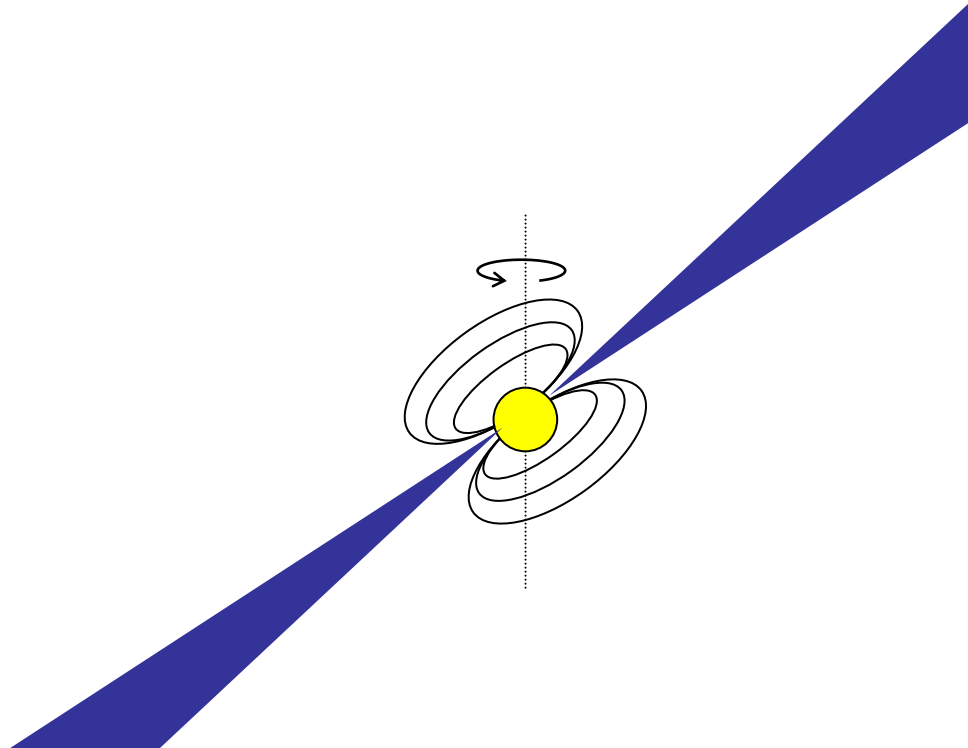
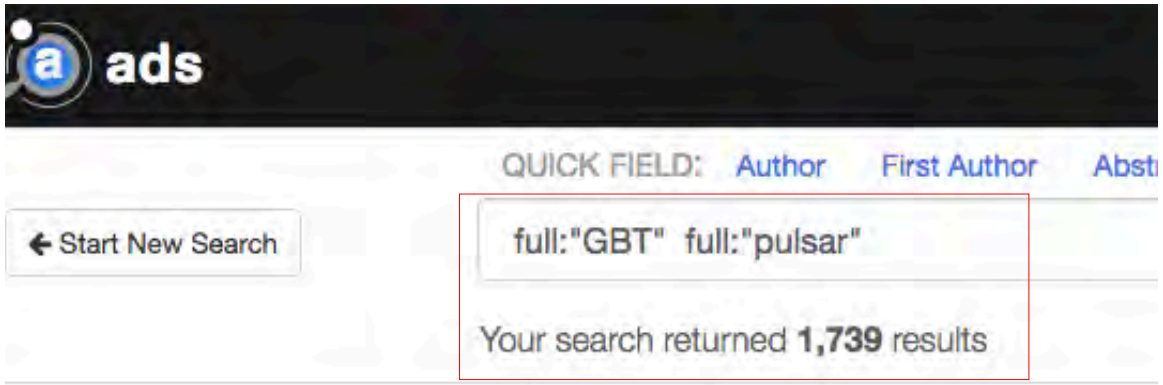
Twenty Years of Pulsars at the GBT

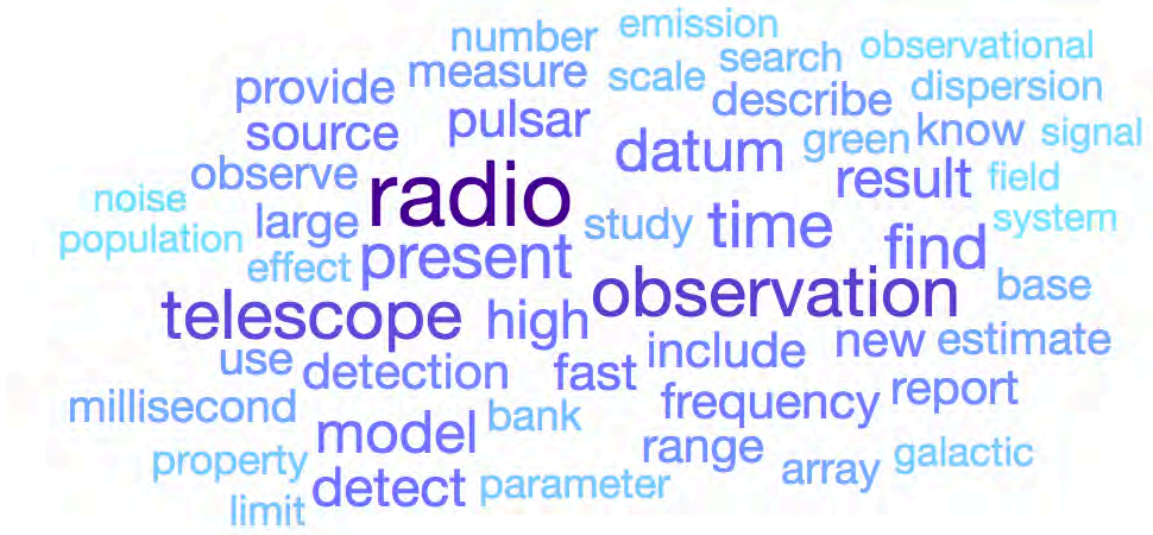
David Nice
Lafayette College

Green Bank Observatory
Virtual Meeting
21 April 2021

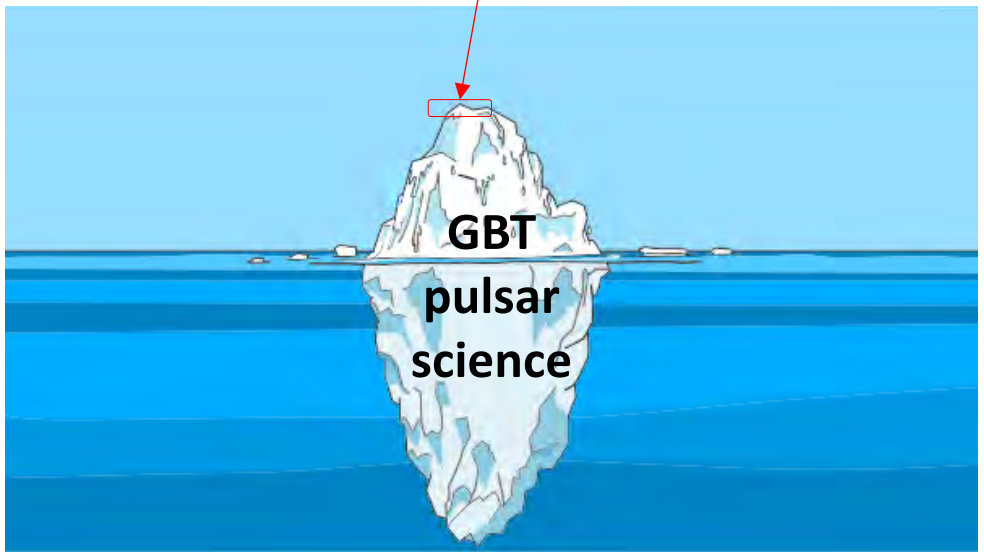
TWENTY YEARS OF
INNOVATION AND DISCOVERY
A Celebration for the Robert C. Byrd Green Bank Telescope

