Credit: John Sarkissian (CSIRO)

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Pulsars = Awesome

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Outline

- Goal 1: What makes pulsars good for use in a timing array?
  - Why do pulsars have these properties?
- Goal 2: Interesting physics that can be done with pulsars
  - (Interesting computer science, electrical engineering, etc. as well, ask us about that later)
  - Inverse of the IPTA question.
- Not going to explicitly address pulsar observation techniques / data analysis / pulsar timing
  - Pulse@Parkes Session
  - Tuesday Talks (Stairs and Manchester)
  - Module 1: (Pulsar timing: from raw data to TOA)

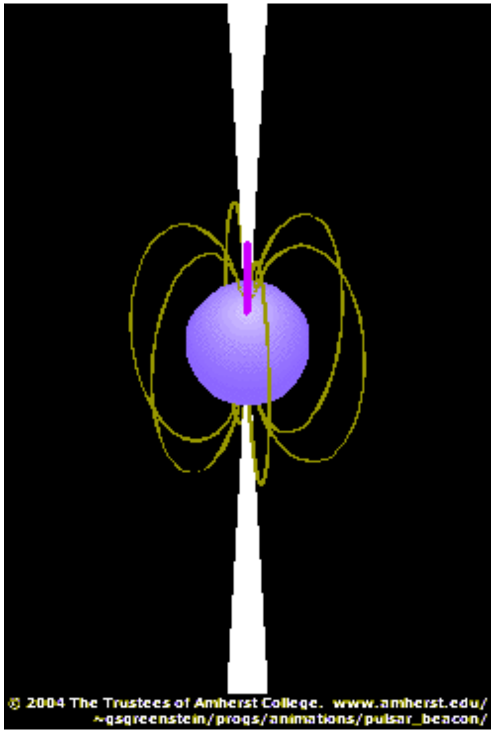
End states of stellar evolution

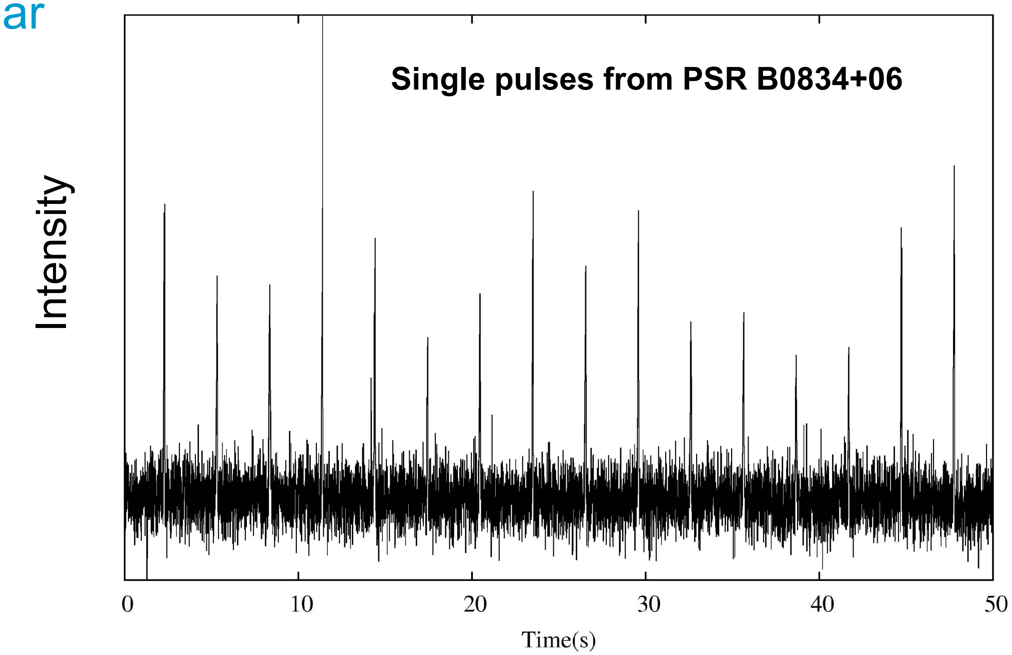
Main sequence star	Compact Remnant
0.1 to 8 M_{sun}	White dwarf (0.1 to ~ 1.2 M_{sun}) Electron degeneracy pressure
	Supernova Explosion
8 to 20 (?) M_{sun}	Neutron star 1.3 to < 3 M_{sun} Neutron degeneracy pressure
> 20 M_{sun}	Black hole >3 M_{sun} Gravity wins

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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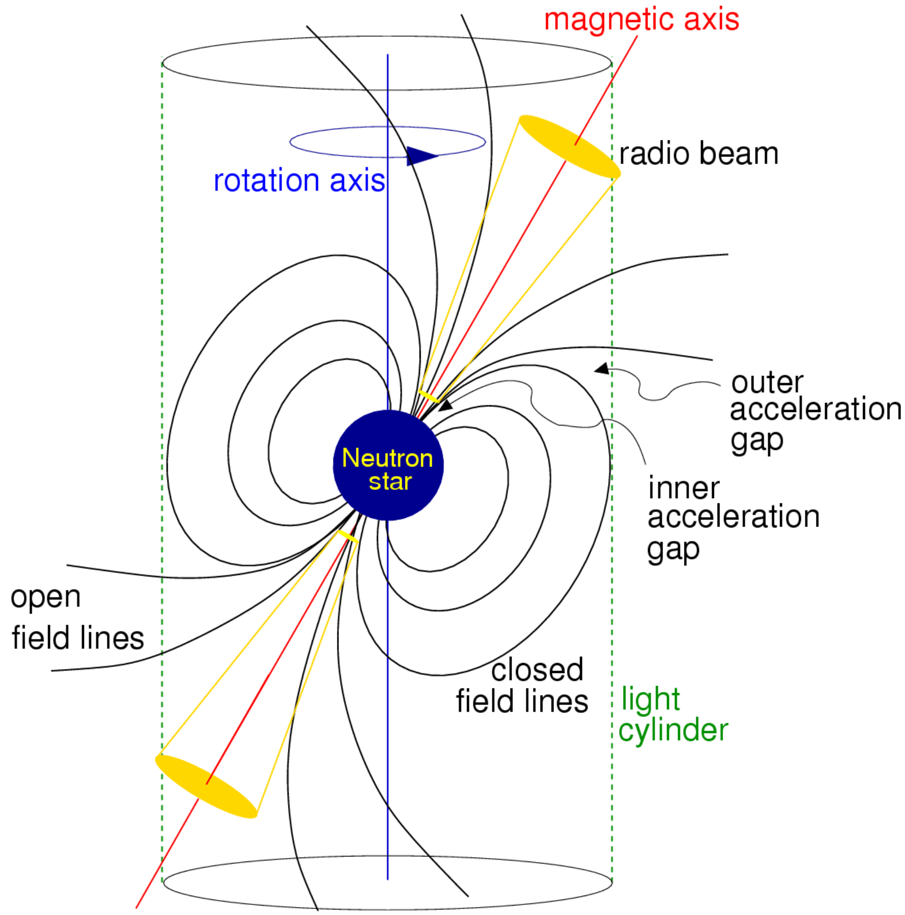
Pulsar Emission Terminology

Important terms:

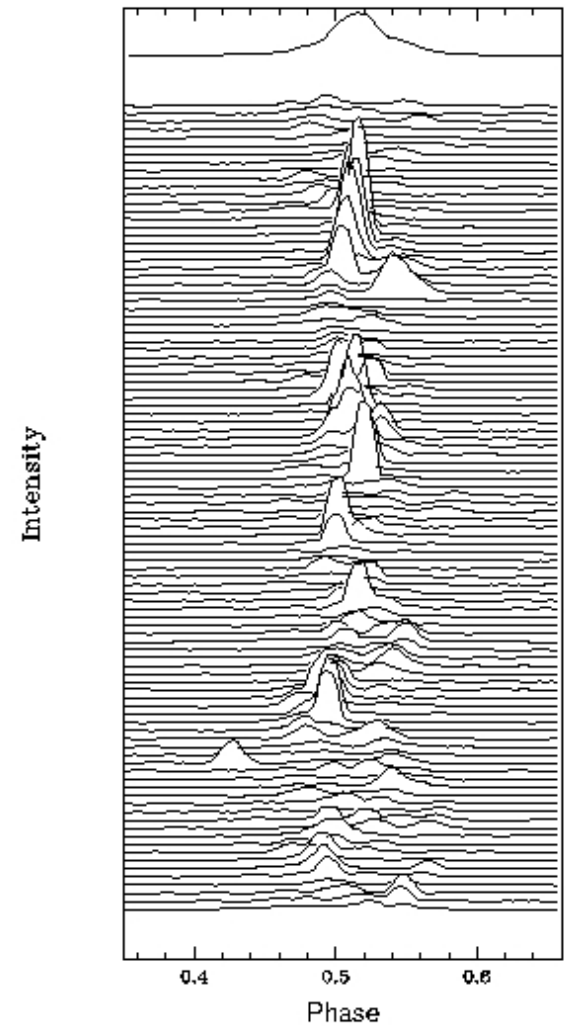
- **Magnetosphere**
- **Light cylinder**
- **“Gaps”**
- **Open field line region**
- **Closed field line region**
- **Polar Cap**
- **Force free**



Pulsar radiation is periodically ***pulsed***

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

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

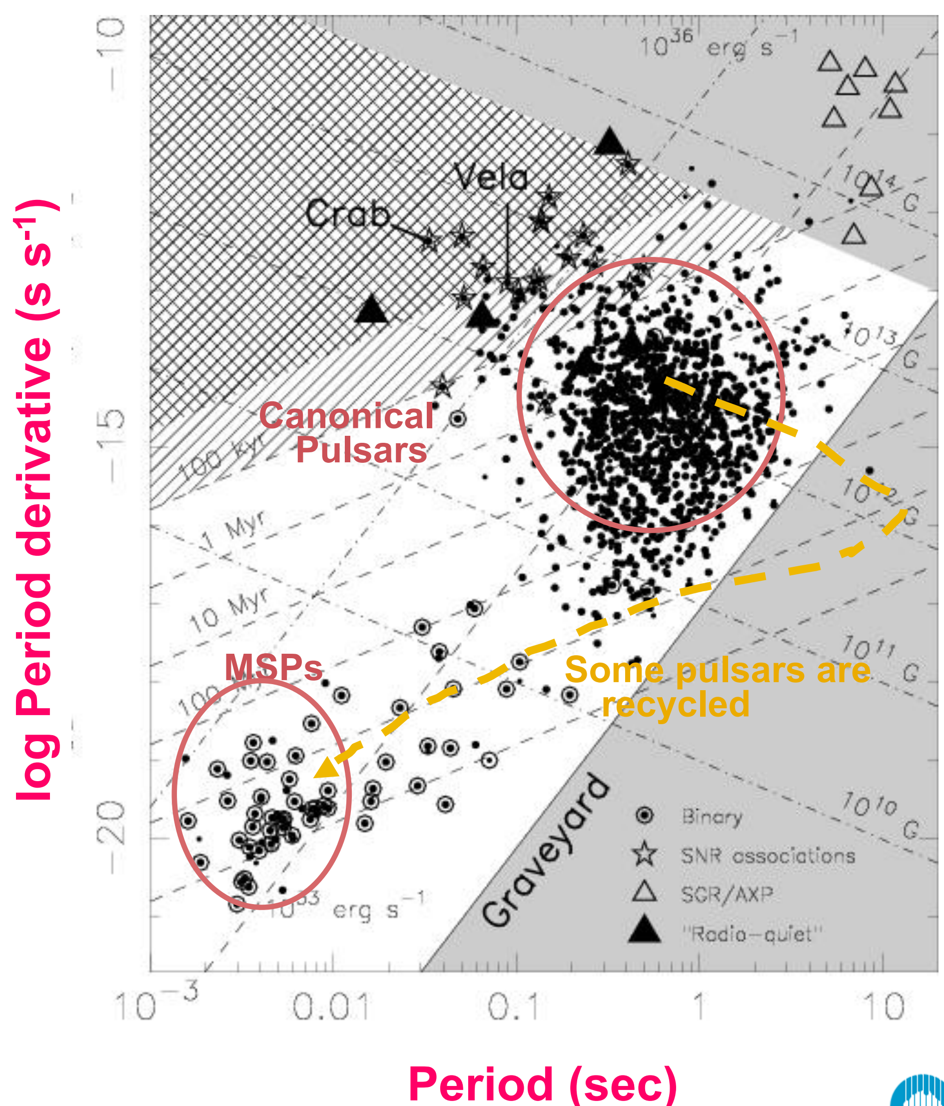


Pulsars have unique ***periods and period derivatives***

- Two most important observable properties of pulsars:
  - Period (frequency)
  - Period derivative (frequency derivative)

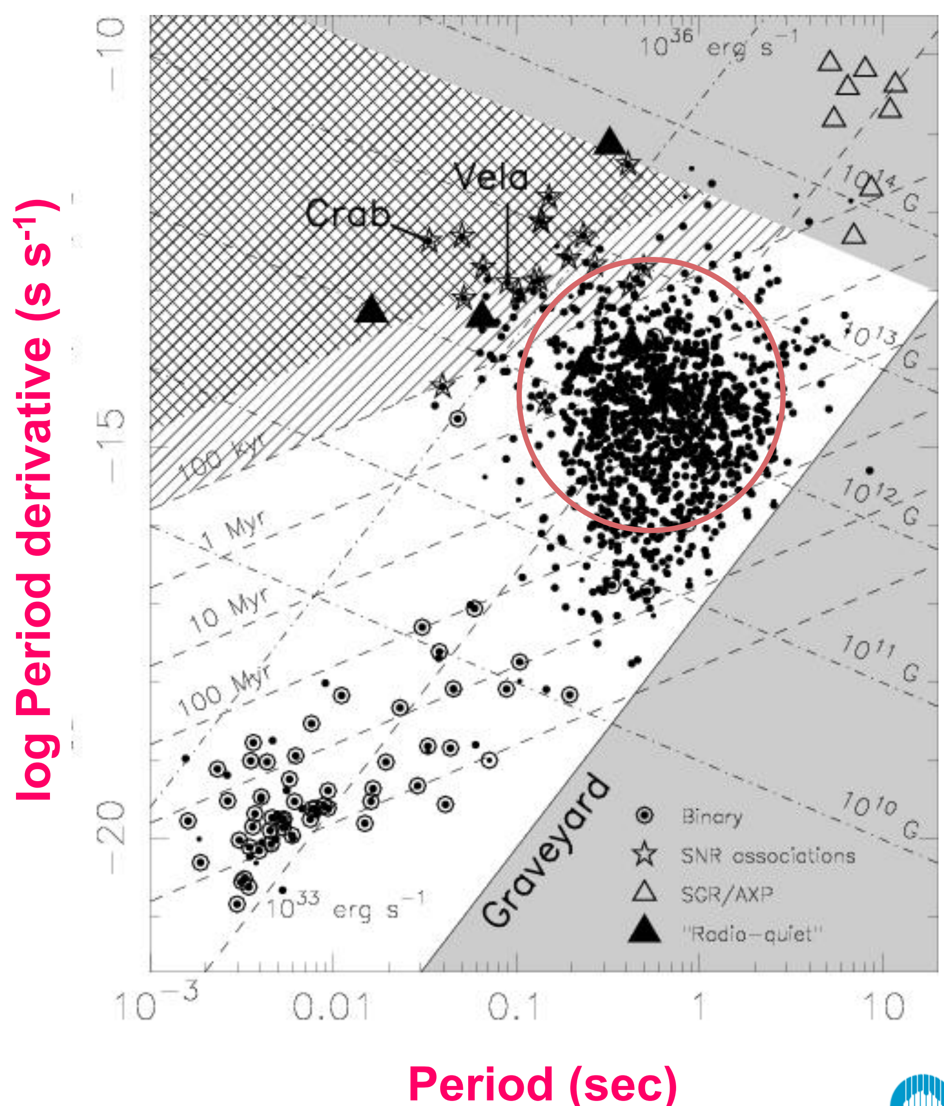
- Tells the story of pulsars
  - Some observational bias

- 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)



Pulsars have unique *periods and period derivatives*

- Canonical Pulsars (CPs)
  - Born after Type II supernova explosion
  - Spin periods ~ 30 ms to 7 s
  - Slowly spinning down
  - Eventually hit "death line" and no longer produce radio emission
- Example: Crab pulsar (SN 1054)



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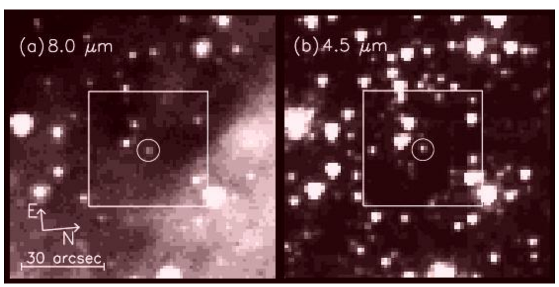
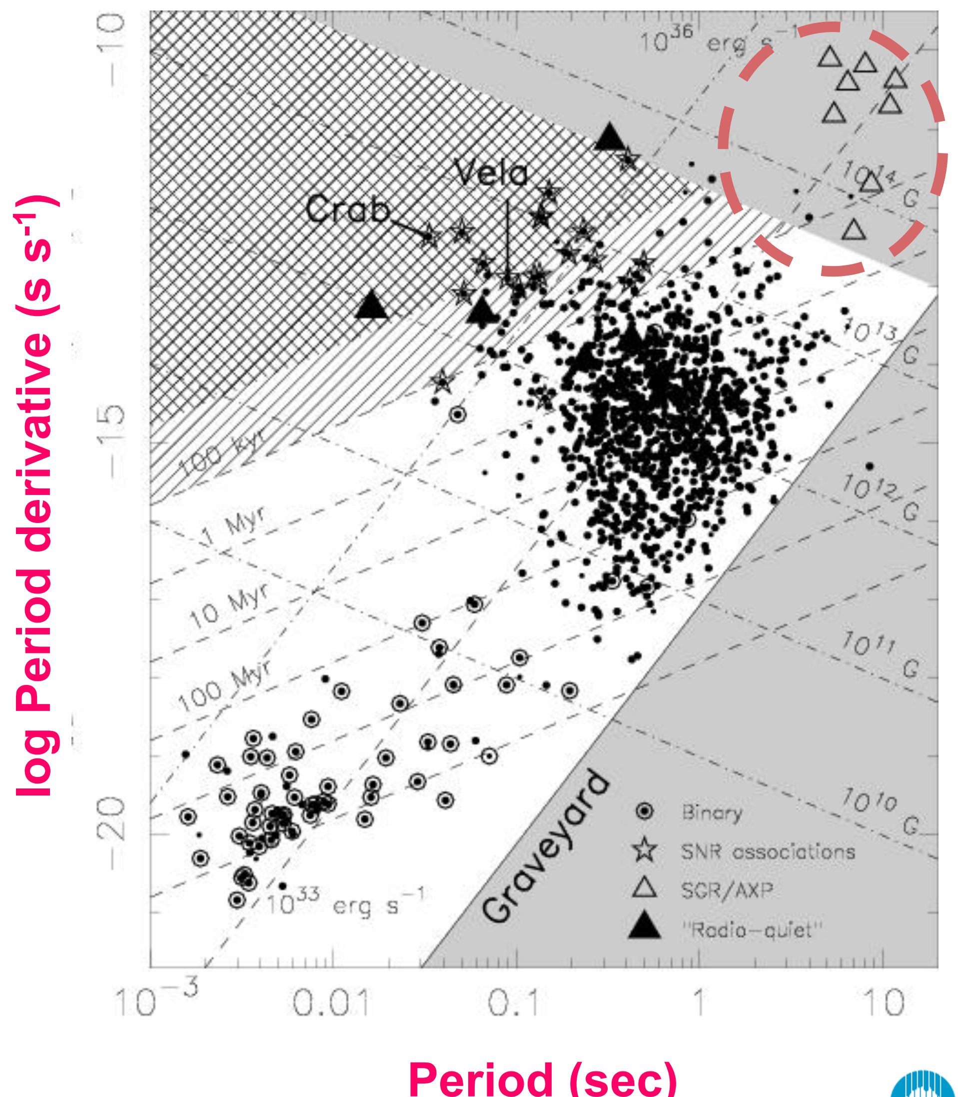
Pulsars have unique *periods and period derivatives*

- Magnetars
  - High magnetic fields
  - Energy loss can exceed spin down energy
  - Powered by magnetic field decay?
  - Large levels of **timing noise**

- Example: 4U 0142+61





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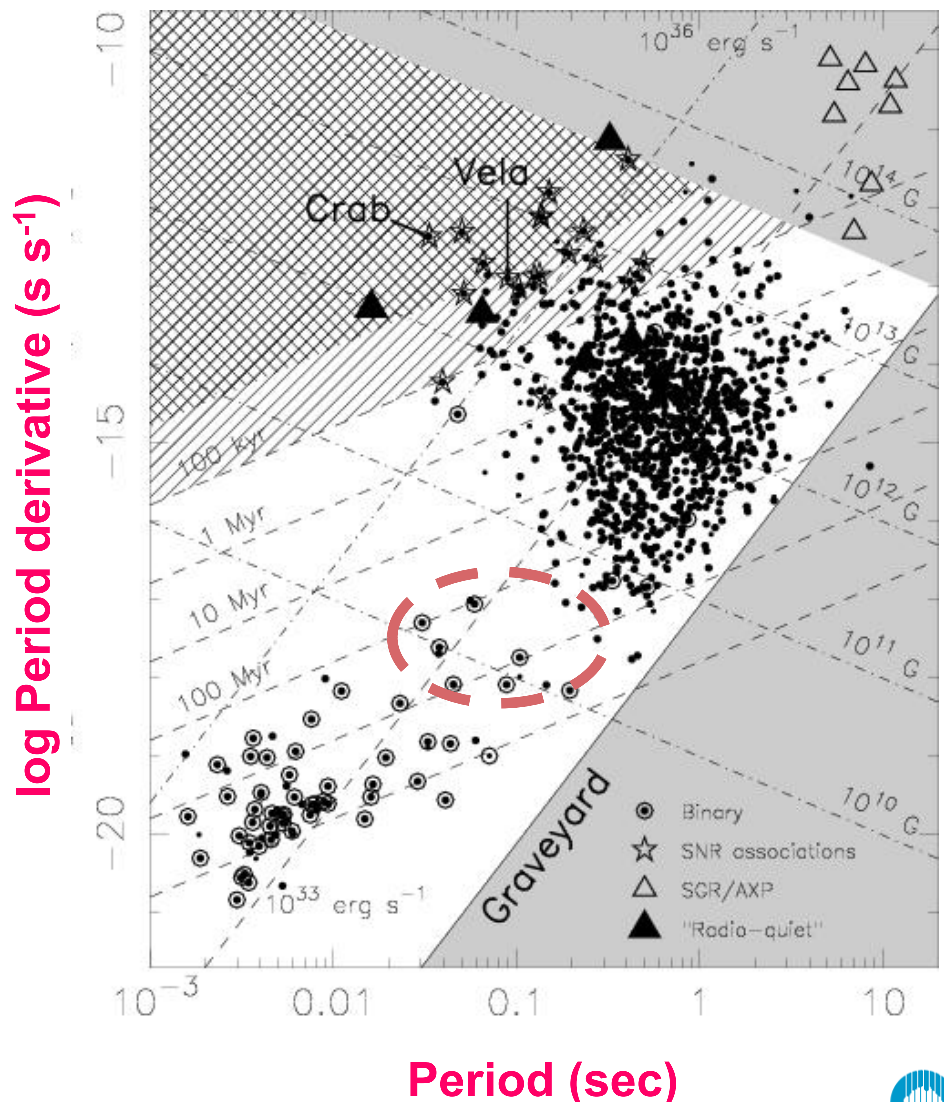
Pulsars have unique *periods and period derivatives*

- Relativistic Binaries
  - Spin period ~ 30 ms
  - Much lower Pdot than CPs
  - Pulsars with neutron star companions
  - Not completely "recycled": larger periods, higher period derivatives
  - Not useful for PTA work (show **timing noise**)

  - Examples:
    - PSR B1913+16 (Hulse-Taylor Pulsar)
    - J0737-3039A, J0737-3039B (Double pulsar system)



