Testing physics with millisecond pulsars

Paul Demorest, NRAO

Talk outline:

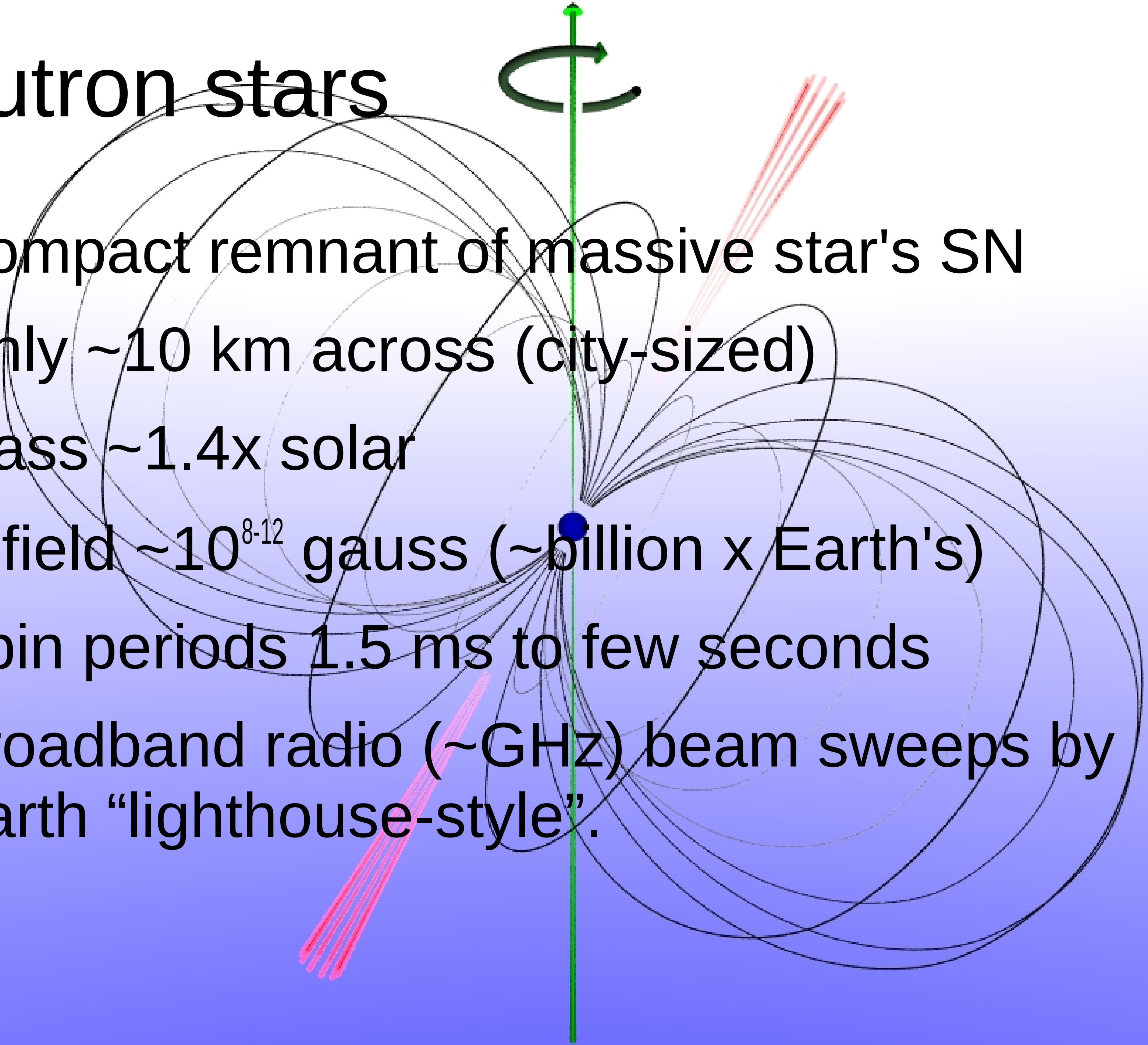
1. Intro: Neutron stars, millisecond pulsars

2. Digital instrumentation for radio pulsar observations

3. Mass of PSR J1614-2230

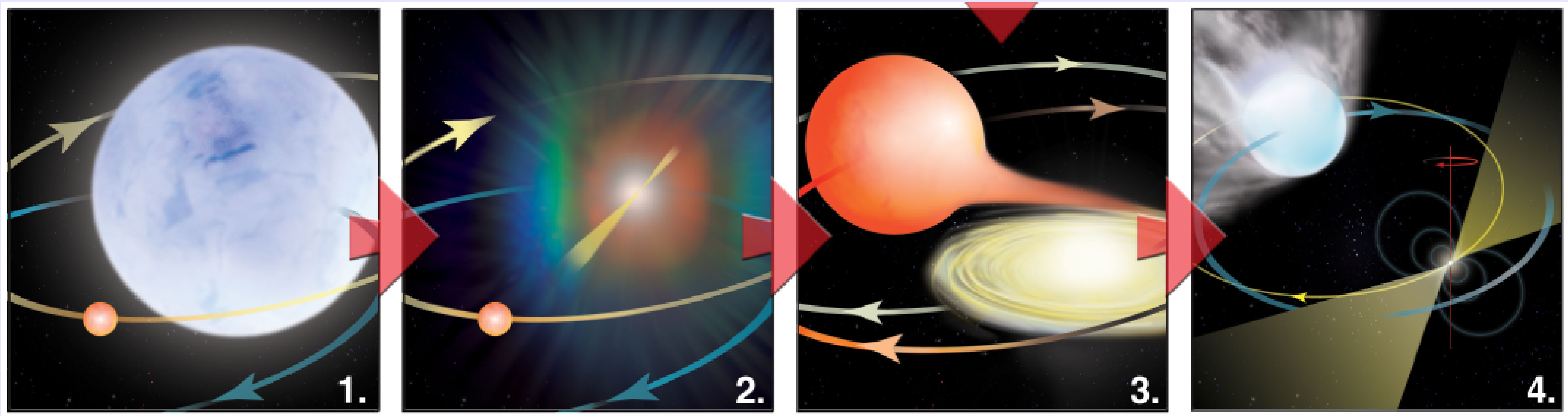
4. NANOGrav gravitational wave detection project

Neutron stars



- Compact remnant of massive star's SN
- Only ~10 km across (city-sized)
- Mass ~1.4x solar
- B-field ~$10^{8\text{-}12}$ gauss (~billion x Earth's)
- Spin periods 1.5 ms to few seconds
- Broadband radio (~GHz) beam sweeps by Earth “lighthouse-style”.

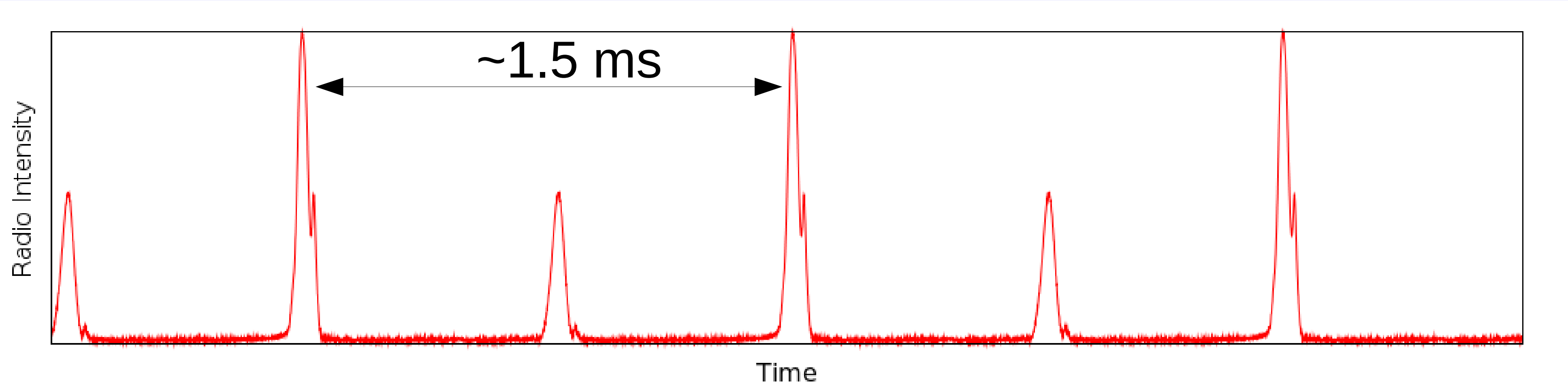
About 10% of observed radio pulsars are “recycled” millisecond pulsars (MSPs). These are spun up by accreting matter from a companion star:



(Image: B. Saxton, NRAO)

This produces very “clean” compact binary systems (NS-WD or NS-NS).

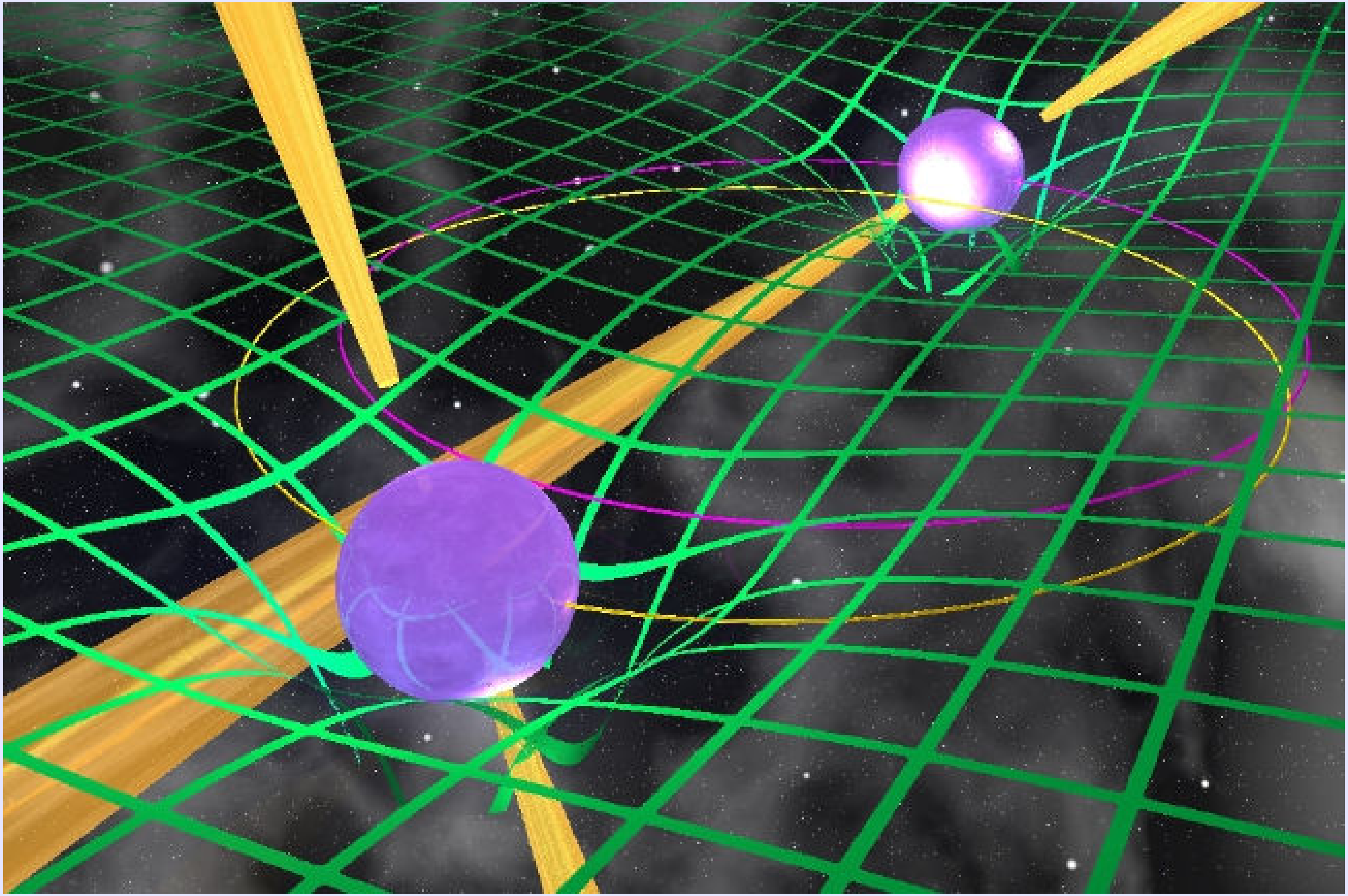
By timing pulses over many years, MSPs act as *extremely* precise astronomical clocks:



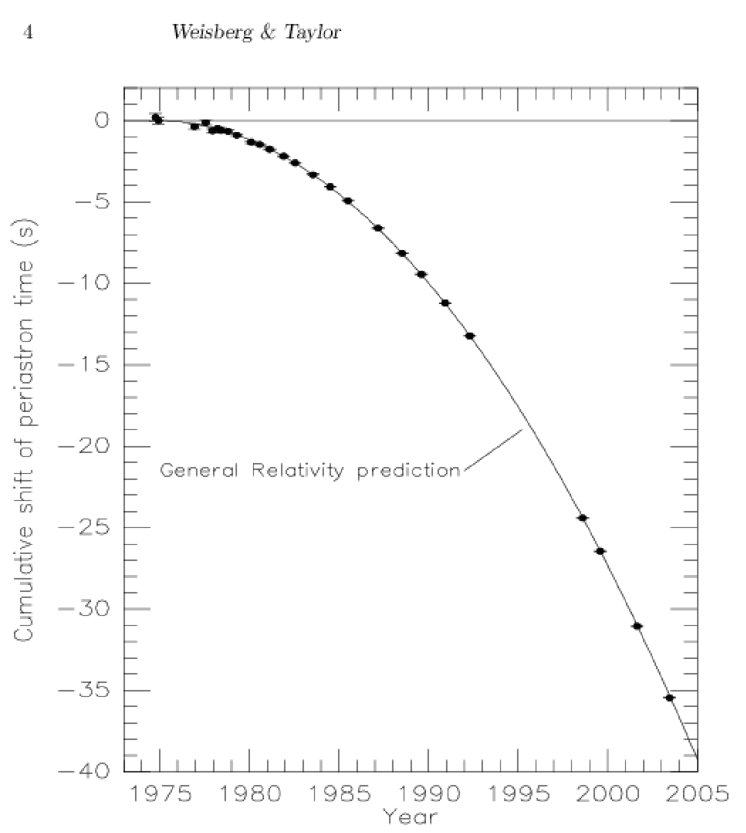
Average spin period of PSR B1937+21 :

P = 1.5578064688197945 ms
+/- 0.0000000000000004 ms !

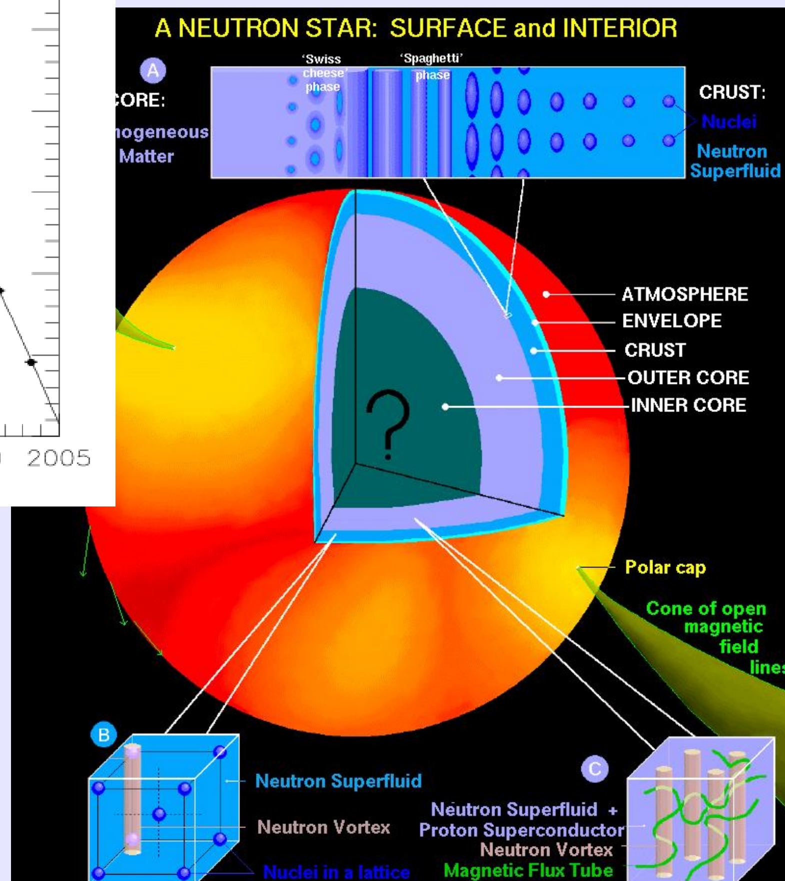
Enables high-precision measurements of orbits and other gravitational effects.



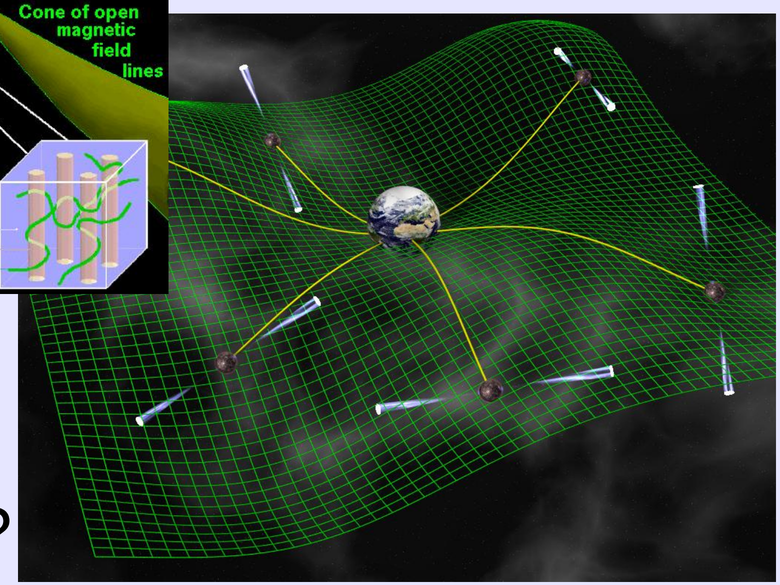
High precision plus extreme environment make them unique astronomical “laboratories”.



