Pulsar Observations

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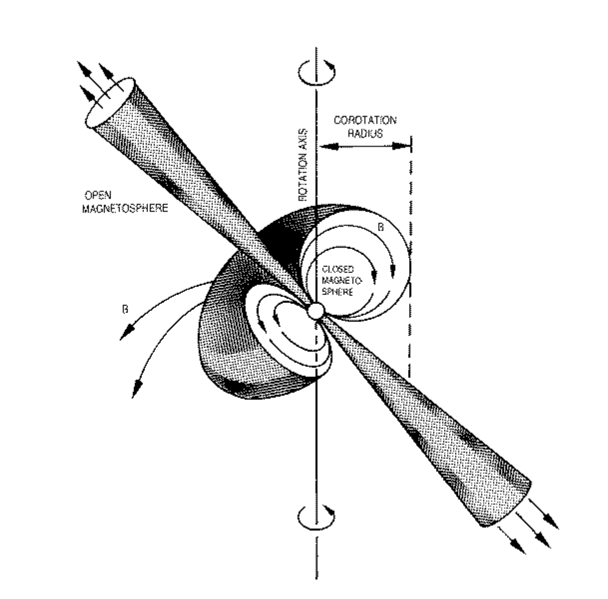
NAIC/NRAO Summer School 12 August 2003

- Basics
  - Propagation effects
  - Dispersion, scattering, scintillations
  - Dedispersion techniques
- Searching
- Timing
- Polarization
- Pulsar distances and astrometry
- Examples of forthcoming surveys

Pulsar Science

- Extreme matter physics
  - **10x nuclear density**
  - **High-temperature superfluid & superconductor**
  - **$B \sim B_q = 4.4 \times 10^{13}$ Gauss**
  - **Voltage drops ~ 10^{12} volts**
  - **$F_{EM} = 10^9 F_g = 10^9 \times 10^{11} F_{gEarth}$**
- Relativistic plasma physics (magnetospheres)
- Tests of theories of gravity
- Gravitational wave detectors
- Probes of turbulent and magnetized ISM (& IGM)
- End states of stellar evolution



Realities & Necessities

- Pulses serve as markers of the spin phase of the NS, which can be used as a clock
- Pulses are strongly affected by propagation in the ISM
- Search & timing programs must minimize propagation effects to achieve the highest sensitivity and precision
- RFI can mimic pulsar signals

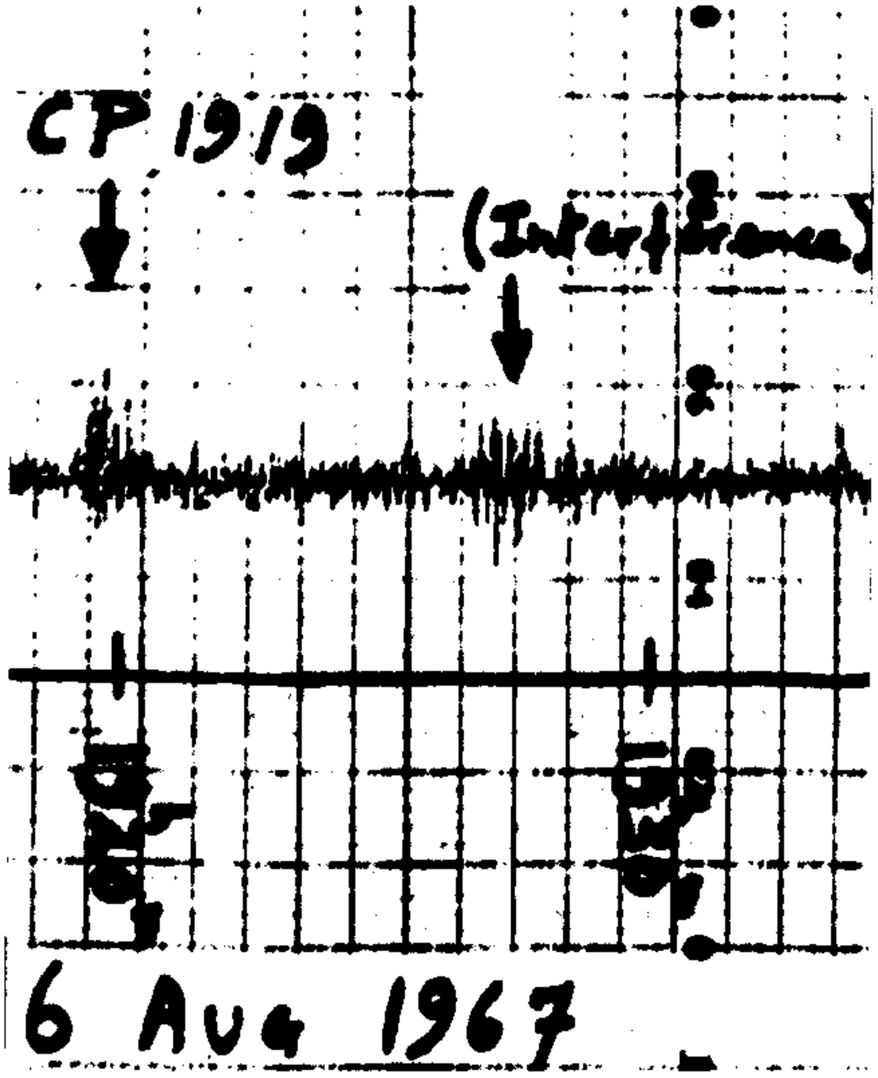
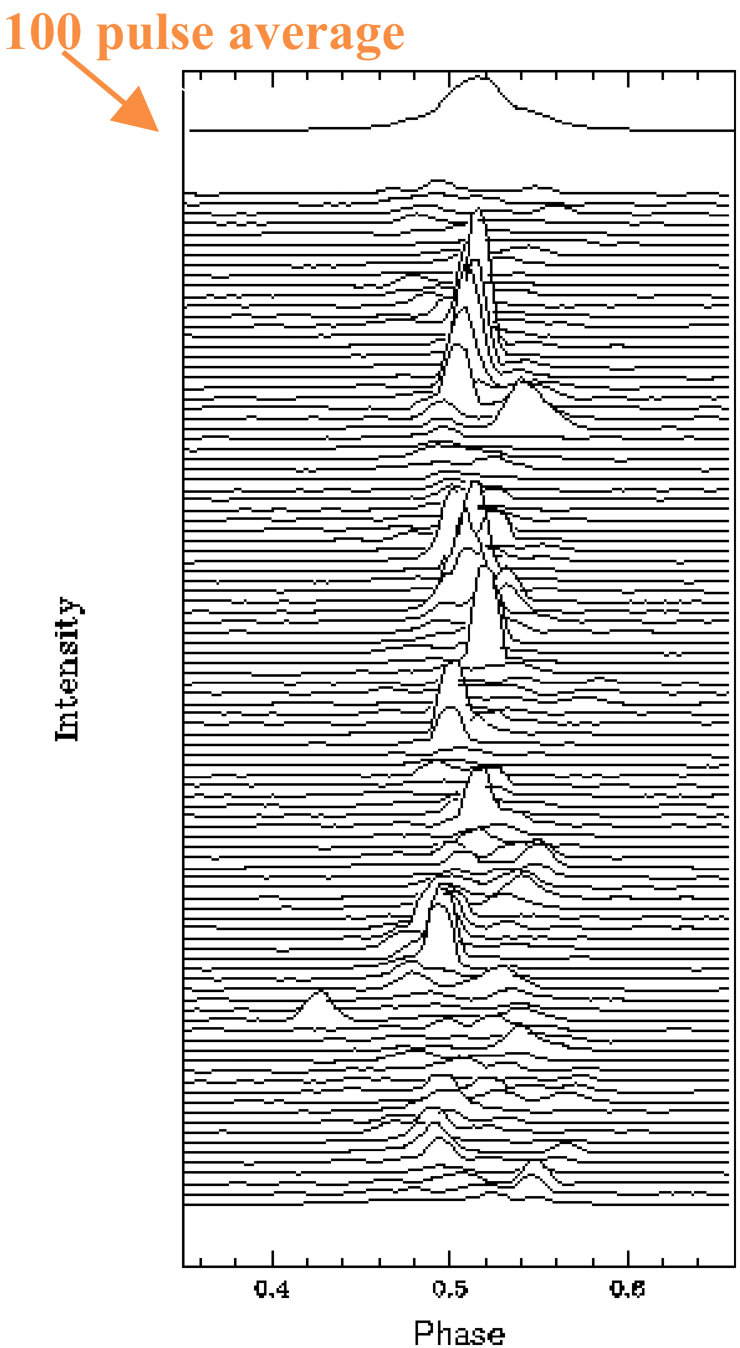


Fig. 6. Low level interference on right compared with scruff (pulsar) on left.

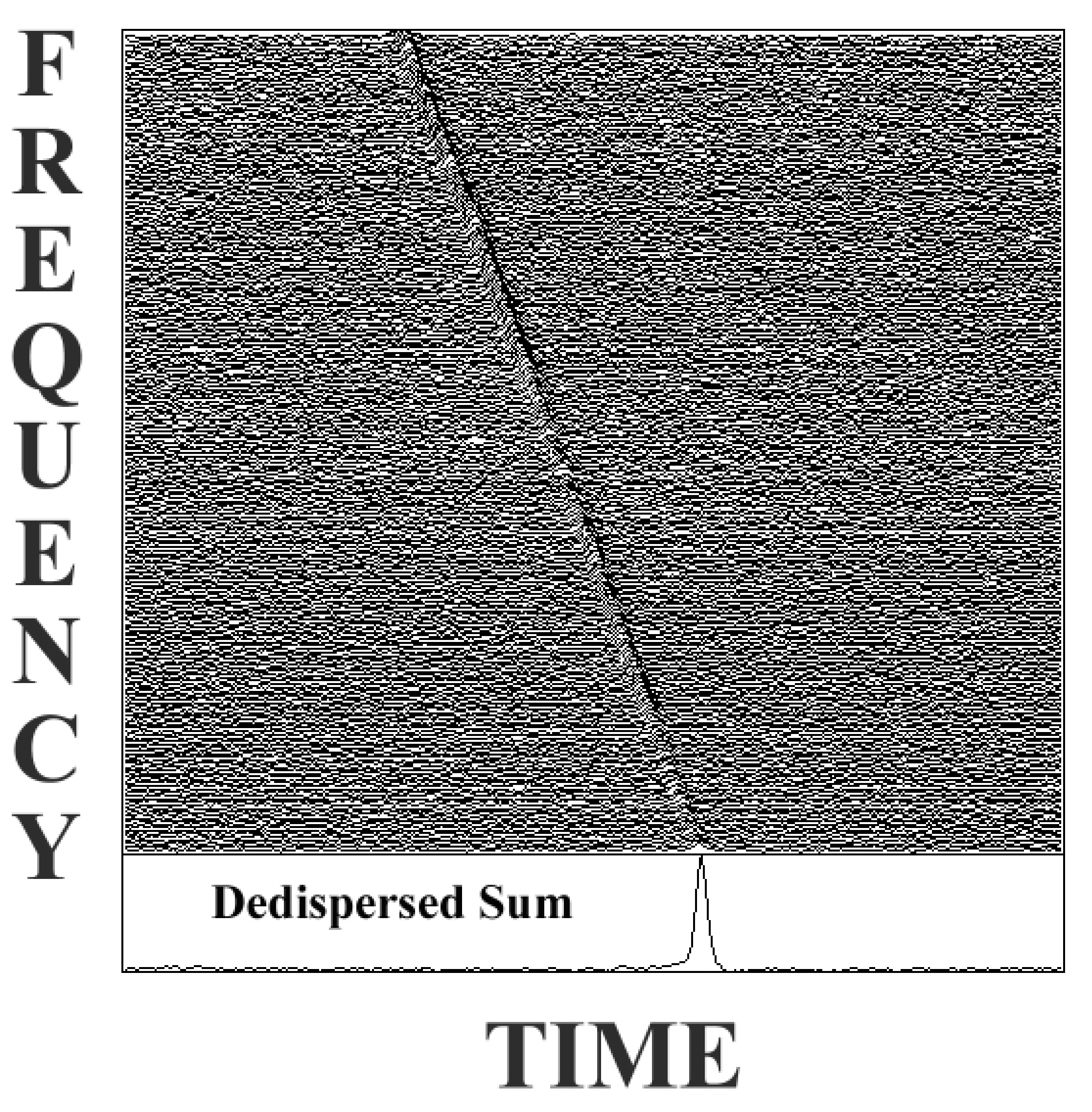


PSR J1740+1000

- amplitude & phase jitter is all intrinsic to the pulsar

- single pulse phase jitter contributes to arrival-time variations ~ W / $N^{1/2}$ for an N-pulse average

INTERSTELLAR DISPERSION



$DM = \int_0^D ds\, n_e(s)$

PSR B1534+12

P = 38 ms

DM = 11.61 pc cm^{-3}

10 MHz bandwidth

@ 0.43 GHz

Refractive indices for cold, magnetized plasma

$$n_{l,r} \sim 1 - \nu_p^2 / 2\nu^2 \mp \nu_p^2 \; \nu_{B||} \, 2\nu^3$$

$$\nu >> \nu_p \sim 2 \text{ kHz} \qquad \nu >> \nu_{B||} \sim 3 \text{ Hz}$$

Group velocity ⇒ group delay = Δ (time of arrival)