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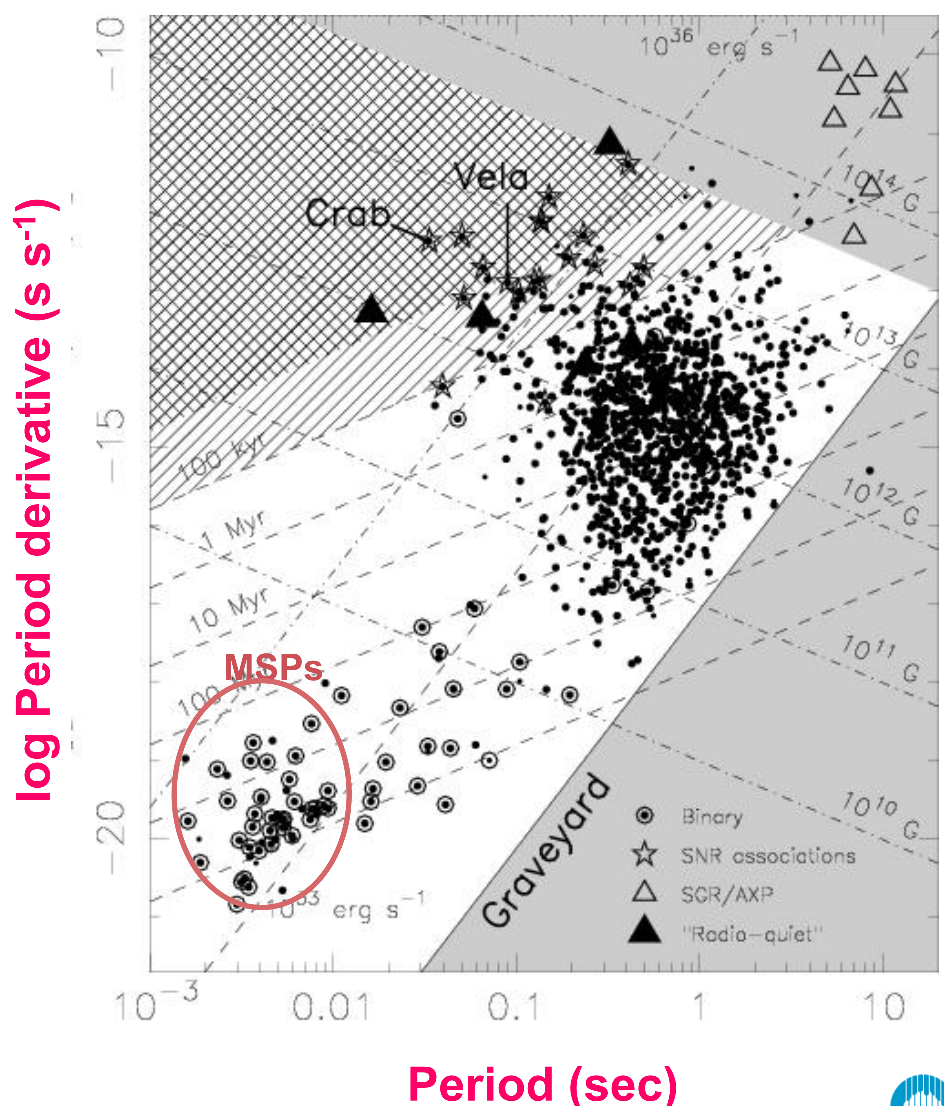
Pulsars have unique ***periods and period derivatives***

- Millisecond Pulsars
  - Spin period < 20 ms
  - White dwarf companions, or isolated
  - Shortest spin periods, smallest period derivatives

- Examples:
  - **B1937+21**
  - **J0437-4715**

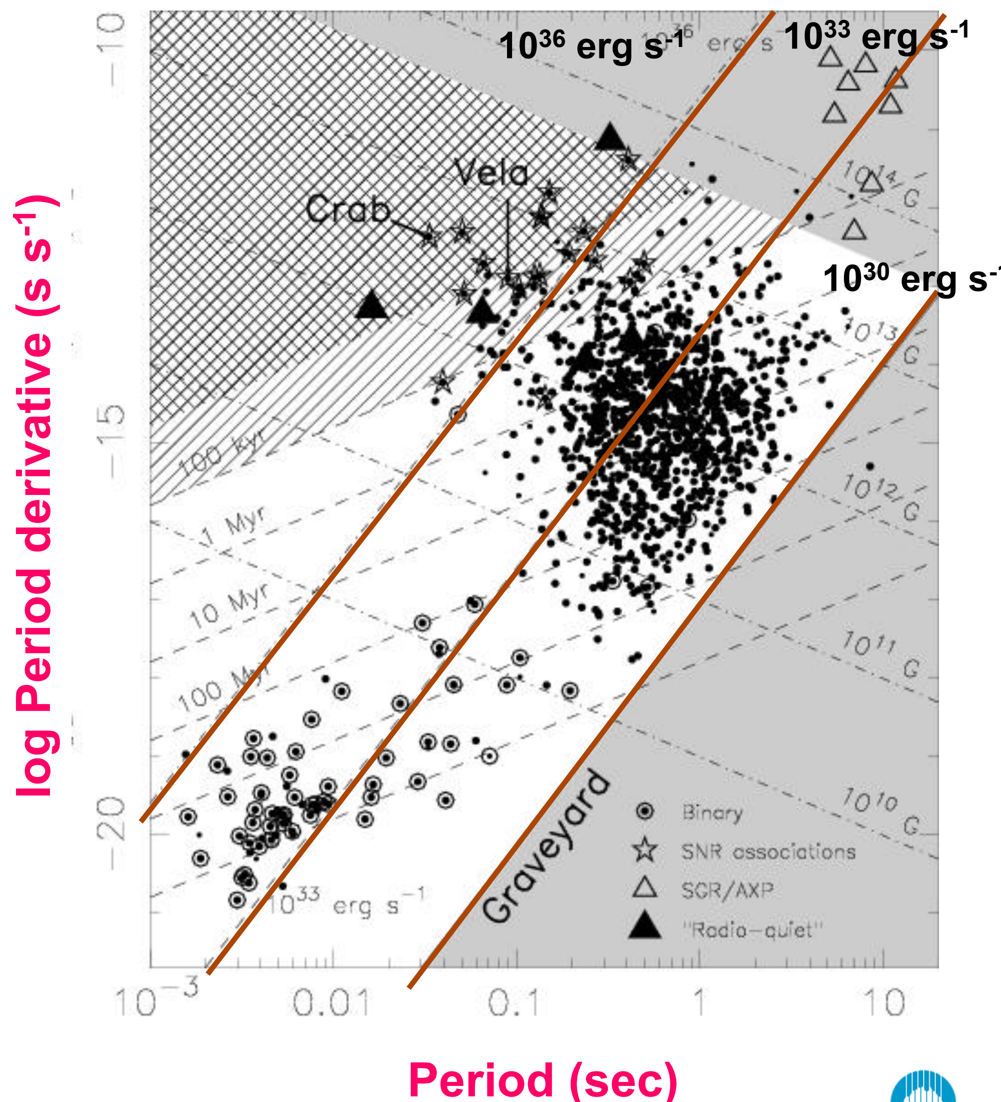


Physics/Numerology of the P-Pdot Diagram

$$E = \frac{1}{2} I \omega^2$$

$$\dot{E} = I\omega\dot{\omega} \propto \dot{P}/P^3$$

- Spin down luminosity
  - Assumption: that moment of inertia is same for all pulsars
  - Spin down luminosity much greater than radio luminosity
  - Majority of emission in high energy photons , wind, Poynting flux.
  - Solar luminosity: 4×10^{33} erg/s
- MSPs: slightly larger spin down luminosity than CPs



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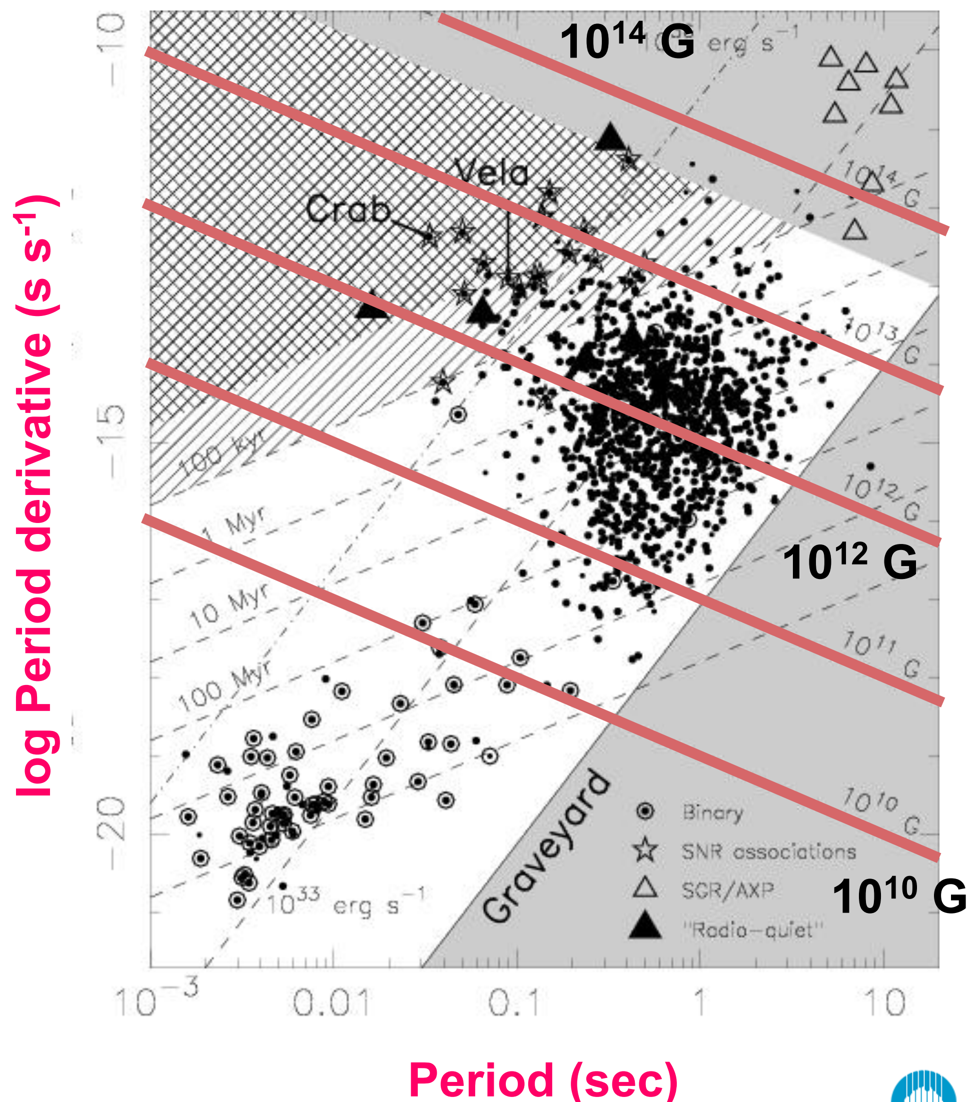
Pulsars have unique *periods and period derivatives*

$$\dot{E} = \frac{2}{3c^3}|m|^2\omega^4 \sin^2\alpha$$

$$m \propto Br^3$$

$$B \propto \sqrt{P\dot{P}}$$

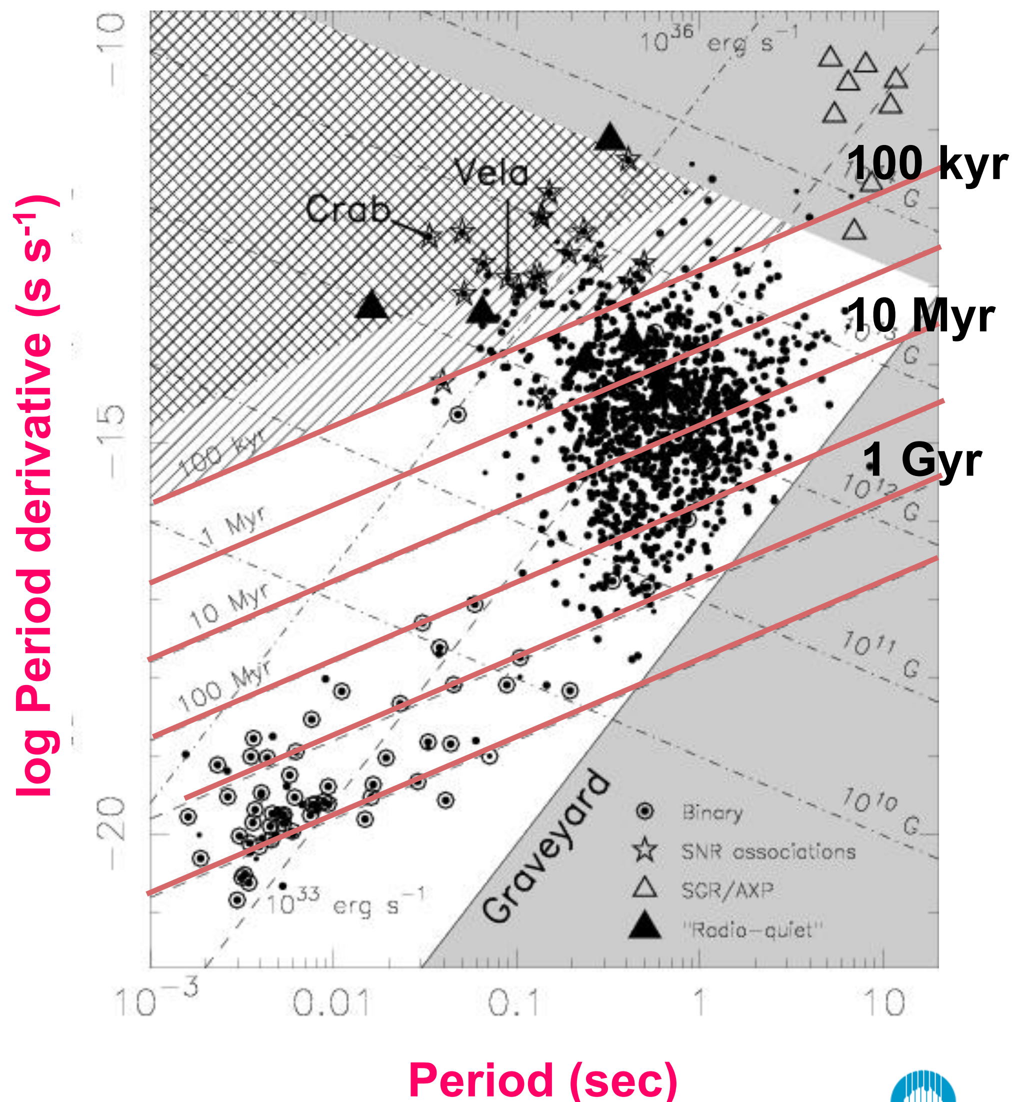
- Magnetic Field Strength
  - Assumption: inclination of magnetic field with respect to spin access.
  - Magnetic field strength of surface of sun: ~1 Gauss
- MSPs: Much weaker surface magnetic fields than CPs



Pulsars have unique *periods and period derivatives*

$$\tau \propto \frac{P}{\dot{P}}$$

- Age
  - Assumption: magnetic field doesn't evolve with age
  - Age of Sun: 5 Gyr
- MSPs: much older than CPs



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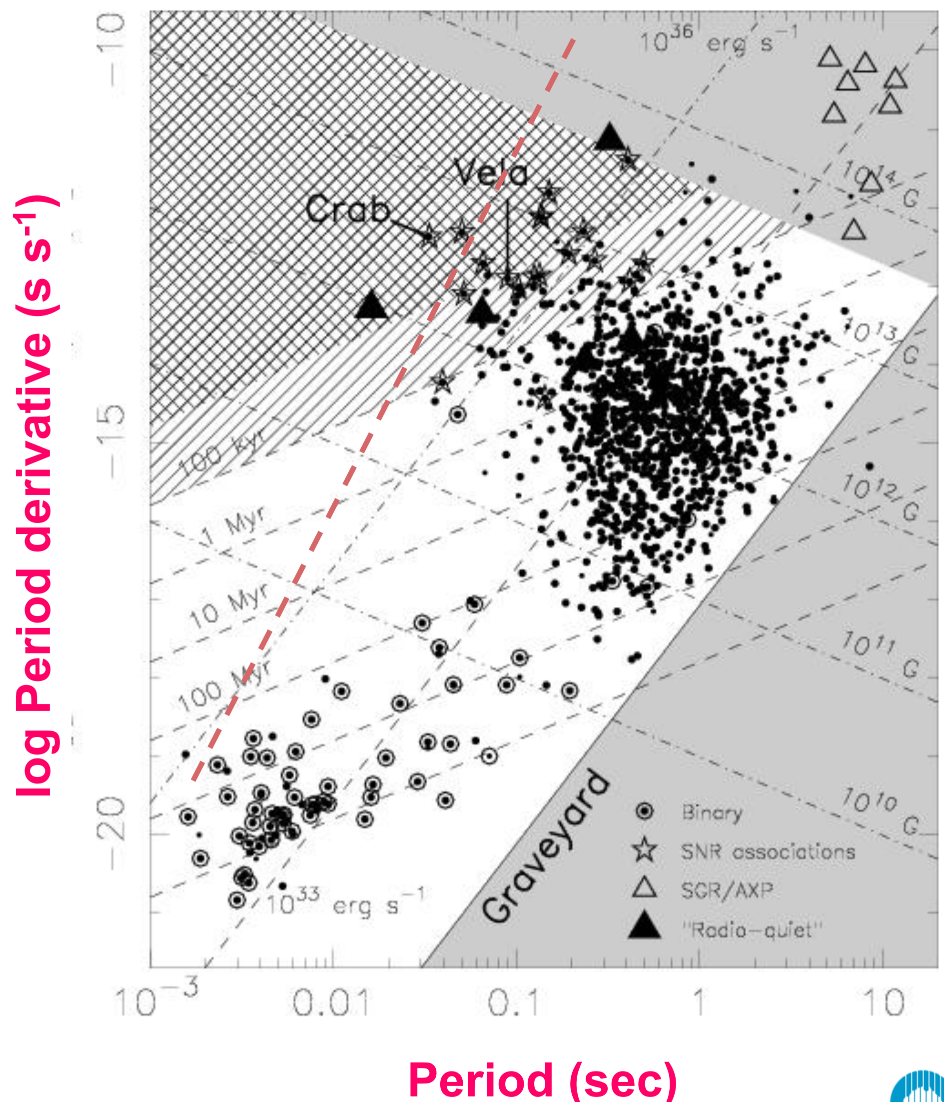
Pulsars have unique *periods and period derivatives*

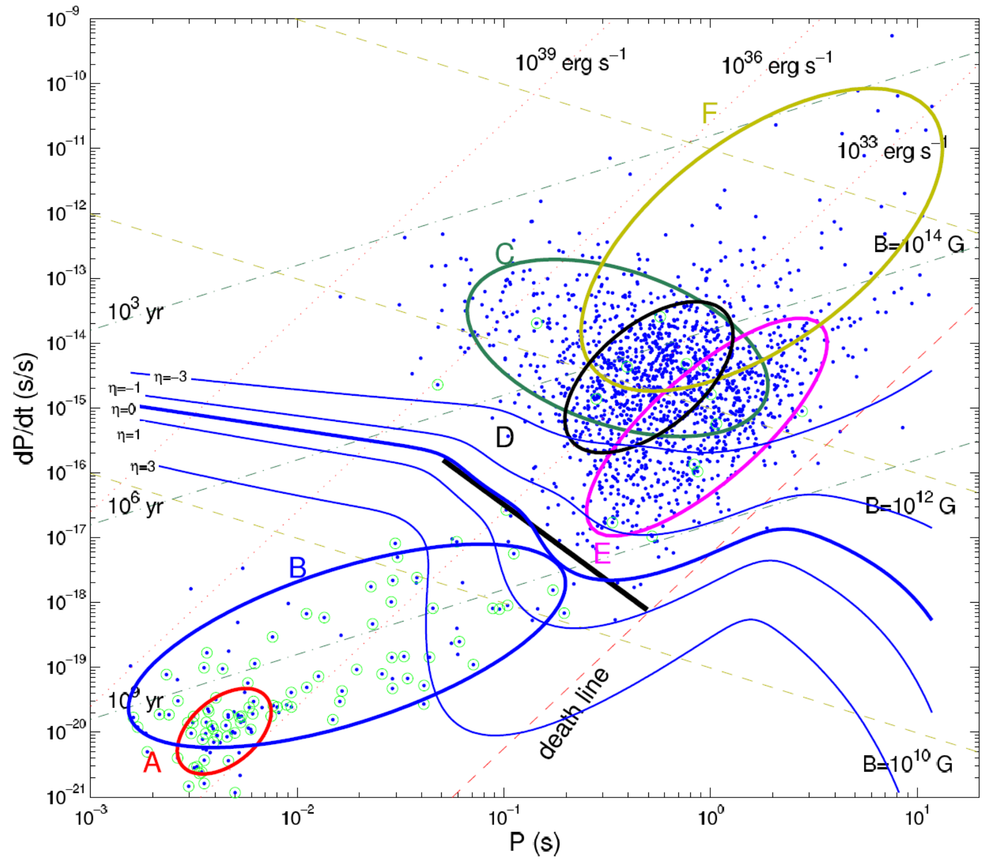
- Others
  - Magnetic field at light cylinder
  - Outer gap death line

- Issues:
  - No particularly strong correlations in P-Pdot
  - “Hidden variables”



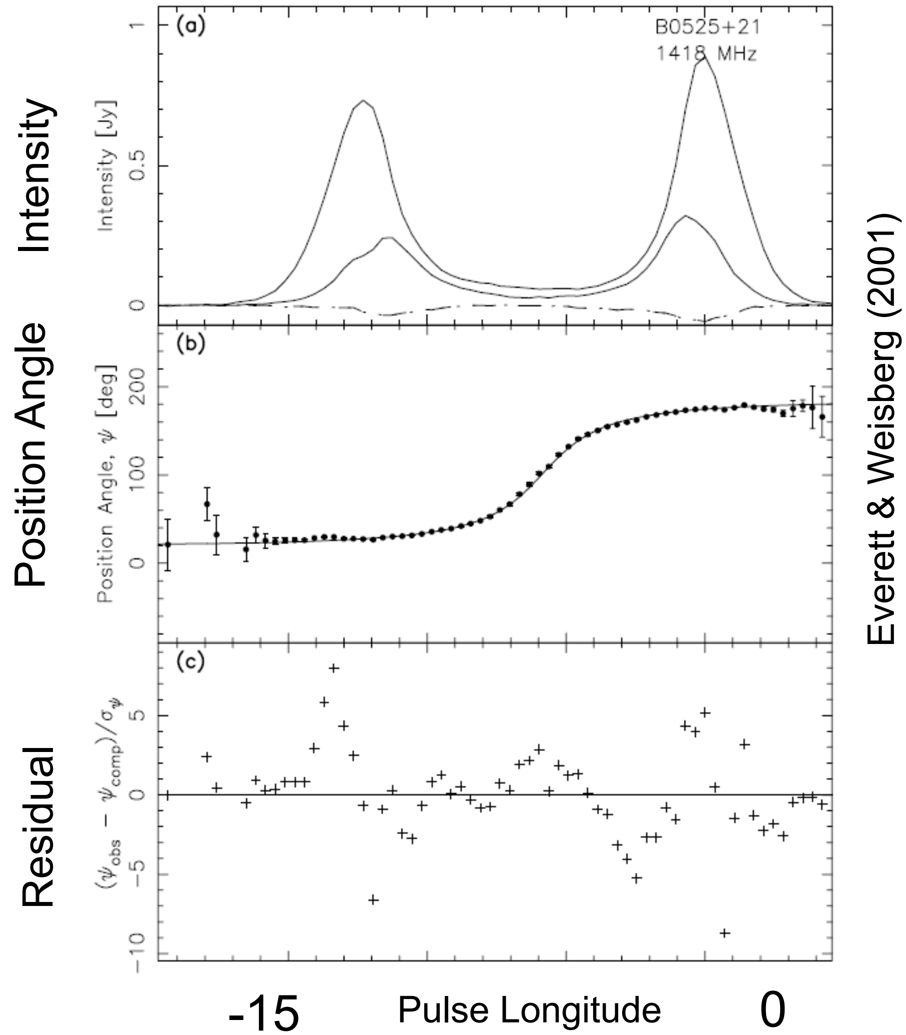
Physics/Numerology of the P-Pdot Diagram

- Statistical analysis of P-Pdot diagram by KJ Lee et al. (2012)
- Gaussian Mixture modelling
- Five overlapping populations of pulsars
- Analysis made use of pulsar catalogue.



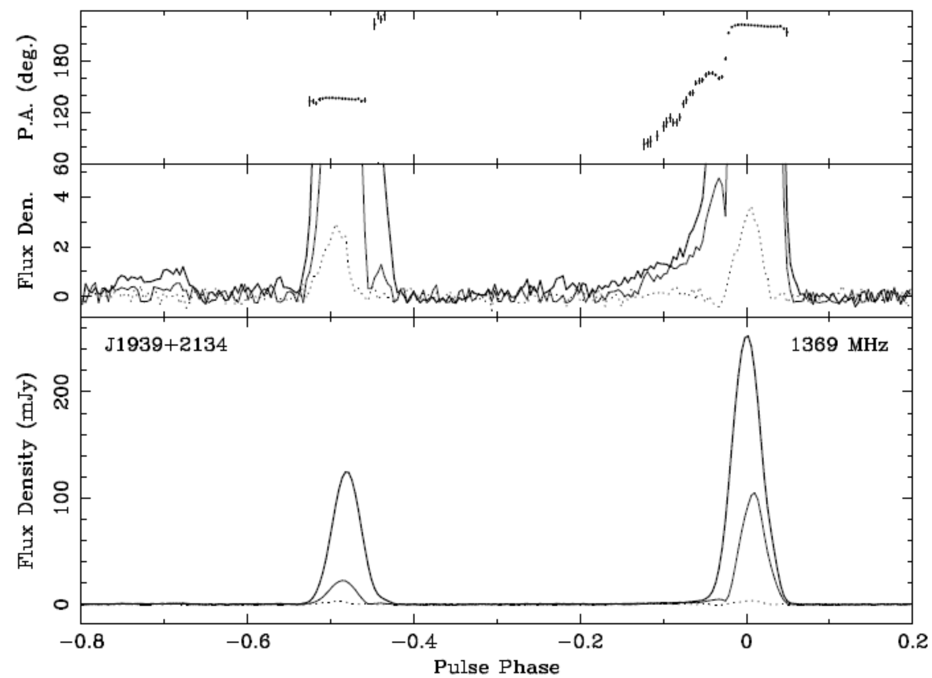
Pulsar radiation is ***polarised***

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



Pulsar radiation is ***polarised***

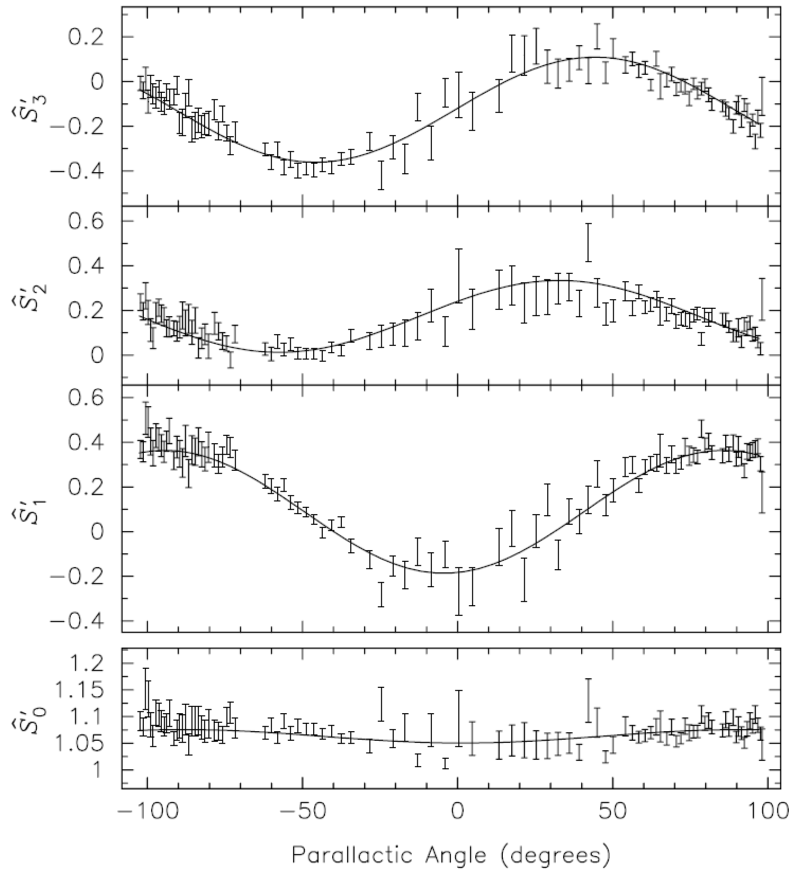
- Corollary 1: To get a good estimate of the pulse profile, we need to have well behaved receivers (or good models of how "bad" our receivers are).



