Holloway/Weltevrede

Jodrell Bank Pulsar Group

Ben Stappers

Who are we?

PDRAs

- Cees Bassa (LEAP)
- Cristobal Espinoza (Fermi/Glitches)
- Rob Ferdman (Precision Timing)(McGill)
- Gemma Janssen (LEAP)
- Sotirios Sanidas (Strings/GWs)

Academic Staff

- Ben Stappers (HOG/All)
- Patrick Weltevrede (Fermi/Emission)
- Michael Kramer (All)

Emeritus

- Andrew Lyne (All)
- Graham Smith (Emission/Books)

Technical/ Engineer Staff

- Christine Jordan (Obs/Software)
- Aziz Ahmedsaid (Technology)

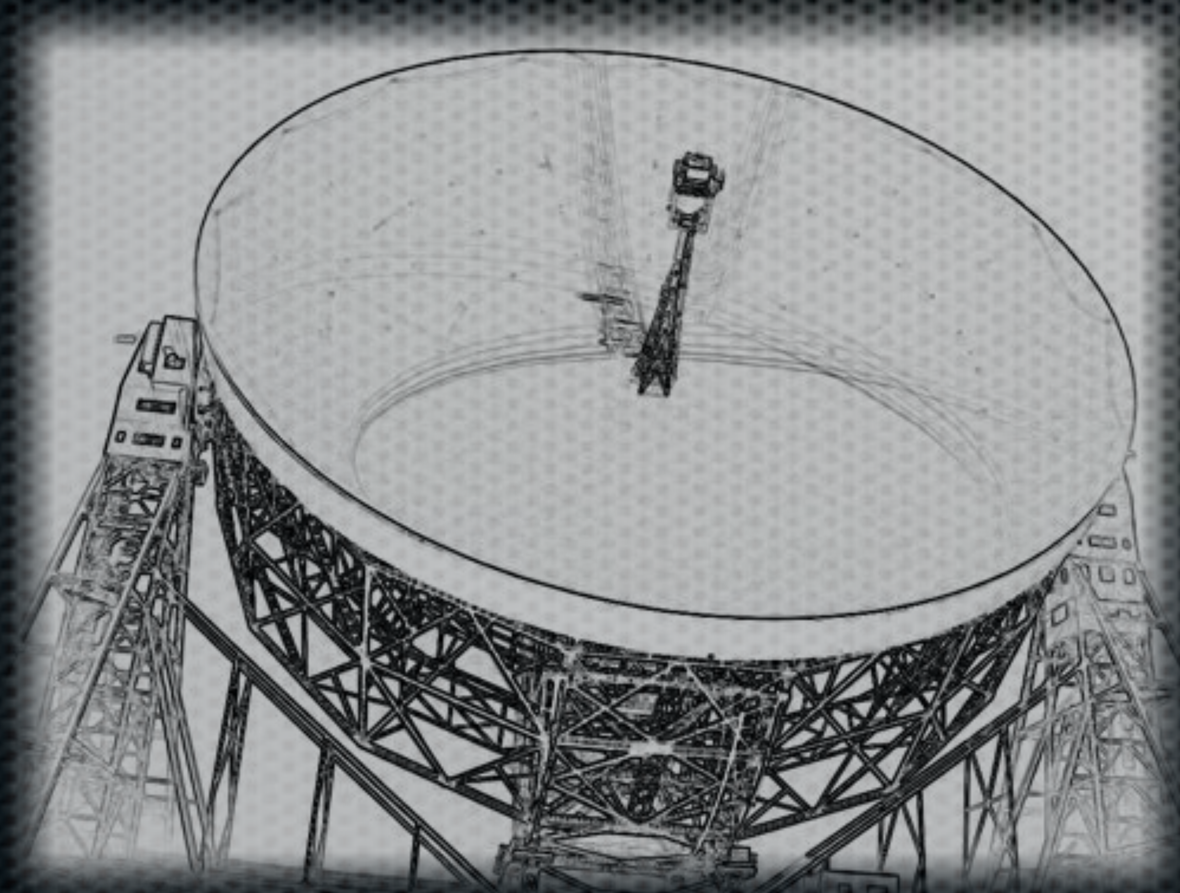
Students

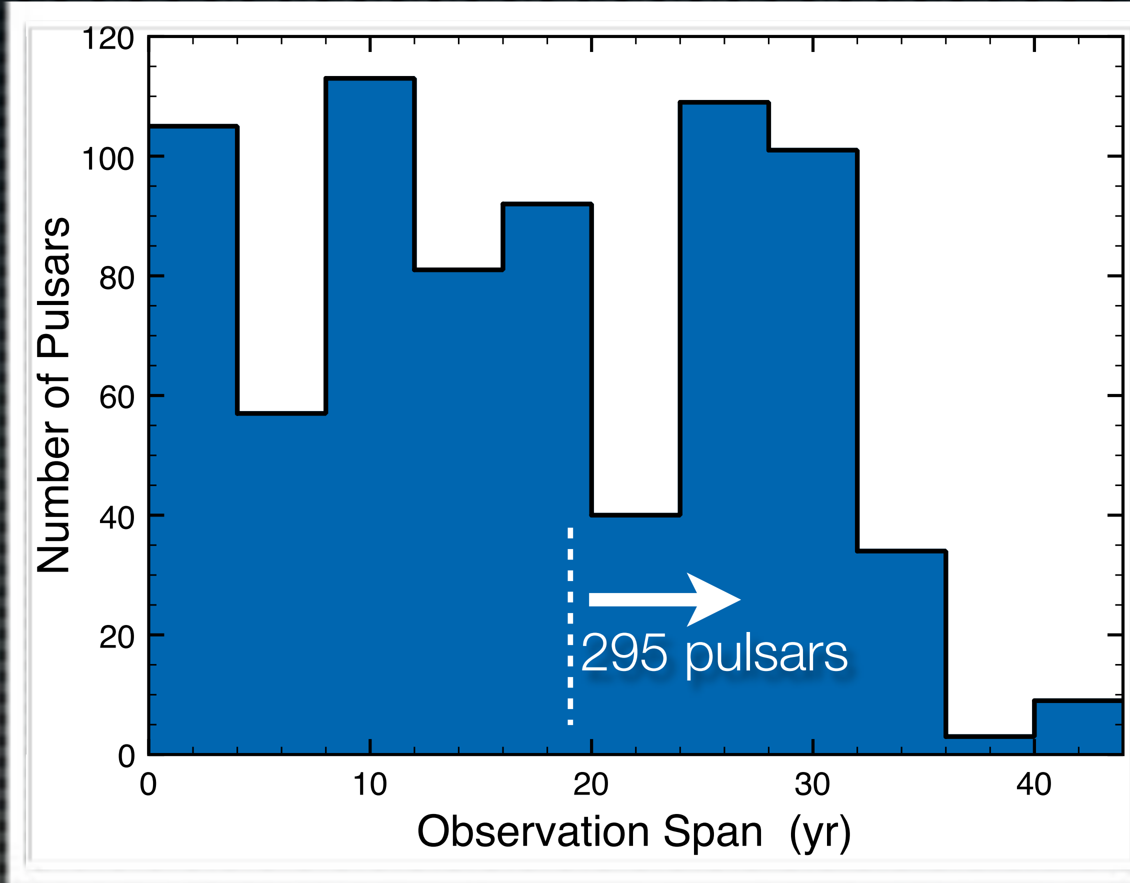
- Math (4th yr, Polarisation)
- Dan Thornton (3rd year, Searches)
- Monika Obrocka (2nd year, MUST)
- Rob Lyon (1st year, Machine Learn)
- Sally Cooper (1st year, LOFAR)
- Simon Rookyard (1st year, Emission)
- Shuxu Yi (visiting China/GWs)
- Helen Johnson (intern/Intermittents)
- Gary Marchiny (visiting WVU/Transients)

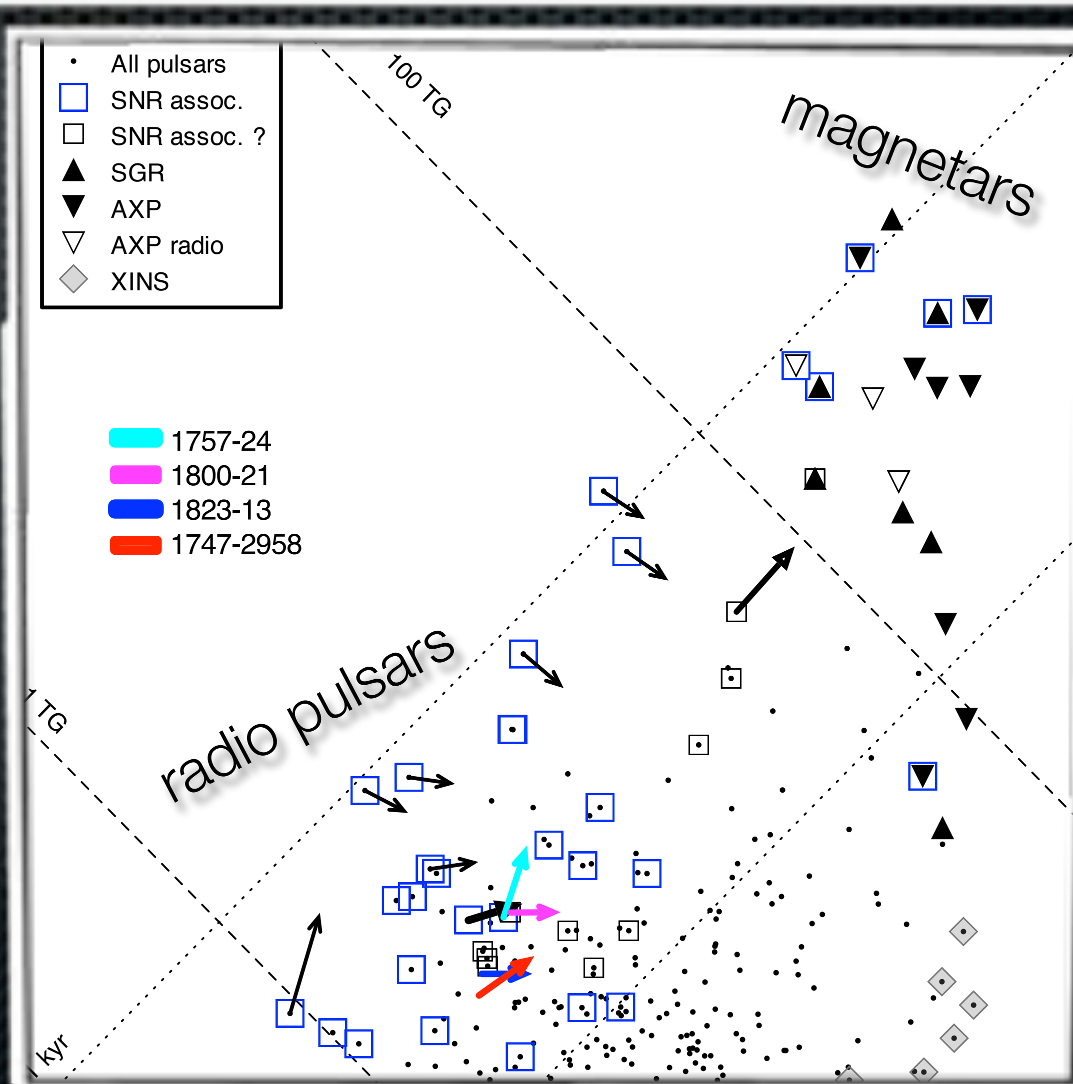
JBO Pulsar Timing database

Unique monitoring of more than 700 pulsars/100 MSPs

- ✦ Long-term spin evolution: B-evolution, population studies.
- ✦ Glitches: large database, interior physics.
- ✦ Timing irregularities, transient phenomena.
- ✦ Support to other projects (GW/high-energy)



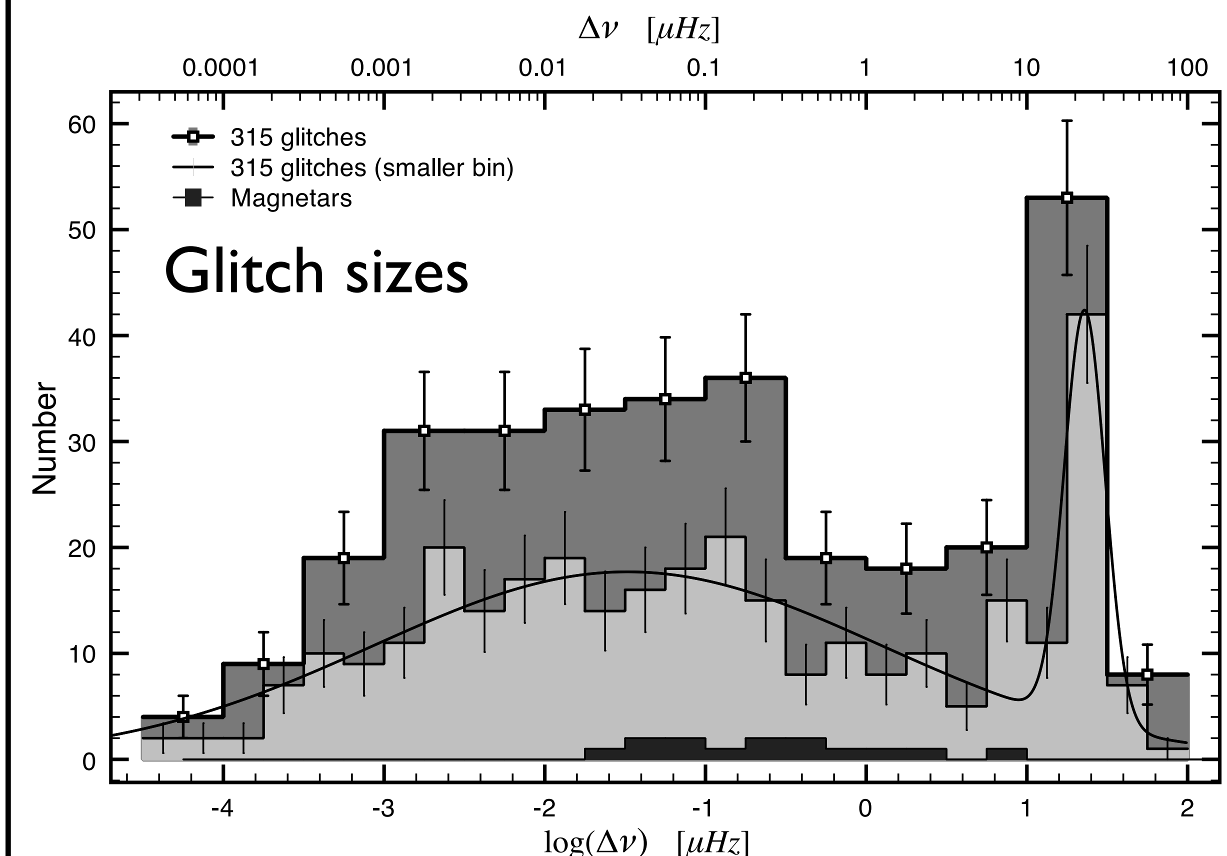


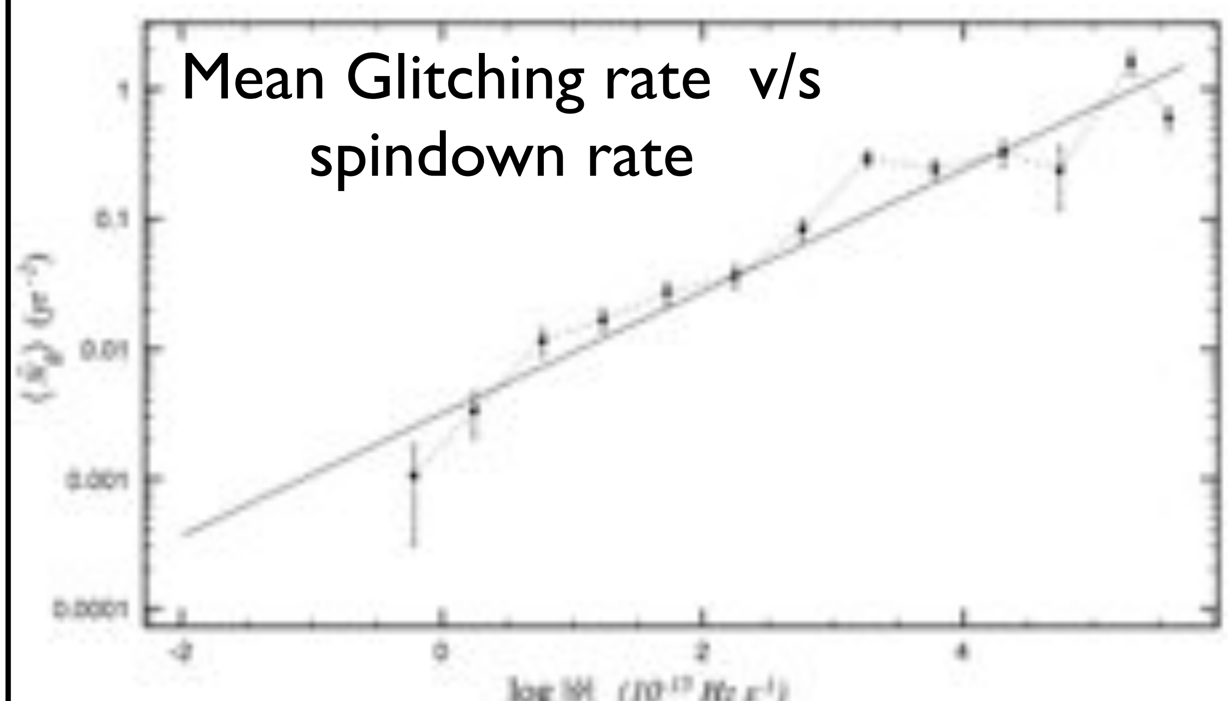


Largest glitch database

- 378 glitches in 130 pulsars
  http://www.jb.man.ac.uk/pulsar/glitches.html
- Glitch size distribution is bimodal; some pulsars only exhibit large glitches.
- Glitch activity is larger for pulsars with higher spindown rates.

Glitches are sudden spin-ups triggered by adjustments of the star caused by the systematic spindown.



