

Pulsar Timing – Backend Systems

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Image credit: NASA

What are pulsars?

Radio Pulsars are not pulsating stars. Instead they are compact stellar objects that generate a constant beam of energy from the magnetic polar regions.

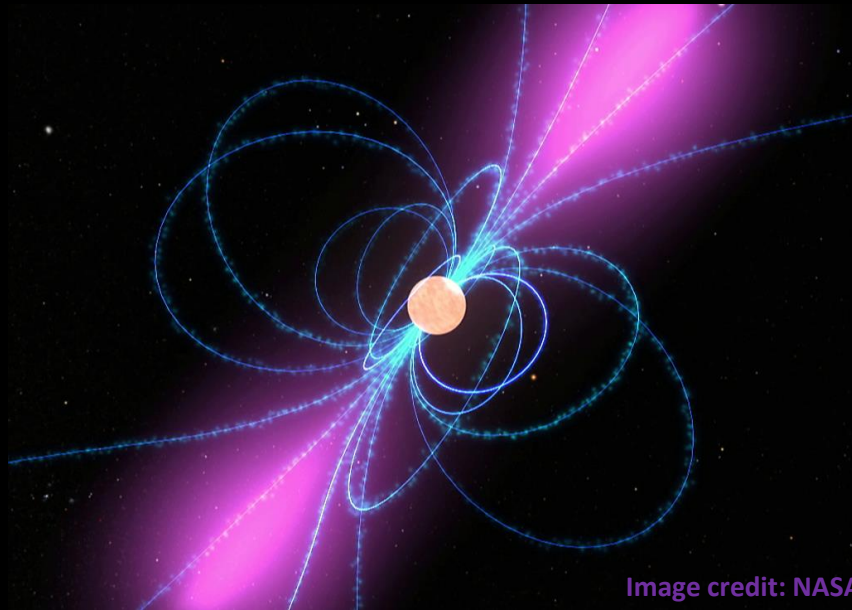


Image credit: NASA

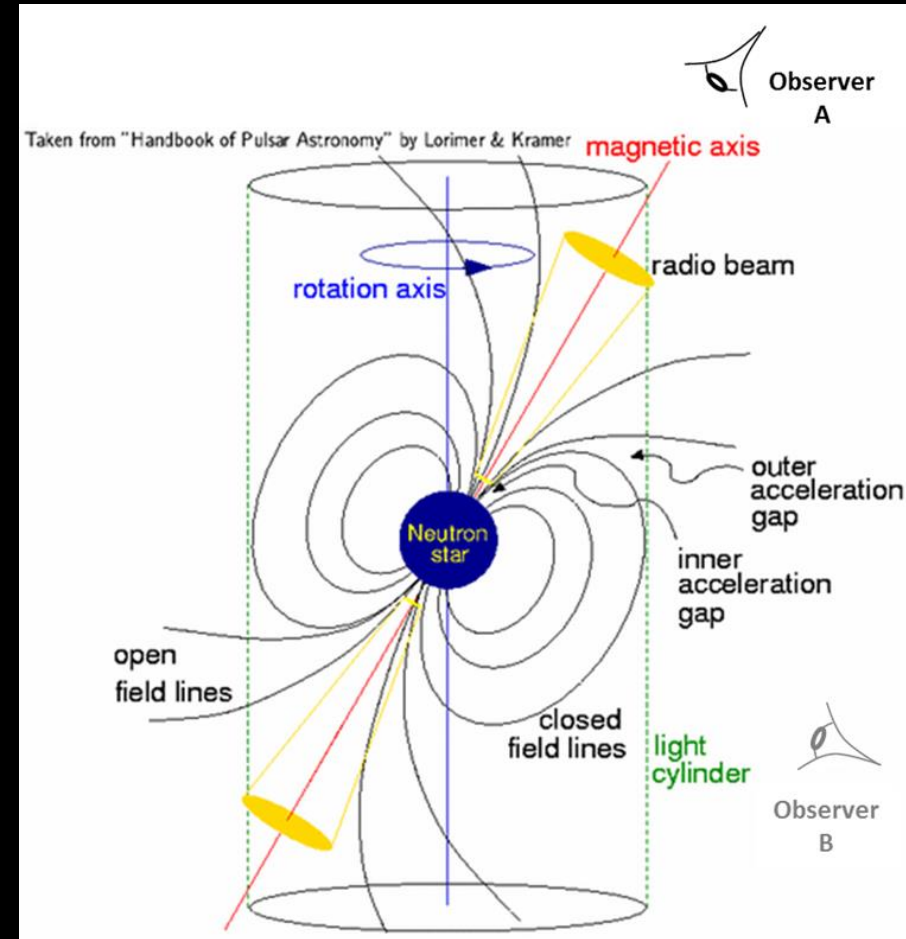


Image Credit: Adapted from Handbook of Pulsar Astronomy

A pulsar is a neutron star, formed from the remnant core of a supernova, where the axis of the magnetic poles is not aligned with the axis of rotation, but which periodically aligns with our line of sight, giving the perception of a regular pulse of radio emission.

Physics with Pulsars

Time of arrival at different frequencies

Frequency dispersion along the line of sight gives us information on the neutral hydrogen / electron number density of the ISM.

By examining the pulse profile

Changes in flux or phase or shape, we can derive an idea of structure present in the emitting regions

Pulsar timing

Spin down rate, RRATs & Nulling emission mode, Glitches (neutron star interiors)

Pulsars in Binary Systems

Interactions between companions (Recycled pulsars Redbacks & Black Widows)

Millisecond pulsars

Post Keplerian Orbital mechanics, tests of General Relativity,
Constrain theories on gravity waves

What is Pulsar Timing?

Creating detailed timing models for individual pulsars by regular monitoring of the rotation of a neutron star based on the time of arrival of radio pulses.

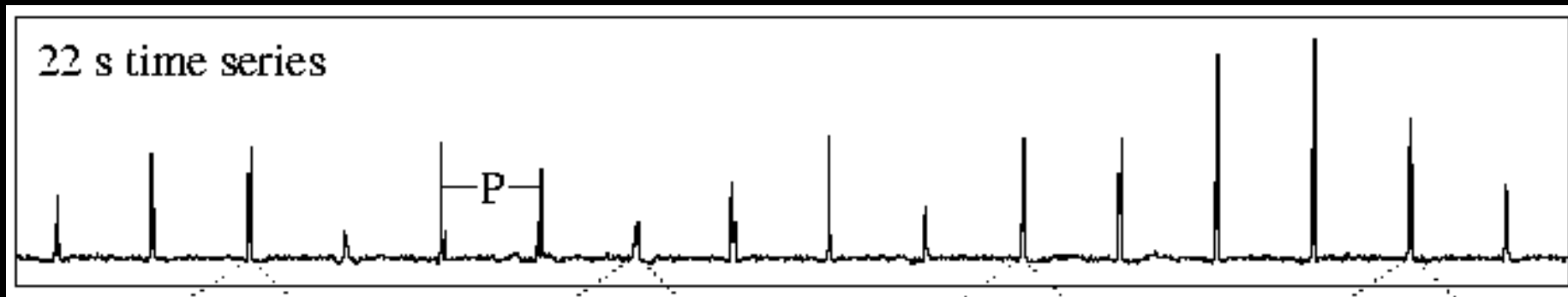


Image Credit: Adapted from Pulsar Astronomy

P is the period between peaks (or a prominent feature on the pulse)

Measuring the Period

Pick a point on the pulse and measure the time delay to the next occurrence

- Simple case: 1 second period, 10% duty cycle, assume our accuracy of the pulse peak is 10% = 0.1s (100ms).

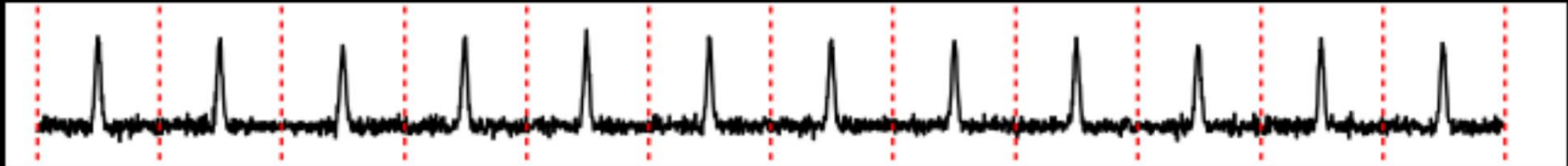


Image Credit: Scott Ransom

- Measure over n pulse periods and we can reduce the error in our estimation of the period by $1/n$

PSR J1737+0747 (a millisecond pulsar)

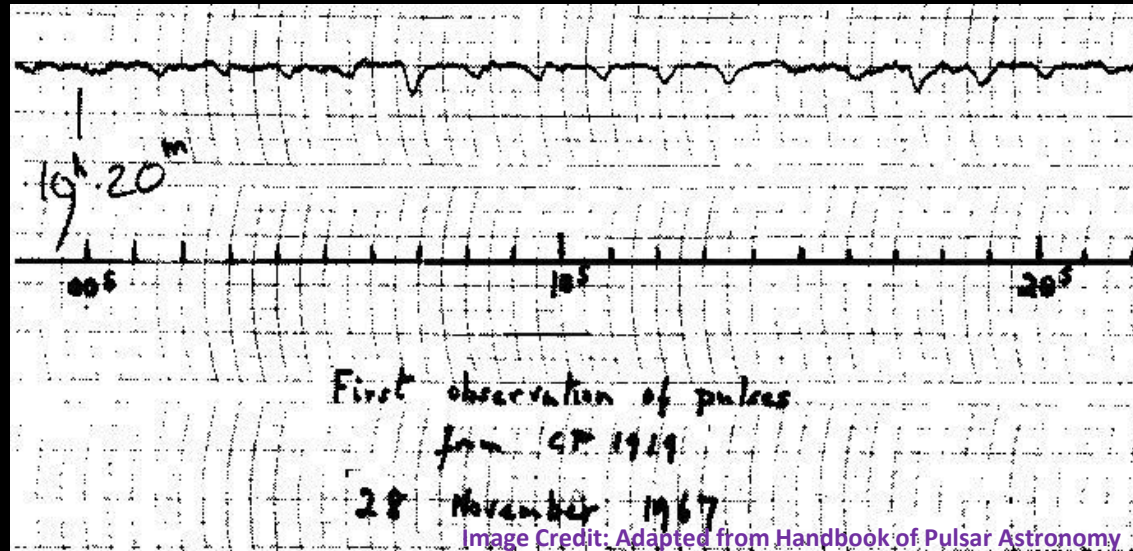
$$P = 4.570136529159926 \text{ ms} \pm 0.1 \times 10^{-8} \text{ ns}$$

Pulsar Backend Systems

- **At a radio observatory there are three type of backend system.**
 - The radio receiver.
 - The signal digitiser.
 - The Pulsar Timing System.

- **We are going to look the Pulsar Timing System.**
 - The original Pulsar Timing Systems were analogue devices.
 - A pen chart recorder
 - Analogue Filterbank

Analogue Systems – Chart Recorder



The first pulsar was detected by observing periodic radio bursts on a pen chart recorder by Jocelyn Bell and Antony Hewish in 1968 (Hewish 1968)

Chart Recorder

- Simple and cheap
- Records are rolls of paper
- Sensitivity / resolution limited by speed of pen.

