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BlackHoleCam: Imaging the Event Horizon of Black Holes

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Gravity is successfully described by Einstein's theory of general relativity (GR), governing the structure of our entire universe. Yet gravity remains the least understood of all forces in nature, e.g., resisting unification with quantum physics. One of the most fundamental predictions of GR are black holes (BHs). Their defining feature is the event horizon, the surface that even light cannot escape and where time and space exchange their nature. However, while there are many convincing BH candidates in the universe, there is no experimental proof for the existence of an event horizon yet. So, does GR really hold in its most extreme limit? Do BHs exist or are alternatives needed?

Here we propose to build a *Black Hole Camera* that for the first time will *take an actual picture of a BH and image the shadow of its event horizon*. We will do this by providing the equipment and software needed to turn a network of existing mm-wave radio telescopes into a global interferometer. This virtual telescope, when supplemented with the new Atacama Large Millimetre Array (ALMA), has the power to finally resolve the supermassive BH in the centre of our Milky Way – the best-measured BH candidate we know of.

In order to compare the image with the theoretical predictions we will need to perform numerical modelling and ray tracing in GR and alternative theories of gravity. In addition, we will need to determine accurately the two basic parameters of the BH: its mass and spin. This will become possible by precisely measuring orbits of stars with optical interferometry on ESO's VLTI. Moreover, our equipment at ALMA will allow for the first detection of pulsars around the BH. Already a single pulsar will independently determine the BH's mass to one part in a million and its spin to a few per cent.

This unique combination will not only produce the first-ever image of a BH, but also turn our Galactic Centre into a fundamental-physics laboratory to measure the fabric of space and time with unprecedented precision.

(images of mm-wave telescopes do not reflect their geographic location)

1 Introduction - State of the Art and Objectives

1.1 General relativity – the fabric of space and time

General relativity (GR) will soon be 100 years old, but it has never been as lively and modern. No other theory of gravity is equally successful at describing the complex phenomenology that astronomical and cosmological observations provide. Both on the scale of the solar system, through the corrections it provides to the GPS navigation system, and on the largest cosmological scales, when describing the expanding universe, GR provides in a single elegant mathematical framework a powerful theory to explain the observations and, most importantly, accurate predictions. In addition, while GR has not yet been tested in its strong-field predictions, a multinational effort is building complex laser interferometers that will lead to the first detection of gravitational waves (GWs), a prediction of the theory that has so far been difficult to verify.

Among the many ideas that Einstein's GR has introduced, there is one which is unique in its revolutionary implications, namely, the existence of *black holes (BHs)*. The first intuition goes back to Michell and Laplace, who in the 18th century speculated the existence of objects with a gravitational field so large to prevent even light from escaping. Already in 1915, a few months after the publication of the Einstein equations, Schwarzschild derived their solution in spherical symmetry and vacuum. However, it was not untill the 1960ies that it was recognized that the "Schwarzschild solution" describes what we now call a BH. The work carried out over the last 50 years has given this concept a robust mathematical basis and has cast it in physical scenarios we encounter in many astronomical observations. Paradoxically, the very idea of BHs, which has puzzled scientists for decades, is now one of the most cherished concepts in modern physics and astrophysics. Uncharged BHs in GR are fully described by two numbers only: their mass and their spin. Hence, they are very simple macroscopical objects – indeed they are the simplest ones known.

Although the idea of BHs is widely accepted, it does come with a number of problems. Some of the properties of BHs still represent genuine challenges for our understanding of gravitation (both classically and quantum-mechanically) and it is obvious that any experimental validation offers insurmountable obstacles. However, the most problematic aspect of BHs is by and large the elusiveness of the *"event horizon"* and thus it is not surprising that the existence of BHs and of their event horizons has actually not been *proven* yet.

The horizon has a simple mathematical definition: it is the surface on which swarms of outgoing photons have zero expansion, that is, it is the surface which photons (but also any particle) can enter but not leave. This "one-way" membrane in the fabric of spacetime defines not only the boundary between regions that are causally disconnected, but it is also the border where time and space exchange their nature. Near this surface, extreme physical conditions can be reached, making its "central engine" powering the most energetic phenomena observed, such as active galactic nuclei and quasars. Also, according to the "cosmic censorship" conjecture (Hawking & Penrose 1970), it is this surface that acts as the "censor", veiling the presence of a classical physical singularity at the centre where the laws of physics, as we know them, must break down.

The implications of an event horizon are far-reaching and it is through the event horizon entropy that we could hope to measure the quantum nature of BHs or understand what happens to space and time when gravity dominates. Until today, however, there is at best indirect evidence for the existence of event horizons (Narayan & McClintock 2008). This is problematic, since plausible, albeit exotic alternatives to BHs, such as gravastars (Mazur & Mottola 2004), could mimic many of their properties (Chirenti & Rezzolla 2007).

