
Credit: John Sarkissian

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Pulsar Observation and Data Analysis

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Outline

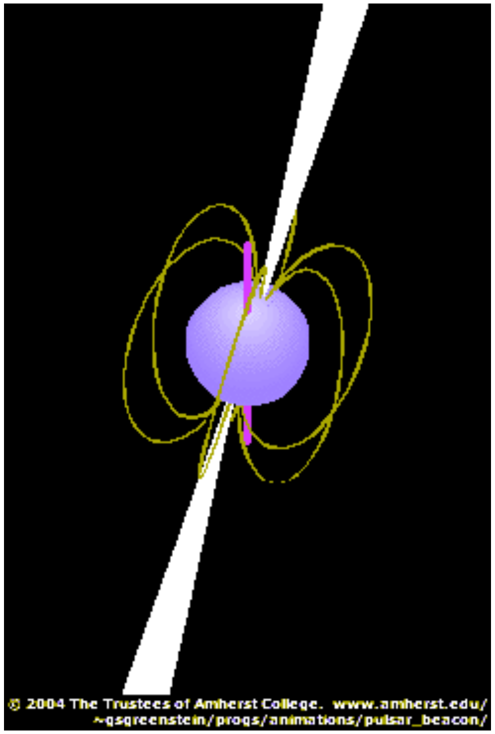
- What are pulsars?
  - What are the requirements for instrumentation/observing strategy?
- Coherent versus Incoherent Dedispersion
- Searching for pulsars
- Timing pulsars
- Other types of pulsar observing

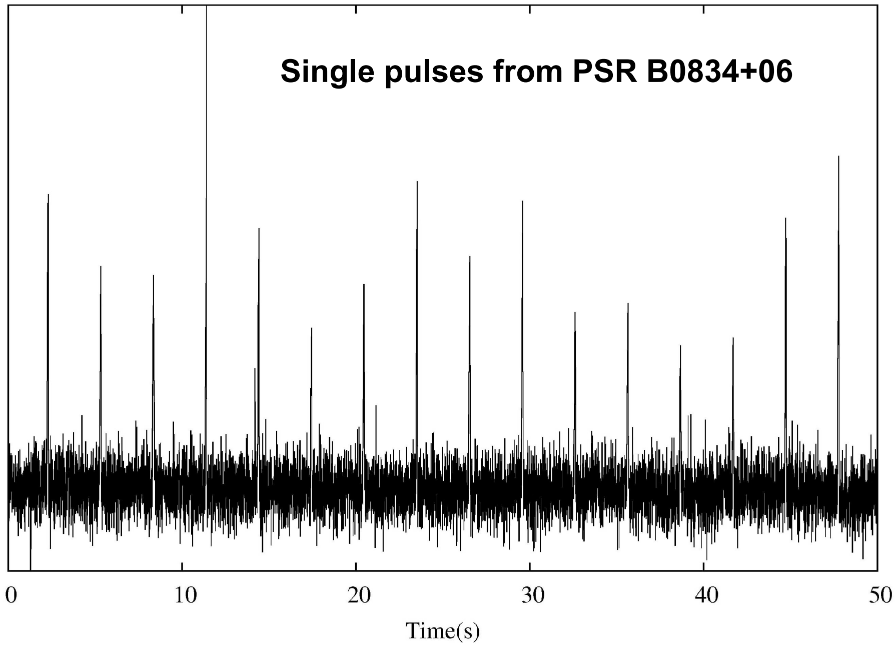
Other pulsary goodness this week:

- Pulsar tutorial: Finding and timing a millisecond pulsar
- Thursday: George Hobbs will Detail the Scientific Motivations for Pulsar Timing

Pulsar radiation is ***pulsed***

- Periodicity of the emission: rotation period of neutron star
  - Spin period for radio-bright neutron stars 1 ms to 10 s
- Emission region: located near magnetic pole of star





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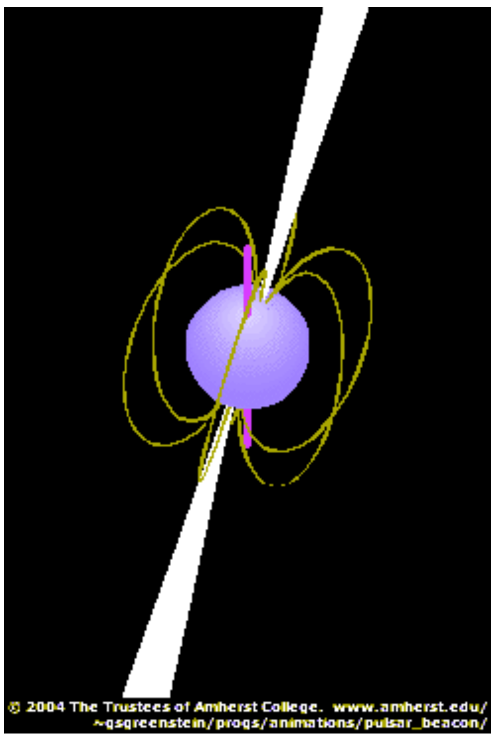
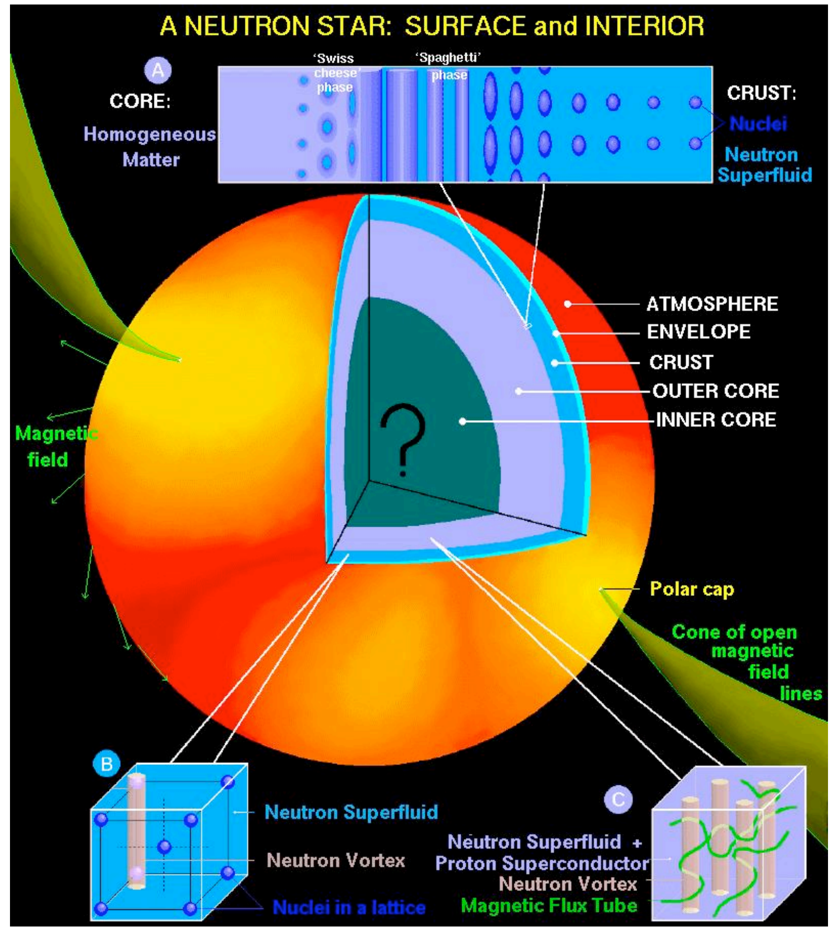
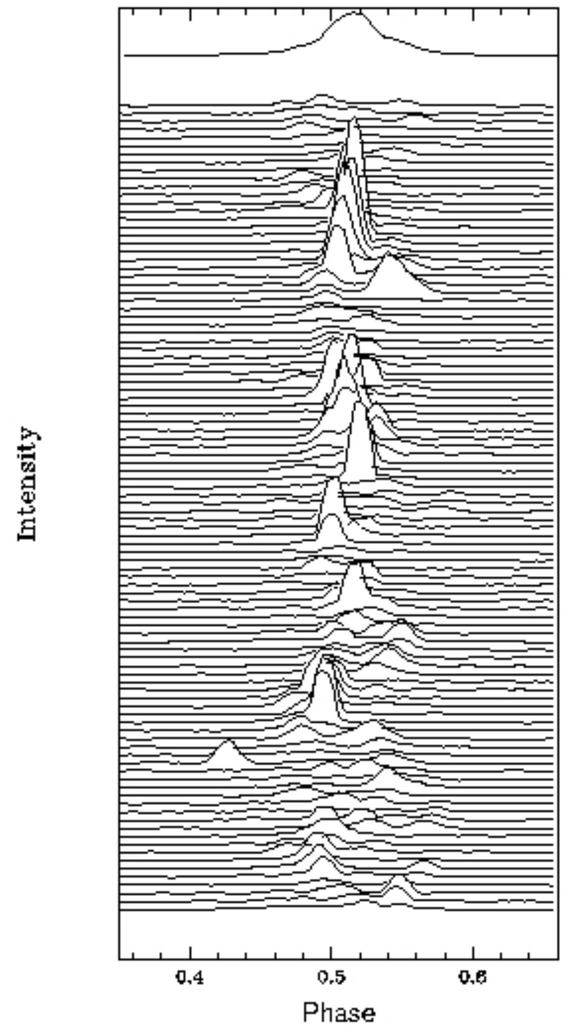




Pulsar radiation is periodically ***pulsed***

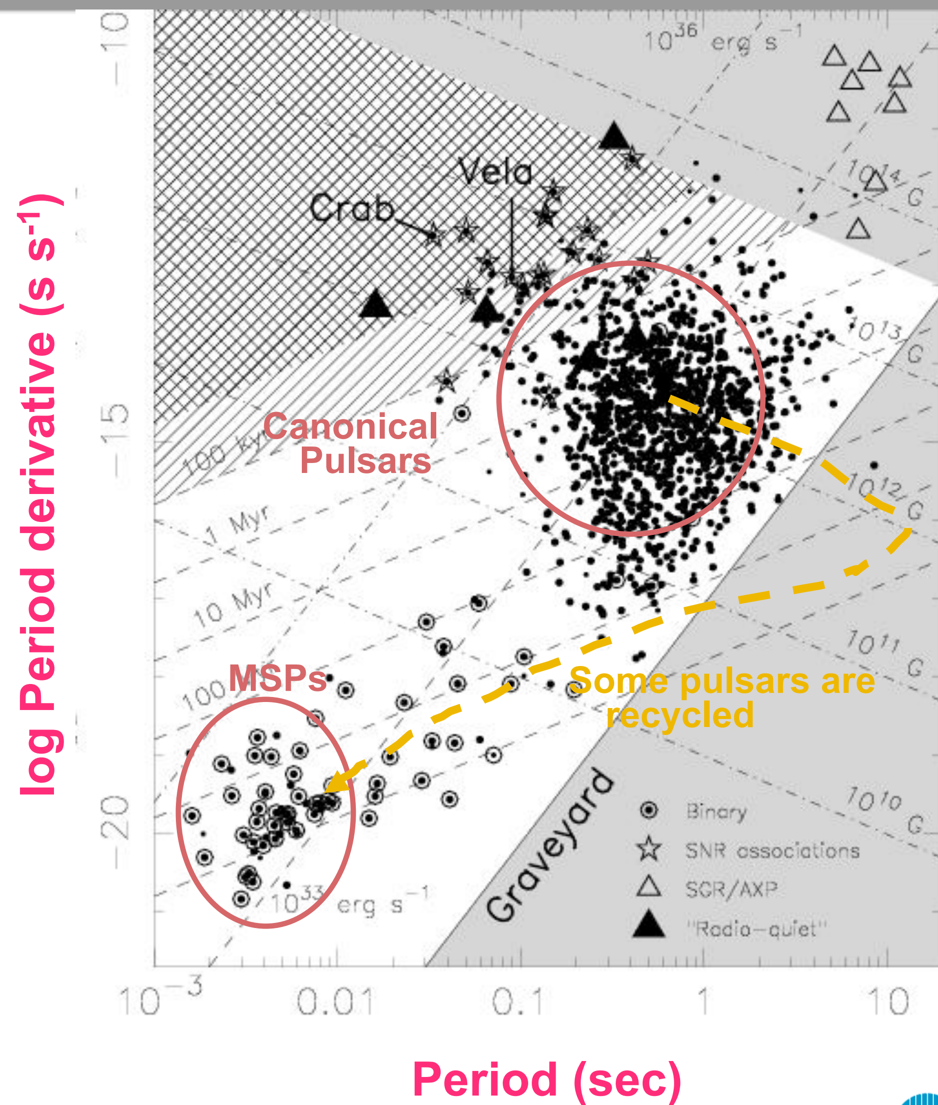
- Each pulsar has a unique fingerprint (**pulse profile**)
  - Pulsed emission averages towards a standard that is *usually* statistically identical at all observing epochs

- If the profile stays the same, we can very accurately track the rotation history of the pulsars
  - Precision pulsar timing: most powerful use of pulsars (next to CMB, the most powerful use of any form of astrophysical radiation)



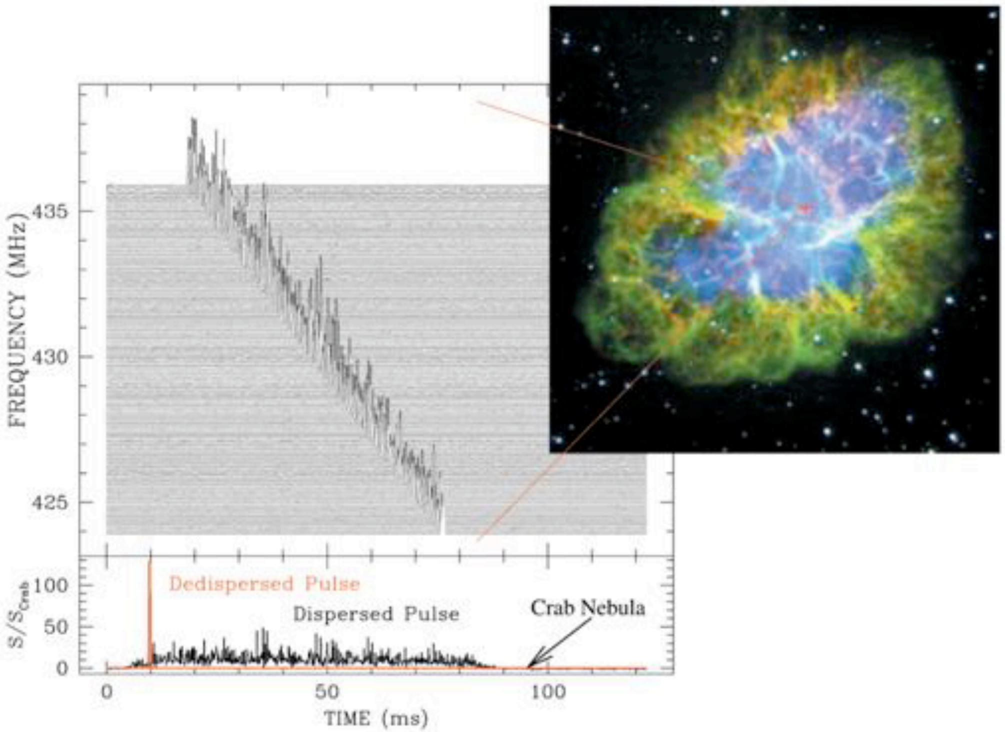
Pulsars have unique *Period and Period derivatives*

- Two fundamental observables of pulsars
  - Period
  - Period derivative
- Tells the story of pulsars
  - With a splash of observational bias
- Estimate other properties based on P and Pdot.
  - Age (10^3 – 10^9 yr)
  - Surface magnetic field strength (10^8 to10^{15} G)
  - Surface voltage potential (10^{12} V)



Pulsar radiation is ***erratic***

- Single pulses vary in shape
- Some pulsars show ultra-bright giant pulses
- Some pulsars occasionally miss pulses (nulling)
- Some pulsars only occasionally emit pulses (rotating radio transients *RRATS*)
- Bottom line: need a variety of data sets and detection tools to get a full census of pulsars



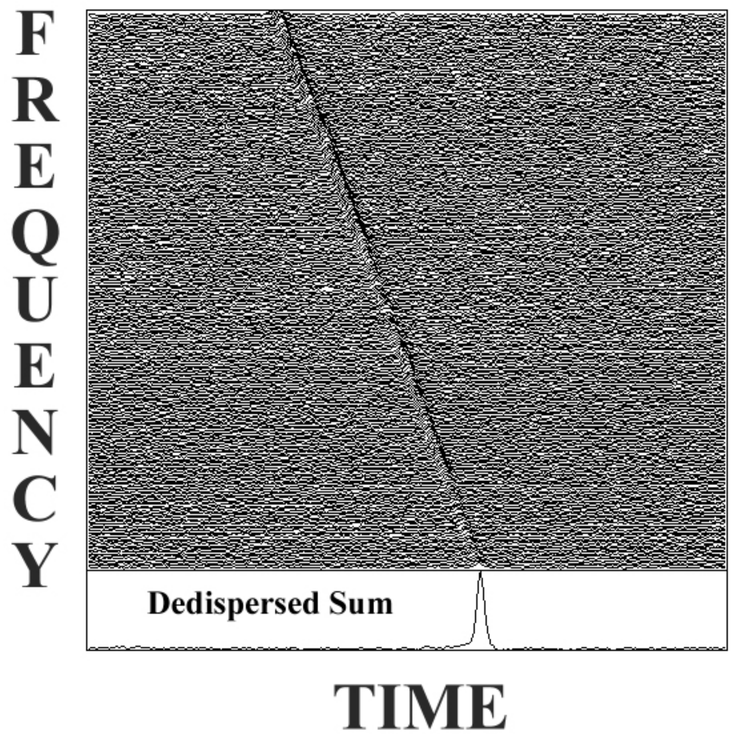
Bhat et. al. 2006

Pulsar radiation is ***dispersed***

- Warm plasma in the ISM is refractive, and the index of refraction depends on RF.
  - At higher frequencies pulsed emission arrive earlier
  - Level of dispersion depends on total column density along the line of sight (Dispersion measure DM).