Testing gravity / GR

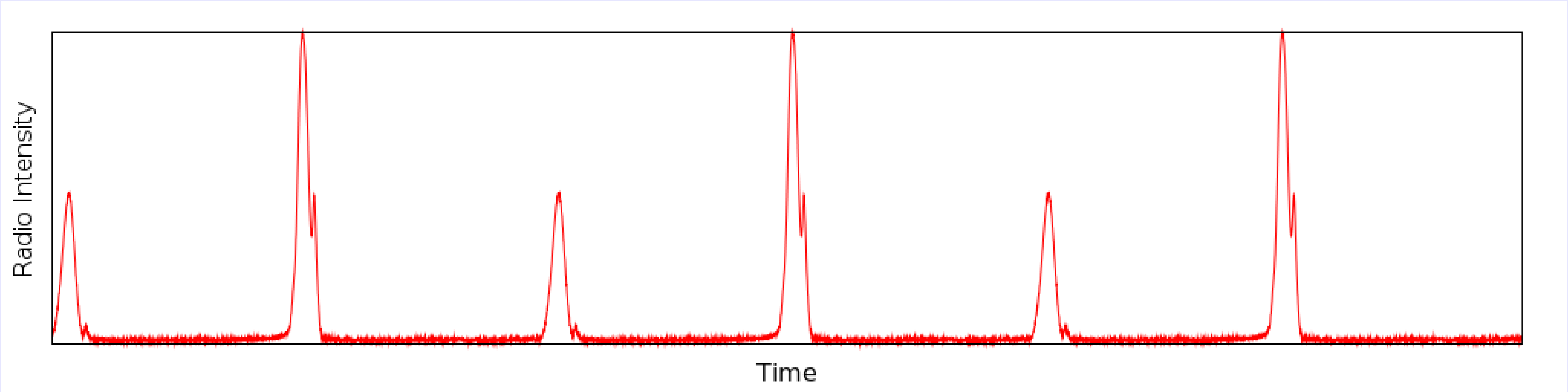


Properties of nuclear matter



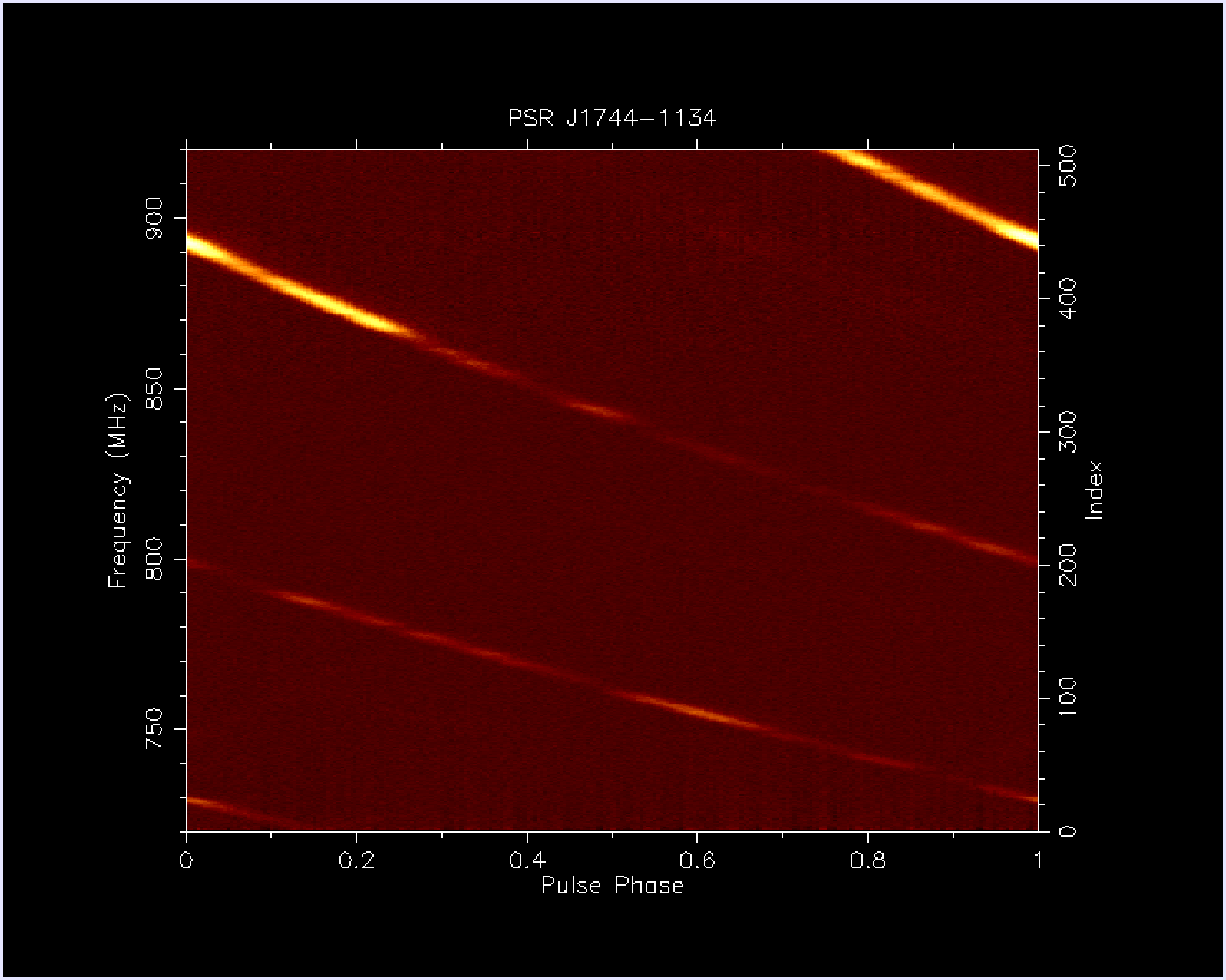
Detecting GW?

- 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

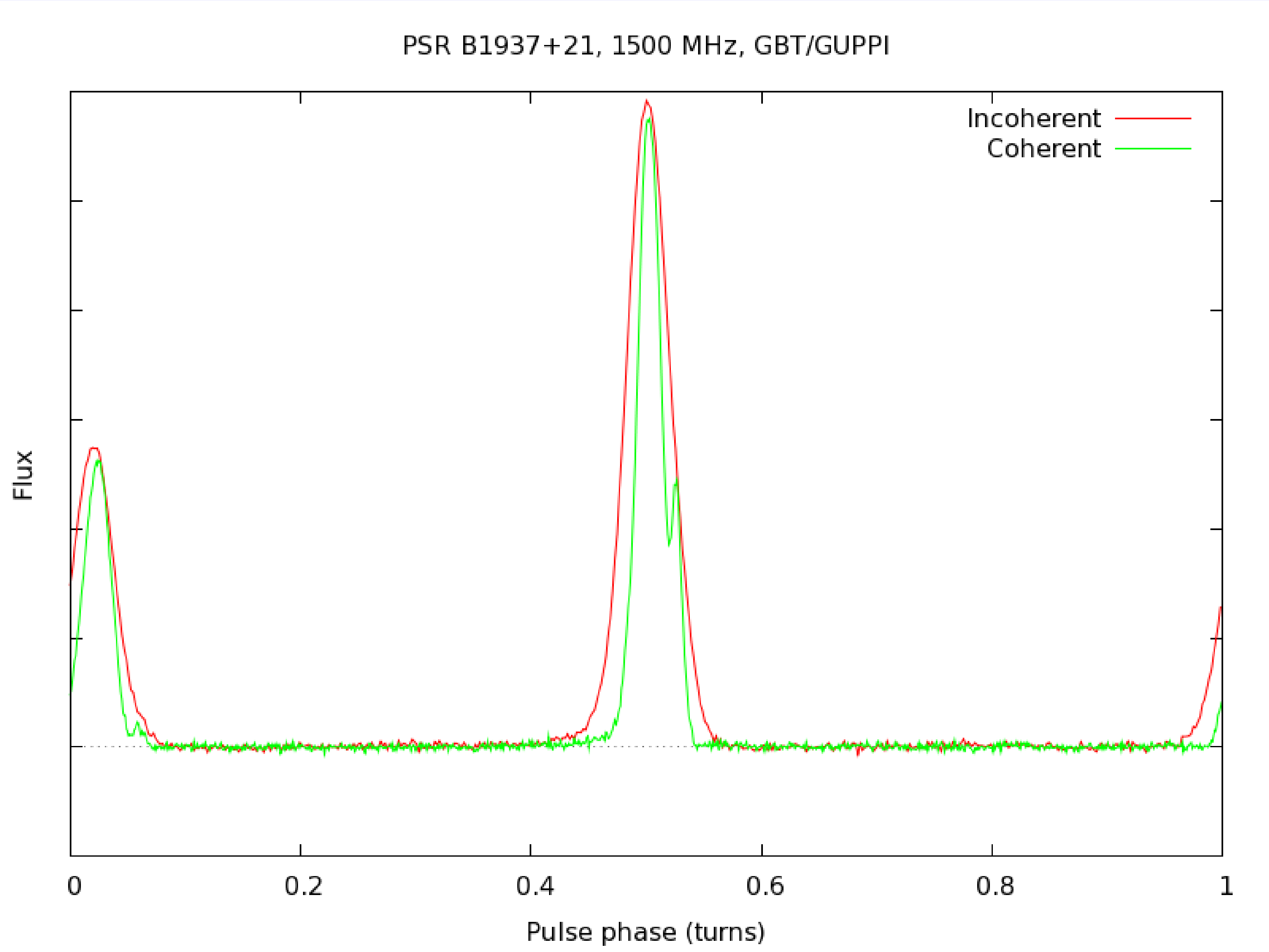
Due to travel of pulsar signal through ionized ISM.



Dispersion measure (slope of signal in plot) proportional to total electron column density.

Coherent dedispersion

DM-specific pre-detection filter sharpens pulses, leading to better TOA measurements:

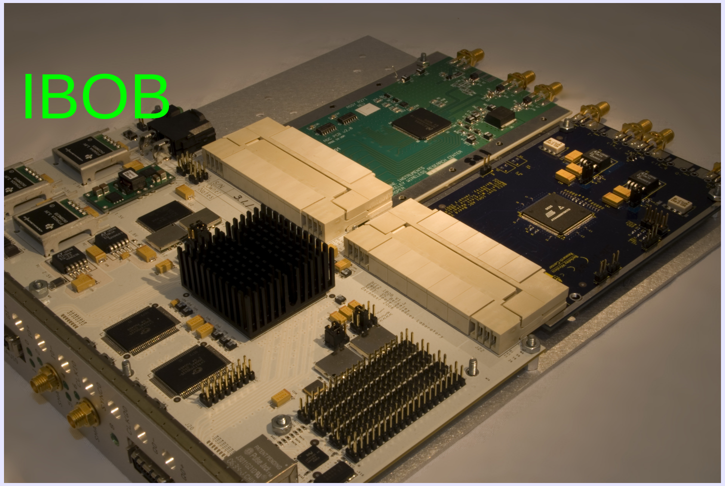


New high-precision timing instrumentation:
(Demorest, Ransom, Ford, McCullough, Ray, Brandt, Duplain)

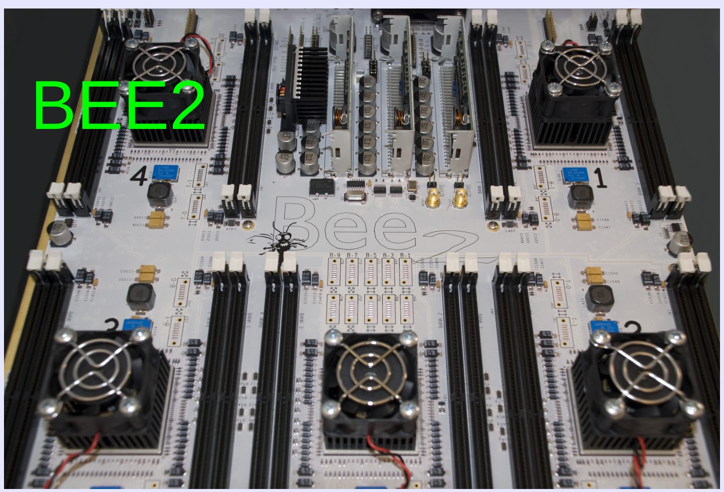
- GUPPI = Green Bank Ultimate Pulsar Processing Instrument
- CASPER (FPGA) HW plus 9-node GPU cluster.
- Incorporates best features of 5 previous backends at GB.
  - Both search and timing/coherent modes.
  - 100, 200, or 800 MHz total BW
  - 8-bit ADCs, full-Stokes, flexible parameters (# channels, integration time, etc).

Green Bank Telescope: 100-m, fully steerable

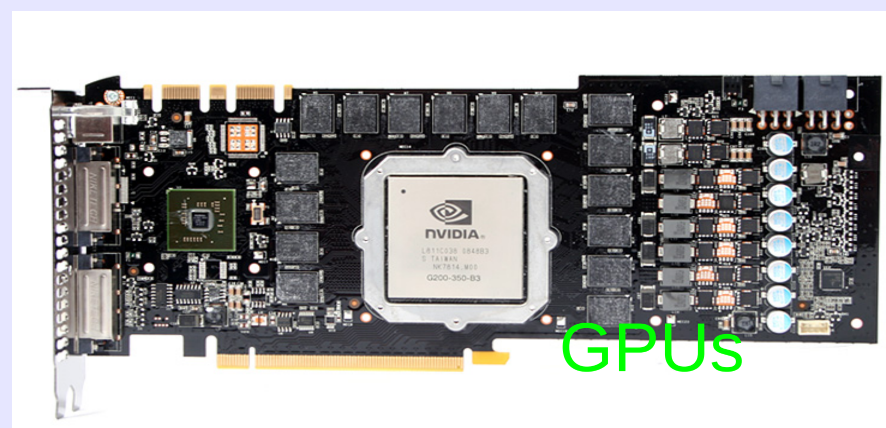
GUPPI architecture:
~1 MHz PFB in FPGAs
Coherent dedisp in GPUs



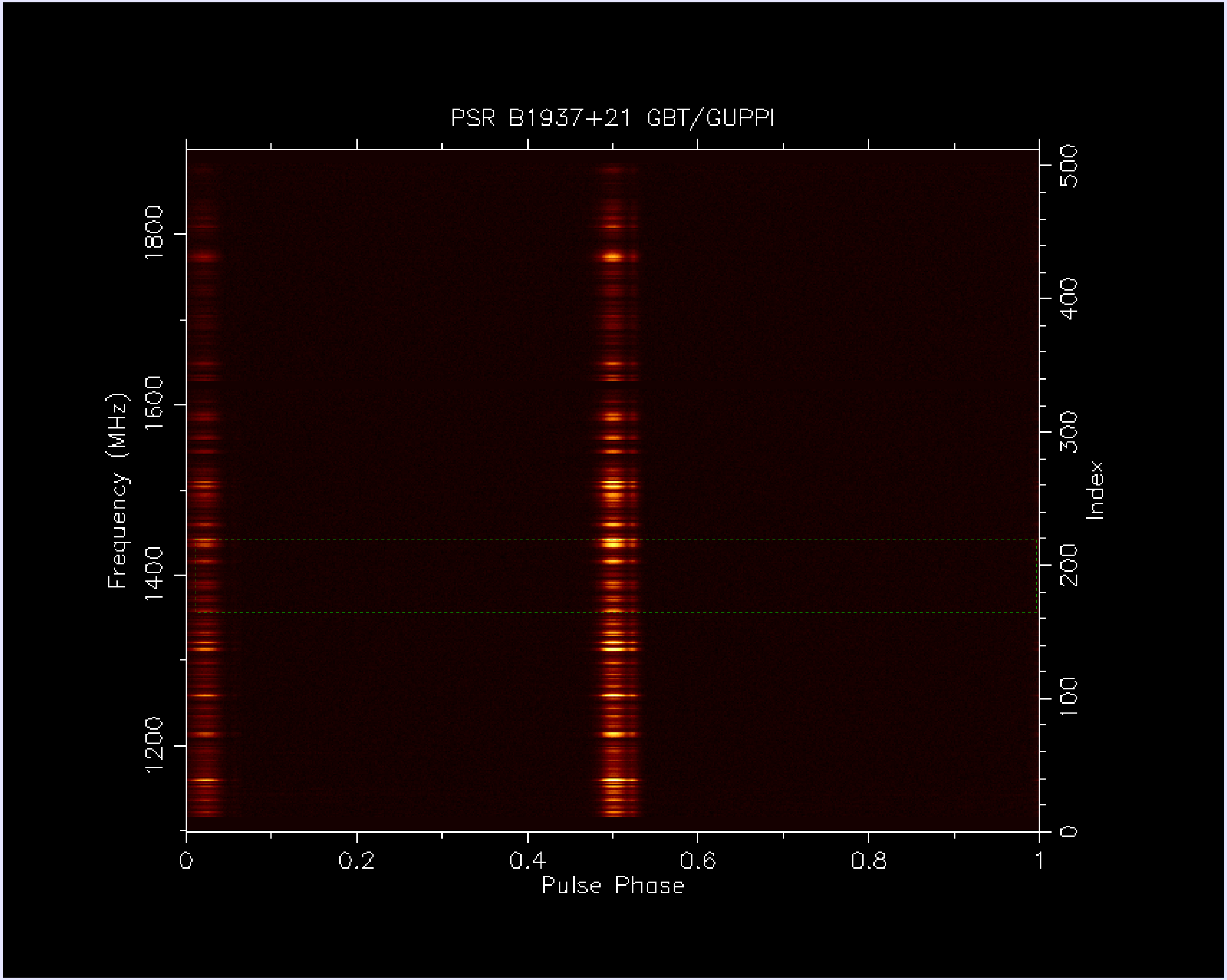
XAUI



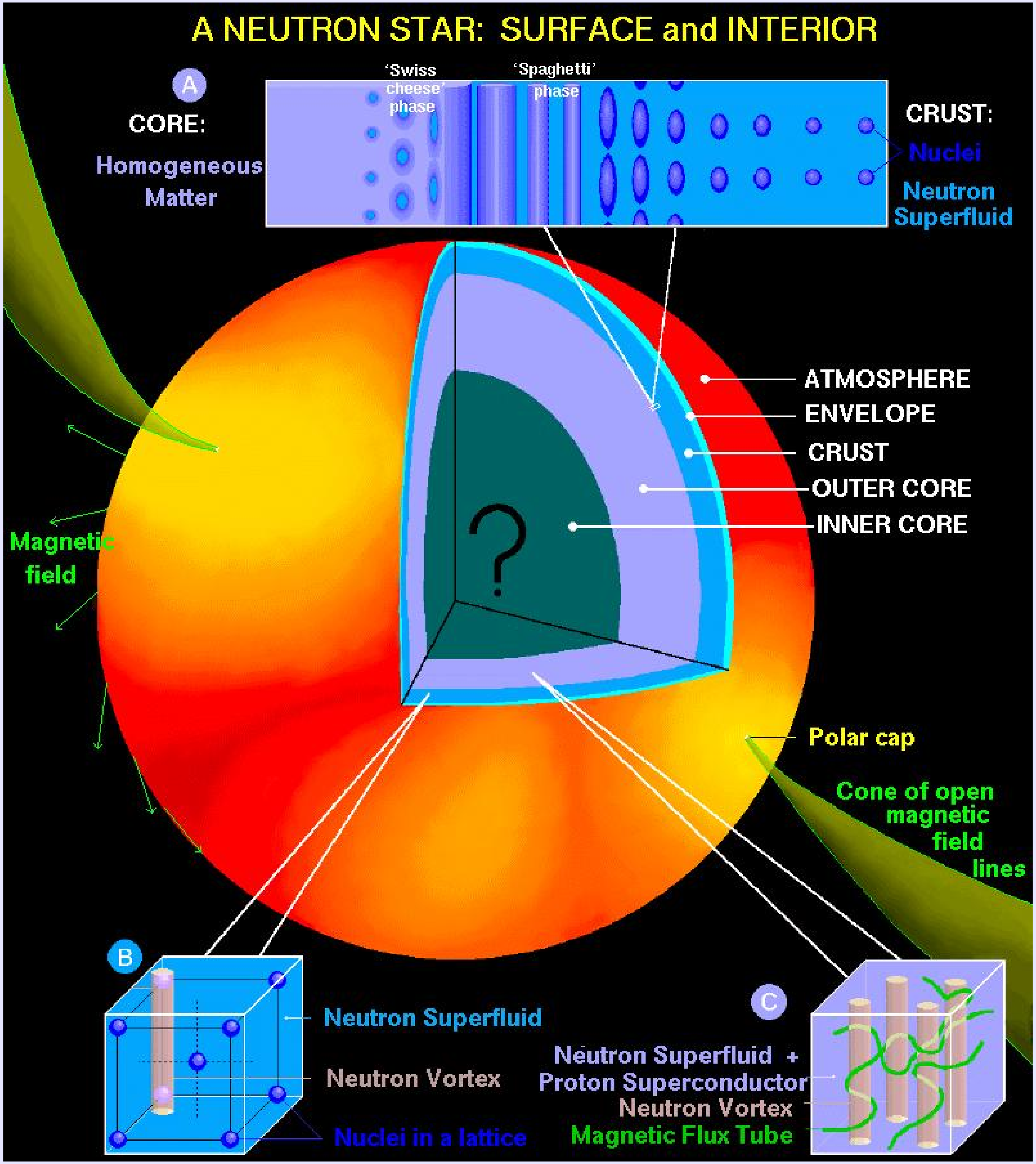
10 Ge
switch;
24 Gb/s



Coherent GUPPI first light
December 2009, PSR B1937+21, 1100--1900 MHz



GASP
band



Central density is several times that of an atomic nucleus.