In the following we will outline how imaging and understanding the event horizon of the closest supermassive BH in the universe can provide us with the much-needed proof of the BH existence, as well as with a cosmic laboratory to investigate the structure of spacetime and GR in its most extreme limit.

1.2 Imaging the Event Horizon

1.2.1 Black holes

BHs come in two basic mass classes: *stellar BHs*, which are essentially the collapsed cores of stars that exploded as supernovae, and *supermassive BHs*, which reside in the nuclei of most, if not all, galaxies. If M_{bh} is the mass of the BH, its characteristic scale is set by the size of the horizon, or Schwarzschild radius, $R_S=2GM_\odot/c^2\sim 3$ km $(M_{bh}/M_\odot)$, where G is the gravitational constant, c is the speed of light, and $M_\odot$ is the mass of the sun. Stellar-mass BHs have masses of order 10 $M_\odot$ and thus sizes of some tens of kilometres, and are frequently found within our own Galaxy at distances of some kpc[1]. Supermassive BHs have masses

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[1] 1 pc = 3×10^{13} km = 3.3 light years – GR = General Relativity, GW = Gravitational Waves, BH = Black Hole

between 10^6-10^{10} $M_\odot$ and are typically found at tens of Mpc to Gpc distances. The angular size of BHs at a distance D is $\theta_{bh}=0.1$ nanoarcsec $(M_{bh}/10M_\odot)$ (kpc$/D$). For stellar BHs, this is far too small to be resolved by any current technology, preventing any direct detection of the event horizon. Supermassive BHs are intrinsically much bigger, but since they are further away, also their angular size is too small to be resolved by any telescope. Fortunately, as we will discuss in Sec. 1.2.2, there are two notable exceptions.

Despite being so small and "black", there is nonetheless some information about BHs reaching us from near the event horizon. Indeed, gas and plasma around BHs is attracted and transported inwards through an accretion flow, heating up the material and emitting large amounts of energy. This energy is radiated across the electromagnetic spectrum from the radio, to infrared, optical, X-ray, and gamma-ray bands. The accretion process onto a BH is the most efficient mechanism of energy generation in the universe, releasing a power $\dot{E} = \eta \dot{M} c^2$, where $\dot{M}$ is the mass accretion rate and the efficiency is $\eta\sim10\%$. This readily explains the extreme brightness of *quasars* as efficiently accreting supermassive BHs at large distances, while the "silent majority" (Falcke 2001) of supermassive BHs in the universe is underfed and underluminous.

The distinction between luminous and underluminous BHs is also reflected in the structure of the accretion flow, which can be in the form of a thin and radiatively efficient accretion disk (Shakura & Sunyaev 1973) or in the form of a puffed up, radiatively inefficient accretion flow (Narayan & Yi 1994). In either case, most of the X-ray and UV-emission should be produced within some tens of Schwarzschild radii. Indeed, the shape of emission lines of highly-ionized iron in some objects suggests that the emitting gas is affected by strong gravity (Tanaka et al. 1995), providing further evidence for the BH interpretation.

Common features of accreting BHs are also relativistic jets – magnetized plasma streams leaving the system at almost the speed of light. Jets seem to be produced near the event horizon (Hada et al. 2011) and are closely coupled to the accretion disk (Falcke et al. 1995). They are responsible for most of the radio and high-energy emission in BHs and are candidate sources of ultra-high energy cosmic rays.

Hence, the physics of accretion flows and the formation of jets is a major field of research in its own right, as this determines how BHs appear to an observer. Currently the focus in this field is on numerical two- and three-dimensional (3D) magneto-hydrodynamic simulations in full GR (GRMHD, see Sec. 2.2.1).

1.2.2 The Galactic Centre – the closest supermassive BH

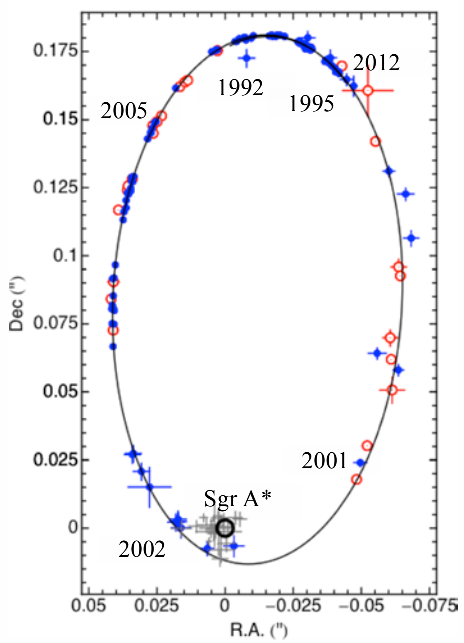

Figure 1: Left: Keplerian orbit measured for a single star around Sgr A* (circle) from 1992-2012 – updated from Gillessen et al. (2009).