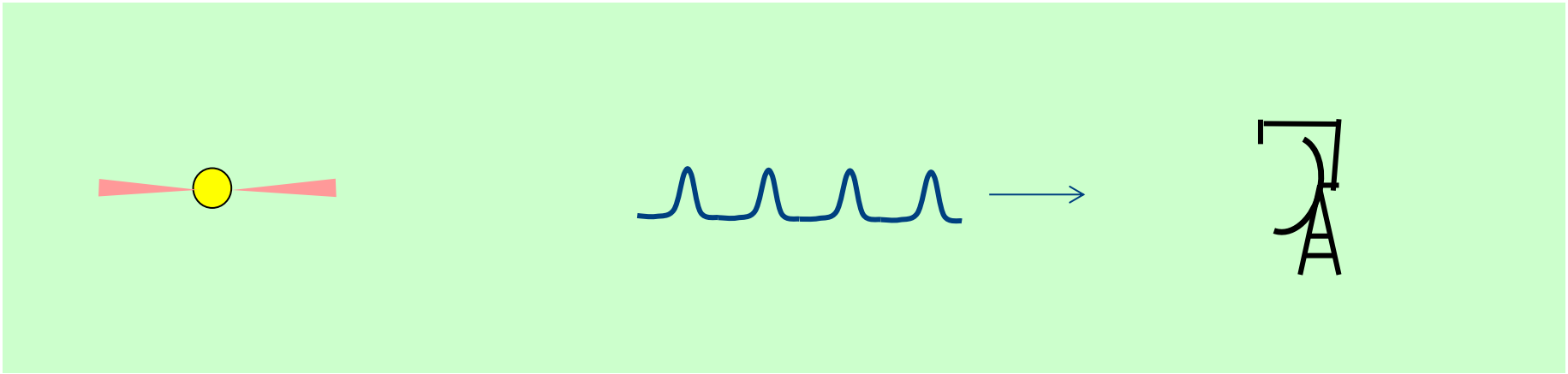


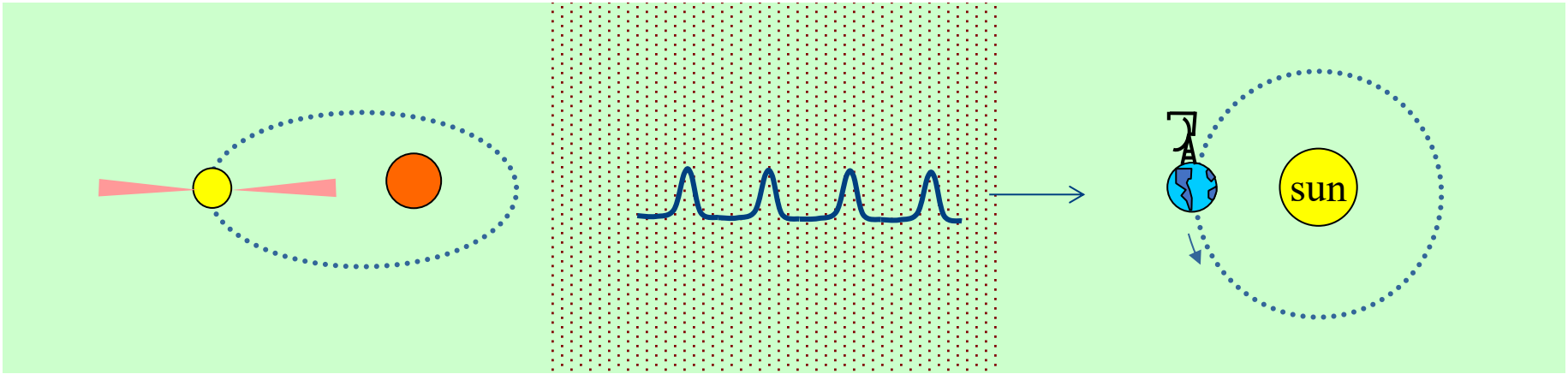




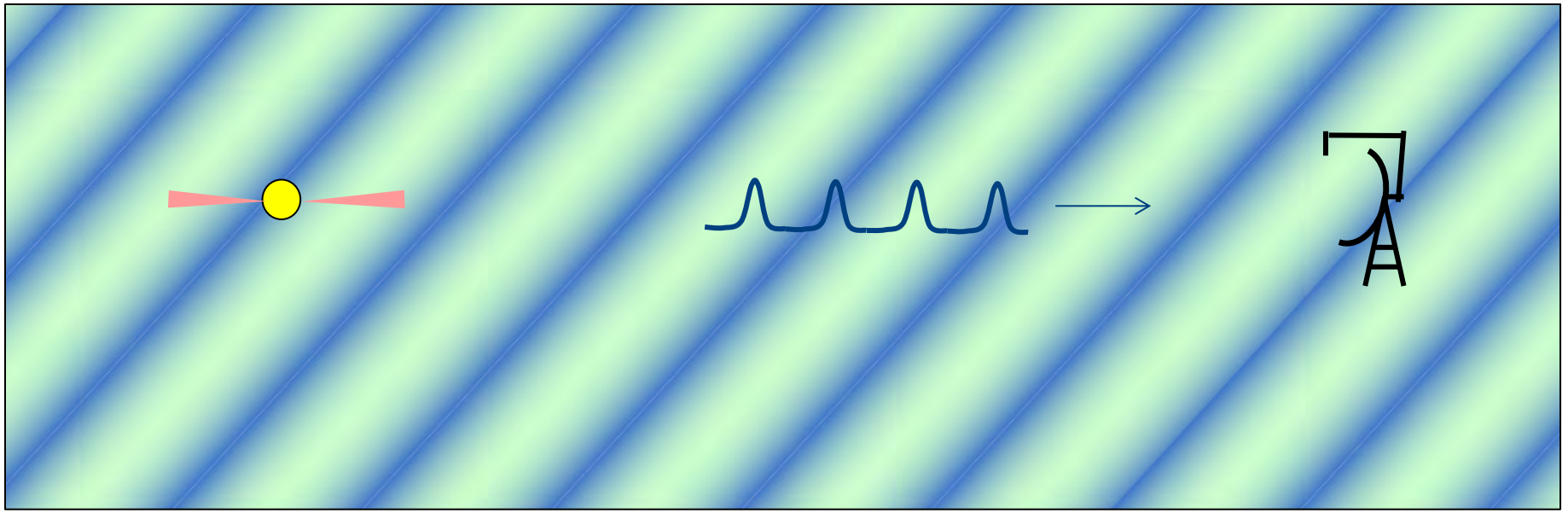
This talk: the tip of the iceberg







rotation period rotation period derivative Keplerian orbital elements relativistic orbital elements kinematic perturbations of orbital elements (secular and annual phenomena)	dispersion measure dispersion meas. variations	position proper motion parallax solar electron density



THE GREEN BANK TELESCOPE

A Radio Telescope for the Twenty–First Century
Final Proposal June 1989

The National Radio Astronomy Observatory is operated by Associated Universities Inc., under cooperative agreement with the National Science Foundation.

There are now eight known pulsars with millisecond periods and eleven binary pulsars whose evolutionary histories are different from those of the ordinary pulsars discussed above. We estimate that a few percent of the new pulsars that will be discovered with the Green Bank Telescope will be in these remarkable categories. Each new binary and millisecond pulsar should lead to fresh insights about the evolutionary paths of massive stars. The first binaries clearly showed that not every binary is disrupted by the supernova explosion. There is evidence for spinup of the neutron star following its formation and subsequent spindown—this is the best explanation for the 1.5 millisecond pulsar detected by Backer *et al.* (1982). The 1987 detection of a millisecond pulsar that is ablating its $0.02 M_{\odot}$ companion illustrates again the unique nature of each pulsar in these categories.

Globular clusters produce low-mass binary stars in copious abundance. Theories for the evolution of these binaries led directly to the detection of millisecond pulsars in globular clusters. Globular clusters are concentrated around the galactic center, a region beyond the reach of the 300-foot telescope and Arecibo. Consequently, the most sensitive possible searches for globular cluster pulsars await the Green Bank Telescope. New objects will certainly be found,

2.1.2. Fundamental Physics. Millisecond and binary pulsars are the most stable clocks known. Precise measurements of their pulse arrival times have already provided data for a number of tests of general relativity and for observational limits on current theories of the early Universe and particle physics. These investigations will continue, both with more sensitive measurements of known objects and with unexpected developments involving newly discovered pulsars.

THE GREEN BANK TELESCOPE

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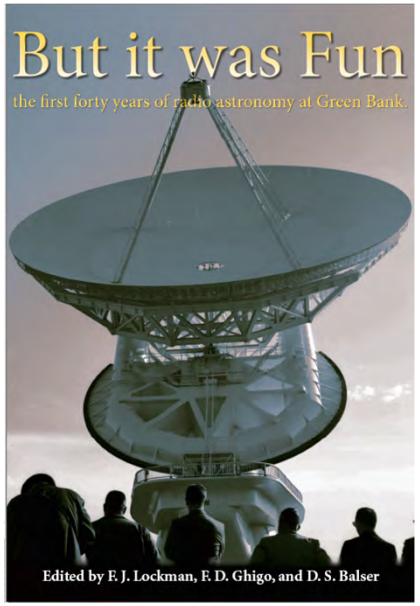
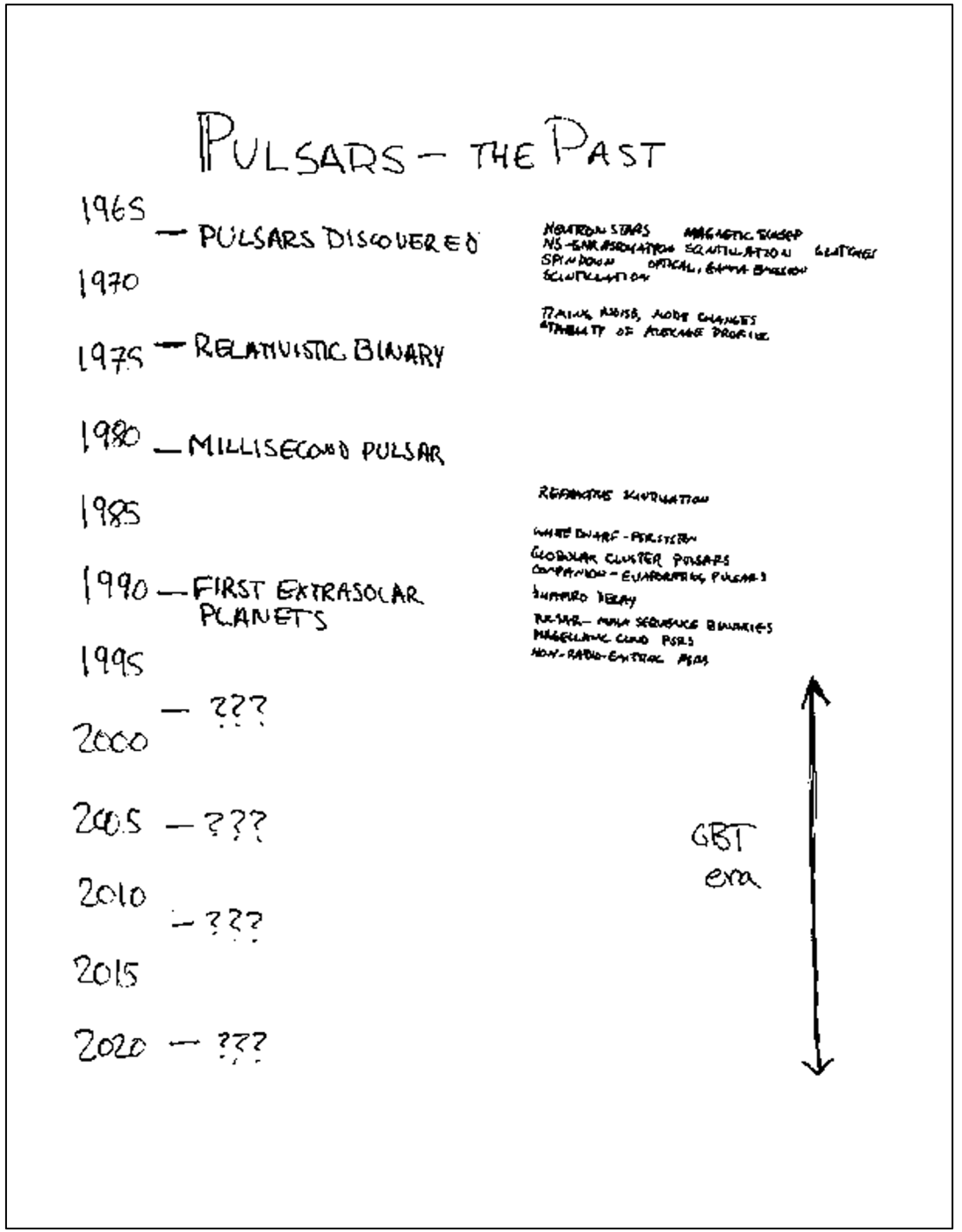
None of the eight known millisecond pulsars has exhibited a timing irregularity, even when compared against the best atomic clocks. This fact sets an already stringent limit on the presence of gravitational radiation left over from the earliest stages of cosmic expansion: broad classes of models predict the existence of long wavelength (light-years) gravitational radiation that would cause irregularities revealed by high-precision pulsar timing. The upper limit on energy density scales very favorably with timing accuracy δt and duration T of the timing effort, as $(\delta t)^2/T^4$. The existing limit ($< 4 \times 10^{-7}$ of the energy density needed to close the Universe) already comes close to excluding cosmic-string models for galaxy formation (see Fig. II-1).