So what is the "?" ....

… just neutrons?

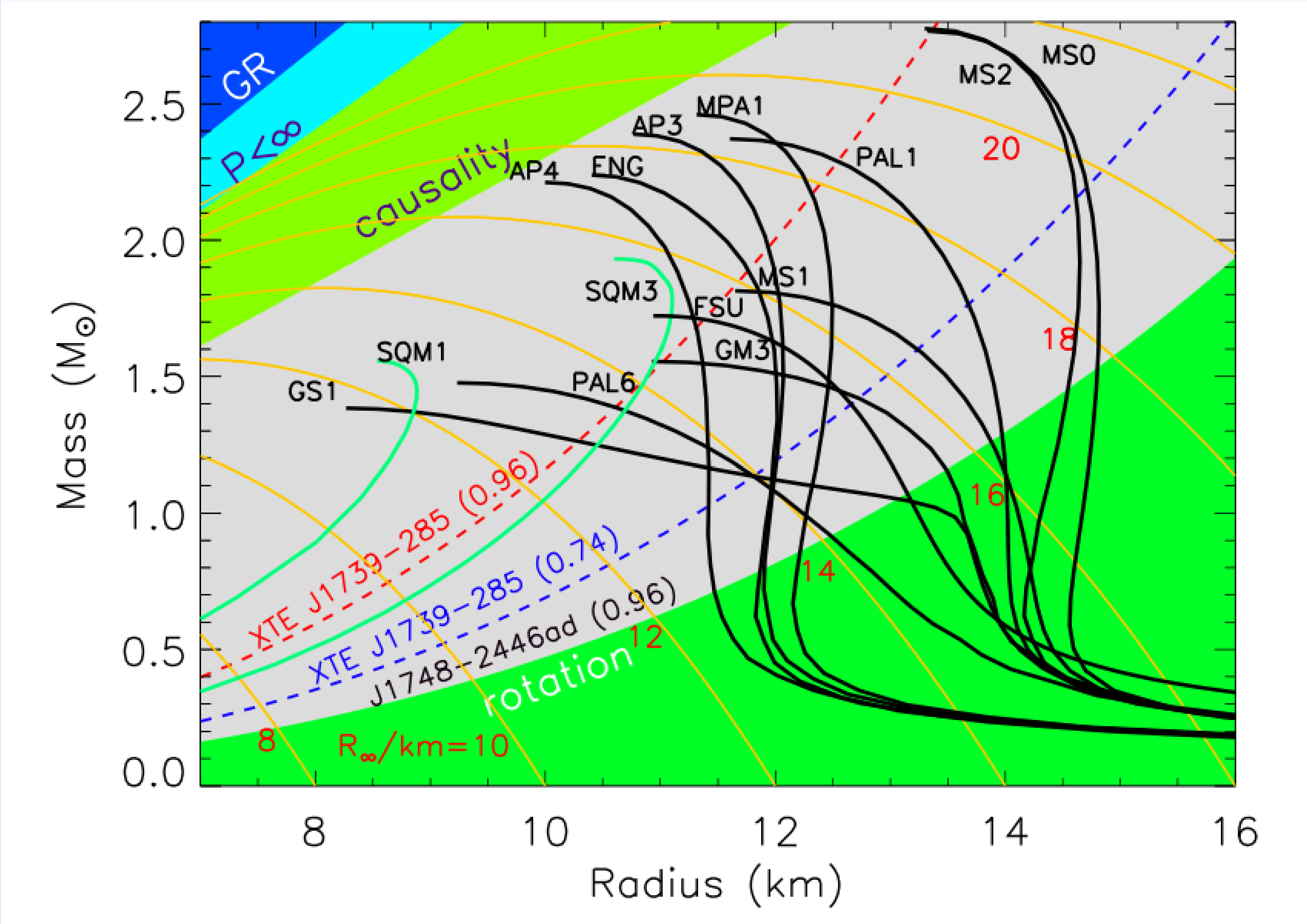
… hyperons?

… kaon condensate?

… free quarks?

Each makes a specific prediction for the NS equation of state.

(see reviews by Lattimer & Prakash, 2004, 2007)



(Lattimer & Prakash, 2007)

Each EOS predicts a specific mass vs radius line.
Mass or radius measurements experimentally constrain the EOS.

Measuring masses via pulsar timing

Besides the normal 5 "Keplerian" orbital parameters (P_{orb}, e, a*sin*(*i*)/c, T_0, ω), General Relativity gives:

$$\dot{\omega} = 3\left(\frac{P_b}{2\pi}\right)^{-5/3} (T_\odot M)^{2/3} (1-e^2)^{-1}$$

(Orbital Precession)

$$\gamma = e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2 (m_1 + 2m_2)$$

(Grav redshift + time dilation)

$$\dot{P}_b = -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) (1-e^2)^{-7/2} T_\odot^{5/3} m_1 m_2 M^{-1/3}$$

$$r = T_\odot m_2$$

$$s = x\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}$$

(Shapiro delay: "range" and "shape")

where: $T_\odot \equiv GM_\odot/c^3$ = 4.925490947 μs, $M = m_1 + m_2$, and $s \equiv \sin(i)$

These are only functions of:

- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
- the mass of the pulsar m_1 and the mass of the companion m_2

(Slide courtesy of S. Ransom)

Measuring masses via pulsar timing

Besides the normal 5 “Keplerian” orbital parameters (P_{orb}, e, a*sin*(*i*)/c, T_0, ω), General Relativity gives:

$\dot{\omega} =$	Need eccentric orbit and time for precession		(Orbital Precession)
$\gamma =$			(Grav redshift + time dilation)
$\dot{P}_b =$	Need compact orbit and a lot of patience		
$r =$	Need high precision, Inclination, and m_2		(Shapiro delay: “range” and “shape”)
$s =$			

where: $T_\odot \equiv GM_\odot/c^3 = 4.925490947\ \mu s$, $M = m_1 + m_2$, and $s \equiv \sin(i)$

These are only functions of:

- the (precisely!) known Keplerian orbital parameters P_b, e, asin(i)
- the mass of the pulsar m_1 and the mass of the companion m_2

(Slide courtesy of S. Ransom)

Multiple relativistic params

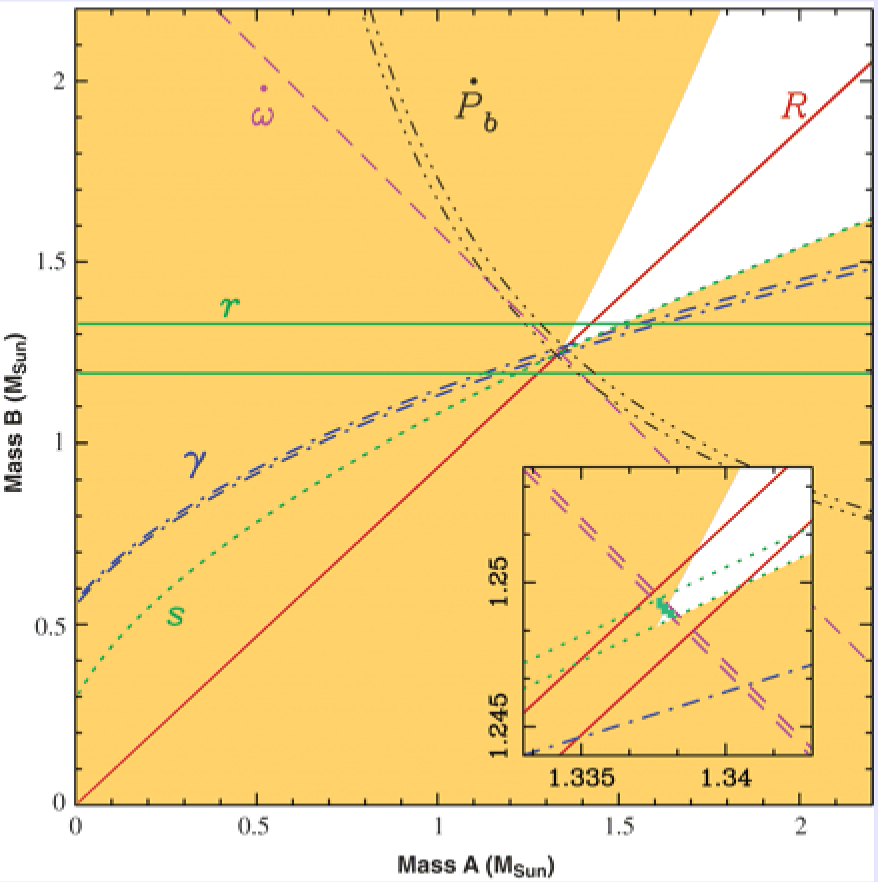
2 PK parameters → measurements of both masses without cos(i) assumptions.

3 or more → tests GR for consistency.

Commonly done in double-NS binaries (eccentric, compact orbits).

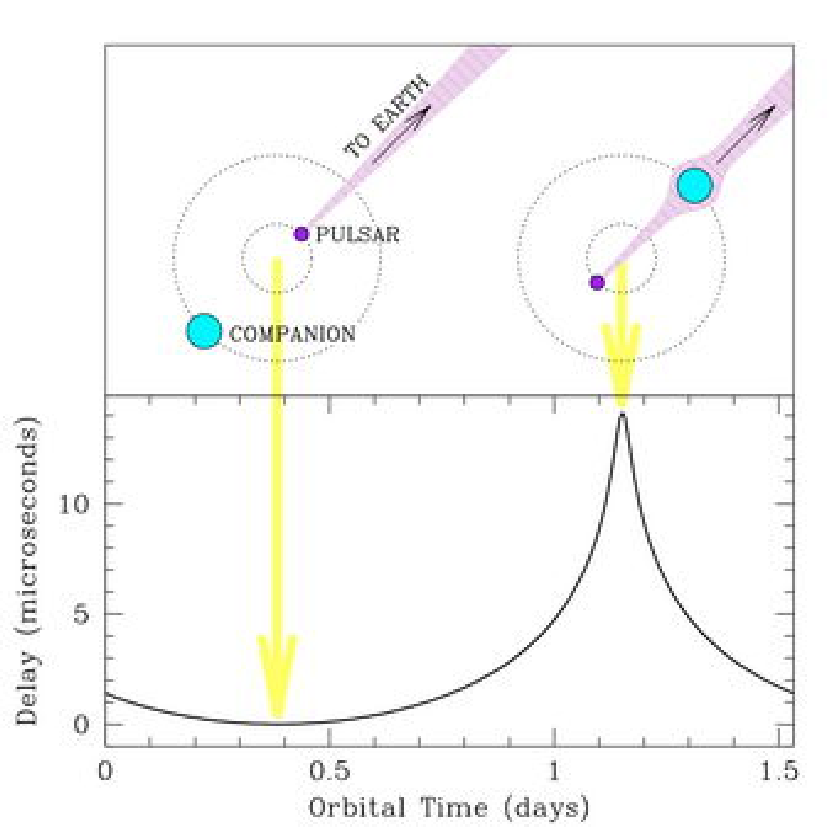
$$
\begin{aligned}
\dot{\omega} &= 3\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}(1-e^2)^{-1} \\
\gamma &= e\left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} m_c(m_p+2m_c) \\
\dot{P}_b &= -\frac{192\pi}{5}\left(\frac{P_b}{2\pi}\right)^{-5/3} f(e) T_\odot^{5/3} m_p m_c M^{-1/3} \\
r &= T_\odot m_c \\
s &= \sin i,
\end{aligned}
$$

"Post-Keplerian" orbital parameters, each provides a different constraint in mass-mass plane:



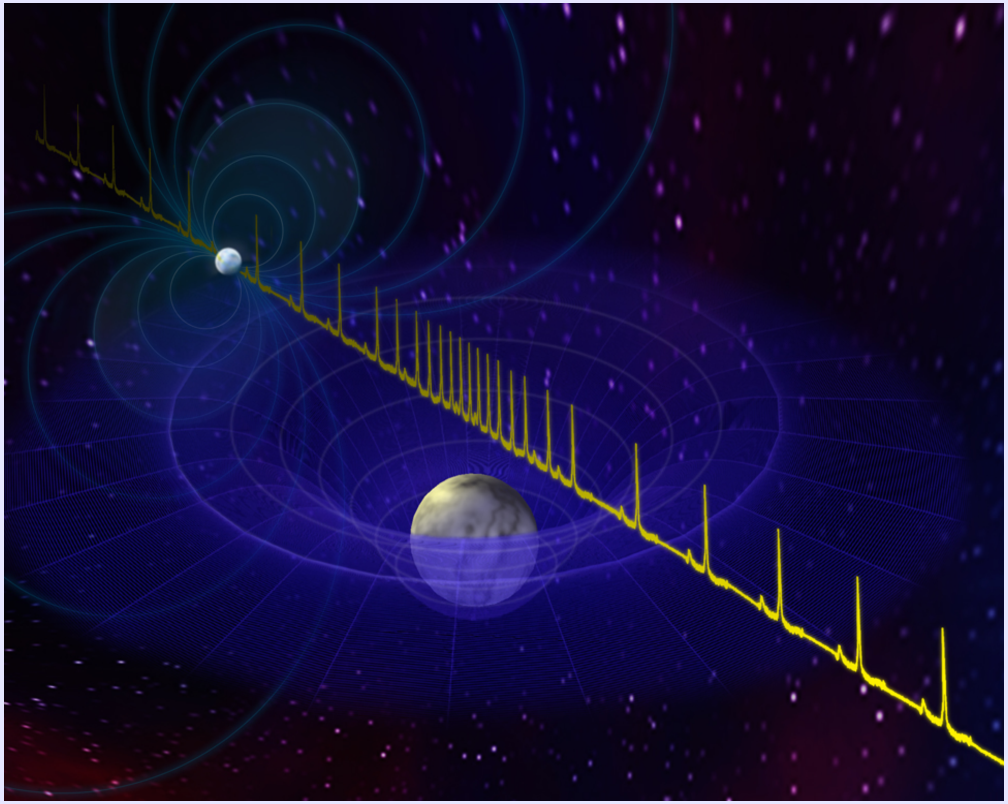
(J0737-3039; Kramer et al. 2006)

Shapiro delay: GR-induced delay as pulses pass by companion star.



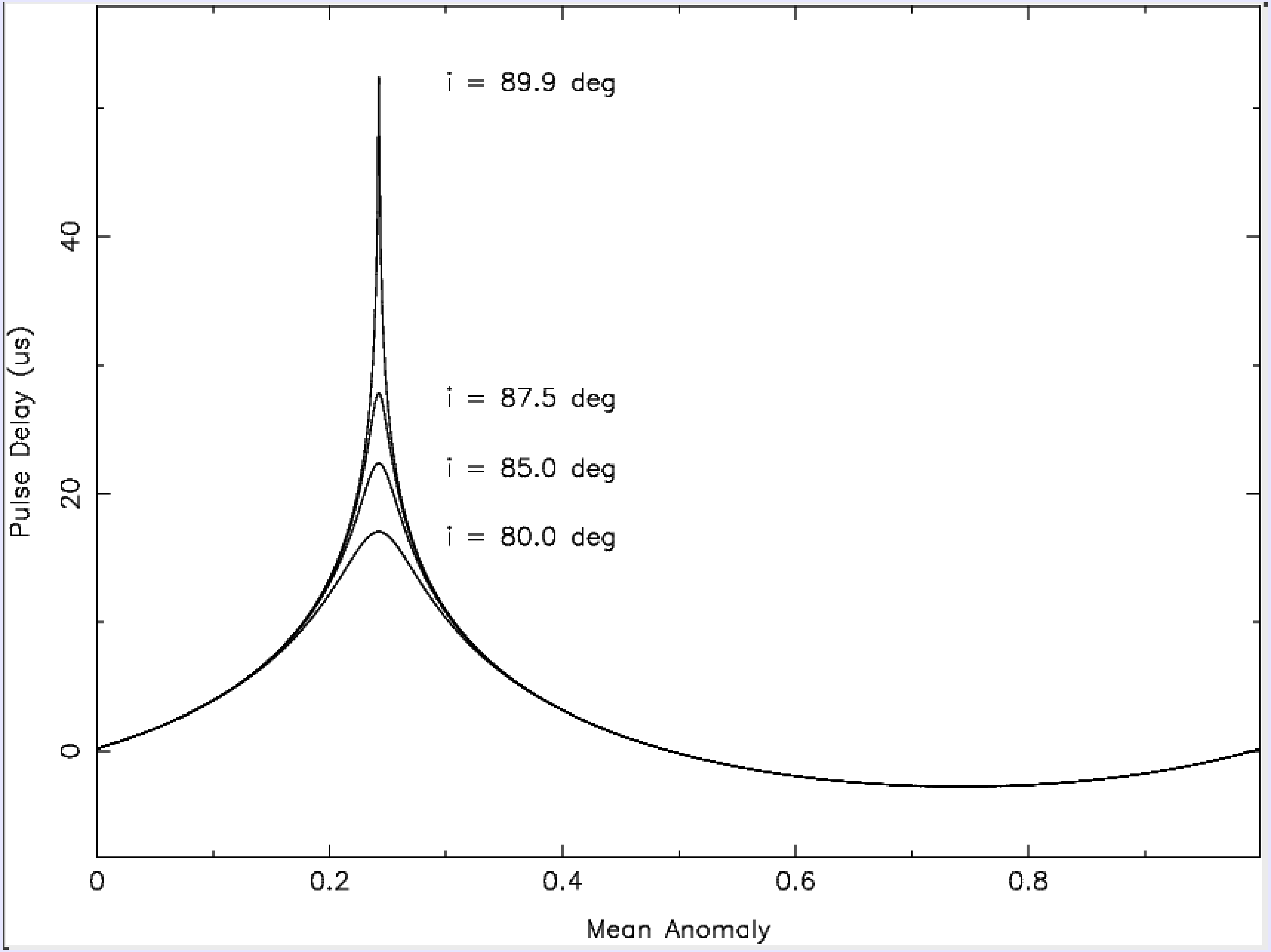
<--- Astronomer version

Graphic artist version --->



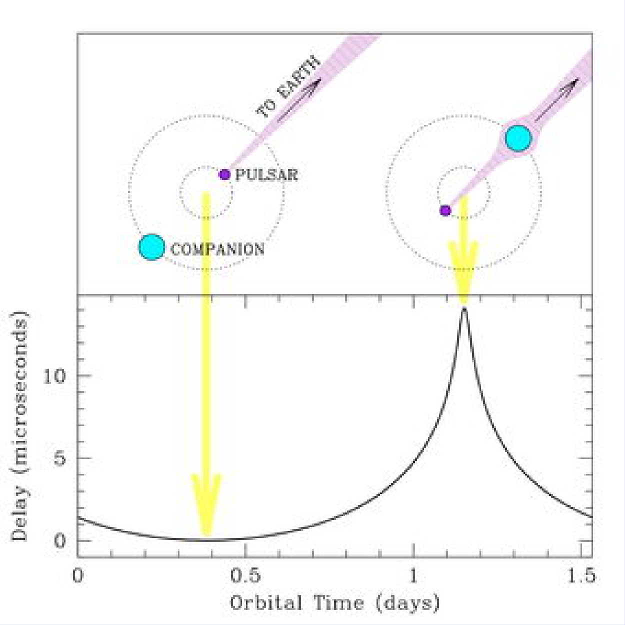
(Image: B. Saxton, NRAO)