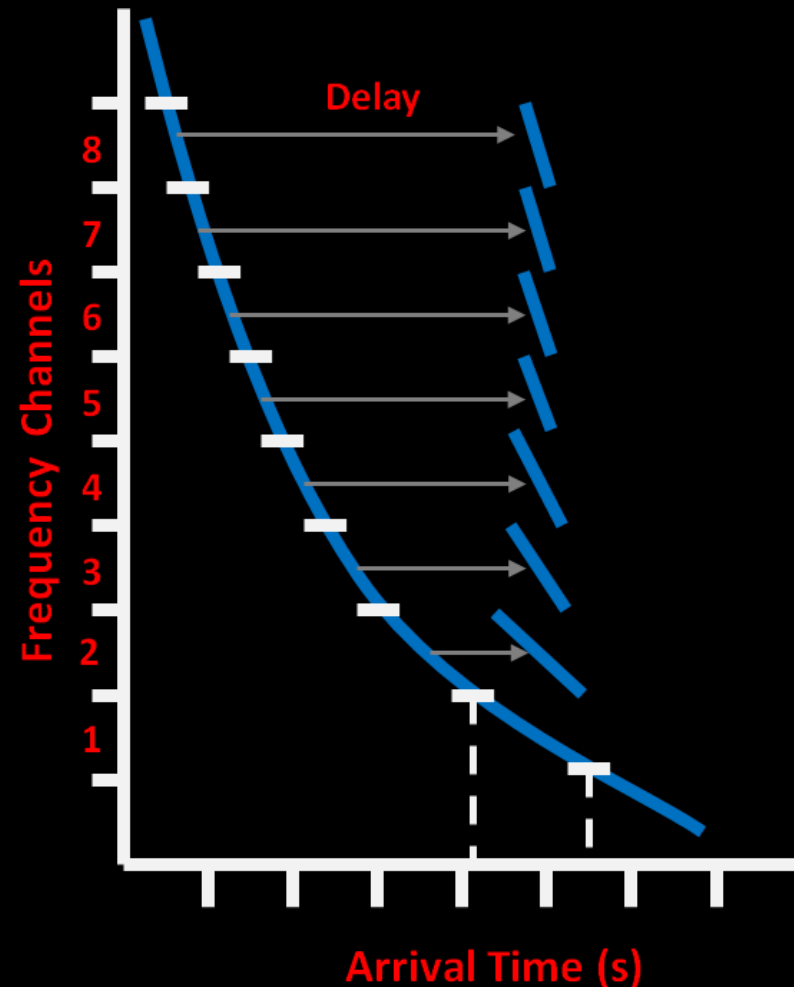
Analogue Systems - Filterbank

Dedispersion using an Analogue Filterbank

- Dispersion by the Interstellar Medium ‘smears’ the signal in time and reduces the signal to noise ratio.
- Dedispersion reduces the above by delaying the signal by different times at different frequencies.
- The uncorrected frequency dispersion in each channel (indicated by the slope of the blue line segments) gives rise to smearing of the pulse profile.

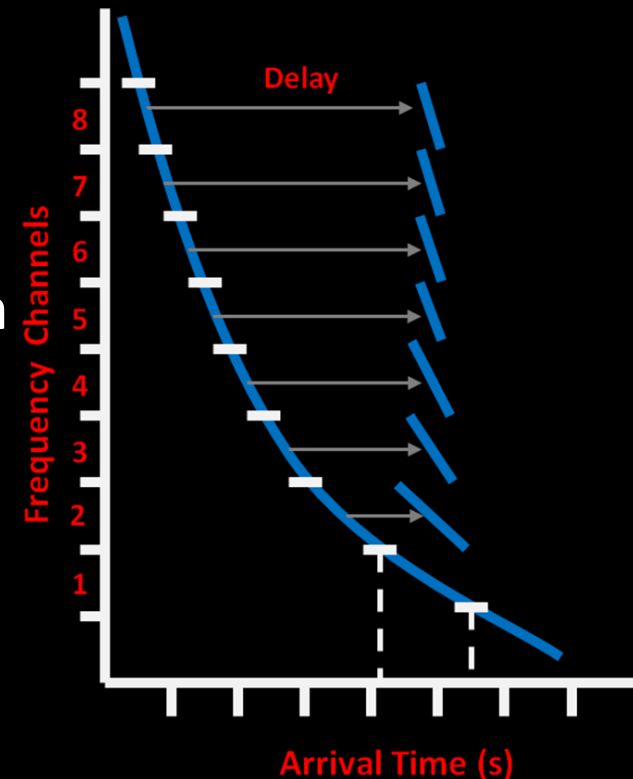
Expensive / Custom Design

- Limited numbers of channels
- Tricky to setup



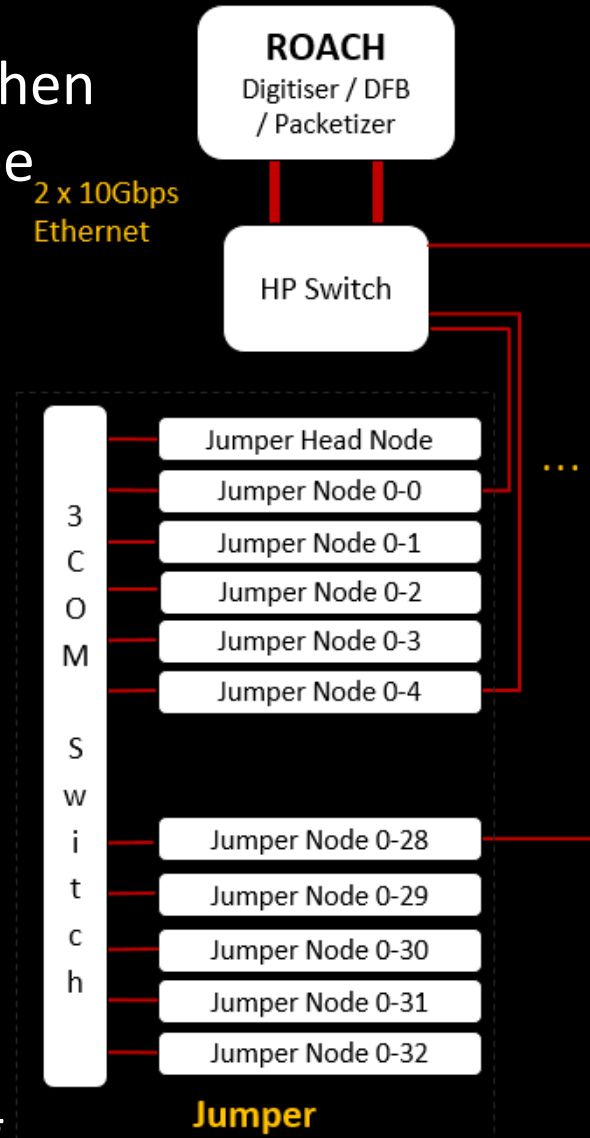
Digital Filterbanks

- Uses bespoke Application Specific Integrated Circuits (ASIC's) and Field Programmable Gate Arrays (FPGA's) for incoherent dedispersion on many frequency channels.
- Dedicated and Fast
- Configurable (but not flexible)
 - New algorithm = new ASIC or FPGA
 - Approximates the cost of a new system
- Expensive and Time consuming to design
 - Very few skilled resources available

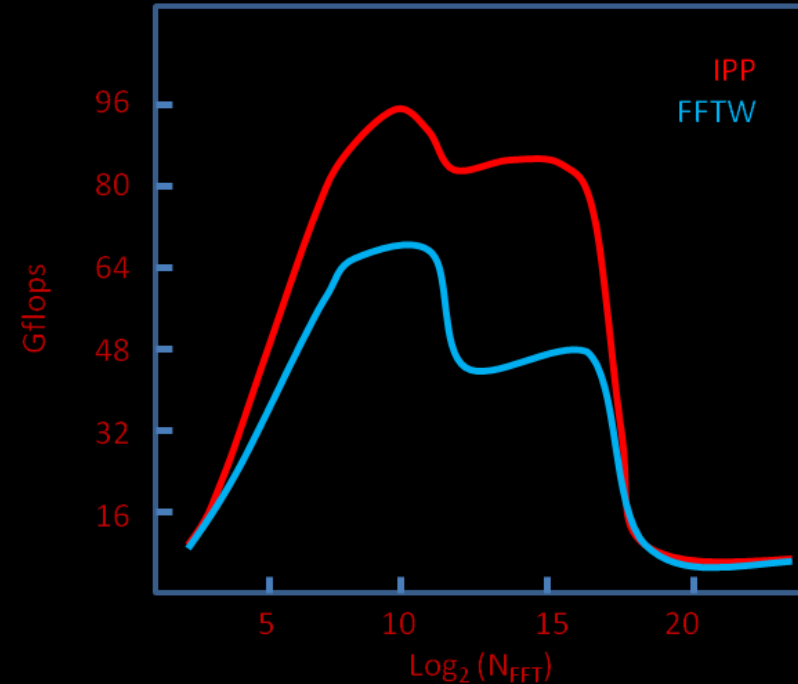
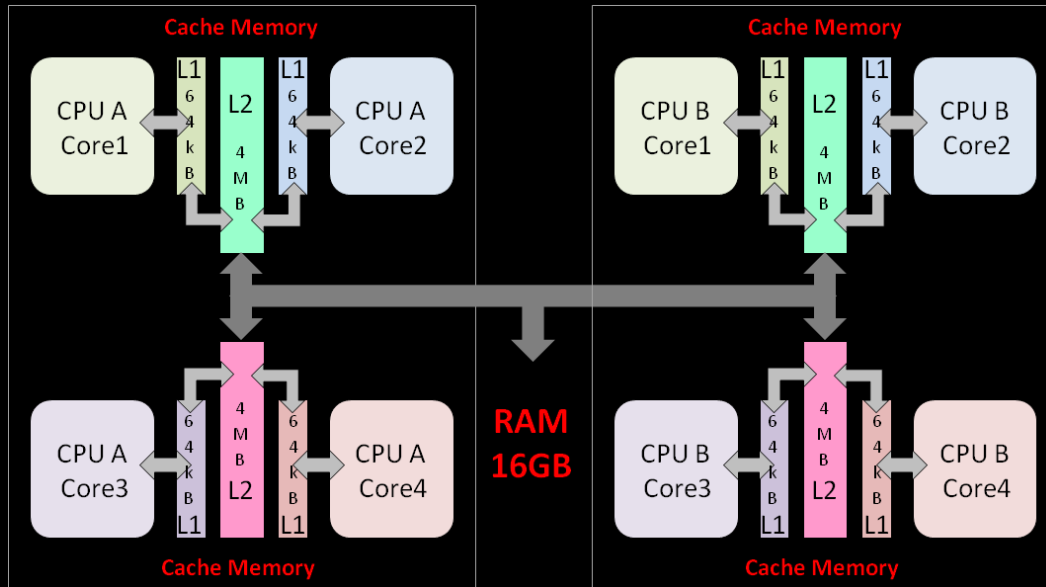


General Purpose Computers

- As CPU compute power increases (Gflops) then 'low cost' general purpose computers can be used.
 - Flexible and programmable
 - Cheaper (off the shelf components)
 - Upgradable
 - Parallel processing
- Limitations
 - Input / Output speed
 - Memory capacity
 - Memory bus limited
- Use Beowulf Clusters to process wider bandwidths / higher data rates
- Implement coherent dedispersion & folding



Processing Throughput



Processing throughput as a function of complexity and workstation design.

In this illustration throughput is proportional to raw compute power and software algorithm (IPP vs FFTW). Until memory cache size and bandwidth become limiting factors and lead to a collapse in throughput.

