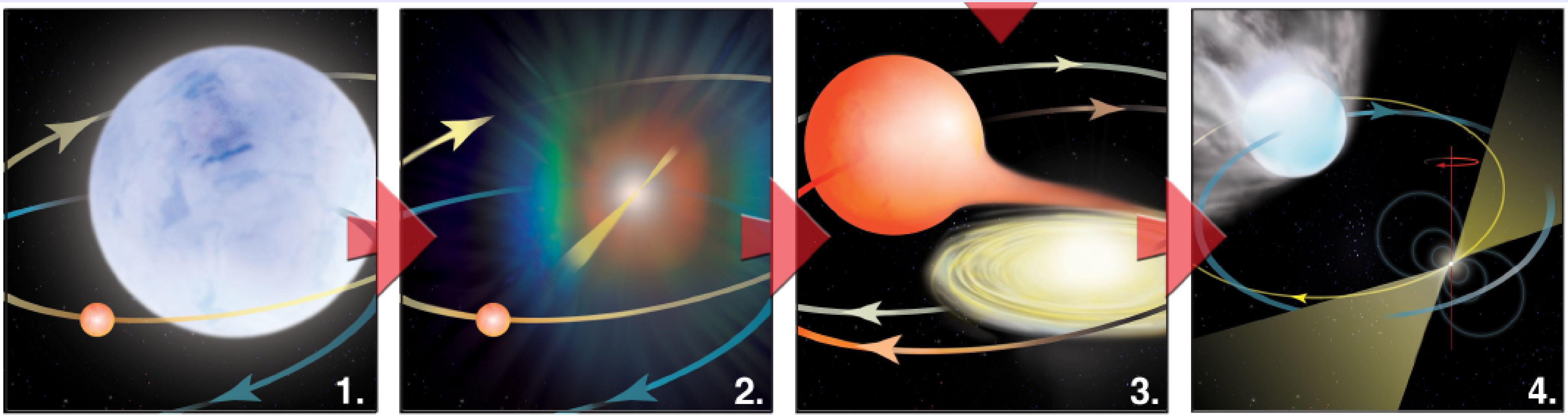
A Pulsar Timing Array for Gravitational Wave Detection

Paul Demorest, NRAO

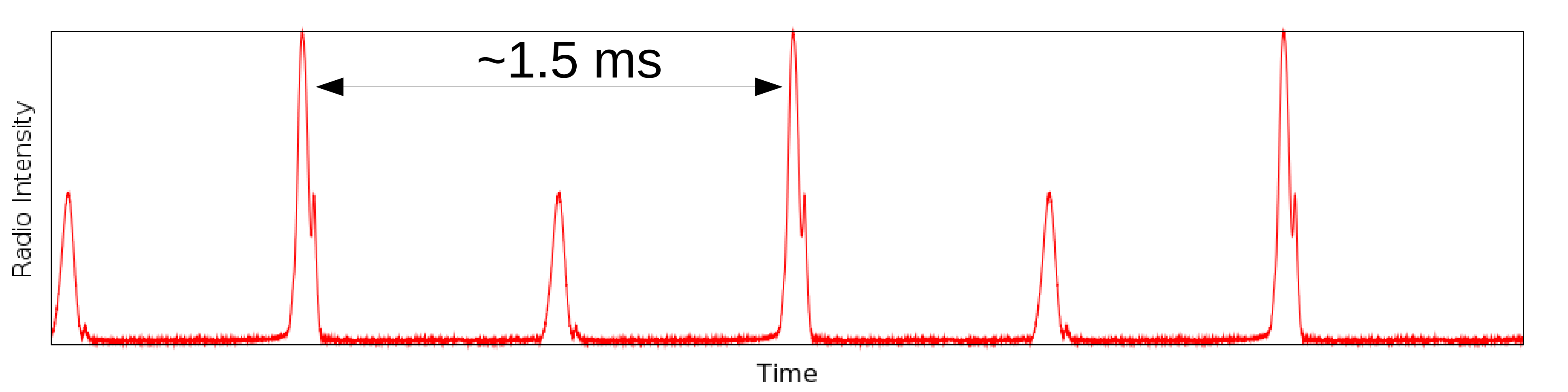
About 10% of known radio pulsars are "recycled" millisecond pulsars (MSPs). These are spun up by accreting matter from a companion star:



(Image: B. Saxton, NRAO)

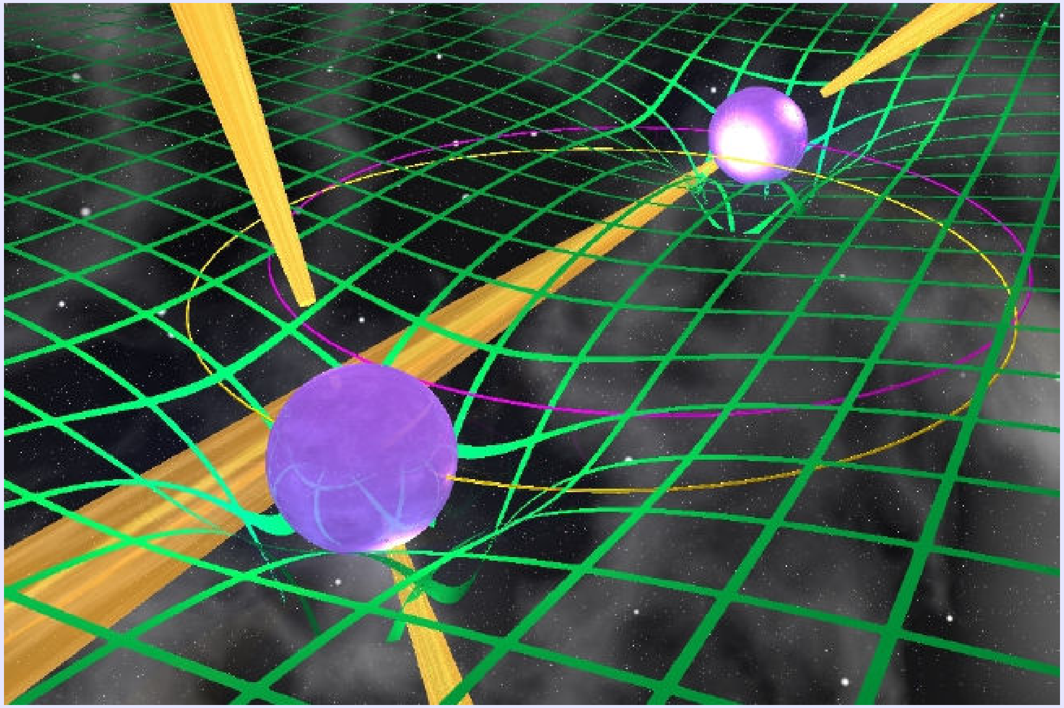
These rare objects are incredibly useful for exploring a variety of extreme physics and astrophysics!

MSPs act as *extremely* precise astronomical clocks:



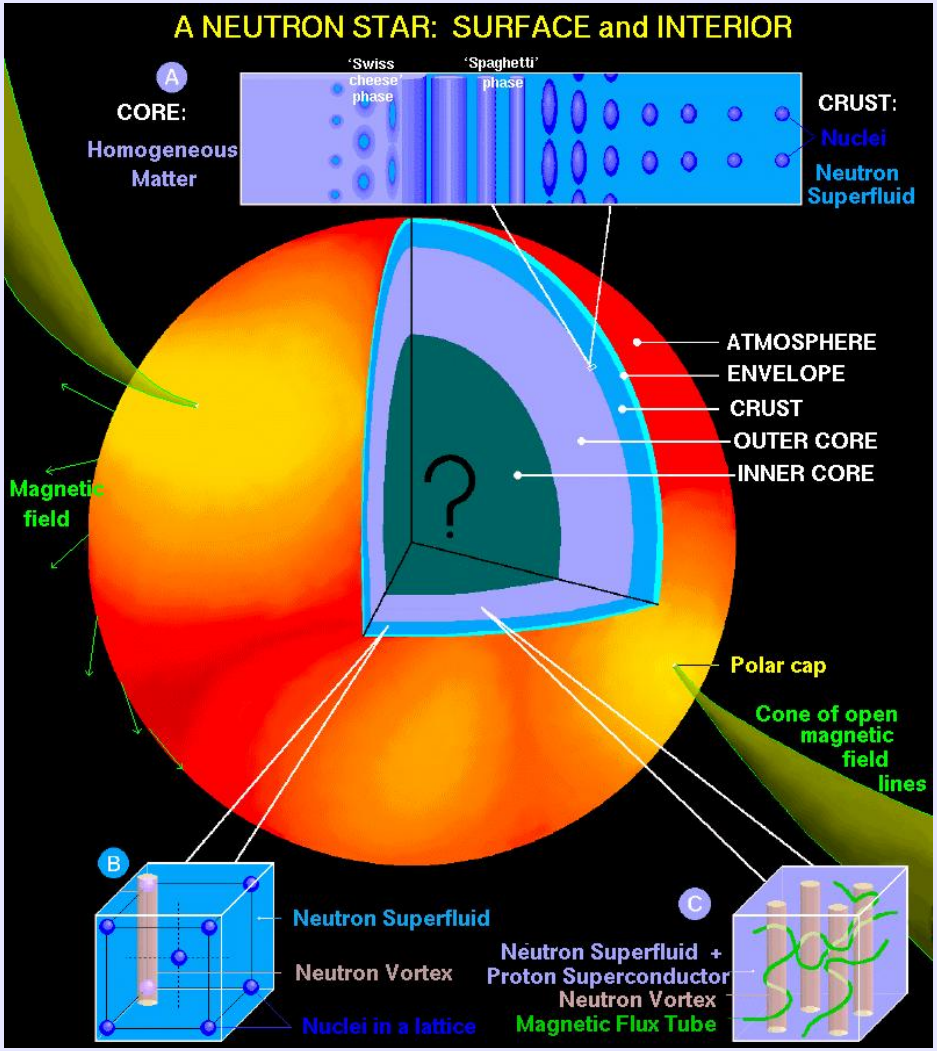
Spin period of PSR B1937+21 at Midnight, December 5, 1998:

P = 1.5578064688197945 ms
+/- 0.0000000000000004 ms !



Timing of binary NS allows tests of gravity / general relativity.

NS mass measurements provide unique tests of the physics of matter at super-nuclear density.



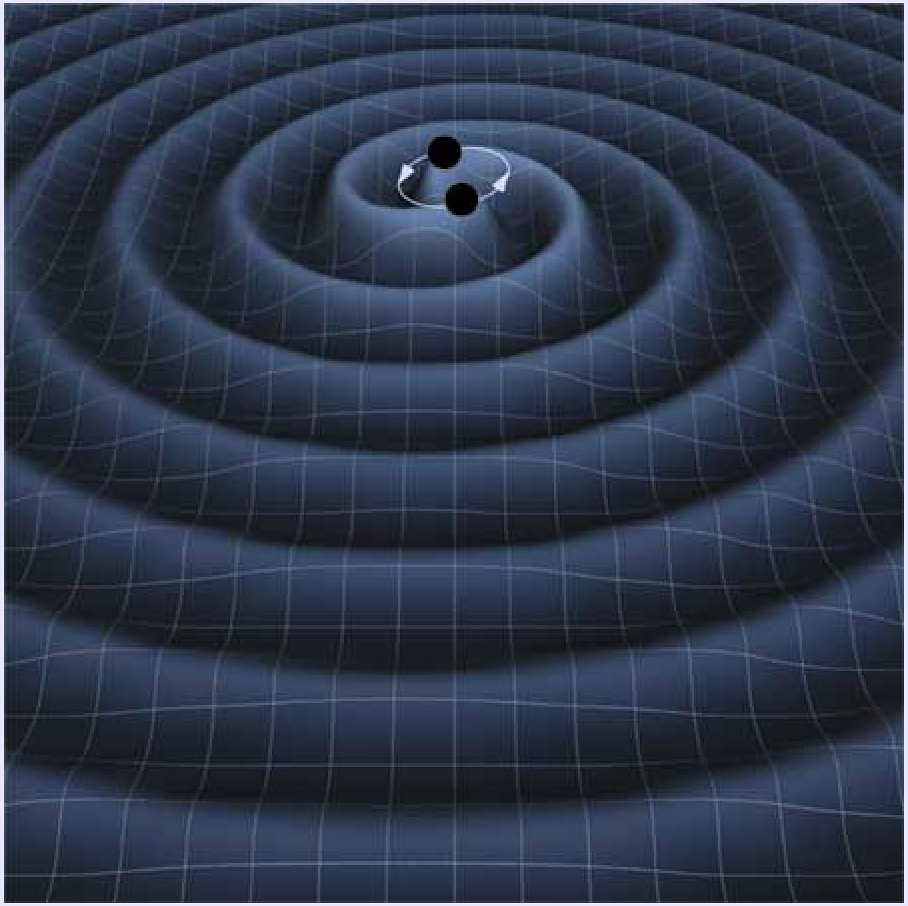
Gravitational waves:

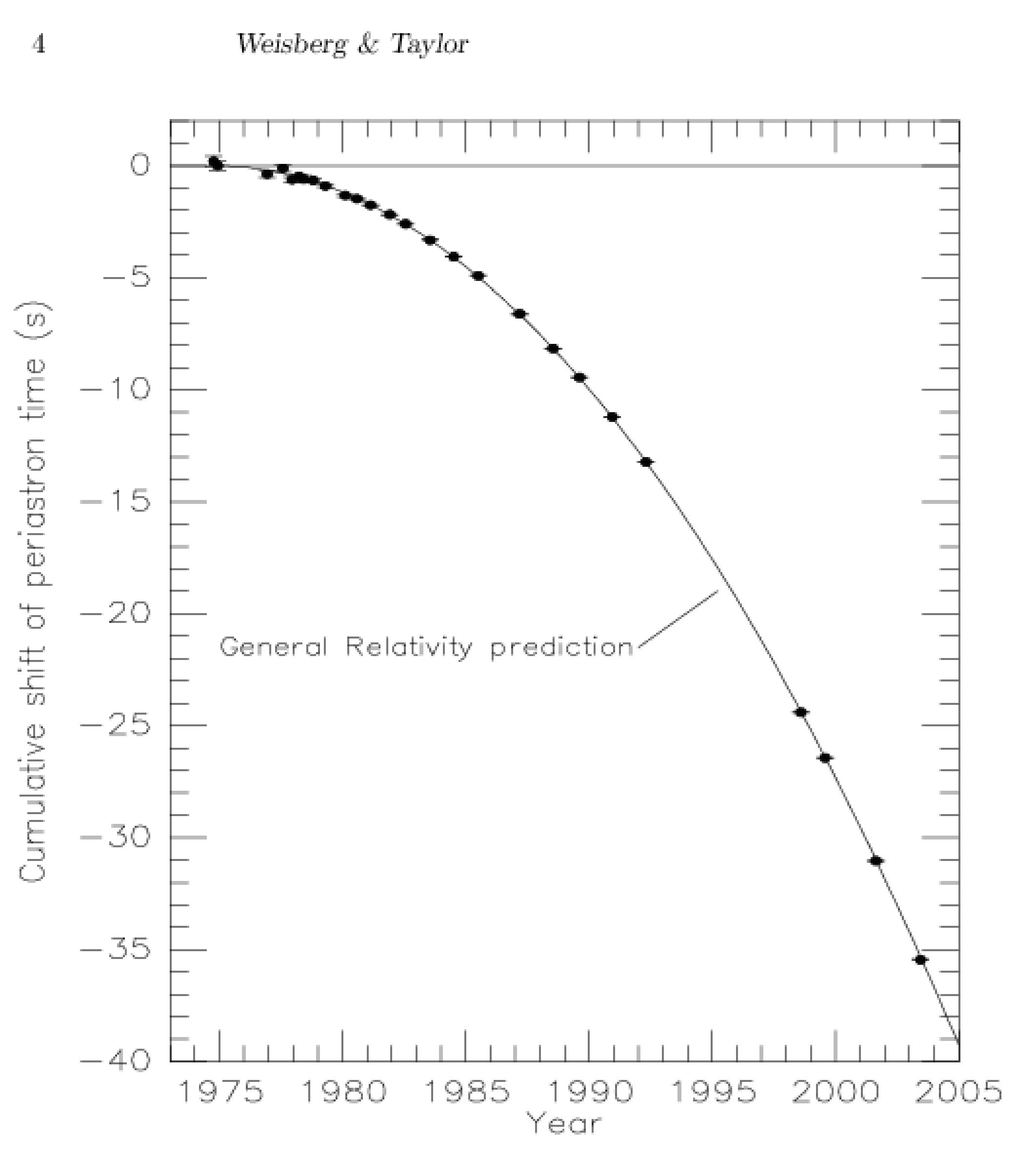
Freely-propagating “space-time ripples” predicted by GR.

Generated by almost any moving mass (binaries, etc).

Are *very* weak and not yet directly detected.

Detection will be another confirmation of GR. And will open up gravitational wave astronomy.



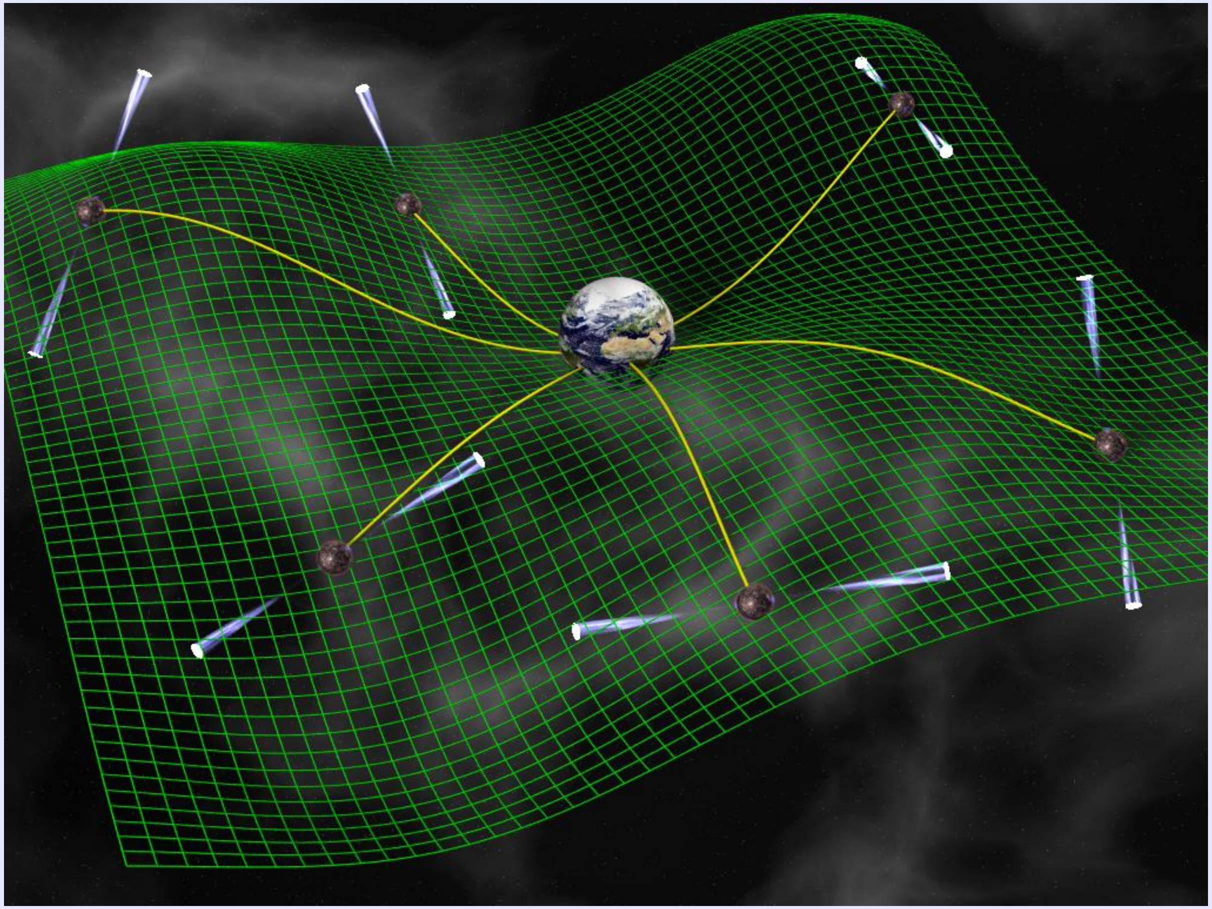


Experimental evidence for GW:

Orbital decay of PSR B1913+16 measured by radio timing *exactly* matches expected energy loss to GW emission.

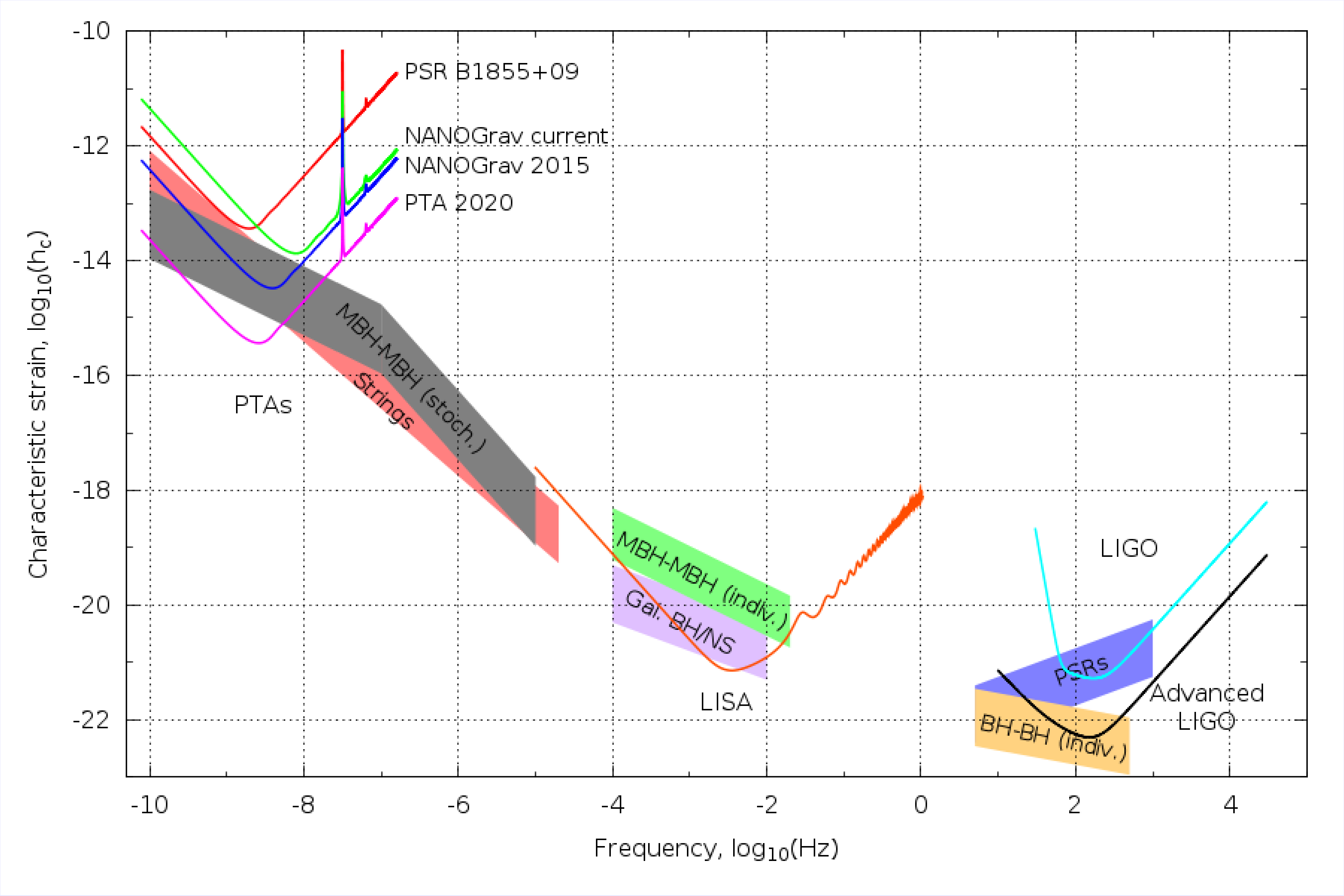
(Physics Nobel prize for Hulse and Taylor in 1993)

Pulsar Timing Array: a galactic-scale gravitational wave detector.



Sensitive to very low frequency (~nHz) grav waves.