- Dispersion is an excellent discriminator
  - Allows us to distinguish pulsars from RFI (radar, microwaves, guitar hero)

- Corollary: Pulsars can be used to study ISM and Galactic Structure



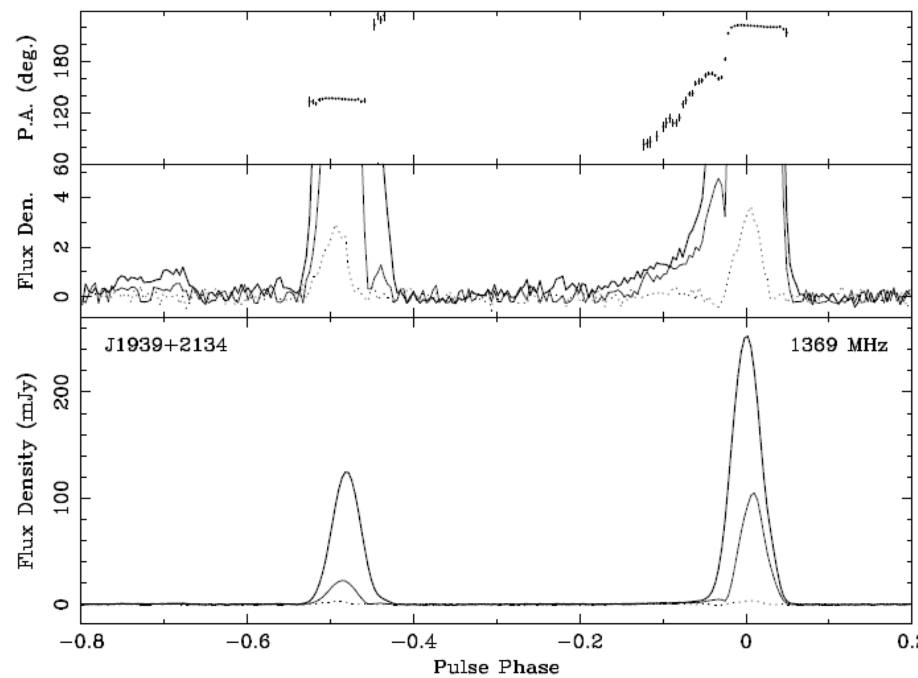
$$\mathrm{DM} = \int_0^d n_e \, dl$$

0 < DM < 1200 for known pulsars

Pulsar radiation is ***polarised***

- Origin for polarisation: High magnetic fields.
    - As pulsar rotates, the orientation of the dipole changes with respect to the line of sight
    - “Rotating Vector Model”: works well for some pulsars, but not others

- Corollary: To get a good estimate of the pulse profile, we need to have well behaved receivers (or good models of how “bad” our receiver are).



Wenming Yan et al. (2011)

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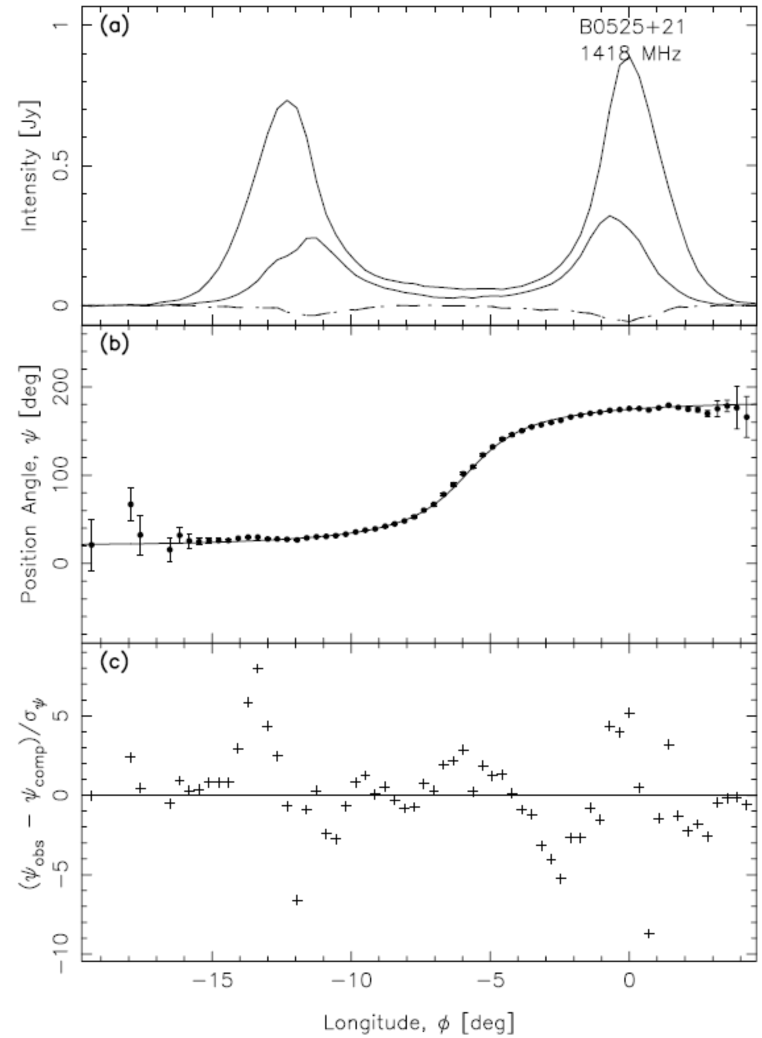
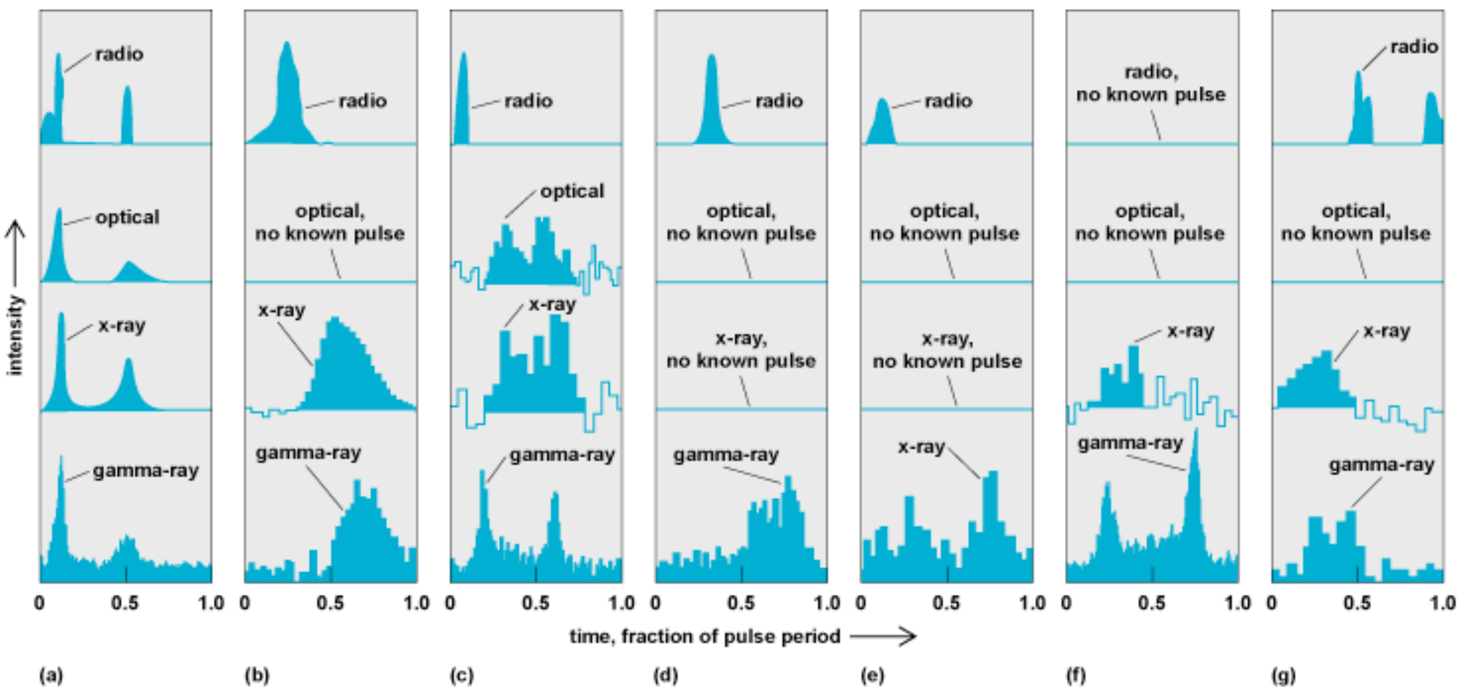


Everett & Weisberg (2001)

Pulsar Radiation is ***Multi-wavelength***

- Non-thermal emission observed across entire EM spectrum
- Some pulsars are prodigious producers of gamma-ray emission.
- Not going to talk about it more in this lecture



- ***The number of high energy pulsars has grown by a factor of 10 since the launch of the Fermi space telescope.***

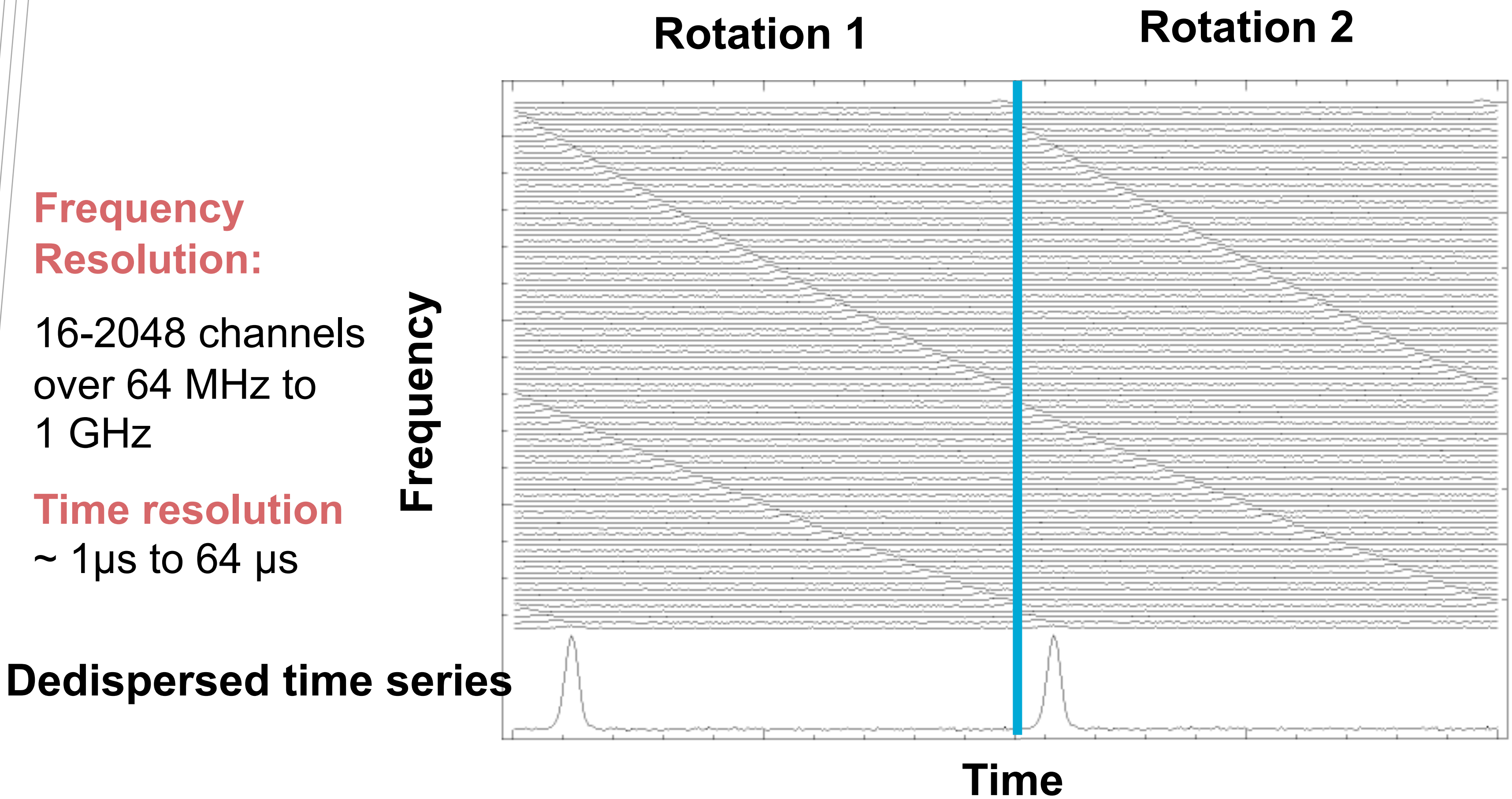
Dynamic Spectra: Pulsar Radiation as a Function of Frequency and Time

Frequency Resolution:

16-2048 channels over 64 MHz to 1 GHz

Time resolution

~ 1μs to 64 μs



It is necessary to remove the effect of dispersion

1) **Increase SNR to detect pulsar; and**
2) **Best study pulsar**

Two Methods for Dedispersion

Need to remove the effect of interstellar propagation before analysing data, e.g. *dedisperse* the data

Coherent:

- operates on the voltage proportional to the electric field accepted by the antenna, feed and receiver
- computationally intensive because it requires sampling at the rate of the total bandwidth
- Exactly removes effect of dispersion

Post-detection (incoherent):

- operates on intensity = $|\text{voltage}|^2$
- computationally less demanding
- an approximation

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Maths of the Coherent Dedispersion Technique

Dispersion delay in the time domain causes a phase perturbation of the electric field in the Fourier domain:

$$\vec{E}_{\mathrm{measured}}(\omega) = \vec{E}_{\mathrm{emitted}}(\omega)e^{ik(\omega)z}$$

Coherent dedispersion involves multiplication of Fourier amplitudes by the inverse function,

$$e^{-ik(\omega)z}$$

For the non-uniform ISM, we have

$$k(\omega)z \rightarrow \int dz\, k(\omega) \propto \omega^2\, \mathrm{DM} + \mathrm{constant}$$

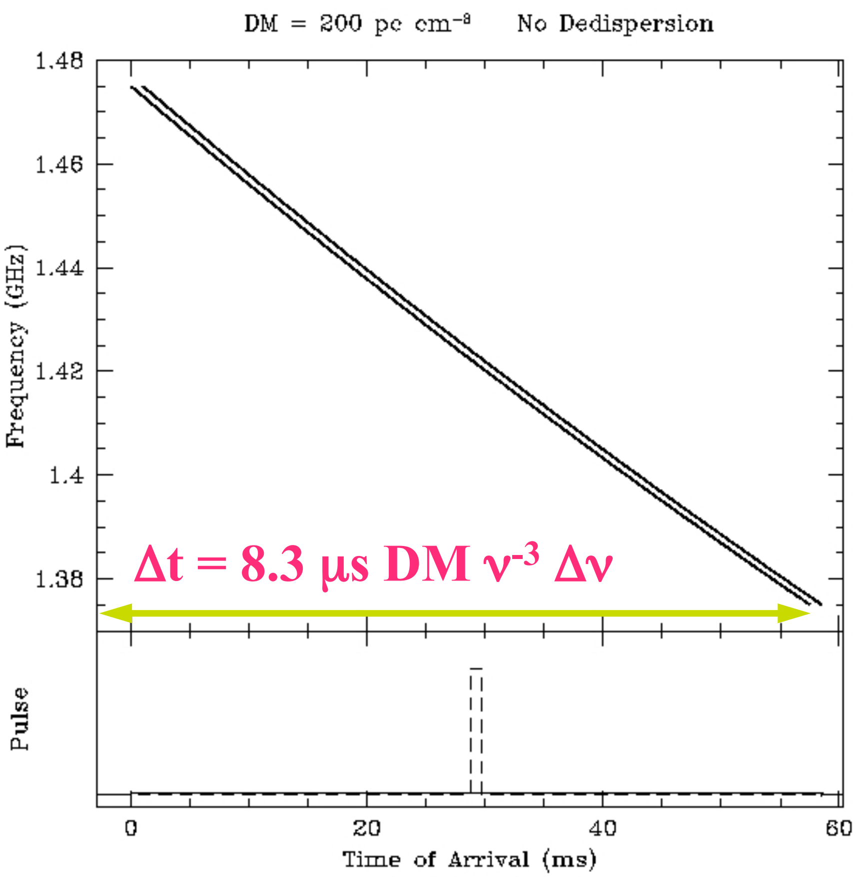
which is known to high precision for known pulsars.

