BlackHoleCam — Testing general relativity with pulsars orbiting Sagittarius A*

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BlackHoleCam is a project funded by a European Research Council *Synergy Grant* to build a complete astrophysical description of nearby supermassive black holes by using a combination of radio imaging, pulsar observations, stellar astrometry and general relativistic magneto-hydrodynamic models. BlackHoleCam* scientists are active partners of the Event Horizon Telescope Consortium†. In this talk I will discuss the use of pulsars orbiting Sagittarius A* for tests of General Relativity, the current difficulties in detecting such sources, recent results from the Galactic Centre magnetar PSR J1745−2900 and how BlackHoleCam aims to search for undiscovered pulsars in the Galactic Centre.

Keywords: Pulsars; Black Holes; Gravity Tests.

1. The science case for observing pulsars orbiting Sagittarius A*

For over 40 years observations double neutron star systems – the collapsed and degenerate remnants of massive stars – where one, or both, stars are active radio pulsars have demonstrated that they form exceptional natural "laboratories" for precision tests of theories of gravitation[1,2]. In this vein, a pulsar in a close orbit around the supermassive black hole at the centre of our Galaxy (Sagittarius A* – Sgr A* for short) would be at the apex of gravity experiments made possible using pulsars[3,4].

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*www.blackholecam.org
†www.eventhorizontelescope.org

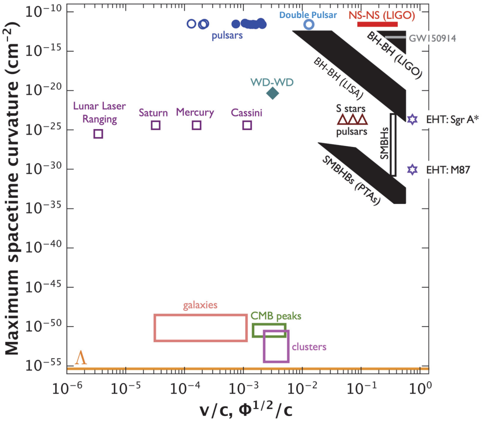

Fig. 1. Parameter space of observations and tests of gravity. On the x-axis, v denotes the typical velocity of the system's components while Φ denotes the gravitational potential being probed by photons propagating in the corresponding spacetime. On the y-axis the maximum spacetime curvature (taken at the horizon for black holes) in the system is indicated as a measure of how much the system deviates from flat spacetime. Filled areas indicate gravitational wave tests, while hollow areas stand for quasi-stationary tests, including accretion onto compact objects. The rightmost hollow blue circle stands for the Shapiro delay test in the double pulsar. Figure and caption reproduced from Ref. 6 with the kind permission of Wex and Kramer.

Such a system will allow the fundamental predictions of black-hole properties in General Relativity (GR) to be tested; properties that Advanced LIGO, which measures the strongly dynamical regime of a merger, potentially cannot[5]. These include the *no-hair theorem* and the *cosmic censorship conjecture*[3,4]. For example, the latter is tested through measurements of frame dragging caused by the spinning black hole, which manifests itself as a contribution to the precession of the pulsar orbit. A Kerr black hole should exhibit a dimensionless spin parameter χ which is no larger than unity; a spin parameter greater would be in conflict with GR posing a direct contest to the theory. Fig. 1 shows how pulsar tests fit into the relativistic regime of other gravity tests past and present. In Fig. 2 (*left* panel) from Ref. 4 the expected signature of the black hole quadrupole moment in pulsar timing residuals for a putative pulsar closely orbiting Sgr A* is displayed. Ref. 7 have shown that by combining measurements of the black hole spin from stellar astrometry, pulsar timing and interferometric imaging of the black hole shadow, an unbiased and quantitative test of the no-hair theorem is possible (Fig. 2 *right* panel).

2. Galactic Centre pulsar searches

Over the last couple of decades a number of searches of the inner tens of parsecs have taken place[8–12]. In 2013, the Galactic Centre (GC) pulsar population[a] was

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[a] Here we define the GC pulsar population as those with pulses detected in radio at a projected offset of less than 0.5° (~73 pc) from Sgr A*.

