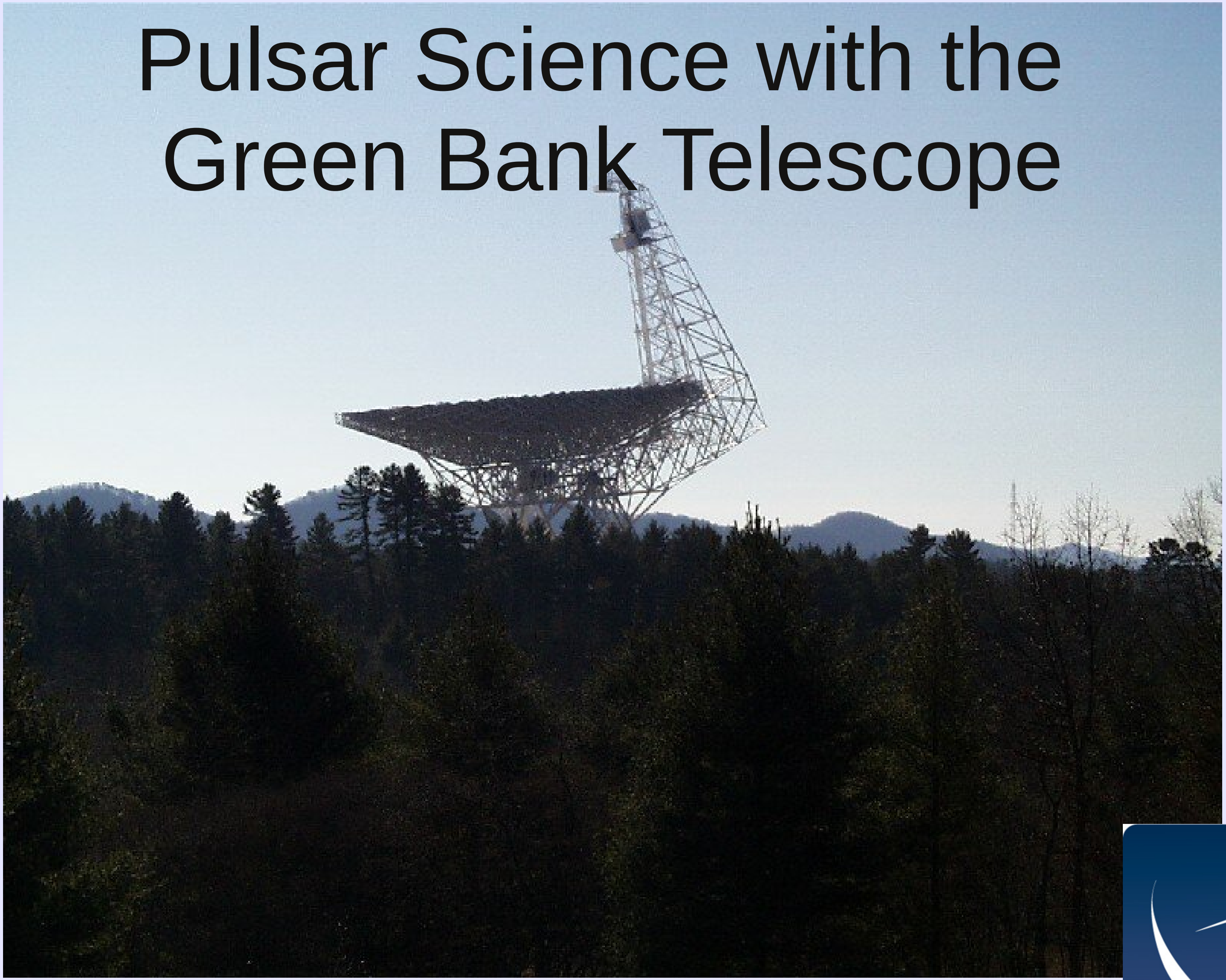
Pulsar Science with the Green Bank Telescope



Paul Demorest, NRAO

Talk Outline:

1. GBT background and history

2. Main (pulsar-relevant) features of the GBT

3. Recent pulsar backend development (GUPPI project).

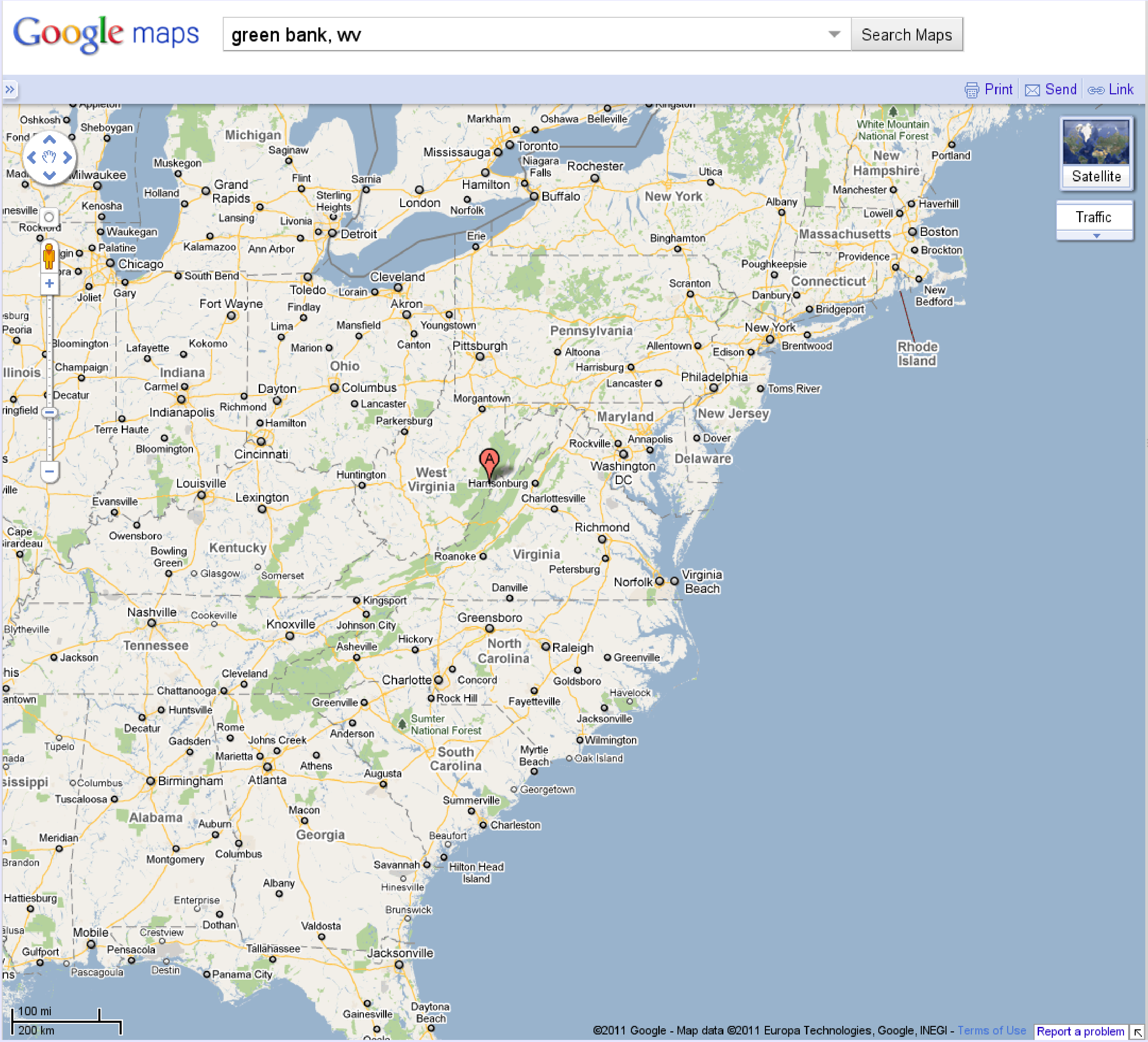
4. GBT pulsar science highlights.

The National Radio Astronomy Observatory

Operates four major radio astronomy facilites (mostly) in the US:

NRAO is funded by the US National Science Foundation (NSF).

These facilities are completely open-access – anyone can propose observations (twice yearly, Febraury 1 and August 1 deadlines).



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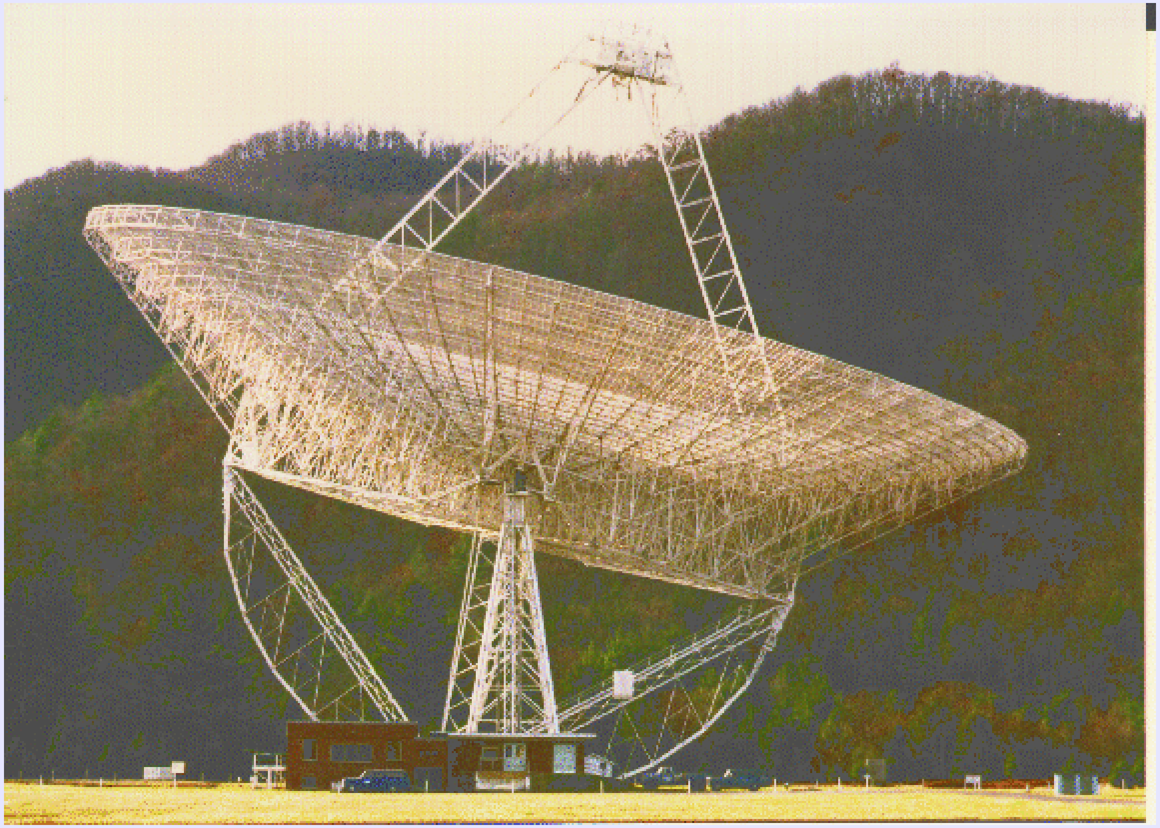
Green Bank history

GB was first NRAO site, opened in 1957. Major historical telescopes were the 140-foot (aka 43-m) and 300-foot telescopes. Both started operating in mid-1960's. 43-m is still in use today...

140-foot (43m) telescope



300-foot telescope

Green Bank history

The 300-m collapsed during usage in 1988, having outlived by far its planned operating lifetime. Plans were soon made for a replacement telescope. Instrumental in securing funding for the new project was US Senator Robert Byrd from West Virginia.

The Robert C. Byrd Green Bank Telescope (GBT):

Construction began 1991, first light in 2000.