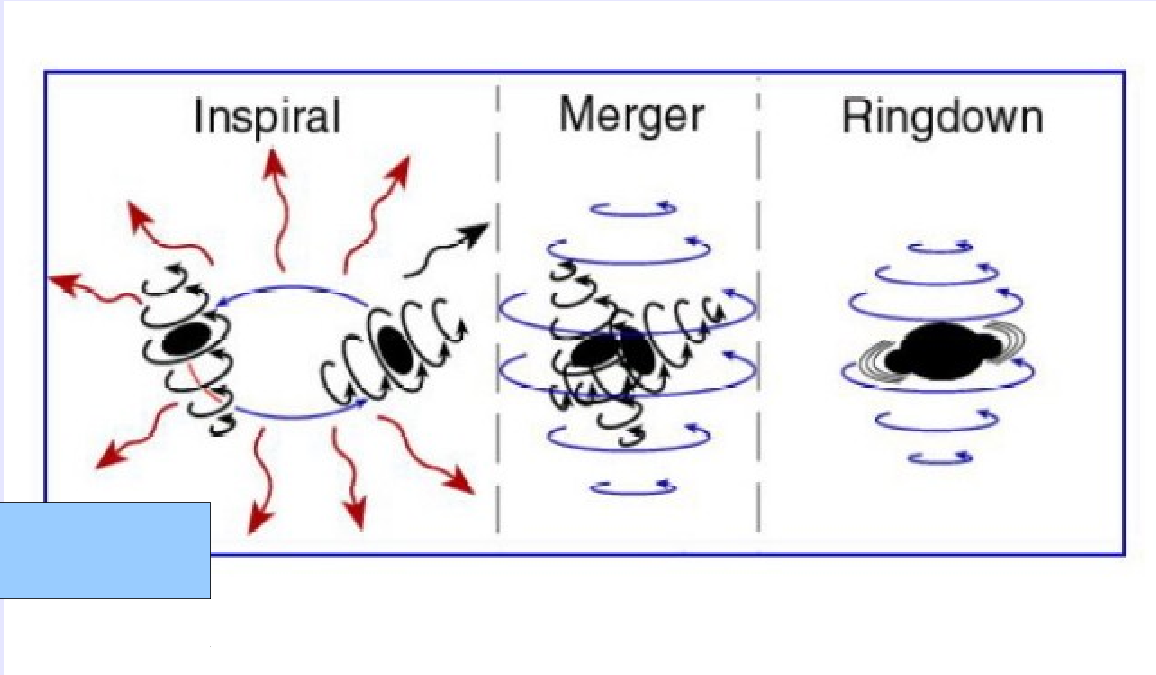
Pulsar Timing Array GW complementarity:



For PTAs, sensitivity h ~ dt / T --> requires 10s of ns over years!

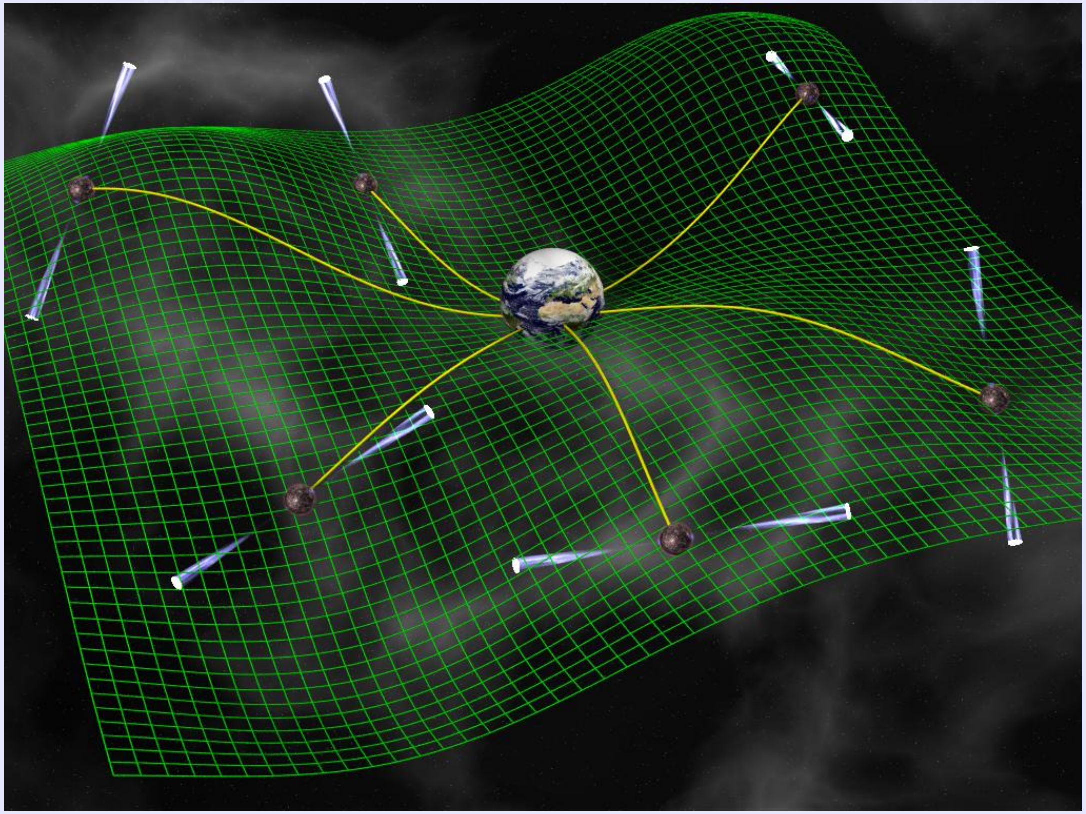
Nanohertz GW sources:

“Monochromatic” MBH-MBH binaries of >10^7 solar mass.



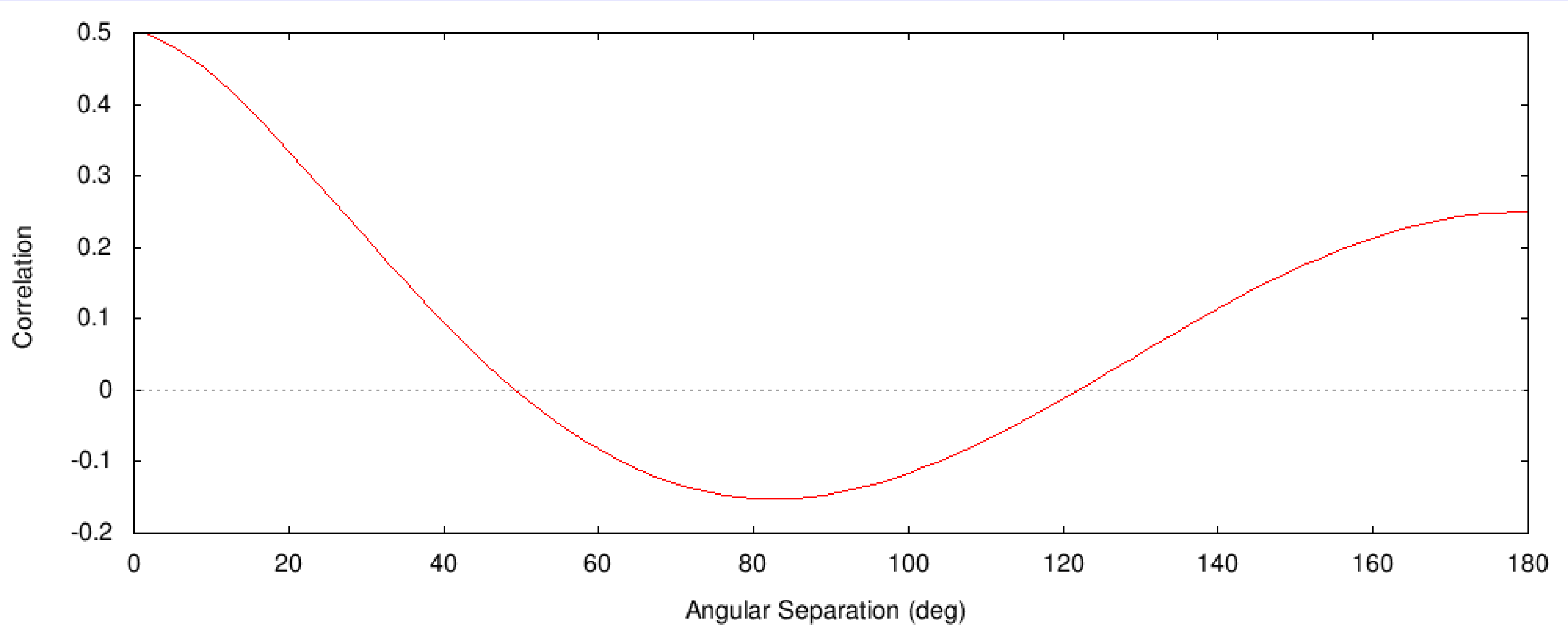
PTA Sources

- Stochastic MBH background (Jaffe & Backer 2003, Sesana et al 2008, ...)
- Resolved MBH sources (Sesana et al 2009, Boyle & Pen 2010, ...)
- Also cosmic strings, other exotica / the unknown!



Isotropic stochastic BG induces correlated timing residuals in pulsar pairs.

Characteristic signature vs pairwise angular separation. ("Hellings/Downs curve")



Pulsar Timing Arrays around the world:

Parkes Pulsar Timing Array (PPTA)

European Pulsar Timing Array (EPTA)

North American Nanohertz Observatory for Gravitational Waves (NANOGrav)

In combination, International Pulsar Timing Array (IPTA)!

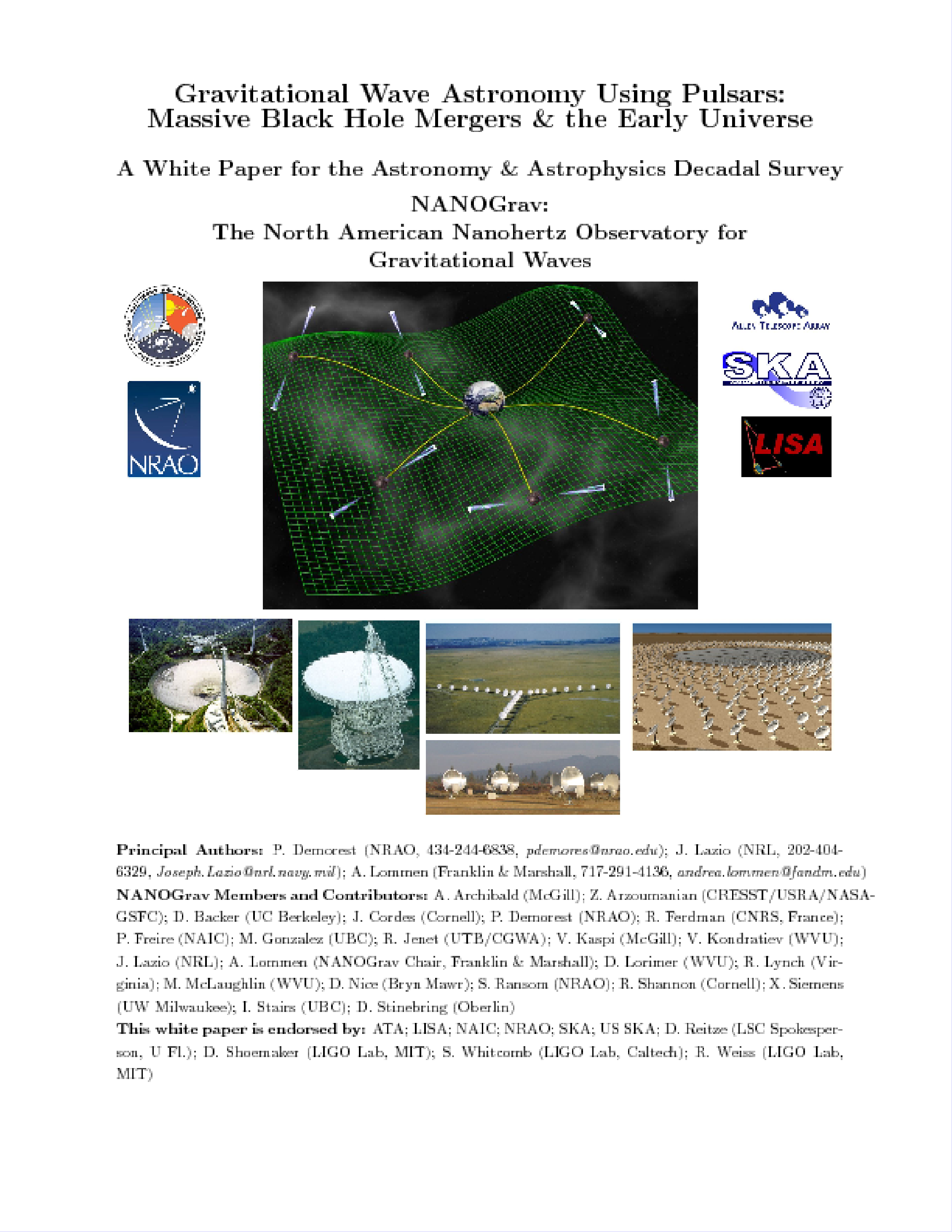
NANOGrav project:
http://www.nanograv.org

Primarily US/Canada-based pulsar timing array project using US radio telescopes.

