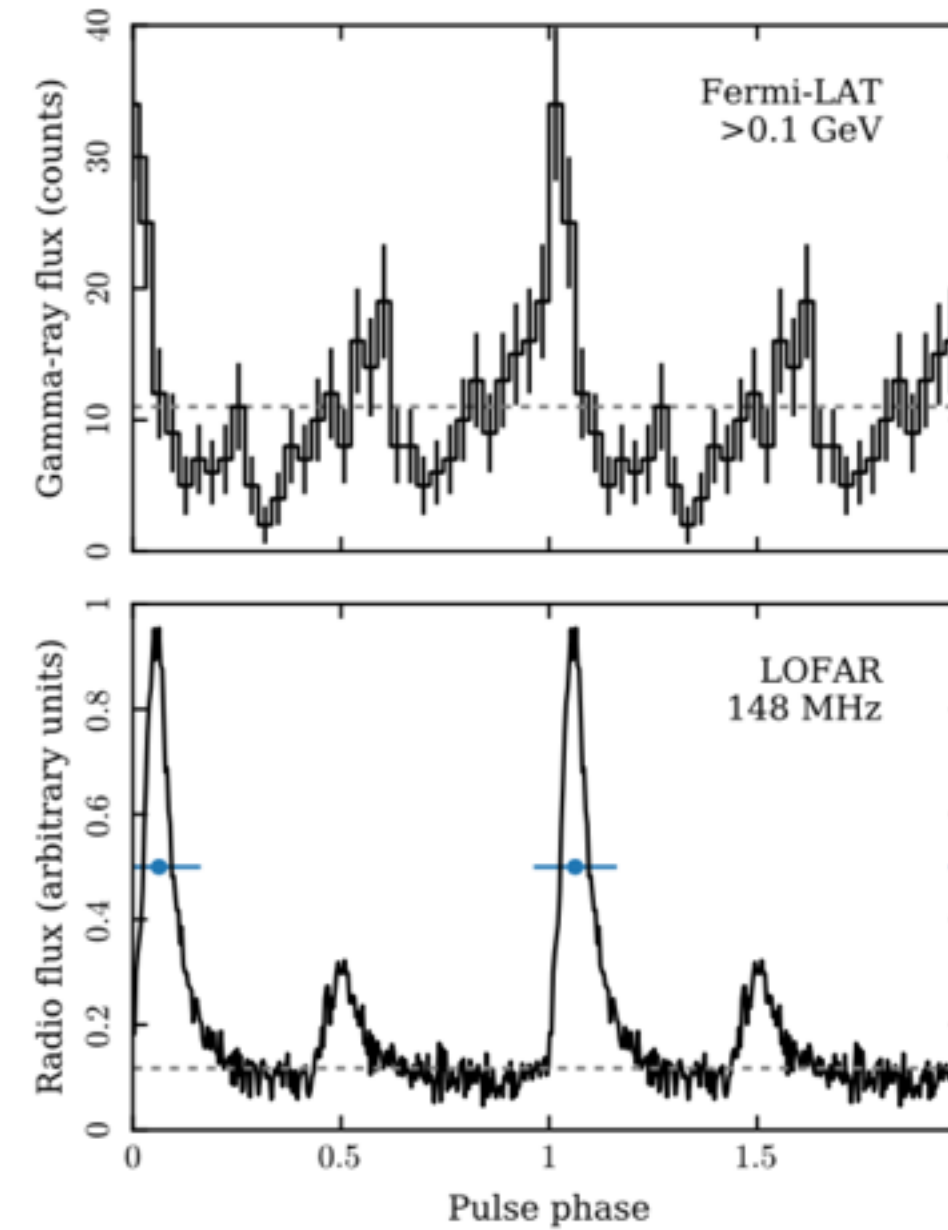
- 80 coherent DM trials up to 80 pc/cc
- 40k incoherent DM trials
- frequency-domain acceleration searches with Presto
- processing on DRAGNET GPU cluster (8 h per 20 min observation)



LOFAR MSP survey of Fermi γ -ray sources

1st Discovery:

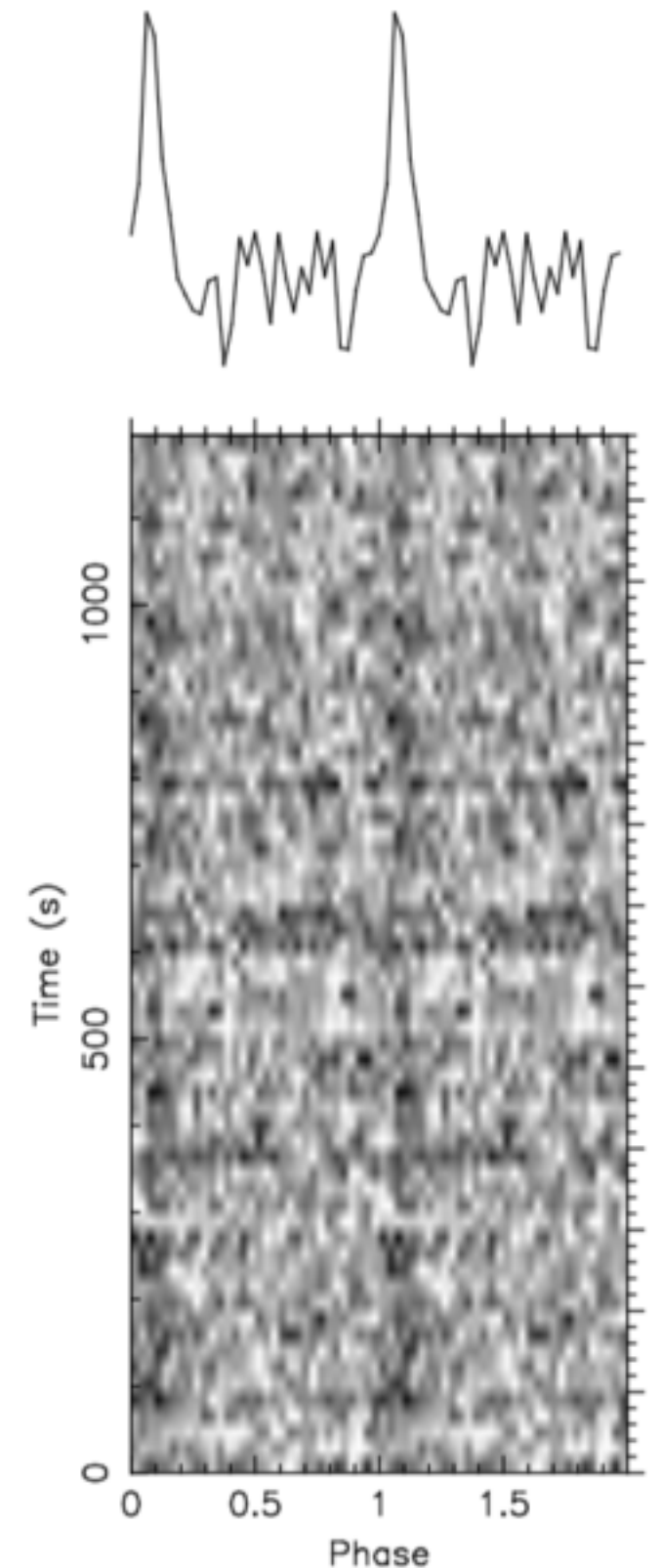
- $P = 2.43$ ms (412 Hz), $DM = 22.90$ pc/cc
- Isolated pulsar
- Steep radio spectrum ($\alpha < -2.8$)
- Radio and γ -ray profiles are aligned



(Pleunis et al. 2017)

3rd Discovery:

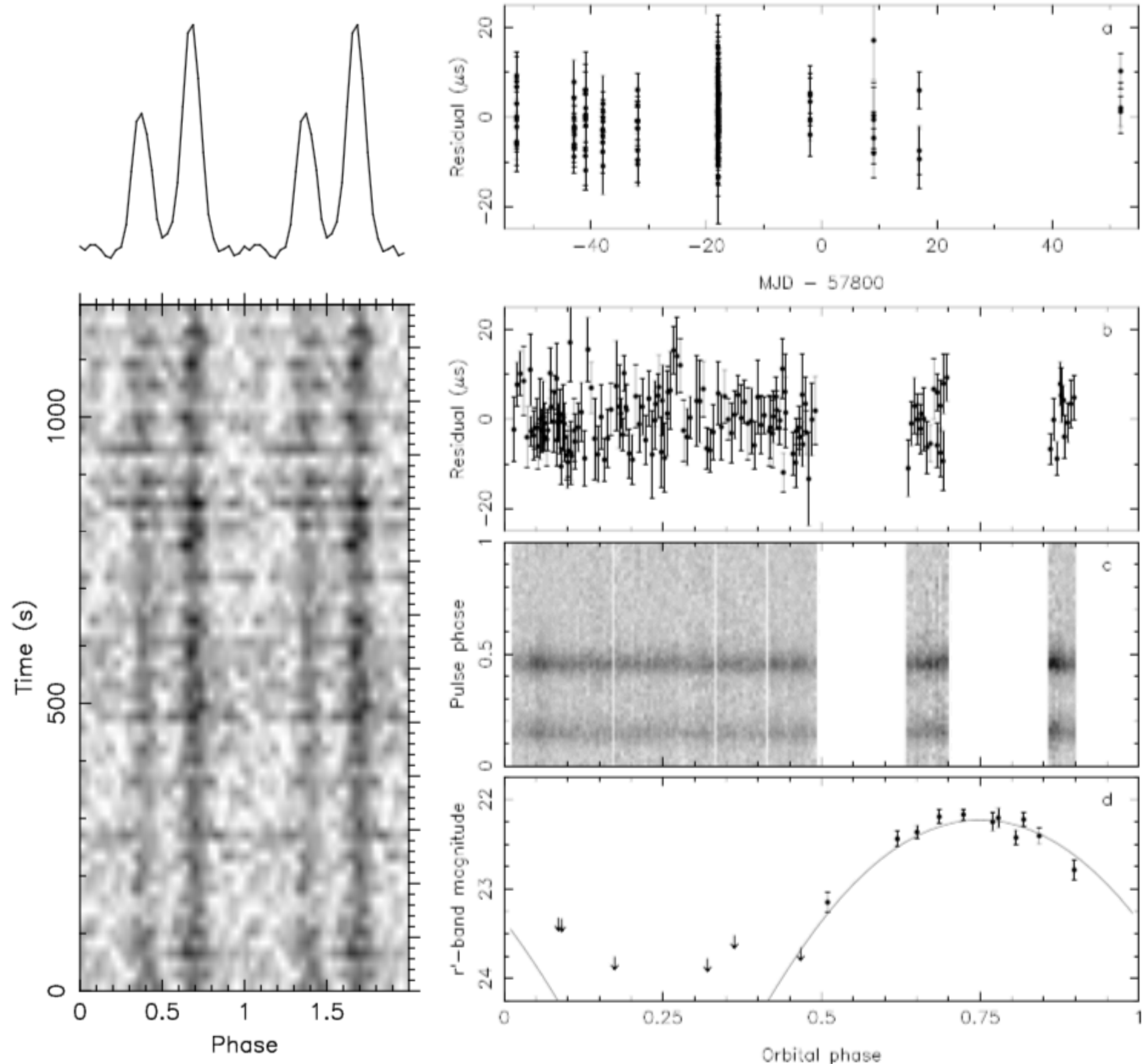
- $P = 4.75$ ms (211 Hz), $DM = 25.54$ pc/cc
- Binary system: $P_b = 5.84$ d,
- probable white dwarf companion ($M_c \sim 0.2 M_\odot$)
- Brighter at 350 MHz, also seen at 1.4 GHz
- Sky location interesting for pulsar timing arrays