The source providing the most convincing case for the existence of a supermassive BH is in the centre of our own Milky Way (Genzel et al. (2010), Melia and Falcke (2001)). First detected in the radio as a point source named Sgr A* (Sagittarius A*), the source is now being studied also at near-infrared and X-ray wavelengths. What makes Sgr A* so special is its proximity at only 8 kpc, coupled with its large mass of about 4 million solar masses. Hence, Sgr A* is a factor of a million larger than stellar BHs in the Galaxy and at least thousand times closer than any other supermassive BH. This makes it the largest BH on the sky and the prime candidate for imaging the event horizon.

Particularly unique is how accurately the parameters of Sgr A* are determined. For many years now, groups in Europe and the USA have detected and monitored stars around Sgr A* (Eckart & Genzel 1997, Ghez et al. 2000) that move with large velocities in Keplerian orbits (Figure 1). These orbits show that the gravitational potential in the centre of the Galaxy is dominated by a central mass of M=4×10^6 $M_\odot$ concentrated within some hundred Schwarzschild radii (e.g., Eisenhauer et al. (2005)).

In contrast to the fast-moving stars, which are accelerated by the force of gravity to speeds of 10.000 km/s in the same region, Sgr A* is moving at <1 km/s, according to accurate radio interferometry measurements (VLBI, Sec. 1.2.4). Hence, the radio source Sgr A* is anchored to at least half a million solar masses (Reid & Brunthaler 2004), and likely more.

Further clues on the nature of Sgr A* come from its radio spectrum, which rises towards higher frequencies, peaking in the "sub-mm bump" at $\nu\sim350$ GHz ($\lambda\sim0.9$ mm). Using theoretical arguments, we predicted that by going to higher frequencies one would also see emission from closer to the BH (Falcke et al. 1993). Later, we showed in one of the first multi-wavelengths campaigns for Sgr A* that the sub-mm bump is in fact due to optically thin synchrotron radiation from a region near the BH and suggested that this would allow for imaging the event horizon with VLBI (Falcke et al. 1998).

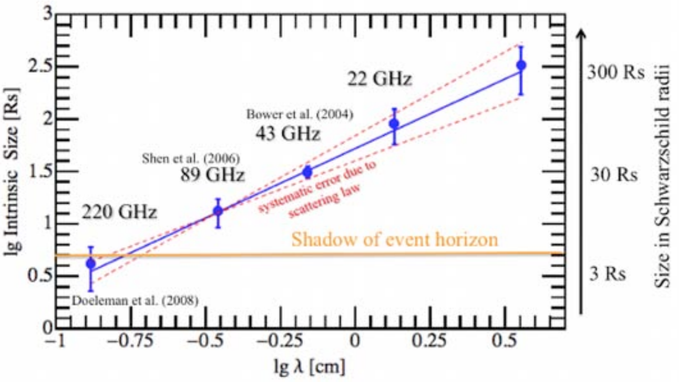

Figure 2: The intrinsic size of Sgr A*, as determined from VLBI, reaching down to event horizon scales (Falcke et al. 2009).

For a long time it has been difficult to determine the size and structure of Sgr A* from direct imaging and thus confirm this picture. Scattering of radio waves in the interstellar medium, in fact, washes out any structure at long radio wavelengths (van Langevelde et al. 1992). In 2004, a group including one of us succeeded for the first time to derive the true intrinsic size (see Figure 2) of Sgr A* with VLBI at 42 and 22 GHz (Bower et al. 2004). This revealed an apparent size of only 24 Schwarzschild radii at 43 GHz, decreasing with frequency. Later experiments at higher frequencies confirmed this picture, showing that the sub-mm bump emission at 220 GHz comes from within 38 µarcsec, i.e., only 4 Schwarzschild radii (Doeleman et al. 2008). Fortunately, the scattering effect reduces with increasing frequency and from 220 GHz onwards becomes small enough that one can directly probe event horizon scales. However, at present the quality of VLBI at 220 GHz is not yet good enough to make an image due to the low sensitivity and small number of telescopes.

In summary, we now know with great confidence that there is a compact object of a few million solar masses in the centre of our Galaxy, compressed in a volume so small that it would naturally match with our expectation for a BH. This mass is associated with a radio source whose emission illuminates the event horizon at frequencies ≳220 GHz. Radio observations at these frequencies have started to resolve this scale.

Apart from Sgr A*, there is only one other BH known to have a comparable large angular size on the sky, namely the one in M87, the central elliptical galaxy in the nearby Virgo cluster. This source is a thousand times more distant than Sgr A*, but also a thousand times more massive, so that the resulting angular size is comparable. Its spectacular radio jet extends down to a few Schwarzschild radii at mm-waves (Hada et al. 2011), making it the second candidate for event horizon imaging. The much larger systematic uncertainties in its mass determination make M87 less suitable for precision tests of GR, but crucial for BH astrophysics.

