Pulsar Detection

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Deep Space Exploration Society

Open House, Sept. 16, 2023

Pulsar Detection with 60 ft Dish: Live Demos and Training

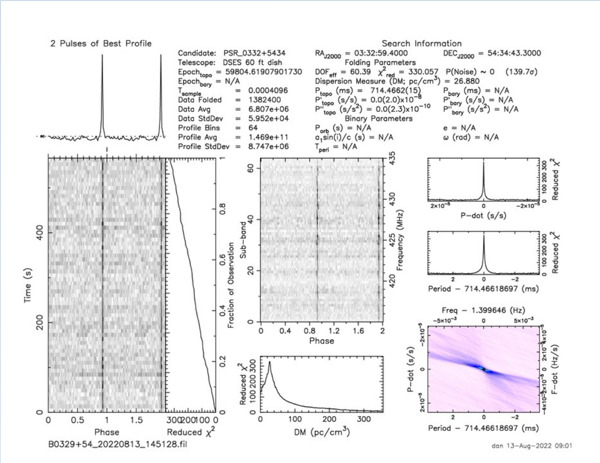
Saturday, October 21, 10 am – 3 pm

Alternate date (weather or construction)
 - Saturday, November 4, 10 am – 3 pm

Plan on minimum of 2 hours
Radio quiet day (no Wi-Fi, no cells, no xmitters)

Please confirm if attending:

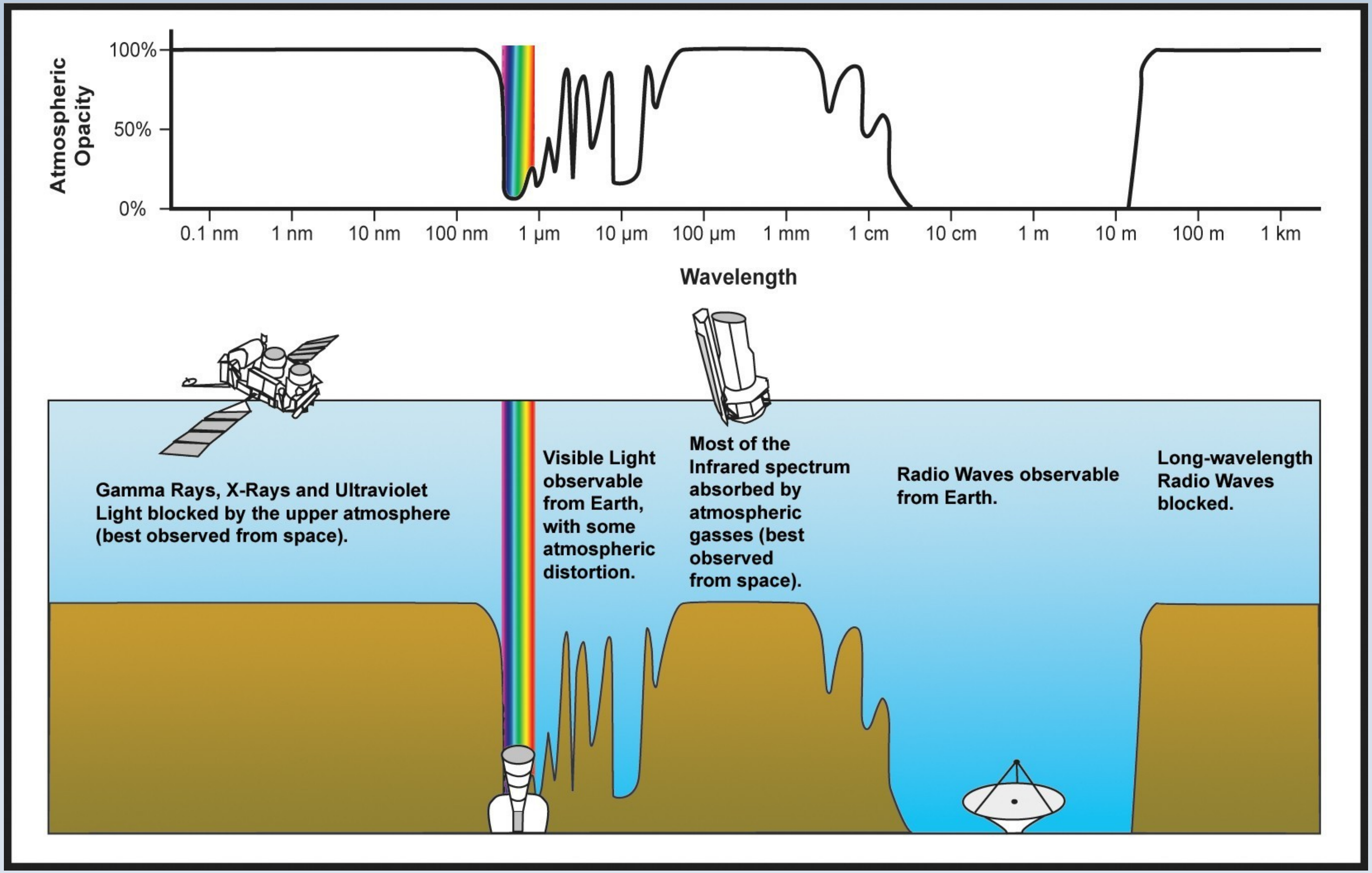
danlayne1@gmail.com



Outline

- Amateur radio astronomy
- Properties of pulsars
- Pulsar detection
- Detecting pulsars with the Plishner 60’ dish
- Pulsars in the news – gravitational waves

Atmospheric Window for Radio Astronomy



The atmosphere is transparent to frequencies from 5 MHz to 30+ GHz

Radio waves are much longer than optical waves. So radio telescopes must be much larger than optical telescopes

Several frequency segments are protected for radio astronomy

Goal: minimize RFI; maximize SNR

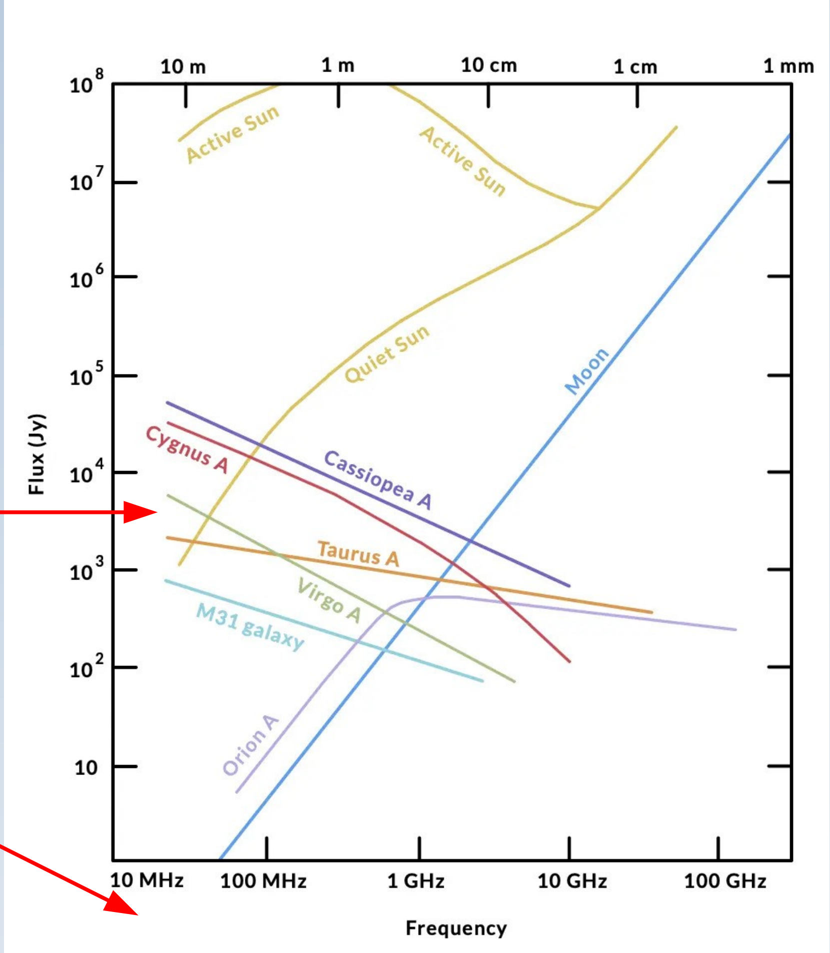
Radio Signals from Space are Weak

Flux density is a measure of signal strength. Units are Jansky (Jy)

Jy = 10^{-26} watts per meter^2 per Hertz

Supernova remnants in the middle

Most pulsars are in milli-Jansky range



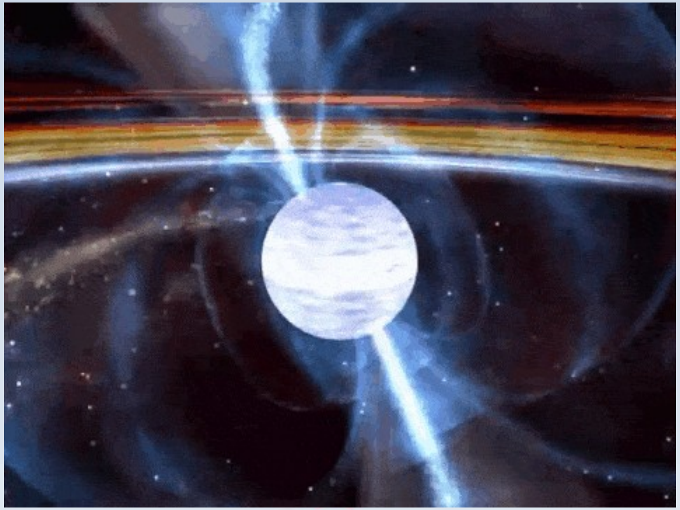
Radio Astronomy With the 60' Dish

- Detect pulsars = broadband emitters
  - 408, 1296, & 1420 MHz
- Detect 21 cm (1420.4 MHz) neutral hydrogen
  - Map the Milky Way; detect supernova remnants & radio galaxies
  - Bright sources (e.g., Cass A) used to calibrate dish tracking
- Detect OH (Hydroxyl) masers (1612, 1665 MHz)
  - 1420 MHz feed being modified to cover 1400 – 1800 MHz (new antenna probe, new LNA)