GBT Overview

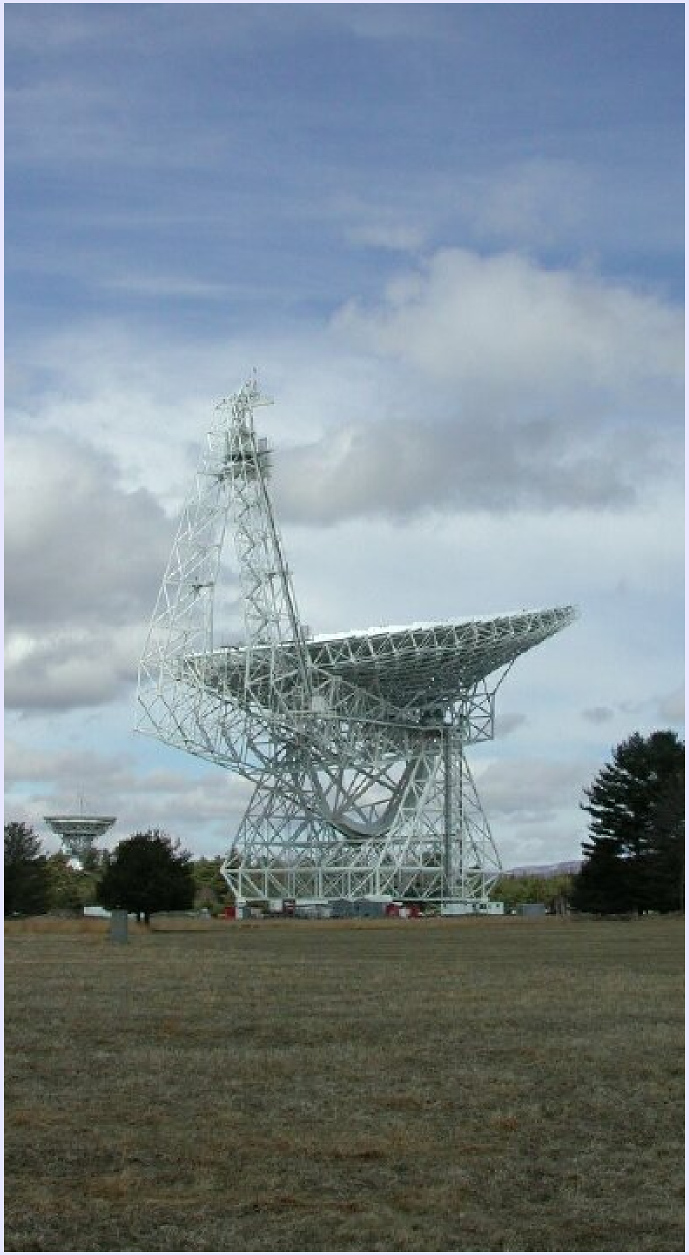
100 meter aperture, fully-steerable down to 5 degrees elevation (declination > -45 deg).

Unblocked optics (off-axis feed arm) improves efficiency and provides clean beam shape.

Set of receivers provide nearly complete frequency coverage between 300 MHz and 100 GHz.

“Active surface” increases efficiency for high-frequency observing.

Pulsar observing is ~30% of total time, and has produced some of the highest-profile GBT results (top 5 papers by citation count).



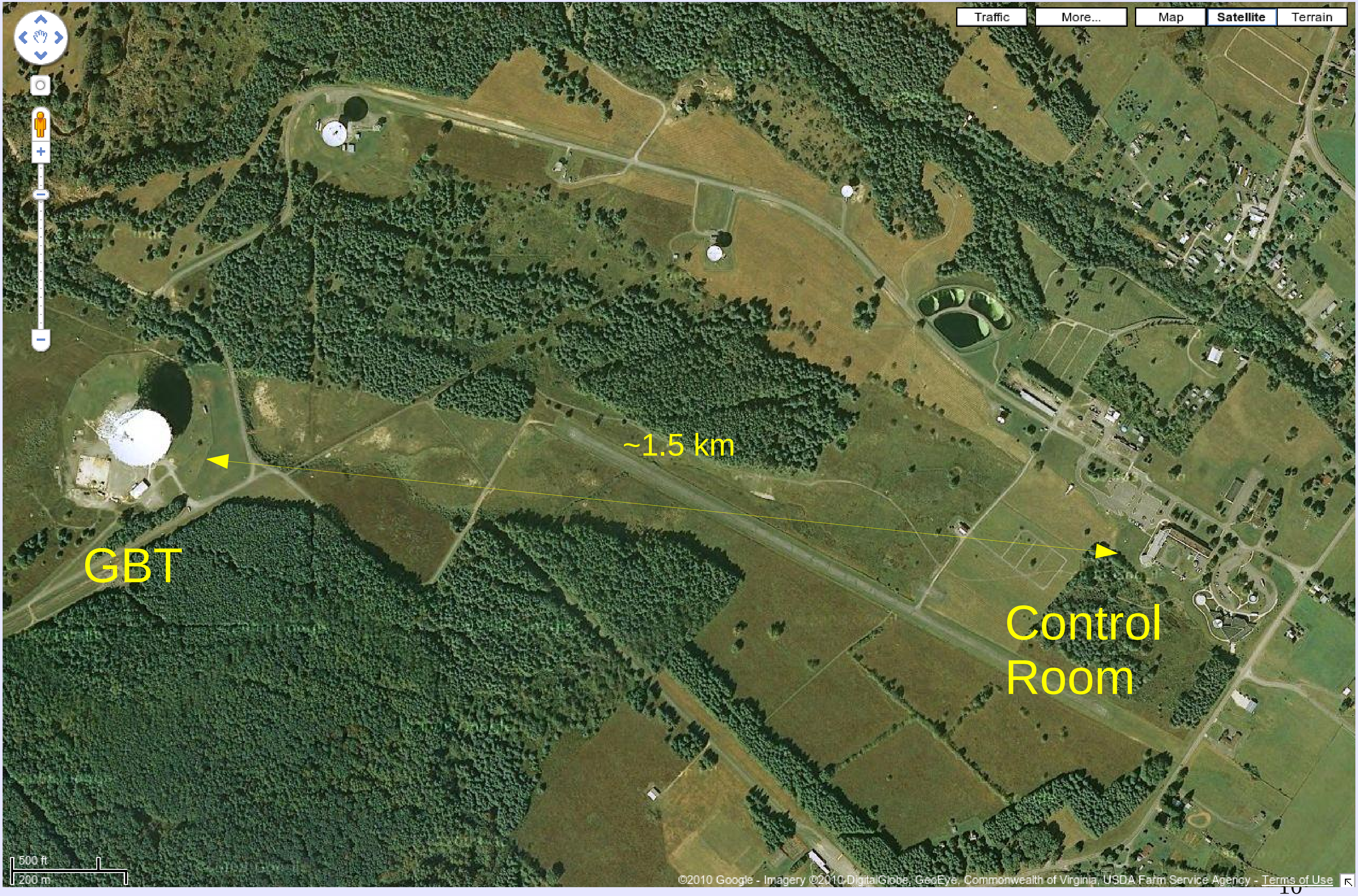
GBT Receivers:

Receiver	Band	Frequency Range (GHz)	Focus	Polarization	Beams	Polarizations per Beam	Beam Separation	FWHM	Gain (K/Jy)	Aperture Efficiency	SEFD (JY)	T_{rec} (K)
PF1	342 MHz	.290-.395	Prime	Lin/Circ	1	2	——	$36'$	2.0	70%	23	12
	450 MHz	.385-.520	Prime	Lin/Circ	1	2	——	$27'$	2.0	70%	22	22
	600 MHz	.510-.690	Prime	Lin/Circ	1	2	——	$21'$	2.0	70%	11	12
	800 MHz	.680-.920	Prime	Lin/Circ	1	2	——	$15'$	2.0	70%	15	21
PF2	——	.910-1.23	Prime	Lin/Circ	1	2	——	$12'$	2.0	70%	9	10
L-Band	——	1.15-1.73	Greg.	Lin/Circ	1	2	——	$9'$	2.0	70%	10	6
S-Band	——	1.73-2.60	Greg.	Lin/Circ	1	2	——	$5.8'$	1.9	70%	11	6-10
C-Band	——	3.95-6.1	Greg.	Lin/Circ	1	2	——	$2.5'$	1.85	70%	8	5
X-Band	——	8.00-10.0	Greg.	Circ	1	2	——	$1.4'$	1.8	70%	15	13
Ku-Band	——	12.0-15.4	Greg.	Circ	2	2	$330''$	$54''$	1.7	70%	18	14
KFPA	——	18.0-26.5	Greg.	Circ	7	2	$96''$	$32''$	1.5	67%	23	$14 - 22$
Ka-Band	MM-F1	26.0-31.0	Greg.	Circ	2	1	$78''$	$26.8''$	1.5	56-64%	27	20
	MM-F2	30.5-37.0						$22.6''$			20	
	MM-F3	36.0-39.5						$19.5''$			43	
Q-Band	——	38.2-49.8	Greg.	Circ	2	2	$58''$	$16''$	1.0	47-56%	67-134	40-70
W-Band 4mm	——	68-92	Greg.	Circ	2	2	TBD	$10''$	TBD	TBD	TBD	TBD
Mustang	——	80-100	Greg.	—-	64	—-	—-	$10''$	—-	20%	—-	—-

For pulsar observing, the primary metric is System-Equivalent Flux Density (SEFD). Lower values are better!

Only one prime-focus receiver is available at any given time. PF receivers are rotated every few weeks. Gregorian recvrs (L-band and higher) are always in place.

Switching from PF to Gregorian takes ~15 minutes.


Traffic
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GBT
Control Room
500 ft
200 m
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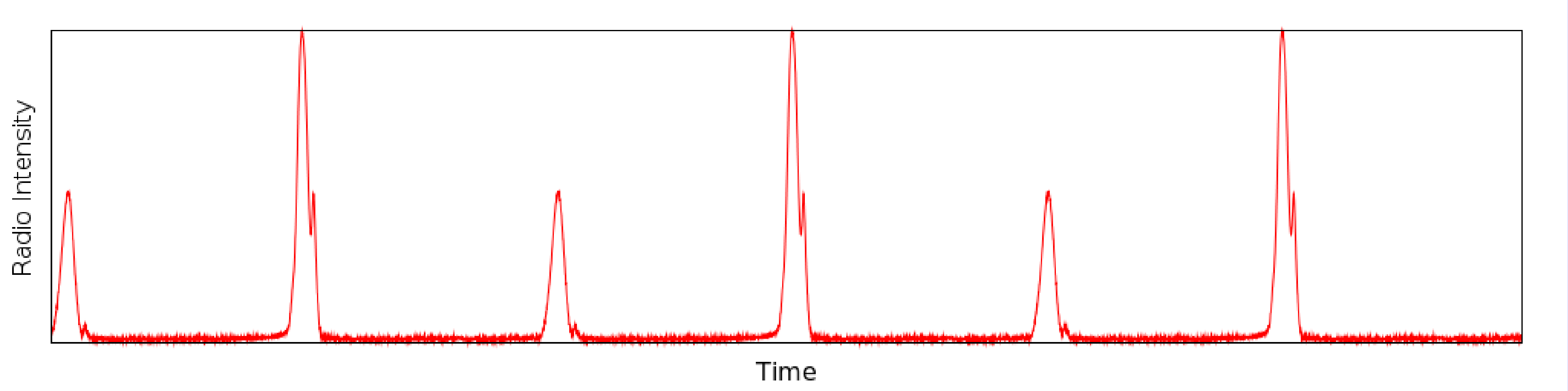
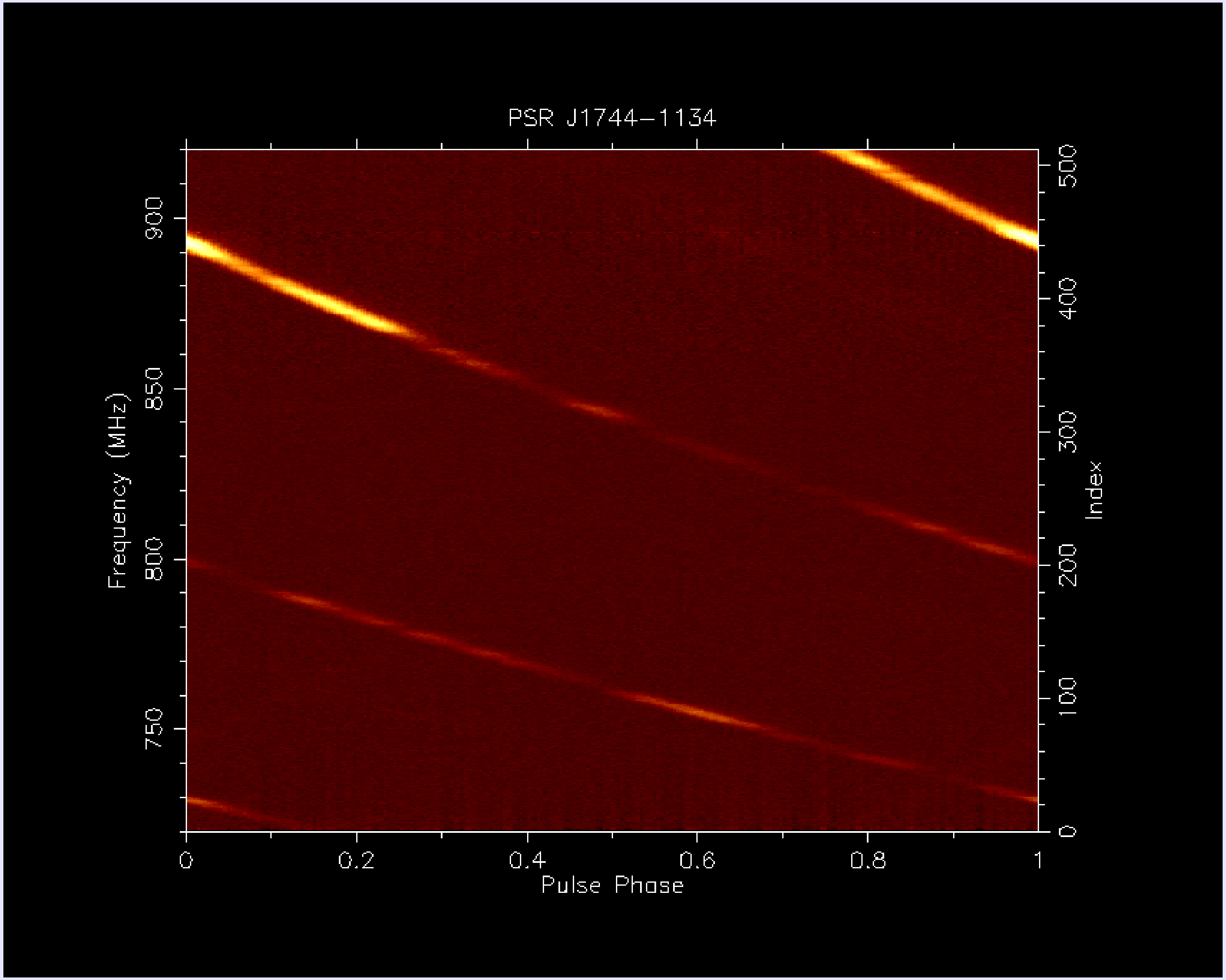
- Pulsars have unique and demanding observational requirements:
  - Broad-band signal (high BW = more S/N)
  - High time resolution (~1 us)
  - High dynamic range (many ADC bits)
  - Highly polarized signal (full Stokes)
  - Interstellar medium disperses the pulses.