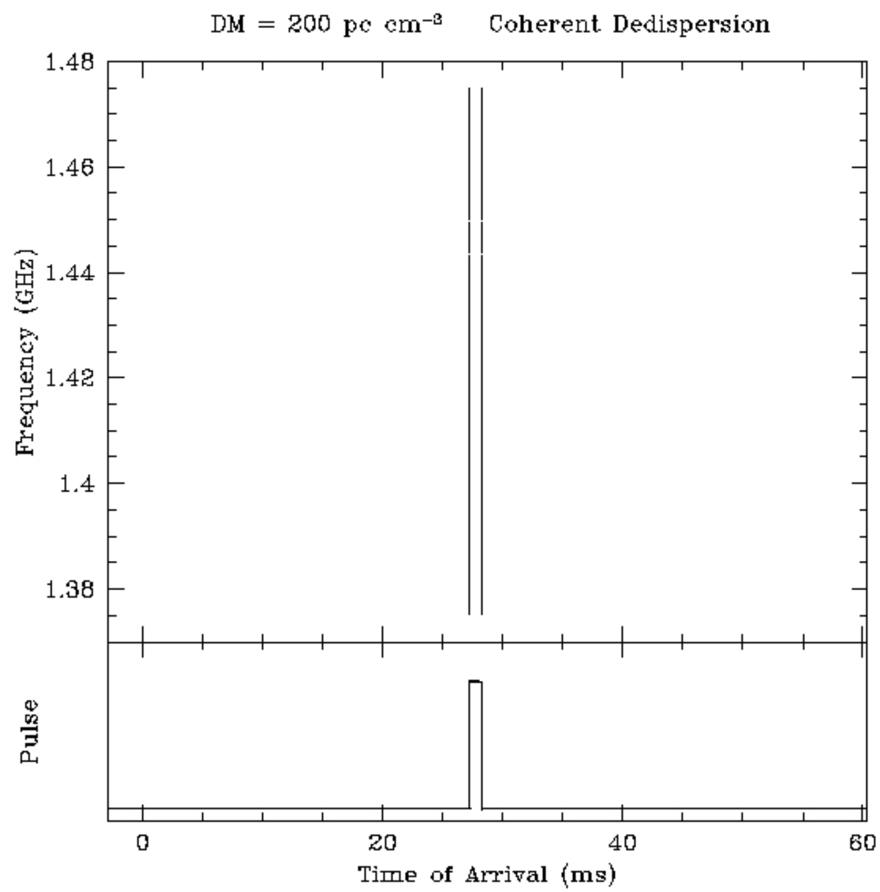
The algorithm consists of

$$\mathrm{IFFT}\{\mathrm{FFT}\,[E_{\mathrm{measured}}(t)] \times e^{-ik(\omega)z}\} \approx E_{\mathrm{emitted}}(t)$$

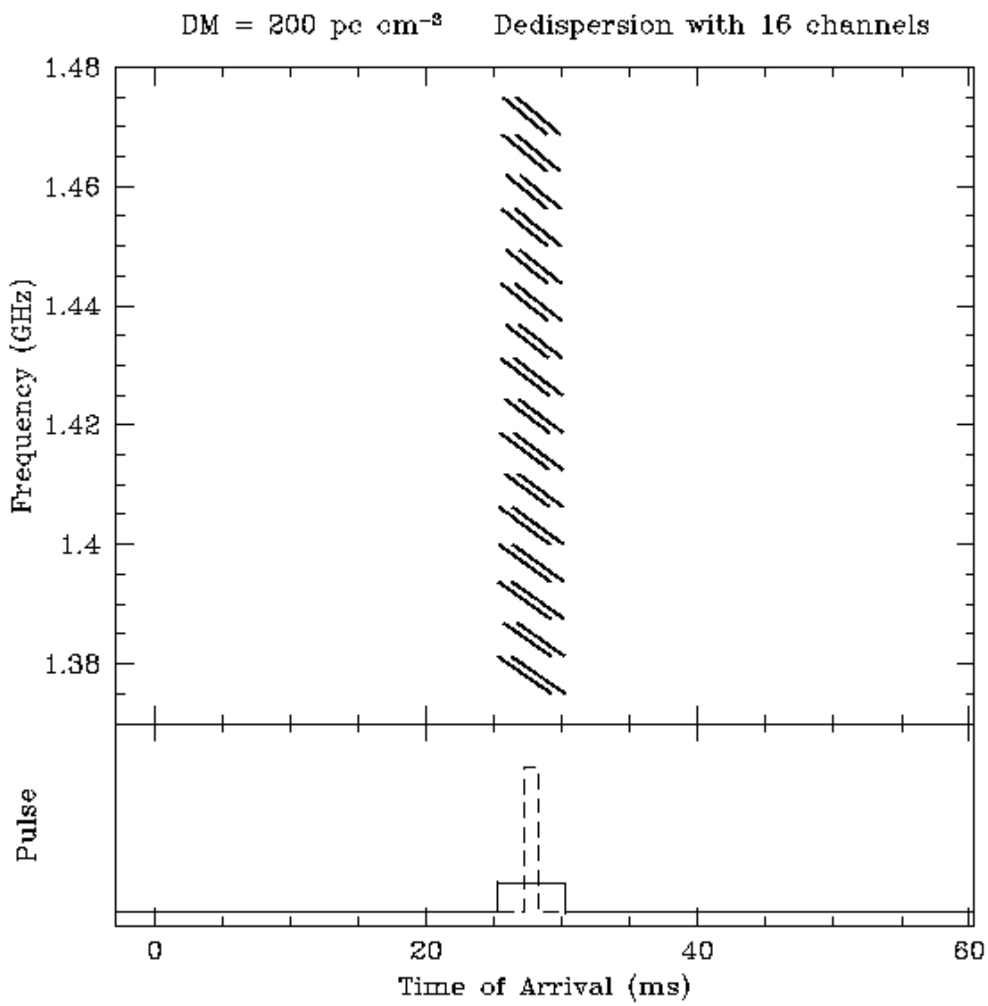
Application requires very fast sampling to achieve usable bandwidths.

Dispersed Pulse   Coherently dedispersed pulse





Post-detection Dedispersion:
Sum intensity over frequency after correcting for dispersion delay



Residual time smearing:

$$\Delta t = \left[\Delta t_{DM}^2 + (1/\Delta\nu)^2\right]^{1/2}$$

$$= \left[(a\Delta\nu)^2 + (\Delta\nu)^{-2}\right]^{-1/2}$$

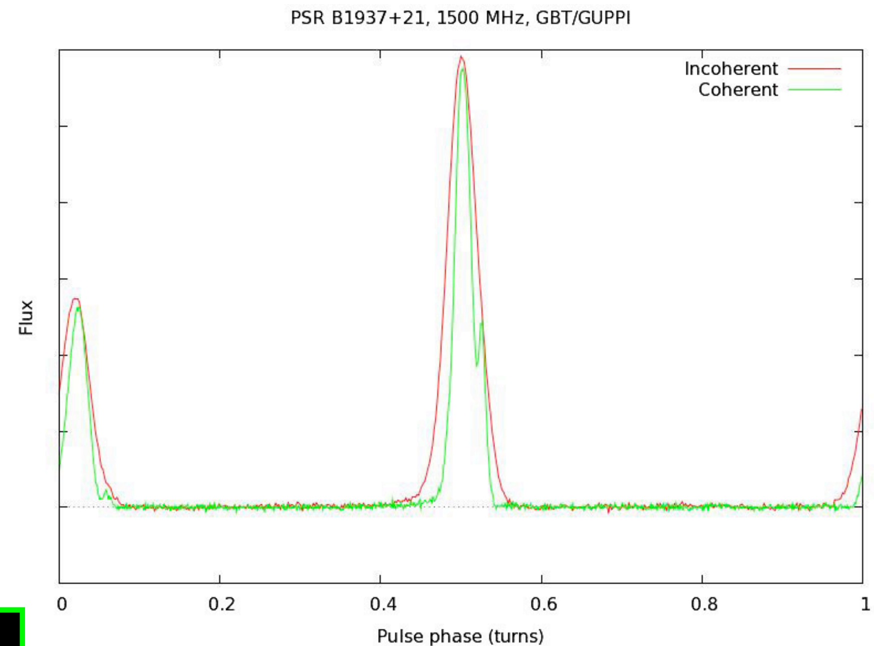
$\Longrightarrow$ minimum smearing time across a channel when

$$\Delta\nu = \left[8.3\ \mu s\, DM\nu^{-3}\right]^{-1/2}$$

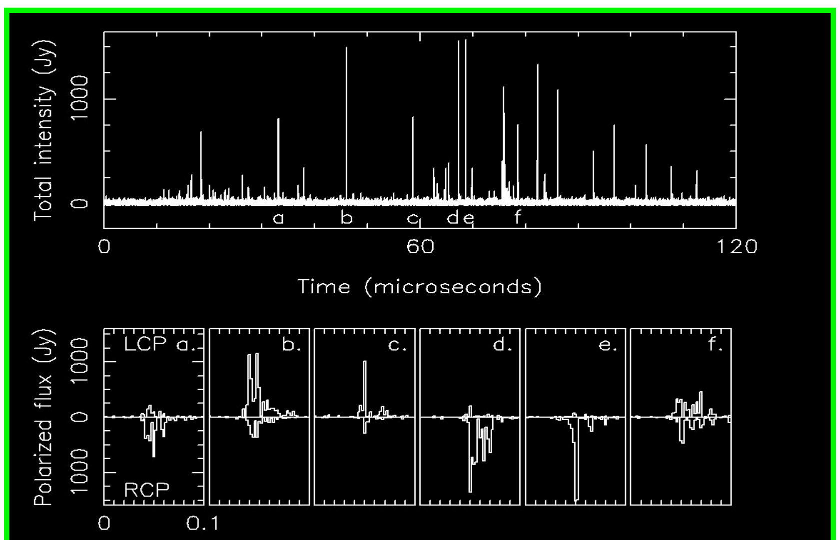
Example of different types of backends

- Examples of fast-dump spectrometers:
  - •Analogue filter banks
  - •Correlators
  - •FFT (hardware)
  - •FFT (software)
  - •Polyphase filter bank
- Examples: AFB, DFB, WAPP

- Coherent Dedispersion – done in software (on CPU or GPU)
  - •Example APSR, CASPSR, GUPPI



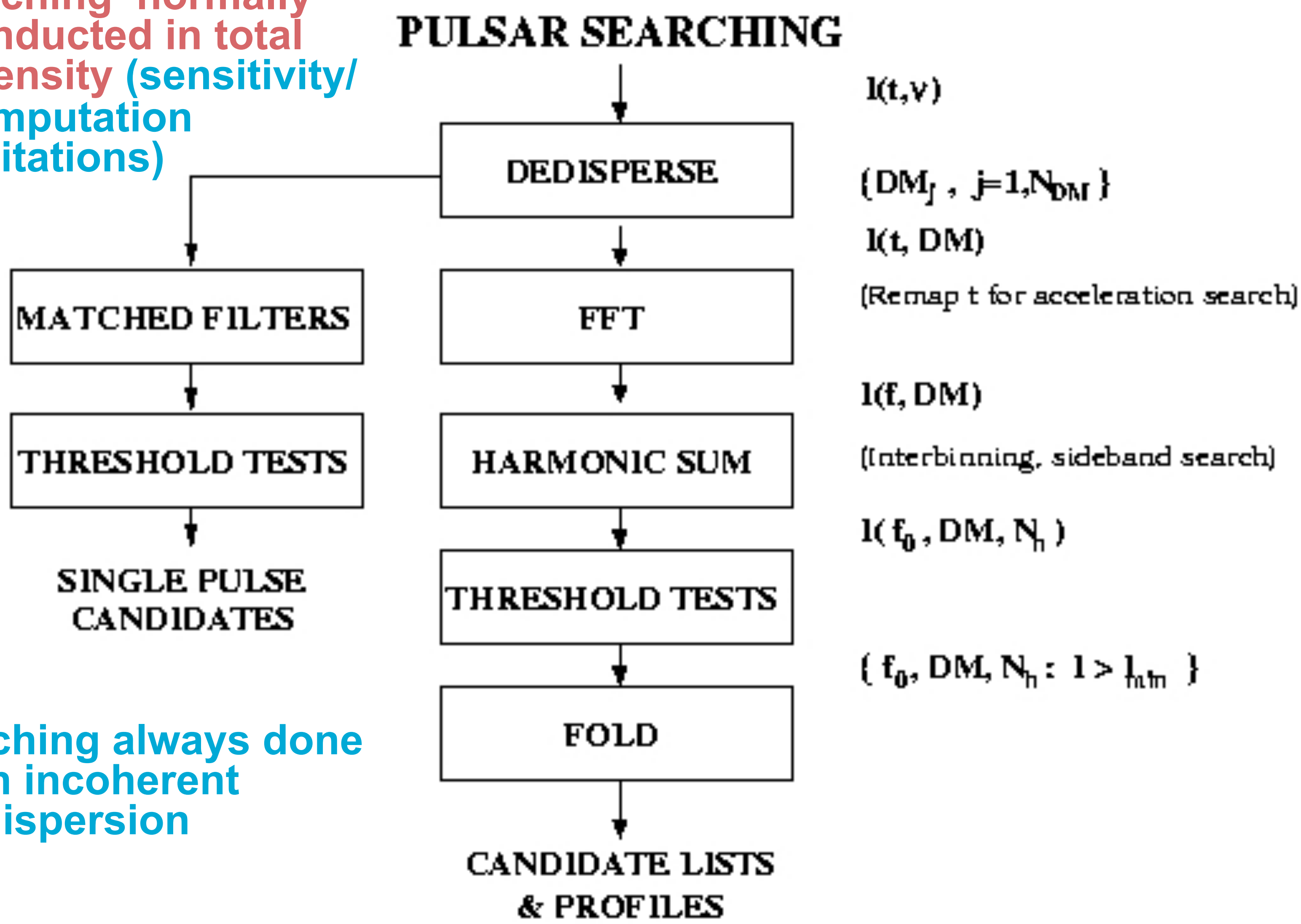
Above: Comparison of Coherent and Incoherent Dedispersion (from Paul Demorest).



Left: Giant pulses from the Crab Pulsar show structure temporally unresolved at the 2 ns level (emitting region 60cm in size)!

Searching for Pulsars: Flow Chart

Searching normally conducted in total intensity (sensitivity/ computation limitations)



Searching always done with incoherent dedispersion

What is a Harmonic Sum?

The FFT of a periodic pulse train is a series of spikes (harmonics) separated by 1/P.

To improve S/N in FFT search, sum harmonics.

