Testing General Relativity with Black Hole-Pulsar Binaries

Brian C. Seymour
Advisor: Professor Kent Yagi, Department of Physics, UVa

Abstract

Gravity is an important macroscopic force in our universe. The current best theory of gravity is called general relativity. This poster will examine how to test the assumption of a gravitational constant G that does not vary with time in general relativity. Historically, predictions of general relativity were tested in a double pulsar, where the gravitational wave emission creates a shortening of the orbital period. However, current and future radio telescopes, such as FAST and SKA, may find a new astrophysical system, a pulsar orbiting around a black hole, which will provide us with a new source for probing gravity. With this, the prospective bound on the time variation of the gravitational constant G is presented if this binary were found. This example demonstrates the utility of testing gravity with radio telescope measurements of a black hole-pulsar binary in extensions to general relativity.

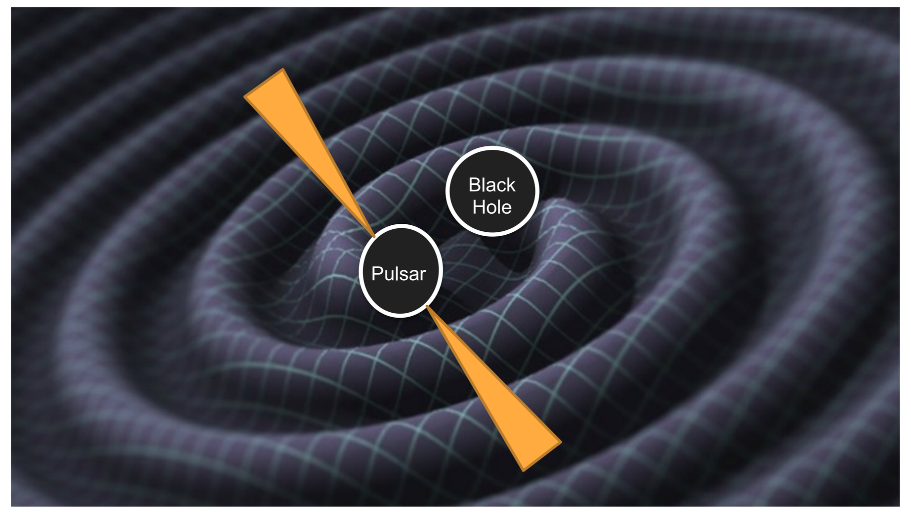
Introduction

- Einstein's theory of *general relativity* improved Newtonian gravity to deal with relatively strong-field experiments.
- Gravity is described as the curvature of spacetime. The dynamical process happens because mass distorts spacetime, and spacetime distortion moves matter.
- General relativity predicts special objects—*black holes* and *pulsars*. Black holes have so much gravity that not even light can escape! A pulsar is as heavy as the sun but around the same size as Washington, DC. Also, pulsars rotate extremely quickly, up to a thousand times a second. Furthermore, they emit a beam of light on both sides.
- Most intriguingly, general relativity also predicts that ripples of spacetime—gravitational waves—are emitted in orbiting bodies. The 2017 Nobel Prize in Physics was awarded to the creators of LIGO which measured gravitational waves directly for the first time.
- General relativity does not work at the quantum scale. This suggests that it is not *a final theory*. The rest of this presentation examines tests of general relativity.