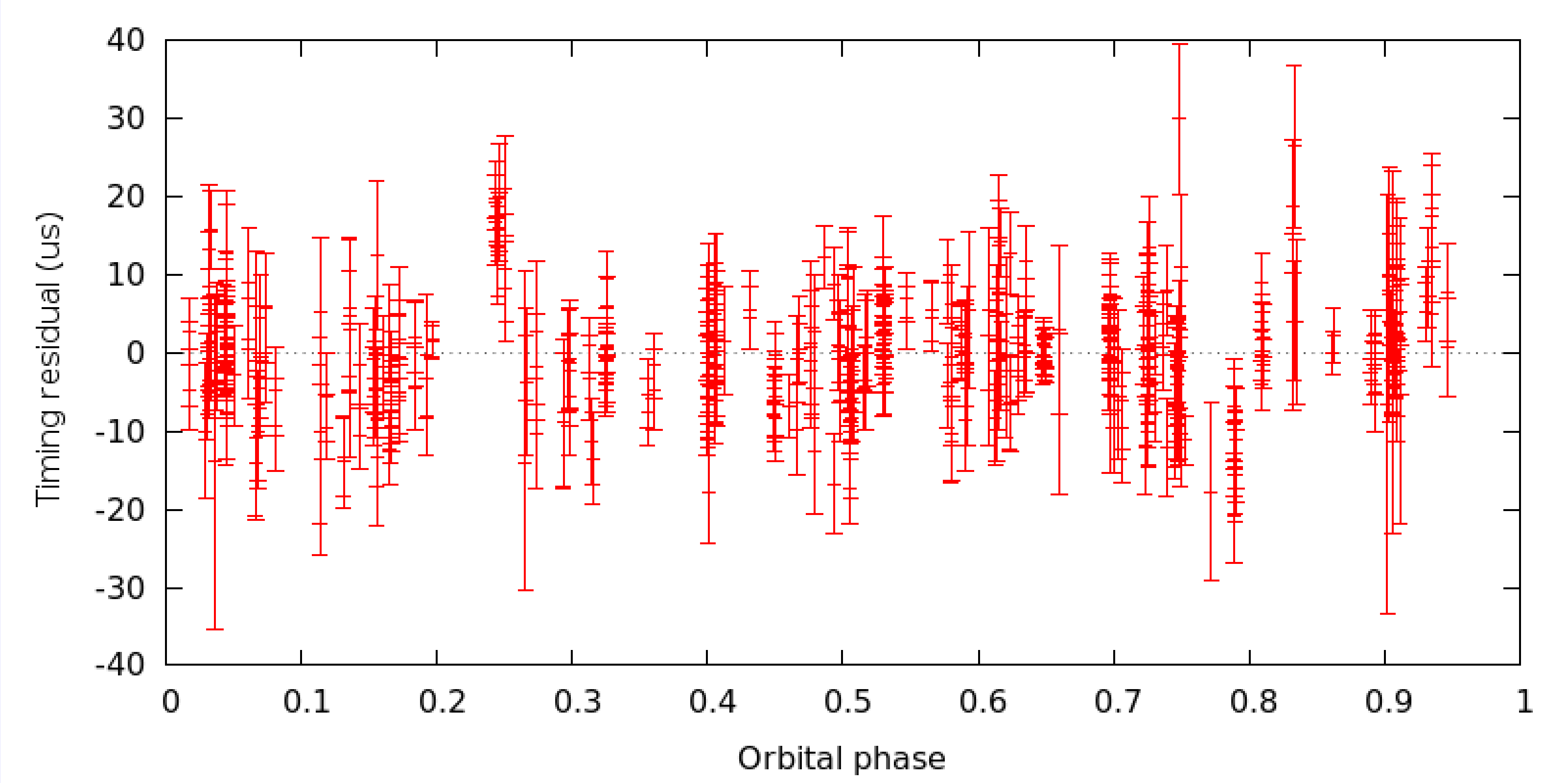
Shapiro delay amplitude strongly dependent on geometry:



PSR J1614-2230 is a 3-ms pulsar in an 8.7-day orbit with a WD.

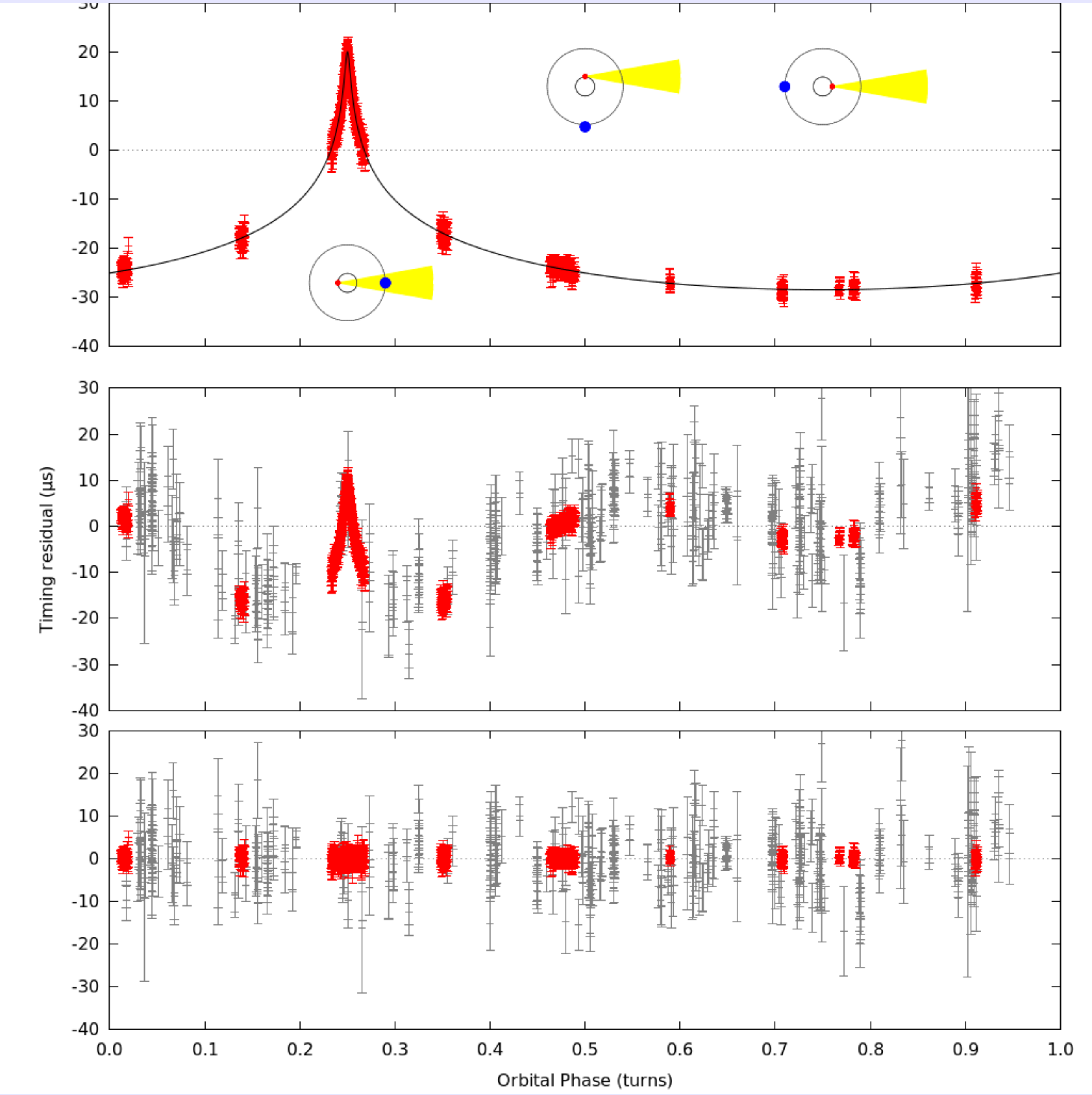
Marginal Shapiro delay after ~7 years of GBT timing with Spigot, BCPM, GUPPI-1, etc:





“Timing residuals” = Observed – predicted (model fit) pulse arrival times

... ~1 week of dense timing observations with coherent GUPPI:



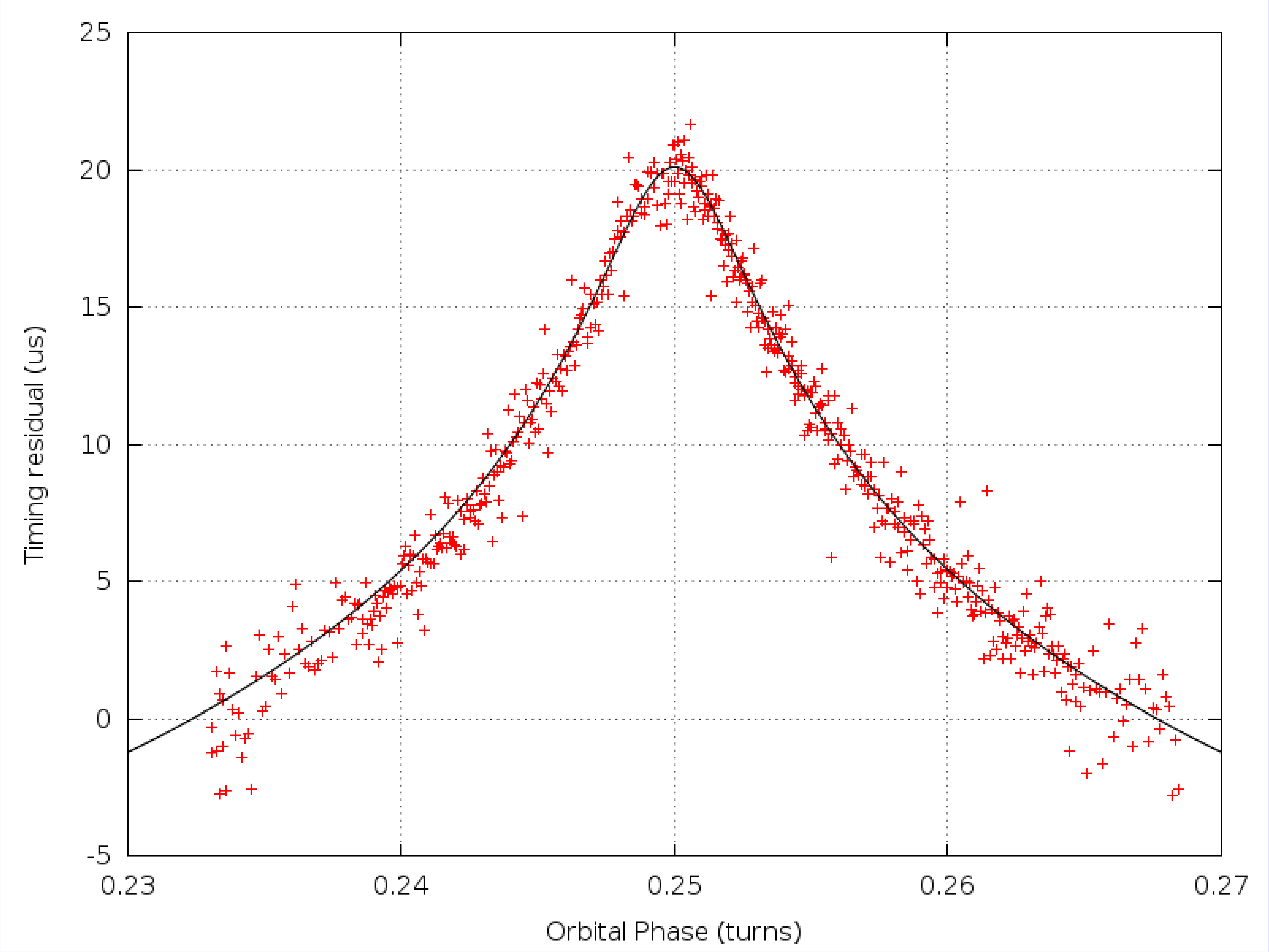
Orbital inclination = 89.17(2) deg!

Companion mass = 0.500(6) solar!

Pulsar mass = 1.97(4) solar!

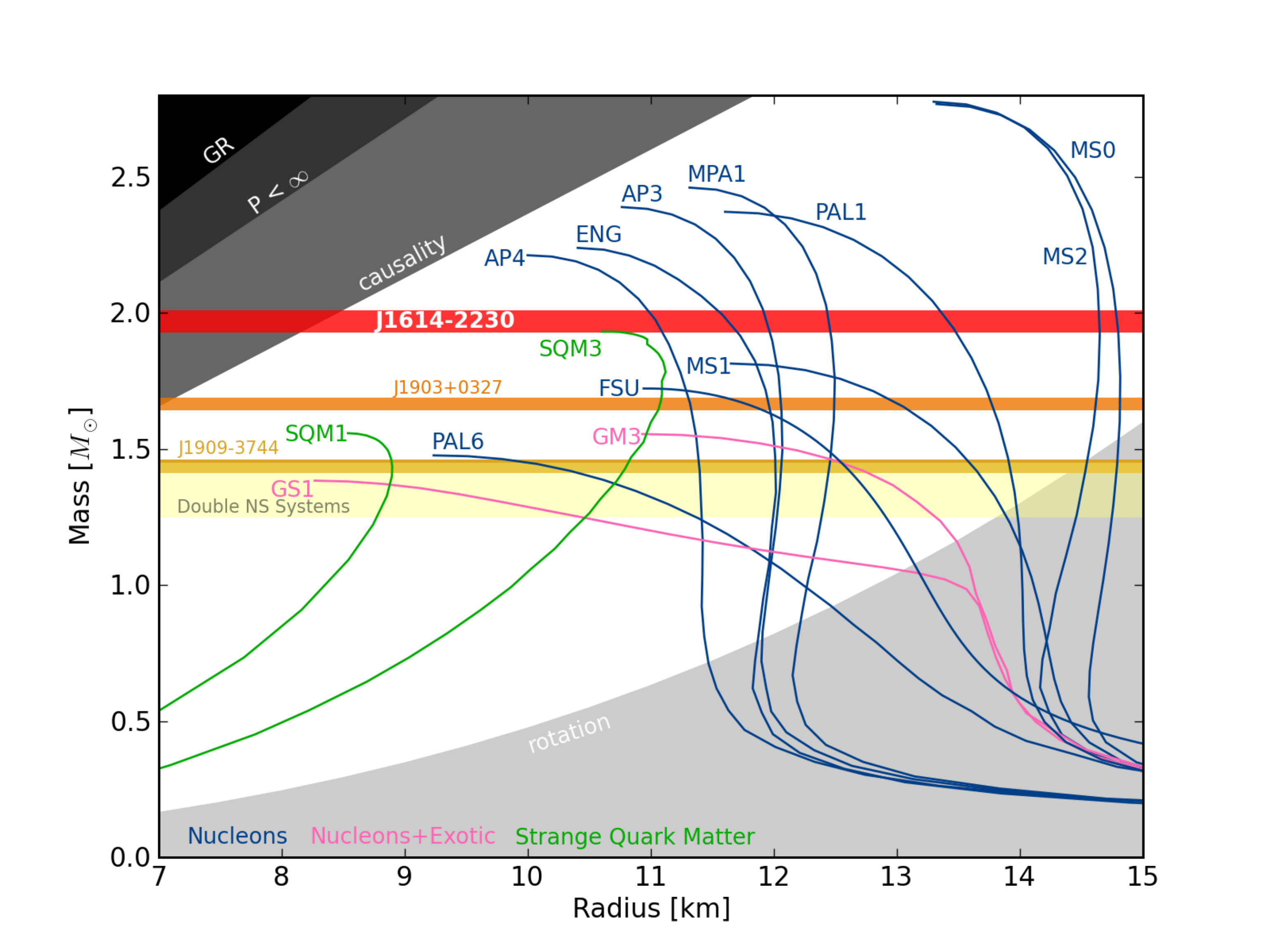
(Demorest, Pennucci, Ransom, Roberts, Hessels, *Nature,* 2010)

Closeup of orbital conjunction:



Time of arrival scatter is ~1us

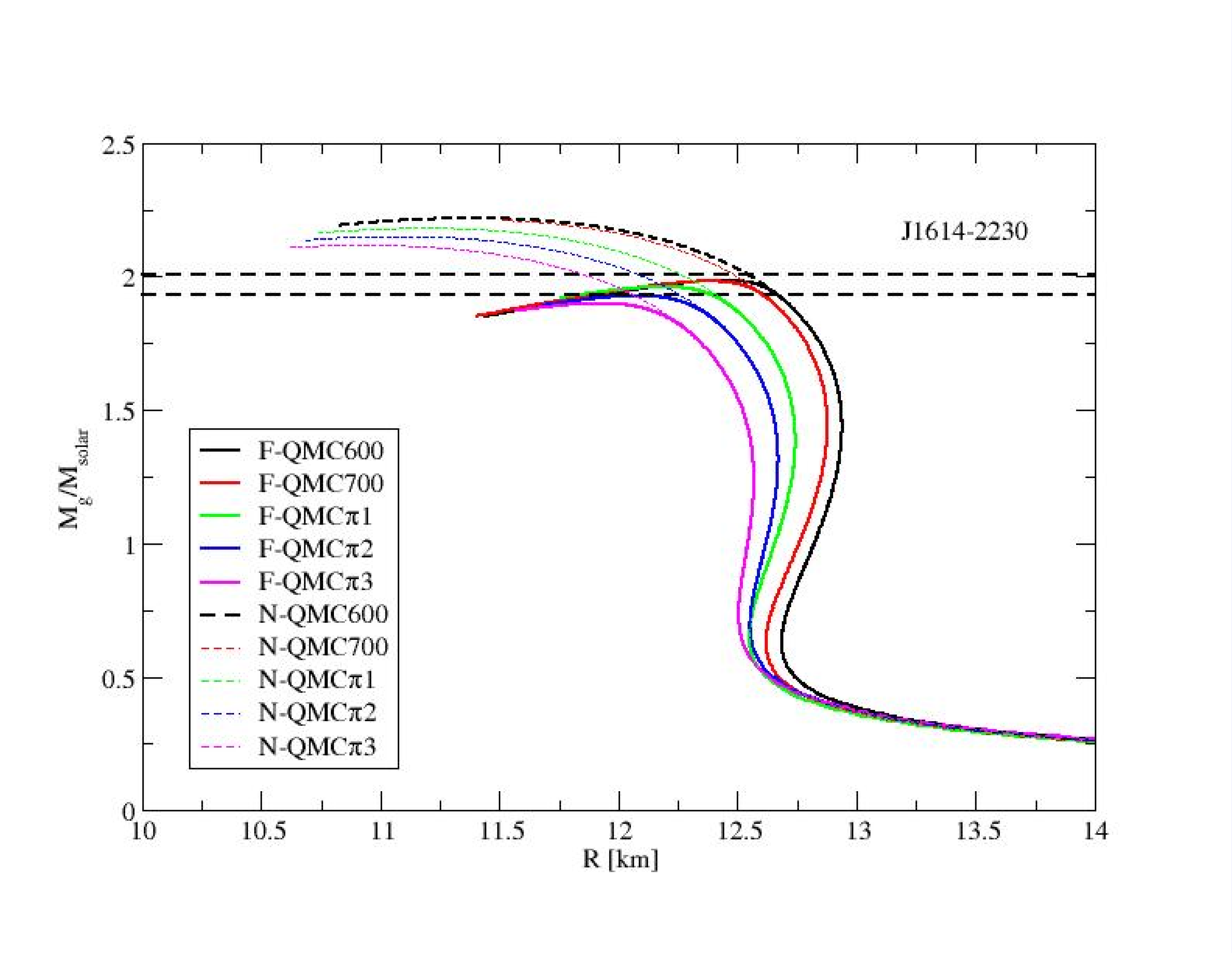
New EOS constraints:



(Demorest et al. 2010)

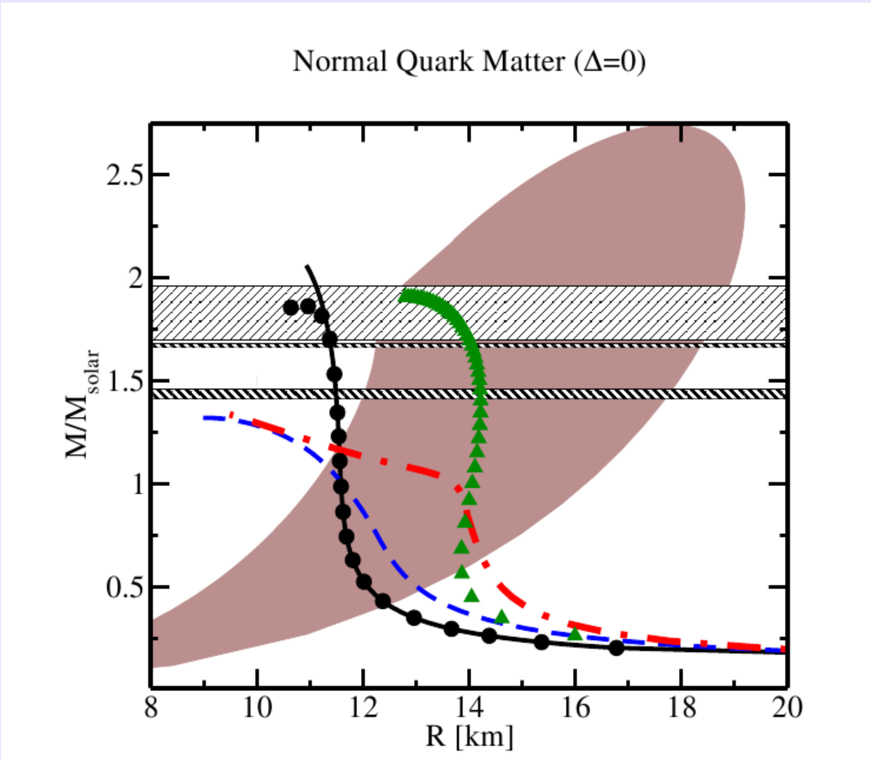
Rules out soft EOS incuding many “exotic” hyperon, kaon models. But the theorists have been busy...