The number of harmonics depends on the pulse "duty cycle" = (pulse width / P) (unknown *a priori*) $\Rightarrow$ need to use trial values of N_h:

$$h(N_h) = N_h^{-1/2} \sum_{j=1}^{N_h} \left| \frac{FFT(j)}{FFT(0)} \right|$$

Sum over harmonics

Noise and RFI conspire to yield spurious candidates.
$\therefore$ Need a high threshold.

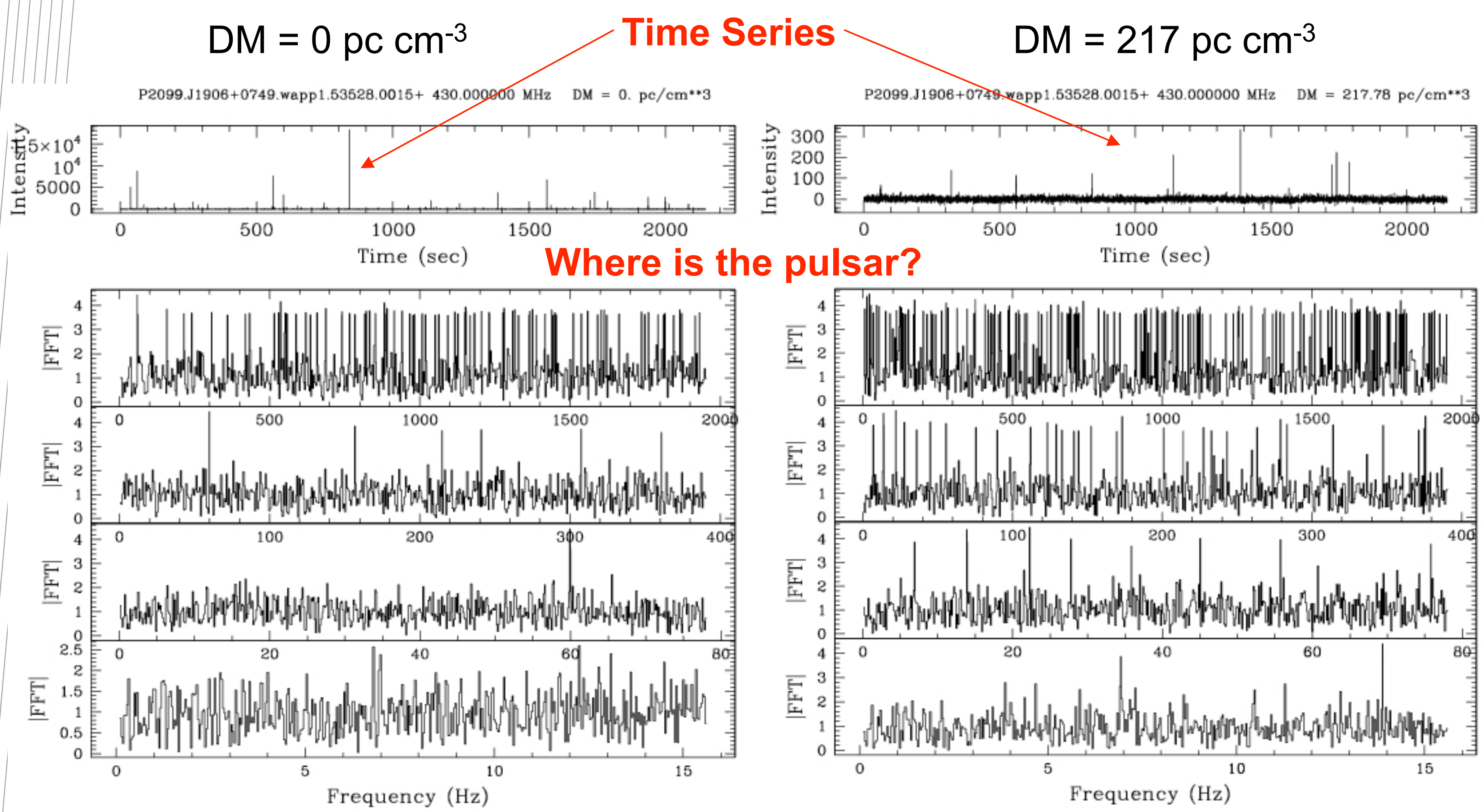
$$S_{min_1} = m \times \sigma_{radiometer}$$
$$m \approx 10$$

$$S_{min} = \frac{S_{min_1}}{h(N_h)}$$

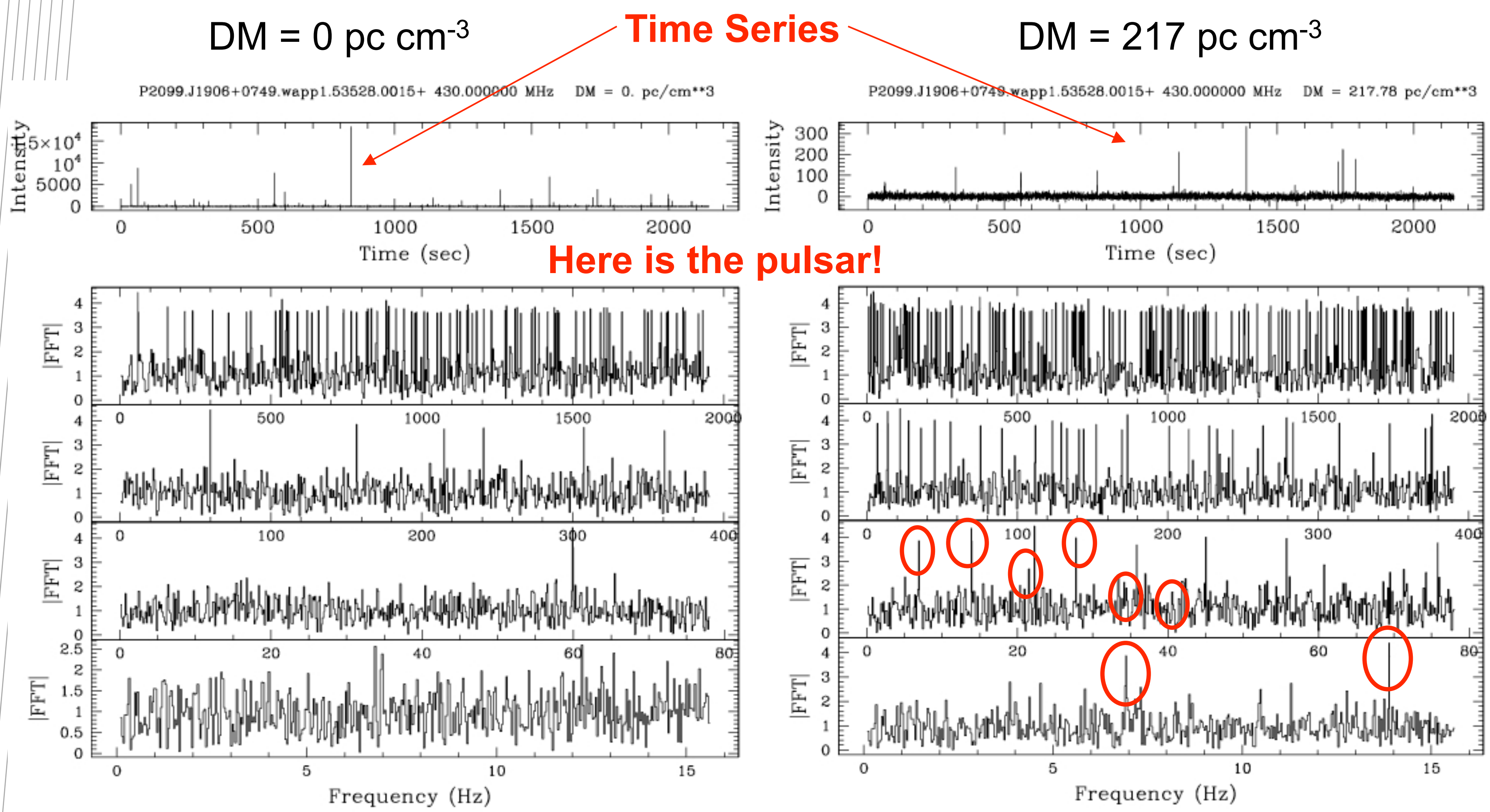
Example Time Series and Power Spectrum for a Pulsar discovery

DM = 0 pc cm^{-3}

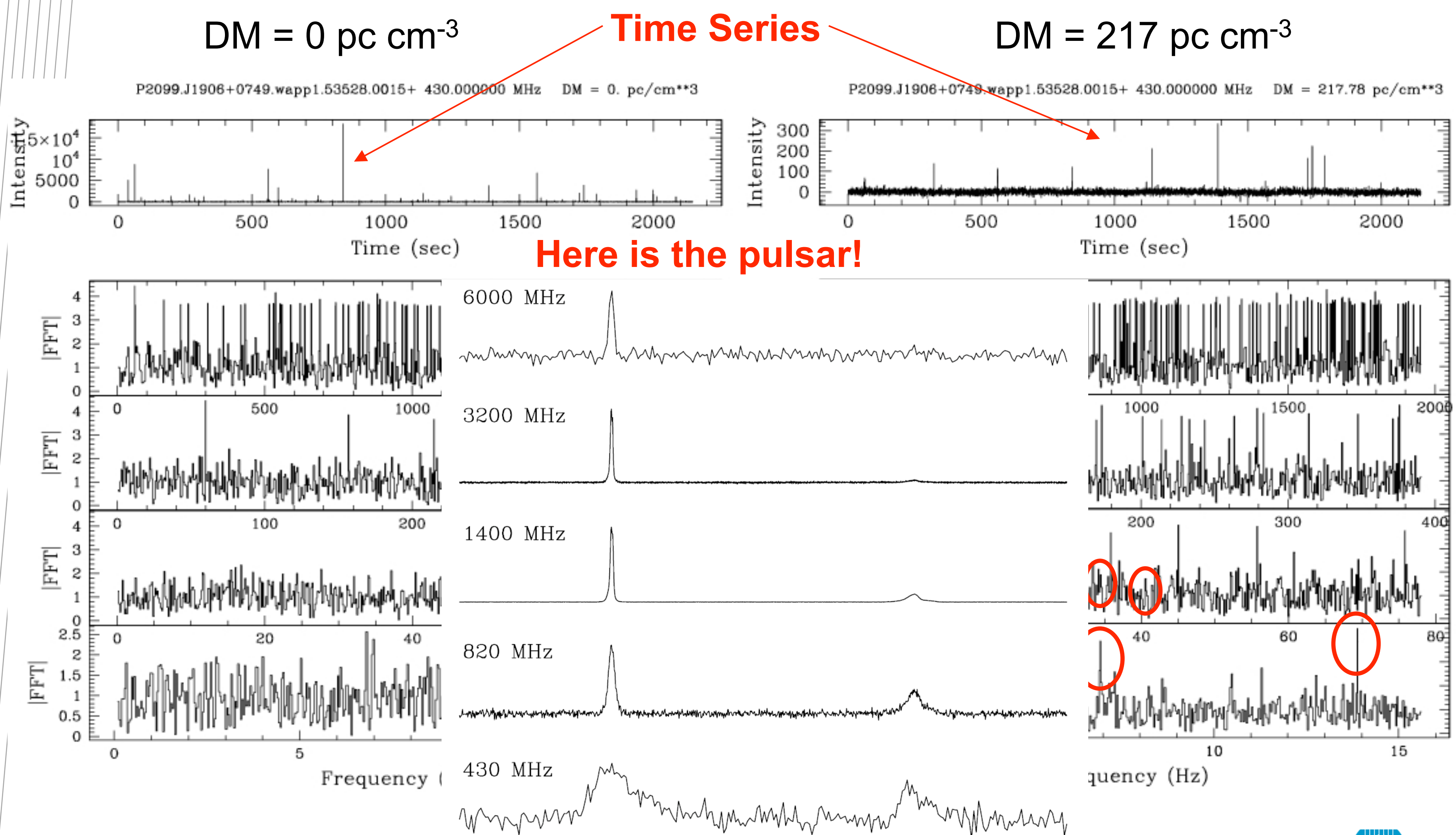
DM = 217 pc cm^{-3}



Example Time Series and Power Spectrum for a PALFA discovery



Example Time Series and Power Spectrum for a PALFA discovery



Dealing With Orbital Motion

Orbital acceleration yields a time-dependent period, potentially destroying the power of the straightforward FFT + Harmonic Search.

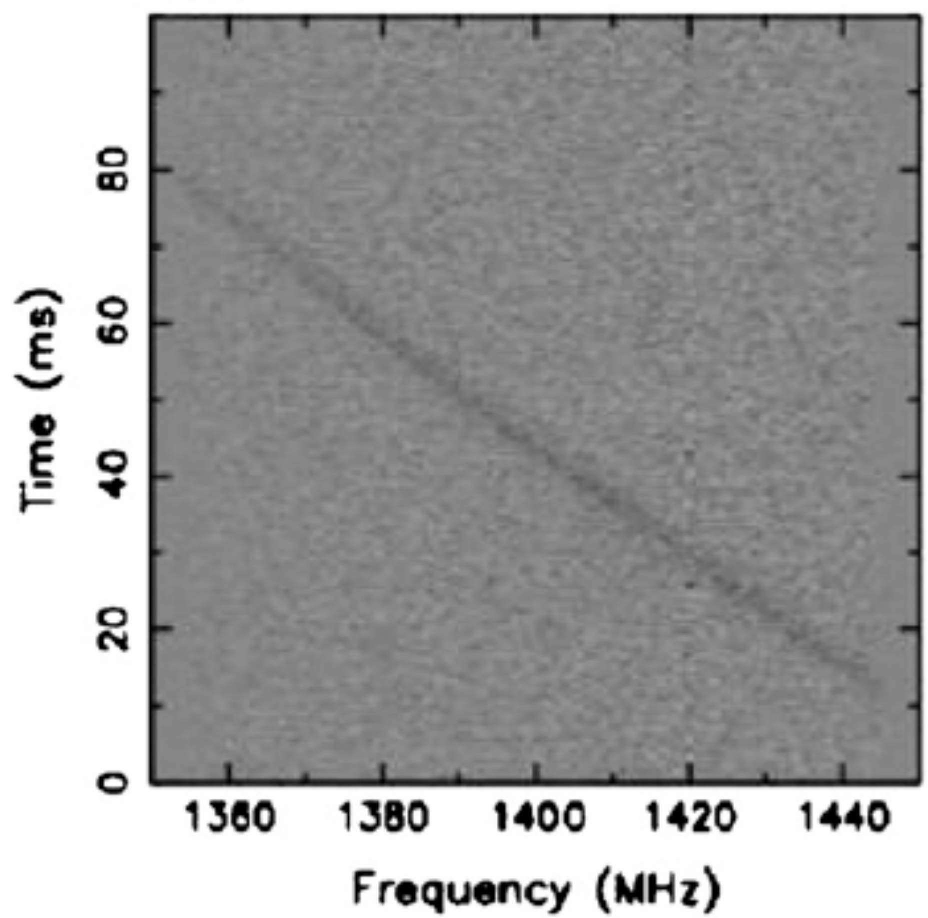
One of the holy grails of pulsar astronomy: pulsar-BH in compact binary orbits

- Long-period binaries: T = data span length << P_{orb}
    - Do nothing different
- Intermediate-period orbits: T < 0.1 P_{orb}
    - Acceleration search: compensate the time domain or match filter in the frequency domain according to an acceleration parameter
- Very short period orbits: T > P_{orb} (potentially >> P_{orb})
    - Do conventional FFT but search for orbital sidebands
    - Talk to Dan Thornton (PhD student Manchester)

Single Pulse Searches

- Use matched filter?
  - Search for box-car shaped bursts in de-dispersed time series
- Types of sources detectable in single pulse searches
  - Giant pulse emission?
  - Extragalactic bursts?
  - RRATs (rotating radio transients)
  - Pulsars that emit particularly "spiky" emission

(a)