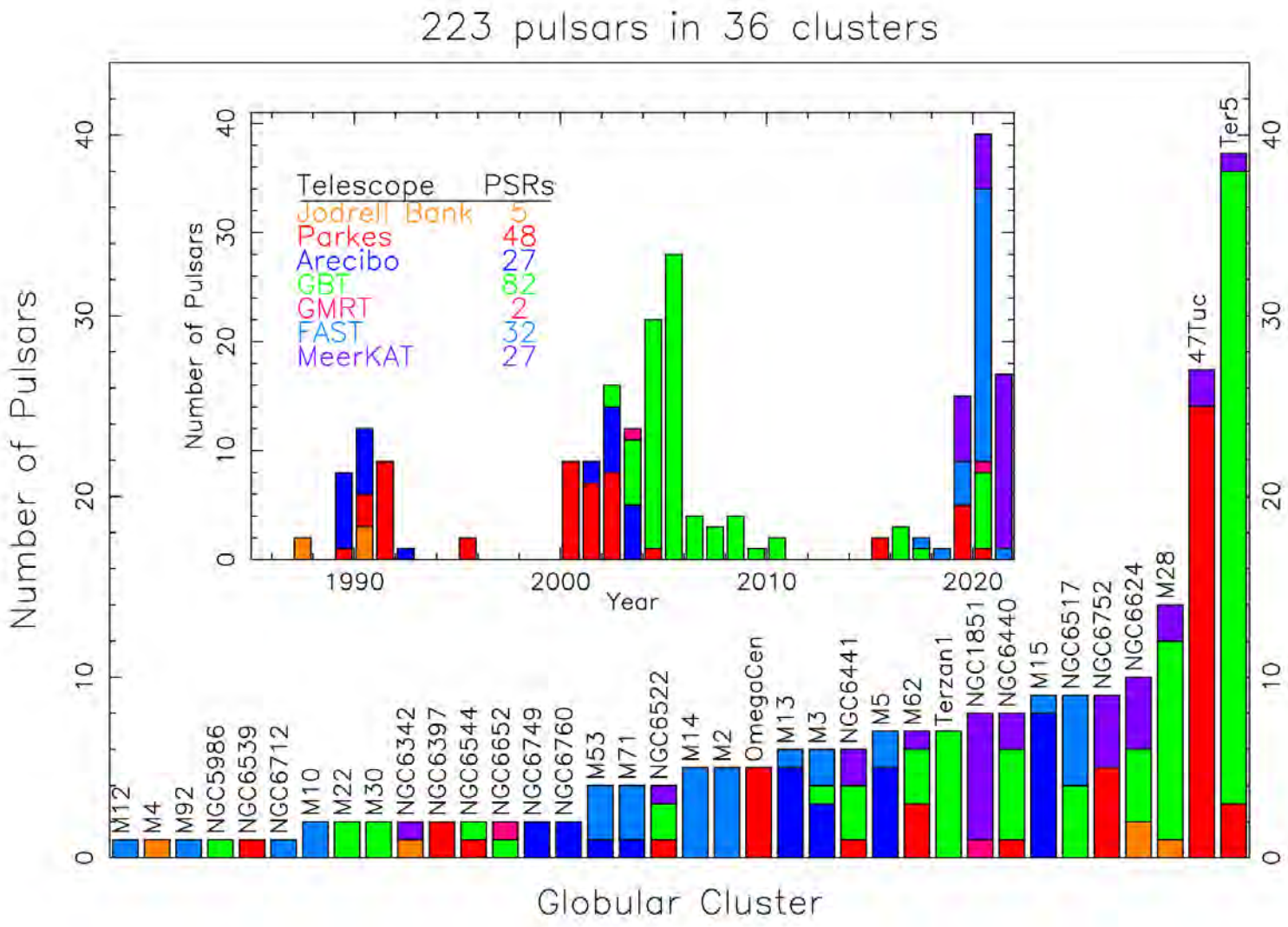
2.1.5. Support for Space Missions. One of the major pulsar projects planned for the 300-foot telescope at the time of its collapse was a timing program in support of the orbiting Gamma Ray Observatory (GRO), planned for launch in 1990. GRO will be searching for pulsed γ-rays from about three-hundred radio pulsars. In order to fold the γ-ray photons at the correct pulsar period and phase, contemporaneous radio timing observations are essential. The 300-foot telescope was to be the primary instrument for timing about one-hundred of these pulsars. The Green Bank Telescope could do this type of job faster and for more pulsars, because of its increased sky coverage, sensitivity, and tracking ability.

Trend noted and prediction made (by me) at the Fortieth Anniversary celebration for the 140 Foot Telescope in 1995 :

One major pulsar discovery every ~7 years.

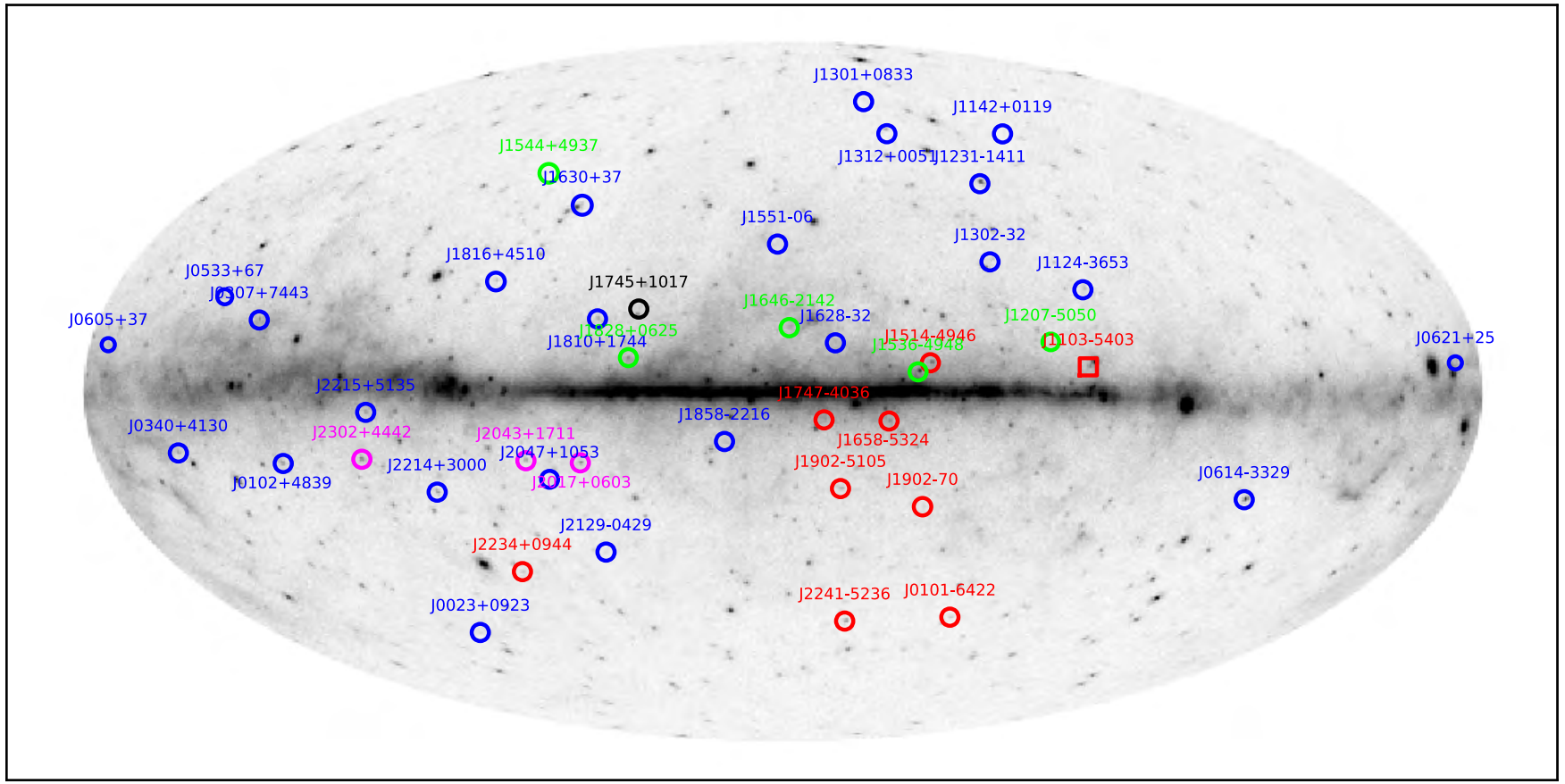






Deep searches of globular clusters

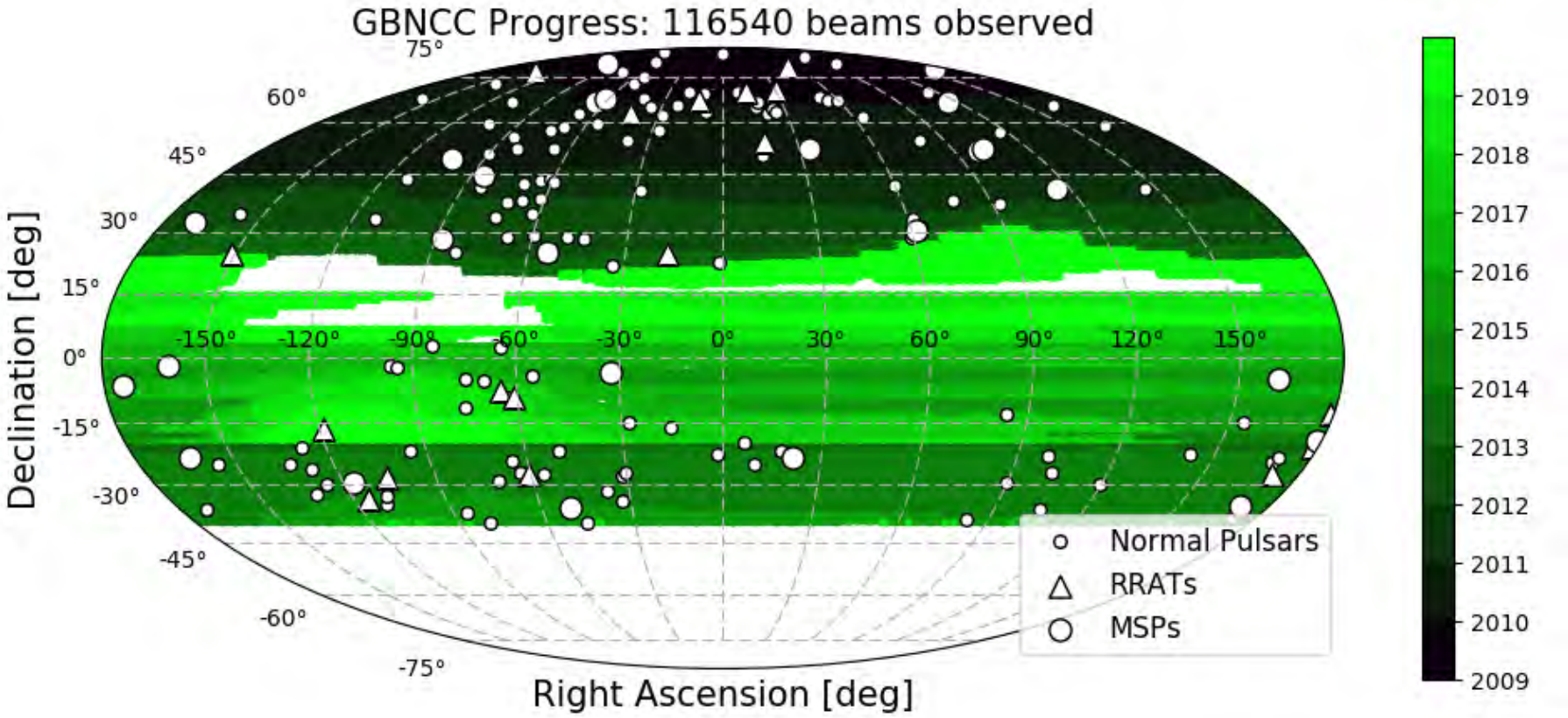
Figure courtesy of Scott Ransom



Millisecond puslars coincident with *Fermi* gamma ray source locations

This figure shows 43 newly discovered millisecond pulsars discovered at Fermi source locations as of 2012. The 24 marked in blue were discovered at the GBT.

