Testing physics with millisecond pulsars

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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 \( \sim 10 \) km across (city-sized)
- Mass \( \sim 1.4x \) solar
- B-field \( \sim 10^{8-12} \) gauss (\( \sim \)billion \( x \) Earth's)
- Spin periods 1.5 ms to few seconds
- Broadband radio (\( \sim \)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:

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:

![Graph showing periodic pulses with a time interval of ~1.5 ms.]

Average spin period of PSR B1937+21:

\[
P = 1.5578064688197945 \text{ ms} \\
+/- 0.00000000000000000004 \text{ ms}!
\]

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).

(Demorest, Ransom, Ford, McCullough, Ray, Brandt, Duplain)
Green Bank Telescope: 100-m, fully steerable
GUPPI architecture:
~1 MHz PFB in FPGAs
Coherent dedisp in GPUs

IBOB

XAUI

BEE2

“beef”

10 Ge switch; 24 Gb/s

GPUs
Coherent GUPPI first light
December 2009, PSR B1937+21, 1100--1900 MHz
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)
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 \((P_{\text{orb}}, e, \text{asin}(\text{i})/c, T_0, \omega)\), General Relativity gives:

\[\begin{align*}
\dot{\omega} &= 3 \left(\frac{P_b}{2\pi}\right)^{-5/3} \left(T_\odot M\right)^{2/3} (1 - e^2)^{-1} \\
\gamma &= e \left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M^{-4/3} m_2 (m_1 + 2m_2) \\
\dot{P}_b &= -\frac{192\pi}{5} \left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) (1 - e^2)^{-7/2} T_\odot^{5/3} m_1 m_2 M^{-1/3} \\
r &= T_\odot m_2 \\
s &= x \left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_2^{-1}
\end{align*}\]

(Orbital Precession)  
(Grav redshift + time dilation)  
(Shapiro delay: “range” and “shape”)

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

These are only functions of:
- the (precisely!) known Keplerian orbital parameters \(P_b, e, \text{asin}(\text{i})\)
- 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 \((P_{\text{orb}}, e, \text{asin}(i)/c, T_0, \omega)\), General Relativity gives:

\[
\begin{align*}
\dot{\omega} &= \text{Need eccentric orbit and time for precession} \\
\gamma &= \text{(Orbital Precession)} \\
\dot{P}_b &= \text{Need compact orbit and a lot of patience} \\
r &= \text{(Grav redshift + time dilation)} \\
s &= \text{Need high precision, Inclination, and } m_2 \\
\end{align*}
\]

where: \(T_0 \equiv GM/\mu^3 = 4.925490947 \, \mu s\), \(M = m_1 + m_2\), and \(s \equiv \sin(i)\)

These are only functions of:
- the (precisely!) known Keplerian orbital parameters \(P_b, e, \text{asin}(i)\)
- 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).

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

“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.
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
Orbital inclination = 89.17(2) deg!

Companion mass = 0.500(6) solar!

Pulsar mass = 1.97(4) solar!

Closeup of orbital conjunction:

Time of arrival scatter is ~1us
New EOS constraints:

Rules out soft EOS including many “exotic” hyperon, kaon models. But the theorists have been busy...
Some hyperon models can just reach ~2.0 M$_{\odot}$:

(Stone et al. 2010; see also Lackey et al. 2006)
Quark star models cover a wide parameter space:

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

(Kurkela et al. 2010)

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

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 (\( a_4 \leq 0.63 \)).
EOS-independent mass density limit:

Other model-independent quantities review by L&P (2010)
Astrophysics: How did J1614-2230 get so massive?

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.