Method

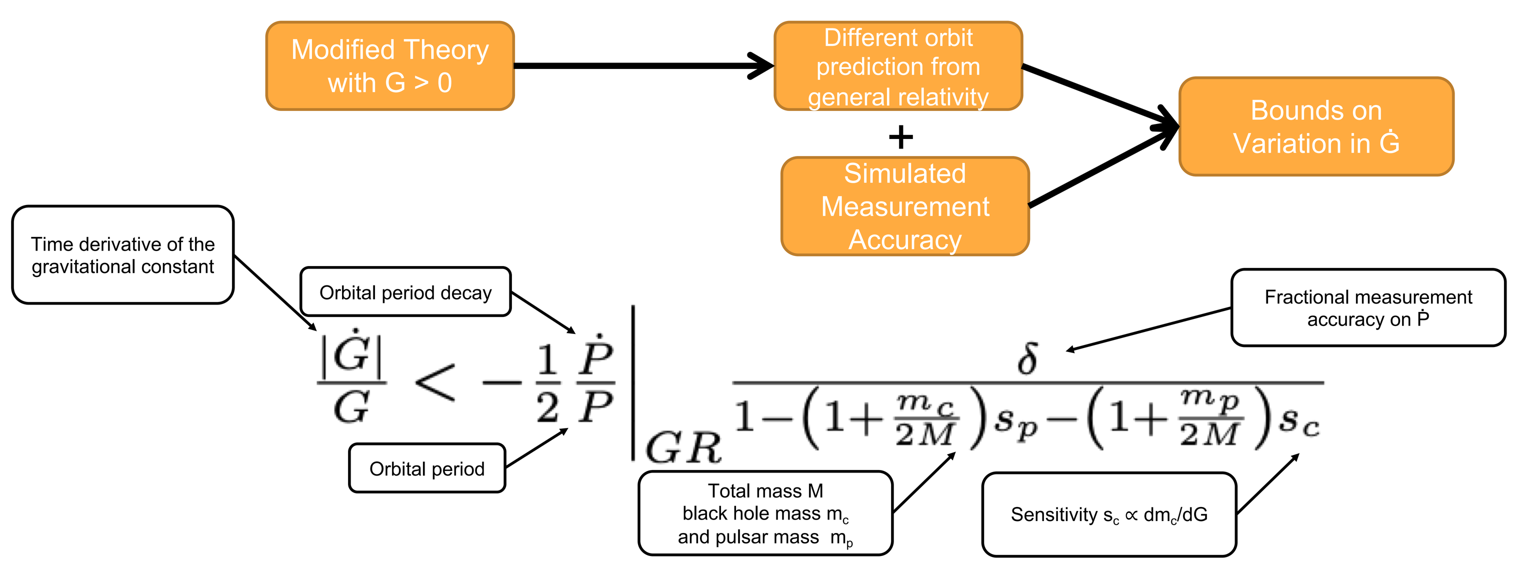
- Astronomers use radio astronomy to measure oscillations in a pulsar's beam of light. This can be used to make high precision observations through a method called *pulsar timing.*
- Pulsar timing can be used to measure the orbital properties of distant binaries.
- For example, an important orbital parameter that is called the *orbital decay rate,* the time derivative of the orbital period, can be measured through pulsar timing.