Reference: Ray et al (2012), 2011 Fermi Symposium, arXiv:1205.3009



Green Bank Northern Celestial Cap Survey

193 pulsars discovered so far, including 33 millisecond pulsars

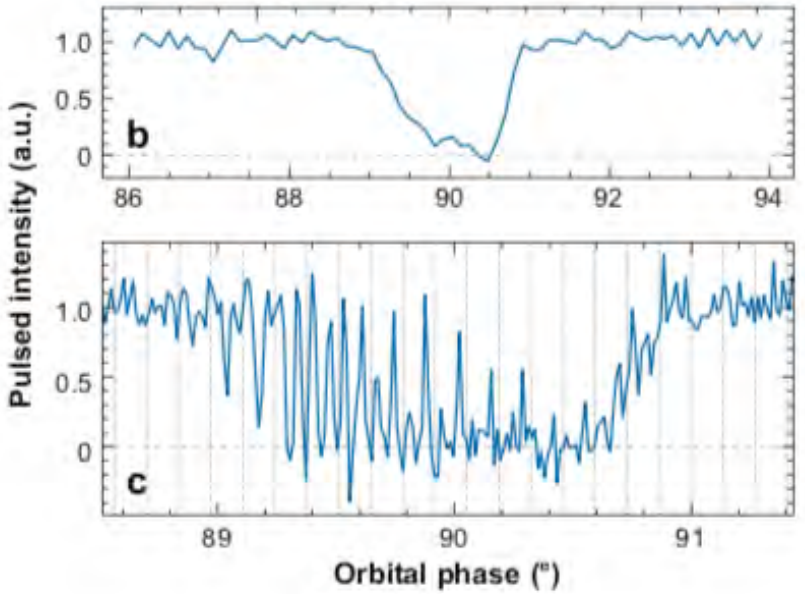
Figure source: http://astro.phys.wvu.edu/GBNCC/

THE DOUBLE PULSAR SYSTEM J0737−3039: MODULATION OF A BY B AT ECLIPSE

M. A. McLaughlin,[1] A. G. Lyne,[1] D. R. Lorimer,[1] A. Possenti,[2] R. N. Manchester,[3] F. Camilo,[4] I. H. Stairs,[5] M. Kramer,[1] M. Burgay,[2] N. D'Amico,[6] P. C. C. Freire,[7] B. C. Joshi,[8] and N. D. R. Bhat[9]

Received 2004 August 16; accepted 2004 October 18; published 2004 October 27

The Astrophysical Journal, 616:L131–L134, 2004 December 1



The Double Pulsar

M. Kramer[1] and I.H. Stairs[2]

Annu. Rev. Astron. Astrophys. 2008. 46:541–72

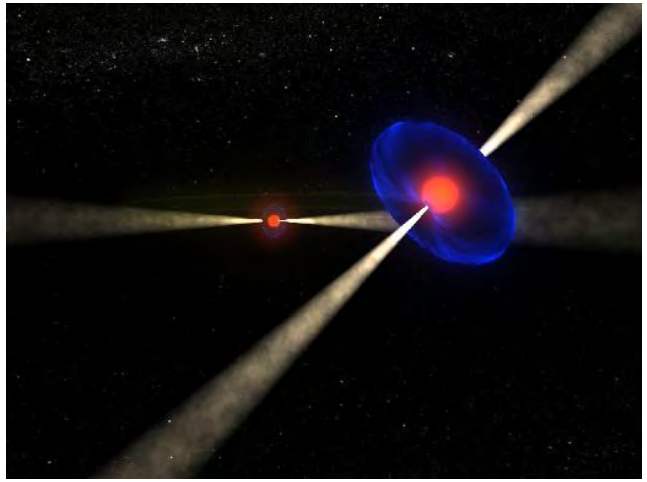


Image credit: Danien Canten/Darwin \Dimensions/McGill University

Pulsar A is eclipsed by pulsar B
The eclipses are modulated by pulsar B rotation

PSRs J0737−3039A and J0737−3039B
Discovered at Parkes
Timing and eclipse studies at GBT

A Radio Pulsar/X-ray Binary Link

Anne M. Archibald,[1*] Ingrid H. Stairs,[2,3,4] Scott M. Ransom,[5] Victoria M. Kaspi,[1] Vladislav I. Kondratiev,[6,5,7] Duncan R. Lorimer,[6,8] Maura A. McLaughlin,[6,8] Jason Boyles,[6,8] Jason W. T. Hessels,[9,10] Ryan Lynch,[11] Joeri van Leeuwen,[9,10] Mallory S. E. Roberts,[12] Frederick Jenet,[13] David J. Champion,[3] Rachel Rosen,[8] Brad N. Barlow,[14] Bart H. Dunlap,[14] Ronald A. Remillard[15]

Radio pulsars with millisecond spin periods are thought to have been spun up by the transfer of matter and angular momentum from a low-mass companion star during an x-ray–emitting phase. The spin periods of the neutron stars in several such low-mass x-ray binary (LMXB) systems have been shown to be in the millisecond regime, but no radio pulsations have been detected. Here we report on detection and follow-up observations of a nearby radio millisecond pulsar (MSP) in a circular binary orbit with an optically identified companion star. Optical observations indicate that an accretion disk was present in this system within the past decade. Our optical data show no evidence that one exists today, suggesting that the radio MSP has turned on after a recent LMXB phase.

SCIENCE VOL 324 12 JUNE 2009

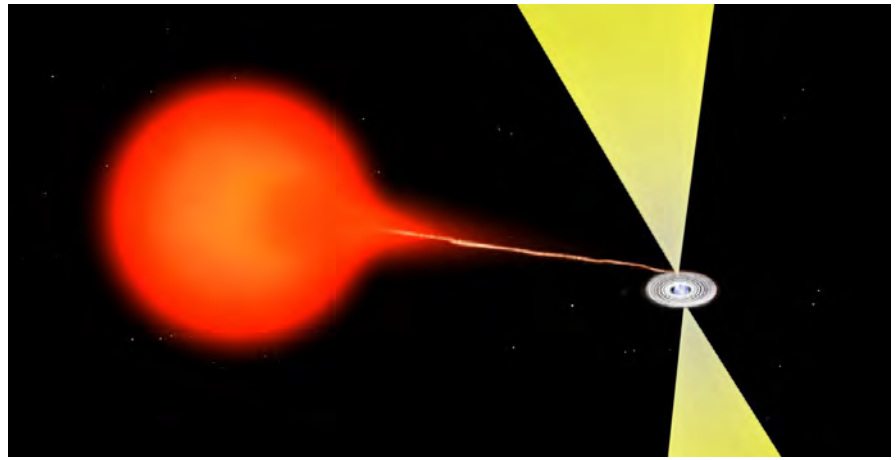


Image credit: Bill Saxton; NRAO/AUI/NSF

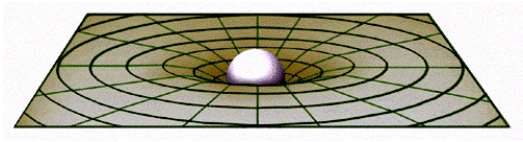
Alternates between accretion and non-accretion states

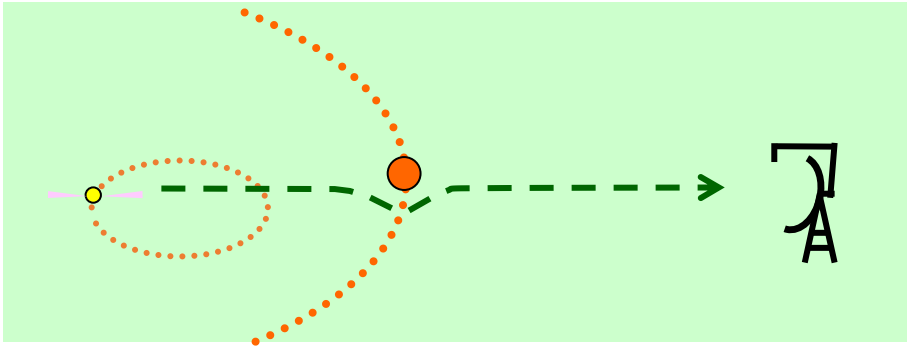
PSR J1024+0038
Discovered at GBT
Timed at GBT+Arecibo+Westerbork+Jodrell Bank+XMM-Newton

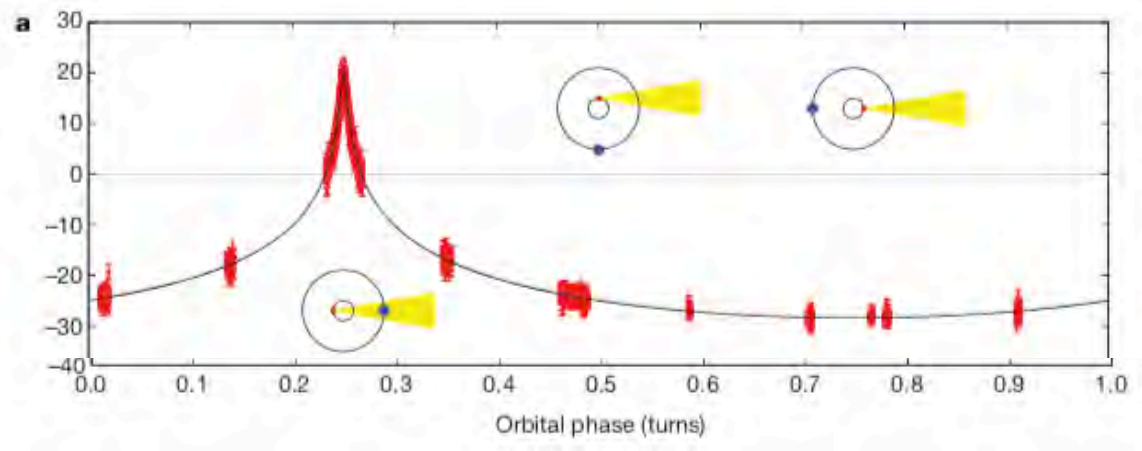
A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

28 OCTOBER 2010 | VOL 467 | NATURE | 1081







Neutron star mass: 1.97 ±0.04 $M_\odot$ (Discovery paper), 1.928 ± 0.017 (Fonseca et al 2016)

PSR J1640-2230
Discovered at Parkes
Timed at GBT

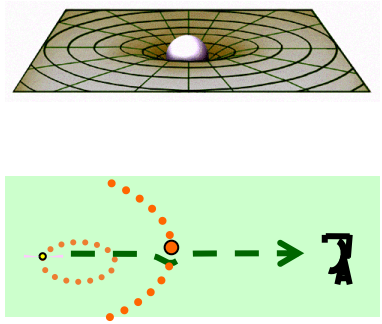
Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar

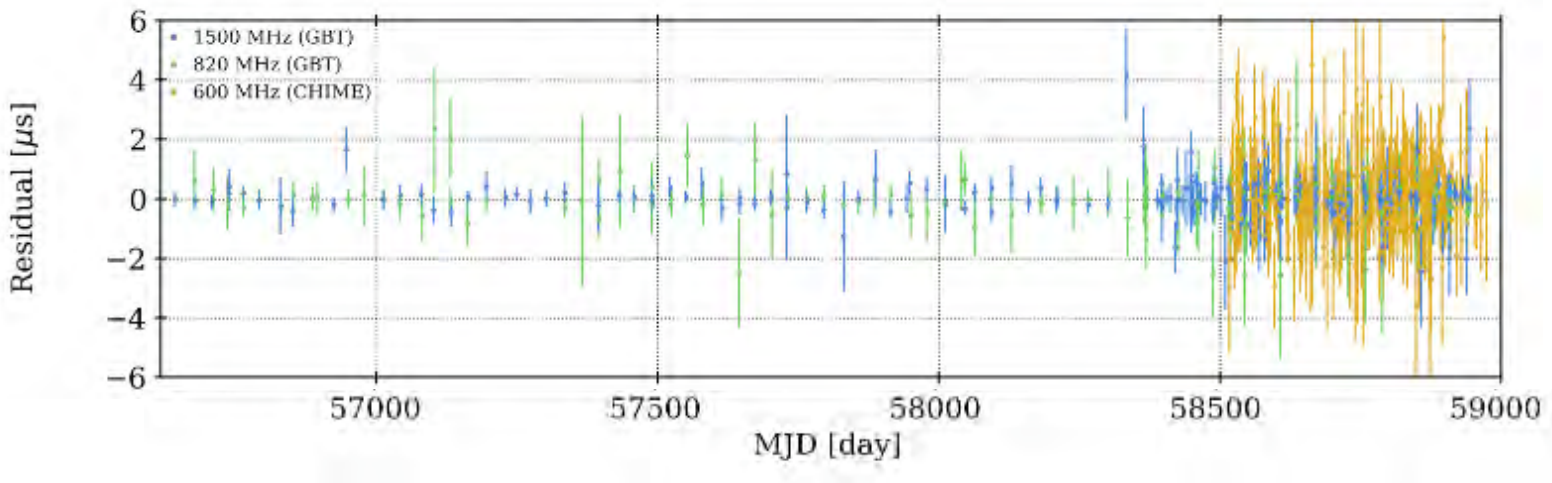
H. T. Cromartie, E. Fonseca, S. M. Ransom, P. B. Demorest, Z. Arzoumanian, H. Blumer, P. R. Brook, M. E. DeCesar, T. Dolch, J. A. Ellis, R. D. Ferdman, E. C. Ferrara, N. Garver-Daniels, P. A. Gentile, M. L. Jones, M. T. Lam, D. R. Lorimer, R. S. Lynch, M. A. McLaughlin, C. Ng, D. J. Nice, T. T. Pennucci, R. Spiewak, I. H. Stairs, K. Stovall, J. K. Swiggum and W. W. Zhu