Wenming Yan et al. (2011)

Example: Forming Calibrated Pulse Profile

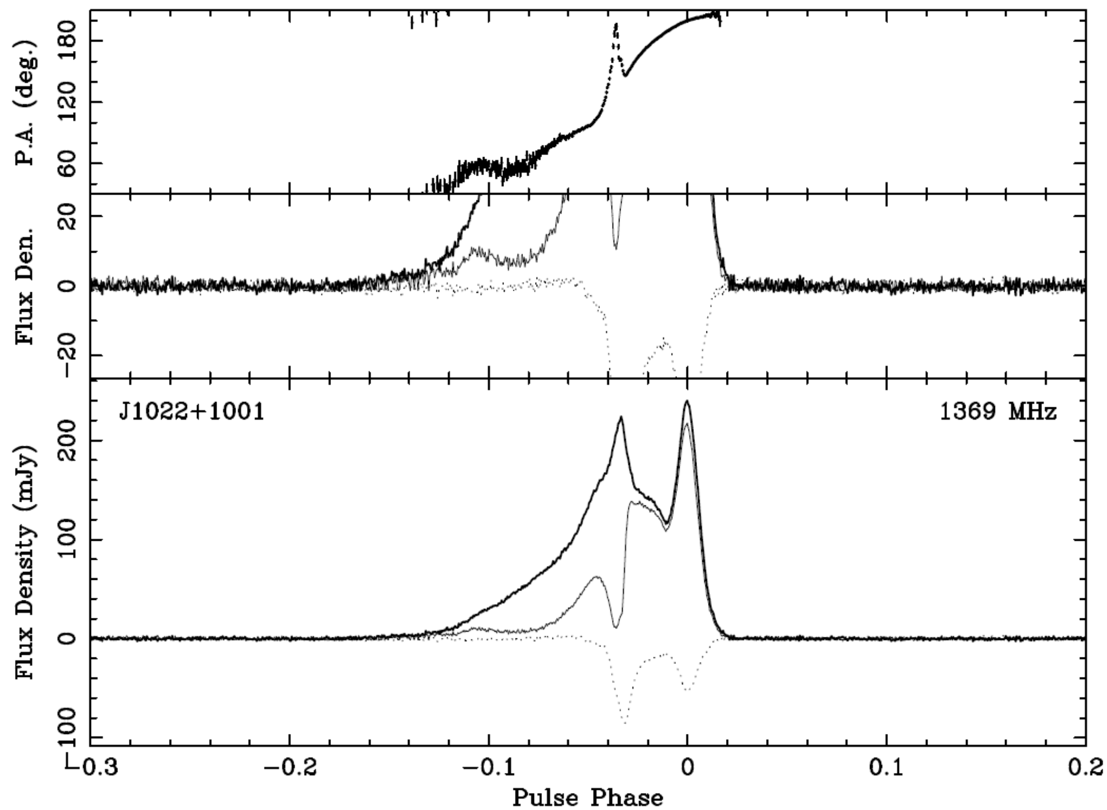
- **Need to form Stokes parameters as a function of pulse phase**
- Calibrate for gain and phase variations between feeds
  - Inject non-polarised or polarised signal into feed
  - Observe non-polarised astronomical source to calibrate the injected signal
- Calibrate ellipticity of the feeds
  - Track 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).

Pulsar radiation is ***polarised***

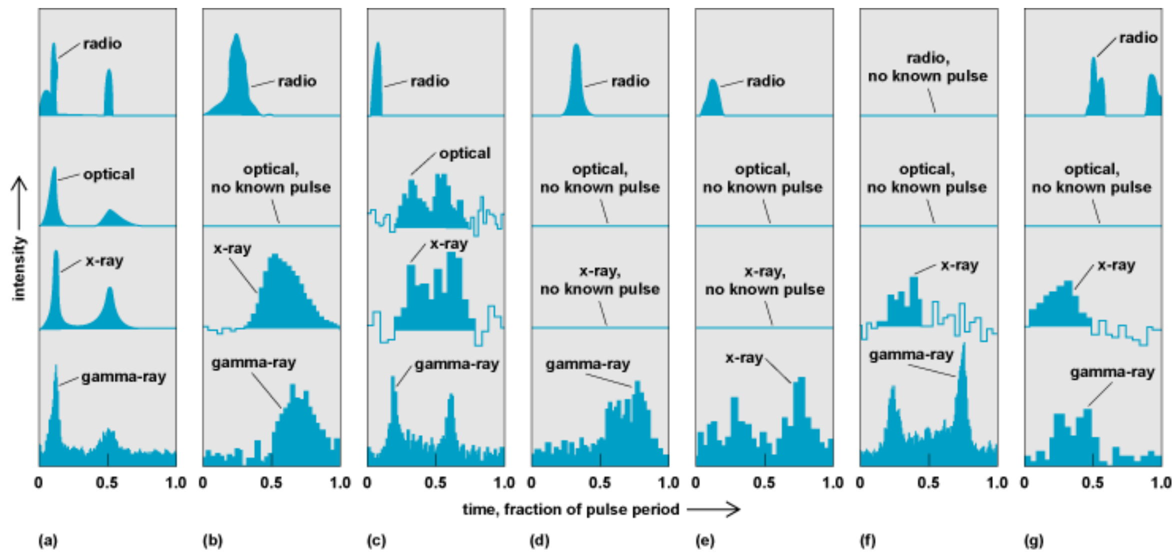
- Corollary 2: Pulse profiles often sharper in single polarization component: timing precision may be higher if all Stokes information is used (van Straten 2006)



Wenming Yan et al. (2011)

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

- Non-thermal emission observed across entire EM spectrum
- Some pulsars (including many MSPs) are prodigious producers of gamma-ray emission.



- ***The number of high energy pulsars has grown by a factor of 10 since the launch of the Fermi space telescope.***
- ***Key factor for PTAs:*** **discover MSPs as targeted searches of Fermi point sources**

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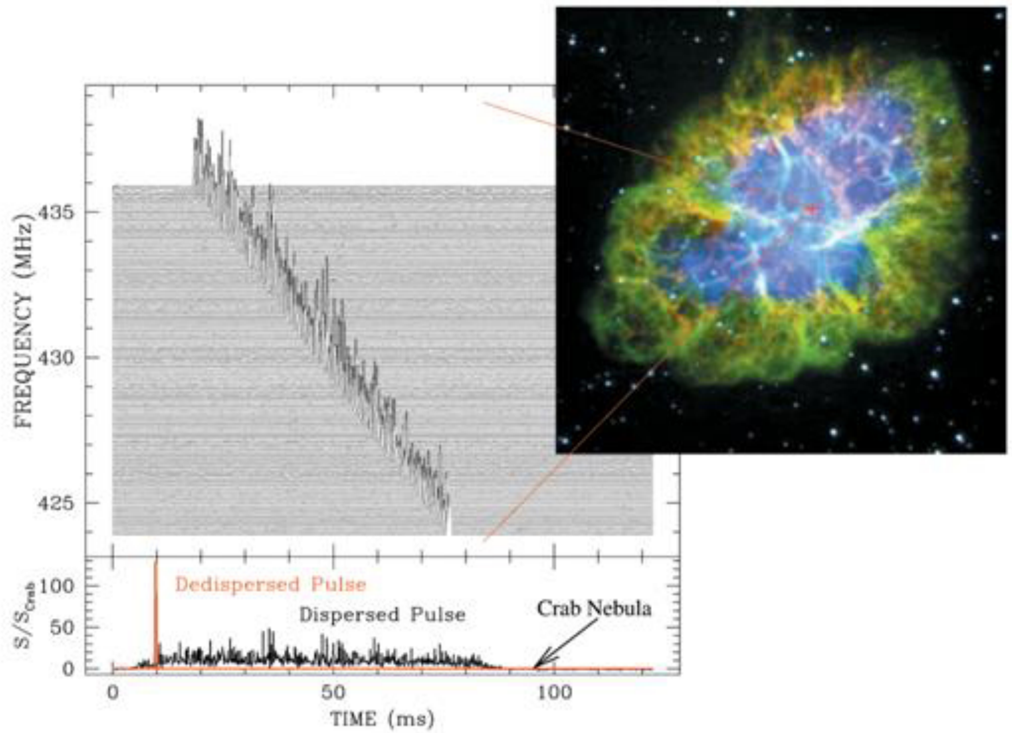
Pulsar radiation is ***erratic***

- 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*)
- Open question: which of these properties do MSPs show?



Bhat, Cordes et al. (2004)

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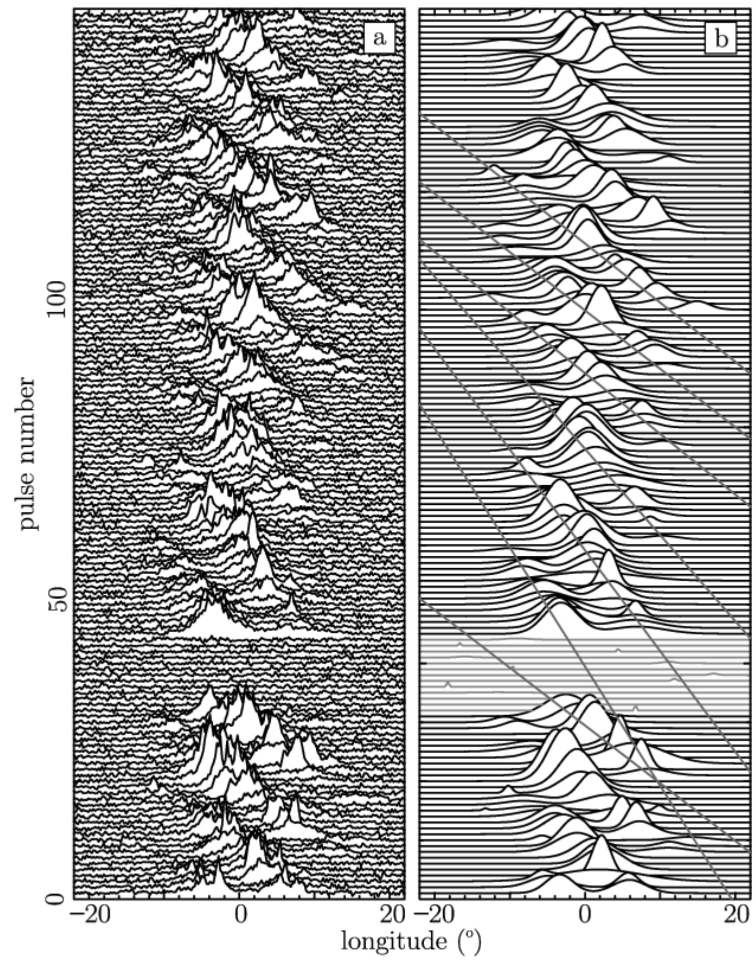
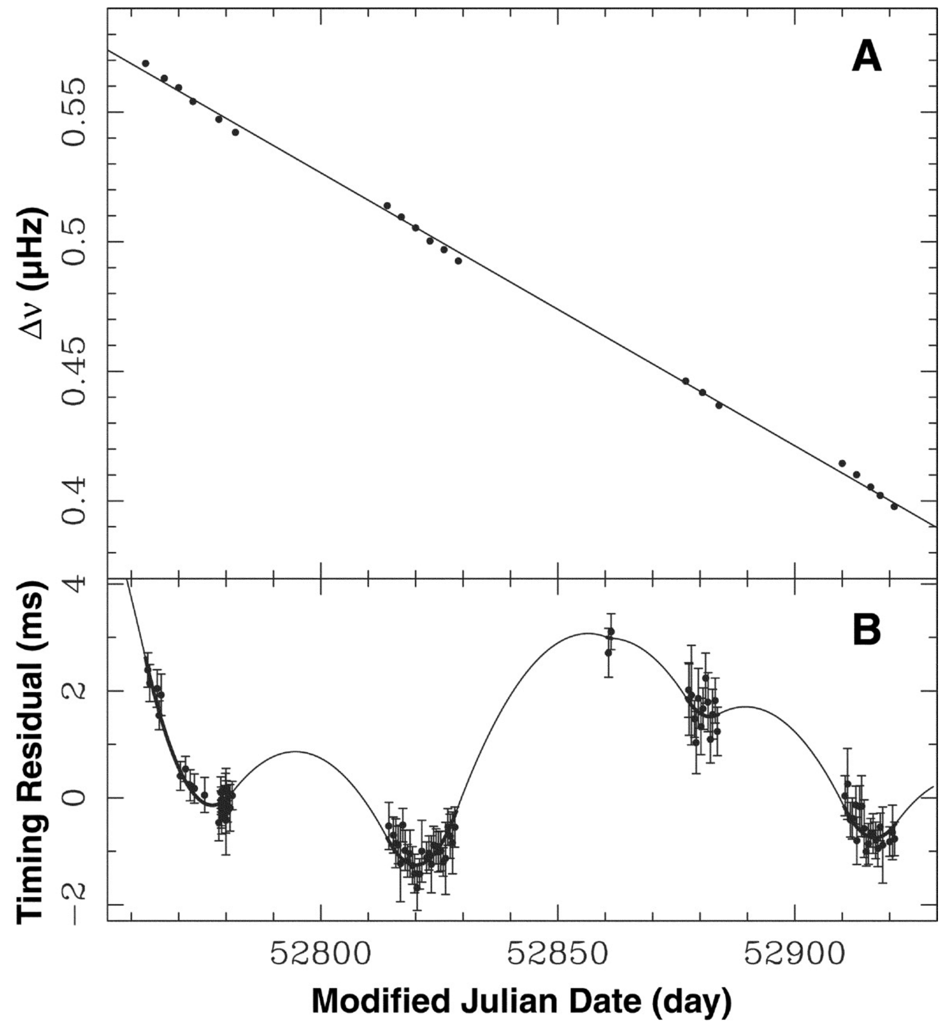


van Leeuwen, Stappers et al. (2003)

Pulsar radiation is ***erratic***

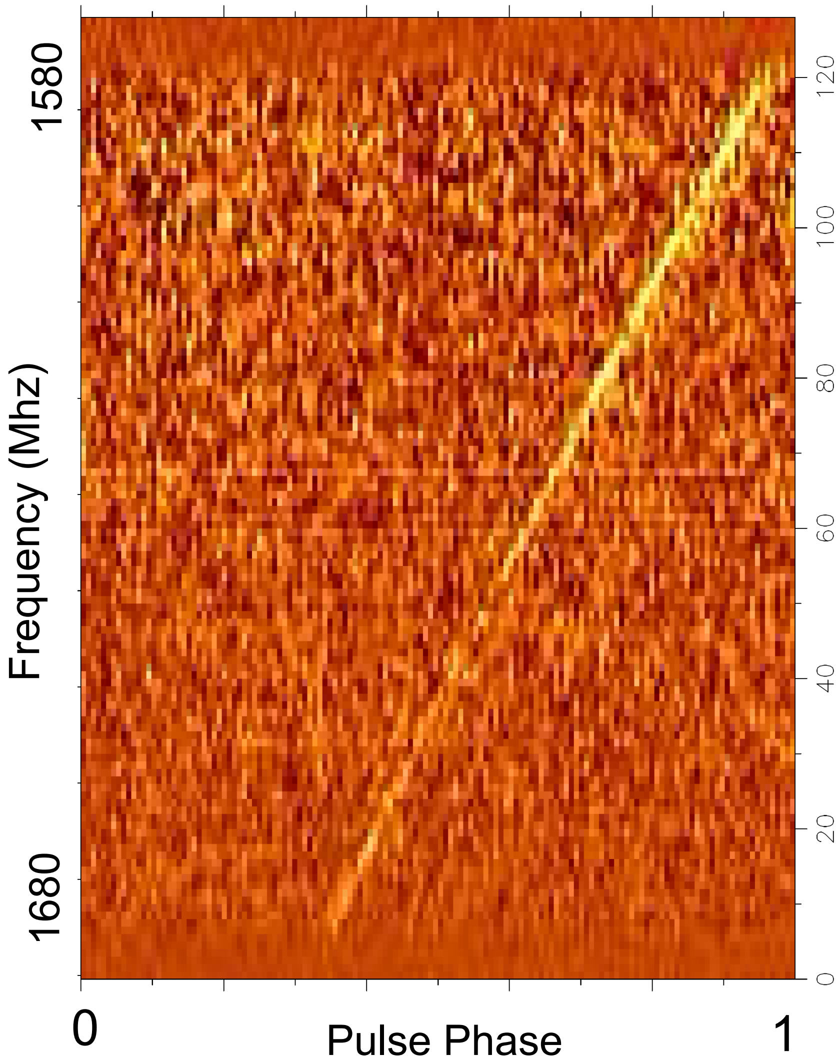
- Intermittent pulsar B1931+24
- Spin down is larger when it is **on** than when it is **off**
- Magnetospheric torque variations
- Open question:
  - Do MSPs show this type of torque variation?



Lyne et al. (2006)

MSP emission is (somewhat) erratic too!

- Example: Four single pulses for J1713+0747
- Arecibo observations at 1600 MHz
- Pulses show different widths, brightness, arrival times
  - Interpretation: pulse phase jitter



MSP emission is (somewhat) erratic too!

- Example: Four single pulses for J1713+0747
- Arecibo observations with L-wide receiver
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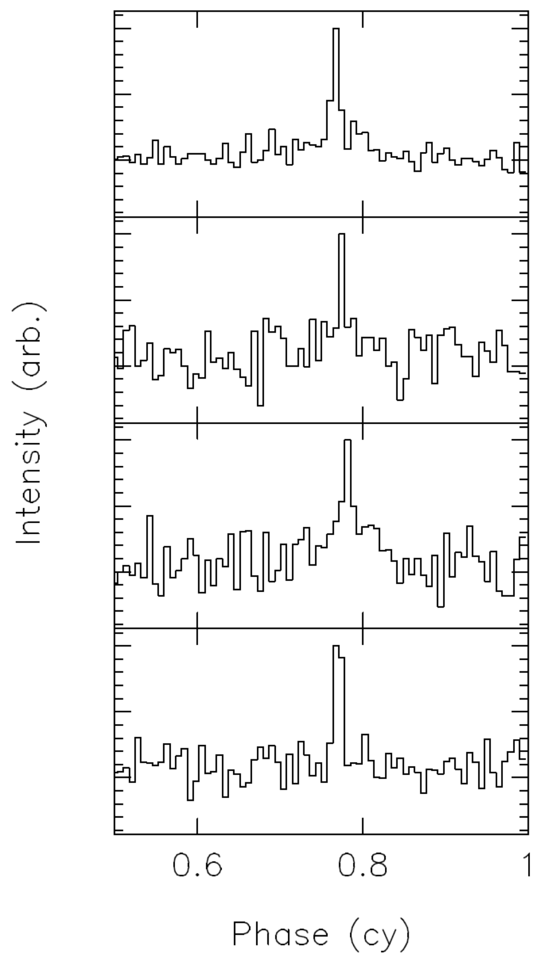

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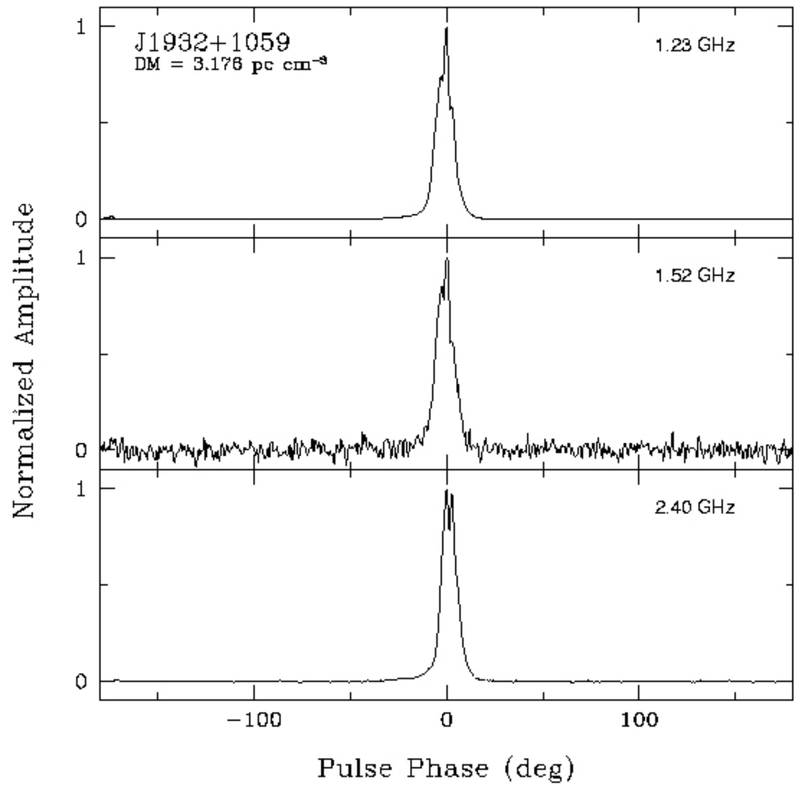
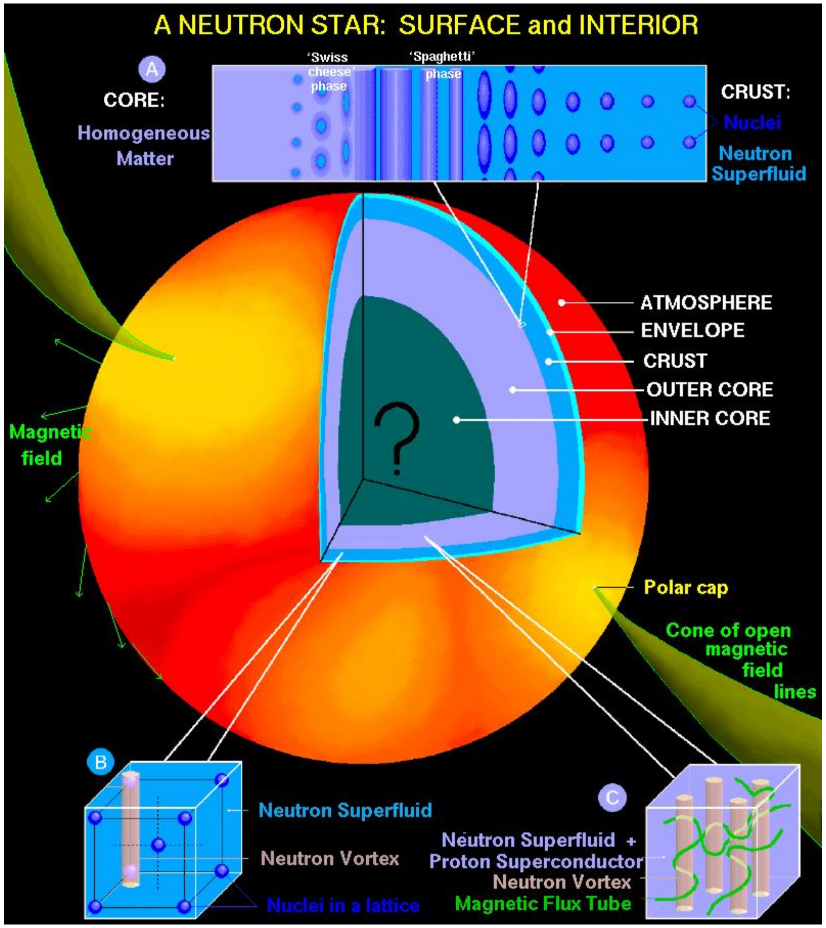
Summary of pulsar emission:

- **Radio Emission**
  - **Broad band** (same origin across wide range of radio frequency)
  - **Brighter at lower radio frequency**
  - **Coherent**
  - **Apparently Stochastic**
  - **Polarised**



Neutron Star Structure

- Surface: Iron
- Interior:
  - Neutron superconducting superfluid
  - Possibly quark matter?
- Constrain Masses of NS through pulsar timing (Ingrid's talk tomorrow)
  - Constrain nuclear equation of state through these masses

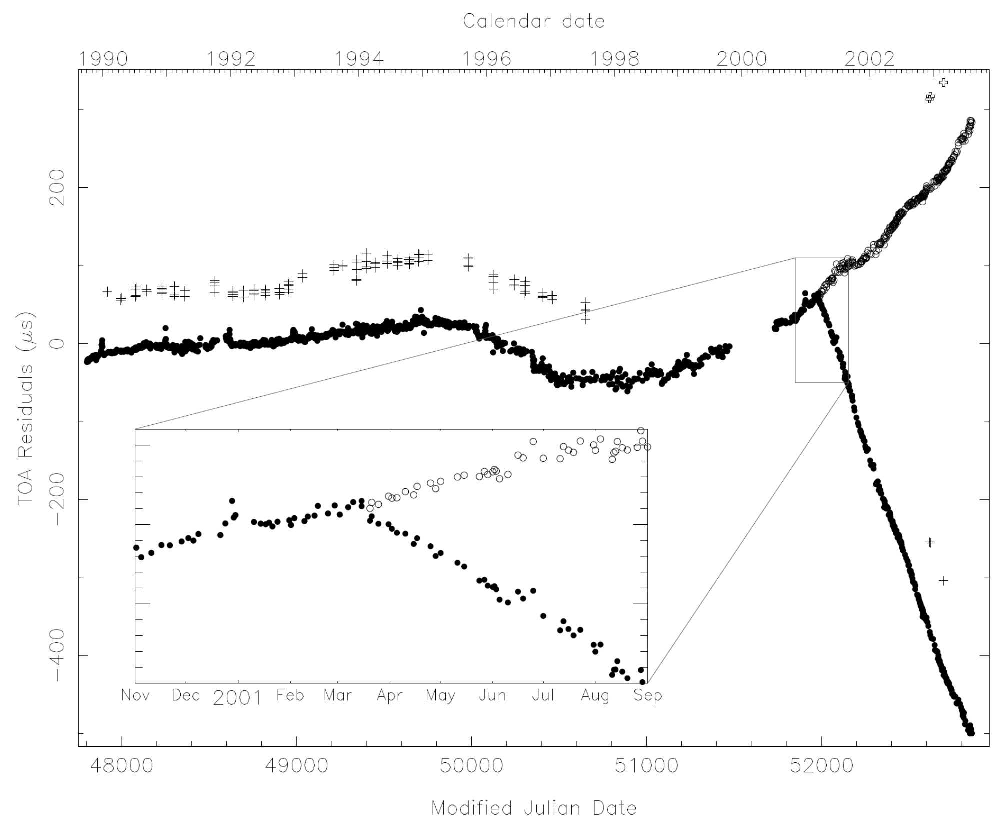


NS Structure: Implications for PTA

- Importance for PTA work
  - Differential rotation between crust and core
  - Angular momentum transfer between crust and core

- Manifestation of Angular Momentum Transfer: rotational irregularities of pulsars
  - **Glitches** (see Sarah Buchner's talk)
  - **Timing Noise** (Jim Cordes / George Hobbs this week, billion talks next week)

- Are the weaker magnetic fields an "out"?