- $\log_2(N_{FFT}) \sim$ complexity and size of sample.
- Based on Dual Quad Core Intel Xeon processor workstation

Challenges – Signal to Noise

- Pulses are not simple consistent shapes
- The signal may be below the noise floor of our instrument
 - Sum many pulses together to improve signal to noise

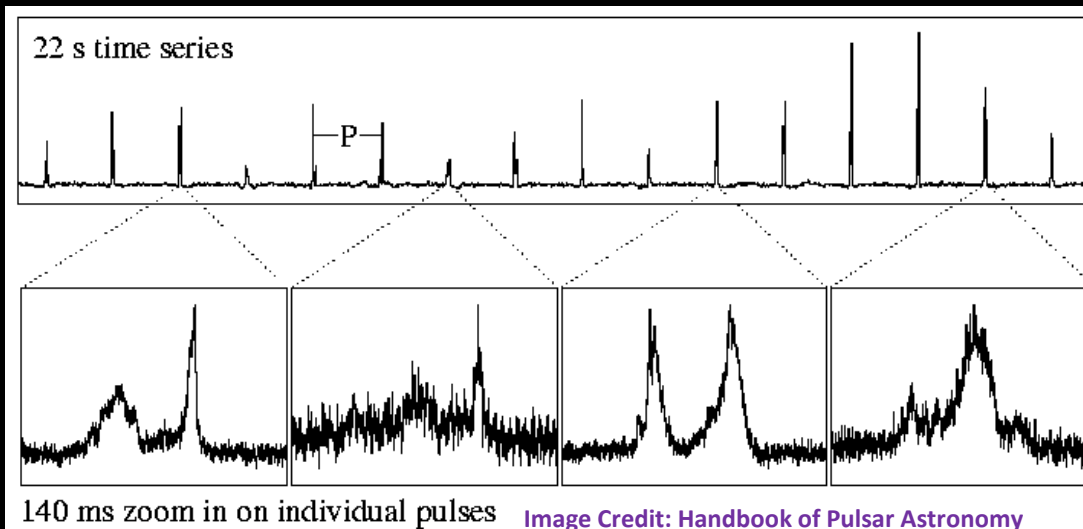
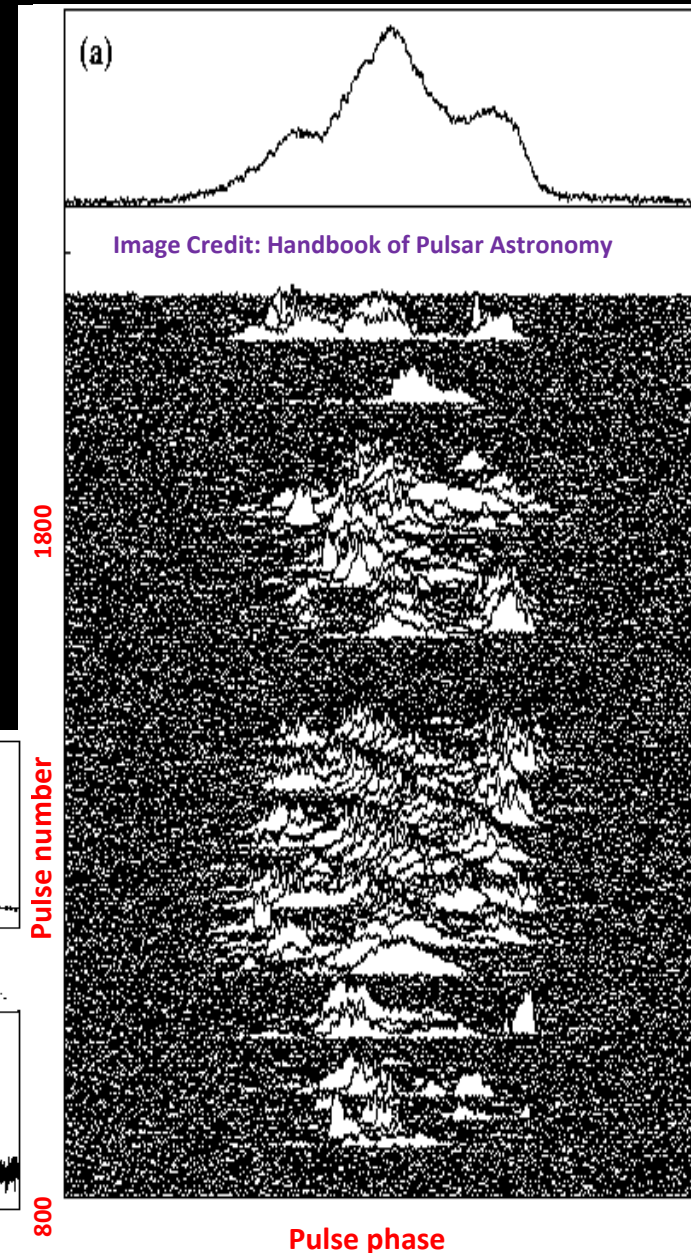


Image Credit: Handbook of Pulsar Astronomy



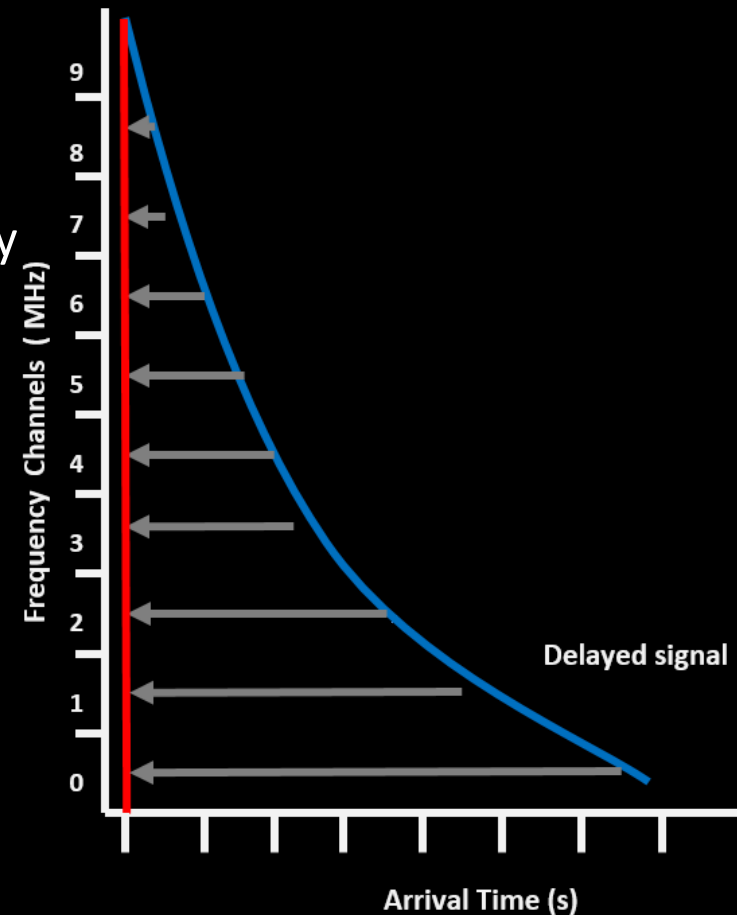
Challenges - Coherent Dedispersion

- **Coherent Dedispersion**

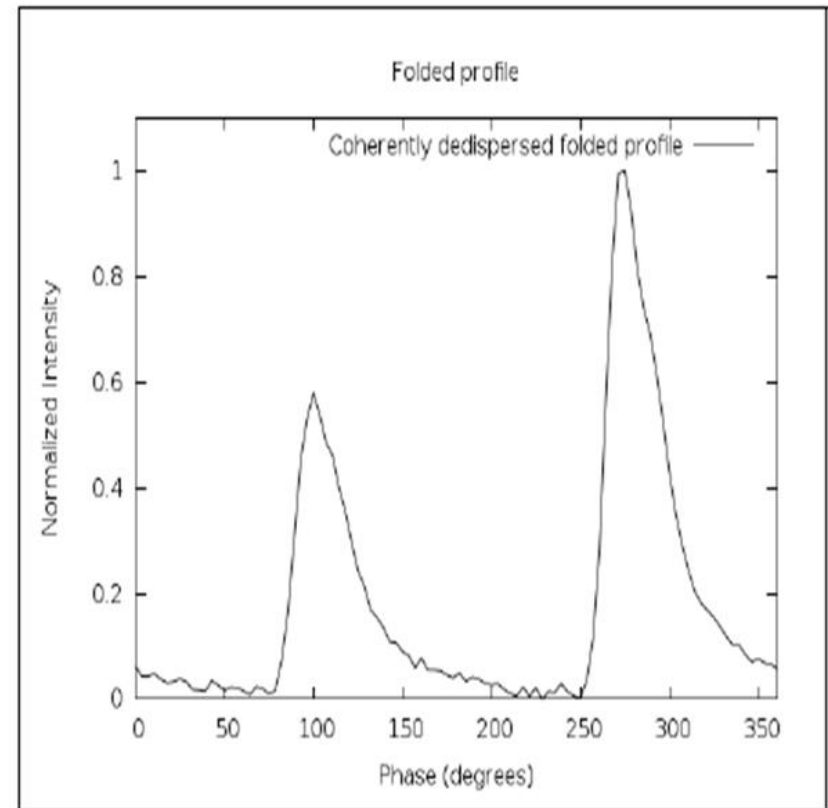
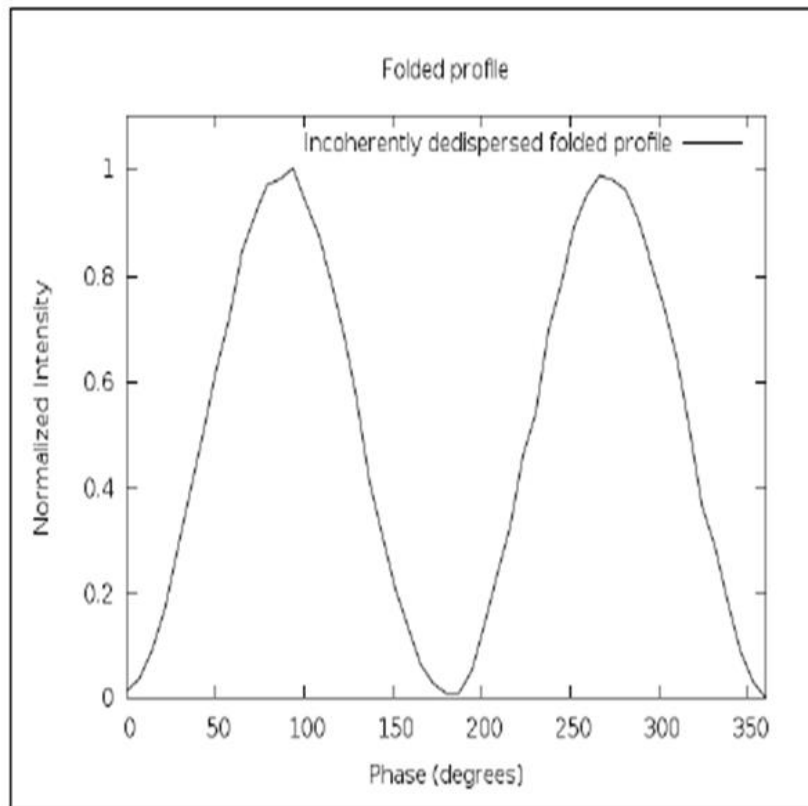
- Use a chirp filter to reverse the effect of the Interstellar Medium on the pulsar signal.
- Gives a much better signal to noise and pulse shape resolution.
- Use a Fast Fourier Transform (FFT) to carry out dedispersion and frequency channel synthesis.
- The processing load is proportional to the Fourier transform length.