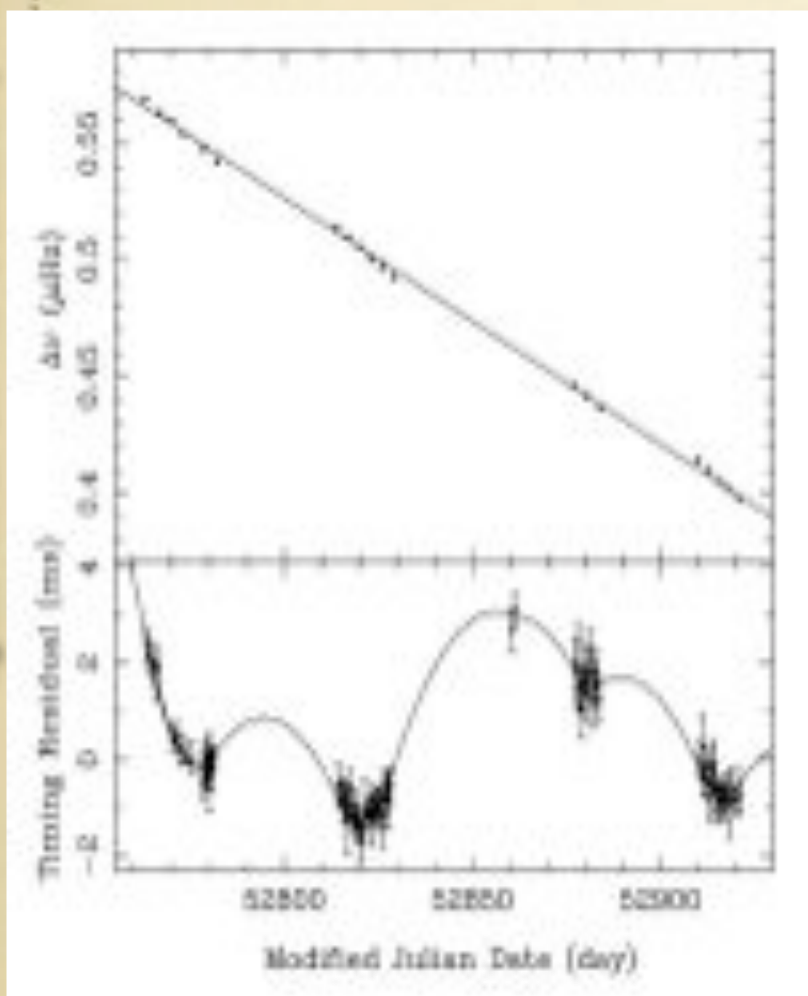


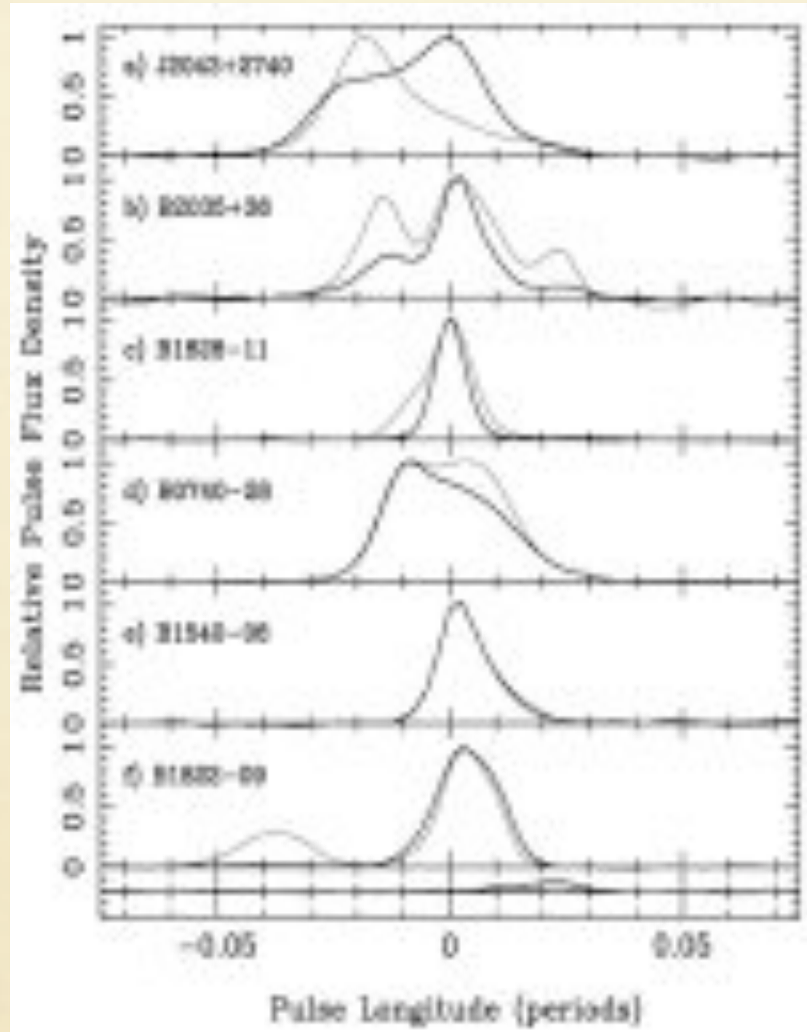
Espinoza et al. (2011)

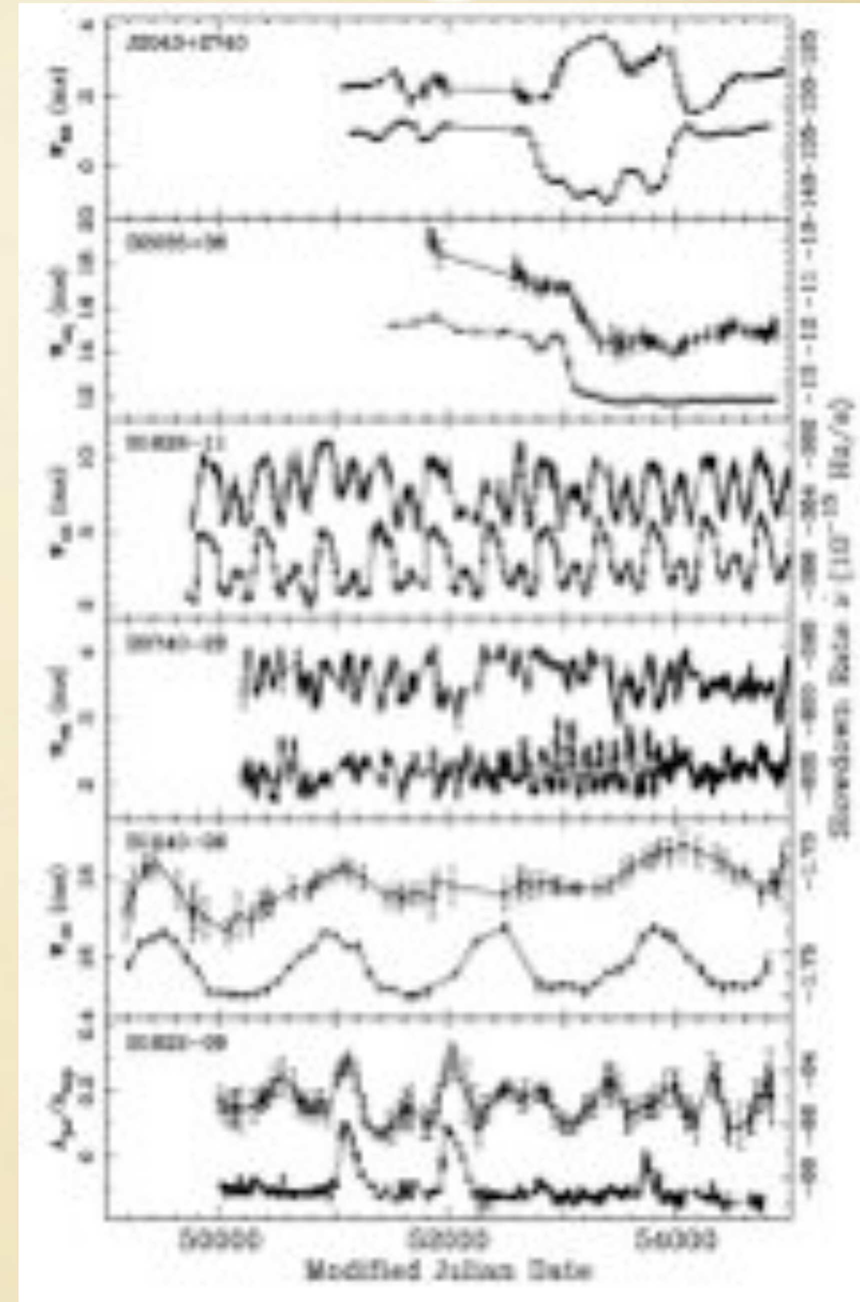
Global Magnetospheric Changes

PSR B1931+24

Lyne et al 2010. Science, 329,408





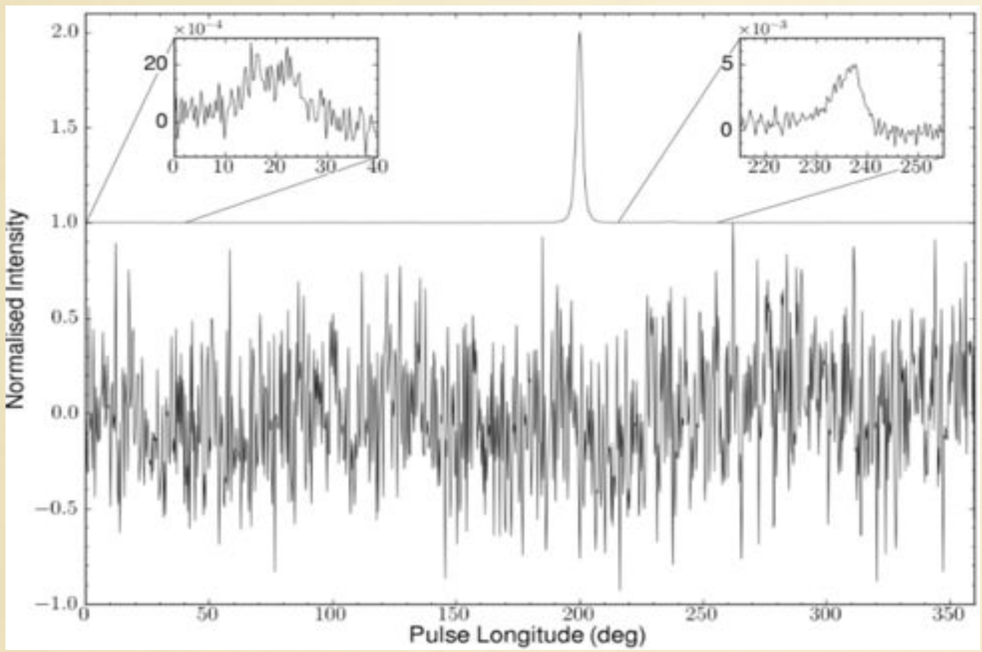


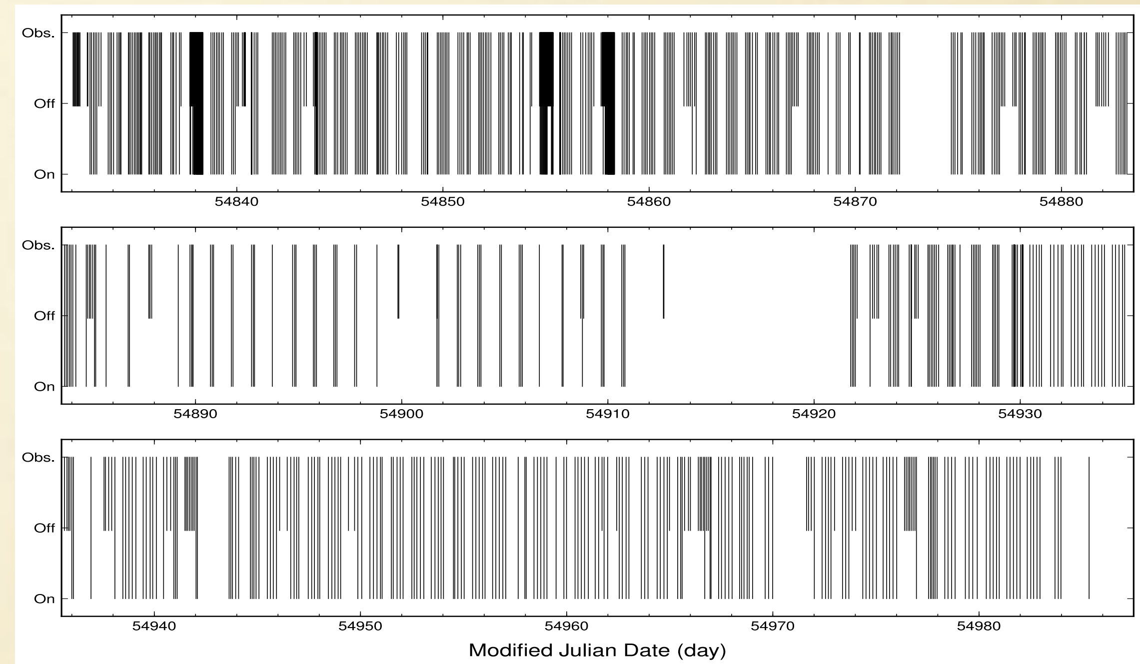
- Pulsar magnetospheres switch between small number of discrete states, usually two
- Changes in current flows cause changes in emission properties and slow-down rate
  - Large f1 associated with enhanced core emission
- Origin of the quasi-periodicities that modulate statistics unknown, possibly free precession ?
- Why discrete states ?

Global Magnetospheric Changes

Lyne et al 2010. Science, 329,408, Young et al MNRAS 2012

PSR B0823+26



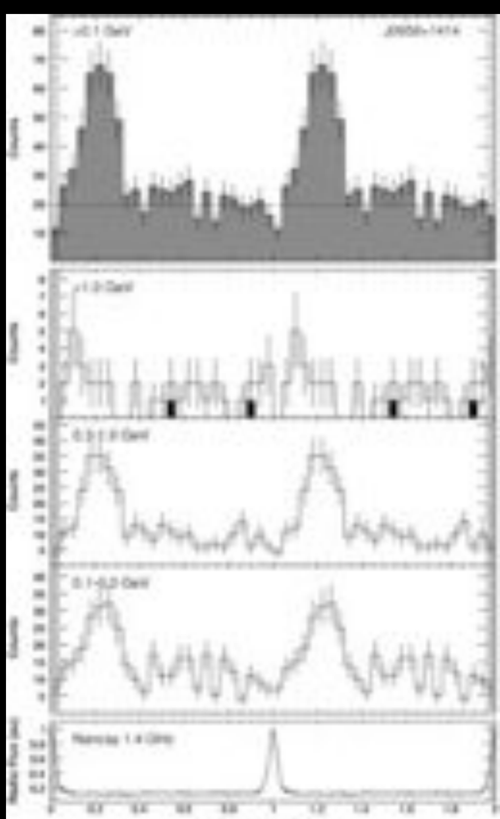


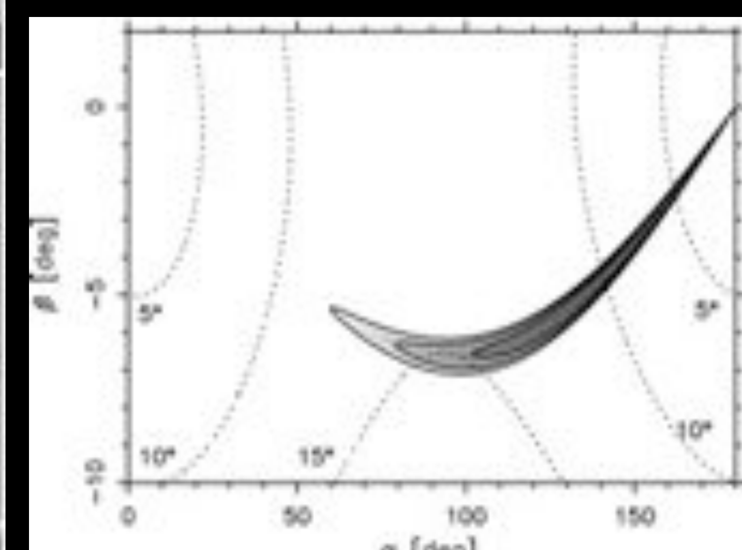
< 6% change

- All sorts of different manifestations
- In all cases can't measure the change in period derivative.
- Nulling may be an extreme form of Mode Changing
- Both are switched phenomena with a similar large range of timescales
- Both influence the spin-down rate
- One telescope's nulling pulsar may be a larger telescope's mode changer !
- These phenomena are widespread (only highest SNR so far)
- These events represent major, instantaneous changes in the pulsars' energy budgets and offer a new opportunity to study both the radiation and spin-down physics.
- Not only unique plasma laboratory but impact on spin-down important as clocks
- It shows that timing noise is not simply noise … and may be corrected for!

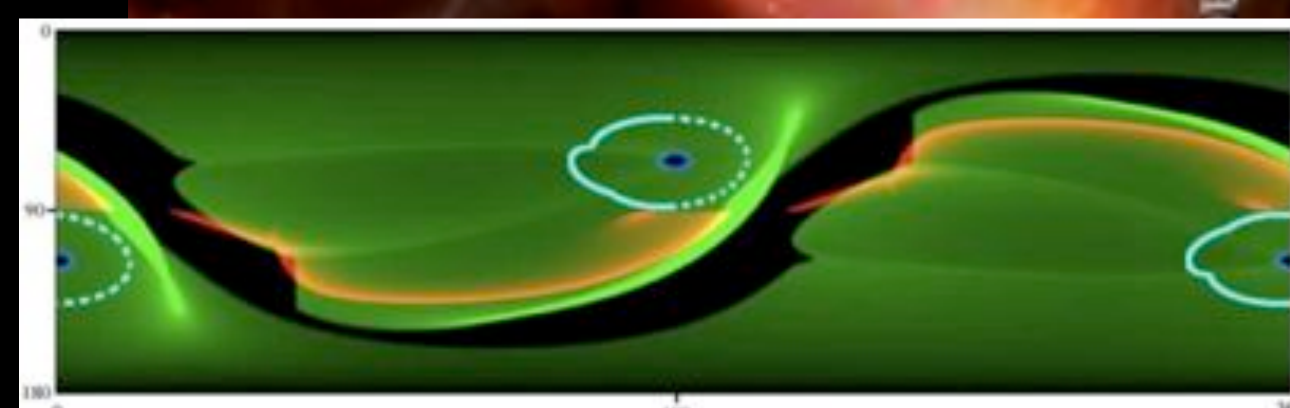
The gamma-ray/radio connection

- 2nd Fermi pulsar catalogue is being worked on at the moment
- Shape of gamma-ray light curves can be predicted if viewing geometry is known (although it is model dependent).
- So if viewing geometry is known, the models can be constrained.
- Radio polarization measurements can constrain the viewing geometry (work done by Simon Rookyard).