NATURE ASTRONOMY | VOL 4 | JANUARY 2020 | 72-76

Updated in Fonseca et al (2021)
Submitted to ApJL, April 2021
arXiv:2104.00880

(residual figure is from this paper)





Neutron star mass: 2.14 ±0.10 $M_\odot$ (Cromartie et al 2020), 2.08 ± 0.07 (Fonseca et al 2021)

PSR 0740+6620
Discovered at GBT
Timed at GBT+CHIME

A millisecond pulsar in a stellar triple system

S. M. Ransom[1], I. H. Stairs[2], A. M. Archibald[3,4], J. W. T. Hessels[3,5], D. L. Kaplan[6,7], M. H. van Kerkwijk[8], J. Boyles[9,10], A. T. Deller[3], S. Chatterjee[11], A. Schechtman-Rook[7], A. Berndsen[2], R. S. Lynch[4], D. R. Lorimer[9], C. Karako-Argaman[4], V. M. Kaspi[4], V. I. Kondratiev[3,12], M. A. McLaughlin[9], J. van Leeuwen[3,5], R. Rosen[1,9], M. S. E. Roberts[13,14] & K. Stovall[15,16]

520 | NATURE | VOL 505 | 23 JANUARY 2014

Universality of free fall from the orbital motion of a pulsar in a stellar triple system

Anne M. Archibald[1,2]*, Nina V. Gusinskaia[1], Jason W. T. Hessels[1,2], Adam T. Deller[3,4], David L. Kaplan[5], Duncan R. Lorimer[6,7], Ryan S. Lynch[7,8], Scott M. Ransom[9] & Ingrid H. Stairs[10]

5 JULY 2018 | VOL 559 | NATURE | 73

Neutron star + white dwarf (1.6 day orbit) + white dwarf (328 day orbit)

Gravitational acceleration of neutron star and white dwarf are the same within 1 part in 2.6×10^{-6}

PSR J0337+1715
Discovered at GBT
Timed at GBT+Arecibo+Westerbork

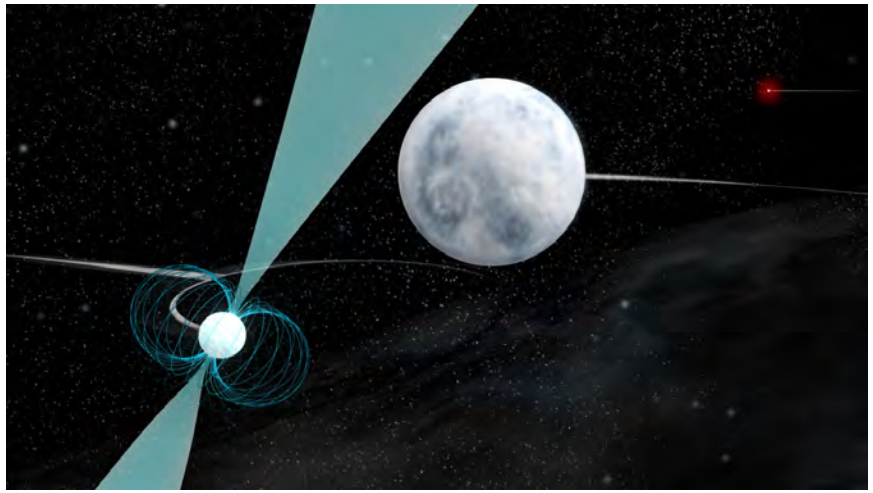
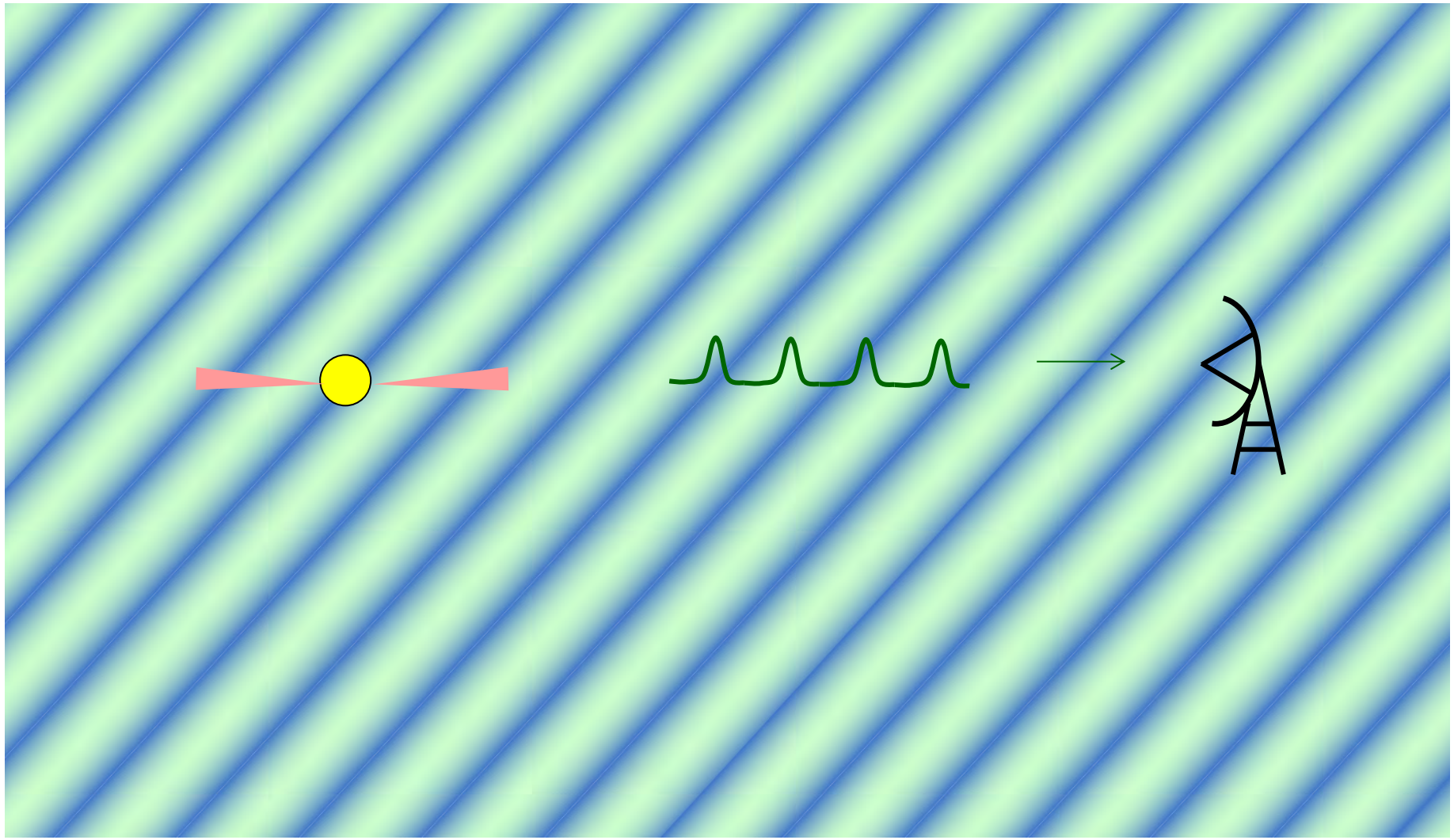
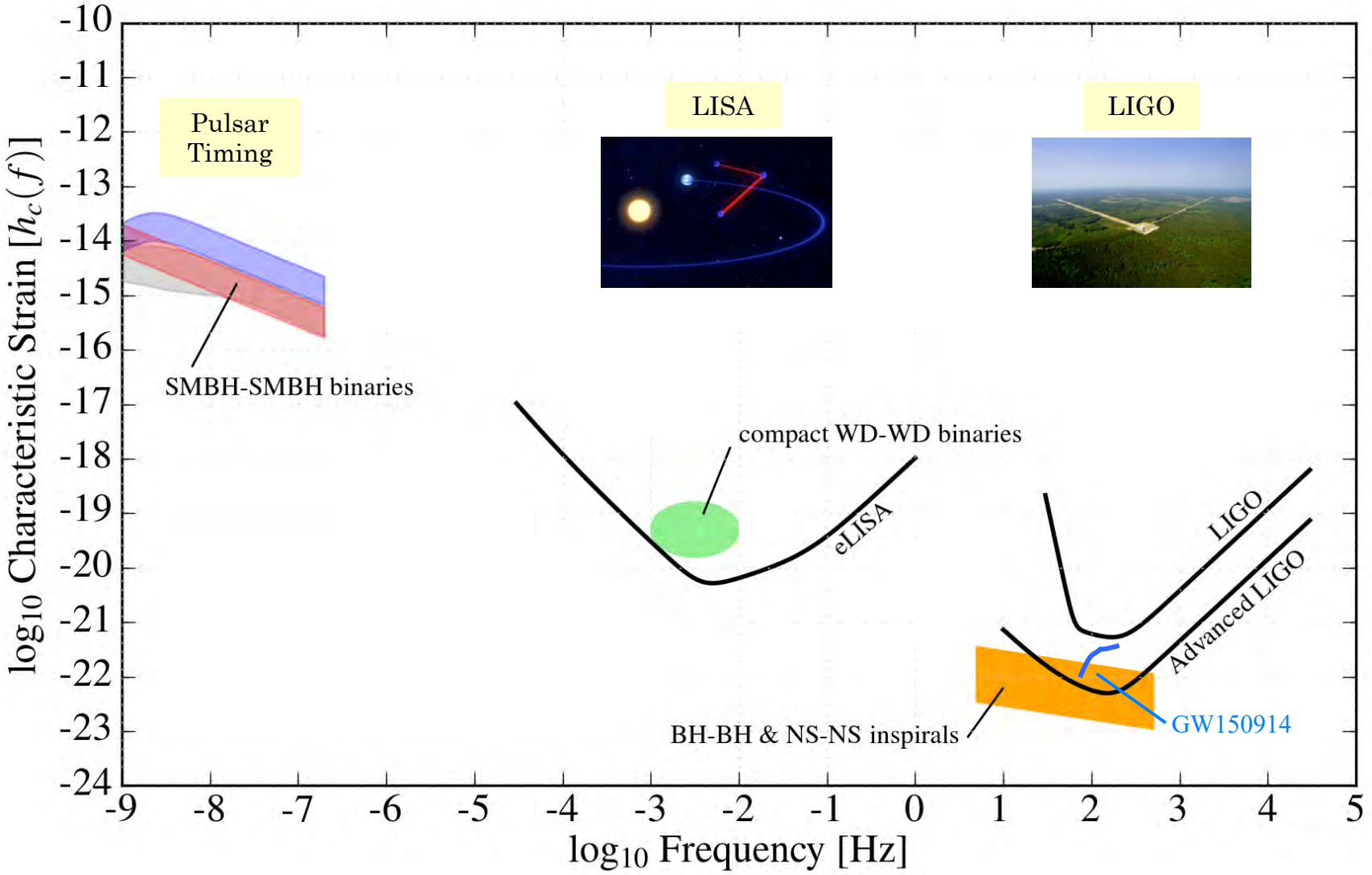


