Sub-GHz Radio Pulsar Emission - Lessons Learned and Predictions for SKA

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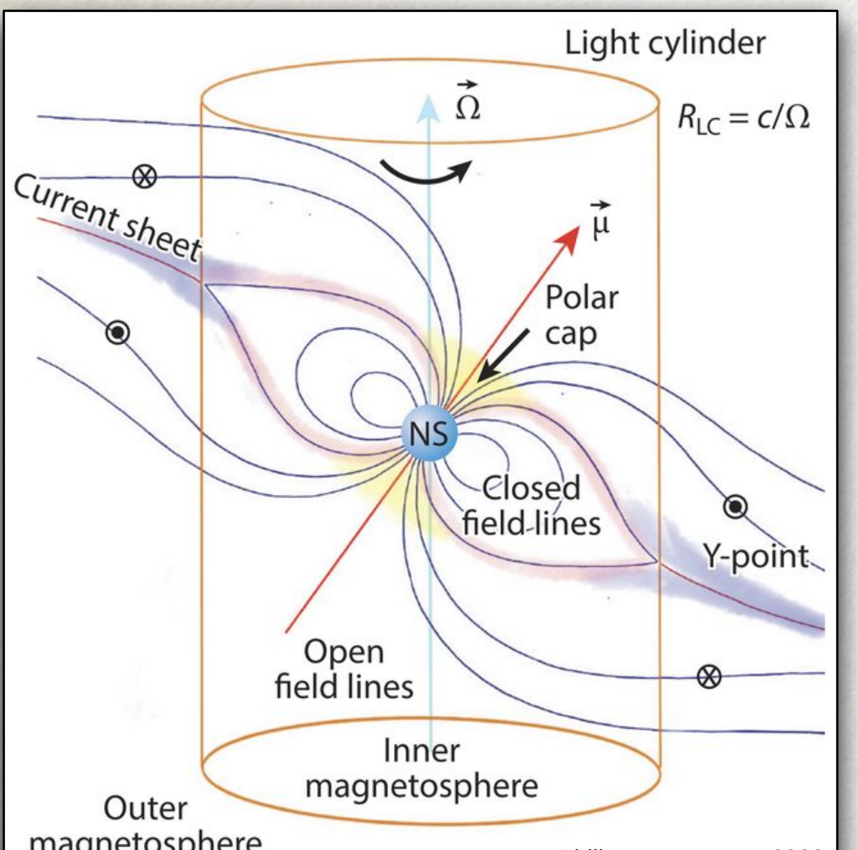
Talk Outline

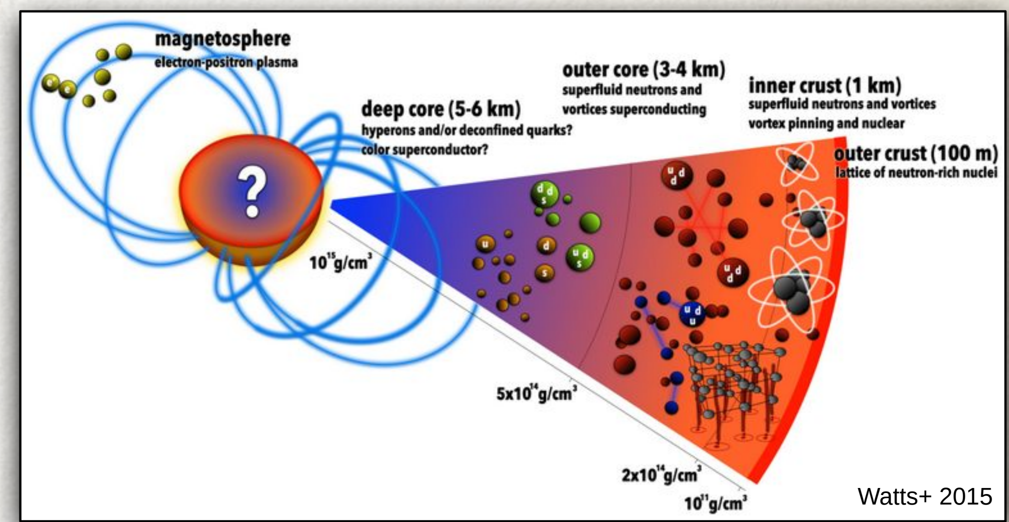
1. Motivation
2. Lessons Learned and Selected Results
3. Predictions for SKA AA*
4. Conclusions

1. Motivation

How does the Pulsar Radio Emission Work?



Philippov & Kramer 2022



Watts+ 2015

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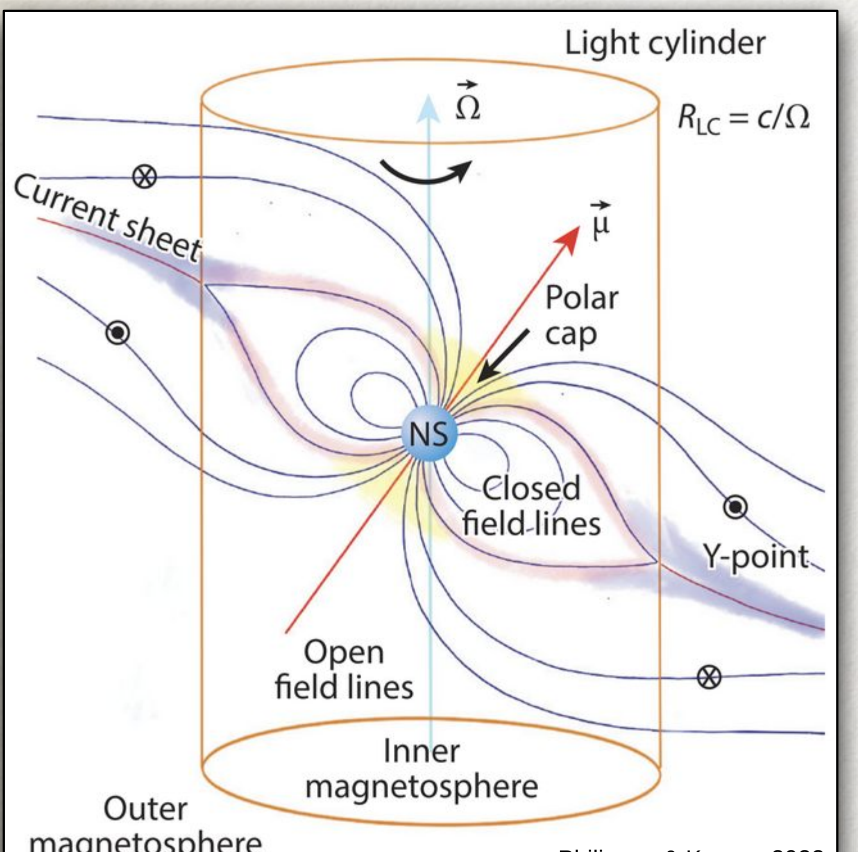

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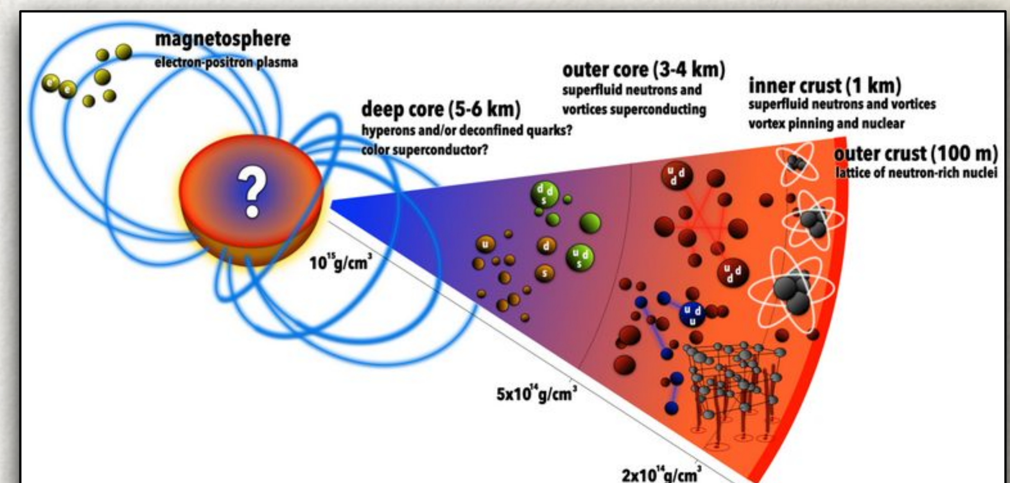