$$t = t_{DM} \pm t_{RM}$$

birefringence

$$t_{DM} = 4.15 \text{ ms DM } \nu^{-2}$$

$$t_{RM} = 0.18 \text{ ns RM } \nu^{-3}$$

$DM = \int ds \, n_e$ pc cm^{-3}

$RM = 0.81 \int ds \, n_e \; B_{||}$ rad m^{-2}

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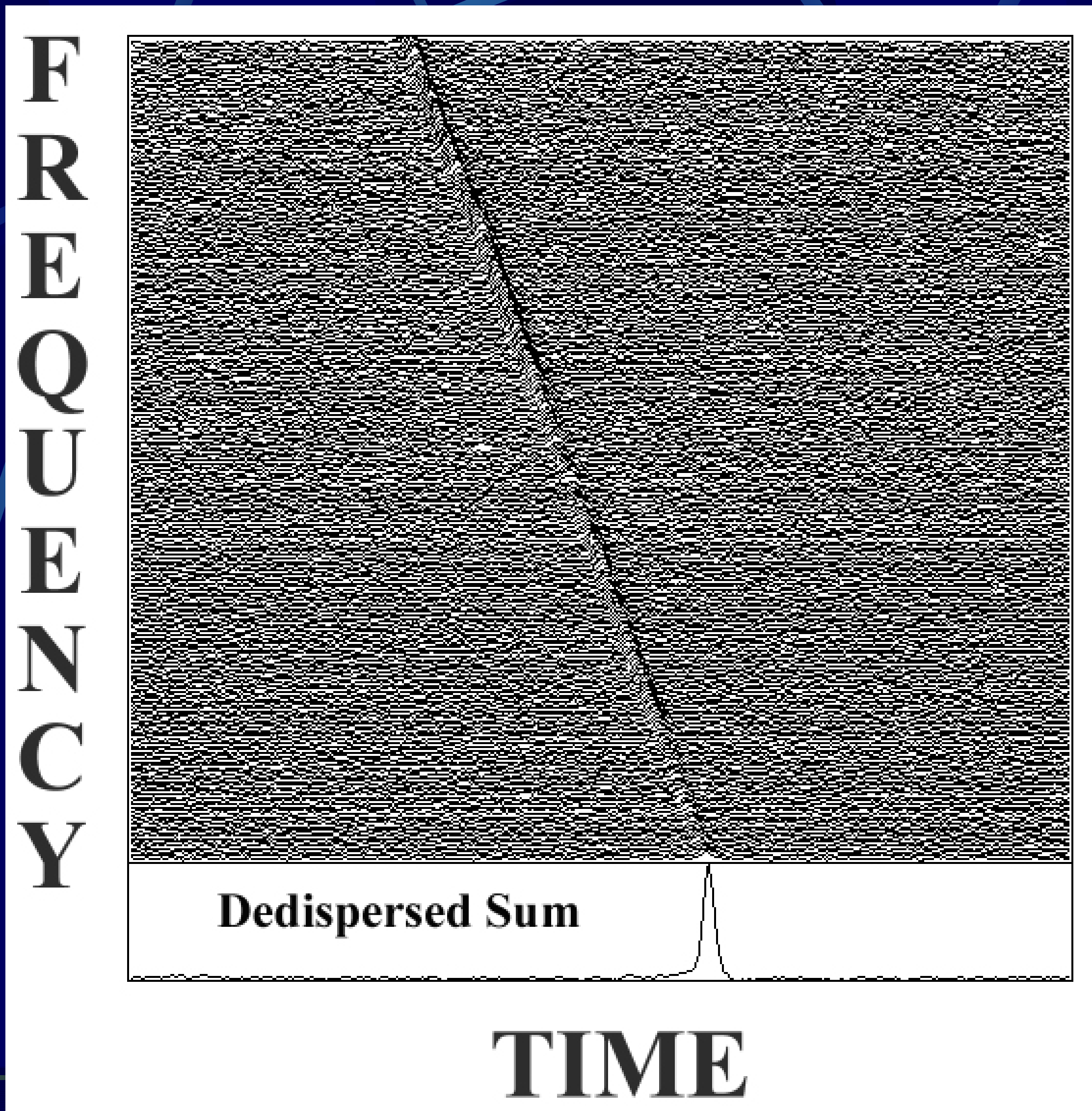
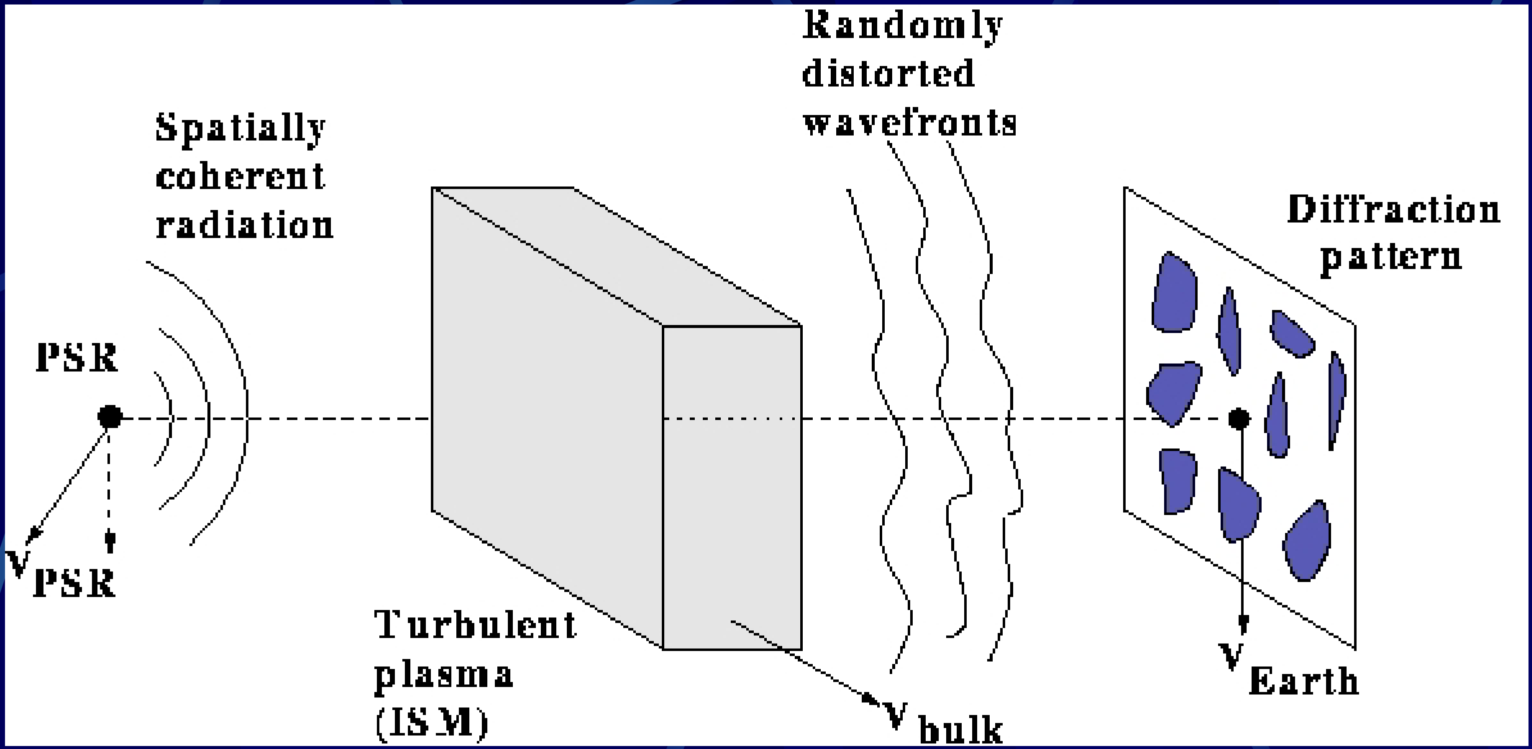
INTERSTELLAR DISPERSION



$$DM = \int_0^D ds\, n_e(s)$$

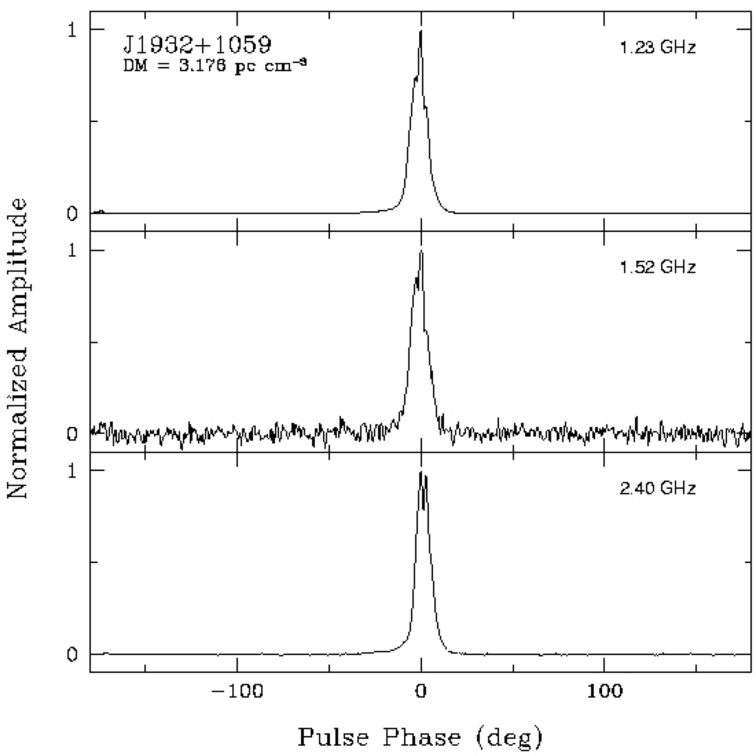
Scattering from δn_e

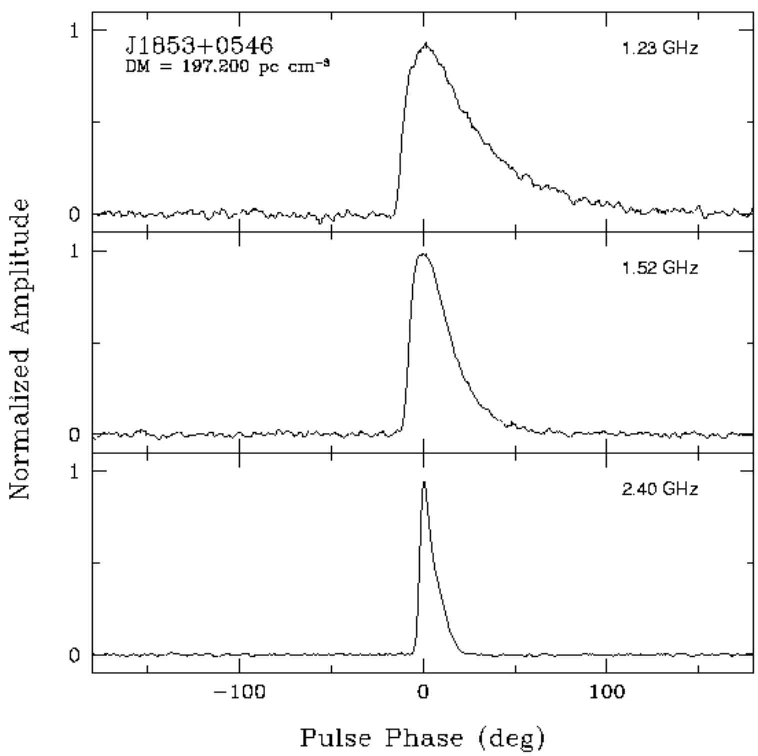


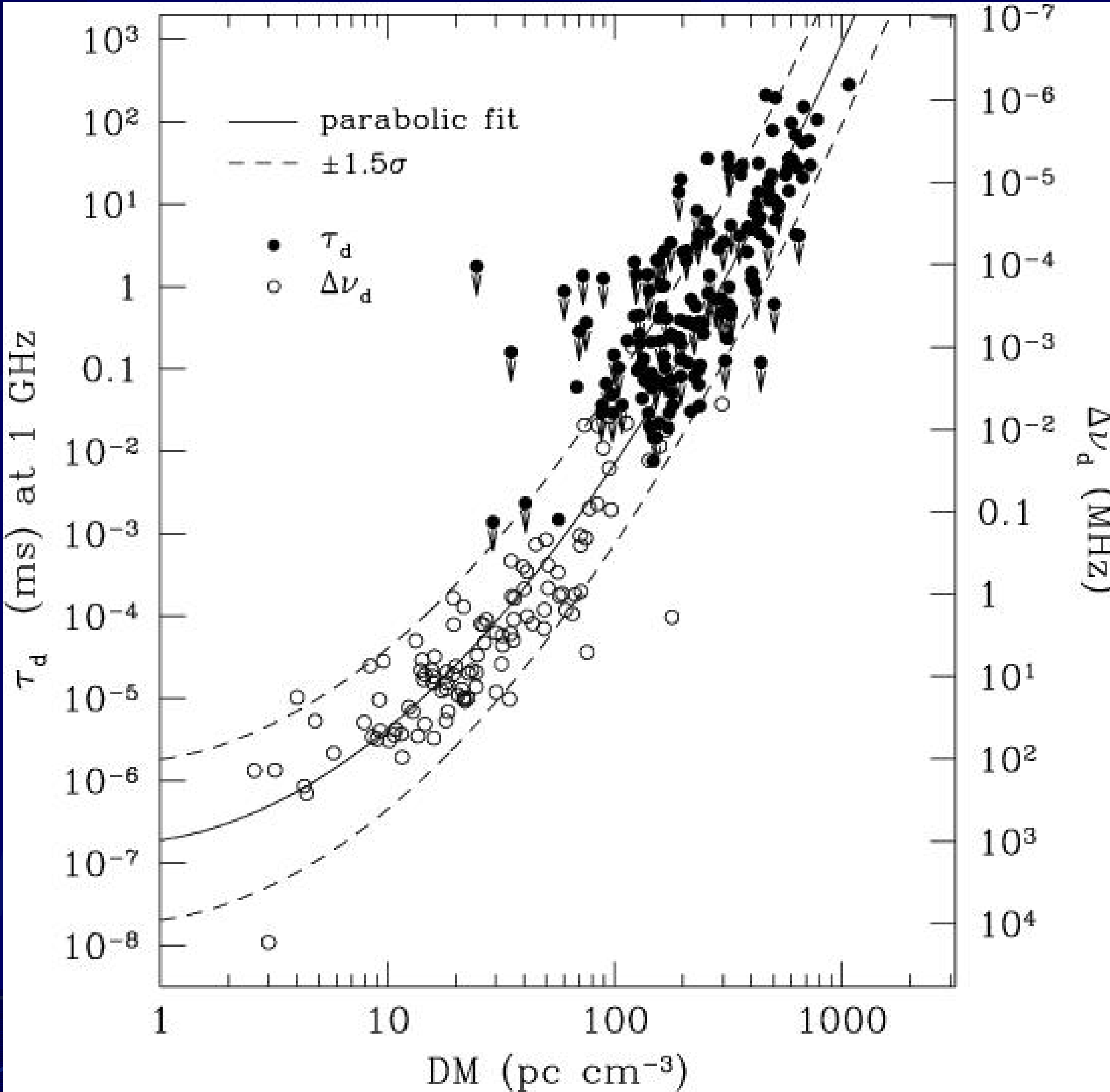
- Pulsar velocities >> ISM, observer velocities
- Scattering is strong for frequencies < 5 GHz
- Electron density irregularities exist on scales from ~ 100's km to Galactic scales

Pulse broadening (recent WAPP results, R. Bhat et al)

$$\tau \sim D\theta^2/2c \propto \nu^{-4}$$



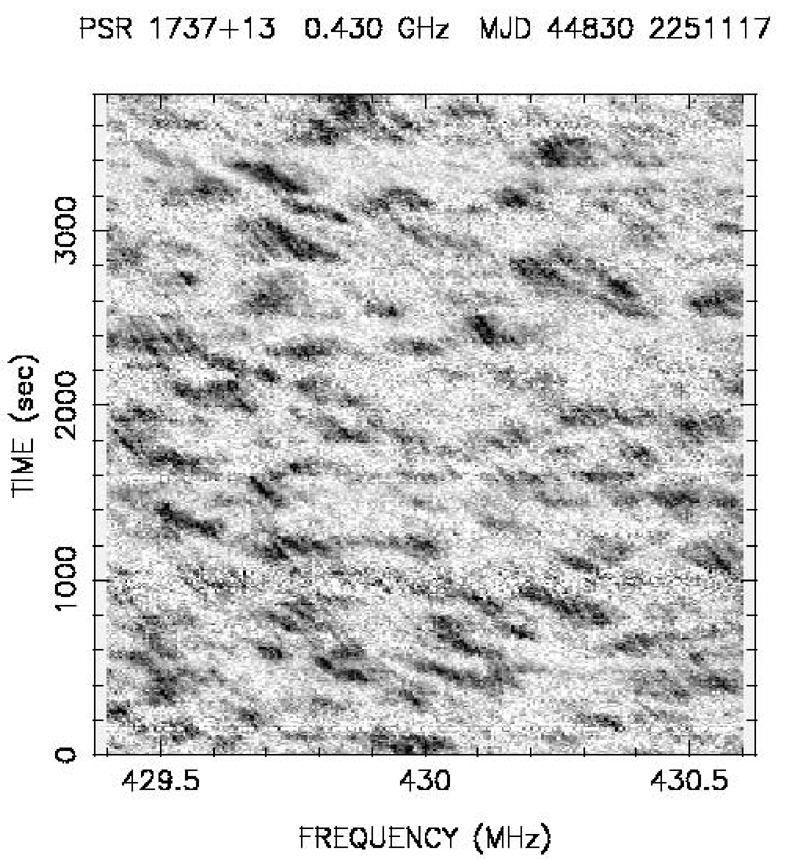


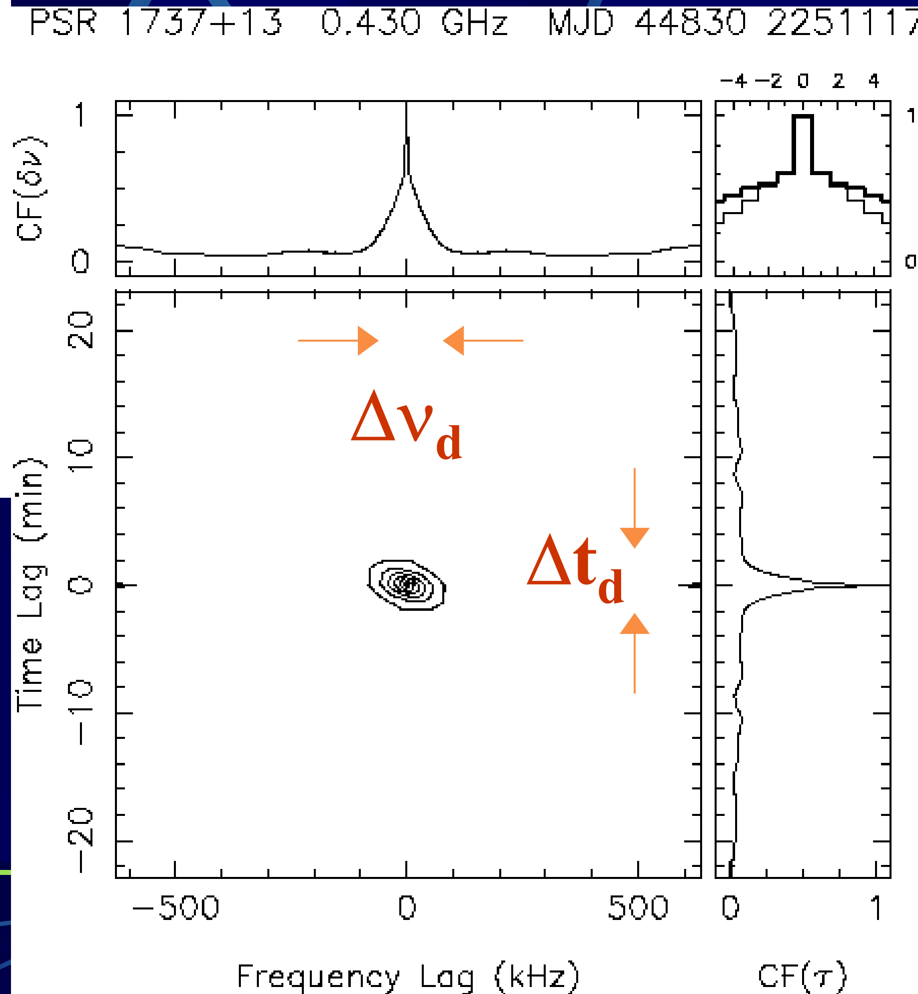


parabolic fit
±1.5σ
τ_d
Δν_d
τ_d (ms) at 1 GHz
Δν_d (MHz)
DM (pc cm^-3)
10^3
10^2
10^1
1
0.1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-7
10^-6
10^-5
10^-4
10^-3
10^-2
0.1
1
10^1
10^2
10^3
10^4
1
10
100
1000