1.2.3 The black hole shadow

So, what would a BH actually look like, if one could resolve it? Bardeen (1973) calculated the visual appearance of a BH passing in front of a star and found that it is determined by the last "photon orbit", i.e., the smallest surface around a BH on which photons can in principle orbit stably. In practice, the photon orbit separates photon trajectories that disappear in the horizon from those escaping to infinity. The probability of a BH passing in front of a star is too small to be observable, but Falcke et al. (2000) showed that a BH embedded in an optically-thin emission region, as the one expected for Sgr A*, would produce an observable signature, namely a *"shadow"* cast by the BH (see top right corner in cover picture). This shadow is essentially a gravitationally lensed image of the event horizon and has a diameter around 5 Schwarzschild radii (49 µarcsec at Sgr A*), with only a 10% dependence of its size on the BH spin.

Since this first study an entire "shadow industry" has emerged, with several groups extending the calculations to a variety of emission models. Despite different assumptions, the basic features, i.e., a *shadow surrounded by a photon ring*, are seen in all models (e.g., Broderick and Loeb 2006, Dexter et al. 2010), so that there is now a general consensus that with sufficient resolution the event horizon should be detectable in Sgr A*. The appearance of the emission surrounding the shadow depends on spin, orientation and on the emission process. E.g, high-inclination, high-spin configurations have a more compact, one-sided structure due to Doppler beaming than low-spin, face-on configurations. This allows one to constrain the BH spin.

1.2.4 High-resolution imaging with very long baseline interferometry

The method to obtain high-resolution radio images is well established and known as very long baseline interferometry (VLBI). At the highest frequencies (≳90 GHz), where radio wavelengths have mm-scale sizes, one speaks of mmVLBI. By recording data at widely separated radio telescopes, one can measure interference fringes that can be used to reconstruct an image of the source. Naturally, the quality of the image increases with the number of telescopes that are available. The achievable image resolution (in radians) of an interferometer is given by $\theta \sim \lambda/d$, where λ is the wavelength observed and d is the separation of the telescopes. Hence, larger frequencies (shorter wavelengths) and larger distances provide the highest resolving power. Intercontinental baselines have been realized already decades ago and the highest resolution ever obtained, yielding θ~28 µarcsec, was achieved in 2012 by a joint MPIfR Bonn-MIT group at 230 GHz for a separation of d~9447 km between telescopes in Hawaii and Chile. Since radio telescopes measure classical electromagnetic waves, these waves can be recorded and brought into interference in software. Therefore, a VLBI experiment can use a heterogeneous set of telescopes at arbitrary locations by supplying them with local recording equipment and atomic clocks. The recorded data from each telescope will then be correlated post-facto by a powerful computer, using time stamps of the atomic clock for synchronization. Calibration and imaging software will turn the correlated data into an image of the source using Fourier transforms and image-cleaning algorithms. Hence, the recording equipment, the correlator, and the software in a VLBI experiment play the role of a lens and camera in optical telescopes.

VLBI has a strong heritage in Europe, as testified by the long-running European VLBI Network (EVN), with its Joint Institute for VLBI (JIVE) in Dwingeloo (NL) and the Global mmVLBI Array (GMVA), coordinated by the VLBI group at the MPIfR Bonn. Also, the first VLBI detection of Sgr A* at the highest frequency (220 GHz) was made in Europe (Krichbaum et al. 1998) with an intra-European baseline using telescopes of IRAM (Institut de Radioastronomie Milimétrique, a joint institute of MPG, CNRS, and IGN).

1.2.5 ALMA

What makes mmVLBI of Sgr A* so timely now is the availability of the Atacama Large Millmetre Array (ALMA) – a joint EU, US, and Japanese project. The final array will consist of 50 individual (sub)mm-wave telescopes, a large fraction of which is already operating. ALMA will be the most sensitive mm-telescope ever built and will increase the sensitivity of mmVLBI by an order of magnitude. Recently, a US/EU project has started to implement a "phased" mode. This means that all antennas are combined to act jointly as a single dish that can operate as one giant element in a VLBI experiment. The mode should be ready in the next three years and will be available to the community through a standard proposal-reviewing process.

1.2.6 The Event Horizon Telescope

At a meeting in January 2009, a small group of scientists, including some of us, gathered to specify more precisely plans for imaging Sgr A* with mmVLBI, coining the term "Event Horizon Telescope (EHT)". The meeting was followed by two larger workshops in Tucson, Az and at ESO in Garching, D (for a summary see Falcke et al. 2012) to discuss the science vision, the technical roadmap, and the organizational structure of the EHT. In recent years, an MIT-led group, including EU partners, has made good progress, performing three-baseline experiments at 220 GHz (Doeleman et al. 2008) using the EHT label now. However, current funding in the US and Europe falls far short of what is required for a large imaging array involving ALMA. *The ERC Synergy grant scheme can now provide the critical funding to realize a true breakthrough.*

It is not yet decided what the structure of the EHT will be and how European groups are represented therein. In the end, the US and European groups within the EHT may cooperate in one formal collaboration or pursue their goals in a more independent way – both options are scientifically meaningful. After all, it is quite common in fundamental discoveries that the data is acquired and analysed by independent teams and there are numerous examples that testify to the importance of this approach, e.g., the proper motion of stars around Sgr A*, the discovery of dark energy, or the detection of the Higgs boson. Similarly, GW experiments are distinct US/European efforts joined by a collaboration of data exchange and validation (LSC/Virgo). This is essential for a convincing revolutionary discovery. Similar models of cooperation can be applied here.

