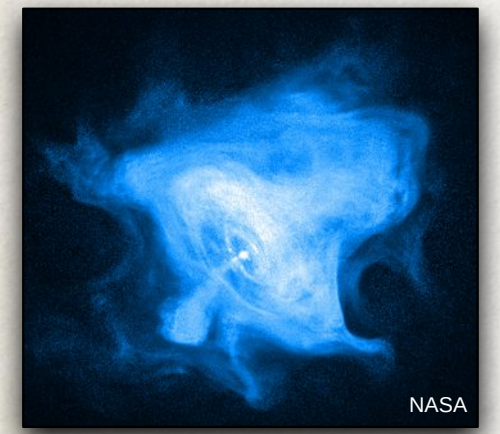
Multi-telescope Pulsar Single-pulse Studies with the Nançay Radio Observatory Telescopes Leading into the SKA Era



Dr. Fabian Jankowski
Researcher
LPC2E, CNRS, Université d'Orléans

Contact
fabian.jankowski@cnrs-orleans.fr
https://fabian.jankowskis.org

Talk Outline

1. Motivation
2. Our Approach
3. Results So Far
4. Preparation for SKA
5. Conclusions

The SUSPECT Project Collaboration

Science Using Single-Pulse Exploration with Combined Telescopes (SUSPECT)

I. The mode-switching, flaring, and single-pulse morphology of PSR B1822−09

F. Jankowski[1⋆], J.-M. Grießmeier[1,2], M. Surnis[3], G. Theureau[1,2,4], and J. Pétri[5]

With Killian Lebreton & Elie Daoura (M2R students),
NenuFAR pulsar team

arXiv: 2407.05156

The SUSPECT Project Collaboration

Science Using Single-Pulse Exploration with Combined Telescopes (SUSPECT)

I. The mode-switching, flaring, and single-pulse morphology of PSR B1822−09

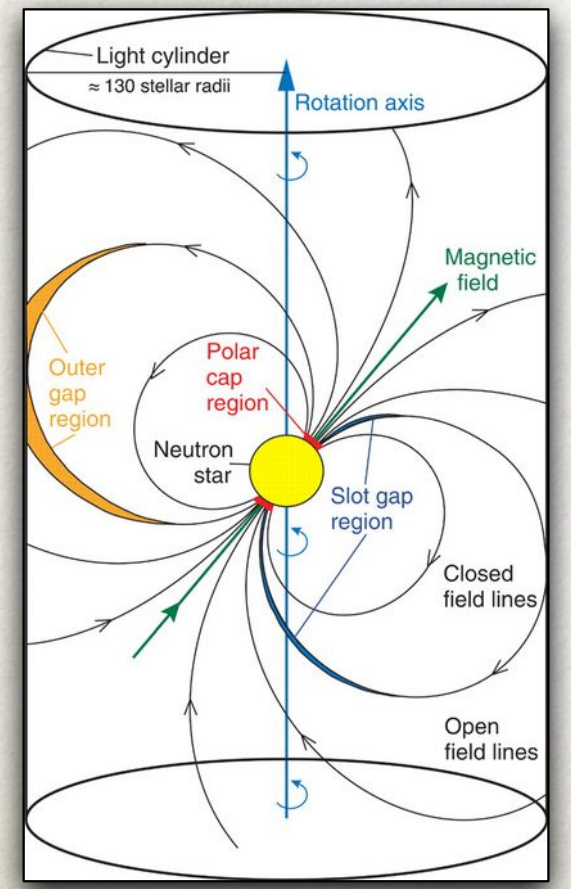
F. Jankowski[1⋆], J.-M. Grießmeier[1,2], M. Surnis[3], G. Theureau[1,2,4], and J. Pétri[5]

With Killian Lebreton & Elie Daoura (M2R students),
NenuFAR pulsar team

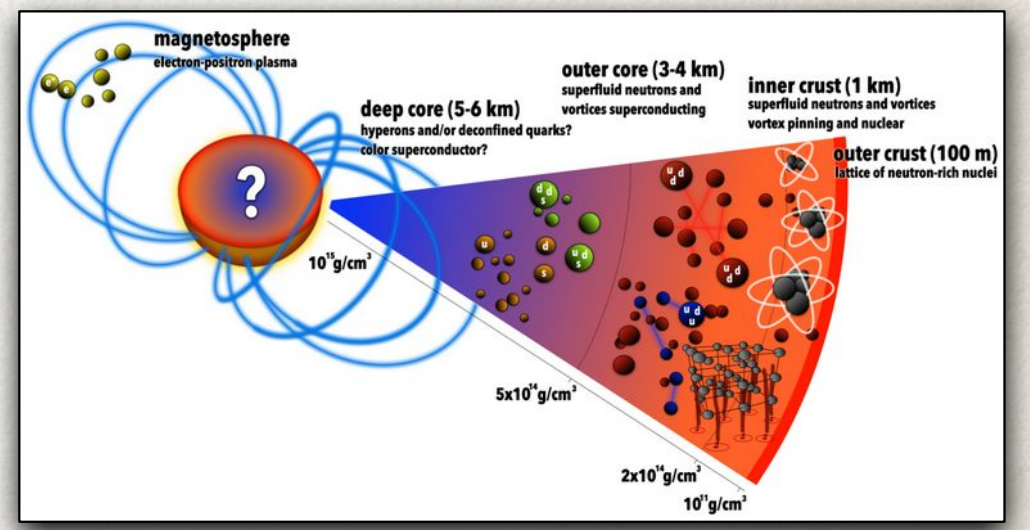
arXiv: 2407.05156

1. Motivation

How does the Pulsar Radio Emission Work?



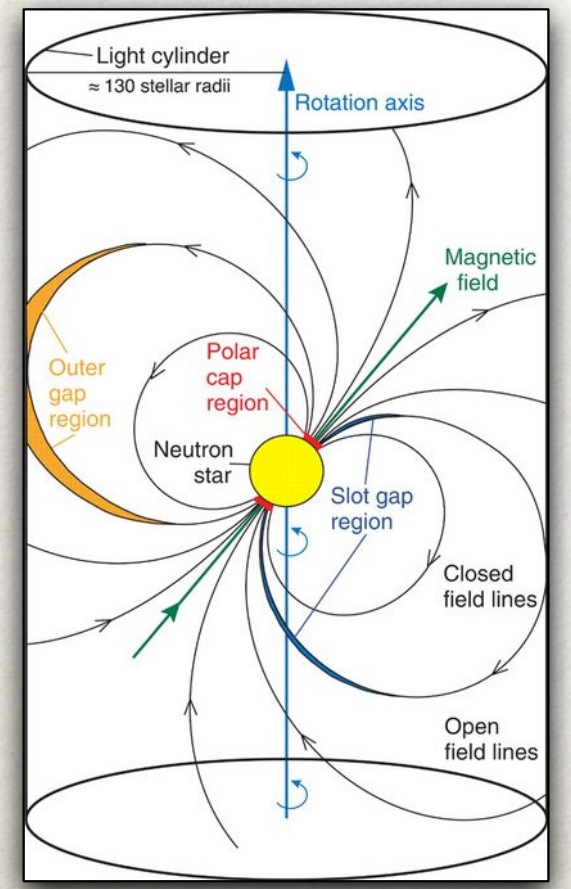
Aliu+ 2008, MAGIC collaboration



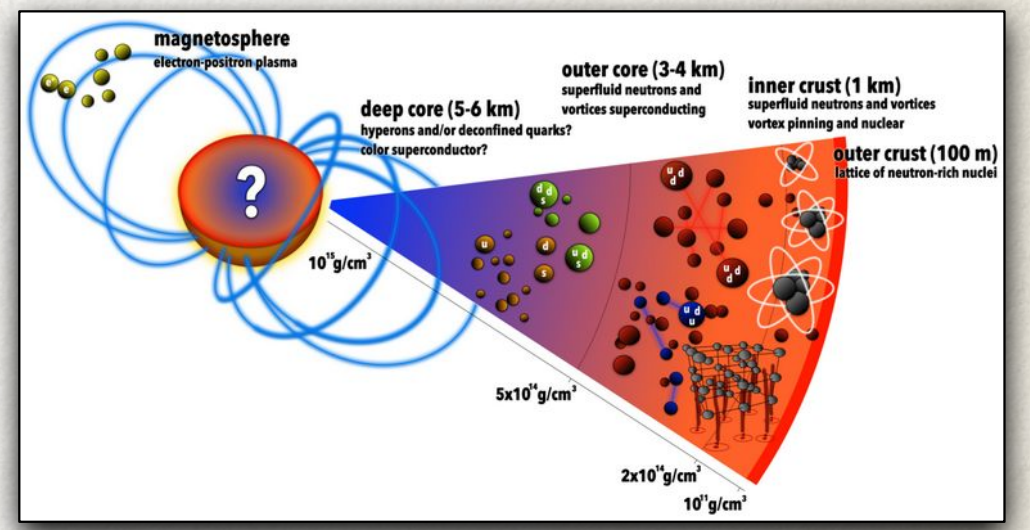
Watts+ 2015

Fabian Jankowski

How does the Pulsar Radio Emission Work?



Aliu+ 2008, MAGIC collaboration



Watts+ 2015

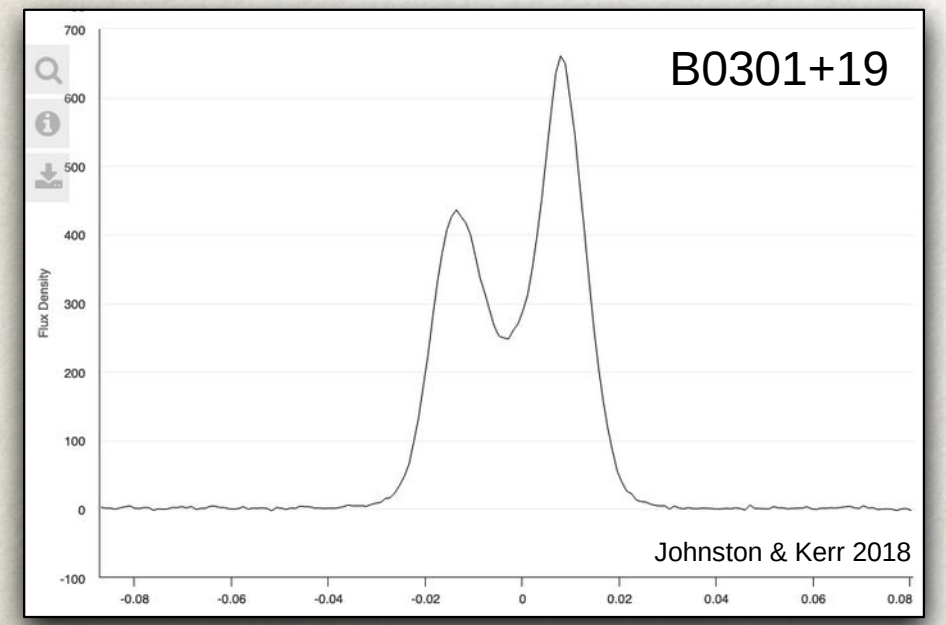
- How do pulsars shine?
- What is the radio emission mechanism?
- Where does the emission originate?
- How can its magnetosphere create the vast array of pulsar phenomena?
- How is a pulsar beam structured? Patchy vs hollow cone?