Interstellar Dispersion

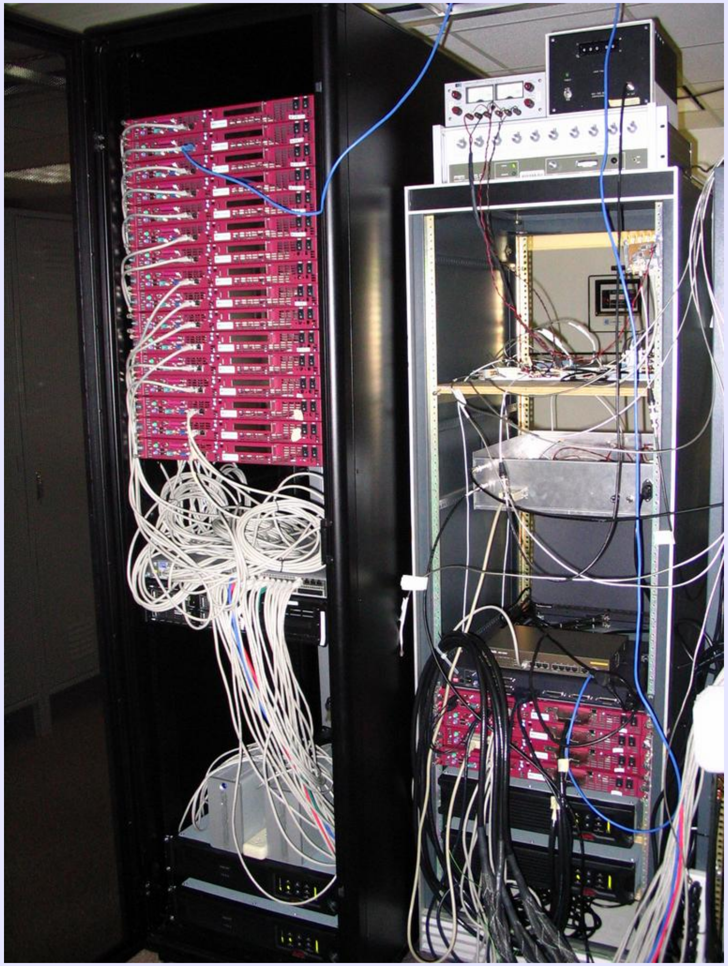


Pulsar Backends

- “Search” backends:
  - Fast-dump spectrometers
  - Time resolution 50 to 100 μs
  - Frequency resolution 25 kHz to 1 MHz
  - Often traded data quality for more BW
- “Timing” backends:
  - Pulse period folding
  - Coherent dedispersion
  - High time resolution, ~1 μs
  - Data quality (# bits, polns, etc) more important

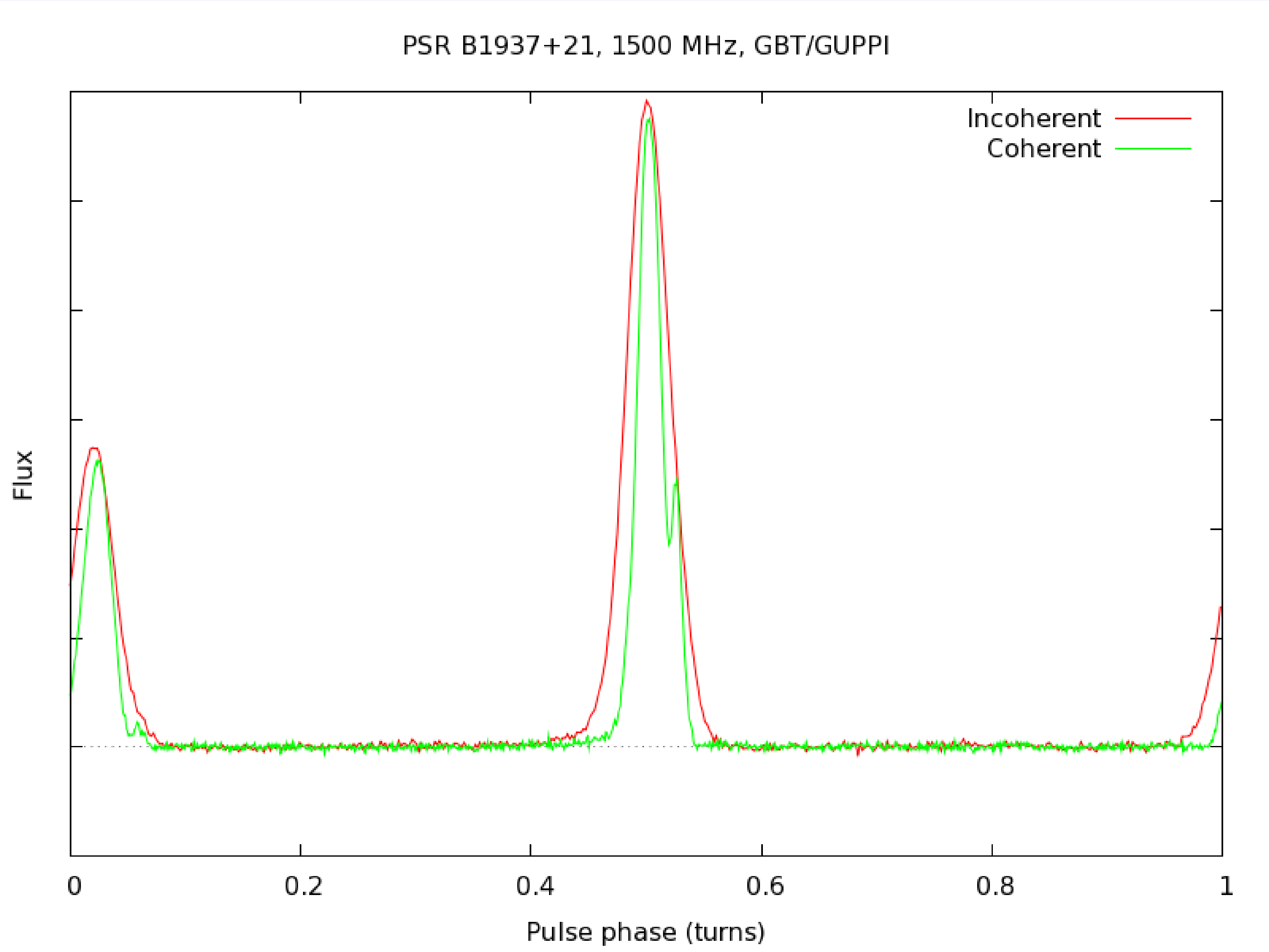
Coherent Dedispersion

- Removes ISM dispersion (for known DM) within a freq channel.
- FIR filter applied pre-detection via FFT convolution; filter length ~k to ~M-point.
- Most previous systems are software based and handle ~100 MHz total BW.

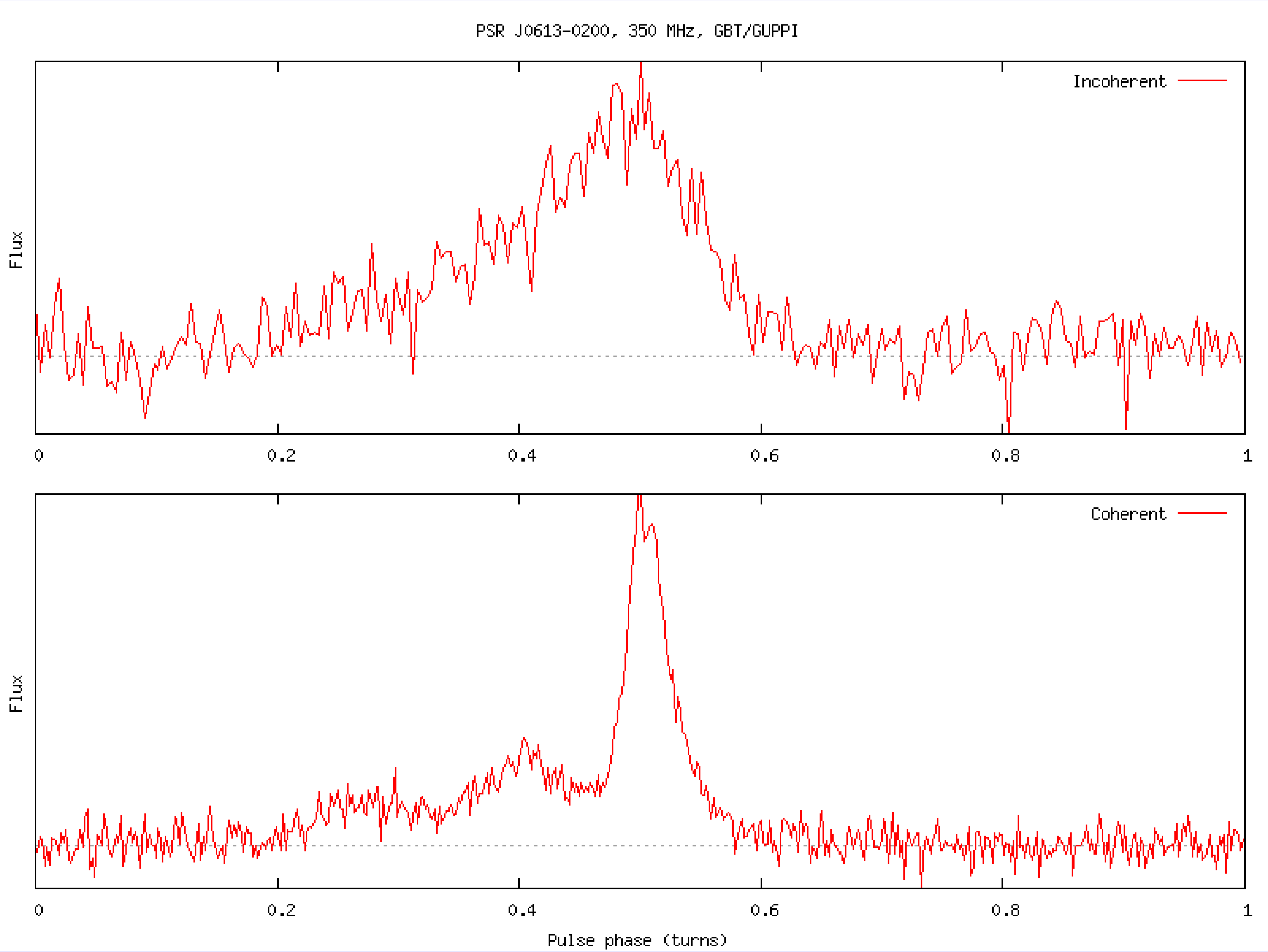


GASP system @ GB

Coherent vs Incoherent



Low-frequency observing



Pulsar Backends at the GBT (pre-GUPPI):

SPIGOT: Primary search / general-purpose instrument through 2008. Spectrometer, 3-level ADCs, 800 MHz BW, no polarization, 2048 channels, 81.92 us time resolution.

BCPM: Previous spectrometer. ~100 MHz BW, 4-bit ADCs.

Spectral Processor: Ancient spectrometer. 6-bit ADCs, full-Stokes, 40 MHz BW.

GASP: Coherent dedisp system, 8-bit ADCs, full-Stokes, 128 MHz BW.

