Fundamental Physics Over 27 Orders of Magnitude With Pulsars

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Image Credit: ESO
Pulsars are clocks...

...that create some of the most extreme environments in the Universe...

...which makes them natural laboratories for studying fundamental physics.
Pulsar Timing

• Track every rotation of a pulsar
• Predict pulse arrival times
  – Deviations from the expected arrival time of a pulse contain useful information
Model
(Prediction)
Residual = Data - Model

Times of Arrival (TOAs)
Many rotations

Residual = Data - Model

Time (weeks to years)
Power of Pulsar Timing

- Spin period can be measured to $\sim \delta/N_{\text{rot}}$
  - For MSPs observed over many years, $N_{\text{rot}} \sim 10^9$
- At 2017-10-17 09:10 EDT the frequency of PSR J0437-4715 is/was

$$173.701580684374 \pm 0.0000000000003 \text{ Hz}$$
Power of Pulsar Timing

\[ a = 10^{11} \text{ cm (1.44 } R_{\text{sun}}) \]

\[ a-b = 18.59 \pm 0.01 \text{ cm} \]

Orbit at \( D = 139 \text{ pc} \) measured to \( 10^{-13} \)!!!
Effects of the Interstellar Medium

- Two frequency-dependent effects: dispersion and scattering
  - Both smear out pulses and are worse at low frequencies
  - They are also timing varying!
White noise residuals

Radiometer noise  Pulse Jitter  DISS

Slide courtesy of Tim Dolch
Red noise residuals

Spin noise + DM variations + GWs (stochastic)

Length of Day

0 1 2 3 4 5
1900 1920 1940 1960 1980 2000

Year

20 June 2013

Slide courtesy of Tim Dolch
Millisecond Pulsar Timing Arrays

- GWs will cause a quadirpolar angular correlation signature
- Requirements: 10-100s ns residuals, full sky coverage, lots of pulsars, precise ISM measurements
GW Sources

- **Coalescing Super-Massive Black Holes**
  - Basically all galaxies have them
  - Masses of $10^6 - 10^9 \, M_\odot$
  - Galaxy mergers lead to BH mergers
  - When BHs within 1pc, GWs are main energy loss
  - For total mass $M/(1+z)$, distance $d_L$, and SMBH orbital freq $f$, the induced timing residuals are:
    \[
    \Delta \tau \sim 10 \, \text{ns} \left( \frac{1 \, \text{Gpc}}{d_L} \right) \left( \frac{M}{10^9 \, M_\odot} \right)^{5/3} \left( \frac{10^{-7} \, \text{Hz}}{f} \right)^{1/3}
    \]
  - Cosmic strings (if they exist) also in this GW frequency range

Slide courtesy S. Ransom
Observational Signatures

- Different source classes have different structure in residuals
- Sensitive to $f_{GW} \sim \text{nHz} / \lambda_{GW} \sim 10^{17} \text{ m}
Complementary Gravitational Wave Detectors

The big picture of gravitational wave astronomy

ELF
- CMB
- Primordial gravitational waves
- Inflation

VLF
- Pulsar Timing
- Space-based interferometers
  - Supermassive Black Hole Binaries
  - Cosmic strings
  - Stellar mass compact binaries
  - Massive black hole mergers

LF
- Moderate Risk
- High Reward

HF
- “High Risk
- High Reward”

Ground-based interferometers
- Neutron star binaries
- Black hole binaries
NANOGrav

- North American PTA
  - Senior/affiliated researchers at over two dozen institutions (US, Canada, Europe)
- Funded by NSF Physics Frontier Center ($14.5M over 5 years)
  - Portion of funding supports GBT operations
- Currently time 45 pulsars at GBT and Arecibo
  - 500 (GBT) + 800 (AO) = 1300 hrs/year
  - Does not include pulsar searches!
  - **Each contributes 50% of overall GW sensitivity**
- International collaboration through IPTA
NANOGrav Data Releases

5 Year (2013)
- ASP + GASP
- 16 MSPs, 1,095 observations, ~16K TOAs

9 Year (2015)
- Transitioned to [GP]UPPI
- 39 MSPs, 4,138 observations, ~170K TOAs

11 Year (2017)
- 45 MSPs, 6,737 observations, ~310K TOAs
“Current” Results

- Ruling out/tightly constraining early models of BH merger rate
- Constraints on shape of GW spectrum contains information about BH environments
Subatomic Physics

$M_{wd} = 0.500(6) \, M\odot$

$M_{psr} = 1.97(4) \, M\odot$

Inclination = 89.17(2) deg!