Fastest pulsar in Galactic Field

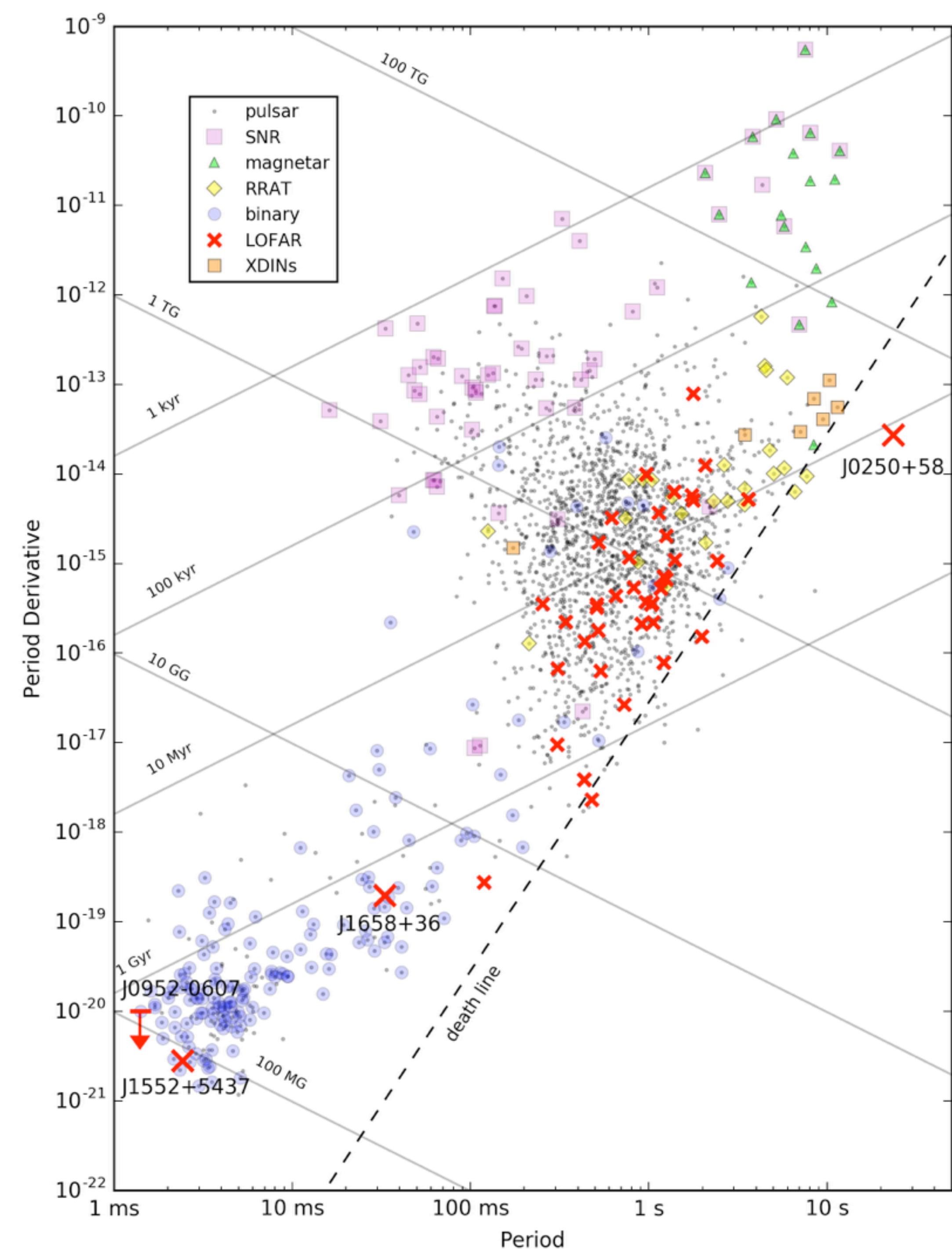
Bassa et al. 2017

- PSR J0952–0607
- $P = 1.41$ ms (707 Hz),
- $DM = 22.41$ pc/cc
- Bright! (S/N ~ 50 in 20 mins)
- Binary system: $P_b = 6.42$ hr,
- $M_c 0.02 M_\odot$; Black Widow
- Highly variable optical companion
- Steep spectrum ($S_\nu \propto \nu^\alpha$ $\alpha \sim -3.3$)
- Proximity - excellent for follow-up
- measure masses through optical spectroscopy/light curve modelling).



LOTAAS Discoveries — P-Pdot Diagram

- Pulsar discoveries at extremes.
- J0250+58 isolated
- High proportion of LOTAAS discoveries near the death line.