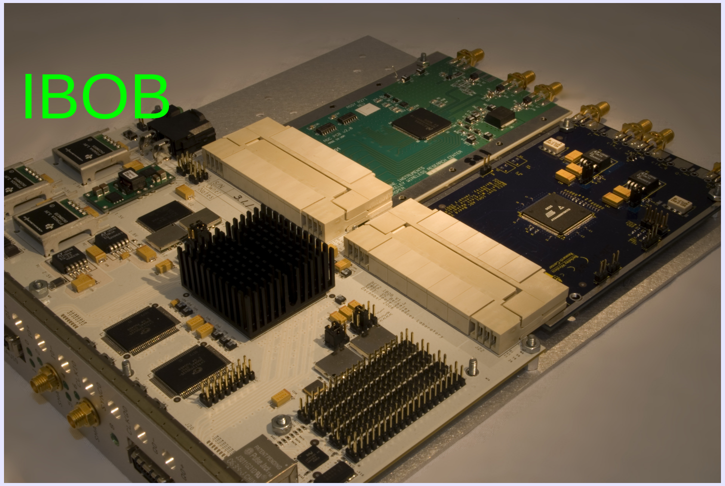
CPSR2: Coherent dedisp, 2-bit ADCs, full-Stokes, 128 MHz BW.

Conclusion: Too many special-purpose instruments!

New GBT pulsar backend, GUPPI

- GUPPI = Green Bank Ultimate Pulsar Processing Instrument
  - Developed at NRAO (Demorest, Ransom, Ford, McCullough, Ray, Duplain, Brandt).
- UC Berkeley's “CASPER” FPGA HW plus 9-node GPU cluster.
- Incorporates best features of 5 previous backends at GB.
  - Both search and timing (real-time folding) modes.
    - Either can be done with or without coherent dedisp.
  - 100, 200, or 800 MHz total BW
  - 8-bit ADCs, full-Stokes, flexible parameters (# channels, integration time, etc).
    - 200 MB/s data rate limit; typical mode is 40.96 us with 2048 channels.
  - Baseband recording up to 200 MHz.

GUPPI architecture:
~1 MHz PFB in FPGAs
Coherent dedisp in GPUs



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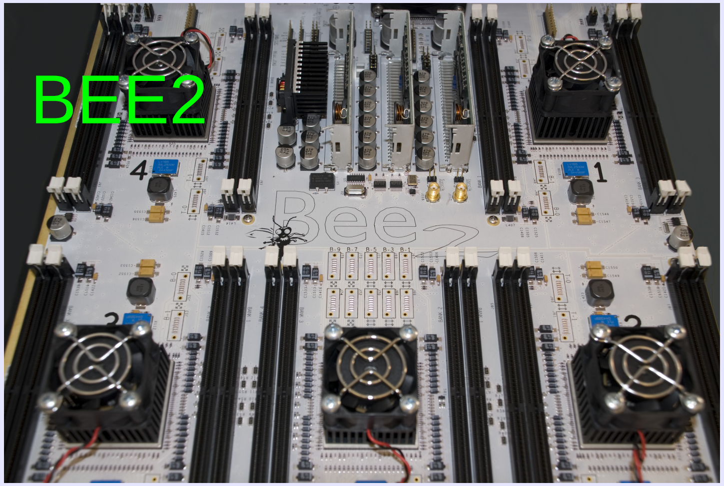
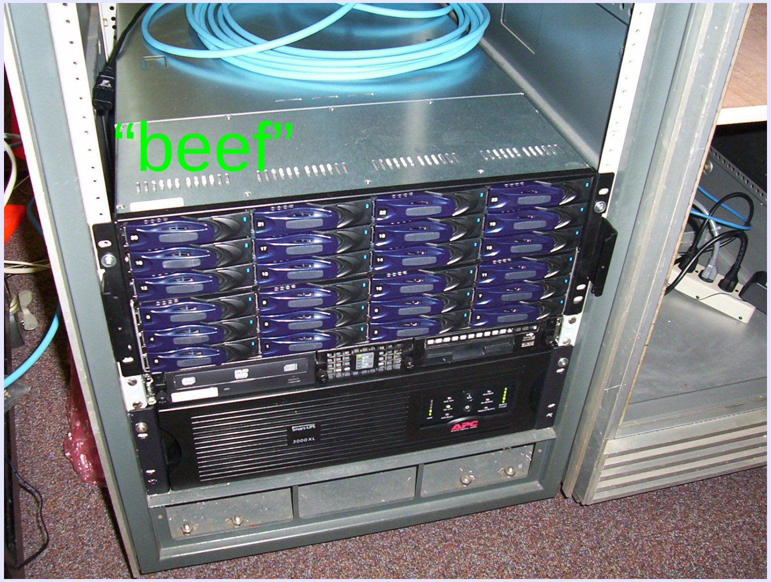


10 Ge switch; 24 Gb/s



GUPPI Timeline

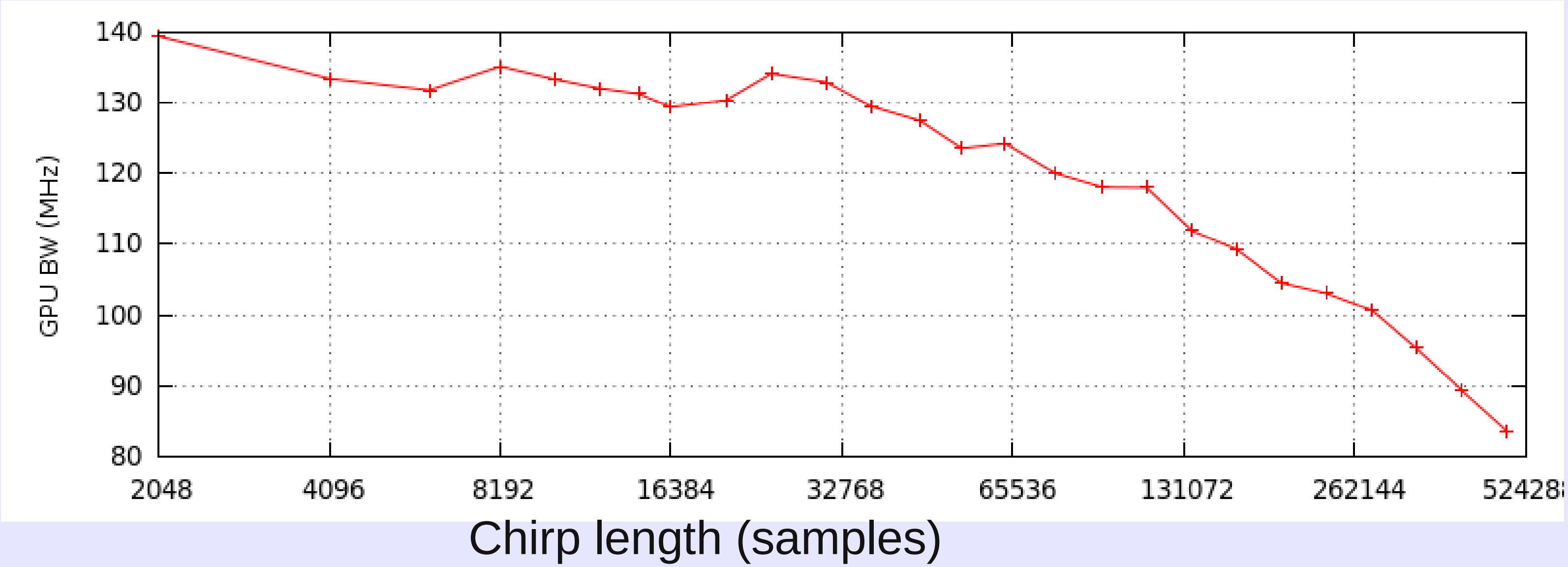
- “Pulsar dream machine” first suggested at Fall 2006 GB instrumentation workshop.
  - At same time, CASPER at UCB is ramping up.
- Initial work in U. Cinn. student project.
- Serious development at NRAO starts Fall 2007.
- GUPPI1 in operation late 2008.
- GPU cluster purchase/development Fall 2009.
- GUPPI2 first light December 2009.

GUPPI Status

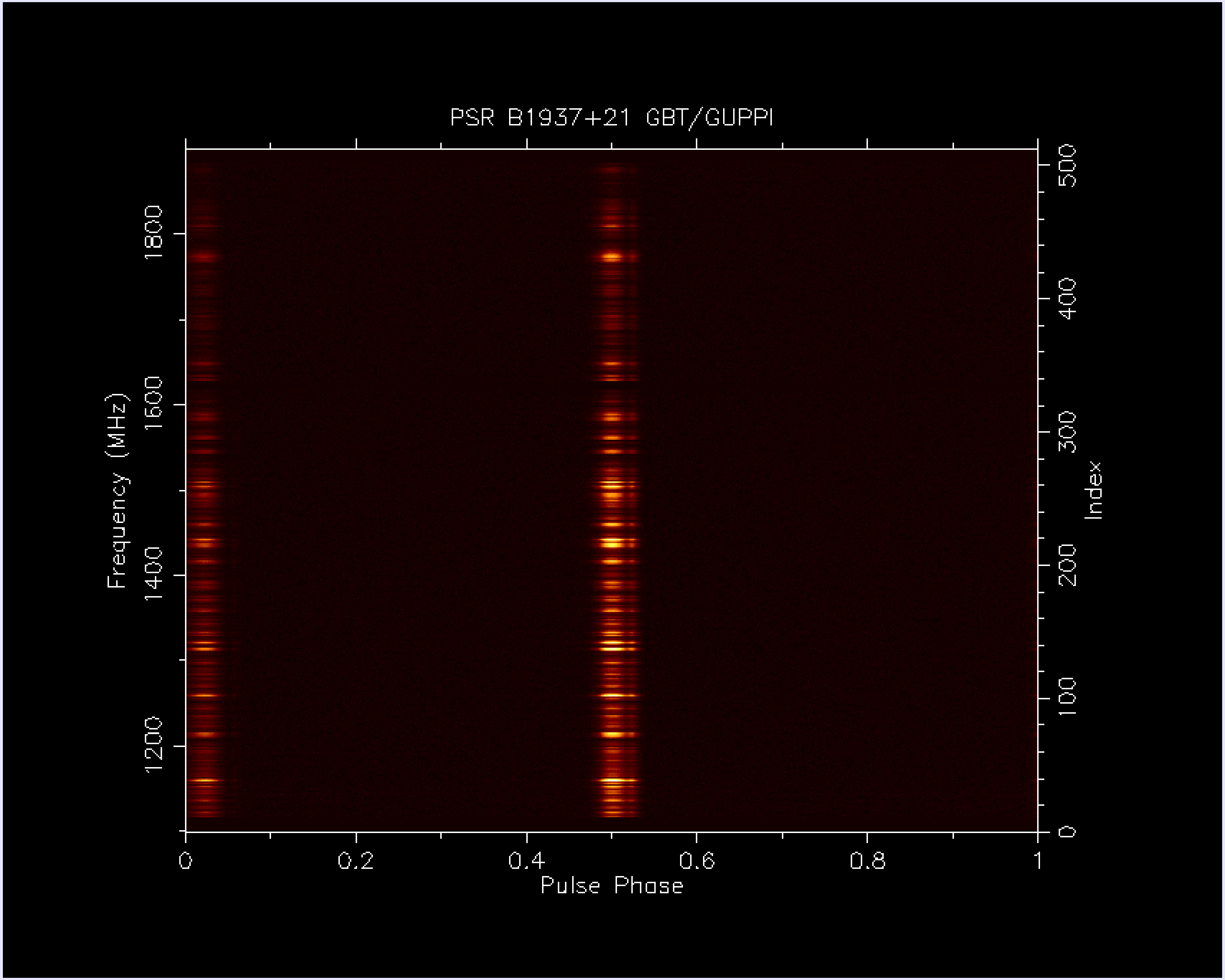
- GUPPI-1 (Search mode)
  - In regular operation since late 2008.
  - Fully integrated with GBT M&C systems!
  - Already many new PSR discoveries.
  - Produces up to 200 MB/s output data rate.
- GUPPI-2 (Coherent dedispersion)
  - Heavy development effort Fall 2009.
  - Reuses many parts of GUPPI-1 design.
  - Achieved first light December 2009!
  - Typically 10's of GB per few-hour obs session.

