High Time Resolution with LOFAR

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Acknowledgements

- Anya Bilous - lots of plots
- Charlotte Sobey - plots
- Vlad Kondratiev - background info
- Aris Noutsos - background info
- LOFAR Pulsar Working Group - commissioning of LOFAR's BF modes

Scope of this lecture

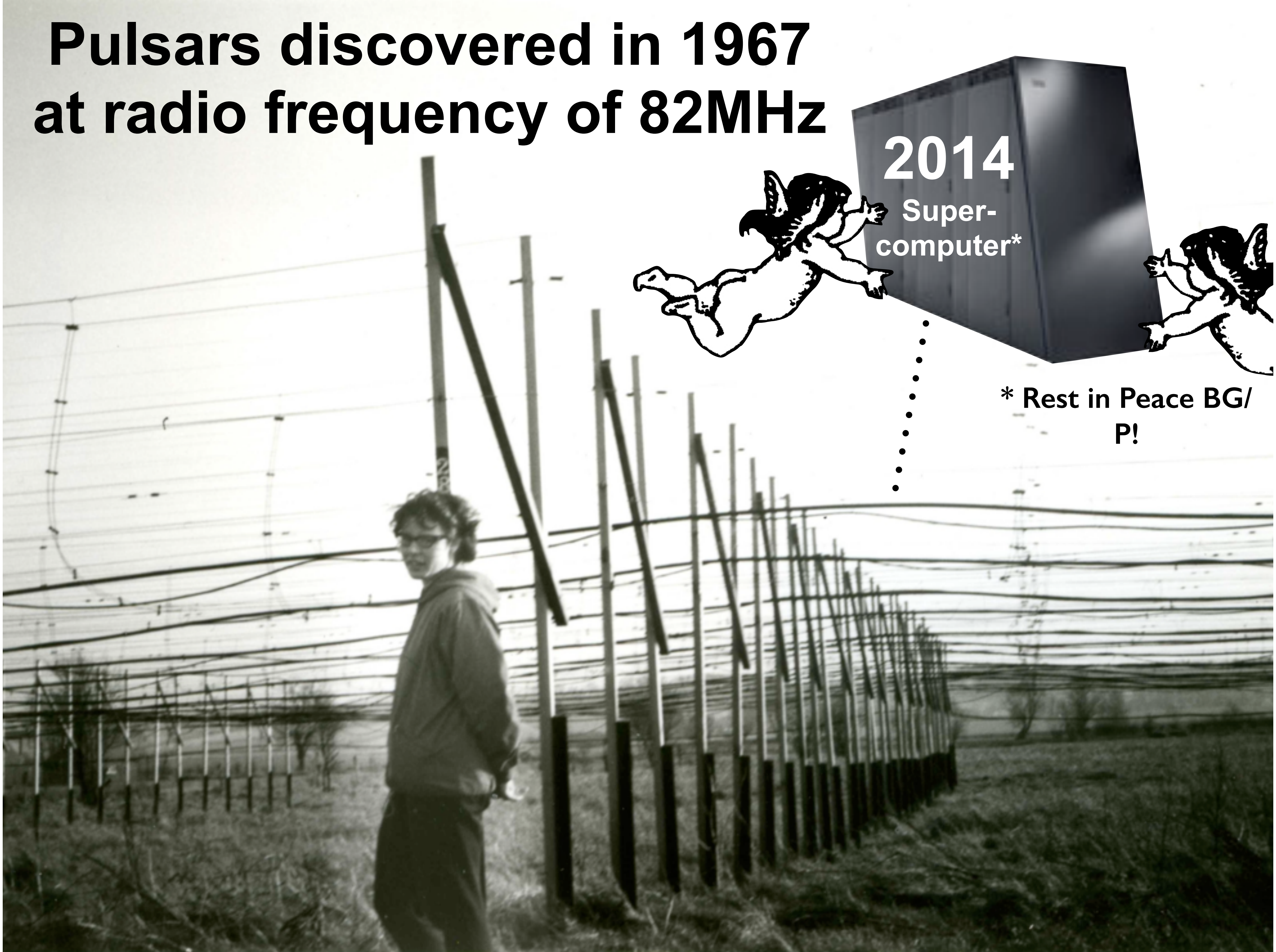
- Introduce LOFAR's high-time-resolution, beam-formed modes.
- Strongly biased to pulsar data analysis.
- Richard Fallow's lecture will complement this, and focus more on analyzing dynamic spectra.
- NB: LOFAR beam-formed modes are also used for scintillation studies, RRLs, solar and planetary studies, and fast radio transients.

Motivation for high time resolution with LOFAR

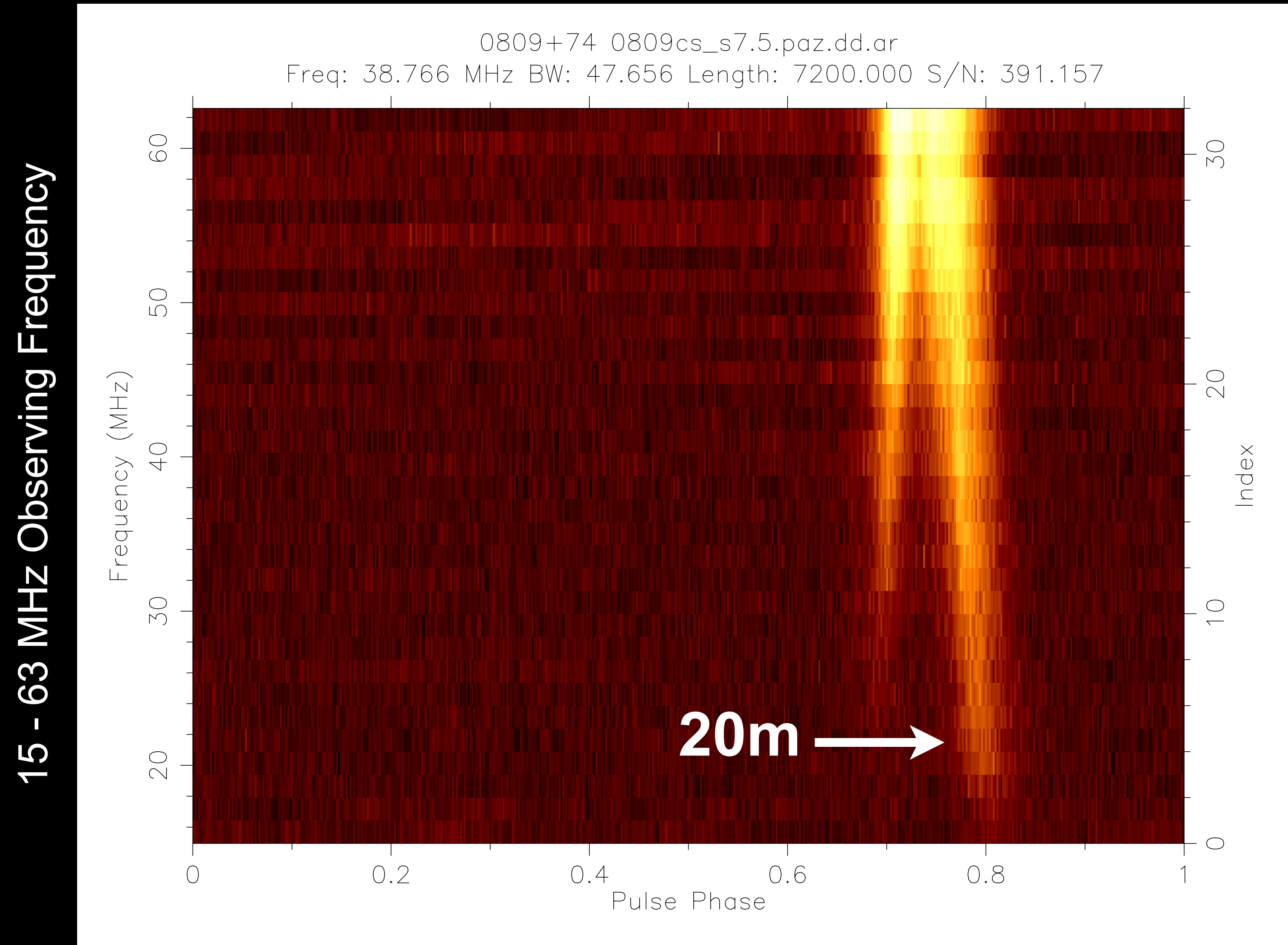
Some example LOFAR science results using the BF modes

Just in case you like laundry lists:

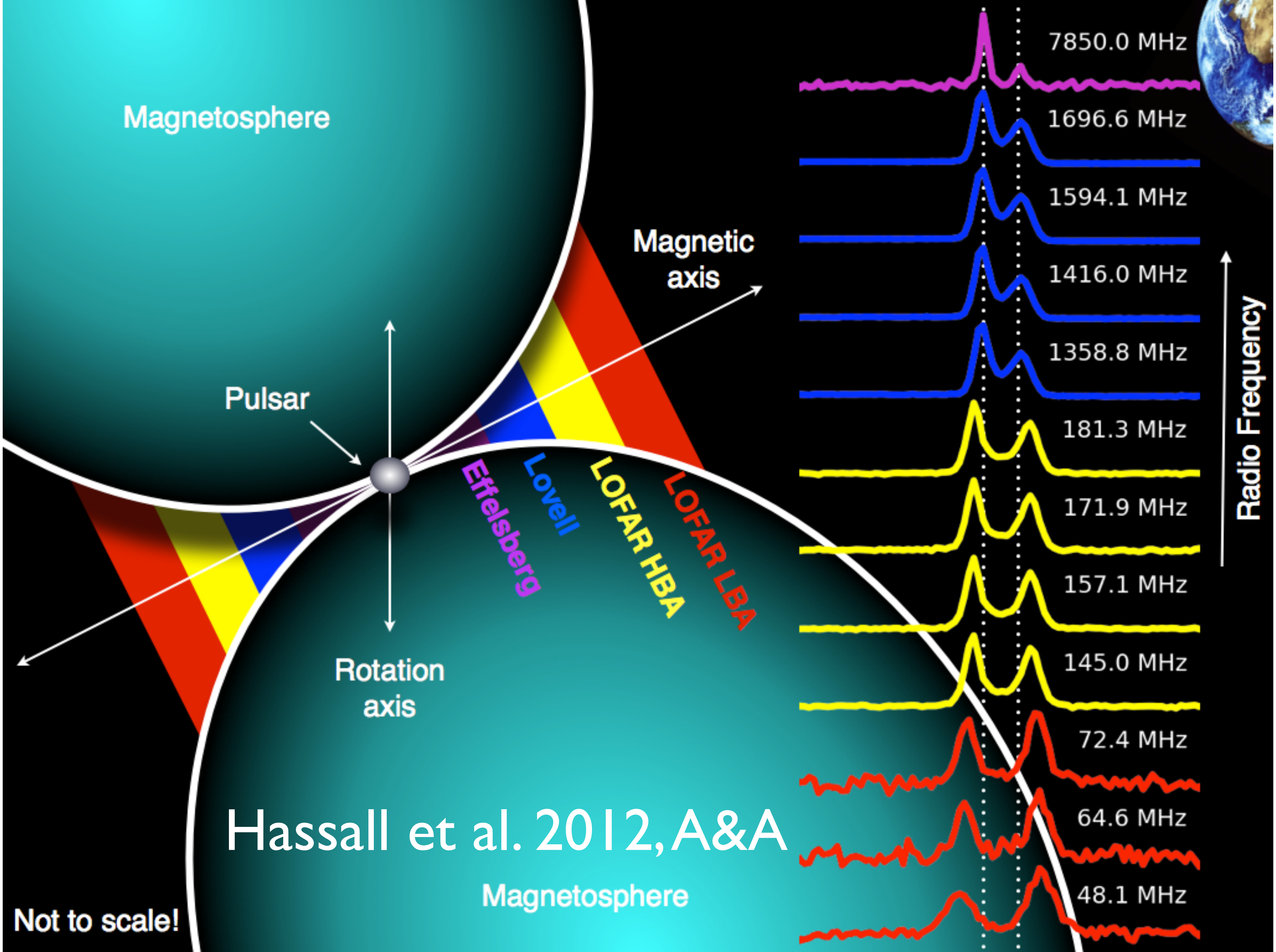
- Kondratiev et al. 2015: *Low-Frequency Profiles of Millisecond Pulsars with LOFAR*
- Sobey et al. 2015: *LOFAR discovery of a quiet emission mode in PSR B0823+26*
- Pilia et al. 2015: *Wide-Band, Low-Frequency Pulse Profiles of 100 Radio Pulsars with LOFAR*
- Bilous et al. 2014: *LOFAR observations of PSR B0943+10: profile evolution and discovery of a systematically changing profile delay in Bright mode*
- Dolch et al. 2014: *A 24 Hr Global Campaign to Assess Precision Timing of the Millisecond Pulsar J1713+0747*
- Stovall et al. 2014: *The GBNCC Pulsar Survey. I. Survey Description, Data Analysis, and Initial Results*
- Archibald et al. 2014: *Millisecond Pulsar Scintillation Studies with LOFAR: Initial Results*
- Coenen et al. 2014: *The LOFAR pilot surveys for pulsars and fast radio transients*
- Hassall et al. 2013: *Differential frequency-dependent delay from the pulsar magnetosphere*
- Hermsen et al. 2013: *Synchronous X-ray and Radio Mode Switches: A Rapid Global Transformation of the Pulsar Magnetosphere*
- Hassall et al. 2012: *Wide-band simultaneous observations of pulsars: disentangling dispersion measure and profile variations*
- Stappers et al. 2011: *Observing pulsars and fast transients with LOFAR*


Pulsars discovered in 1967
at radio frequency of 82MHz
2014
Super-
computer*
* Rest in Peace BG/
P!

PSR B0809+74 detected all the way down to 16MHz!

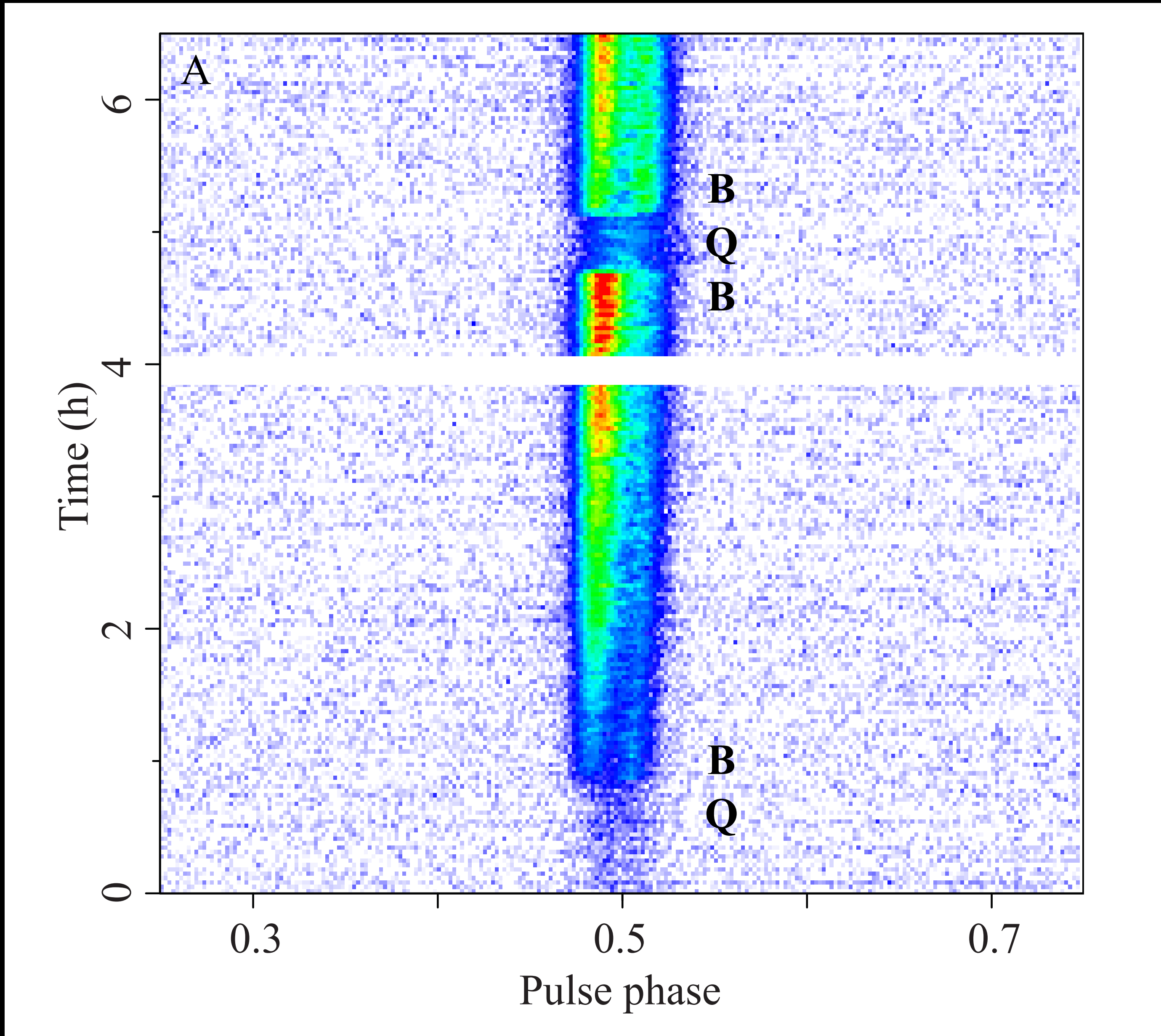


Kondratiev & Hessels



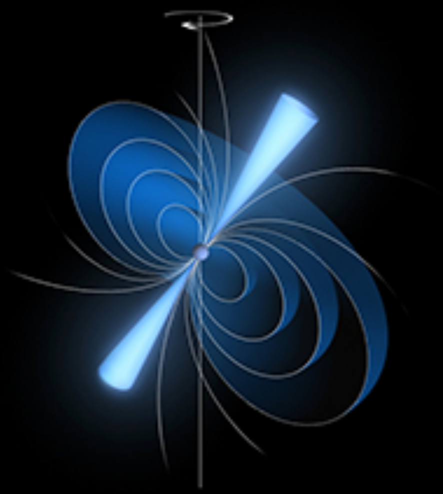
Hassall et al. 2012, A&A

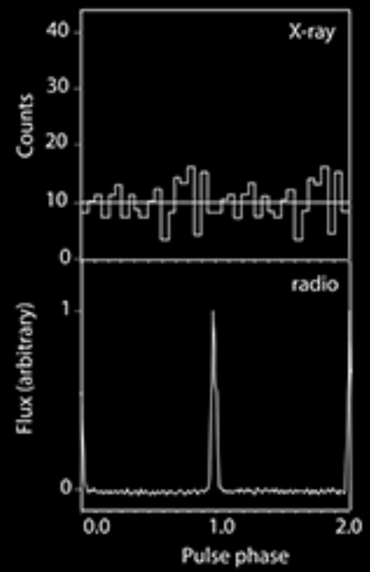
PSR B0943+10 Switching Modes



Hermsen et al. 2013, *Science*

Magnetospheric mode switching

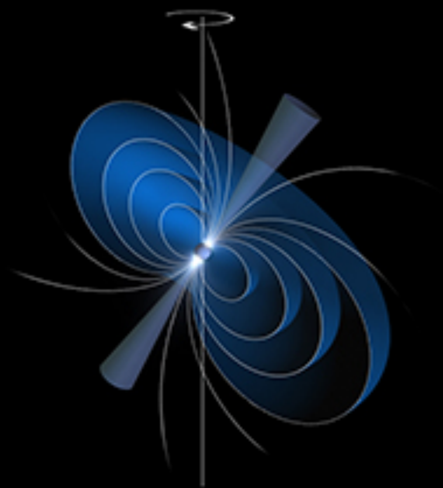


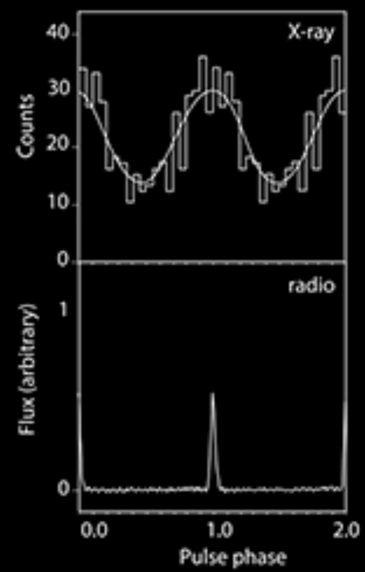


X-ray dim

Radio bright

`Bright’ Mode





X-ray bright

Radio dim

`Quiet’ Mode

Hermsen et al. 2013, *Science*

Observing with LOFAR at high time resolution

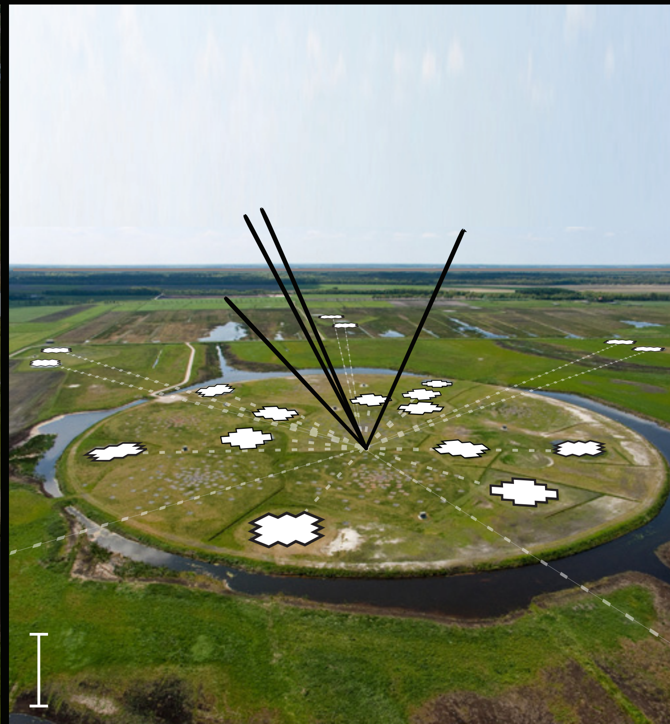
Terminology

So many types of beams...

van Leeuwen - From Stappers et al. 2011

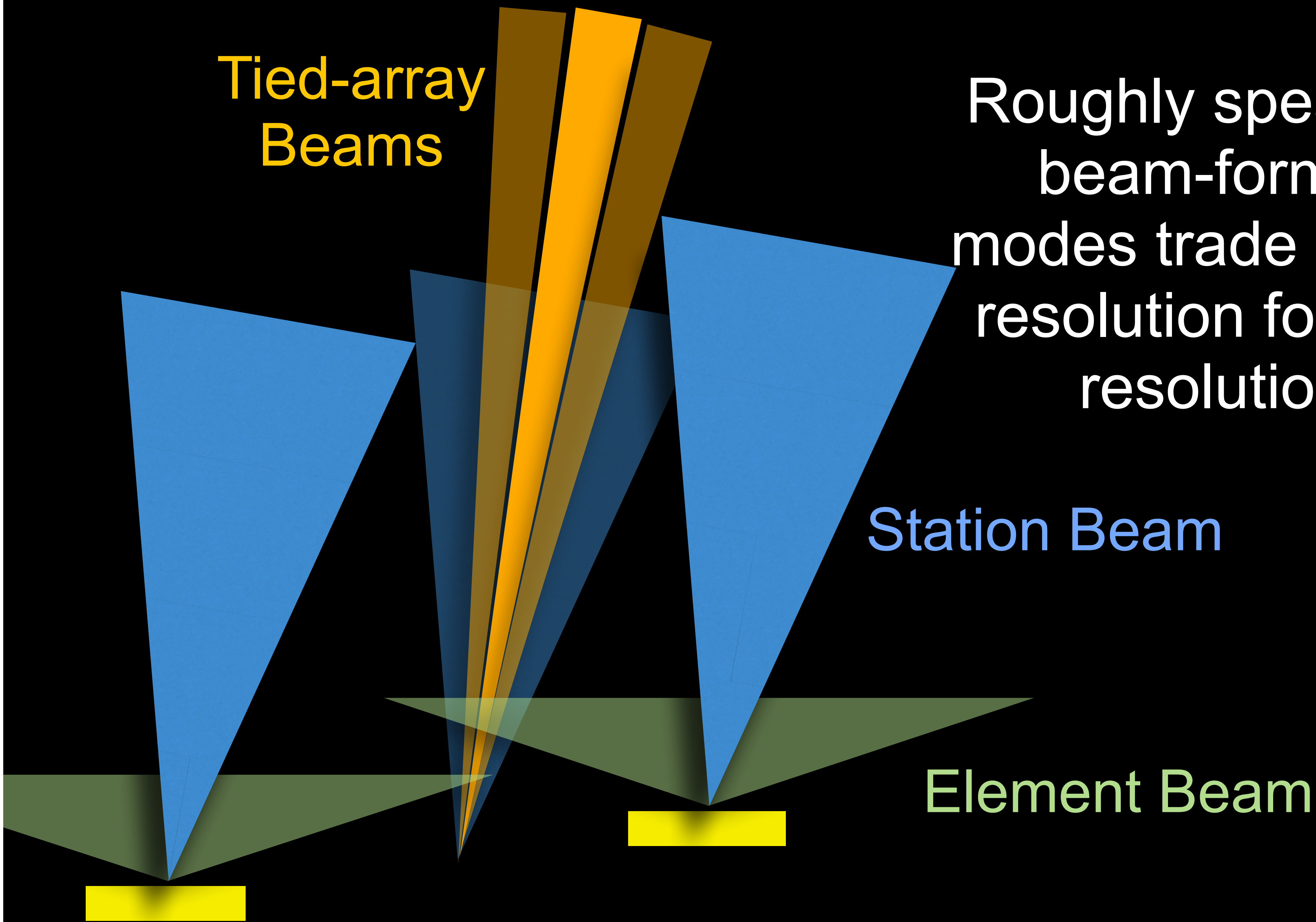
Element Beam
or
Tile Beam

Station Beam
or
Sub-Array Pointing (SAP)



Array Beam
or
Tied-array Beam

Array Beam Forming

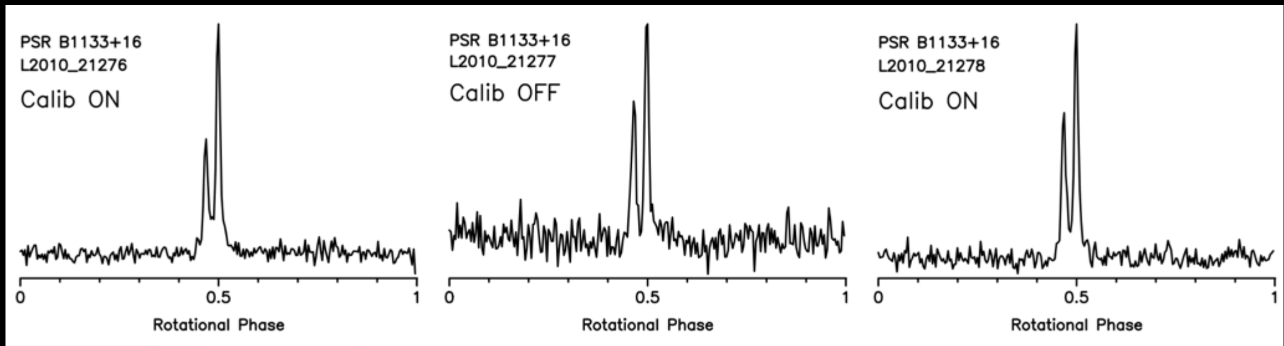


Roughly speaking, beam-formed modes trade spatial resolution for time resolution.

Station beam calibration

Sequence of 3 BF observations

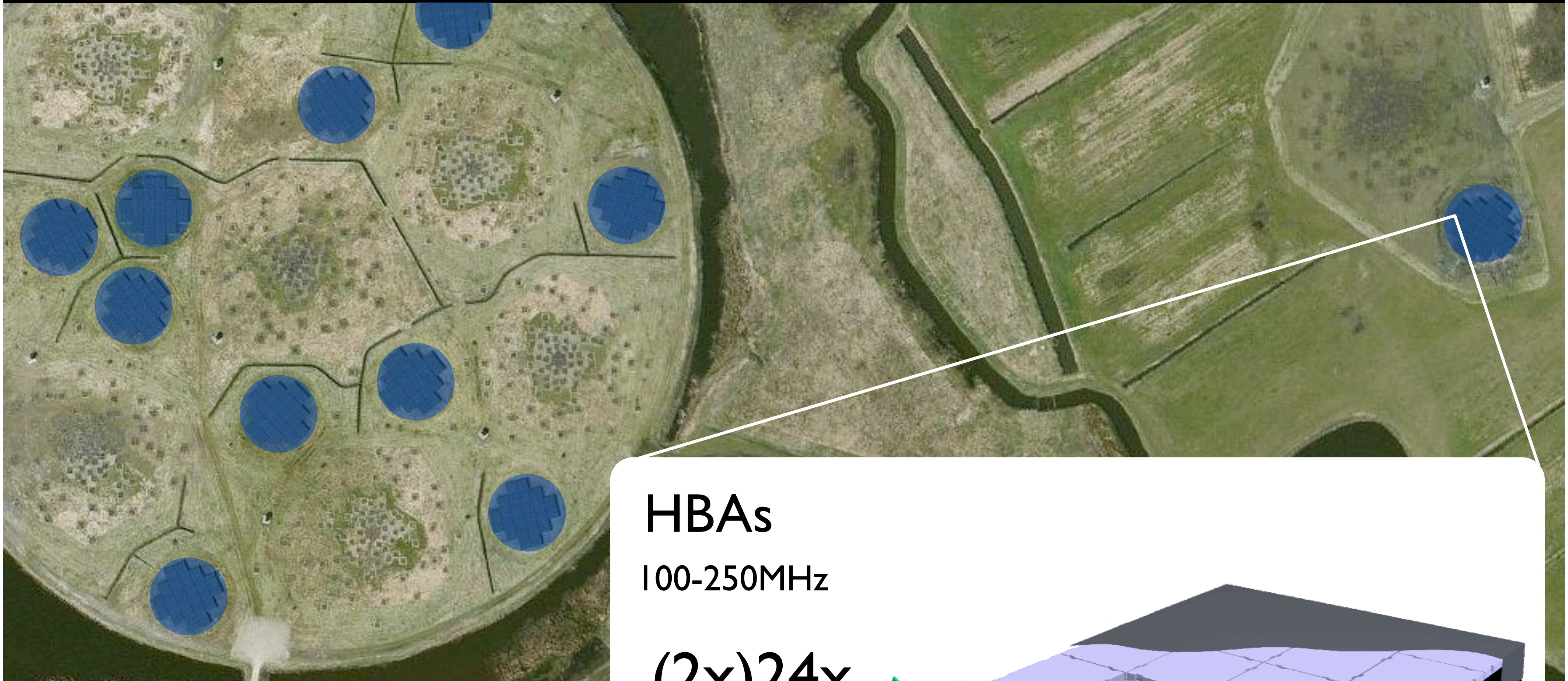
Calibration ON **Calibration OFF** **Calibration ON**



- Station calibration is critical for getting the maximum station sensitivity and the right beam shape.