Dynamic Spectrum

(Diffractive Interstellar Scintillations)

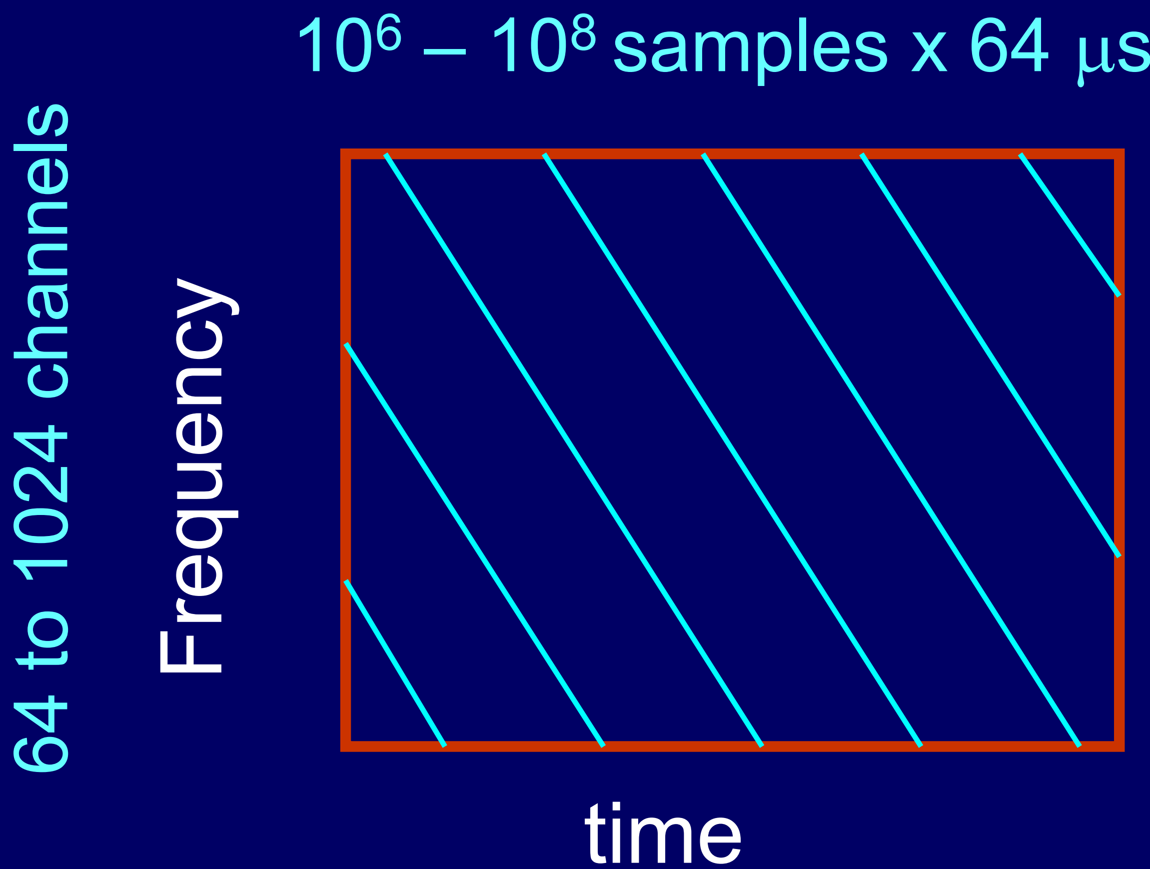




2D Autocorrelation Function ⇒ Characteristic DISS frequency and time scales

Dedispersion

Basic data unit = a dynamic spectrum



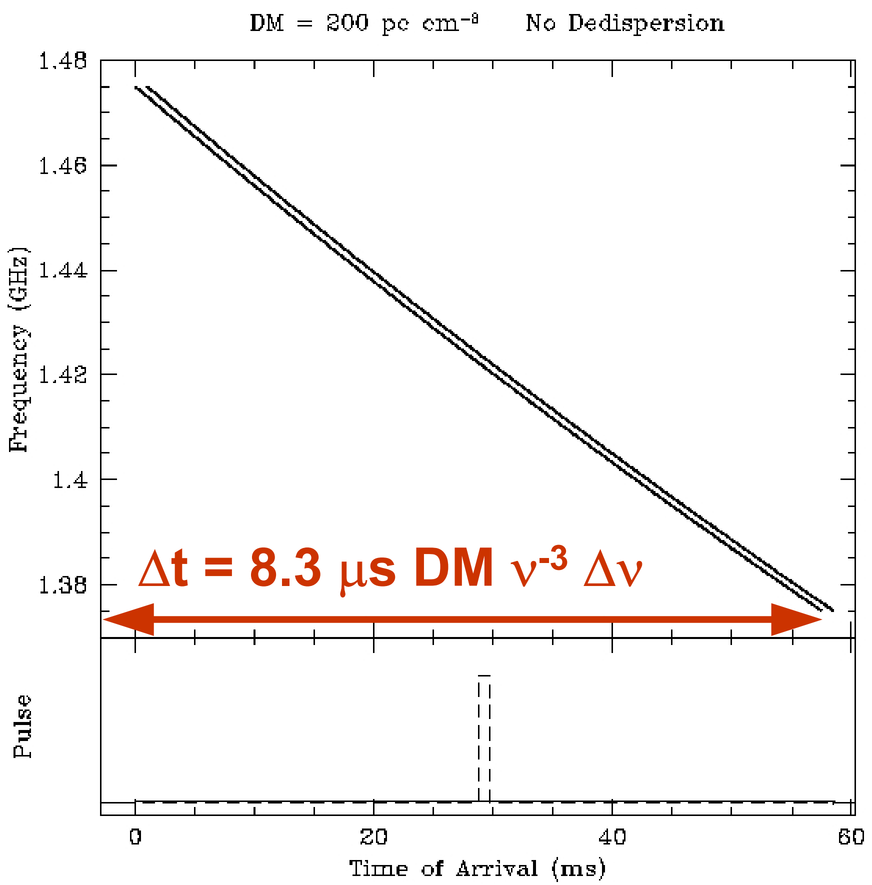
Fast-dump spectrometers:

- **Analog filter banks**
- **Correlators**
- **FFT (hardware)**
- **FFT (software)**
- **Polyphase filter bank**

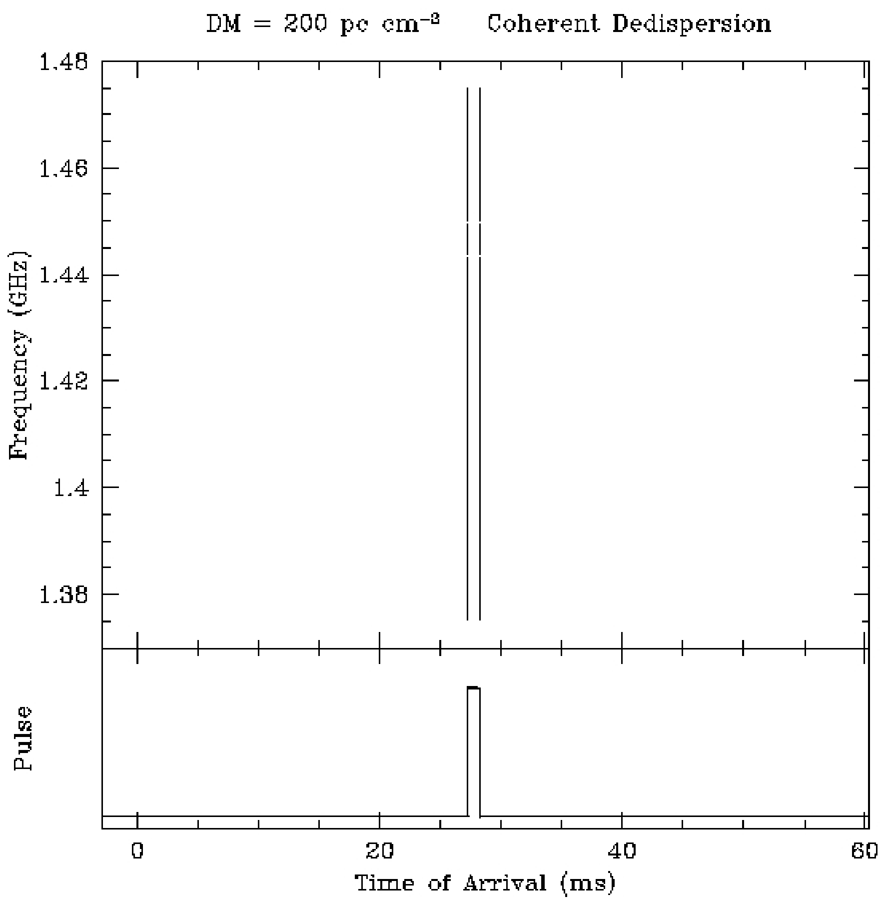
E.g. WAPP, AOFTM,

GBT correlator + spigot card

Dispersed Pulse



Coherently dedispersed pulse



Coherent Dedispersion

pioneered by Tim Hankins, c. 1971

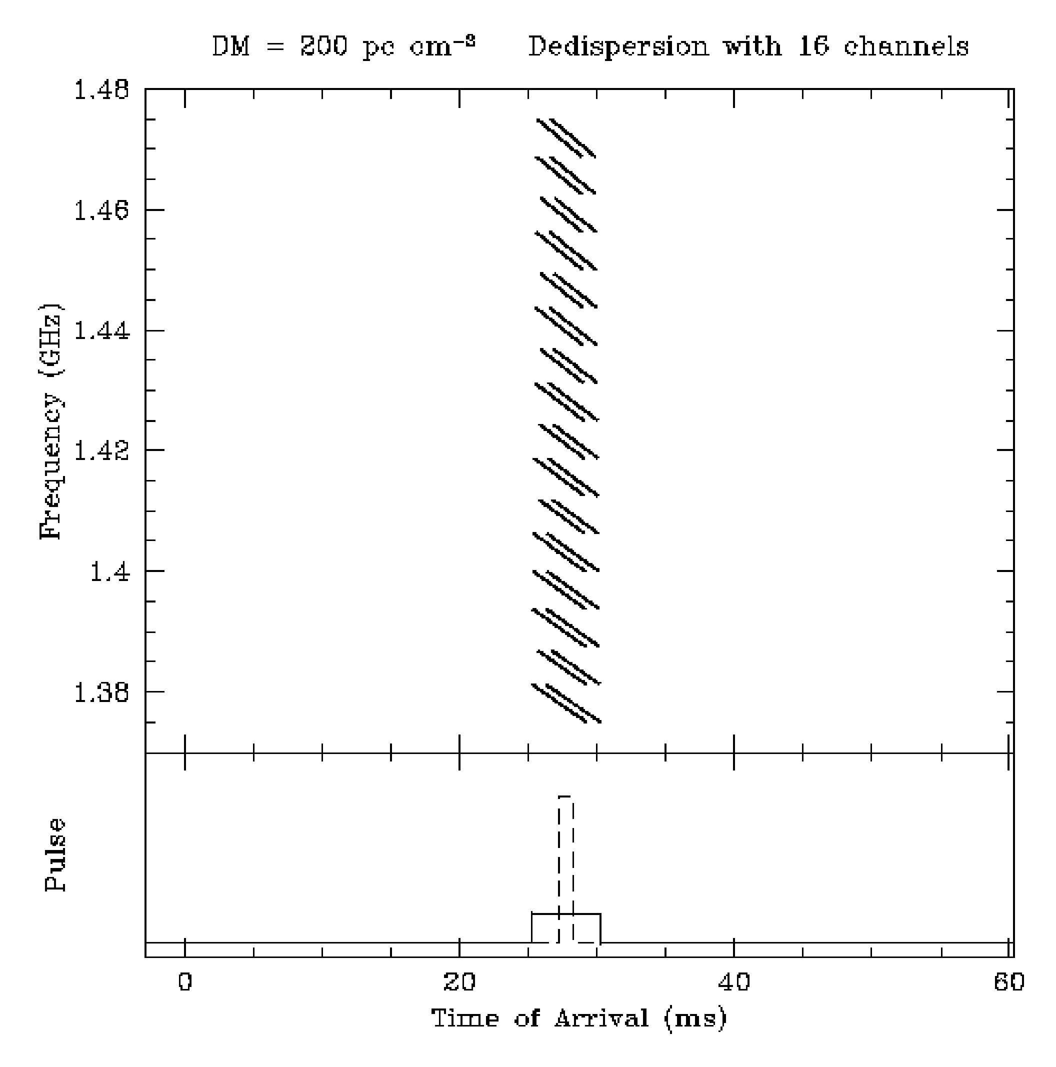
Dispersion delays represent a phase perturbation of the Fourier components of the electric field:

$E_{meas}(\omega) = E_{emitted}(\omega)\ e^{ik(\omega)z}$ $[k(\omega)z \rightarrow \int dz\ k(\omega)]$

Coherent dedispersion involves multiplication of Fourier amplitudes by the inverse function, $e^{-ik(\omega)z}$, which is known to high precision for known pulsars.

See section 2.1 of I. Stairs paper

Postdetection dedispersion (align outputs of channels) leaves residual dispersion across channels