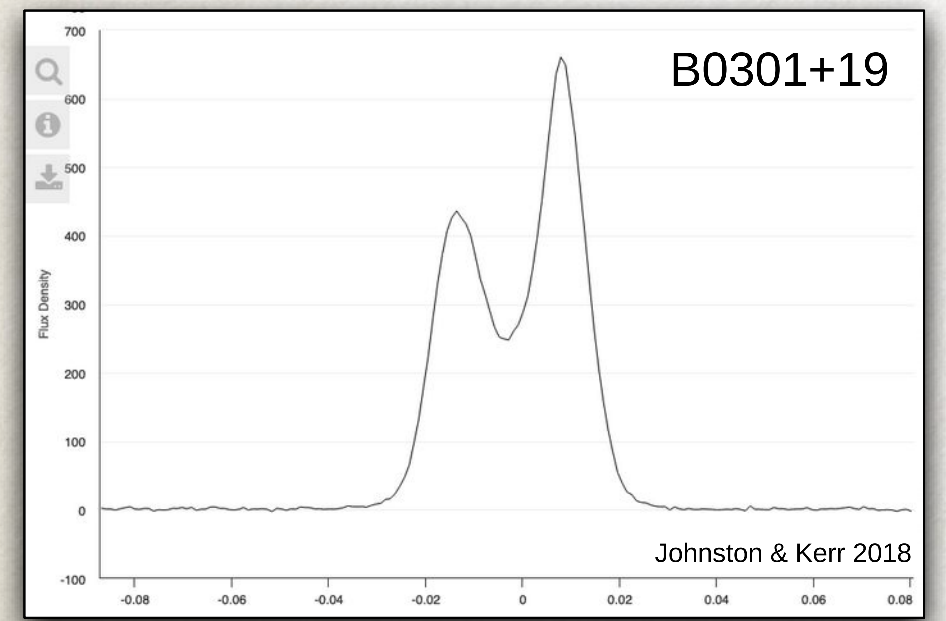
Watts+ 2015

- 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?

Integrated Pulse Profile vs Single Pulses

Integrated profile

O(10k) pulses averaged,
stable fingerprint



Integrate to increase S/N

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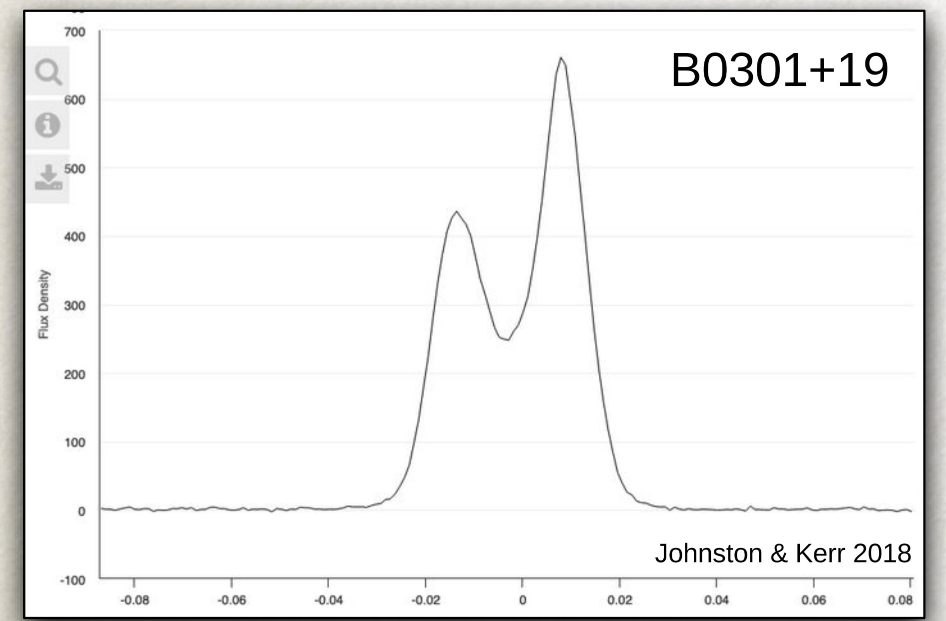
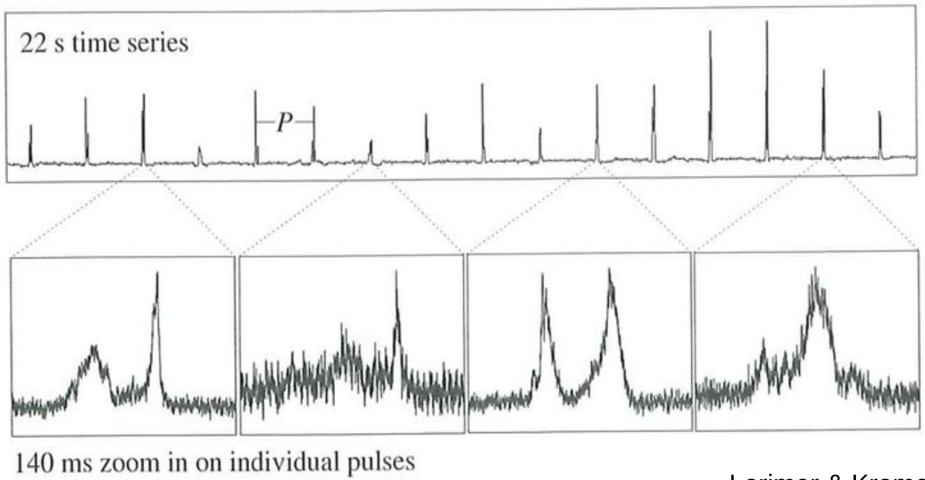


Johnston & Kerr 2018

Integrate to increase S/N

Individual single pulses

Pulse variability due to changes in magnetosphere



Lorimer & Kramer

Fig. 1.1. A 22 s time series from the Arecibo radio telescope showing single pulses from PSR B0301+19. Insets show expanded views of selected pulses.