Hessels & Wijnholds

LOFAR HBAs

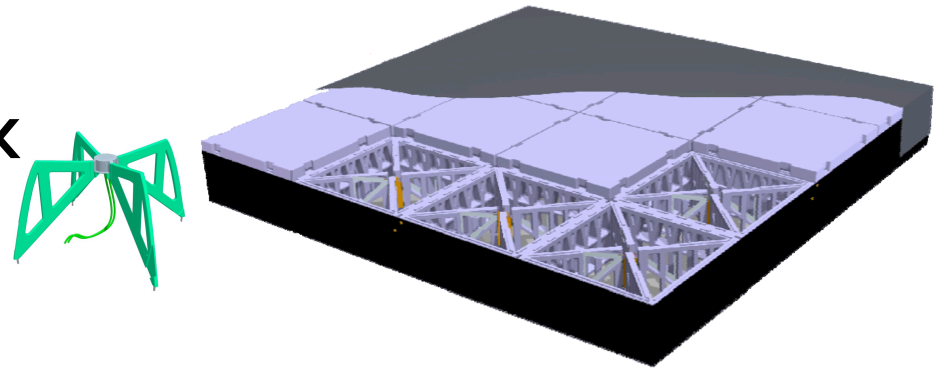


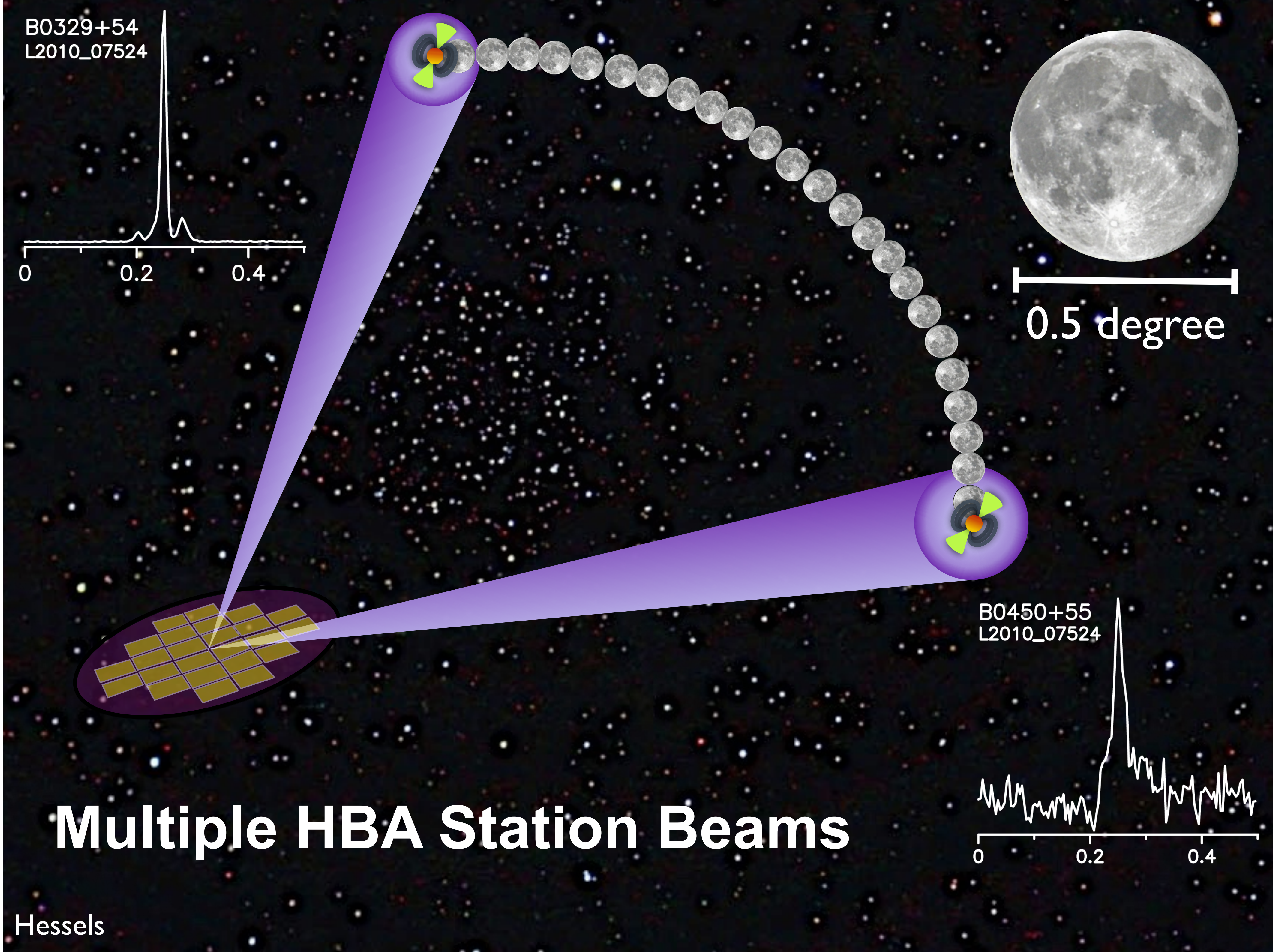
Hassall

HBAs

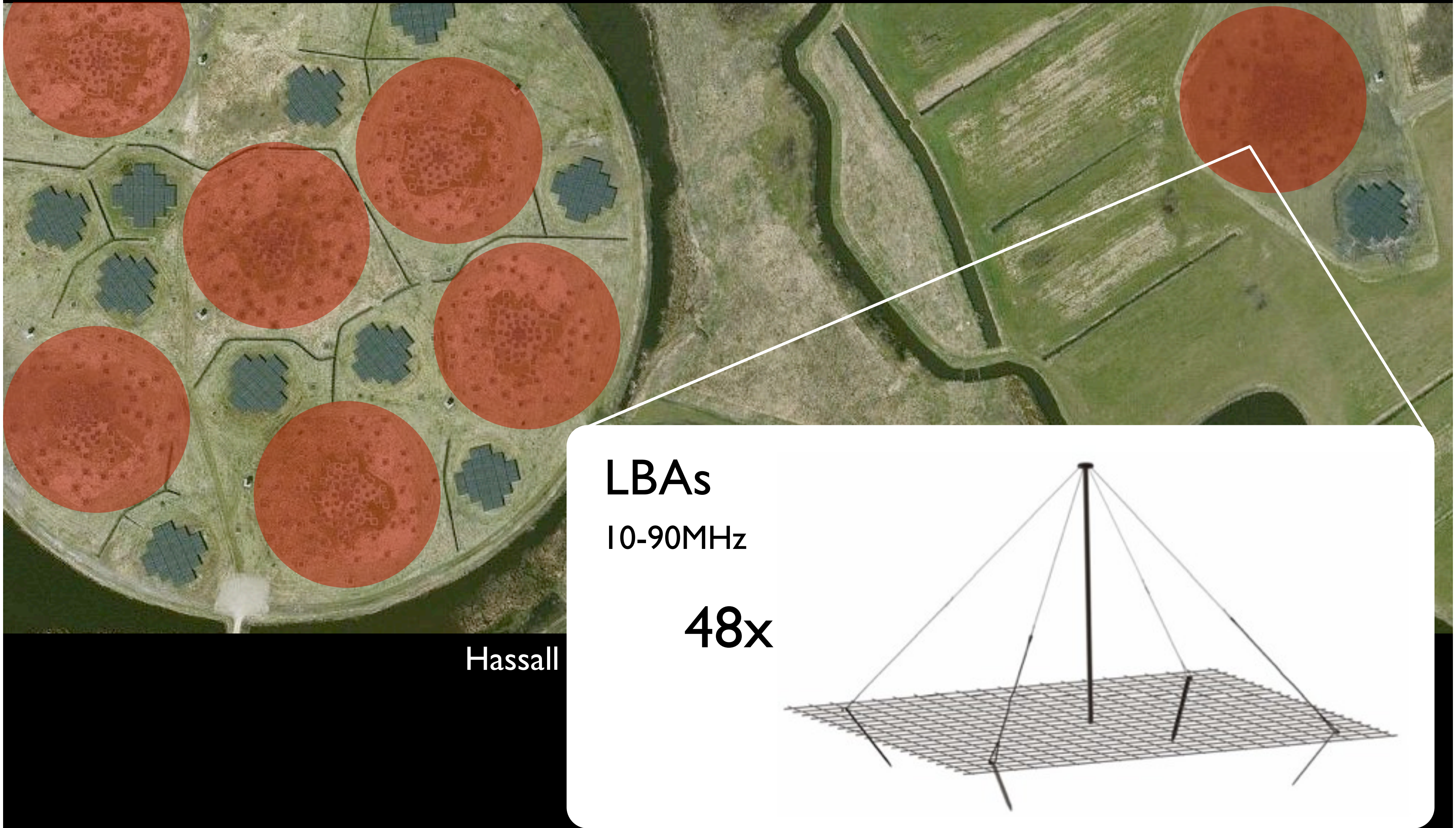
100-250MHz

(2x)24x




B0329+54
L2010_07524
0
0.2
0.4
0.5 degree
B0450+55
L2010_07524
0
0.2
0.4
Multiple HBA Station Beams
Hessels

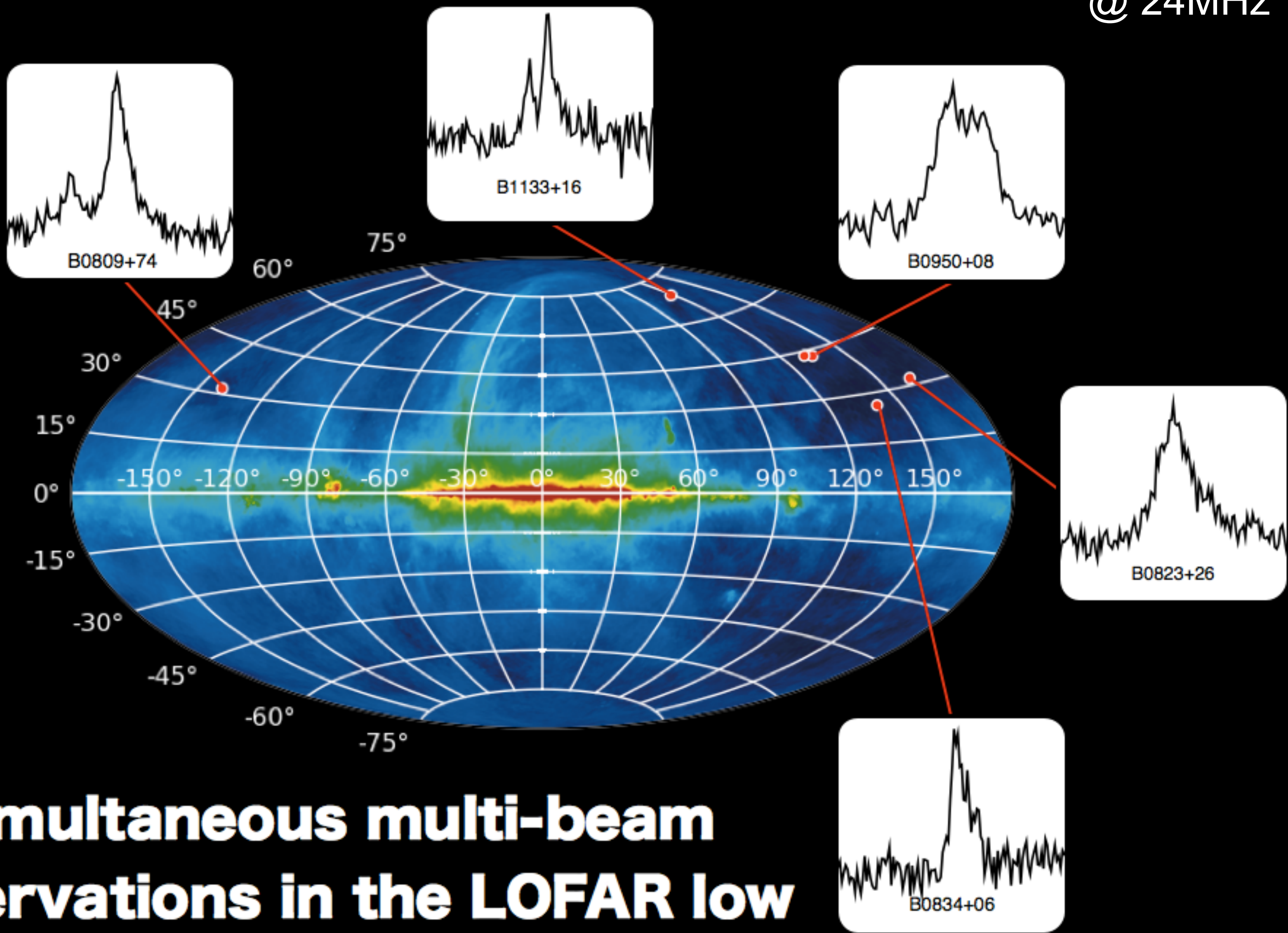
LOFAR LBAs



Hassall

LOFAR LBA Multi-beaming

@ 24MHz



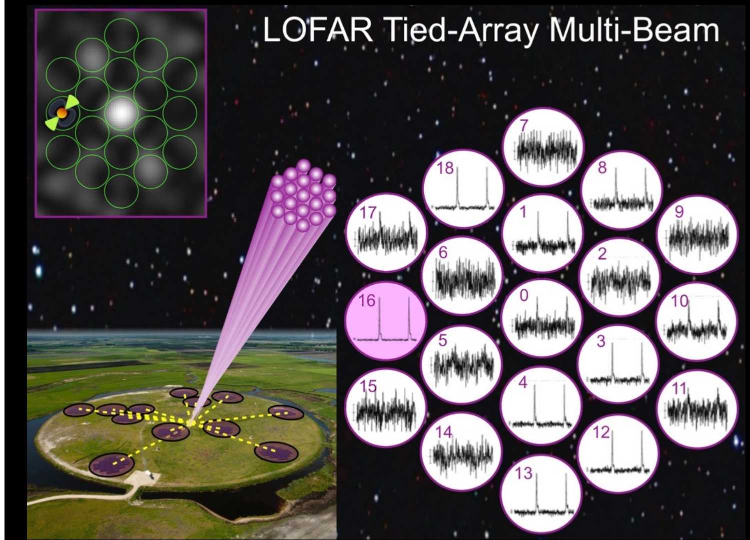
simultaneous multi-beam observations in the LOFAR low band

Haslam 408 MHz map courtesy of LAMBDA

Hassall & Hessels

Standard beam-formed modes

- *Incoherent Stokes* (IS)
- *Coherent Stokes* (CS)
- *Fly's Eye* (FE)
- *Complex Voltage* (CV; subset of CS)
- *Beam-formed+Imaging* (BF+IM)



Hessels

Incoherent Stokes (IS) mode

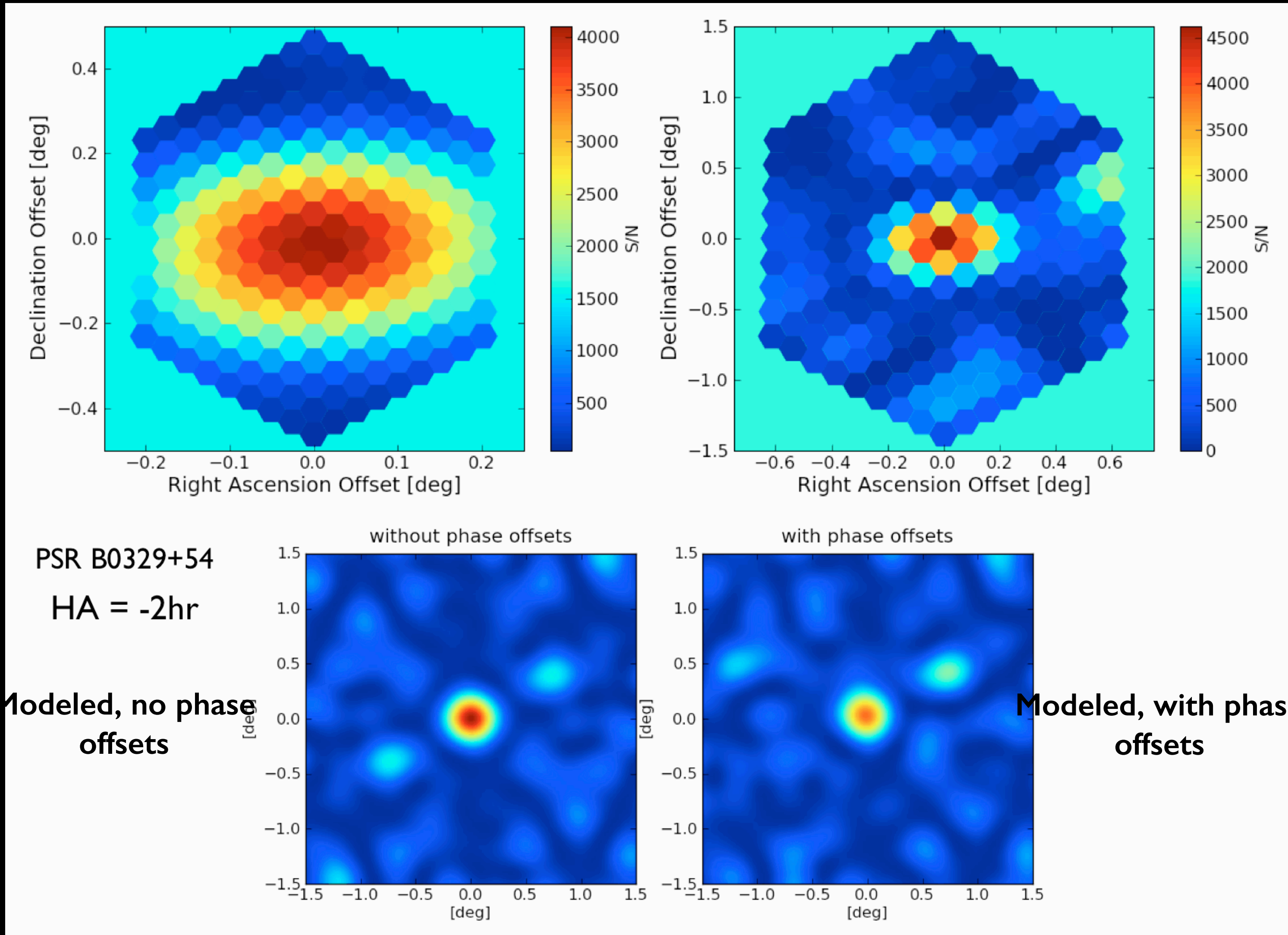
- The individual station beams (SAPs) are `detected’ and subsequently summed on COBALT.
- The phase information of the signals is lost.
- The full FoV of the stations is maintained, regardless of the baseline between them.
- RFI from different stations can pile up.
- Sensitivity increases only as the sqrt(#stations).

Coherent Stokes (CS) mode

- The individual station beams (SAPs) are added on COBALT *before* `detection'.
- A time delay/phase calibration table is applied.
- The FoV depends on the maximum baseline and *uv*-distribution.
- Many CS beams can be synthesized within a single SAP.
- Fairly robust to RFI.
- Sensitivity increases *roughly* with the number of stations included.

Tied-array coherency and beam shape

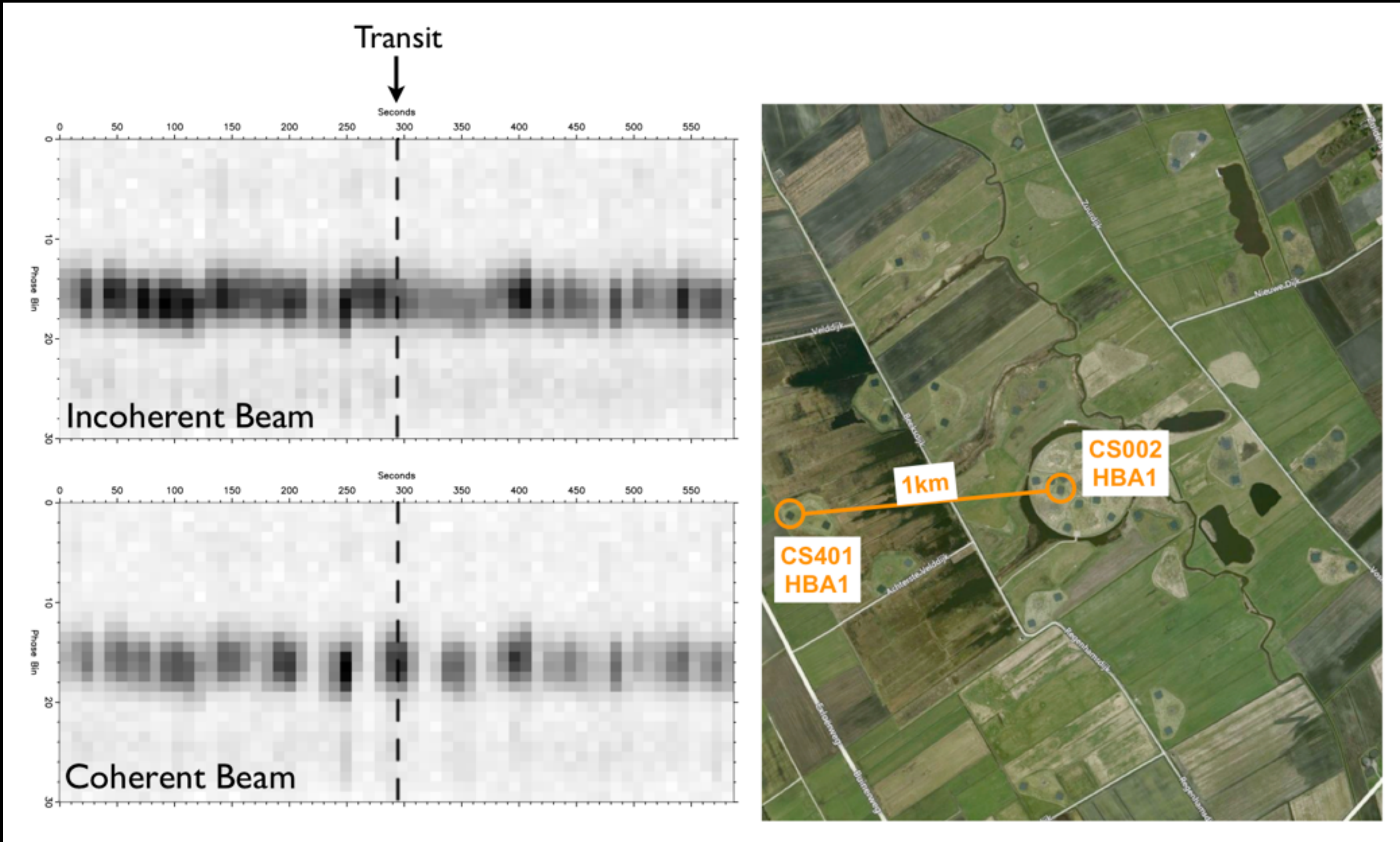
Observed, zoomed in **Observed, zoomed out**



Hessels & Wucknitz

CS vs. IS mode

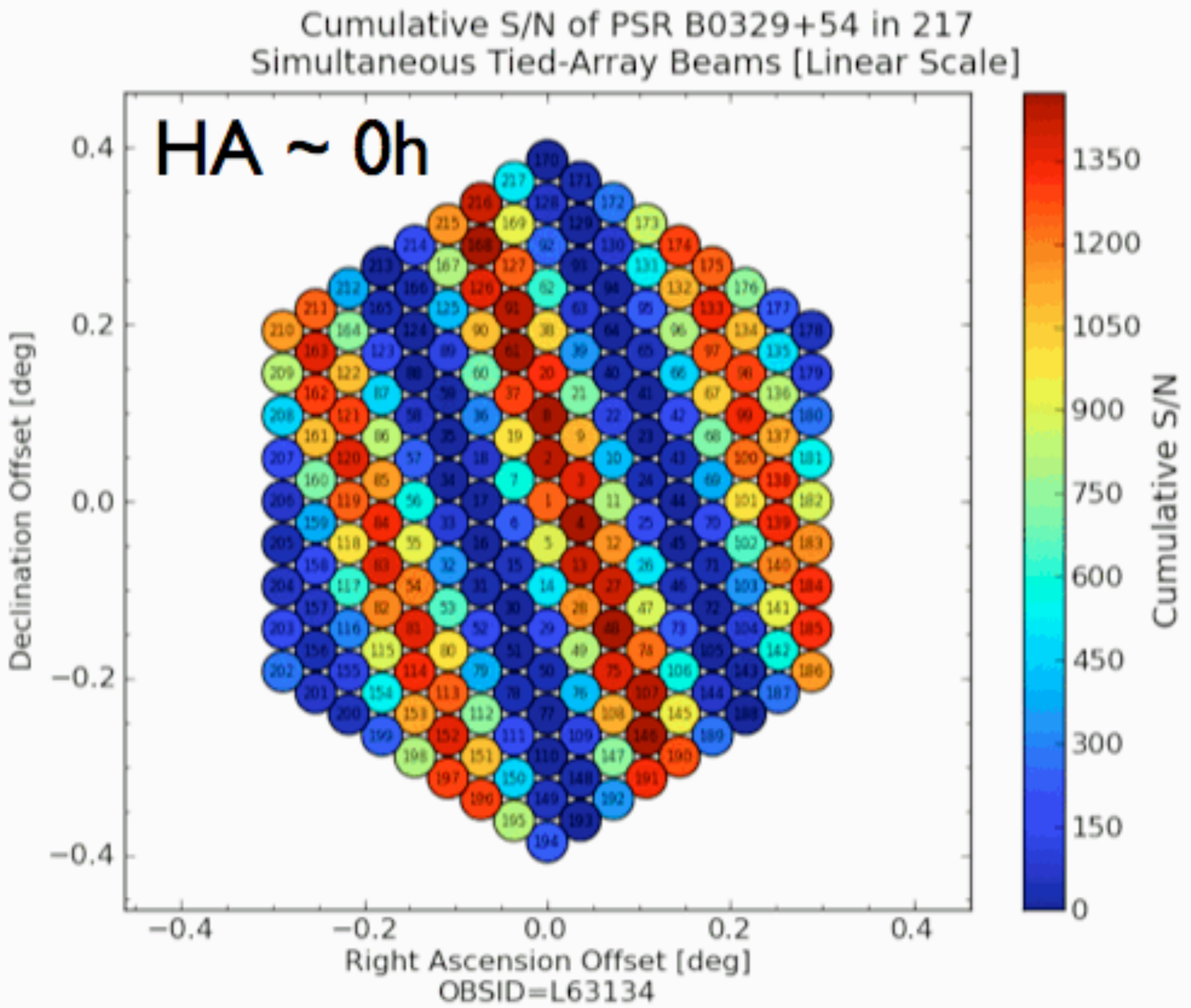
Transit experiment PSR B0329+54

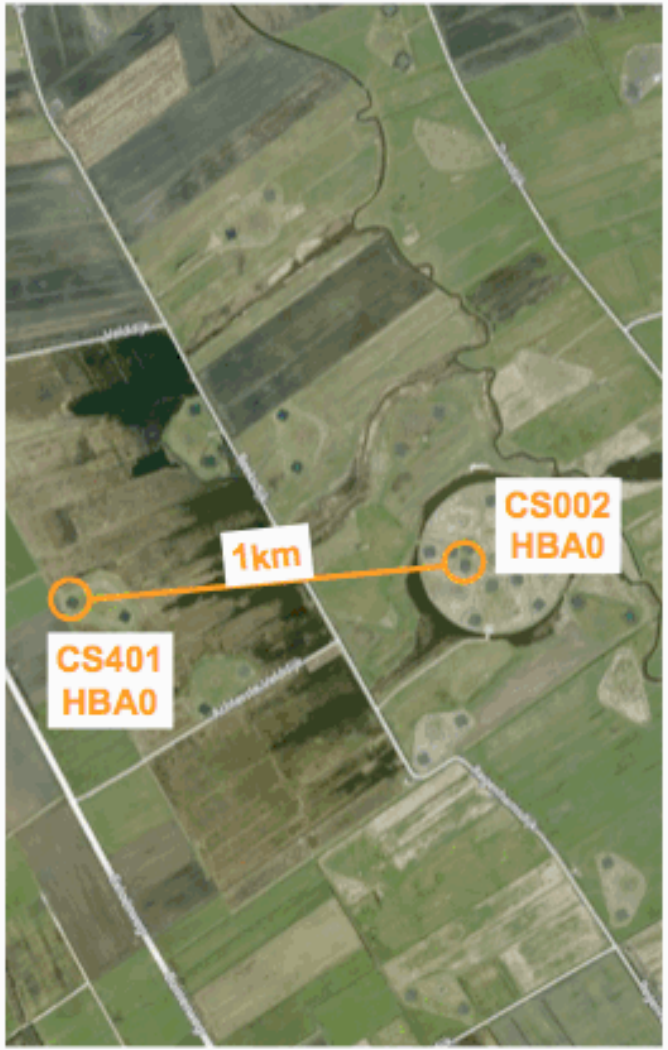


Hessels

CS vs. IS mode

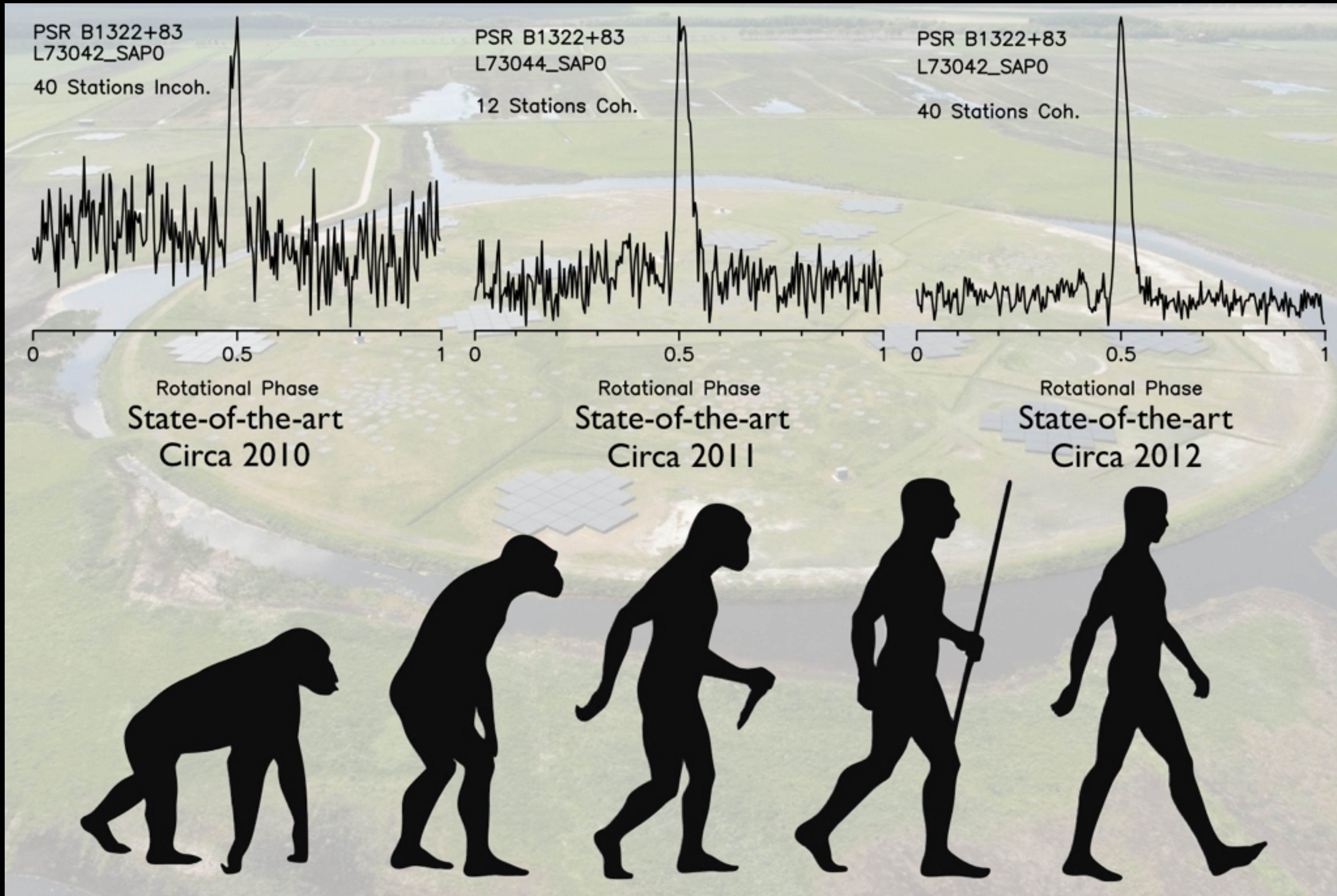
Tracking PSR B0329+54 with 2 stations and 217 CS beams





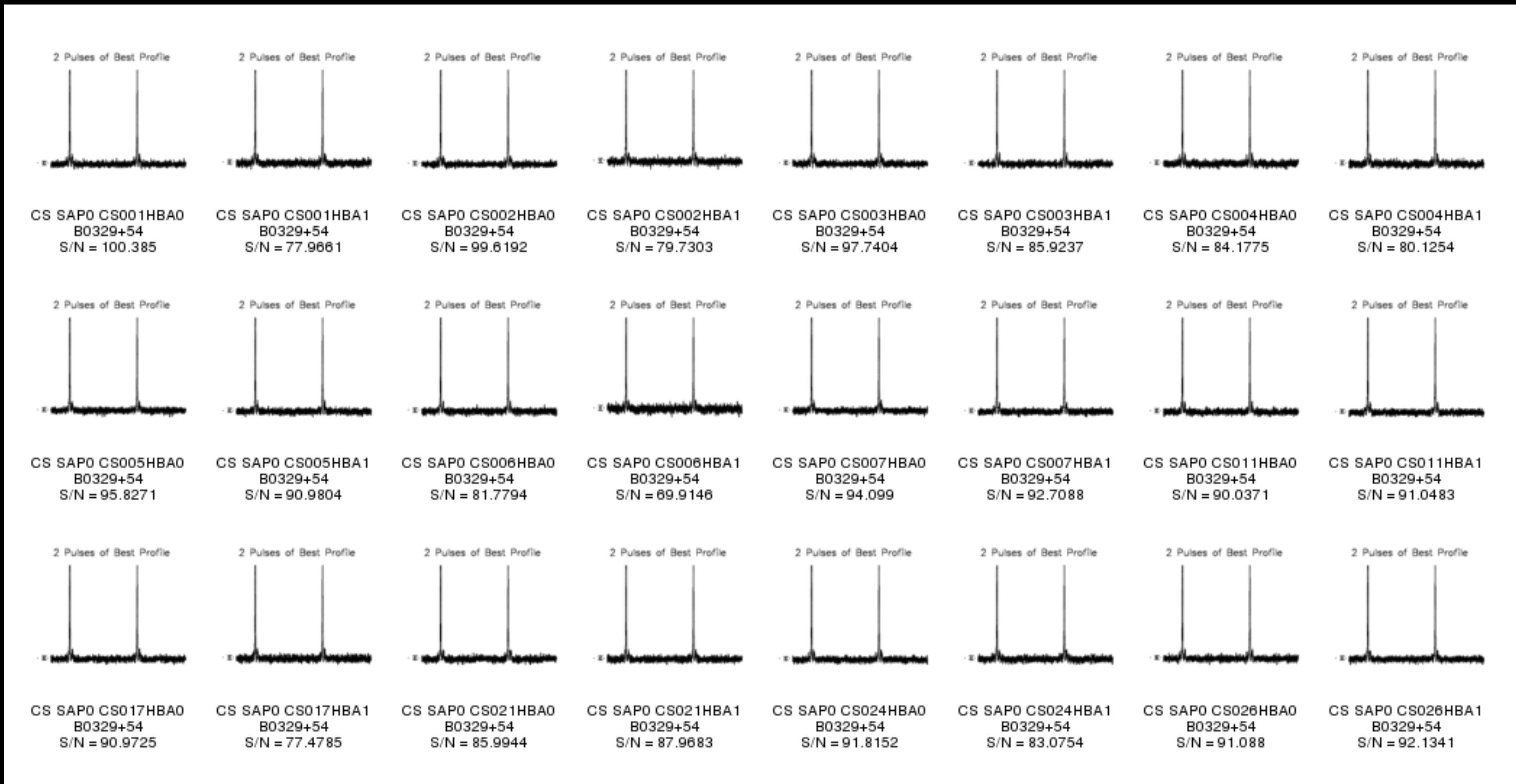
Hessels

An evolving telescope



Fly's Eye (FE) mode

- Each station beam (SAP) is processed separately on COBALT.
- Mainly used for testing.
- Could be used for science in the future.