Weltevrede et al. 2010



Watters et al. 2009

- European Pulsar Timing Array
- Collaboration between 5 large radio telescopes/ institutions in Europe + theory groups
- Direct detection of GWs using a pulsar timing array
- Working towards global effort: IPTA

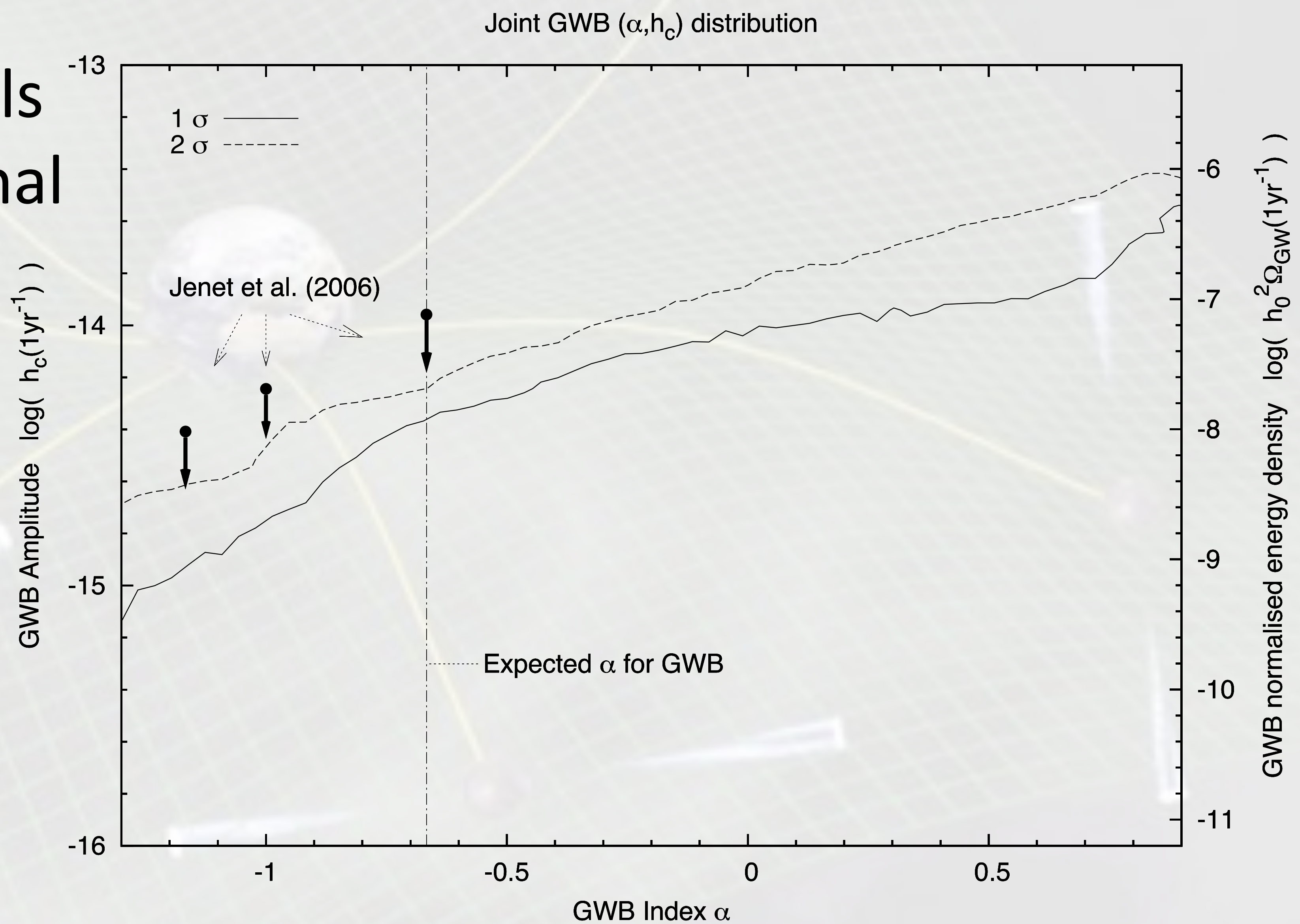
EPTA GWB limit:

Van Haasteren, Levin, Janssen et al. 2011, MNRAS 414, 3117

Bayesian analysis of residuals to set limit on red noise signal common to all pulsars.

Not restricted to assumption of α

5 pulsars, 3 telescopes: best limit produced so far

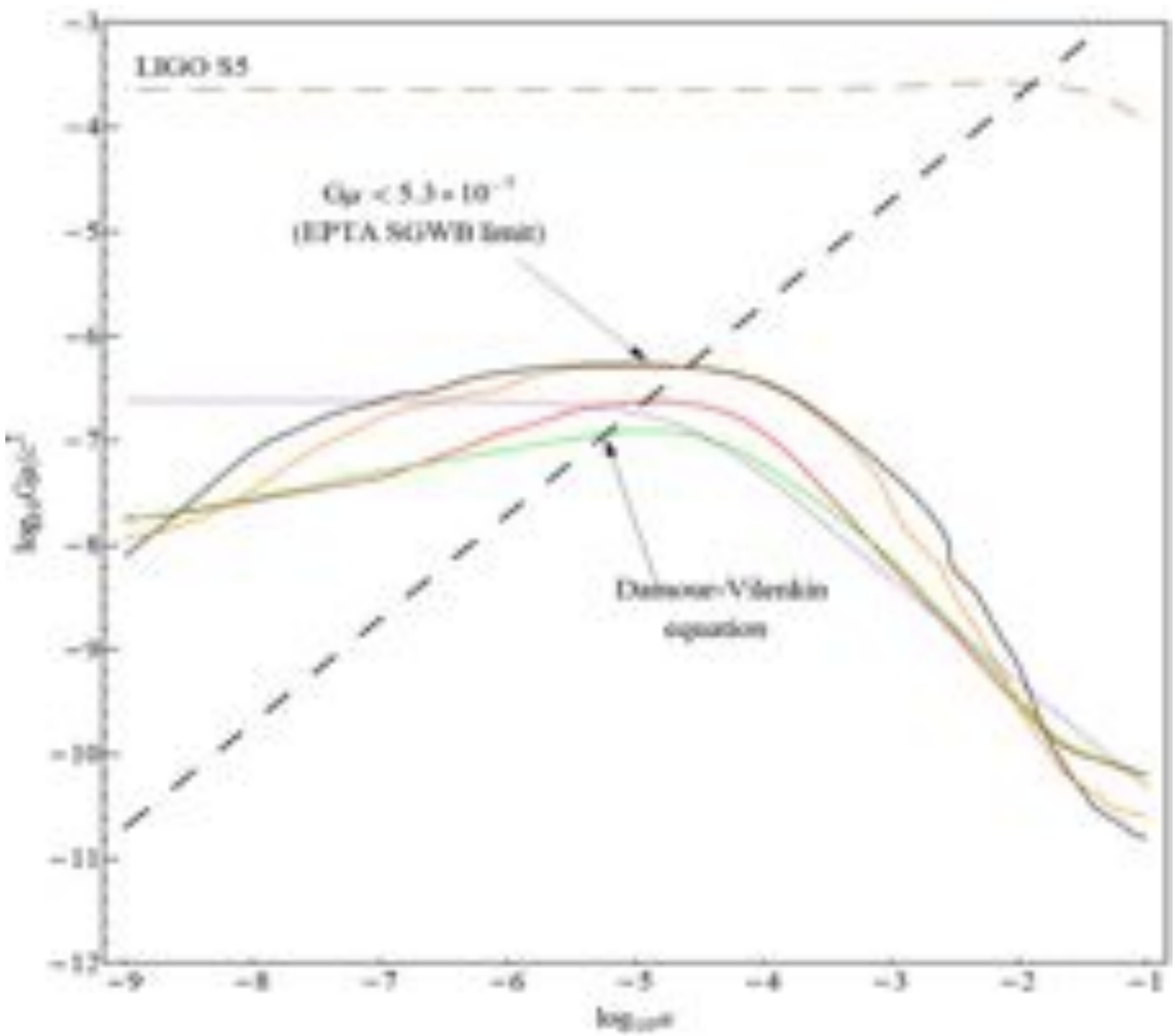


α=-2/3 (SMBHBs): $h_c \leq 6\times10^{-15}$

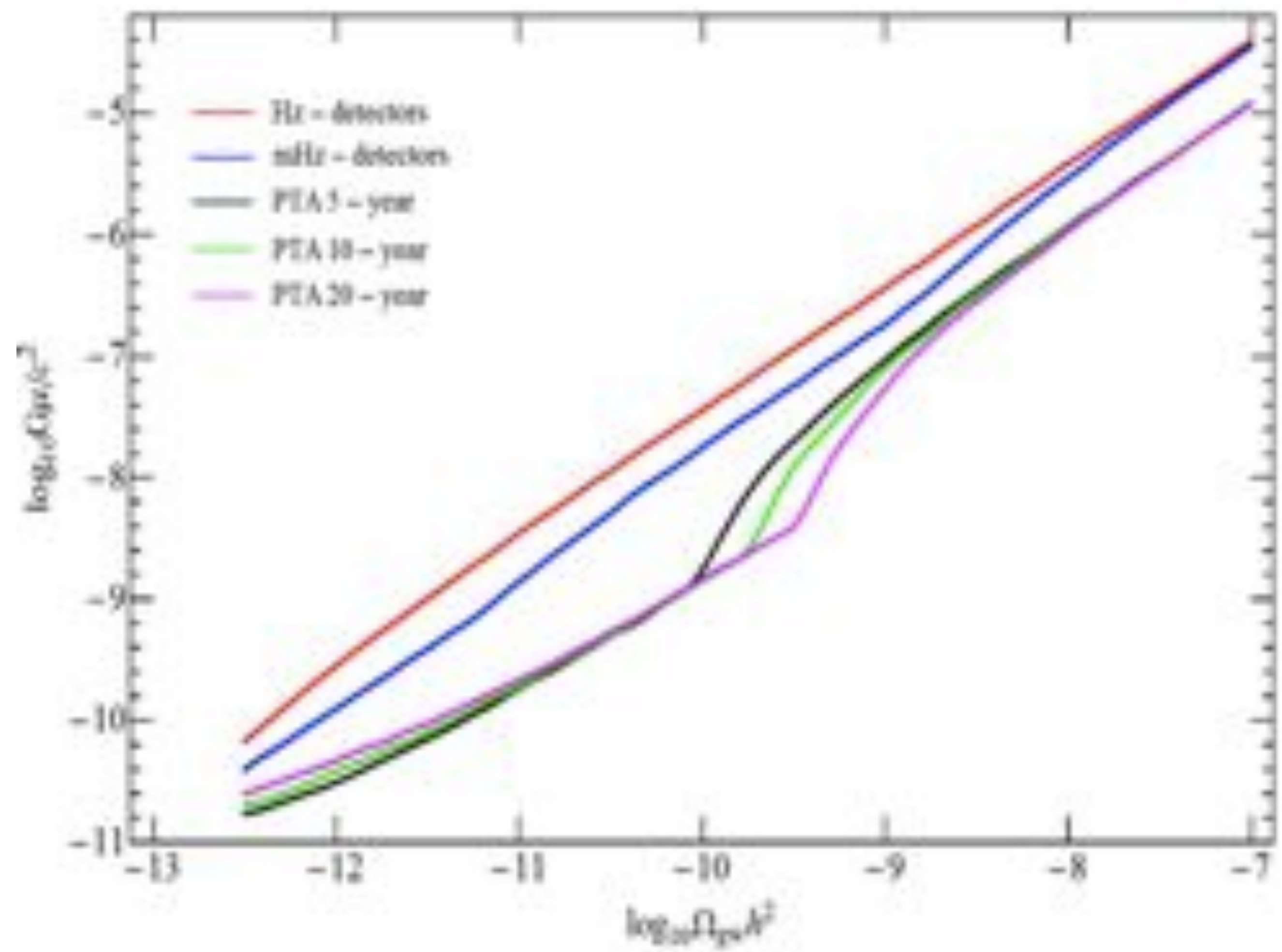
α=-7/6 (Cosmic string tension): $G\mu \leq 4\times10^{-9}$

Constraints on the cosmic string energy scale

- Upper limit on the string tension set by the EPTA SGWB limit; constraint similar to those set by CMB/GL
- Constraint independent of assumptions on other one-scale model parameters



Sanidas, Battye, Stappers PRD 85 2012



Sanidas, Battye, Stappers, to be submitted

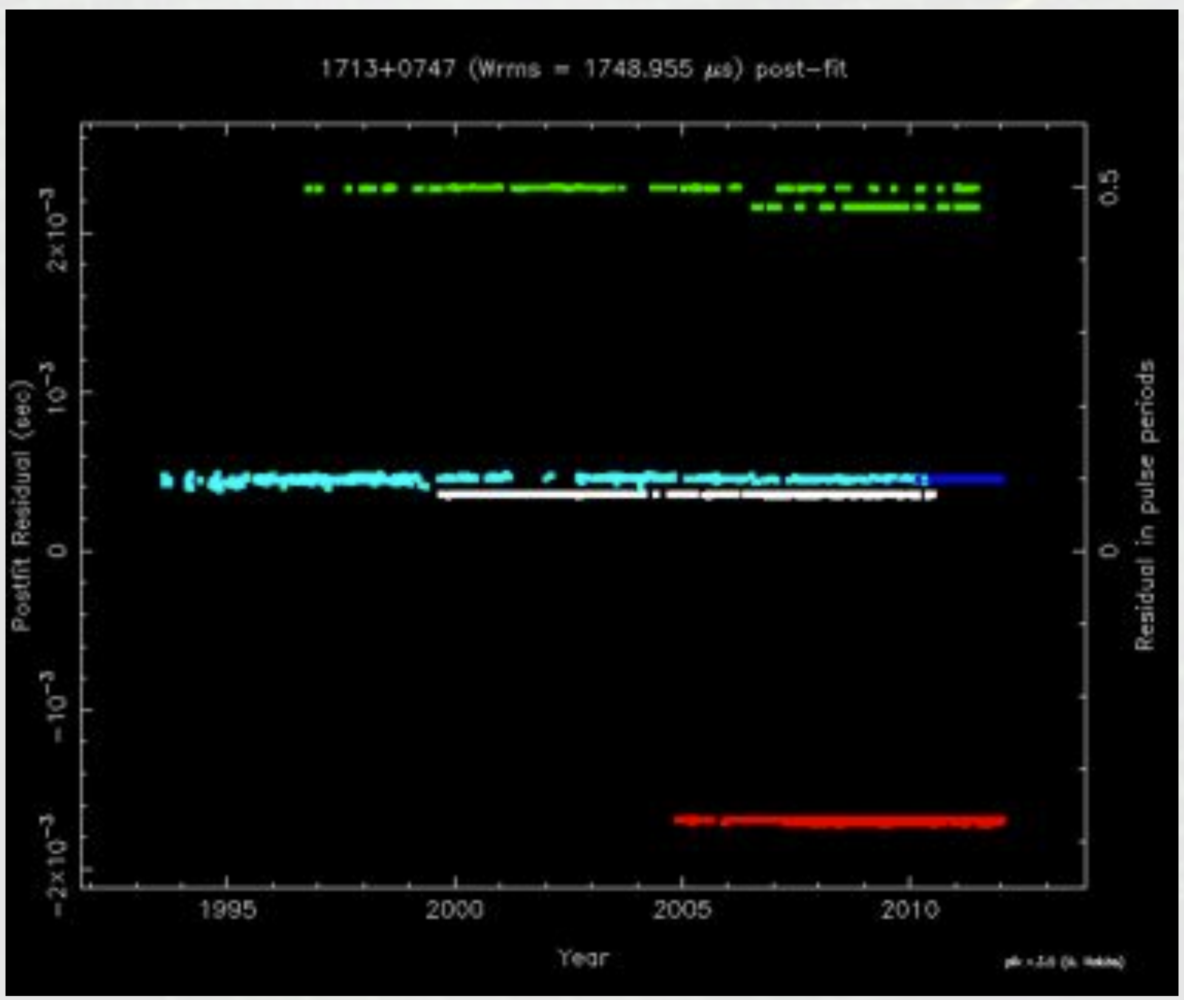
- Projected contraints for present/future GW detectors
- PTAs inherently outperform any ground/ space based GW detector