Cannot integrate, instantaneous gain crucial

2. Lessons Learned and Selected Results

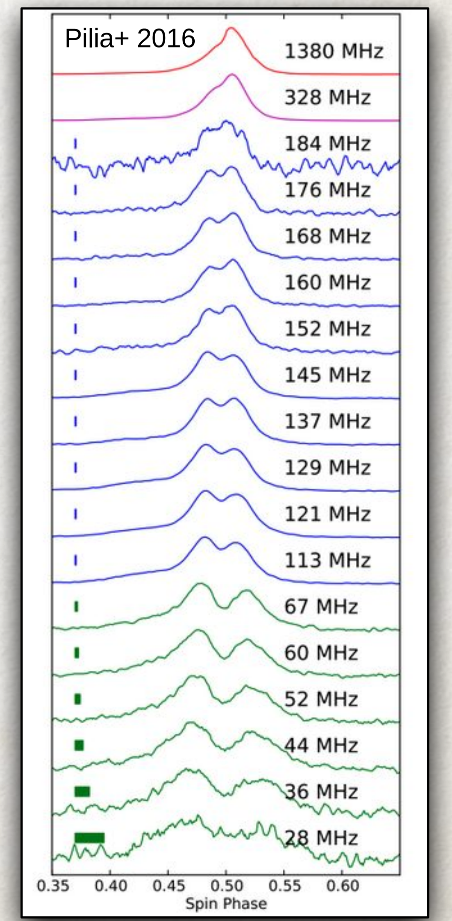
Relevant for SKA-Low and SKA-Mid Band-1

Fabian Jankowski

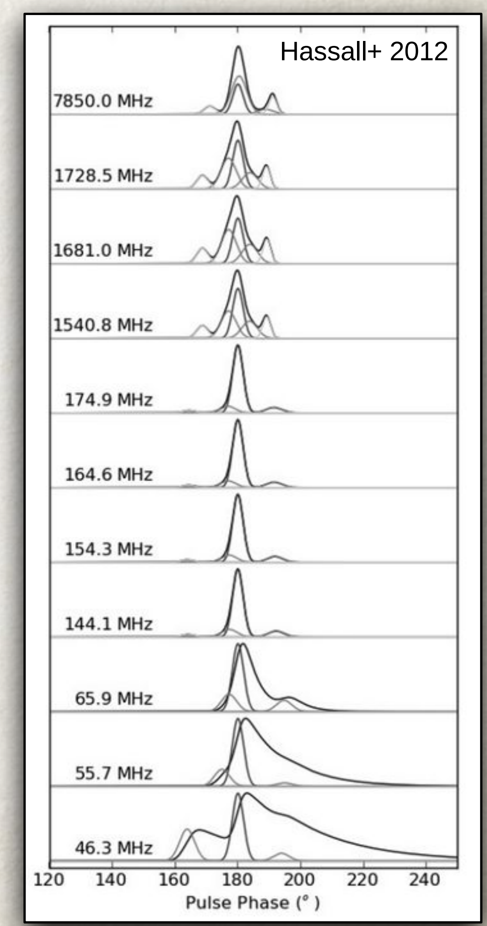
Early Low-Frequency Work

- 2012 – 2020
- Pulse profiles (Hassall+ 2012, Pilia+ 2016, Kondratiev+ 2016, Bilous+ 2020, Bondonneau+ 2020)
- Profile evolution (Hassall+ 2012, Pilia+ 2016)
- Radio spectra (Bilous+ 2016, 2020, Kondratiev+ 2016)
- Polarisation (Noutsos+ 2015)
- LOFAR (above), MWA (e.g. Bhat+ 2018), LWA (e.g. Stovall+ 2015), UTR-2 (e.g. Zakharenko+ 2013), GMRT (e.g. Basu+ 2016)

B0950+08



B0329+54



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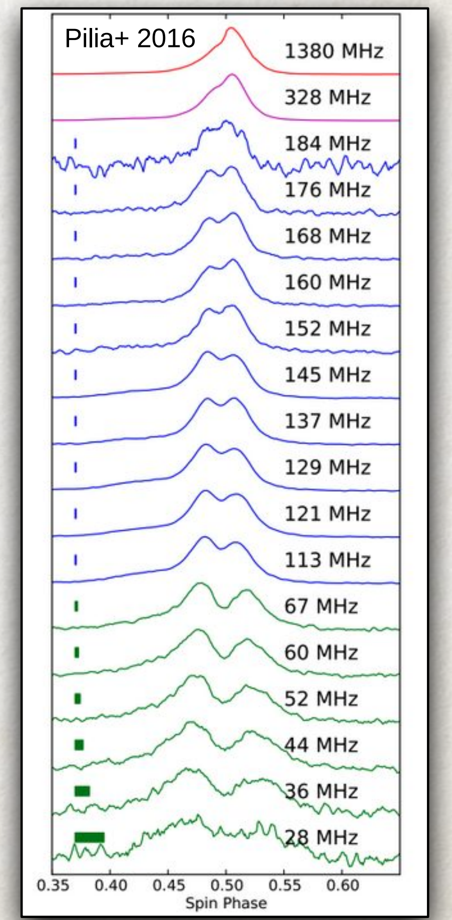
- Polarisation (Noutsos+ 2015)
- LOFAR (above), MWA (e.g. Bhat+ 2018), LWA (e.g. Stovall+ 2015), UTR-2 (e.g. Zakharenko+ 2013), GMRT (e.g. Basu+ 2016)
- Focussed mostly on pulsar detectability and integrated profiles

Census observations important. What pulsars are observable and how do they look like?

B0950+08



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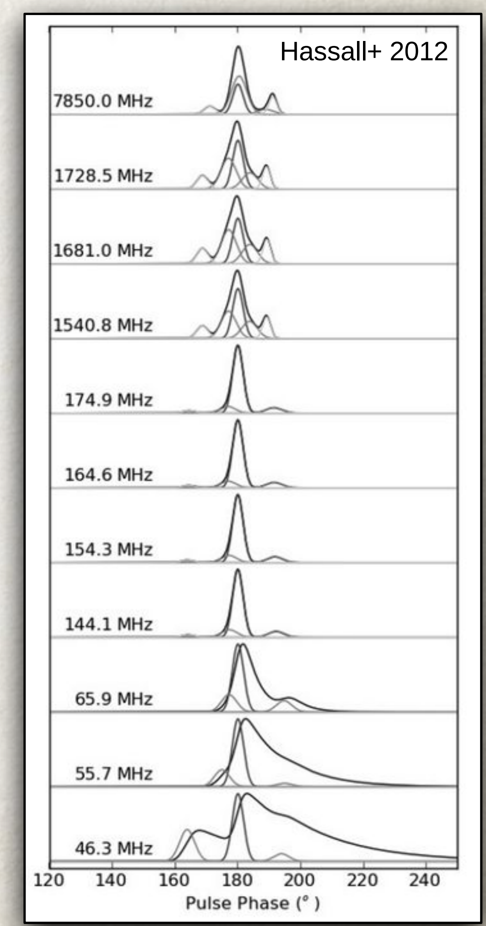
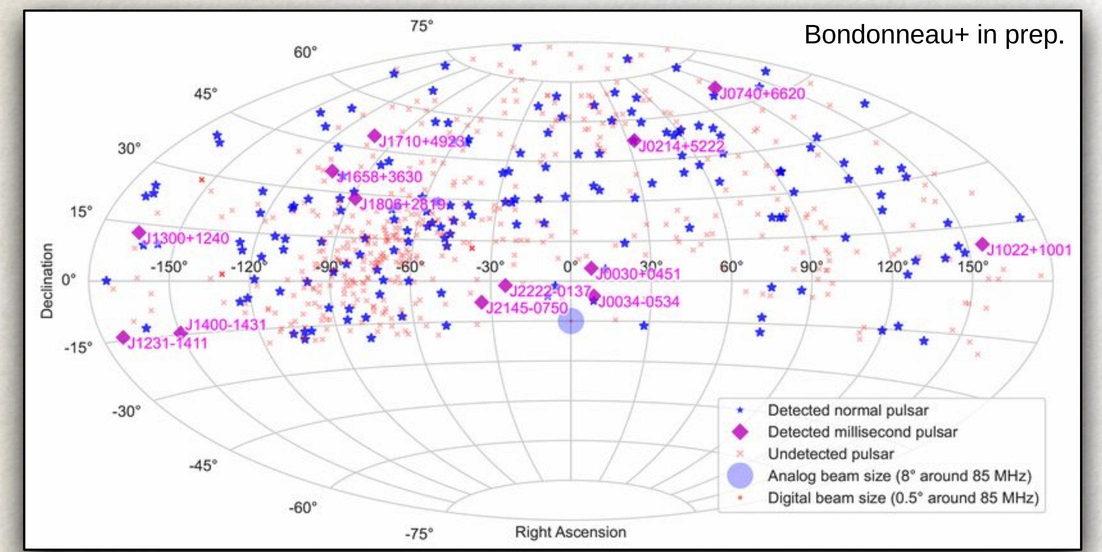


Pulsar Emission at the Lowest Radio Frequencies

NenuFAR Pulsar Census



- Early science (~50 % collecting area)
- ~700 known pulsars observed at 10–85 MHz
  - $\delta \geq -20$ deg, DM ≤ 100 pc cm^{-3}
- ~180 canonical pulsars detected, ~100 for the first time below 100 MHz
- 13 MSPs detected, 10 for the first time below 100 MHz
- >24 PSRs in single pulses