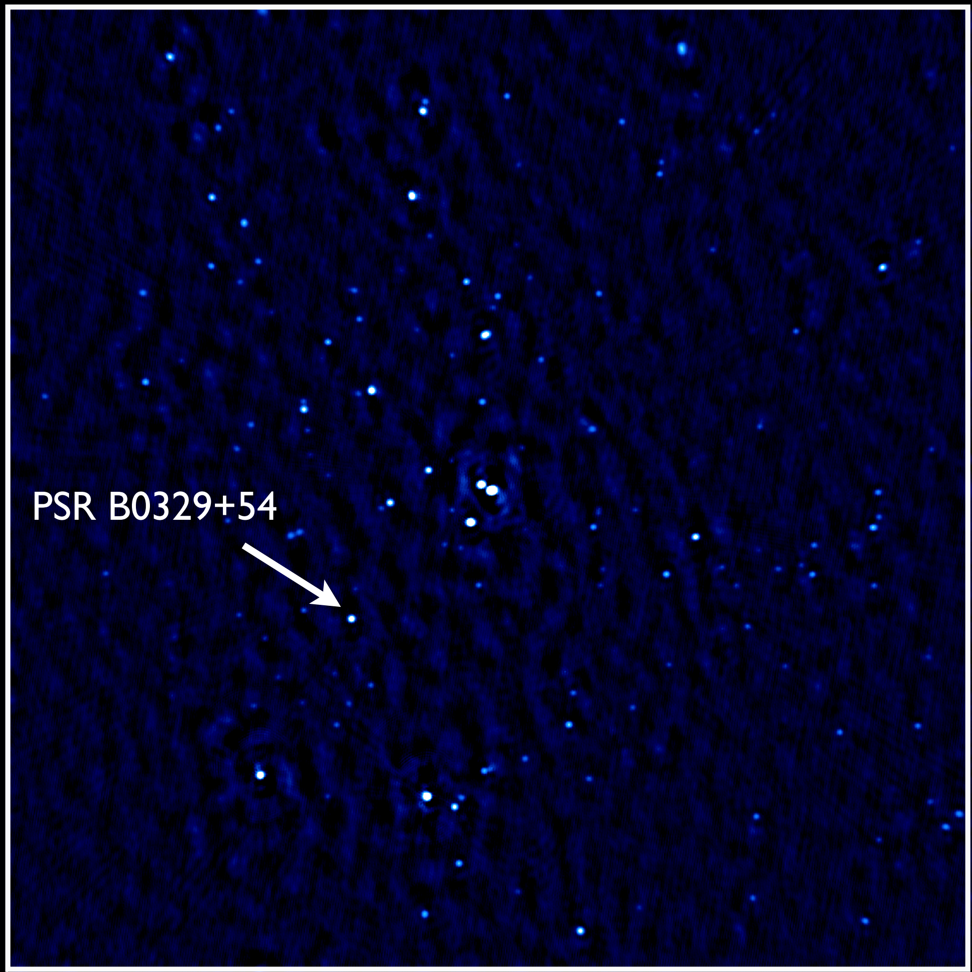


Kondratiev

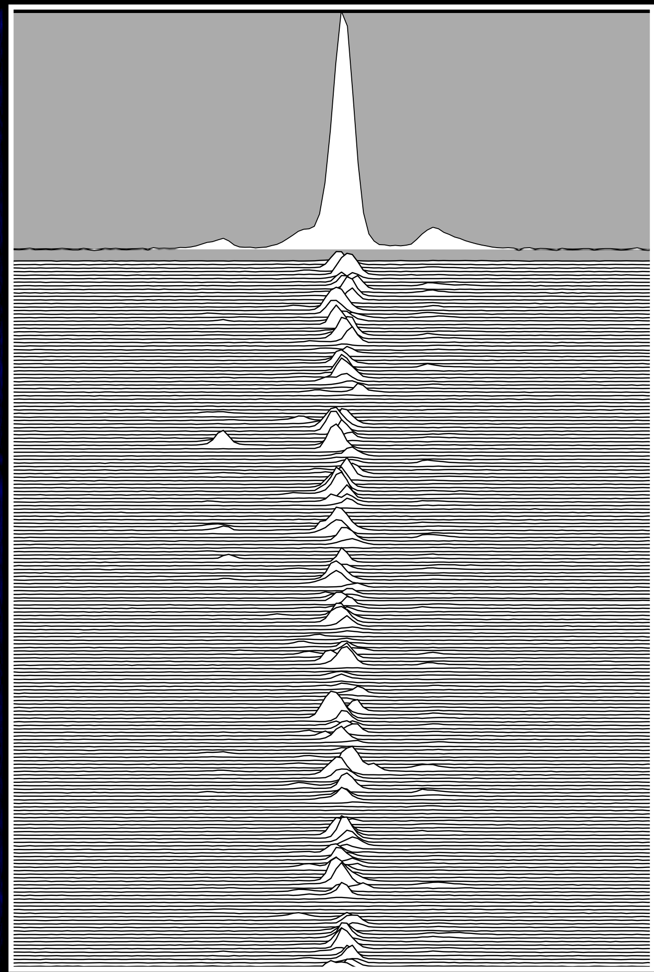
Simultaneous beam-formed and imaging (BF/IM) mode

NB: both data types currently have to use the same station set

Heald & Hessels

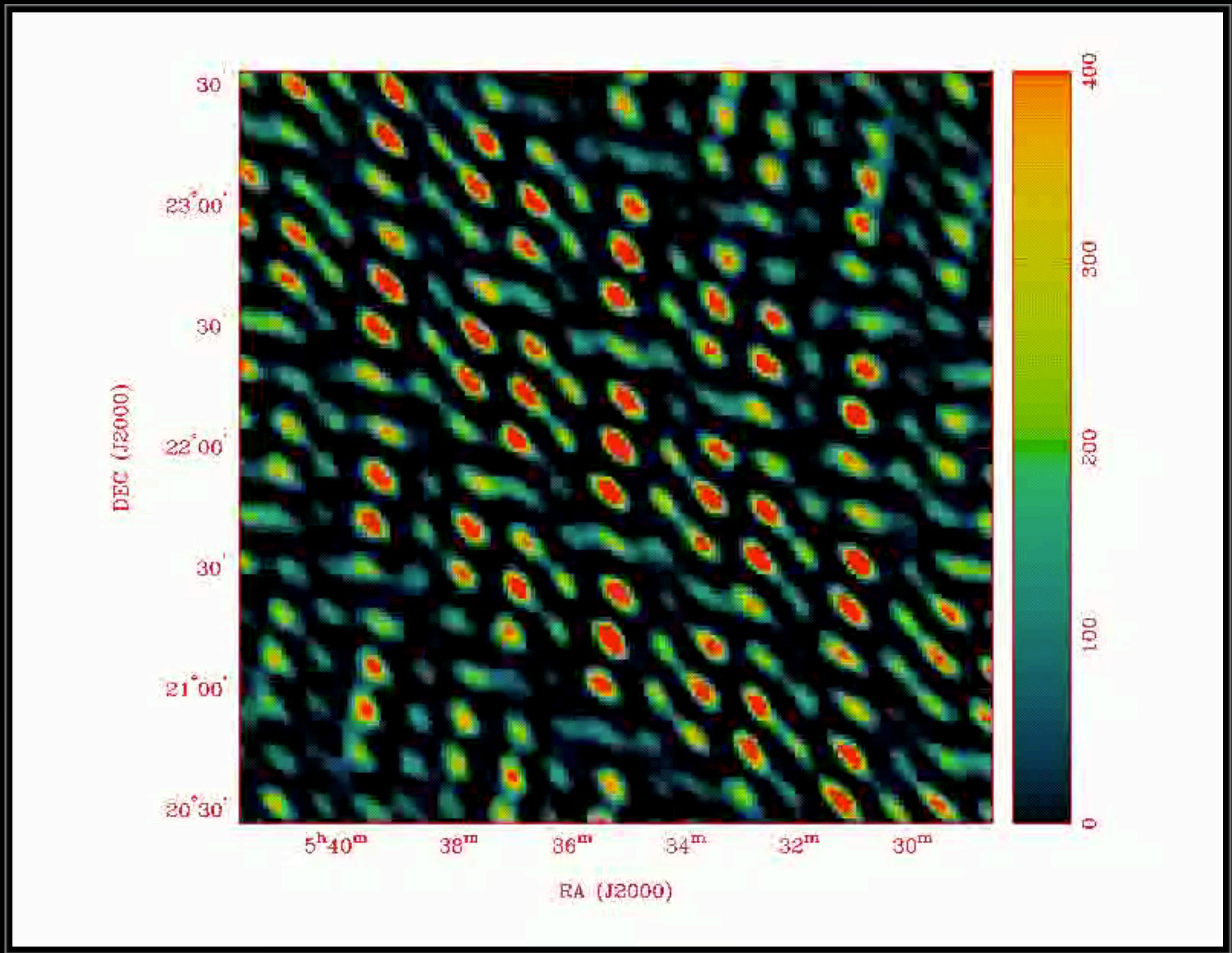


1-s time res.



1-ms time res.

Fast Imaging Exists...



Law - *Not* LOFAR data

- Movie showing imaging of a Crab giant pulse at 1/40th of the actual speed.
- Dedispersion required.

Customizing BF modes

Choice of time/frequency resolution

- Just like IM mode, can chose 16, 32, 64, 128, 256, etc. channels per subband.
- Possible to *skip* the 2PPF.
- Can also sum channels post 2PPF.
- Typically, one uses 16 or 64 channels (12 or 3 kHz) frequency resolution in the HBA and LBA bands, respectively.
- Time resolution is: $5.12\mu\mathrm{s} \times N_{\mathrm{chan}} \times N_{\mathrm{down}}$
- Time resolution is $5.12\mu\mathrm{s}$ or $\geq 81.92\mu\mathrm{s}$

Choice of Stokes (or not!) parameters

- Can record just *Stokes I* - e.g. for pulsar or transient search experiments.
- For polarimetry, can record *Stokes I,Q,U,V*.
- For more advanced offline signal processing, can record *XX, XY, YX, YY*. This option is also referred to as *Complex Voltage* (CV) mode.

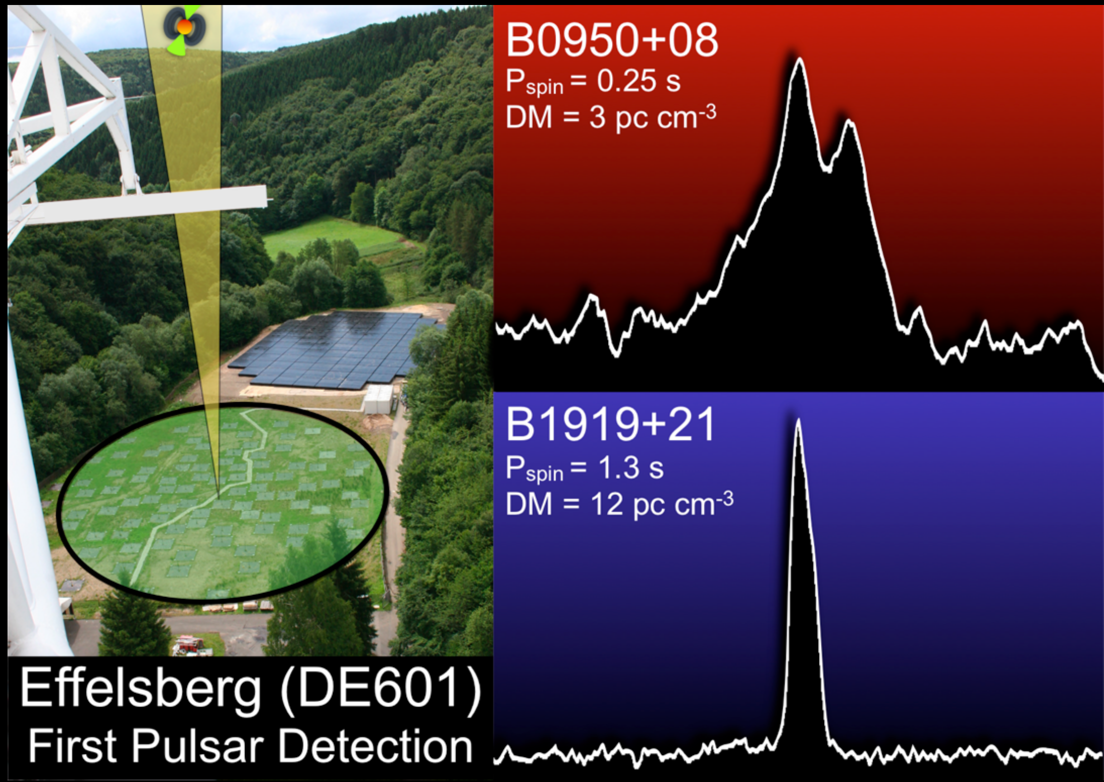
Other observing modes

Standalone mode

• Each International LOFAR HBA/LBA station has 1/3 the sensitivity of the Superterp!

• Standalone backends at these stations can record beam-formed data separate from COBALT.

• Ideal for high-cadence monitoring experiments of very bright sources.



Hessels & Anderson

Raw UDP dumps

- It is also possible to record the *raw* station data, as it arrives at COBALT.
- Recording such data then allows one to repeatedly run the data through COBALT and create different types of observations.
- Data rate is 3Gb/s (full band), so only ~12 stations can be recorded at full bandwidth.
- This mode is only used for testing, currently.

Observing challenges

Propagation effects

- Dispersion.
- Scattering.
- Scintillation.
- Faraday rotation.
- Ionospheric phase delays.

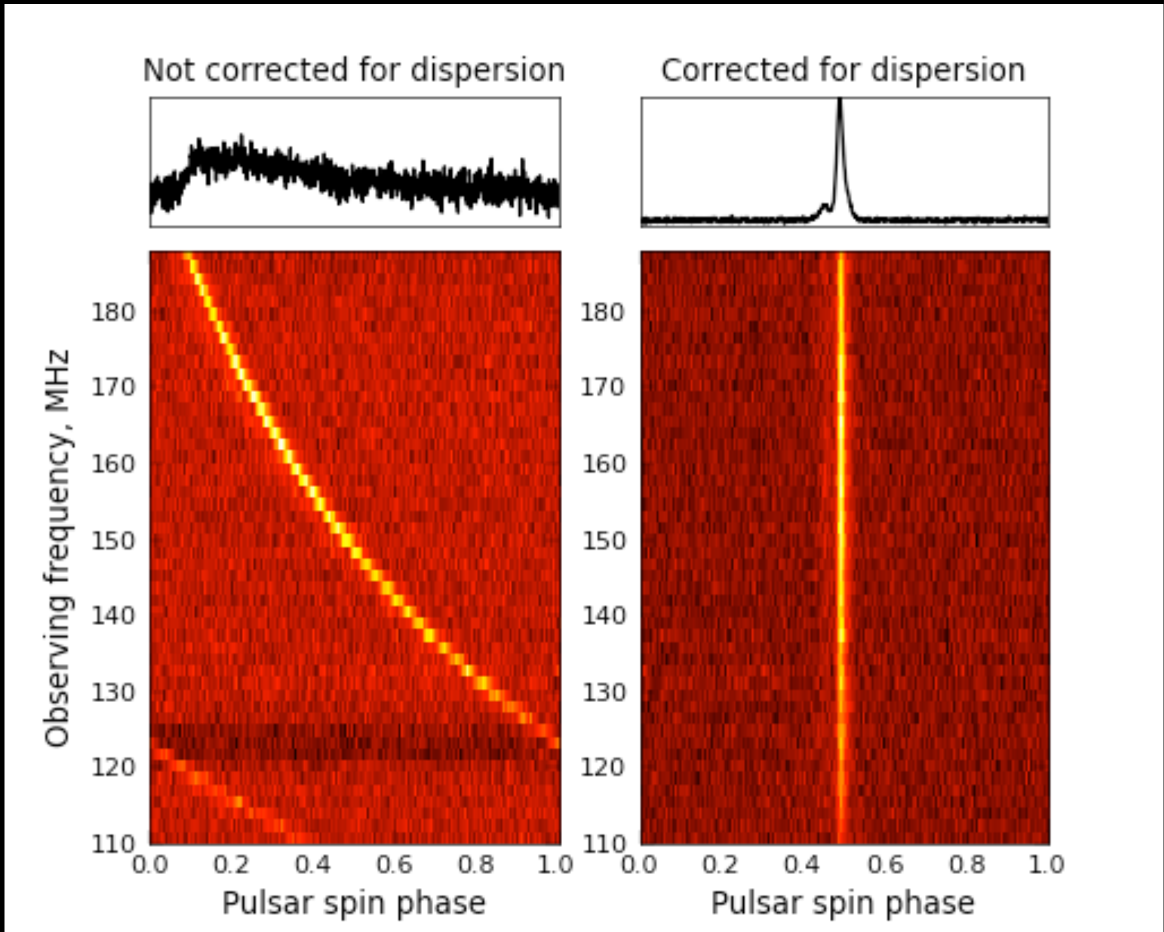
$$I(t) = g_r g_d S(t) * h_{\mathrm{DM}}(t) * h_d(t) * h_{\mathrm{Rx}}(t) + N(t)$$

- These effects are strongly chromatic, increasing drastically in magnitude towards low radio frequencies.
- High-time-resolution (millisecond timescale) signals are often not detectable without correcting for these effects!

Propagation effects

Dispersion

PSR B2021+51



Bilous

- DM [pc cm^{-3}] measures the integrated column density of free electrons along the LoS.
- Can correct using (in)coherent dedispersion.

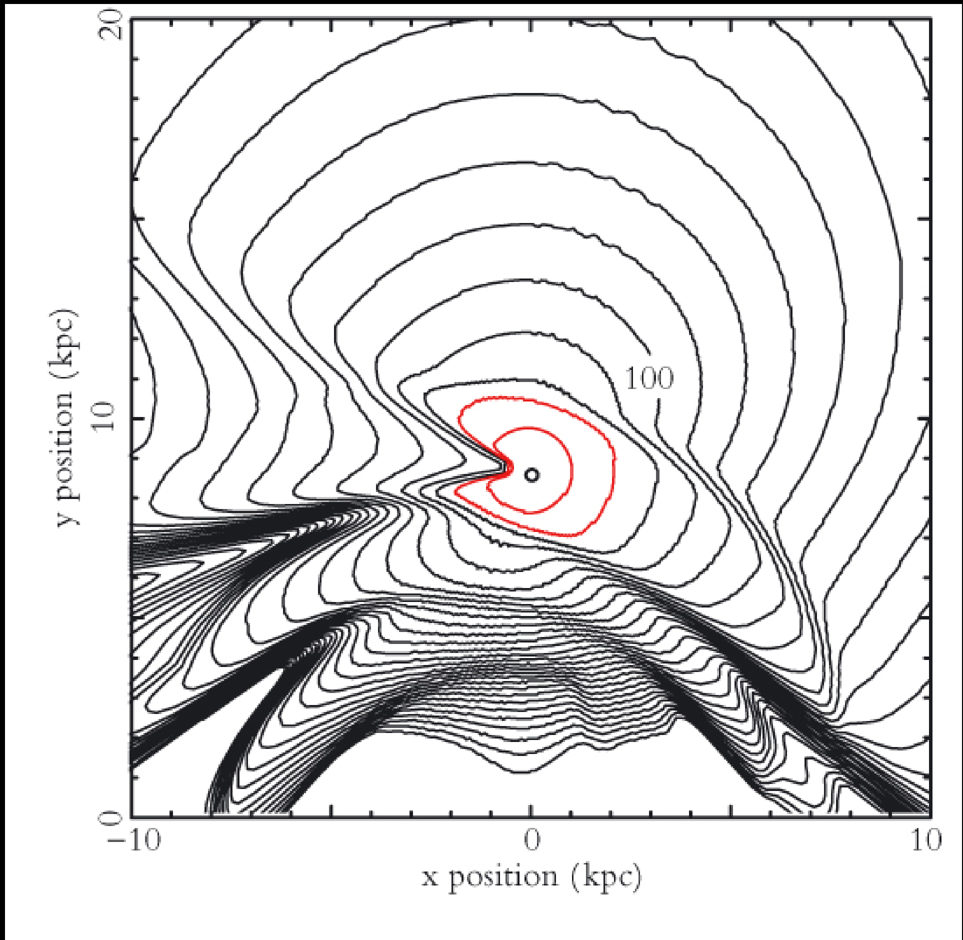
$$\Delta t_{\mathrm{DM}} \propto \nu^{-2}$$

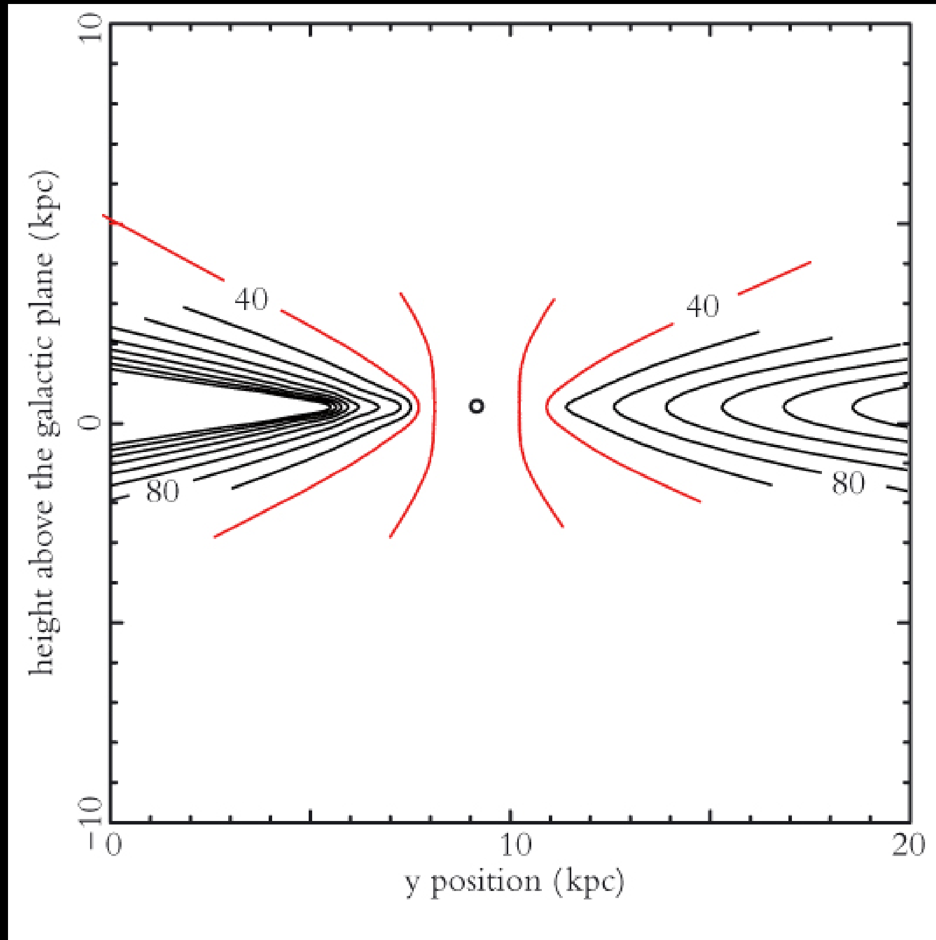
DM off by only 3 pc cm^{-3}!

Galactic dispersion measures

Loose correlation with amount of scattering.

Creates a `horizon' for Galactic LOFAR observations.

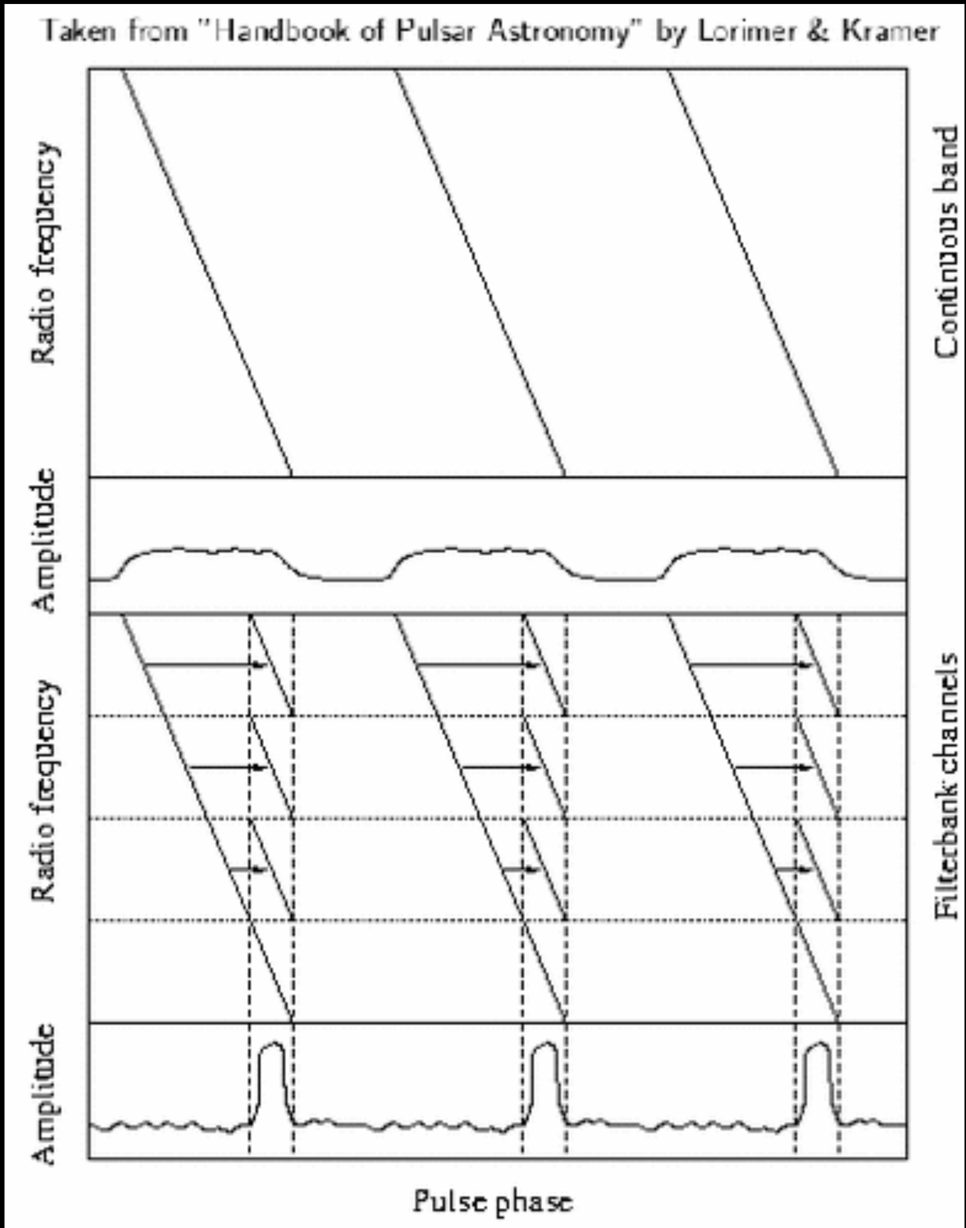




van Leeuwen

NE2001 model of Cordes & Lazio (2001)

Dedispersion



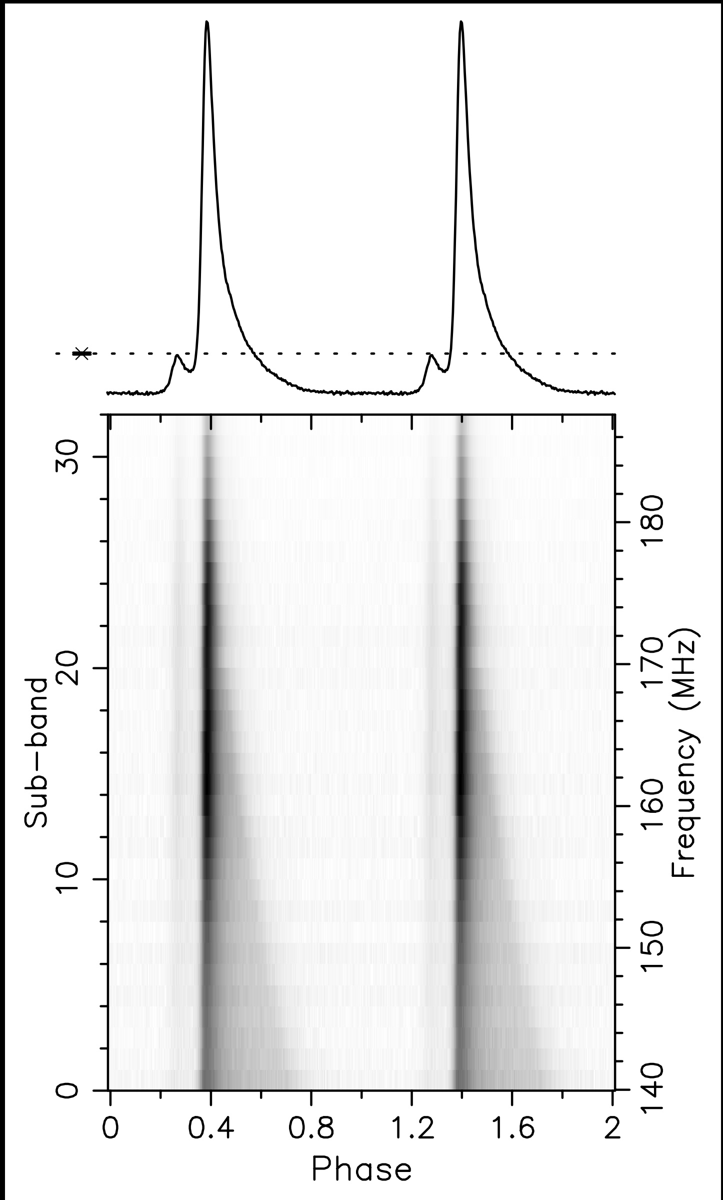
- Incoherent dedispersion works by shifting channels in time.
- Coherent dedispersion is more computationally expensive and requires the raw voltages.