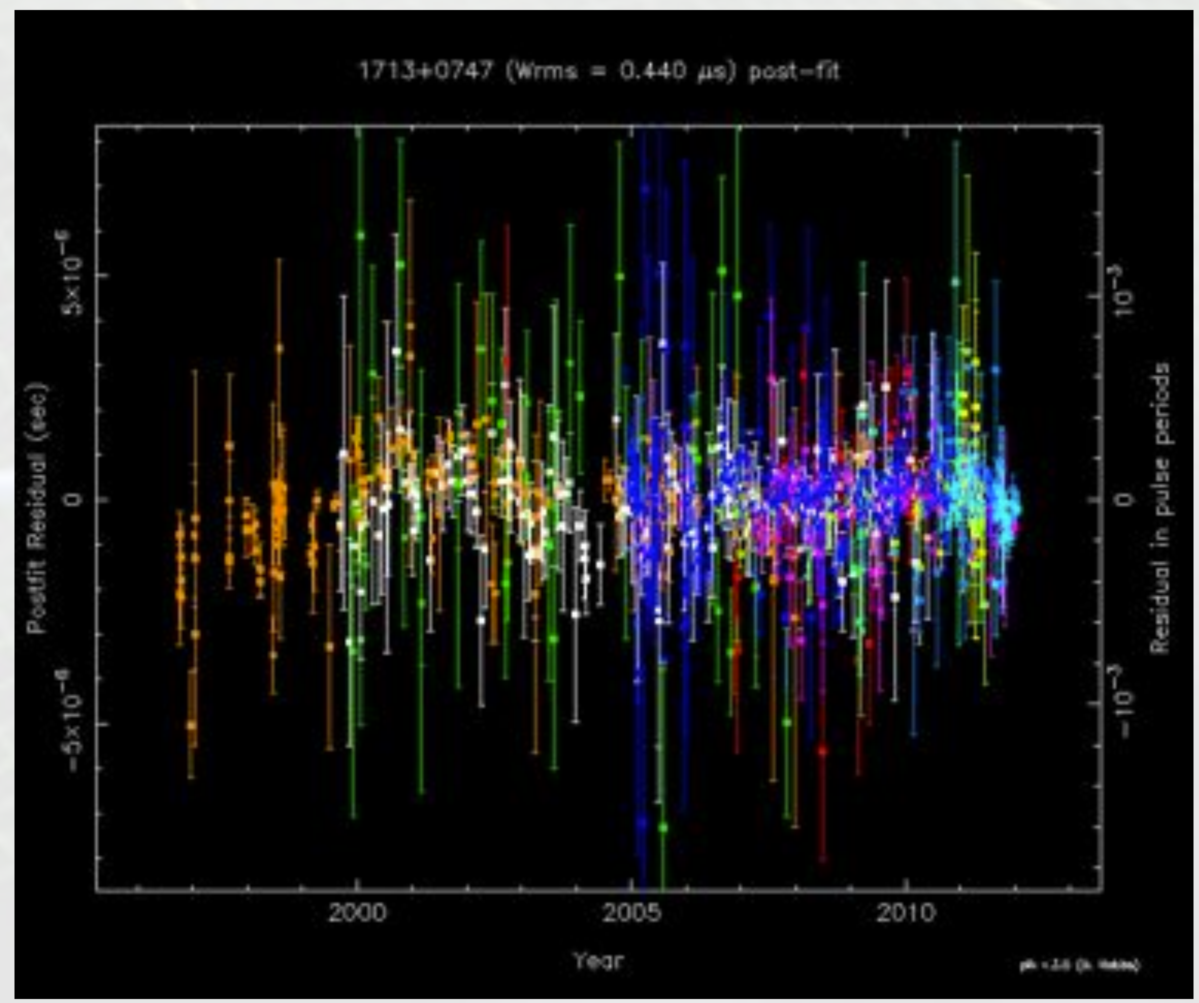
Combining EPTA data sets: IPTA data release

Janssen et al

- EPTA is mini-IPTA:
- Needs understanding of different telescopes, systems, clocks
- More telescopes = more data = better timing for each pulsar
- All essential to optimally combine data sets from multiple telescopes
- LEAP will play a key role in determining offsets between telescopes

- EPTA has selected 20 best pulsars for PTA work
- All “legacy” EPTA data now combined and provided to IPTA for first projects -> IPTA data release, IPTA GW limit, solar system studies, pulsar timescale





red=nancay, blues=jb, white=wsrt, green=eff

Bassa et al

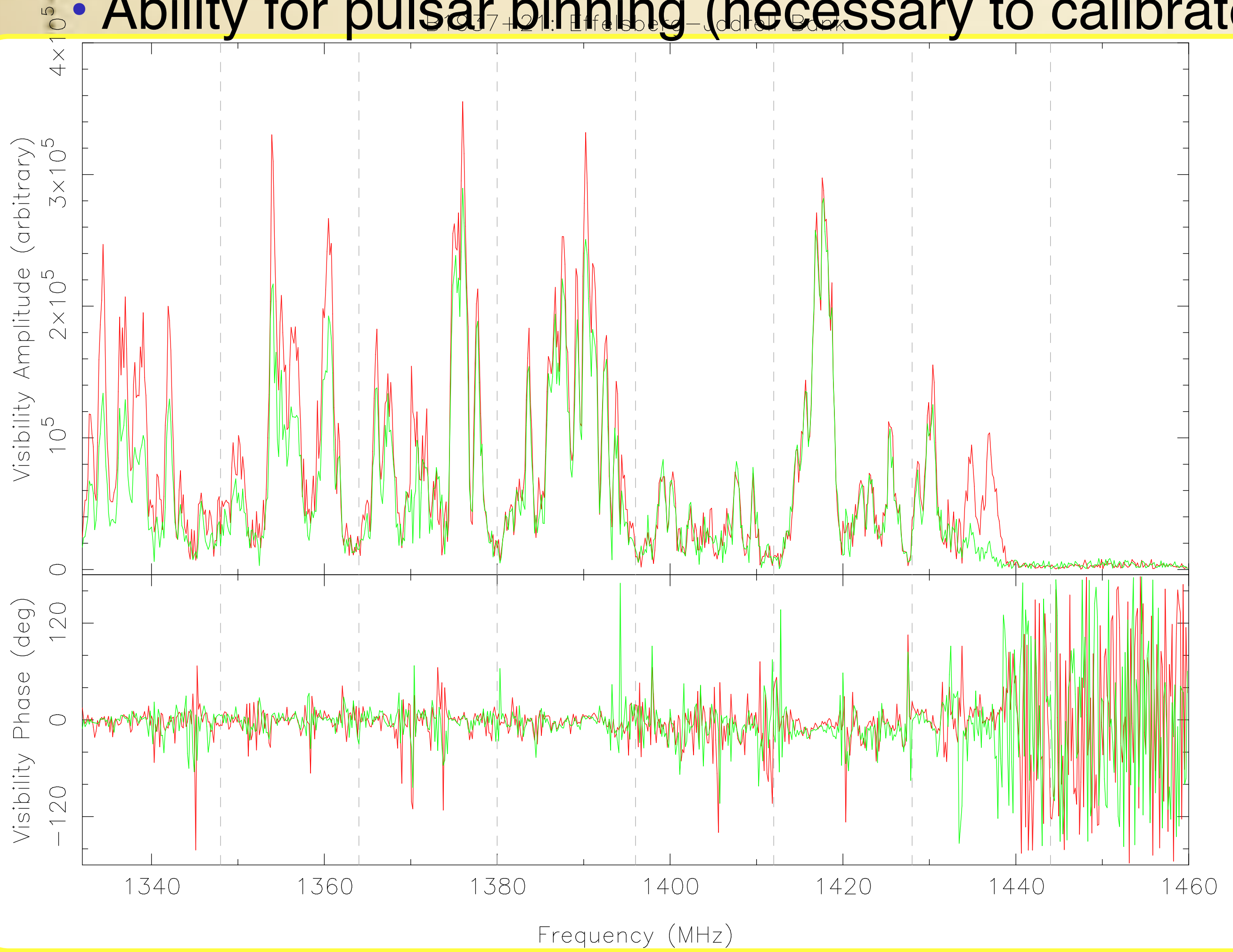
LEAP

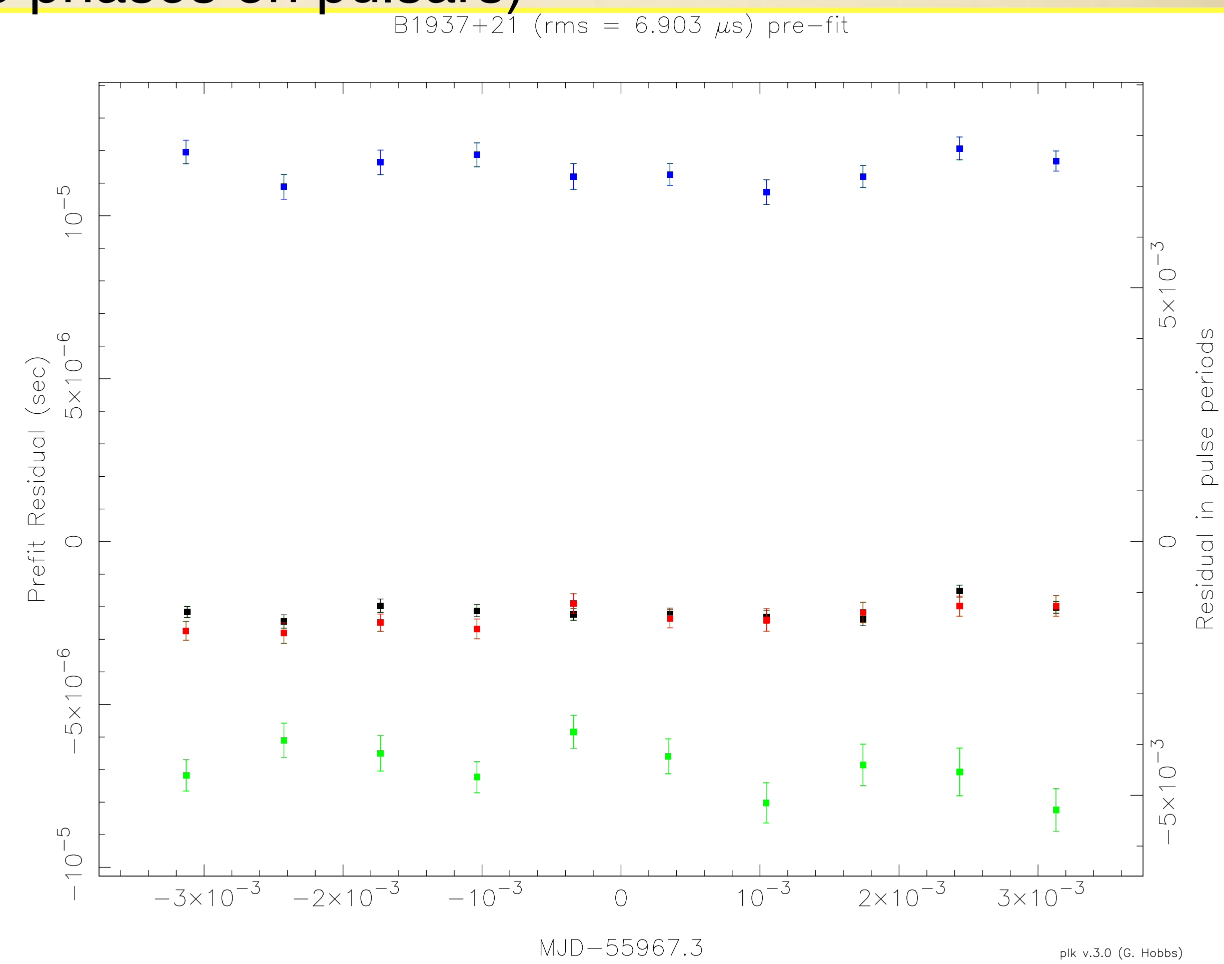
Storage/processing hardware:

- 24 hour session @ 128 MHz BW → 40 TB of data per telescope
- Storage servers at each telescope with 100 TB of storage
- Jodrell Bank gets another 4 storage servers to match remote observatories
- Data transfer by shipping disks between storage servers or copy over internet (presently @ 80 MB s^{-1} for Eff-JB, WSRT-JB)
- 400 CPU HPC cluster is in place at Jodrell Bank for processing Correlation/tied array

Software:

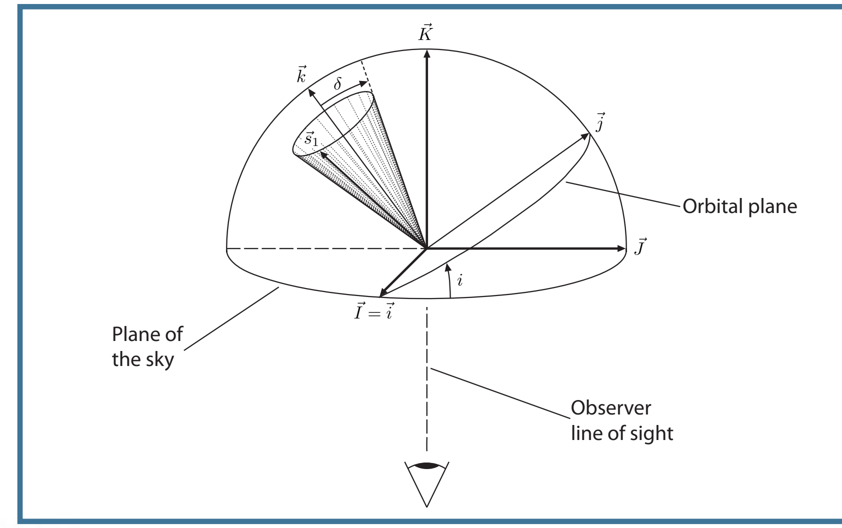
- Developed from scratch
- Fringe fitting of closure phase (after Schwab & Cotton 1983)
- Uses CALC model for geometric delays (also used by VLBI)
- Ability for pulsar binning (necessary to calibrate phases on pulsars)

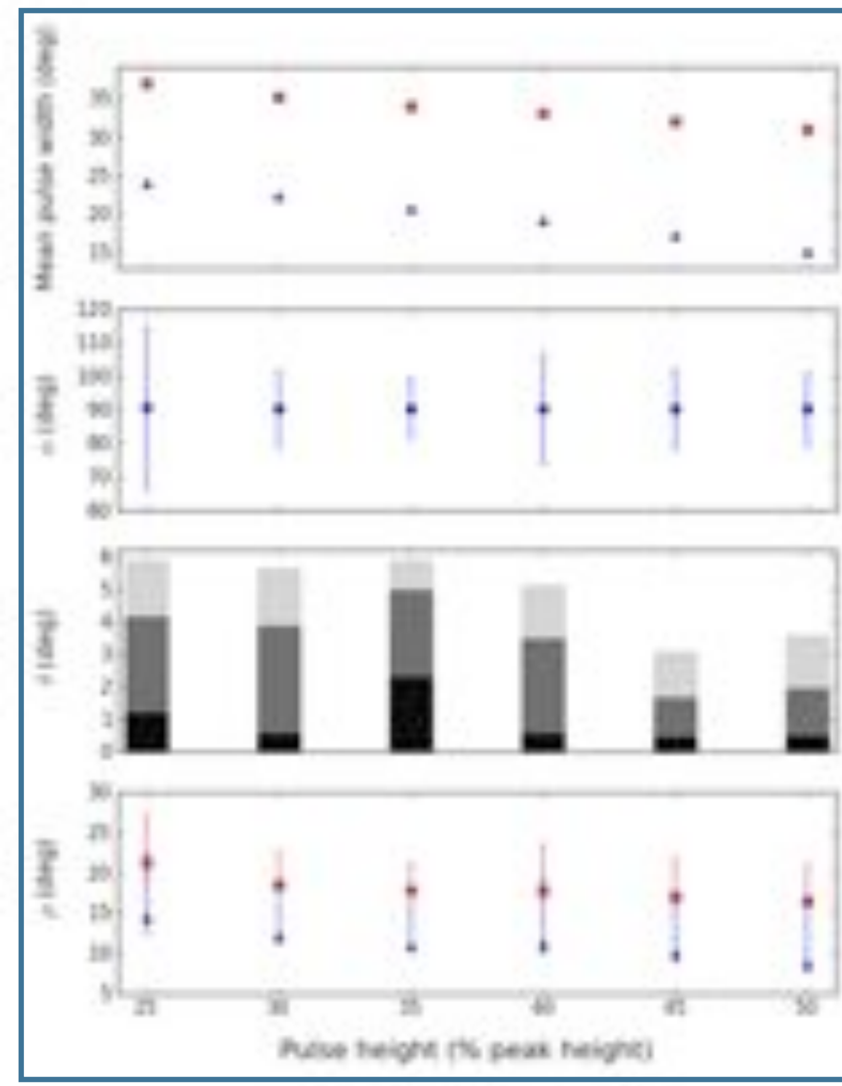




The double pulsar: a neutron star formed without iron core collapse

- Pulse width measurements
  - over time, affectred by geodetic precession
  - PSR J0737–3039A: $P_{\rm prec}$ = 75 years
  - much shorter than PSRs B1913+16, B1534+12
  - do not see any significant change in over 6 years
- Fit to widths over time: ***low misalignment angle*** between spin and orbit
- **Also**: low space velocity (~10 km/s), low-mass 2nd-formed NS (1.25 $M_\odot$), low eccentricity (0.088)
  - indicative of a symmetric, low mass-loss supernova
  - possibly electron capture scenario