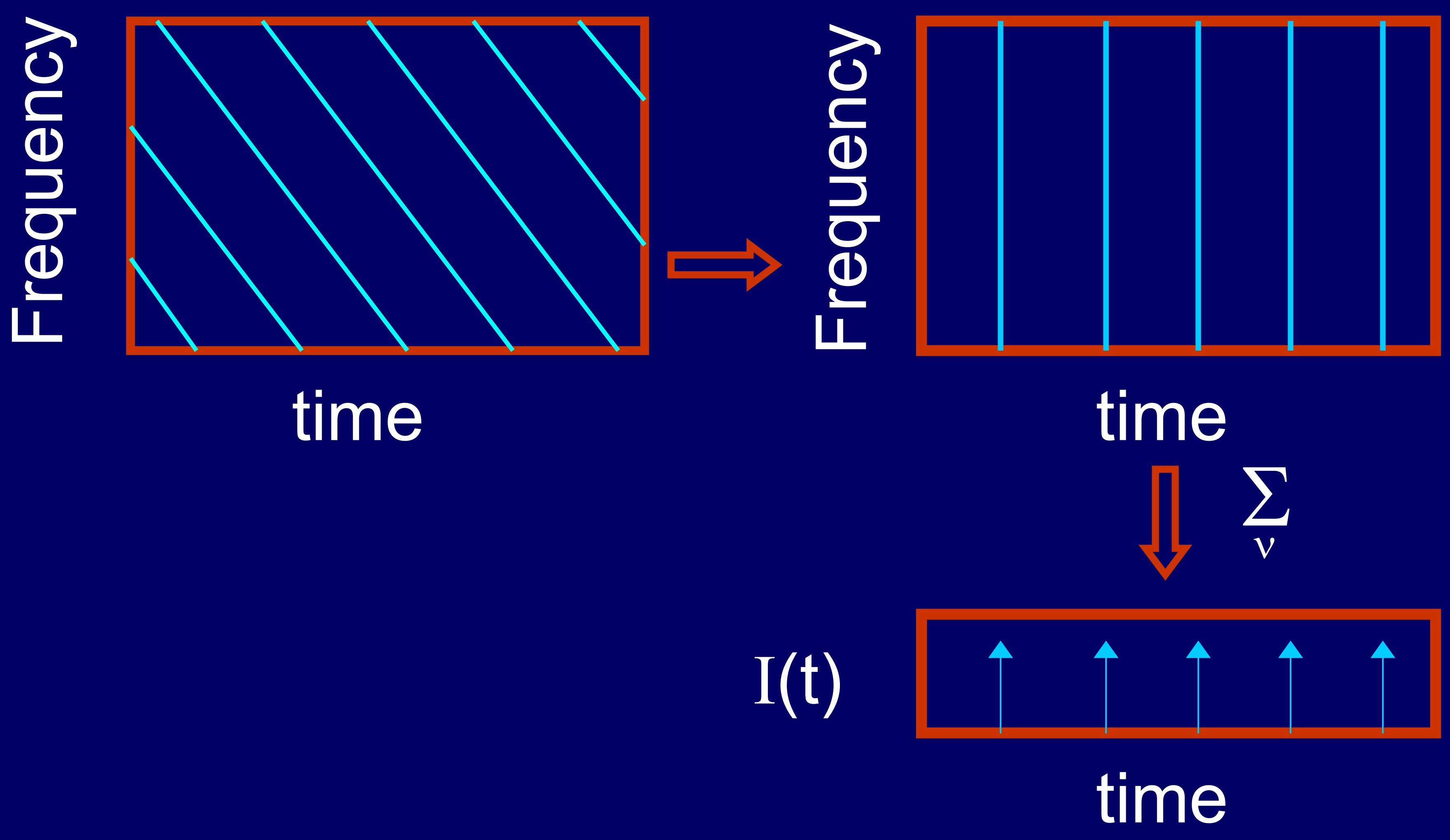
Δt = quadratic sum of

$\Delta t_{DM} \propto \Delta\nu$

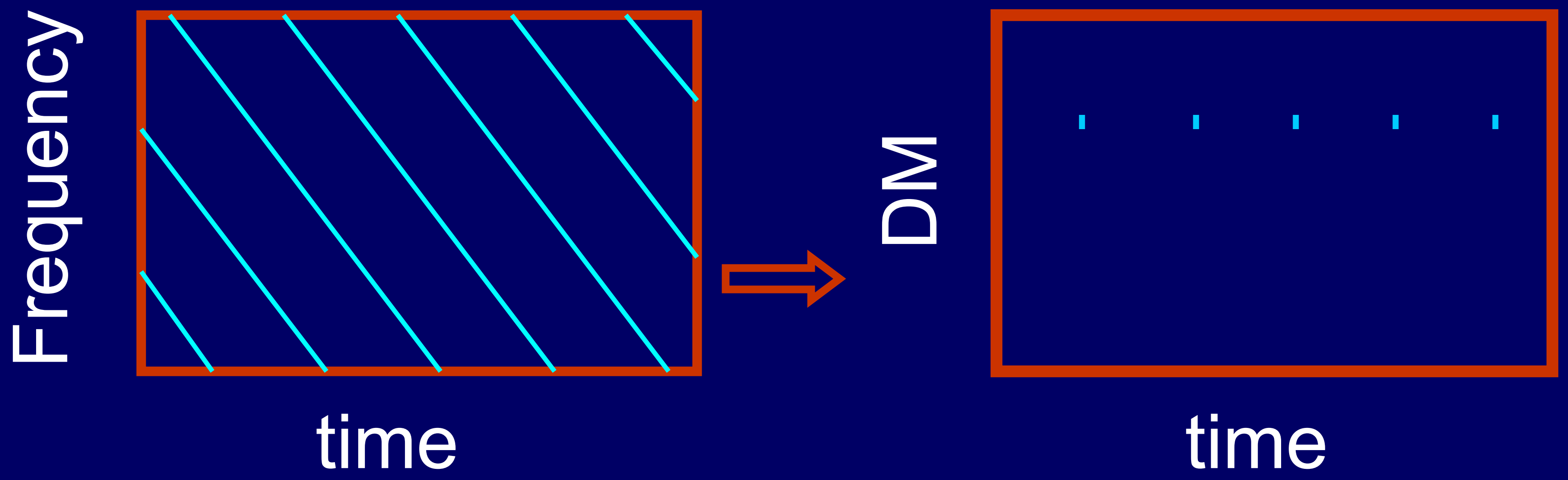
$\Delta t_f \sim 1 / \Delta\nu$

$\Rightarrow$ Optimal channel bandwidth $\Delta\nu$ that minimizes Δt

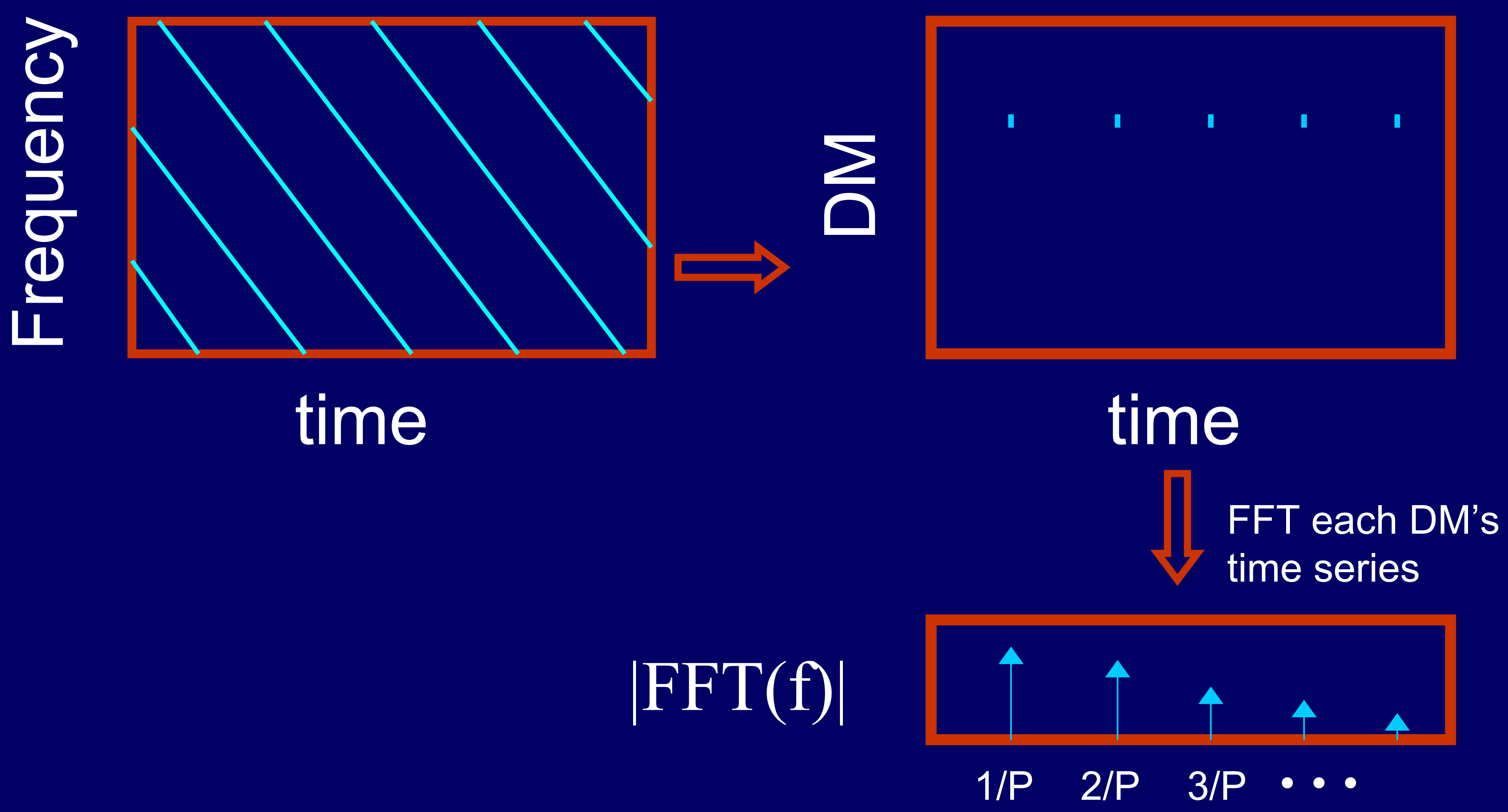
Dedispersion at a single known DM



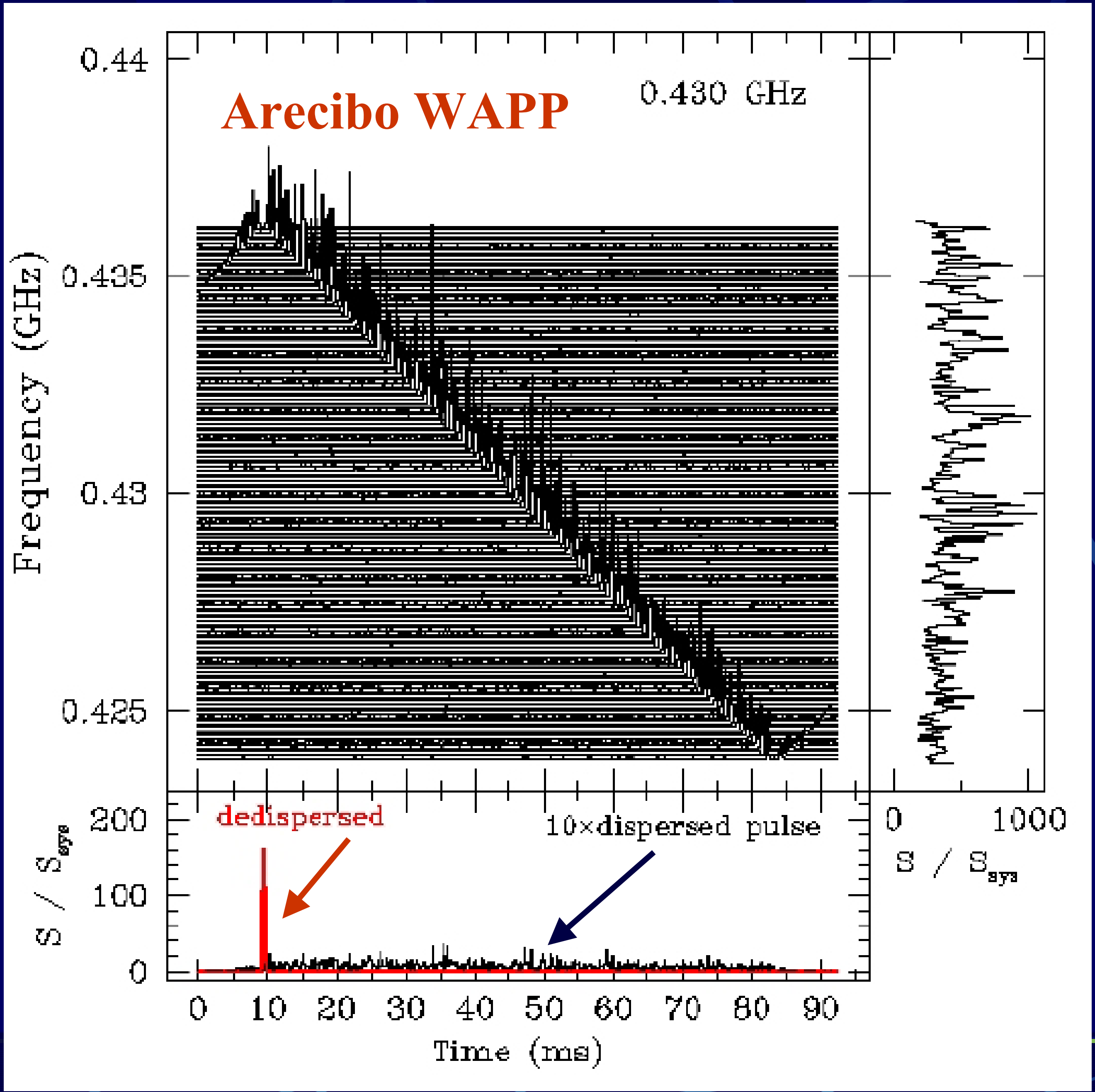
Dedispersion over a set of DMs



Pulsar Periodicity Search



Single Pulse Studies & Searches



Giant pulse from the Crab pulsar

S ~ 160 x Crab Nebula

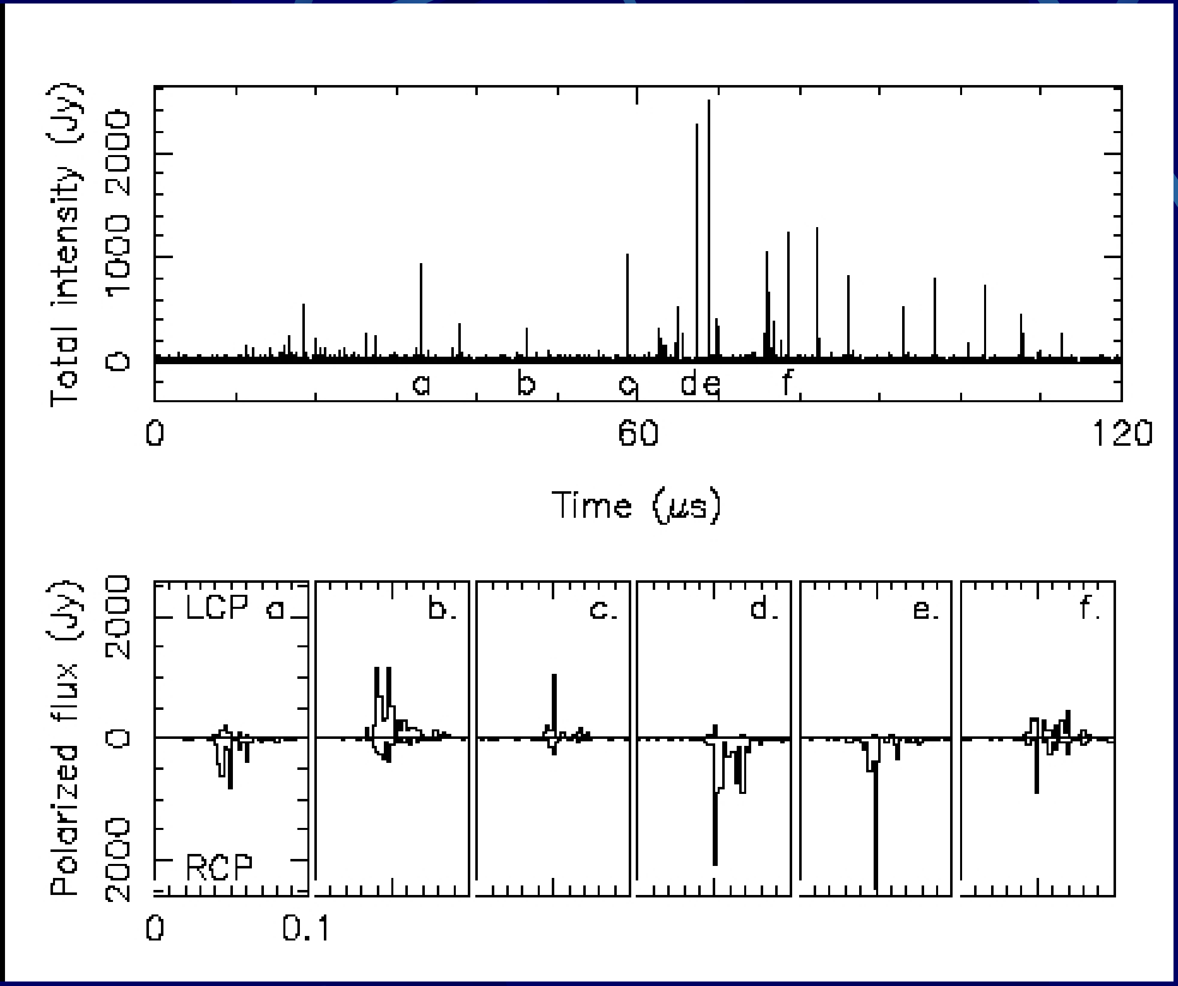
~ 200 kJy

Detectable to ~ 1.5 Mpc with Arecibo

2-ns giant pulses from the Crab: (Hankins et al. 2003)

Giant Pulses seen from B0540-69 in LMC (Johnston & Romani 2003)

Nano-giant pulses (Hankins et al. 2003)