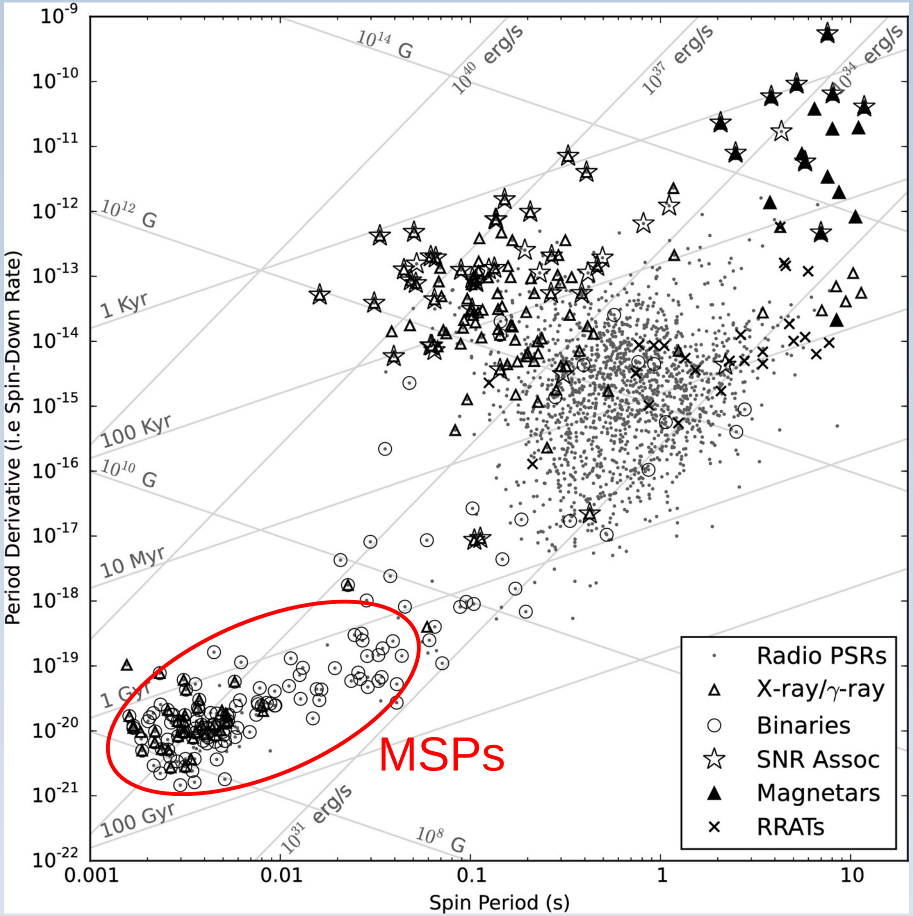
Pulsar Properties & Detection

Pulsars

- Pulsars are highly magnetized, rapidly rotating neutron stars
  - Formed from collapsed core of a supernova explosion
  - Appear to emit periodic short pulses of radio radiation
- Observables are spin period and period derivative
  - Pulse timing is very consistent. Periods range from msecs to secs
- Propagation effects
  - ISM dispersion: higher freq arrive earlier
  - Scintillation: multipath interference
  - Doppler shift: motion of observer



Pulsar Properties



Credit: Essential Radio Astronomy, Condon & Ransom

The $P\dot{P}$ diagram shows properties derived from period (P) and period derivative ($\dot{P}$), including

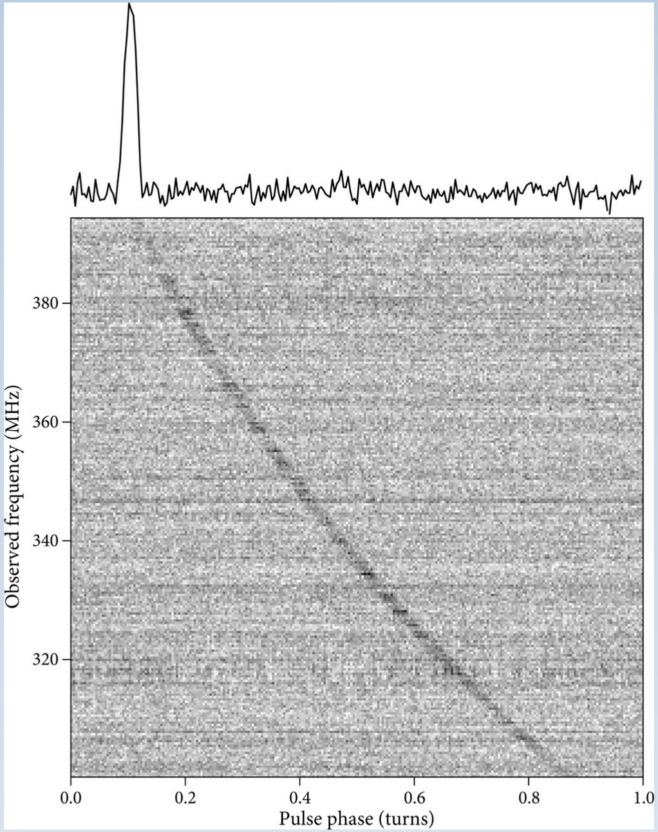
- Characteristic age
- Minimum magnetic field strength
- Spin-down luminosity

Old, stable millisecond pulsars (MSPs) in lower left are mostly binaries that were "recycled" via accretion from their companion stars

Dispersion

- Higher frequencies detected slightly before lower frequencies due to pulse dispersion through interstellar medium
  - Gray scale shows uncorrected delay
  - Dedispersed, integrated profile at top
- Dispersion Measure (DM) is proportional to density of electrons along line of sight
  - DM can indicate distance, depending on look direction
  - Dedispersion corrects the delay

$$\Delta t = 8.3 \, x \, DM \, x \, BW / \nu^3 [units: \Delta t \, \mu s, DM \; pc \, cm^{-3}, BW \; MHz, \nu GHz]$$

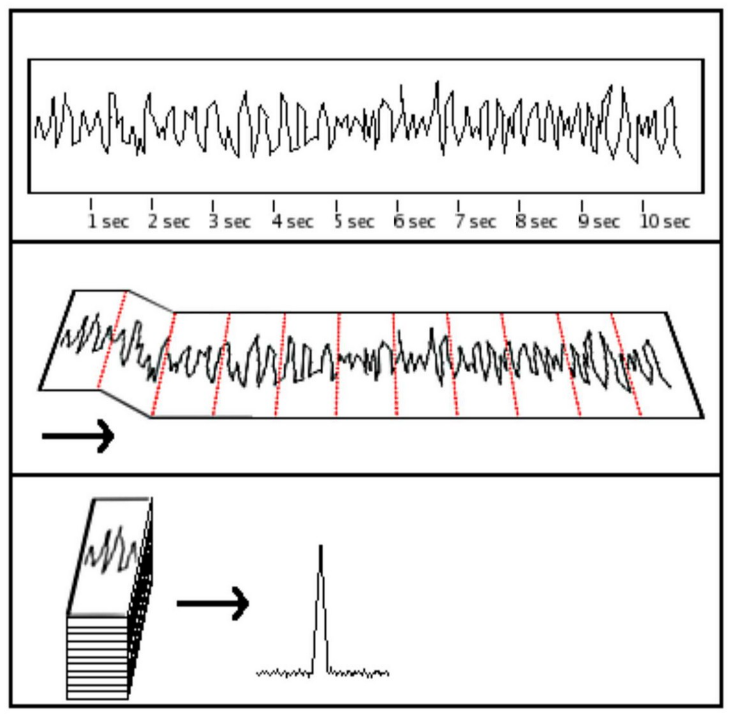


Credit: Essential Radio Astronomy, Condon & Ransom

Pulsar Data Folding

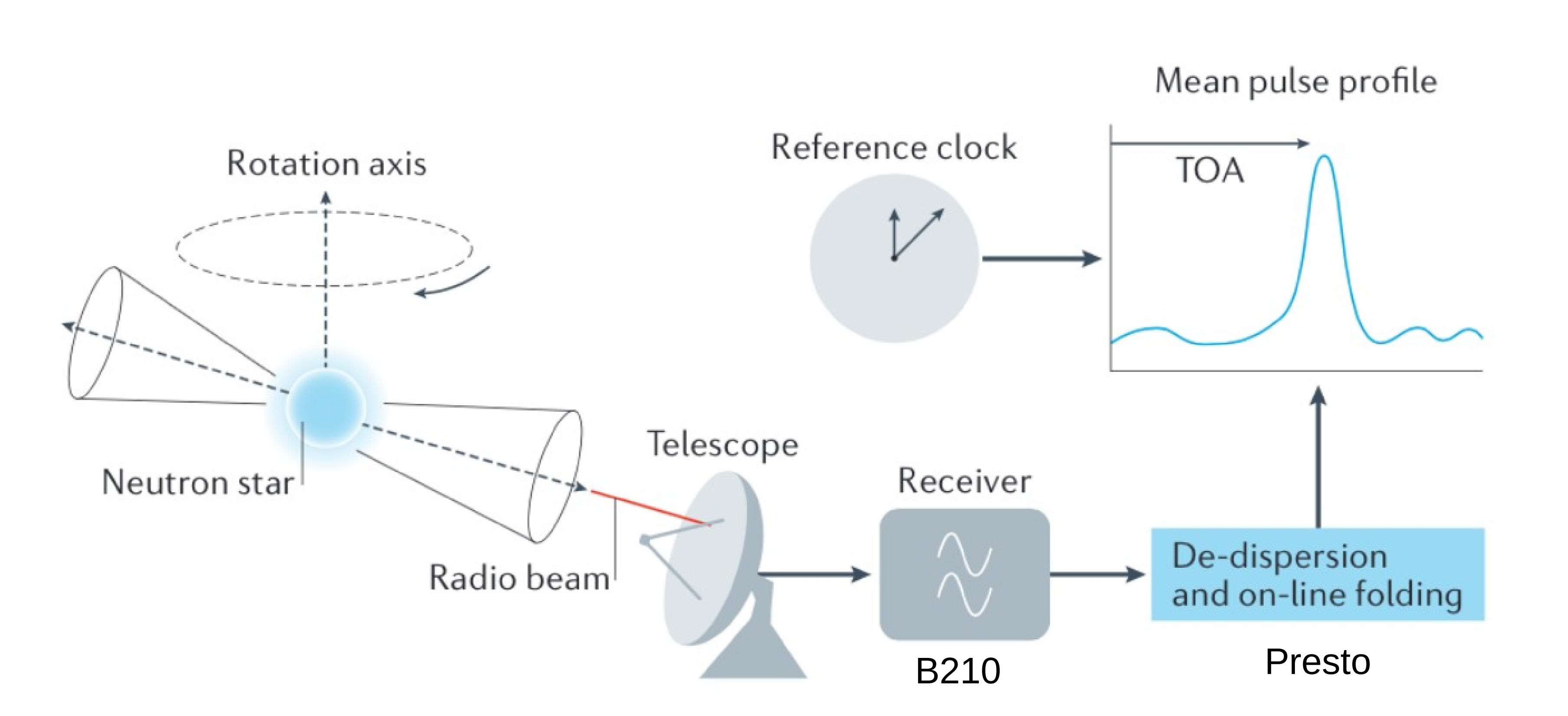
- Top: Weak pulsar signal buried in noise
- Middle: Fold at desired period (known or search trial)
- Bottom: Add (integrate) small contributions until pulse appears
  - Shape of individual pulse varies, while the average pulse profile is stable at given freq
- Performed in frequency domain or time domain
- Use published values for P, DM, etc.