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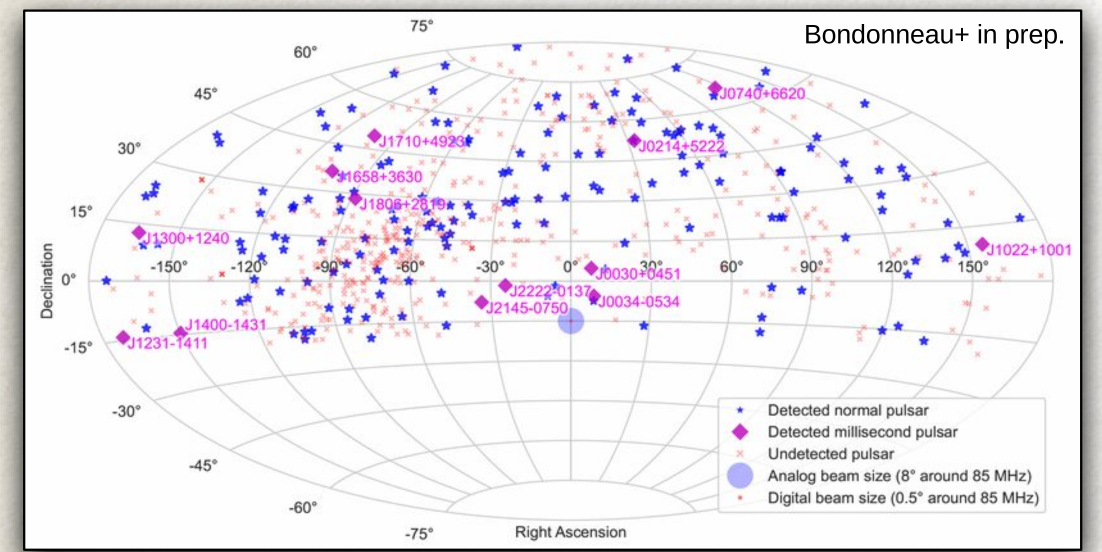
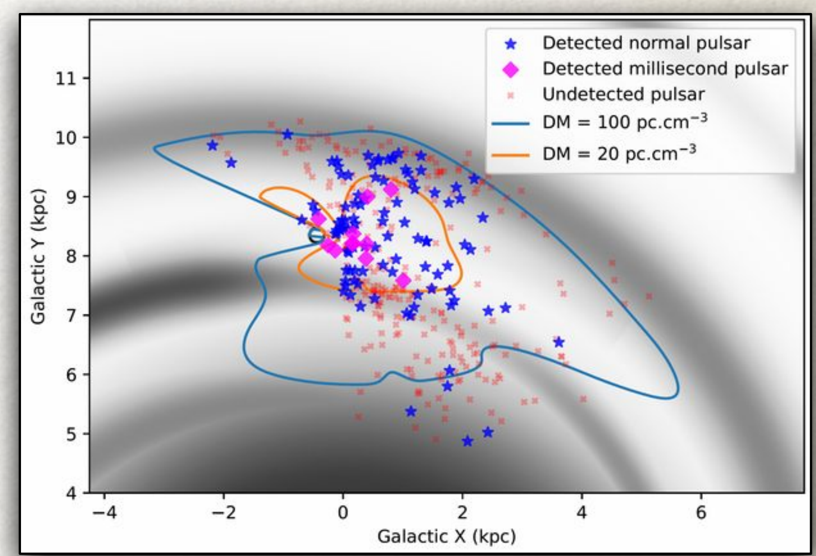
NenuFAR Pulsar Census

Credit: L. Bondonneau





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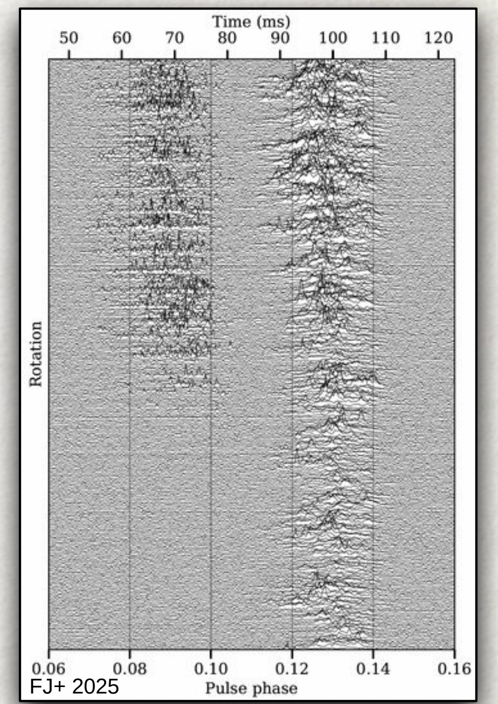
- Evidence for selecting steeper spectral index pulsars (v.d. Wateren+ 2023)
- First leap for VHF pulsar science

Despite this, low-frequency pulsar sky is still underexplored. Excellent SKA-Low sensitivity will help.

Single Pulse Work

- Including NenuFAR (Bilous+ 2022)
- GMRT projects (Mitra+, Basu+, Polish teams)
- Arecibo P-band (Rankin+)
- SUSPECT Project (FJ+, 2023 – present)
    - Spin-off work (Limaye+ in prep.)



PSR B1822-09 uGMRT

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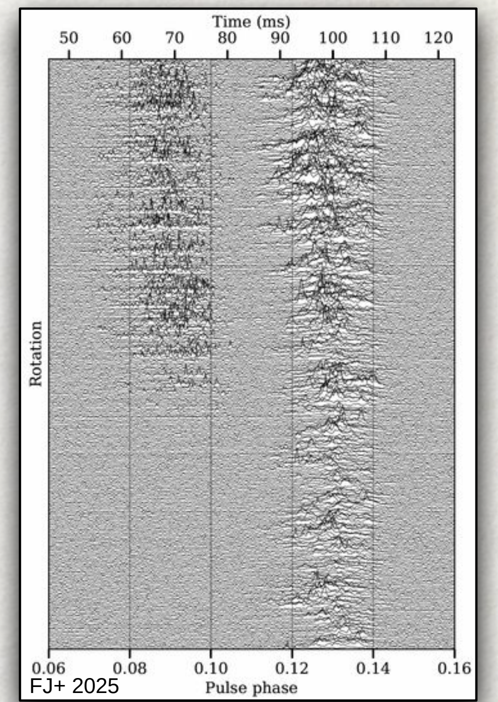
- Still discovering new phenomena (e.g. *swooshing*, amplitude modulation, weak or rare modes, profile components)
  - Better data
  - Refined data analysis methods
  - *'Looking at things'* (more eyeballs on data)



FJ+ 2025

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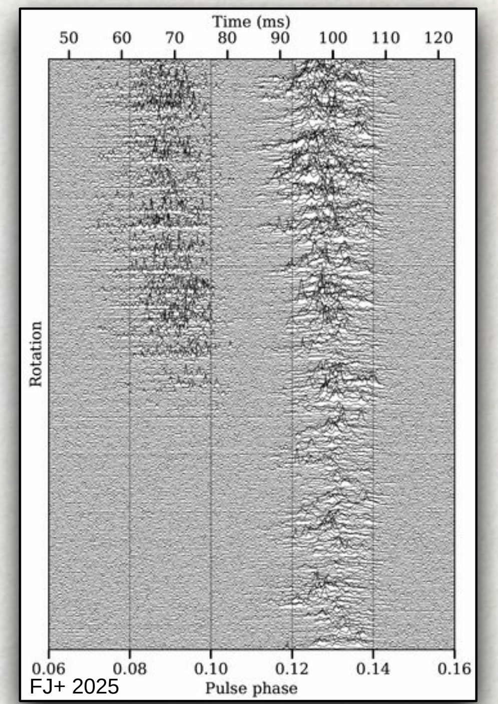
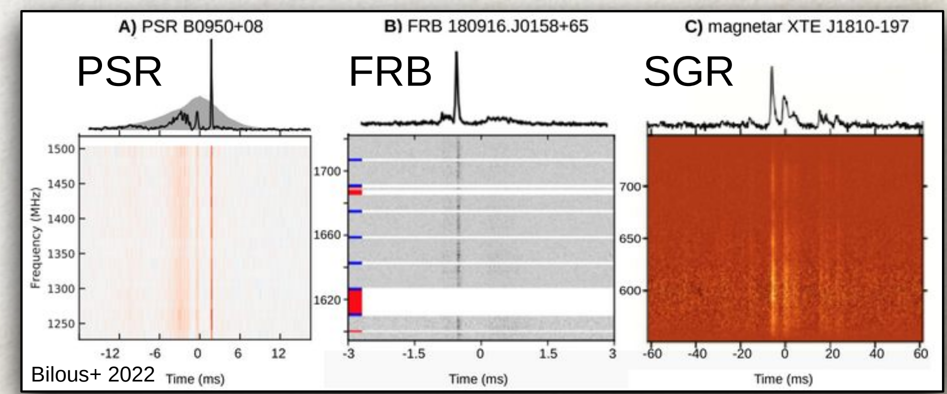
- Similarities with magnetars and FRBs



PSR B1822-09 uGMRT

Highly relevant, timely, and high discovery potential.