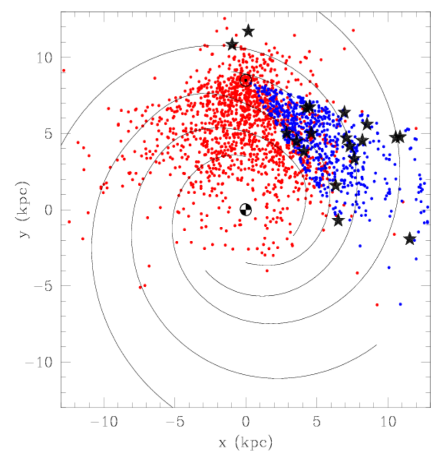
Cognard & Backer (2004)

Glitch observed in MSP B1821-24

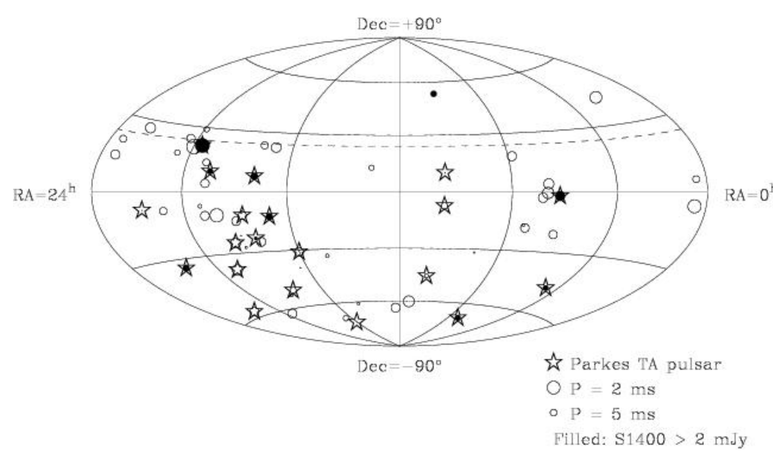
Pulsars are a Galactic population

- Galaxy (0 – 20 kpc)
  - Young pulsars: regions of massive star formation, most found close to the Galactic disk (Galactic plane)
  - Asymmetric SN explosion: pulsars are born with kicks
- Globular Clusters (0 – 50 kpc)
  - Many MSPs are found in globular clusters
  - Interactions between pulsars and the cluster potential make render them useless(?) for PTA work
- Magellanic Clouds (50 kpc)
  - Nearest galaxies
- Other galaxies:
  - **Issue: Sensitivity**
  - **Distance to Andromeda (1 Mpc)**
  - Best bet: giant pulse emission
- **Key point: We don't know distances to pulsars to sufficient precision to form a completely coherent detector!**

Distribution on pulsars on Galactic Plane

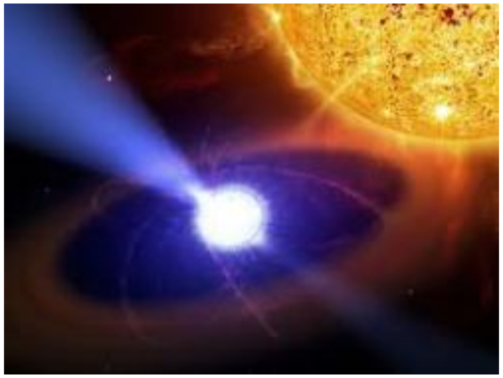


Distribution of PPTA pulsars

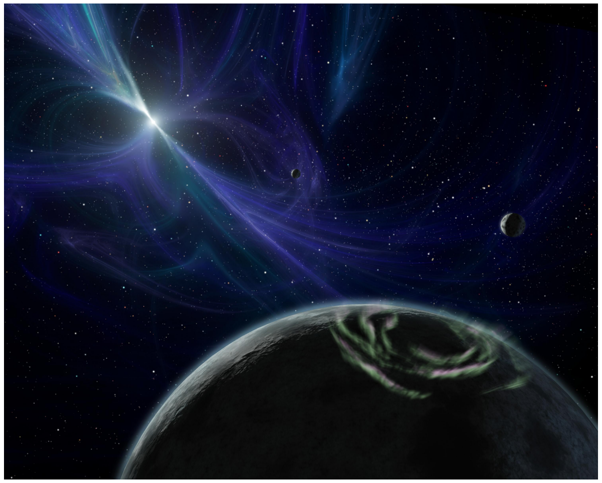


Pulsars have companions

- Most stars are in binary systems
- If SN occurs favourably, star remains bound after the supernova explosion
- Result: neutron star / pulsar with main sequence companion
- As second star evolves off of the main sequence, material will overflow Roche lobe and accrete onto NS
  - Recycling process produces relativistic binaries and MSPs



Artists impression of the PSR B1259-63/LS 2883 system (above) and Pulsar planet system (below)



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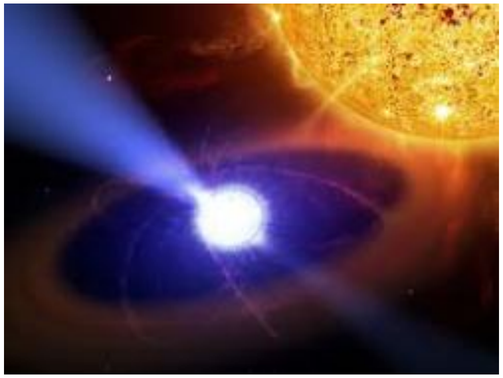
Pulsars have companions

Implications for precision timing:

- Existence of MSPs (good thing)
- Many of the best timing MSPs have WD companions
- Need best model to obtain best TOAs
- Potentially use observations of orbital parameters to detect GWs (Kopeikin 2006)



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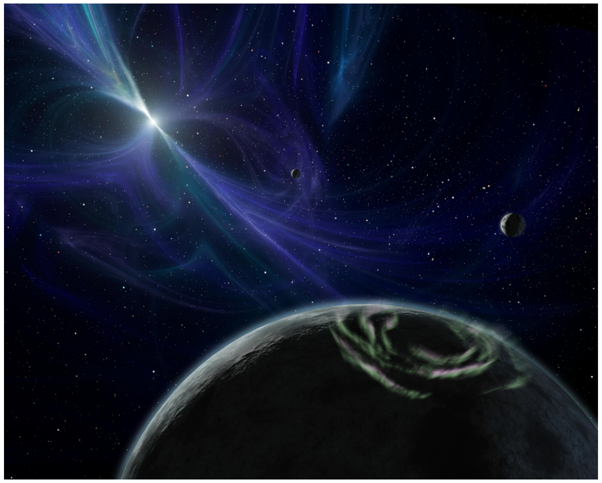
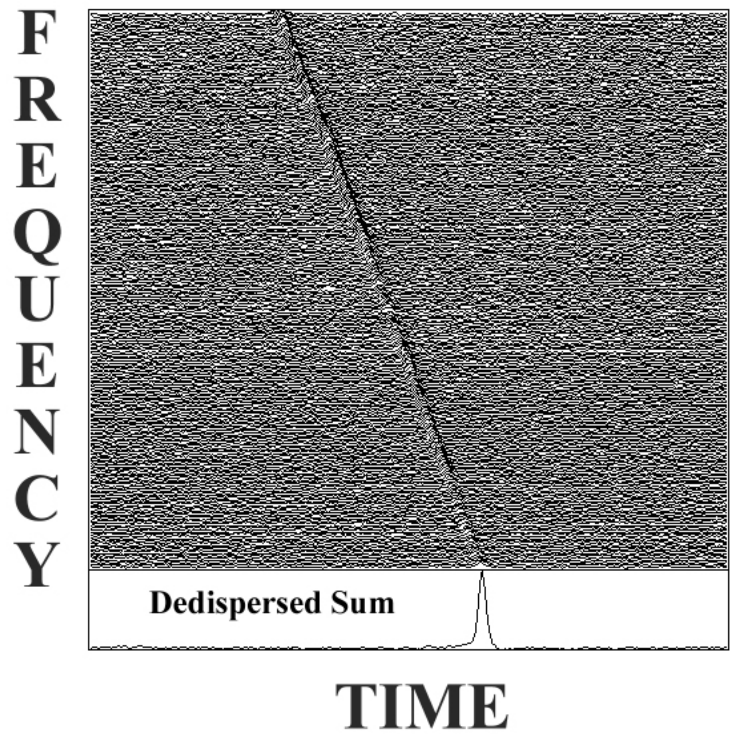


Pulsar radiation is ***dispersed***

- 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).
  - **DM** measured in pc cm^{-3}



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

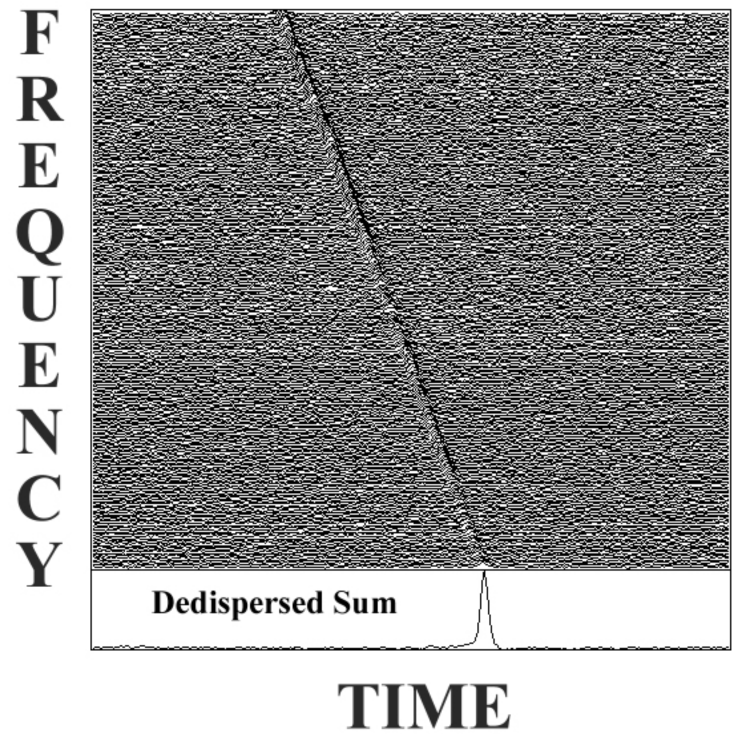
0 < DM < 1200 for known pulsars

The ISM is good

- 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

- Corollary: Distances to pulsars can be estimated from disperson measure.



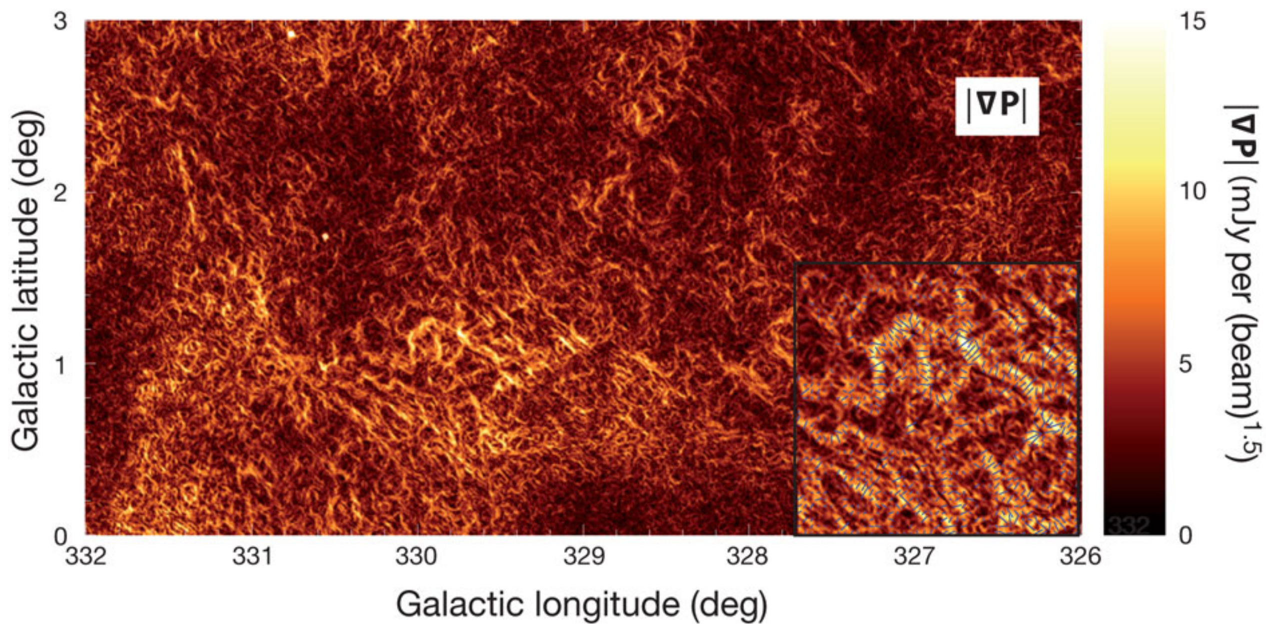
$$\mathrm{DM} = \int_0^d n_e \, dl$$

0 < DM < 1200 for known pulsars

The ISM is evil

- ISM is not perfectly smooth
  - Turbulence: collision cascade
  - Other physical processes / discrete blobs

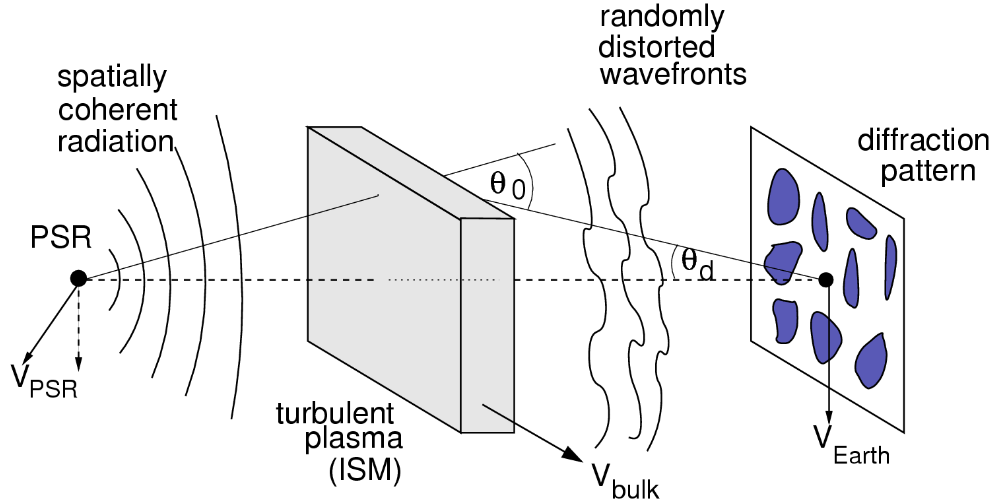
Gaensler et al. (2011)



The ISM is a nuisance

- Density variations -> column density variations as pulsar-earth line of sight samples different patch of ISM

- Density variations variable refractive index
  - **Dispersion measure variations**
  - **Refractive and diffractive** scintillation
  - Pulse broadening / shape distortions



The ISM is evil

- Density variations:
  - Pulsar earth lines of sight samples different patches of ISM
- Density variations variable refractive index
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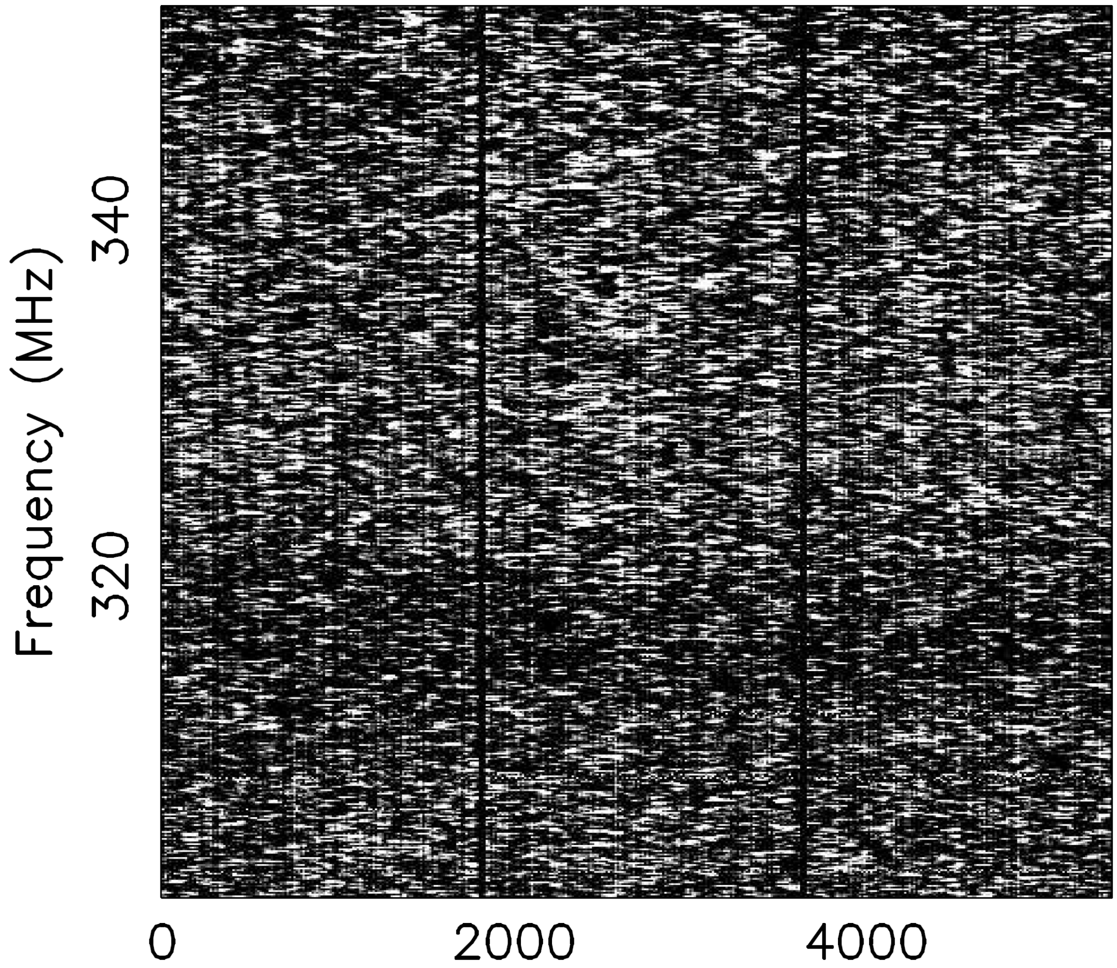

PSR B1737+13
(DM = 49 pc cm^{-3})

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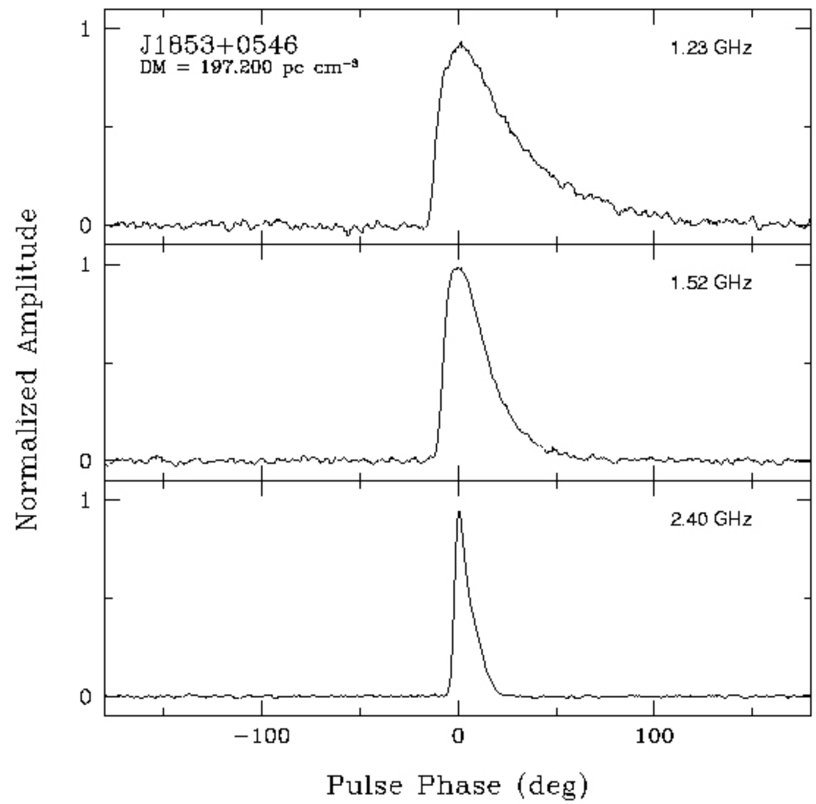
The ISM is evil

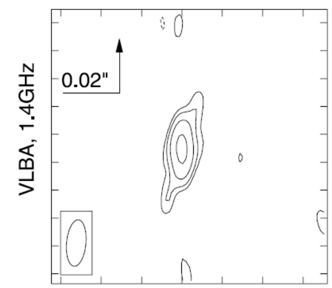
- Pulse Broadening: distortions in pulse shape cause by ISM
- Variations along the line of sight will cause variable levels of pulsar broadening
- Descattering techniques (talks next week by Stinebring, Palliyaguru, Jones)

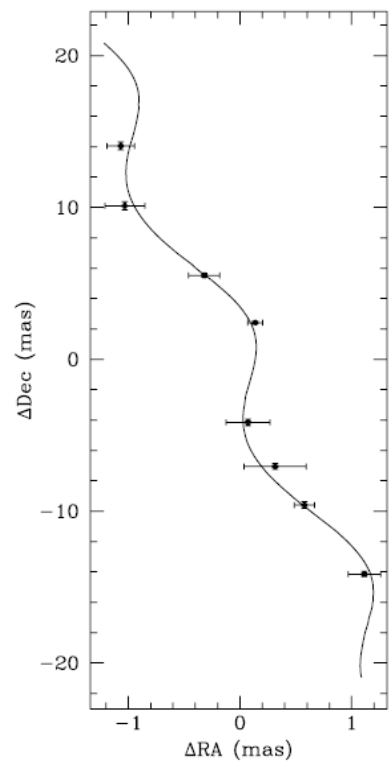


Bhat et al. (2004)

Measuring distances to pulsars

- Standard candle?
  - Can't predict based on P, Pdot how bright pulsar will be
  - Not yet! (Not ever?)
- Astrometric Parallax
  - Very long baseline interferometry to measure variations in pulsar variation in the sky
- Timing Parallax
  - Ingrid's talk
- Dispersion Measure + Model of Galactic structure

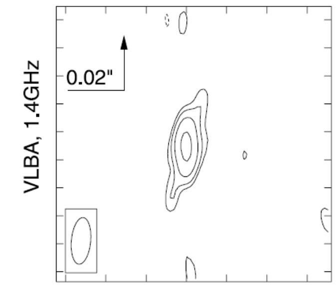




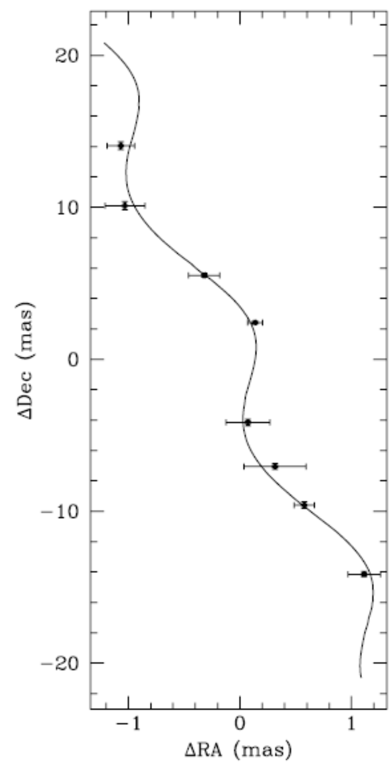
Chaterjee et al. 2009

Measuring distances to pulsars

- Upshot: Don't know distances to sufficient precision as a phase coherent detector of GWs
  - Need to know distance to fraction of wavelength of GW (less than a light year in our case)



Contours = 2.0 mJy * (-2, -1, 1, 2, 4, 8, 9.5)



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Why do we use MSPs for Timing Arrays?