Example of bursty emission

Single Pulse Searches

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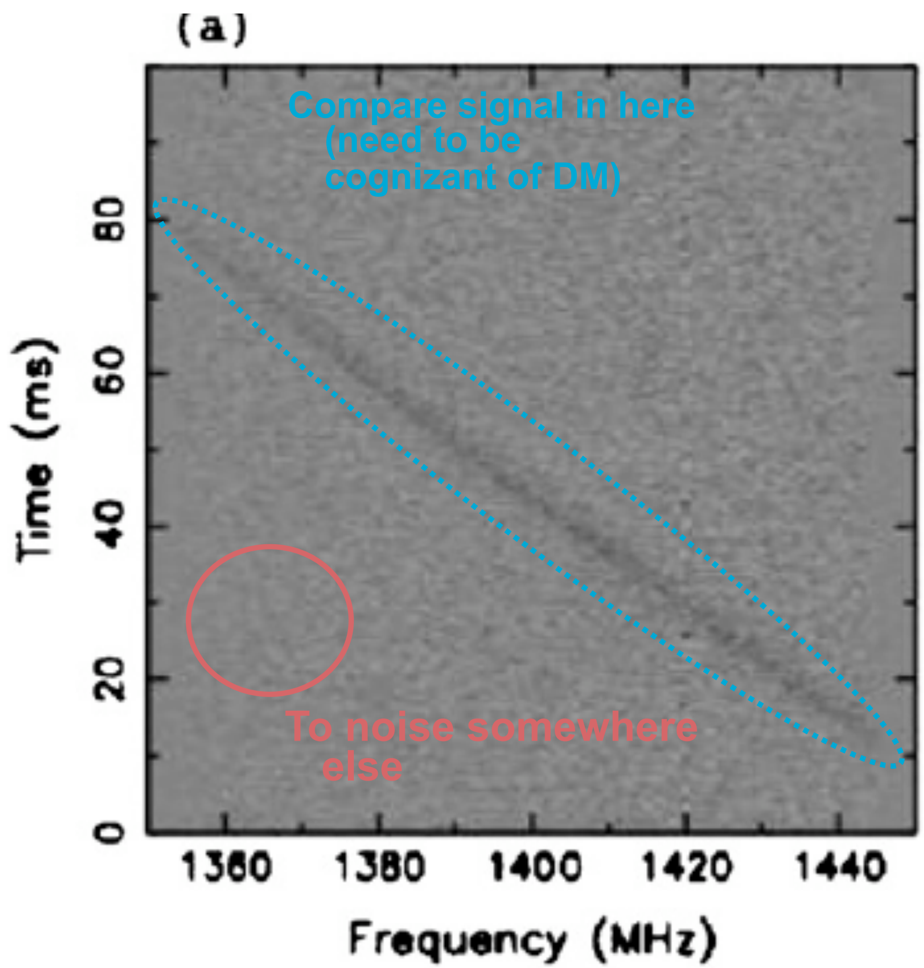
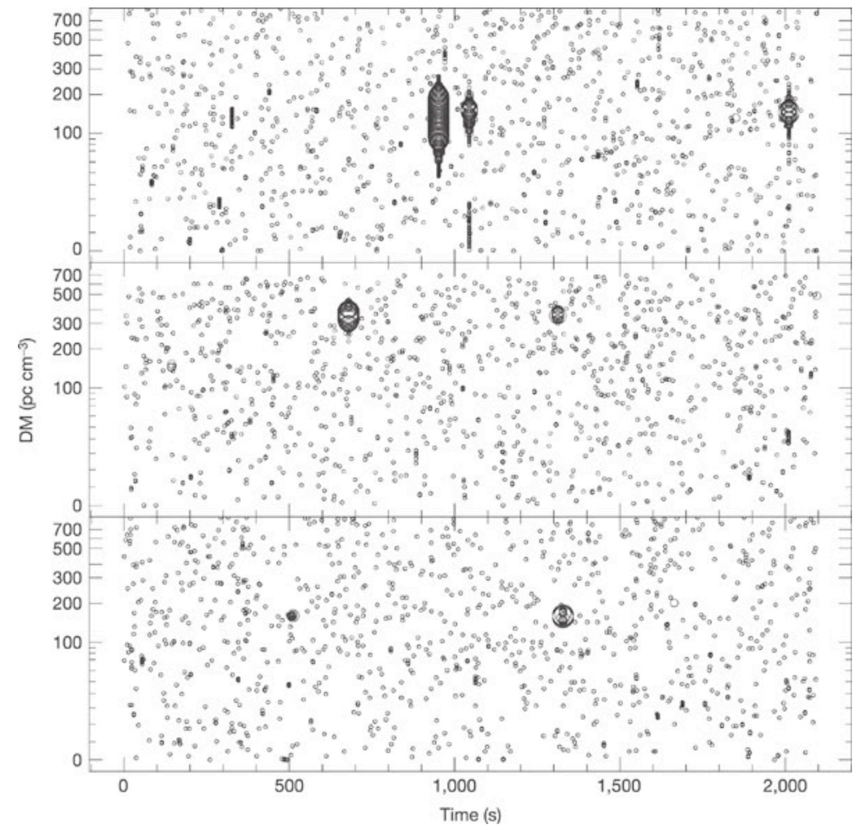


Example: Single Pulse Search

Use a matched filter template to search for dispersed pulses.

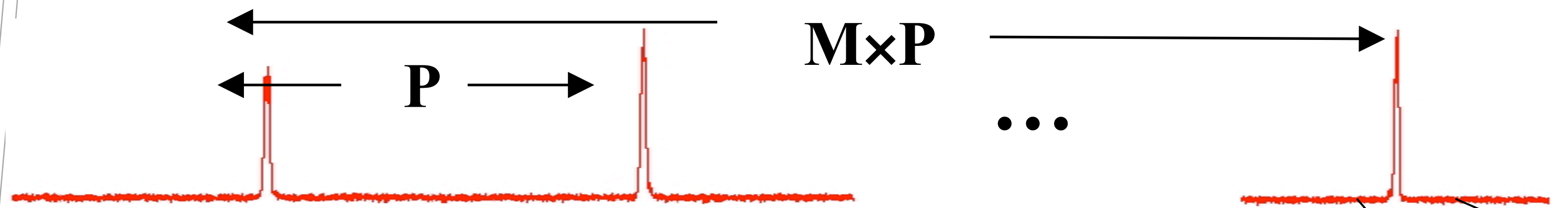
Plot event SNR versus DM

If observe multiple events at same dispersion measure (from the same position in the sky) you have confidently detected object.

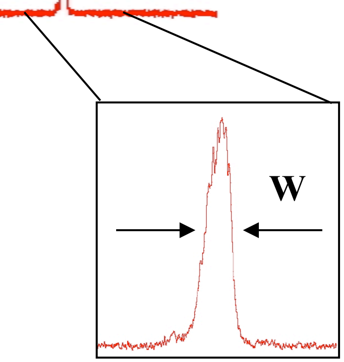


Size of circle denotes event signficance. McLaughlin et al. (2006)

Pulsar Timing: The Basics of Pulsars as Clocks



- Stack M pulses (M=1000s)
- Time-tag using template fitting



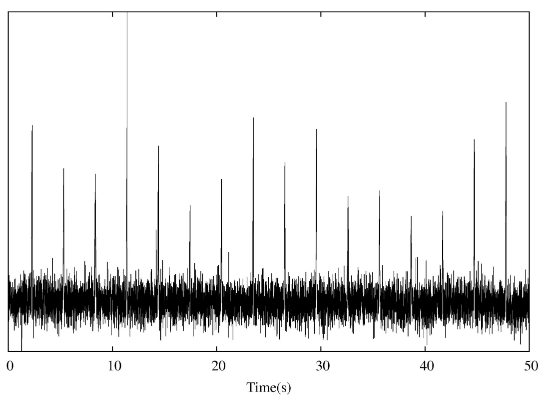
$$t_j = \mathsf{TOA} + \delta\mathsf{TOA}$$
$$\delta\mathsf{TOA} \sim \frac{W}{\mathsf{S/N}} \sim 0.1\,\mu\mathsf{s\,to\,1\,ms}$$

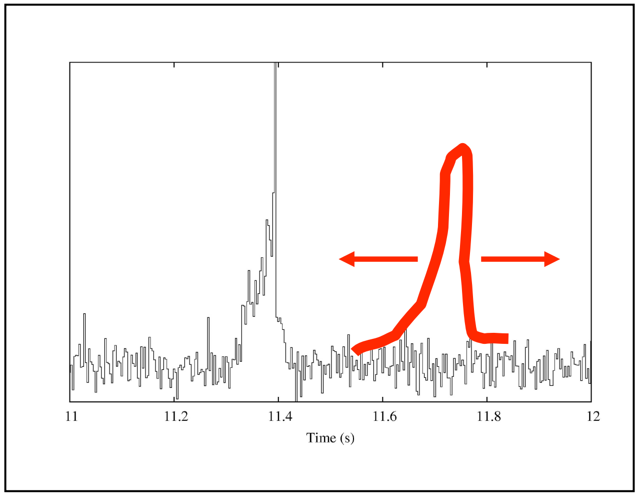
- Repeat for L epochs spanning N=T/P spin periods (T=years)
- N ~ $10^8 - 10^{10}$ cycles in one year
- Period determined to $\delta P \sim \frac{\delta TOA}{N} \sim 10^{-16}$ to 10^{-14} s

- B1937+21: **P = 0.0015578064924327±0.0000000000000004 s**
- J1909-3744: **eccentricity < 0.00000013 (Jacoby et al. 2006)**

Matched Filtering (Template Fitting)

- Optimal Estimation of Arrival Time
- Cross correlate U(t) with T(t) and find the lag of maximum correlation
    - $C_{UT}(\tau) = U(t)*T(t+\tau) = aC_{TT}(\tau - t_0) + T(t+\tau)*n(t)$
    - $C_{UT}(\tau)$ maximizes at $\tau_{max}=t_0$ <u>in the mean</u>
    - Error in τ_{max} is due solely to n(t)





Realities of Matched Filtering (Template Fitting)

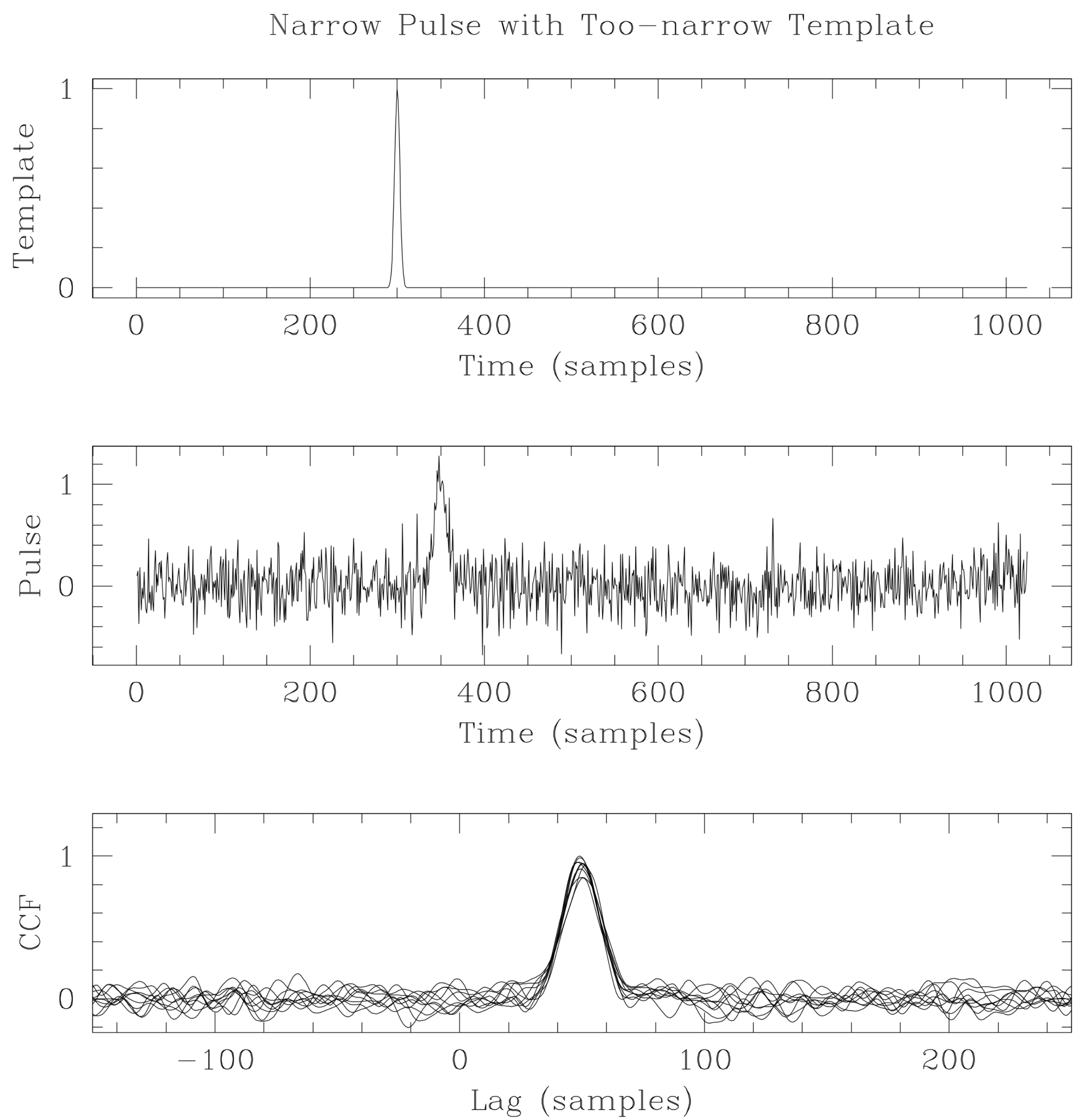
- Easier to find τ_{max} in the Fourier domain (sampling issues)
  - delay in time ←→ phase slope in Fourier transform

- If shape of U(t) ≠ shape of T(t), there are additional errors in the TOA estimate
    - this is the real situation with pulsar signals

- Examples:
  - finite number of pulses summed → errors ("self noise")
  - pulsar shapes do not converge <u>exactly</u> to the same shape

It is important to have a the correct template.

If the template is incorrect, then you will make a poor estimate of the TOA (and also have a poor estimate of the **TOA error**)



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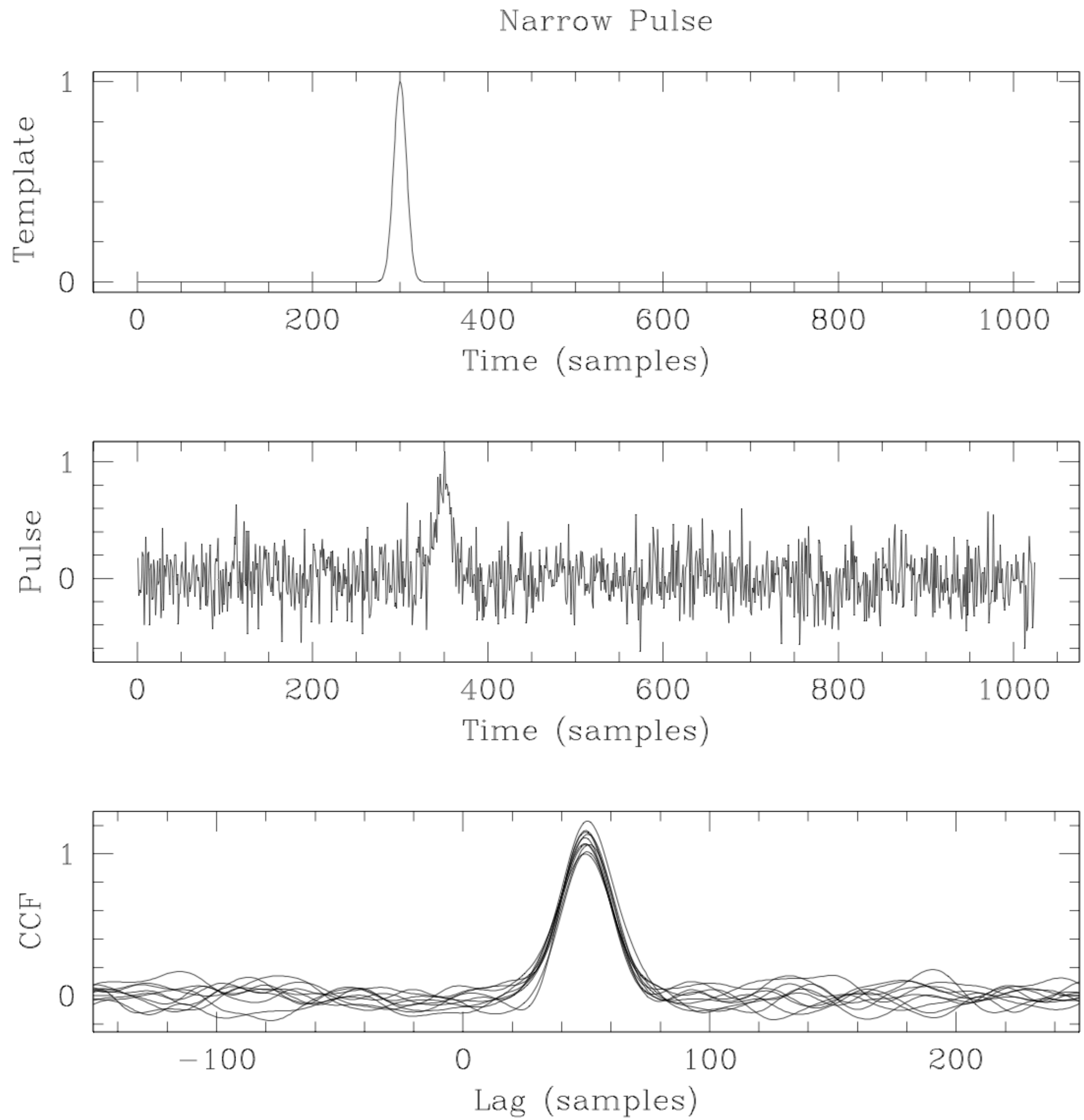