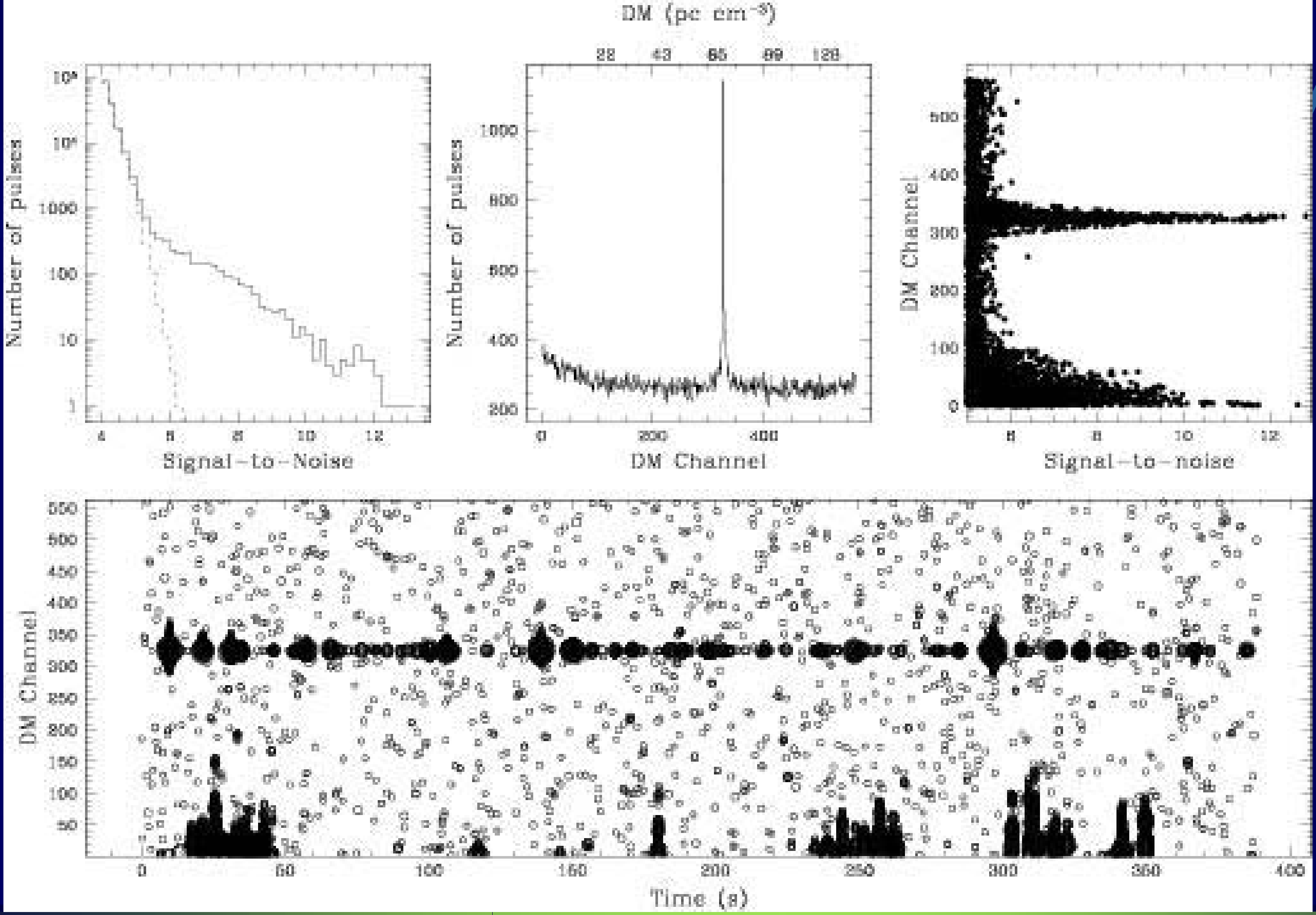
Arecibo

5 GHz

0.5 GHz bw

coherent dedispersion

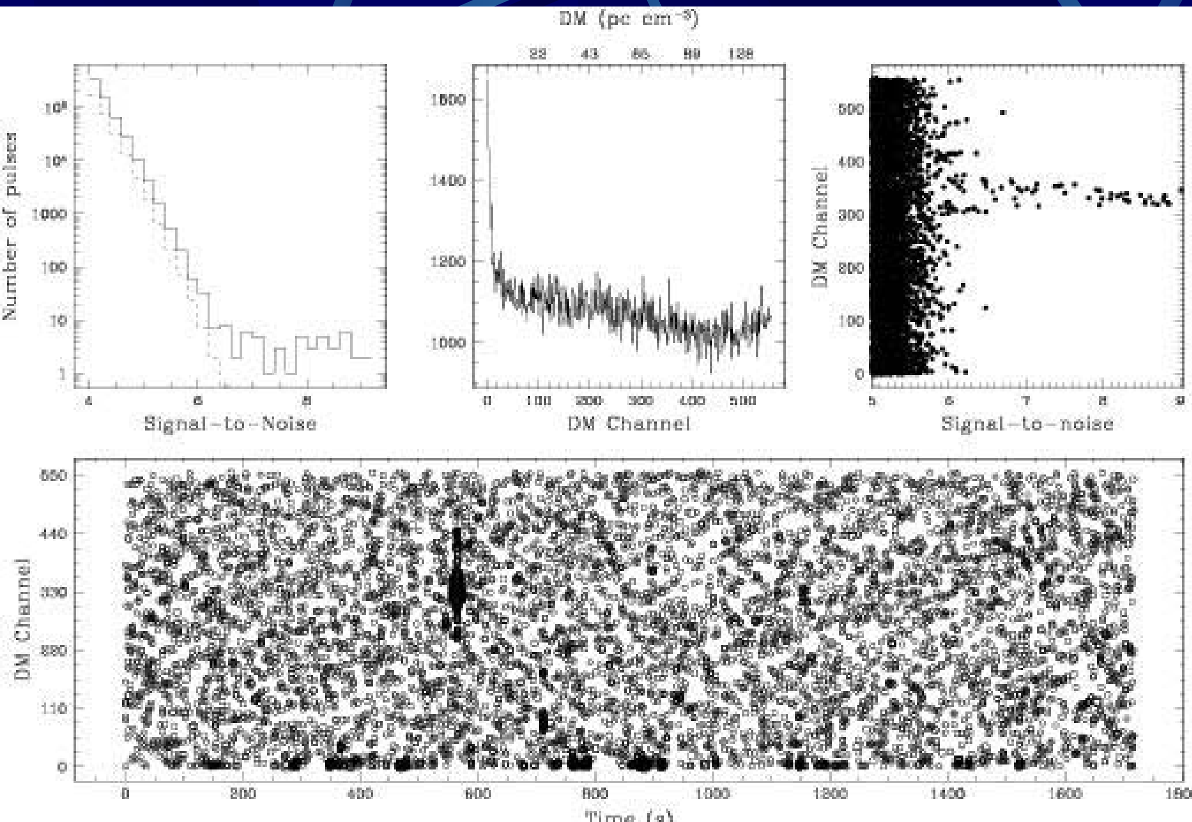
Giant pulse searches

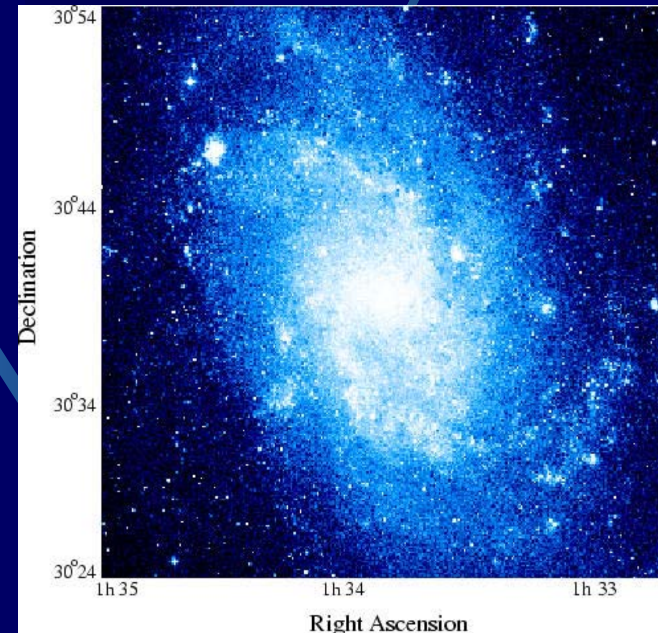


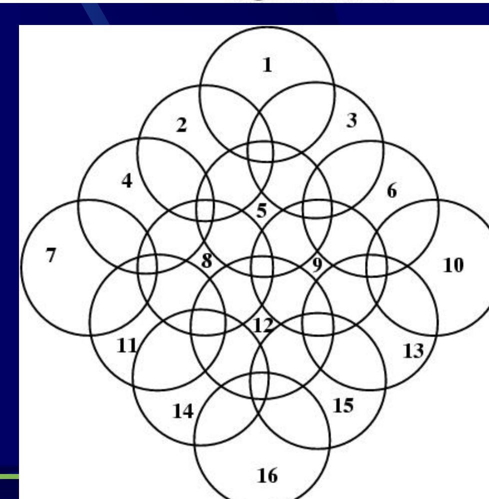
Giant pulses from M33

Arecibo observations

(Mclaughlin & Cordes, ApJ in press; astro-ph)

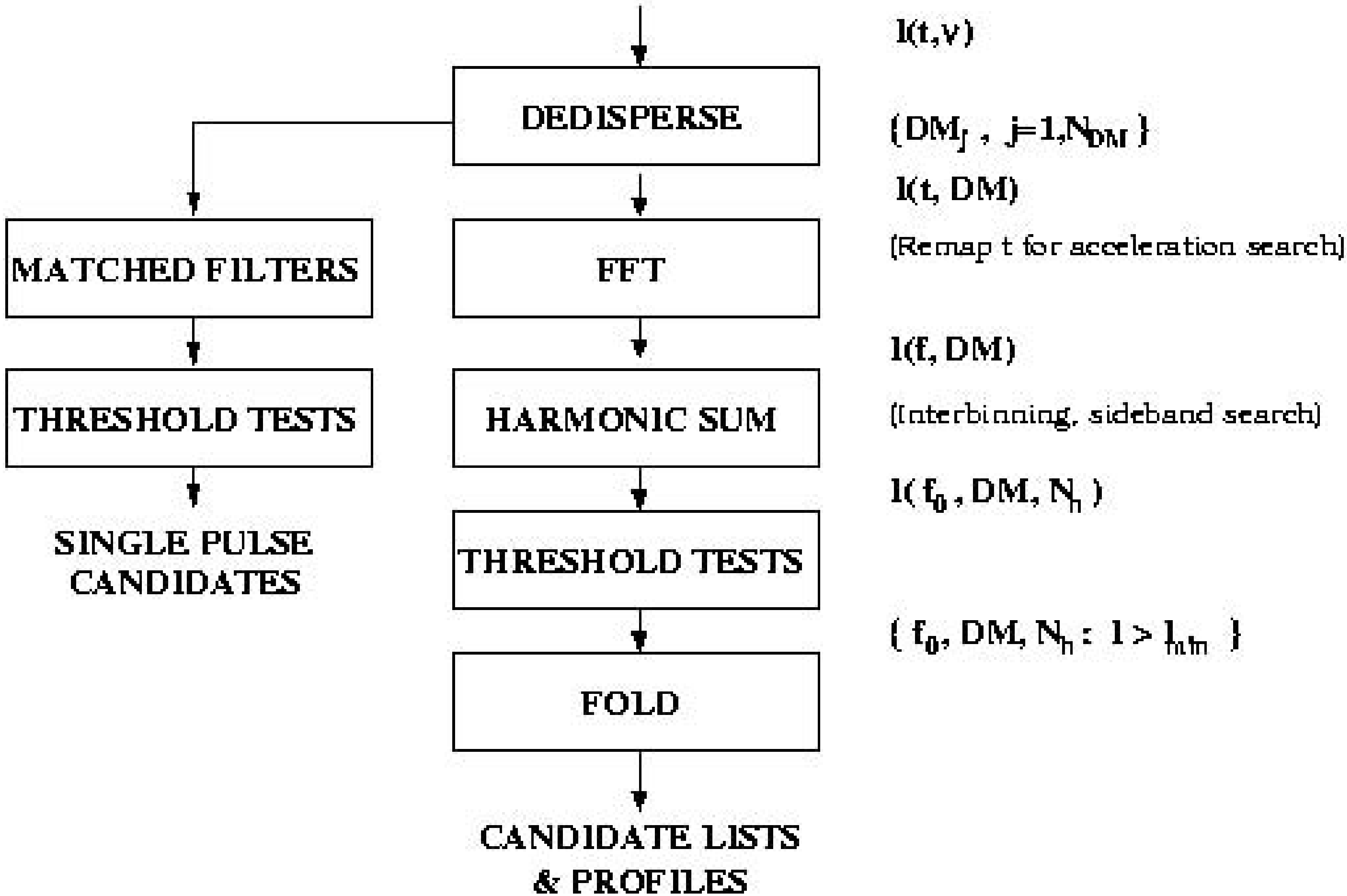






Pulsar Periodicity Searches

PULSAR SEARCHING



Harmonic Sum

The FFT of periodic pulses consists of a series of spikes (harmonics) separated by 1/P.

To improve S/N, sum harmonics.

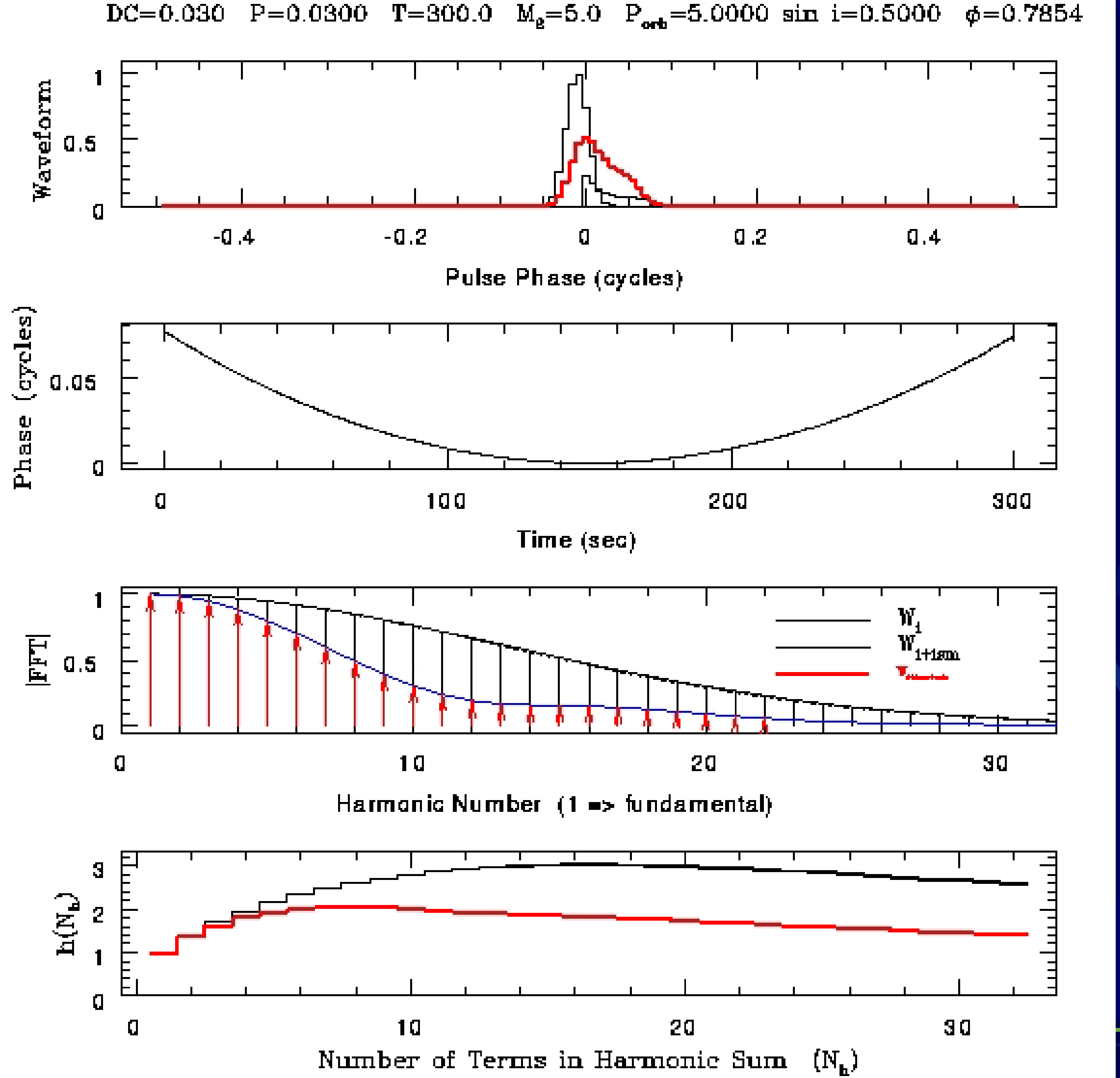
How many? The answer depends on the pulse "duty cycle" = (pulse width / P) $\Rightarrow$ need to use trial values of N_h.