The SUSPECT Project

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 (M2 students),
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Jankowski+ 2025

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Understanding the Pulsar Radio Emission

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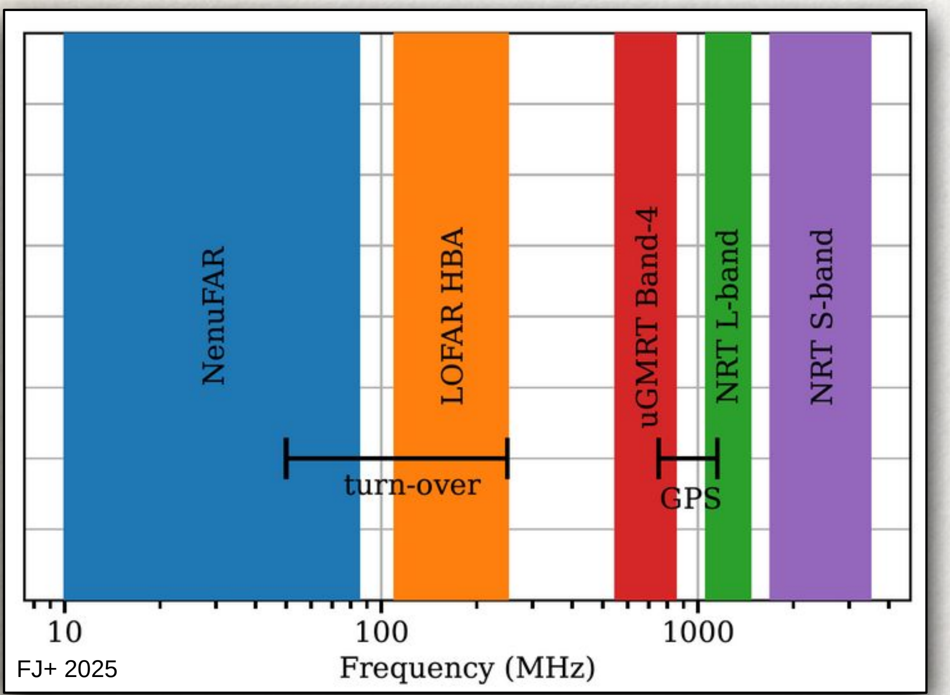

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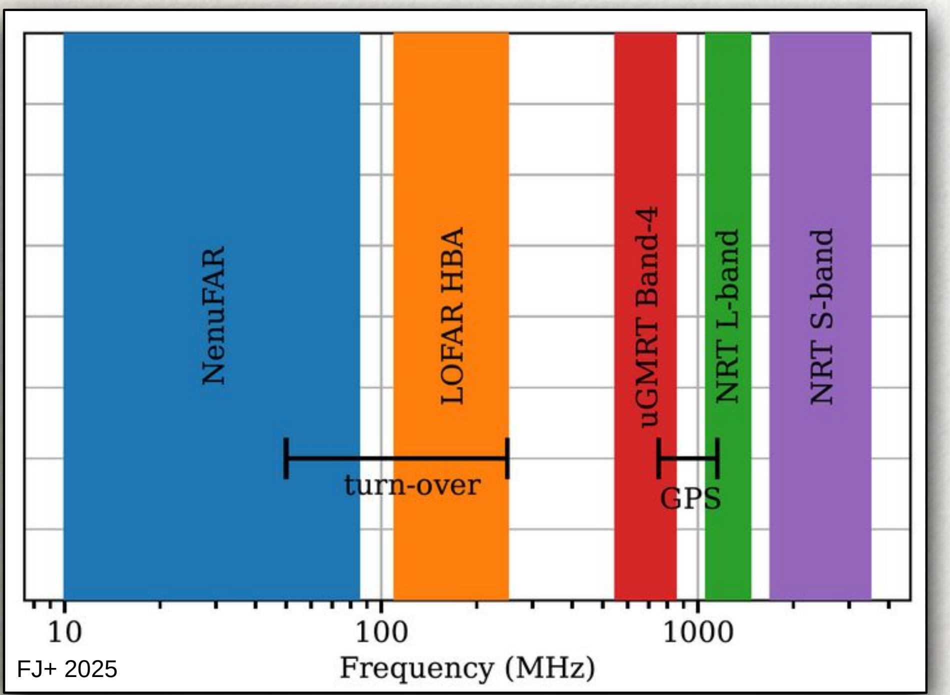

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  - Study single-pulse properties (PE distributions, modulation)
  - Others: pulse profiles, radius-to-frequency mapping

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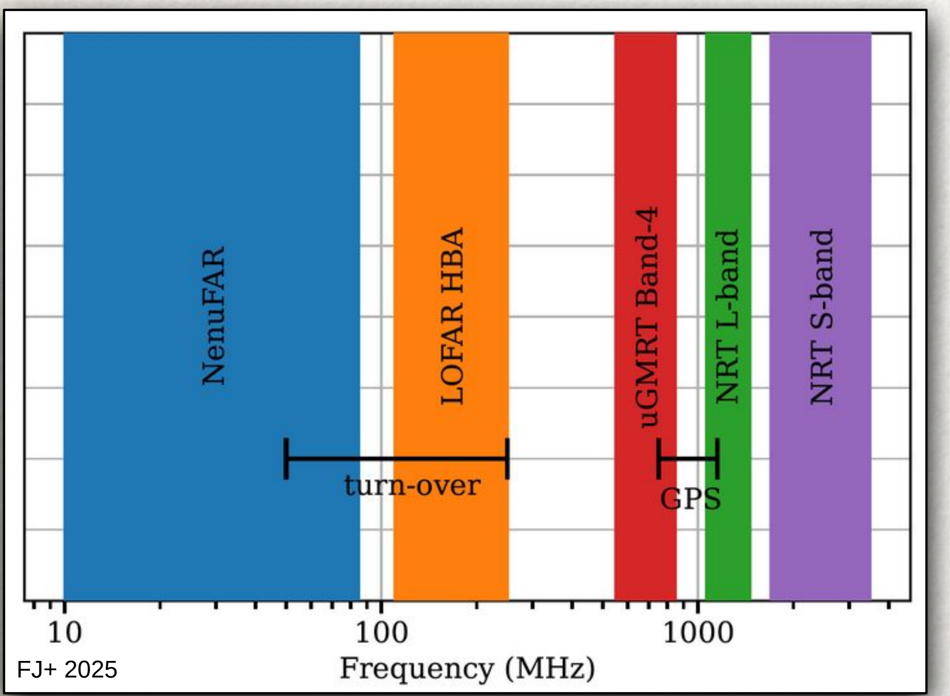