- **Undertake processing in real time**

- Alternatively store the input data and process later.
- Accumulating at 1.536 GBytes per second*



Incoherent vs Coherent Dedispersion



(a) Incoherently dedispersed and normalized folded profile for B1937+21. (b) Coherently dedispersed and normalized folded profile for B1937+21.

Challenges – Volume of Data

Data Rates

- Event duration ~ 100's ns, high bandwidth and fast sampling to get that time resolution
- 512MHz sampled at 1 GHz = 1GByte of data per second

Volume of Data

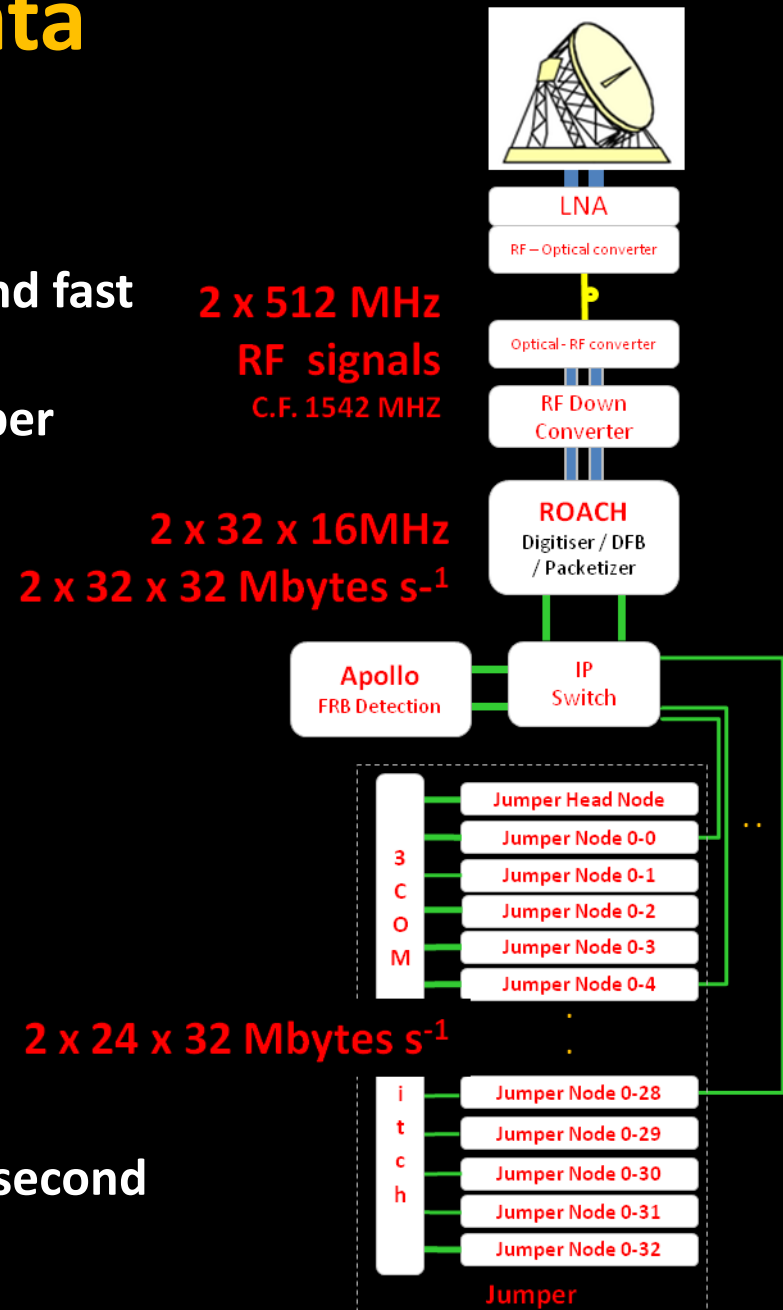
- Normal pulsar: 1 s period ~ 1 GByte of data to dedisperse per pulse
- Millisecond pulsar: 10ms period ~ 10MBytes of data to dedisperse per pulse

High Dispersion Measure Pulsars

- A pulse may be spread over many periods

Processing the data in Real Time

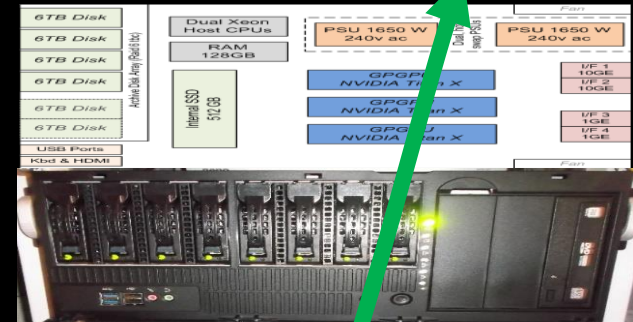
- Each frequency channel ~ 2 x 32 Mbytes per second
- Each channel processed by a separate node



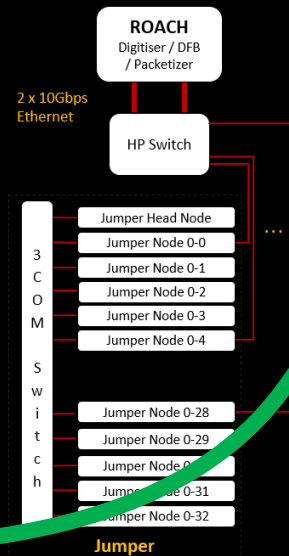
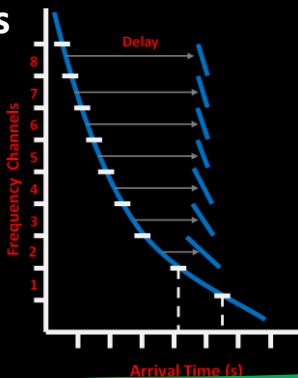
Evolution of Pulsar Timing Systems

Processing
Power

Hybrid Cluster of CPUs & GPUs in a single server
(4.5 - 6 TFLOPS)

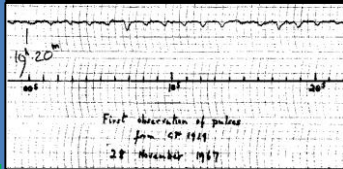


Analogue and Digital
Filter banks



Coherent
dedispersion on a
32 node Beowulf
Cluster
(~3 TFLOPS)

Pen Chart Recorder



1967

2018

Analogue | Digital

GPU Based Processing

- **Massively parallel processing, for a correctly designed program**
GPU>>>CPU
 - 1000 + ALU per card
 - 12 Gbytes memory per card
 - Teraflops of processing capacity per card
- **Independent computational operations in each core**
 - Reduced synchronisation and signalling requirements
 - Faster bulk transfer of data rather than single memory read/write operations
- **Contention for shared resources**
 - Intermediate cache memory, system transfer buses, means overall performance may only be ~60% of the potential maximum
- **Limitations**
 - Do Not Branch ! – requires slow main memory accesses
 - As before memory and bandwidth limitations

GPU Architecture

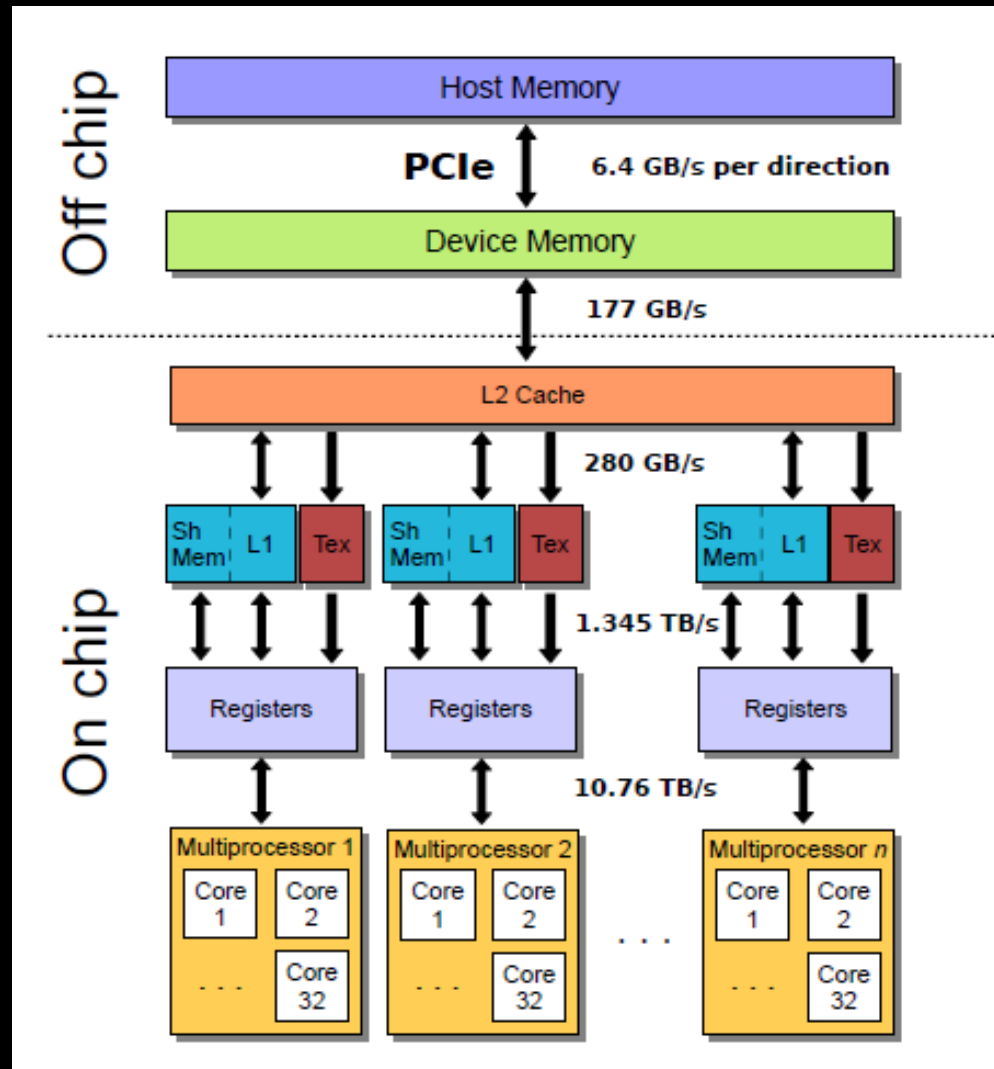


Image Credit:

adapted from Clark, LaPlante & Greenhill 2011

NVIDIA® Fermi GPU architecture

Not All GPUs are equal

Two Types of GPU devices

- **Gaming** : more powerful for compute intensive operations
- **Scientific** : better I/O capabilities