Hence, the next step will be to perform highly sensitive mmVLBI experiments on Sgr A* with ALMA. This requires sufficient data-acquisition hardware, data analysis pipelines, and a good team to run the experiment.

Our first objective is therefore to set up a focussed effort to build a "BH camera" targeted at imaging the event horizons of the BHs in the Galactic Centre and, later, in M87 ***(Objective 1)****.*

1.3 More than just an image – measuring BH parameters and testing gravity

While making the first image of an event horizon will be a breakthrough discovery in itself, this will not be sufficient to provide a *precision test of GR*. Any experiment is only as good as its theoretical interpretation and the ability to reduce free parameters and contaminating effects. For example, for Sgr A* it will be important to determine the spin and orientation of the BH independently from the imaging. Only in this way, and comparing images with model predictions, it will be possible to detect or constrain deviations from GR.

The expectation for what we should see as the BH shadow is firmly based on the assumption that Einstein's theory of GR is the correct description of gravity. While GR represents the most successful theory of gravity to date, it is not the only one being discussed. For example, observational evidence for "dark matter" has led to alternative theories based on scalar fields. Similarly, the evidence for a dominating and unknown type of energy, responsible for the observed acceleration of the universe ("dark energy"), has led to the development of a large class of alternative theories (Sec. 2.2.2). These theories provide a natural explanation of the cosmological expansion and thus represent a direct challenge to the validity of GR. The predictions for the shadow are different in these theories and some of them even suggest that Sgr A* is not a BH at all, but an ultra-compact solid object whose properties are almost indistinguishable from those of a BH.

Hence, our goal is to make more than just a pretty image: by combining event-horizon imaging, pulsar dynamics and BH modelling, BlackHoleCam can turn the Galactic Centre into a precision-astrophysics laboratory for testing gravitational theories and explore the fine structure of spacetime.

1.3.1 Stellar orbits with the VLTI

So far, the best constraints on the BH mass come from stellar orbits measured with 8-m class telescopes. This will improve further by applying interferometric techniques also in the optical band. A European consortium (Eisenhauer et al. 2011) is currently building GRAVITY, a second-generation Very Large Telescope Interferometer (VLTI) instrument for precision astrometry and interferometric imaging. By providing astrometry with a precision of the order 10 μarcseconds and imaging with a resolution of 4 milliarcsecond, GRAVITY will push the sensitivity and accuracy of optical astrometry and interferometric imaging far beyond what is possible today. Though direct imaging of the event horzon is not possible, stars with even closer orbits around Sgr A* can be observed and their orbits will be determined more precisely. The general-relativistic periastron shift and the Lense–Thirring precession of the orbital angular momentum will influence such stellar orbits and, for stars passing at small distances from the BH, the timescale of these relativistic effects is short enough to be within the reach of GRAVITY, thus allowing one to determine the BH spin from stellar orbits.

Hence, an important task for the future will be to cross-check and combine BH parameters derived from optical (GRAVITY) and radio (BlackHoleCam) observations.

1.3.2 Pulsars as probes of gravity

The best and most stringent strong-field tests of GR performed so far, as well as the most precise determinations of orbits, have been achieved by pulsar timing, albeit not yet in the Galactic Centre. Pulsars are compact, rotating neutron stars that act like cosmic lighthouses in some of the strongest gravitational fields possible. When a pulsar is found in a binary orbit, it can be used as a test mass (with a precision clock attached) that "free falls" in the gravitational potential of the companion. This fall can then be compared with the predictions of GR, but also any other theory of gravity.

If the companion is a second neutron star, as in the Nobel-prize-winning Hulse-Taylor binary or in our famous "double pulsar" (Lyne et al. 2004), GR can be tested in the presence of strong gravitational fields with unrivalled precision (Kramer et al. 2006). For example, the shrinkage of the orbit due to GW emission can be measured to a precision of a micrometer per day by pulsar timing with the world's largest radio telescopes (Lorimer & Kramer 2005). Alternative theories of gravity are, however, best tested if the pulsar companion is of a different composition (rather than a second neutron star), as other theories usually predict that self-gravitating bodies with different compositions fall differently in strong gravitational fields. Our tests of pulsar-white dwarf systems already challenge alternative theories of gravity that were suggested to explain dark matter through the existence of scalar fields common in many field theories (Freire et al. 2012).