Future

- New LOTAAS v2.0 pipeline (Sanidas)
 - ▶ various improvement (~30% performance increase)
- Higher time resolution
 - ▶ reducing sampling time to 246 μs or 164 μs
- Expanding survey coverage to $\delta = -10$
- Adding Fast Folding Algorithm (FFA) to search pipeline (Vincent Morello)
 - ▶ FFA more sensitive to long period pulsar and/or pulsars with small duty cycle

Conclusions

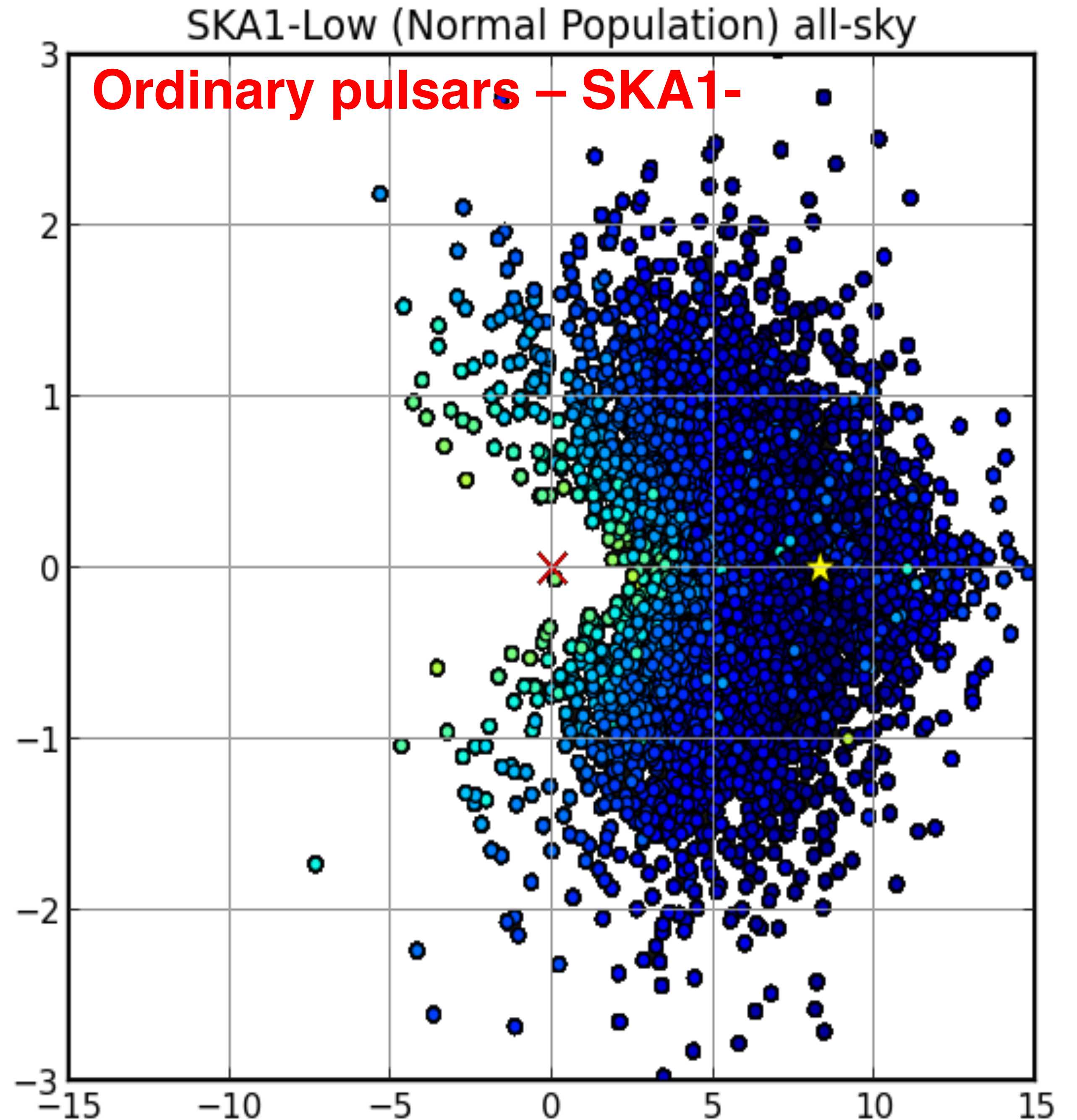
- LOTAAS is the deepest low-frequency pulsar survey ever performed
- >60 pulsars + 5 RRATs found so far — expect >100 new discoveries by end of survey
- Timing of the discoveries to understand the population better
 - some evidence for closer to death line than other pop^{ns}
- Optical follow up on J1658+36 planned
- X-ray follow up to J0250+58 planned
- LOFAR is also able to find MSPs and extreme ones at that.
- Interesting limits on “variable” sources too from multi-pass.
- **Great indicator of the potential of success of SKA1-LOW**