Five fold price difference

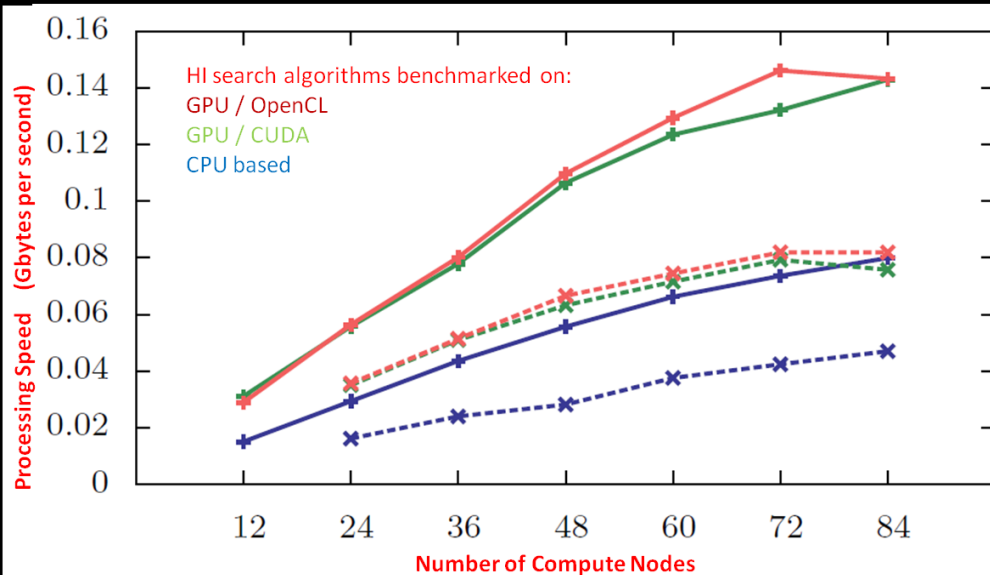


Image Credit: Adapted from Westerlund & Harris 2015

NVIDIA GPU Card comparison (vs GTX980)

Gaming: GTX580, GTX780 & Titan X
Scientific: M2090, K40 & K80

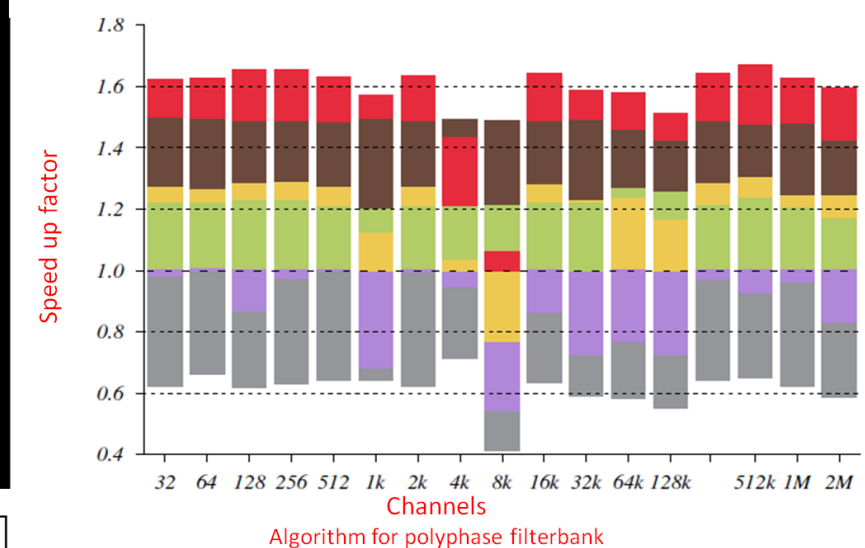
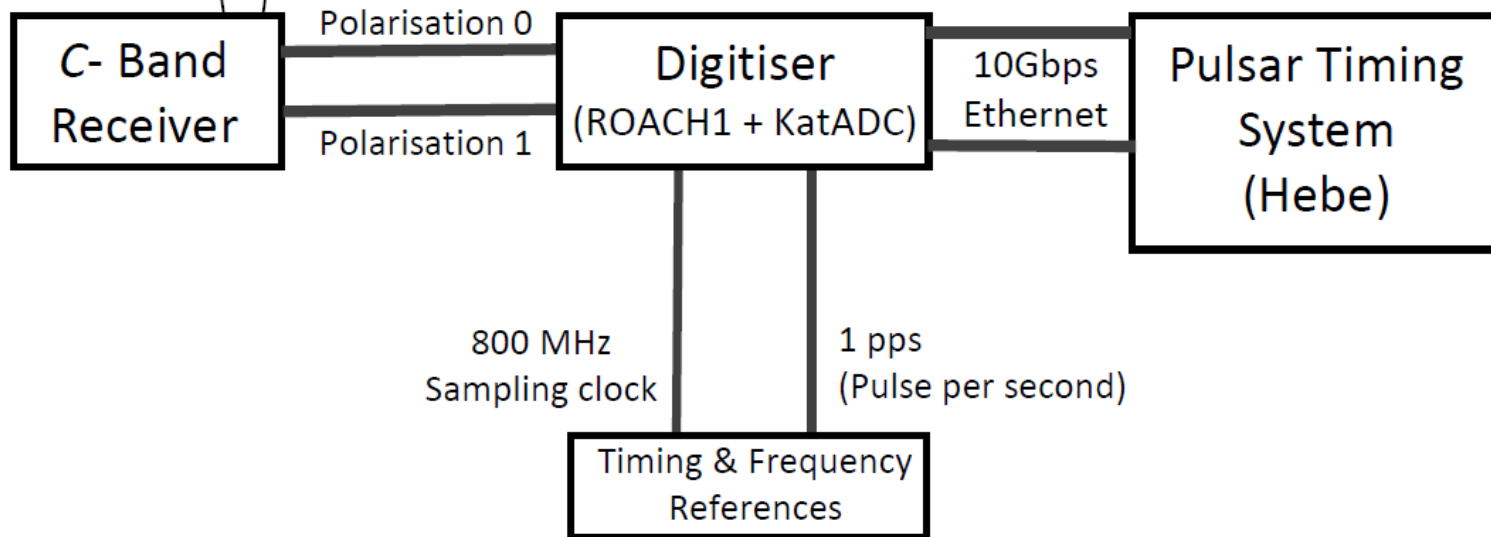
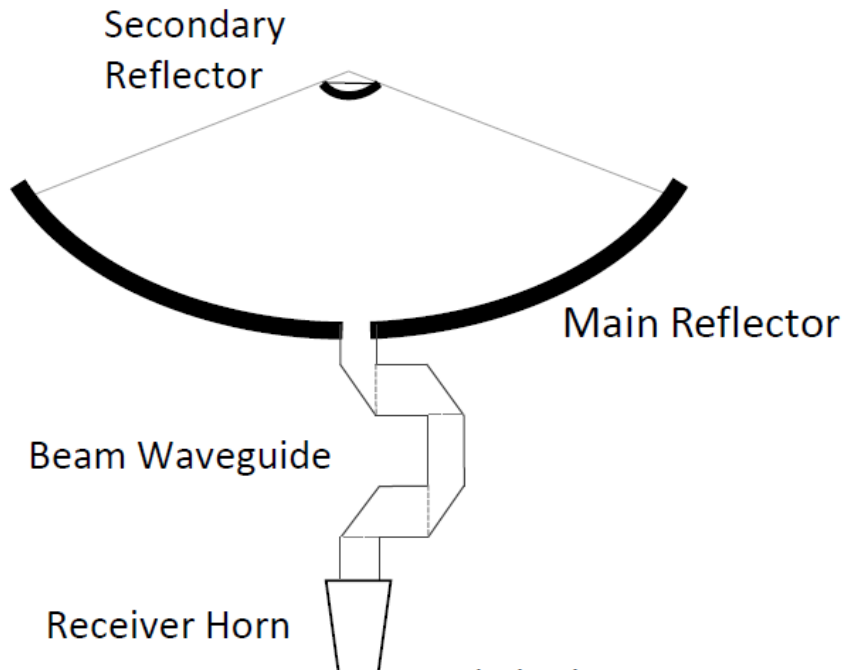


Image Credit:
adapted from Adamek, Novotny & Armour 2015

Impact of Software Environment:

- CUDA : NVIDIA Proprietary
- OpenCL : Open standard

Ghana Radio Astronomy Observatory



GRAO Pulsar Timing System

Analogue Receiver

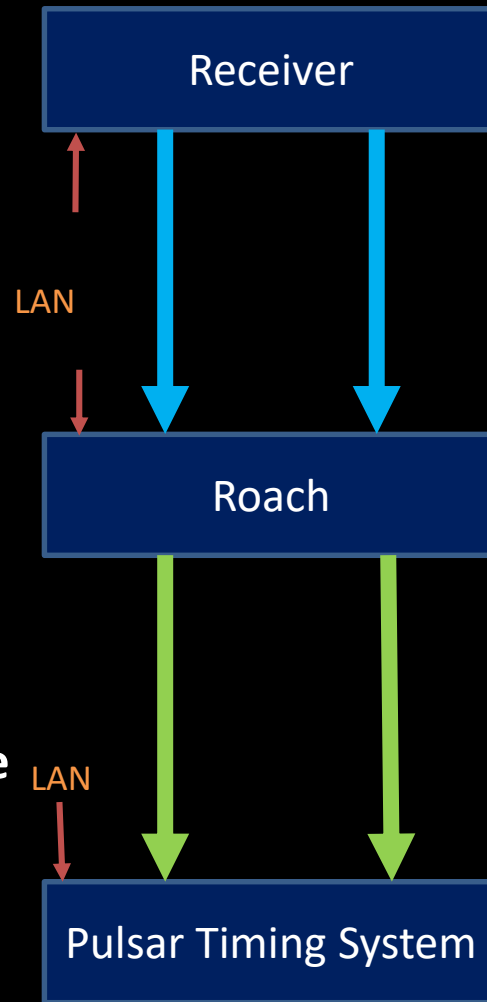
- 5 GHz / 7.8 GHz
- 154MHz / 670MHz

Digitiser

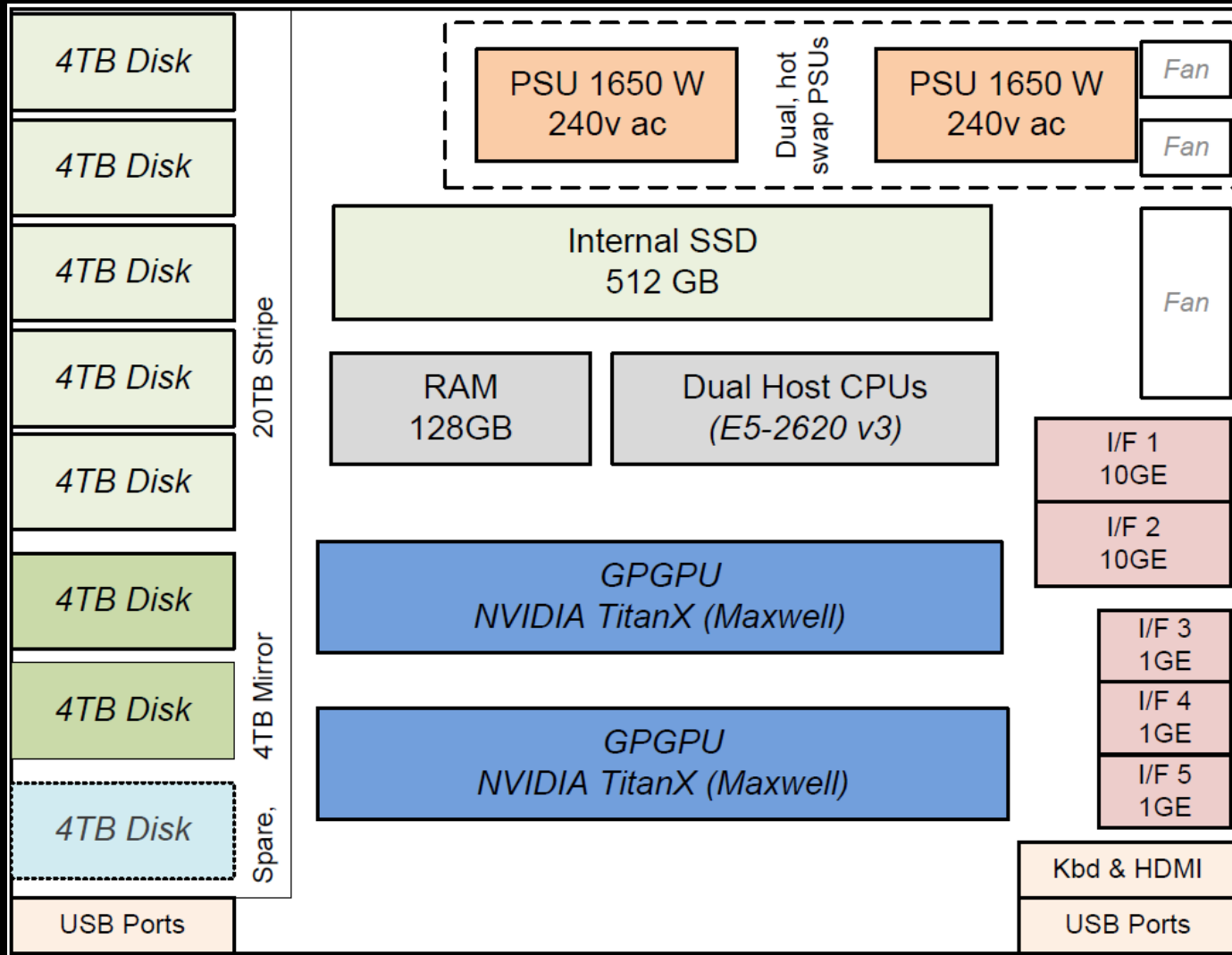
- 80 ms sampling
- 400MHz bandwidth
- 8 bit resolution
- Output 2 x 10GE