Image credit: Bill Saxton; NRAO/AUI/NSF

Searching for Gravitational Waves



Gravitational Wave Spectrum

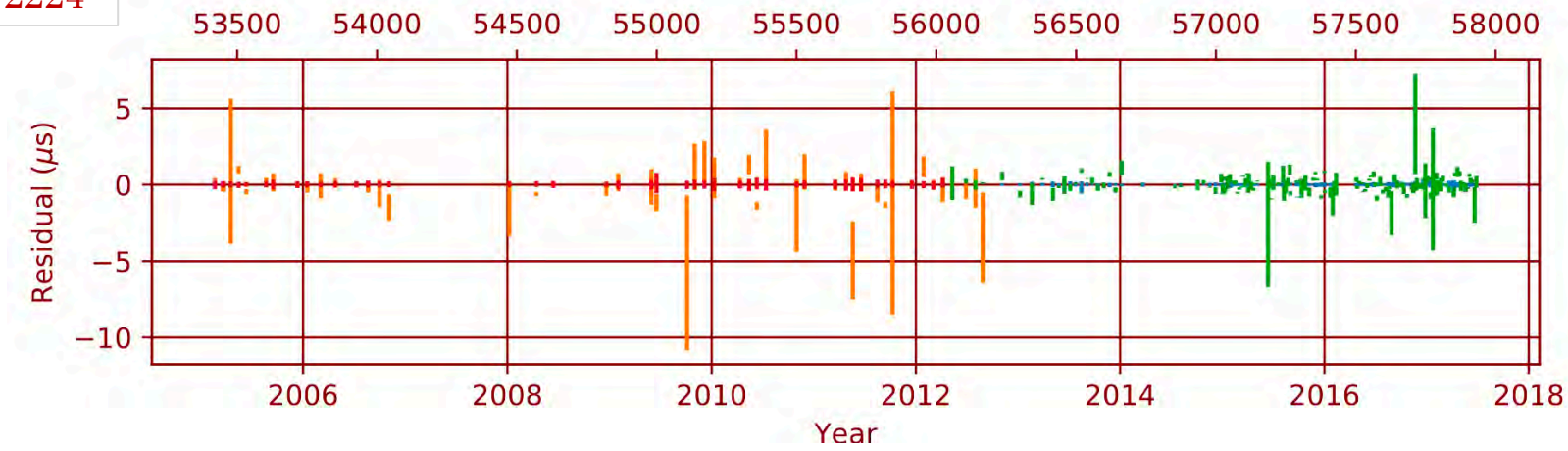


Show Me The Residuals

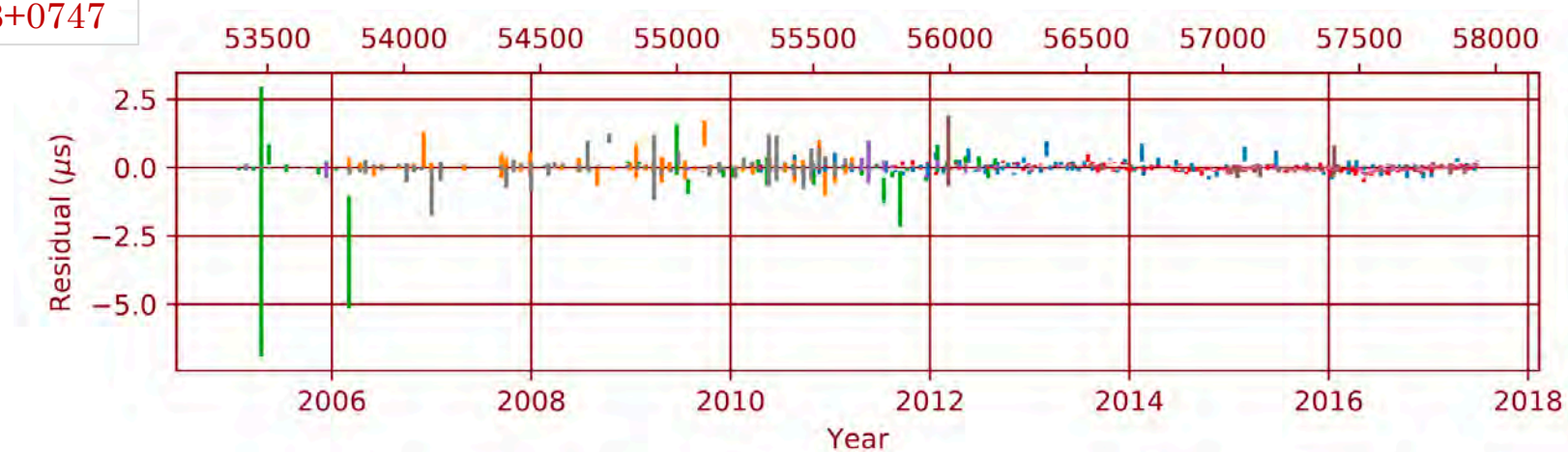
NANOGrav 12.5-year data set, showing 2 of 48 pulsars