https://www.atnf.csiro.au/research/pulsar/psrcat/



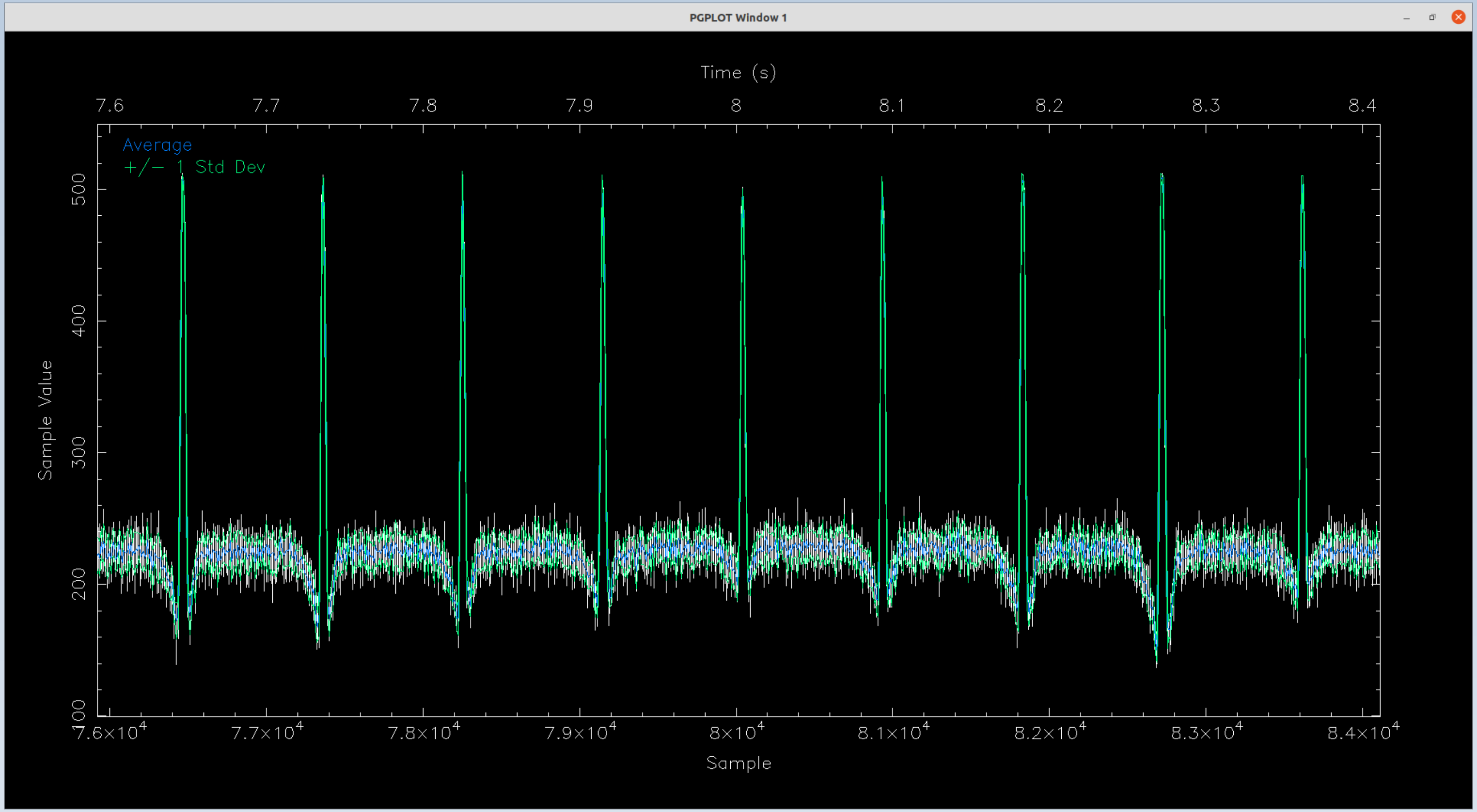
Credit: “Searching for and Identifying Pulsars,” R. Lynch

Pulsar Detection



Credit: “Handbook of Pulsar Astronomy”, Lorimer & Kramer (2005)

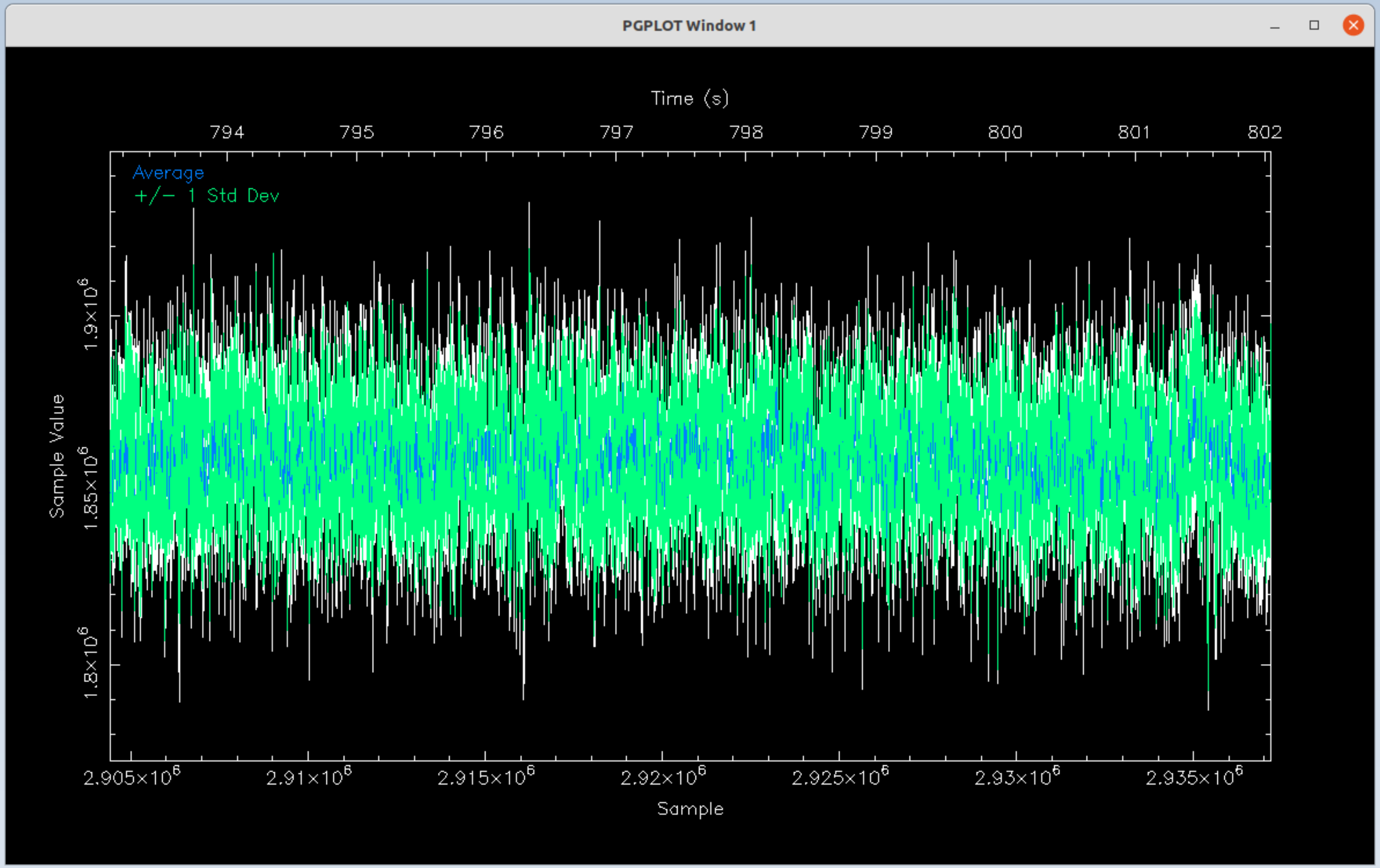
Parkes Example: B0833-45 (Vela)



Period = 0.089328 sec, S1400 = 1050.0 mJy Brightest pulsar (time series plot via Presto exploredat)

Parkes 64 m 1Bit_FB data from CSIRO https://data.csiro.au/domain/atnf

Typical Plishner Sample: B0835-41



Period = 0.751625 sec, S1400 = 35.0 mJy (time series plot via Presto exploredat)

Plishner 60’ data collected June 4, 2022, Haswell, CO

Amateur Pulsar Detection

- Amateurs have detected pulsars using EME equipment
  - 3 meter dish with Airspy SDR
  - Twin 23 element Yagi with RTL-SDR
  - Need to track pulsar several hours and integrate data
- Best fishing frequencies (requires different antennas)
  - 408 MHz (70 cm); 1296 MHz (23 cm); 1420 MHz (21 cm)
- DSES has detected 24 (known) pulsars
  - 60’ dish means we don’t need to track as long as smaller dishes
  - Safety requirements: no remote ops, 2-person rule
  - Scripts run GnuRadio (data collection) and Presto (pulsar processing)

DSES
System Configuration

Plishner 60’ dish, Haswell, CO
- GPS clock sync
- 32-core, Ubuntu 22.04 host
- USRP B210 (56 MHz) SDR