Pulsar Timing System

- 400 MHz in Real Time



Ghana : Pulsar Timing System



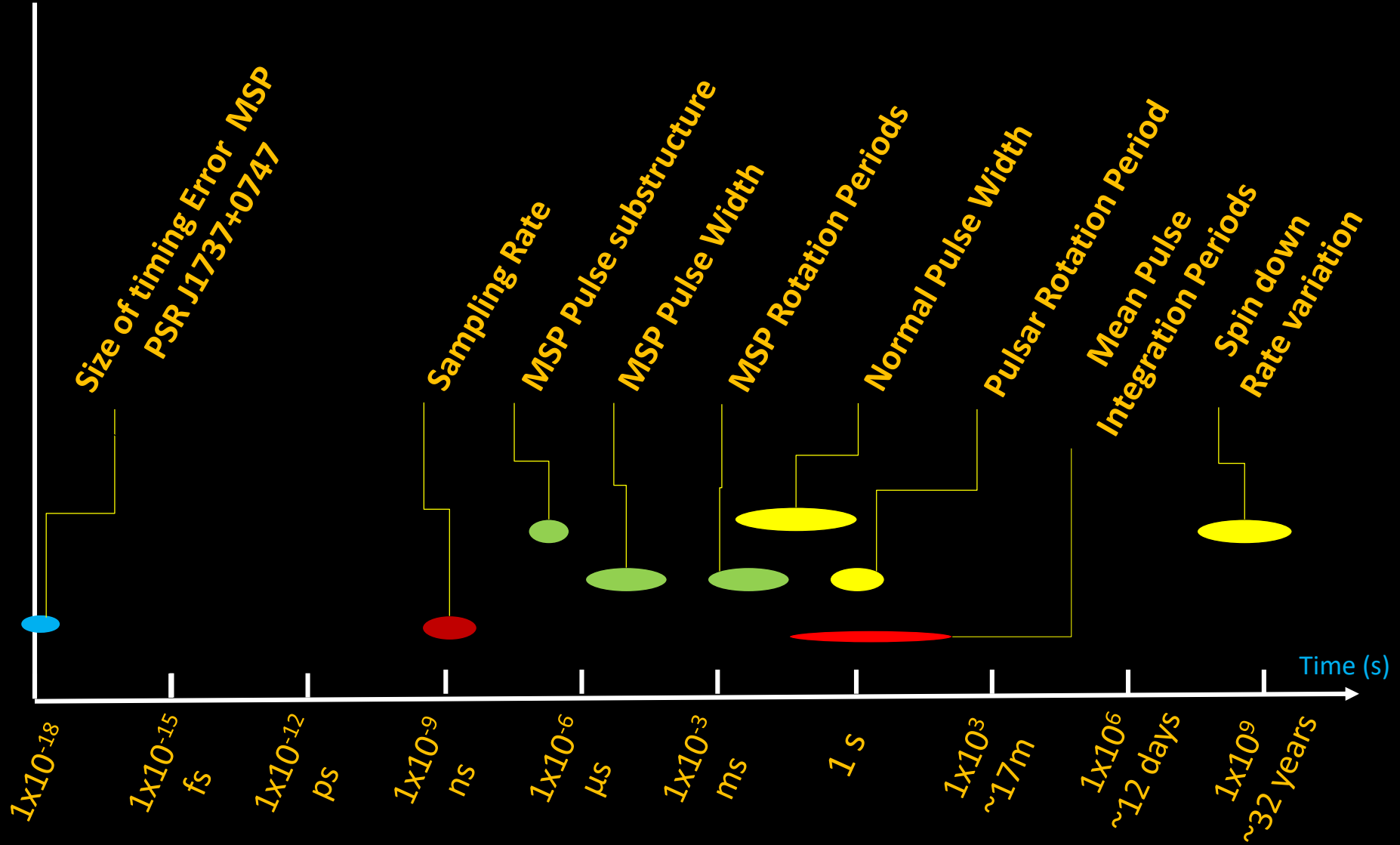
Hybrid Cluster of compute elements

Future Demands

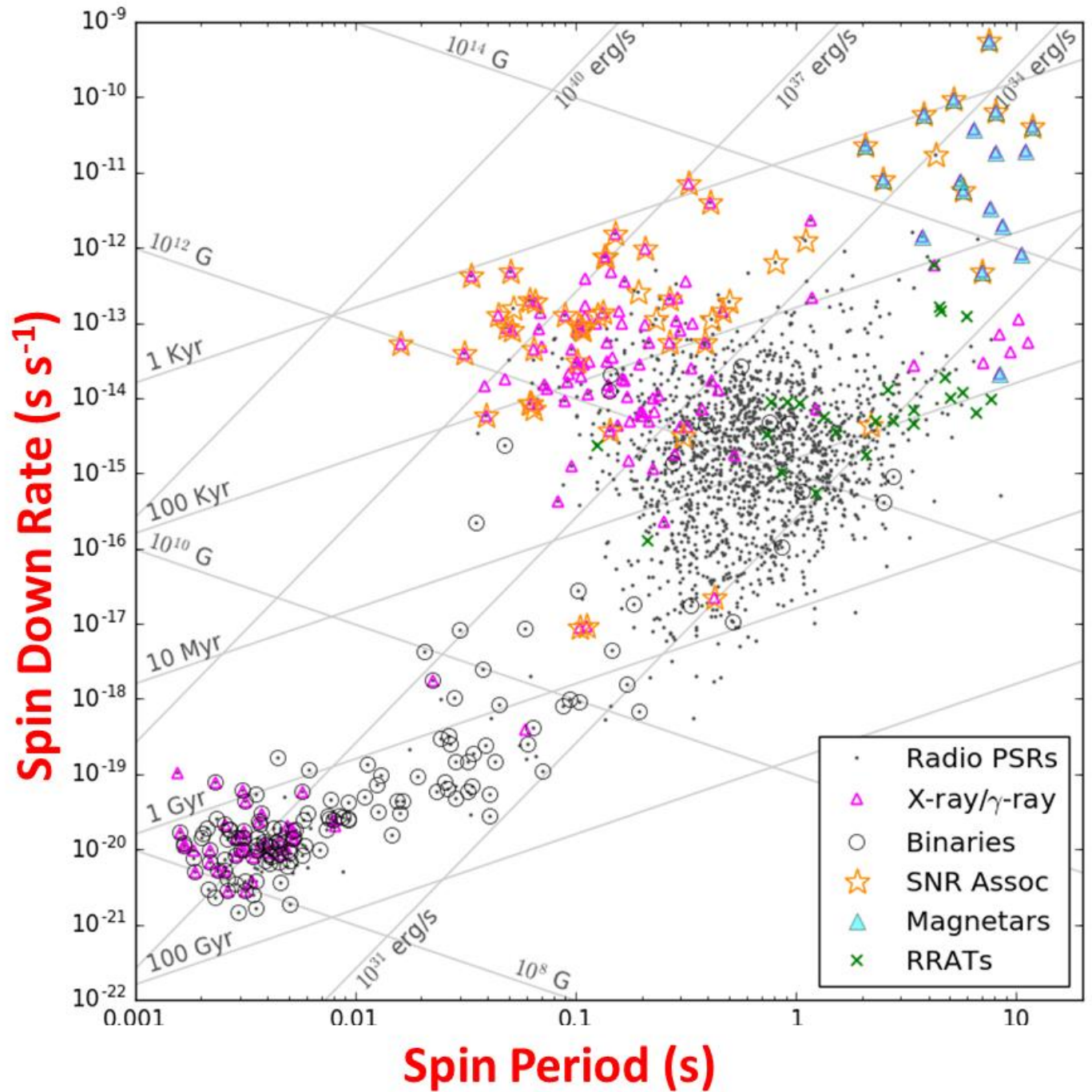
- **Multiple receivers**
 - More sky coverage
 - More data to process / more GFLOPS required
- **Phased Array Feeds**
 - Many more beams
 - Beams move on the sky as the telescope tracks central source
 - Real time beamforming very difficult
 - Signal processing of data from the individual beams.
- **Ultra wide bandwidth receivers**
- **New Phenomena:**
 - Fast Radio Bursts
 - Extragalactic