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  - Master's M2R projects
    - 2023: Killian Lebreton
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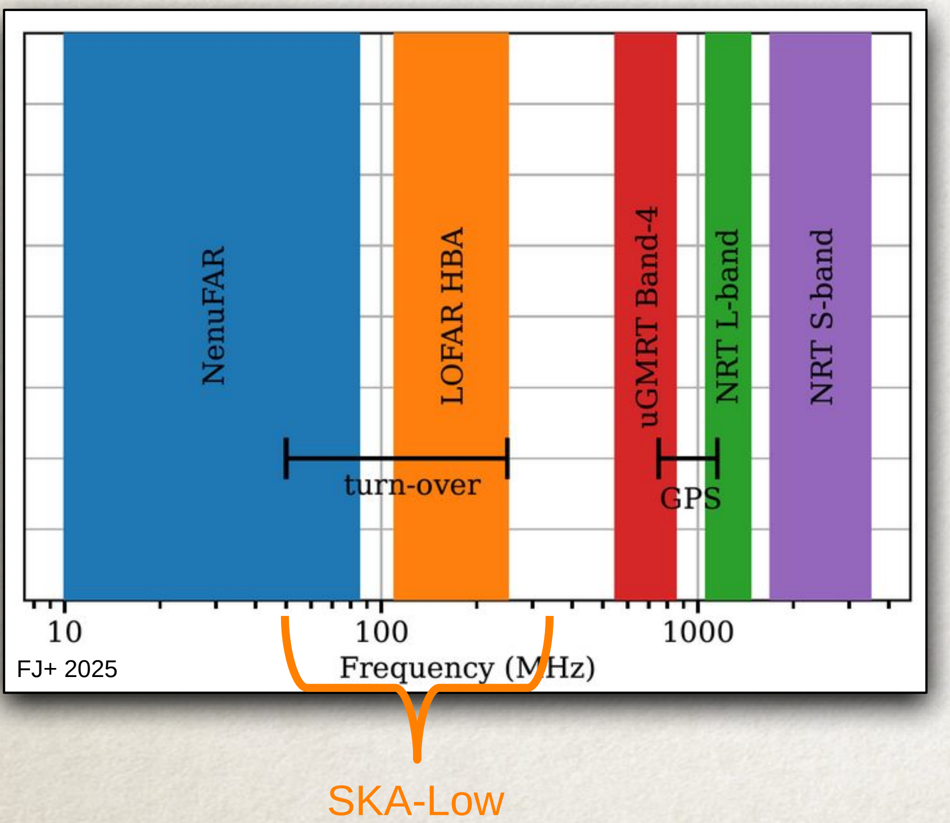

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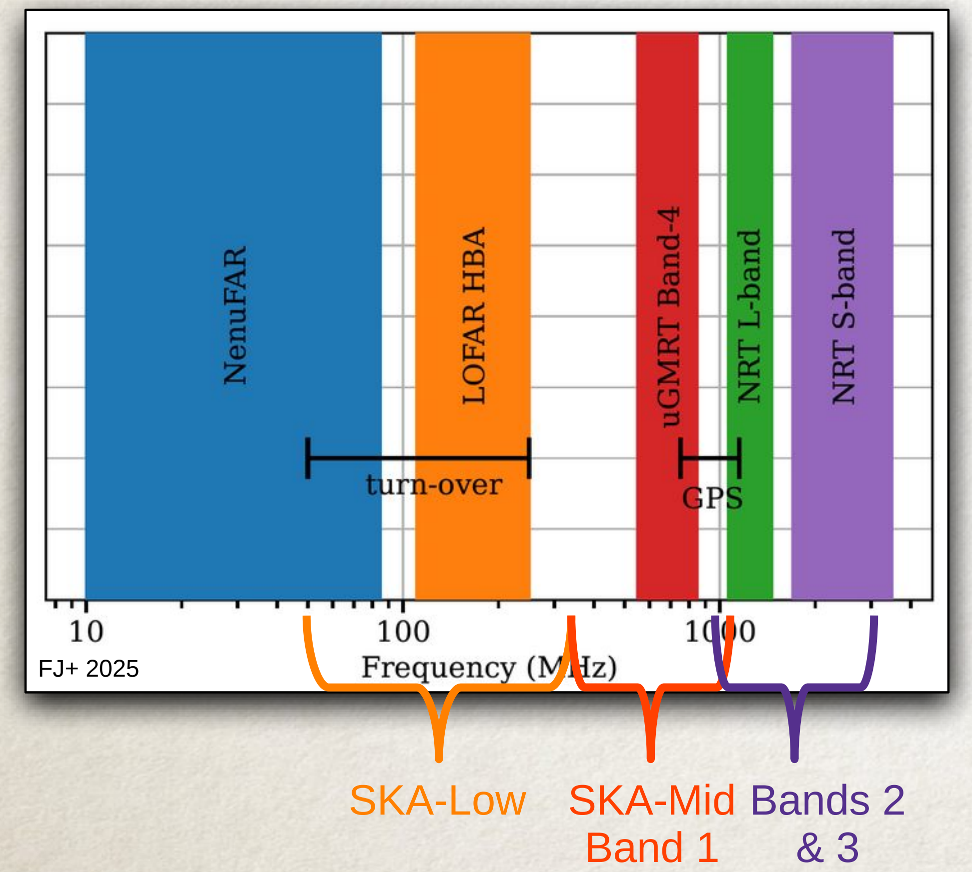

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Understanding the Pulsar Radio Emission

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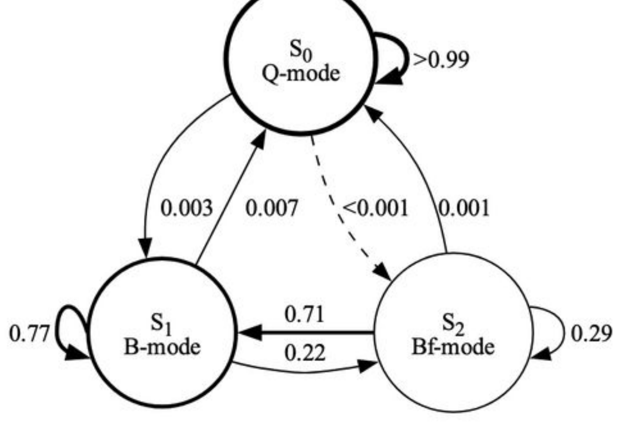
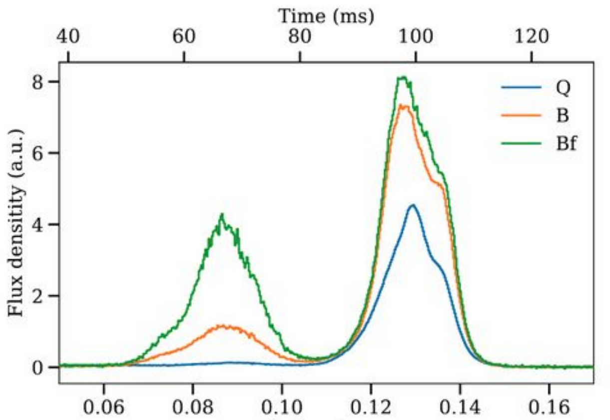
  - Hidden Markov Model with autoregressive emissions (atomic transitions)
  - Investigated other new approaches

FJ+ 2025





FJ+ 2025

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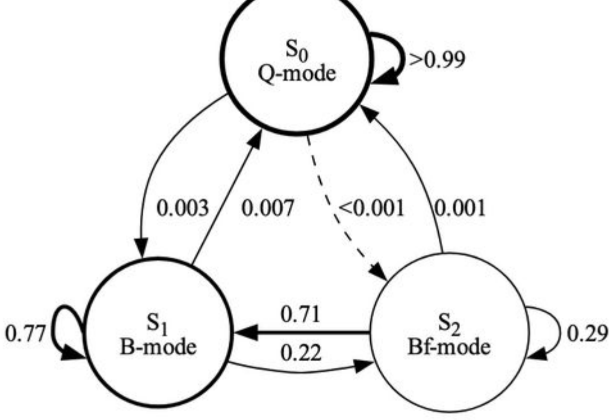
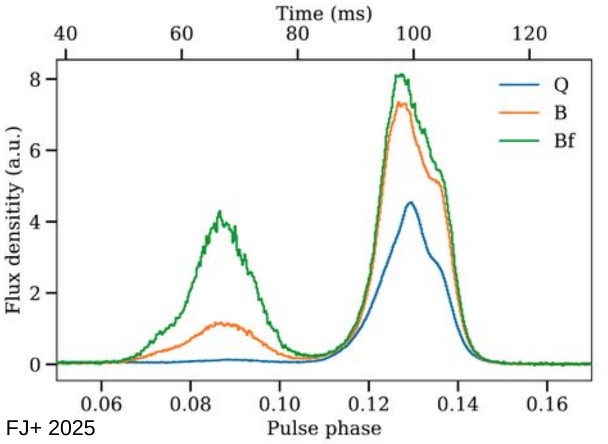
- Microstructure analysis & modulation
- Also: PE distributions, 2D amplitude distribution, profile evolution, sub-pulse drifting