SKA1-LOW

SKA1_LOW expected to find:

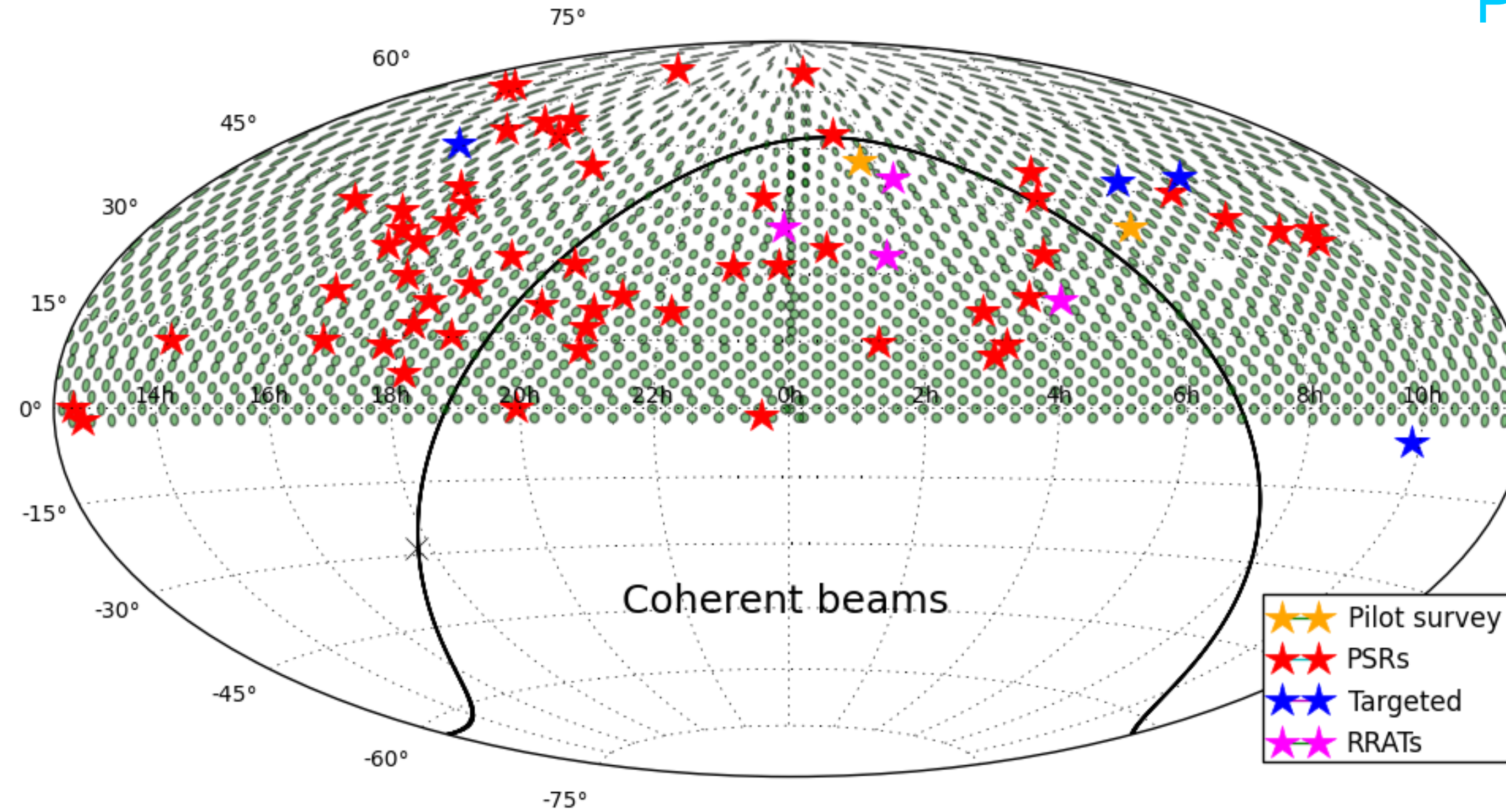
2500-3500 pulsars

400-900 MSPs



Sky Coverage

Pass B



- 648/651 pointings completed in Pass B
- 60 pointings into Pass C