Why canonical pulsars are good:

- On average brighter than MSPs

Why canonical pulsars are bad:

- Glitches and Timing Noise **(biggest reason)**
- Jitter is more severe
- Wide pulses (in absolute sense):
  - Timing precision is proportional to pulse width

- What type of MSPs are the best?
  - Non-eclipsing systems
  - Bright (why not observe at lower RF?)
    - Sky background larger
    - ISM effects worse
  - Low levels of timing noise
    - Do MSPs show spin timing noise?

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Physics with pulsars and how it relates to the PTA

- Goal: obtain most precise TOAs
  - In order to obtain the best TOAs, we want the best possible model for the system
- General relativity
  - Weak field: PTA
  - Strong field: relativistic binaries
- Nuclear/condensed matter physics
  - What are neutron stars made of?
  - Physical models of timing noise.
- Electrodynamics
  - Pulsar magnetosphere: How do pulse profiles vary with frequency?
  - Wave propagation in ISM: How badly does the ISM mangle TOAs, how well can we correct it.
- Astrophysics:
  - MSP population: How many good timing array pulsars are out there?
  - Galactic structure: What is the origin of the structures that cause interstellar scintillation?

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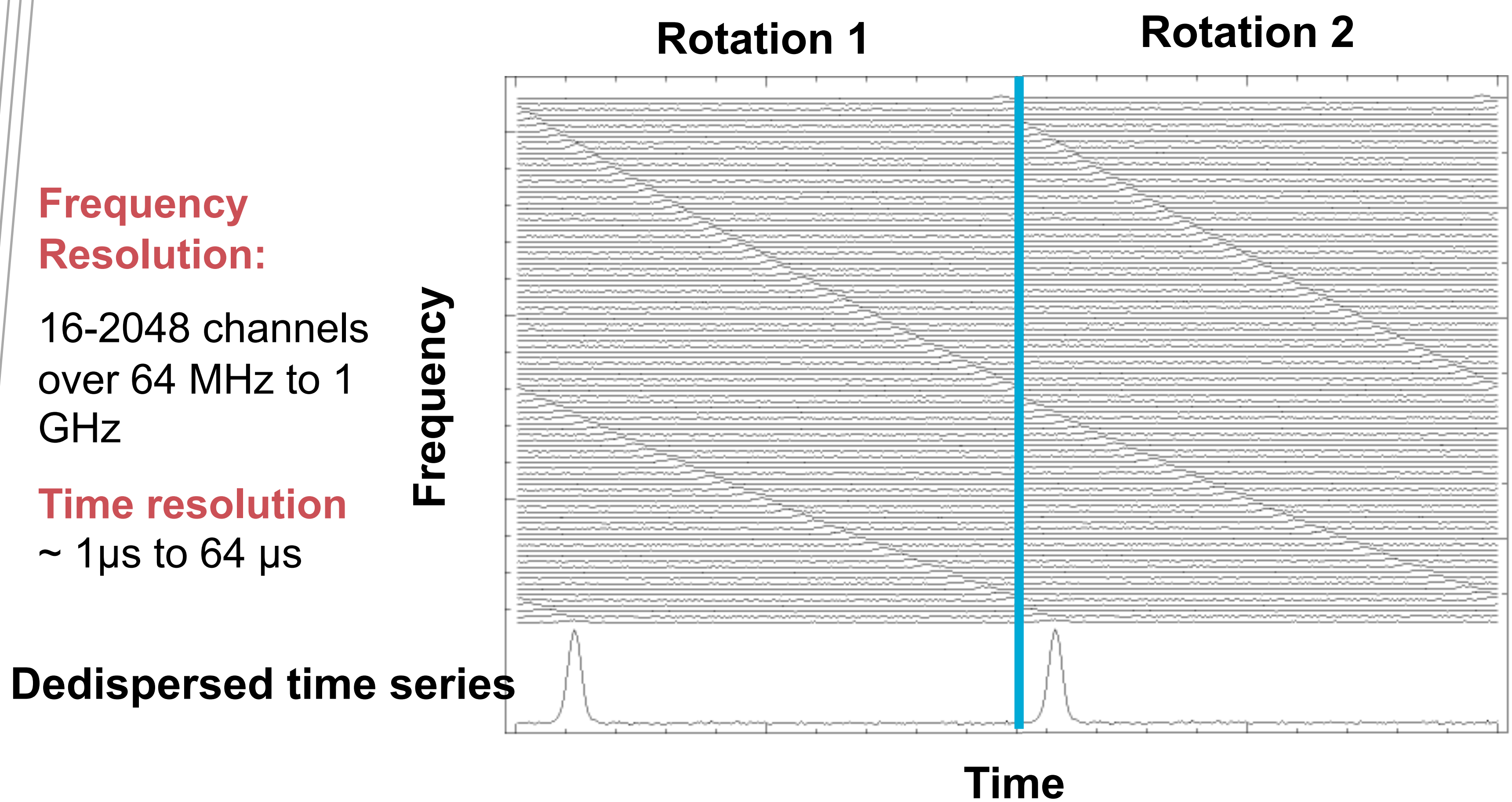
Any questions?

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

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.

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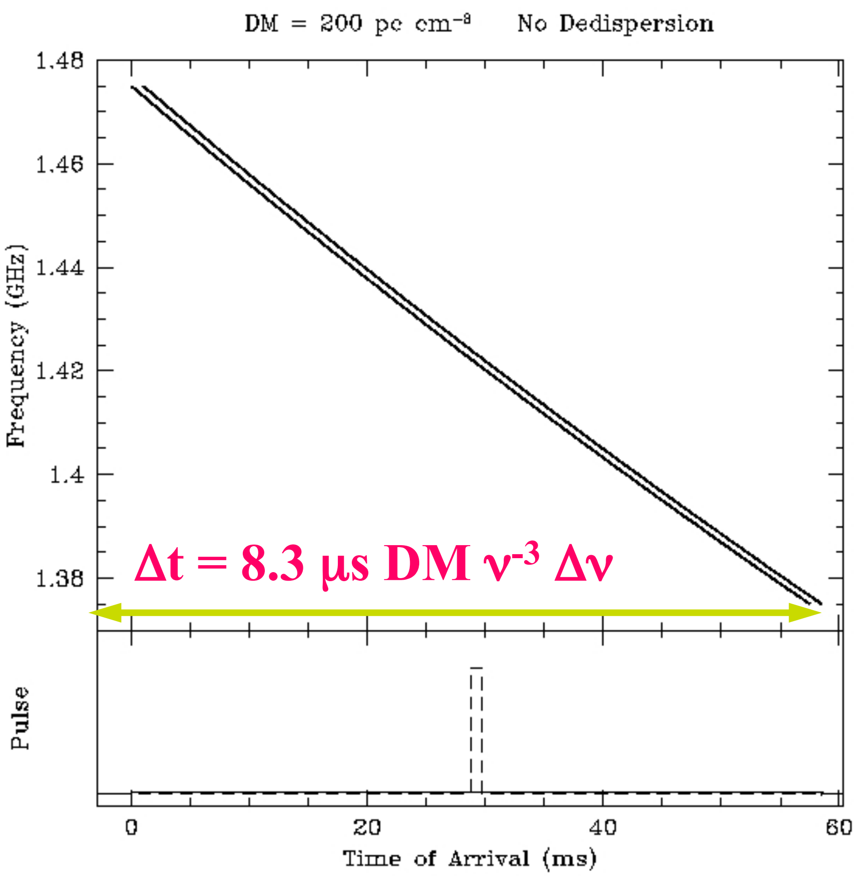
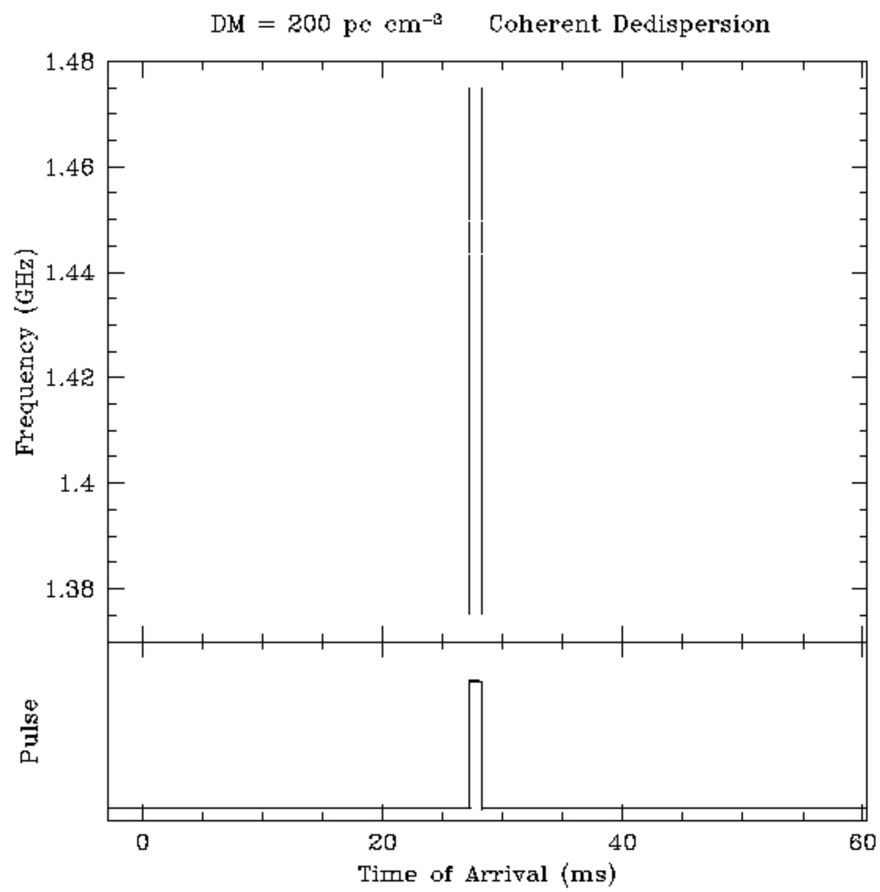
Dispersed Pulse Coherently dedispersed pulse





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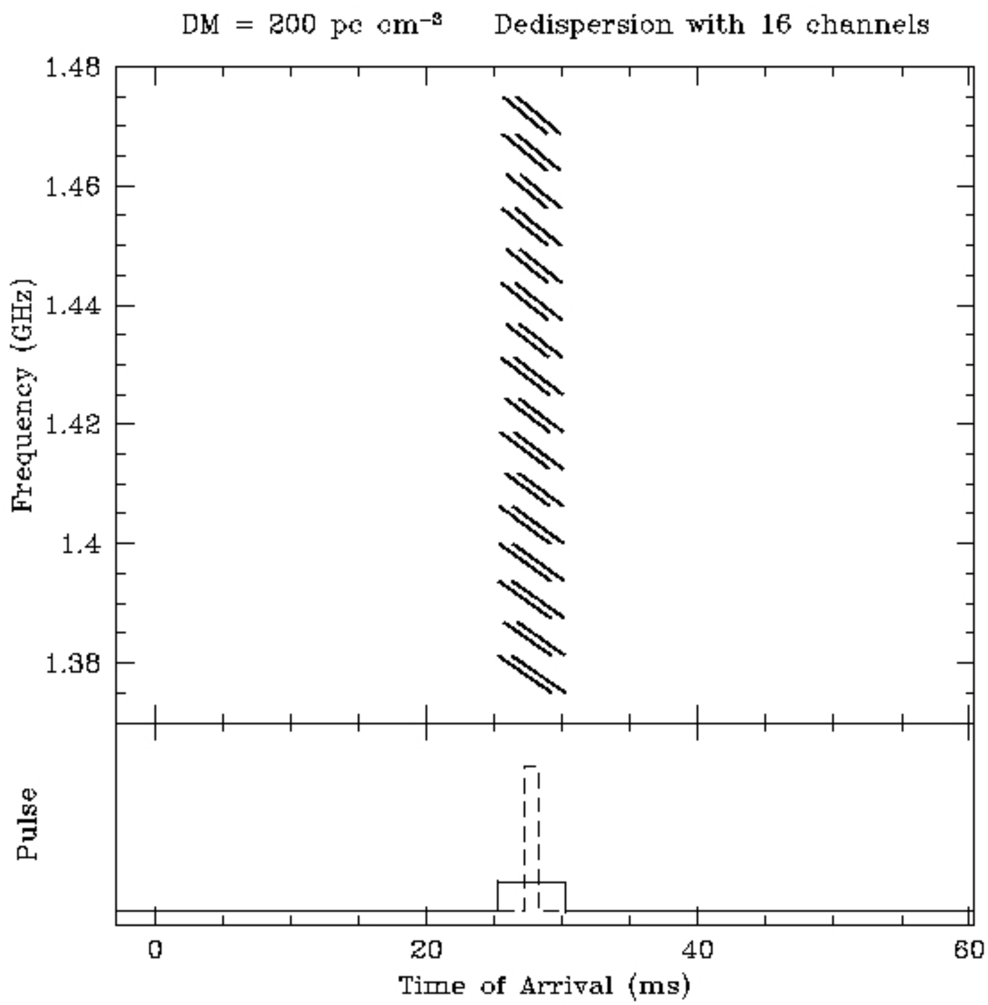
Post-detection Dedispersion: Sum intensity over frequency after correcting for dispersion delay



Residual time smearing:

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

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

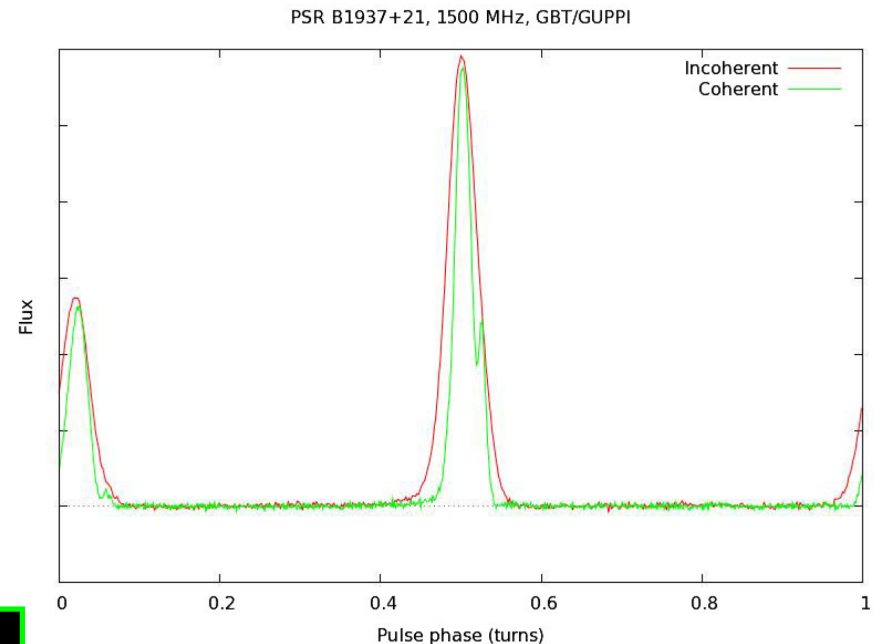
$\Longrightarrow$ minimum smearing time across a channel when

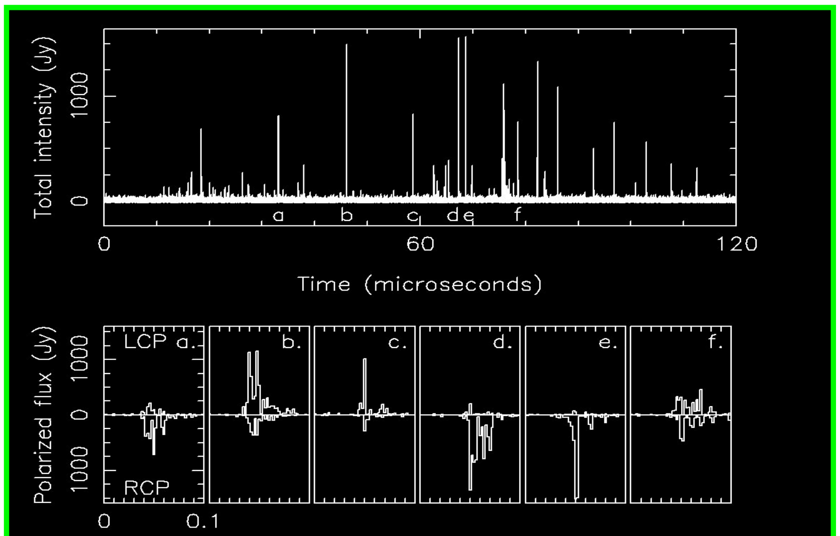
$$\Delta\nu = \left[8.3\ \mu{\rm s}\,{\rm DM}\nu^{-3}\right]^{-1/2}$$

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)!

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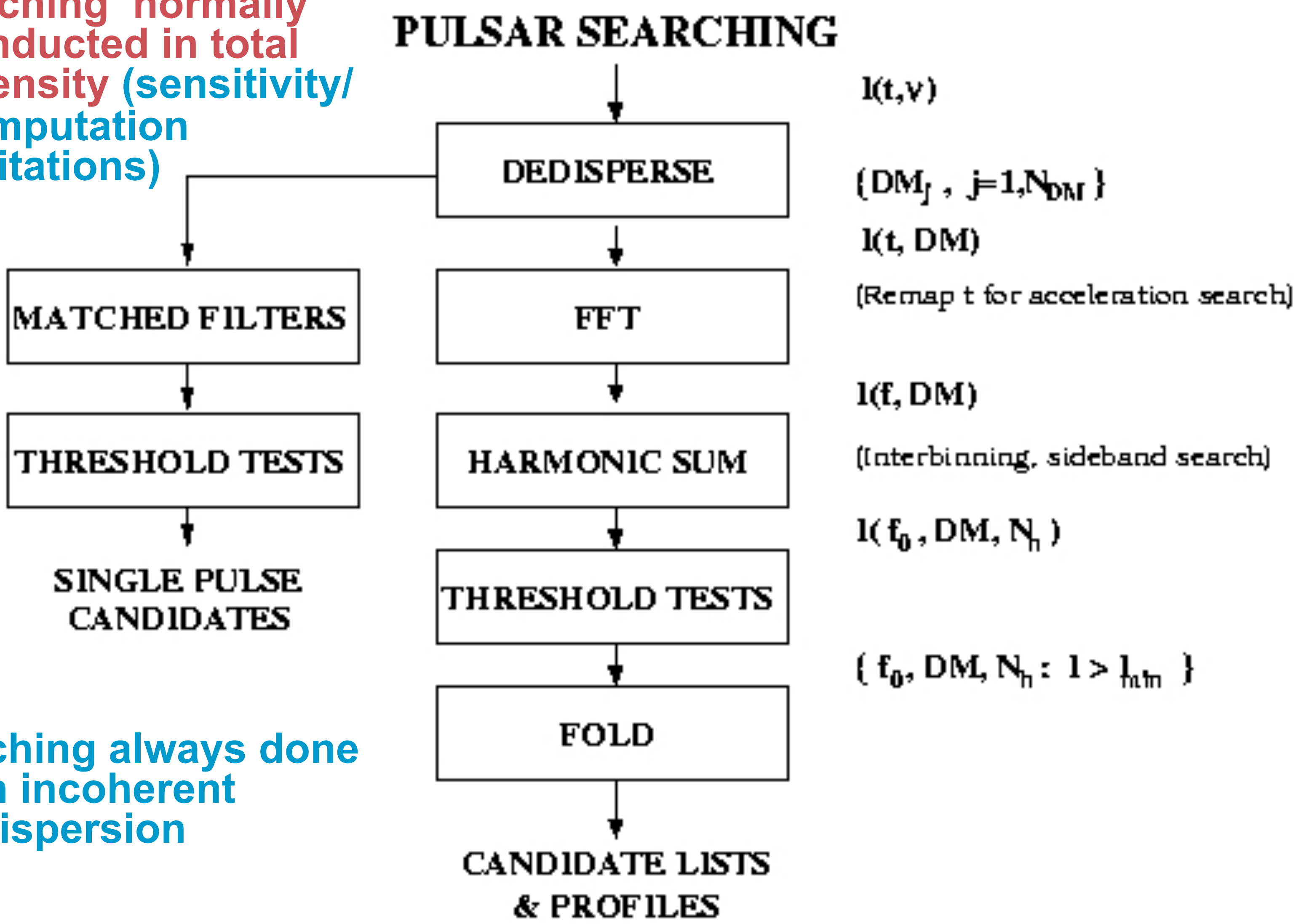
Searching for Pulsars: Flow Chart

- 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:

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

Sum over harmonics

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

$$S_{\mathrm{min}_1} = m \times \sigma_{\mathrm{radiometer}}$$
$$m \approx 10$$

$$S_{\mathrm{min}} = \frac{S_{\mathrm{min}_1}}{h(N_h)}$$

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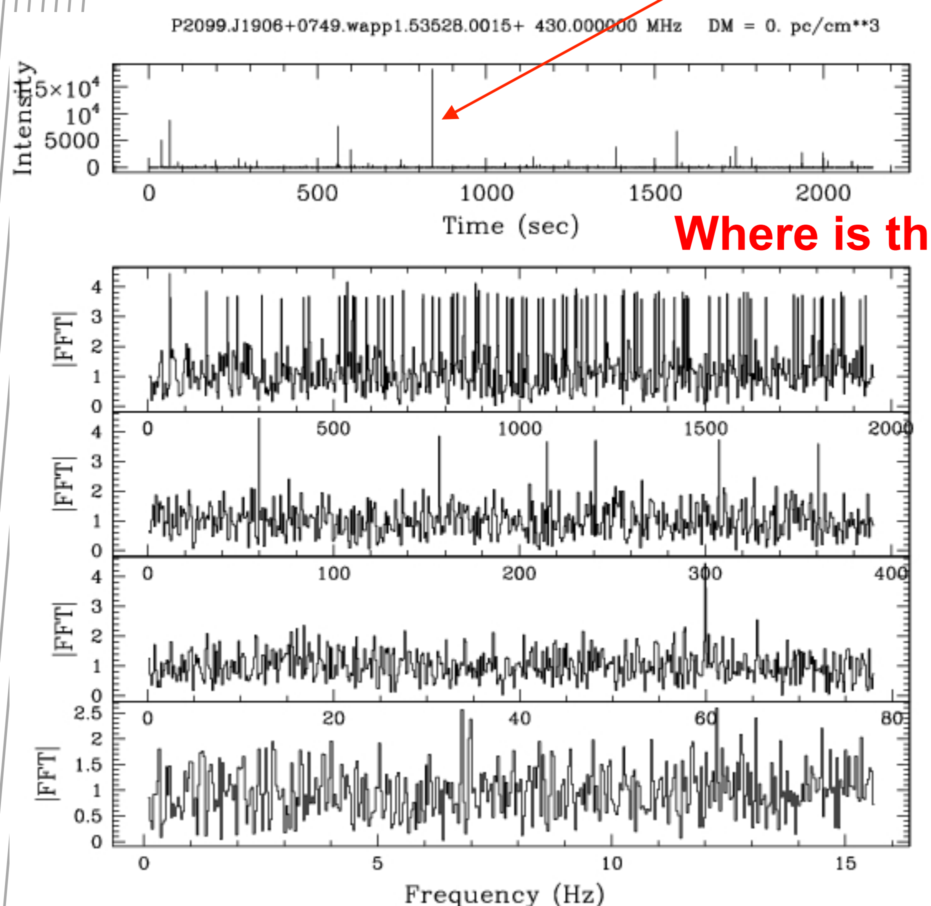
Example Time Series and Power Spectrum for a Pulsar discovery