Lorimer & Kramer

Propagation effects

Scattering

PSR B2111+46



Hessels

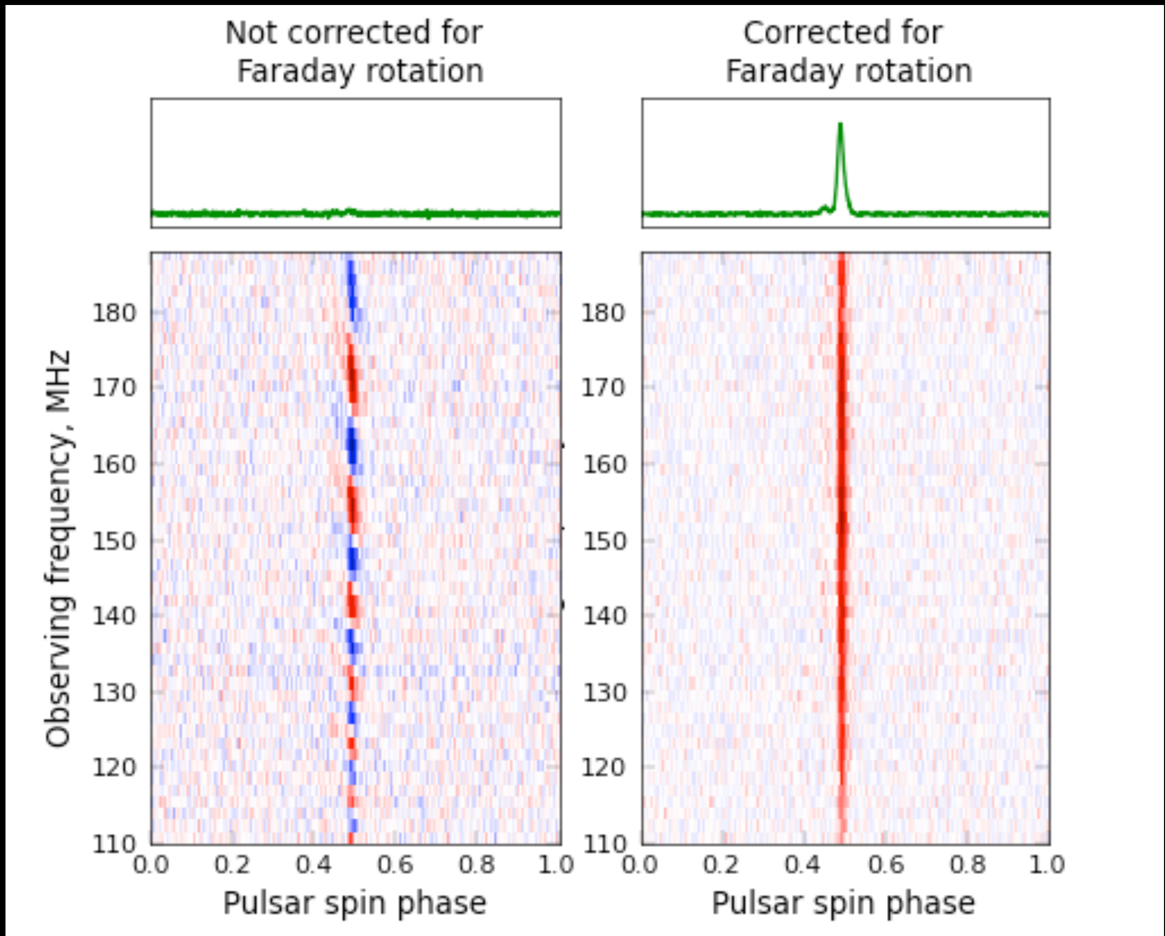
- Scattering reflects the inhomogeneity in the medium.
- No easy way to correct for this.
- Creates a sort of Galactic horizon for short-duration radio signals.

$$\Delta t_{\rm Scatt} \propto \nu^{-4}$$

Propagation effects

Faraday rotation

PSR B2021+51

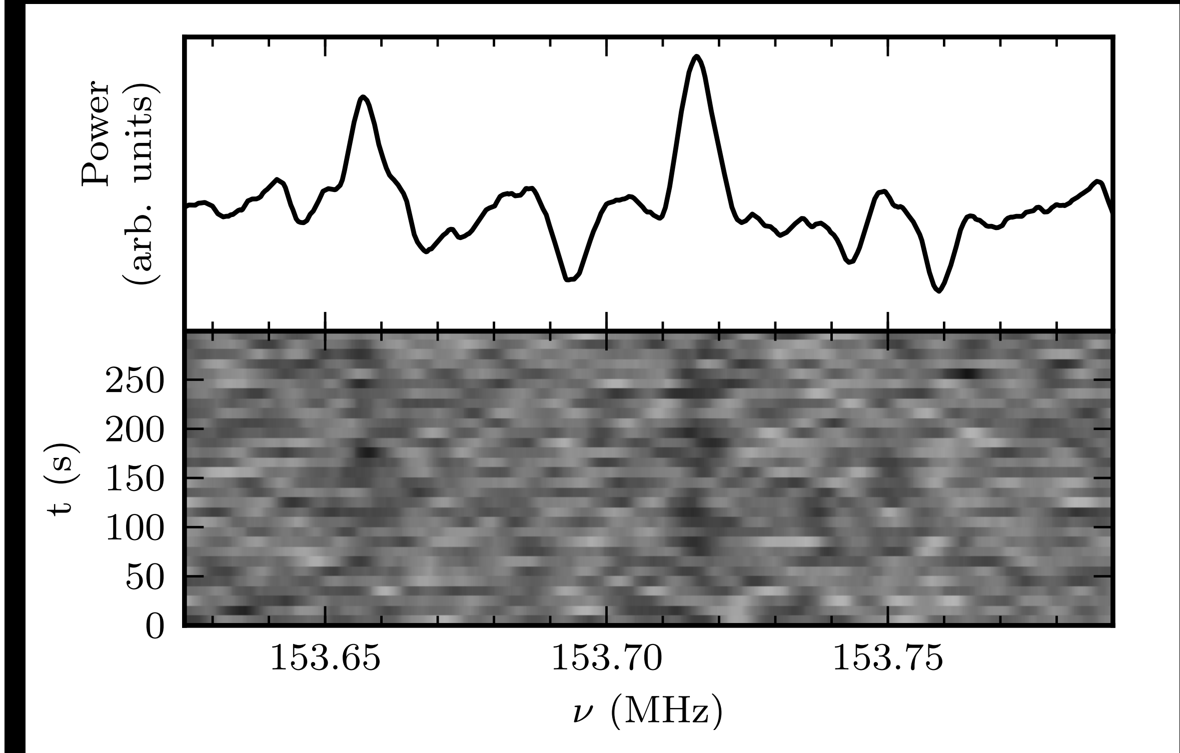


Bilous

- RM [rad m^{-2}] measures the electron-density-weighted magnetic field along the LoS.
- Ionospheric depolarization.

Propagation effects

Scintillation



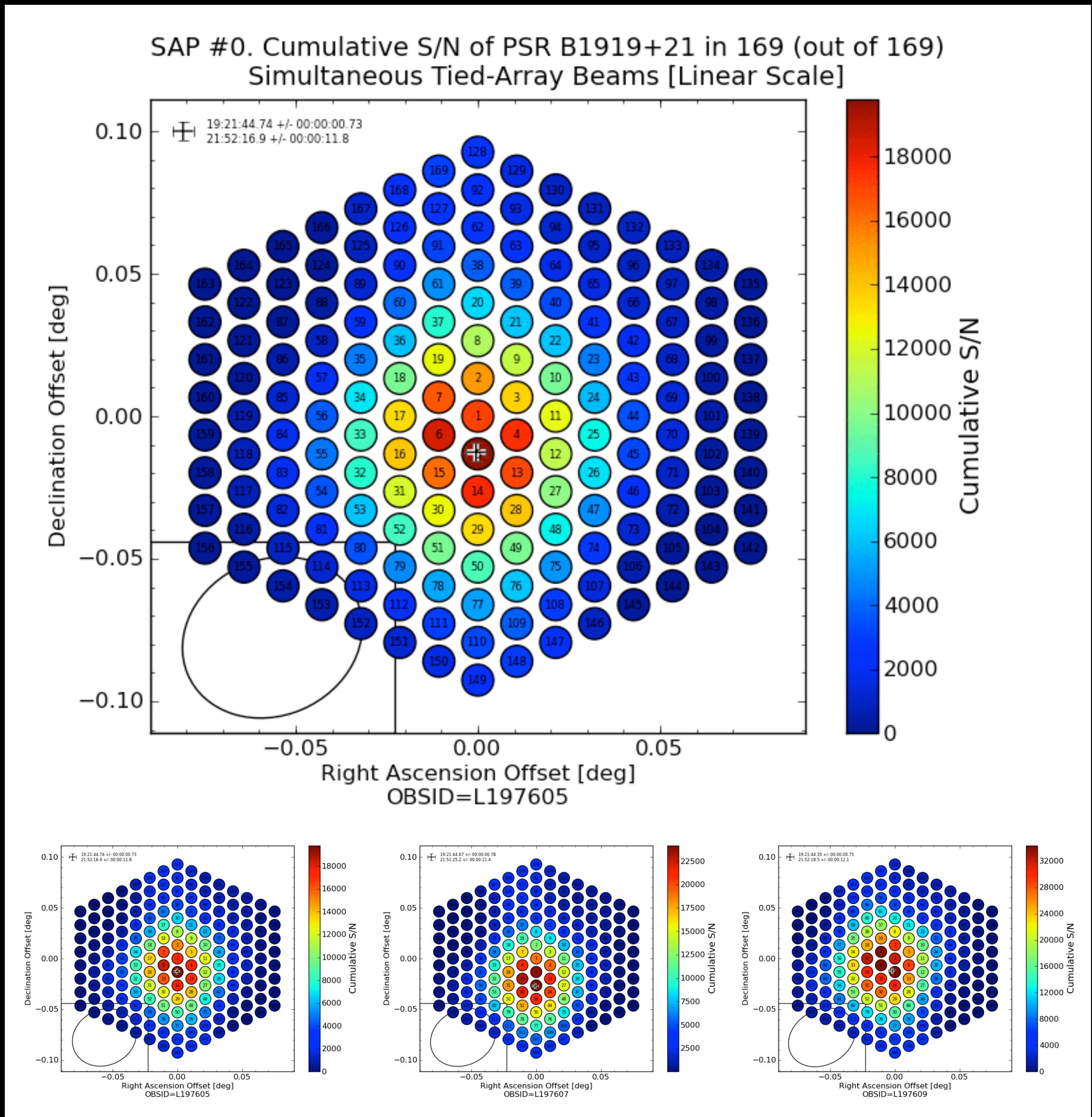
Archibald

These scintles are only ~1kHz wide!

- Scintillation is due to (de/con)-structive interference of the signal due to the intervening material (refractive and diffractive).
- At LOFAR frequencies, we typically average over many scintles.

Propagation effects

Ionospheric beam wobble



- Differential ionospheric phase delays between stations can cause the tied-array beam position to wobble on the sky.
- Likely a much bigger problem for the Full Core than the Superterp.
- Some periods will be worse than others.

Frieswijk, Kodratiev & Hessels

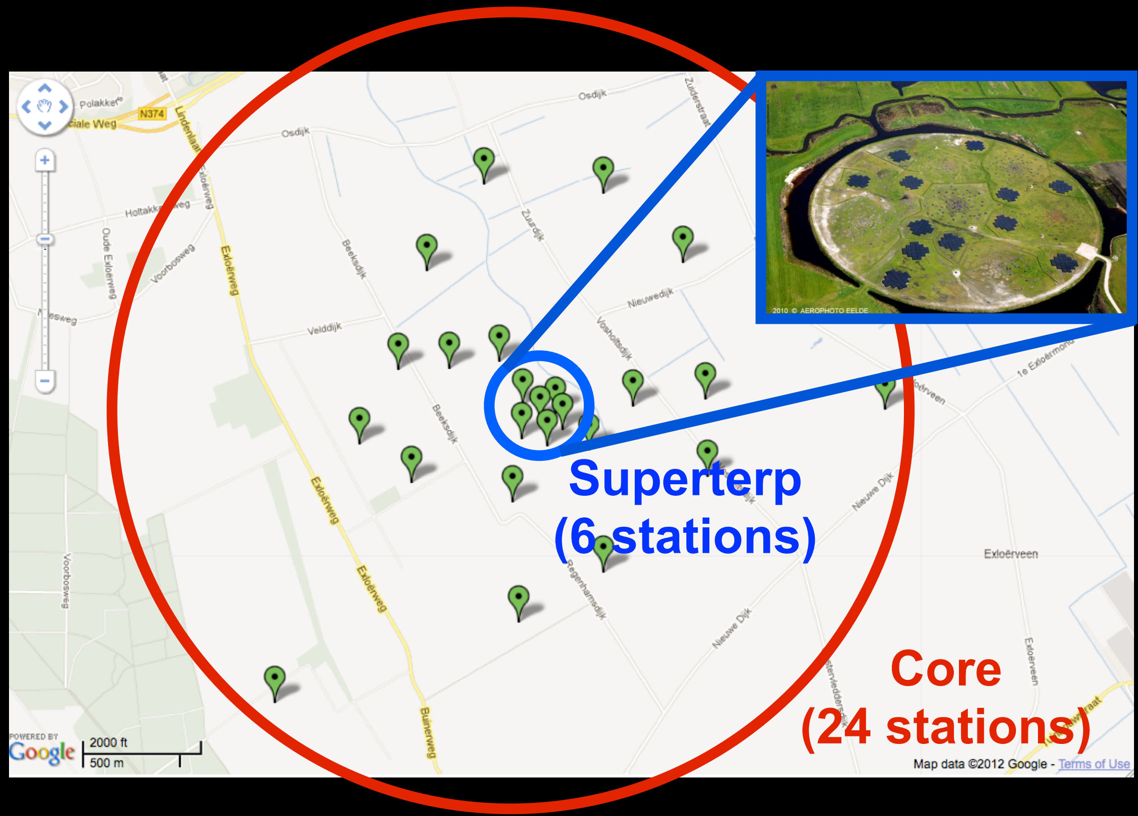
Planning an observation

Data volume

- BF mode data volumes can be very large (after all, we're recording thousands of samples per second, many beams, and many frequency channels).
- A single-beam, *Complex Voltage* observation takes 4.1TB/hr.
- Maximum system throughput is ~40Gb/s and is used in the 222-beam pulsar survey observations.
- You may need to spread your beams and bandwidth over many CEP2 nodes.

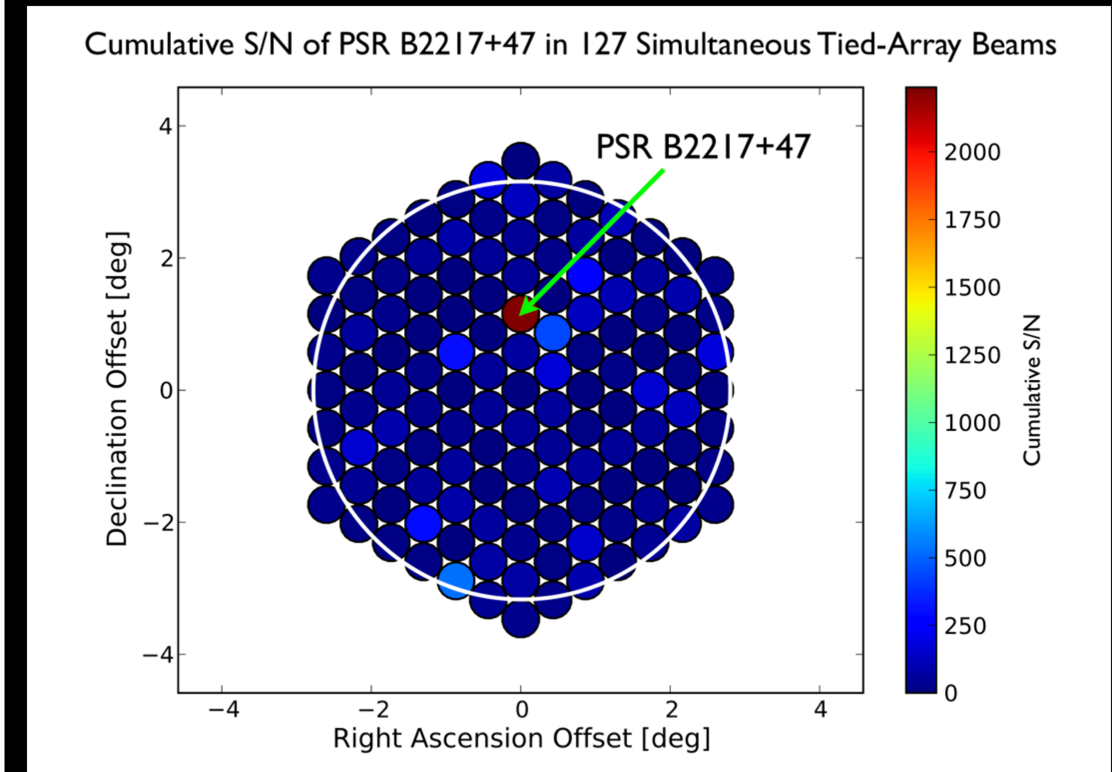
Choosing the right stations

- Only the Core stations are on the LOFAR *Single Clock*.
- Max sensitivity: Full Core (24 stations, 5 arcmin beam).
- Max survey FoM: Superterp (6 stations, 30 arcmin beam).
- Need to be really careful not to include malfunctioning stations (use FE results as your guide).

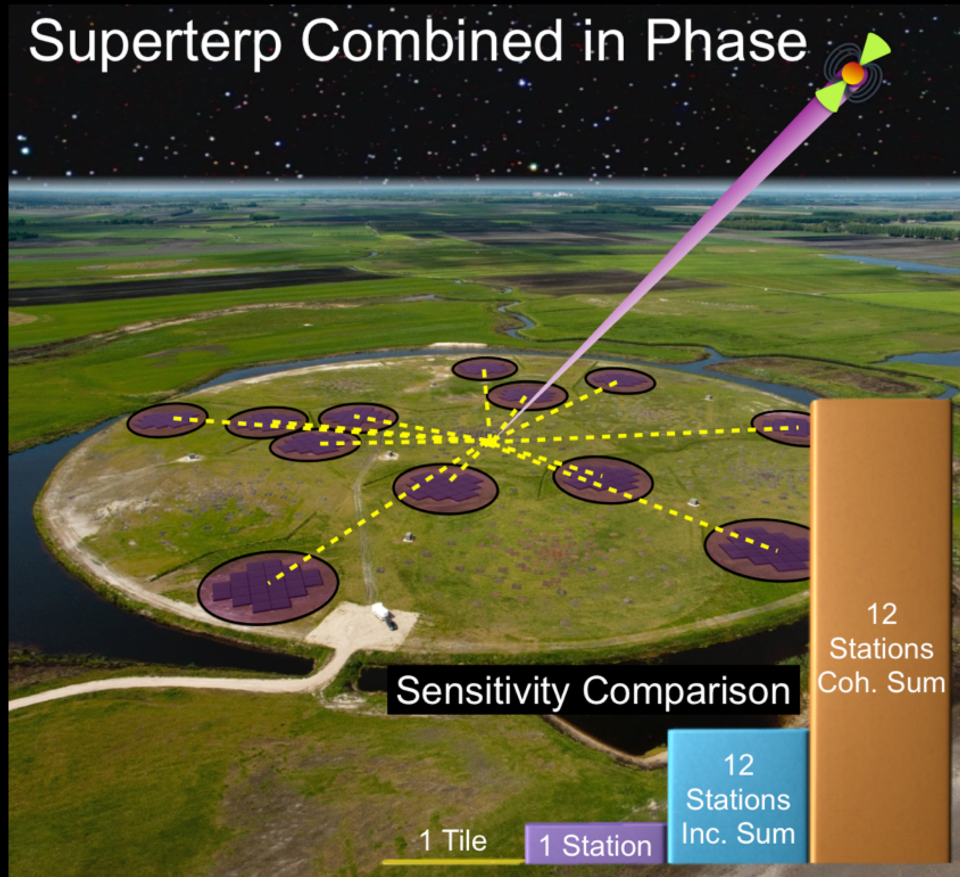


Choosing CS vs. IS mode

- IS is useful for piggy-backing, but only if you're looking for something relatively bright and rarely occurring.



Hessels



Hessels

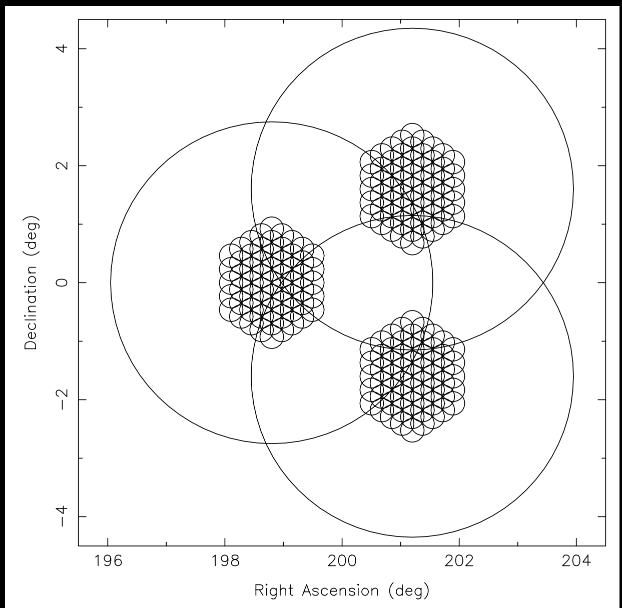
Choosing time/frequency resolution

- Frequency resolution is often dictated by the requirement to dedisperse (or resolve a spectral line).
- Higher frequency resolution - even if you don't need it - will also help with RFI excision.
- Time resolution can be anywhere from 5 microseconds up to 100s of milliseconds.

Choosing number of beams

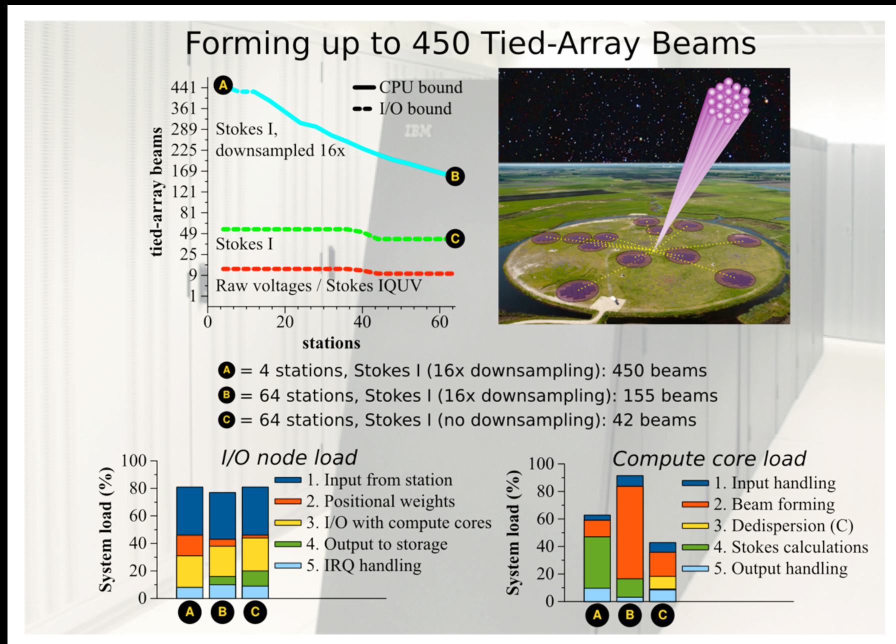
- You can use anywhere from 1 to hundreds of beams - as necessary, but limited by maximum data rate and computing power on COBALT.
- CS + IS can be run in combination.

222-beam LOTAAS pointing



Hessels

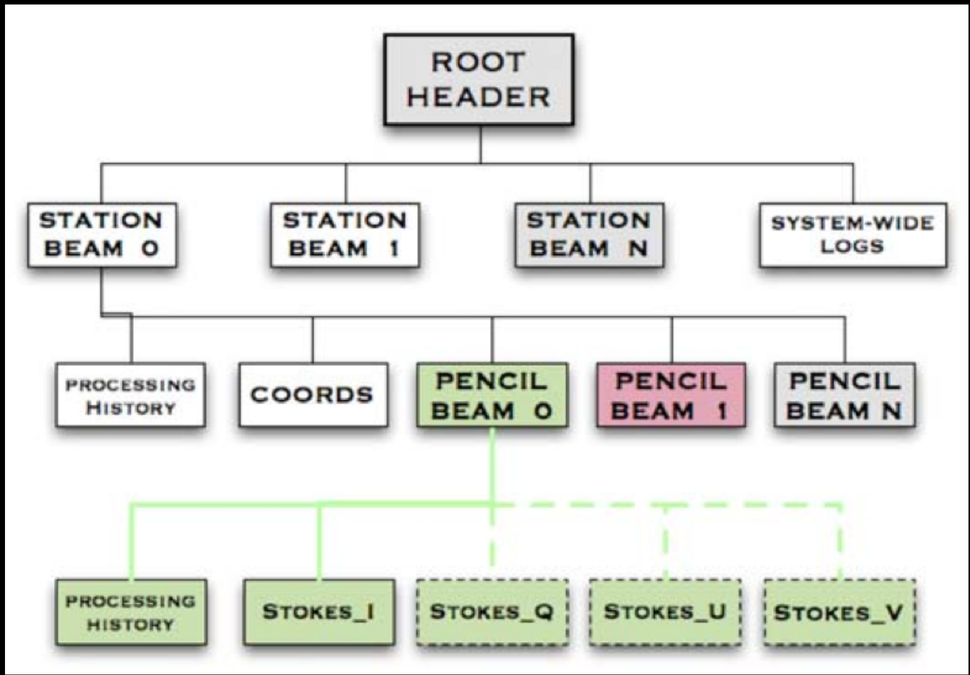
Check with Science Support for the latest performance numbers



Mol & Romein

Analyzing LOFAR BF data

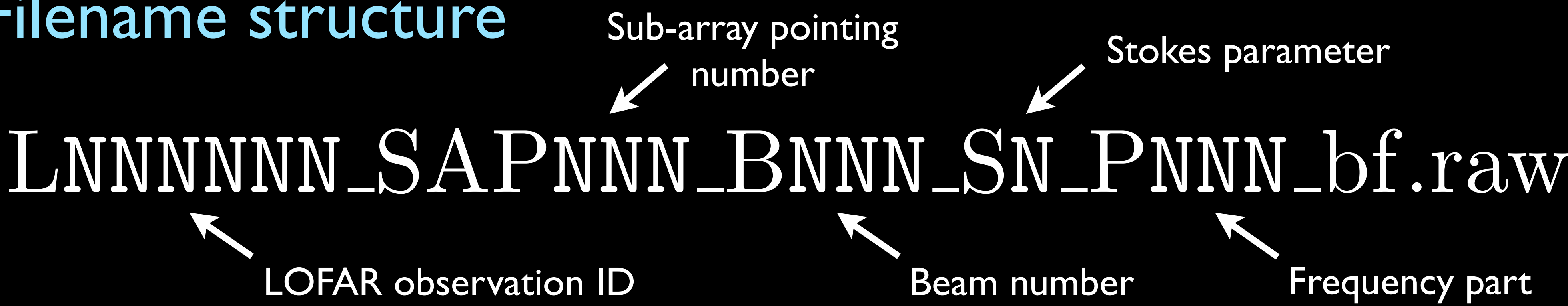
HDF5 format



Alexov - see documentation for LOFAR ICD3

- Separate .raw (data) and .h5 (metadata) file.
- No more than one beam per file.
- One beam can be split into multiple frequency bands.

Filename structure

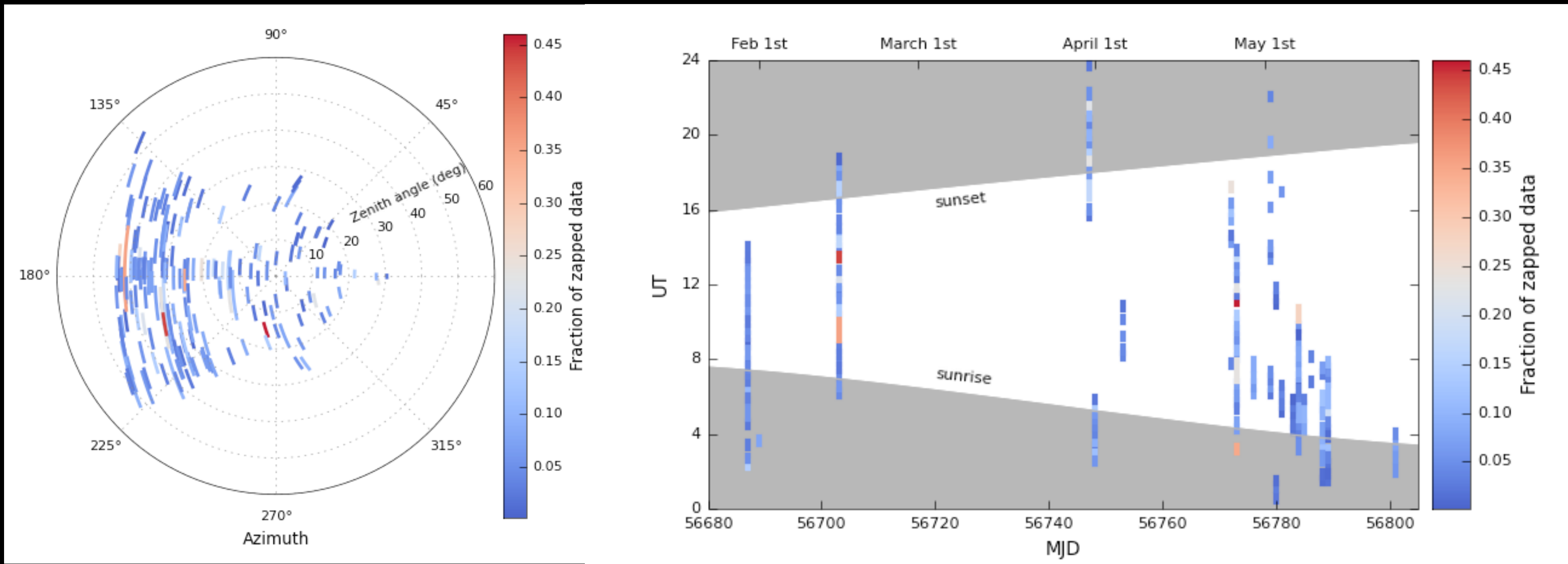


PSRFITS format

- The 32-bit HDF5 data is sometimes converted to 8-bit PSRFITS format.
- Allows direct reading into standard 3rd party software packages like PRESTO and PSRCHIVE.
- Quite a bit of the `raw’ data in the LTA is in this format.

RFI excision

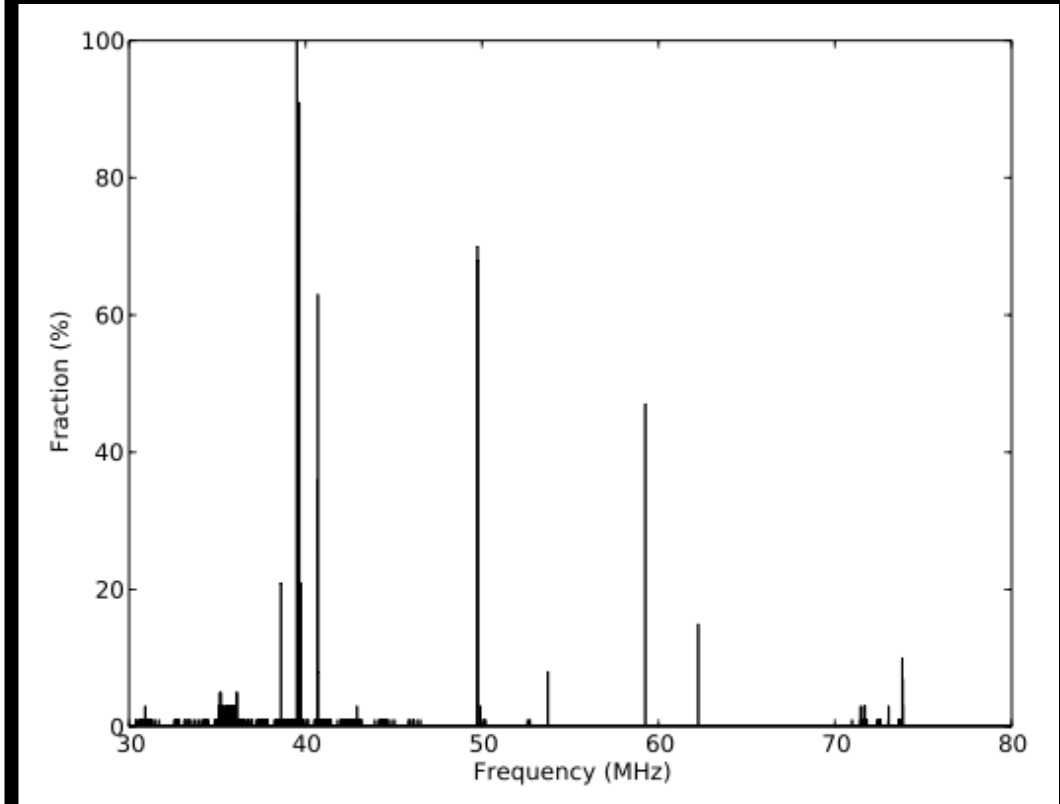
- On average 5-10% of the data need to be excised.
- Signals often very short in time or very narrow in frequency.
- Standard tool is PRESTO's `rfifind'.