Collaboration formally started in 2007.

Current chair: Maura McLaughlin, WVU.

$6.7M / 5-yr NSF PIRE award.


Gravitational Wave Astronomy Using Pulsars:
Massive Black Hole Mergers & the Early Universe

A White Paper for the Astronomy & Astrophysics Decadal Survey

NANOGrav:
The North American Nanohertz Observatory for Gravitational Waves

Principal Authors: P. Demorest (NRAO, 434-244-6838, *pdemores@nrao.edu*); J. Lazio (NRL, 202-404-6329, *Joseph.Lazio@nrl.navy.mil*); A. Lommen (Franklin & Marshall, 717-291-4136, *andrea.lommen@fandm.edu*)
NANOGrav Members and Contributors: A. Archibald (McGill); Z. Arzoumanian (CRESST/USRA/NASA-GSFC); D. Backer (UC Berkeley); J. Cordes (Cornell); P. Demorest (NRAO); R. Ferdman (CNRS, France); P. Freire (NAIC); M. Gonzalez (UBC); R. Jenet (UTB/CGWA); V. Kaspi (McGill); V. Kondratiev (WVU); J. Lazio (NRL); A. Lommen (NANOGrav Chair, Franklin & Marshall); D. Lorimer (WVU); R. Lynch (Virginia); M. McLaughlin (WVU); D. Nice (Bryn Mawr); S. Ransom (NRAO); R. Shannon (Cornell); X. Siemens (UW Milwaukee); I. Stairs (UBC); D. Stinebring (Oberlin)
This white paper is endorsed by: ATA; LISA; NAIC; NRAO; SKA; US SKA; D. Reitze (LSC Spokesperson, U Fl.); D. Shoemaker (LIGO Lab, MIT); S. Whitcomb (LIGO Lab, Caltech); R. Weiss (LIGO Lab, MIT)

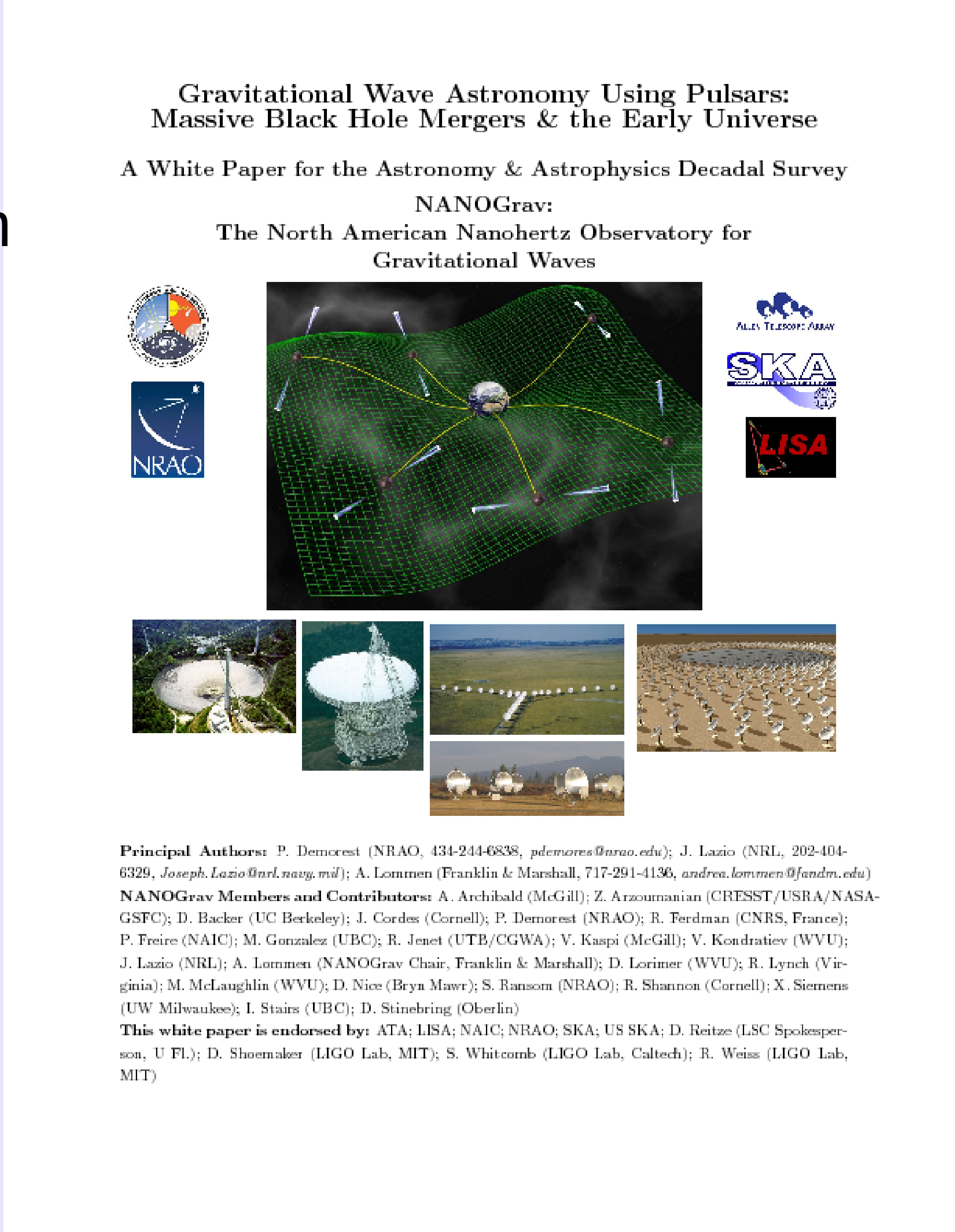
NANOGrav project:
http://www.nanograv.org

Favorable response from Astro2010:

GW astronomy one of 5 key discovery areas.

PTAs highly recommended by RMS panel.

NANOGrav listed as a contender for proposed Mid-Scale NSF funding.



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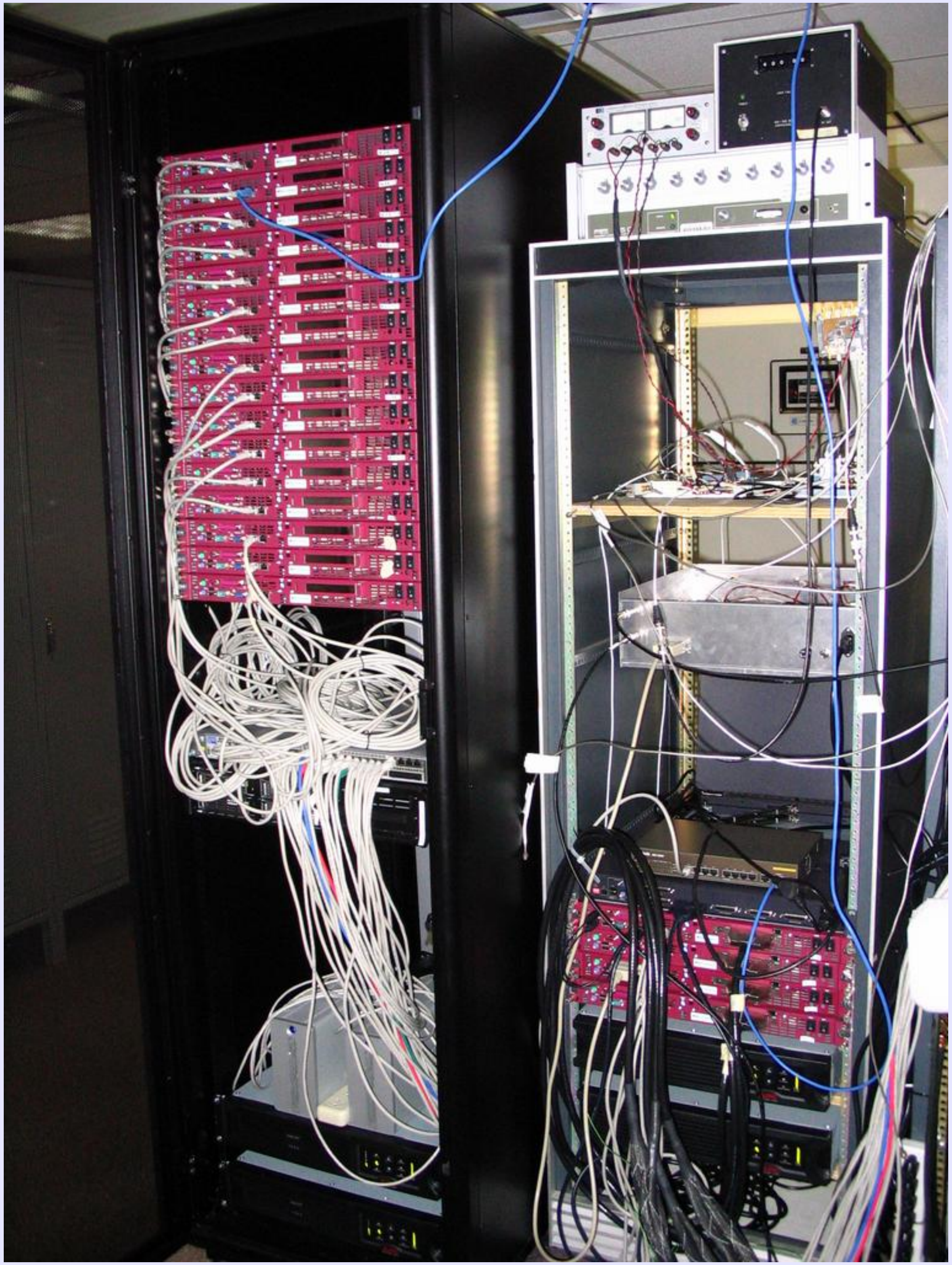
NANOGrav observing:

Monitor ~20 pulsars monthly, starting in 2005. 5-yr data analysis underway!

Dual-freq: 820, 1400 MHz (GBT); 327, 430, 1400, 2300 MHz (AO).

Typically 30 min per source per band each epoch.