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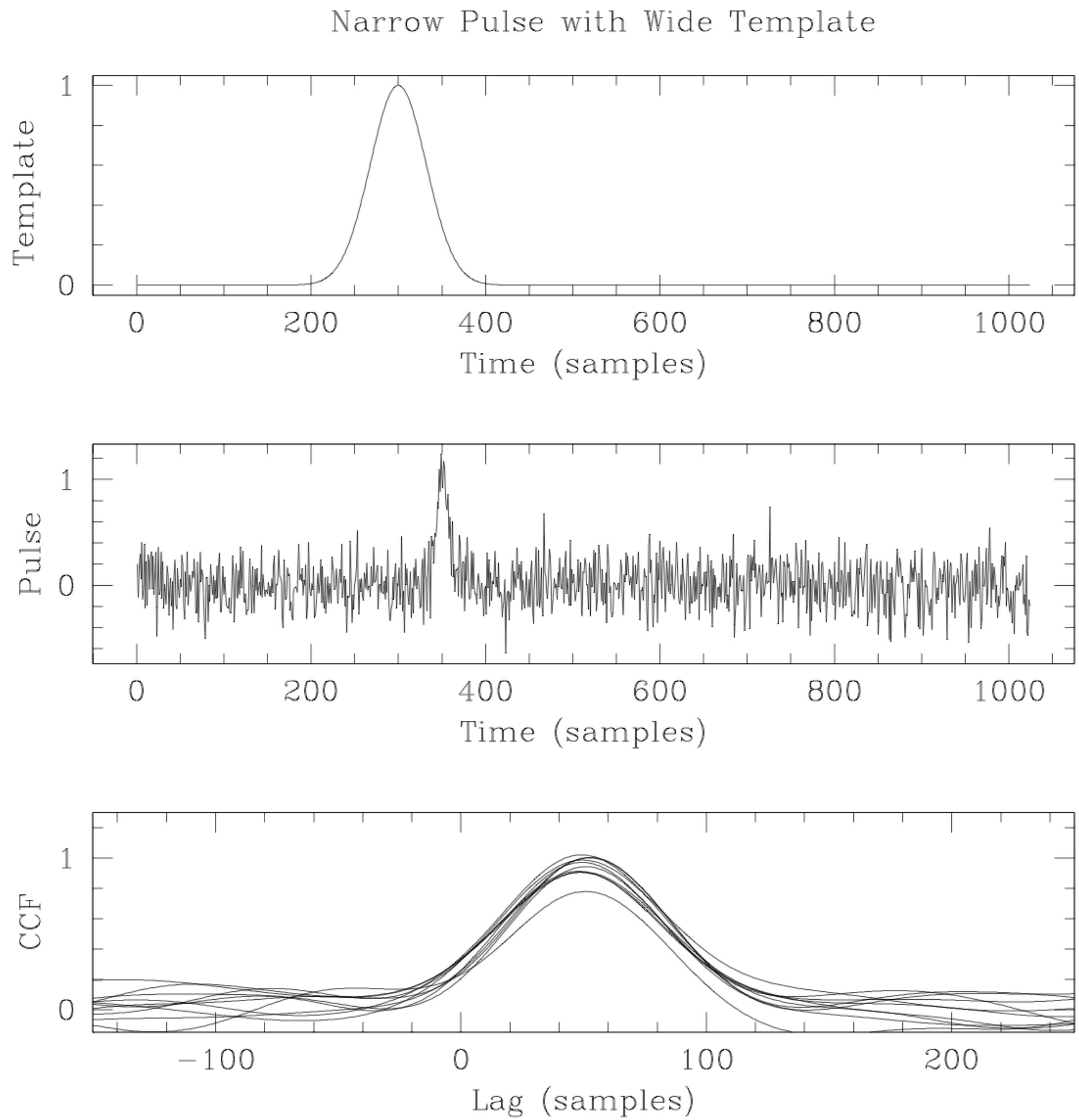
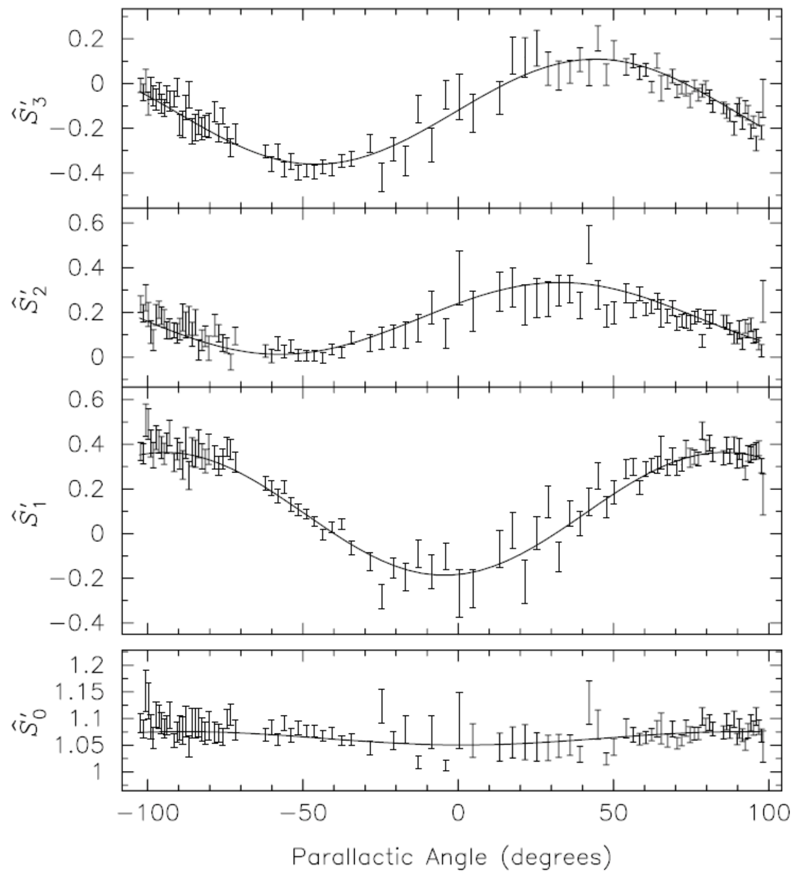


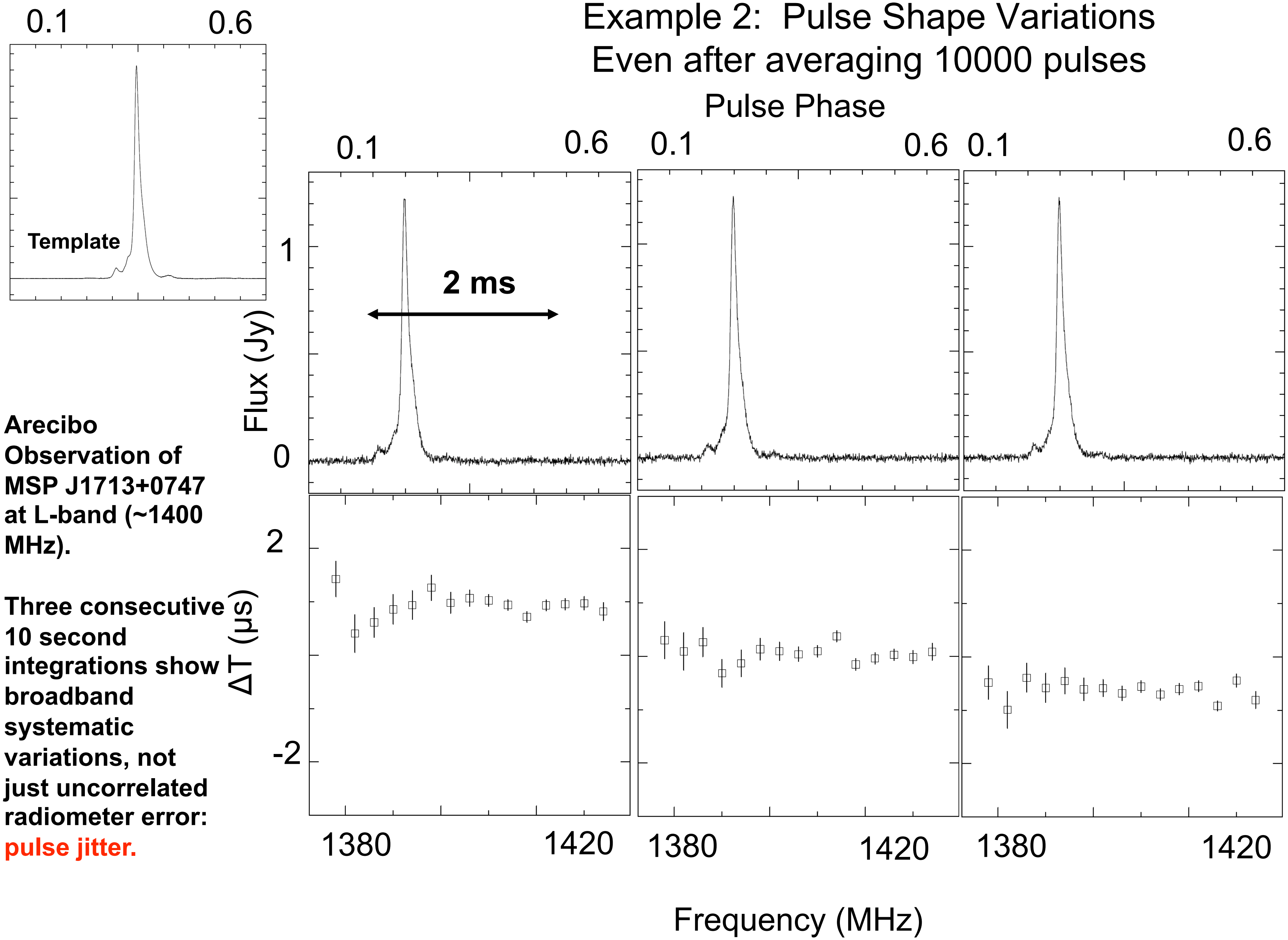
Example 1: Forming Calibrated Pulse Profile

- **Need to form Stokes parameters as a function of pulse phase**
- Calibrate for gain and phase variations between feeds
  - Inject non-polarised or polarised signal into feed
  - Observe non-polarised astronomical source to calibrate the injected signal
- Calibrate ellipticity of the feeds
  - Track polarized source as a function of parallactic angle
  - These calibration observations are done at Parkes every ~ 3-6 months (happening this week)



Observed Stokes Parameters as a Function of Parallactic Angle (van Straten 2004).

Example 2: Pulse Shape Variations
Even after averaging 10000 pulses



Arecibo Observation of MSP J1713+0747 at L-band (~1400 MHz).

Three consecutive 10 second integrations show broadband systematic variations, not just uncorrelated radiometer error: pulse jitter.

Summary to this point

- Find a pulsar
- Determine a pulse time of arrival
- Next step: time the pulsar

What influences pulsar arrival times?

t_r

$t_e = t_r - D/c^2$ — Path length

$+ DM/\nu^2$ — Plasma dispersion (ISM)

$+ \Delta_{R\odot} + \Delta_{E\odot} + \Delta_{S\odot}$ — Solar system (Roemer, Einstein, Shapiro)

$- \Delta_R - \Delta_E - \Delta_S$ — Binary pulsar (R,E,S delays)

$+ \delta TOA_{ISM}$ — ISM scattering fluctuations

$+ \delta TOA_{\text{orbit noise}}$ — Orbital perturbations

$+ \delta TOA_{\text{spin noise}}$ — Intrinsic spin (torque) noise

$+ \delta TOA_{\text{grav. waves}}$ — Gravitational wave backgrounds

$+ \ldots$

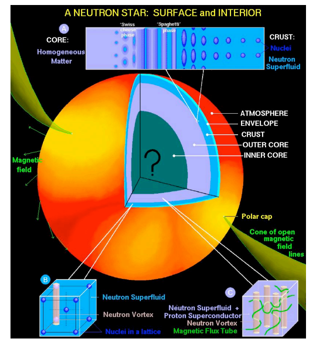
What influences pulse arrival times?

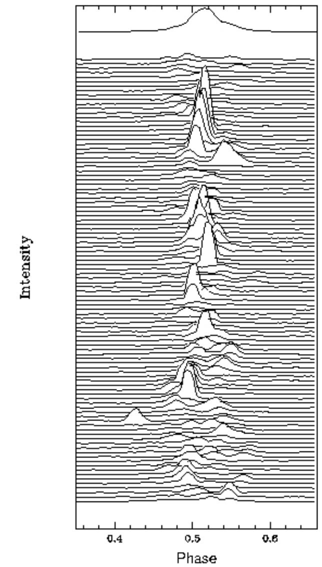
- Pulsar spindown
- ***Stochastic spindown variations***
- **Intrinsic variation in shape and/ or phase of emitted pulse (jitter)**
- **Reflex Motion from companions**
- ***Gravitational Waves***
- Pulsar position, proper motion, distance
- ***Warm electrons in the ISM***
- Solar system
  - Mass of planets (Champion et al. 2010)
  - Location of solar system barycentre

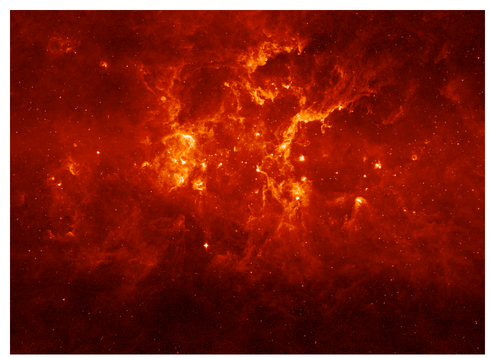
Pulsar

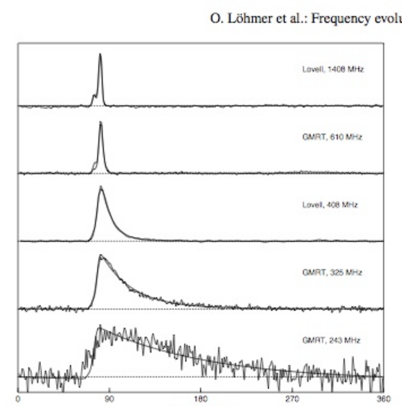
Earth

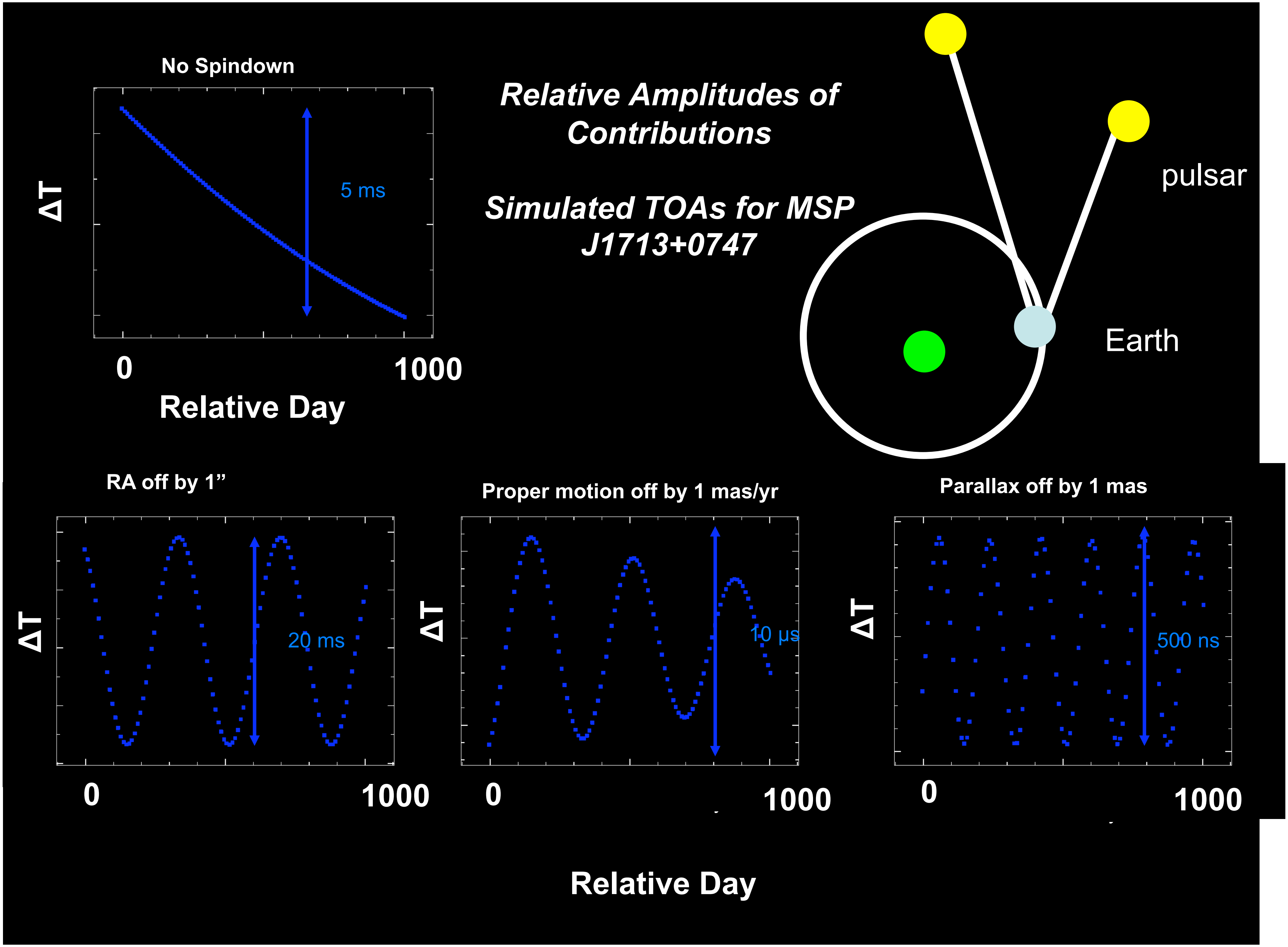
Goal: including as many of the perturbations as possible in timing model.