Fabian Jankowski

Integrated Pulse Profile vs Single-pulses

Integrated profile

O(10k) pulses averaged,
stable fingerprint

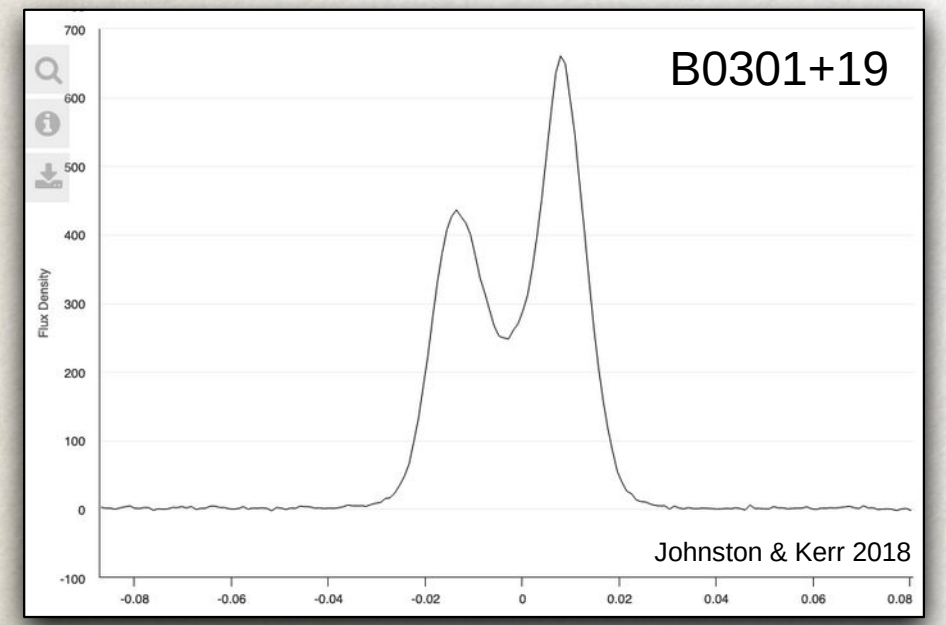


Fabian Jankowski

Integrated Pulse Profile vs Single-pulses

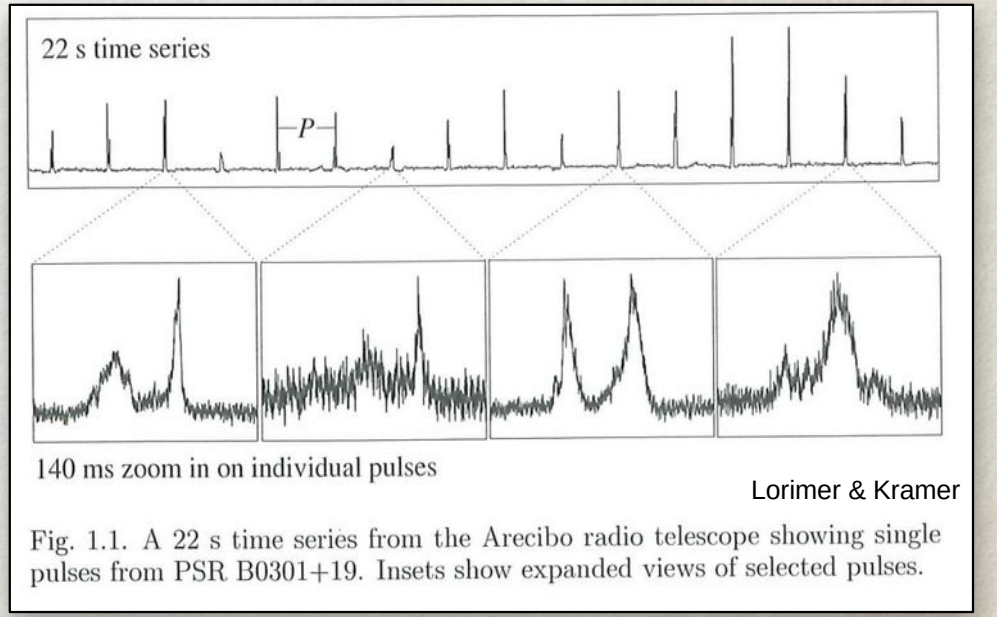
Integrated profile

O(10k) pulses averaged,
stable fingerprint



Individual single pulses

Pulse variability due to changes in
magnetosphere

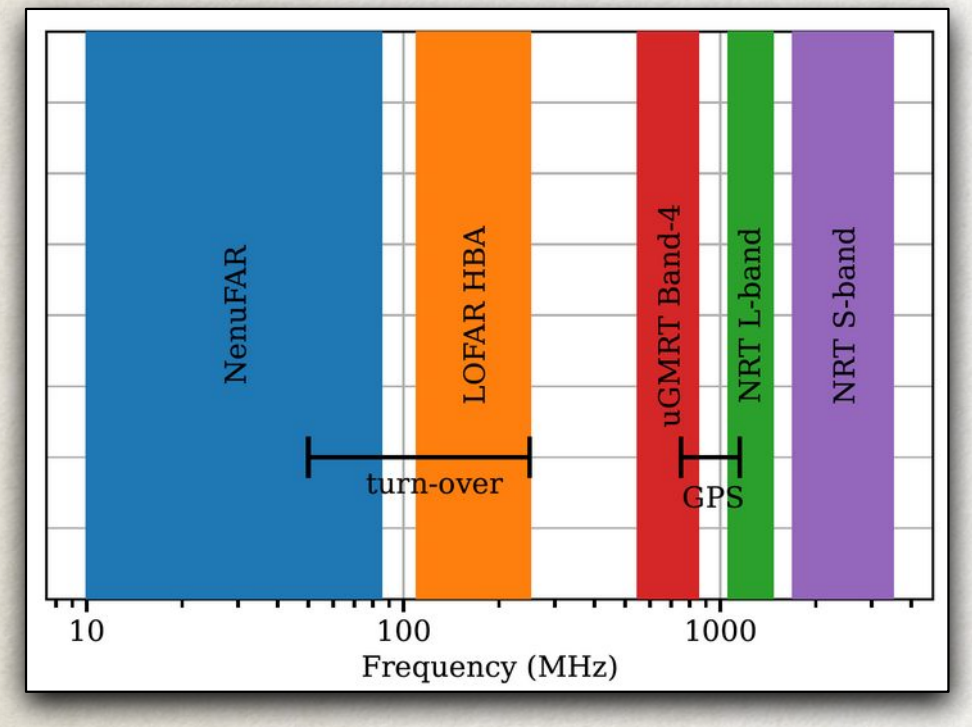


Fabian Jankowski

2. Our Approach

Understanding the Pulsar Radio Emission

Science **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT Project)

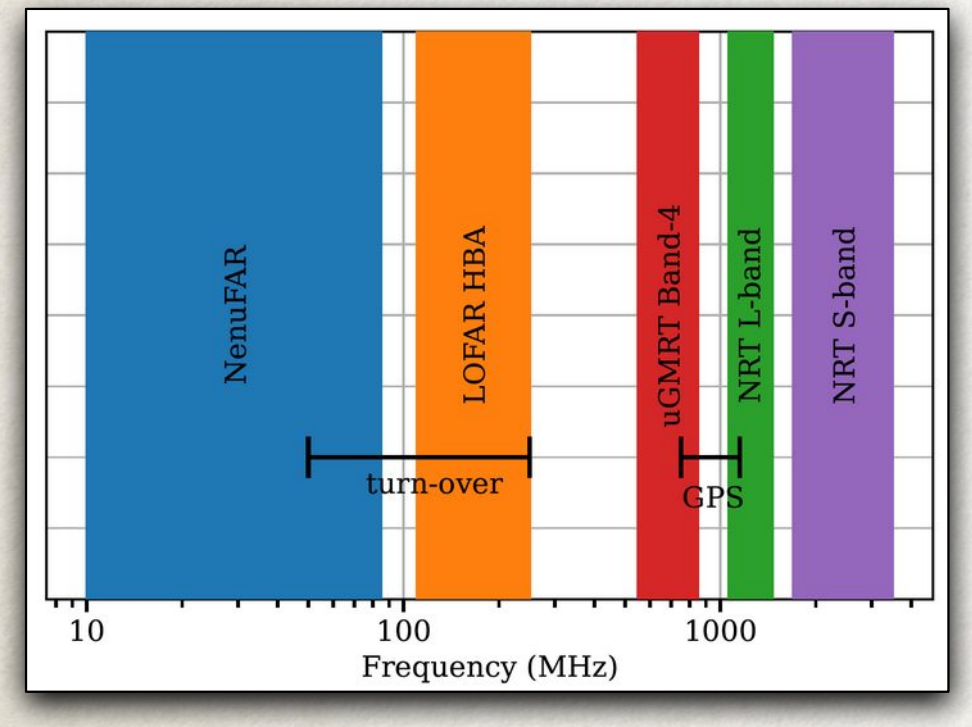


FJ+ under review

Fabian Jankowski

Understanding the Pulsar Radio Emission

Science **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT Project)



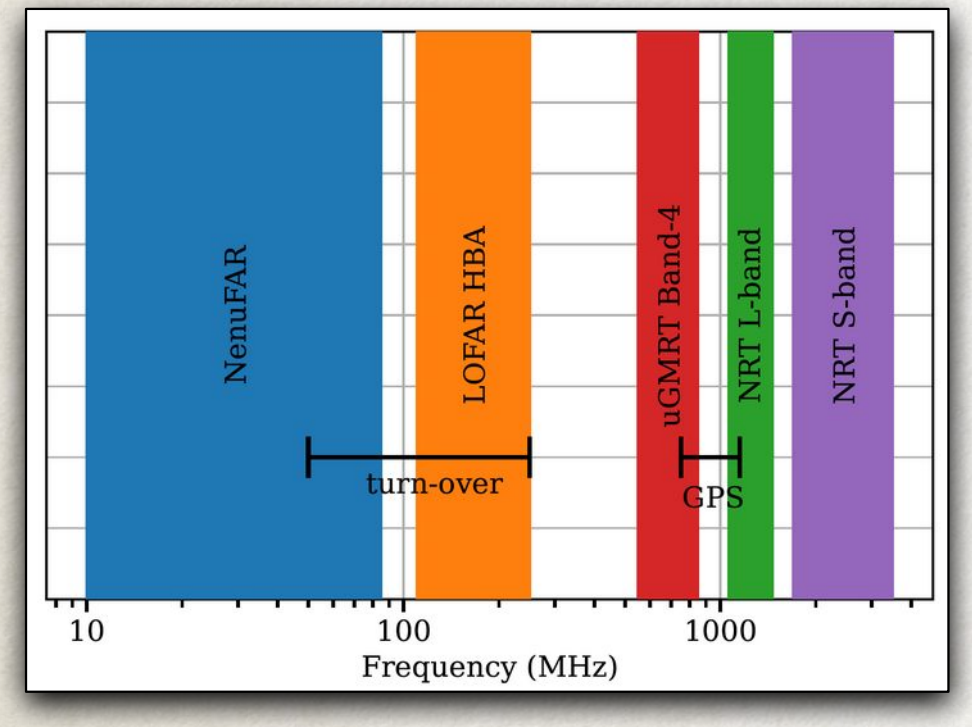
FJ+ under review

- Aims
  - Understanding the wide-band single-pulse properties of radio pulsars
  - Study single-pulse properties (PE distributions, modulation)
  - Others: pulse profiles, radius-to-frequency mapping