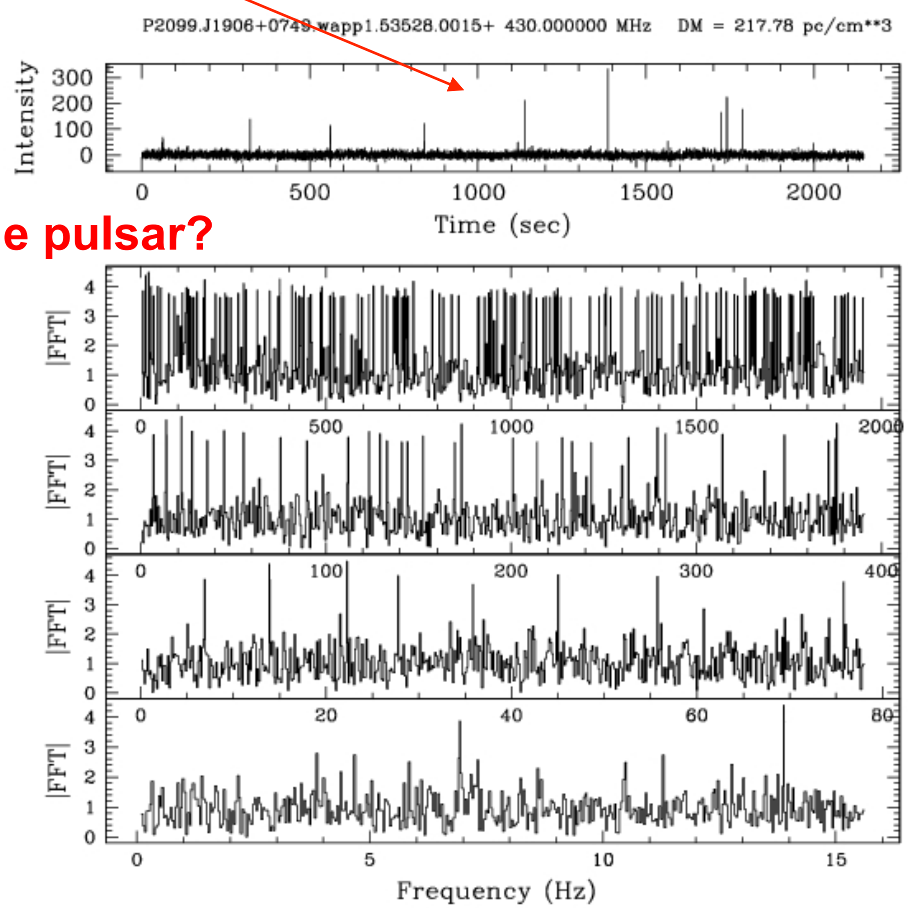
DM = 0 pc cm^{-3}

Time Series

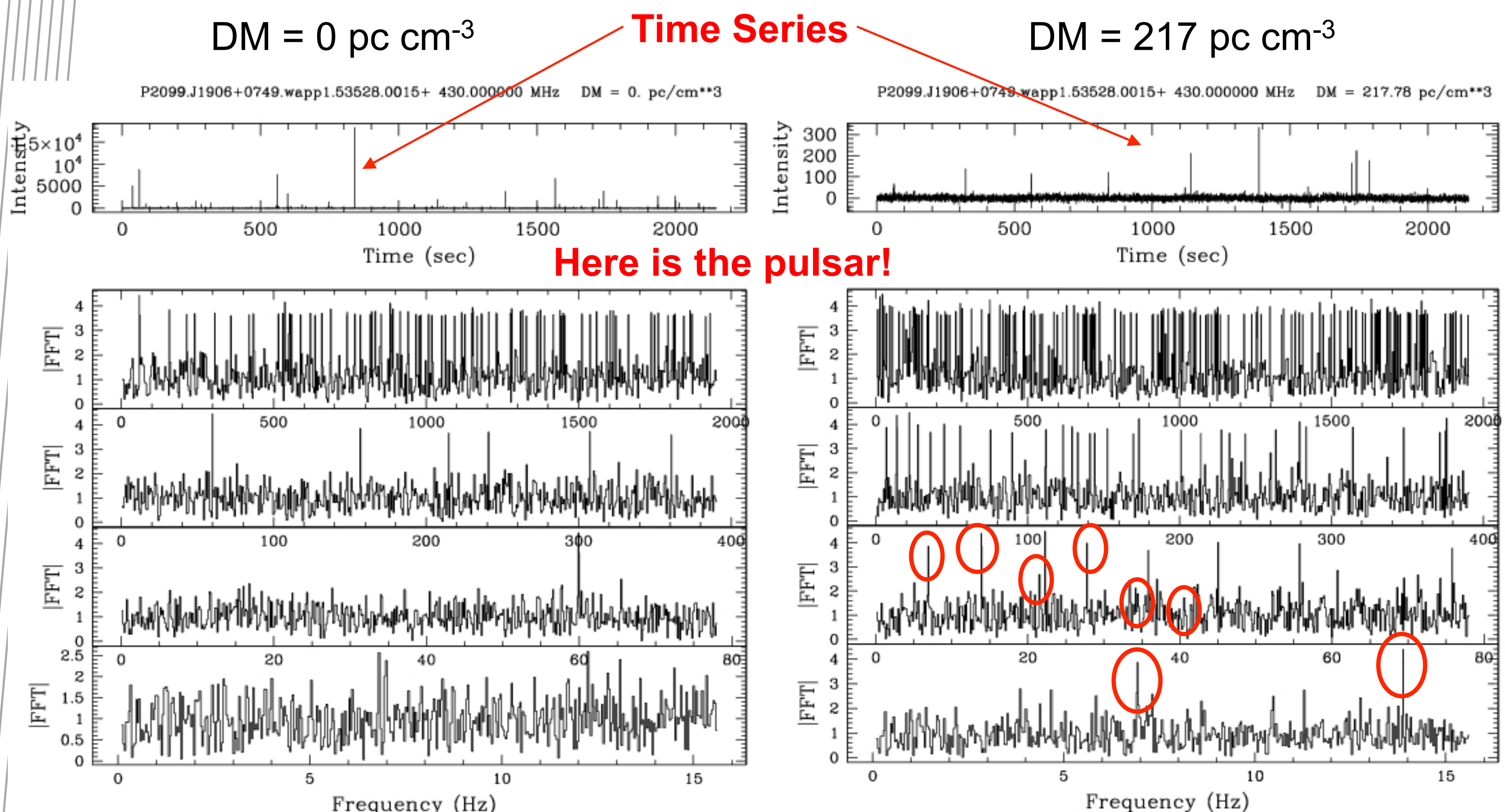
DM = 217 pc cm^{-3}



Where is the pulsar?



Example Time Series and Power Spectrum for a PALFA discovery



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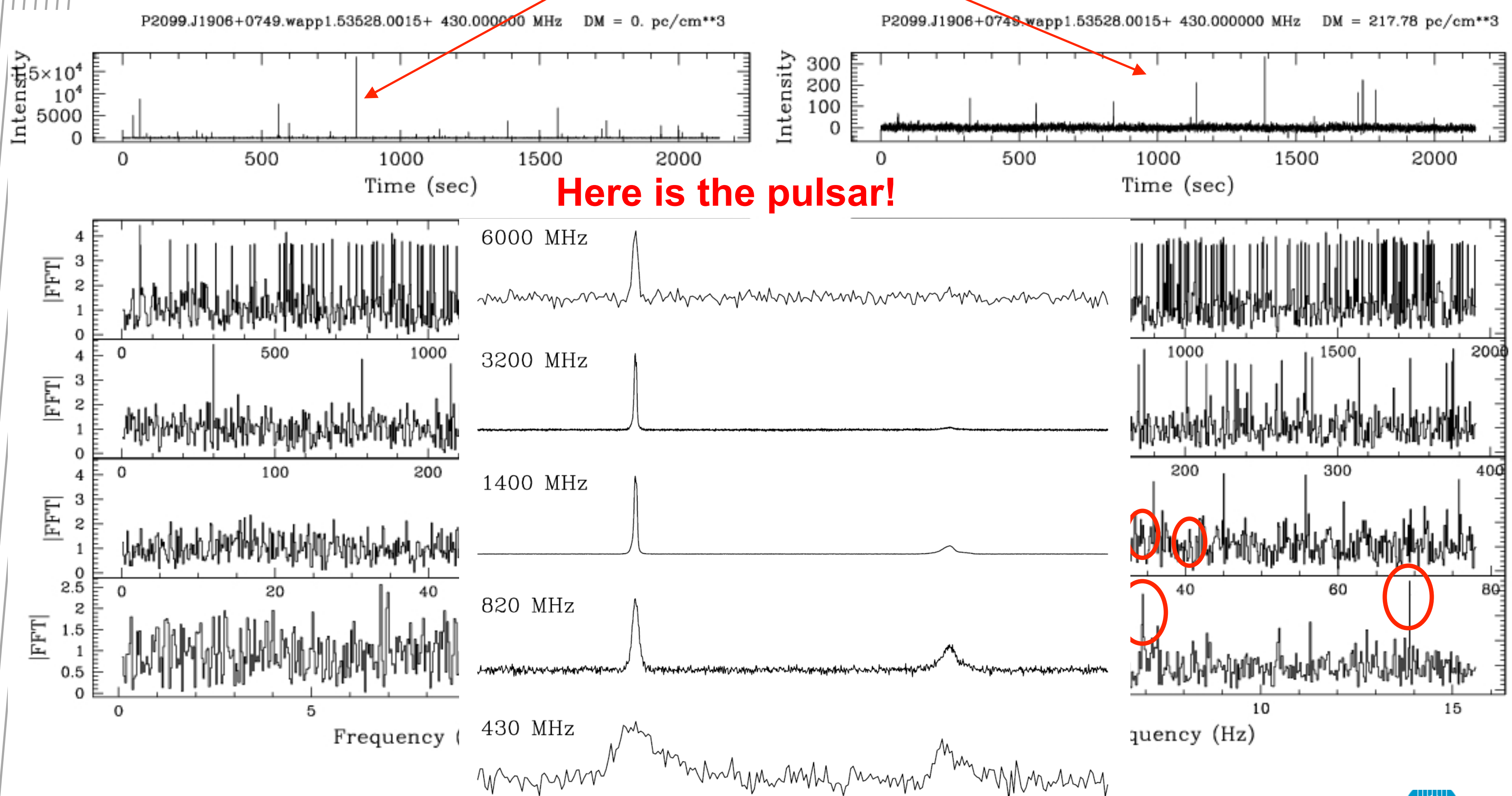
Example Time Series and Power Spectrum for a PALFA discovery

DM = 0 pc cm^{-3}

Time Series

DM = 217 pc cm^{-3}



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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)

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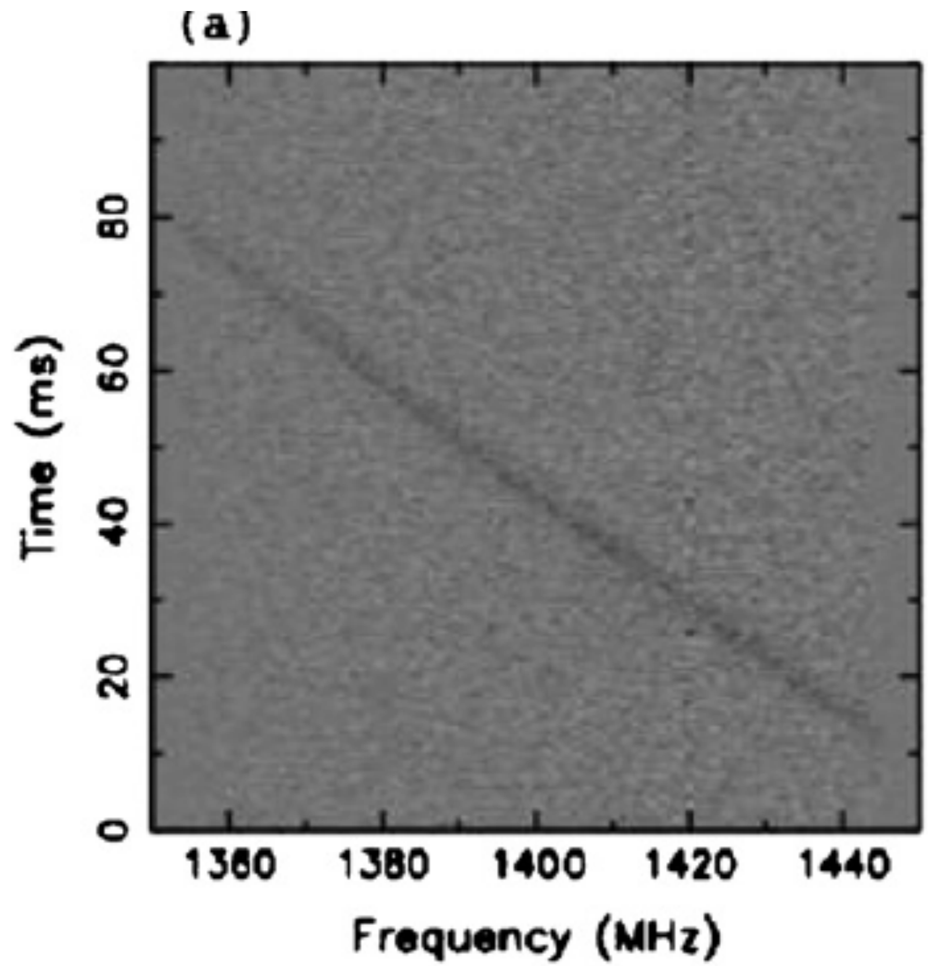
Single Pulse Searches

- 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



Example of bursty emission

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)
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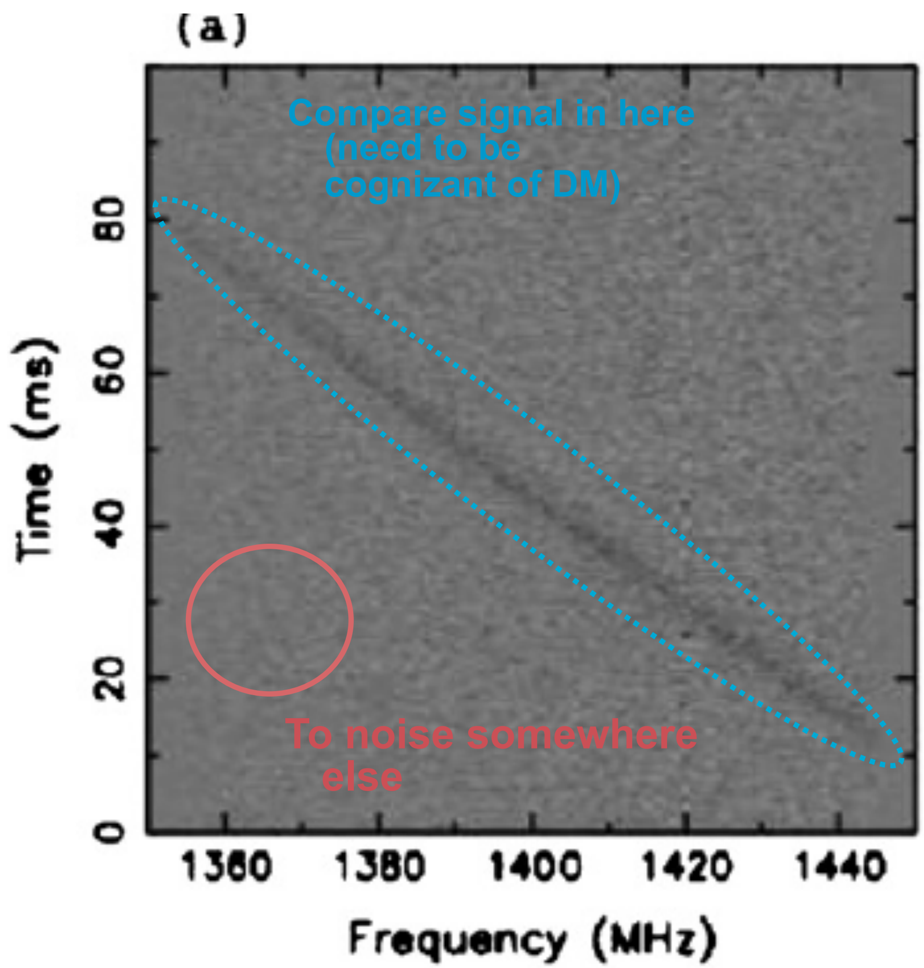
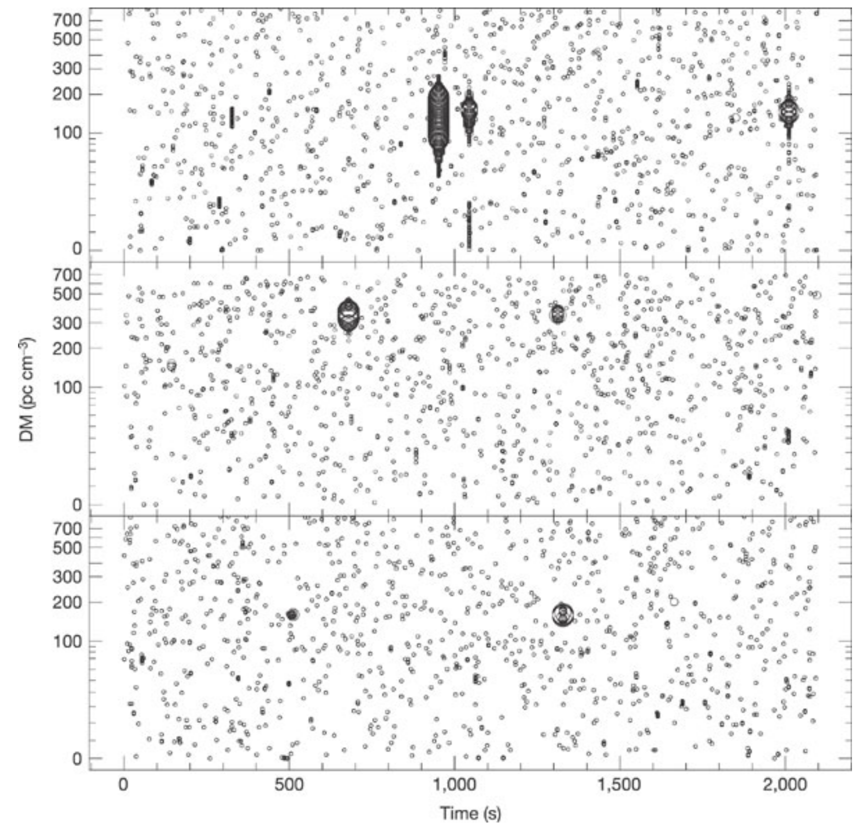


Example: Single Pulse Search

Use a matched filter template to search for dispersed pulses.

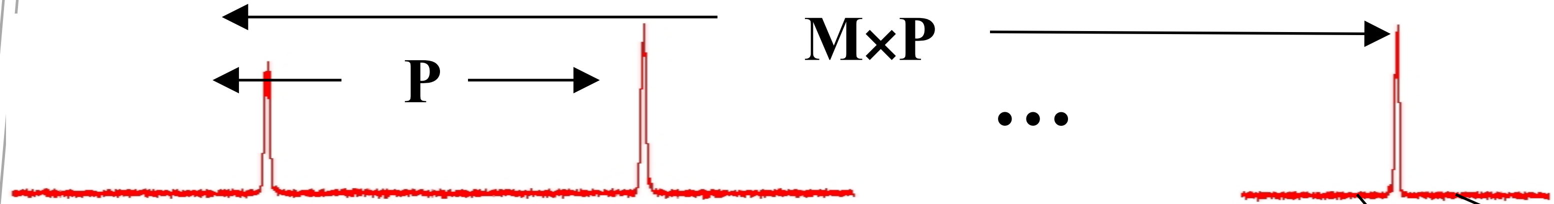
Plot event SNR versus DM

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

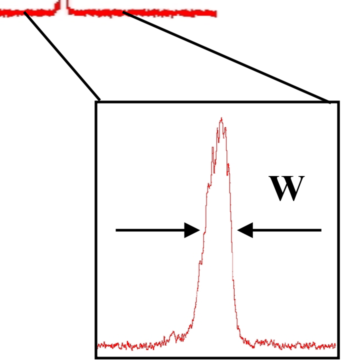


Size of circle denotes event signficance. McLaughlin et al. (2006)

Pulsar Timing: The Basics of Pulsars as Clocks



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



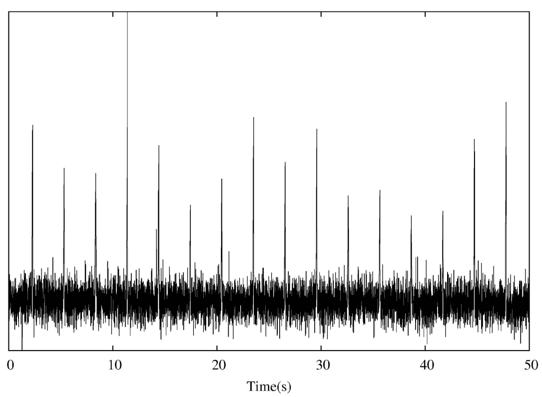
$$t_j = \mathrm{TOA} + \delta\mathrm{TOA}$$
$$\delta\mathrm{TOA} \sim \frac{W}{\mathrm{S/N}} \sim 0.1\,\mu\mathrm{s\ to\ 1\ ms}$$

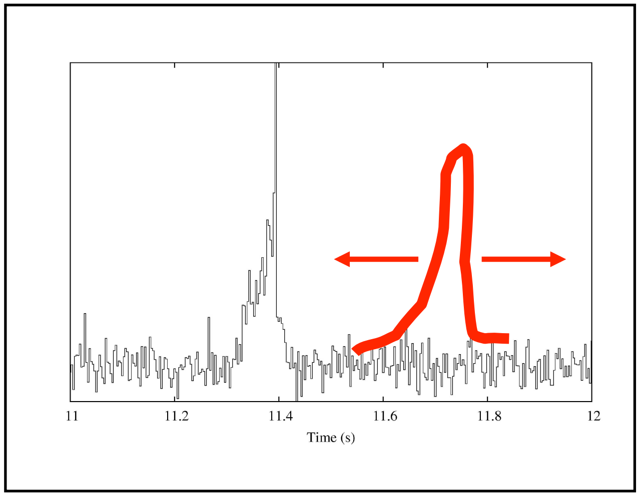
- Repeat for L epochs spanning N=T/P spin periods (T=years)
- N ~ $10^8 - 10^{10}$ cycles in one year
- Period determined to $\delta P \sim \frac{\delta TOA}{N} \sim 10^{-16}$ to 10^{-14} s

- 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
    - $C_{UT}(\tau) = U(t)*T(t+\tau) = aC_{TT}(\tau\text{-}t_0) + T(t+\tau)*n(t)$
    - $C_{UT}(\tau)$ maximizes at $\tau_{max}=t_0$ <u>in the mean</u>
    - Error in τ_{max} is due solely to n(t)

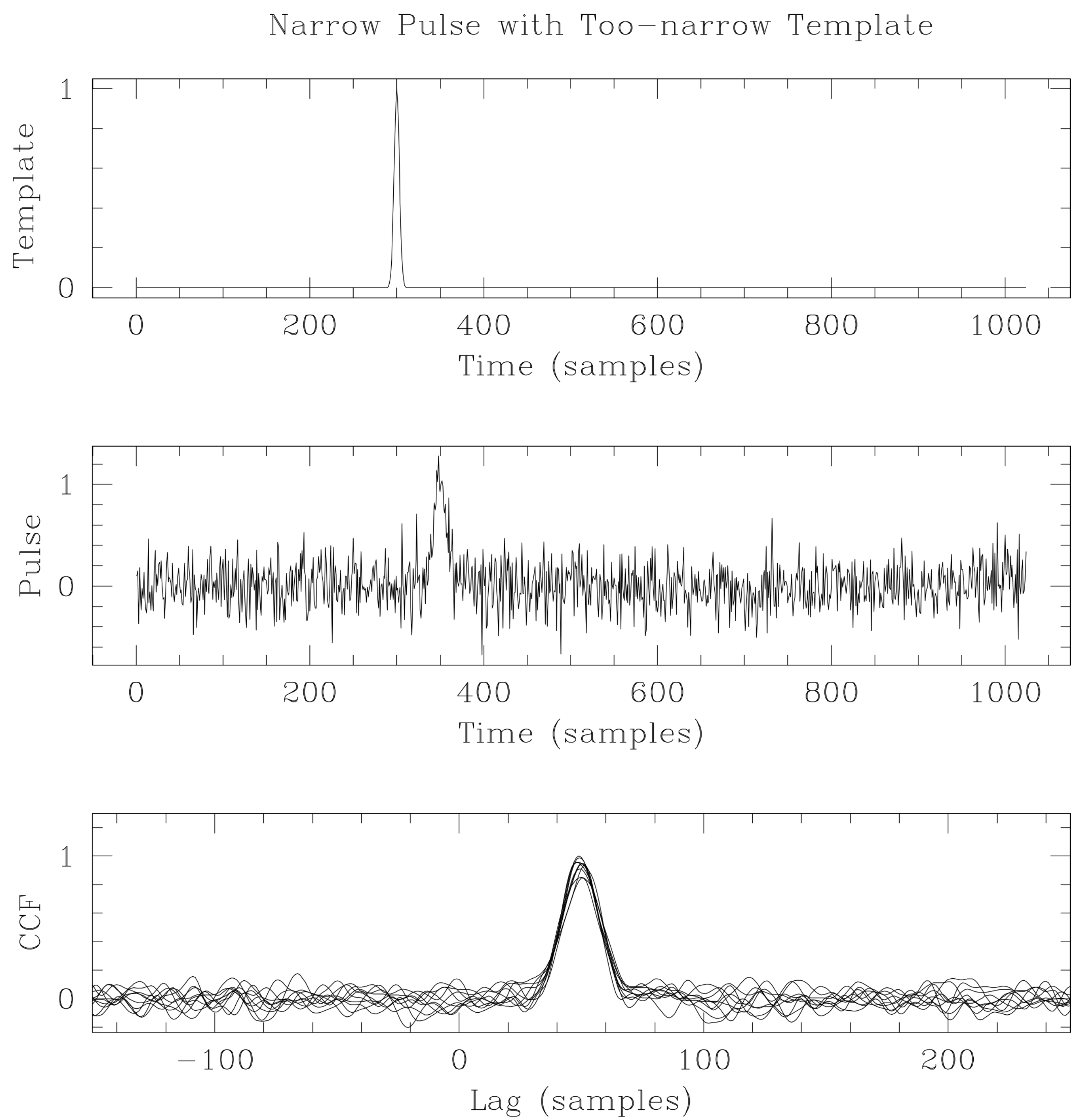




Realities of Matched Filtering (Template Fitting)