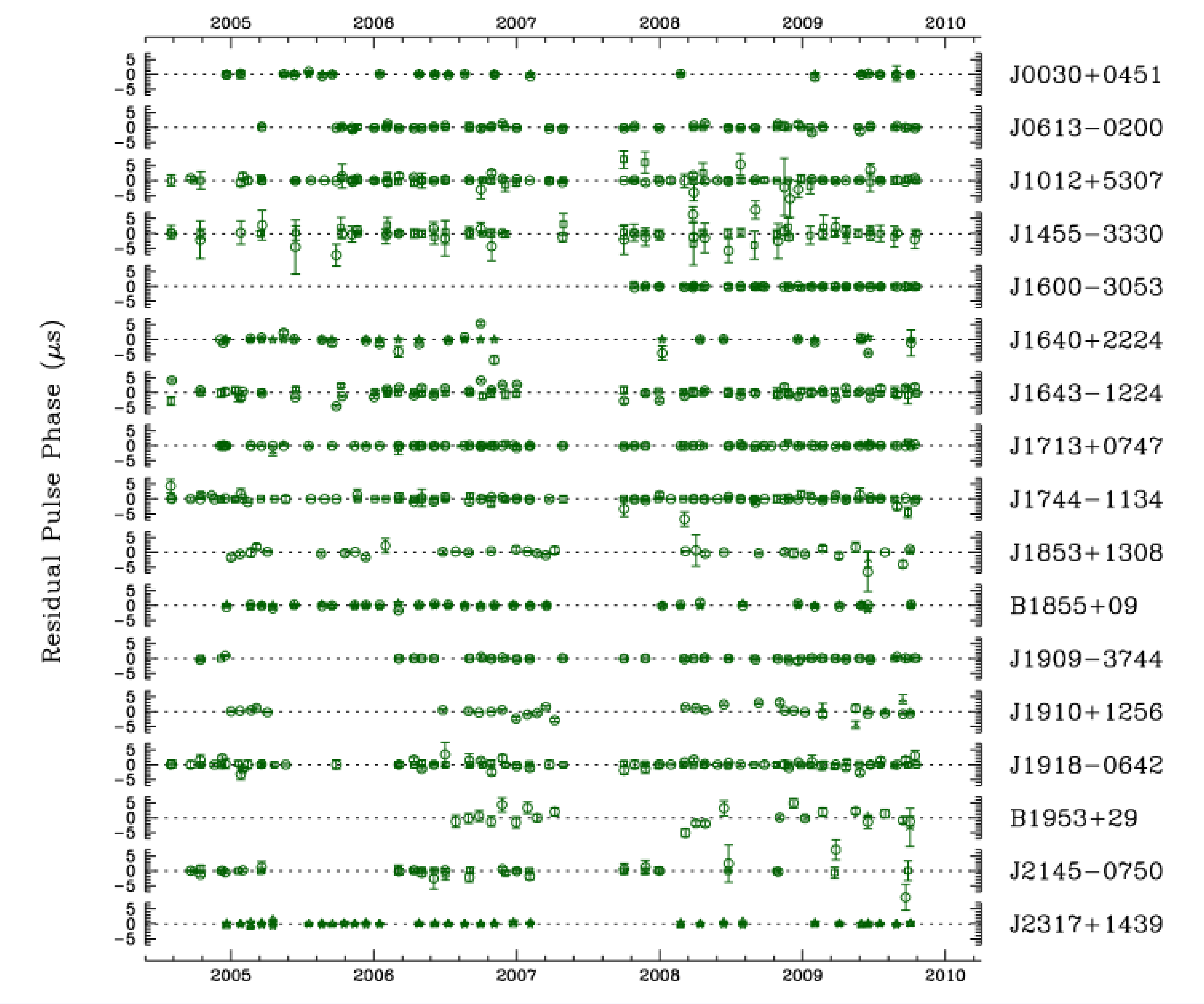
Uses ASP pulsar backends (~64 MHz coherent dedisp).



Arecibo observatory: 305-m fixed reflector

Green Bank Telescope: 100-m, fully steerable

NANOGrav 5-year timing results overview:



(plot: D. Nice)

NANOGrav 5-year timing results summary
(analysis ongoing; PD, M. Gonzalez, D. Nice, I. Stairs, S. Ransom, R. Ferdman)

Source	Per-channel RMS, μs	χ^2	Daily RMS, μs	Hi-freq RMS, μs
J1713+0747	0.106	1.48	0.030	0.041
J1909–3744	0.181	1.95	0.038	0.047
B1855+09	0.395	2.19	0.111	0.101
J0030+0451	0.604	1.44	0.148	0.328
J1600–3053	1.293	1.45	0.163	0.141
J0613–0200	0.781	1.21	0.178	0.519
J1744–1134	0.617	3.58	0.198	0.229
J2145–0750	1.252	1.97	0.202	0.494
J1918–0642	1.271	1.21	0.203	0.211
J2317+1439	0.496	3.03	0.251	0.155
J1853+1308	1.028	1.06	0.254	0.271
J1012+5307	1.327	1.40	0.276	0.345
J1640+2224	0.562	4.36	0.409	0.601
J1910+1256	1.394	2.09	0.708	0.710
J1455–3330	4.010	1.01	0.787	1.080
B1953+29	3.981	0.98	1.437	1.879
J1643–1224	2.892	2.78	1.467	1.887

Analysis features:

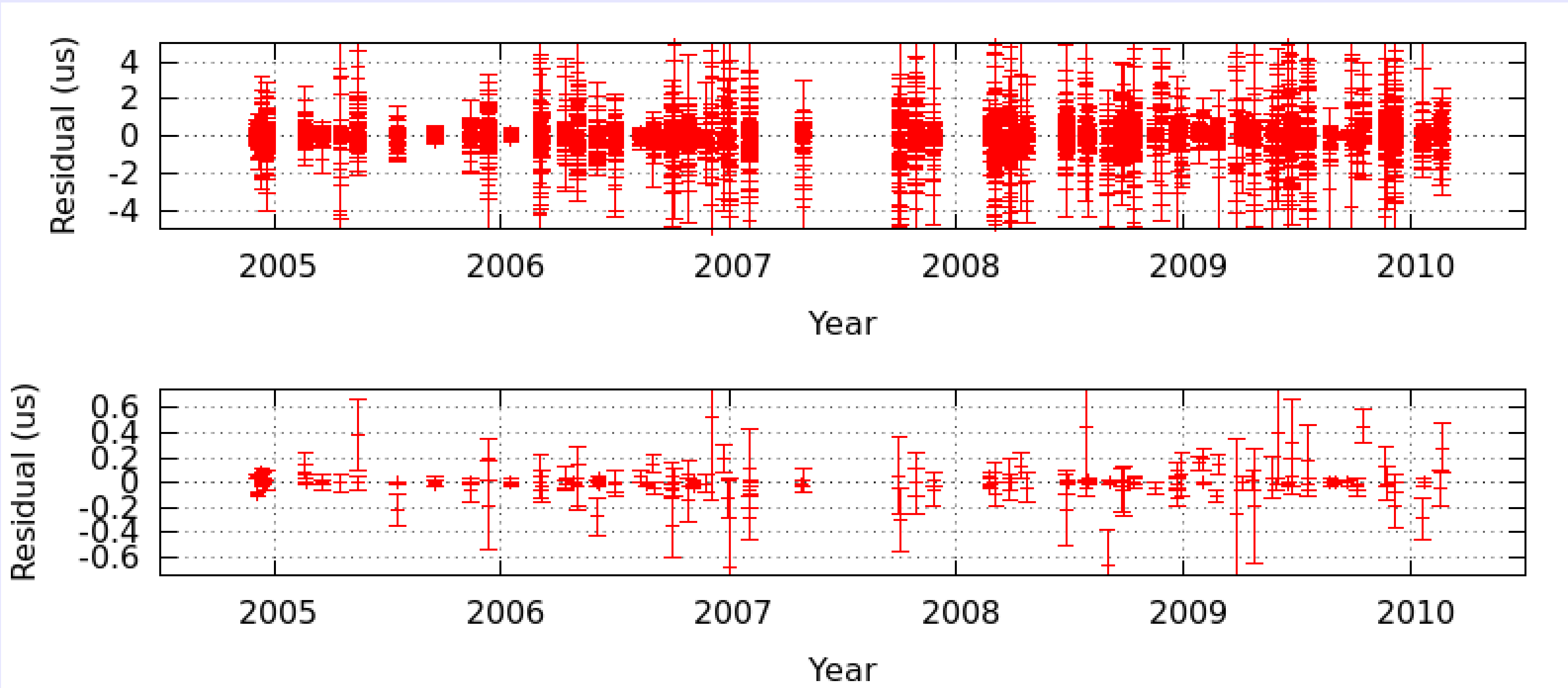
2 PSRs at ~40 ns!

Two independent calibration/processing pipelines

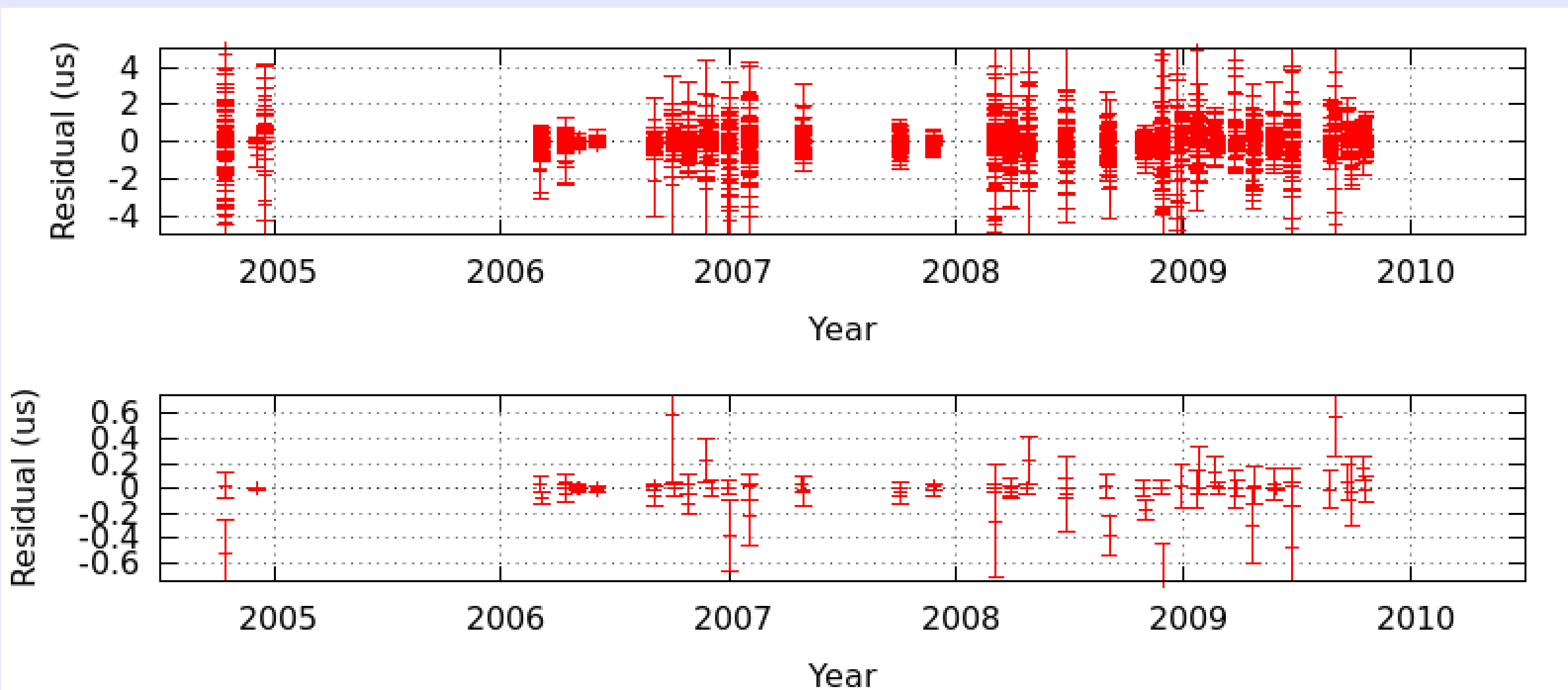
DM(t) and timing model in single fit.

Fit includes systematic timing vs freq correction (profile shape evolution).

Best timing residuals versus time:

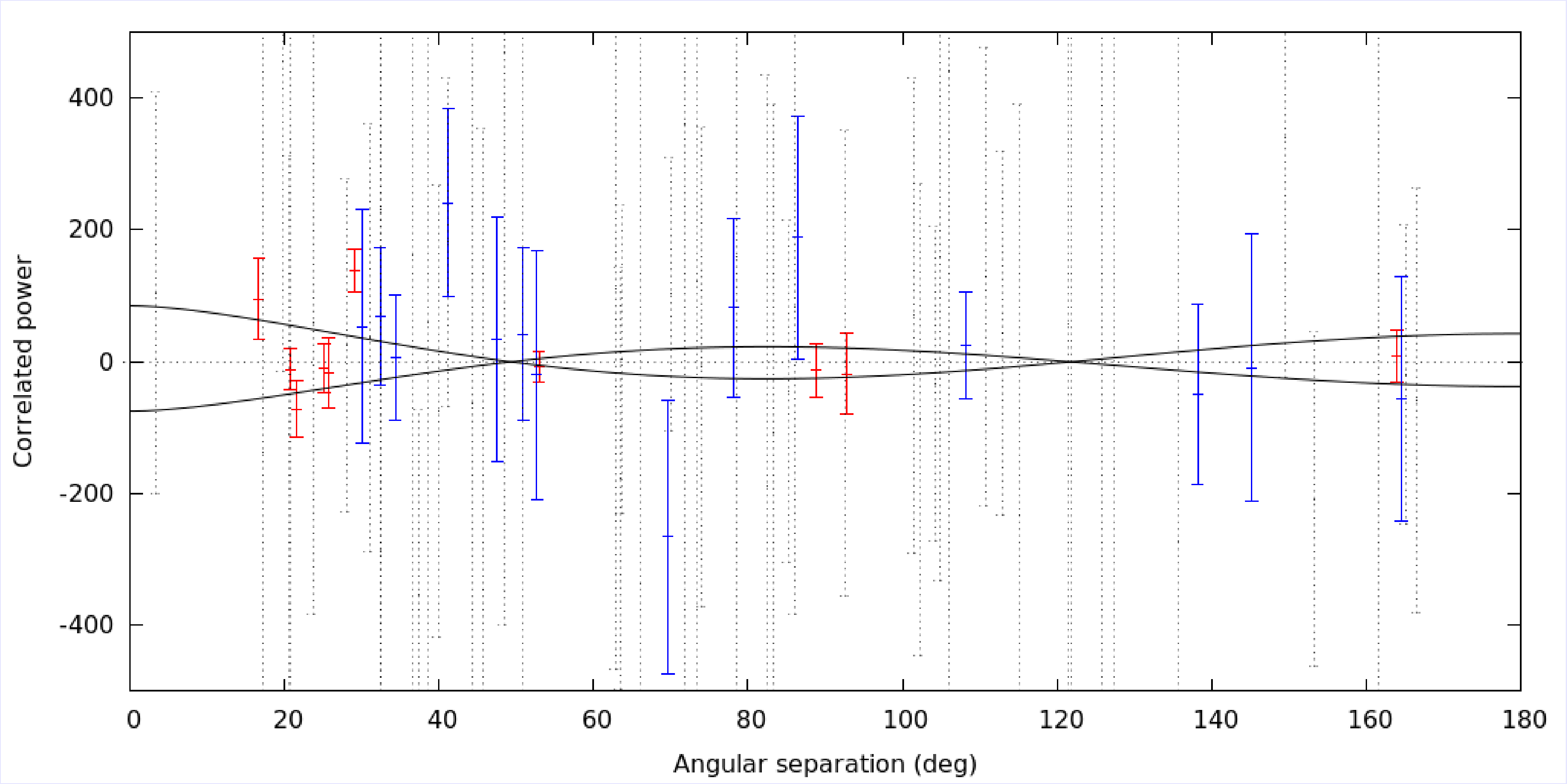


J1713+0747



J1909-3744

5-year NANOGrav GW cross-correlation analysis

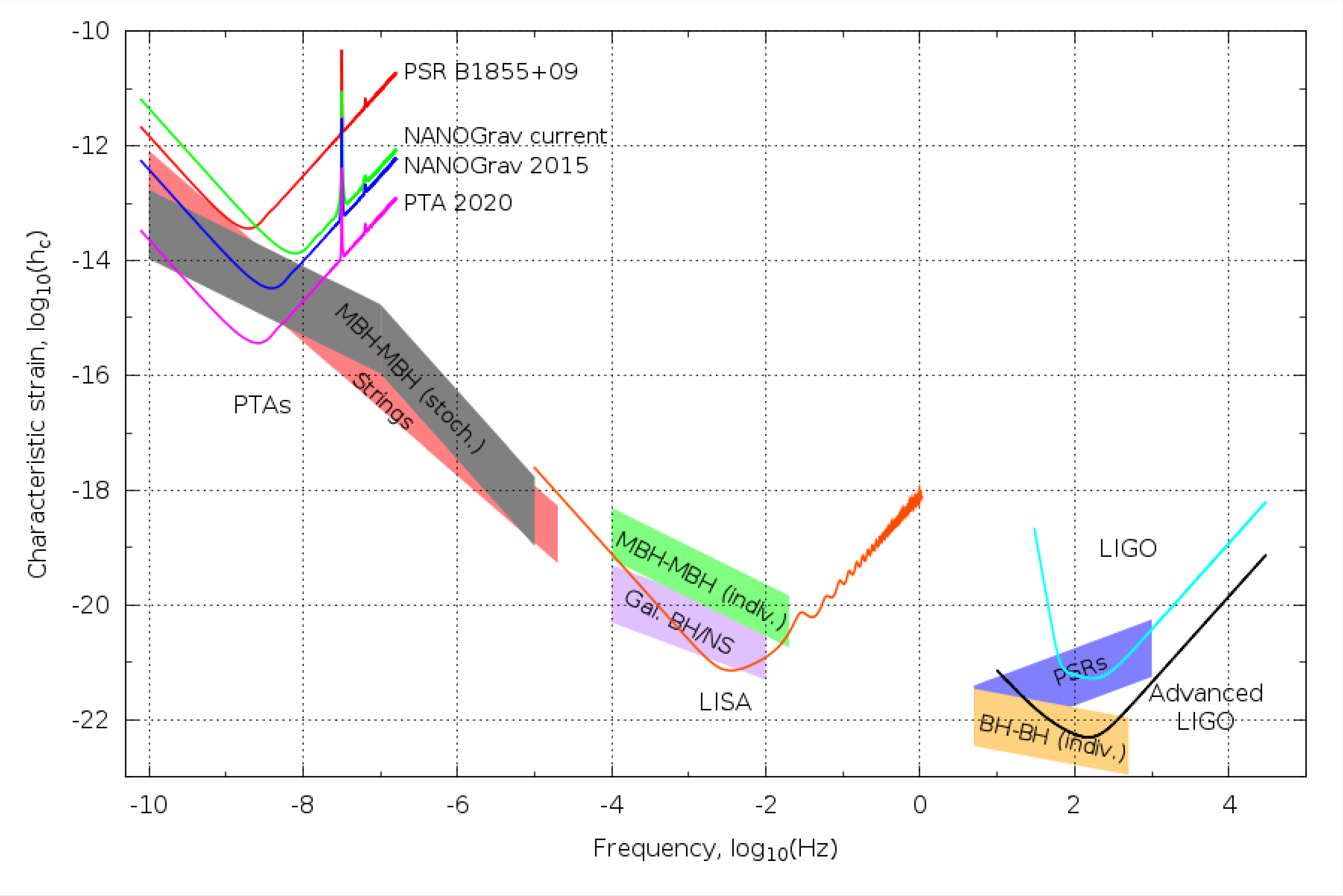


Computed using methods from Demorest (2007):

- Assumes/optimized for -2/3 power law GW spectrum.
- Current work: Inject/characterize simulated GW signals.

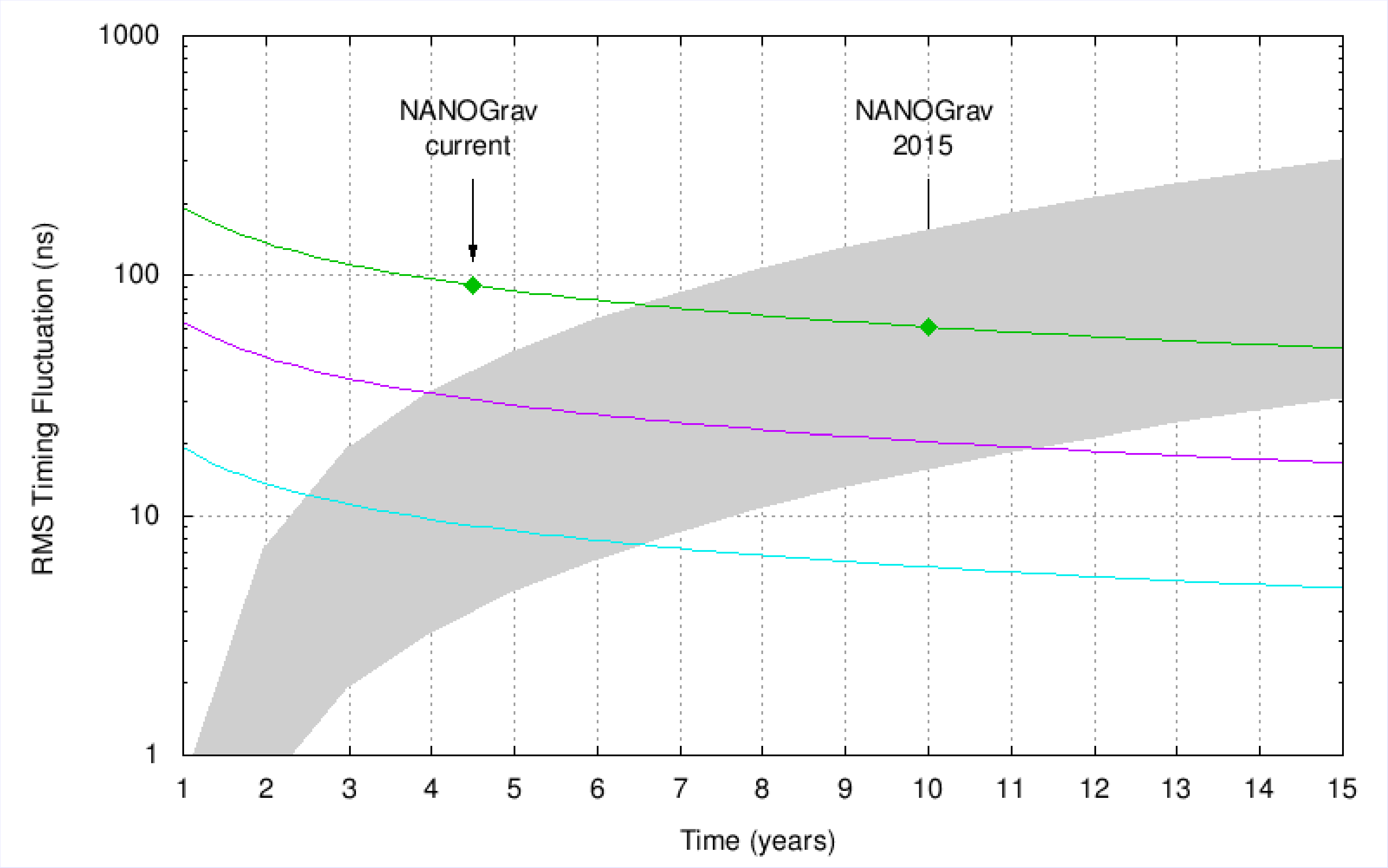
How to improve the measurement?

Easy way: Do nothing!



PSR B1855+09
NANOGrav current
NANOGrav 2015
PTA 2020
MBH-MBH (stoch.)
Strings
PTAs
MBH-MBH (indiv.)
Gal. BH/NS
LISA
LIGO
PSRs
Advanced LIGO
BH-BH (indiv.)
Characteristic strain, $\log_{10}(h_c)$
Frequency, $\log_{10}$(Hz)
-10
-12
-14
-16
-18
-20
-22
-10
-8
-6
-4
-2
0
2
4

Expected GW sensitivity improvement vs time:



How to improve the measurement?

Easy way: Do nothing!

Currently happening:

- Discover/add more pulsars
- Better instrumentation
- Improved data analysis (more GW signals; ISM)