Fabian Jankowski

Understanding the Pulsar Radio Emission

Science **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT Project)



FJ+ under review

- Aims
  - Understanding the wide-band single-pulse properties of radio pulsars
  - Study single-pulse properties (PE distributions, modulation)
  - Others: pulse profiles, radius-to-frequency mapping
- Focus on mode-changing and sub-pulse drifting pulsars
  - Master’s M2R projects
    - 2023: Killian Lebreton
    - 2024: Elie Daoura

Fabian Jankowski

Understanding the Pulsar Radio Emission

Science **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT Project)

GMRT

NenuFAR, LOFAR, NRT

Fabian Jankowski

Understanding the Pulsar Radio Emission

Science **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT Project)

GMRT

NenuFAR, LOFAR, NRT

- Wide-band data
- Several telescopes
- (Quasi)-simultaneous data

Fabian Jankowski

Understanding the Pulsar Radio Emission

Science **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT Project)

GMRT

NenuFAR, LOFAR, NRT

Two complementary approaches

- Wide-band data
- Several telescopes
- (Quasi)-simultaneous data

Fabian Jankowski

Understanding the Pulsar Radio Emission

Science **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT Project)

GMRT

NenuFAR, LOFAR, NRT

Two complementary approaches

1) Highest S/N single pulses, intermediate frequencies (~600 MHz), low scattering

→ probe the **intrinsic** emission

- Wide-band data
- Several telescopes
- (Quasi)-simultaneous data

Fabian Jankowski

Understanding the Pulsar Radio Emission

Science **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT Project)

GMRT

NenuFAR, LOFAR, NRT

- Wide-band data
- Several telescopes
- (Quasi)-simultaneous data

Two complementary approaches

1) Highest S/N single pulses, intermediate frequencies (~600 MHz), low scattering

→ probe the **intrinsic** emission

2) Long-term observing campaigns, low frequencies (10s – 100s MHz), timing models, rare modes, time evolution, DM & scattering

→ **intrinsic** and **extrinsic**

Fabian Jankowski

Understanding the Pulsar Radio Emission

Science **U**sing **S**ingle-**P**ulse **E**xploration with **C**ombined **T**elescopes (SUSPECT Project)

GMRT

NenuFAR, LOFAR, NRT

- Wide-band data
- Several telescopes
- (Quasi)-simultaneous data

Two complementary approaches

1) Highest S/N single pulses, intermediate frequencies (~600 MHz), low scattering

→ probe the **intrinsic** emission

GMRT (& NRT)

2) Long-term observing campaigns, low frequencies (10s – 100s MHz), timing models, rare modes, time evolution, DM & scattering

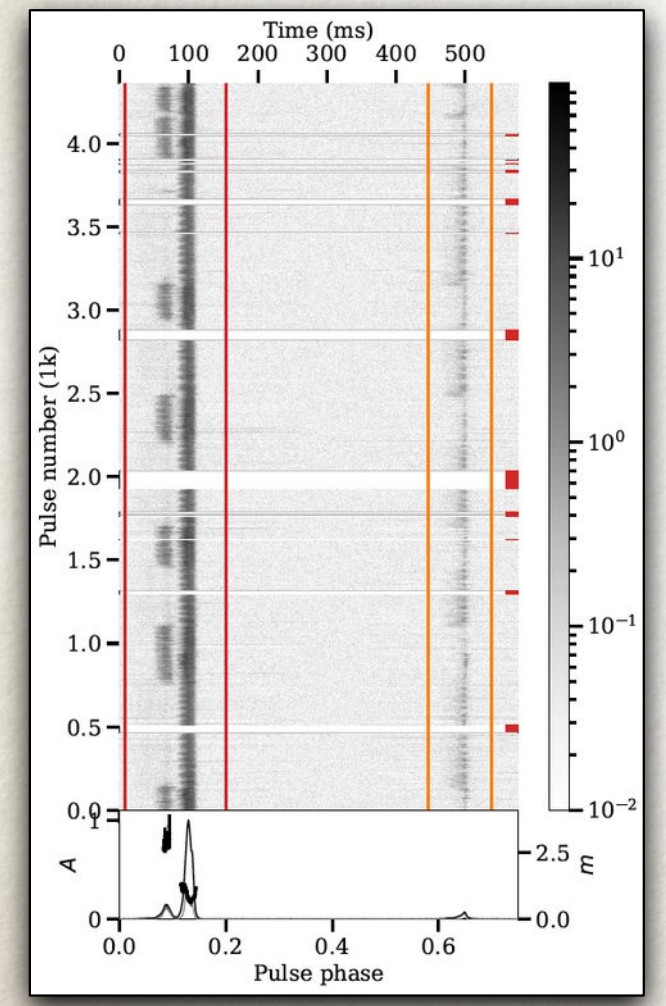
→ **intrinsic** and **extrinsic**

NenuFAR & LOFAR

Fabian Jankowski

3. Results So Far

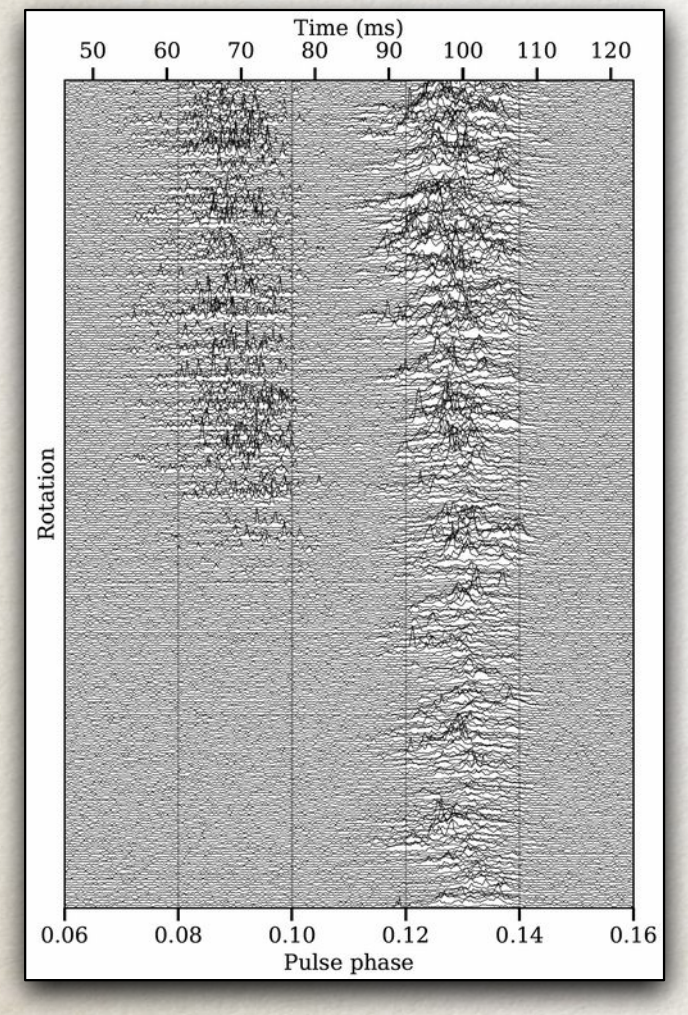
Data and Single-pulse Stacks



PSR B1822-09, GMRT data

- 16 pulsars observed so far (NenuFAR & FR606 & GMRT)
  - +6 pulsars time granted
- Initial data reduction completed for all
- ~6 worked on in more detail (M2R projects, paper)
- First step is getting a clean single-pulse stack
- Shows pulse number vs rotational phase
- High sensitivity and excellent data quality

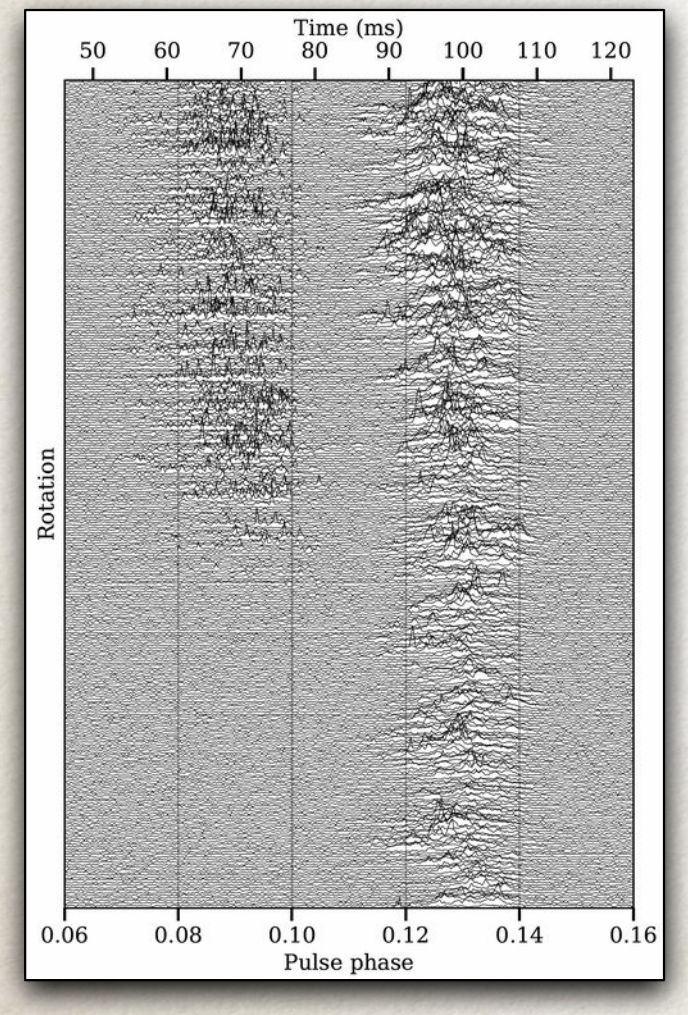
A Model for the Mode-changing Phenomenon



Single pulse number

PSR B1822-09, GMRT data

A Model for the Mode-changing Phenomenon

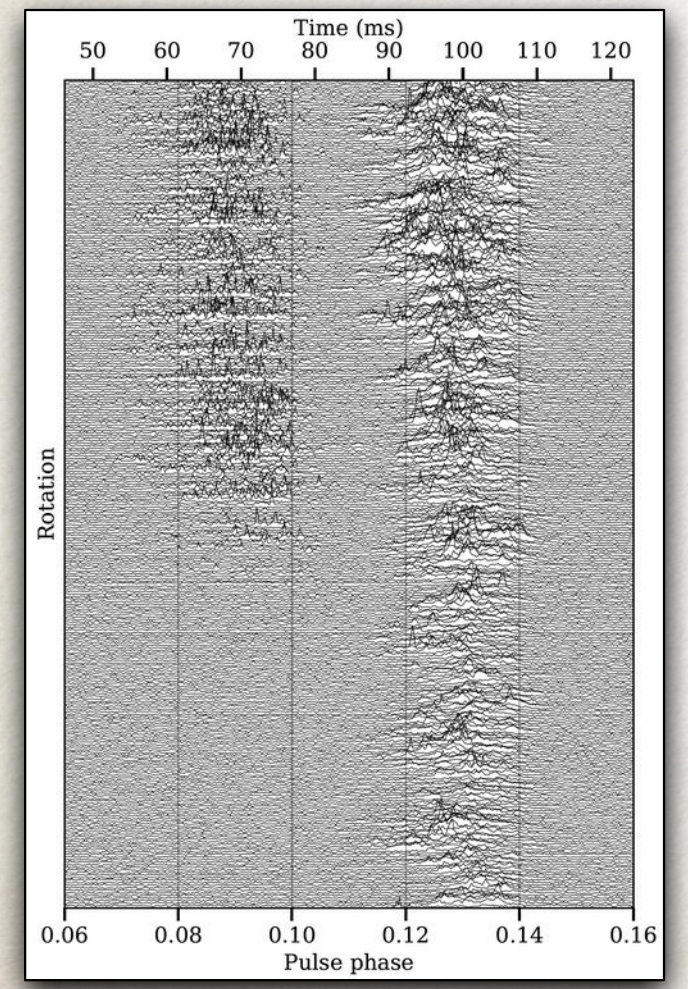


Single pulse number

PSR B1822-09, GMRT data

- Some pulsars do strange things
- This pulsar quasi-randomly switches between several emission modes
  - Stable configurations of the plasma in the magnetosphere
- We want to understand the physics behind it
- Can we understand and model it?