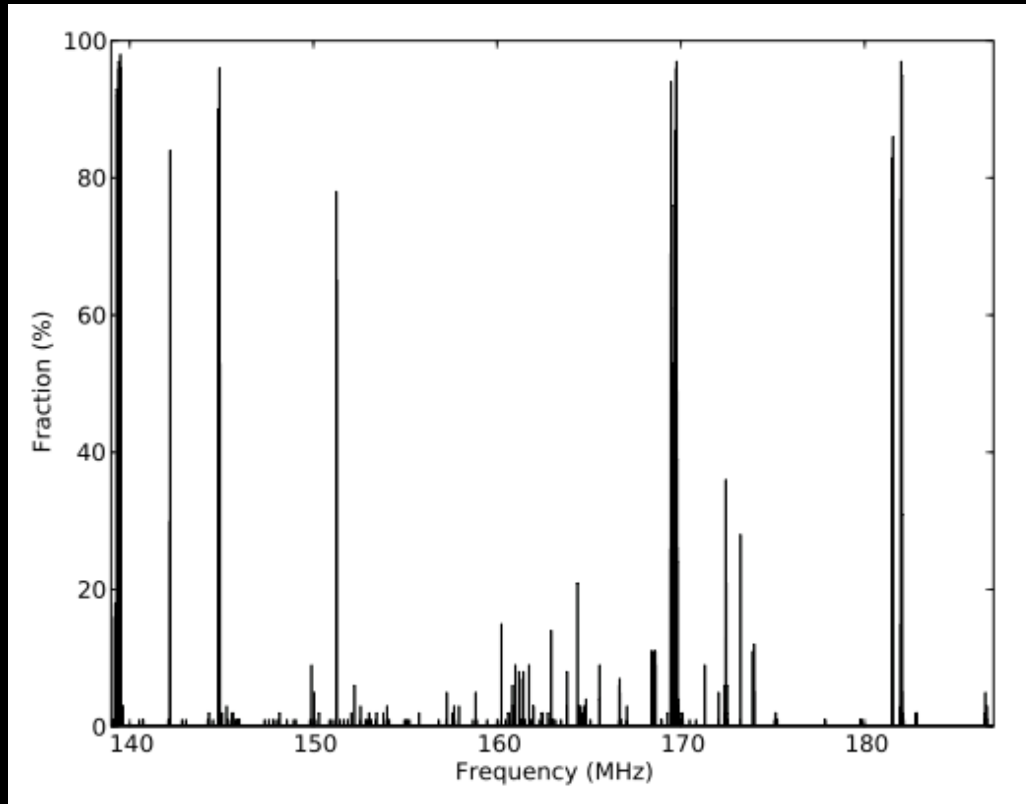
Bilous - Data from LOFAR pulsar census

RFI excision

LBA - 12-kHz resolution

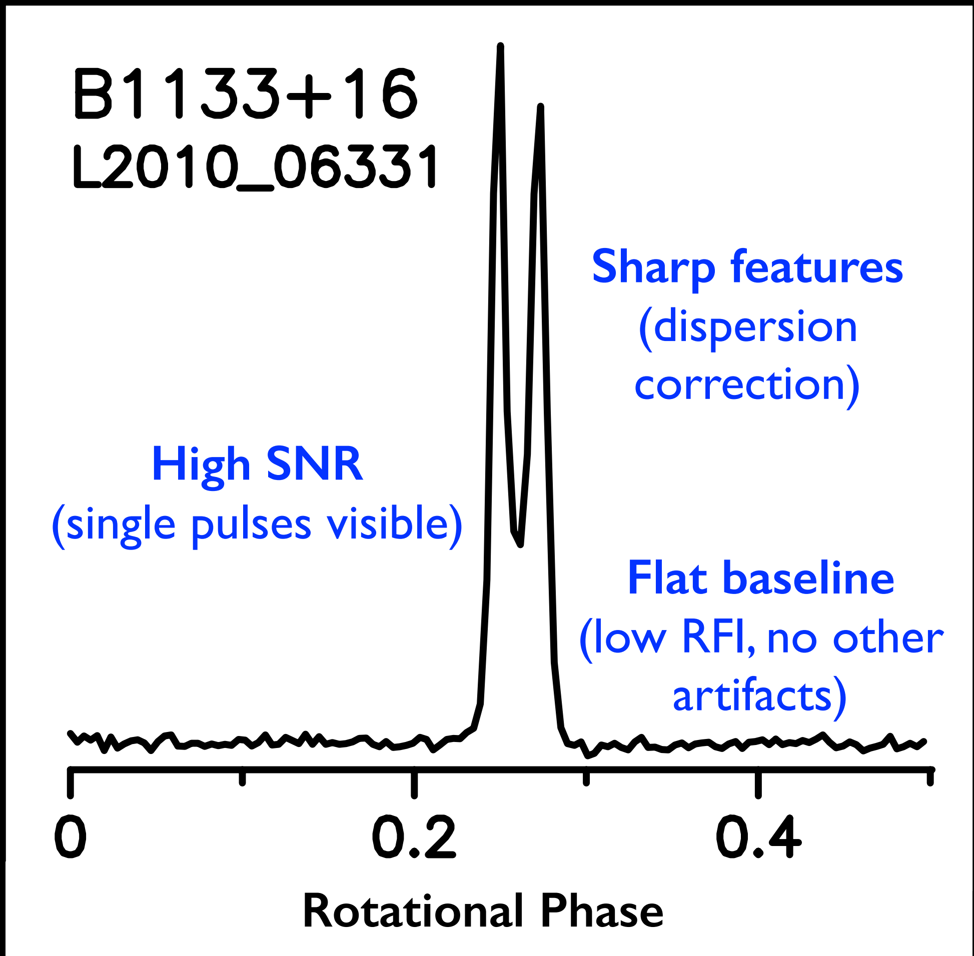


HBA - 12-kHz resolution



Kondratiev - From Stappers et al. 2011

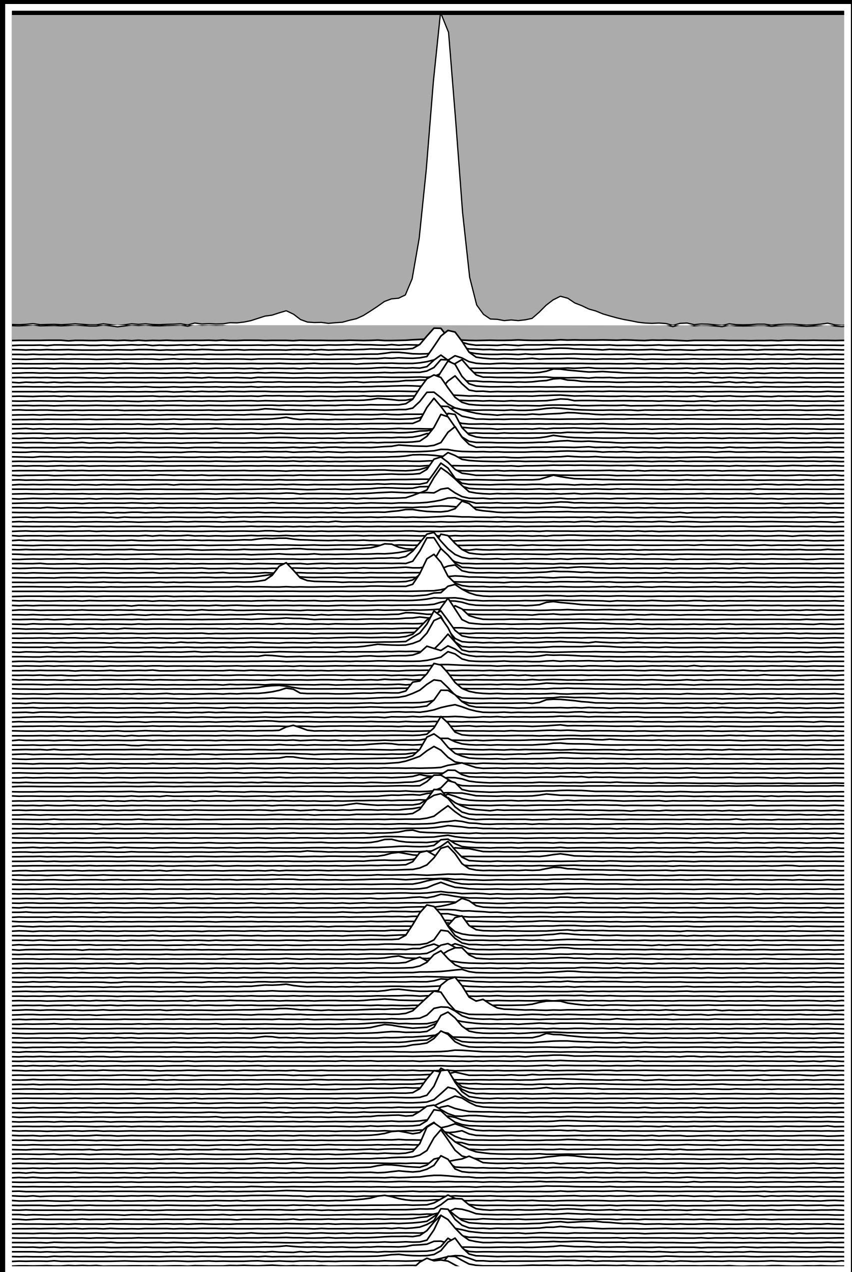
Dedispersion



Hessels

- Standard tools are: PRESTO's `prepsubband' and the dspsr package.
- Be careful: at very low observing frequencies and/or very high DMs, the dispersive sweep can be a significant fraction of the observation length (or longer!).
- Intra-channel dispersion can also be severe for LOFAR.

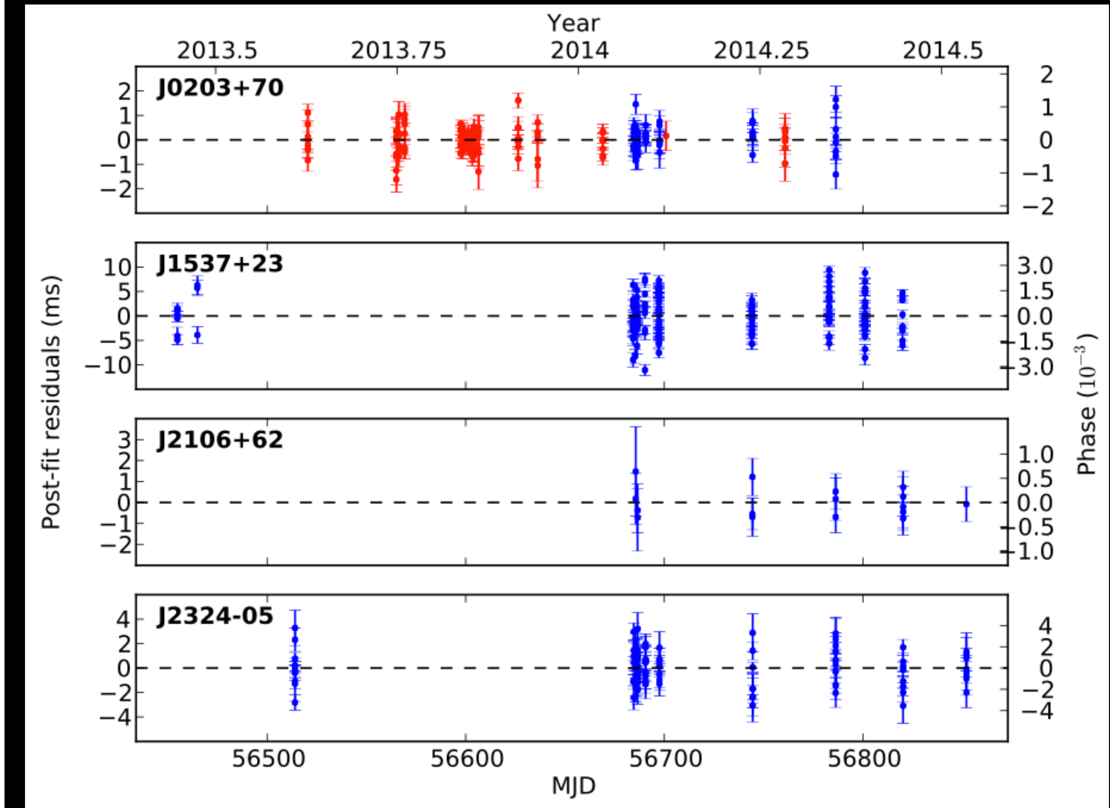
Pulsar folding



Hessels

- dspsr and PRESTO's `prepfold' will both dedisperse and fold the data given an ephemeris or separate input parameters.

Timing

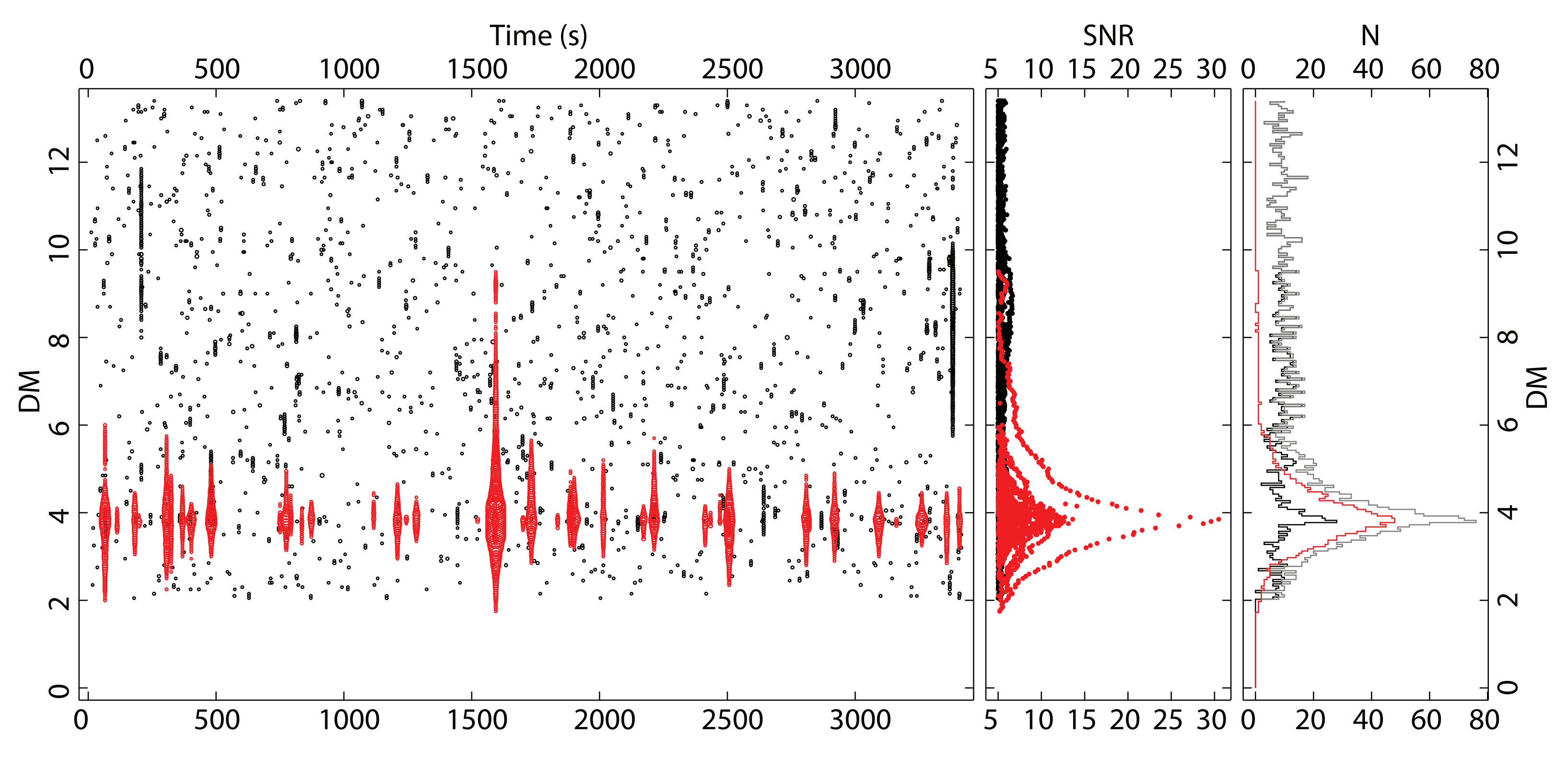


Karako

- LOFAR is known to the standard packages, i.e. TEMPO & TEMPO2.
- LOFAR's position (phase center) is always CS002/LBA.
- Standalone observations will use that station's position.

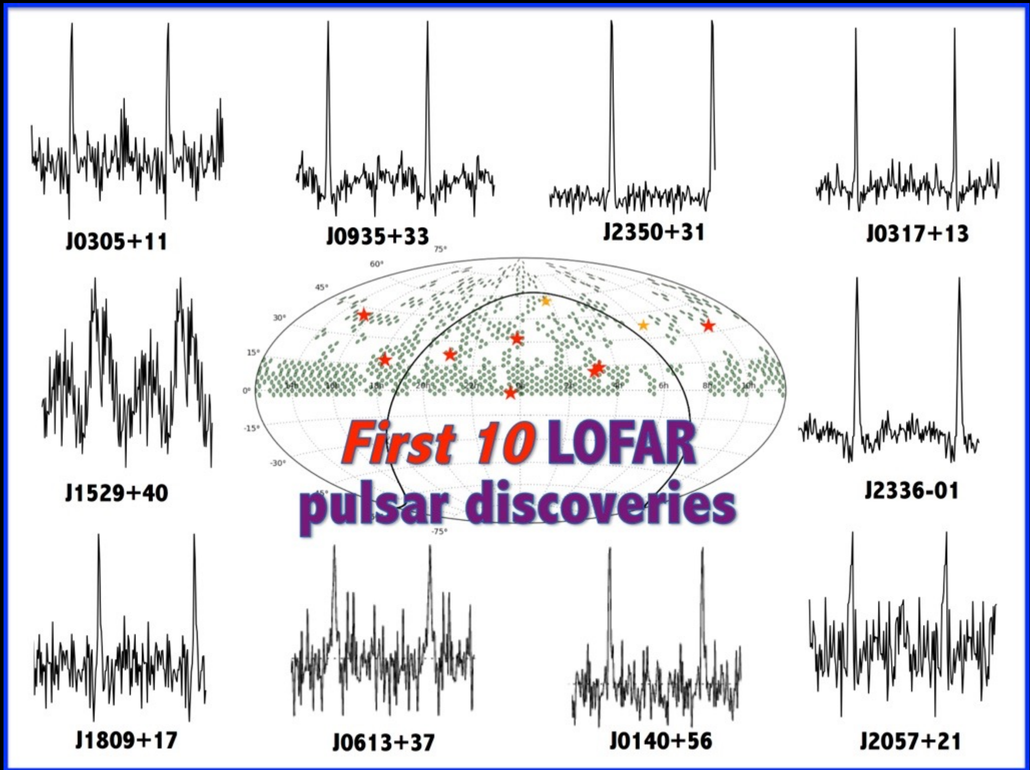
Single-pulse searches

- Standardly use PRESTO's *single_pulse_search.py*.
- A *huge* amount of events can be generated.
- Talk to Daniele Michilli (UvA) about sifting through these.



Coenen

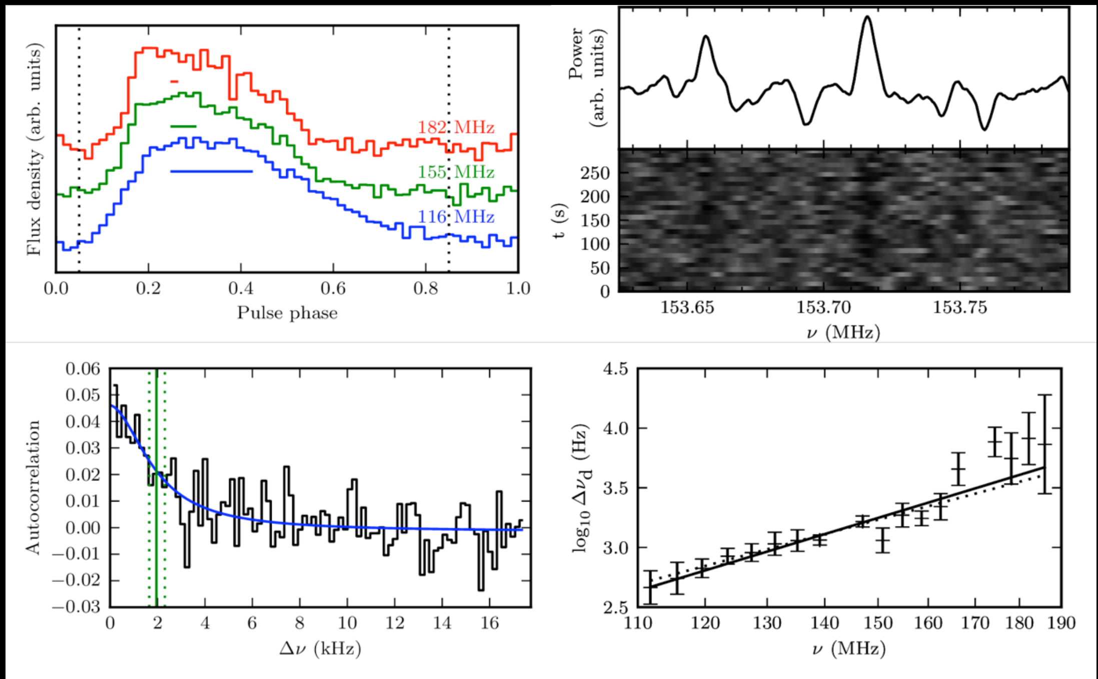
Periodicity searches



Cooper - LPPS, LOTAS & LOTAAS surveys

- Standardly use PRESTO's *accelsearch*.
- Very large numbers of dispersion measure trials needed.
- Processing doesn't fit on CEP2.

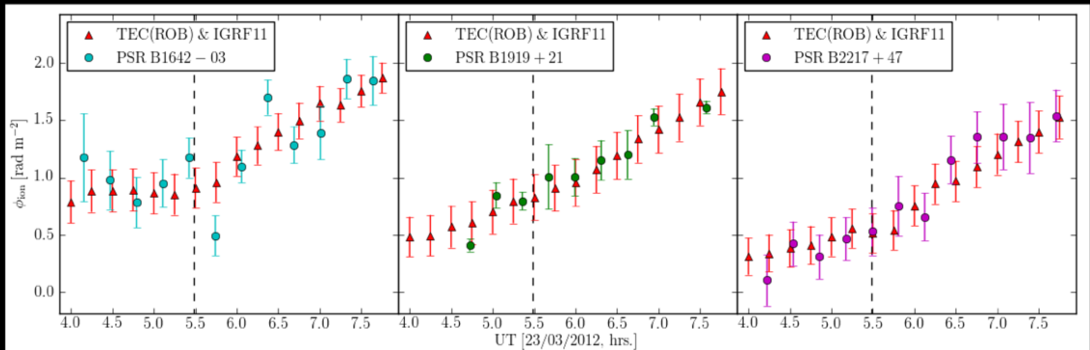
Cyclic spectroscopy

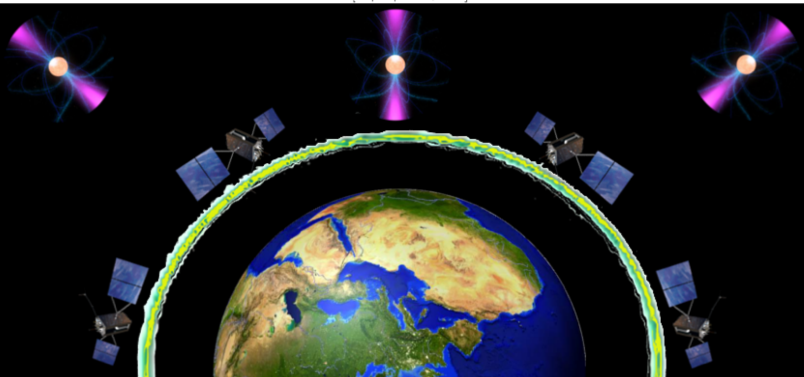


Archibald - From Archibald et al. 2014

- Advanced technique that exploits the periodic nature of the pulsar signal to get both high time resolution on the pulsar phase *and* high frequency resolution.

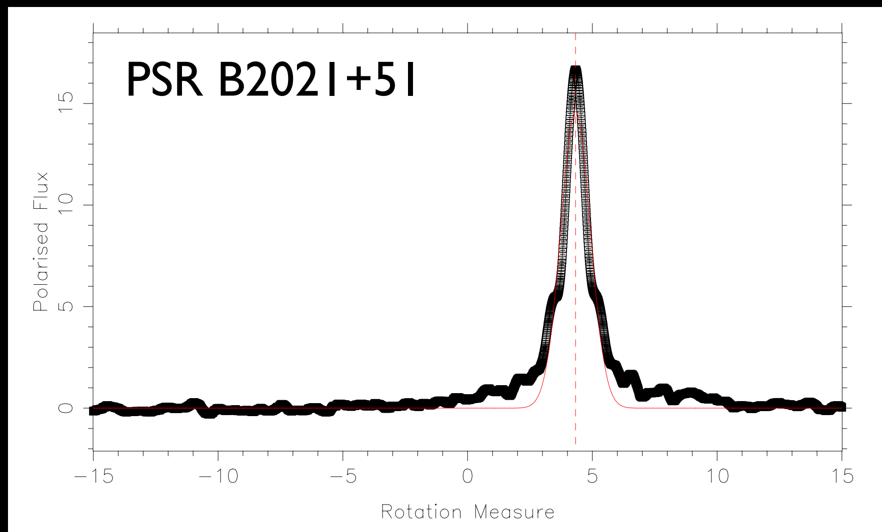
Deriving and applying rotation measures (RMs)





Sobey - From Sotomayor-Beltran et al. 2013

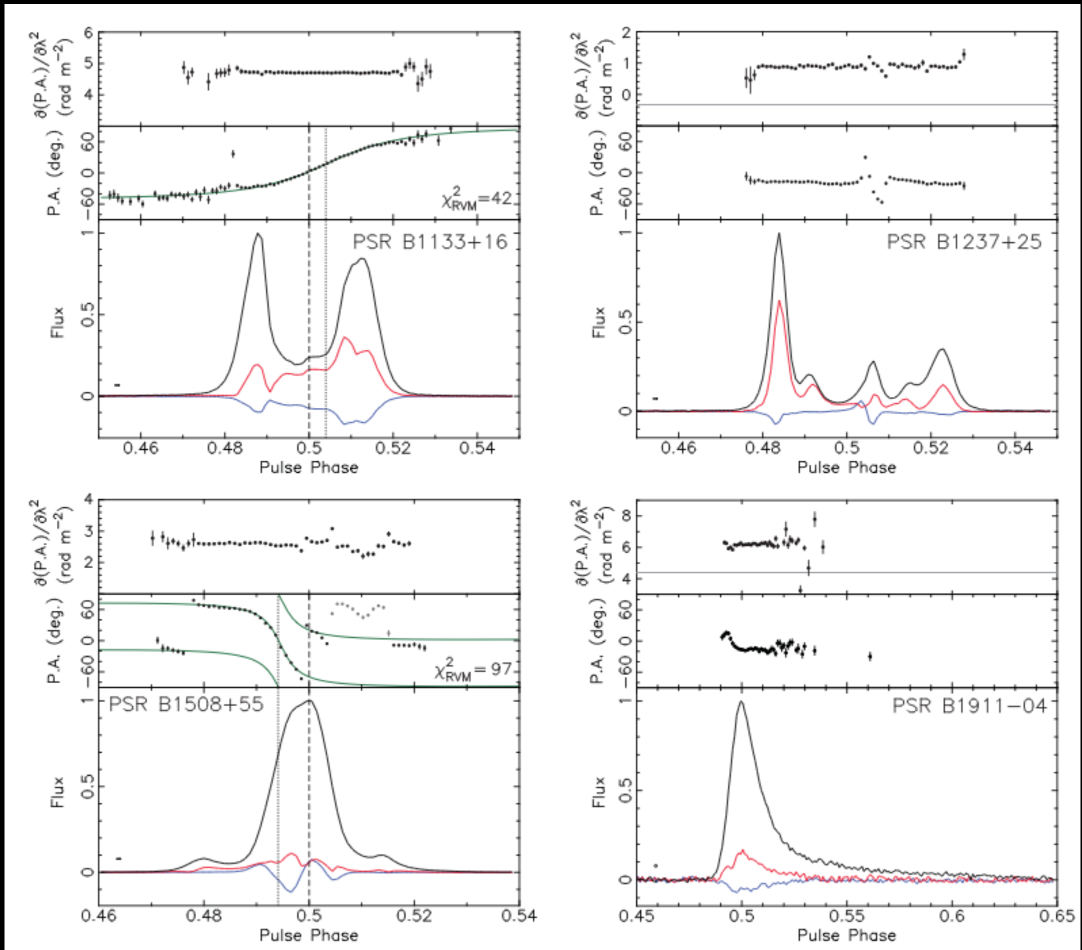
- RM's can be determined very precisely, *but* accuracy may be dominated by ionospheric contribution.



Sobey

Polarimetric calibration

Black profiles = total intensity
Red profiles = linearly polarized intensity
Blue profiles = circularly polarized intensity



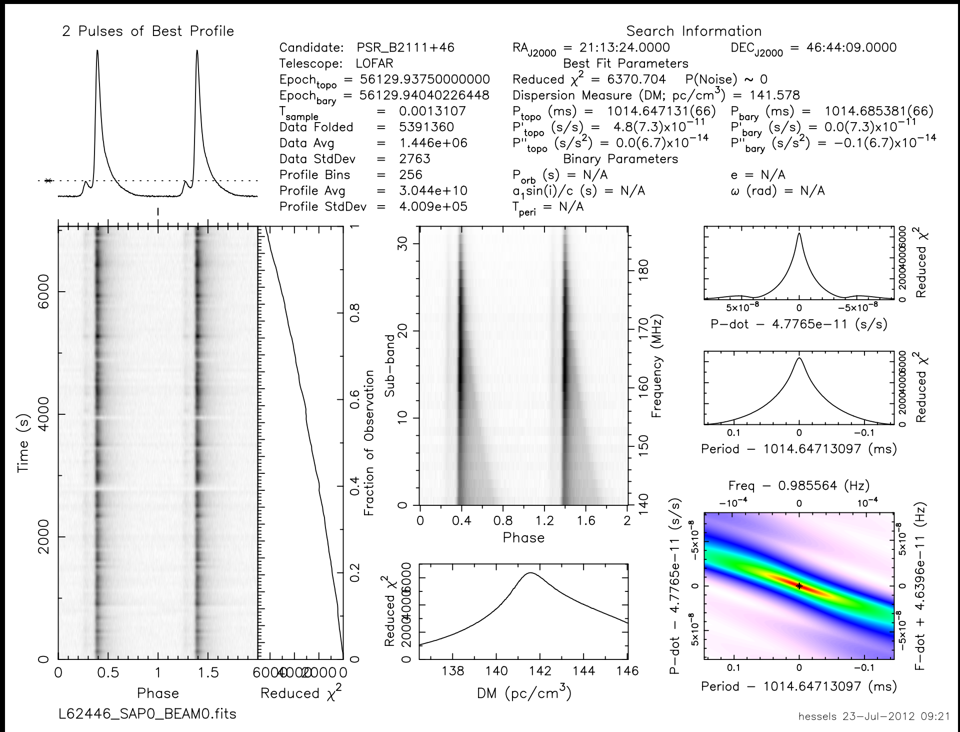
- Standardly implementing polarimetric calibration in the LOFAR Pulsar Pipeline is nearly done.

Noutsos - From Noutsos et al., submitted

The LOFAR Standard Pulsar Pipeline (PulP)

- Written by Vlad Kondratiev and Anastasia Alexov.
- Makes use of 3rd party software suites like PRESTO, PSRCHIVE, dspsr, TEMPO, etc.
- Recently incorporated into the LOFAR MoM/Scheduler framework.
- Runs dedispersion, folding, data conversion, RFI excision, limited searches, etc.
- Pulsar equivalent of the Standard Imaging Pipeline.