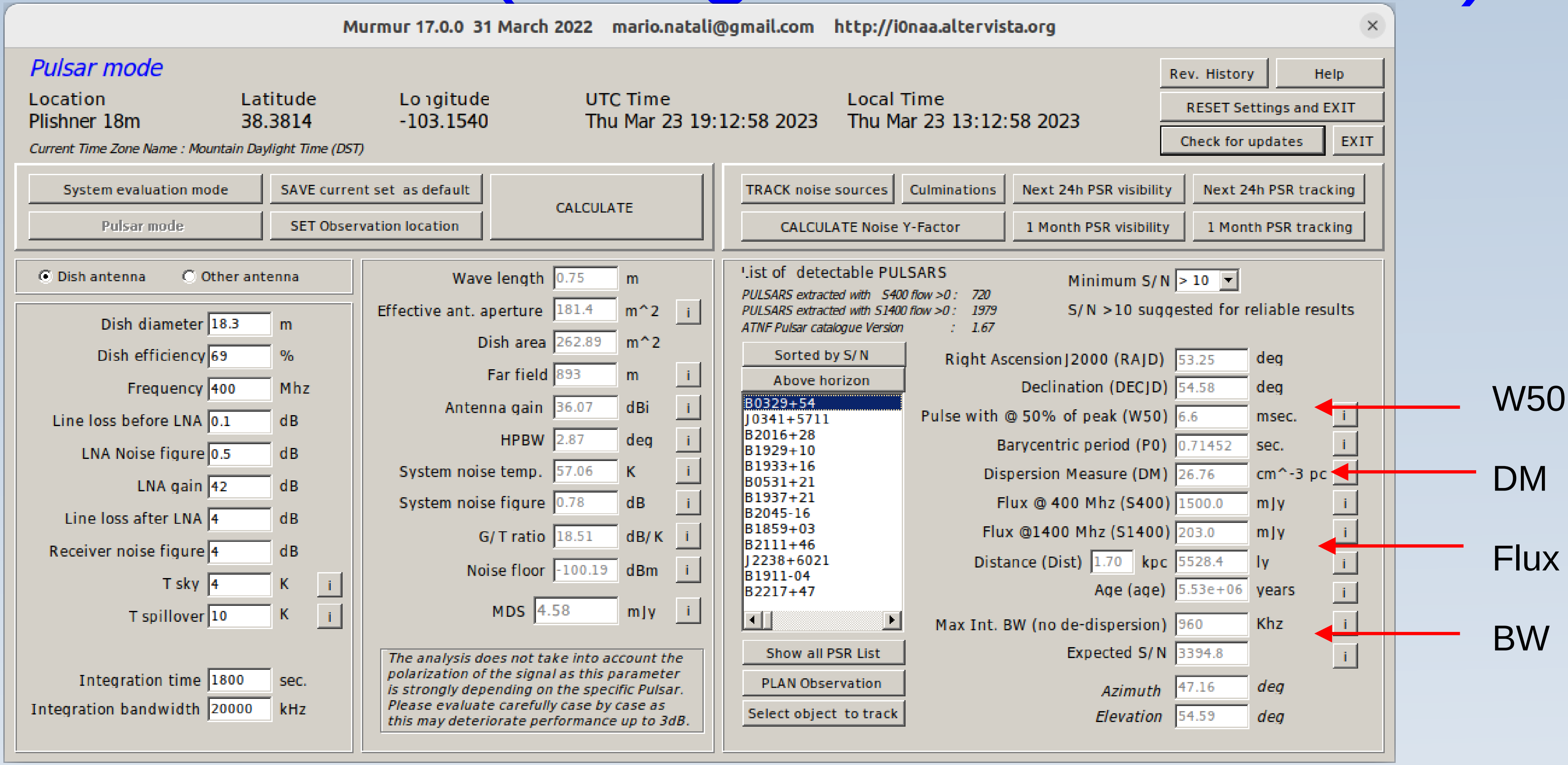
Feedhorn	Pol.	LNA	Filter
408 MHz	Lin.	30 db	90 MHz
1296 MHz	Circ.	30 db	30 MHz
1420 MHz	Circ.	35 db	60 MHz

Software Tool	Purpose
I0NAA Murmur, Stellarium	Plan observations
ATNF database	Ephemeris data (.par)
DSES System 1 Dish Control	Dish pointing and tracking
Spectrum analyzer	Calibrate gain, check RFI
GnuRadio 3.10 filterbank	Data recording (SDR)
PRESTO 4.0 with TEMPO	Pulsar detection
RIPTIDE 0.2.4	Pulsar detection
SIGPROC, watutil, Pint	Misc utilities

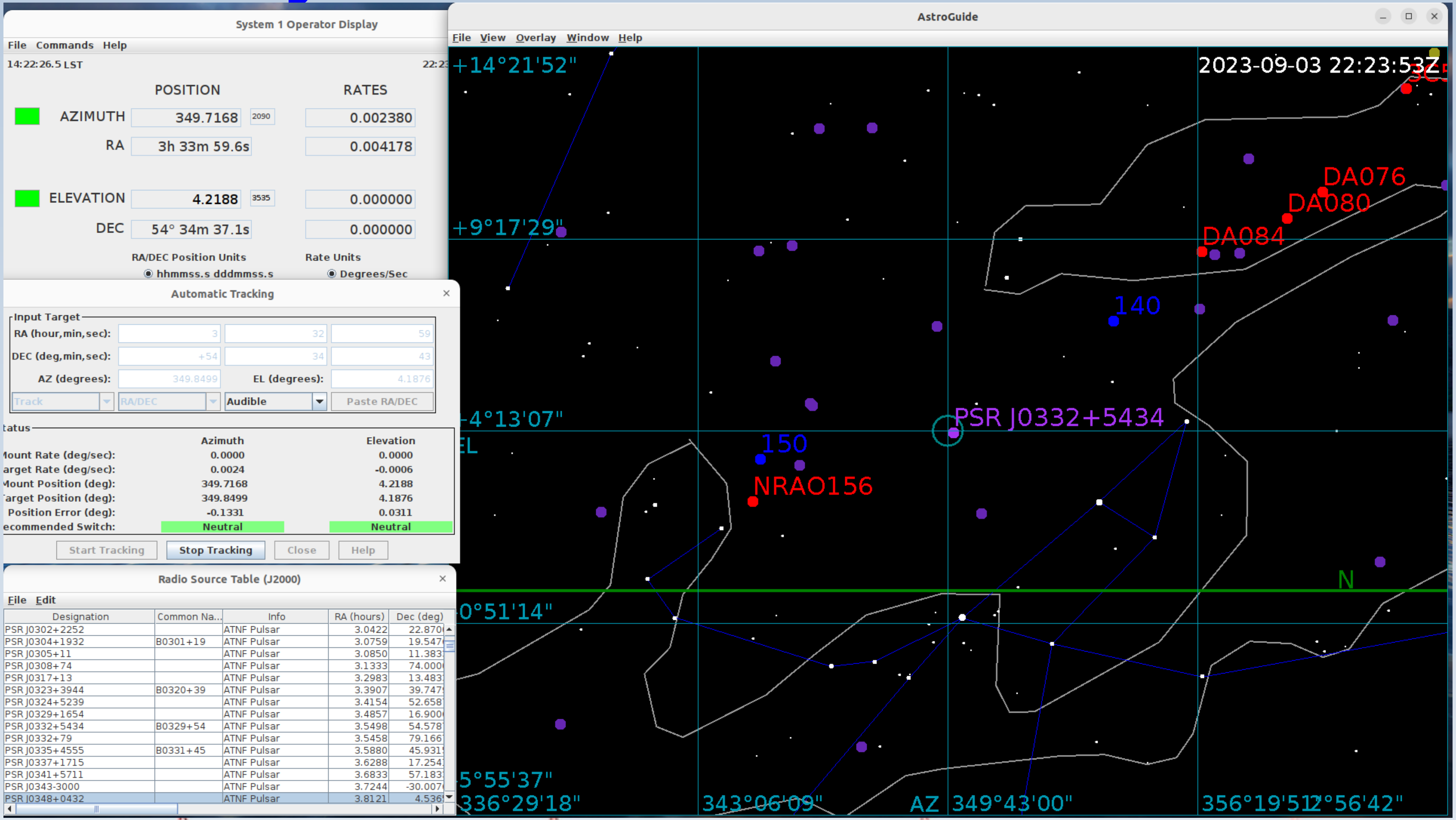
DSES Pulsar Catalog

#	PSR Name	First Detection	Period (sec)	Pulse Width (ms)	DM	S400 (mJy)	S1400 (mJy)	Feed horn MHz	Int. Time (min)
1.	B0329+54	09-2020	0.714	6.6	26.7	1500		408	15
2.	B0355+54	07-2022	0.156	3.9	57.4		46	1296	240
3.	J0437-4715	08-2021	0.005	0.1	2.6		150	1420	30
4.	B0531+21	07-2020	0.033	3.0	56.7	550		408	60
5.	B0628-28	07-2022	1.244	63.3	34.4		32	1296	60
6.	B0736-40	06-2022	0.375	22.7	160.9		112	1296	90
7.	B0740-28	09-2020	0.167	4.2	73.7	296		408	30
8.	B0833-45	09-2020	0.089	1.4	67.7	5000		408	15
9.	B0835-41	06-2022	0.752	4.4	147.2		35	1296	90
10.	B0950+08	09-2020	0.253	8.9	2.9	400		408	60
11.	B1133+16	09-2020	1.118	5.9	4.8	257		408	240
12.	B1508+55	09-2020	0.739	10.9	19.6	114		408	60
13.	B1556-44	11-2022	0.257	6.5	55.9		37	1296	180
14.	B1641-45	08-2021	0.455	8.0	478.6		300	1420	30
15.	B1642-03	09-2020	0.388	3.4	35.8	393		408	90
16.	B1749-28	09-2020	0.563	6.1	50.4	1100		408	20
17.	B1859+03	11-2022	0.655	9.0	402.0	165		437	180
18.	B1929+10	09-2020	0.227	5.7	3.2	303		408	90
19.	B1933+16	09-2020	0.359	6.0	158.5	242		408	60
20.	B1946+35	09-2020	0.717	19.3	129.4	145		408	240
21.	B2016+28	09-2020	0.558	14.9	14.2	314		408	90
22.	B2020+28	03-2022	0.343	12.0	24.6		38	1296	180
23.	B2021+51	09-2021	0.529	7.4	22.5		27	1420	30
24.	B2111+46	02-2022	1.014	32.1	141.3		19	1296	90