A Model for the Mode-changing Phenomenon

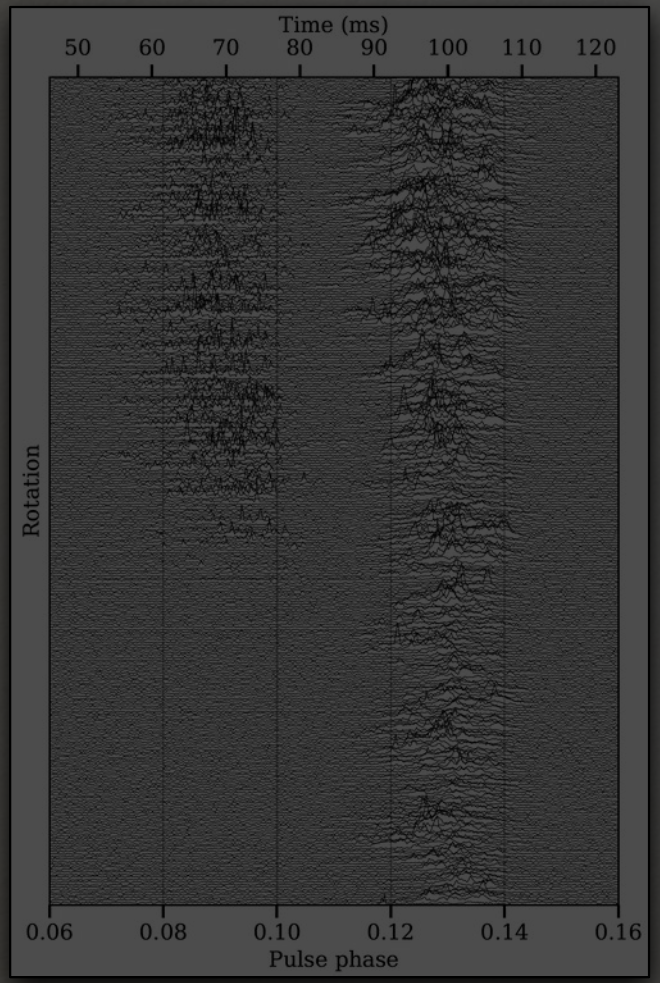


Single pulse number

PSR B1822-09, GMRT data

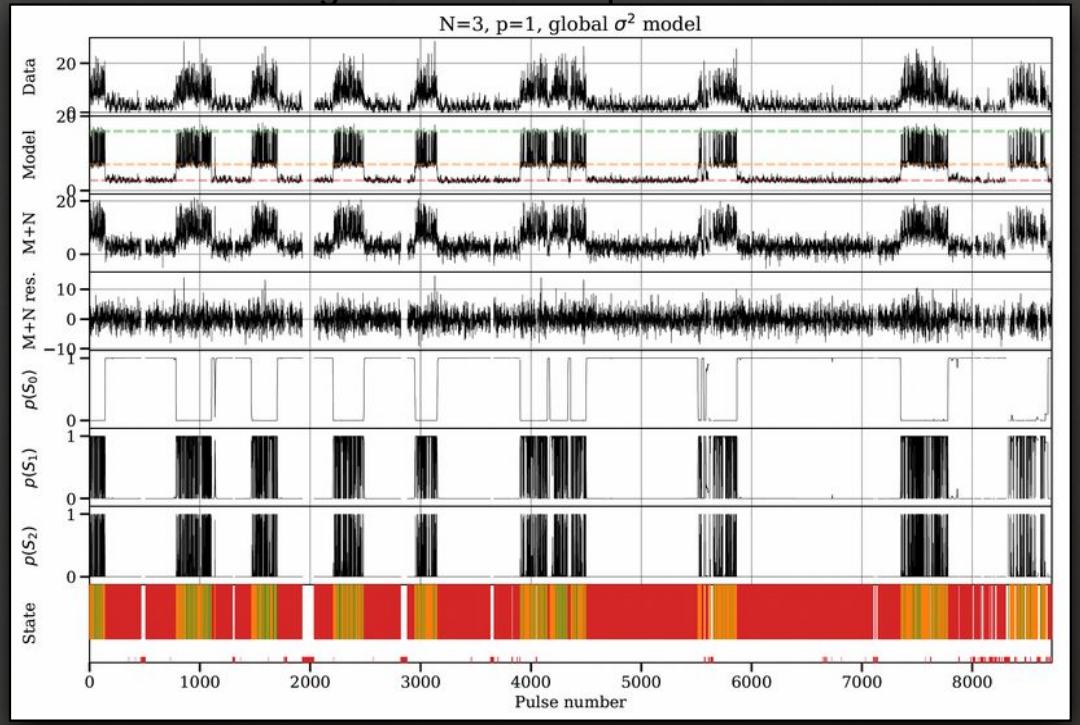
- Some pulsars do strange things
- This pulsar quasi-randomly switches between several emission modes
  - Stable configurations of the plasma in the magnetosphere
- We want to understand the physics behind it
- Can we understand and model it?
  - Yes! Hidden Markov model with autoregressive emissions
  - Automatic mode classification
  - Mode detection and their number

A Model for the Mode-changing Phenomenon



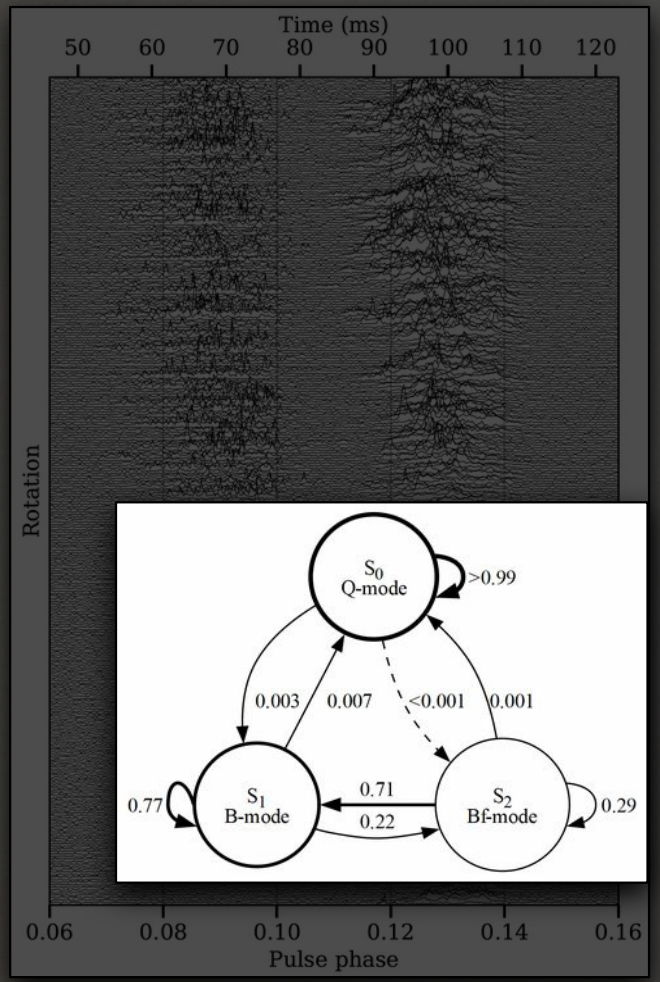
PSR B1822-09, GMRT data

- Some pulsars do strange things
- This pulsar quasi-randomly switches between several emission modes
  - Stable configurations of the plasma in the