FJ+ 2025





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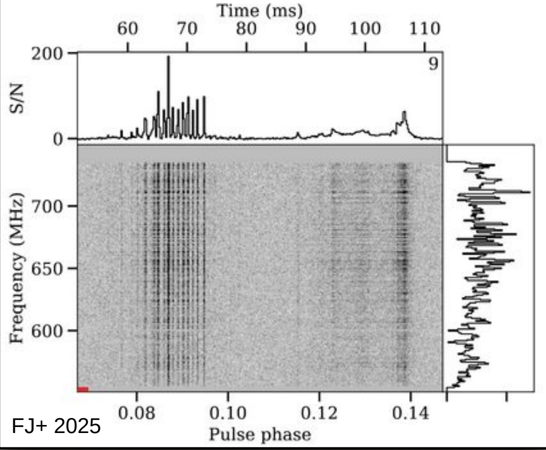
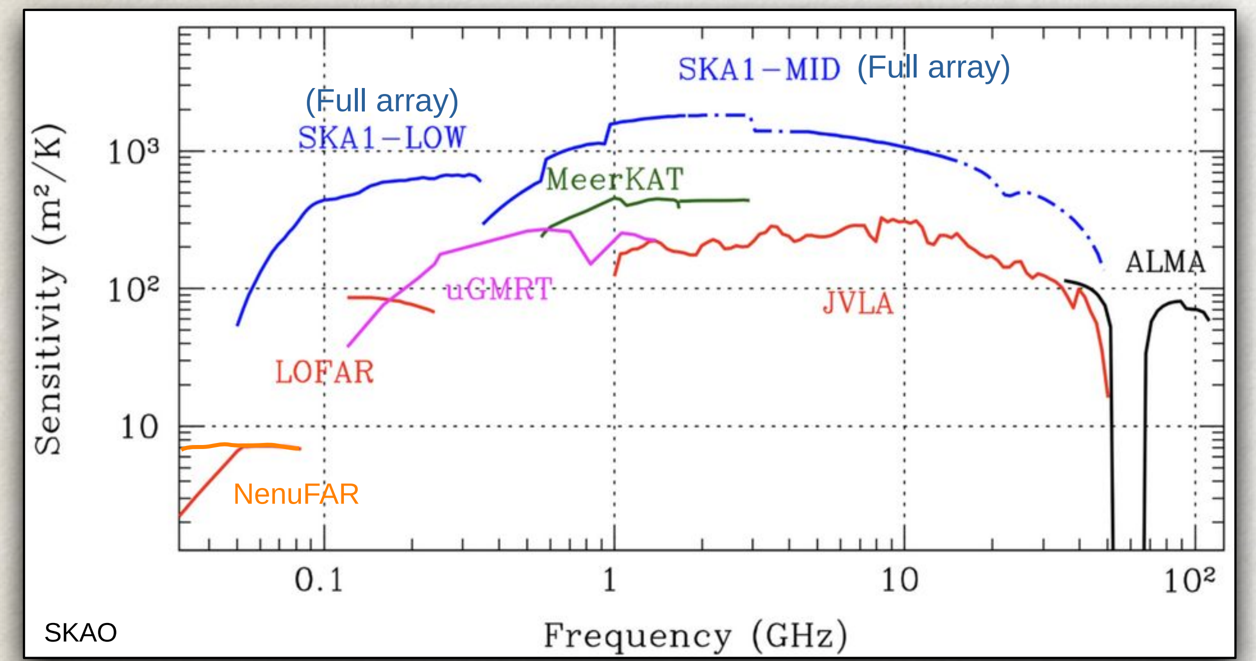


FJ+ 2025

4. Predictions for SKA AA*

Instantaneous Sensitivity and Frequency Coverage



- Scaling for AA*
  - Low: 60 % (307 / 512 stations)
  - Mid: 73 % (80 + 64) / 197 dishes

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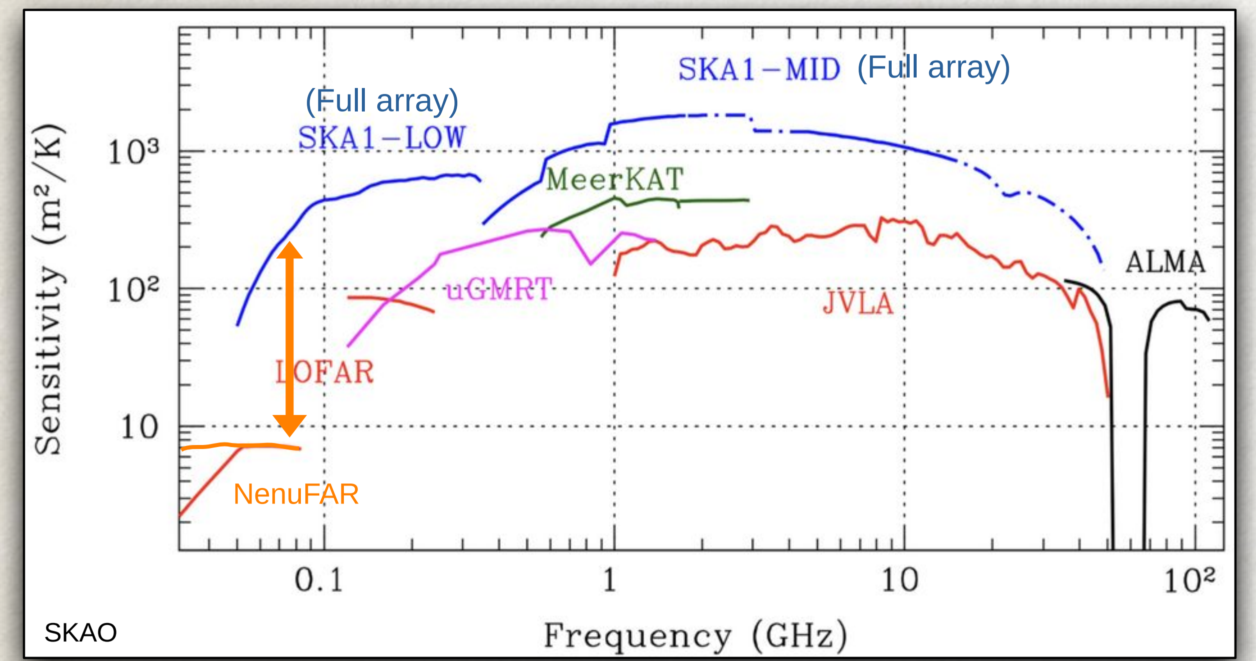

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  - ~4x LOFAR HBA
  - ~20x LOFAR LBA
  - ~2x uGMRT Band-4
  - ~2x MeerKAT UHF
- Also
  - Better RFI environment
  - Wider instantaneous bandwidths