GUPPI GPU Processing

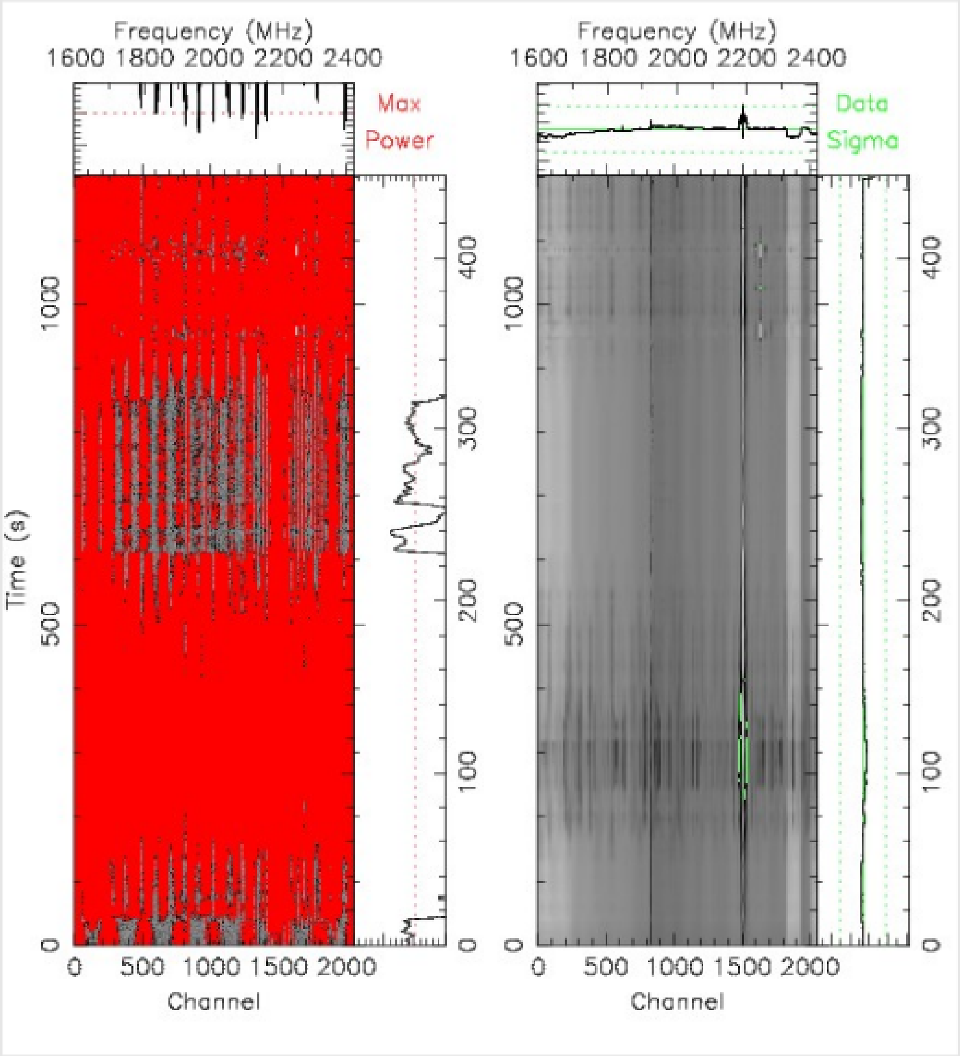
- NVIDIA GTX 285, programmed w/ CUDA
- Each card can dedisperse (FFT-X-IFFT) and fold >100 MHz BW in real time.
- Performance vs DM:
  - Max DM ~ 3000 at L-band!



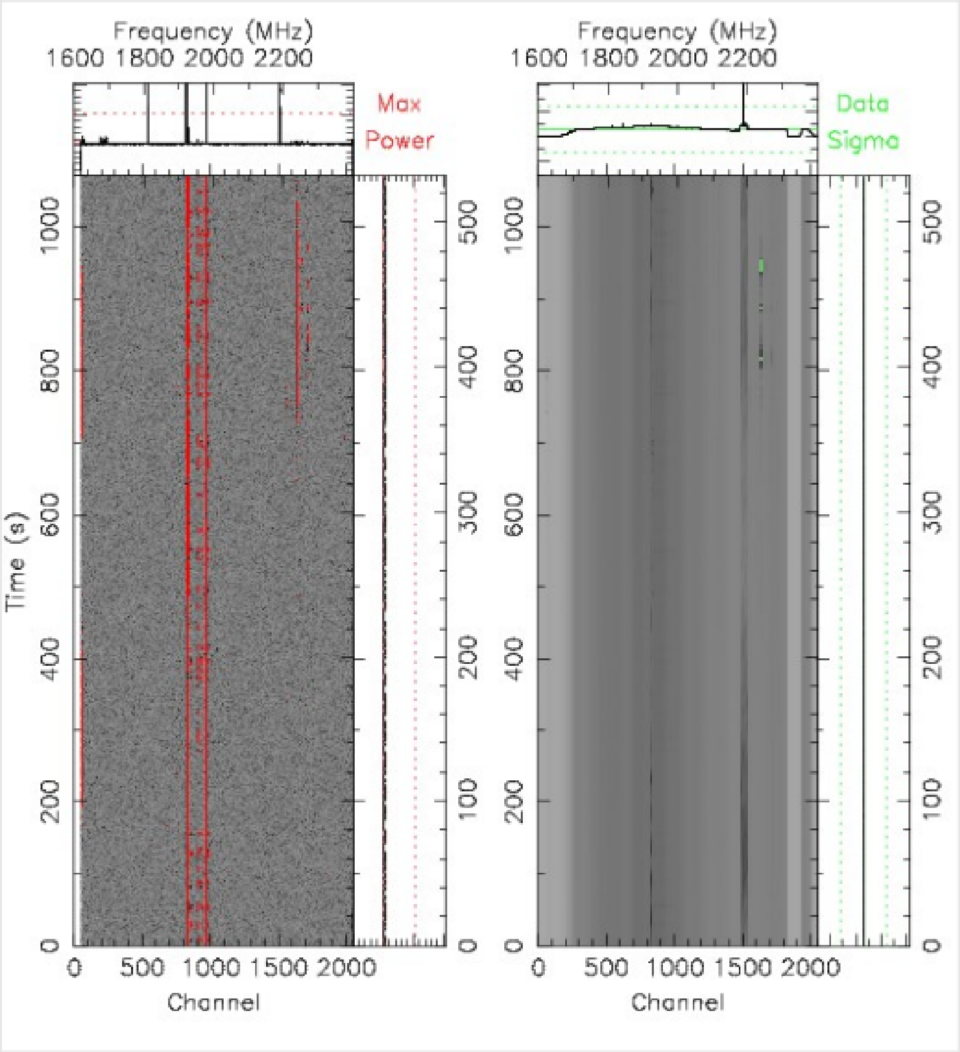
Coherent GUPPI first light, December 2009:



Improved RFI resistance:



Spigot
(3-level, ACF)



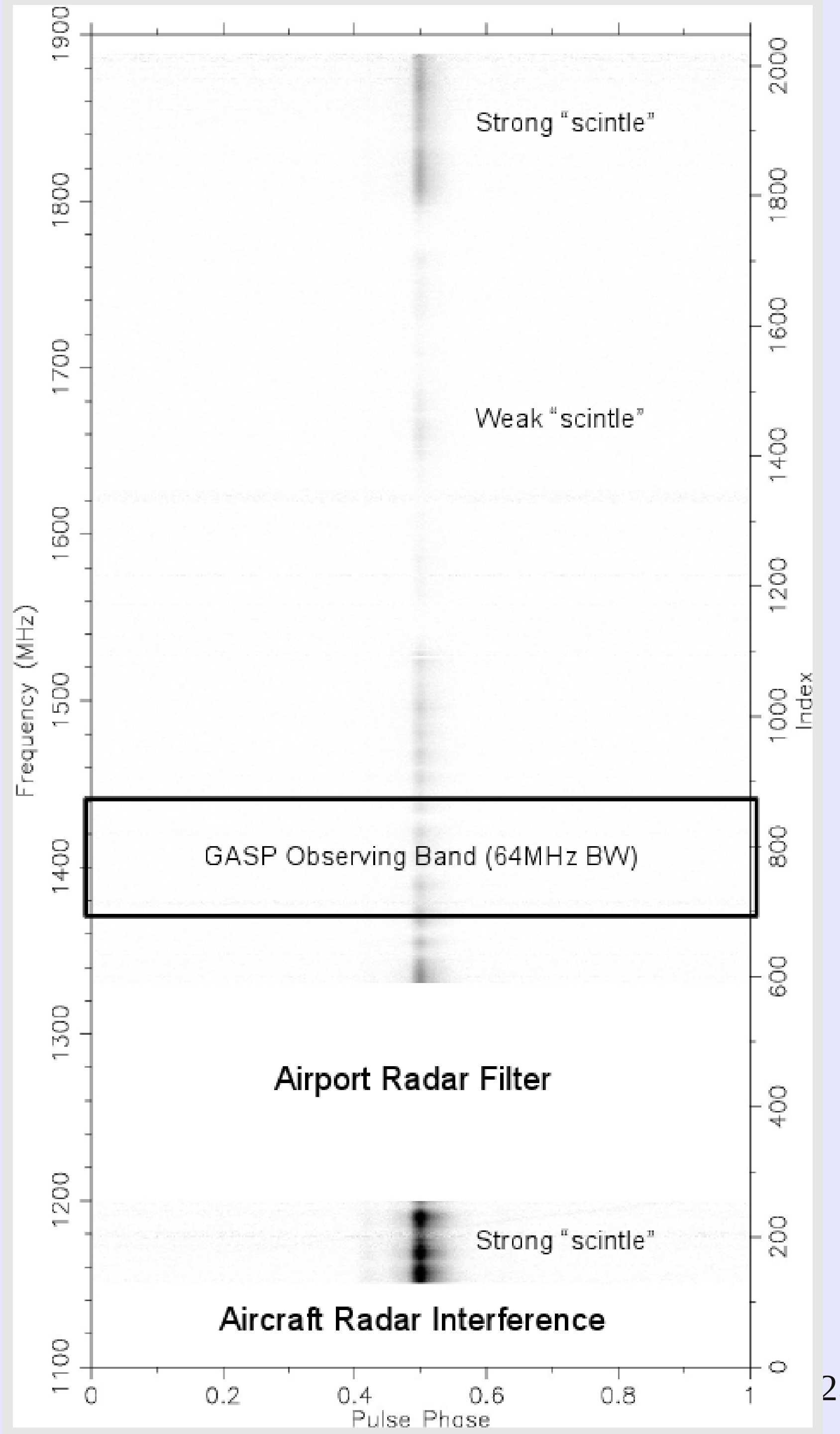
GUPPI
(8-bit, PFB)

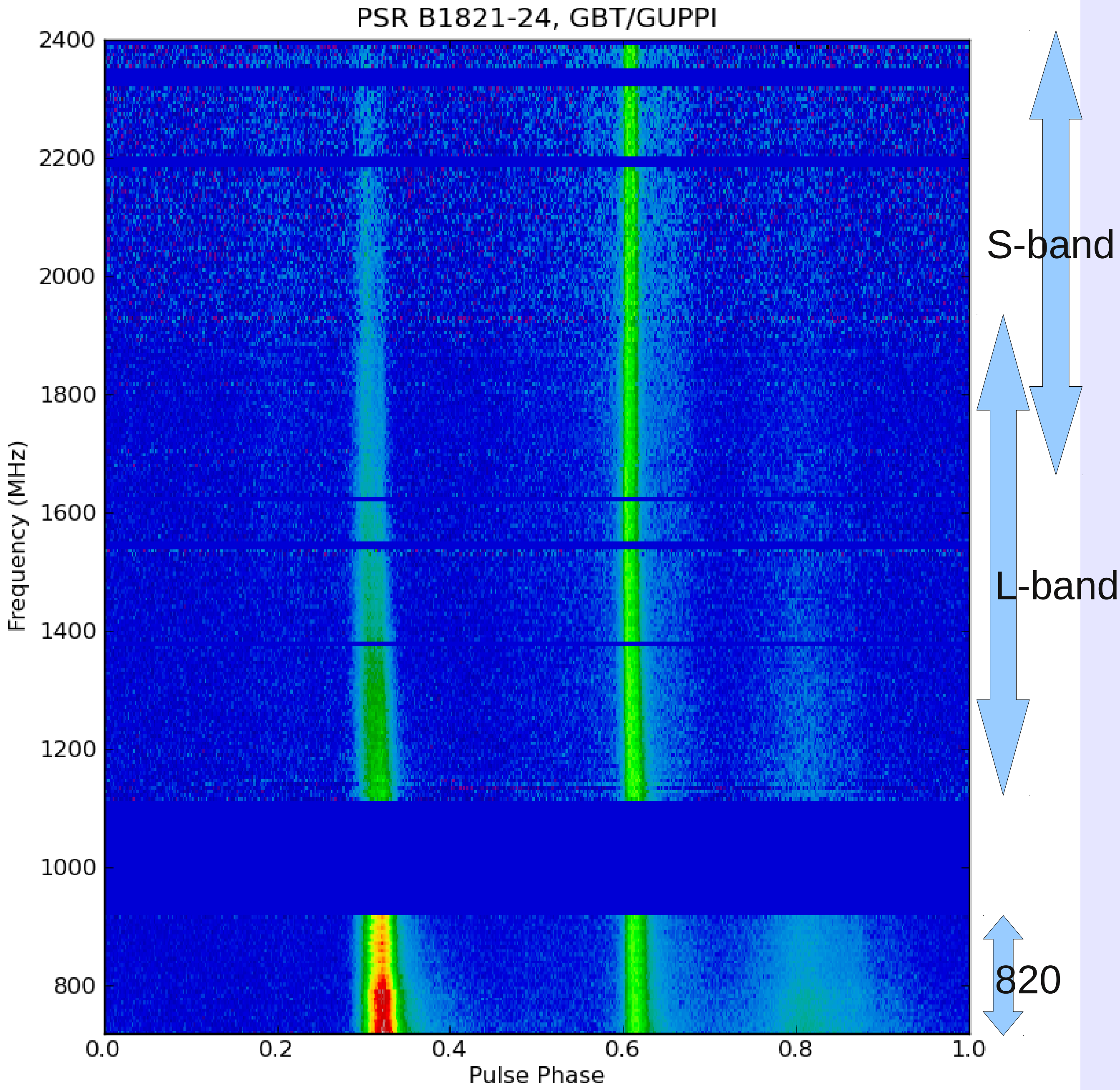
>10x improvement in BW vs older coherent systems!