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

<table>
<thead>
<tr>
<th>Name</th>
<th>P(ms)</th>
<th>Pb(d)</th>
<th>E</th>
<th>M&lt;sub&gt;cm&lt;/sub&gt;</th>
<th>M&lt;sub&gt;tot&lt;/sub&gt;</th>
<th>M&lt;sub&gt;pm&lt;/sub&gt;med</th>
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<td>Ter5ai</td>
<td>21.228</td>
<td>0.85</td>
<td>0.440</td>
<td>0.49</td>
<td>1.883(4)</td>
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<td>Ter5J</td>
<td>80.338</td>
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<td>0.350</td>
<td>0.34</td>
<td>2.19(2)</td>
<td>1.73</td>
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<td>0.21</td>
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<td>0.761</td>
<td>0.22</td>
<td>1.79(1)</td>
<td>1.53</td>
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<td>Ter5U</td>
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<td>3.57</td>
<td>0.605</td>
<td>0.39</td>
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<td>5.00</td>
<td>0.302</td>
<td>0.25</td>
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<td>M5B</td>
<td>7.947</td>
<td>6.85</td>
<td>0.138</td>
<td>0.13</td>
<td>2.3(1)</td>
<td>2.12</td>
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<td>M28C</td>
<td>4.158</td>
<td>8.08</td>
<td>0.847</td>
<td>0.26</td>
<td>1.631(1)</td>
<td>1.33</td>
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<td>NGC6441A</td>
<td>111.601</td>
<td>17.33</td>
<td>0.712</td>
<td>0.59</td>
<td>2.0(2)</td>
<td>1.35</td>
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<td>4.991</td>
<td>18.79</td>
<td>0.888</td>
<td>0.92</td>
<td>2.44(5)</td>
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<td>NGC6440B</td>
<td>16.760</td>
<td>20.55</td>
<td>0.570</td>
<td>0.08</td>
<td>2.8(3)</td>
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<td>Ter5Q</td>
<td>2.812</td>
<td>30.30</td>
<td>0.722</td>
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<td>2.4(2)</td>
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<td>M28D</td>
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<td>30.41</td>
<td>0.776</td>
<td>0.38</td>
<td>1.2(7)</td>
<td></td>
</tr>
</tbody>
</table>

Table by Scott Ransom  
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.
For PTAs, sensitivity $h \sim dt / T \rightarrow$ 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 --> $h \sim dt/T$ (not $dL/L$).
2. T sets freq scale --> very short wavelength limit.
3. Pulsar parameters not known a priori.

\[ dt = \int h \, ds \]
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)

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).

<table>
<thead>
<tr>
<th>Source</th>
<th>Per-channel RMS, $\mu$s</th>
<th>$\chi^2$</th>
<th>Daily RMS, $\mu$s</th>
<th>Hi-freq RMS, $\mu$s</th>
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<tbody>
<tr>
<td>J1713+0747</td>
<td>0.106</td>
<td>1.48</td>
<td>0.030</td>
<td>0.041</td>
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<td>0.181</td>
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<td>0.038</td>
<td>0.047</td>
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<td>0.111</td>
<td>0.101</td>
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<td>1.44</td>
<td>0.148</td>
<td>0.328</td>
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<td>J1600–3053</td>
<td>1.293</td>
<td>1.45</td>
<td>0.163</td>
<td>0.141</td>
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<td>0.198</td>
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<td>J2145–0750</td>
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<td>0.202</td>
<td>0.494</td>
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<td>1.271</td>
<td>1.21</td>
<td>0.203</td>
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<td>J1455–3330</td>
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<td>B1953+29</td>
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<td>1.437</td>
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<tr>
<td>J1643–1224</td>
<td>2.892</td>
<td>2.78</td>
<td>1.467</td>
<td>1.887</td>
</tr>
</tbody>
</table>
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
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 \(\sim 3\%\) total time at GBT/Arecibo.

Wideband receiver upgrades (\(\sim 0.5-3\) GHz)

“PUPPI” for Arecibo is in progress.

EVLA provides \(\sim\)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 \(\sim 0.5-3.0\) GHz.

- **MeerKAT** (South Africa)
  - 64 13.5-m dishes. \(\sim\)GBT sensitivity, but in the **southern hemisphere**.

- **FAST** (China)
  - One **500-m dish!** \(\sim 3x\) Arecibo sensitivity

- Dedicated PTA telescope or SKA?
Expected GW sensitivity improvement vs time:

![Graph showing expected GW sensitivity improvement over time for different systems.](image)
Conclusions/Summary:

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

2. **J1614-2230 mass** is $1.97(4) \, M_{\odot}$, 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 $\sim 40 \, \text{ns level}$. GW detection is possible within the next $\sim 5-10$ 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
- $M_p \sim 2.40 +/- 0.12 M_{\odot}$
- $M_p > 1.66 M_{\odot}$

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