- 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 exactly 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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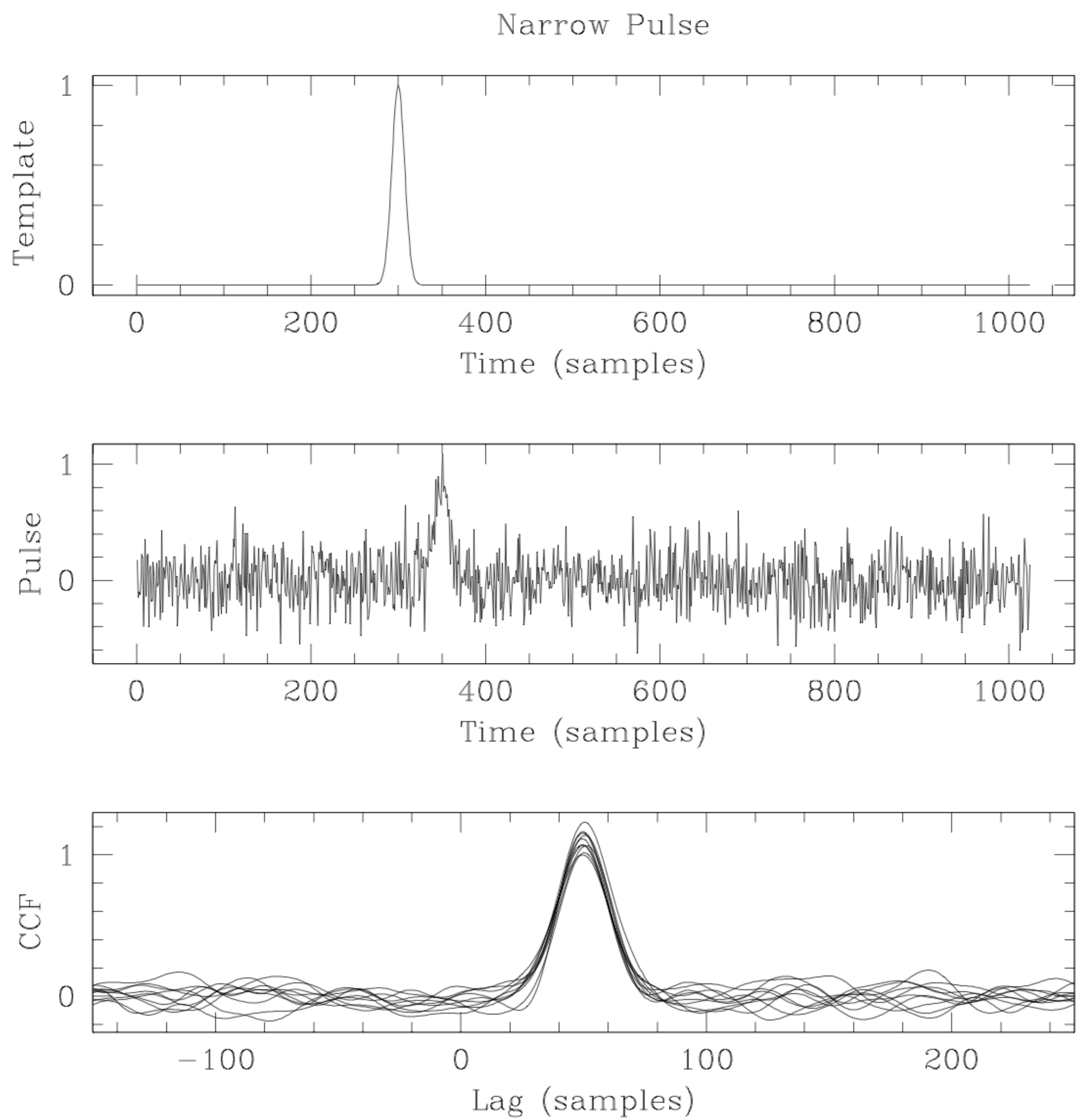

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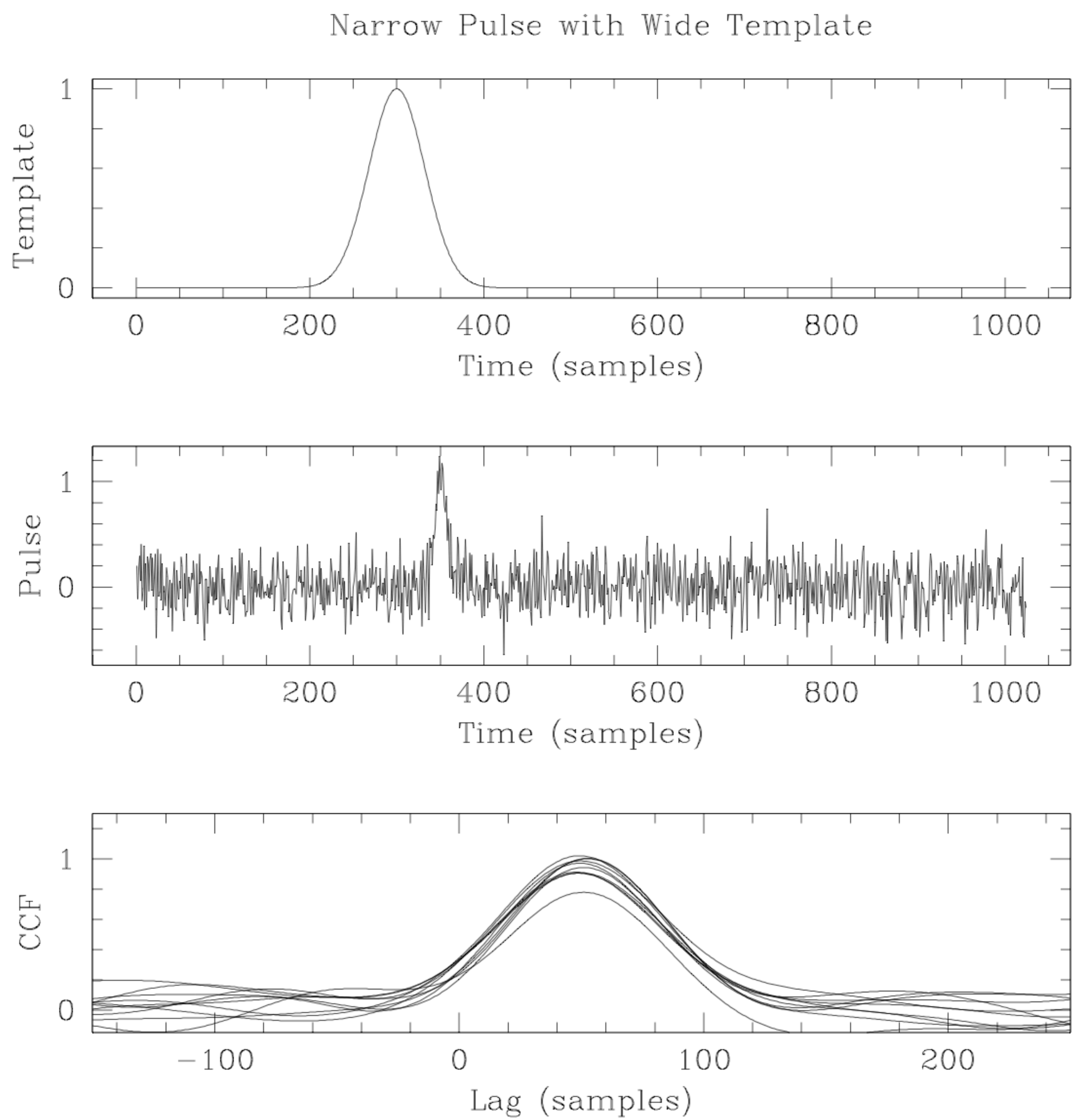
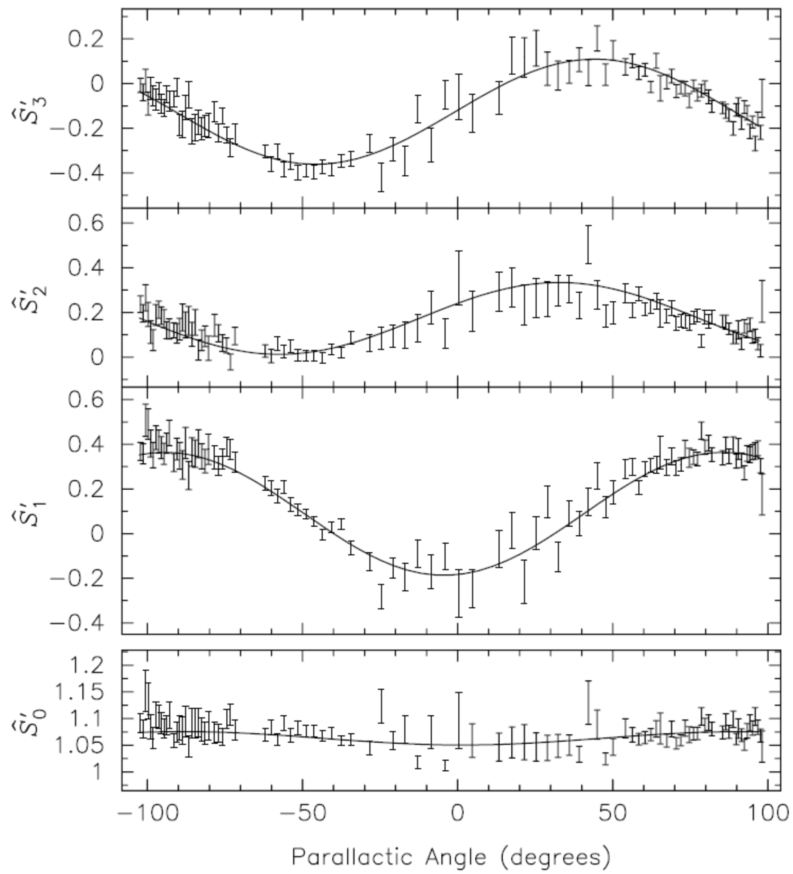


Example 1: Forming Calibrated Pulse Profile

- **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).

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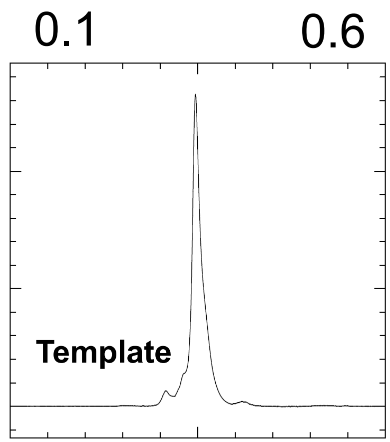
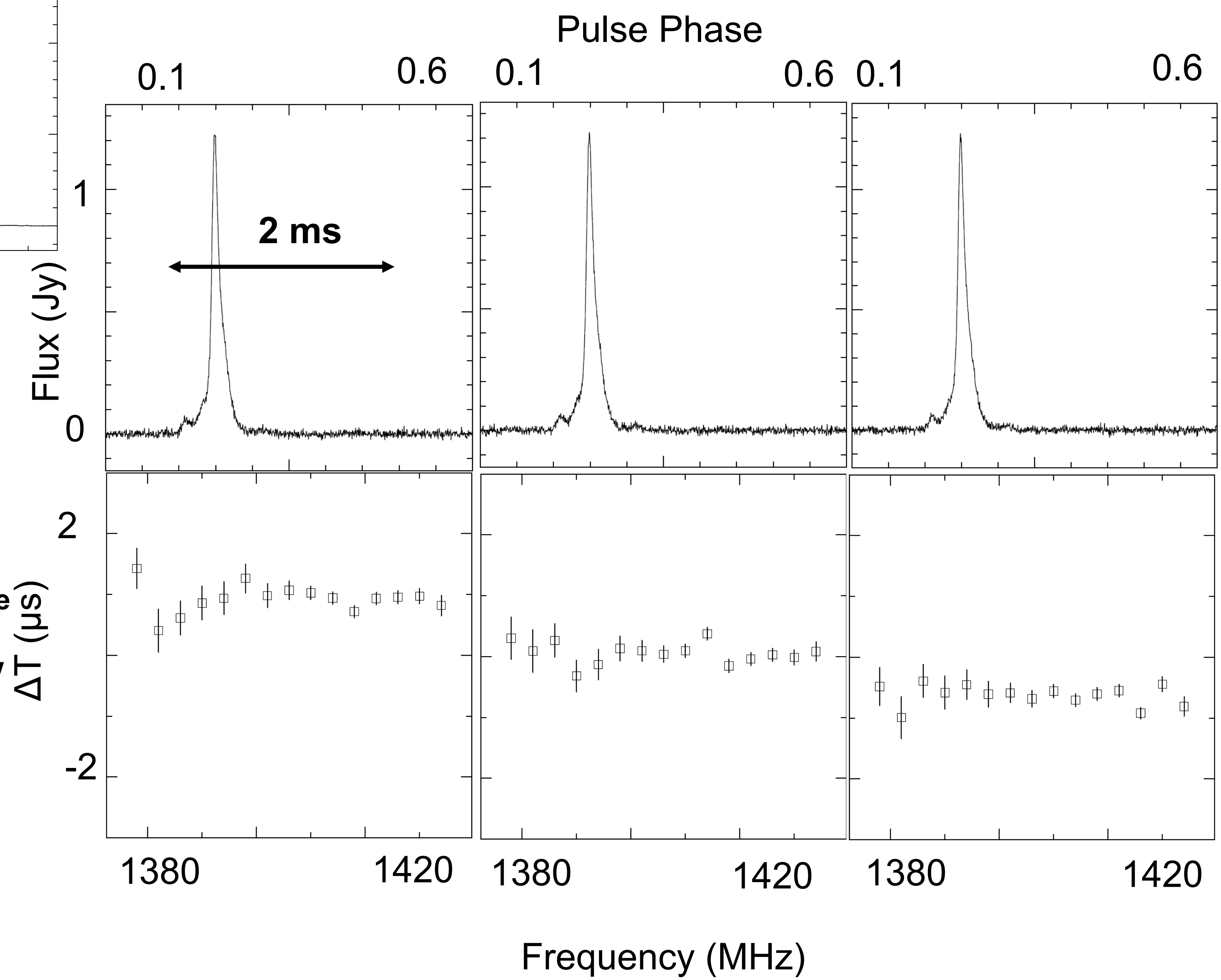
Example 2: Pulse Shape Variations





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

$t_e = t_r – D/c^2$

$+ DM/\nu^2$

$+ \Delta_{R\odot} + \Delta_{E\odot} + \Delta_{S\odot}$

$- \Delta_R - \Delta_E - \Delta_S$

$+ \delta TOA_{ISM}$

$+ \delta TOA_{\text{orbit noise}}$

$+ \delta TOA_{\text{spin noise}}$

$+ \delta TOA_{\text{grav. waves}}$

$+ \ldots$

Path length

Plasma dispersion (ISM)

Solar system (Roemer, Einstein, Shapiro)

Binary pulsar (R,E,S delays)

ISM scattering fluctuations

Orbital perturbations

Intrinsic spin (torque) noise

Gravitational wave backgrounds

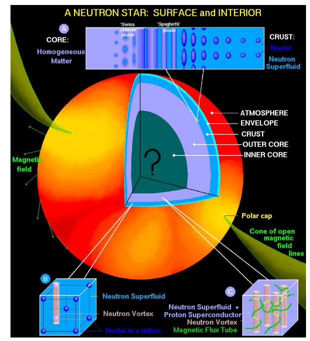
What influences pulse arrival times?

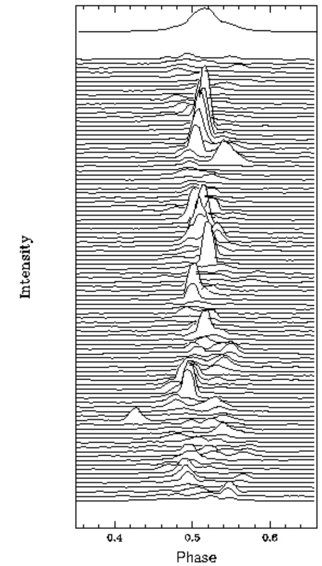
- Pulsar spindown
- ***Stochastic spindown variations***
- **Intrinsic variation in shape and/ or phase of emitted pulse (jitter)**
- **Reflex Motion from companions**
- ***Gravitational Waves***
- Pulsar position, proper motion, distance
- ***Warm electrons in the ISM***
- Solar system
  - Mass of planets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

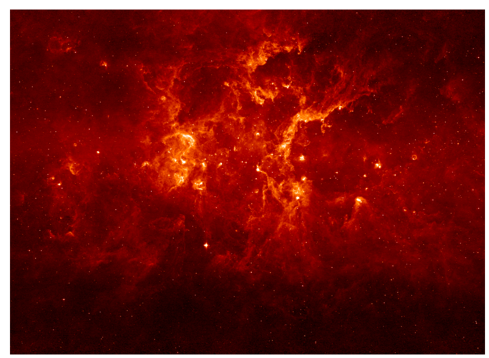
Pulsar

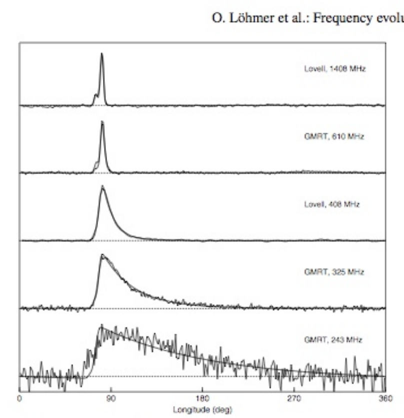
Earth

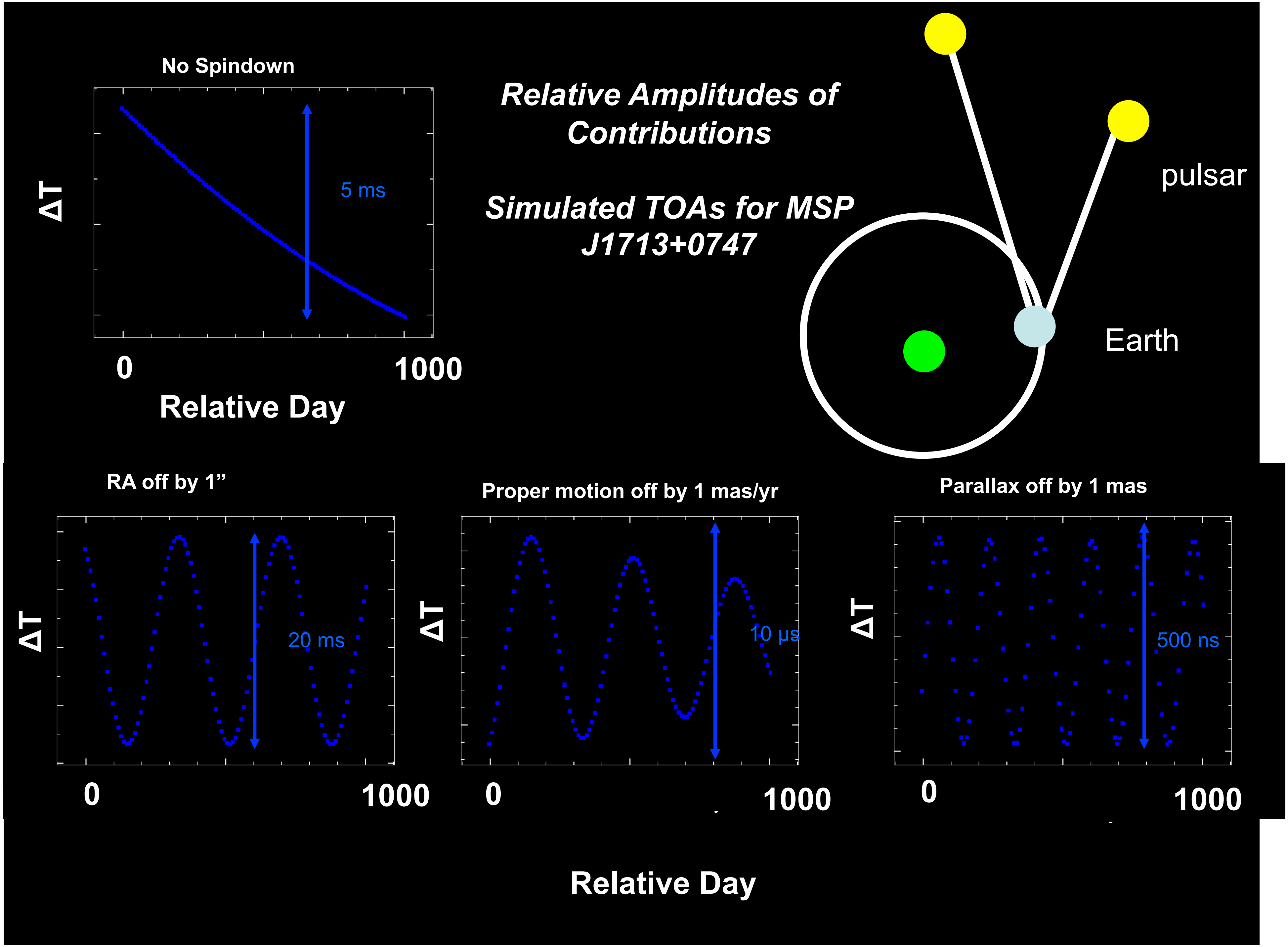
Goal: including as many of the perturbations as possible in timing model.