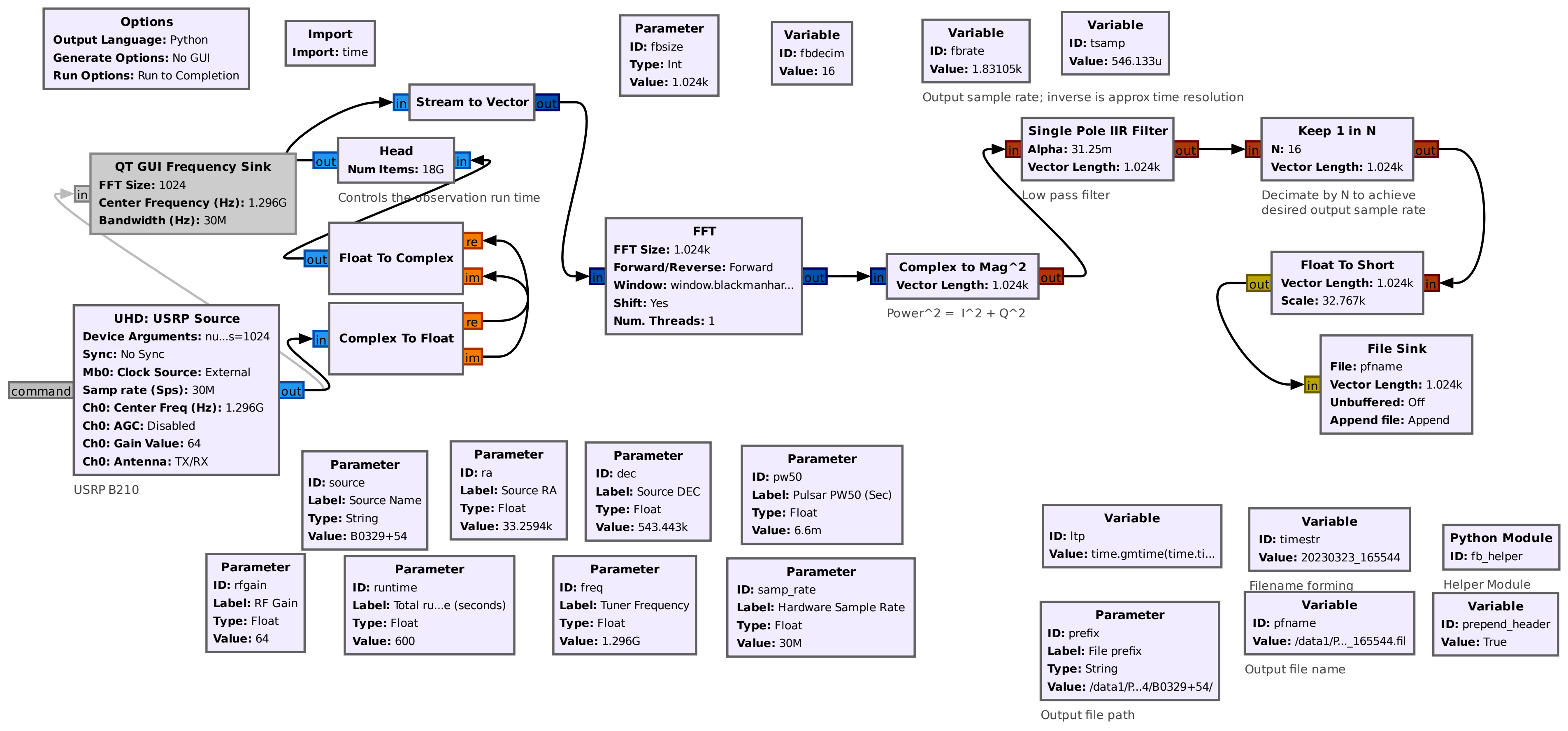
Murmur (using ATNF database)



System 1 Dish Control



GnuRadio Filterbank Data Collection

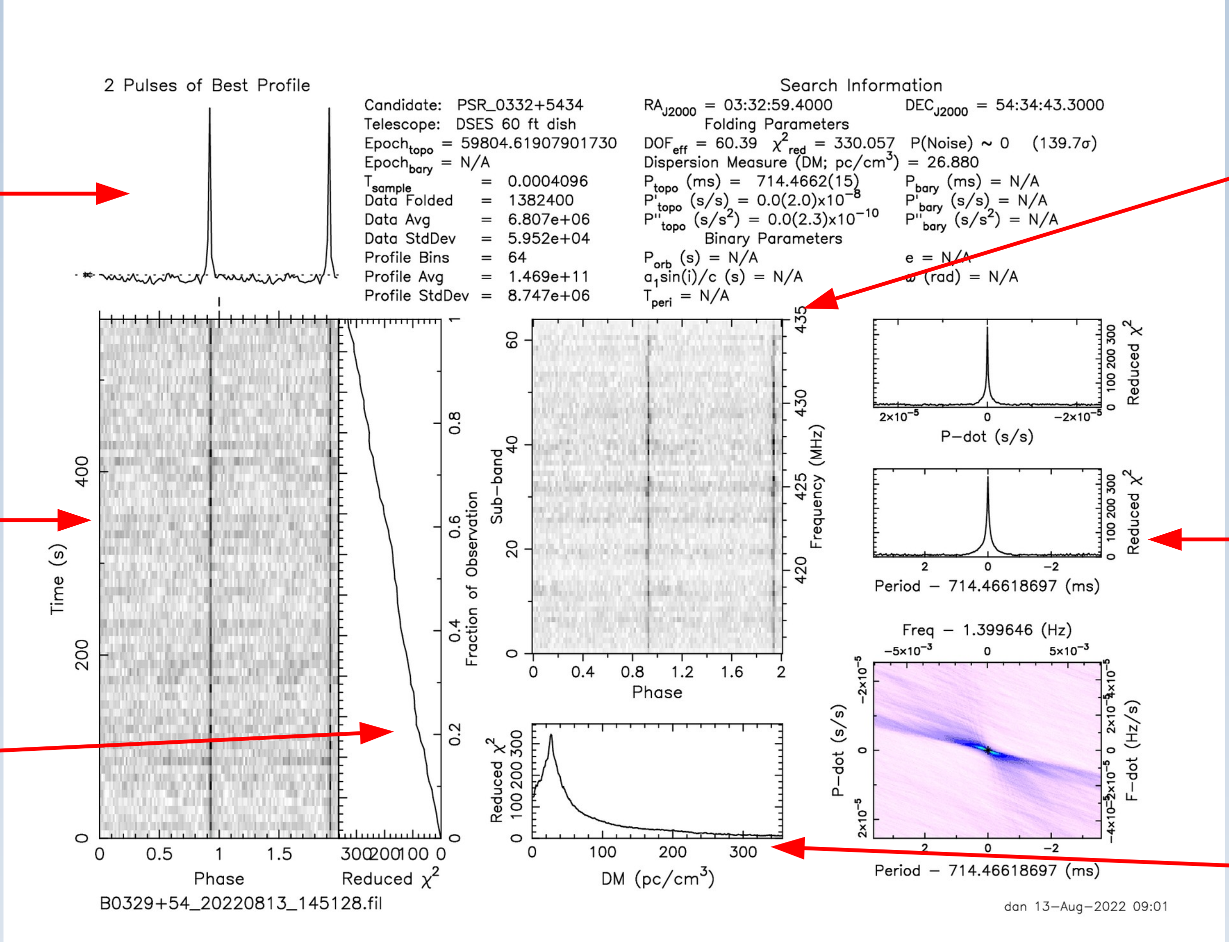


Resulting Presto Plot: PSR B0329+54

Strong folded pulse (two phases)