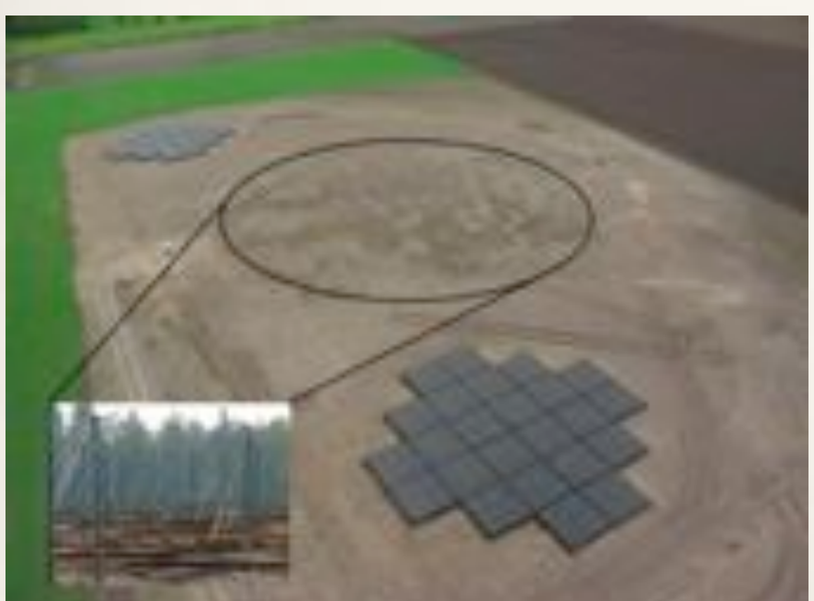


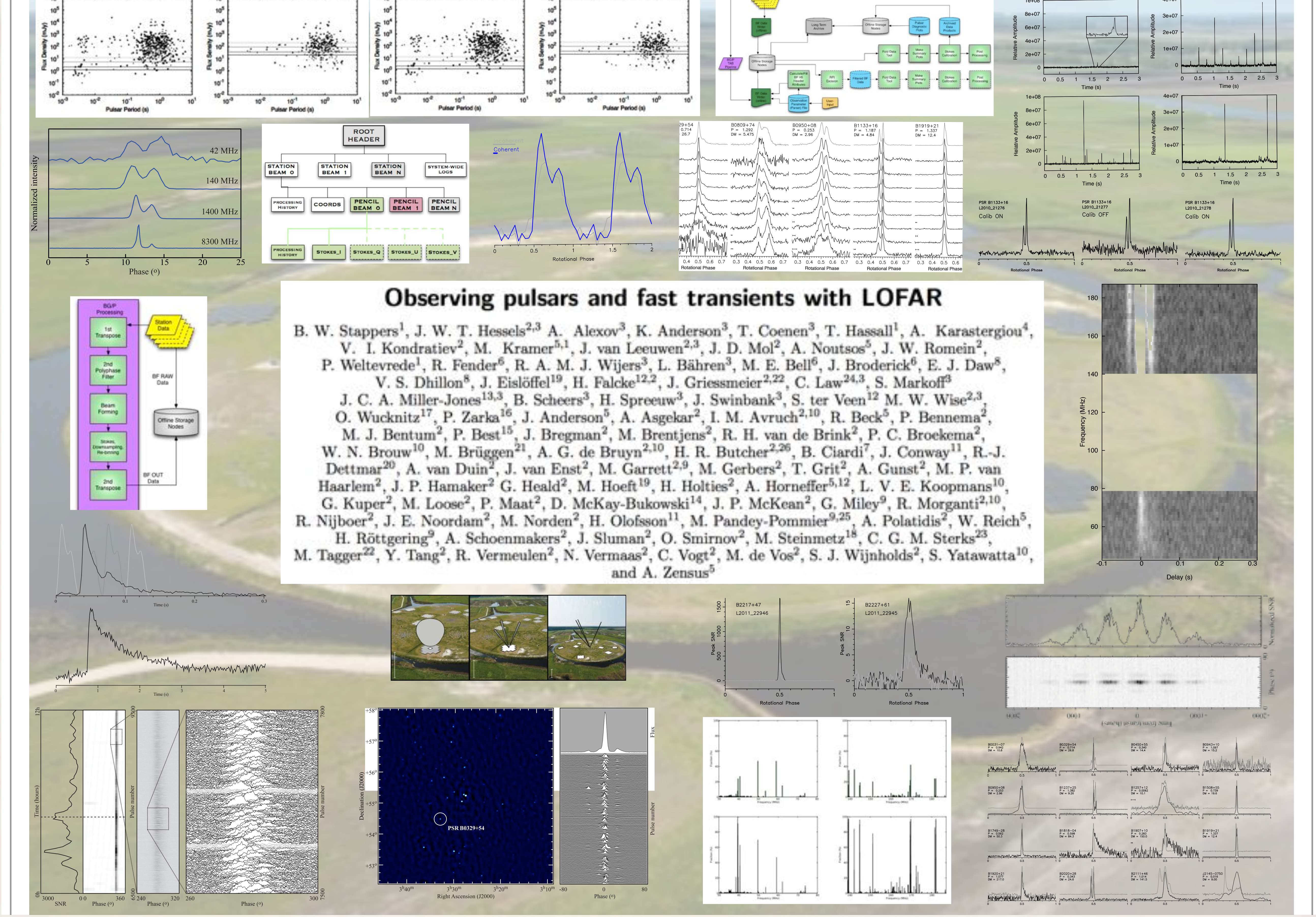
(Ferdman et al., 2012)

LOFAR: LOw Frequency ARray

- Distributed in NL & EU
- 30 - 240 MHz
- LBA & HBA
- > 30000 dipoles
- 20 Core/18 NL/>10 EU
- 2.5km/100km/1000km

Single station - GBT like, Superterp - Arecibo like, Full Array - unparalled!

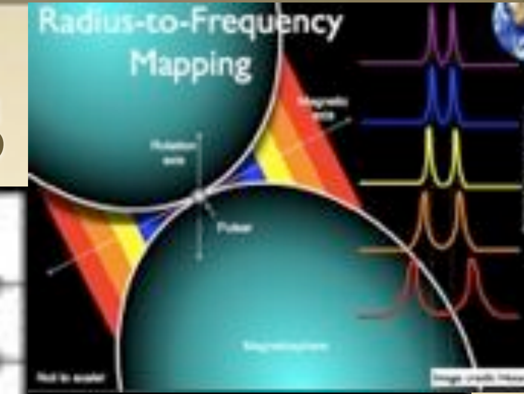




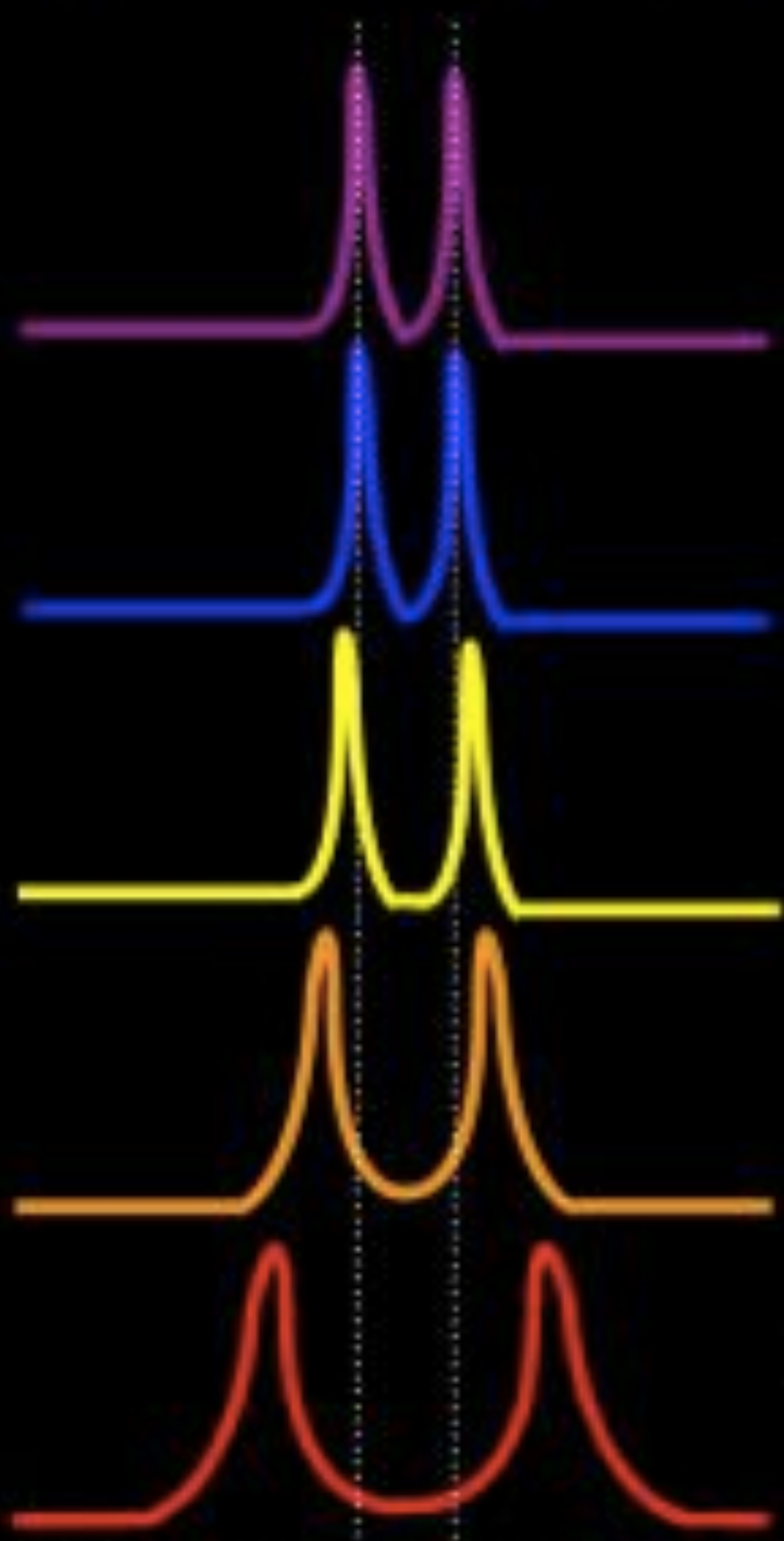
Stappers et al 2011 A&A 530A 80S

LOFAR Emission Physics

Hassall et al 2012



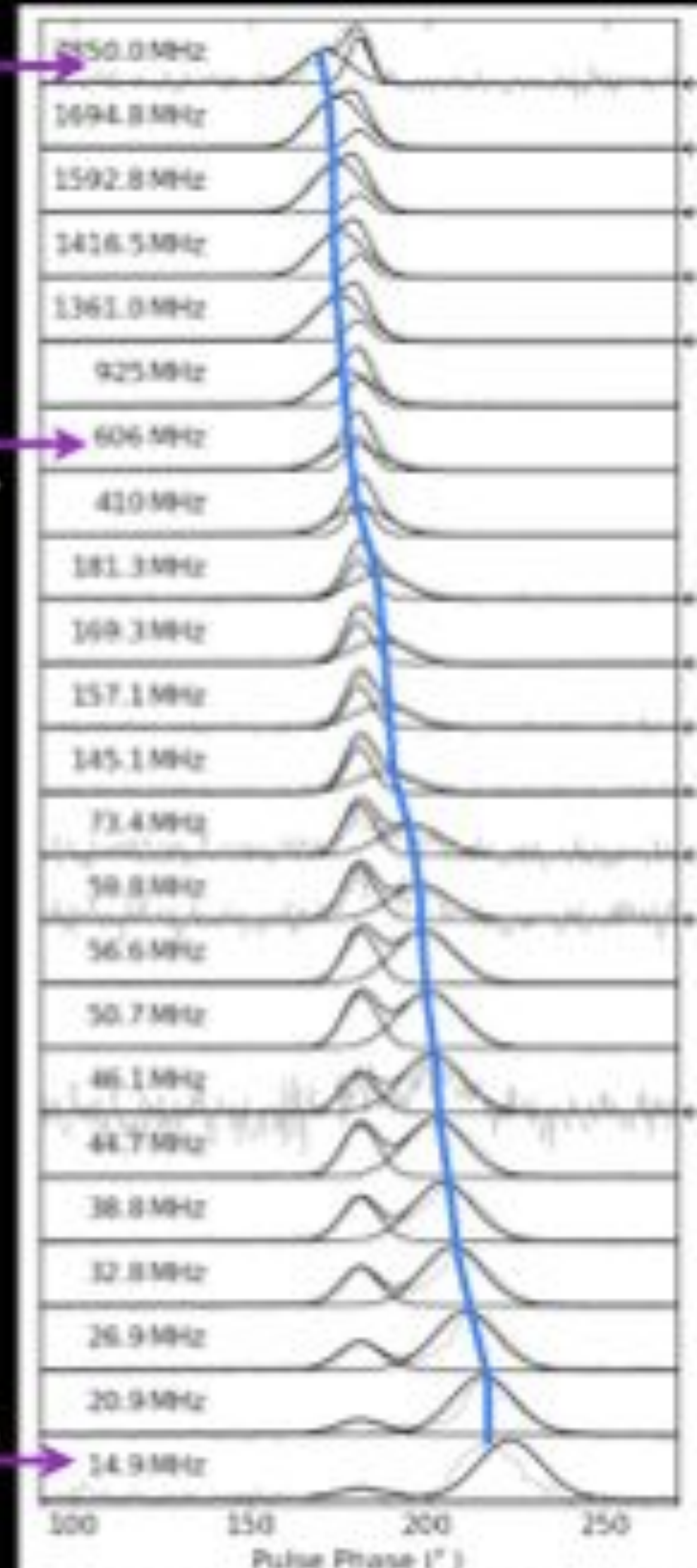
PSR B0809+74



Starts broad

Gets narrower

Broadens again

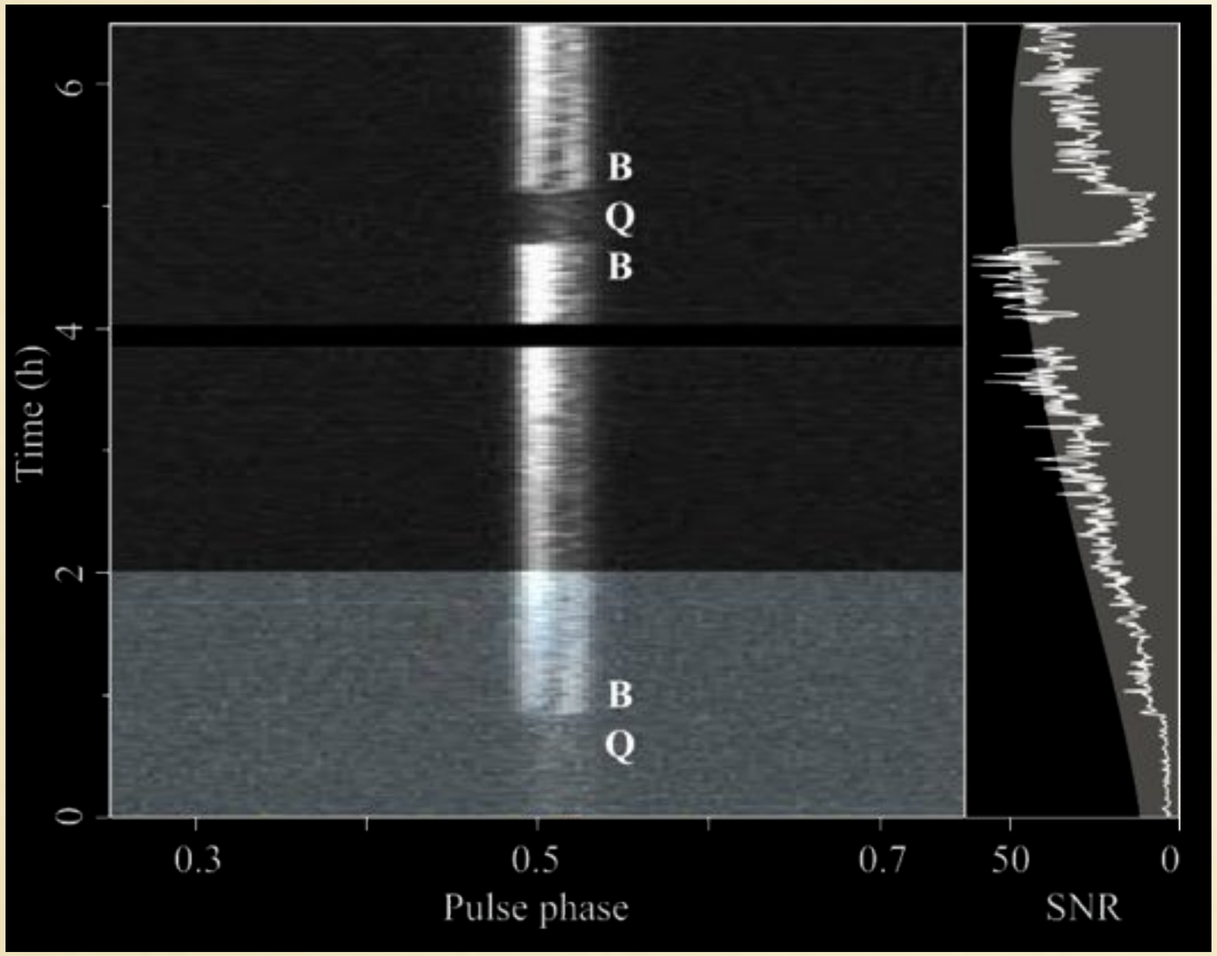


But this happens in a very smooth way

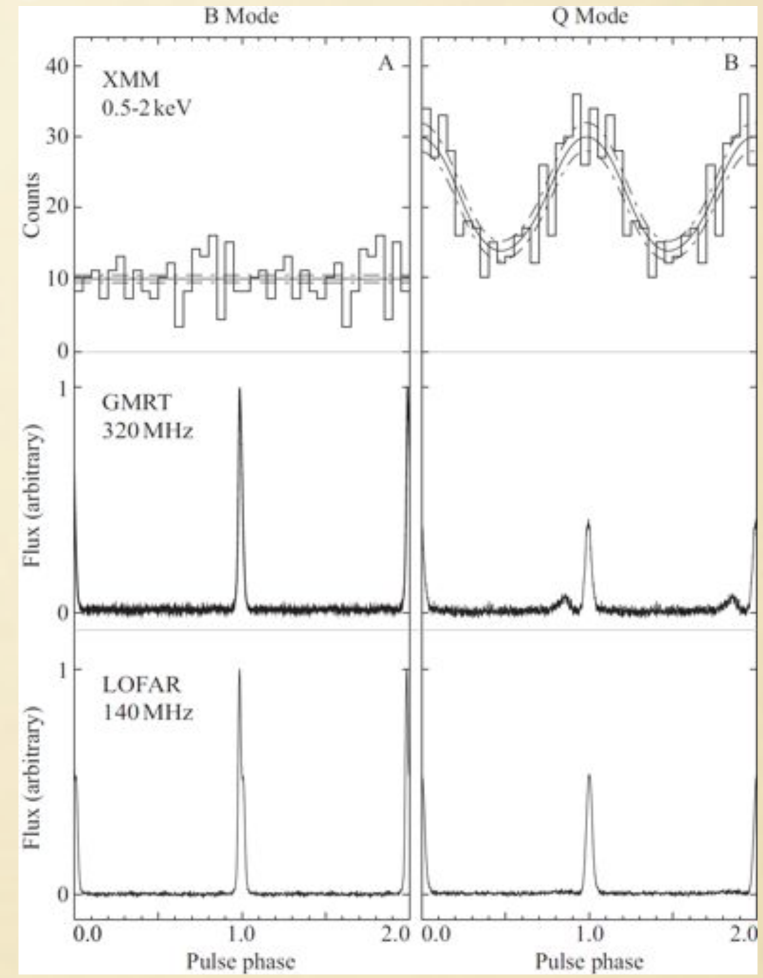
Looks like one component is moving and one is fixed

Hermsen et al submitted to Science, don't tweet!