Fully utilizes all GBT low-freq receivers (“ultimate”).

Improved S/N ratio, also reduces scintillation variability.

PSR J1713+0747
plot: S. Ransom





Future pulsar development at GBT:

Potential super-wide-band receiver to cover ~0.5 to 3.0 GHz.

Expanded 'GUPPI++' backend to process this whole bandwidth.

Tradeoff: Worse T_{sys} than current receivers.

Benefit: Better instantaneous DM measurement for high-precision timing.

Pulsar science highlights from the GBT:

(Note, this list is by no means comprehensive!)

Searches:
- Searches of globular clusters
- 350 MHz drift scan survey
- Pulsar Search Collaboratory educational project
- Green Bank North Celestial Cap (GBNCC) survey
- Targeted searches of Fermi point sources

Timing:
- Double pulsar (J0737-3039) timing
- Globular cluster timing
- NANOGrav pulsar timing array project
- Mass of J1614-2230

GBT 350 MHz drift scan surveys.

Observed during summer 2007 track replacement.

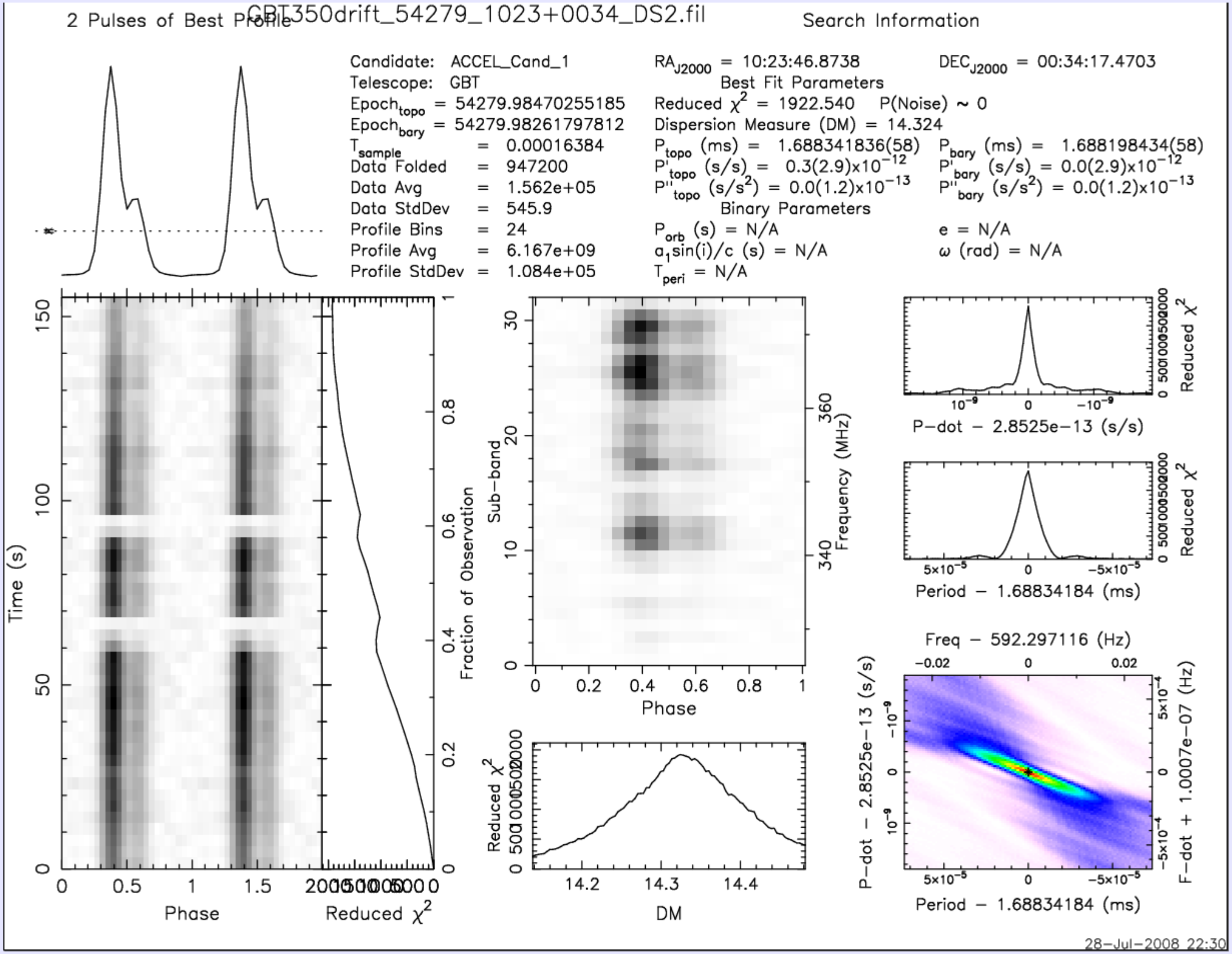
~1500 total telescope hours.

Data split between astronomers and PSC educational project.

26 new pulsar discoveries, including 5 MSPs, and 'missing link' PSR J1023+0038.

J1028+0038: The “Missing Link” pulsar

Bright, eclipsing MSP. Previously observed as a LMXB, thought to be an object in transition between these two types (Archibald et al., *Science*, 2009).



Pulsar Search Collaboratory

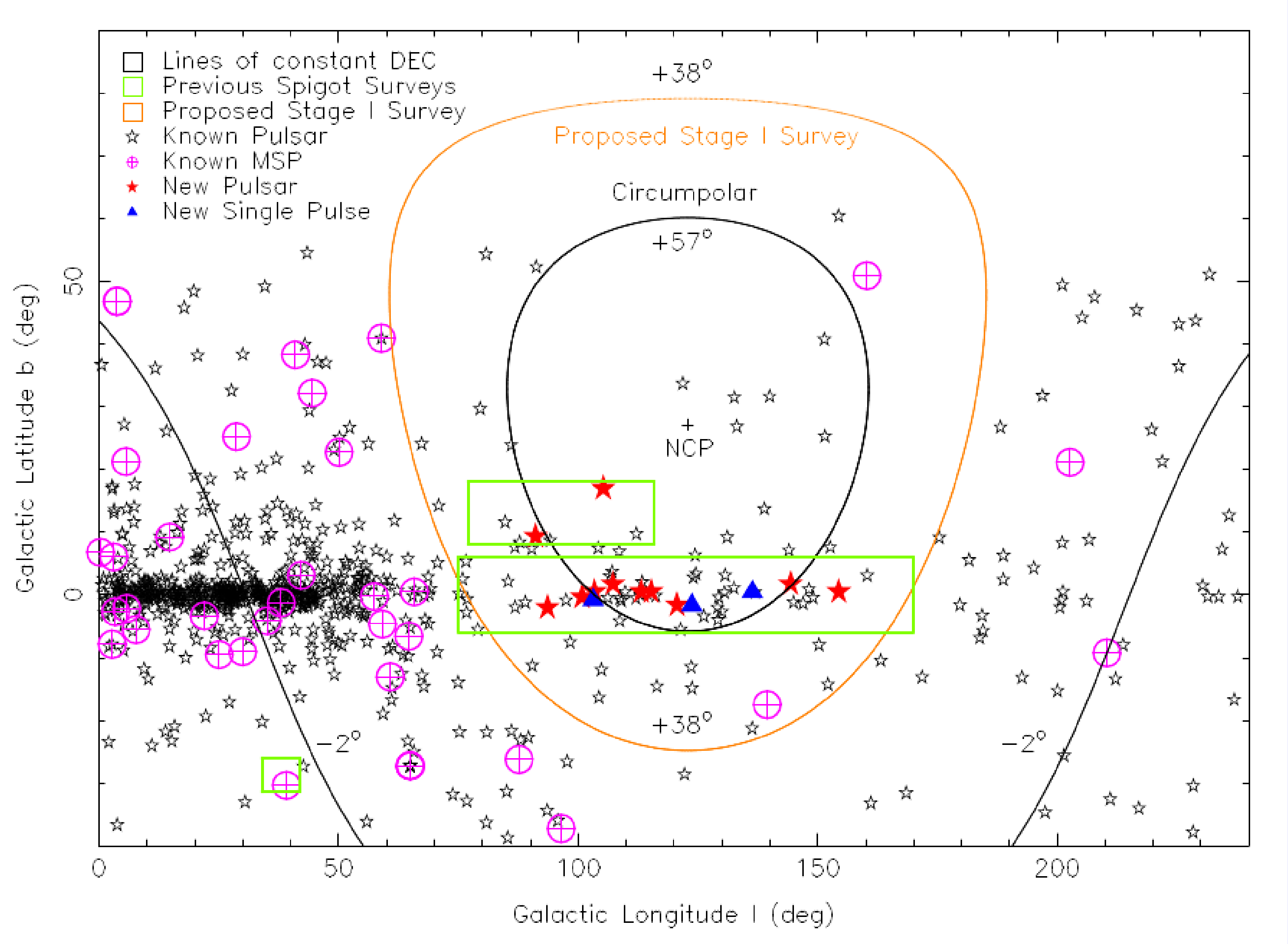
Educational project lets WV high school students sort through pulsar candidates from GBT drift scan data.

Collaboration between WVU (Maura McLaughlin, Dunc Lorimer) and NRAO (Sue Ann Heatherly).

Includes visits to GB, training for teachers and students.

Pulsar discoverer Lucas Bolyard

350 MHz GBNCC Pulsar Survey



Covers all sky north of 38 degrees dec.

~28,000 2-minute pointings.

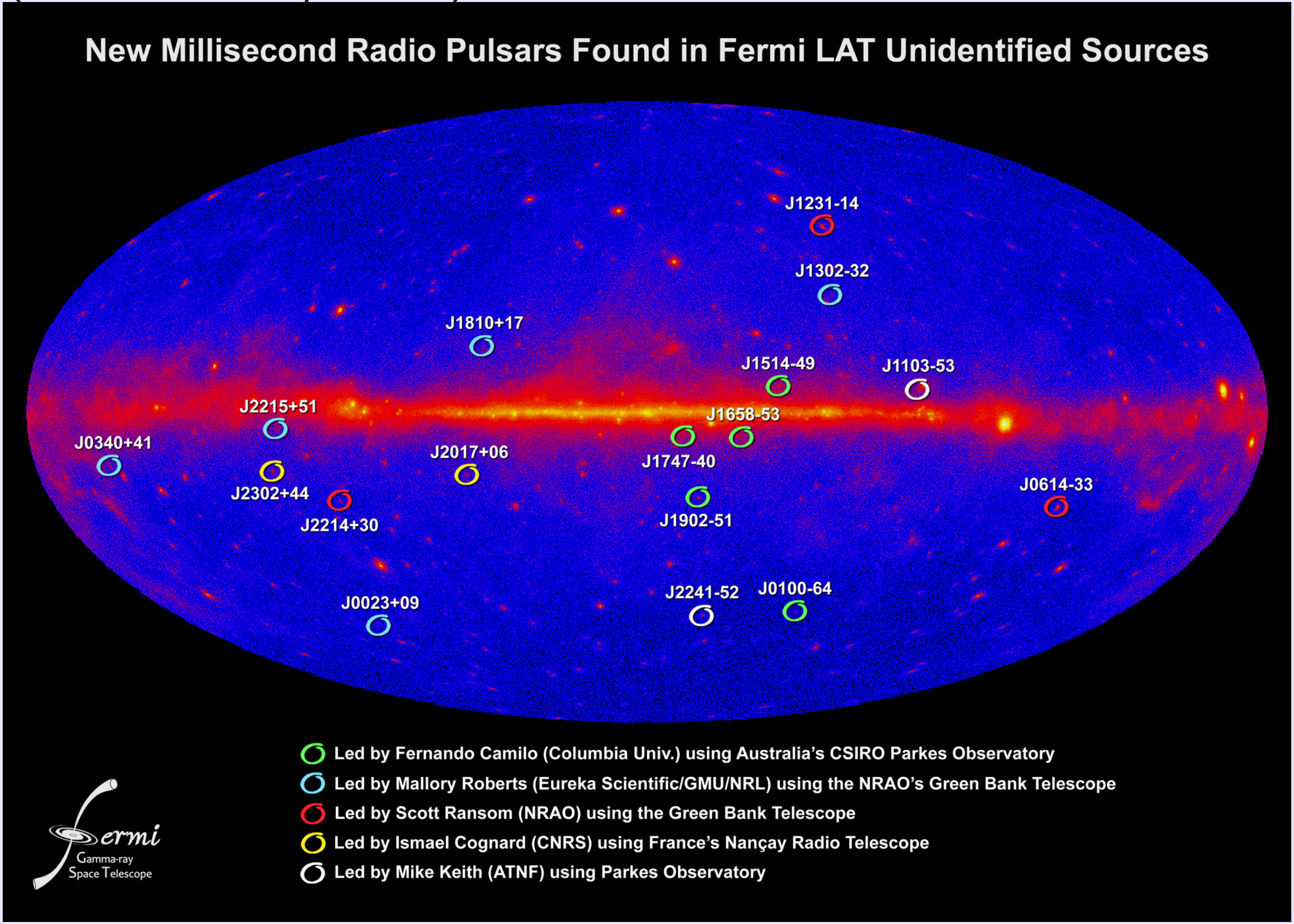
GUPPI backend; 100 MHz BW; 4096 channels, 81.92 us time resolution.