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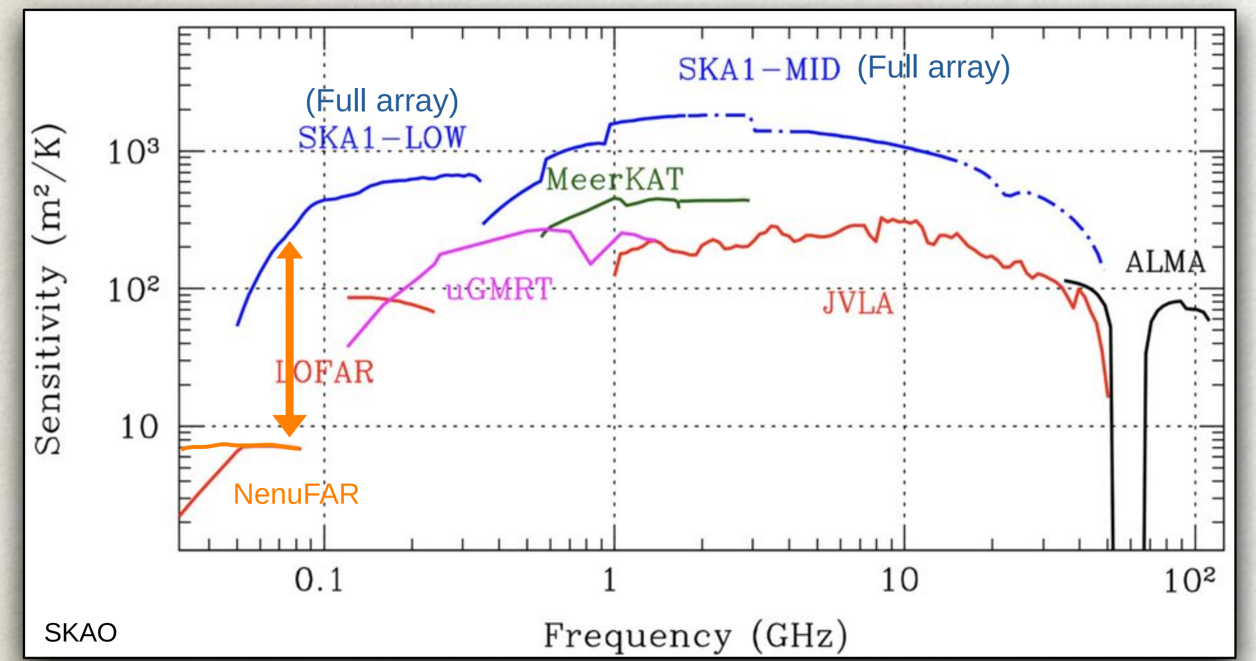

- Instantaneous sensitivity crucial for single pulse studies (cannot integrate)

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Pulsar science at LBA – HBA frequencies will receive huge boost.

Predictions for SKA-Low and Mid Band-1

- SKA will allow:
  - High-S/N single-pulse studies of a larger pulsar sample
  - Study the known pulsars in greater detail
    - And for longer durations (sub-arrays)
- Examples:
  - Thousand Pulsar Array (see previous talks)
  - GMRT projects
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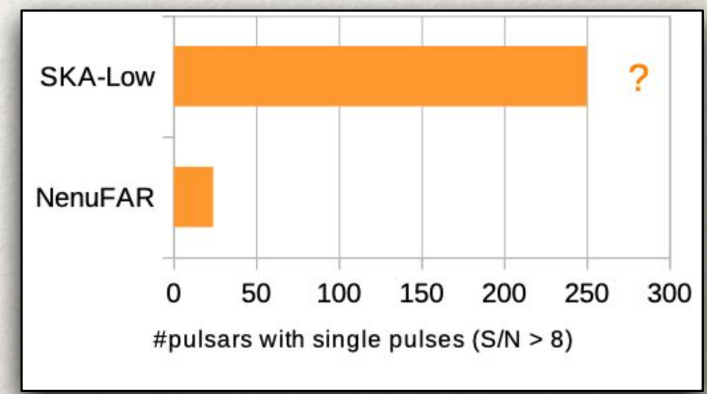

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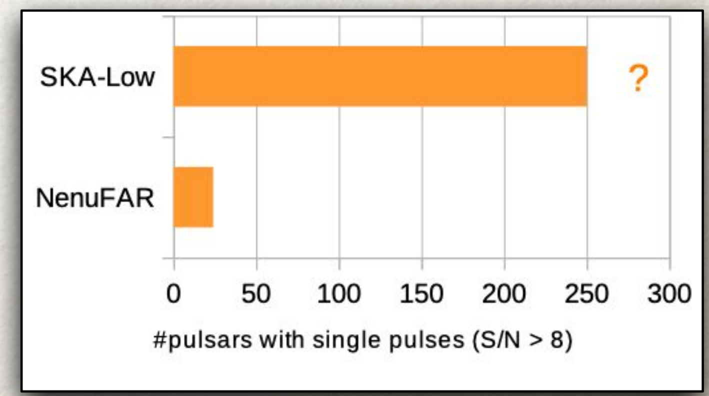
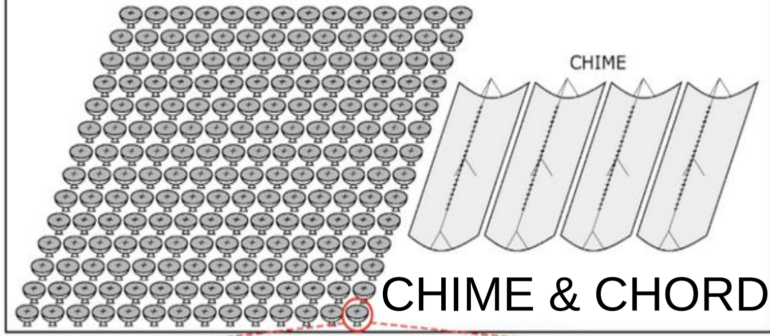
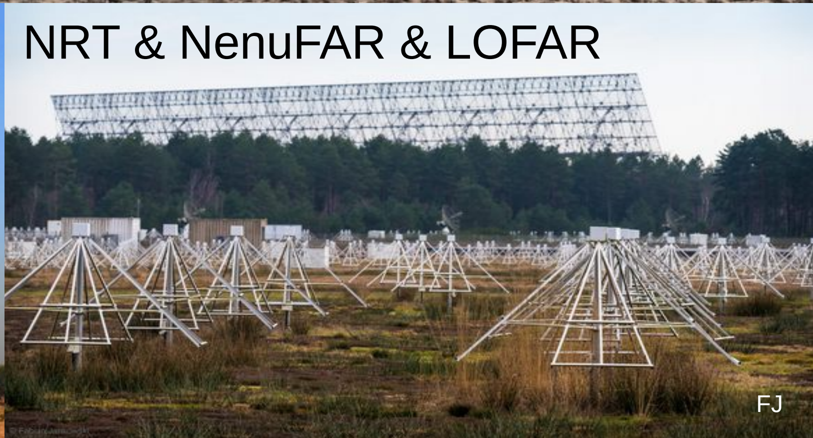
- We expect to discover:
  - Many more peculiar pulsars
  - Known phenomena in more pulsars (nulling, mode switching, drifting, giant pulses, *swooshing*)
  - New single-pulse phenomena in new and known pulsars
  - More (types of) profile variability



SKA Northern Hemisphere Synergies

- Complementary pulsar programmes with northern hemisphere telescopes
  - GBT, NRT, FAST+, CHIME, CHORD, DSA-2000, Effelsberg, LOFAR 2.0, NenuFAR, JBO, JVLA





Need Improved Data Analysis Tools

As we enter the SKA AA* era

- Excellent data quality (S/N)
- Wide fractional bandwidths
  - 300 MHz Low; >700 MHz Mid

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- Data analysis tools must keep up!
  - Sensitivity to more subtle physical effects
  - Wide bandwidths & profile evolution
  - Inherent assumptions
  - Objective classification
  - Runtime performance
  - Verification
  - Systematics

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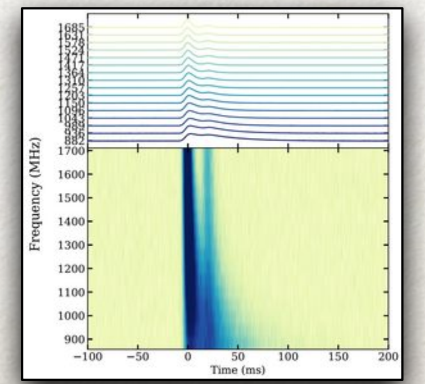
Our Efforts

- *spanalysis* (Python) – Single pulse data analysis suite
- Mode switching detector (Python) – Hidden Markov switching model
- *fitpdf* (Python) – Bayesian unbinned distribution fitting
- *scatfit* (Python & Cython) – Pulse/FRB simulation and scattering fit suite

Simulated data & fit



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ASCL: 2208.003

https://github.com/fjankowsk/scatfit

5. Conclusions

Conclusions

Challenges

- DM(t)
- Scattering
- Sky temperature
- Sensitivity
- Software tools

Predictions

- Huge sensitivity jump below 100 MHz
- Large increase < 1 GHz
- Larger sample of PSRs
- Discover new single-pulse phenomena
- More types of profile variability

Synergies

- Complementary with northern hemisphere pulsar programmes
- Well aligned with upcoming (survey) telescopes

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