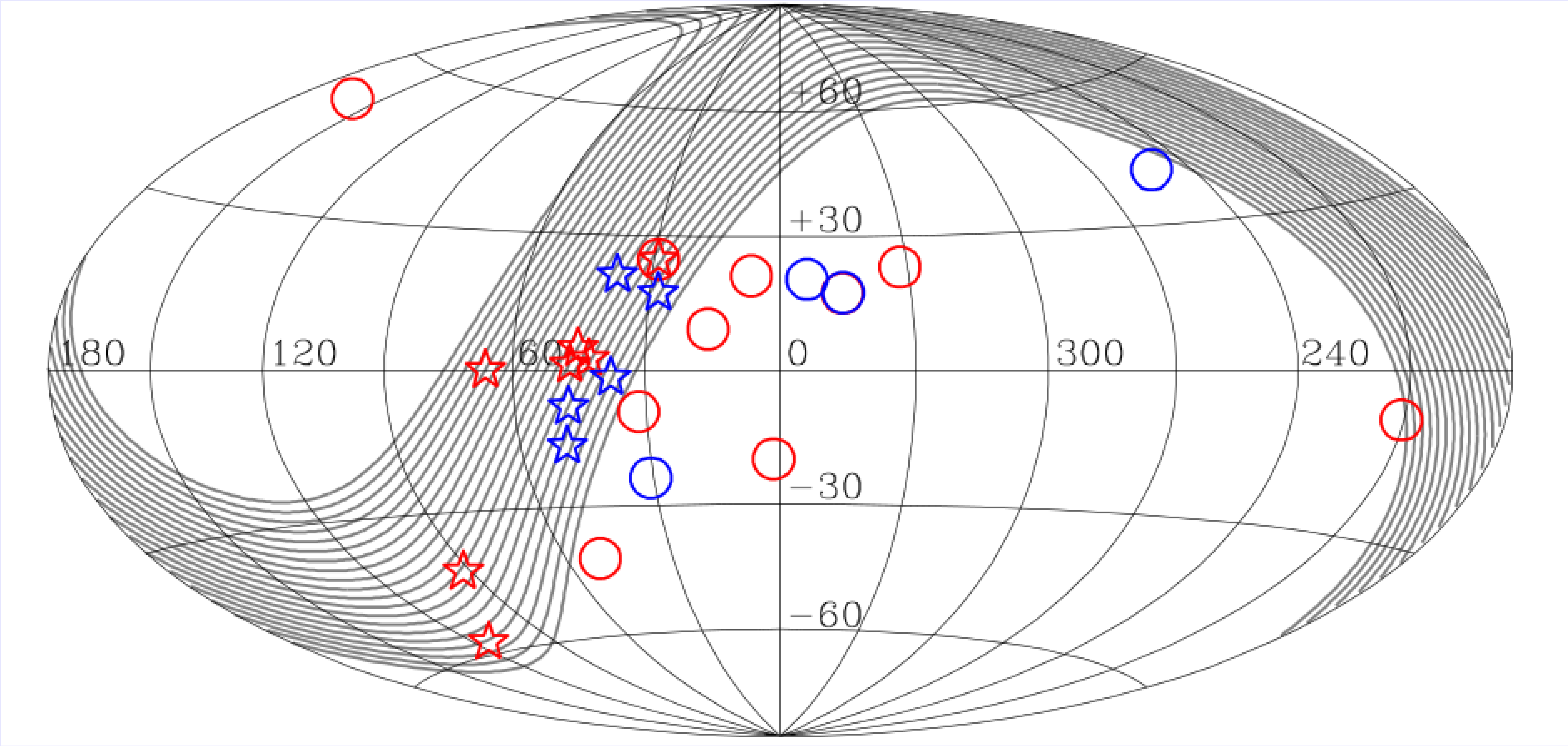
Near future:

- Increase observing time on current telescopes.
- Receiver upgrades

Long-term:

- More collecting area (larger telescopes).

Rapidly increasing number of MSPs:



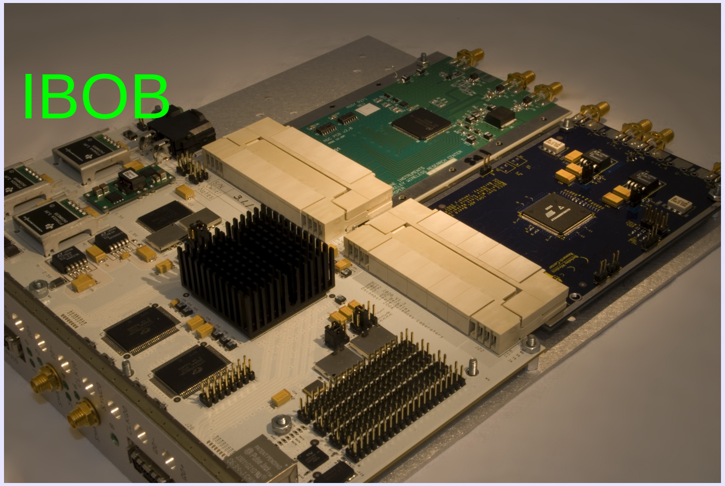
NANOGrav pulsars (in galactic coords):
red="classic", blue=recently added (past ~year)
From 17 orig sources -> 27 by later this year.

Driven by Fermi MSP discoveries; also GBNCC (GBT), PALFA (Arecibo), HTRU (Parkes) ongoing pulsar surveys.

New high-precision timing instrumentation:

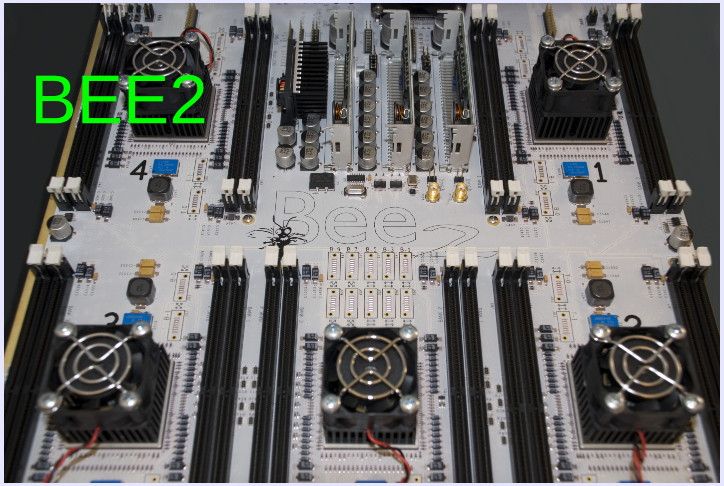
(Demorest, Ransom, Ford, McCullough, Ray, Brandt, Duplain)

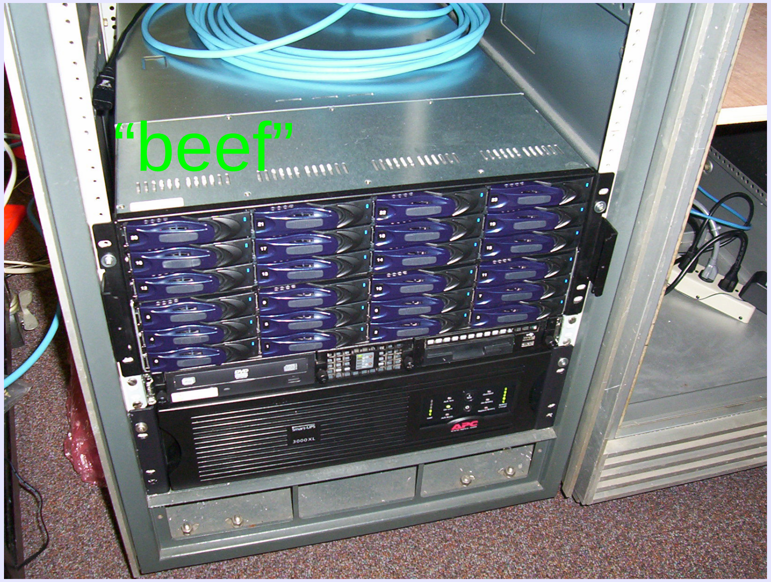
- GUPPI = Green Bank Ultimate Pulsar Processing Instrument
- Fully utilizes GBT low-freq receivers.
- Incorporates best features of 5 previous backends at GB.
  - Both search and timing/coherent modes.
  - 100, 200, or 800 MHz total BW
  - 8-bit ADCs, full-Stokes, flexible parameters (# channels, integration time, etc).