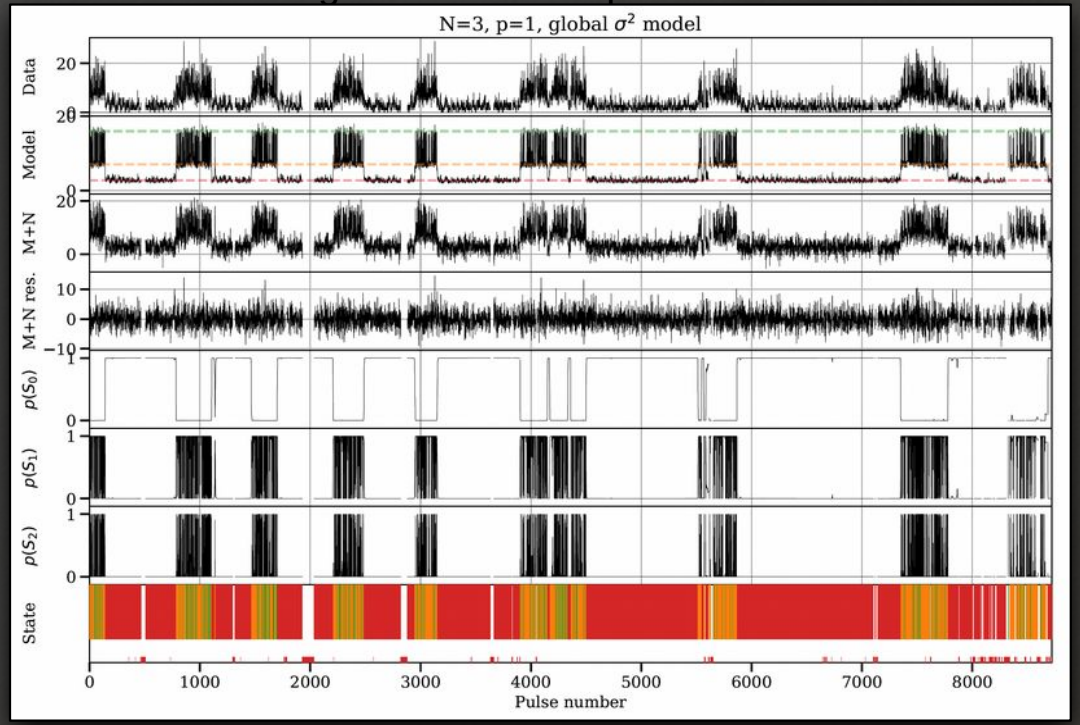


FJ+ under review

A Model for the Mode-changing Phenomenon



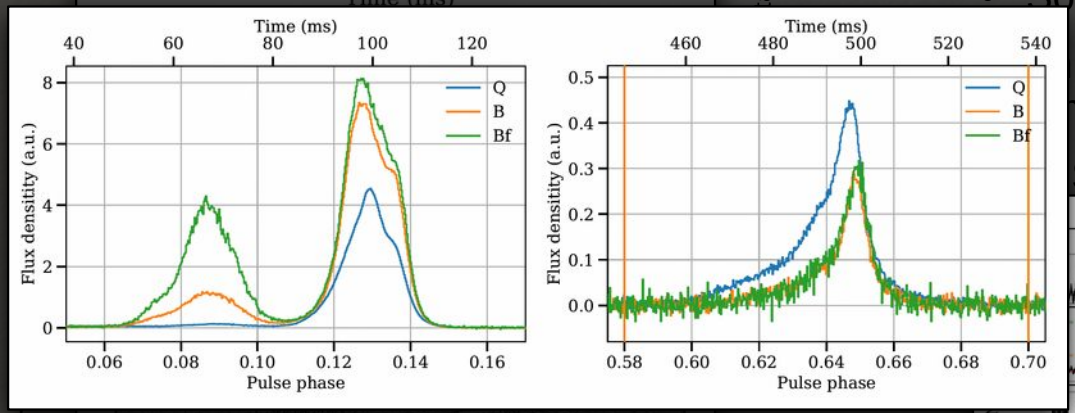
- Some pulsars do strange things
- This pulsar quasi-randomly switches between several emission modes
  - Stable configurations of the plasma in the

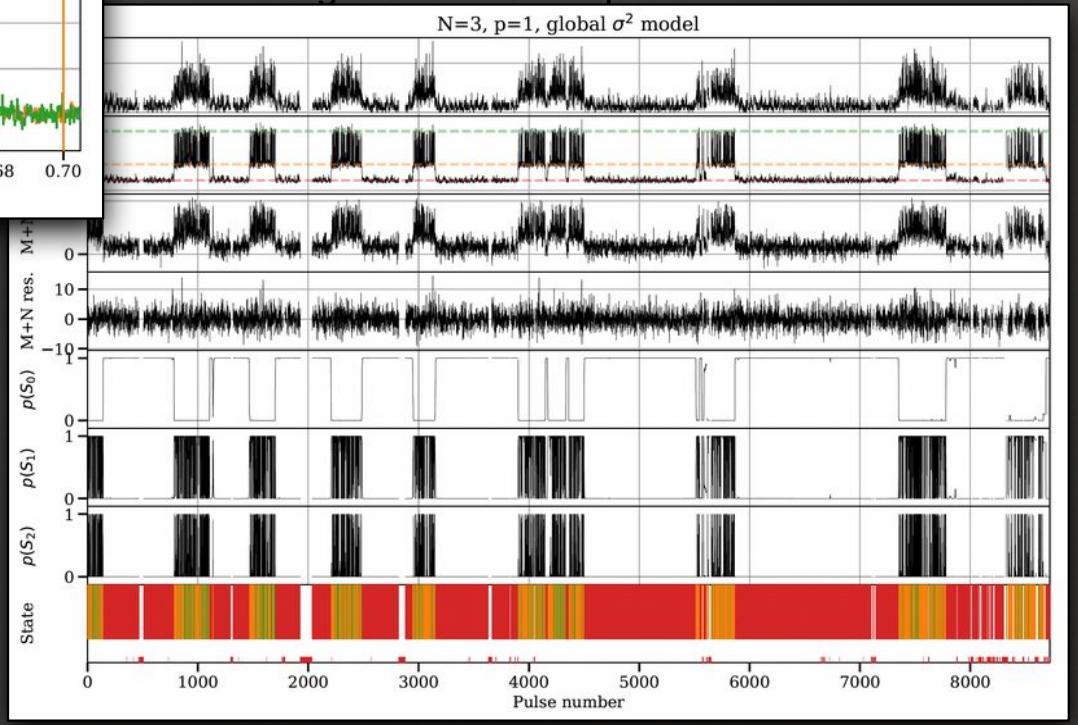


FJ+ under review

A Model for the Mode-changing Phenomenon

- Some pulsars do strange things
- is pulsar quasi-randomly switches between several
  ission modes
- Stable configurations of the plasma in the



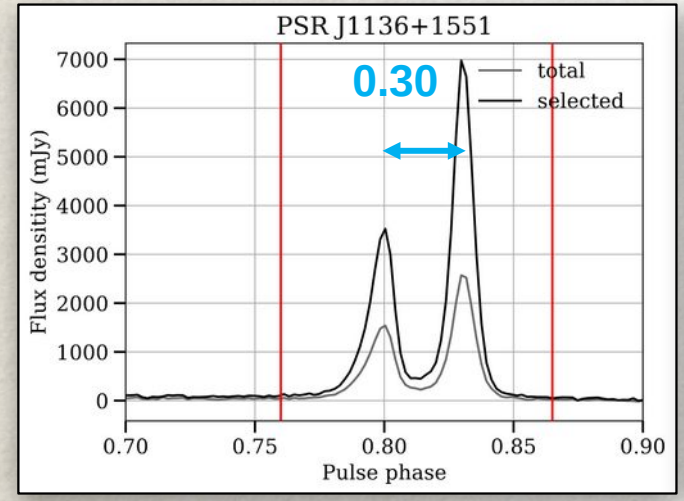


FJ+ under review

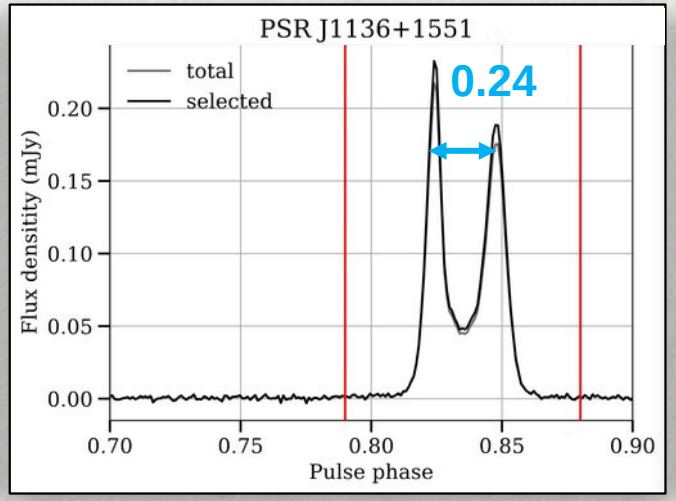
Pulse Profile Evolution with Frequency

Simultaneous observation of PSR B1133+16 with NenuFAR, FR606 and GMRT

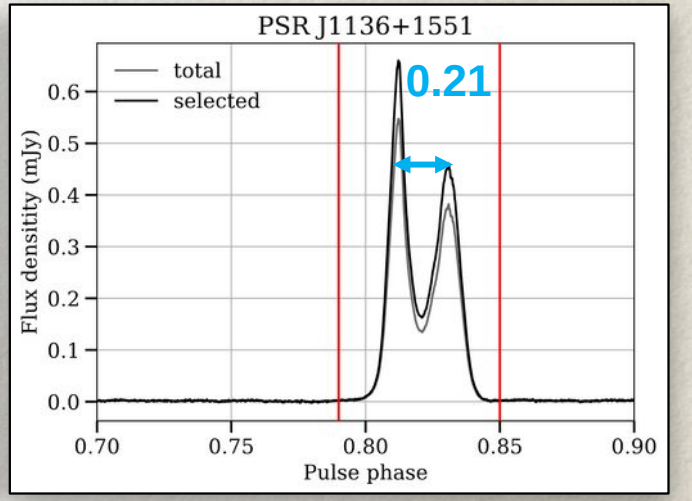
Credit: K. Lebreton



NenuFAR (10 – 85 MHz)



FR606 (110 – 270 MHz)

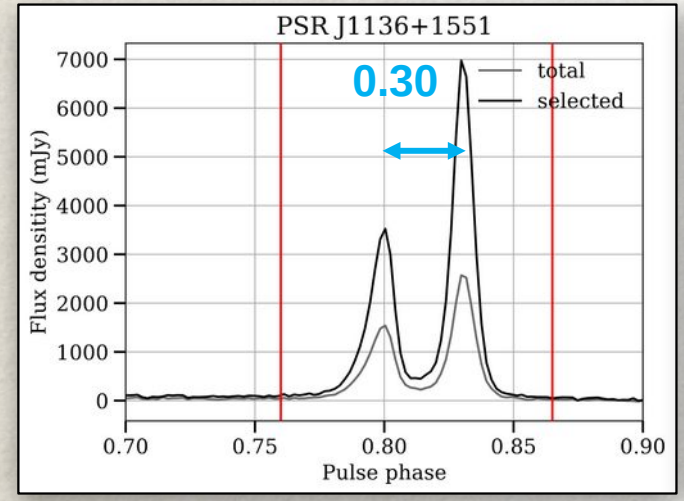


GMRT (550 – 750 MHz)

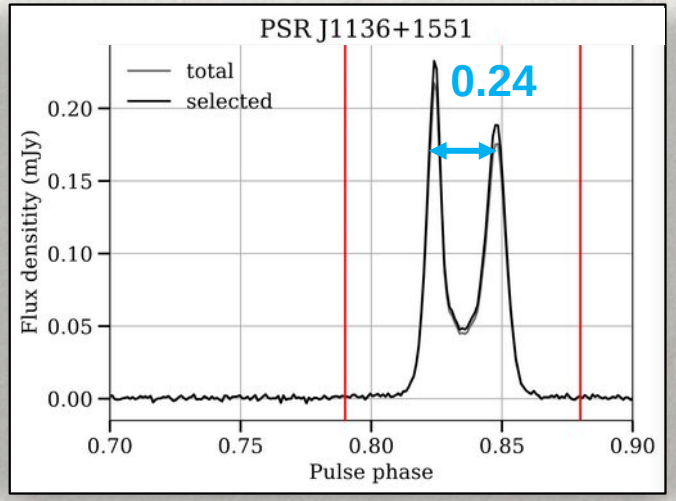
Pulse Profile Evolution with Frequency

Simultaneous observation of PSR B1133+16 with NenuFAR, FR606 and GMRT

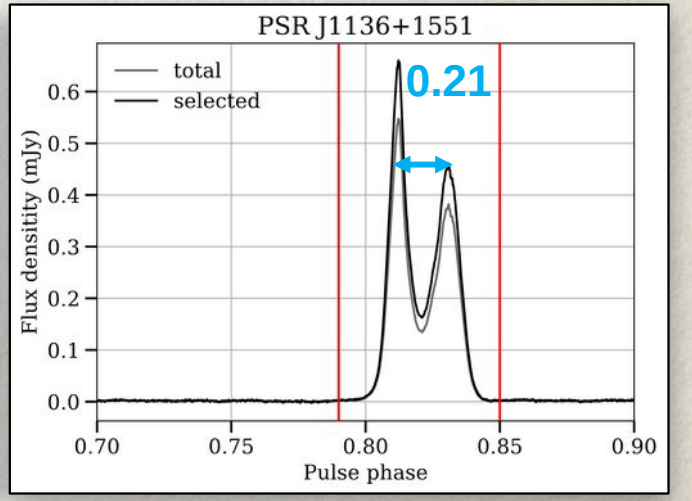
Credit: K. Lebreton



NenuFAR (10 – 85 MHz)