Demorest et al. 2010, Nature, 467, 1081D

Most highly cited GBT paper (1,550+)
Subatomic Physics

Rules out most or all EOSs with exotic material in the cores
Strong Field GR Tests

- Double Pulsar is the premier system for studying strong-field GR
  - Light from one pulsars passes within 10,000 km of the other
- Seeing 2\textsuperscript{nd} order post-Newtonian effects

\[ i = 89.29 \pm 0.05 \text{ deg} \]
(as determined from geodetic precession)

\[ \sim 10,000\text{km} \]

Courtesy of Michael Kramer
Testing the Strong Equivalence Principle

- PSR J0337+1717: First MSP in a stellar triple system
  - Discovered in GBT survey
- Three body dynamical effects cause secular changes in orbital parameters
  - Allow us to precisely solve for the **geometry and masses** of all stars and orbits
- All bodies fall at the same rate (?)
- MSP & inner WD falling in gravity of outer WD

Image credit: Ransom et al. (2014, Nature, 505, 520)
Testing the Strong Equivalence Principle

• Violations parameterized by differential acceleration
  Currently dominated by systematics
  Sensitive to Solar wind DM variations

Look for Archibald et al. (early 2018)
Testing TeVeS Gravity Theories

- J0348+0432: Relativistic MSP/WD binary
  - Discovered by GBT
- Pulsar + WD spectroscopy → double-line binary
- Get masses + system geometry
- Pulsar is 2 $M_{\text{sun}}$ – most massive known (by a hair)
  - Does not significantly improve on EOS constraints
- But...

Antoniadis et al. (2013, Science, 340, 448)
Testing TeVeS Gravity Theories

- Relativistic orbit and mass asymmetry provide unique test of tensor-vector-scalar gravity theories
  - Different “compactness” would produce dipolar GWs

Antoniadis et al. (2014, Science, 340, 448)

- Significant parameter space for scalar coupling constants ruled out thanks to high binding energy and relativistic orbit
Where Are We Going?

~0.6-4 GHz in one shot
CASPER-based backend
**Improve timing by 20-100%**

Bandwidth:
- Improves S/N (as $\sqrt{\text{BW}}$)
- Scintillation protection
- Much better ISM (i.e. DM) removal

ASP / GASP
GUPPI / PUPPI
Wideband

Fig: Paul Demorest
Where Are We Going?

- Daily observations of all NANOGrav MSPs w/ CHIME
  - All pulsars with ~ few weeks cadence
- Large FOV
- No moving parts – digital telescope
- Relatively inexpensive way to get collecting area
Where Are We Going?

• Stochastic GW background detected by 2022
  – Assumes steady growth in current observing program
• Not just a number!
  – Spectral shape encodes information about supermassive BH environments
  – Find the solution to the last parsec problem
• Detect single GW sources?
• Burst events?
  – Bursts with memory provide deep test of GR
• Constrain (detect?) cosmic strings
• Eventually measure anisotropies in GW background
Where Are We Going?

• More pulsars! Always more pulsars!
  – **Every time we find new pulsars, we find true gems**
  – Take advantage of new capabilities (PAFs, UWB Rx)

• Next generation surveys (FAST, MeerKAT, SKA) will find many thousands of new pulsars
  – Eventually all the pulsars

• 3 $M_{\text{sun}}$ neutron stars? Sub-millisecond pulsars?
  – Solve the NS EOS?

• Pulsar – BH binary? (“Holy Grail” for gravity tests), Pulsars around Sgr A*
  – Test no-hair theorem
  – Maybe, finally, find breakdown of GR?
Summary

- NANOGgrav is on track to detect GWs in the next 5 years
  - Opening the full GW spectrum
- We are on the cusp of a new wave of pulsar discoveries
  - There will undoubtedly be unique and powerful physical laboratories among them
- The GBT (and Arecibo) are the best instruments in the world for precision pulsar timing
  - Wideband systems could make them even better
  - Can leverage new telescopes to maximize scientific return