Good signal in time-phase plot

SNR increases with observation time



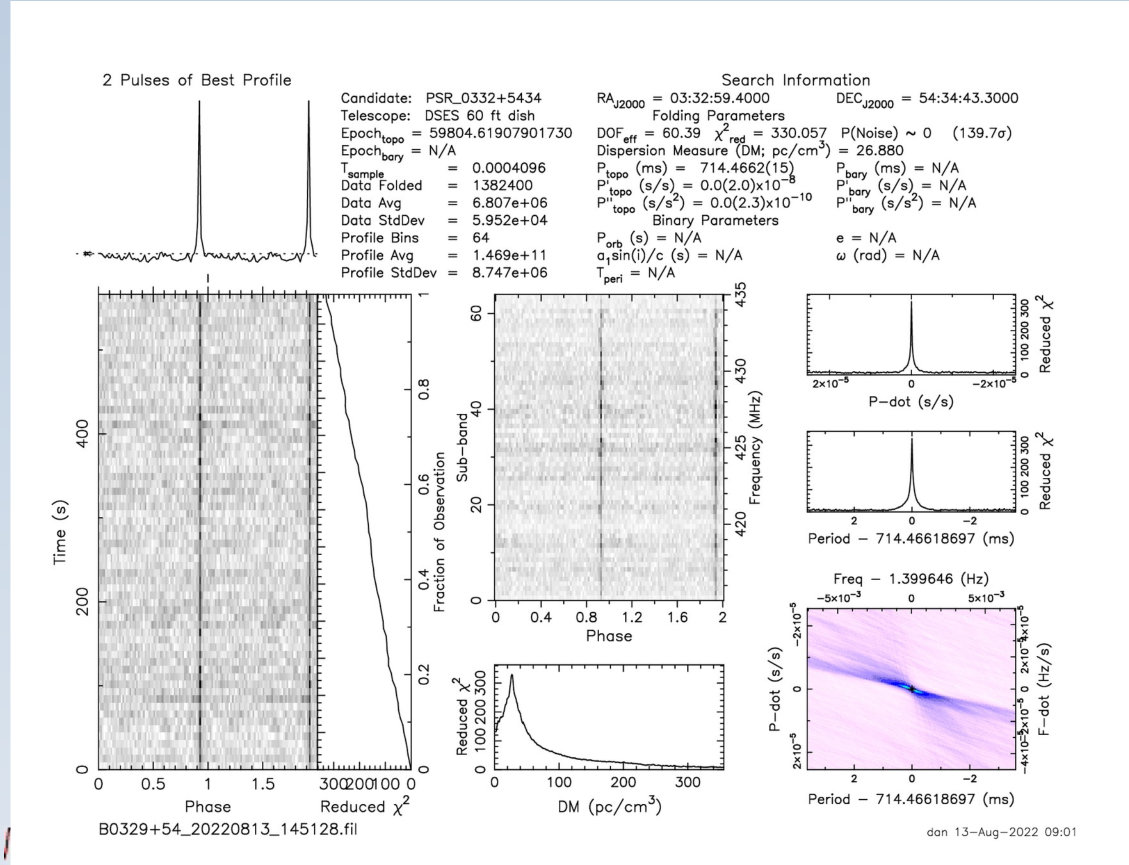
Broadband signal in freq-phase plot

Peak SNR at P = 714.467 ms

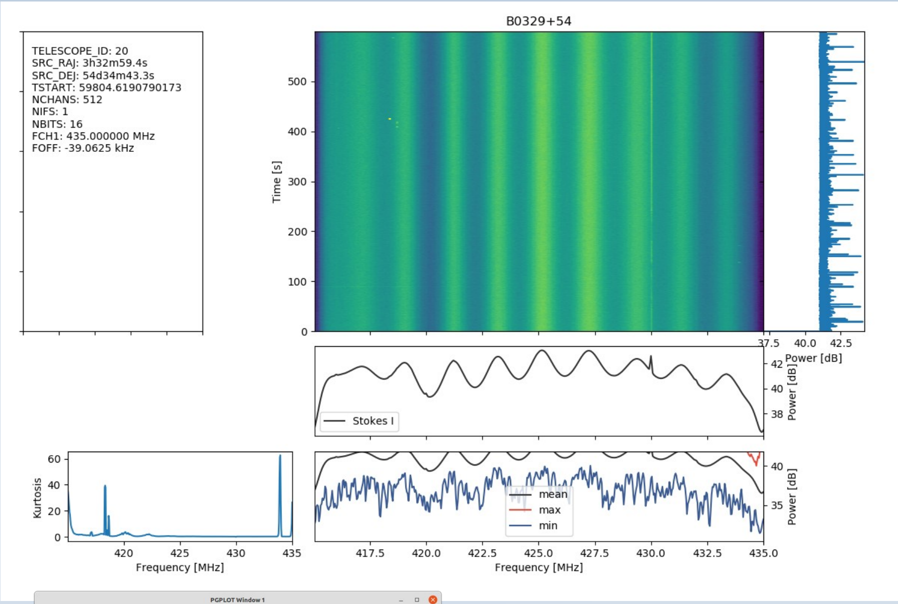
Peak SNR at DM = 26.7

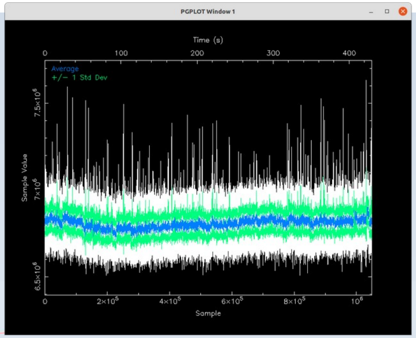
PSR B0329+54 Analysis

437 MHz dual helical antenna
10 minutes at 30 MHz, Aug. 13, 2022
Automatic Presto plot via ATNF pulsar ephemeris



Clean spectrum, some ripple is okay



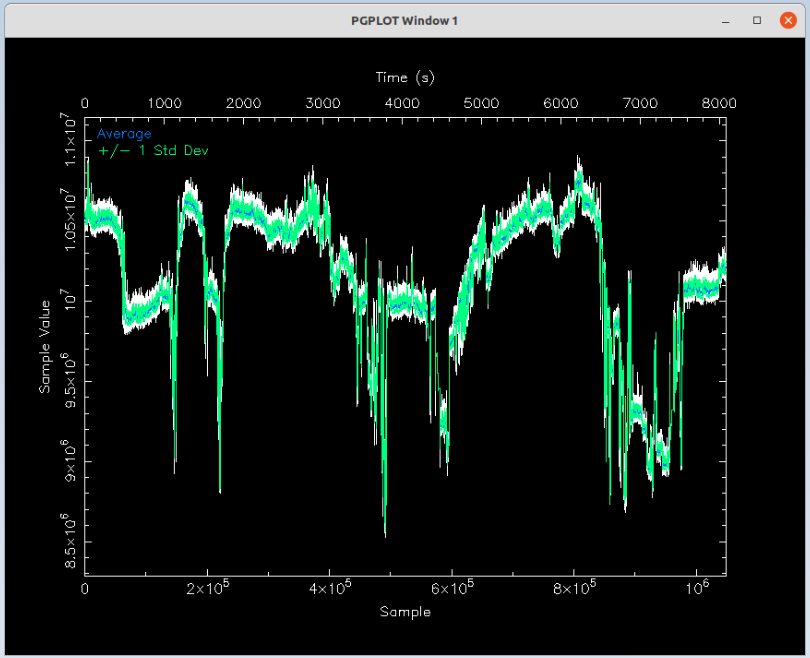


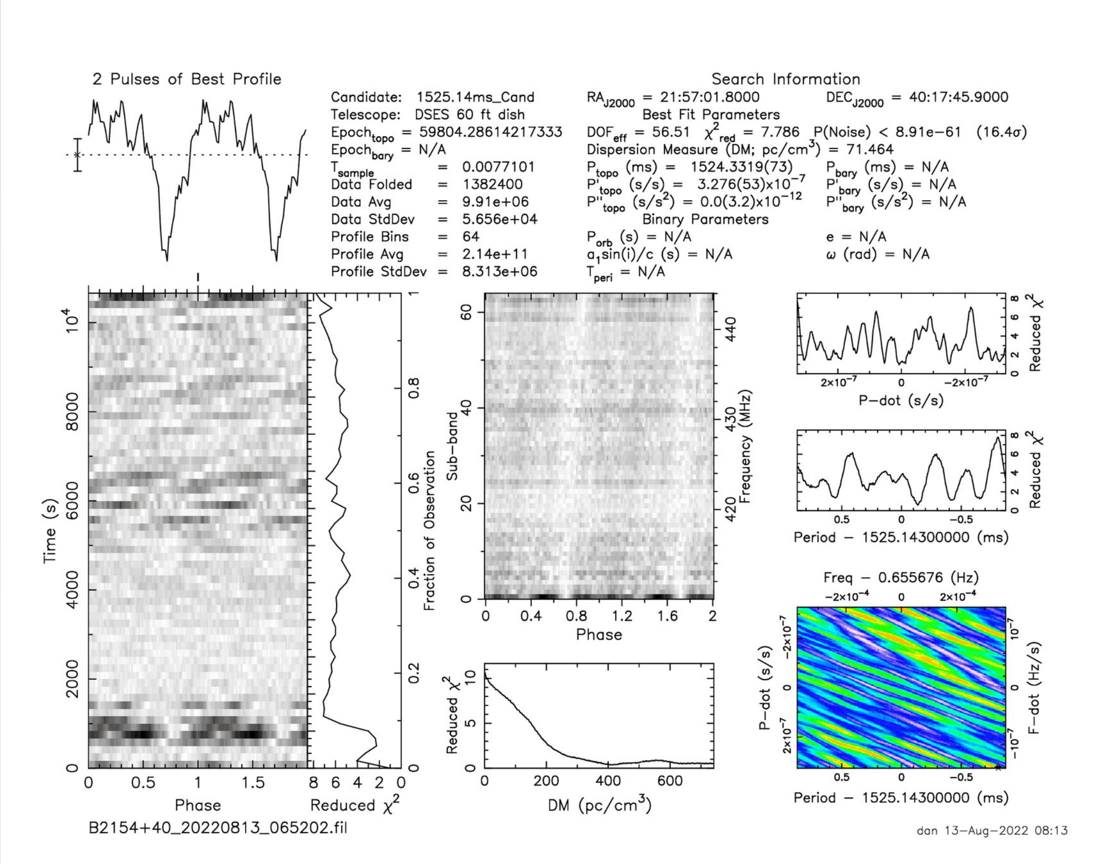
Flat time-series

PSR B2154+40 Failure

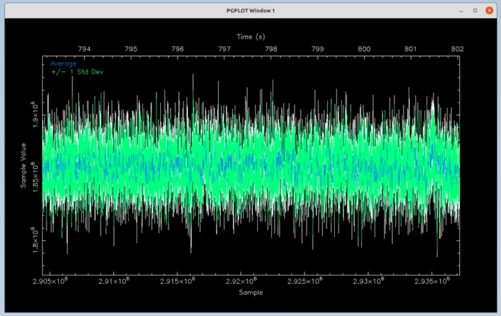
No response. 3 hours, S400 = 105 mJy

RFI and red-noise decreases S/N, causing problems folding slow pulsars

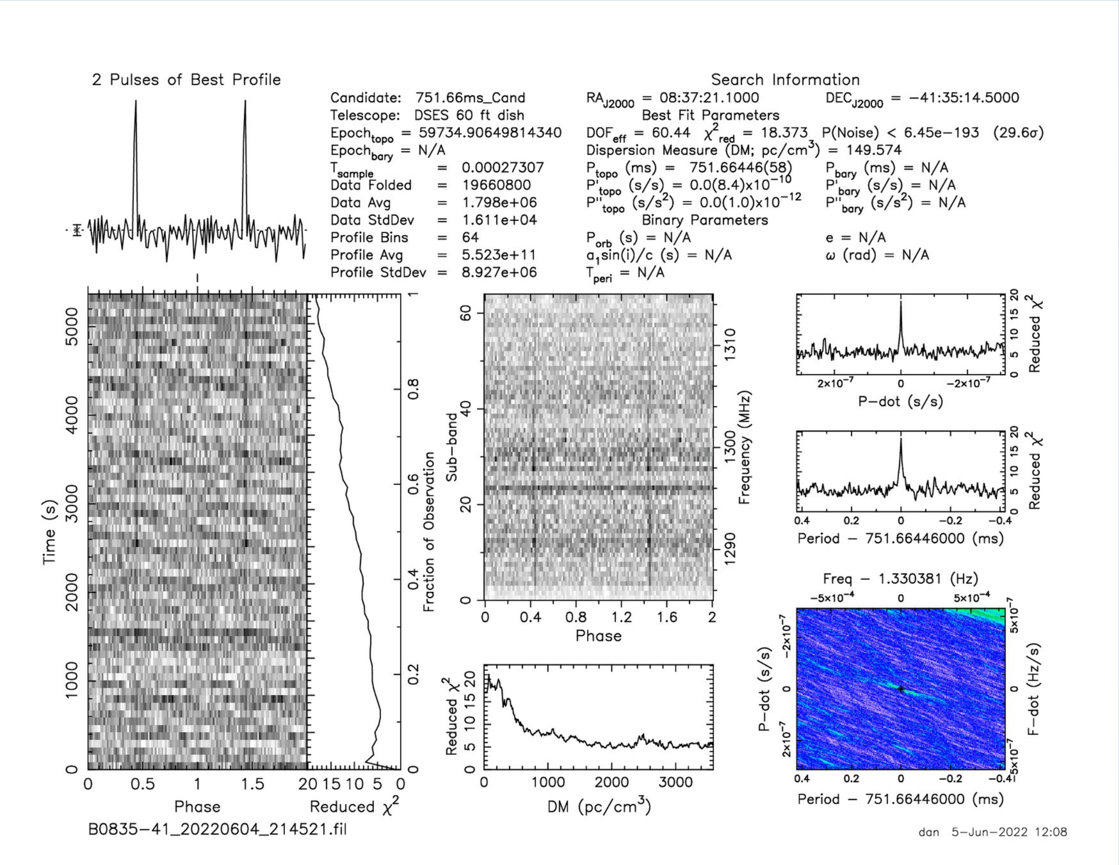