FR606 (110 – 270 MHz)



GMRT (550 – 750 MHz)

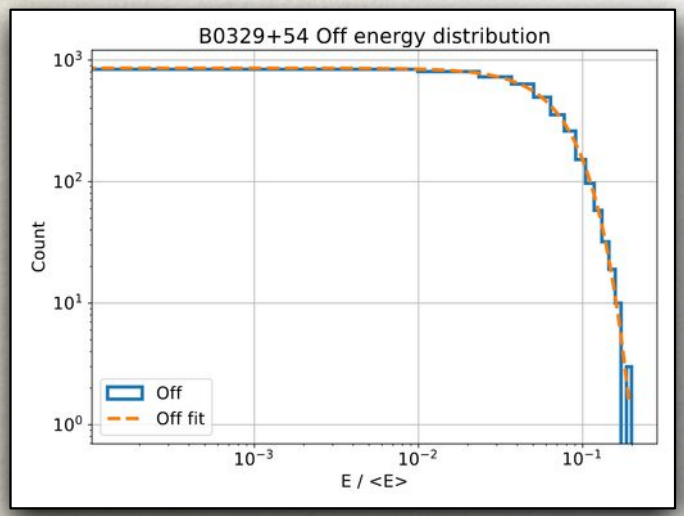
Pulse width, component separation, and relative intensity change
→ different emission altitudes or processes

Pulse Energy Distributions

Examples (all from NenuFAR data)

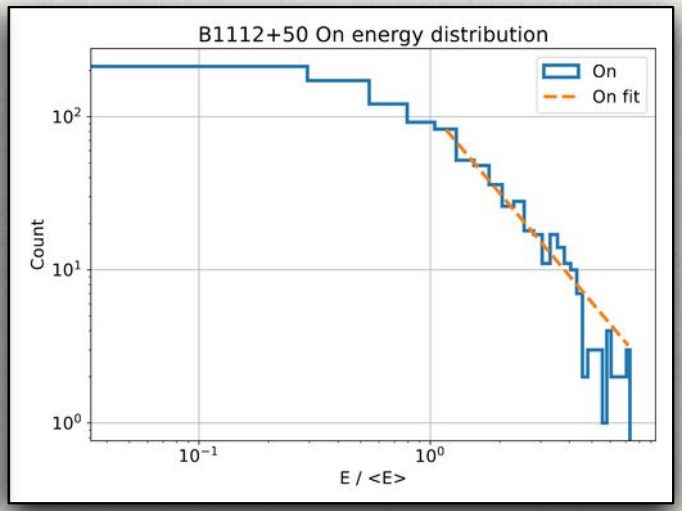
Credit: K. Lebreton

B0329+54



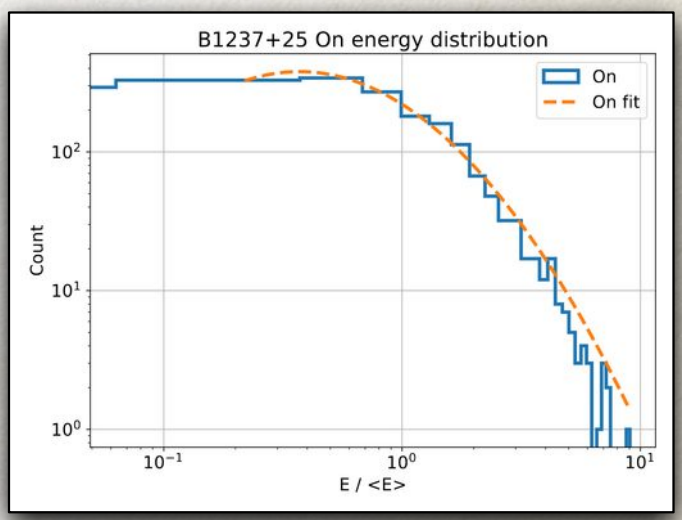
Off-pulse with a Gaussian fit

B1112+50



On-pulse with a power law fit

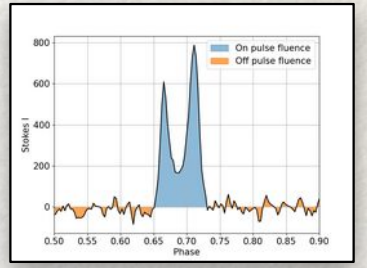
B1237+25



On-pulse with a lognormal fit

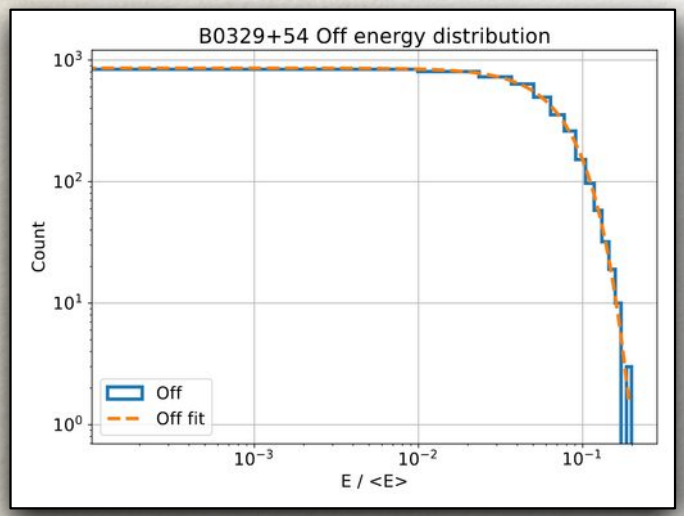
Pulse Energy Distributions

Examples (all from NenuFAR data)



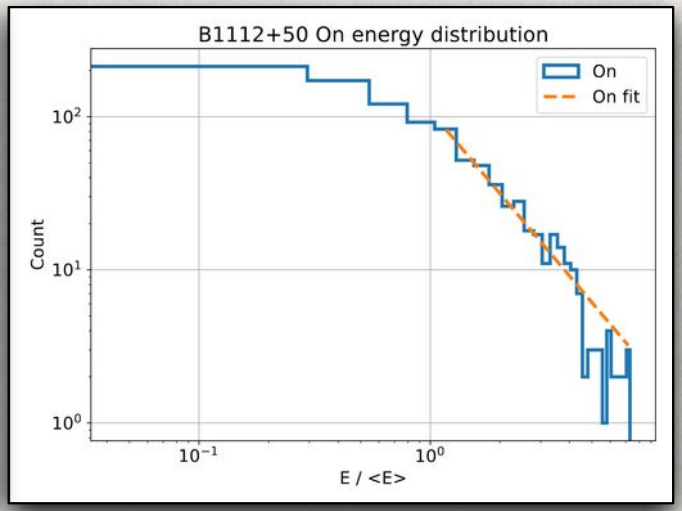
Credit: K. Lebreton

B0329+54



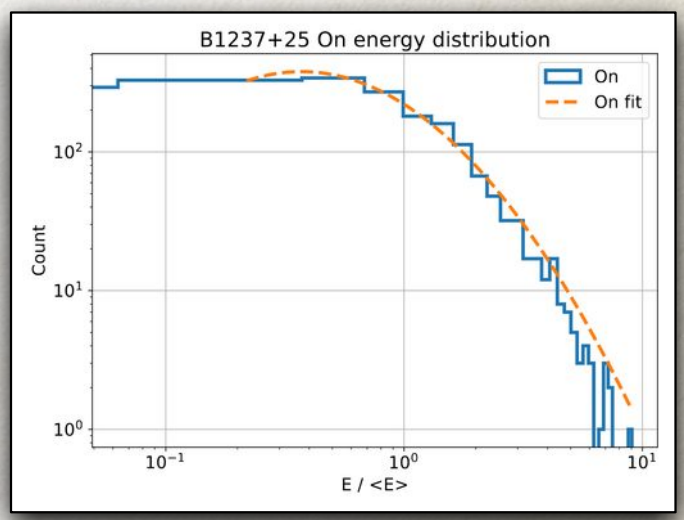
Off-pulse with a Gaussian fit

B1112+50



On-pulse with a power law fit

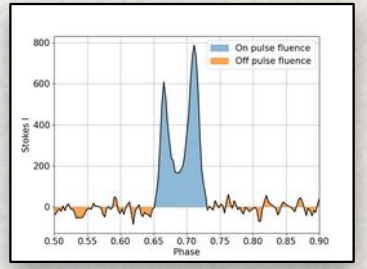
B1237+25



On-pulse with a lognormal fit

Pulse Energy Distributions

Examples (all from NenuFAR data)