Observing ongoing, nearly 100% complete. Full processing starts this summer

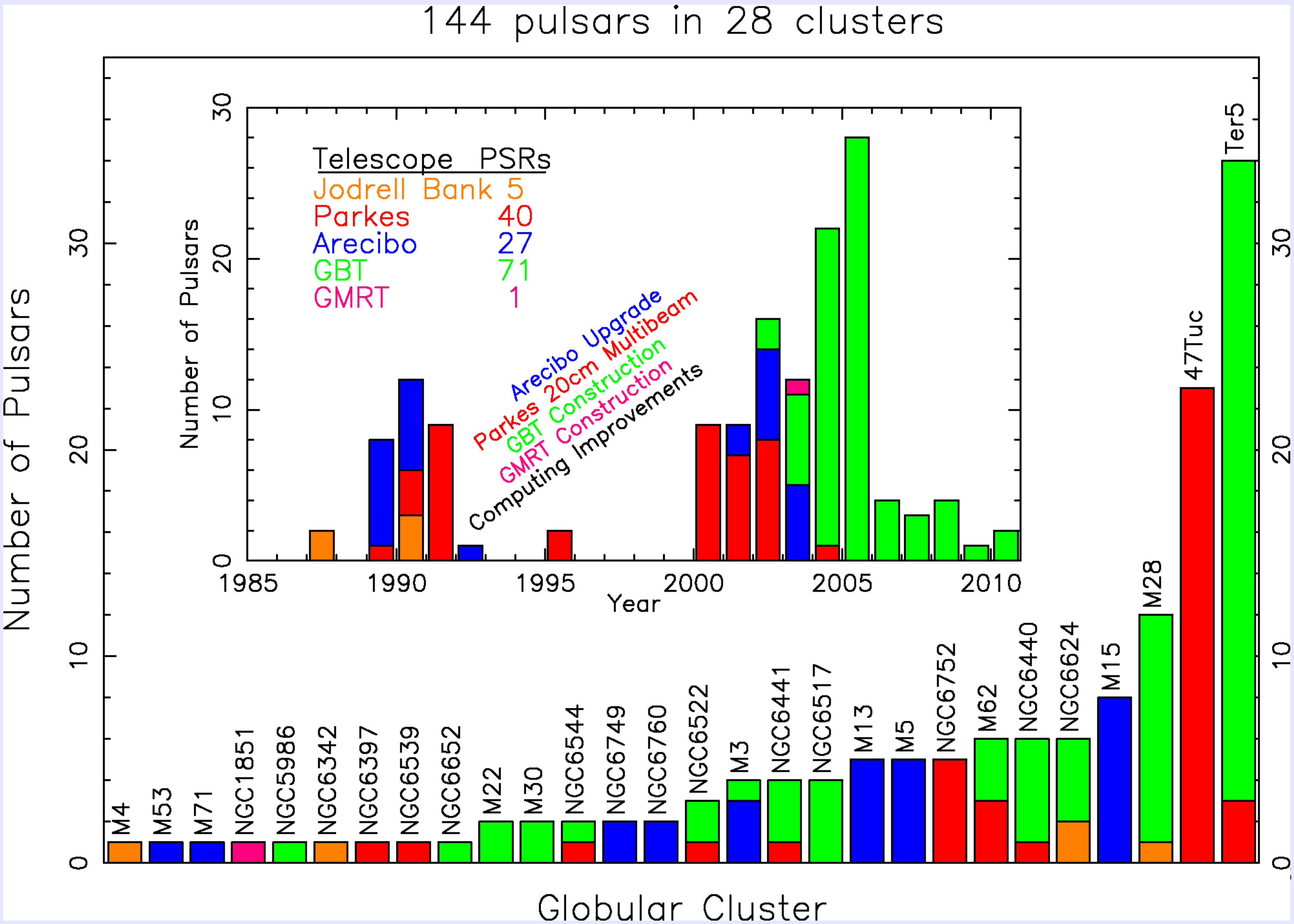
From quick looks so far, 4 new pulsars, including one MSP and one 20-ms PSR.

Fermi targeted searches: 34 new MSPs! (20 from GBT)

(Ransom et al, ApJ, 2011)



Globular cluster pulsar searches



Globular cluster science results:

34 pulsars (and counting) discovered in the Terzan 5 cluster (Ransom et al., *Science*, 2005)

Fastest-spinning MSP known, Ter5ad at 716 Hz (Hessels et al., *Science*, 2006).

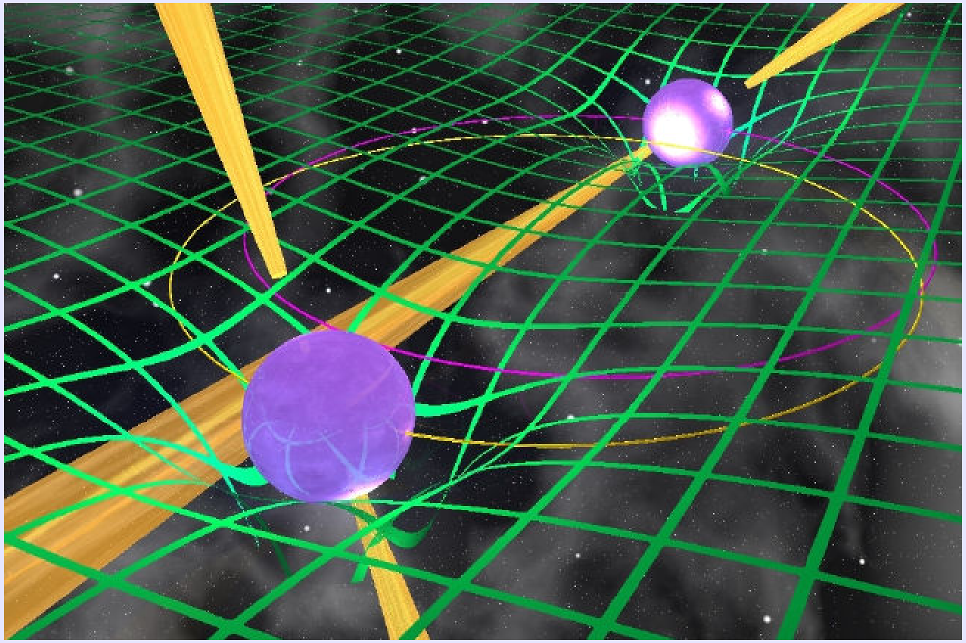
Eccentric binary systems (useful for mass measurements!) in NGC 6440 and NGC 6441 (Freire et al., ApJ, 2008).

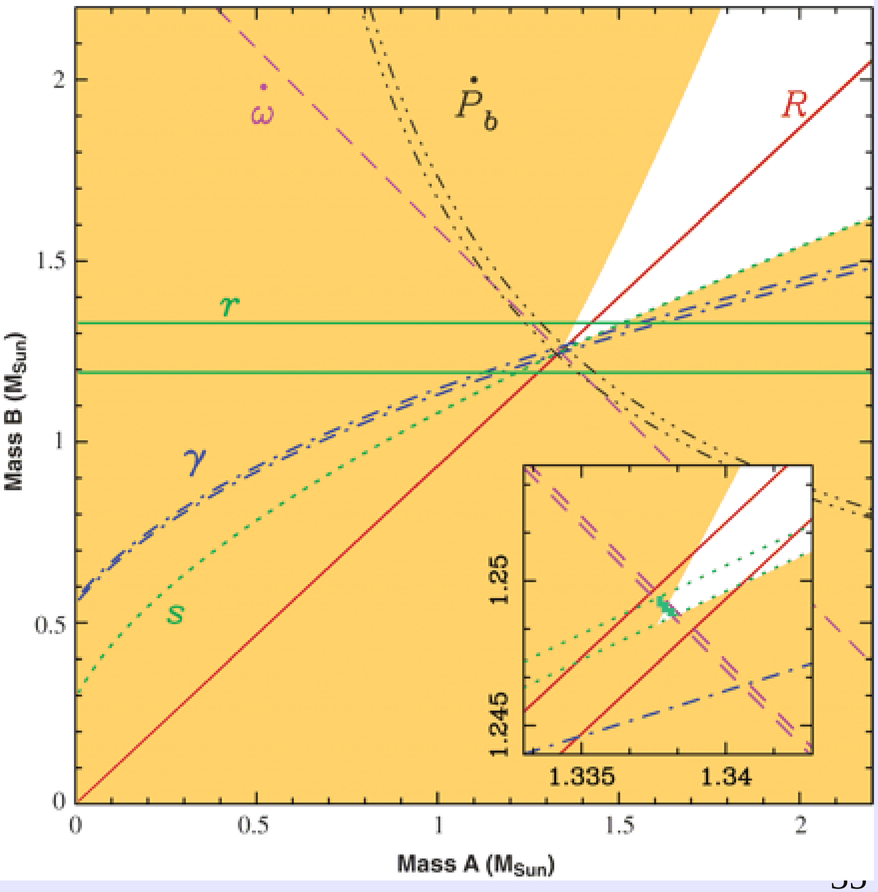
Ongoing searching and timing of many clusters.

The Double Pulsar, J0737-3039

GBT / GASP timing of the double pulsar tests consistency of general relativity at the ~0.05% level (Kramer et al, *Science*, 2006).

Ongoing long-term GBT timing of this unique source.





The Double Pulsar, J0737-3039

GBT "Eclipse timing" of J0737-3039 gives alternate method for GR tests (Breton et al, *Science*, 2008):

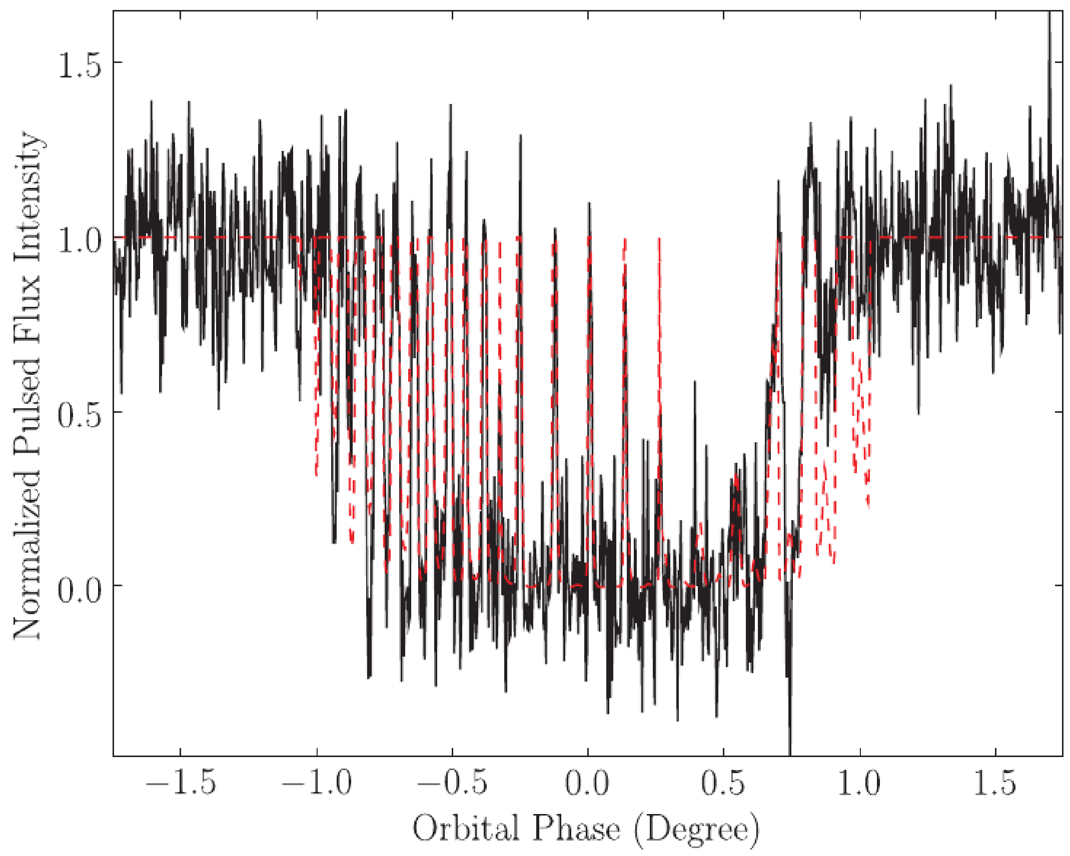


Fig. 3. Average eclipse profile of pulsar A consisting of eight eclipses observed at 820 MHz over a 5-day period around 11 April 2007 (black line) along with a model eclipse profile (red dashed line). The relative pulsed flux density of pulsar A is normalized so that the average level outside the eclipse region is unity. The resolution of each data point is ~91 ms, whereas 1° in orbital phase corresponds to 24.5 s. Near orbital phase 0.0, the spikes are separated by the spin period of pulsar B.