Some hyperon models can just reach ~2.0 M_sun:



(Stone et al. 2010; see also Lackey et al. 2006)

Quark star models cover a wide parameter space:



(Kurkela et al. 2010)

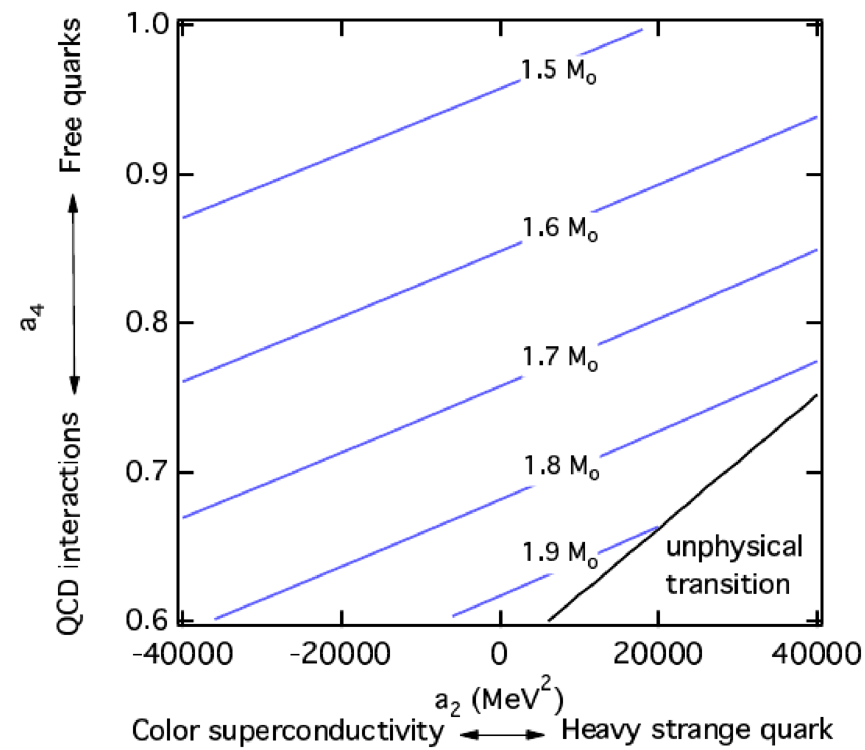
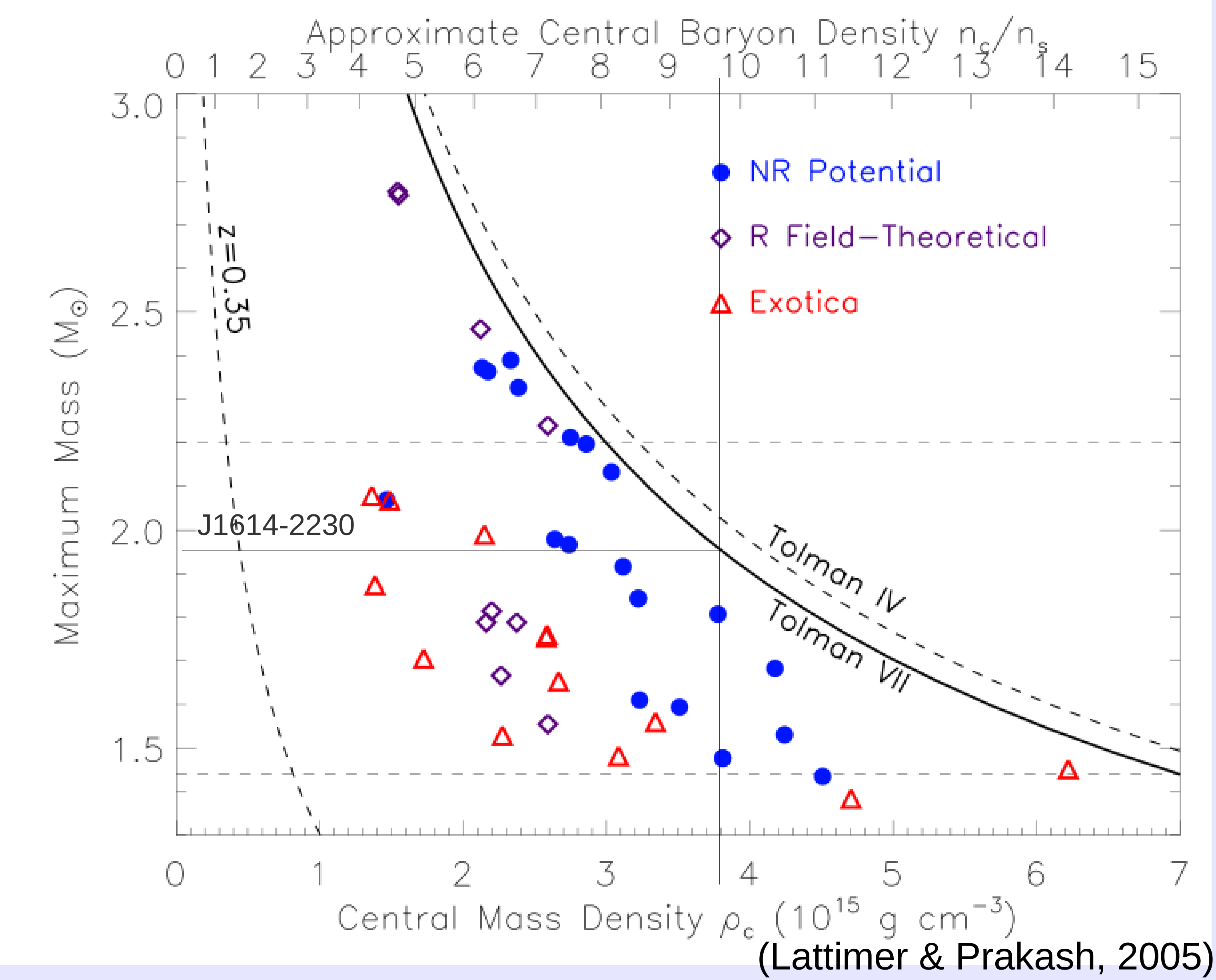


FIG. 1.— The maximum neutron star mass as a function of two parameters of quark matter when the density at which the transition from nucleonic to quark matter occurs is equal to 1.5 times the nuclear saturation density. The measurement of a pulsar mass of $\geq 1.93\ M_\odot$ from Shapiro delay observations indicates that, if the transition to quark matter occurs at densities that are relevant to neutron star interiors, such a massive star can be supported against collapse only if the quarks are strongly interacting ($a_4 \leq 0.63$).

(Ozel et al. 2010; also Alford et al 2005)

But our measurement places constraints on the quark interaction parameters; the quarks are not “free”.

EOS-independent mass density limit:



(Lattimer & Prakash, 2005)

Other model-independent quantities review by L&P (2010)

Astrophysics: How did J1614-2230 get so massive?

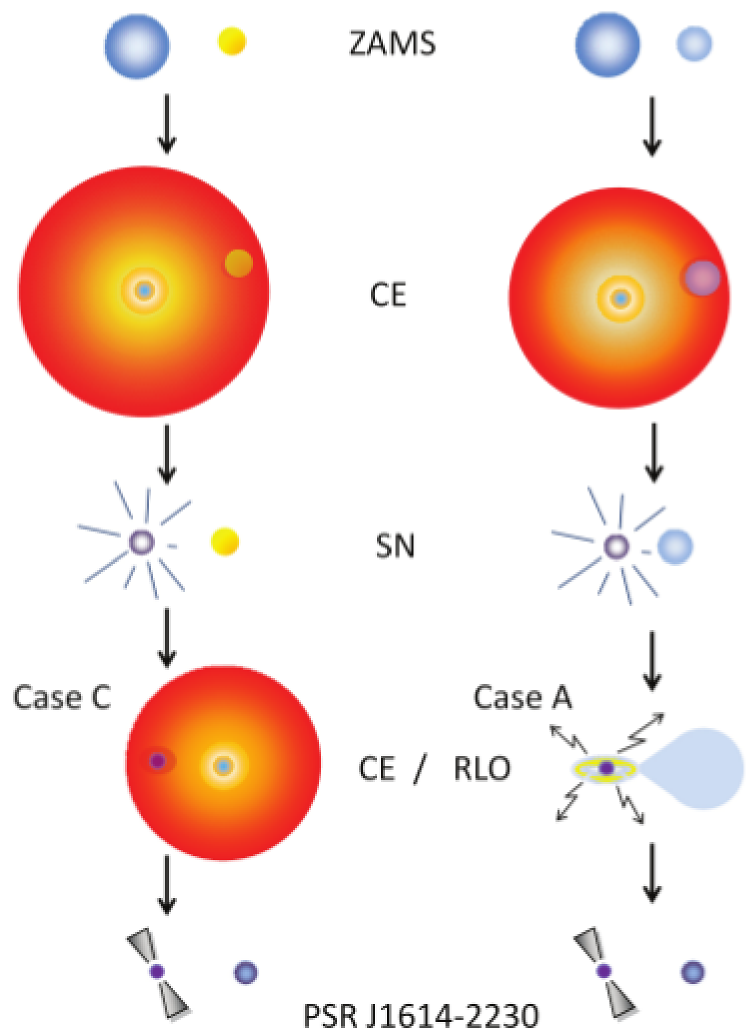


Figure 10. An illustration of the progenitor evolution leading to the formation of PSR J1614–2230 for both Case A and Case C. Only a few evolutionary epochs are shown for simplicity.

Large mass transfer is not necessary to spin up an MSP.

Detailed binary evolution models by Tauris et al (2011) show J1614-2230 was probably born massive, with a initial mass of either 1.95 or (more likely) 1.7 Msun.

Are there even higher neutron star masses?
13 Eccentric (e>0.3) PSRs in Clusters:

Name	P(ms)	Pb(d)	E	Mcmin	Mtot	Mpmed
Ter5ai	21.228	0.85	0.440	0.49	**1.883(4)**	**1.39**
Ter5J	80.338	1.10	0.350	0.34	**2.19(2)**	**1.73**
Ter5I	9.570	1.33	0.428	0.21	**2.171(3)**	**1.87**
Ter5Z	2.463	3.49	0.761	0.22	**1.79(1)**	**1.53**
Ter5U	3.289	3.57	0.605	0.39	**2.26(1)**	**1.73**
Ter5X	2.999	5.00	0.302	0.25	**1.91(5)**	**1.60**
M5B	7.947	6.85	0.138	0.13	**2.3(1)**	**2.12**
M28C	4.158	8.08	0.847	0.26	**1.631(1)**	**1.33**
NGC6441A	111.601	17.33	0.712	0.59	**2.0(2)**	**1.35**
NGC1851A	4.991	18.79	0.888	0.92	**2.44(5)**	**1.34**
NGC6440B	16.760	20.55	0.570	0.08	**2.8(3)**	**2.68**
Ter5Q	2.812	30.30	0.722	0.46	**2.4(2)**	**1.79**
M28D	79.835	30.41	0.776	0.38	**1.2(7)**	

Table by Scott Ransom
M5B: Freire et al 2008, ApJ, 679, 1433

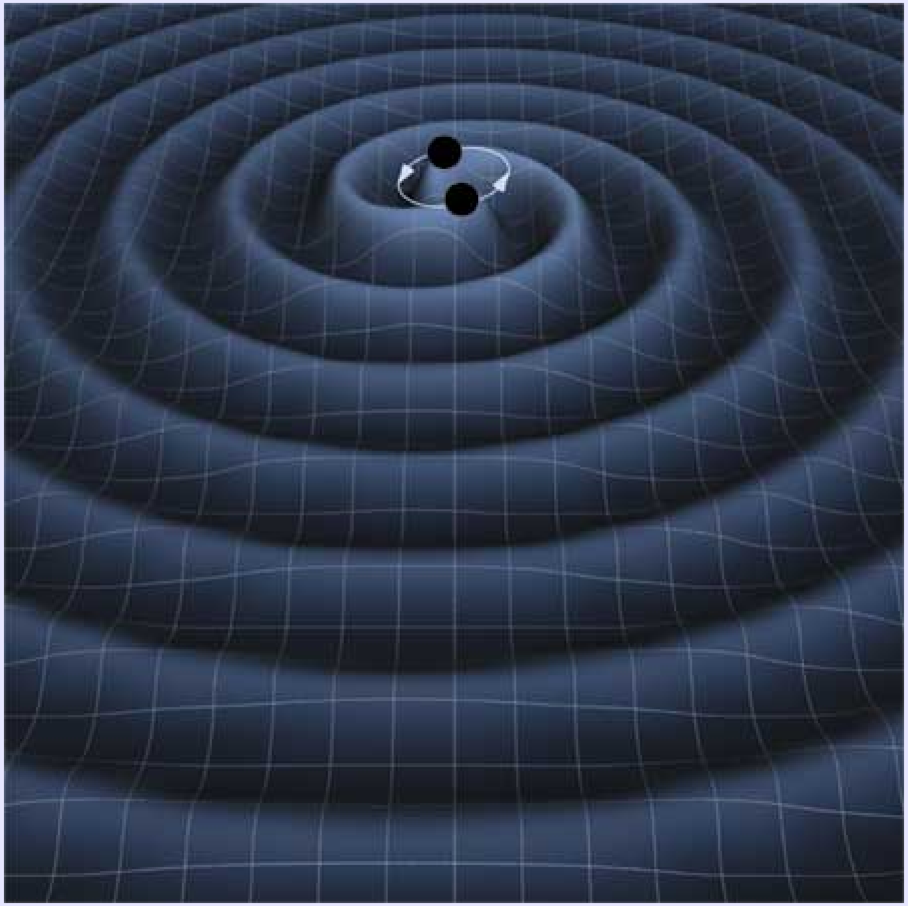
Gravitational waves:

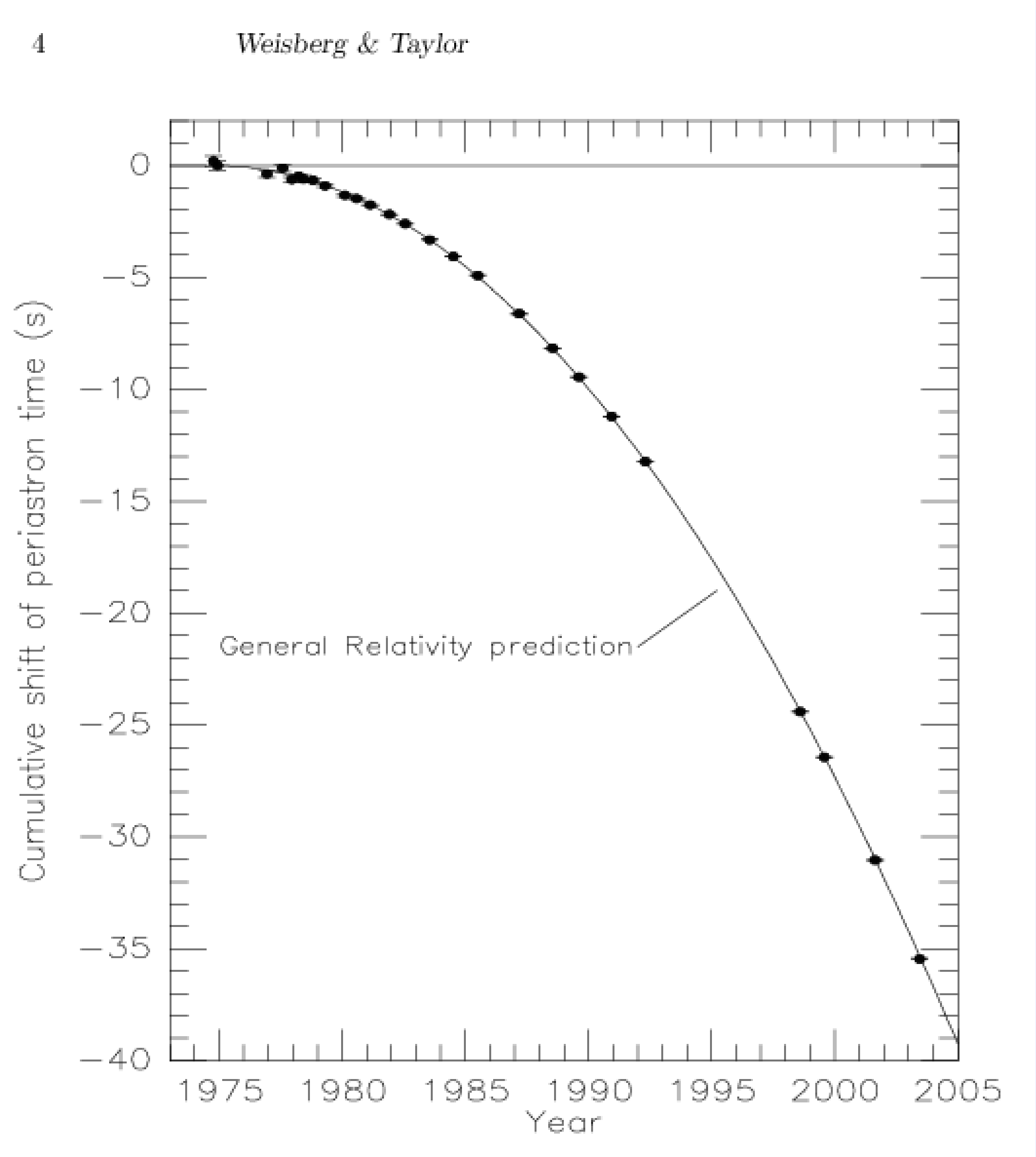
Freely-propagating "space-time ripples" predicted by GR.

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.