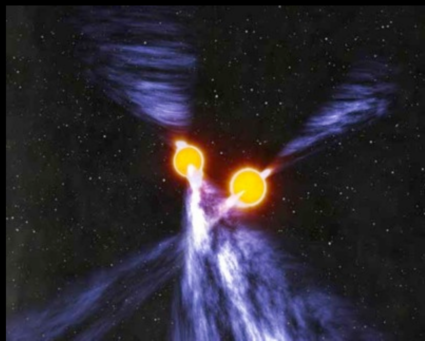






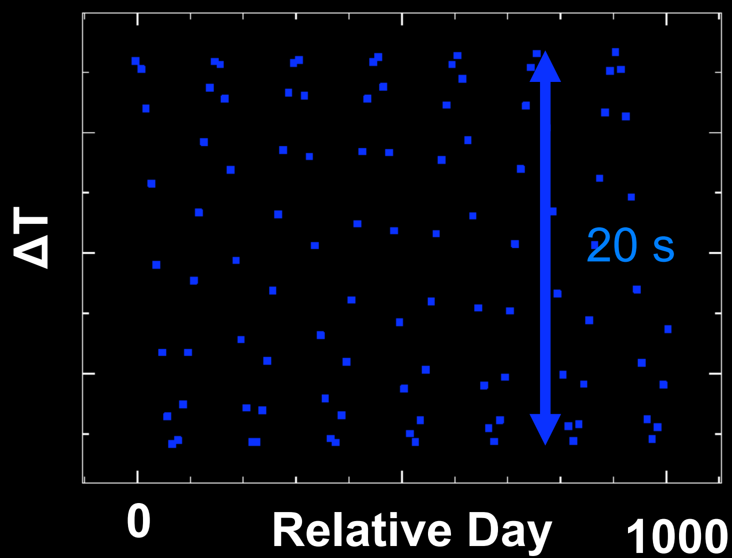


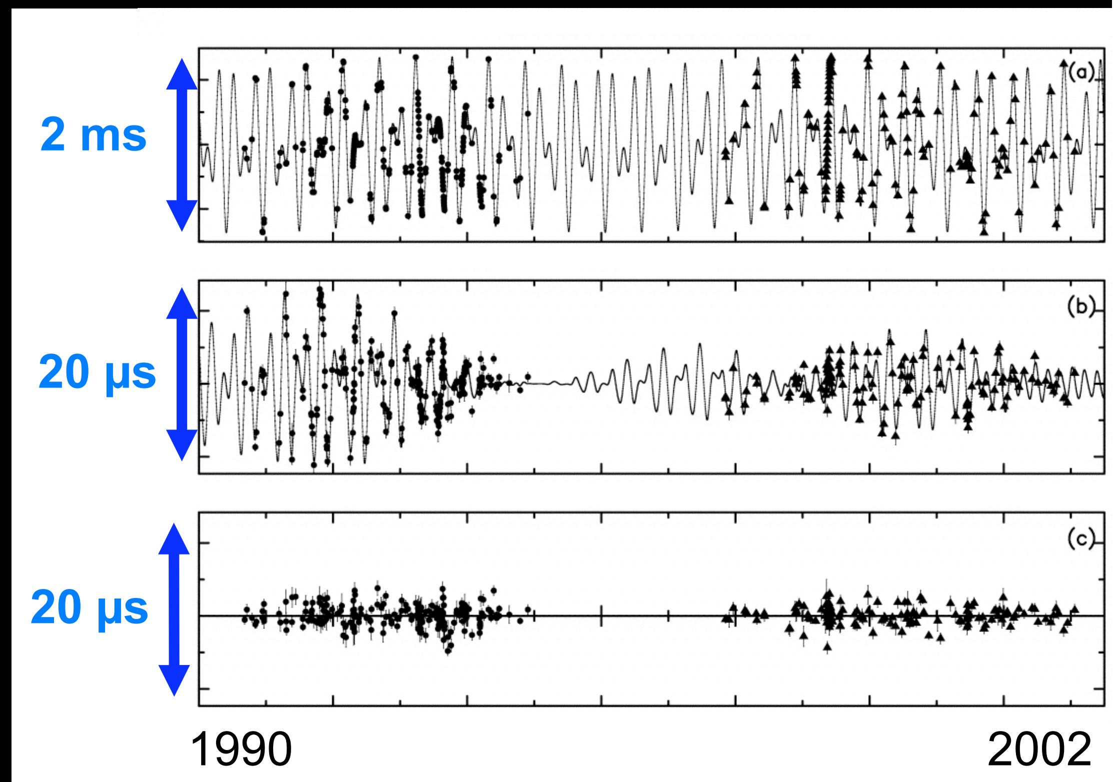
Relative Amplitudes of Contributions
Simulated TOAs for MSP J1713+0747
No Spindown
ΔT
5 ms
0
1000
Relative Day
pulsar
Earth
RA off by 1”
20 ms
Proper motion off by 1 mas/yr
10 μs
Parallax off by 1 mas
500 ns
0
1000
Relative Day



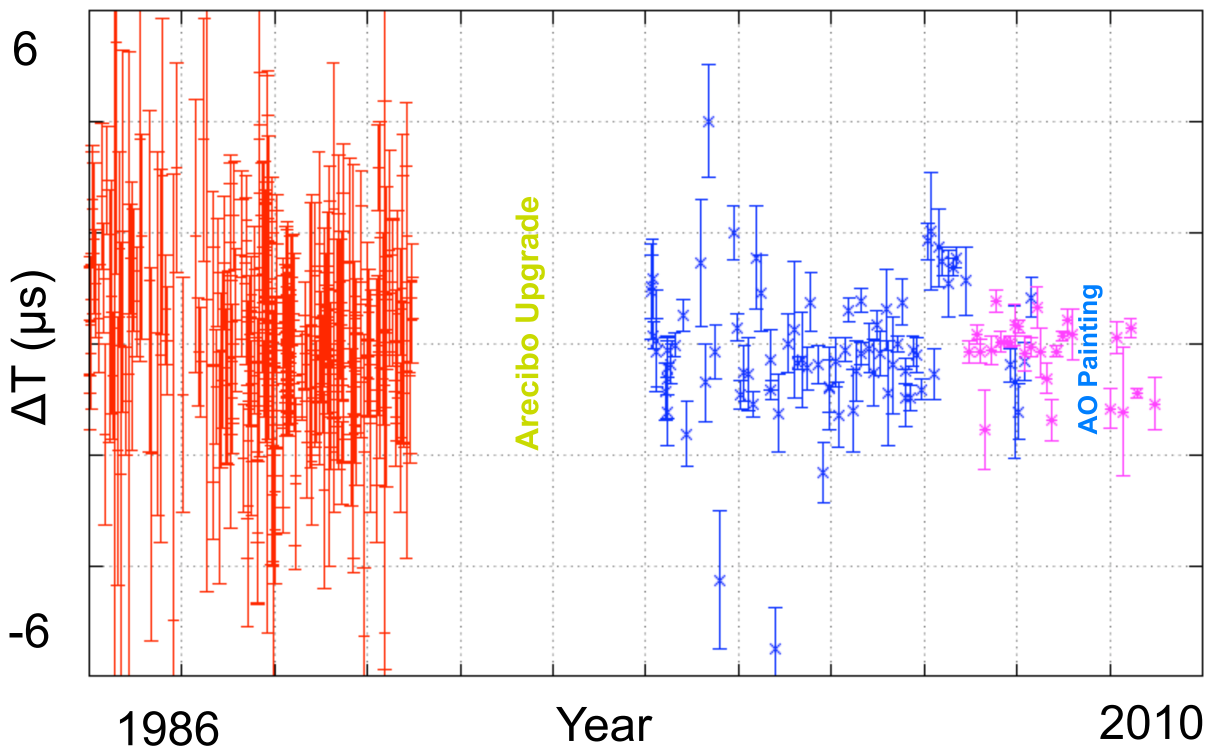
Konacki & Wolszczan (2004): Three planets around MSP B1257+12: 4.3 M_{Earth}, 3.9 M_{Earth}, and 0.02 M_{Earth}

Massive (white dwarf) companion



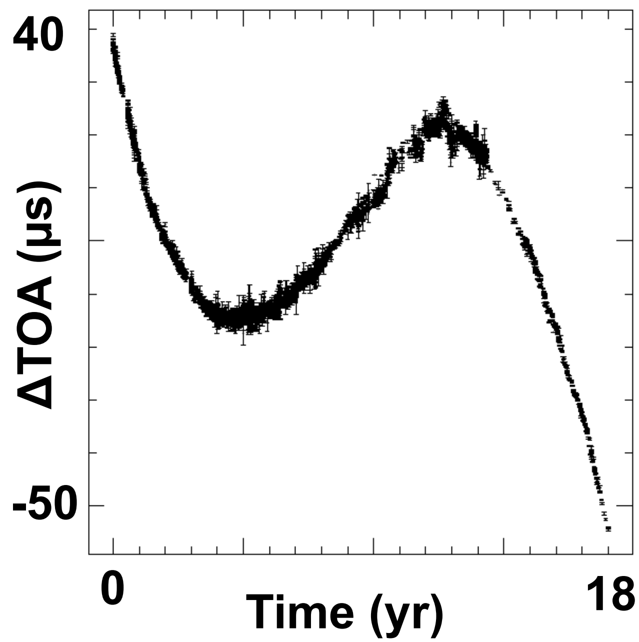


Example: What pulsar residuals ought to look like: PSR B1855+09



The Residuals are quite white! (Time series from D. Nice)

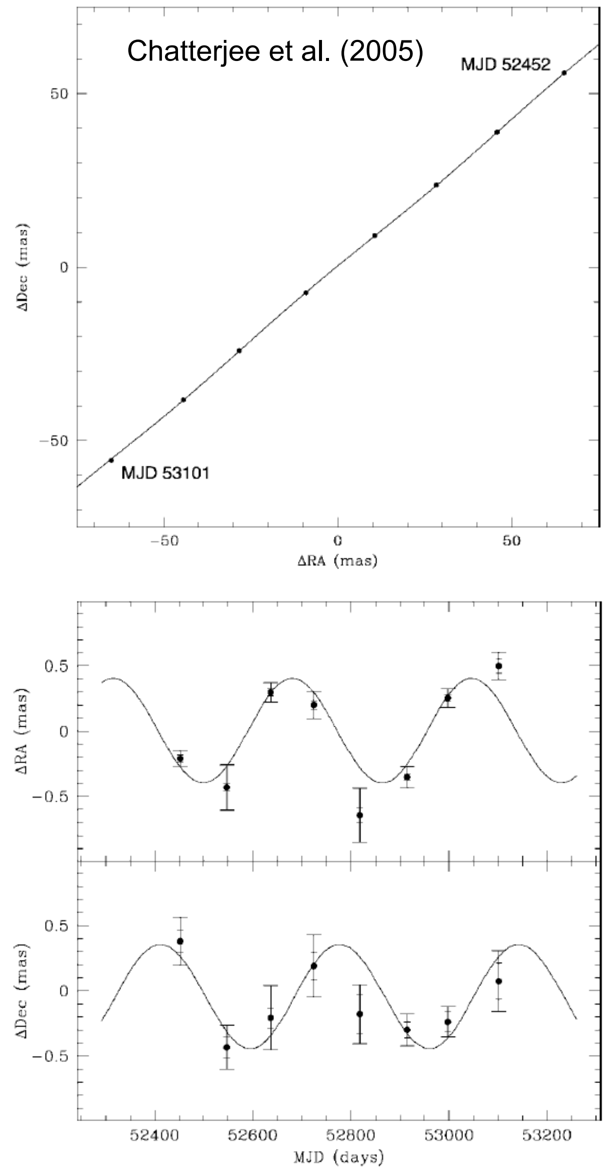
Example: What Residuals from Most Pulsars Look Like



CSIRO

Other types of Pulsar Observations

- VLBI: parallax, proper motion
  - Pulsar distance:
    - NS Population model
    - Luminosity (particularly for high energy emission)
    - Constrain Galactic electron density model/ Galactic structure
  - Pulsar velocity: High velocity some > 1000 km/s (escape the Galaxy)
    - Physics of supernvova explosions
- Synthesis imaging: Pulsar environment / Pulsar wind nebulae (PWN)
  - Interactions between pulsar wind and the ISM produce synchrotron emission



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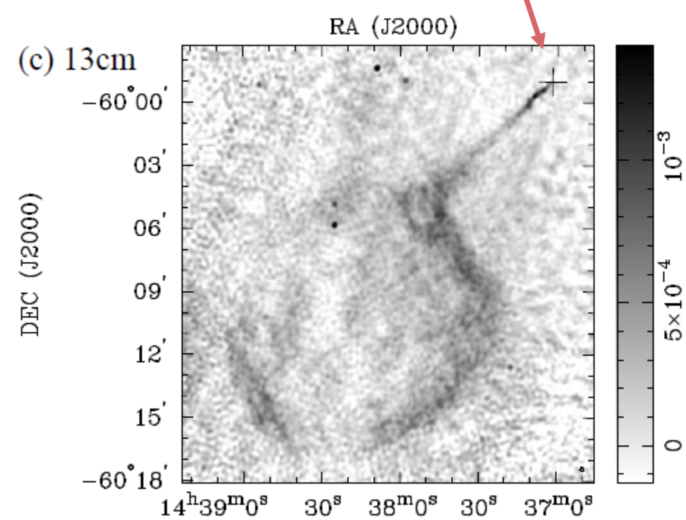
Pulsar shooting out of SNR!



Ng et al. (2011)

Summary

- Unique radio instrumentation is required to observed pulsars.

- For searching, incoherently dedispersed time series are searched for periodic signals and bursts using an arsenal of techniques.