NANOGrav Physics Frontiers Center

PSR J1640+2224

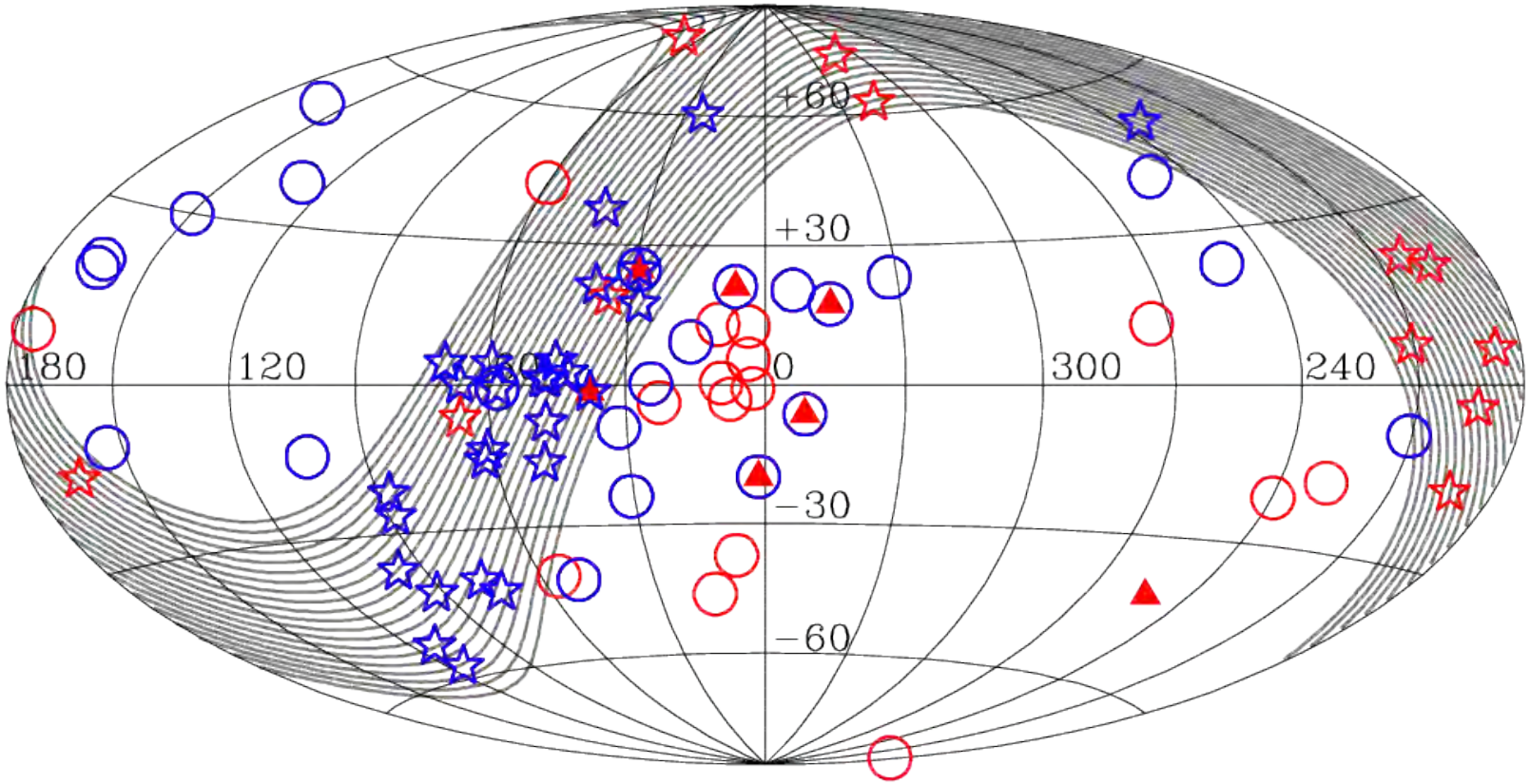


PSR J1713+0747



Observing Program: ~~77~~ Pulasrs

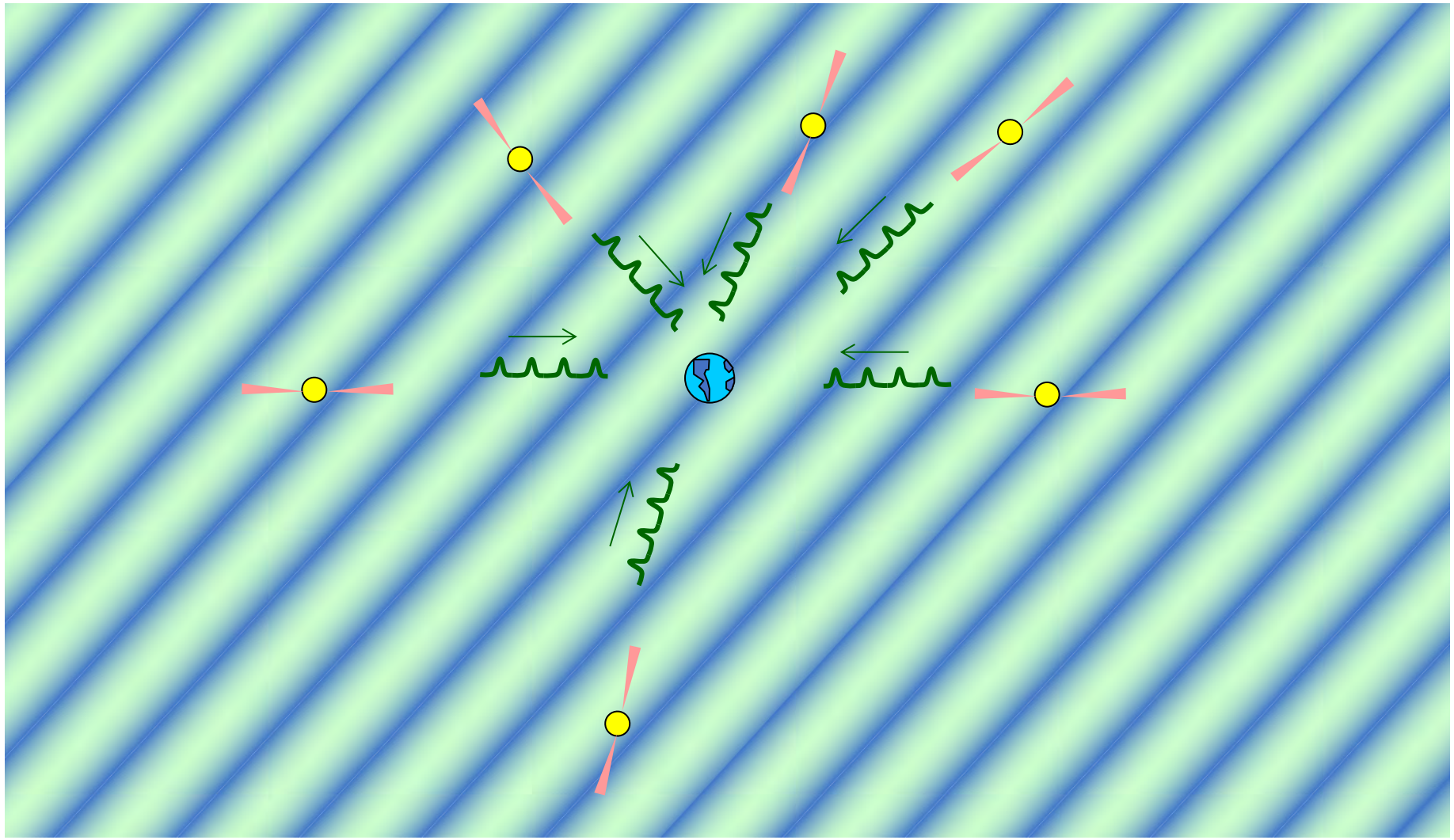
72

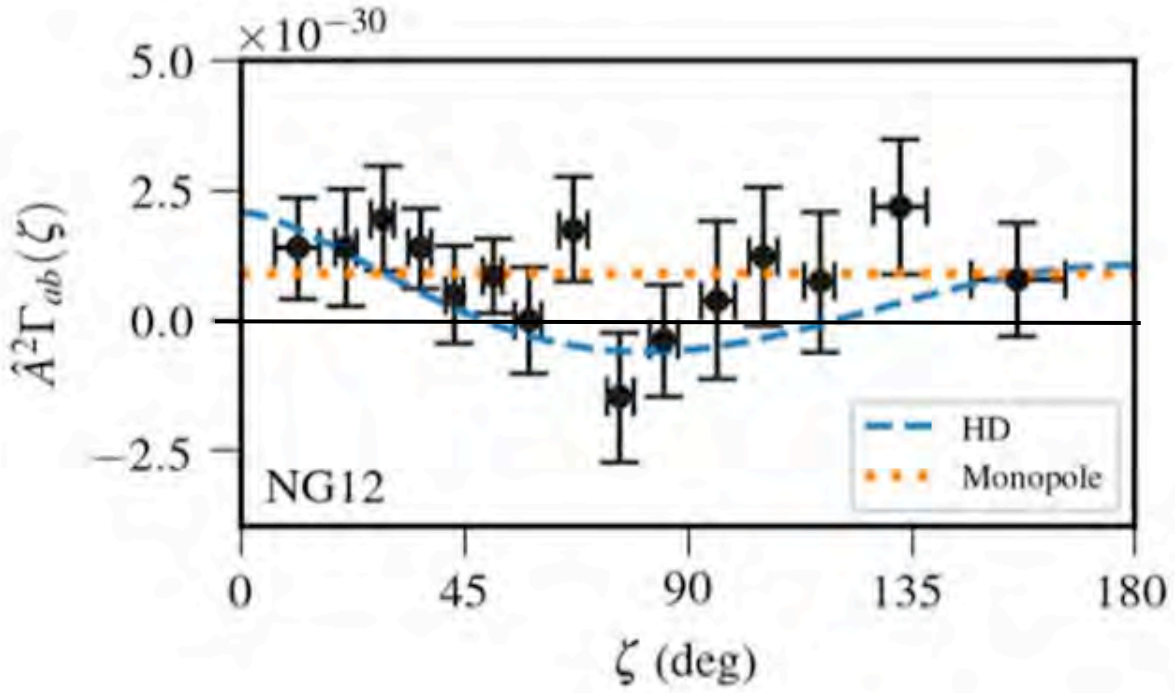


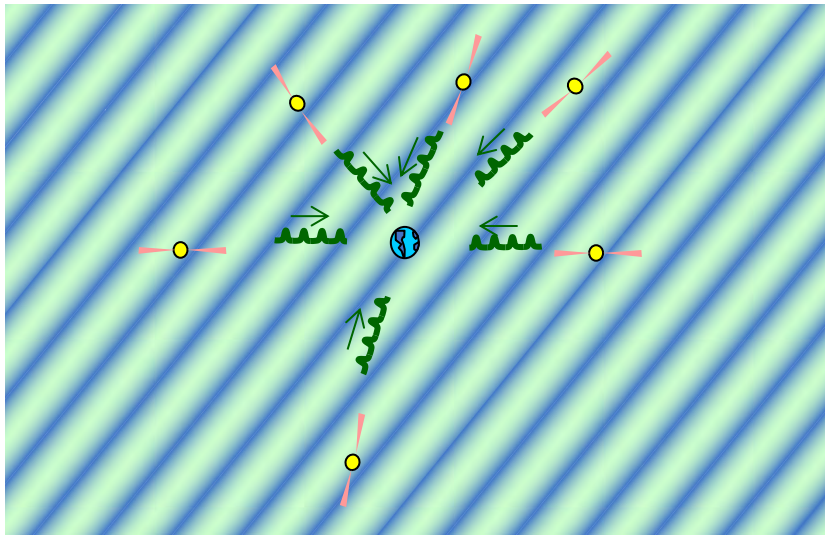
AO GB VLA

12.5−Year Data Set

More Recent Additions







The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background

The Astrophysical Journal Letters, 905:L34 (18pp), 2020 December 20

Zaven Arzoumanian[1], Paul T. Baker[2], Harsha Blumer[3,4], Bence Bécsy[5], Adam Brazier[6,7], Paul R. Brook[3,4], Sarah Burke-Spolaor[3,4,8], Shami Chatterjee[6], Siyuan Chen[9,10,11], James M. Cordes[6], Neil J. Cornish[5], Fronefield Crawford[12], H. Thankful Cromartie[6,13], Megan E. DeCesar[14,15,43], Paul B. Demorest[16], Timothy Dolch[17], Justin A. Ellis[18], Elizabeth C. Ferrara[19], William Fiore[3,4], Emmanuel Fonseca[20], Nathan Garver-Daniels[3,4], Peter A. Gentile[3,4], Deborah C. Good[21], Jeffrey S. Hazboun[22,43], A. Miguel Holgado[23,24], Kristina Islo[25], Ross J. Jennings[6], Megan L. Jones[25], Andrew R. Kaiser[3,4], David L. Kaplan[25], Luke Zoltan Kelley[26], Joey Shapiro Key[22], Nima Laal[27], Michael T. Lam[28,29], T. Joseph W. Lazio[30], Duncan R. Lorimer[3,4], Jing Luo[31], Ryan S. Lynch[32], Dustin R. Madison[3,4,43], Maura A. McLaughlin[3,4], Chiara M. F. Mingarelli[33,34], Cherry Ng[35], David J. Nice[14], Timothy T. Pennucci[36,37,43], Nihan S. Pol[3,4,38], Scott M. Ransom[36], Paul S. Ray[39], Brent J. Shapiro-Albert[3,4], Xavier Siemens[25,27], Joseph Simon[30,40,44], Renée Spiewak[41], Ingrid H. Stairs[21], Daniel R. Stinebring[42], Kevin Stovall[16], Jerry P. Sun[27], Joseph K. Swiggum[14,43], Stephen R. Taylor[38], Jacob E. Turner[3,4], Michele Vallisneri[30], Sarah J. Vigeland[25], and Caitlin A. Witt[3,4]
The NANOGrav Collaboration

Pulsar receivers and backends

Two narrow bands (GASP)

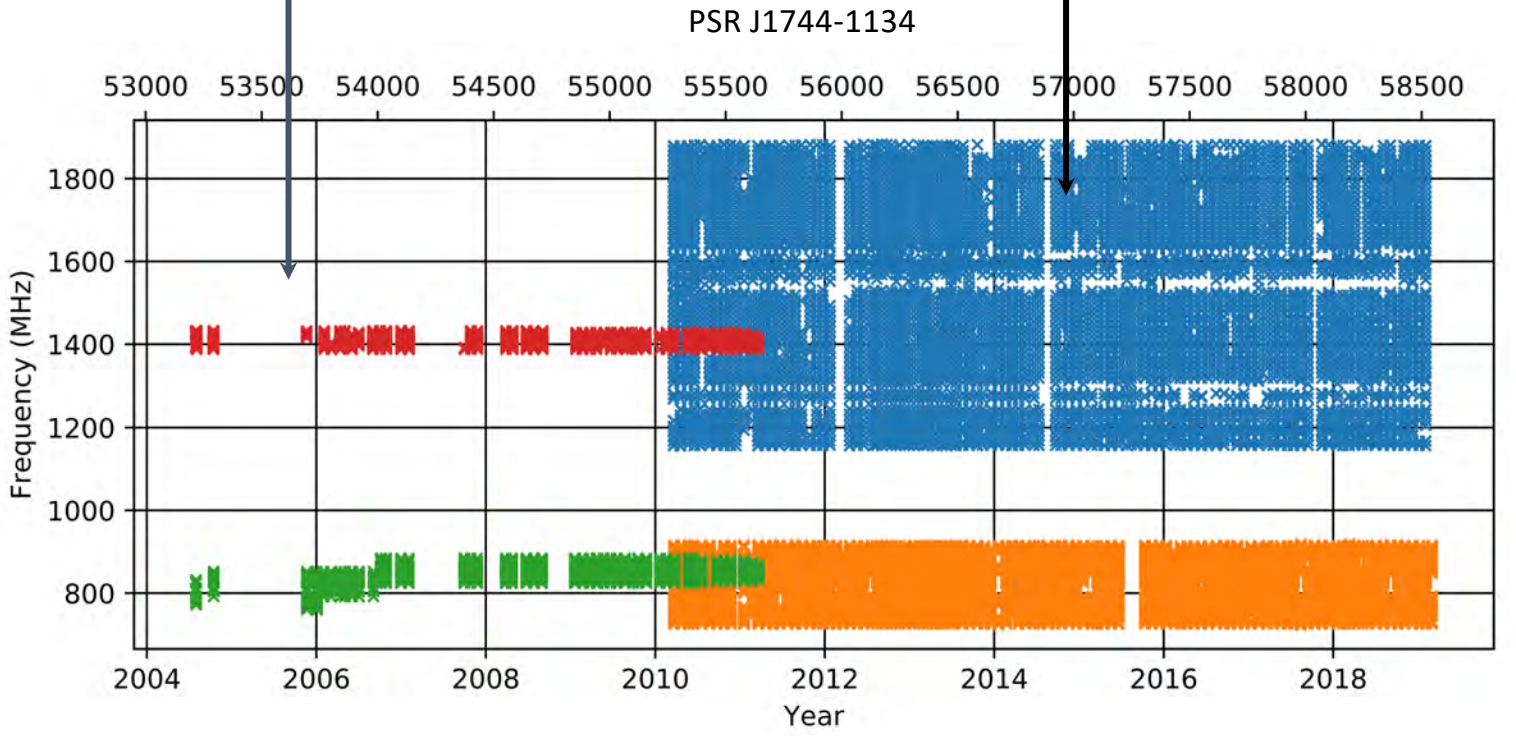
- 2004–2010

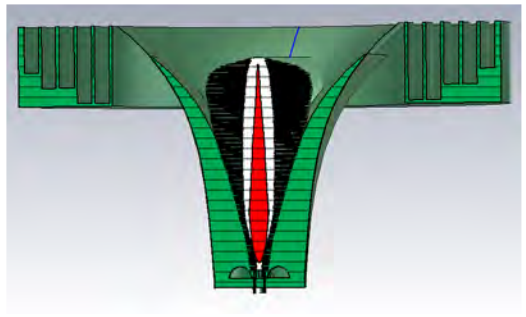
Two wider bands (GUPPI)

- 2010–
- Better sensitivity
- Better interstellar medium mitigation
- Better match to telescope receivers

Wideband receiver

under development to cover 700 to 4000 MHz simultaneously. (Funded by the Gordon and Betty Moore roundation.)