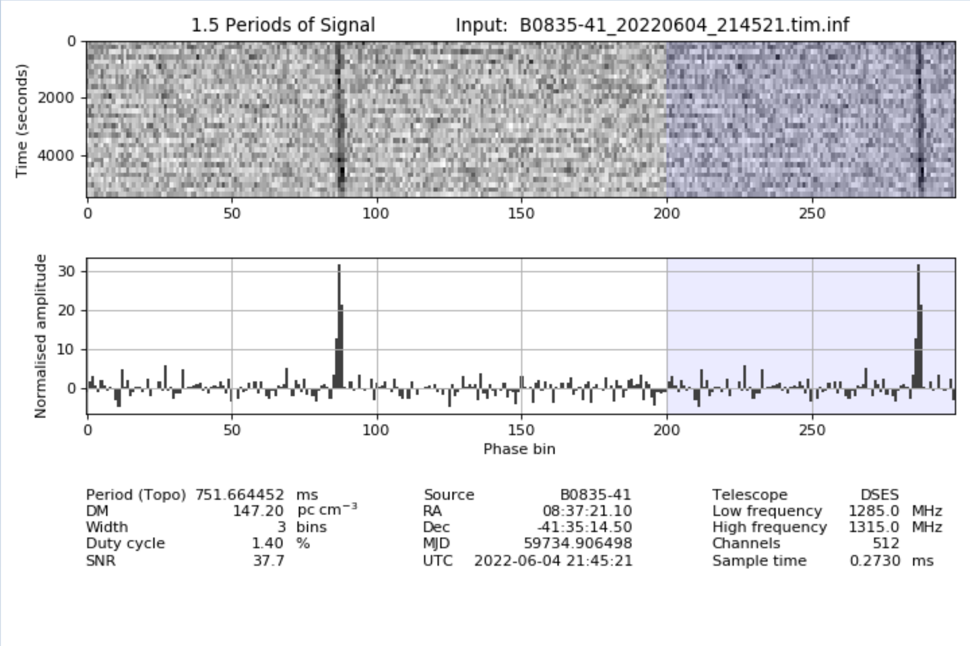


B0835-41



Time series shown earlier

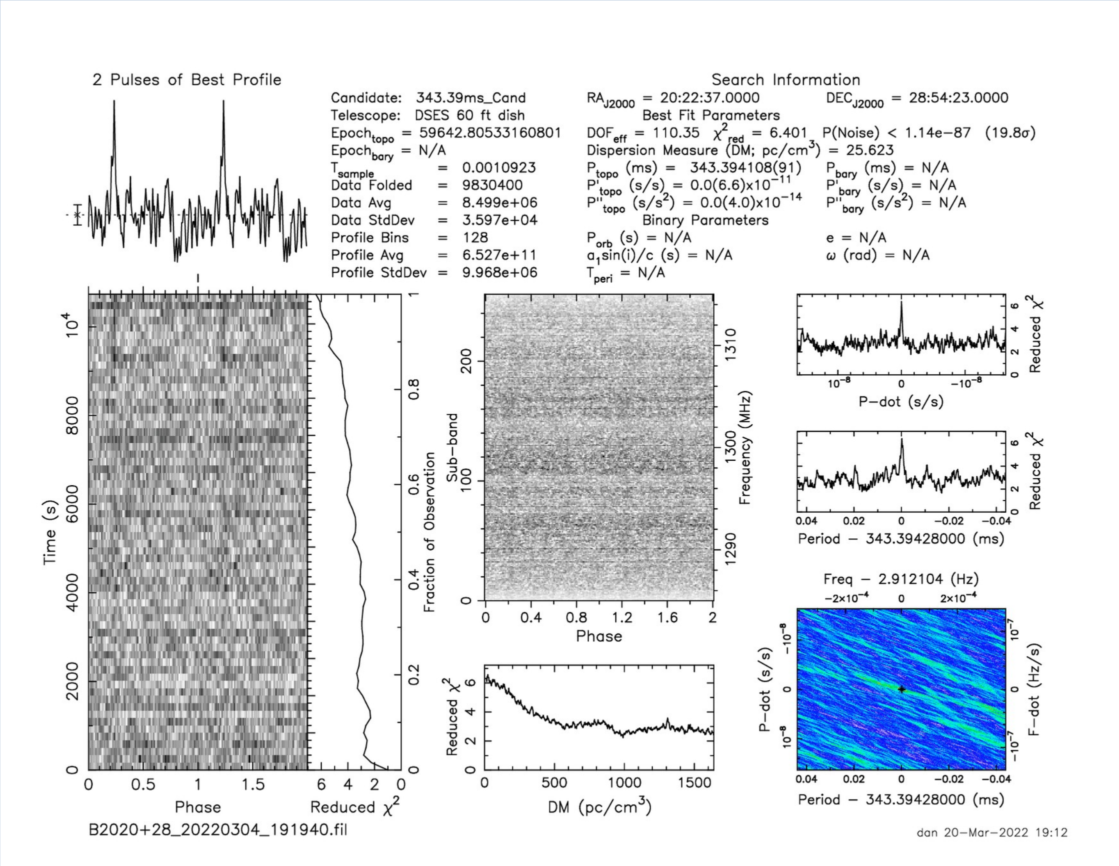




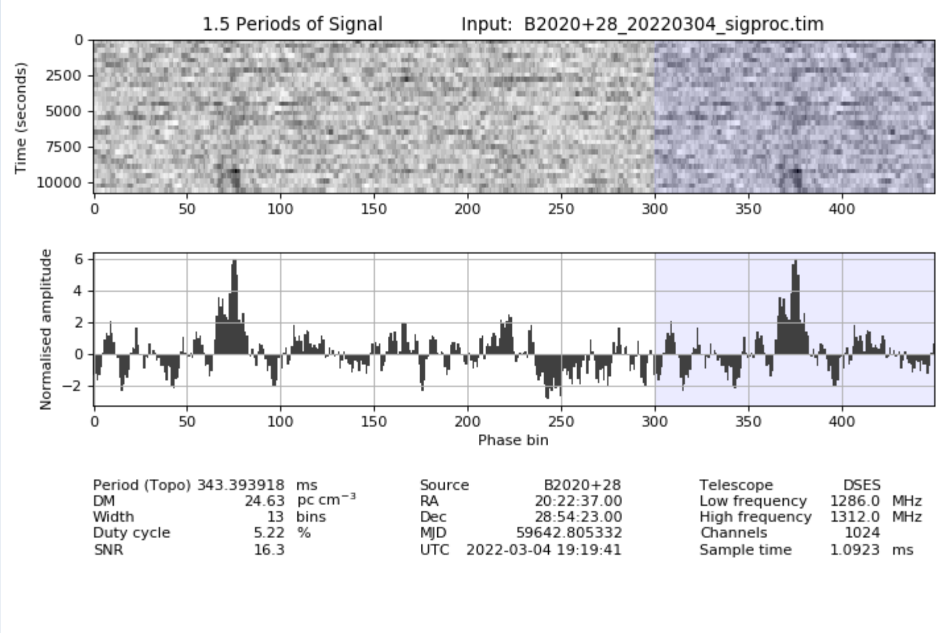
RIPTIDE Period = 751.66445 ms, SNR_{ffa} = 37.7

PRESTO Period = 751.66446 ms, SNR_{fft} = 12.7

B2020+28



Double-peak pulse (mode-changing)
Pulse at end of collection: Scintillation



RIPTIDE Period = 343.393918 ms, SNR_{ffa} = 16.3

PRESTO Period = 343.394280 ms, SNR_{fft} = 4.8

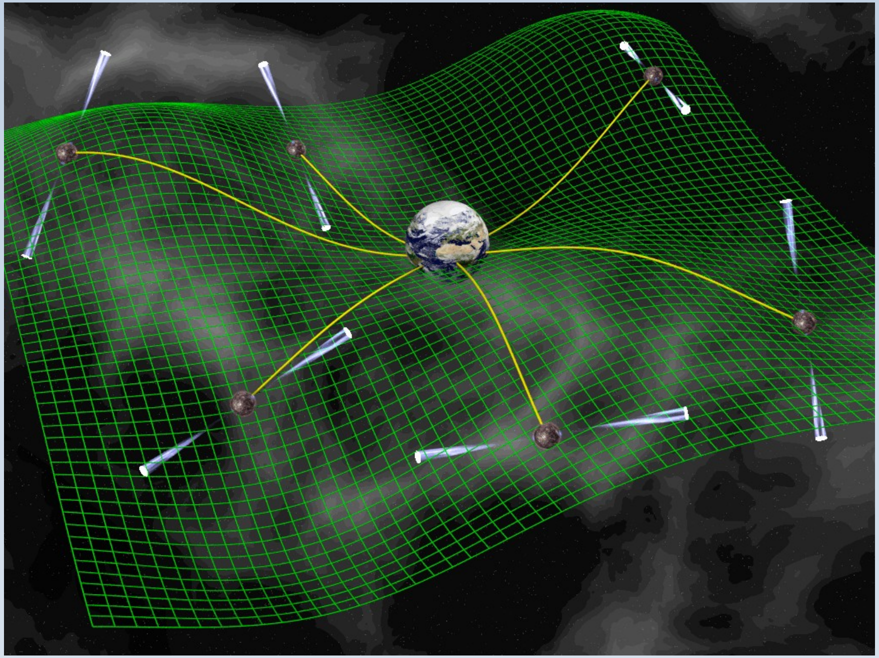
Pulsars in the News: Gravitational Wave Detection

- NANOGrav* found (Bayesian) evidence for gravitational waves that oscillate with periods of years to decades

- The 15-year data set uses high-precision radio timing of millisecond pulsars (MSPs)