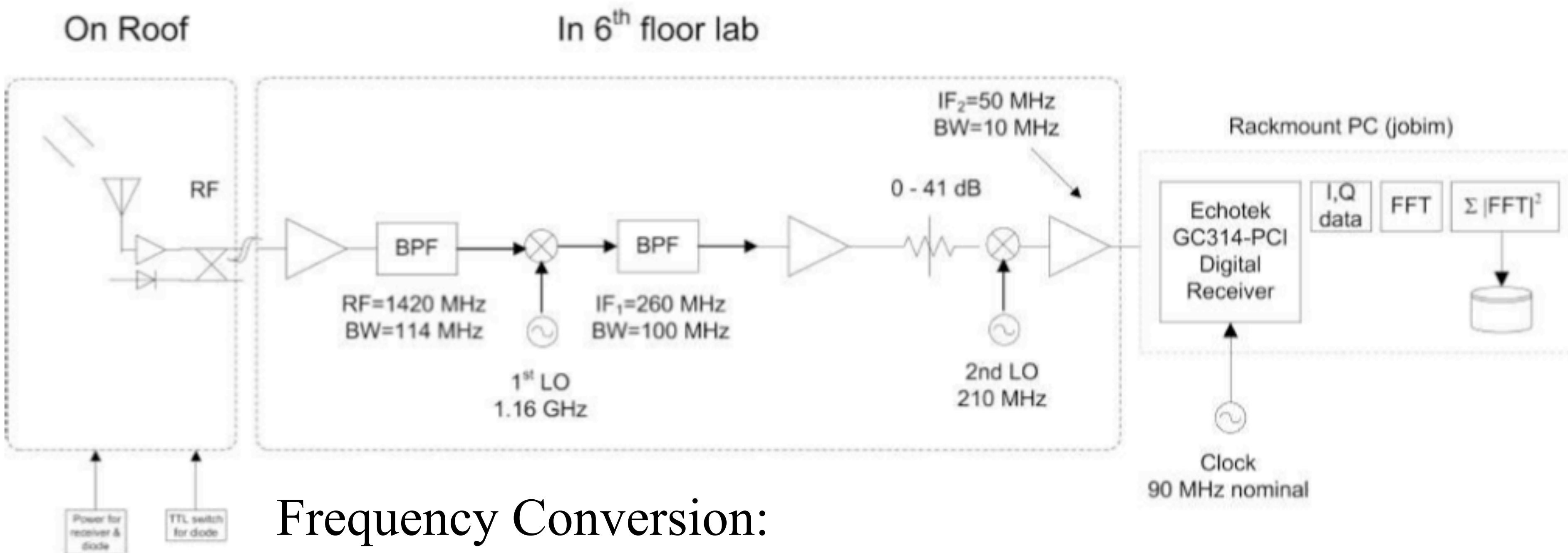
- For timing observations, incoherently or coherently dedispersed time series are folded and calibrated to produce average pulse profiles that are correlated with a template to obtain a time of arrival that is used in timing analysis.

- Thank you!

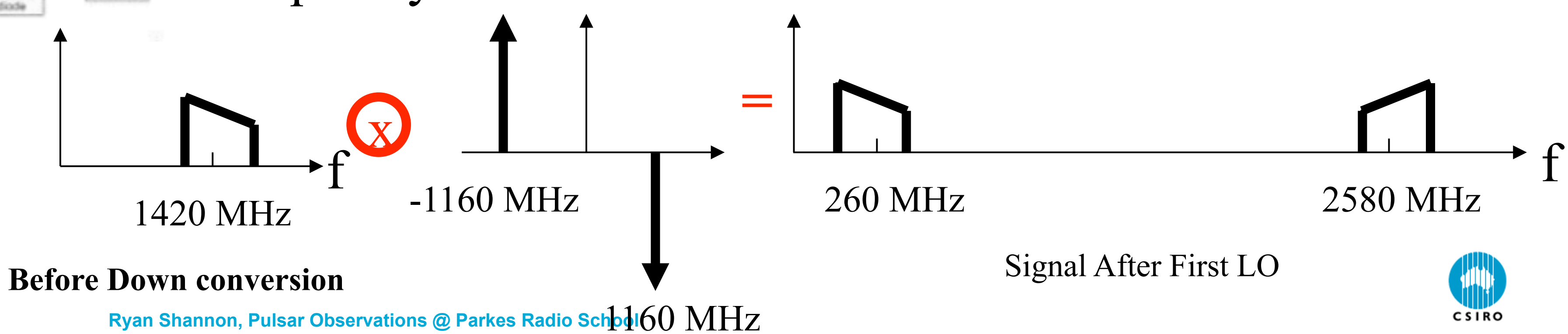
Photo: Mike Keith

Example Receiving System

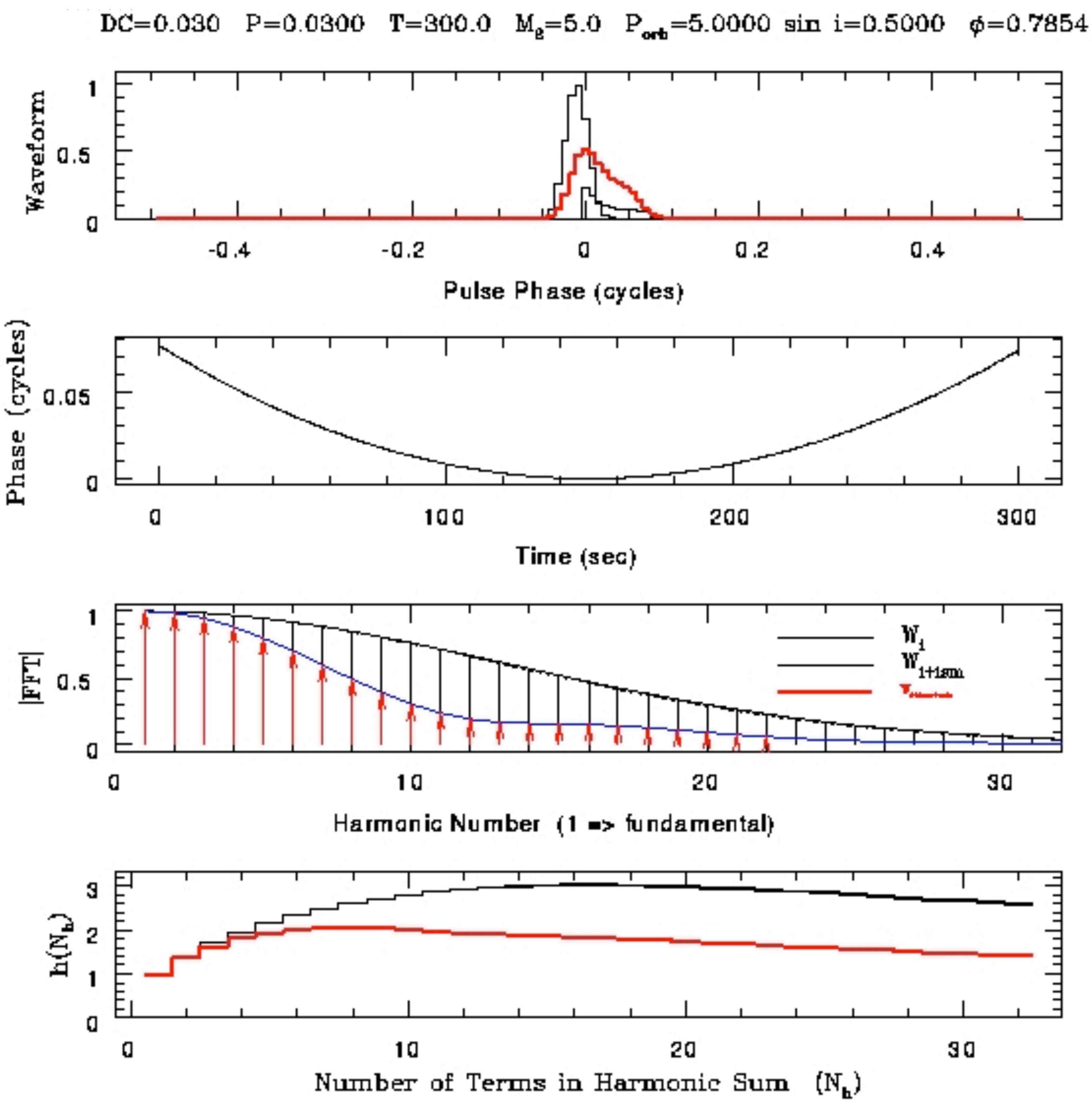
A410/A520 L-band Receiver



Frequency Conversion:

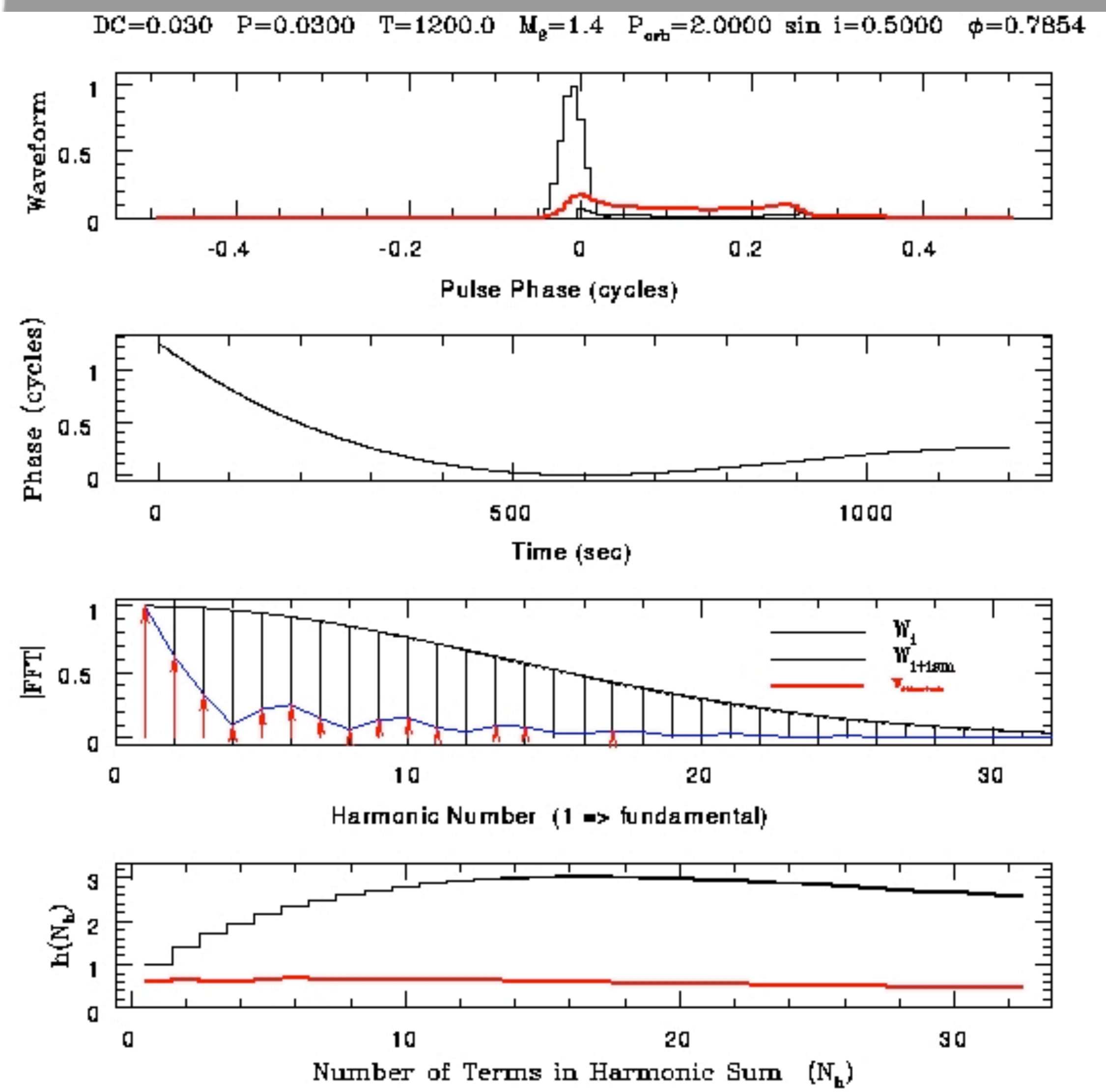


Pulse shape



Effects that broaden pulses reduce the harmonic sum, which is bad

Survey Selection Against Binaries



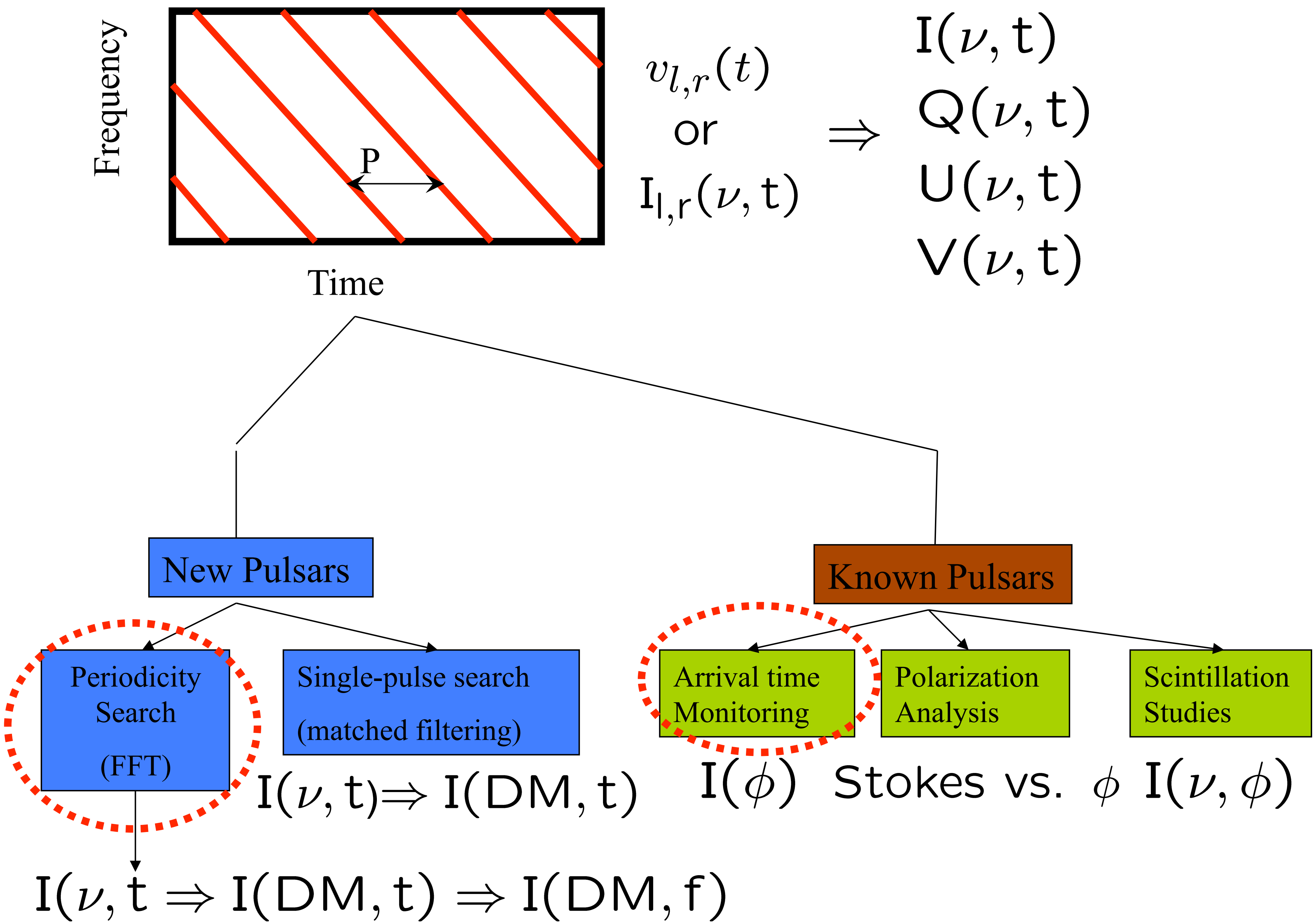
NS-NS binary

Pulse shape

Phase perturbation

FFT harmonics

Harmonic Sum


Frequency
P
Time
$v_{l,r}(t)$
or
$I_{l,r}(\nu, t)$
$\Rightarrow$
$I(\nu, t)$
$Q(\nu, t)$
$U(\nu, t)$
$V(\nu, t)$
New Pulsars
Known Pulsars
Periodicity Search (FFT)
Single-pulse search (matched filtering)
Arrival time Monitoring
Polarization Analysis
Scintillation Studies
$I(\nu, t) \Rightarrow I(DM, t)$
$I(\phi)$
Stokes vs. ϕ
$I(\nu, \phi)$
$I(\nu, t \Rightarrow I(DM, t) \Rightarrow I(DM, f)$