PulP Data Products
(also in the LTA)



Hessels - Automatically generated by PulP

- Raw data in 8-bit format.
- Diagnostic plots.
- RFI mask.
- Data cubes for known sources.
- Source localization.
- Simple dynamic spectra.

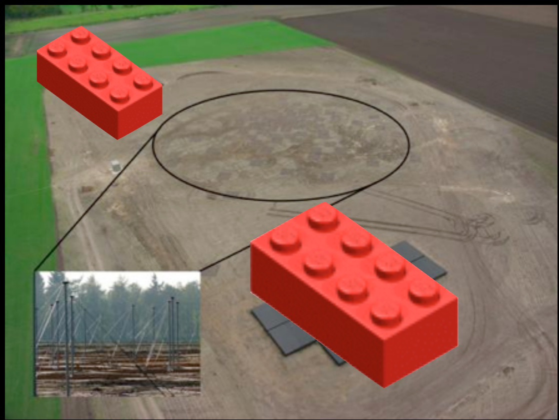
Scrunched cube of pulsar brightness with time, rotational phase, and observing frequency.

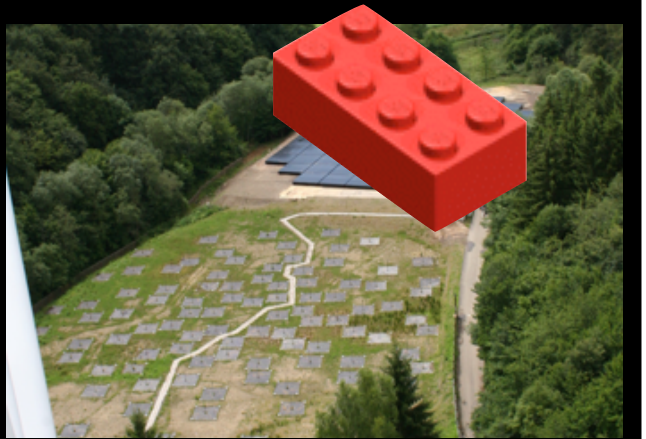
Future prospects

- Separate station lists for BF/IM data.
- Parallel observing and sub-arraying.
- Online RFI excision - i.e. on a *per station* basis.
- Online coherent dedispersion.

Sub-arraying

Customize your own telescope





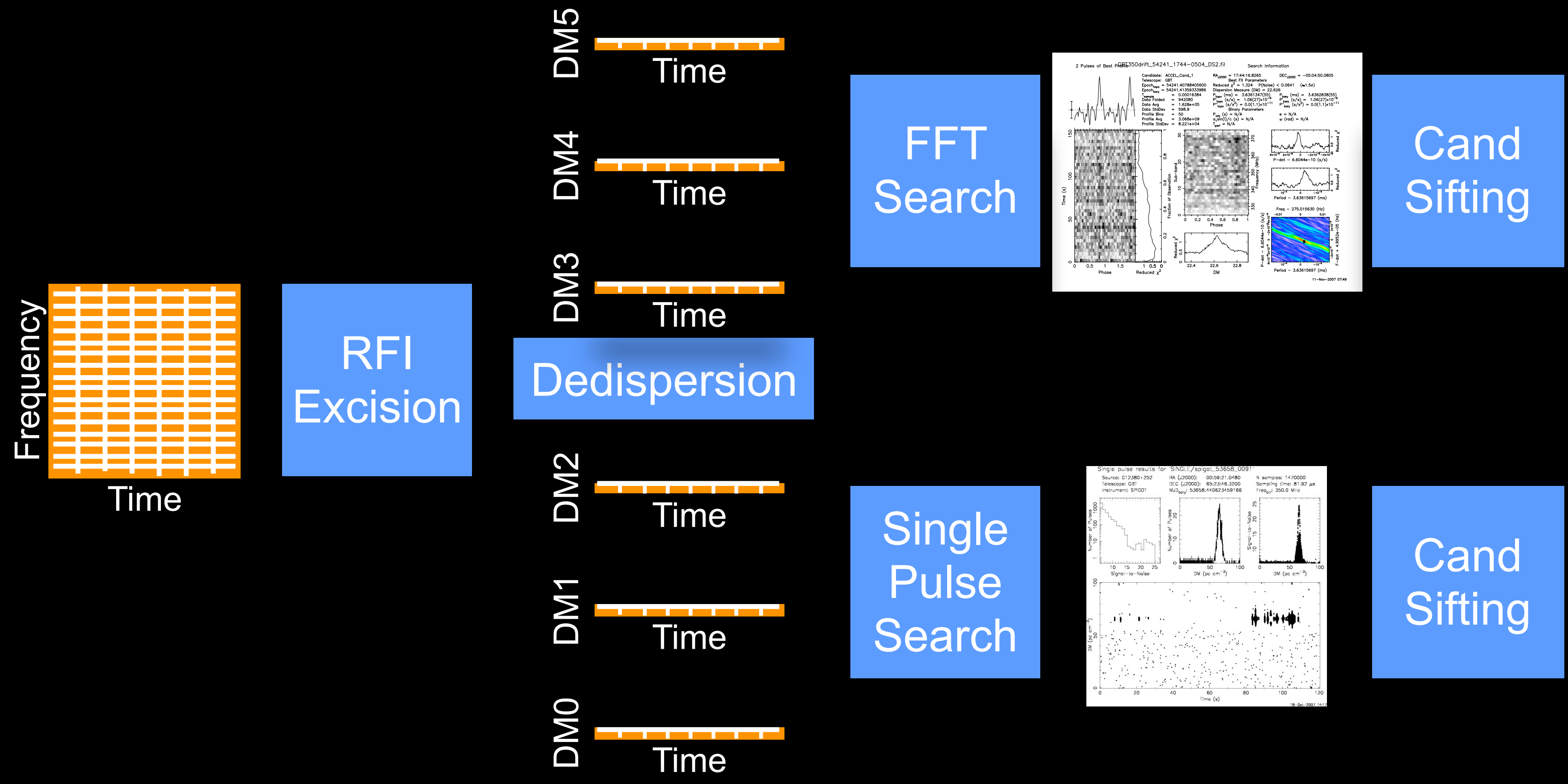
48	16	8
Dutch Core	**Dutch Remote**	**International**
Stations	Stations	Stations