Radio Telescope



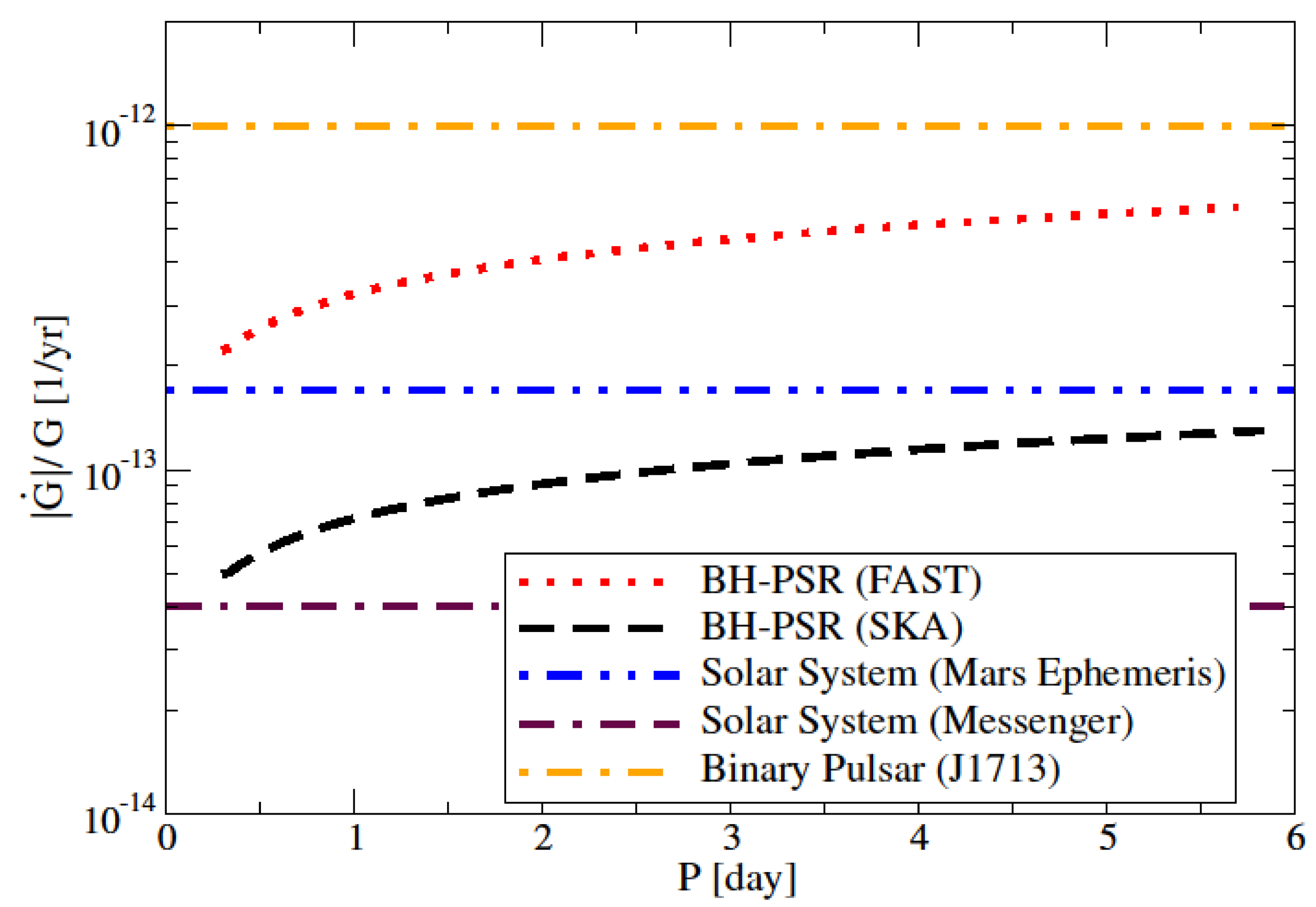
Procedure

- A black hole pulsar binary has not been found yet, so we used a pulsar timing simulation to figure out how well we can measure the orbital decay rate of the binary [1].
- In general relativity, the time variation of the gravitational constant, Ġ, is zero.
- If however, Ġ is nonzero, this would cause the orbital decay rate to deviate from general relativity.
- Thus, measuring the orbital decay rate's deviation from general relativity provides a way to bound the time variation in the gravitational constant.



$$\frac{|\dot{G}|}{G} < -\frac{1}{2}\frac{\dot{P}}{P}\Bigg|_{GR}\frac{\delta}{1-\left(1+\frac{m_c}{2M}\right)s_p-\left(1+\frac{m_p}{2M}\right)s_c}$$

Results



- Black hole pulsar bounds on the variation in G are shown in red and black. This figure is taken from our paper [2].
- They provide stronger bounds than binary pulsar constraints, but are weaker than some current solar system bounds.

Discussion

- Solar system bounds are in the 'weak field' because gravity is significantly weaker than the 'strong field' of compact astrophysical sources (e.g. a pulsar or black hole).
- While black hole-pulsar bounds were not the strongest, they provide important constraints on general relativity because the Ġ effect can be enhanced in the strong field. For some systems, this can be up to two orders of magnitude [3].
- Thus, the black hole-pulsar bound provides a strong field independent check on variation in G complementary to weak field solar system measurements.

Summary/Implications

- Radio astronomy is effective for testing theories of gravity with pulsar timing.
- If found, a black hole-pulsar binary would give a promising new way to constrain theories of gravity.
- The combination of black hole-pulsar, binary pulsar, solar system, and gravitational wave bounds will be used in the future to better constrain gravity and search for deviations from general relativity.

References

[1] [28] K. Liu, R. P. Eatough, N. Wex, and M. Kramer, Mon. Not. Roy. Astron. Soc. 445, 3115 (2014), arXiv:1409.3882 [astro-ph.GA].

[2] B. Seymour and K. Yagi, (2018) arXiv:1808.00080 [gr-qc].

[3] N. Wex, (2014), arXiv:1402.5594 [gr-qc].