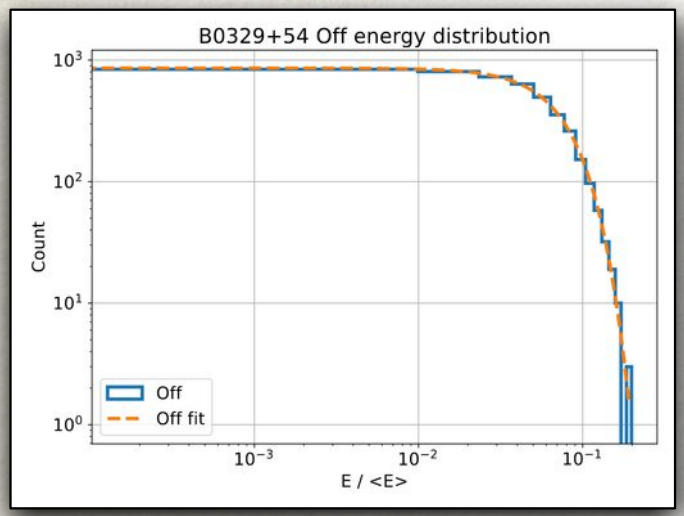


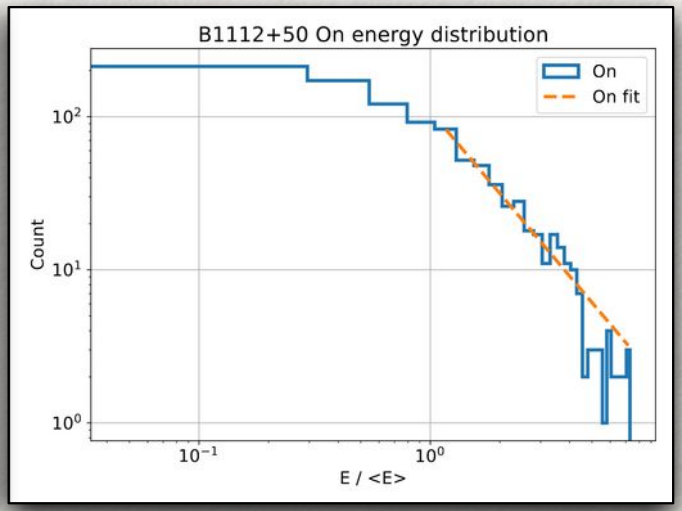
Credit: K. Lebreton

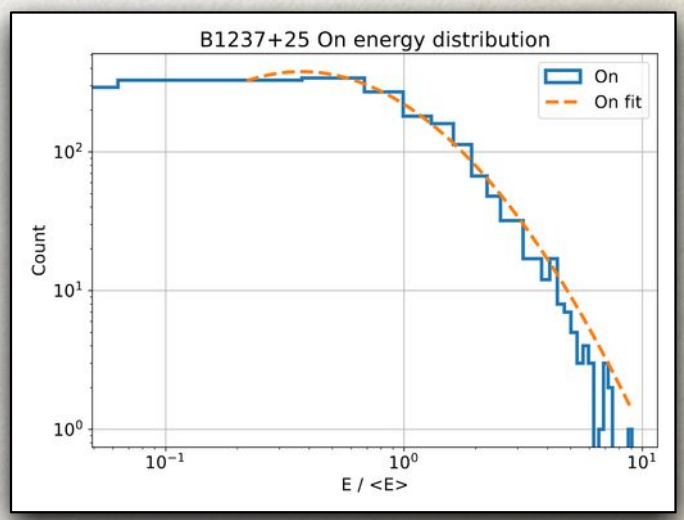
B0329+54

B1112+50

B1237+25







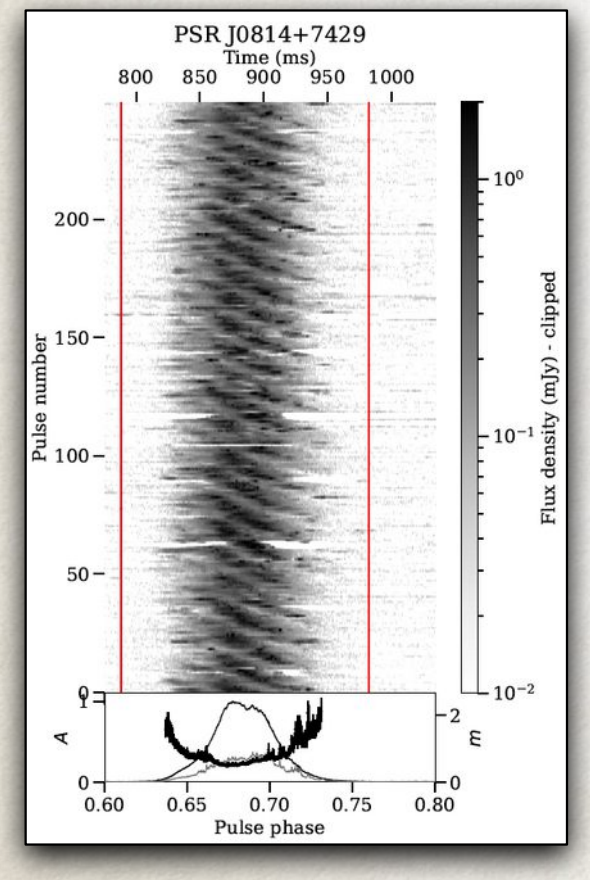
Off-pulse with a Gaussian fit

On-pulse with a power law fit

On-pulse with a lognormal fit

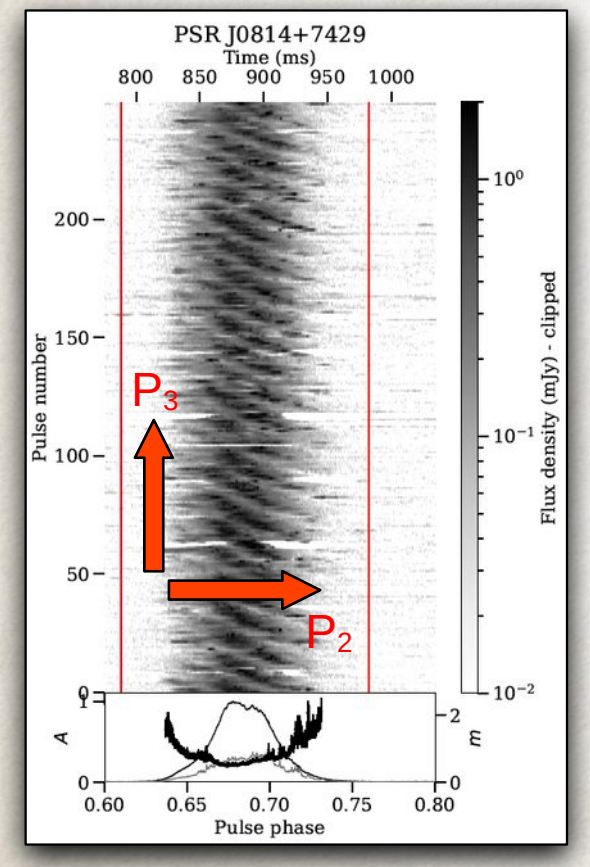
→ Indicates energetic pulses and
traces the particle acceleration physics

Fluctuation Spectral Analyses



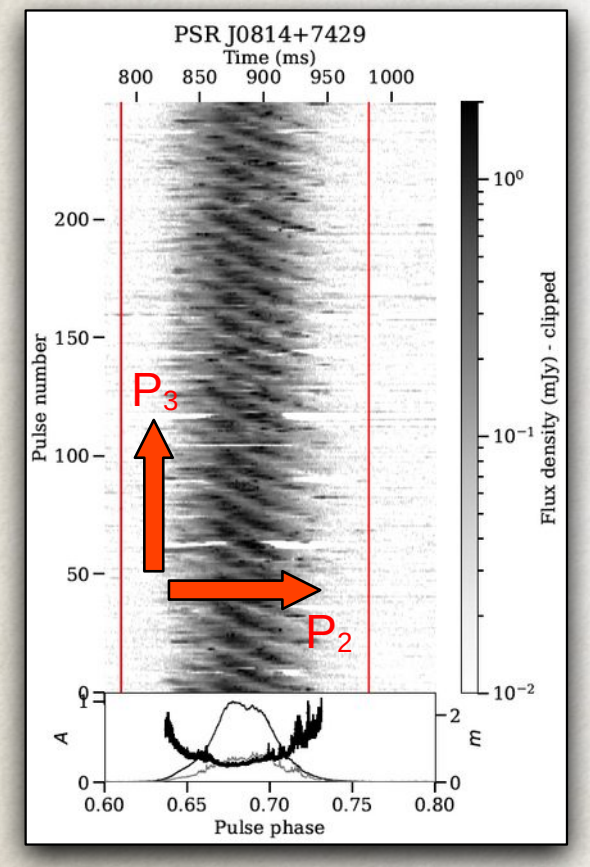
Fabian Jankowski

Fluctuation Spectral Analyses



Fabian Jankowski

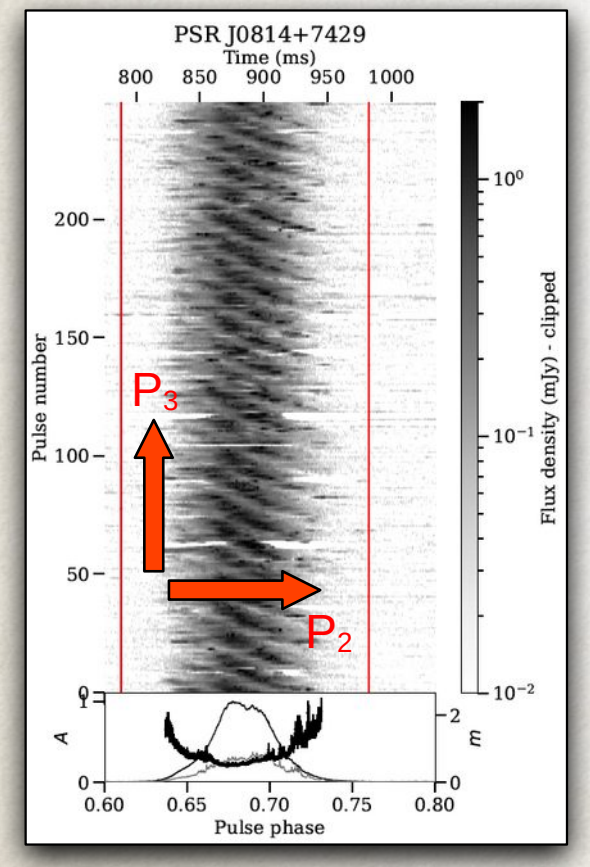
Fluctuation Spectral Analyses



- Measure single-pulse periodicities
  - Drifting sub-pulses
  - Longitude-stationary amplitude modulation

Fabian Jankowski

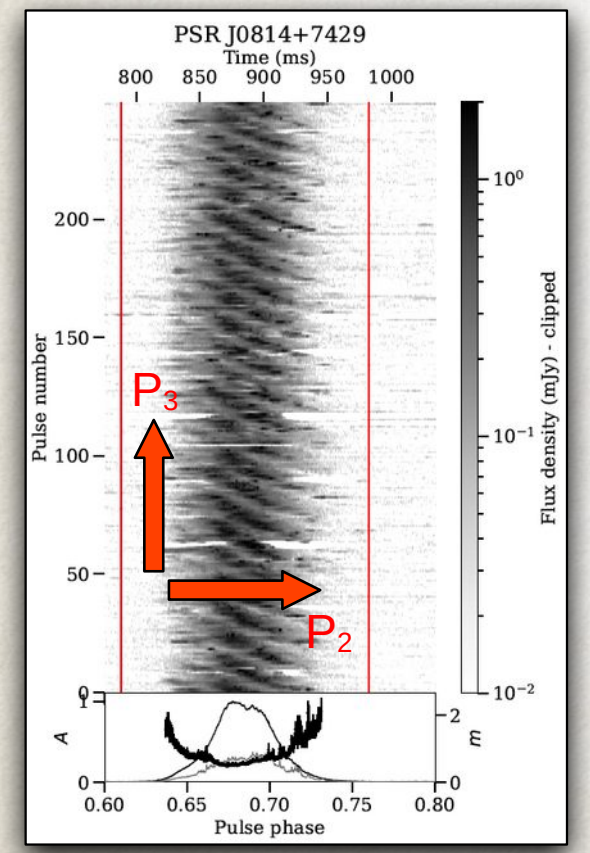
Fluctuation Spectral Analyses



- Measure single-pulse periodicities
  - Drifting sub-pulses
  - Longitude-stationary amplitude modulation
- Tools
  - Longitude-resolved fluctuation spectrum (LRFS)
  - 2-dimensional fluctuation spectrum (2dFS)