PSR B0943+10: X-ray vs Radio



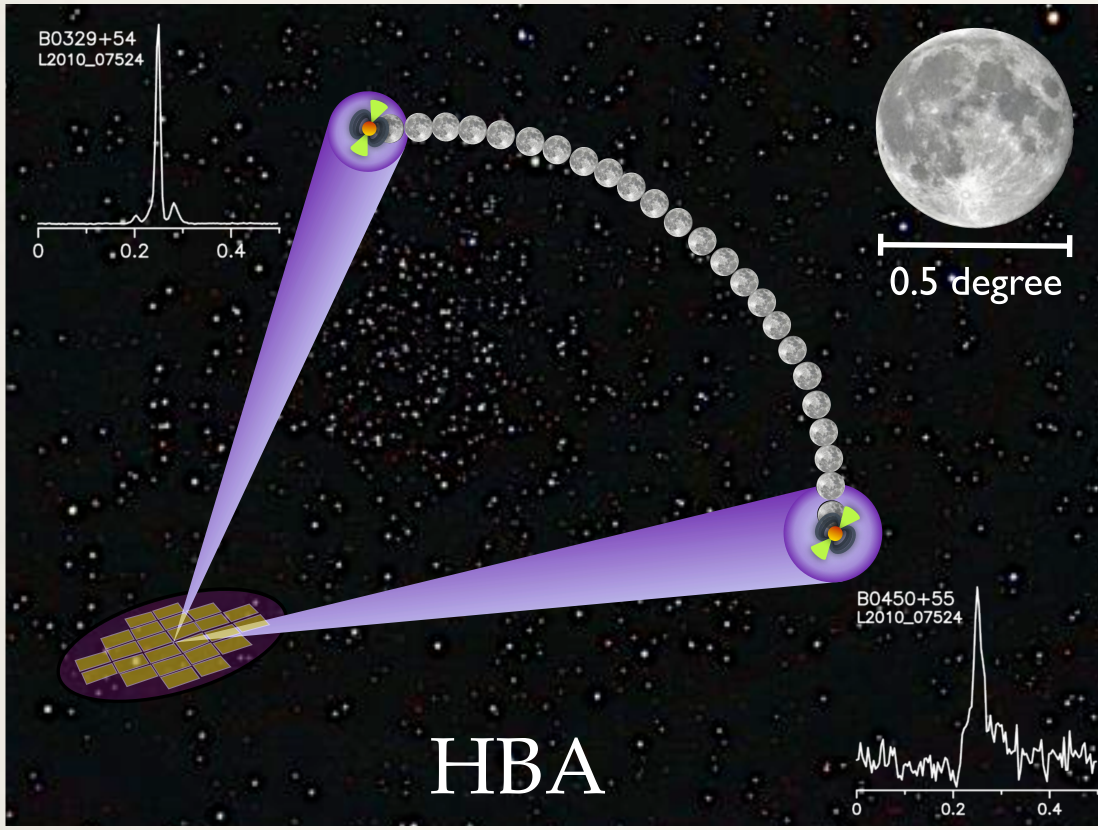
Lofar & GMRT

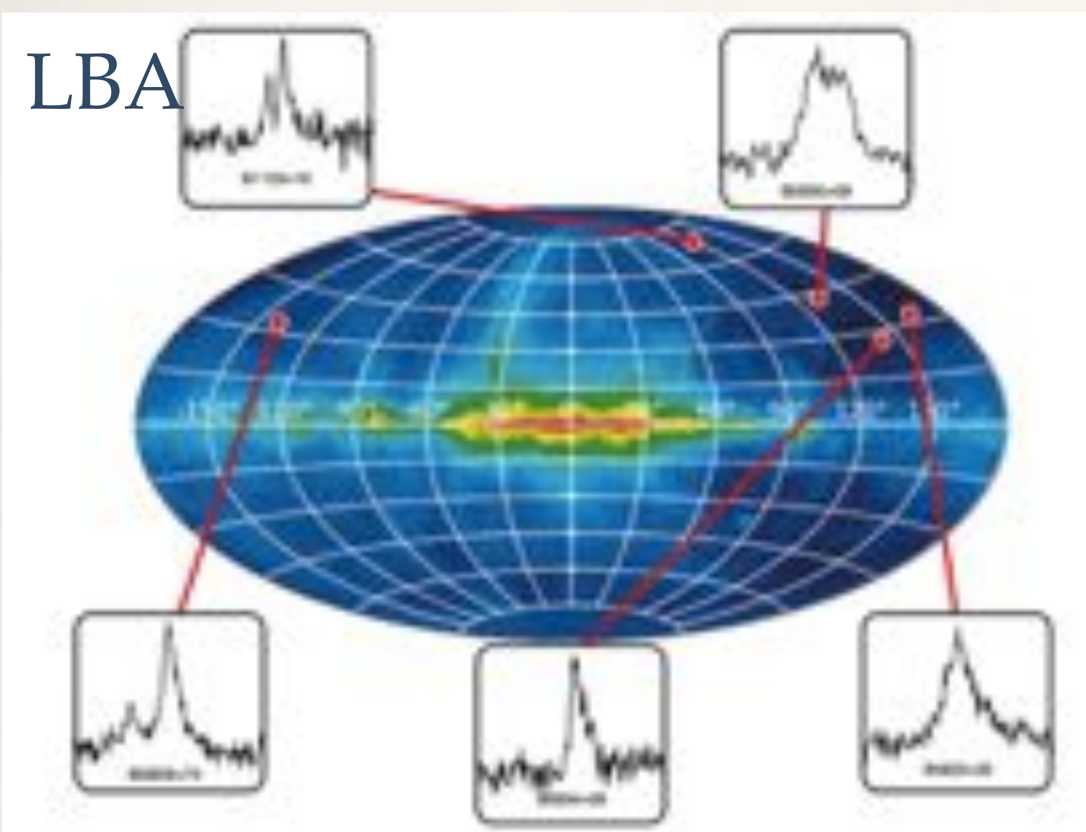


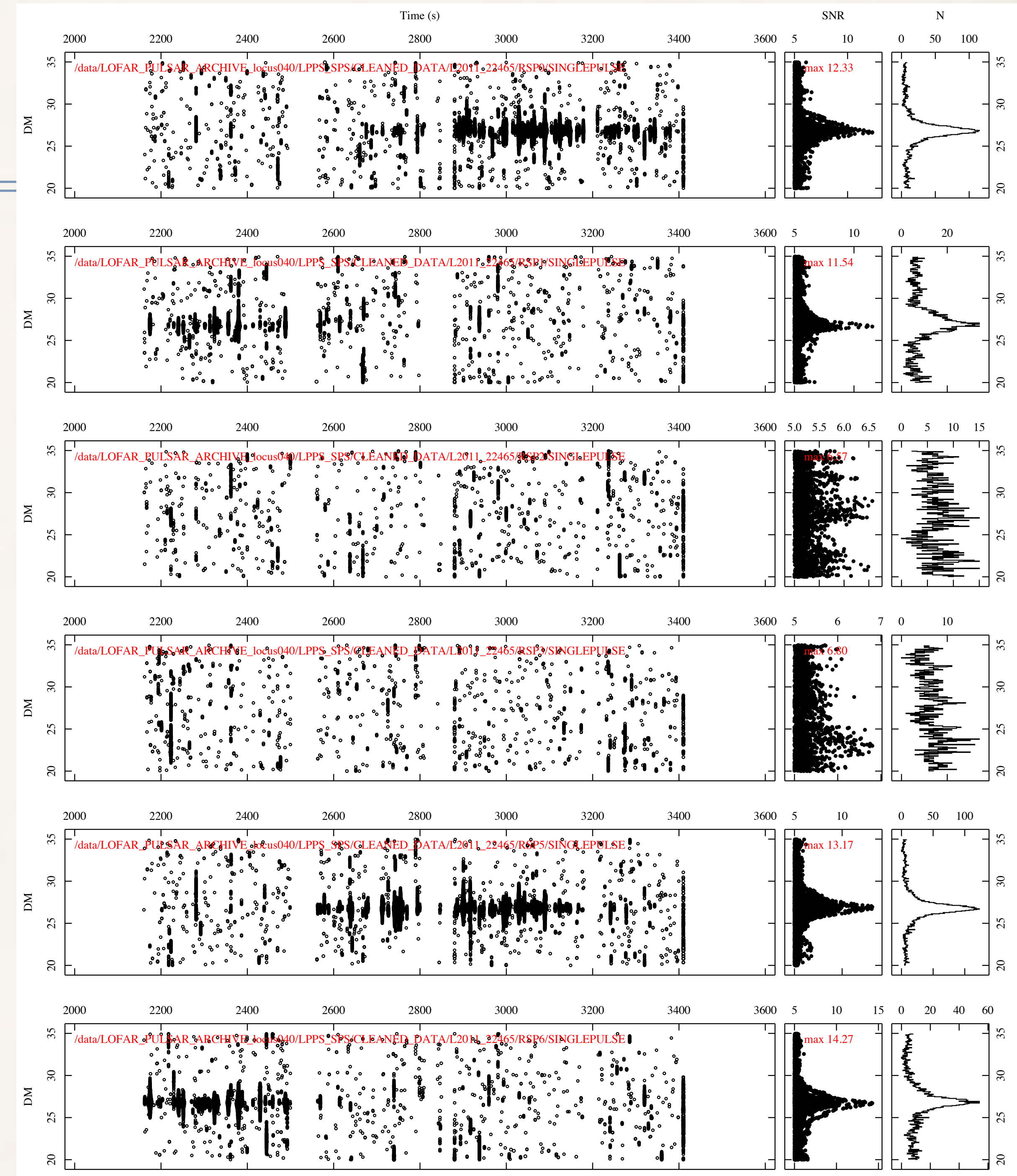
- synchronous switching in the radio and X-ray emission properties of PSR B0943+10.
- radio 'bright' mode, the X-rays show only an un-pulsed, non-thermal component.
- radio 'quiet' mode, the X-ray luminosity more than doubles and a 100%-pulsed thermal component is observed along with the non-thermal component.
- This indicates rapid, global changes to the conditions in the magnetosphere, which challenge all proposed pulsar emission theories.

Mode total / pulsed	Model	BB (kT) keV	PL index Γ ($\alpha E^{-\Gamma}$)	BB flux, unabs (0.5 - 8 keV) 10^{-15} erg cm^{-2} s^{-1}	PL flux, unabs (0.5 - 8 keV) 10^{-15} erg cm^{-2} s^{-1}	χ^2_{red} / dof
Q total	BB+PL	0.277±0.012	2.60±0.34	7.52±2.20	7.55±1.81	0.81 / 20
Q pulsed	BB	0.319±0.012		7.81±1.64		0.38 / 3
B total	PL		2.29±0.16		7.69±1.00	0.74 / 10

LOFAR: Wide FoV & Multi-beaming





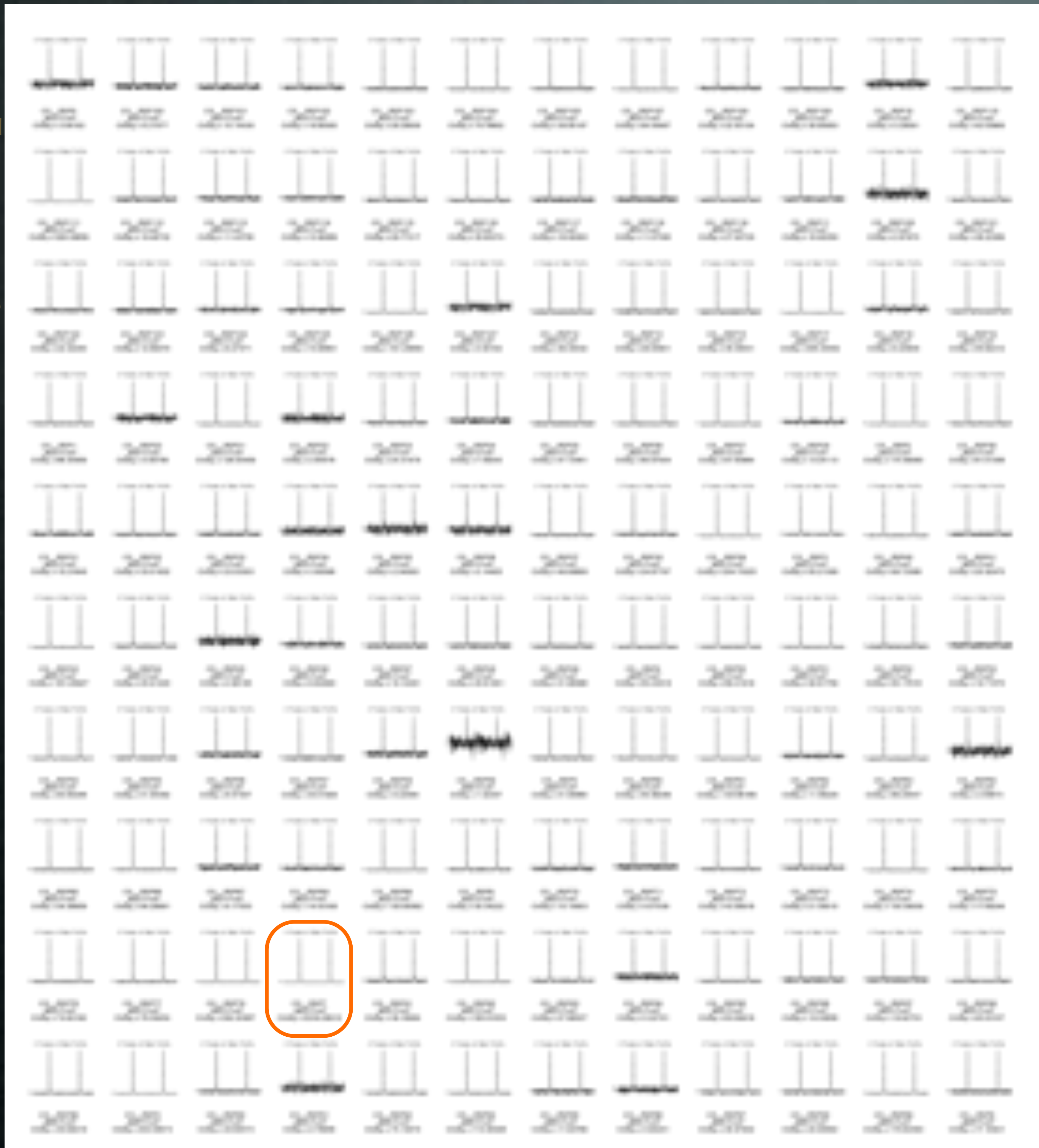


Distinguishing single pulses

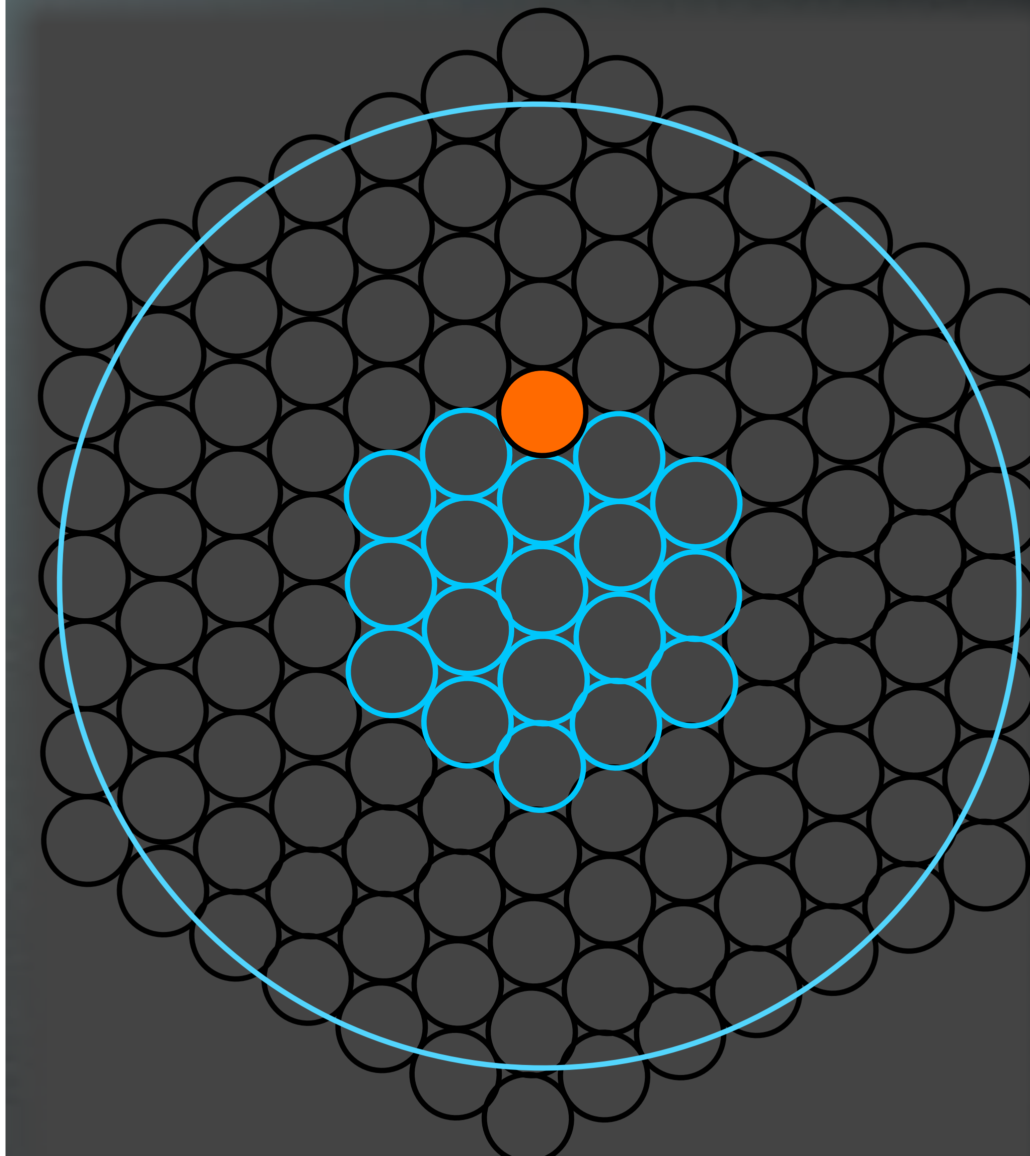
Hessels, Hassall, Stappers, Coenen & LOFAR PWG

LOFAR 127-beam Tied-Array!!