THE END

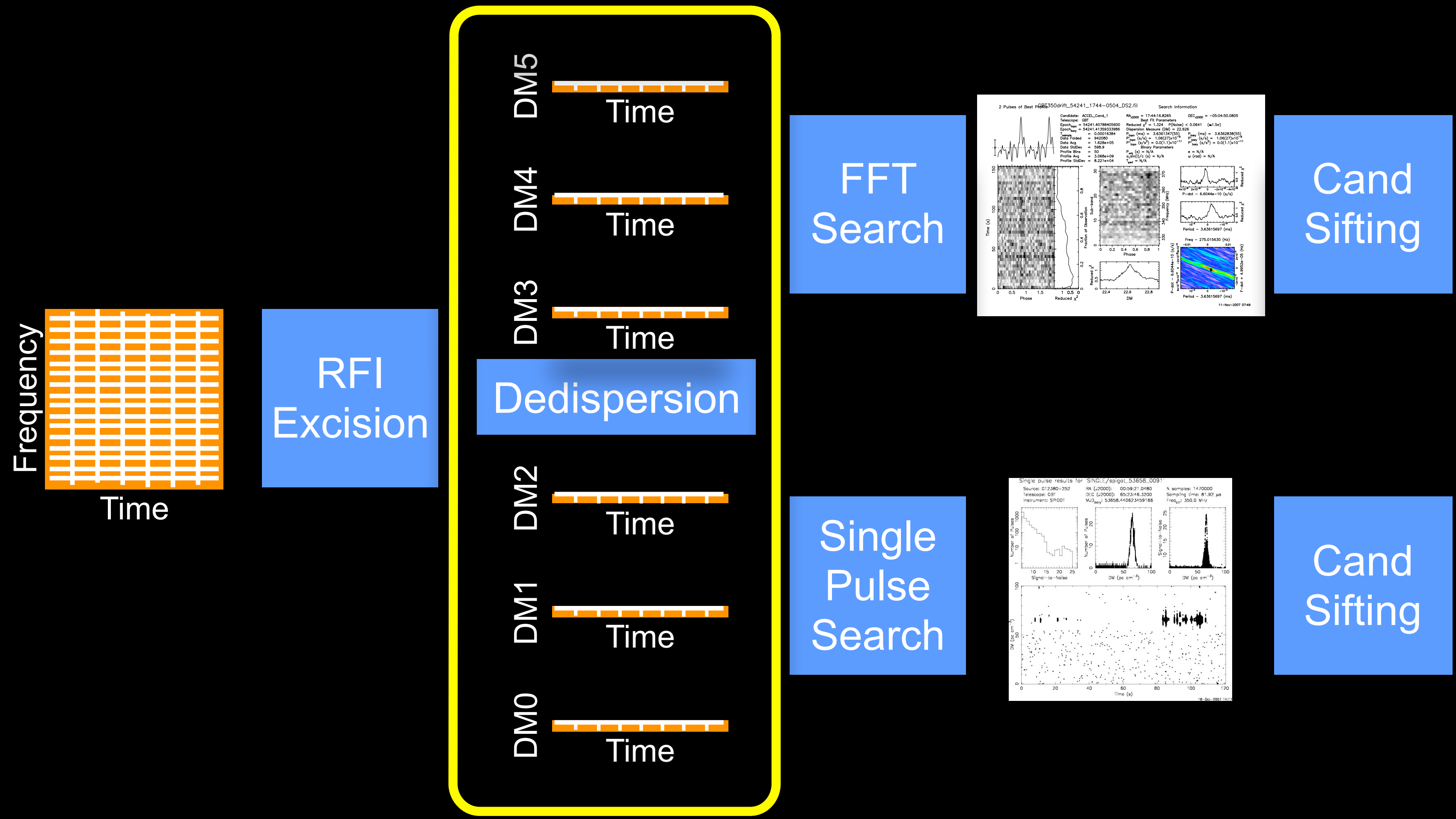
Appendices

Appendix A:
Pulsar searching

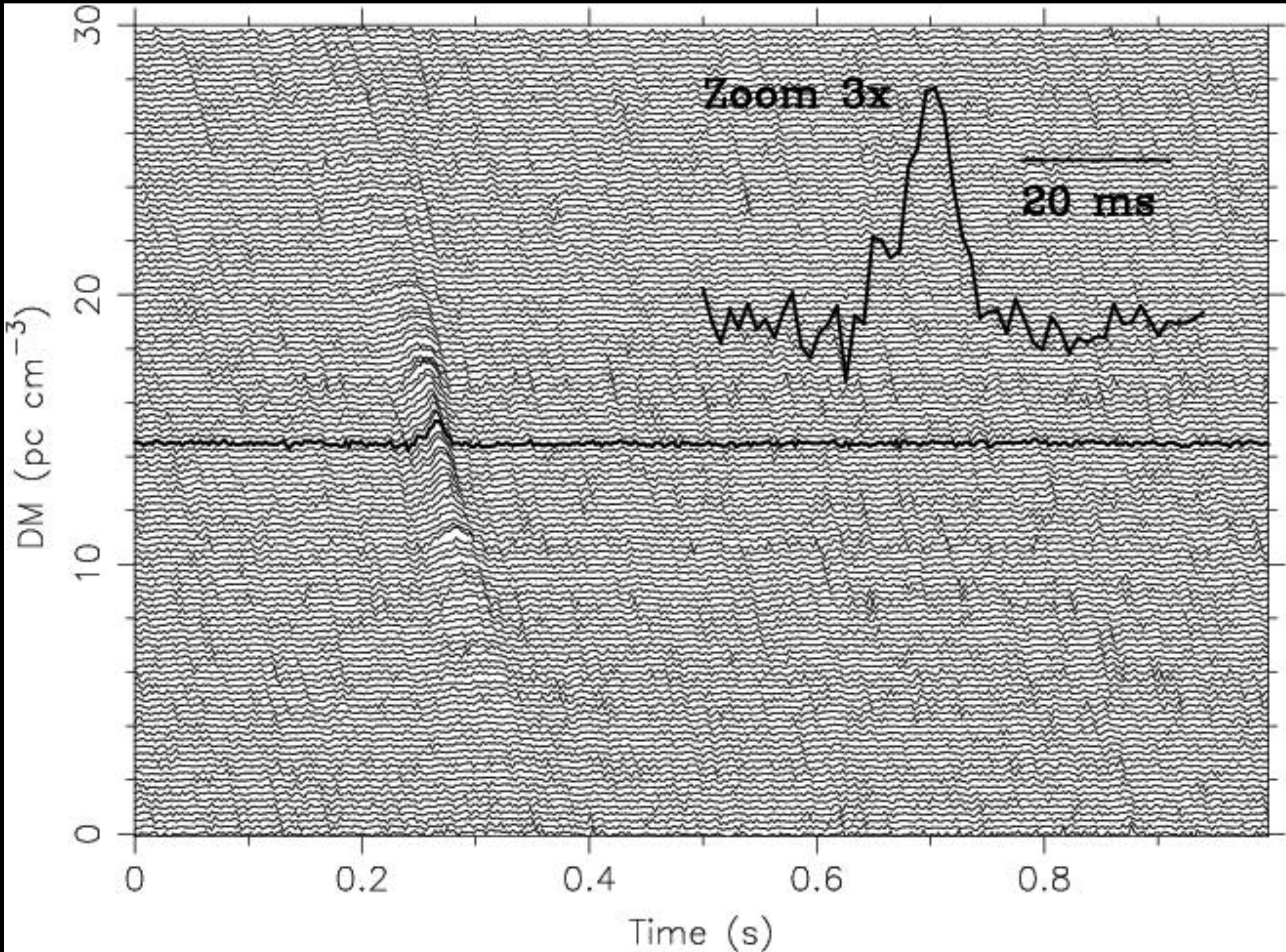
Standard Pulsar/Fast Transient Search



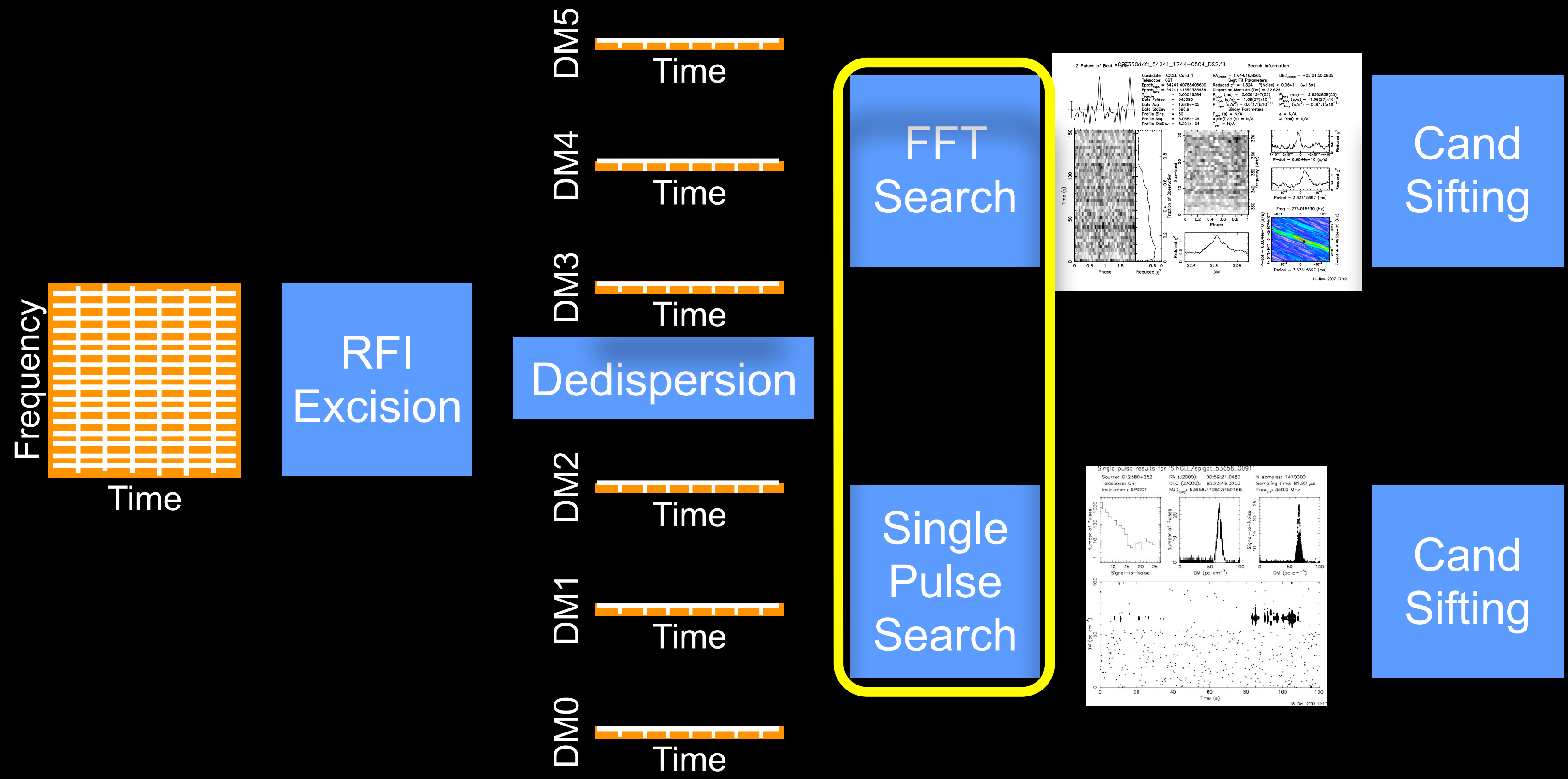
Standard Pulsar/Fast Transient Search



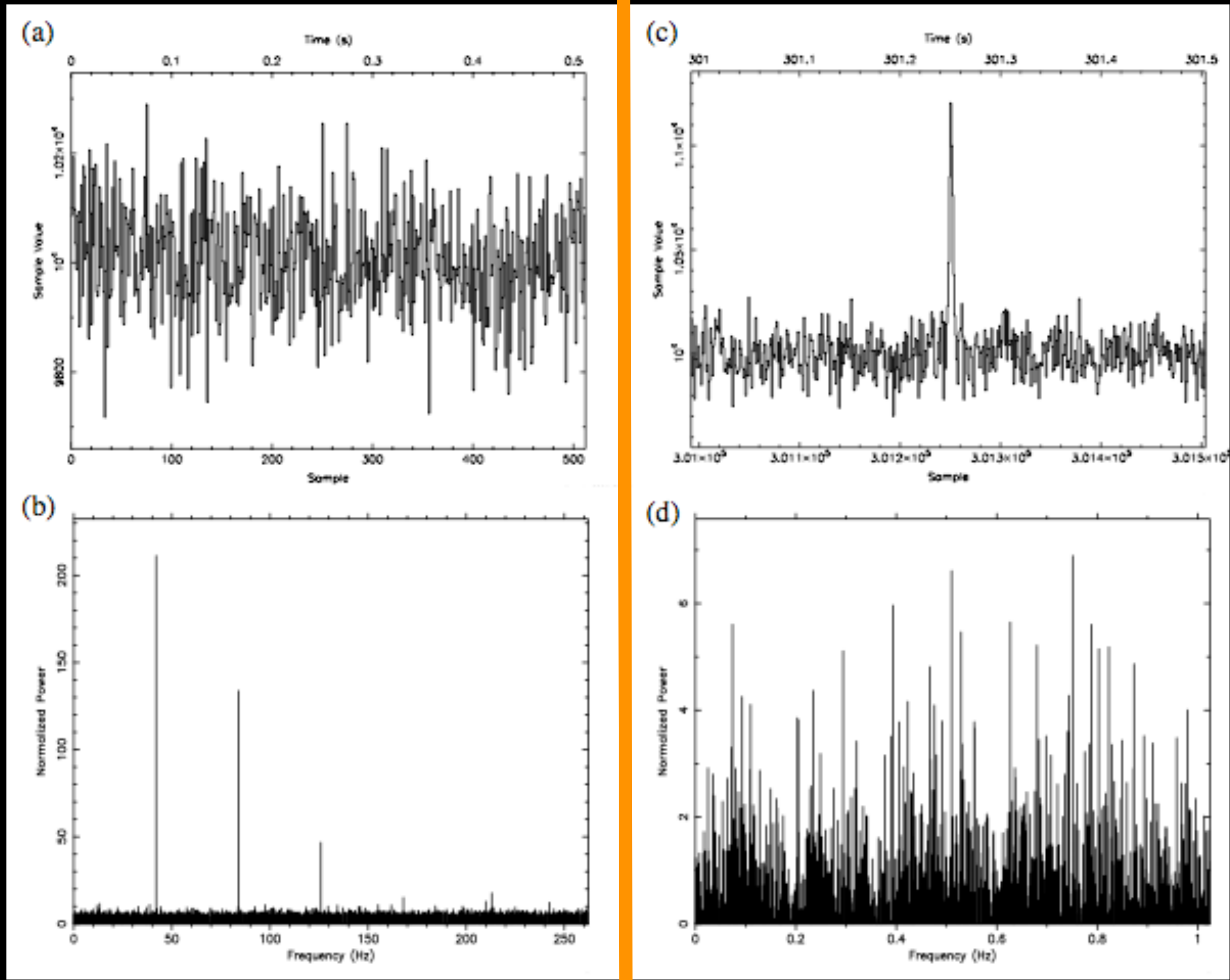
Searching over dispersion measure



Standard Pulsar/Fast Transient Search

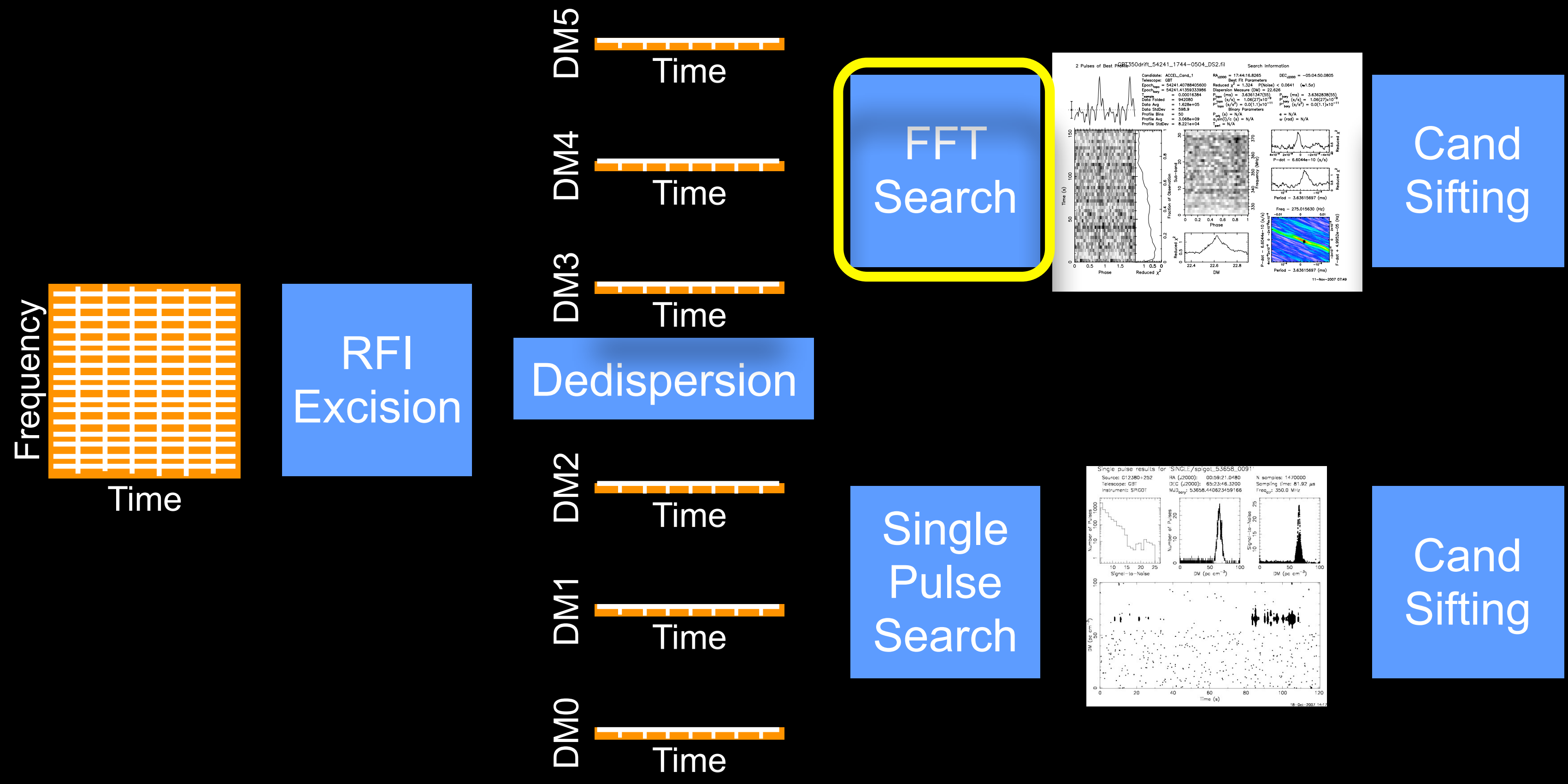


Periodic signals vs. bursts

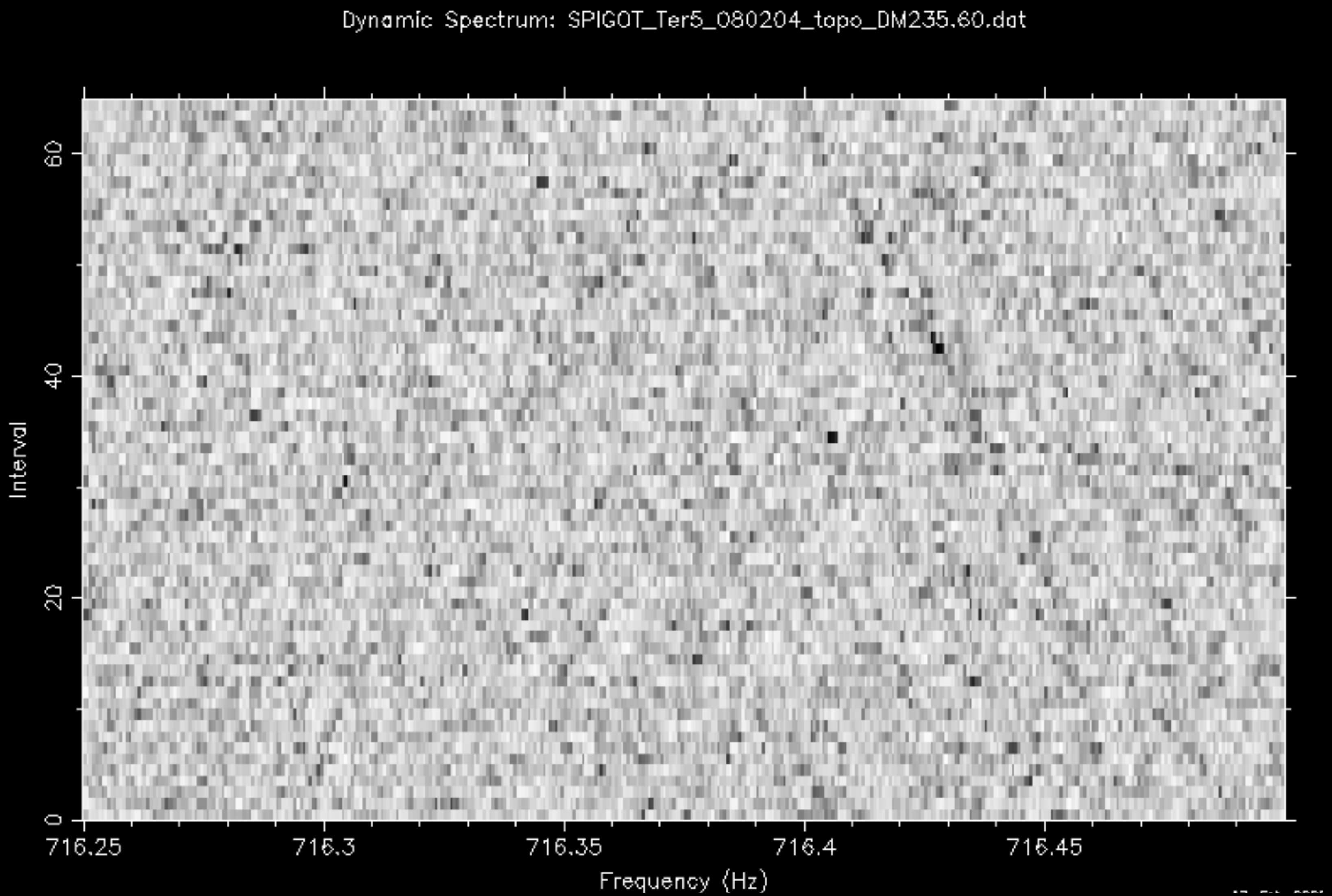


Fourier techniques | Time-series techniques

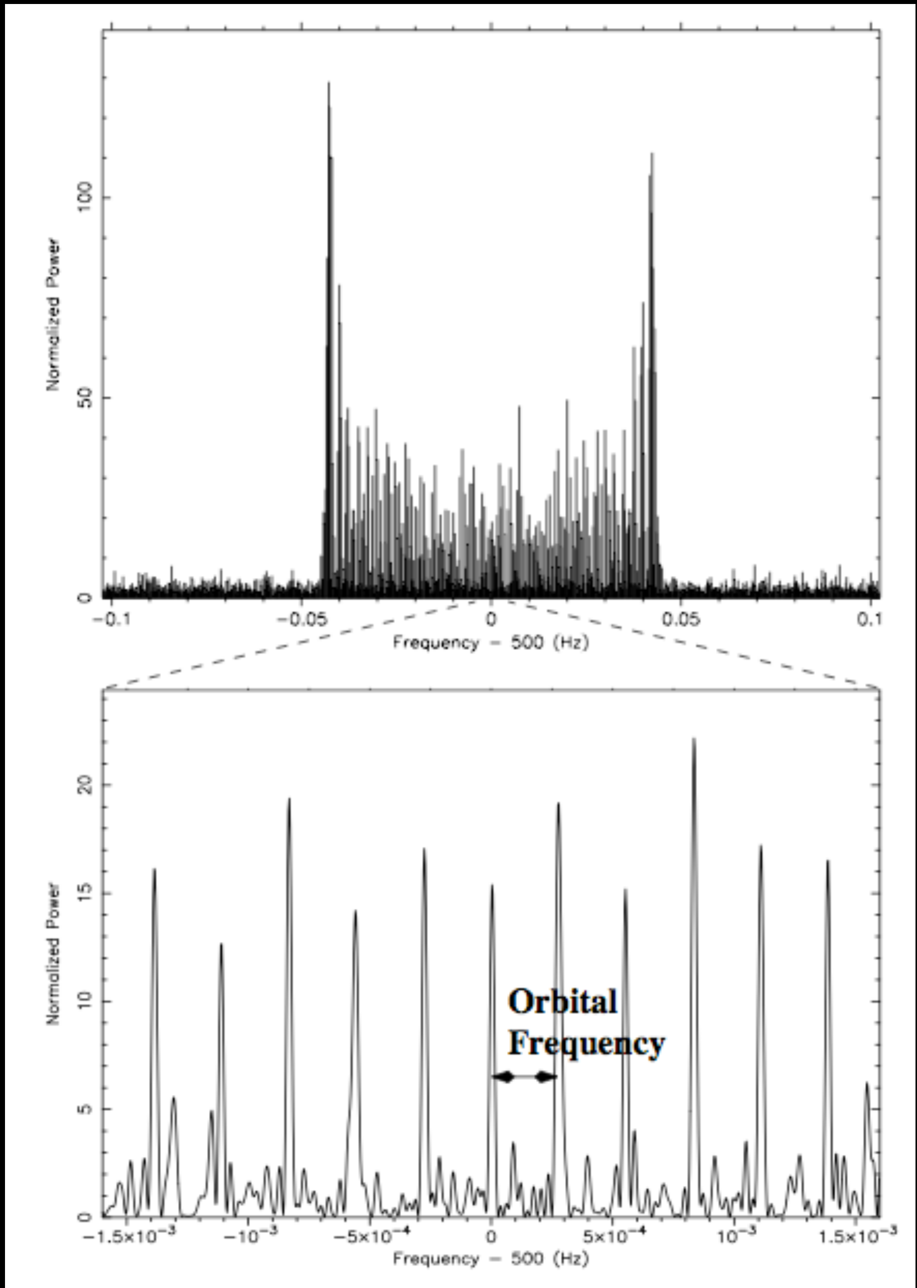
Standard Pulsar/Fast Transient Search

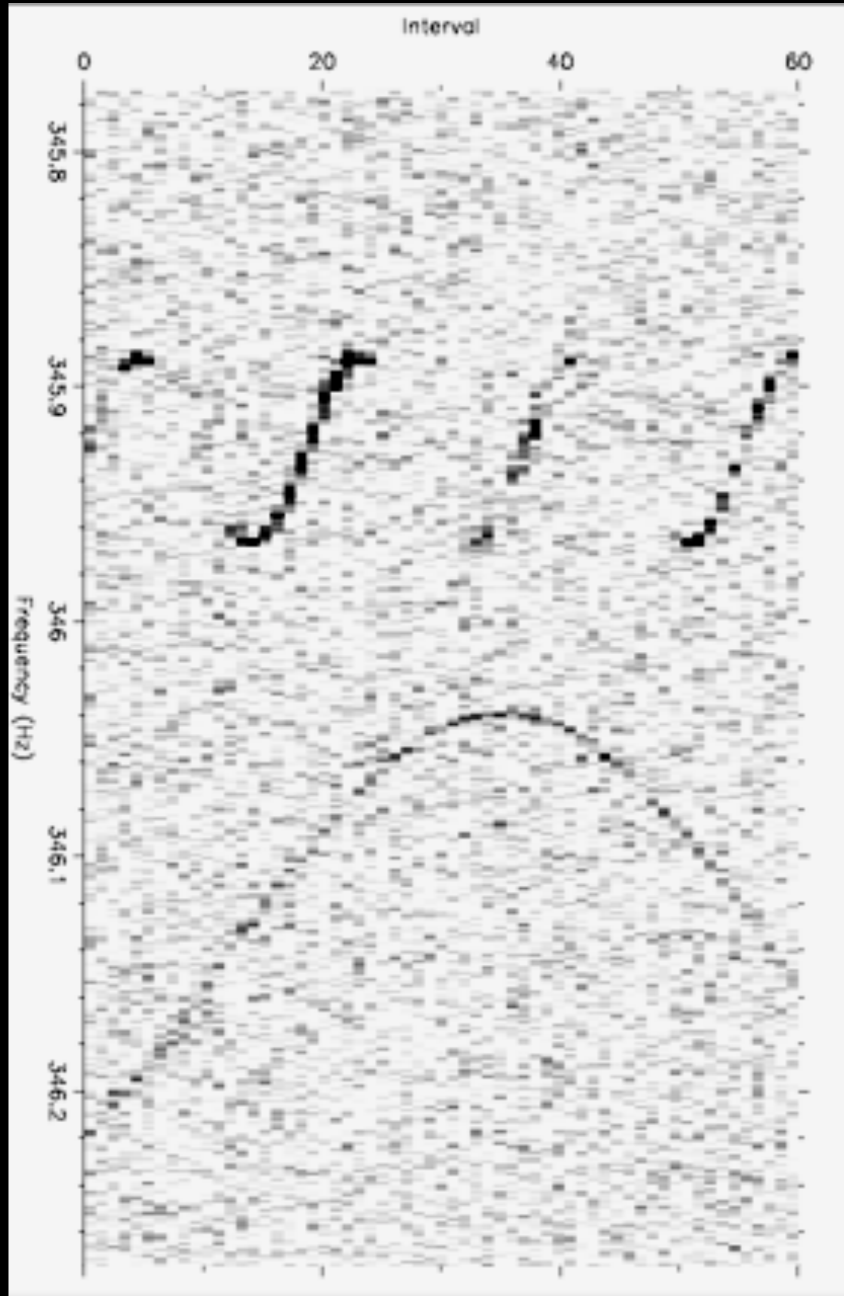


Detecting Binary Pulsars

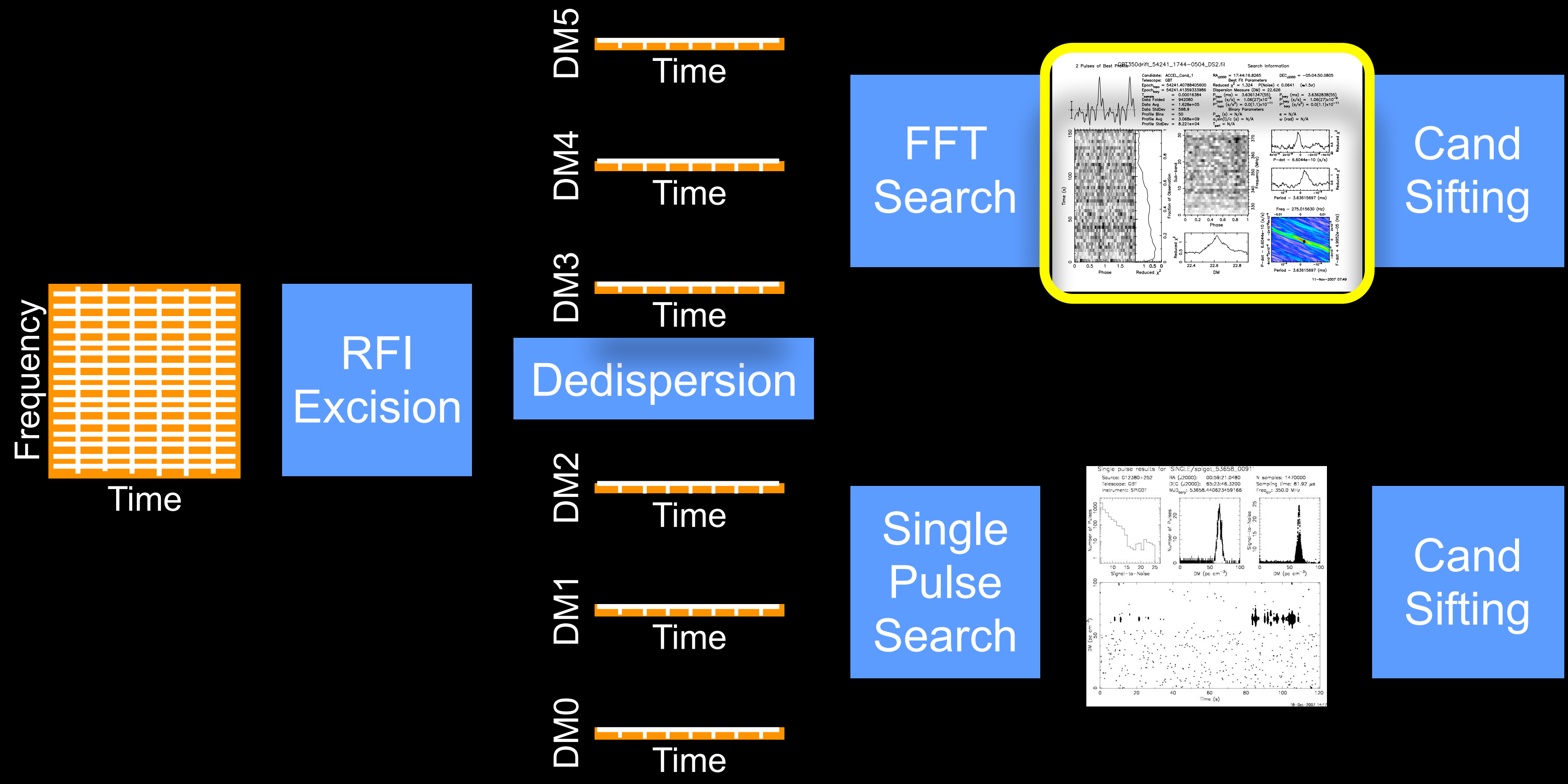


Detecting Binary Pulsars

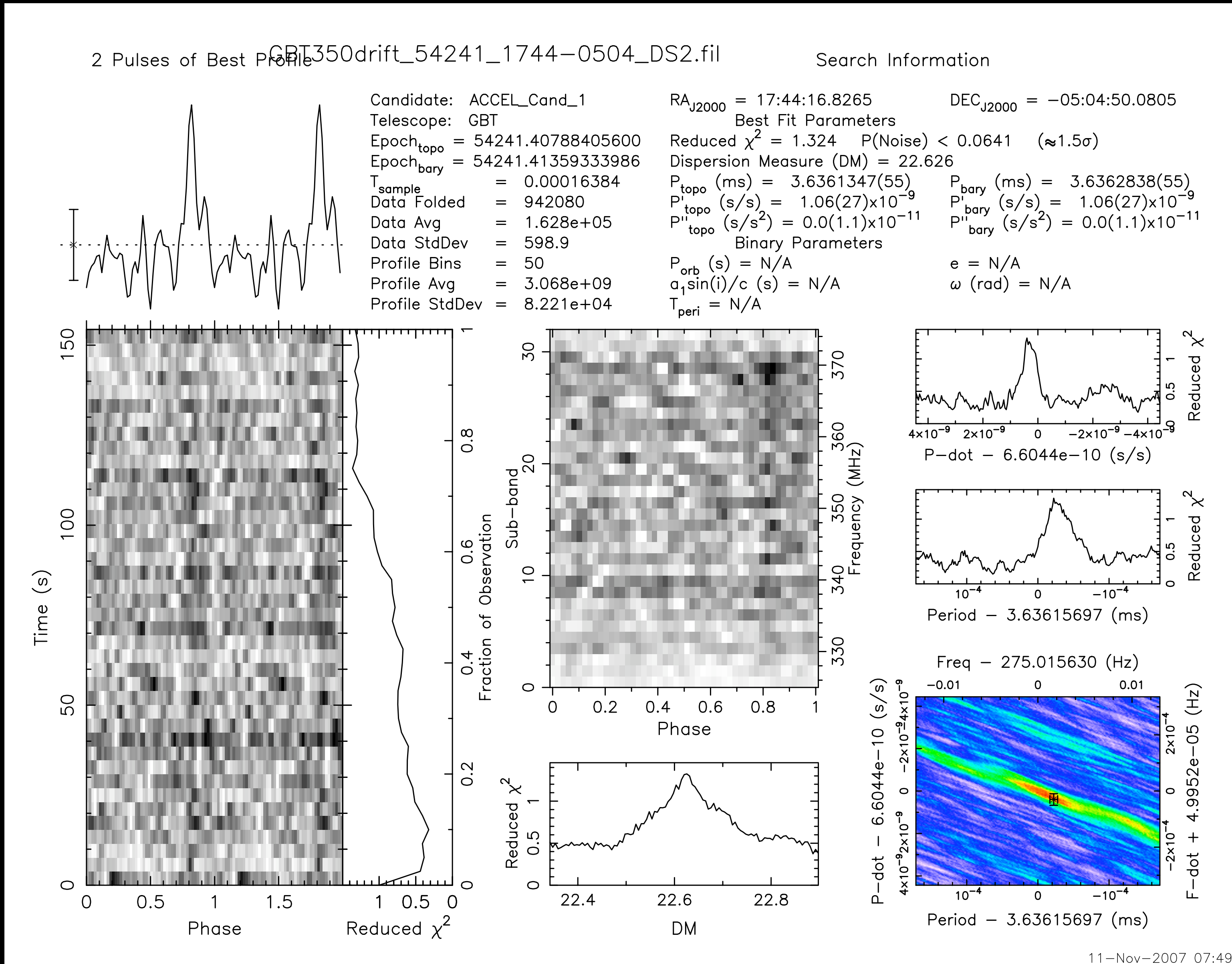




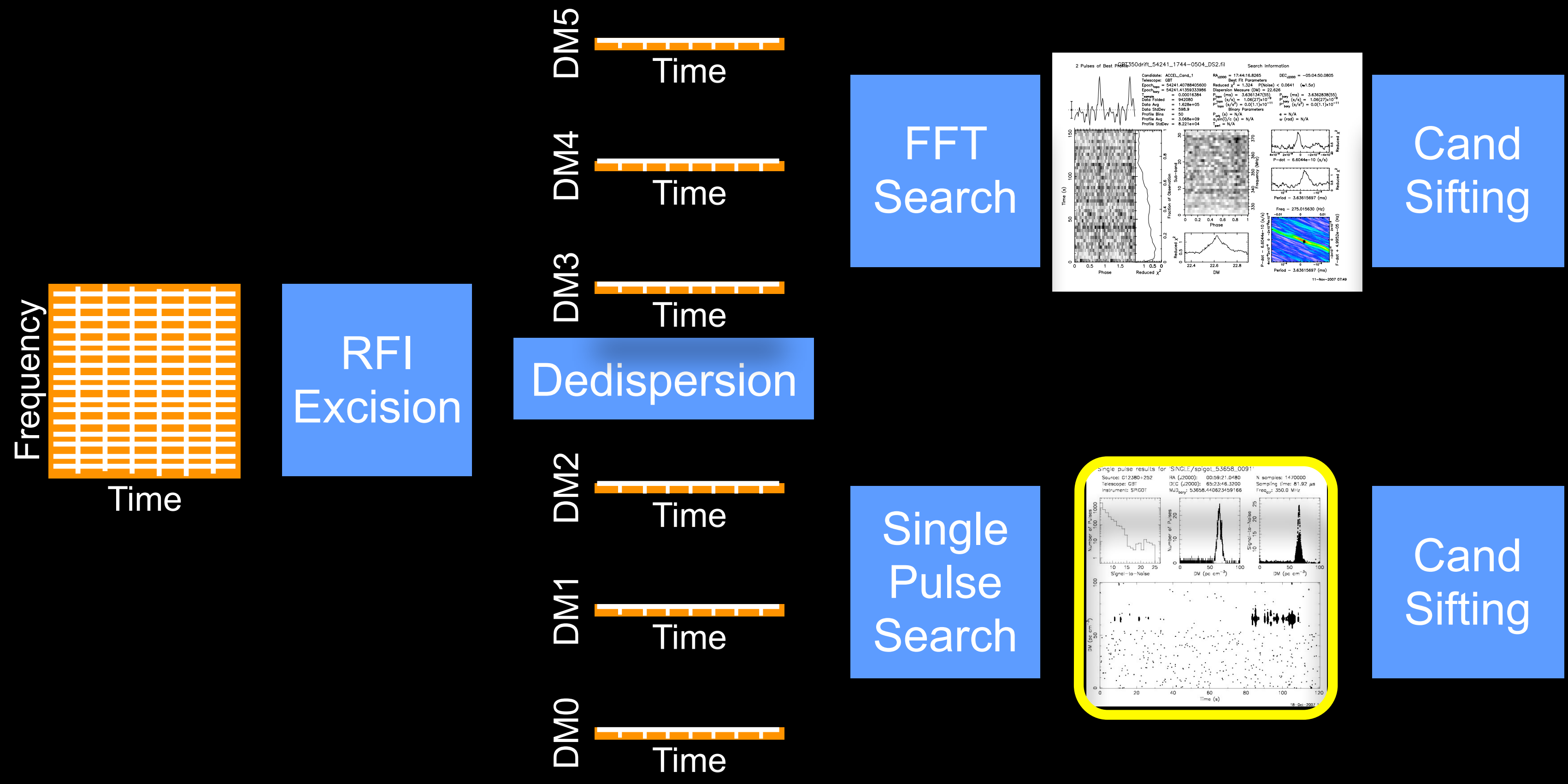
Standard Pulsar/Fast Transient Search



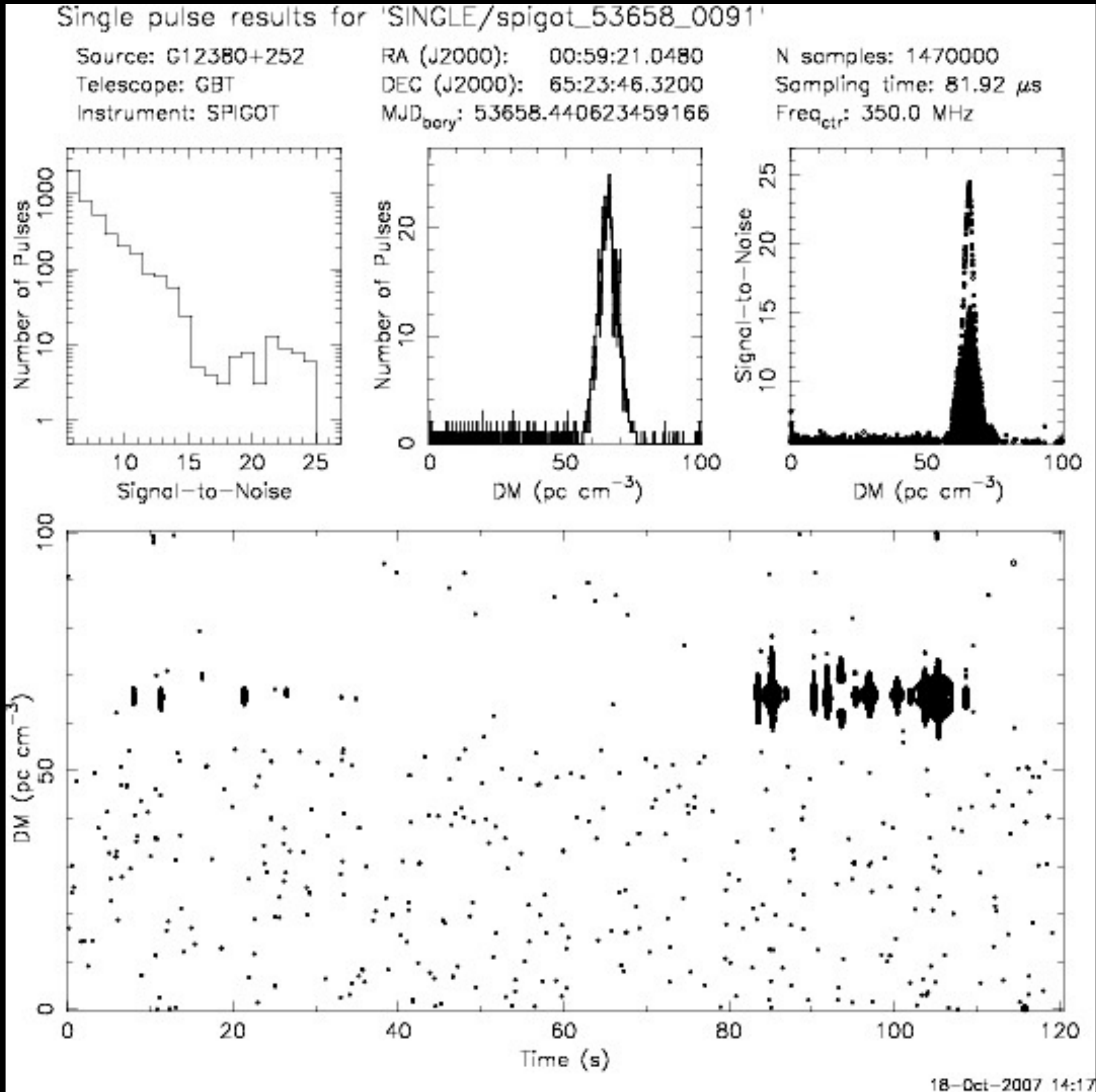
FFT (acceleration) searches



Standard Pulsar/Fast Transient Search



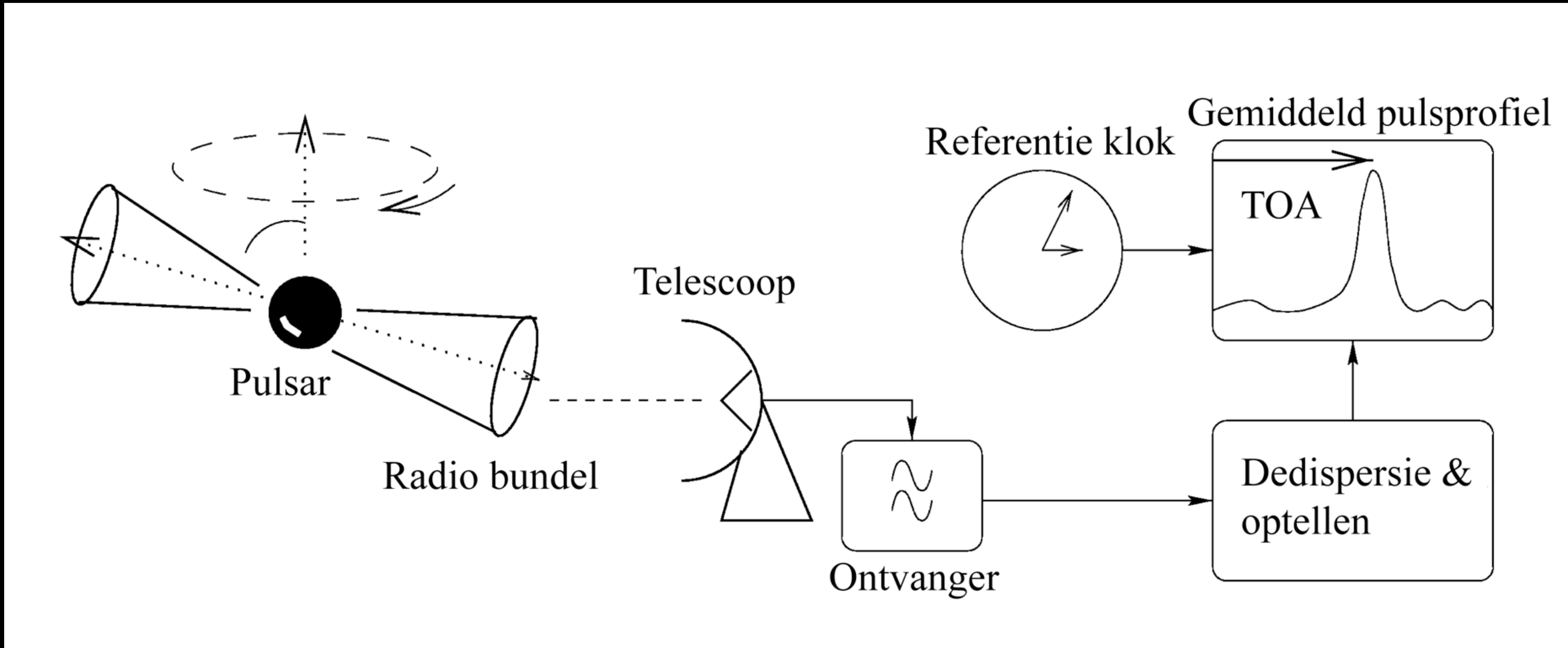
Single pulse searches



Appendix B:
Pulsar timing

Basics of Pulsar Timing

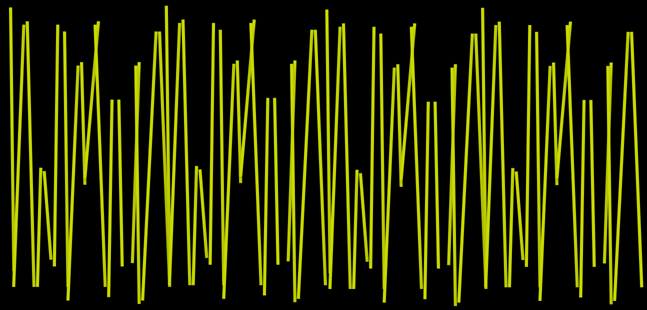
Instrumentation



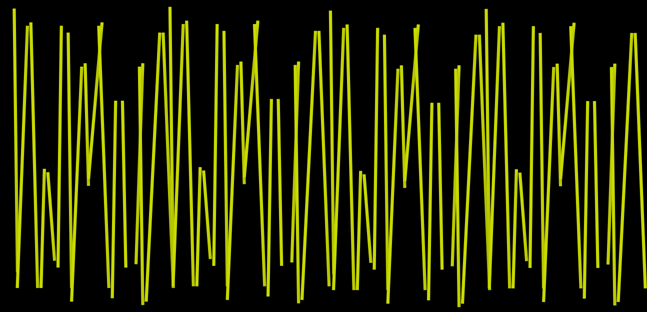
Clock corrections are essential

Also need to transfer to the SSB

Basics of Pulsar Timing



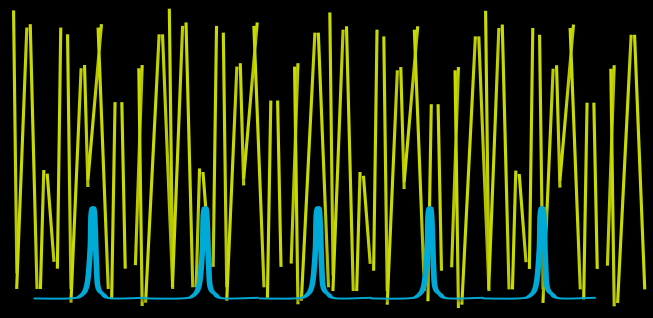
Folding

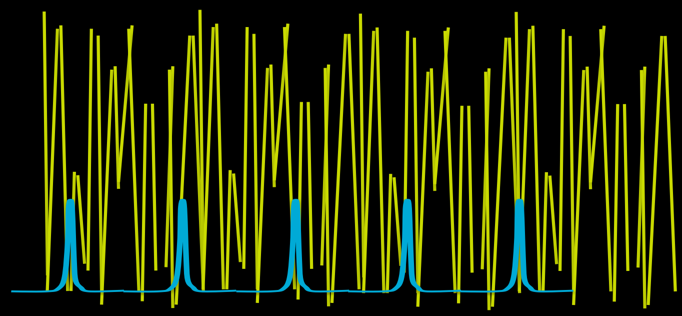


dedispersed data

Basics of Pulsar Timing

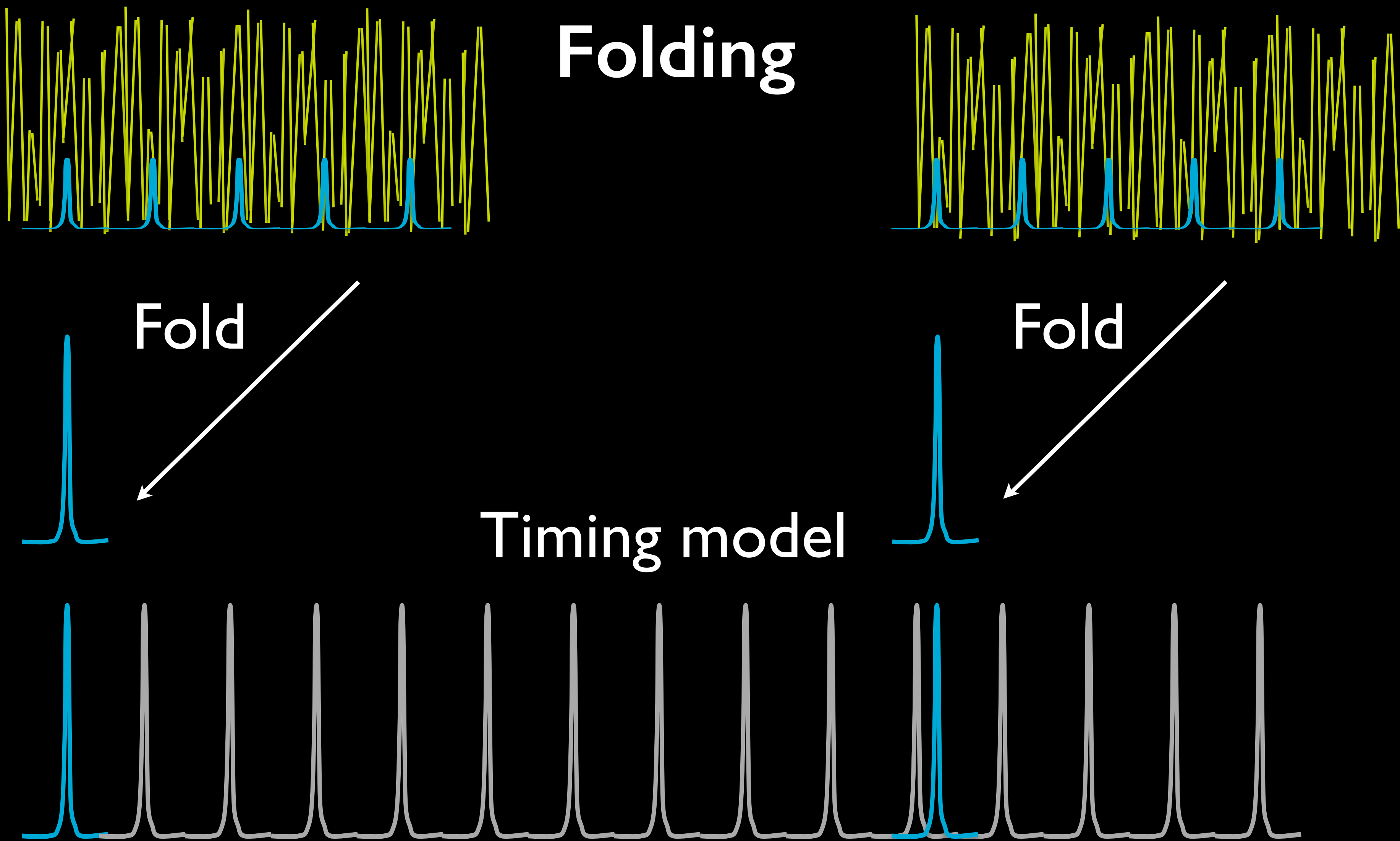
Folding





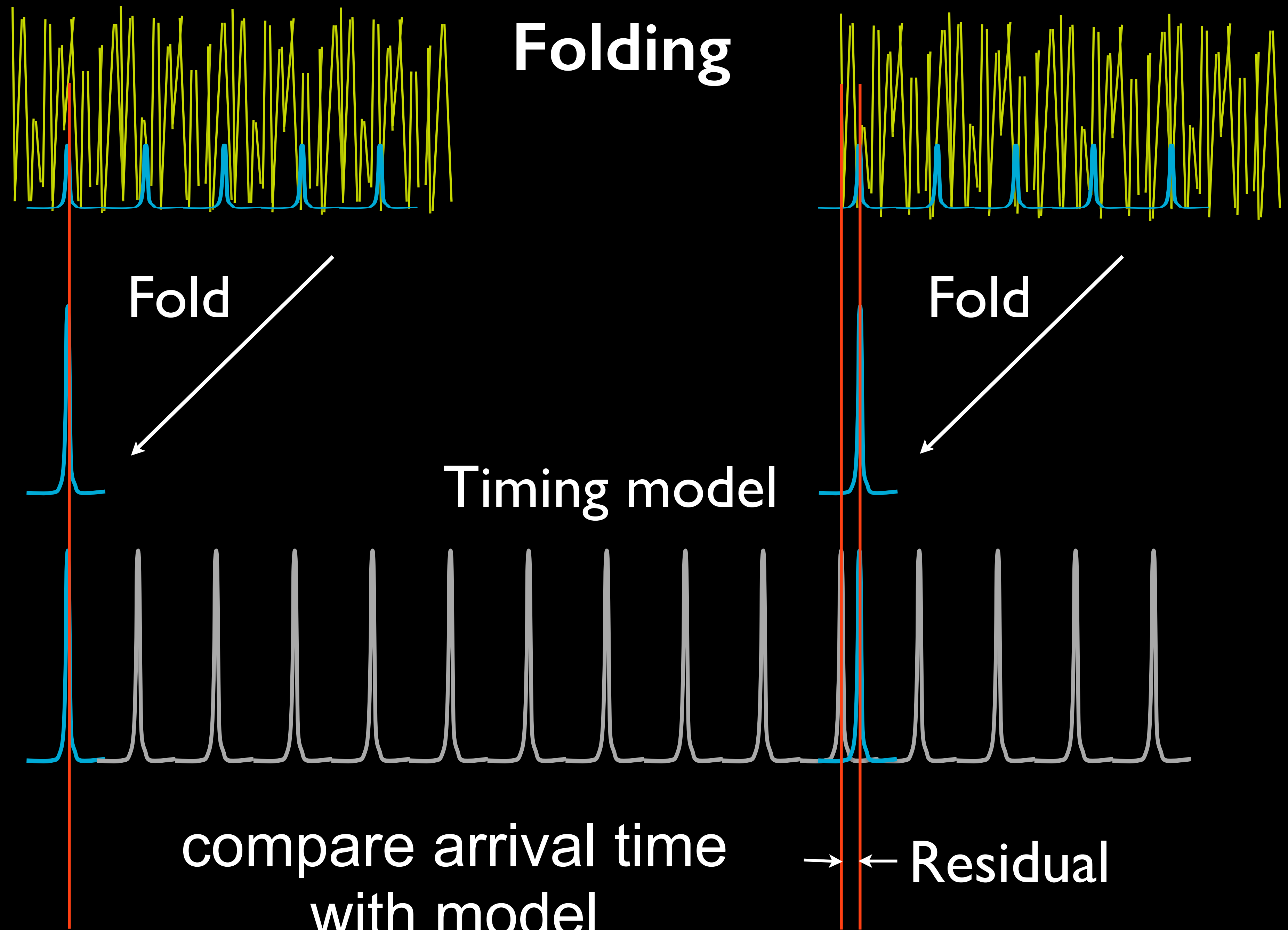
individual pulses are buried in the noise

Basics of Pulsar Timing



how many rotations are there between observations?