Still, the most stringent test of these alternative theories would be provided by a pulsar orbiting a BH (Damour & Esposito-Farèse 1998). In such a case, we would not only expect the largest deviations from GR, but we could also measure the properties of the BH, such as its mass, spin and quadrupole moment precisely. Such a measurement would allow us to test the "cosmic censorship" conjecture, but also the "no-hair" theorem, which states that all BH properties, including the quadrupole and higher-multipoles of the spacetime, are determined only by the mass and the spin of the BH (Sec. 2.2.2).

Hence, our ability to measure with pulsar timing all these quantities will yield some of the most accurate tests of BHs in GR and in alternative theories (Liu et al. 2012).

1.3.3 Pulsars in the Galactic Centre

Pulsar-BH systems are unique benchmarks of theories of gravity, but are expected to be very rare and not very promising in the case of stellar BHs, since the effects related to the quadrupole moment scale with the cube of the BH mass and are thus very difficult to measure. Despite intense efforts (e.g., Eatough et al. 2013), a pulsar-BH system has not been found yet, but the prospects of finding such a system can increase enormously near the Galactic Centre, where we expect a large number of pulsars orbiting Sgr A*. Indeed, the inner *parsec* of the Galaxy could harbour as many as ~1000 radio pulsars beamed towards Earth (Wharton et al. 2012). At the same time, the enormous mass of Sgr A* would make the measurement of the effects a much simpler and more accurate task (Liu et al. 2012).

With the advent of a phased-ALMA, the hunt for pulsars around Sgr A* will enter a new phase. Given the huge rewards in finding and timing pulsars around Sgr A*, various efforts have been conducted in the past to survey the Galactic Centre (e.g., Kramer et al. 2000, Macquart et al. 2010). None of these efforts has been successful so far. This is explained by severe interstellar scattering, which leads to pulse broadening that cannot be removed by instrumental means. This effect renders a source essentially undetectable as a pulsar if the scattering time exceeds the pulse period. Fortunately, the scattering time decreases as a strong function of frequency ($\propto\nu^{-4}$, e.g., Lorimer and Kramer 2005), so that pulsar searches are being conducted at ever increasing frequencies, with the latest being conducted around 20 GHz. However, finding pulsars at such high frequencies is far from easy, as the flux density of pulsars decreases steeply with increasing frequency.

ALMA will change these prospects completely. A phased-ALMA, potentially combined with other dishes, will finally provide us with a sufficiently large sensitivity to perform very deep searches of the Galactic Centre. So far, the number of pulsars that have been detected at very high frequencies is rather small (9 at 32 GHz, 4 at 43 GHz and 1 at 87 GHz, Löhmer et al. 2008) and has been limited by the sensitivity of available mm-telescopes. In contrast, a phased-ALMA would allow the first systematic survey for pulsars at frequencies as high as 90 GHz or more. With only 5 hours of integration time, a search at 90 GHz would be competitive with the best searches at 20 GHz (but, in contrast, facilitates the detection of the valuable *millisecond pulsars*), while a search at 43 GHz would be sensitive to 10-15% of the normal pulsar population. With about 1000 pulsars expected in the Galactic Centre, roughly a dozen pulsars should be found at 90 GHz. Hence, ALMA will finally be able to find pulsars in the Galactic Centre, providing us with superb tools to probe the spacetime around Sgr A*.

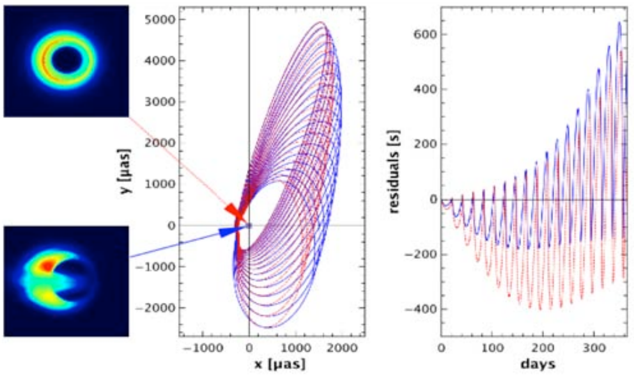

Figure 3: Simulated images of Sgr A* for two orientations (red/green) of the spin axis (left) w/o instrumental effects, compared to potential pulsar orbits (middle) and timing signals (right) for these configurations. A rather extreme orbit has been chosen for display purposes.