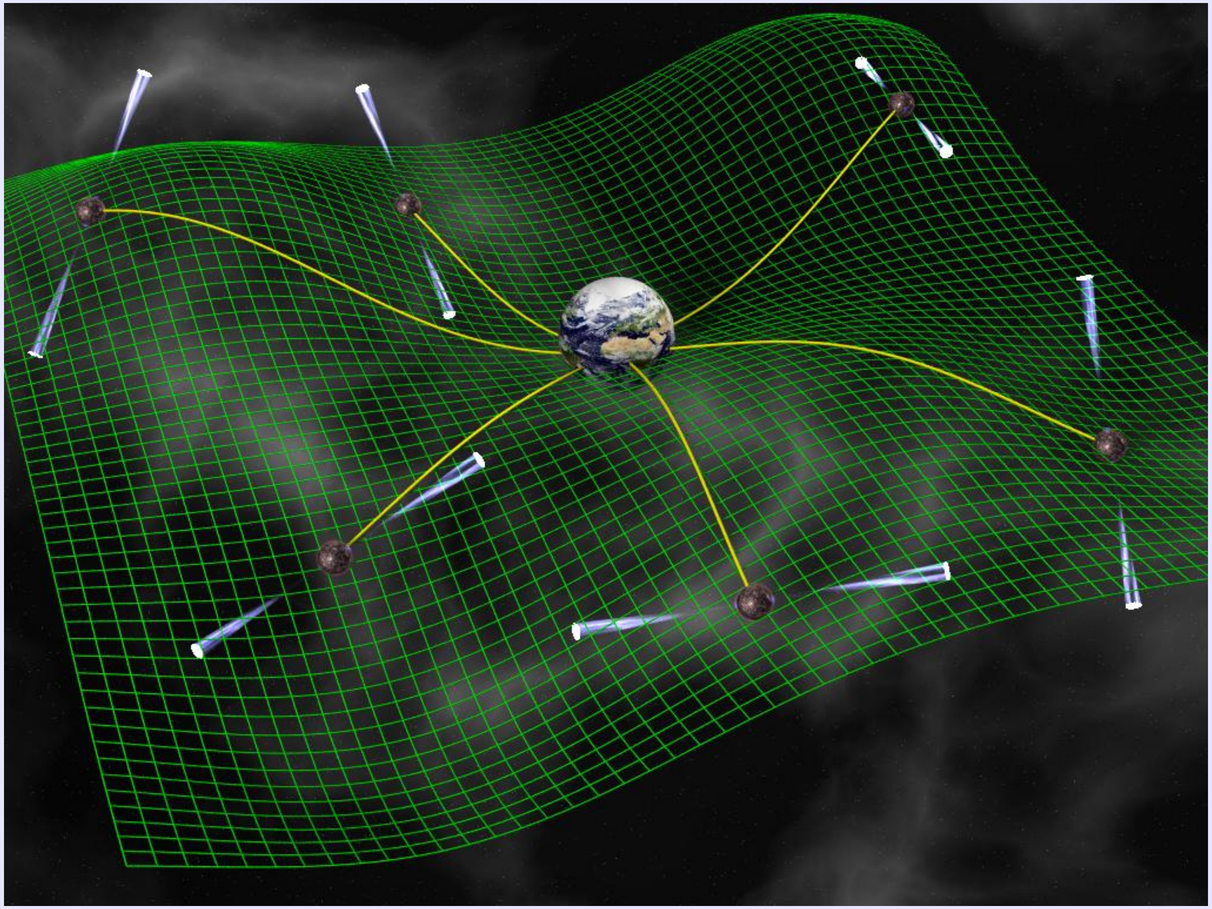


Experimental evidence for GW:

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

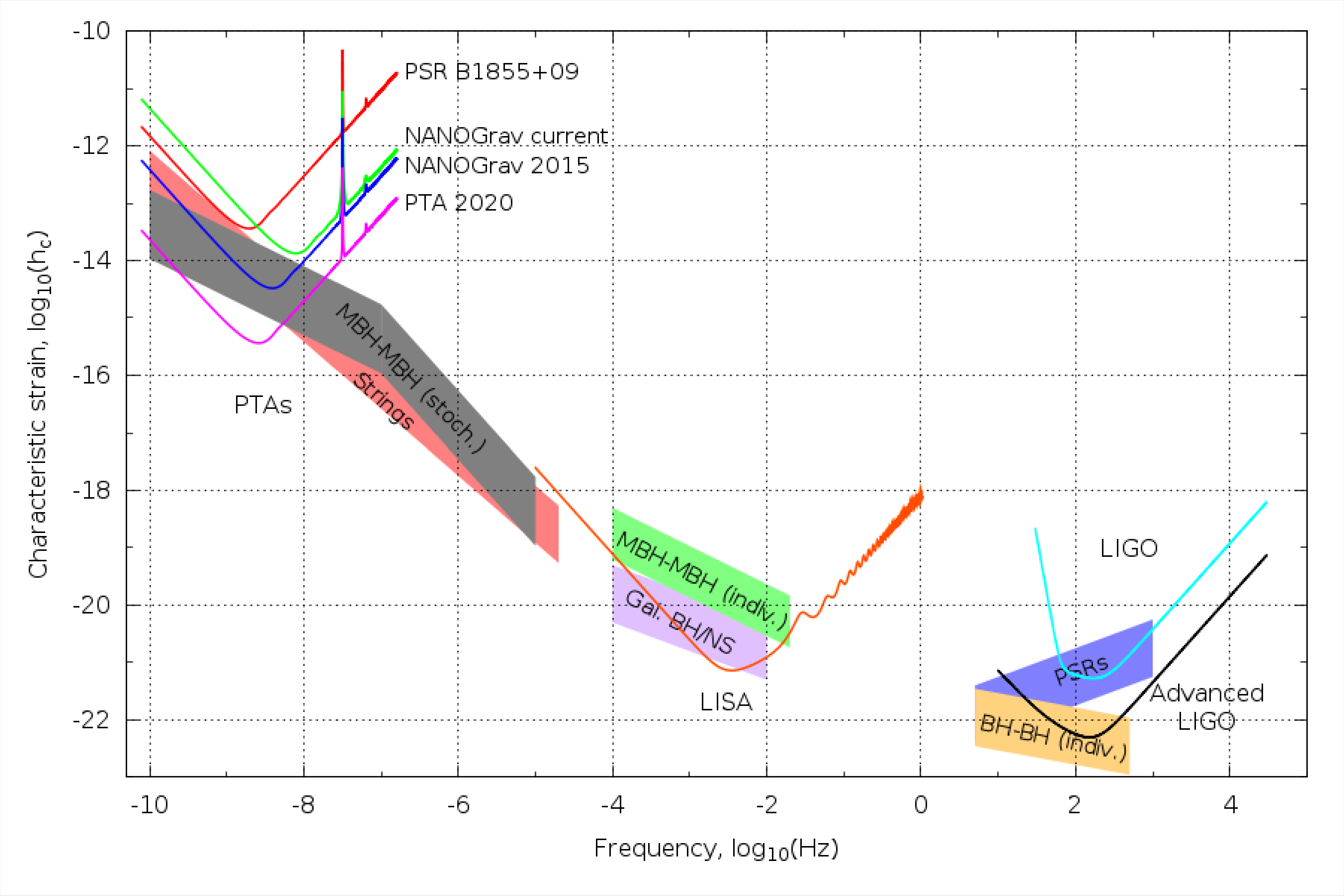
(Physics Nobel prize for Hulse and Taylor in 1993)

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



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

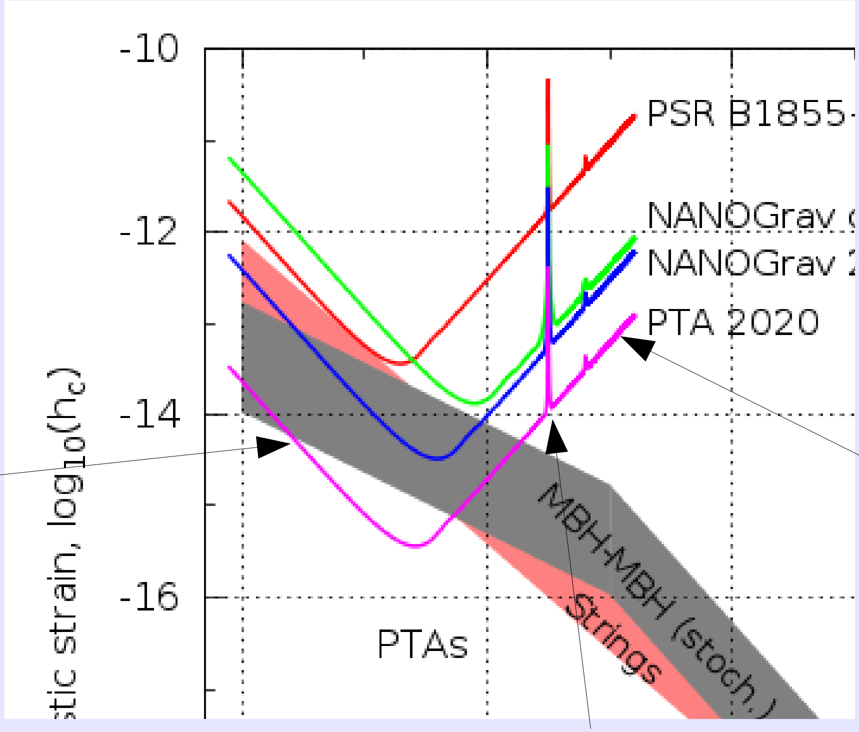
Pulsar Timing Array GW complementarity:



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

PTAs work on the same principle as laser experiments. Some differences in the details:

1. Obs time (T) much less than light travel time
   --> h ~ dt/T (not dL/L).
2. T sets freq scale --> very short wavelength limit.
3. Pulsar parameters not known a priori.



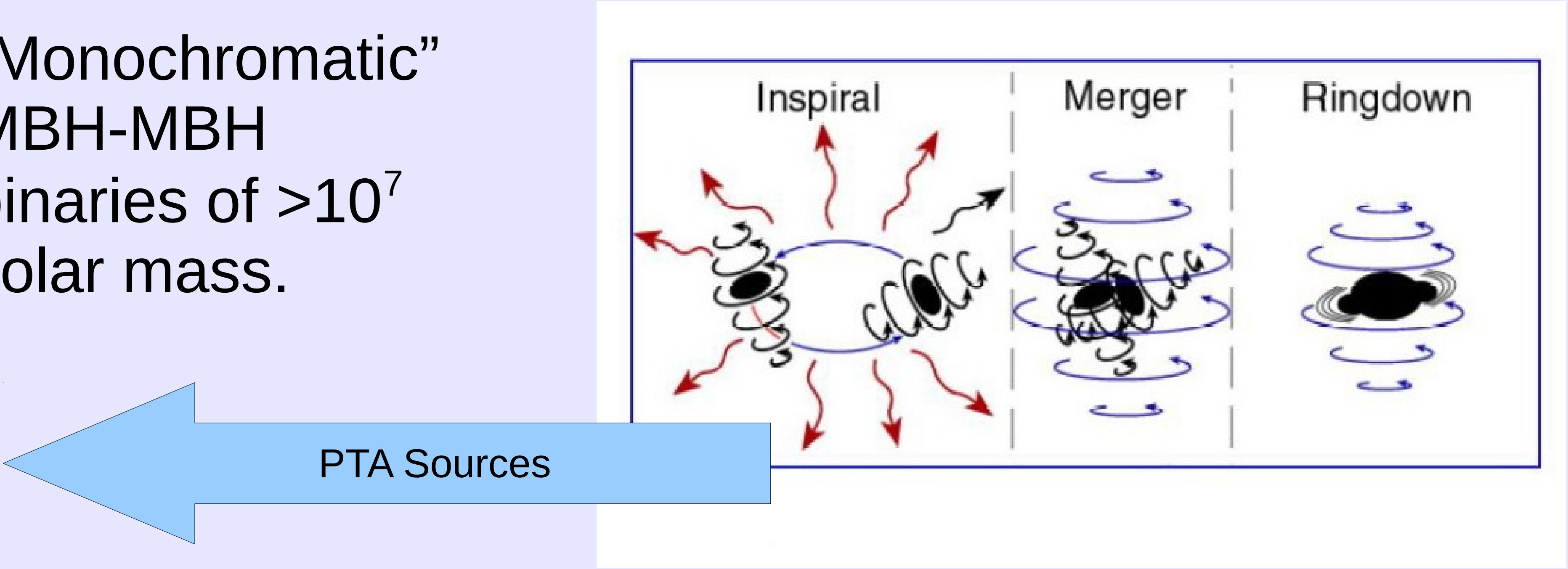
Fit for P, spindown

“ $dt = \int h\, ds$ “

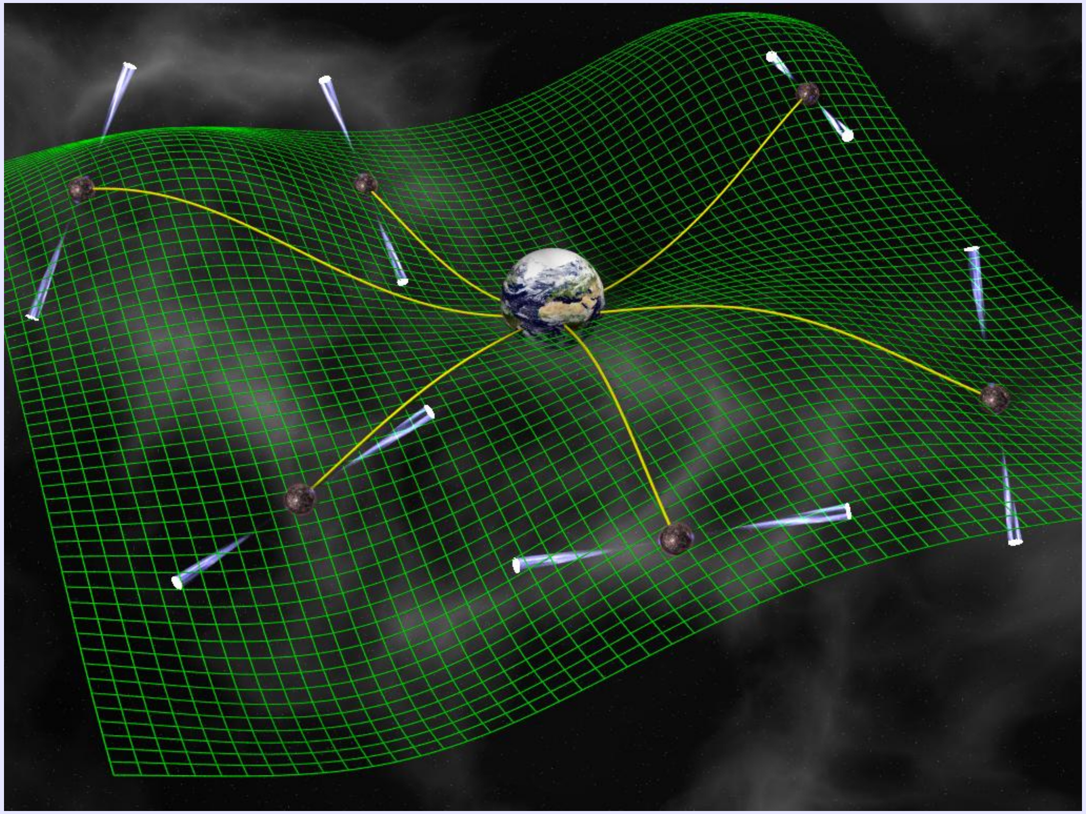
Fit for position, parallax

Nanohertz GW sources:

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

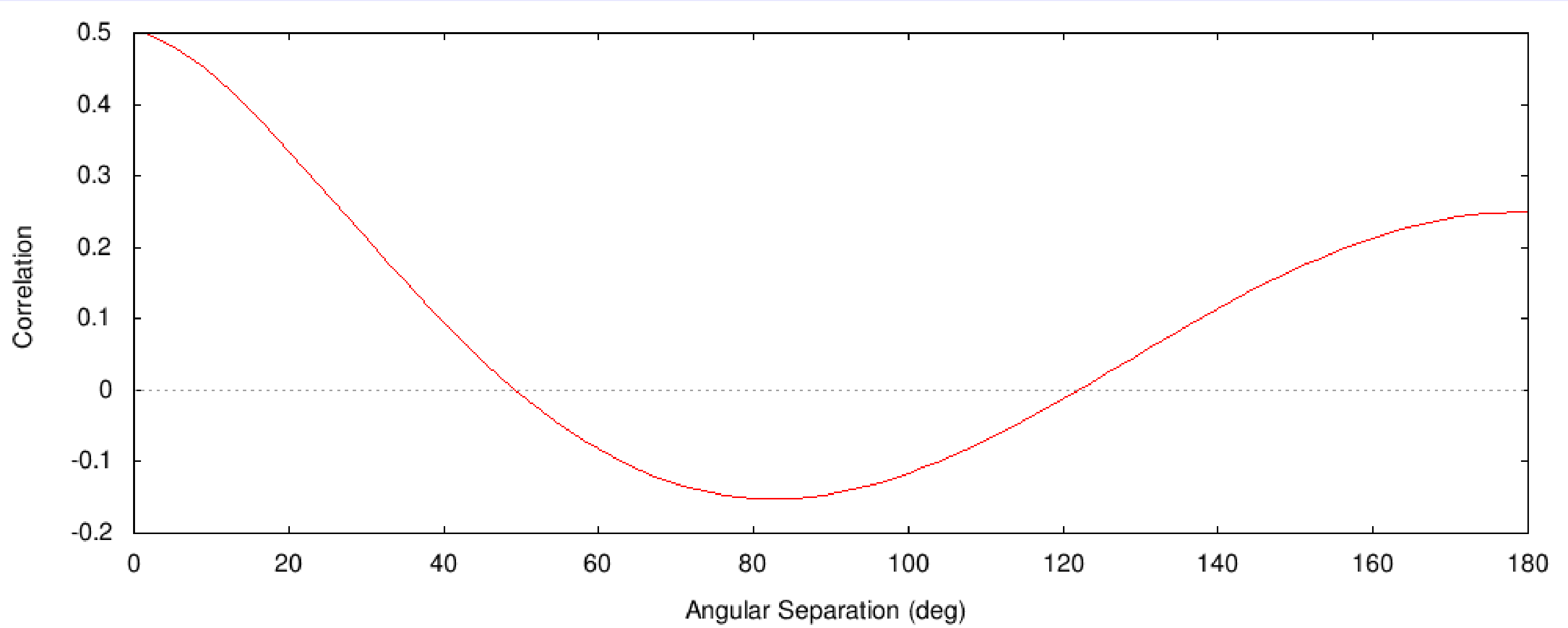


- Stochastic MBH background (Jaffe & Backer 2003, Sesana et al 2008, ...)
- Resolved MBH sources (Sesana et al 2009, Boyle & Pen 2010, ...)
- Also cosmic strings, other exotica / the unknown!



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)!