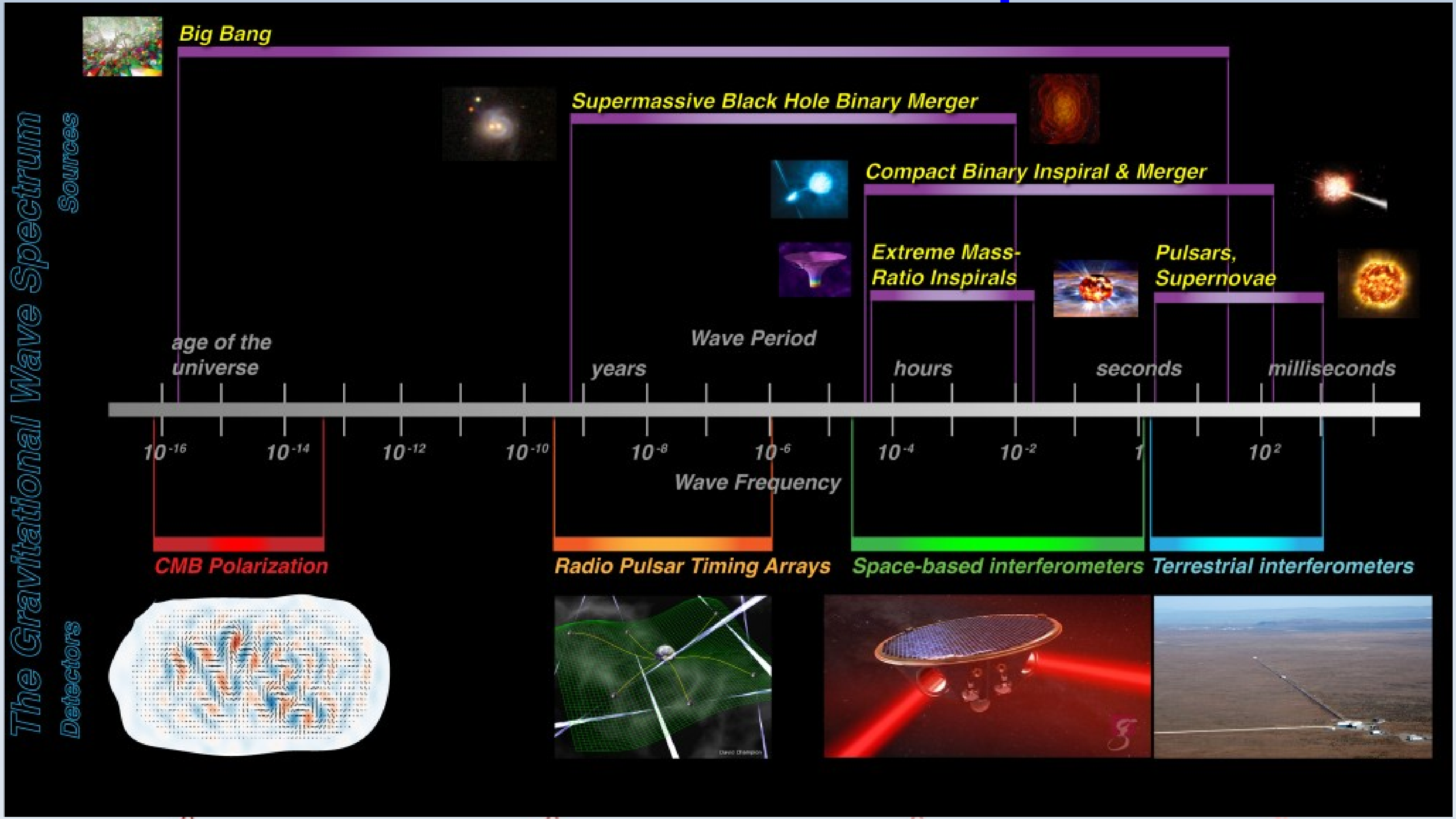
*NANOGrav = North American Nanohertz Observatory for Gravitational Waves

nanograv.org



Pulsar Timing Array (PTA) Illustration

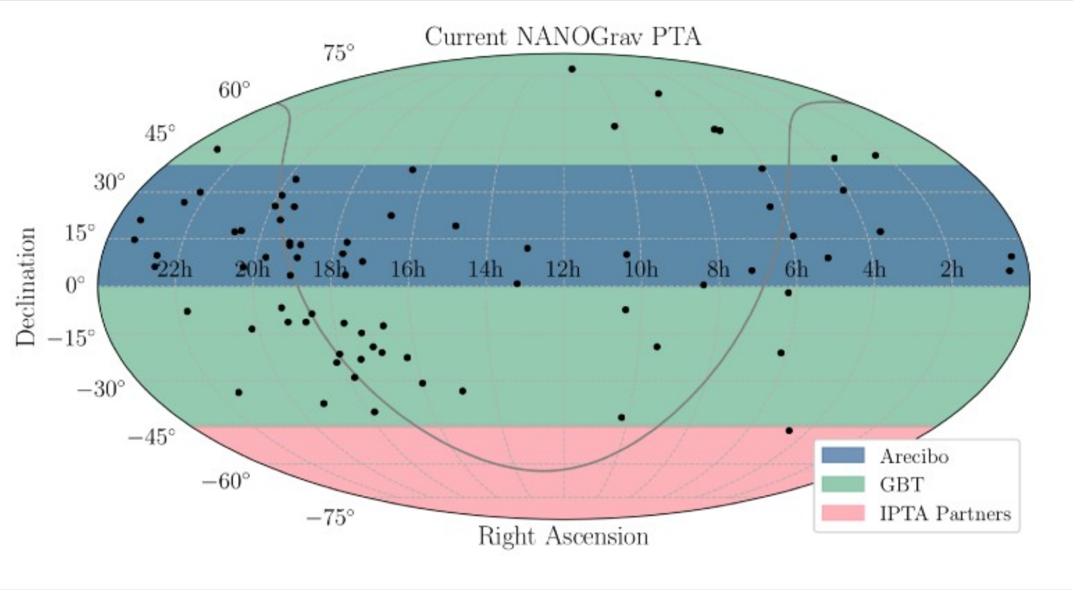
Gravitational Wave Spectrum



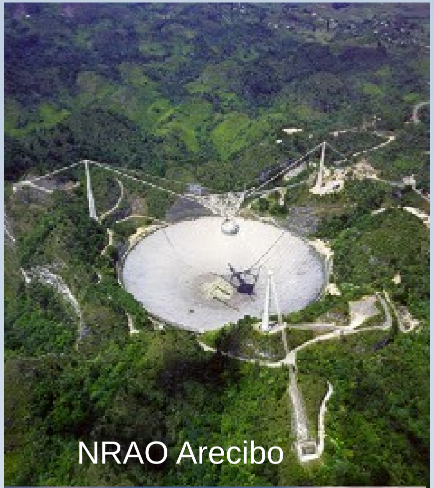
Credit: NASA/GSC

NANOGrav 15-Year PTA

79 MSPs at two frequencies (from 800 MHz to 3 GHz) every one to four weeks for roughly 20-30 min using Arecibo (41 MSPs), the GBT (39 MSPs), and the VLA (7 MSPs)

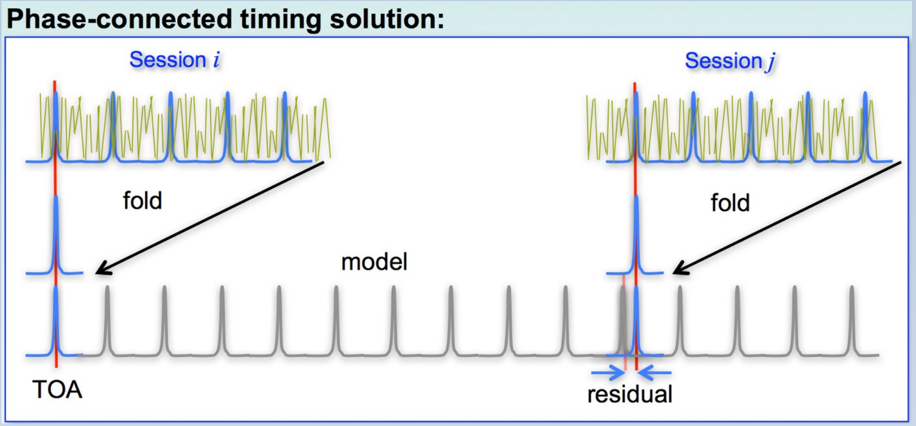


The NANOGrav Collaboration, 2018, ApJS, 235, 37



GBT & CHIME replaced Arecibo

Pulsar Timing Residuals

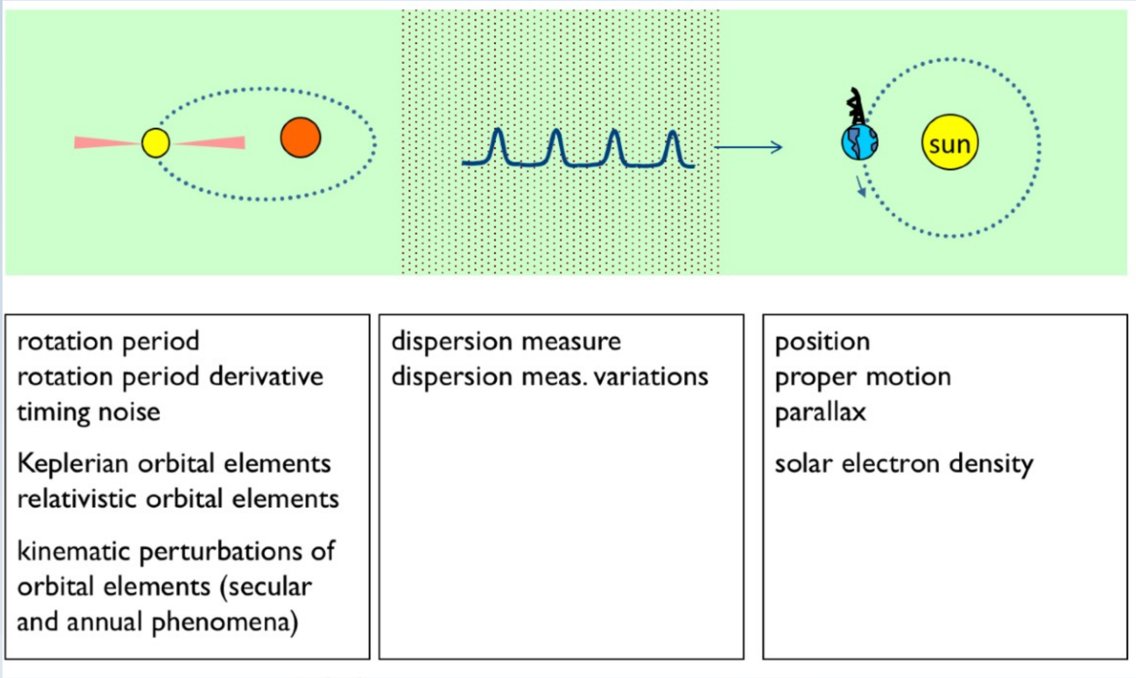


Credit: D. Champion, K. Liu 2017

- TOA = pulse Time Of Arrival
- Residual = observed TOA – modeled TOA
- Every pulse accounted for via phase alignment

- Disturbances to pulse arrival times →

- Timing residuals show scatter in excess of that predicted by formal timing uncertainties



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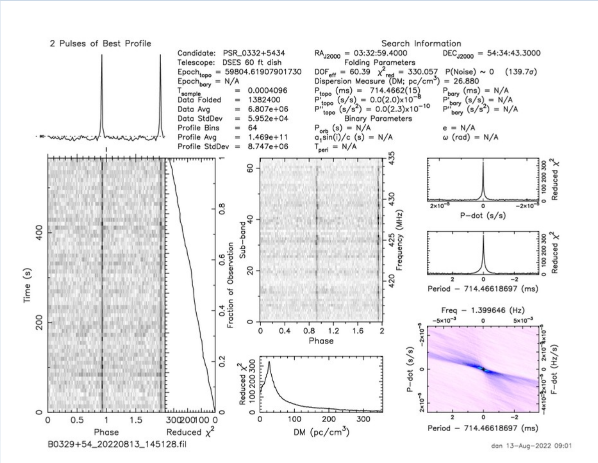

Questions?