Thank you

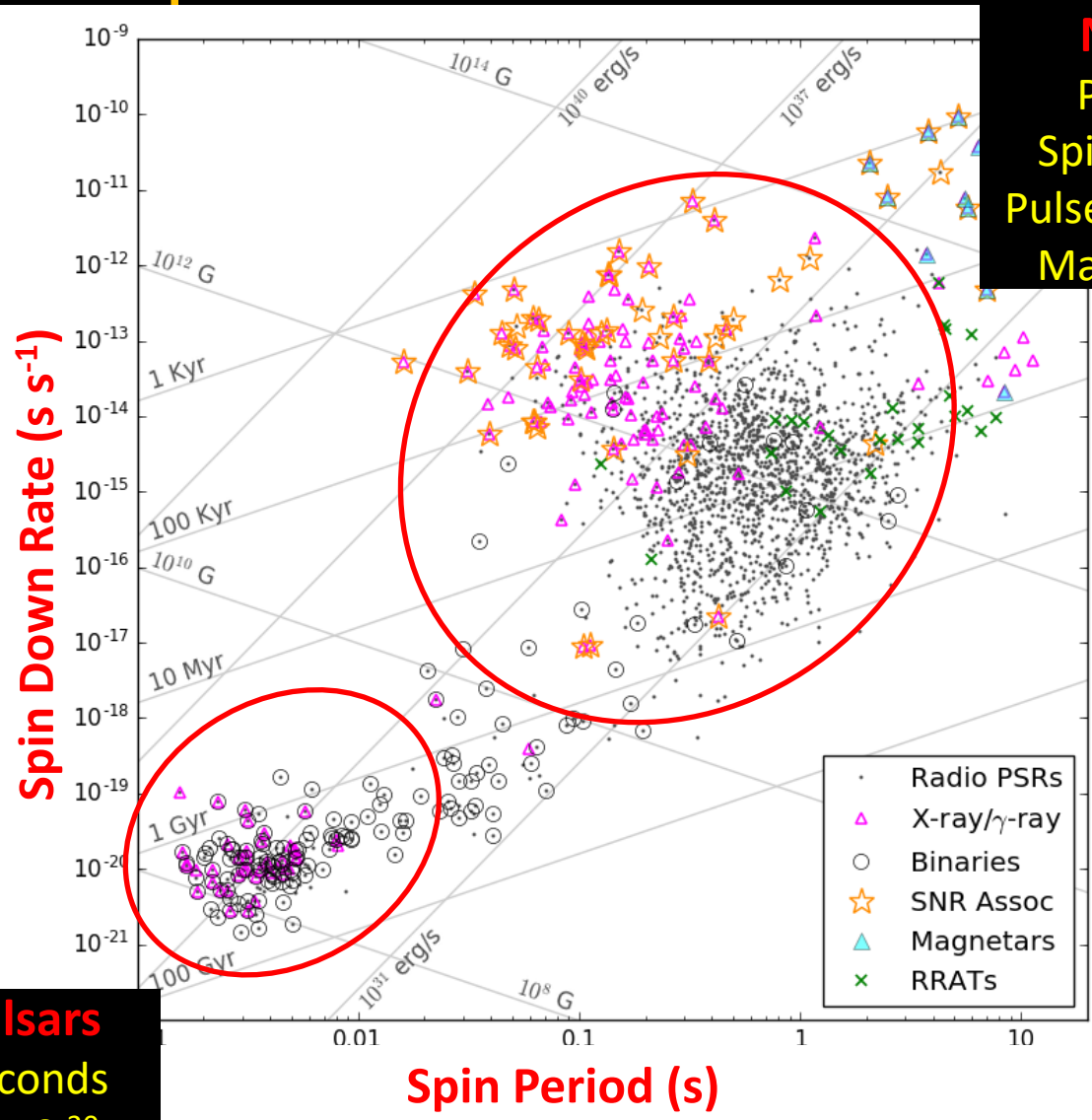
Pulsar Timing Timescales



P vs \dot{P} Diagram

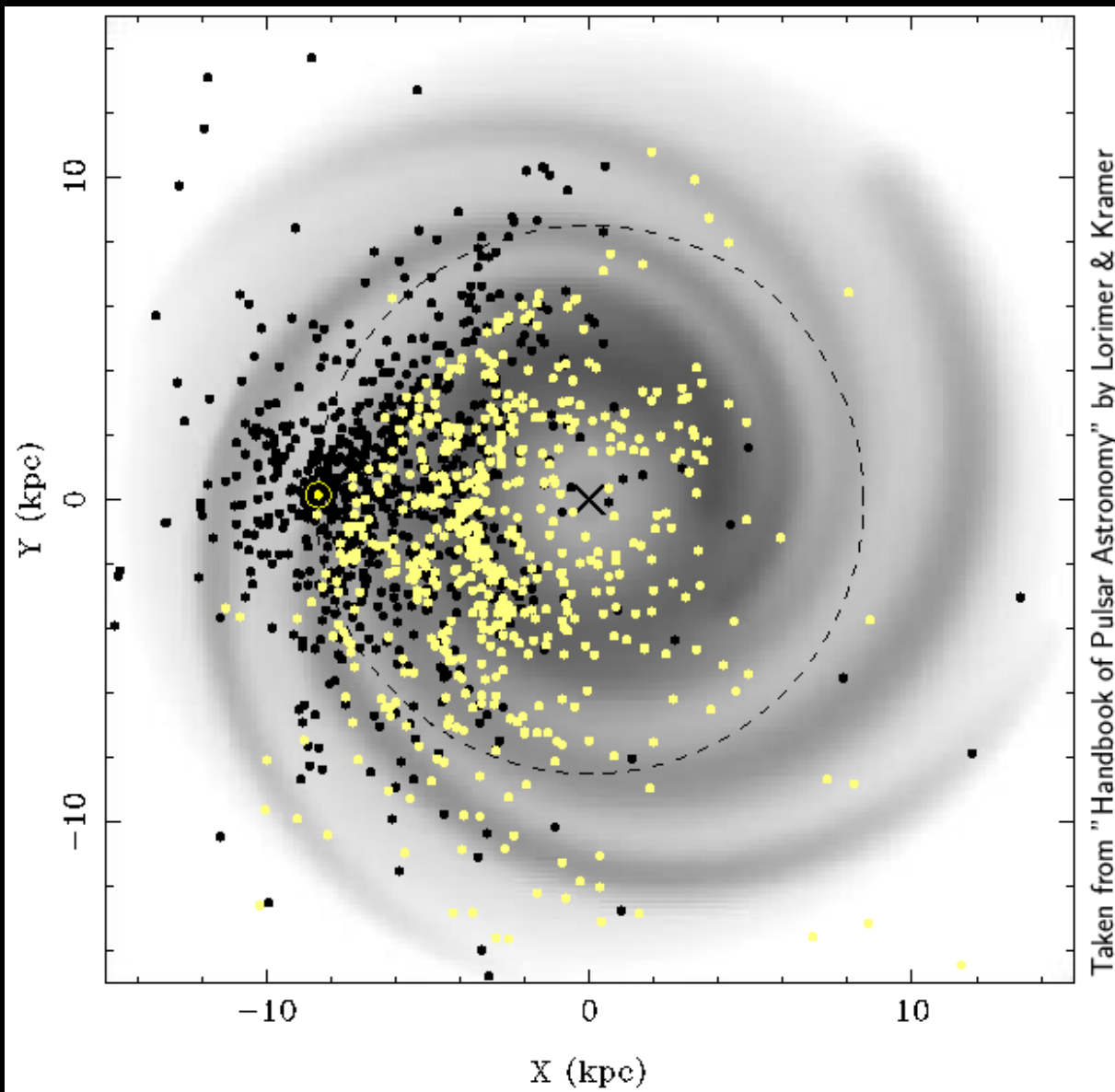


Two Main Populations



Normal pulsars
 Period \sim seconds
 Spin down rate $\sim 10^{-15}$
 Pulse widths 100's of ms
 Magnetic fields 10^{12}G

Millisecond pulsars
 Periods \sim milliseconds
 Spin down rate $\sim 10^{-20}$
 Pulse widths $\sim \mu\text{s}$
 Magnetic fields 10^8G



ISM Electron density distribution model NE2001 - Cordes and Lazio (2002a)

Pulsars detected at ~430MHz are black dots, detected at ~1.4GHz yellow dots

Darker grey corresponds to higher electron number density

Signal path

- Receiver mounted in the roof of the control room
- Four 'mirrors' in RF signal path



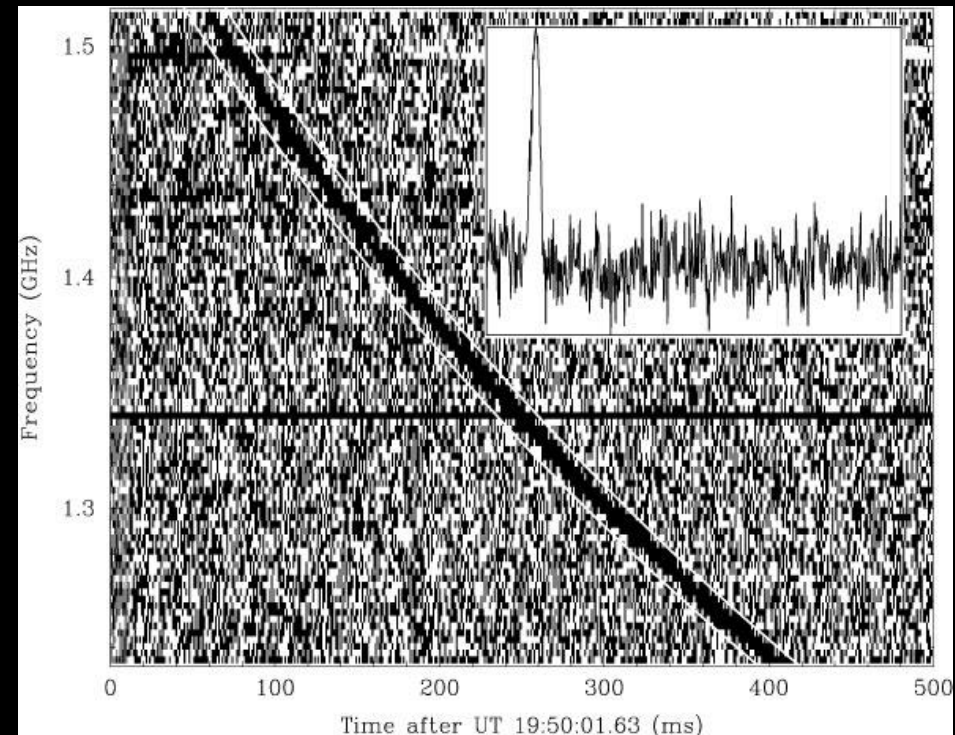
Fast Radio Bursts

A bright millisecond radio burst of extragalactic origin

Duncan Lorimer (West Virginia University, USA), Matthew Bailes (Swinburne University), Maura McLaughlin (West Virginia University, USA), David Narkevic (West Virginia University, USA) and Fronefield Crawford (Franklin & Marshall College, USA)

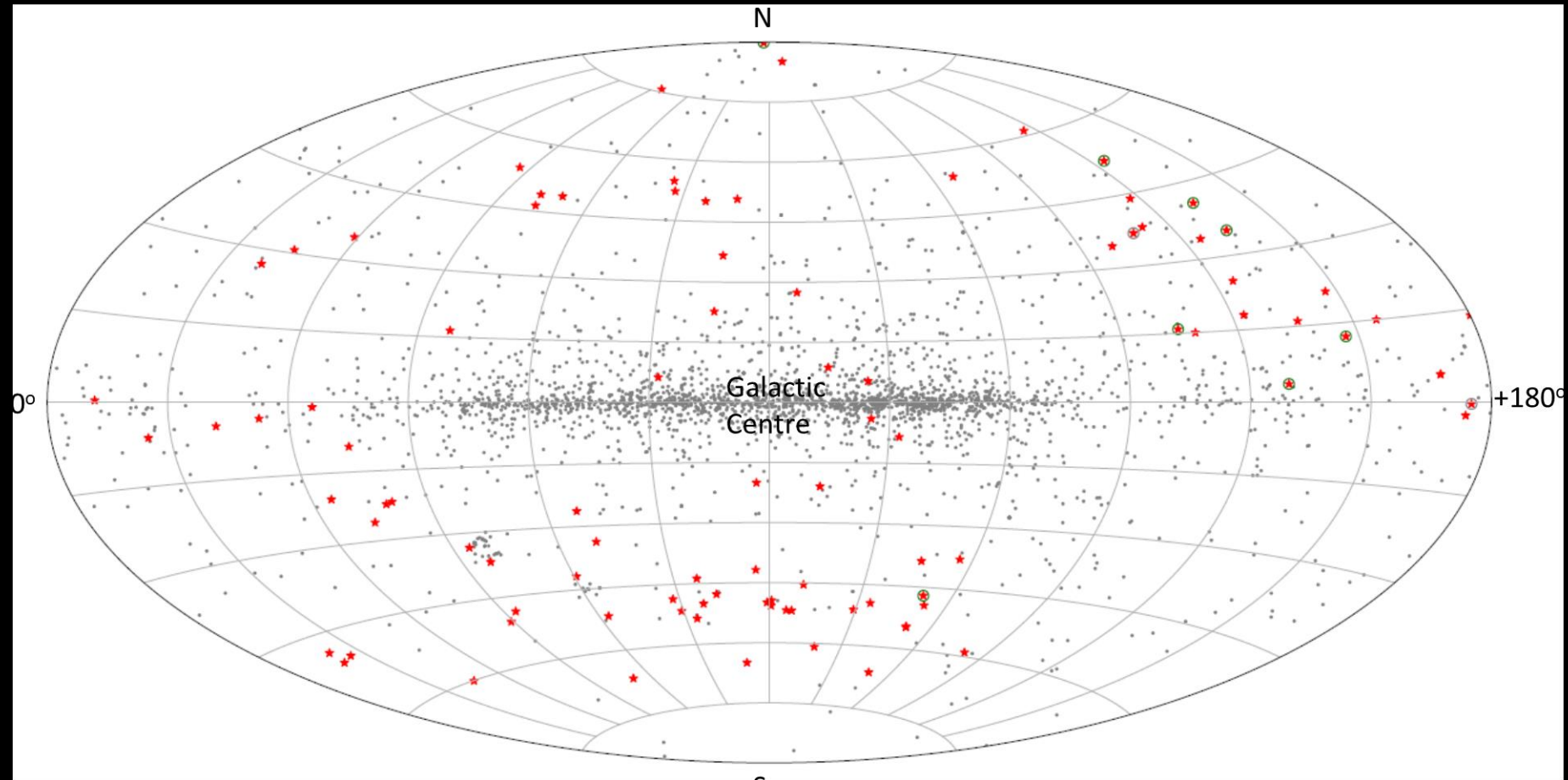
Frequency evolution and integrated pulse shape of the radio burst shown as a two-dimensional “waterfall plot” of intensity as a function of radio frequency versus time. Pulse dispersion is clearly seen as a quadratic sweep across the frequency band, with broadening towards lower frequencies due to scattering. The two white lines separated by 15 ms that bound the pulse show the expected behavior for the cold-plasma dispersion law. Inset: the total-power signal after a dispersive delay correction. The time axis on the inner figure also spans the range 0 – 500 ms.