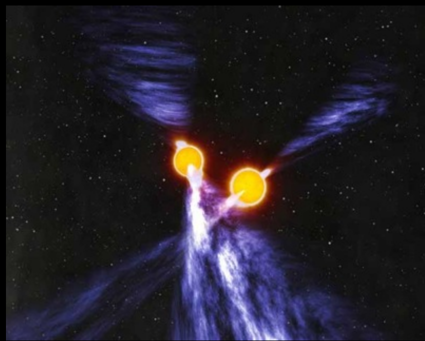






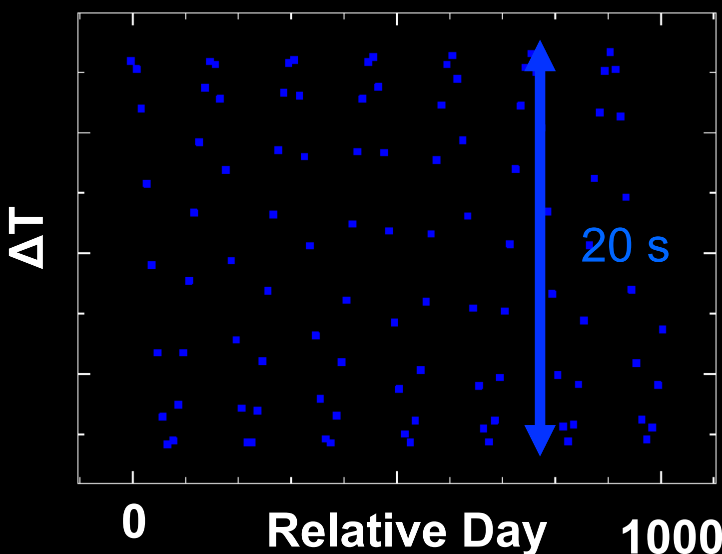


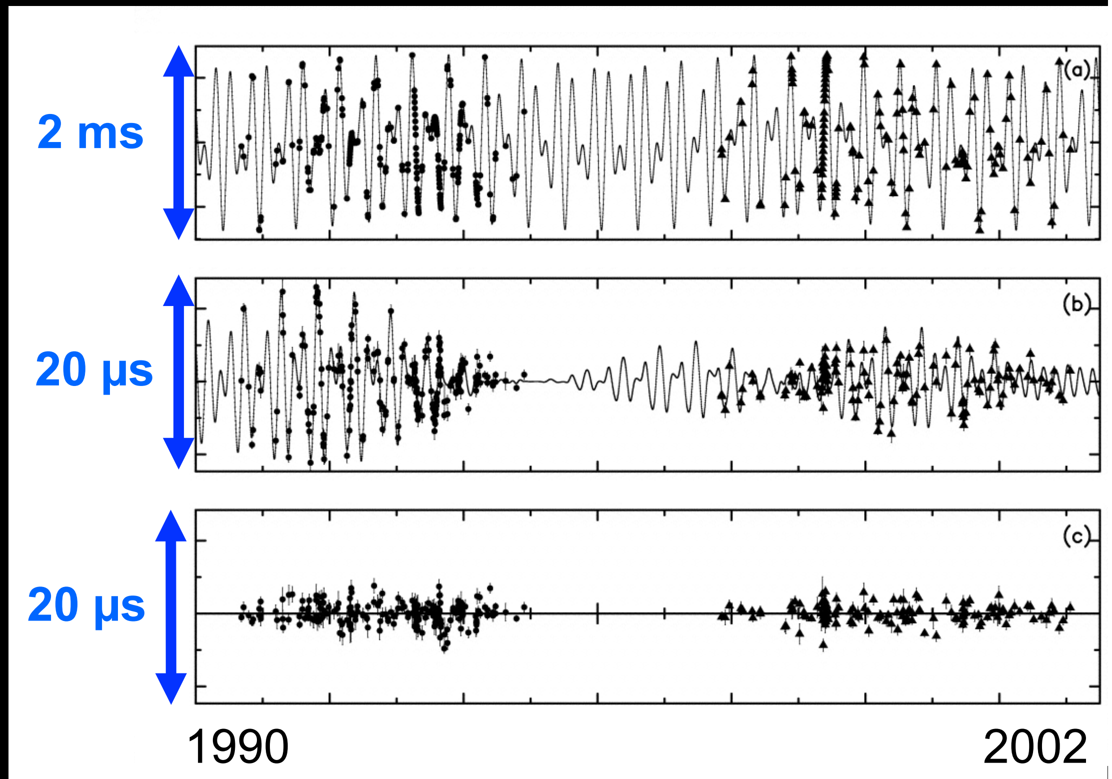

Relative Amplitudes of Contributions
Simulated TOAs for MSP J1713+0747
No Spindown
ΔT
5 ms
0
1000
Relative Day
pulsar
Earth
RA off by 1"
ΔT
20 ms
Proper motion off by 1 mas/yr
ΔT
10 μs
Parallax off by 1 mas
ΔT
500 ns
0
1000
0
1000
0
1000
Relative Day



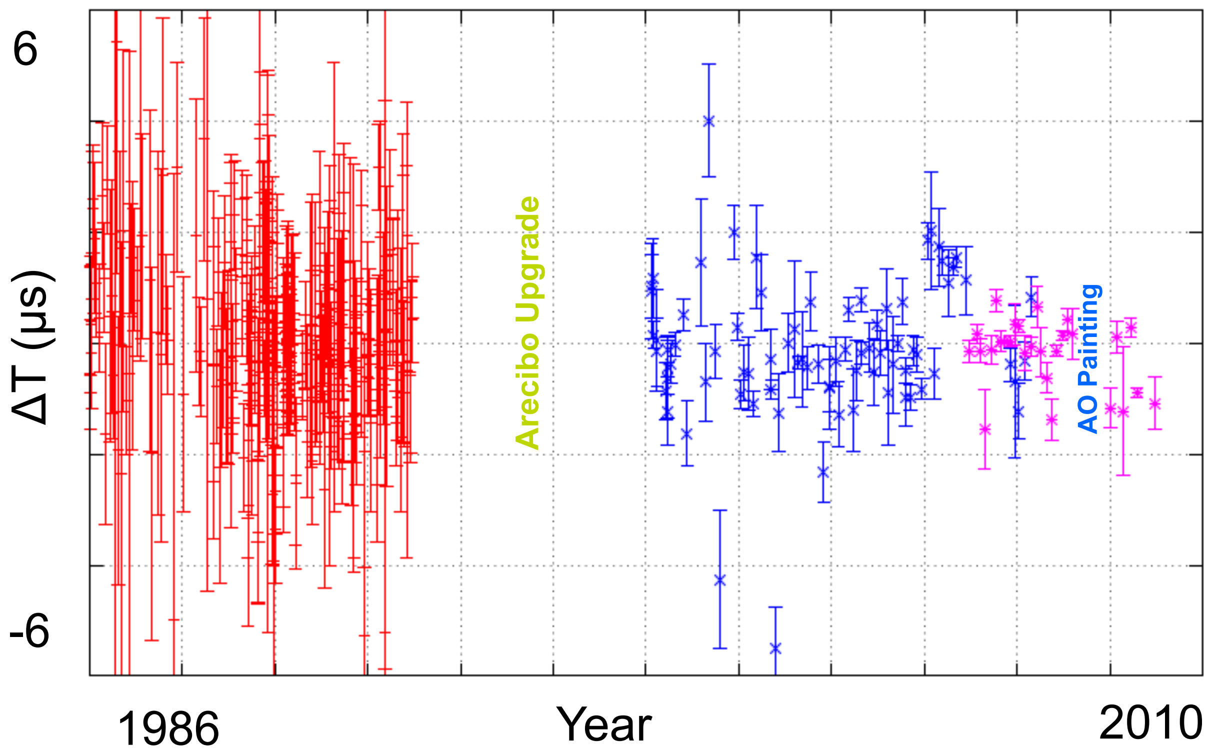
Konacki & Wolszczan (2004): Three planets around MSP B1257+12: 4.3 M_{Earth}, 3.9 M_{Earth}, and 0.02 M_{Earth}

Massive (white dwarf) companion



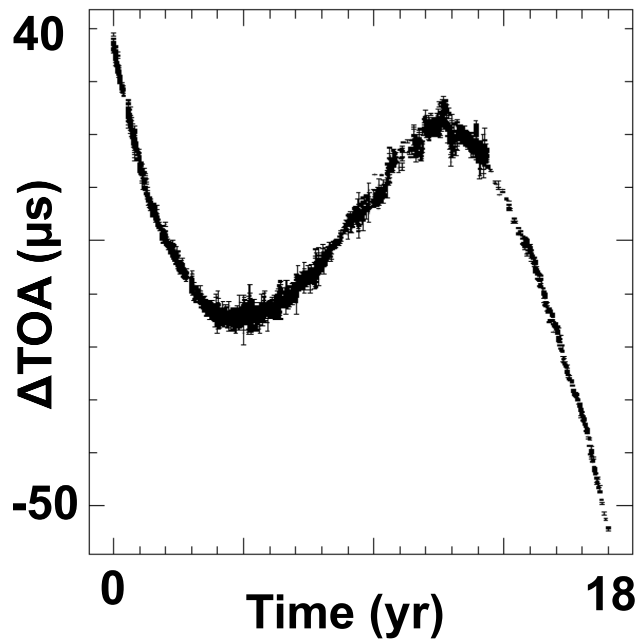


Example: What pulsar residuals ought to look like: PSR B1855+09



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

Example: What Residuals from Most Pulsars Look Like



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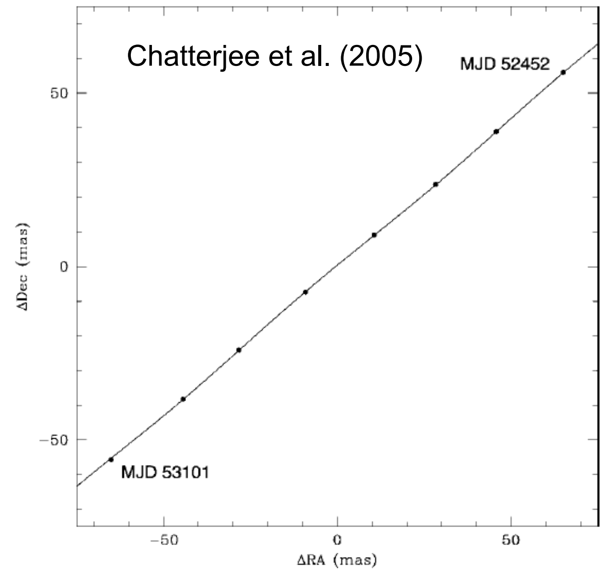
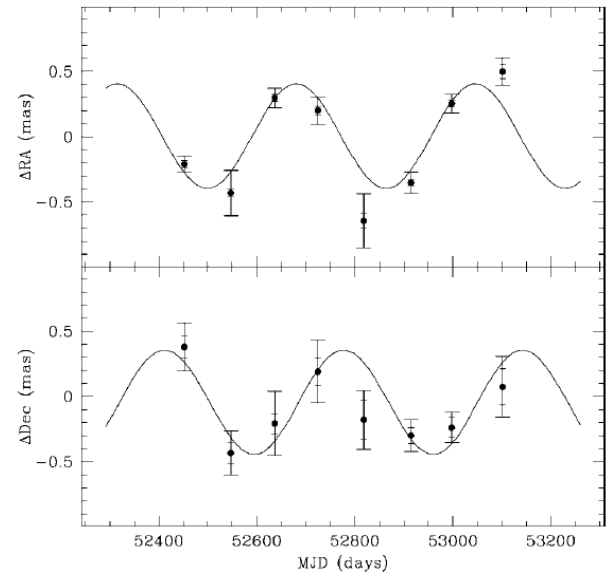
Other types of Pulsar Observations

- 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





Other types of Pulsar Observations

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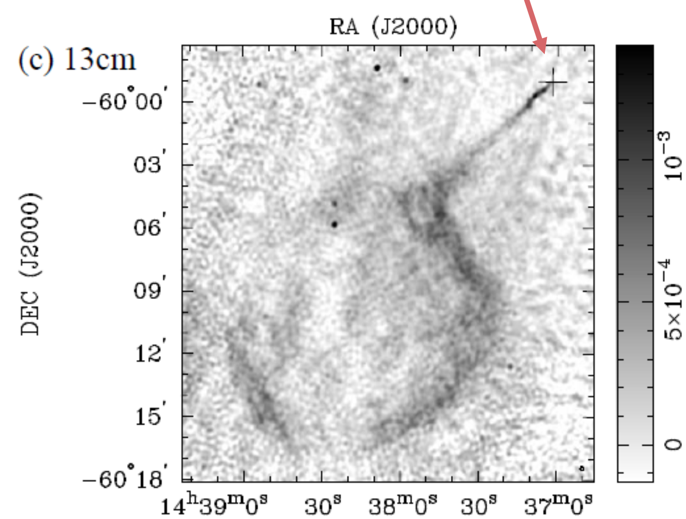
Pulsar shooting out of SNR!



Ng et al. (2011)

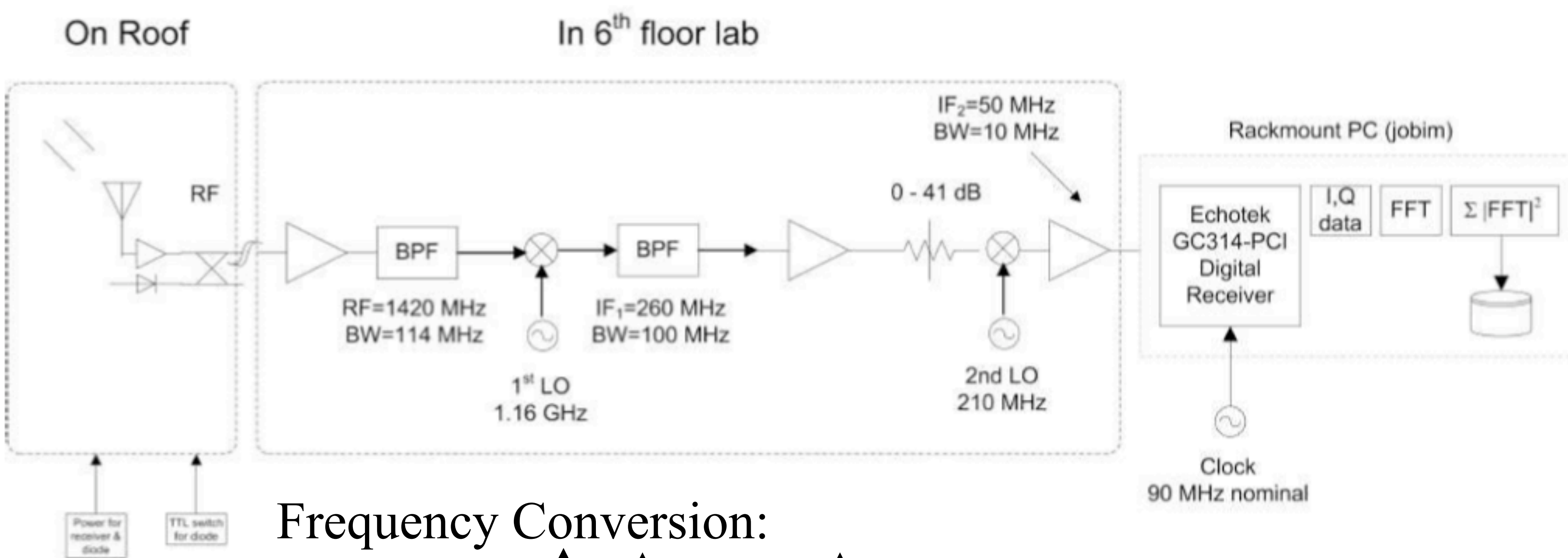
Summary

- 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!

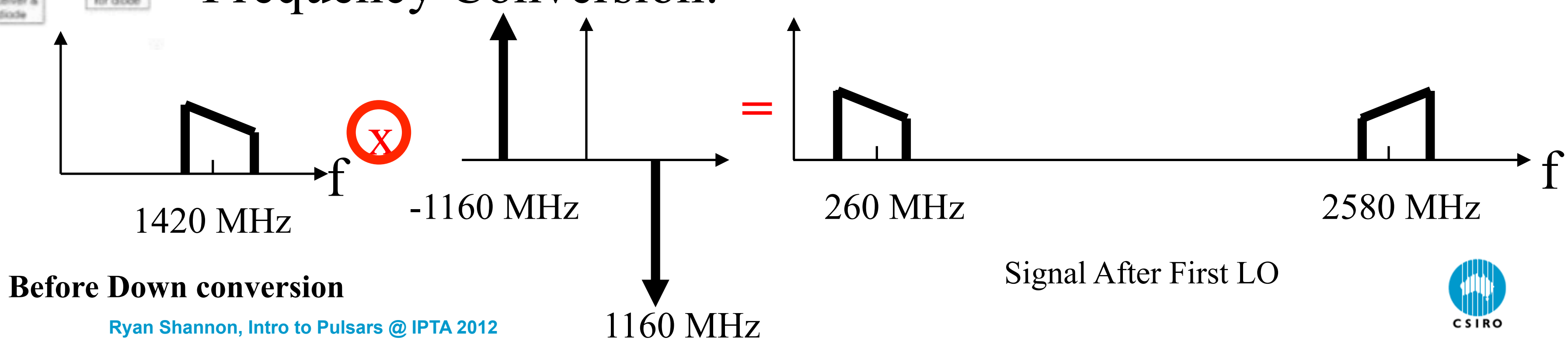
Photo: Mike Keith

Example Receiving System

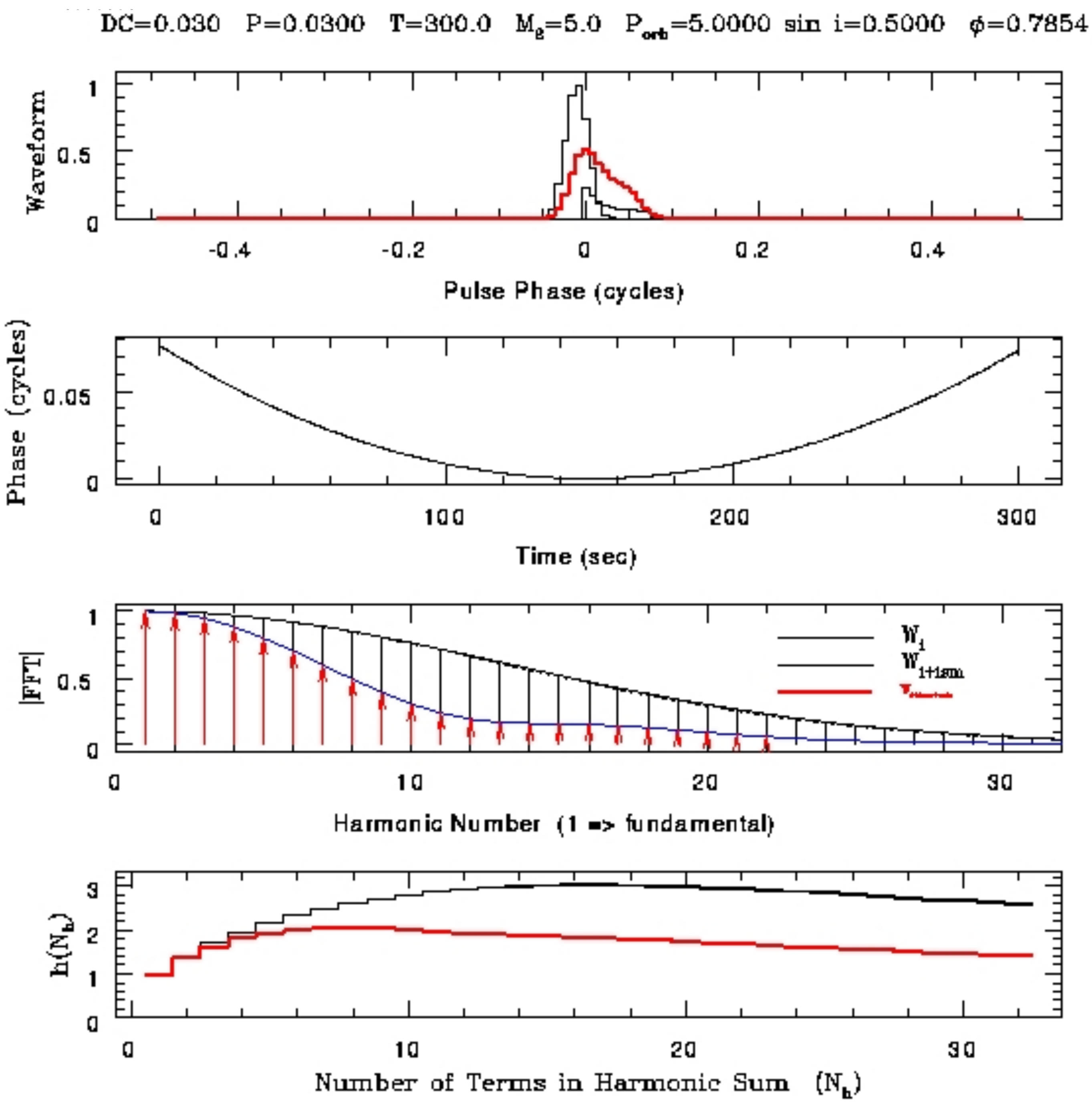
A410/A520 L-band Receiver



Frequency Conversion:

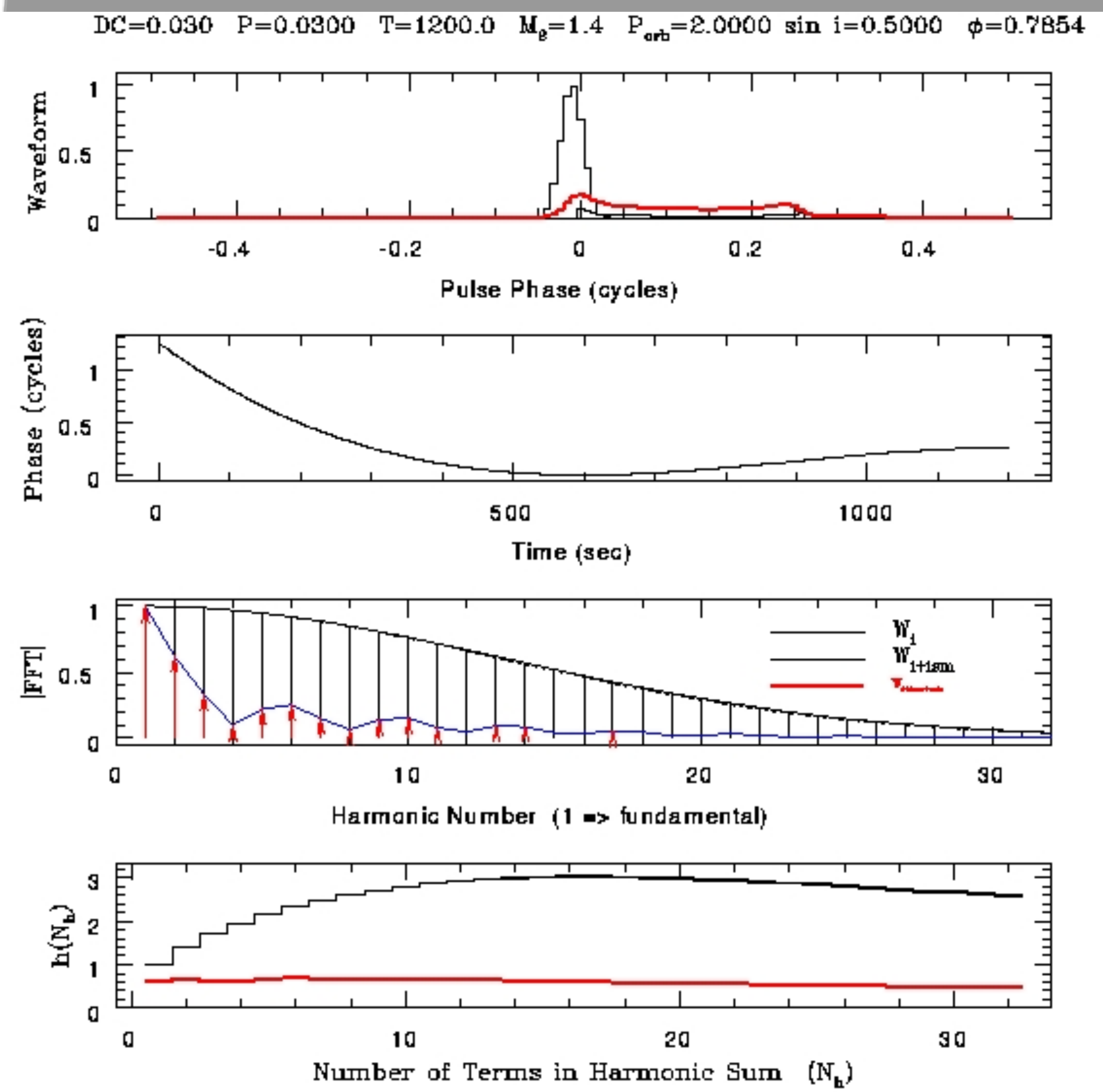


Pulse shape



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

Survey Selection Against Binaries



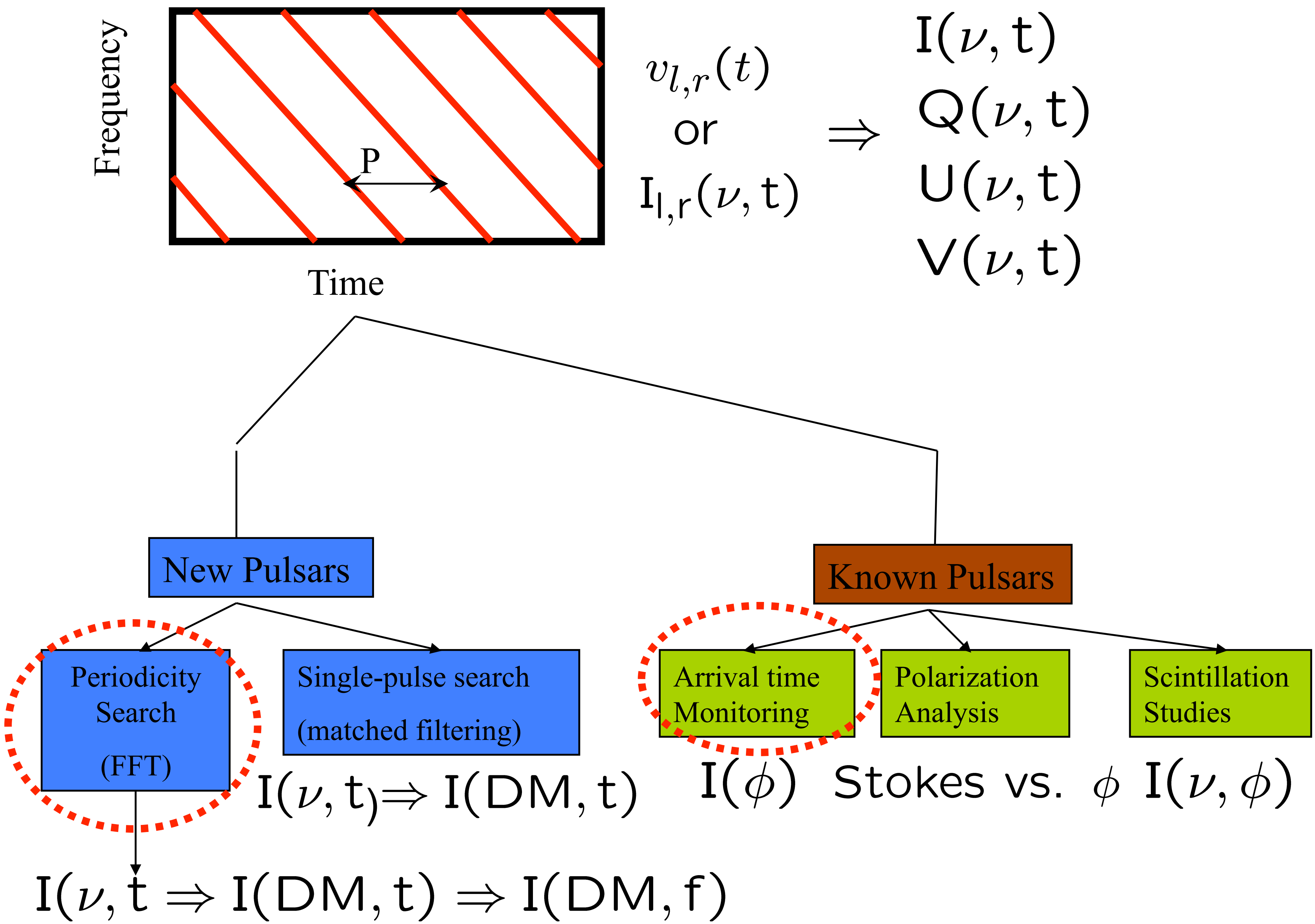
NS-NS binary

Pulse shape

Phase perturbation

FFT harmonics

Harmonic Sum


Frequency
Time
P
$v_{l,r}(t)$
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
$I(\nu, \phi)$
$I(\nu, t \Rightarrow I(DM, t) \Rightarrow I(DM, f)$