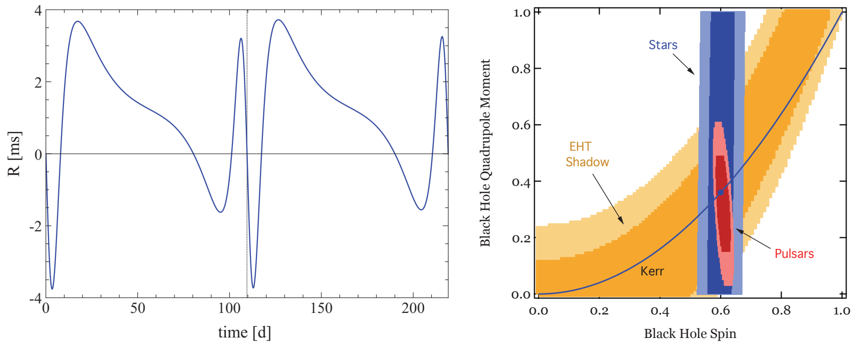

Fig. 2. (*left*) A simulation showing the effect of the quadrupole moment of Sgr A* "imprinted" upon pulsar timing residuals over two orbital cycles. Here an orbital period of 0.3 yr, an eccentricity of 0.5 and a dimensionless black hole spin parameter of unity were assumed. Figure reproduced from Ref. 4. (*right*) Comparison of the posterior likelihood of measuring the spin and quadrupole moment of Sgr A* using the orbits of two stars (blue), timing of three periapsis passages of a normal pulsar (red) and the shape of the black hole shadow from radio interferometric imaging (gold). The solid curve shows the expected relation between the two quantities for a Kerr metric. The filled circle marks the assumed spin and quadrupole moment. Figure reproduced from Ref. 7.

brought to a total of six with the detection of PSR J1745−2900, first through its gamma ray emission[13,14] and then finally in radio[15,16].

As radio telescope hardware and analysis techniques are improved, GC pulsar searches are carving out additional areas of parameter space neglected by previous searches. An example is the progression to higher than "normal" pulsar observing frequencies ($f_{\rm obs} \gtrsim 10\,{\rm GHz}$) where the deleterious effects of interstellar dispersion and scattering (effects that are at their highest in GC) are reduced. Unfortunately, improvements in sensitivity by choosing higher frequencies are limited by the steep spectrum of pulsar emission, where detection signal-to-noise ratio S/N is typically $\propto f_{\rm obs}^{\sim -1.7}$. This is one case where competing selection effects affect the performance of GC pulsar searches (Table 1). In general, higher observing frequencies and longer integration lengths $T_{\rm obs}$ (given the large distance of the GC) are more favourable, however this predisposes searches to flatter spectrum isolated pulsars. Binary pulsar searches can become computationally prohibitive above certain $T_{\rm obs}$ where even single parameter acceleration search computations C_a scale with $T_{\rm obs}^3$.

3. BlackHoleCam pulsar work

BlackHoleCam[18], and members of the Event Horizon Telescope (EHT) Consortium, aim to tackle these observational constraints by using the largest and most sensitive telescopes operating at millimetre wavelengths which form elements of the EHT telescope. Because both EHT VLBI imaging and pulsar observations can utilise the same raw data product from each array element, EHT VLBI and pulsar observations can be commensal.

Table 1. Competing observational selection effects for GC radio pulsar searches. Pulse broadening effects, such as dispersion smearing τ_{ch}, scatter broadening τ_{s} and acceleration broadening τ_a, add in quadrature to the intrinsic pulse width W making W_{eff}, which scales with the detection signal-to-noise ratio as $\text{S/N} \propto \sqrt{(P - W_{\text{eff}})/W_{\text{eff}}}$ where P is the spin period. ✓ indicates favourable observational configurations while ✗ are unfavourable.

Observing frequency related	Higher f_{obs}	Lower f_{obs}
Intra-channel pulse dispersion smearing ($\tau_{\text{ch}} \propto f_{\text{obs}}^{-3}$)	✓	✗
Pulse scattering broadening ($\tau_{\text{s}} \propto f_{\text{obs}}^{-3.8}$)	✓	✗
Intense GC background continuum emission[17] ($\text{S/N} \propto f_{\text{obs}}^{-0.8}$)	✓	✗
Pulsar spectra ($\text{S/N} \propto f_{\text{obs}}^{\sim -1.7}$)	✗	✓
Integration length related	Longer T_{obs}	Shorter T_{obs}
GC distance ($\text{S/N} \propto \sqrt{T_{\text{obs}}}$)	✓	✗
Pulse broadening from acceleration ($\tau_a \propto T_{\text{obs}}^2$)	✗	✓
Pulse broadening from jerk ($\tau_j \propto T_{\text{obs}}^3$)	✗	✓
Computational operations for acceleration search ($C_a \propto T_{\text{obs}}^3$)	✗	✓

Thus far, pulsar search efforts have concentrated on analysing data from the single most sensitive element of the EHT: "fully phased" ALMA. In the future we can envisage using a phased array of the largest components of the EHT to further increase sensitivity or to mitigate site specific interference contamination.

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