Basics of Pulsar Timing



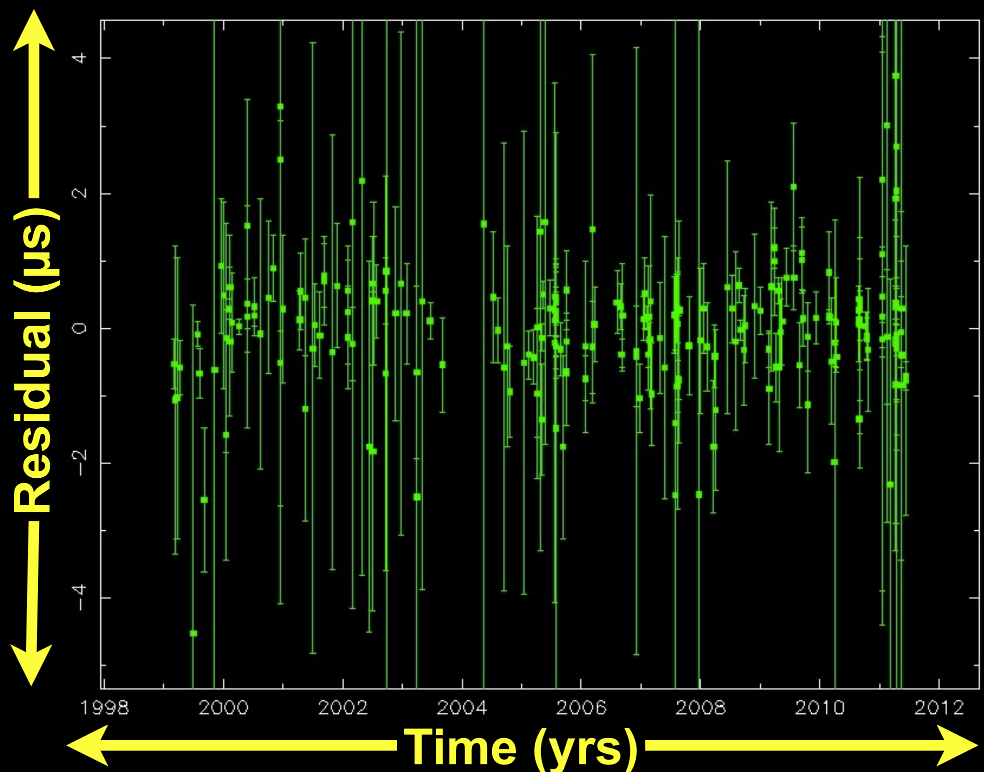
Pulsar Timing Model

Basic Method:

Actual Pulse TOA

— Theoretical Model

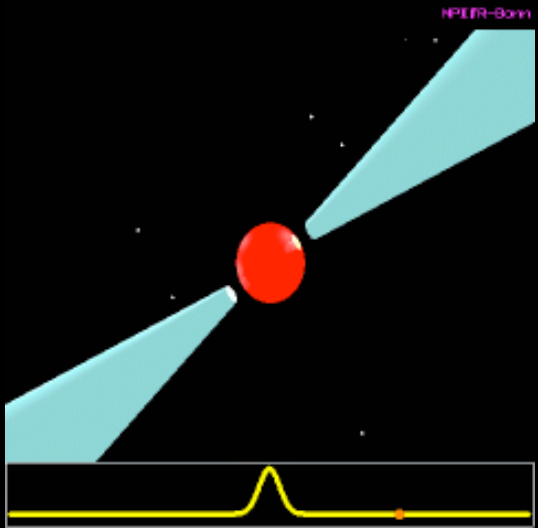
= Timing Residual



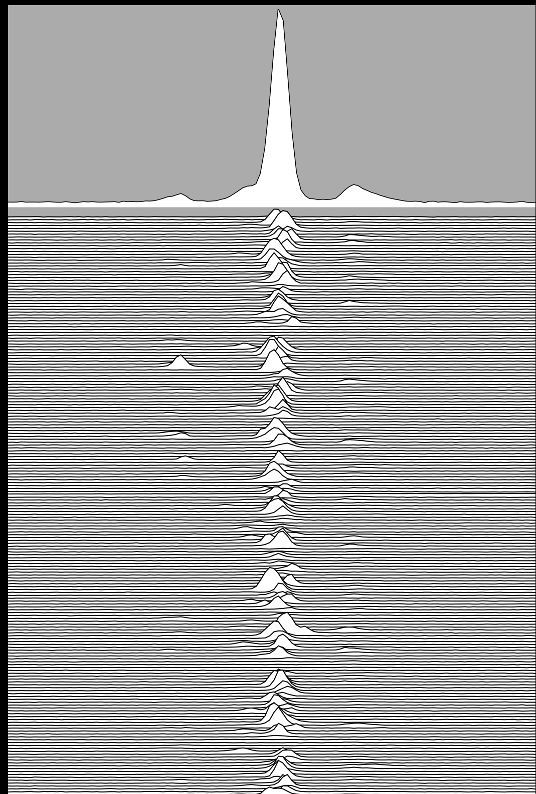
Courtesy Andrew Jameson (Swinburne)

$$T_{\rm th} = \nu t + \frac{1}{2}\dot{\nu}t^2 + D\frac{\int_0^d n_e dl}{f^2} - \frac{1}{c}\left(\vec{r}\cdot\hat{s}\right) + \frac{V_{\rm T}^2 t^2}{2cd} - \frac{\left(\vec{r}\times\hat{s}\right)^2}{2cd} + \ldots$$

Pulsars timing process



Collect pulses



Dedisperse, fold and cross-correlate with template

54255.1231254524233
54255.2643443523453
54255.3123524545899
54255.3513745623467
54255.4418456543355
54255.5001234234688

Times of arrival (TOAs)

TOA Precision

Big, Sensitive Telescope (duh)

Long Observations,
Wide Bandwidth

Fast, Bright Pulsar

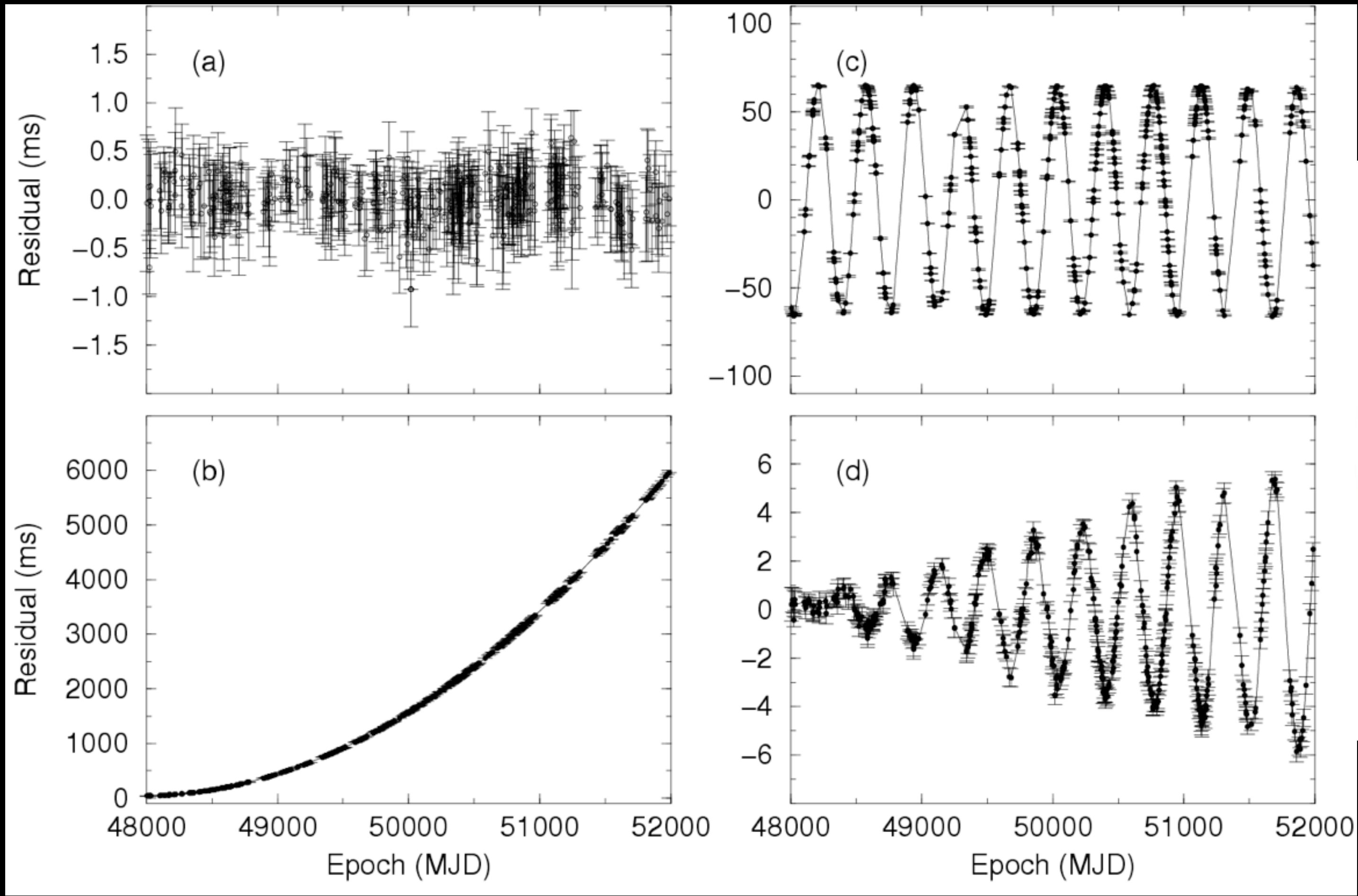
$$\sigma_{\mathrm{TOA}} \propto \frac{T_{\mathrm{sys}}}{A_{\mathrm{eff}}} \times \frac{1}{\sqrt{T_{\mathrm{obs}}\Delta\nu}} \times \frac{P\delta^{3/2}}{S_{\mathrm{PSR}}}$$

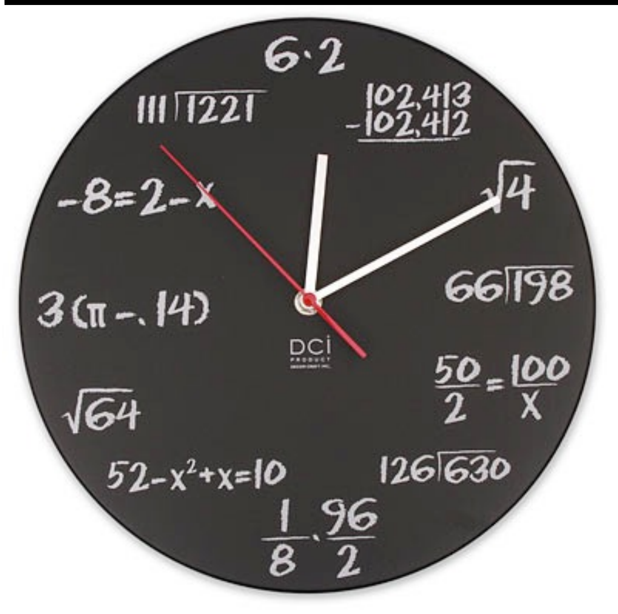
Important Note:

$$S_{\mathrm{PSR}} \propto \nu^{\alpha}$$

with $\alpha \approx -1.6 < 0$

Pulsar Timing Model





Coherent timing: use TOAs to unambiguously count every single rotation of pulsar over timescales of years.

Warning: some parameters are covariant!!!

Pulsar Timing
“Phase connecting”

Coherent timing: use TOAs to unambiguously count every single rotation of pulsar over timescales of years.

Rotational ephemeris can provide:

Precise astrometry (sub-arcsecond)
Proper motion
Glitches in rotation
...

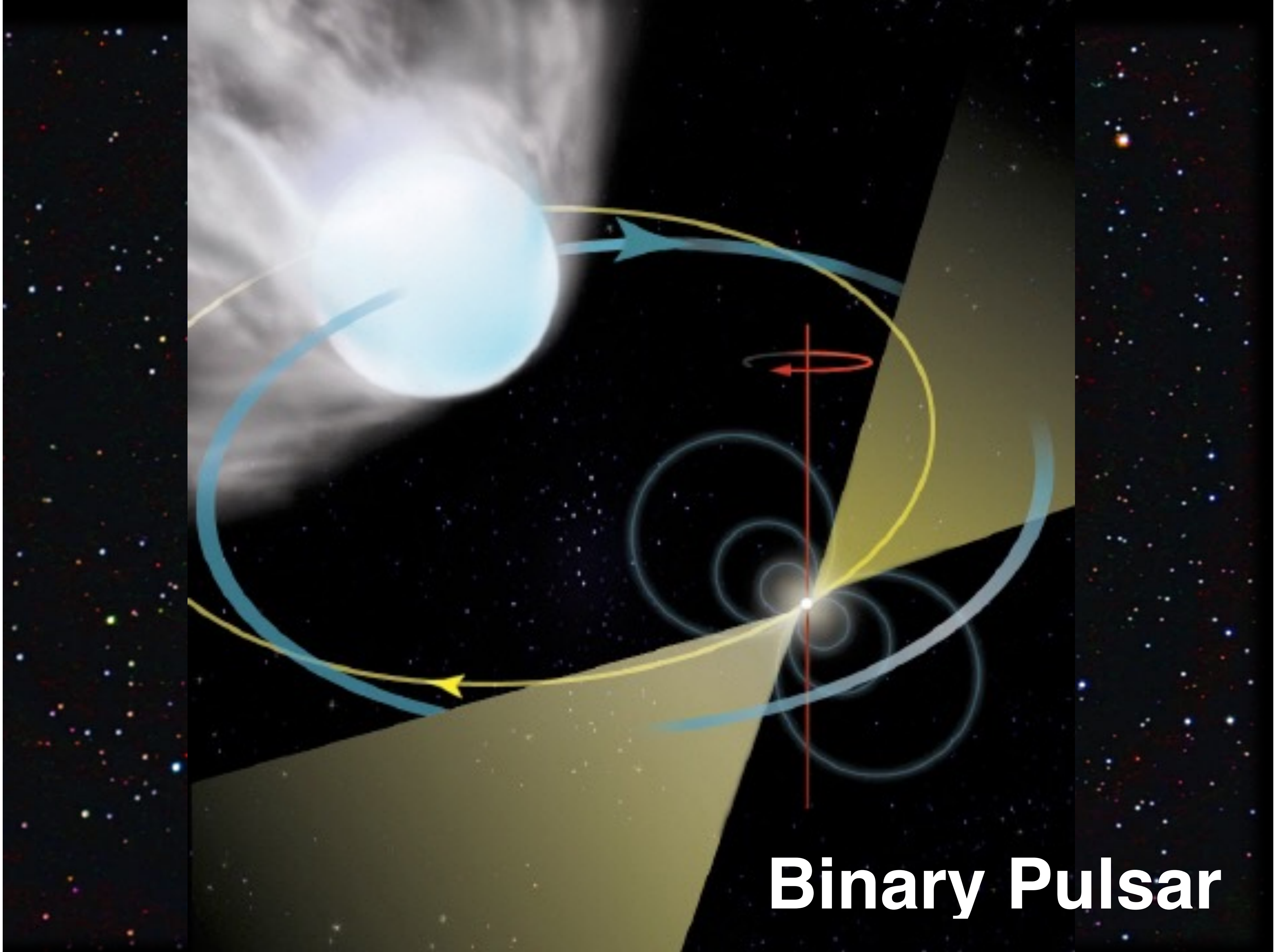
Pulsar Timing

“Phase connecting”

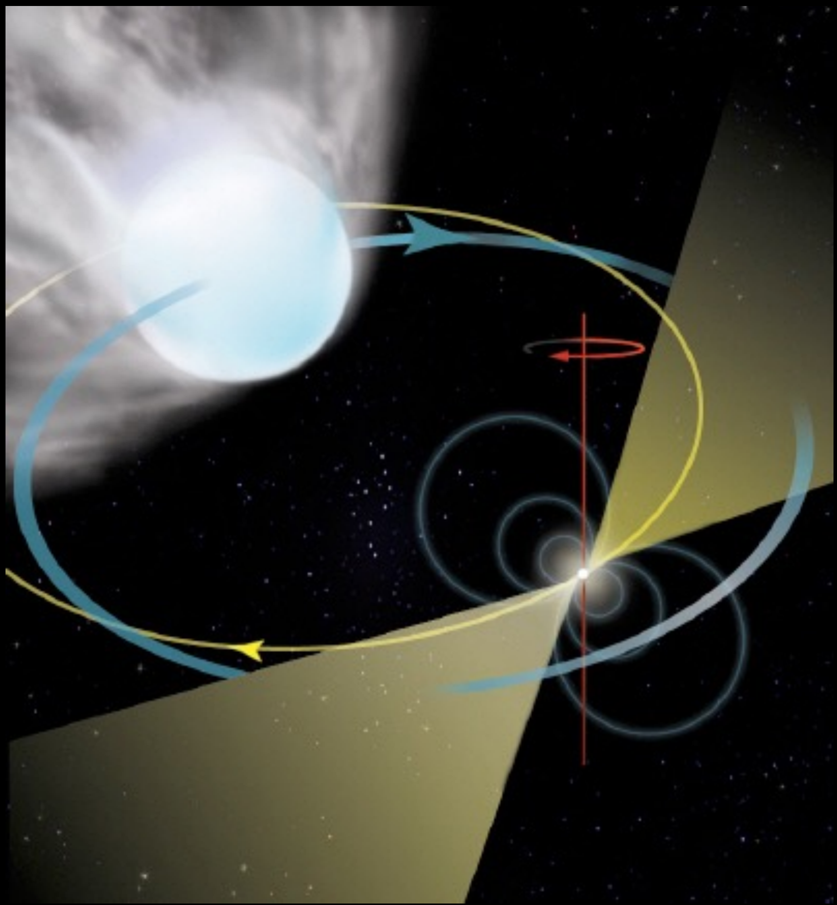
Results for PSR J1022+1001

RMS pre-fit residual = 5.551 (us), RMS post-fit residual = 4.204 (us)
Fit Chisq = 328 Chisqr/nfree = 328.02/80 = 4.10028 pre/post = 1.32036
Number of points in fit = 90

PARAMETER	Pre-fit	Post-fit	Uncertainty	Difference	Fit
RAJ (rad)	2.71821351132165	2.71821366970554	4.5793e-07	1.5838e-07	Y
RAJ (hms)	10:22:58.1188834	10:22:58.1210613	0.006297	0.0021779	
DECJ (rad)	0.175100786106638	0.175101202092881	1.1575e-06	4.1599e-07	Y
DECJ (dms)	+10:01:57.12972	+10:01:57.21552	0.23875	0.085803	
F0 (Hz)	60.7794489670958	60.7794489674466	1.2099e-10	3.5076e-10	Y
F1 (s^-2)	-1.69337759279488e-16	-1.70739820420136e-16	4.6312e-19	-1.4021e-18	Y
PEPOCH (MJD)	50250	50250	0	0	N
POSEPOCH (MJD)	50250	50250	0	0	N
DM (cm^-3 pc)	10.1340857485791	10.1323540071461	0.00032389	-0.0017317	Y
T0	50246.7162463696	50246.7162473185	8.2856e-07	9.4889e-07	Y
PB	7.80513016588816	7.80513016328438	2.1745e-09	-2.6038e-09	Y
A1	16.7654150843515	16.7654147901821	3.3958e-07	-2.9417e-07	Y
OM	97.67	97.67	0	0	N
ECC	9.73177041814313e-05	9.73614863096607e-05	4.0439e-08	4.3782e-08	Y
TRACK (MJD)	0	0	0	0	N


Binary Pulsar

Pulsar Timing
Orbital Parameters



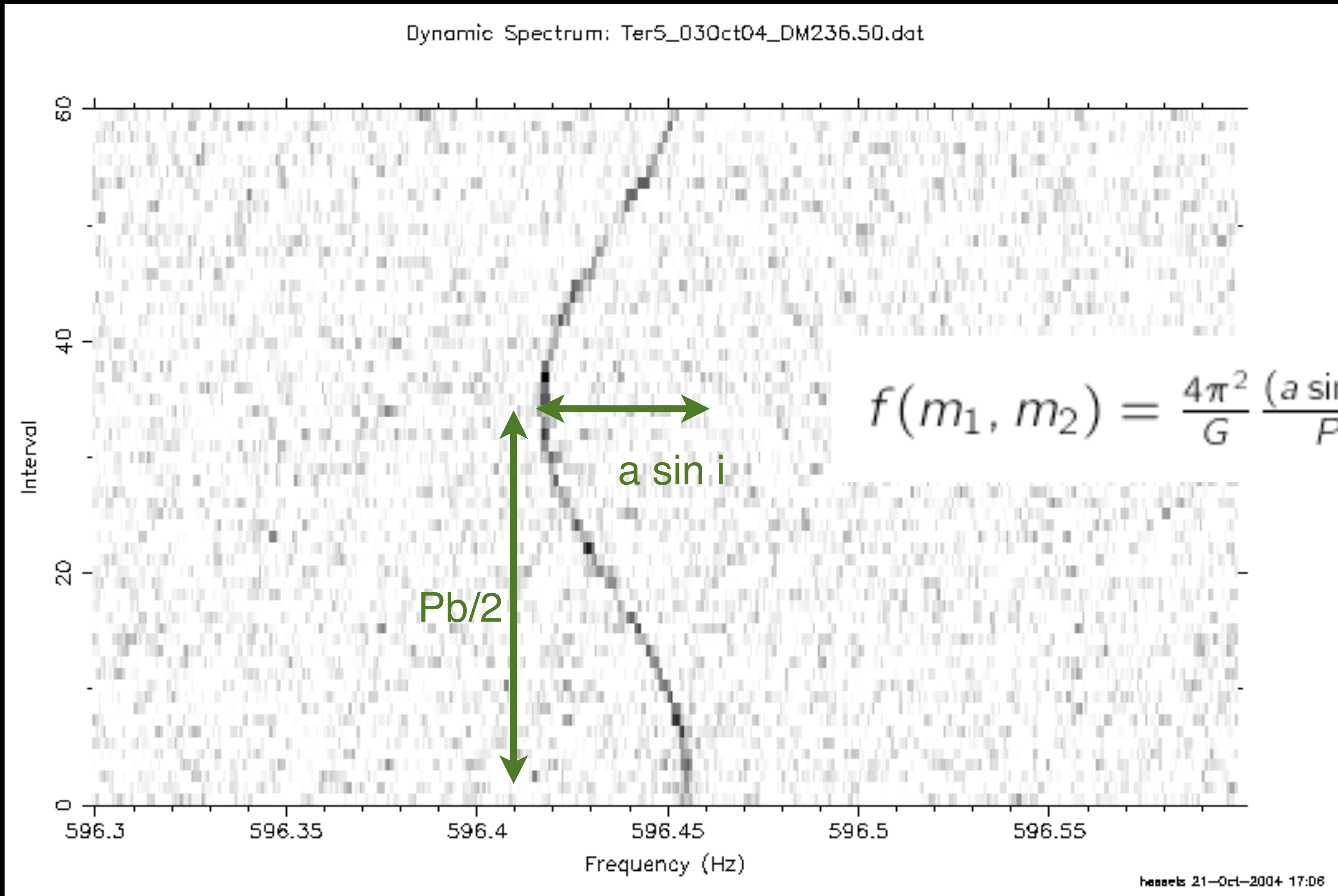
Keplerian Parameters

Projected semi-major axis (a sin i)
Time of periastron (To)
Longitude of periastron (w)
Orbital Period (Pb)
Eccentricity (e)

$$f(m_1, m_2) = \frac{4\pi^2}{G} \frac{(a \sin i)^3}{P_b^2} = \frac{(m_2 \sin i)^3}{(m_1 + m_2)^2}$$

Mass function
(compare with single-line spectroscopic binary)

Pulsar Timing
Orbital Parameters



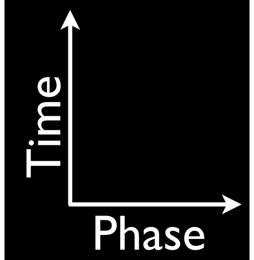
$$f(m_1, m_2) = \frac{4\pi^2}{G}\frac{(a \sin i)^3}{P_b^2} = \frac{(m_2 \sin i)^3}{(m_1+m_2)^2}$$

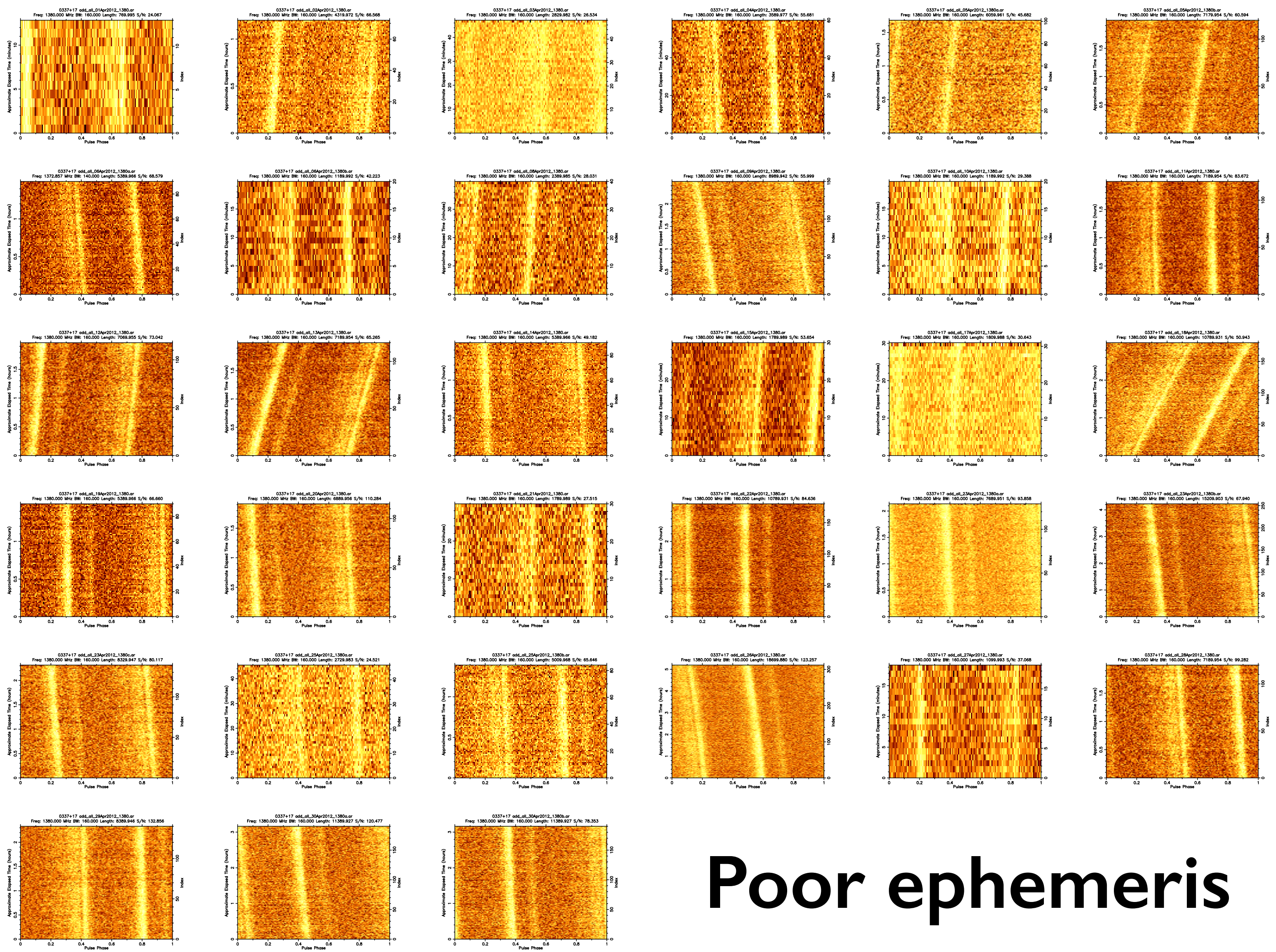
Can est. m2's min. mass

Need mass function + two other equations for m1, m2, and i

Basics of Pulsar Timing

Rotational Ephemeris

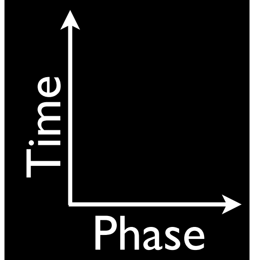


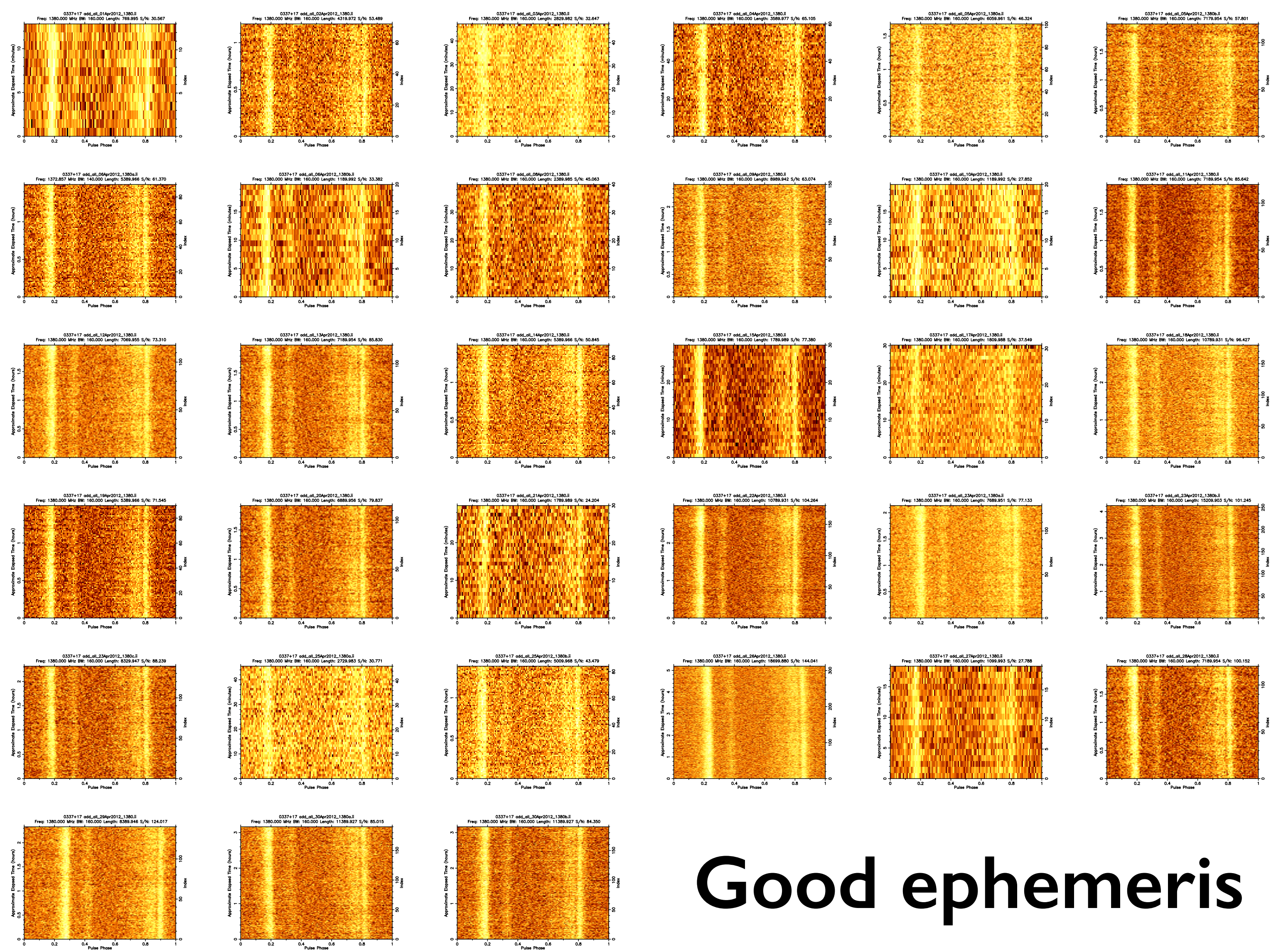


Poor ephemeris

Basics of Pulsar Timing

Rotational Ephemeris





Good ephemeris