Transient radio sources are difficult to detect, but can potentially provide insights into a wide variety of astrophysical phenomena. Radio pulsar surveys offer one of the few opportunities to monitor even a small fraction ($\sim 10^{-5}$) of the radio sky for impulsive burst-like events with millisecond durations. Motivated by the recent discovery of rotating radio transients (neutron stars which exhibit only occasional sporadic bursts of emission) in the Parkes multibeam pulsar survey data, a team led by Duncan Lorimer at West Virginia University has been searching for transient events in a recent Parkes survey of the Magellanic Clouds. The raw data are de-dispersed to produce times series at multiple trial dispersion measures. For each time series, events which exceed six times the local standard deviation are saved for visual inspection. A highly significant signal with a peak flux of 30 Jy shown in Figure 1 was found by student David Narkevic in late 2006. The burst was so strong that it saturated the digitizers and was detected in three out of the 13 beams of the multibeam system!

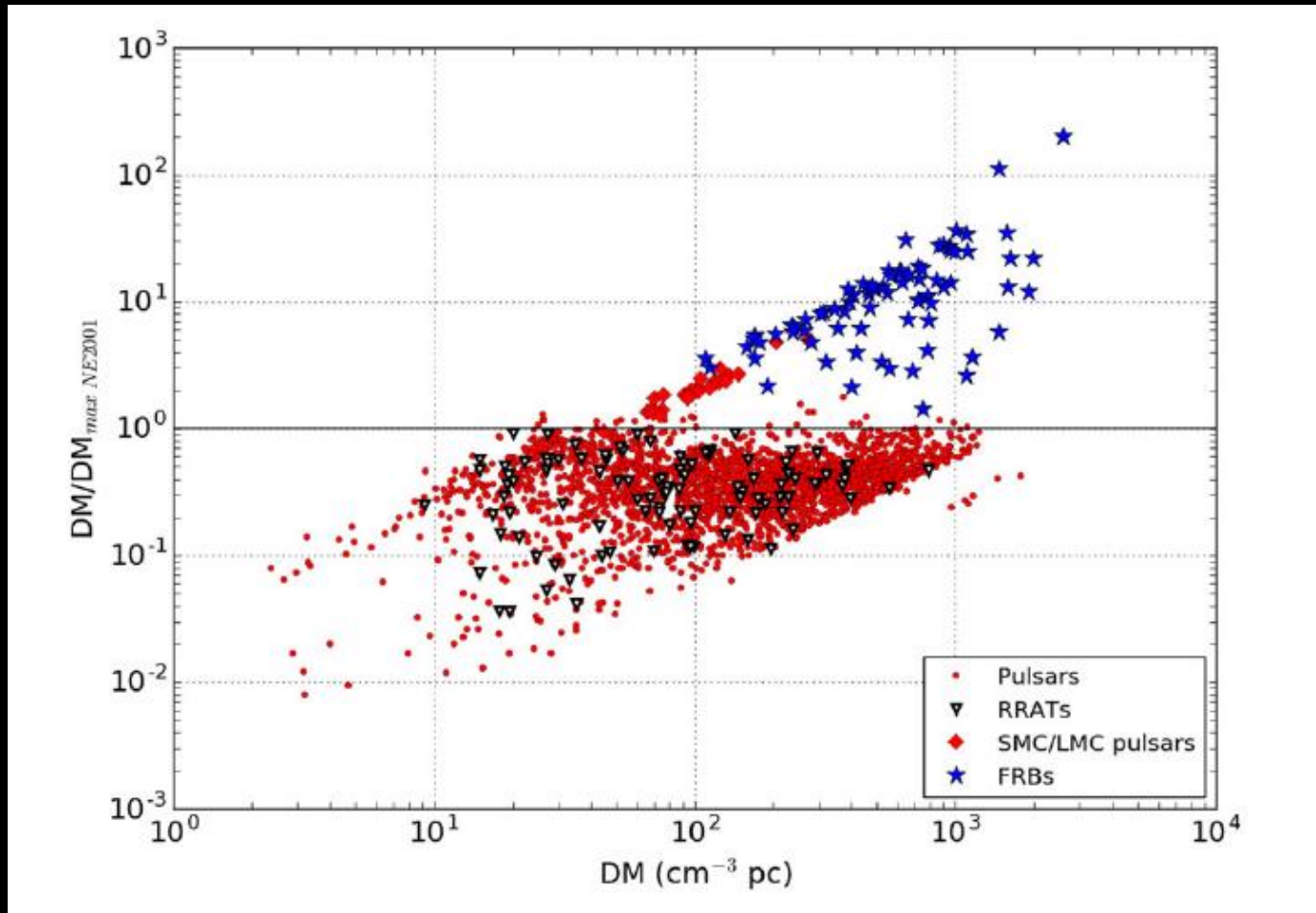


Distribution of 99 FRBs

November 2019
(Feb 2021 – 289)



FRB vs Pulsars



Excess DM values of FRBs compared with expected DM along the line of sight in the milky way

Fluence / Flux Density / Units

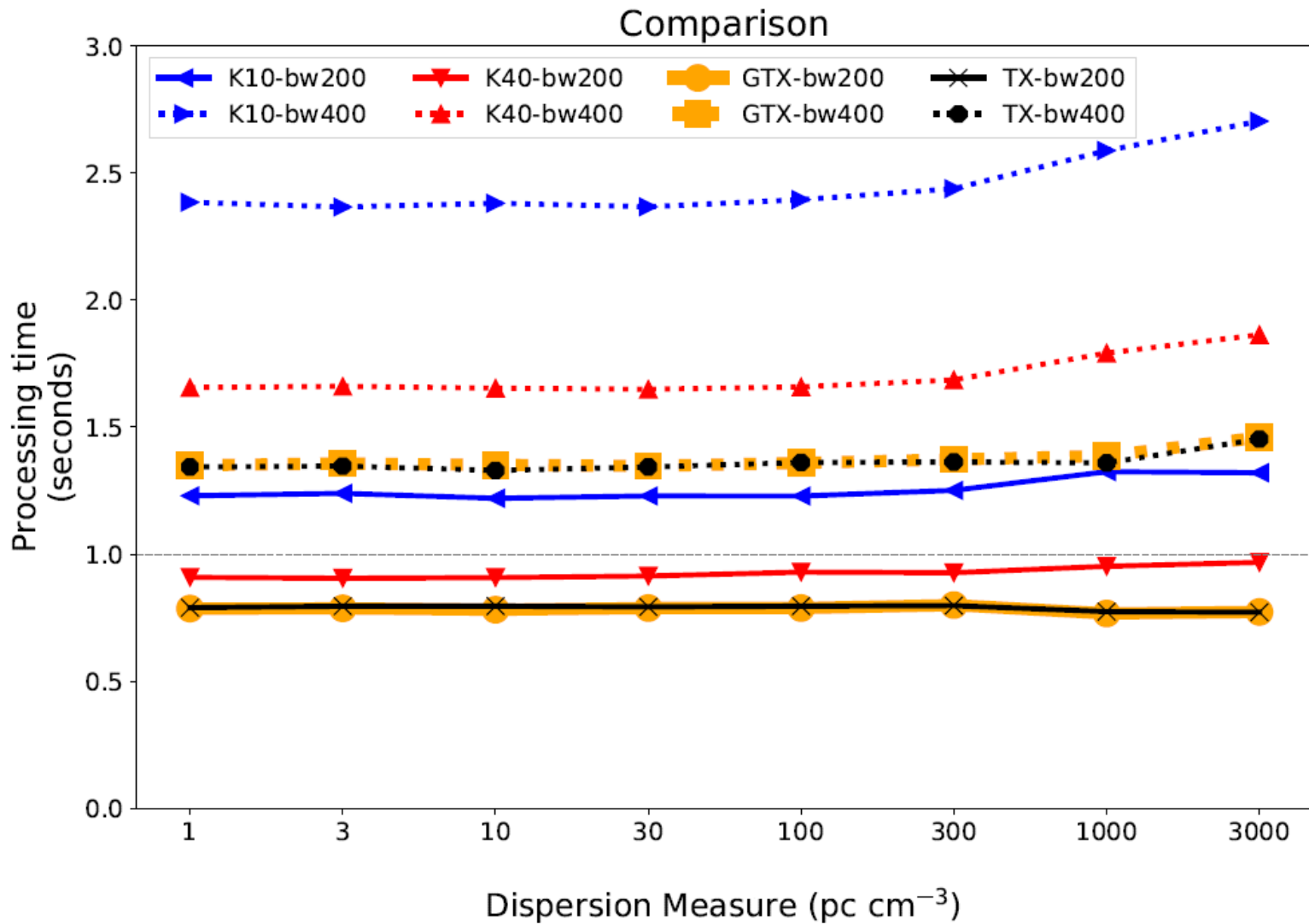
Jansky (Jy): Power received per unit area per bandwidth

- $1 \text{ Jy} = 10^{-26} \text{ W m}^2 \text{ Hz}^{-1}$

Fluence (Jy ms): Janskys per millisecond

<i>Value (Jy)</i>	<i>Source</i>
110,000,000	RFI from a GSM phone transmitting 0.5 W at 1.8 GHz at a distance of 1 km (RSSI of -70 dBm)
20,000,000	Disturbed Sun at 20 MHz (Karl Guthe Jansky's initial discovery, published in 1933)
4,000,000	Sun at 10 GHz
1,600,000	Sun at 1.4 GHz
1,000,000	Milky Way at 20 MHz
10,000	1 Solar flux unit
2,000	Milky Way at 10 GHz
1,000	Quiet Sun at 20 MHz
1.05	<i>Vela (4.5ms)</i>
0.014	<i>Crab (4.7ms)</i>

GPU Performance



Pulsar Observation at Kuntunse