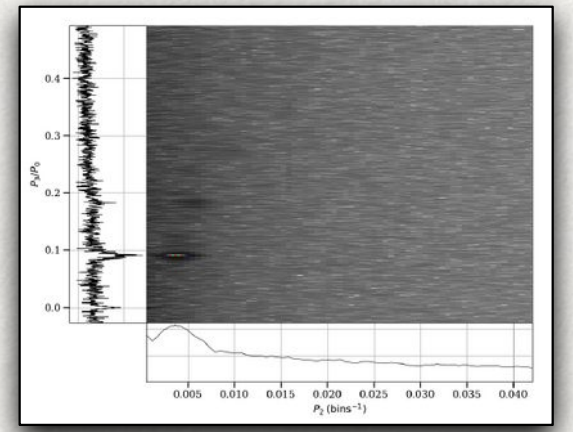
Fabian Jankowski

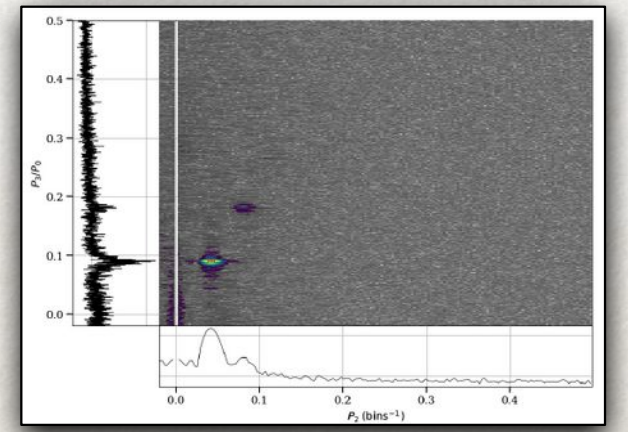
Fluctuation Spectral Analyses



Fabian Jankowski

GMRT



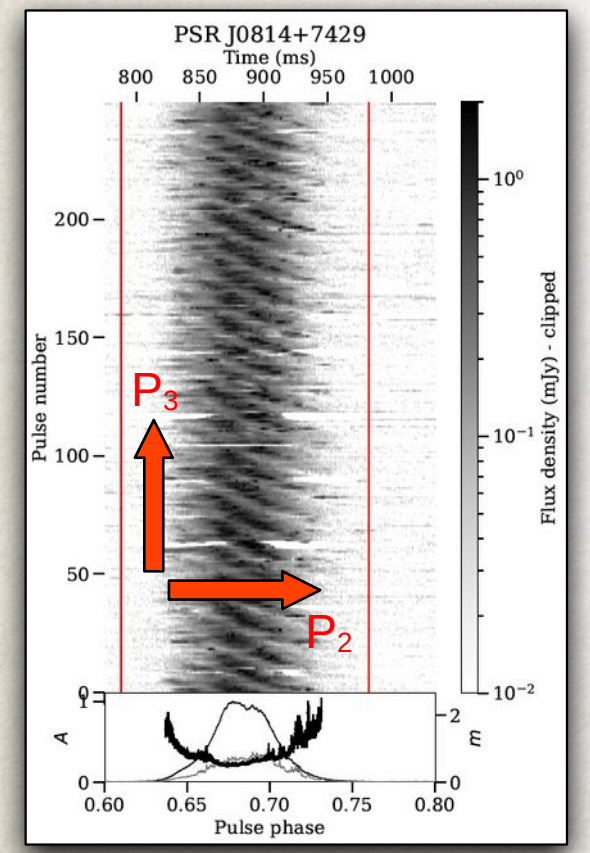


NenuFAR

Credit: K. Lebreton

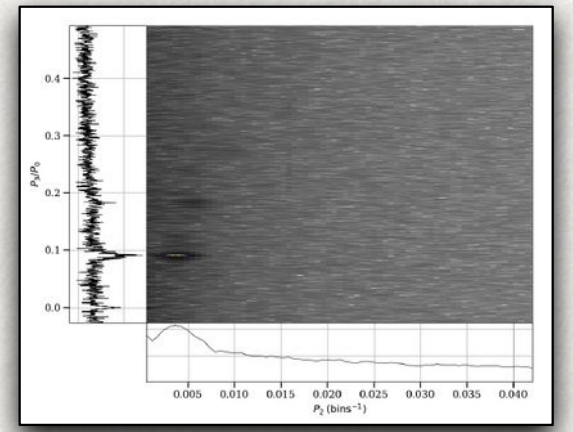
- Measure single-pulse periodicities
  - Drifting sub-pulses
  - Longitude-stationary amplitude modulation
- Tools
  - Longitude-resolved fluctuation spectrum (LRFS)
  - 2-dimensional fluctuation spectrum (2dFS)

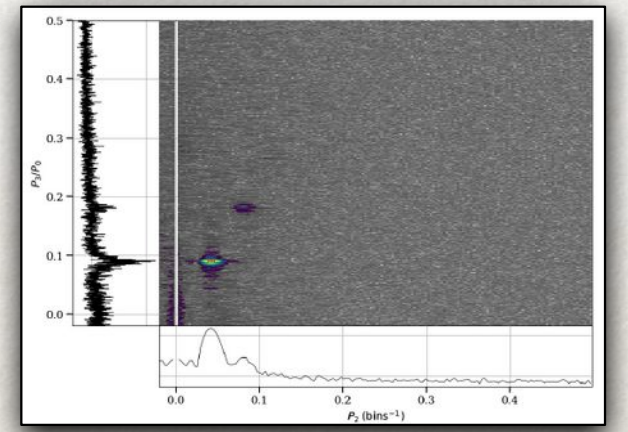
Fluctuation Spectral Analyses



Fabian Jankowski

GMRT





NenuFAR

Credit: K. Lebreton

- Measure single-pulse periodicities
  - Drifting sub-pulses
  - Longitude-stationary amplitude modulation
- Tools
  - Longitude-resolved fluctuation spectrum (LRFS)
  - 2-dimensional fluctuation spectrum (2dFS)
- Example:
  - Comparison NenuFAR & GMRT
  - → No frequency dependence

4. Preparation for SKA

Fabian Jankowski

Preparation for the SKA Era

- NenuFAR & GMRT are SKA pathfinders

Preparation for the SKA Era

- NenuFAR & GMRT are SKA pathfinders
- SKA will allow:
  - High-S/N single-pulse studies of a larger pulsar sample
  - Study the existing pulsars in greater detail
- Example: Thousand Pulsar Array (TPA) at MeerKAT

Preparation for the SKA Era

- NenuFAR & GMRT are SKA pathfinders
- SKA will allow:
  - High-S/N single-pulse studies of a larger pulsar sample
  - Study the existing pulsars in greater detail
- Example: Thousand Pulsar Array (TPA) at MeerKAT

- We expect to discover:
  - Many more peculiar pulsars
  - New single-pulse phenomena in new and known pulsars
- Improved data analysis tools
  - *spanalysis* (Python-based)
- SKA-low scheduling tool likely very similar to uGMRT one

5. Conclusions

Conclusions and Future Work

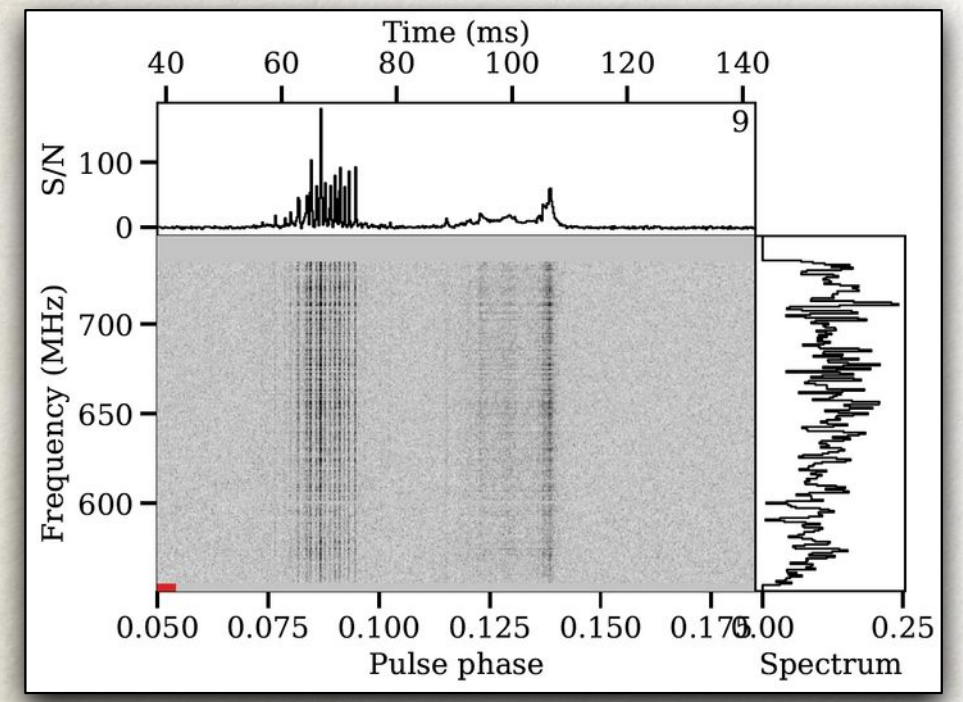
- The combination of high-S/N data with long-term observations is extremely powerful
- The NenuFAR data contribute significantly
- Having multi-frequency data allows many interesting tests
- Managing observations at several telescopes is non-trivial

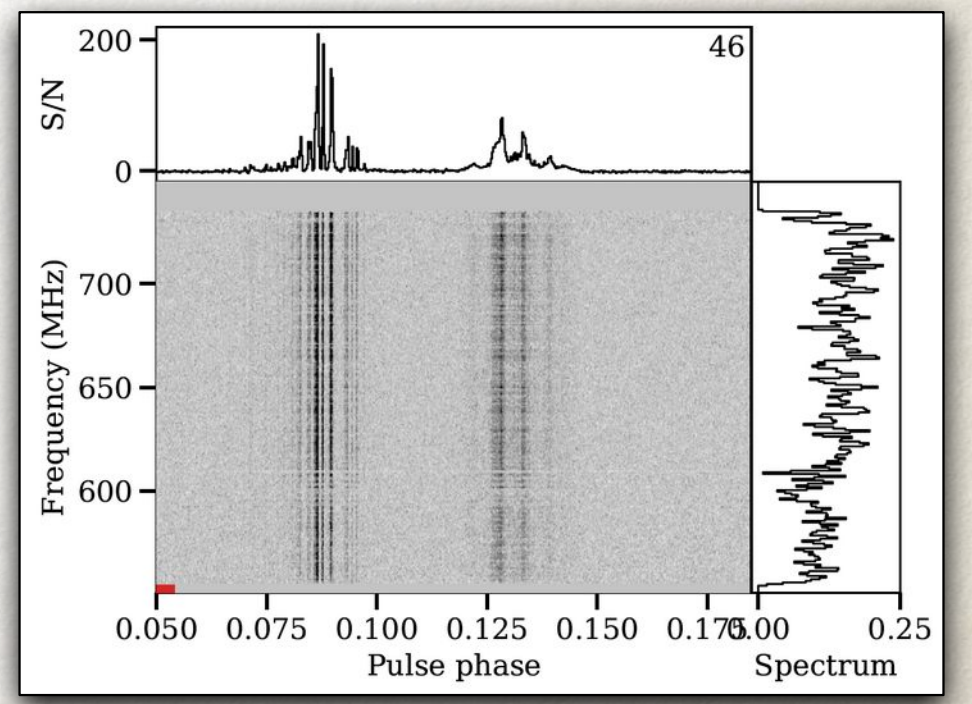
- We have barely scratched the surface of what is possible with this data set
- Lots of work still ahead to characterise more pulsars
- Probably work for several years
- SUSPECT project overview paper is under review
- Further papers are in preparation

Backup slides

SUSPECT Project – Single Pulse Morphology

Pulse Microstructure





FJ+ submitted

- Shot-like emission. Short-lived sparks.

Fabian Jankowski