Arecibo observatory: 305-m fixed reflector

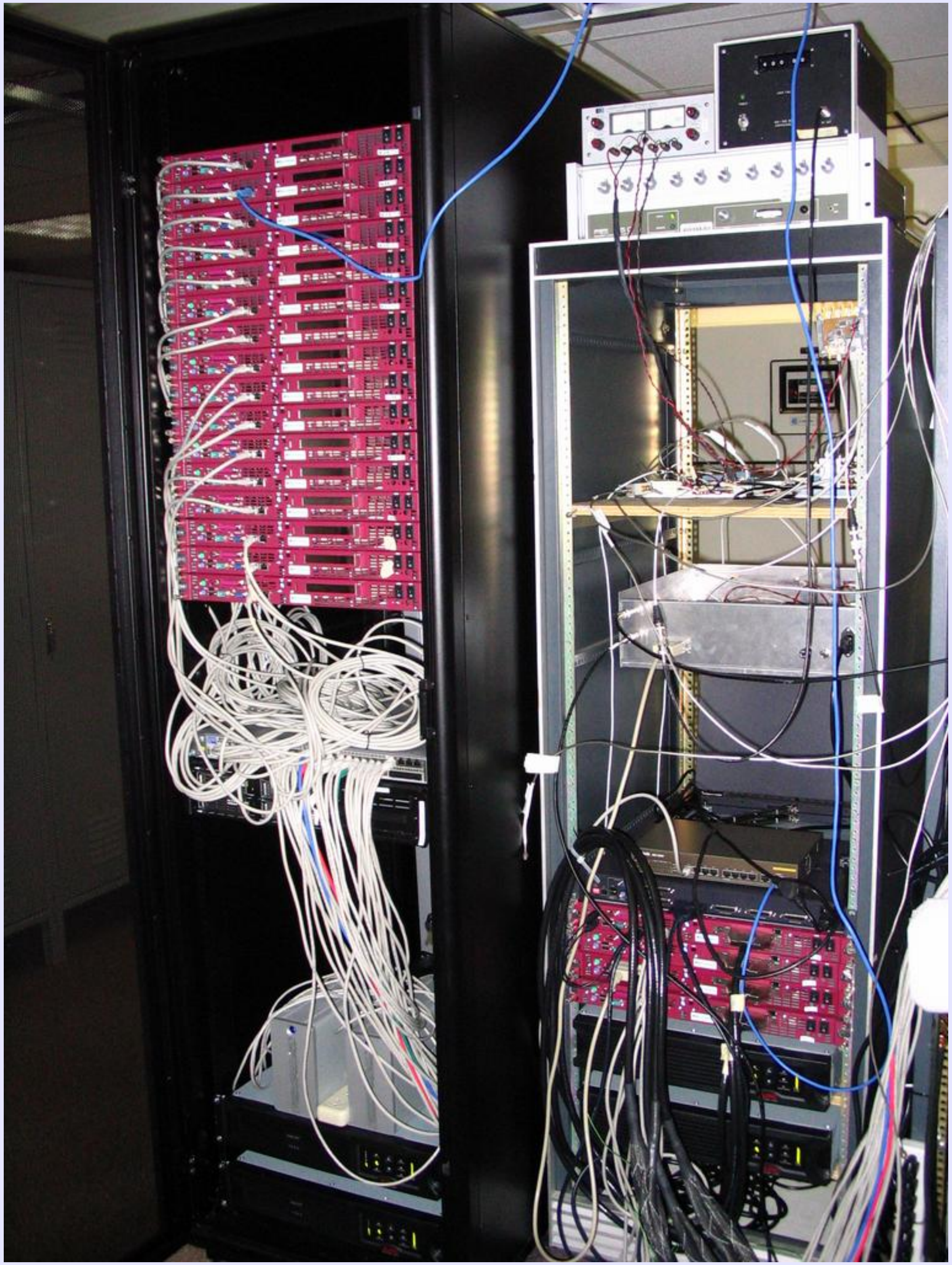
NANOGrav observing:

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

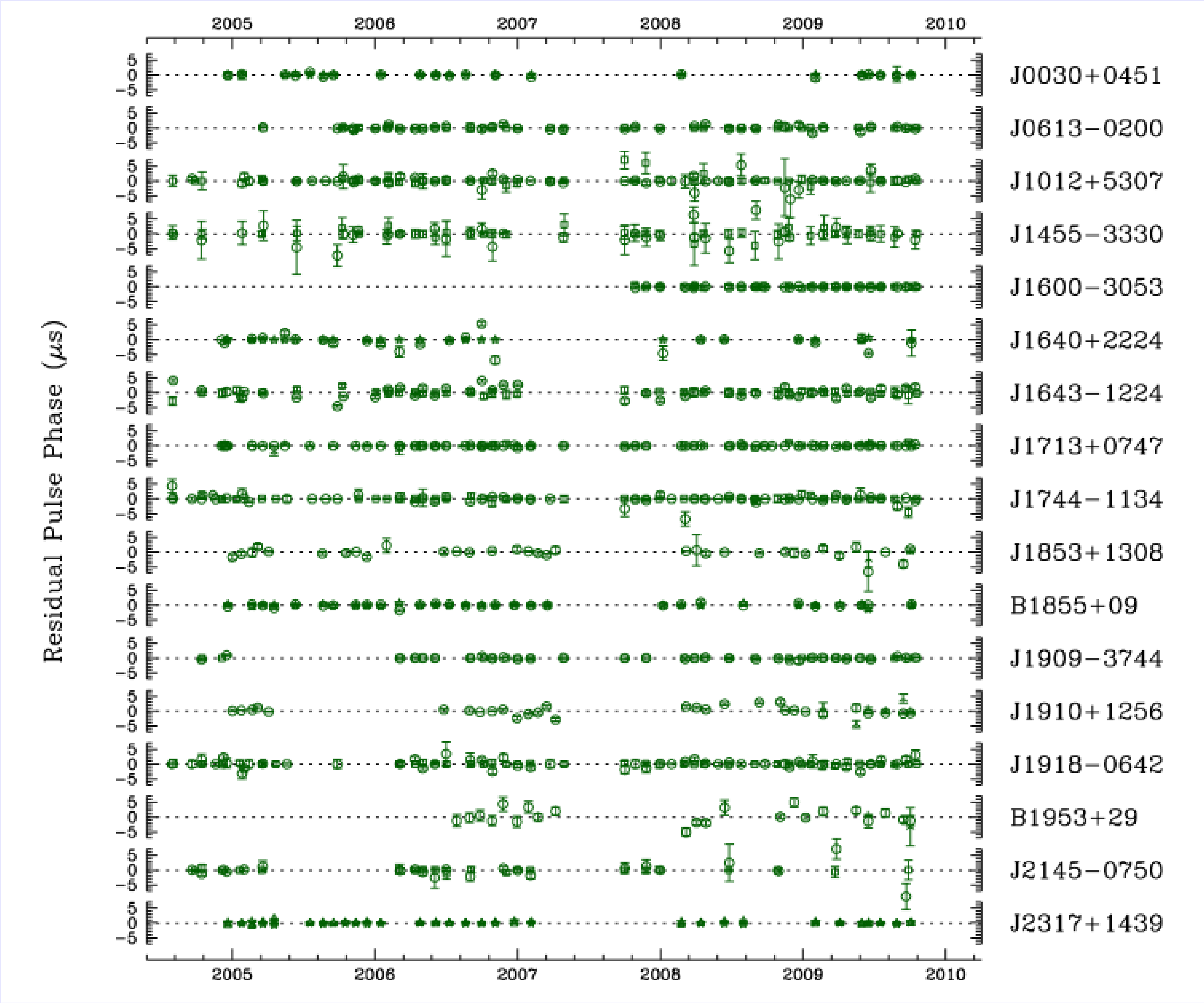
Dual-freq: 820, 1400 MHz (GBT); 327, 430, 1400, 2300 MHz (AO).

Typically 30 min per source per band each epoch.

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



NANOGrav 5-year timing results overview:



(plot: D. Nice)

NANOGrav 5-year timing results summary
(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:

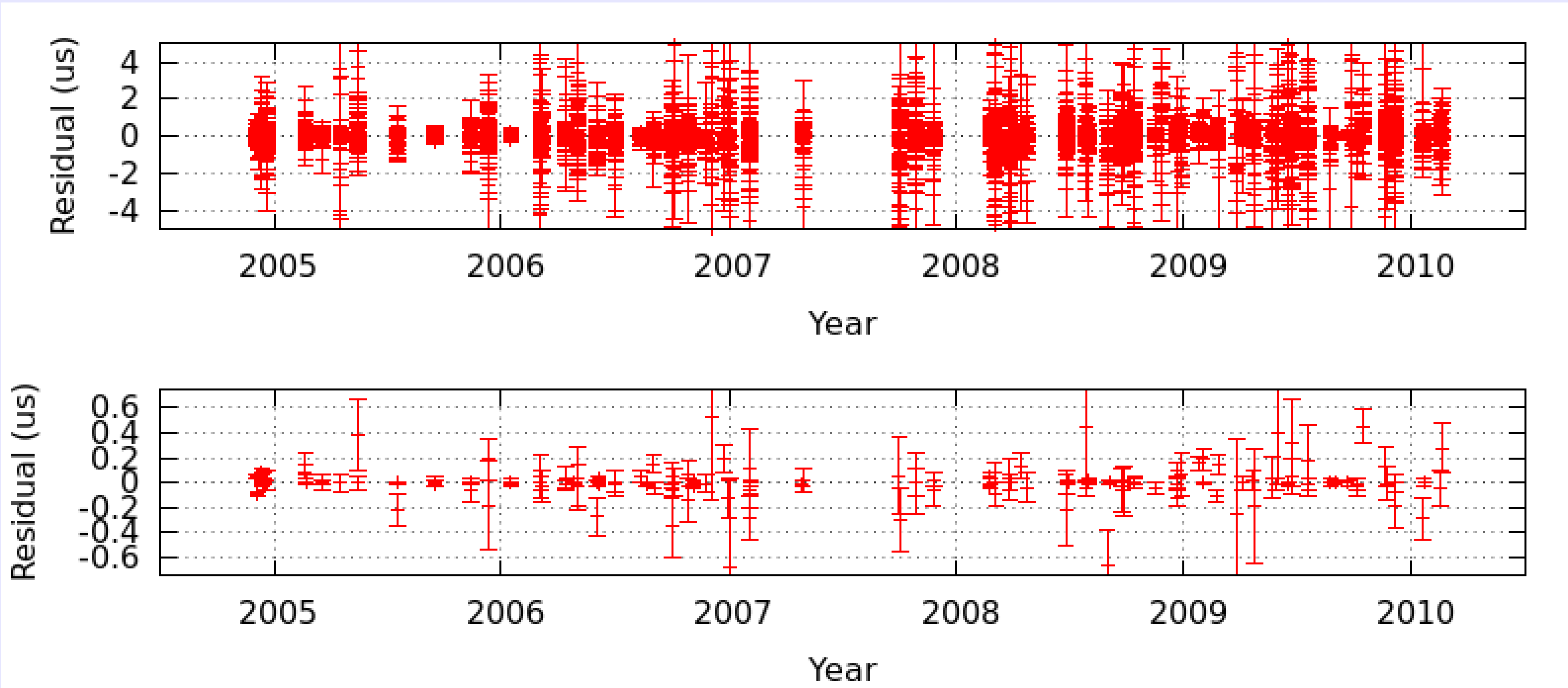
2 PSRs at ~40 ns!

Two independent calibration/processing pipelines -- psrchive and ASPfitsreader

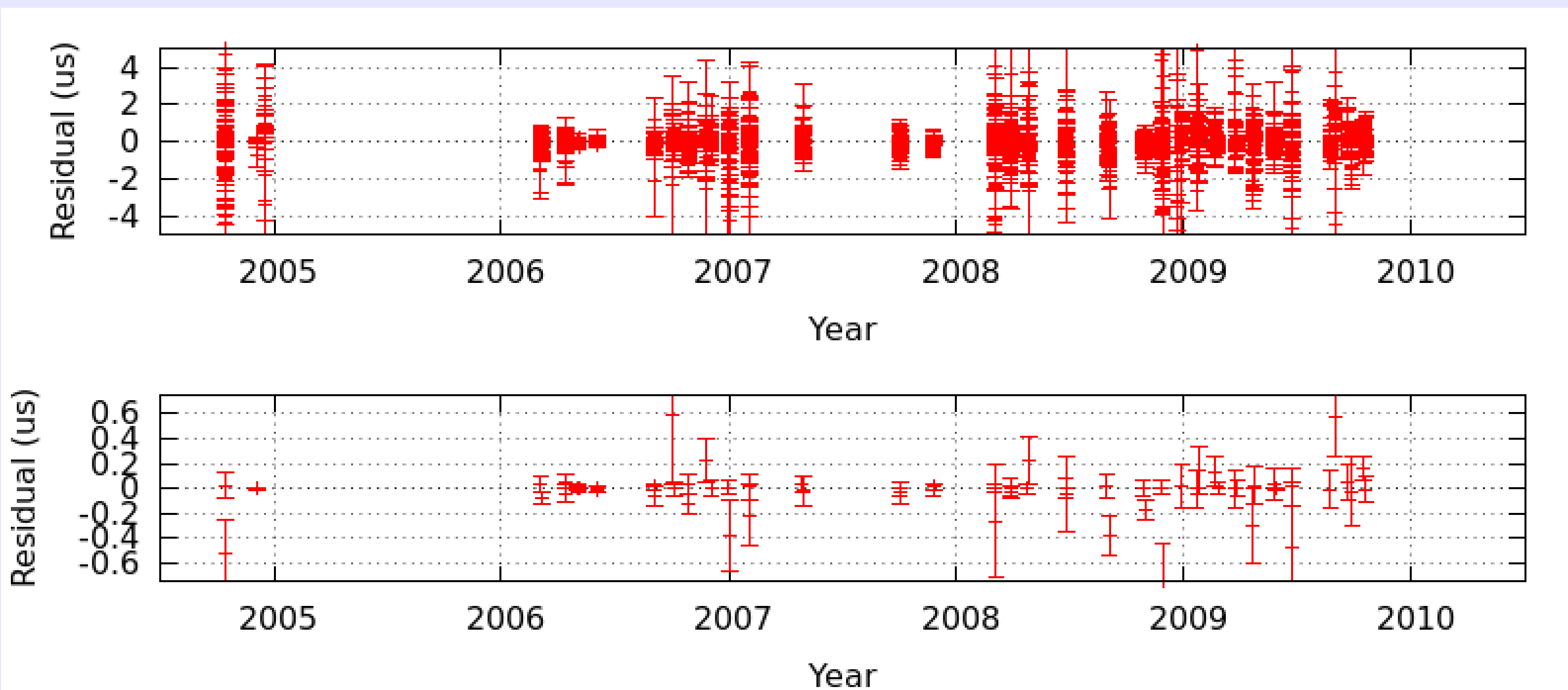
DM(t) and timing model in single fit.

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

Best timing residuals versus time:

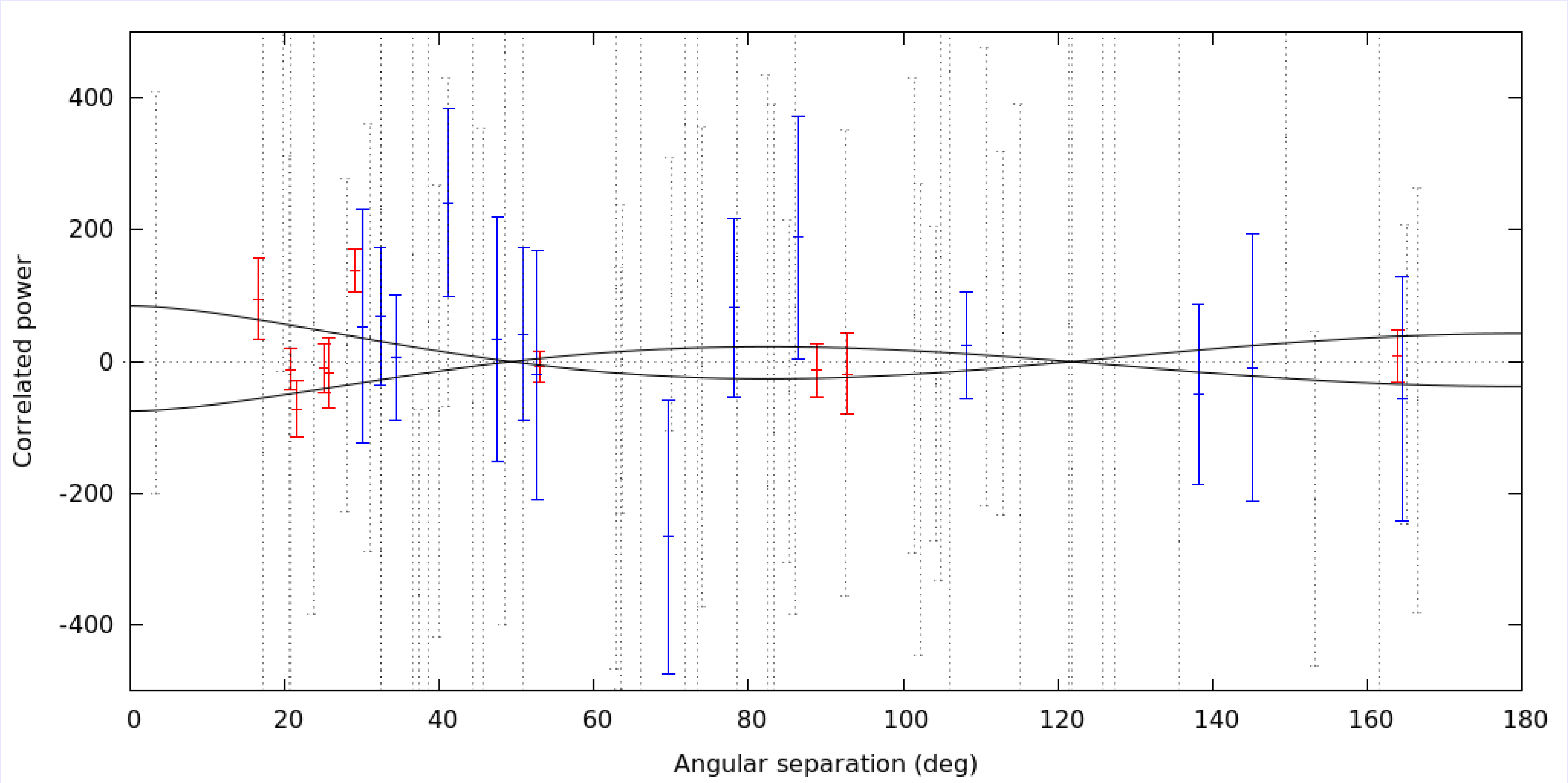


J1713+0747



J1909-3744

5-year NANOGrav GW cross-correlation analysis

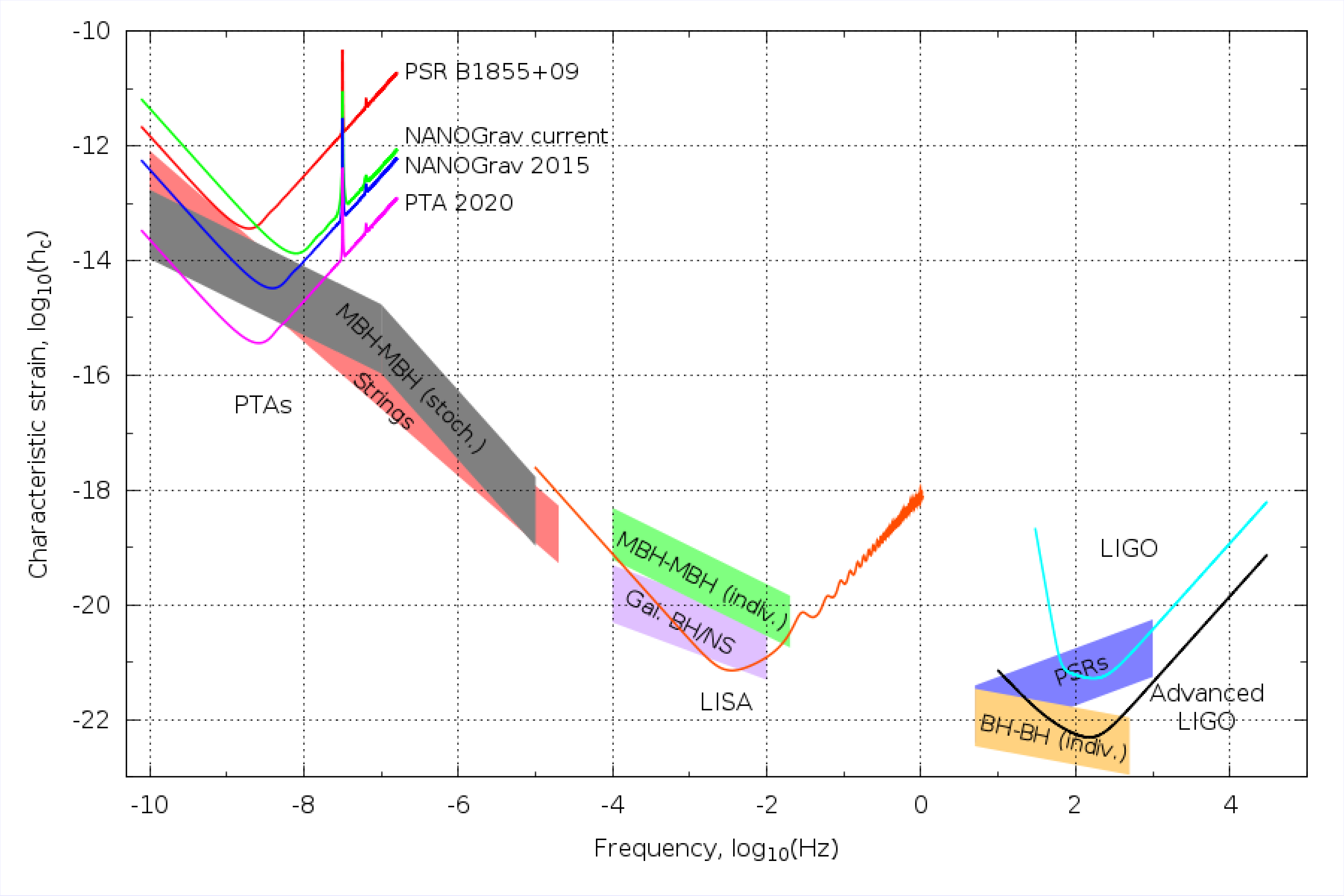


Computed using methods from Demorest (2007):

- Optimized for -2/3 power law GW spectrum.
- Tested with simulated GW signals from Tempo2.
- No detection at ~ 7 x 10^{-15} level.