S_{min1} = m x rms radiometer noise, $m \approx 10$

$S_{min} = S_{min1} / h(N_h)$

j-th harmonic

$h(N_h) = N_h^{-1/2} \sum R_j$, where $R_j = |FFT(j) / FFT(0)|$

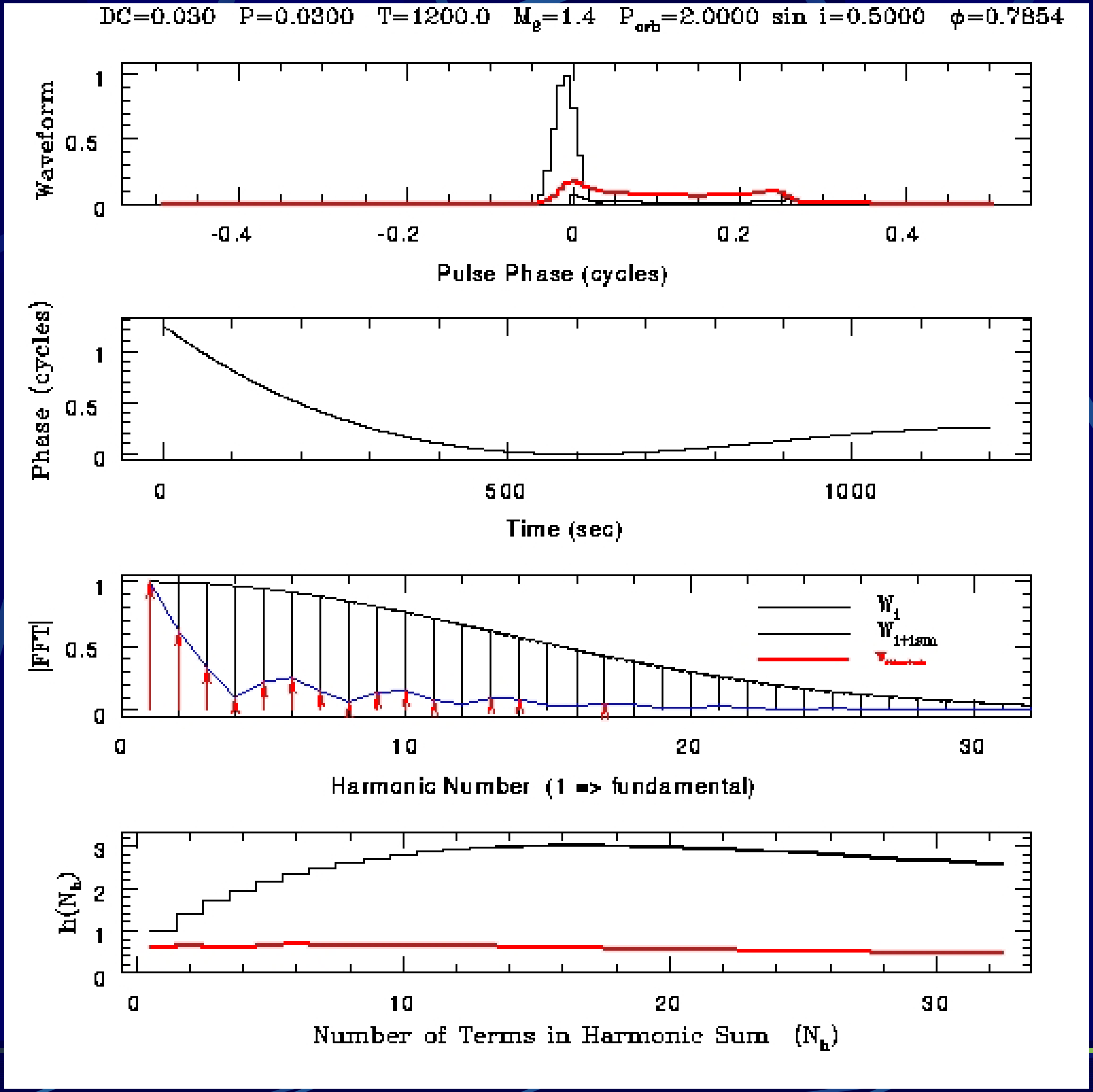


Pulse shape

FFT

Harmonic sum

Survey Selection Against Binaries



NS-NS binary

Pulse shape

Phase perturbation

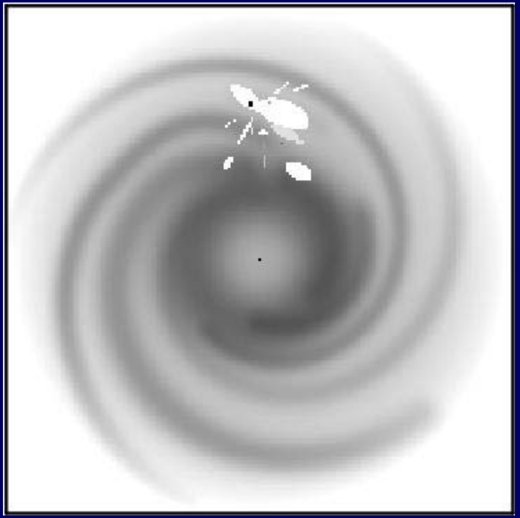
FFT harmonics

Harmonic Sum

Why more pulsars?

- Discover rare, extreme objects (odds $\propto N_{psr}$)
  - $P < 1$ ms — $P > 8$ sec
  - $P_{orb} <$ hours — $B >> 10^{13}$ G (link to magnetars?)
  - $V > 1000$ km s^{-1} — strange stars?
  - NS-NS and NS-BH binaries, planets
  - Extragalactic pulsars
  - Galactic center pulsars orbiting Sgr A* black hole

Large N $\Rightarrow$ Galactic tomography



- **Large $N_{psr} \Rightarrow$ Galactic tomography of $B + \delta B$, $n_e + \delta n_e$**

Branching ratios for compact object formation:

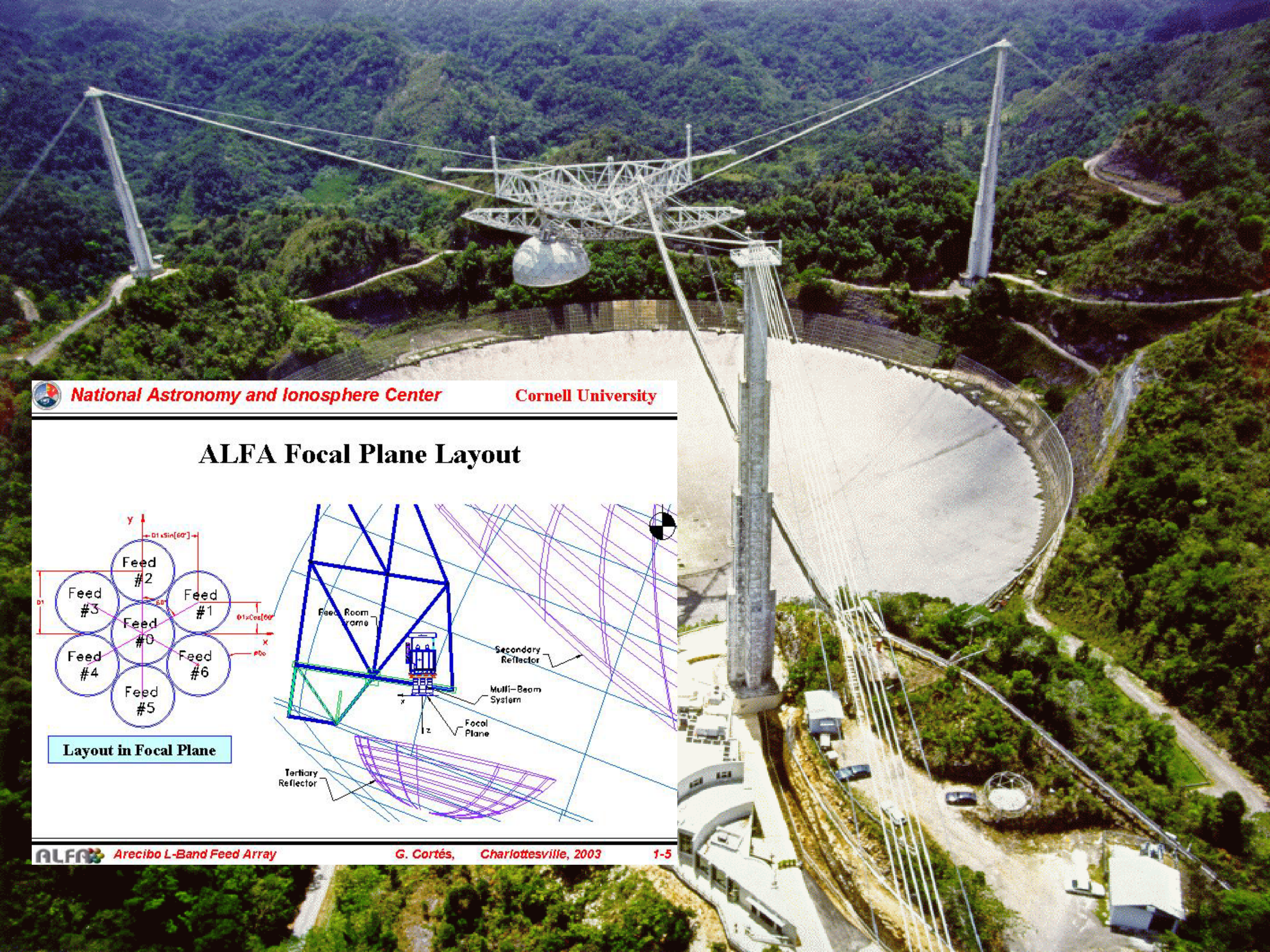
- **NS (normal, isolated)**
- **NS (recycled, binaries)**
- **NS (magnetar)**
- **BH (hypernovae)**
- **Strange stars?**

I. Arecibo Galactic-Plane Survey

(using ALFA = Arecibo L-band Feed Array)

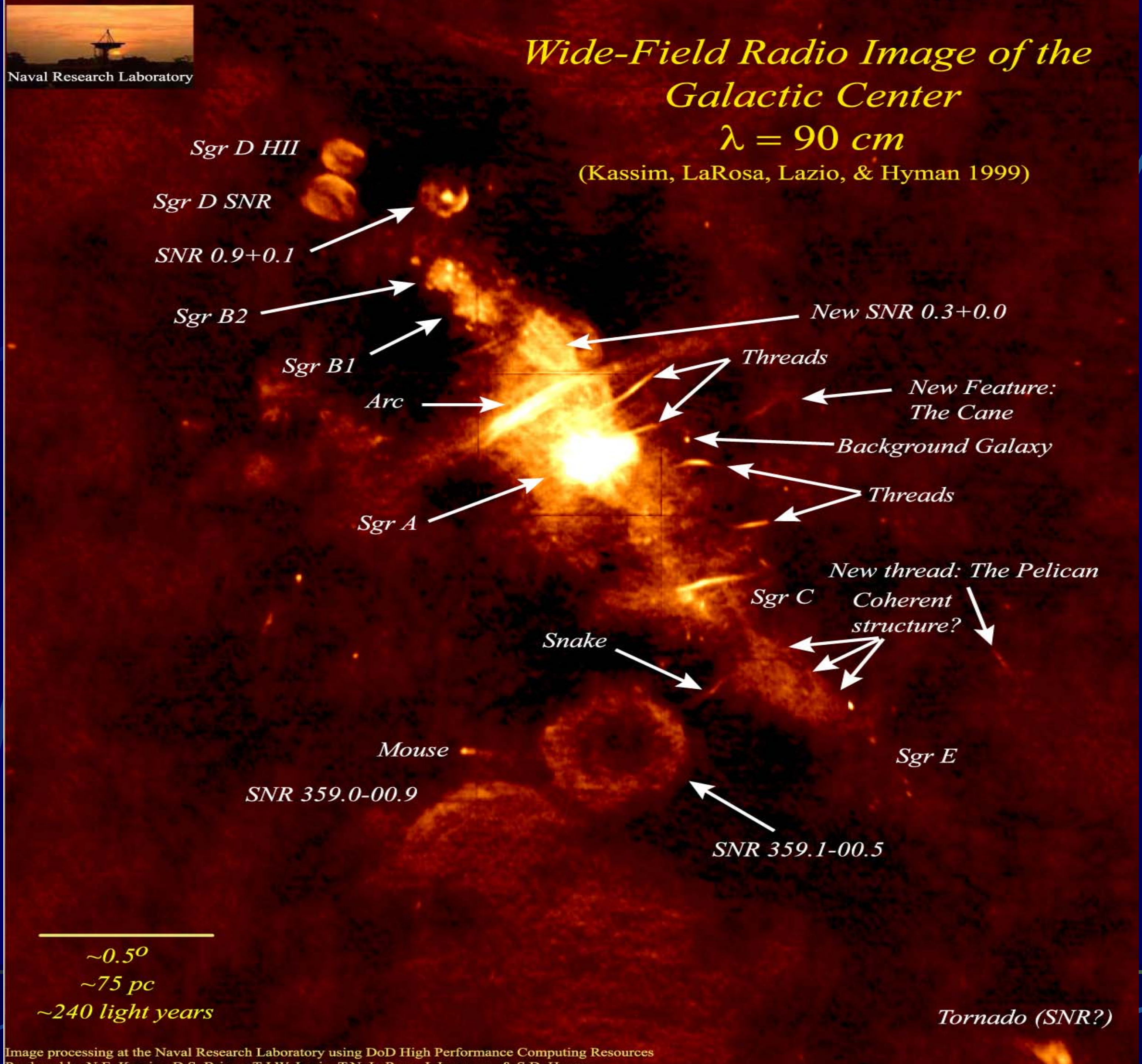
- $|b| < 5$ deg, 32 deg $< l <$ 80 deg
- 1.4 GHz total bandwidth = 300 MHz
- polyphase filter backend (1024 channels)
- multibeam system (7 feeds)
- 300 s integrations, 2000 hours total
- Can see 2.5 to 5 times further than Parkes (period dependent)
- Expect at least 1000 new pulsars


Parkes MB Feeds


National Astronomy and Ionosphere Center
Cornell University
ALFA Focal Plane Layout
y
x
Feed #2
Feed #3
Feed #1
Feed #0
Feed #4
Feed #6
Feed #5
Layout in Focal Plane
Feed Room Frame
Secondary Reflector
Multi-Beam System
Focal Plane
z
Tertiary Reflector
ALFA
Arecibo L-Band Feed Array
G. Cortés,
Charlottesville, 2003
1-5

II. GBT Galactic Center Survey

- Many NS expected in central star cluster
- Payoffs:
  - stellar evolution in GC
  - ISM in GC
  - probe central black hole (if lucky)
- Pulse broadening ~ 300 s at 1 GHz
- P ~ 0.2 requires ν > 8 GHz
- Millisecond pulsars not possible
- Search ~ 0.5 deg^2 with long integrations
- Full binary searches



Naval Research Laboratory
Wide-Field Radio Image of the Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
Arc
New SNR 0.3+0.0
Threads
New Feature: The Cane
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (SNR?)
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources

III. High Galactic Latitude Surveys

Search for:

- **Millisecond pulsars**
  (z scale height ~ 0.5 kpc)

- **High-velocity pulsars (~50% escape)**
  (scale height = ∞)

- **NS-NS binaries (max z ~ 5 kpc)**

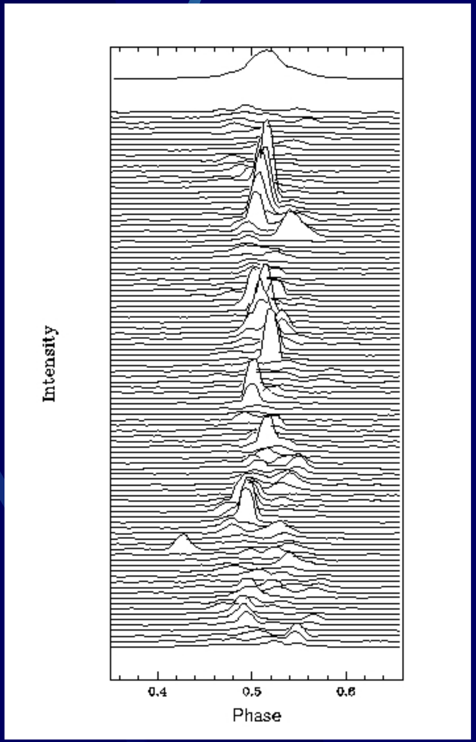
- **NS-BH binaries (max z ~ few kpc ?)**

Pulse Timing

- Goals:
  - Spin properties of pulsar (P, $\dot{P}$)
  - Precise DM (from TOAs at widely spaced frequencies)
  - Detection of orbital companions
    - MS stars, WD, NS, planets (BH?)
  - As gravitational wave detectors (long periods)

Times of Arrival (TOAs)

- Time tagging of data samples to ~ 100 ns precision (transfer of UTC via GPS)
- Obtain TOA by matched filtering a ‘template’ pulse to a sample average profile
- Transform the TOA to the solar system barycenter (≈ an intertial frame) (Eq. 23 of IHS)
- Analyze in terms of pulse phase