Pulsar people at NRAO/GBO

1989

2021

Walter Brisken
Paul Demorest
Dale Frail
Ryan Lynch
Mark McKinnon
Toney Minter
Scott Ransom

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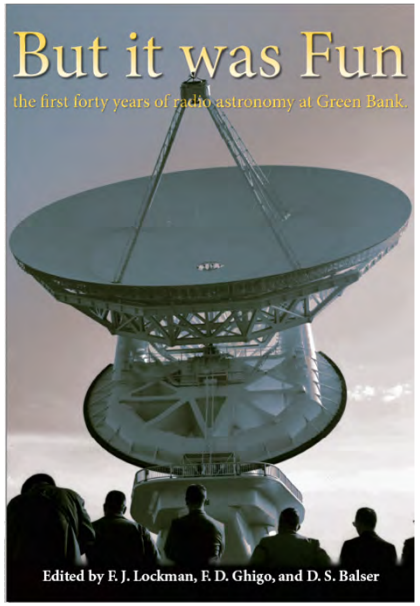
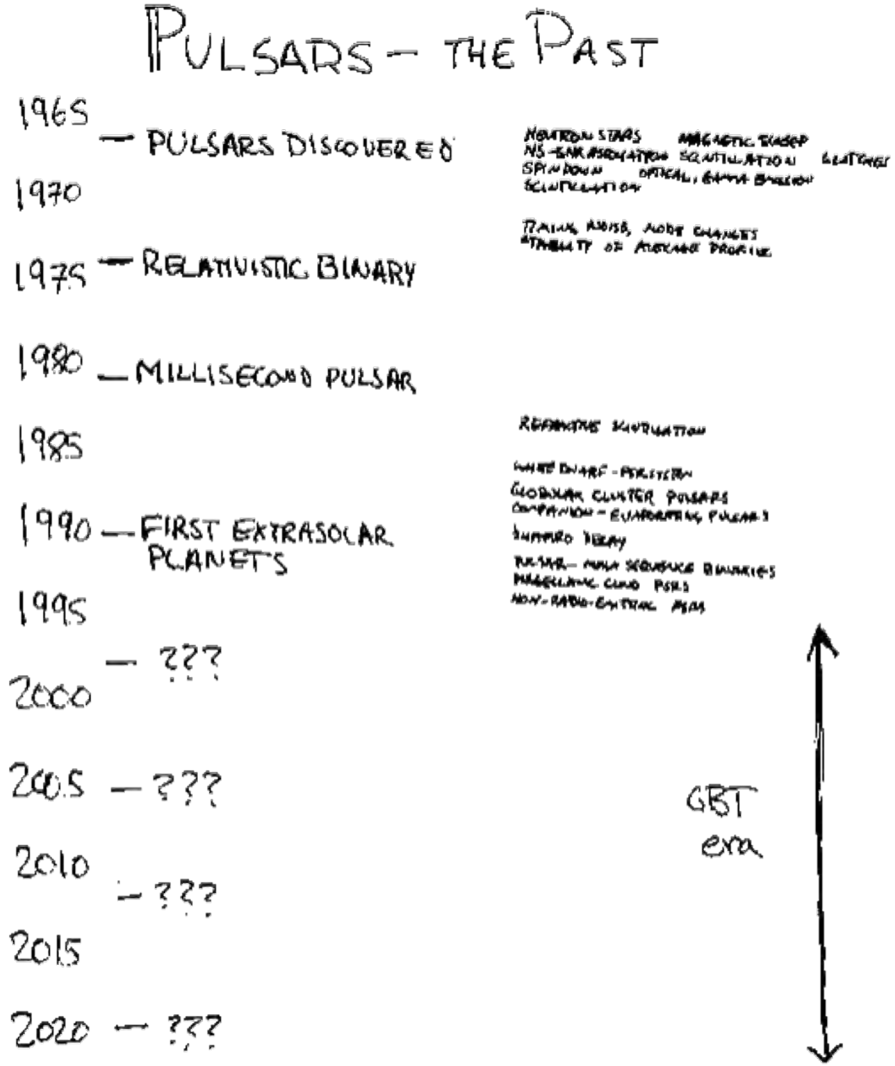
One major pulsar discovery every ~7 years.





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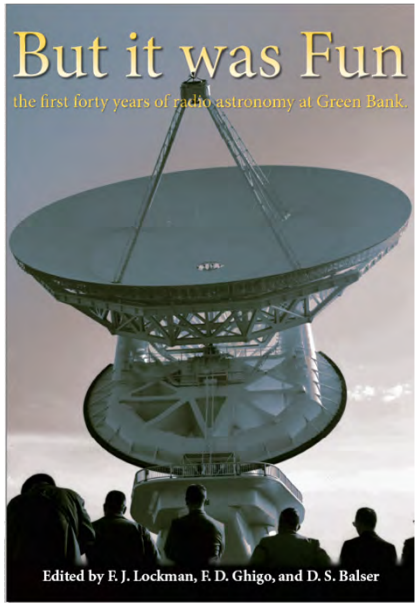
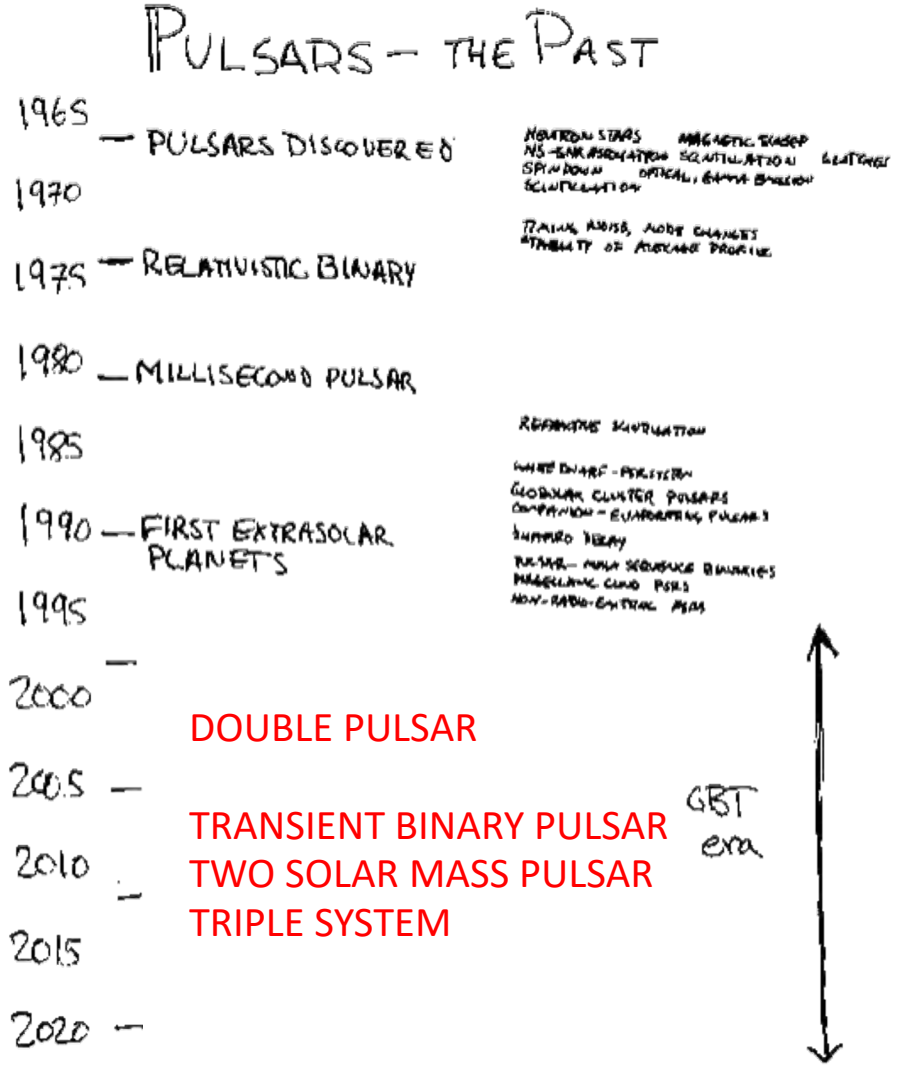
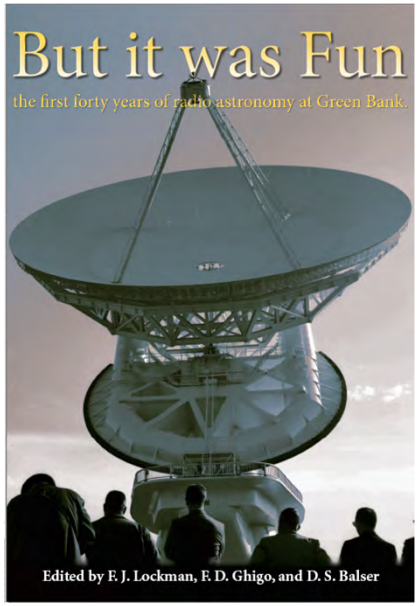
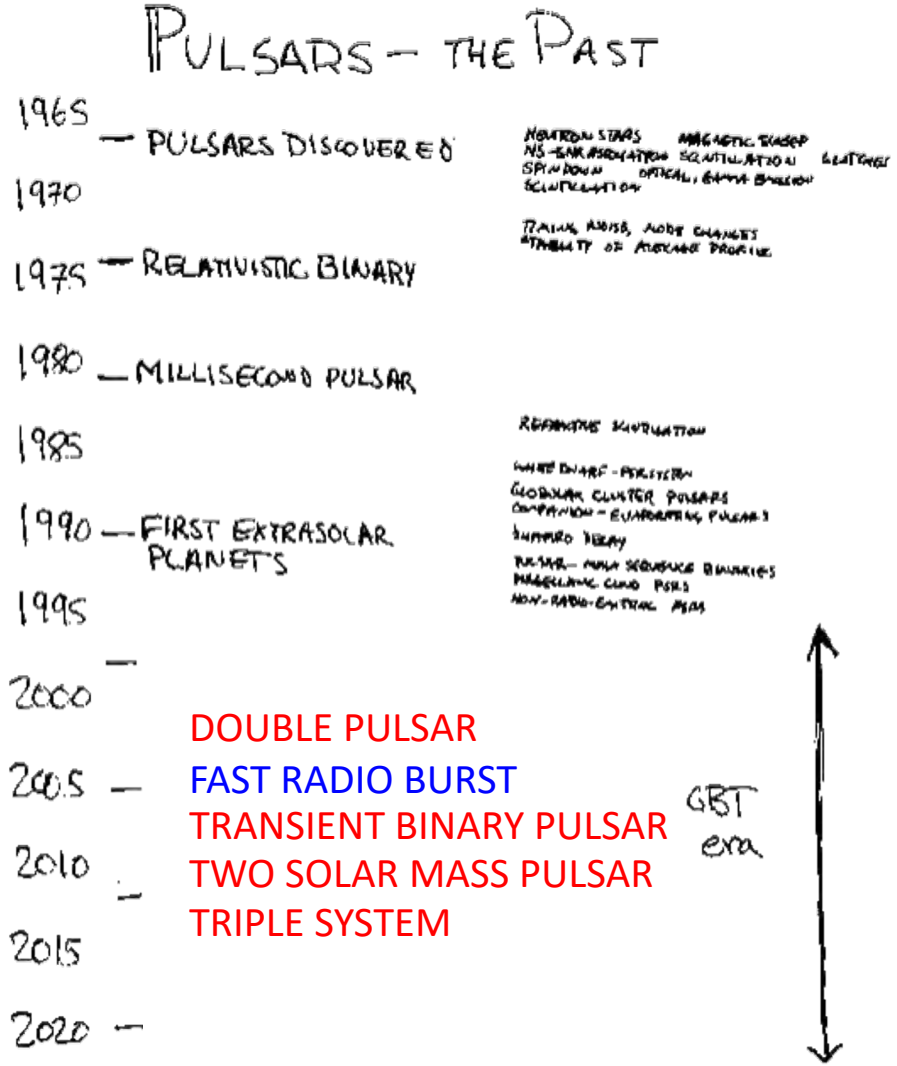




Trend noted and prediction made (by me) at the Fortieth Anniversary celebration for the 140 Foot Telescope in 1995 :

One major pulsar discovery every ~7 years.





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THE NEXT 20 YEARS ON THE GBT:
A LOT MORE FUN!