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

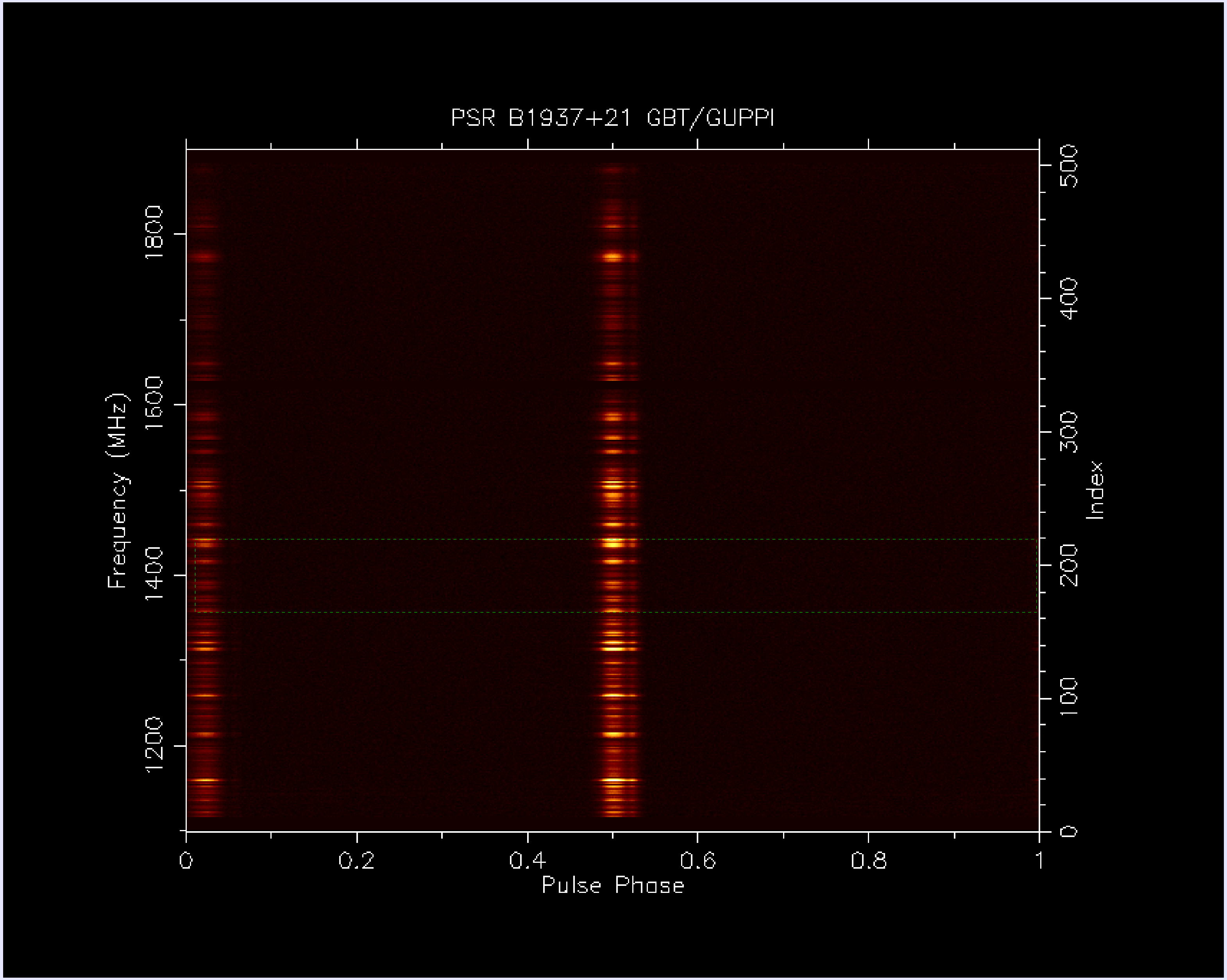
XAUI





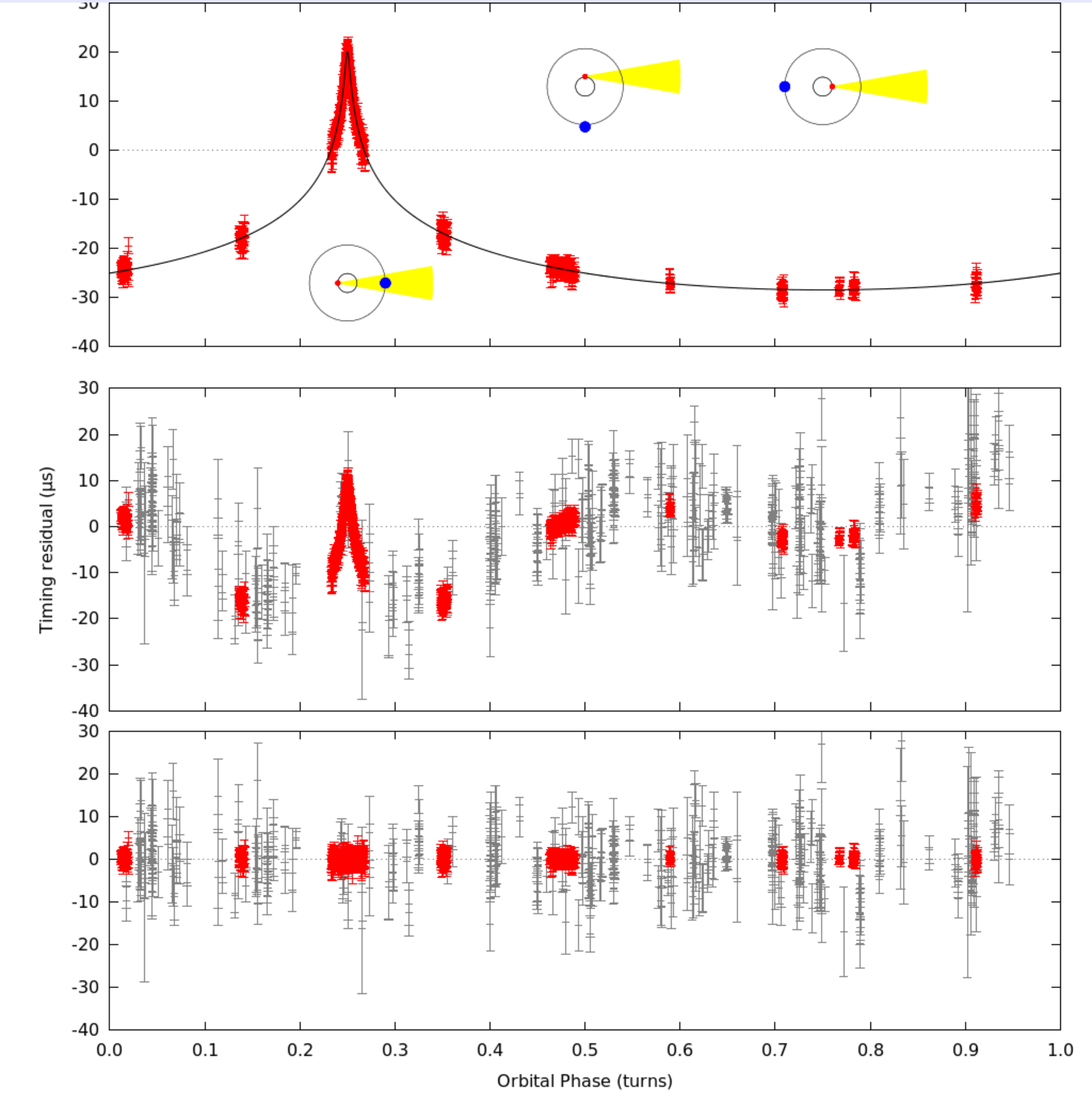
10 Ge
switch;
24 Gb/s

Coherent GUPPI first light
PSR B1937+21, 1100--1900 MHz



GASP band

J1614-2230 Shapiro delay timing with coherent GUPPI:



J1614-2230 is a NANOGrav PTA target

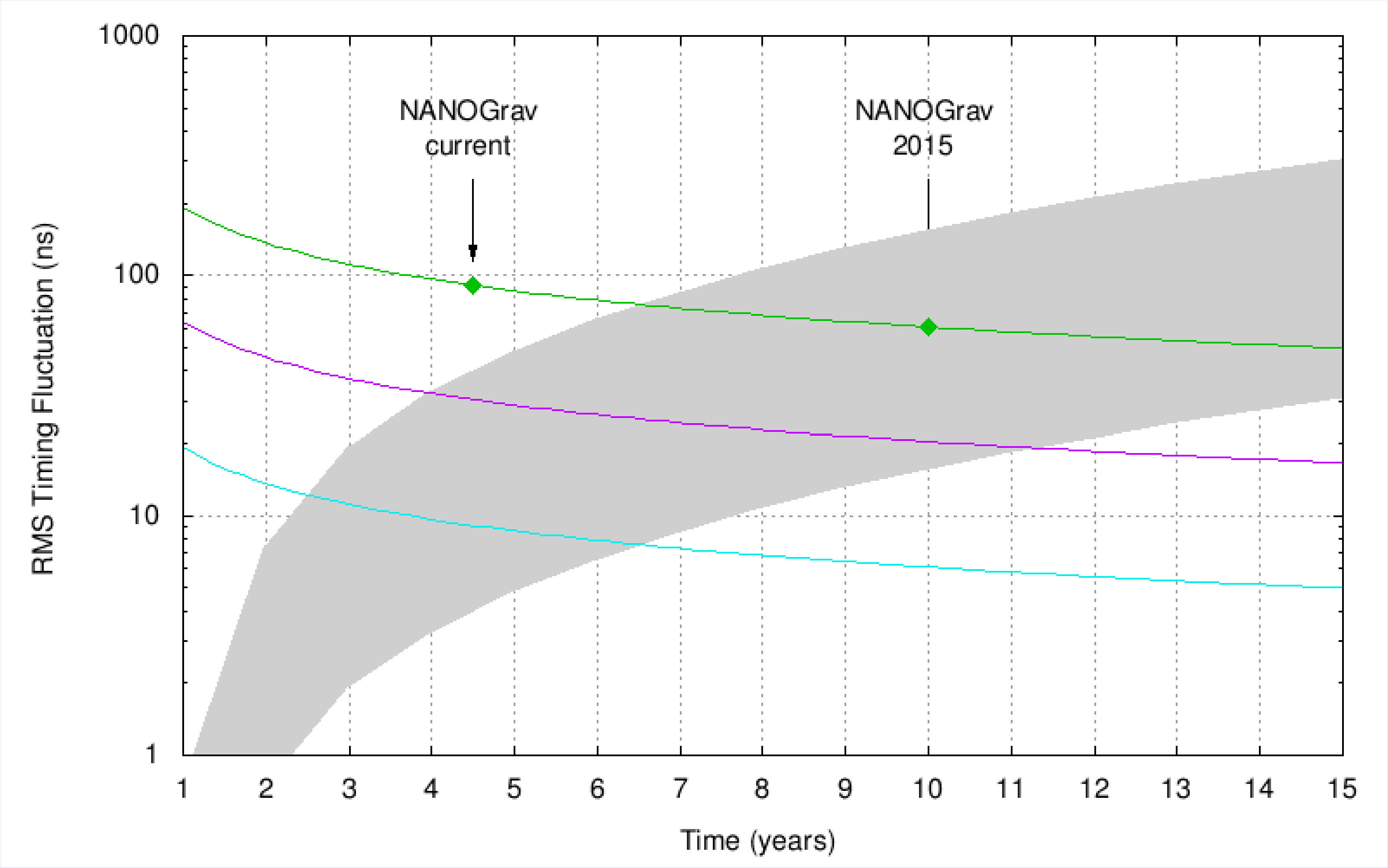
GUPPI gives 1 us timing in 1 minute.

Orbital inclination = 89.17(2) deg!

Pulsar mass = 1.97(4) solar!

(Demorest, Pennucci, Ransom, Roberts, Hessels, *Nature,* 2010)

Expected GW sensitivity improvement vs time:



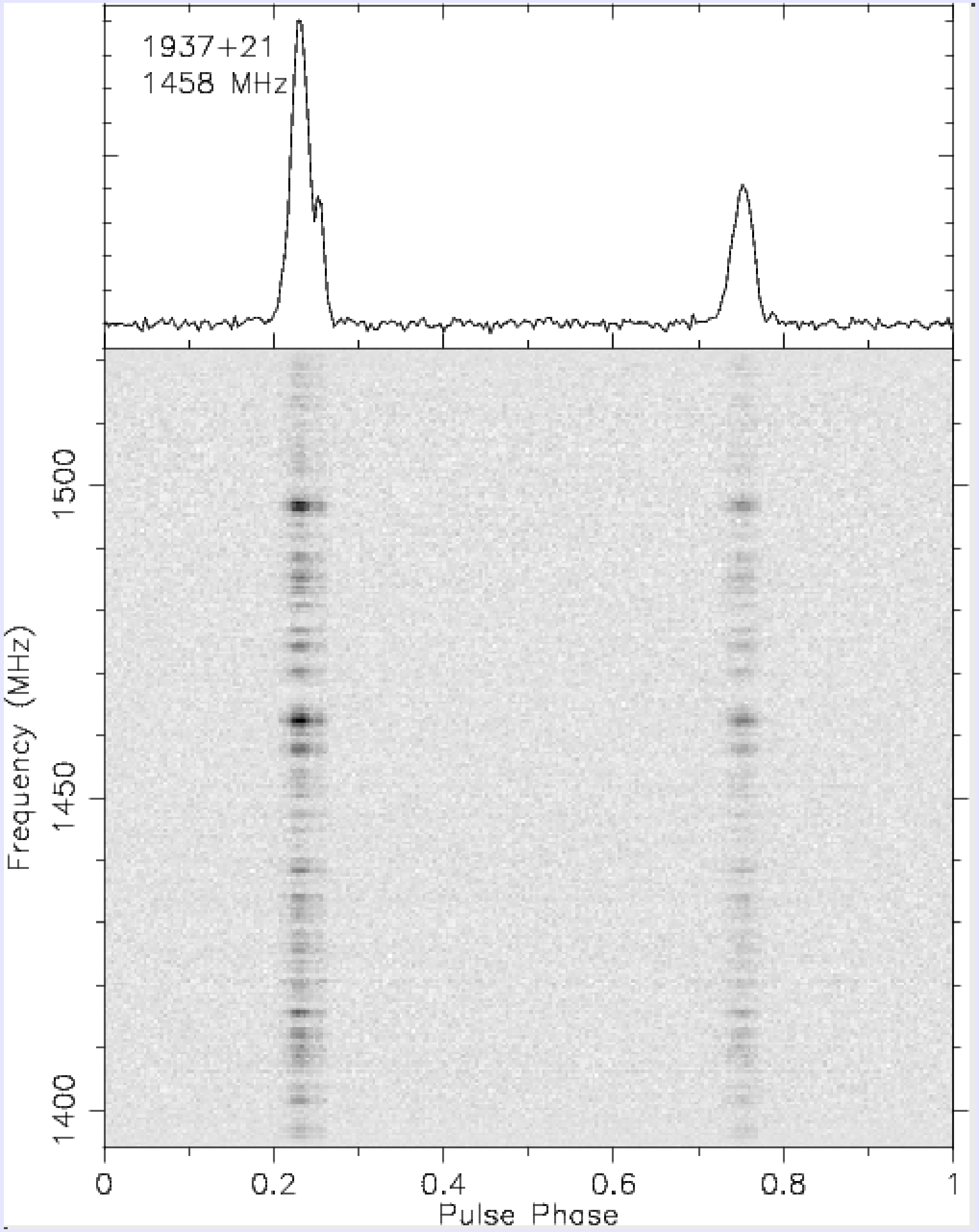
Improving existing telescope resources:

Current usage ~3% total time at GBT/Arecibo.

Wideband receiver upgrades (~0.8-3 GHz)

"PUPPI" for Arecibo is in progress.

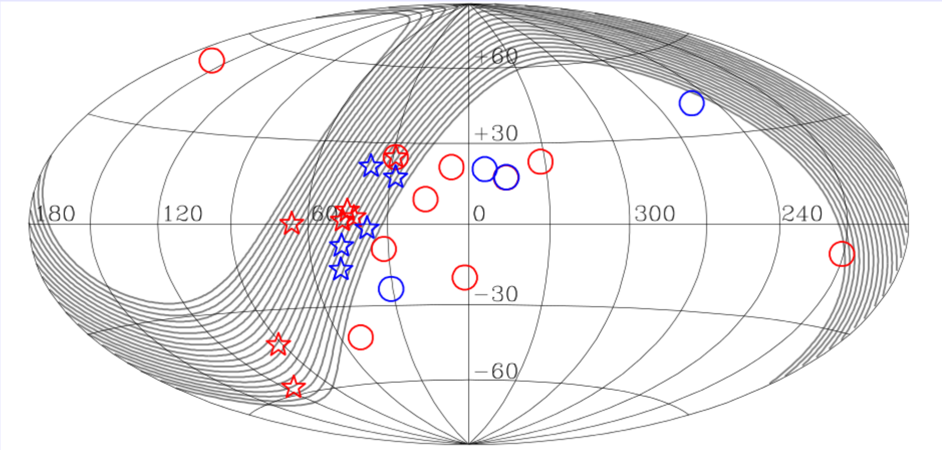
EVLA provides ~GBT sensitivity, and octave-BW receivers.



First EVLA pulsar detection!
(Feb 2011, PD, A. Deller)

Future telescopes

Main criteria: size (G/T) and location (sky coverage). Freq coverage ~0.8-3.0 GHz.



- MeerKAT (South Africa)
  - 64 13.5-m dishes. ~GBT sensitivity
  - Contributions: Add'l area, receivers, backends, expertise.
- FAST (China)
  - One 500-m dish! ~3x Arecibo sensitivity
- Dedicated PTA telescope?

Conclusions/Summary:

1. NANOGrav project aims to detect nHz-freq GW using pulsar timing.

2. Current best timing results at the ~40 ns level. GW detection is possible within the next ~5-10 years.

3. Ongoing discovery of new MSPs.

4. GUPPI instrument provides order-of-magnitude observational improvement.

5. Exciting near-future improvement from new telescopes (EVLA, MeerKAT, FAST, ...).