North American Nanohertz Observatory for Gravitational Waves

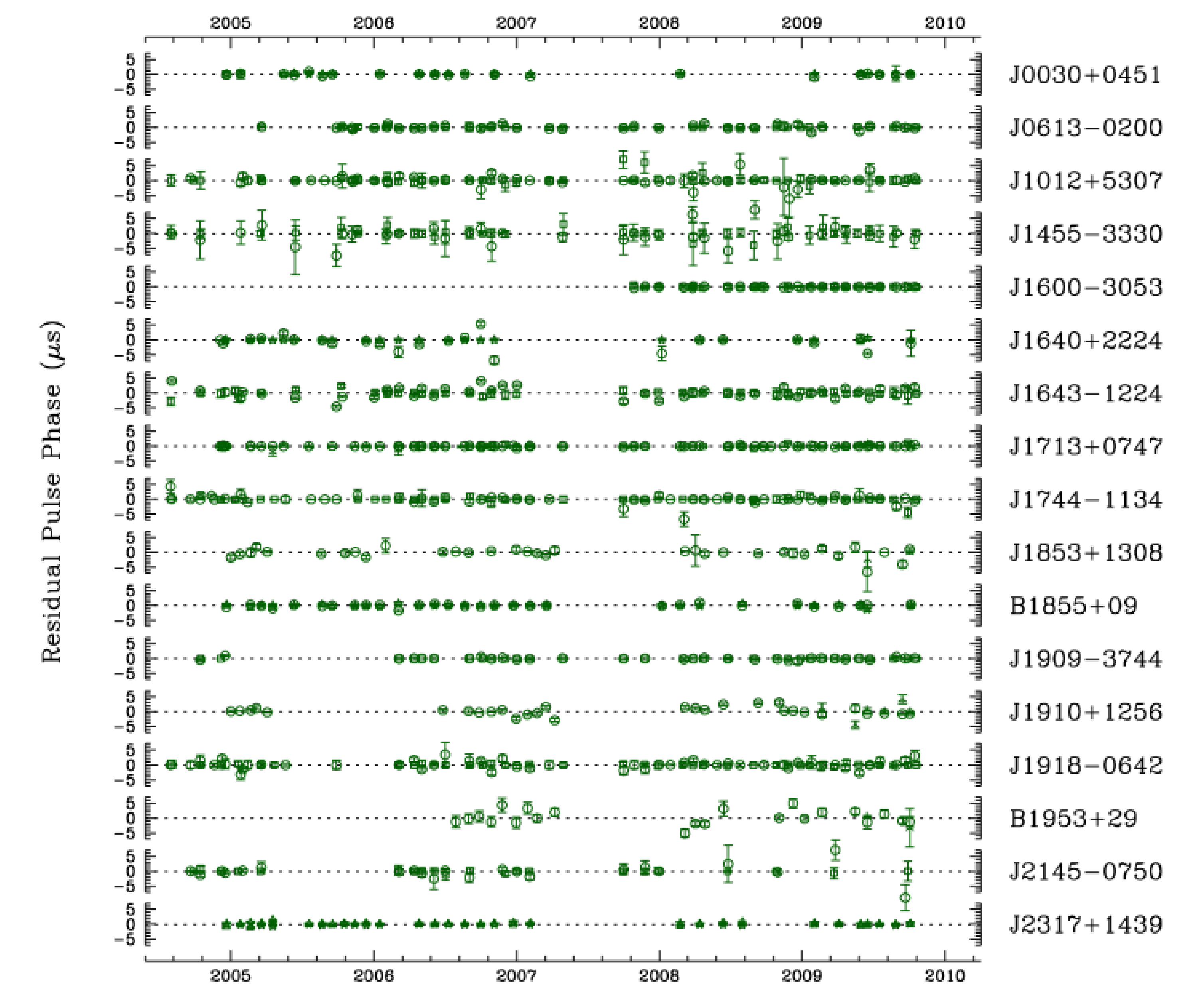
NANOGrav

Pulsar timing array project for detection of nHz-frequency gravitational waves.

Monthly observations of 27 pulsars using GBT and Arecibo.

Collaboration between many US and Canadian astronomers, observations started 2005.

Current NANOGrav status:



5-year timing analysis (Demorest et al, in prep).

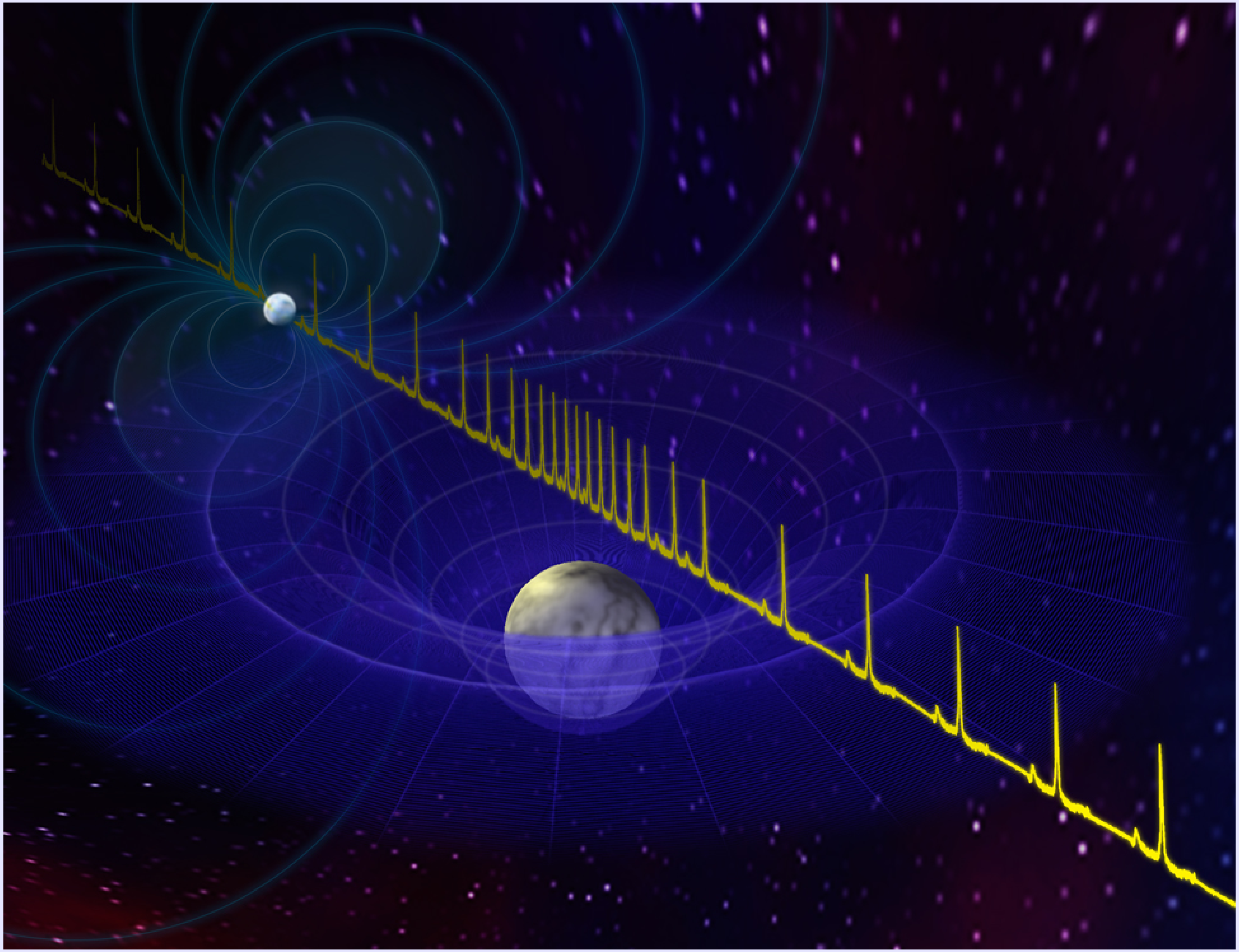
Two pulsars (1714+0747, 1909-3744) with ~40 ns timing.

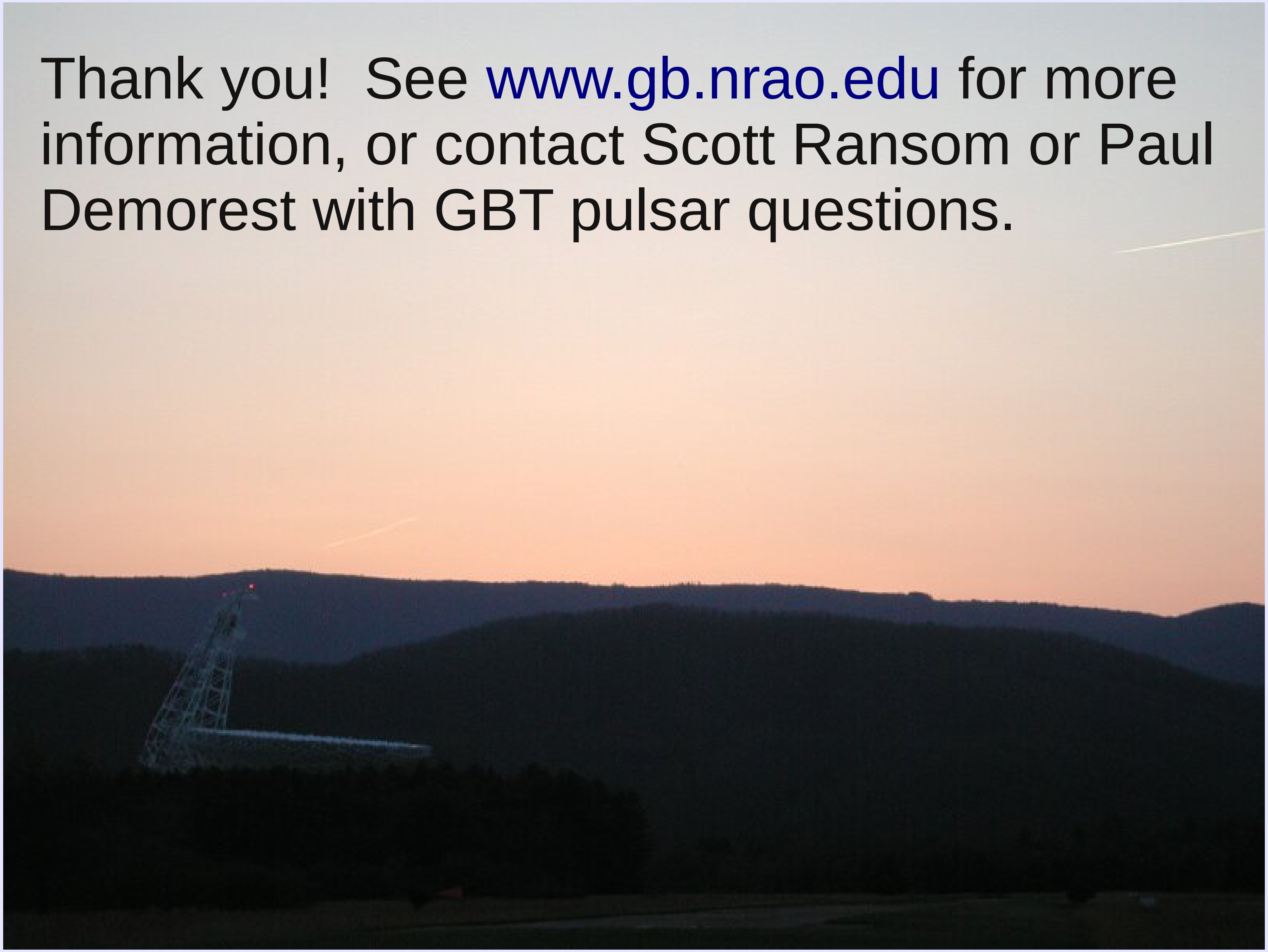
Many others with few x 100 ns.

Mass of PSR J1614-2230 from Shapiro delay

(Demorest et al, *Nature*, 2010)

GUPPI timing reveals 1.97 +/- 0.04 solar mass neutron star! See my talk tomorrow for more details.





Thank you! See www.gb.nrao.edu for more information, or contact Scott Ransom or Paul Demorest with GBT pulsar questions.