It is worth emphasizing that it is already sufficient to find and time a *single* normal, slowly rotating pulsar in an orbit similar to that of stars targeted by GRAVITY, to measure the mass of Sgr A* with a precision of 1 solar mass, i.e., a relative precision of $<10^{-6}$. *Such a pulsar would also enable us to test the cosmic censorship conjecture, by measuring multipole moments of the spacetime, to a precision of about 0.1%, and to test the no-hair theorem to a precision of 1%.* Thanks to the large mass of Sgr A*, this is already possible with a rather modest timing precision of 100μs and even allows for the measurement of frame-dragging due to the rotation of Sgr A* (Liu et al. 2012). Furthermore, ALMA at 90 GHz can detect millisecond pulsars and further improve upon these predictions. *However, until now there was no "pulsar machine" planned for ALMA.*

Already on their own, the measurements of spacetime around a BH will be ground-breaking, but, when cross-correlated with the "shadow images" predicted within GR, it will represent an *independent measurement and fundamental test of the validity of GR*. This is illustrated in Figure 3, where we show two projected precessing pulsar orbits and the resulting timing residuals together with the expected VLBI images for the same two BH spin-orientations as shown in Figure 4. Both configurations have distinctive signatures in the image and in the timing, thereby over-constraining the model. Any difference between imaging, GR modeling, and pulsar timing will thus indicate the precision of the measurement of Sgr A*'s mass and spin, but also of its nature, namely, whether it is a BH or an exotic object (Chirenti & Rezzolla 2007). An independent third measure would come from GRAVITY and eventually all three methods should intersect for a proper theory.

Interestingly, the pulsar community (e.g., the ERC AG project LEAP led by MK) has started to use VLBI techniques to coherently combine data from different telescopes. In practice, they are using similar telescopes, data products ("base-band data"), and recorders. Consequently, the same data obtained for VLBI could be used directly for pulsar searches, thereby increasing the scientific yields of the observations.

Hence, an important objective for us will be to equip the phased-ALMA with a powerful pulsar machine, usable also for VLBI, to find pulsars orbiting Sgr A.* ***(Objective 2)***.

1.4 Was Einstein right?

Ultimately, all data needs to be compared with theoretical predictions. The modelling needs to address not only the "standard" astrophysical behaviour of plasma around a BH, GR included, but also the non-standard behaviour that develop in alternative theories of gravity. Particularly in Europe, the GW community has acquired a deep theoretical understanding of GR and of BHs, developing sophisticated numerical methods. *Because this expertise has not been applied to Sgr A* yet, it provides an invaluable new resource we will add to BlackHoleCam*. In turn, the results from Sgr A* can have important reverberations on GW *astronomy*.

GWs are ripples in spacetime that travel as transverse waves at the speed of light. Already predicted by Einstein, they have not yet been detected directly, even though indirect evidence comes from the dynamics of binary pulsars. For a direct detection of GWs, and thus for another fundamental proof of the correctness of GR, a multinational effort has begun to build advanced interferometric detectors in the USA (LIGO), Europe (Virgo), and Japan (KAGRA), that are expected to lead to detections, possibly starting from 2016.

Binary systems of stellar-mass BHs are the optimal sources for these advanced detectors. Their signals, however, are expected to be only a few times larger than the noise (often already near the quantum limit of the detector). Hence, detecting GWs through a technique known as "matched filtering" requires the a-priori knowledge of the signal shape produced by these binaries. Nowadays, the signal can be computed through accurate and computationally intensive numerical-relativity calculations, which, in turn, have led to a better theoretical understanding of GR in the vicinity of BHs and to powerful computer codes (Rezzolla 2009). In a large-scale effort, scientists from several countries in Europe, USA and Japan, have started to compute a large variety of waveforms and to build a database to be compared with the noisy experimental data.

Naturally, a crucial assumption in this line of arguments is that GR is the correct theory of gravity and that BHs do behave as predicted in Einstein's theory. Should an experiment like BlackHoleCam reveal that GR is the correct theory of gravity to a sufficient level of accuracy, this would boost confidence that the theoretical effort of the GW community can indeed be used for detecting GWs or place upper limits. On the other hand, should BlackHoleCam demonstrate that GR is incomplete the waveforms produced so far need revisions.

In many respects, observations contradicting GR would provide an even larger conceptual breakthrough, with consequences that are considerably more far-reaching. BHs and horizons, in fact, are not a unique prediction of GR, but are present also in many alternative theories of gravity. Indeed, Kerr BHs, when meant as axisymmetric and stationary solutions of the field equations, are present in a wide variety of theories of gravity, where they have the same properties as in GR, but differ in their response to perturbations (Barausse & Sotiriou 2008, Psaltis et al. 2008). Hence, observations confuting GR would also rule out many of those theories that predict the existence of BHs. Similarly, observations finding a horizon with properties different from those expected in GR would rule out theories whose predictions in terms of horizons coincide with GR.

Hence, an important objective for us will be to model the dynamics and emission of matter around Sgr A and devise meaningful and quantitative tests of the validity of GR using the observational data* ***(Objective 3)***.

BlackHoleCam will give theoretical physicists an enormous opportunity to test GR, to validate the approach followed so far in modeling sources of GWs, to exclude some theories, and to develop new ones if needed. At the same time, the input from gravitational physics will make of BlackHoleCam's observations much more than the first image of a BH. It will provide, in fact, the theoretical background to translate these observations into a better description of gravity and its relation with the other interactions in nature. As we outline in Sec. 2.2.2, this will ultimately lead to a deeper understanding of space and time.