How to improve the measurement?

Simple: Longer observational timespan


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

How to improve the measurement?

Simple: Longer observational timespan

Ongoing:

- Improved data analysis (more GW signal types, ISM corrections, etc)
- Discover/add more pulsars
- Better instrumentation (eg GUPPI)

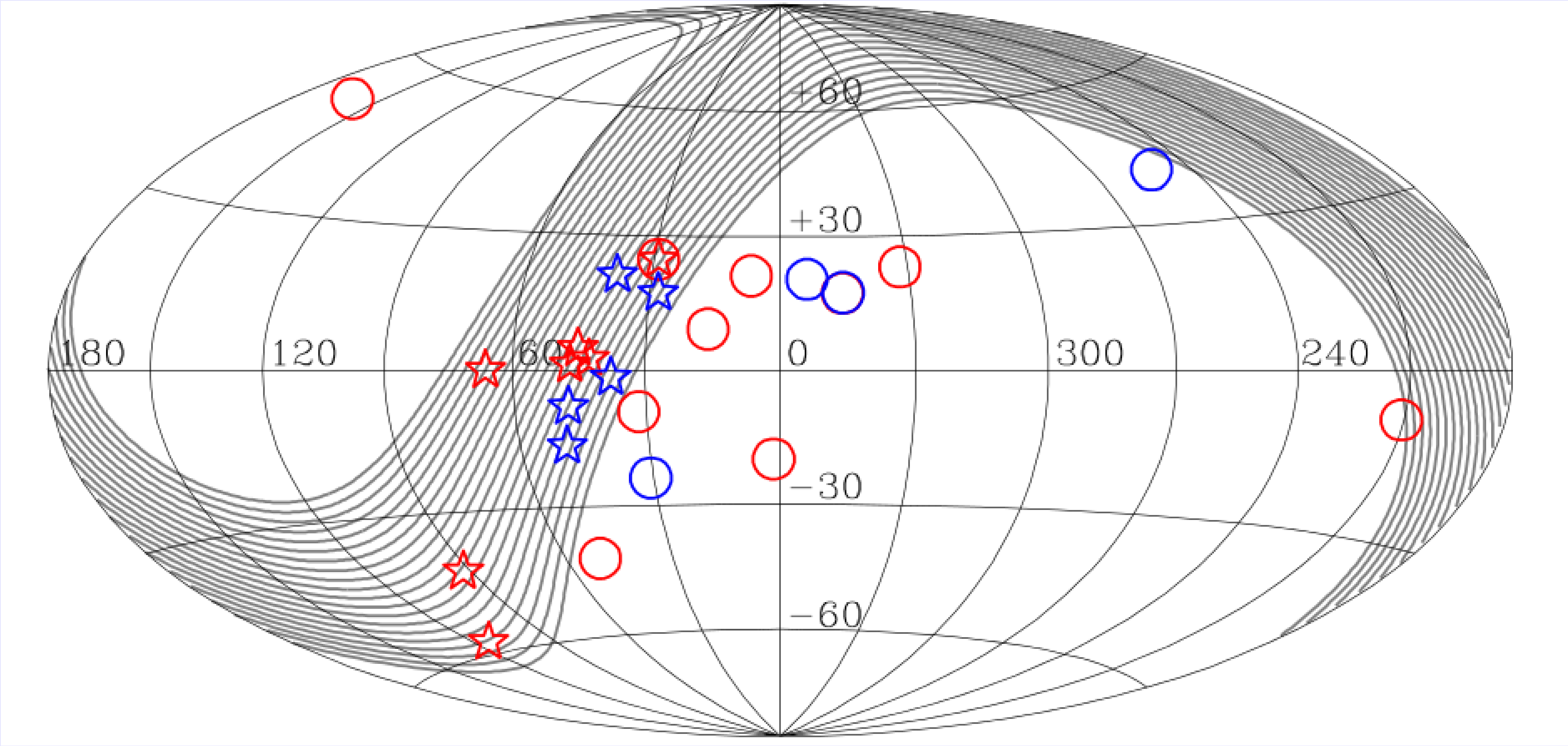
Near future:

- Increase observing time on current telescopes.

Long-term:

- More collecting area (larger telescopes).

Rapidly increasing number of known 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.

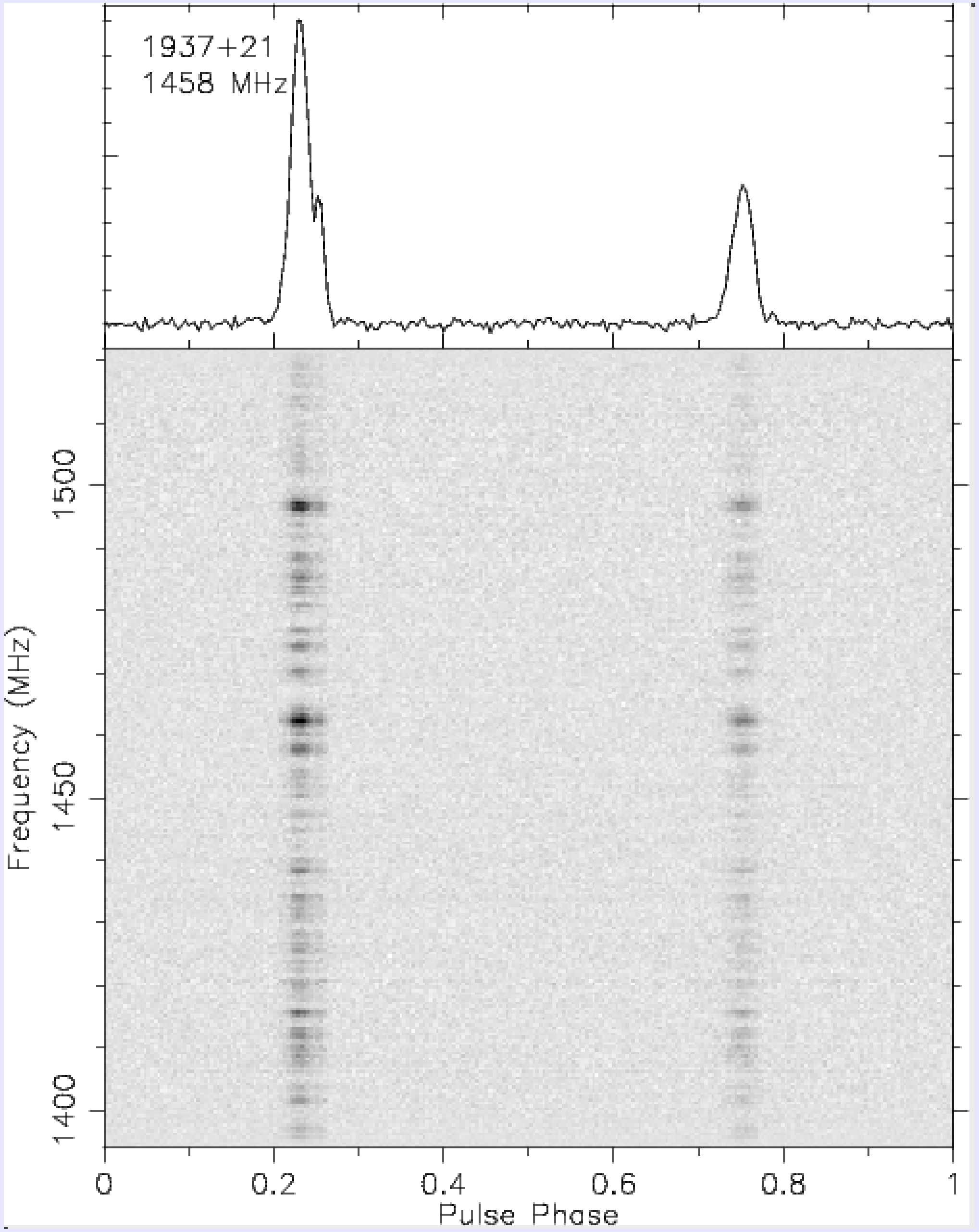
Improving existing telescope resources:

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

Wideband receiver upgrades (~0.5-3 GHz)

"PUPPI" for Arecibo is in progress.

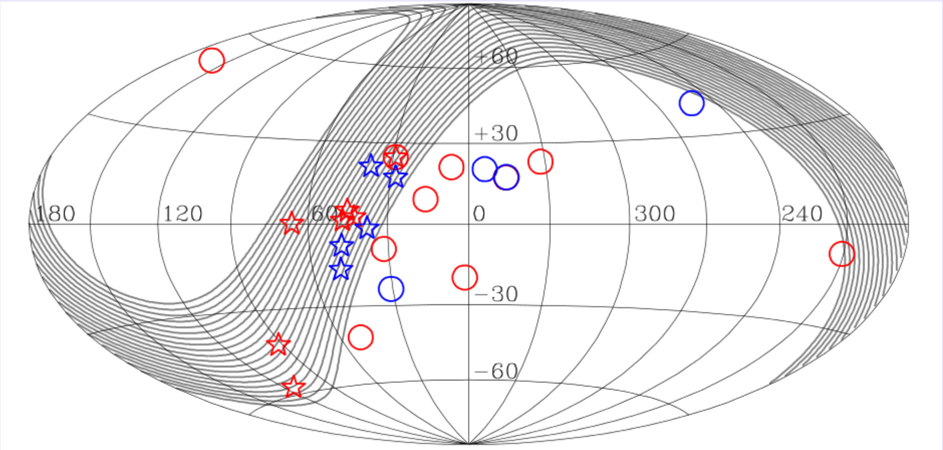
EVLA provides ~GBT sensitivity, and octave-BW receivers.



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

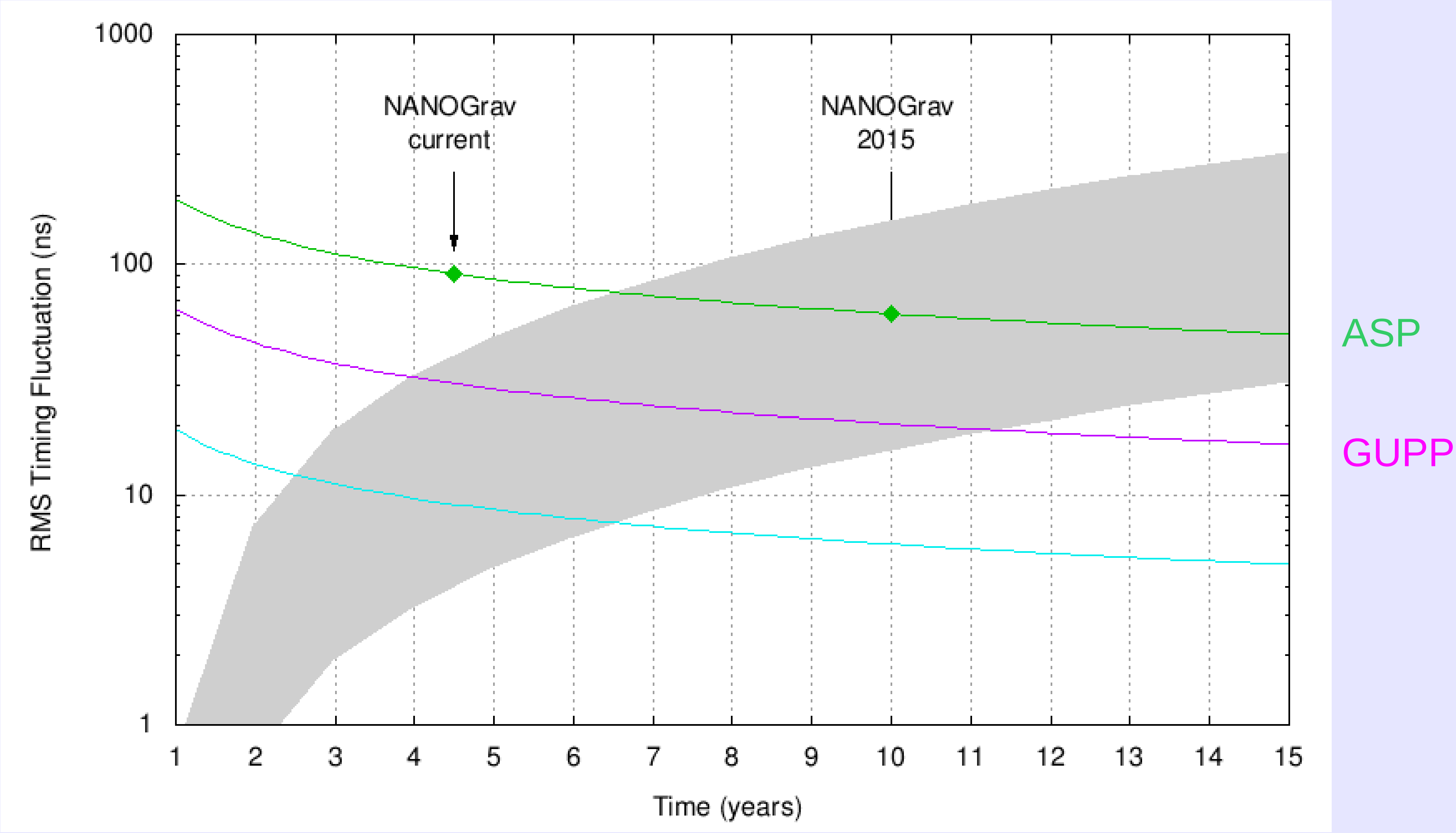
Future telescopes

Main criteria: size (G/T) and location (sky coverage). Freq coverage ~0.5-3.0 GHz.



- MeerKAT (South Africa)
  - 64 13.5-m dishes. ~GBT sensitivity, but in the southern hemisphere.
- FAST (China)
  - One 500-m dish! ~3x Arecibo sensitivity
- Dedicated PTA telescope or SKA?

Expected GW sensitivity improvement vs time:



Conclusions/Summary:

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

2. J1614-2230 mass is 1.97(4) M_{sun}, highest precise NS mass.

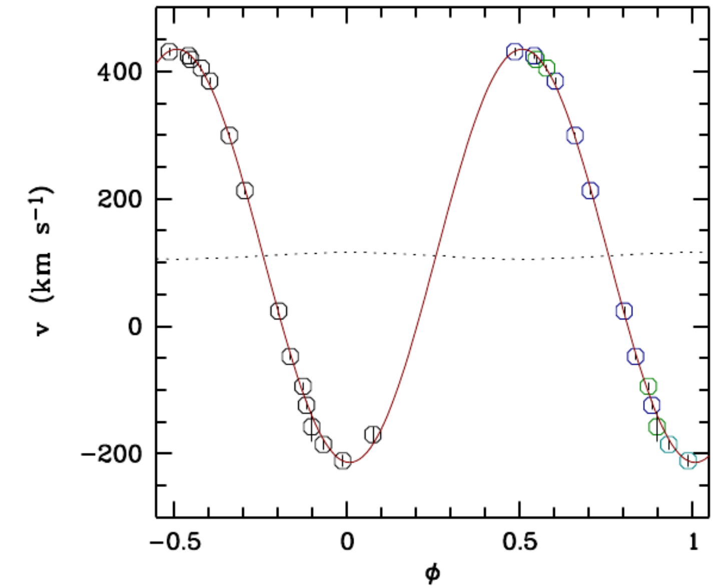
3. Many exotic EOS are ruled out, and quark matter properties are constrained.

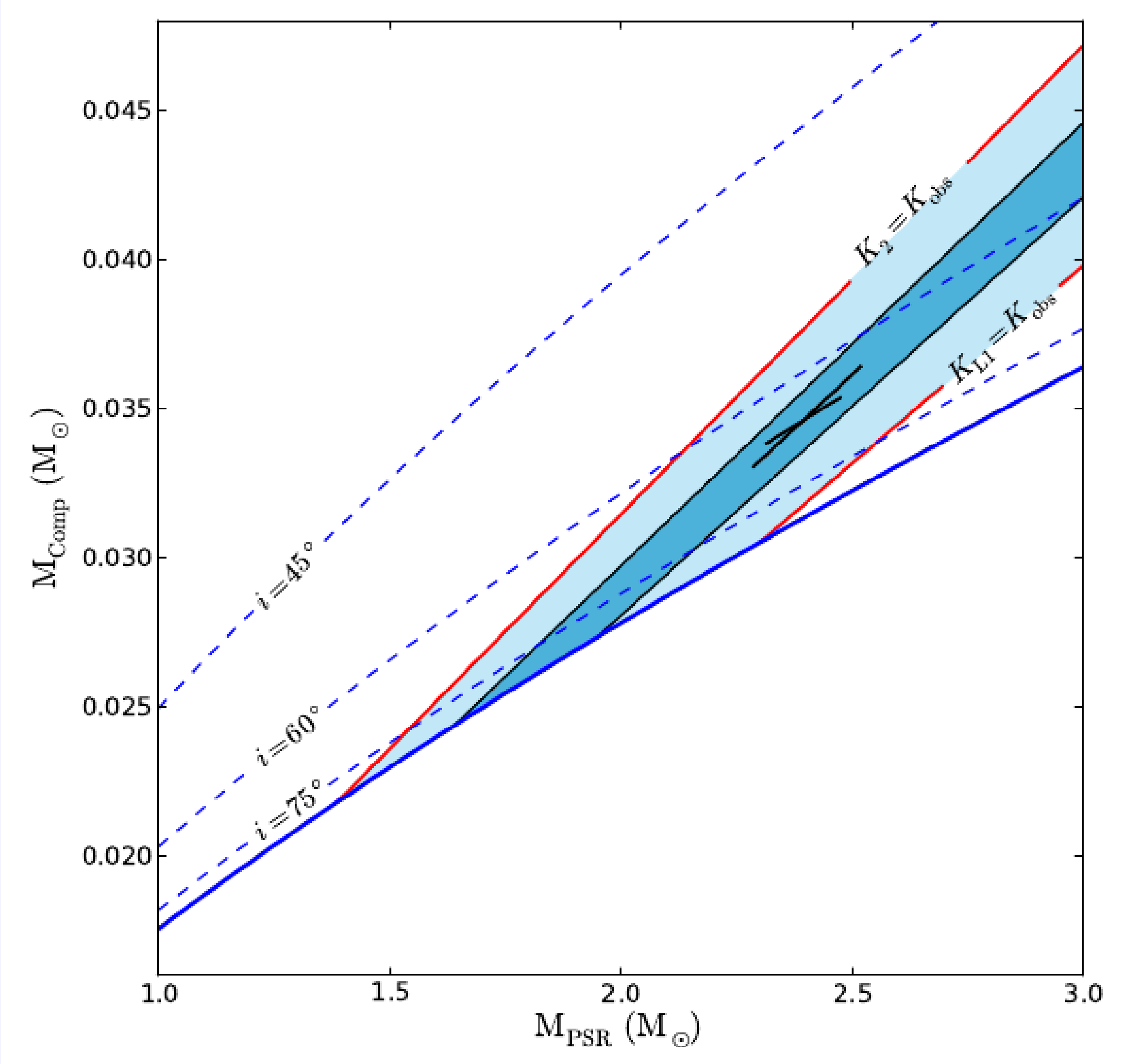
4. NANOGrav project aims to detect nHz-freq GW using pulsar timing.

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

“Black Widow” PSR B1957+21

- New radial vel curve: 353(4) km/s amplitude (corr. for ctr-of-light)
- i=65(2)deg from lightcurve models
- Mp ~ 2.40+/-0.12Msun
- Mp > 1.66 Msun





van Kerkwijk, Breton, & Kulkarni, 2011 ApJ, 728, 95