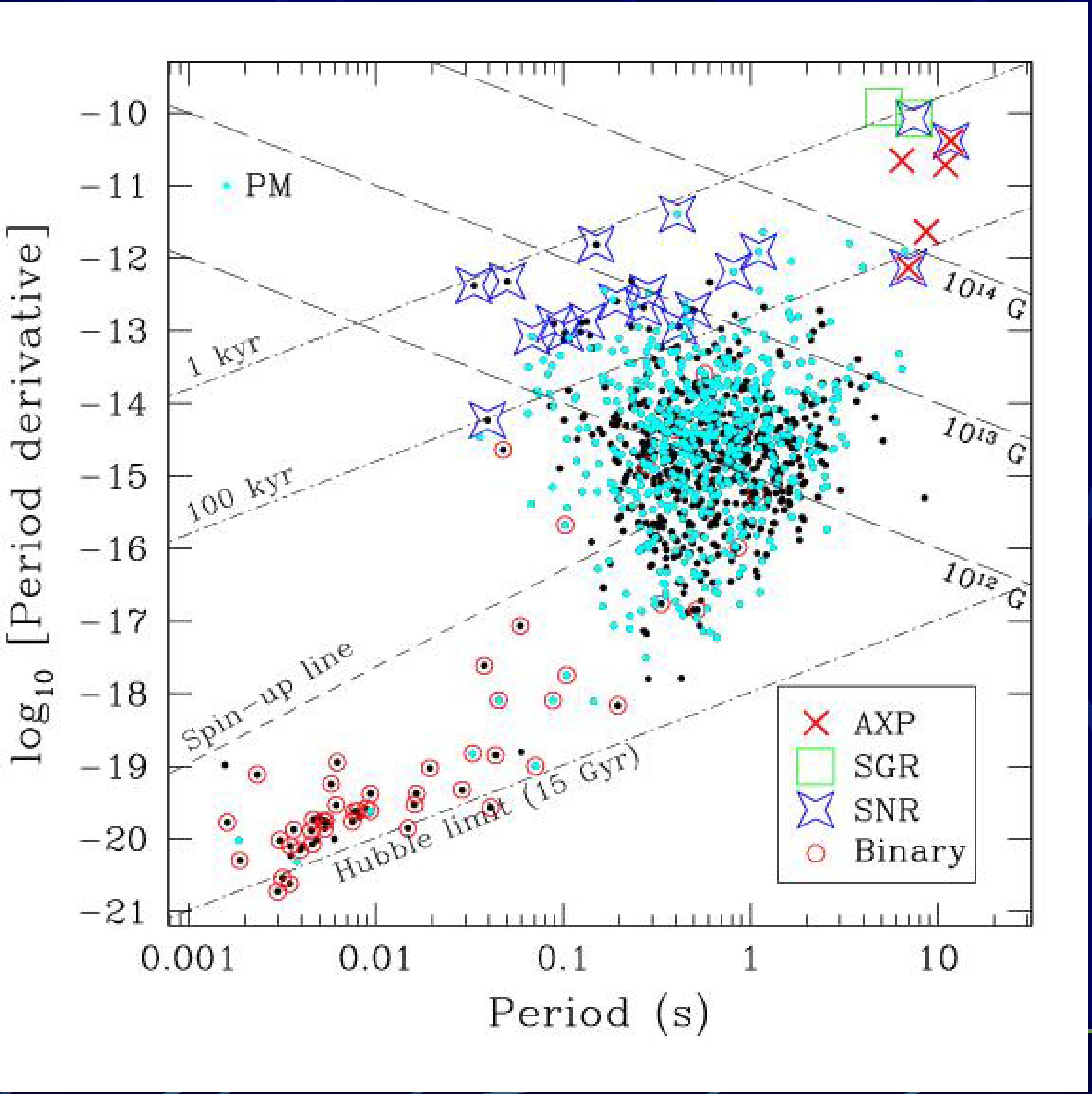
Pulse Phase Model

t = TOA

Spin-down model = low-order polynomial:

$$\varphi(t) = \varphi(0) + f\,t + \tfrac{1}{2}\,\dot{f}\,t^2 + 1/6\,\ddot{f}\,t^3 + \ldots$$

Additional contributions to φ are from 'timing noise' (intrinsic spin noise), from pulsar motion, parallax, orbital motion, etc.

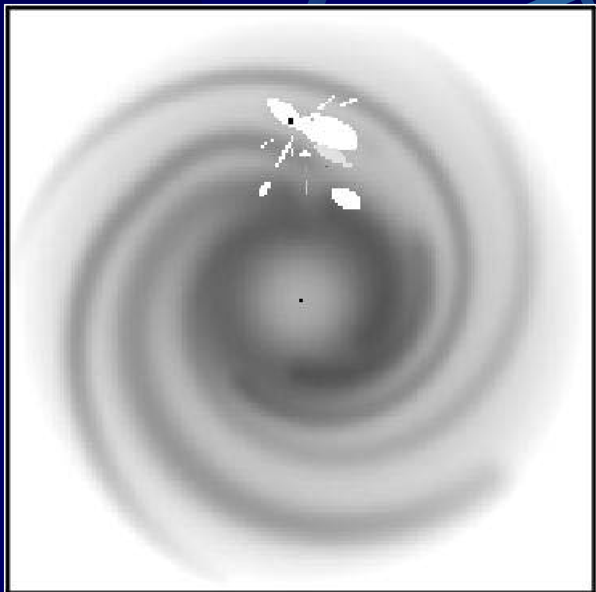


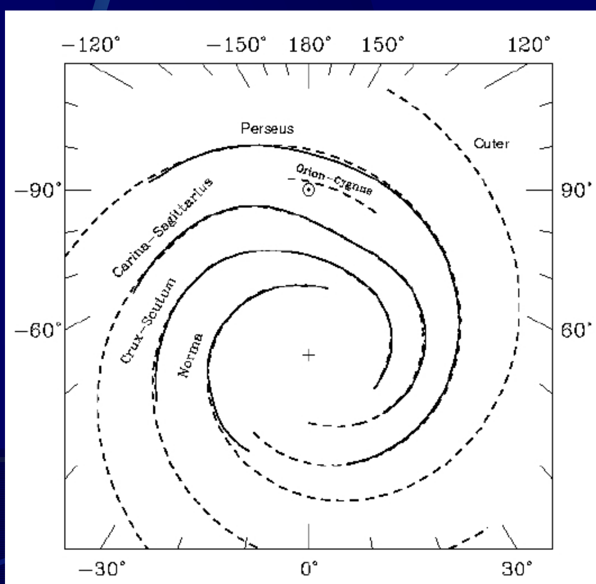
log10 [Period derivative]
Period (s)
PM
1 kyr
100 kyr
Spin-up line
Hubble limit (15 Gyr)
10¹⁴ G
10¹³ G
10¹² G
AXP
SGR
SNR
Binary

Pulsar Distances

Type	Number	Comments
Parallaxes:		
Interferometry	~13	1 mas @ 1 kpc
timing	~ 5	1.6 μs @ 1 kpc
optical	~ 1	HST, point spread function
Associations	SNRs 8 GCs 16 LMC,SMC ~8	false associations
HI absorption	74	bright pulsars, galactic rotation model
DM + n_e model	all radio pulsars (~ 1400)	ISM perturbations

NE2001 (uses data through 2001)





Electron density projected onto the Galactic plane:

Two disk components, spiral arms, Galactic center, clumps and voids

Paper I = the model (astro-ph/0207156)

Paper II = methodology & particular lines of sight (astro-ph/0301598)

Code + driver files + papers:

www.astro.cornell.edu/~cordes/NE2001

But … if you want a good distance, measure the parallax !

e.g. Arecibo + GBT + VLA$_\varphi$

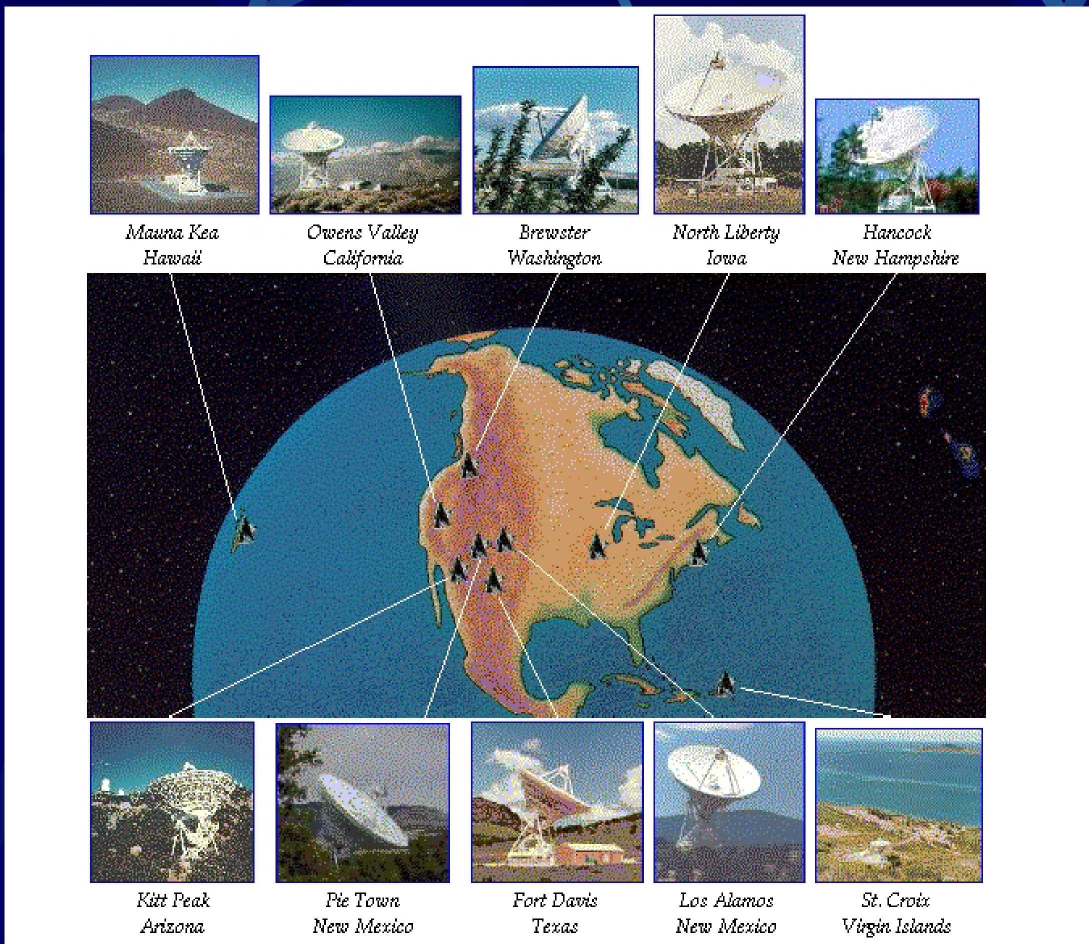
+

VLBA

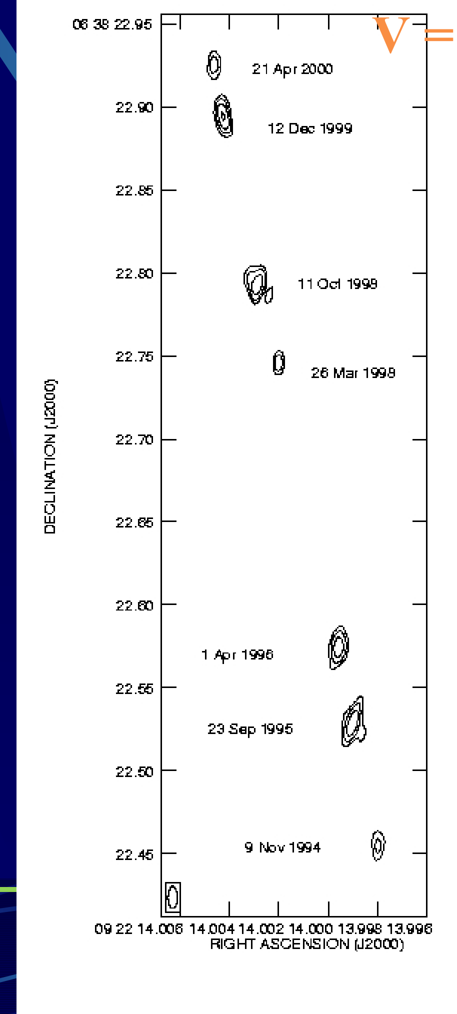
will be a powerful parallax and proper motion machine

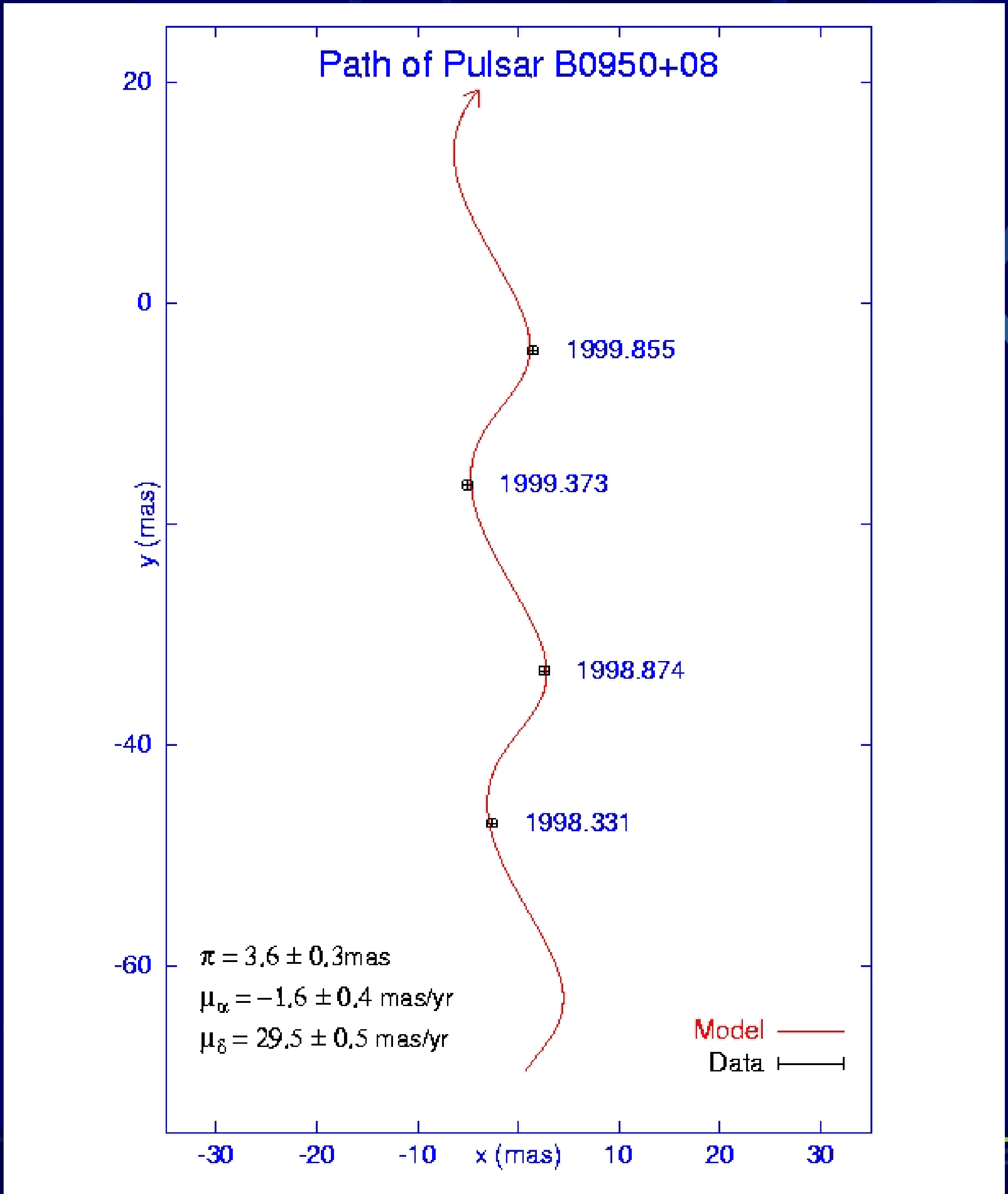
Very Long Baseline Array

PSR B0919+06
S. Chatterjee et al. (2001)
$\mu = 88.5 \pm 0.13$ mas/yr
$\pi = 0.83 \pm 0.13$ mas