Pulsar working group w/ Sally Cooper



Shifted 1 deg south

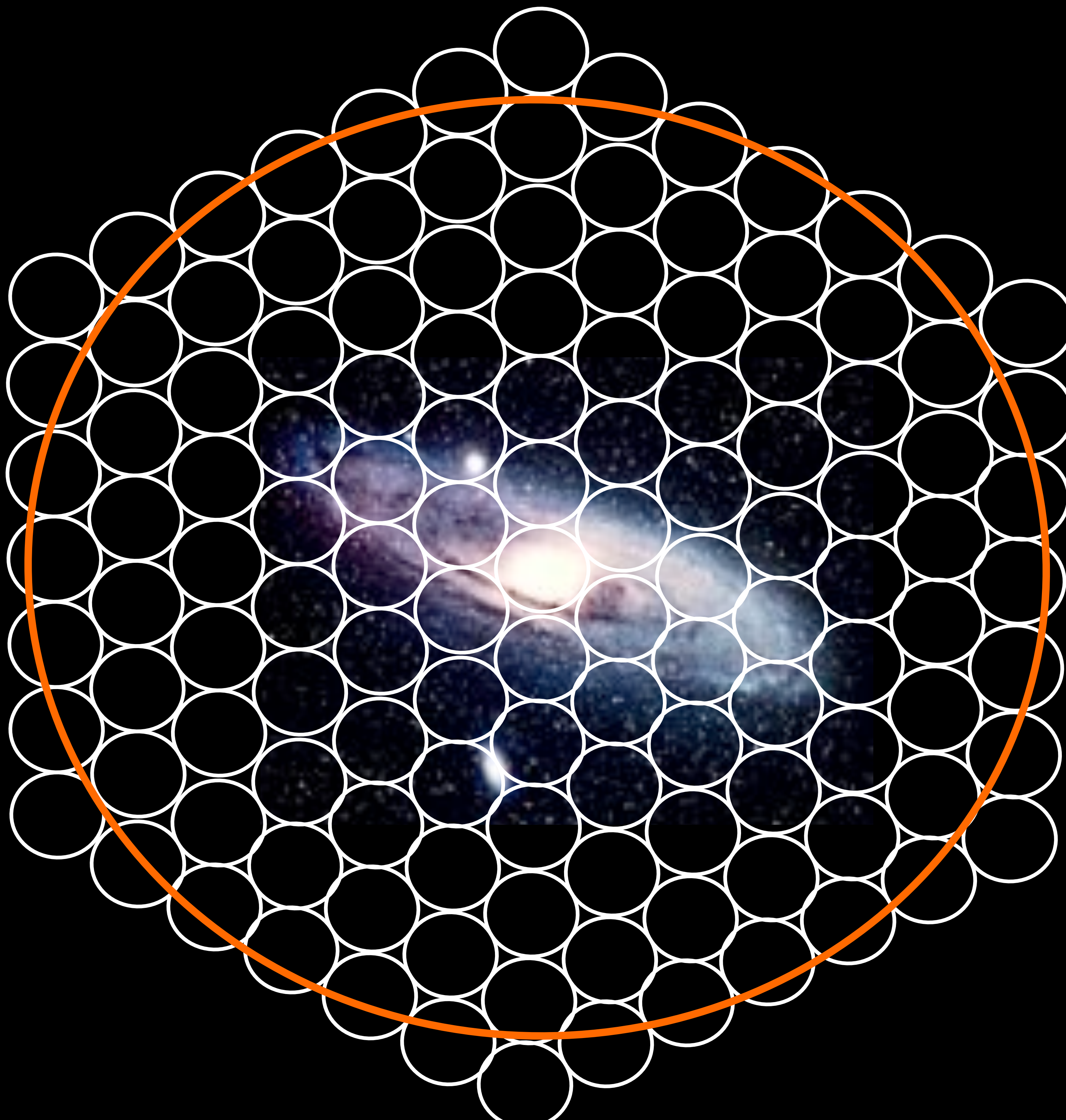


Pulsar is 10x brighter in the correct beam (beam 7)!

Credit: Alexov & Hessels

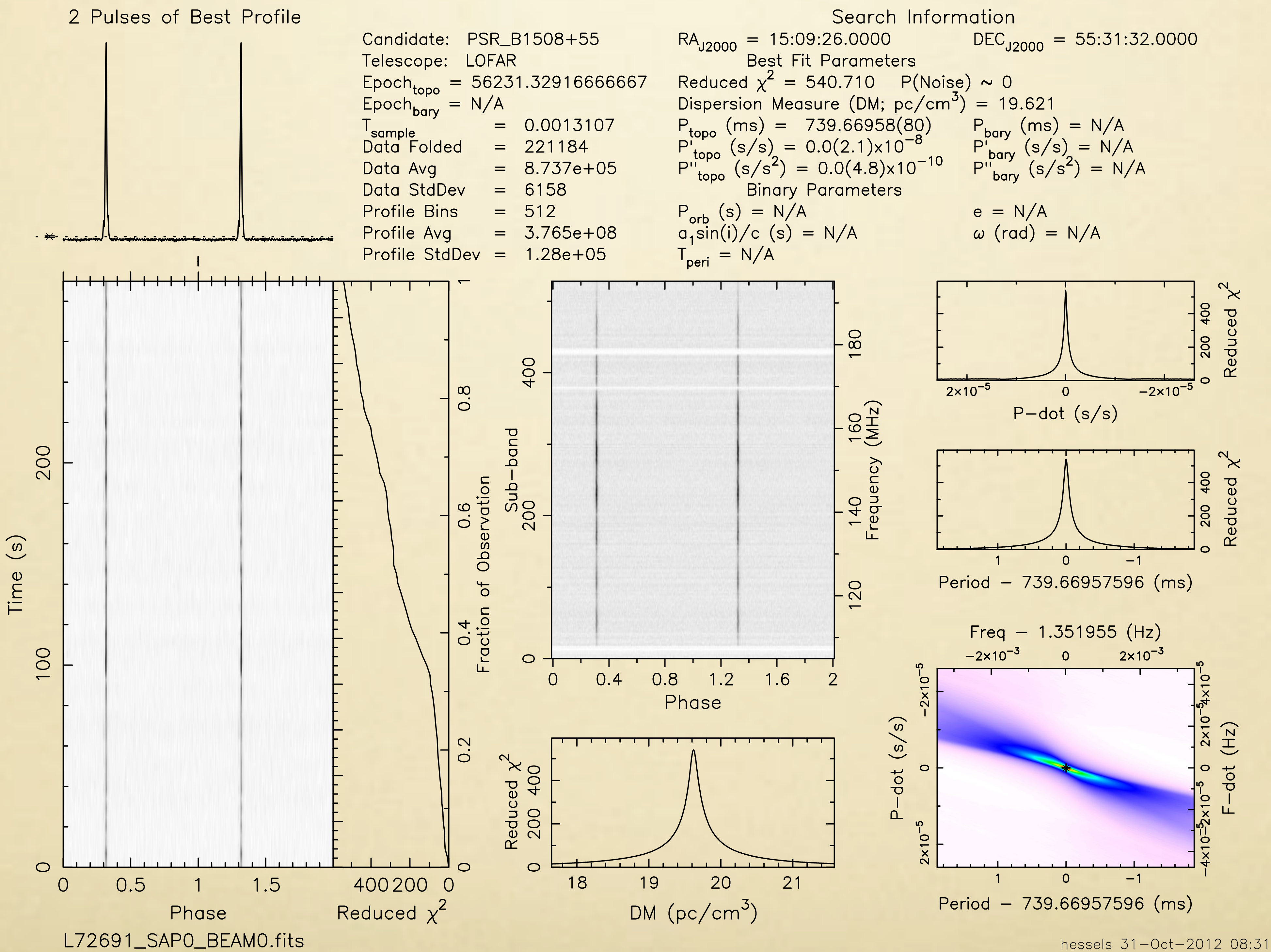
Date

Andromeda



Credit: Hessels

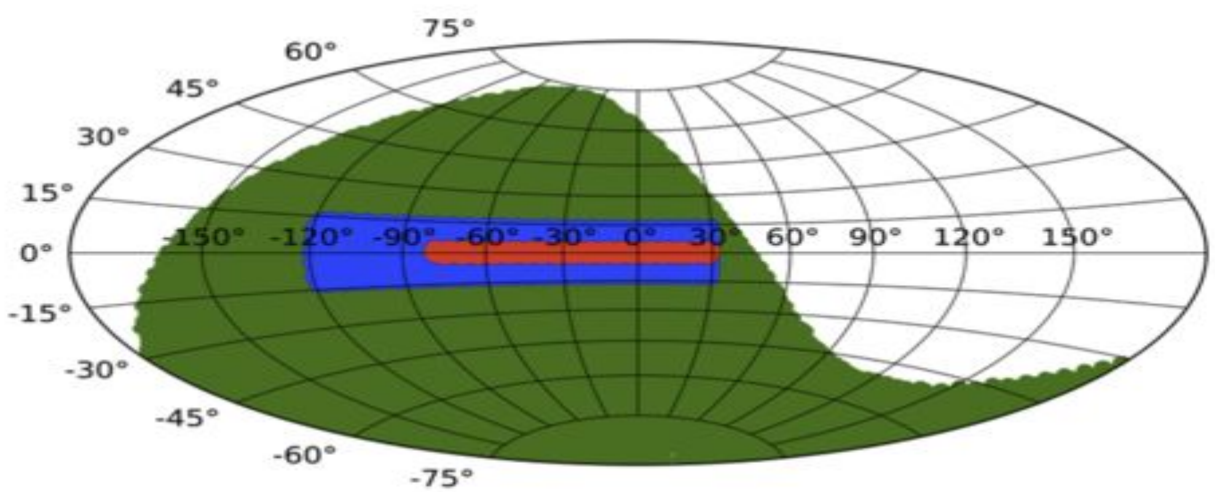
Hot off the press....



The High Time Resolution Universe survey (HTRU) South

- Pulsar & radio transients survey from Parkes
- Making discoveries across the neutron star phase space and beyond.
  - >100 “normal” pulsars
  - >20 millisecond pulsars (isolated & binary)
  - 1 magnetar
  - 1 “diamond” planet

f_{centre}	1381 MHz
BW	340 MHz
t_{samp}	64 μ.sec



Survey Region	Total pointings when complete	%'tage complete
Low – Latitude	15990	84
Med – Latitude	95056	100
High – Latitude	443287	60

Currently timing many as yet unpublished HTRU pulsars with the Lovell Telescope

Highlights include:

- P_{spin} = 1.099 s pulsar in 98 day binary with massive companion ($M_{comp, min}$ = 0.237 M_{solar}) unusual formation history; why isn't this pulsar an MSP?
- P_{spin} = 2.719 ms isolated MSP – relatively unusual and likely from a binary disrupted by supernova
- P_{spin} = 3.46 ms MSP in 7hr binary with a $M_{comp,min}$ = 0.00076 = 0.8M_{Jovian} another “Planet Pulsar”!

Thornton et al

Finding pulsars with Machine Learning.

Lyon et al

Survey	Candidates
High Frequency Southern Sky Survey	150,000
Parkes Southern Pulsar Survey	40,000
Parkes Multibeam Pulsar Survey	8,000,000
Swinburne Intermediate Latitude Survey	"Several hundred thousand"
Arecibo P-Alfa	5,000,000
HTRU (LOW)	1,600,000
HTRU (MED)	9,505,600
HTRU (HIGH)	44,328,700

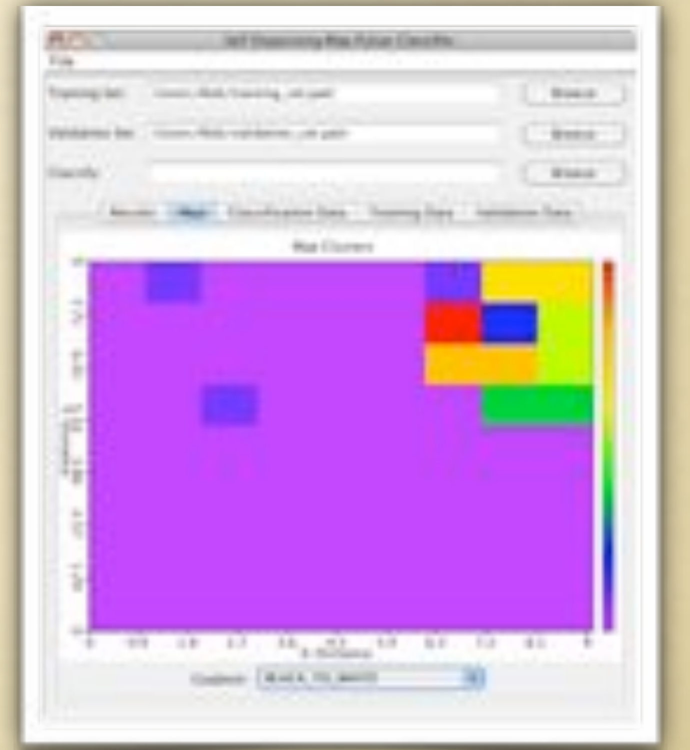
Table 1. The number of candidates generated by selected pulsar surveys.

Survey	Year	Data per beam	Data rate	Total
High Frequency Southern Sky Survey	1988	1 MB	13 KB/s	0.6-1.1 TB
Parkes Southern Pulsar Survey	1991	18.6 MB	120 KB/s	805 GB
Parkes Multibeam Pulsar Survey	1997	100 MB	640 KB/s	5 TB
Swinburne Intermediate Latitude Survey	1998	27 MB	1.3 MB/s	1.6 TB
Arecibo P-Alfa	2004	1.6 GB	87 MB/s	> 1000 TB*
HTRU (LOW)	2008	16 GB	52 MB/s	250 TB
HTRU (MED)	2008	2GB	52 MB/s	190 TB
HTRU (HIGH)	2008	1 GB	52 MB/s	435 TB
LOFAR	2010	-	1 GB/s	2.5 PB
FAST	2016	15-47 GB	0.5 GB/s	16.7 PB
SKA	2020	-	0.43-1.45 TB/s	-

Pulsar survey telescope data rates and volumes (not raw

Current Investigations:

- Testing the performance of SOM classifier on large, adversarial data sets (1 positive example to 10,000 negative).
- Investigating decision trees, random forests, and support vector machines as alternative classifiers.
- Investigating semi-supervised learning techniques.
- Looking at fast highly scalable classification algorithms, to asses if they can be modified to meet our needs.

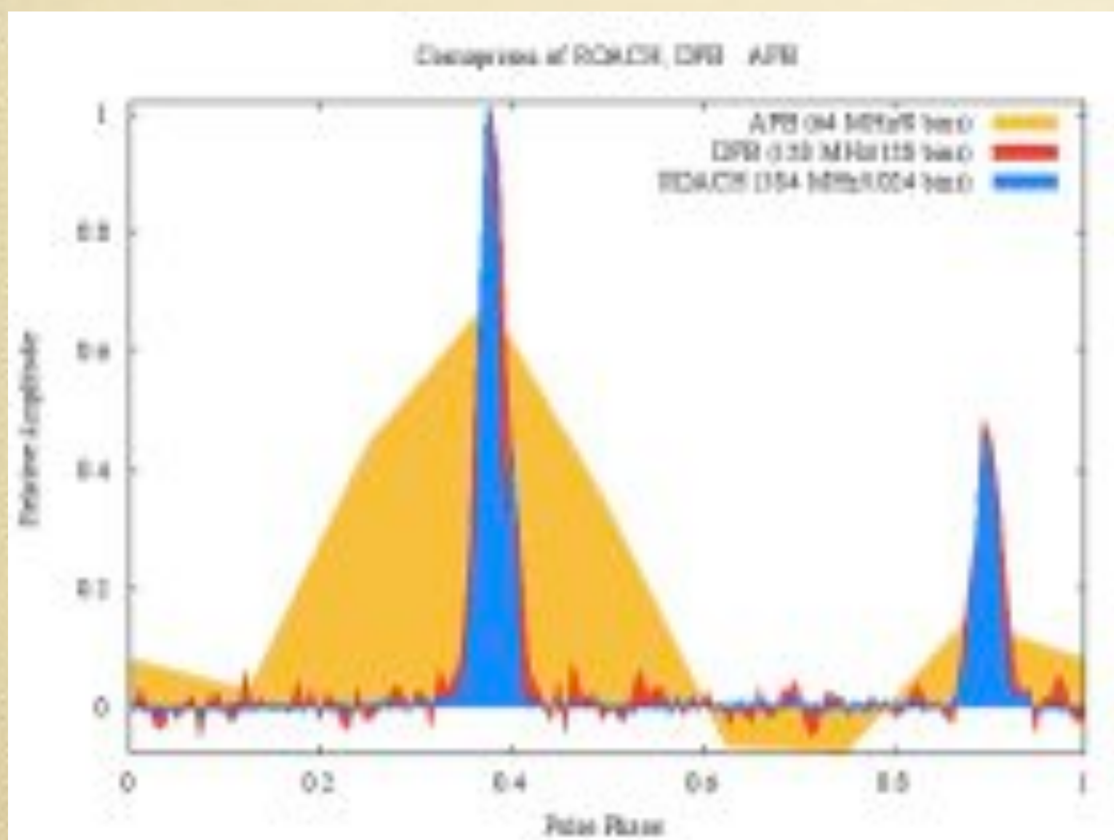


SOM showing the clustering of patterns that represent actual

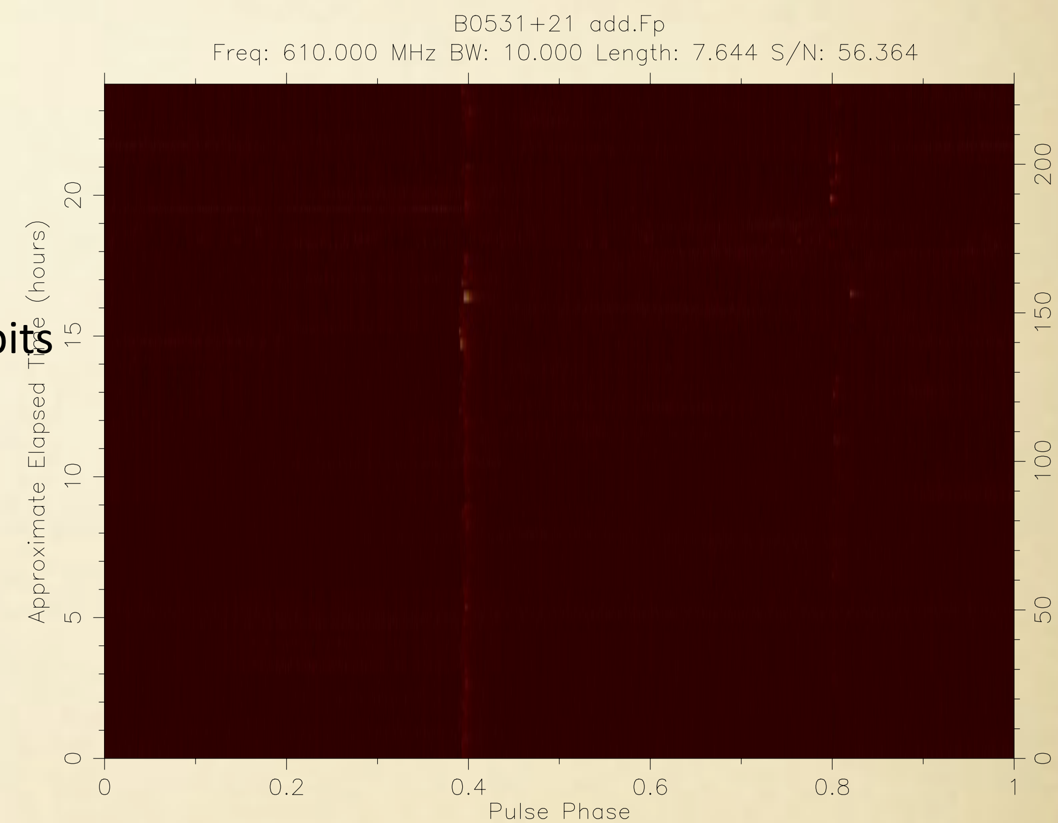
New Backends, Uniboard 1 & 2, Apollo

- Legacy incoherent filterbank system, up to about 100 MHz
- ATNF Digital Filterbank (DFB), incoherent dedispersion, 384 MHz, BW, 8 bits
- ROACH-board system, 400 MHZ BW, 8 bits, Since early 2011