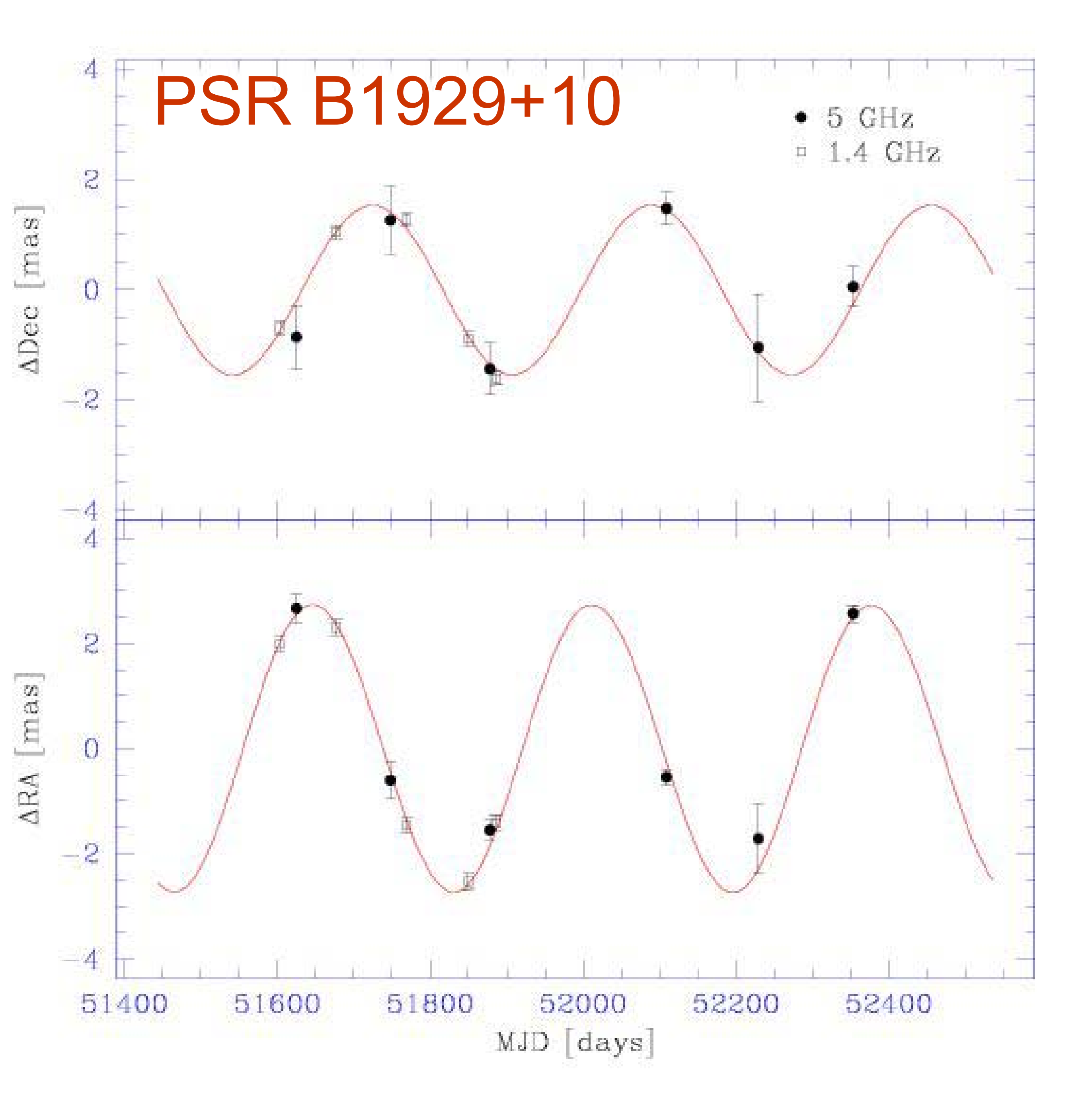


D = 1.2kpc
V = 505 km/s





Proper motion and parallax using the VLBA (Brisken et al. 2001)



Chatterjee et al. 2003

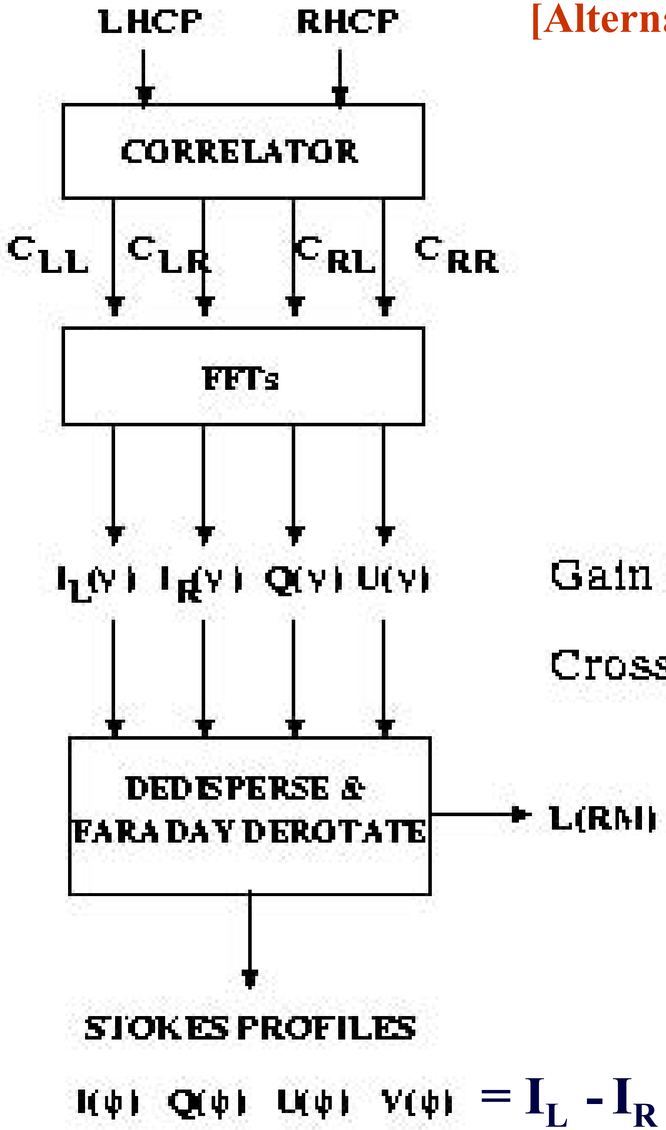
Polarimetry

- Predetection approach:
  - Record voltages $\propto E_L$, E_R or E_x, E_y
  - Dedisperse and compute cross products to get Stokes parameters

- Postdetection approach:
  - Use a correlator to obtain auto-and-cross products of voltages

CORRELATOR POLARIMETRY

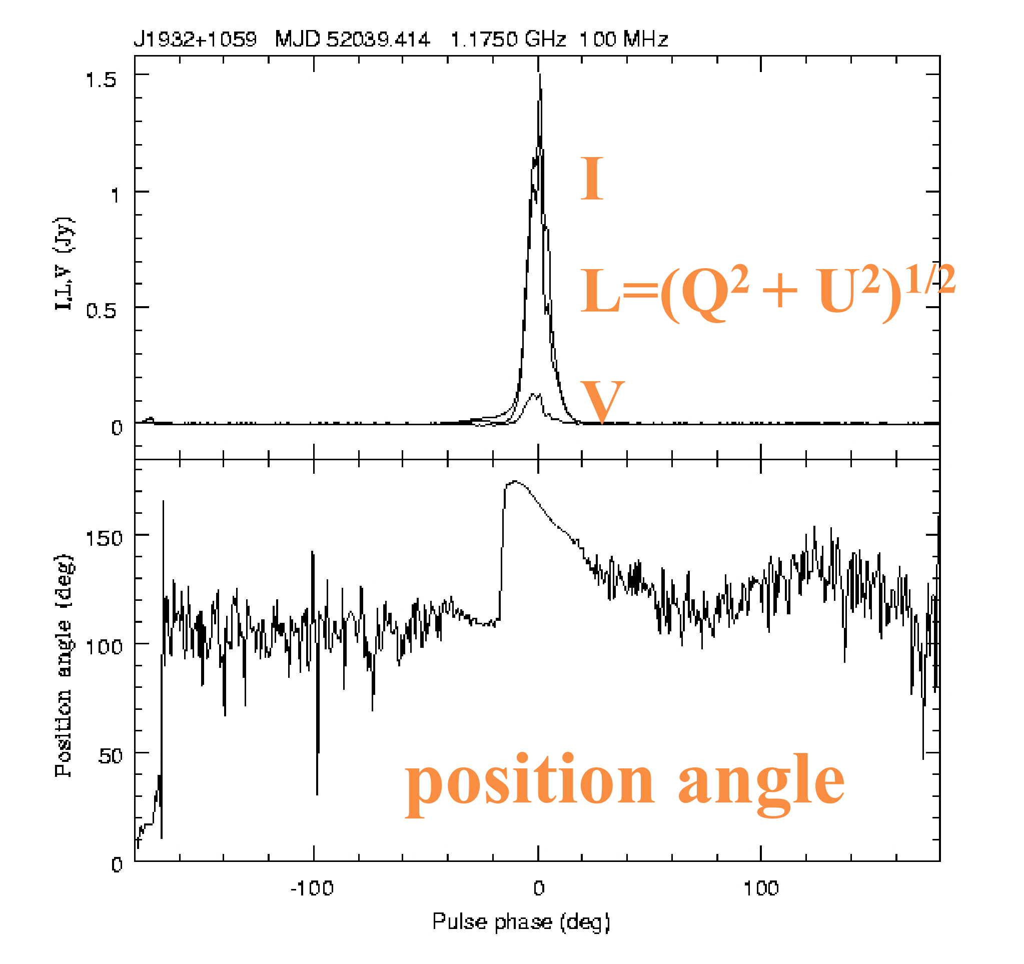
[Alternative: use E_x, E_x as input]



$= I_L - I_R$

Gain calibration

Cross coupling correction

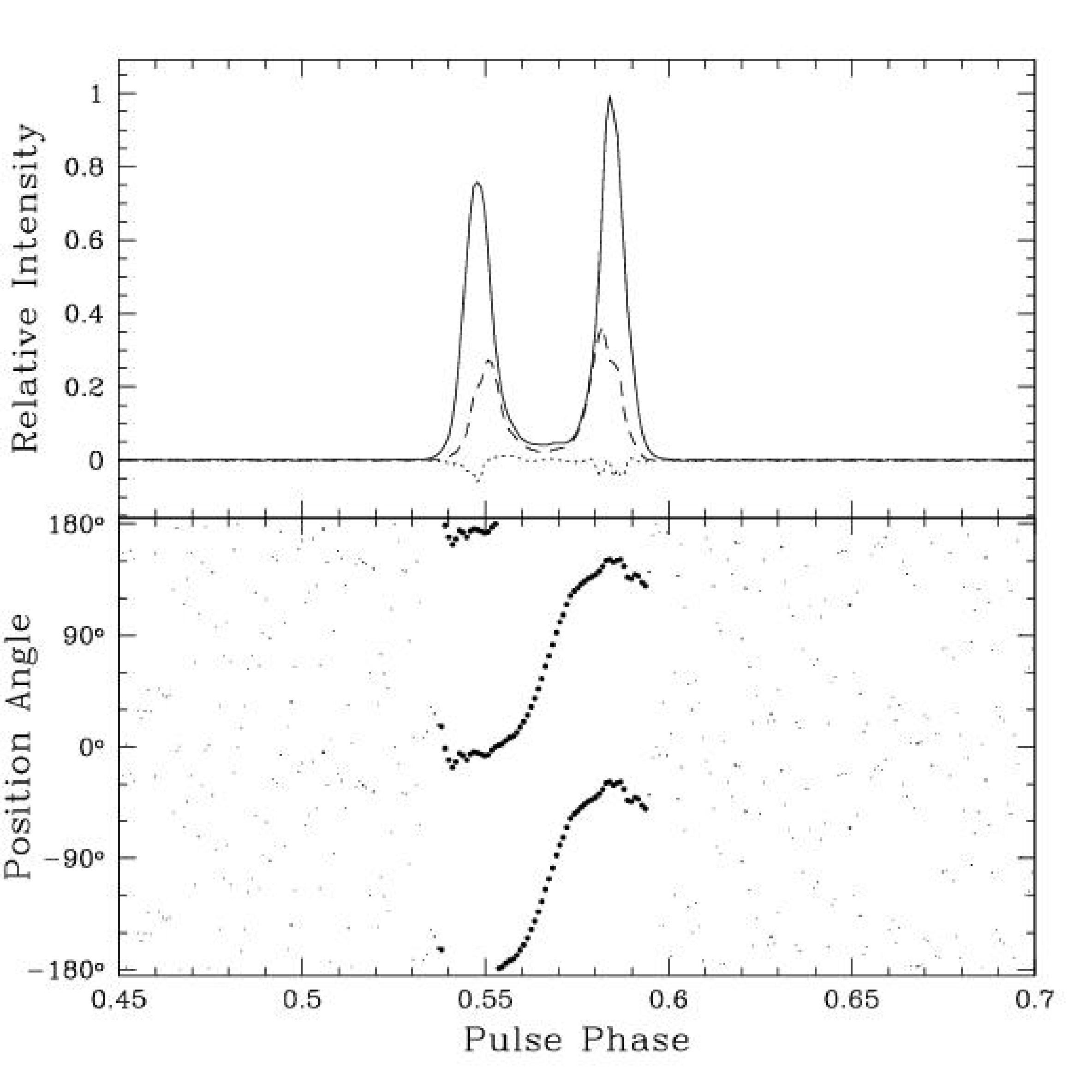


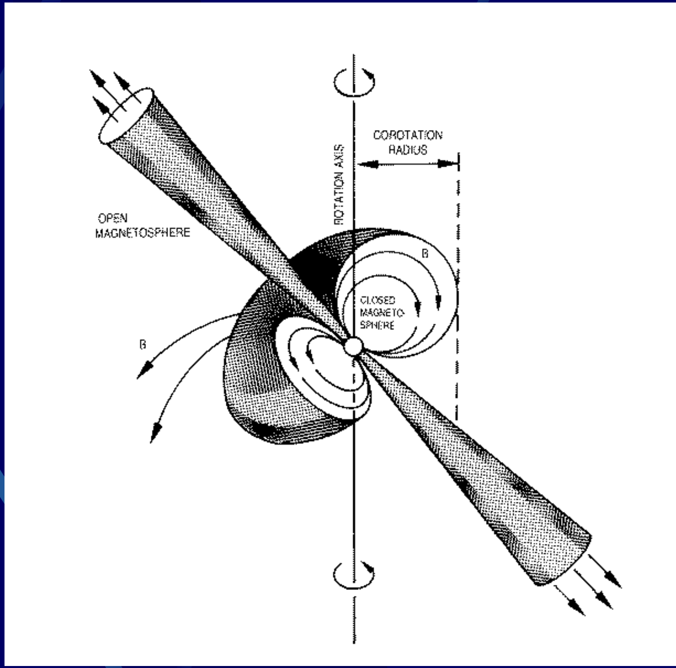
Pulsar B1929+10

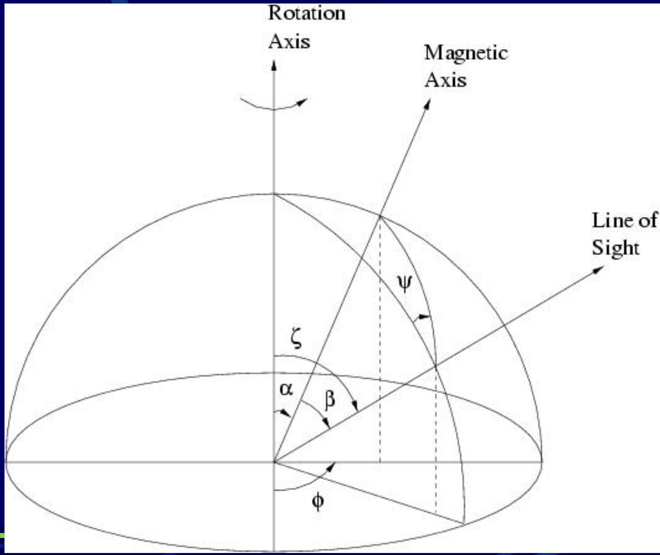
- 90% linear polarization
- polarized flux over entire period (atypical)
- position angle vs. ϕ measures projection of magnetic field as NS rotates (model curves with dipolar fields fit very well).

Stokes V here is uncorrected for instrumental polarization (TBD)

PSR B0525+21, 1.41 GHz, Effelsberg







Quick Summary

- Pulsar astronomy has many exciting payoffs in the next 5 yr (AO & GBT surveys)
- For pulsars, you can ignore all that was said about confusion limits and beam switching
- learn VLBI too