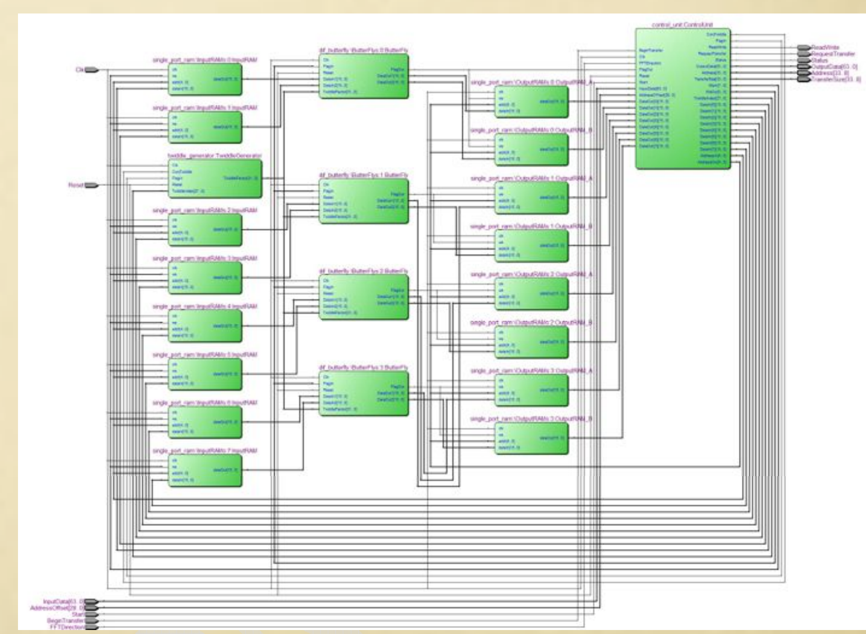
  observing in two widely-spaced bands at L-band, baseband RFI rejection
- HPC computing cluster for ROACH and LEAP processing
- Apollo will piggyback on _ALL_ Lovell observations for transients!



Crab GPs (hundreds/day) with 42ft telescope!



Uniboard - Coherent Dedispersion - FFT module



Bassa, Jordan, Ahmedsaid, Stappers et al

MUST Digital Back-end

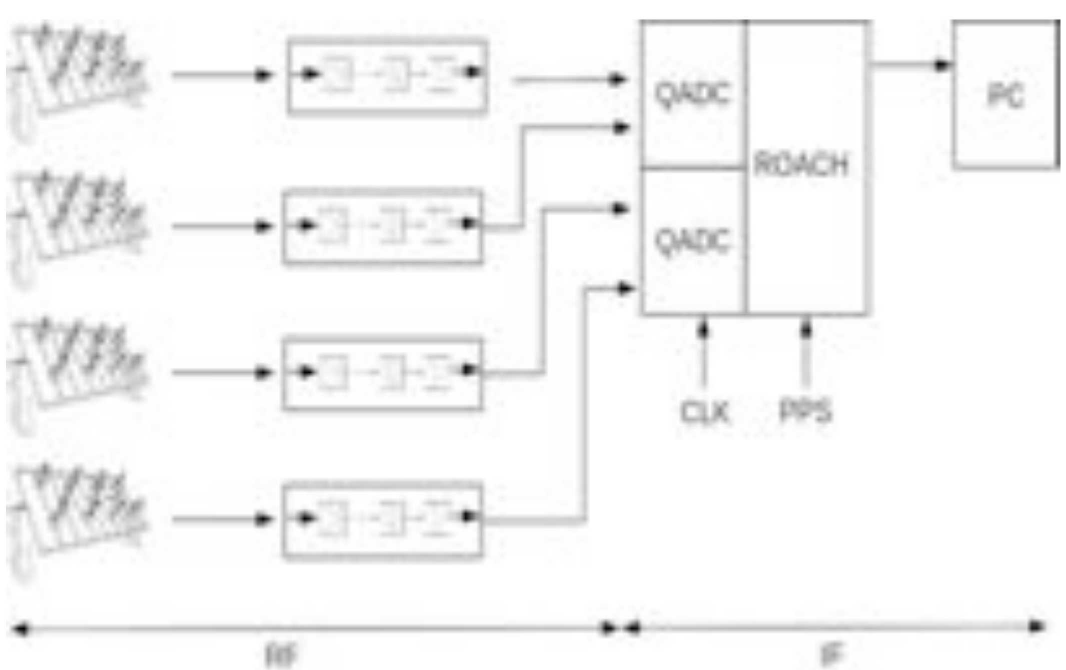
Developed on the Reconfigurable Open Architecture Computing Hardware (ROACH) board. ROACH is a standalone FPGA processing board.

The design environment is the Collaboration for Astronomy Signal Processing and Electronic Research (CASPER) toolflow.

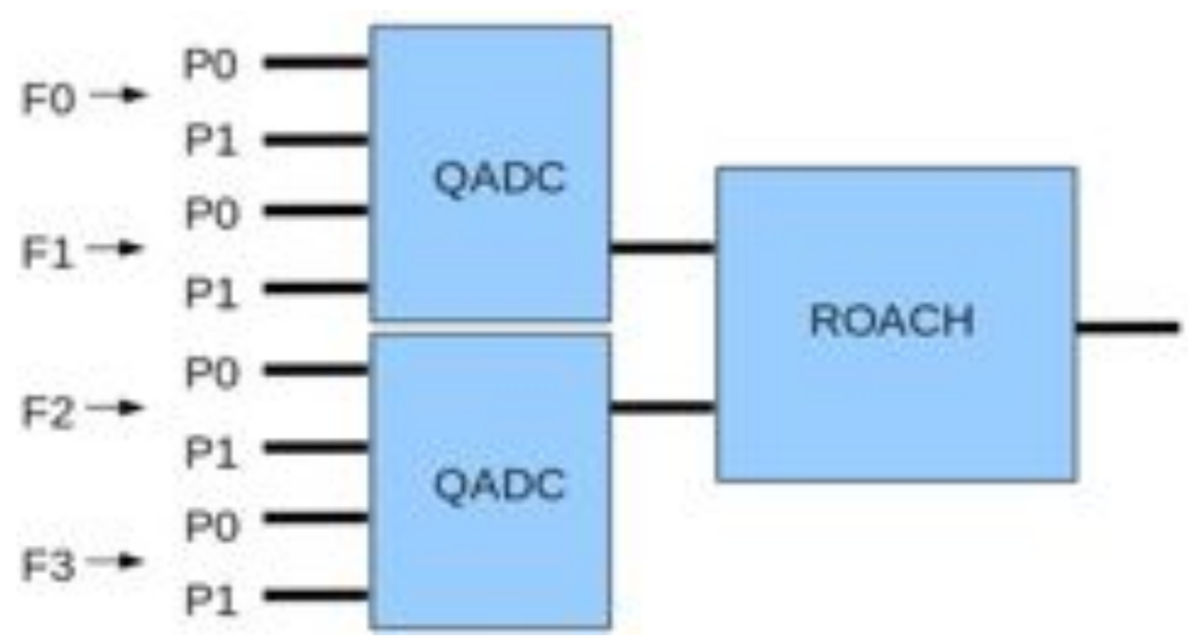
The project deliverables are:

- MUST digital back-end -- building towards full array
- Fractional delay block for CASPER library and possible MeerKAT deployment
- Comparison of frequency-domain and time-domain beamformer

MUST system overview



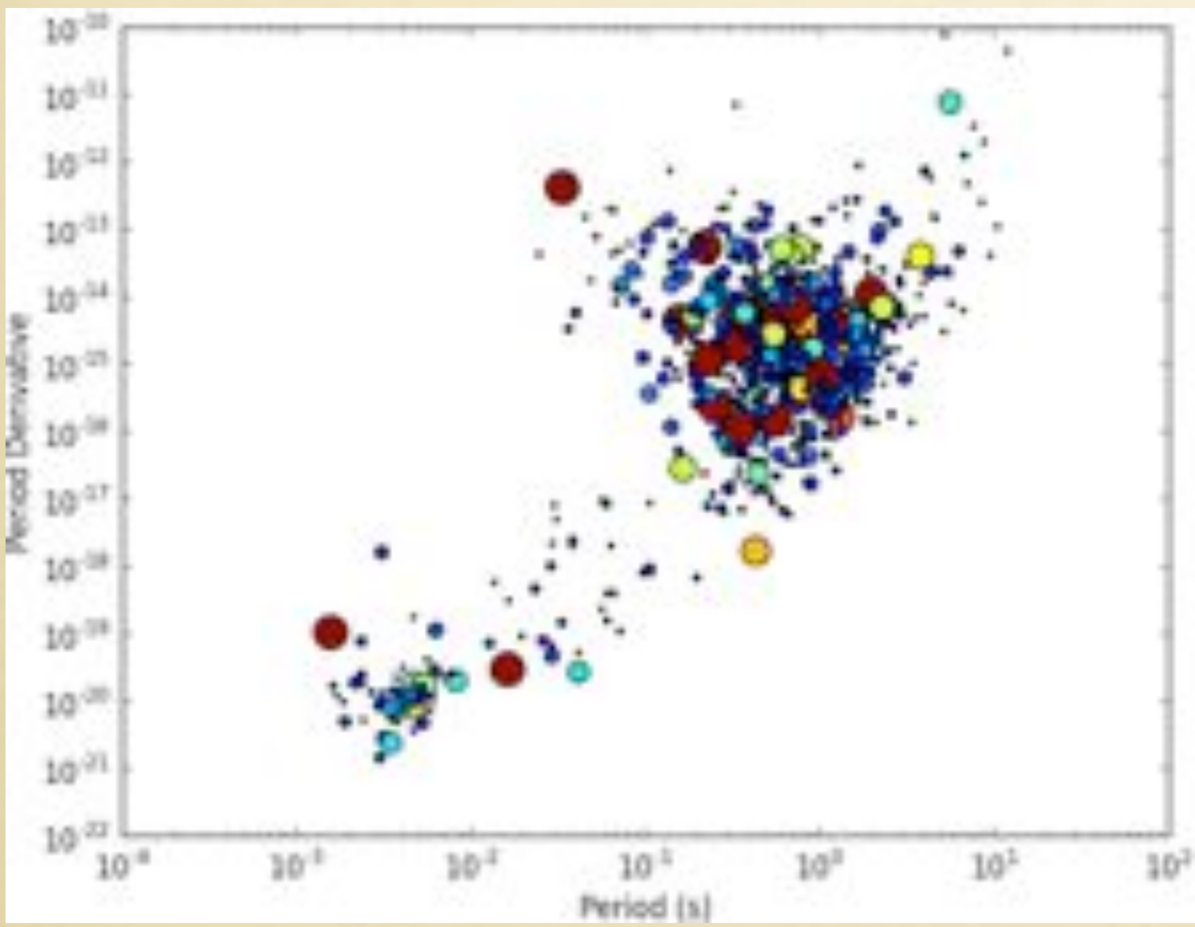
MUST signal chain

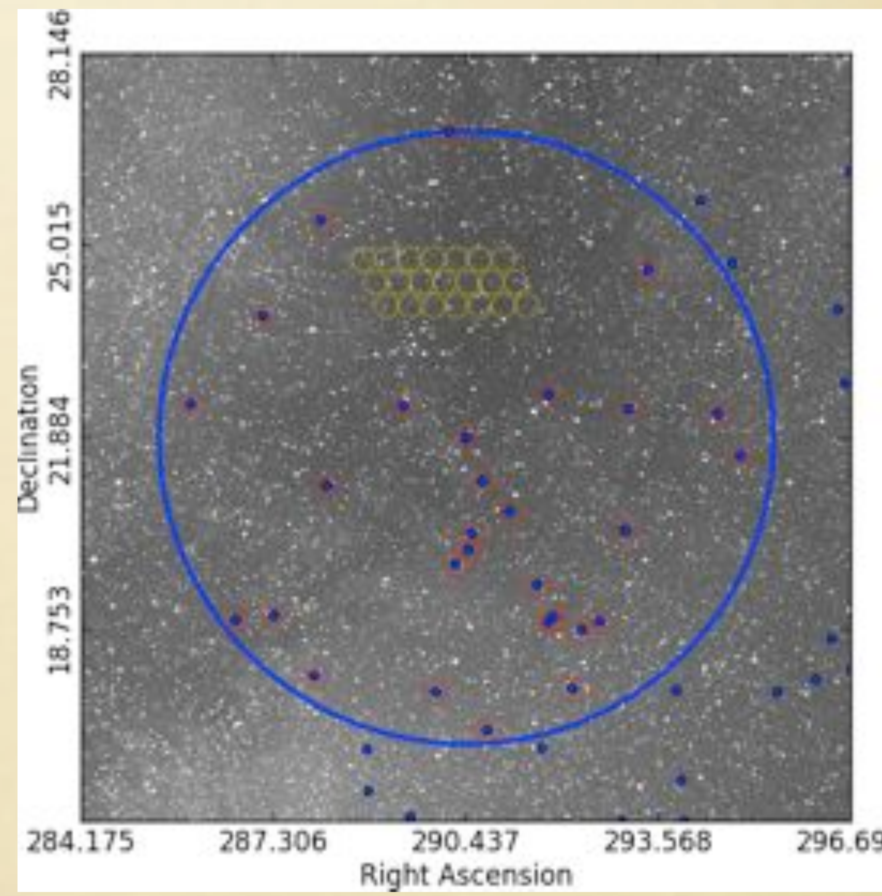


RAPIDE

Key Properties of RAPIDE

Frames	100
Yagis/frame	32x2 poln.
Collecting Area	~2000 m^2
Frequency	600 MHz
Bandwidth	50 MHz
Coherent Beams	50
Field-of-view (Incoherent)	~75 square degrees
Field-of-view (Coherent)	~10 square degrees





Time > 900 (80% of visible) pulsars / twice weekly

Weekly detection of extragalactic bursts

TRAPUM

Targeted pulsar searches of SNRs, PWNe, and high-energy point sources

- Rich locations for pulsars, in particular young pulsars, and energetic MSPs
- Relatively "point like" so not many beams needed
- High gain of meerKAT beats current Southern telescopes

Globular Cluster Searches

- Rich locations for pulsars, in particular MSPs and interesting binaries
- Relatively "point like" so not many beams needed
- High gain of meerKAT beats current Southern telescopes

Extragalactic searches

- Relatively "point like" so not many beams needed
- High gain of meerKAT beats current Southern telescopes
- Predictions indicate that should be able to find a "few'

Using Radio Pulsars to Probe Gravity, Dark Matter and Stellar Populations in the Galactic Center

- Unique high frequency capability of meerKAT
- Implemented later when these frequencies became available
- Extremely interesting science

Galactic plane survey

- Ambitious, requires about 500 tied-array beams
- Will be developed in collaboration with meerKAT team
- An absolutely vital step towards the SKA

Fast transients: expanding the parameter space

- Search all of the pulsar obs, but also commensal high time resoln.

3000 hours Allocated

Commensal & Targetted

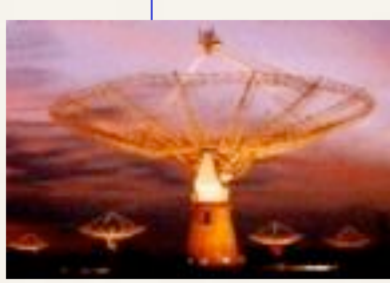
Many new/improved radio facilities (coming) online.

- SKA is ultimate goal
- Precursors and many pathfinders in existence or under construction
  - ASKAP and MeerKAT being built on proposed sites
  - Thunderkat, TRAPUM, COAST, CRAFT, VAST, VFASTR....
- ➢ Data challenges before SKA comes on-line
- ➢ We are involved in all pathfinders, leading in LOFAR, MeerKAT and also leading non-imaging processing WPs - see RS talk





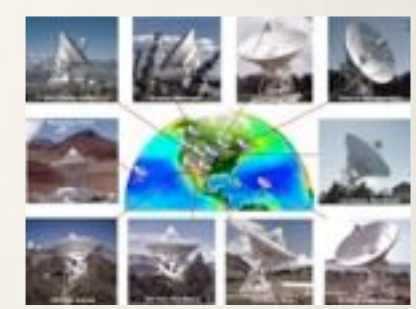











Summary

- Lovell timing database is unparalleled - giving us vital clues about how pulsars work - and how to make them better clocks!
- The EPTA and LEAP timing projects are putting us at the forefront of the race to directly detect gravitational waves
- The HTRU survey w/Parkes is revealing all sorts of interesting new pulsar systems and transients!
- LOFAR is already revolutionising our understanding of pulsar emission and will soon be a premier pulsar/transient search machine
- We are actively involved in SKA pathfinders at both a technical and scientific level and are aiming to play a lead role in SKA itself.
- MUST --> RAPIDE provide us with an excellent opportunity to build a unique instrument for pulsar timing and finding transients.
- Not able to cover everything here...