2 Methodology

The first task of this proposal is to build a flexible VLBI camera that can use ALMA and other mm-wave telescopes, to image a BH and detect pulsars in the Galactic Center (**Task 1**). The second task is to analyse and interpret the observational data and to compare it with the predictions within GR and other theories of gravity, and to make it accessible to the scientific community at large and to the general public (**Task 2**).

2.1 A black hole camera: how to image a black hole

2.1.1 The VLBI system

While VLBI up to 43 GHz is already routine, higher frequency VLBI is far from that. The higher the frequency, the bigger the challenges: atomic clocks and receiver chains need to be more stable, data-rates go up, and the distortion of the wave fronts by the troposphere needs to be corrected for. Nonetheless, the first detection of Sgr A* in a 220 GHz single-baseline experiment was already achieved more than a decade ago (Krichbaum et al. 1998), followed by a three-baseline experiment ten years later (Doeleman et al. 2008). The digital recording and processing technology has advanced further and – as a true revolution – ALMA is coming online. Hence, the pace of development will now accelerate rapidly.

VLBI at 220 GHz works, but all observations so far have more or less an experimental character, requiring a major effort from the teams preparing them. Often the scarce equipment needs to be shipped back and forth between different participating sites, setting-up of the equipment takes days, and the post-processing still takes many months. Also, scheduling of VLBI experiments is non-trivial as it requires concurrent block reservations of observing time at all telescopes often long in advance. However, ALMA will operate with dynamical scheduling and the mode of operation of the network will need to change.

Consequently, the next step is to provide a "VLBI camera" that operates robustly with a high level of flexibility and for a range of different telescopes. *This does not mean reinventing the wheel, but rather to make it spin faster and more smoothly.* The ultimate goal is a setup in which the VLBI equipment is on standby and largely *remote-controlled on all sites*, providing a minimum burden on local operations for a maximum scientific return. The first component of this camera system is to develop and acquire sets of hardware components that can be provided to any participating radio telescope (**D1.1.a**). This will essentially be a small cabinet consisting of a stable atomic clock ("maser"), fast VLBI recording equipment, interfaces, housing, and a monitoring and control system. All aspects of the system will be controllable remotely. The system needs to be modular to allow for already existing equipment at the sites. Masers and recorders are commercially available and a VLBI standard interface specification exists, so most of the work will focus on system integration, interfacing to telescopes, and on the remote control software (**D1.1.b**).

Scheduling the telescopes, which involves a lot of emailing today, will be streamlined with an efficient software tool. The standard observing protocol must include quick error-checking and bug-fixing. Where the network infrastructure allows, we will implement (almost) real-time fringe verification on short data packets. This will provide an end-to-end system check before observation (**D1.1.d**). The complete cabinets can be shipped to any telescope for system roll-out and installation. Manpower is needed to adapt, install, test, and maintain the system at the various telescope sites and thus to provide a stable VLBI network **(D1.2.a**).

For smooth operation and cooperation, it is beneficial to station one scientist temporarily at some of the participating sites. A similar scheme was successfully used in the LEAP project of MK. Telescopes that have already been used for VLBI are (see cover): the Combined Array for Research in Millimeter-wave Astronomy (CARMA) in California, the Submillimeter Array (SMA) and JCMT in Hawaii, the Submillimeter Telescope Observatory (SMTO) in Arizona, the IRAM 30m telescope on Pico Veleta in Spain, the IRAM Plateau de Bure interferometer in France, and the Atacama Pathfinder Experiment (APEX). Some telescopes already have masers and recorders, some have loaned equipment, and some have outdated equipment. Here, the modular design of the system will be crucial. Some of the existing telescopes also have suboptimal receivers or other deficiencies that can be improved. Moreover, an important addition could be the South Pole Telescope (SPT), which yet needs to be equipped for VLBI, and the Large Millimeter Telescope (LMT) in Mexico once it is finished. We thus envisage contributing to outfitting or upgrades of telescopes (**D1.2.b**). Providing hardware and manpower can also help in obtaining more observing time.

Of course, we will not and do not want to be in control of the operation of radio telescopes. While some are under threat to be decommissioned in the coming years, others are expected to come on line. That is why we do not primarily focus on telescopes, but on the camera aspects. Our equipment can be shipped from one site to another, while the software and control shall transcend individual telescopes. On the other hand, mmVLBI may become an important argument for some telescopes to obtain additional operating funds in the future.

Finally, for the entire system to work a data-analysis pipeline needs to be in place to allow for efficient data reduction with minimal manual intervention (**D1.3.a**). This is now realized in many large VLBI programs.

2.1.2 Detector simulations

To understand the results properly, every experiment needs a good detector simulation. For radio interferometry a number of simulation packages already exist. However, mmVLBI comes with its own challenges (tropospheric variations, new telescopes, etc.) that need to be addressed in a simulation. For this, we plan to adapt the interferometry simulation software "MeqTrees" (Noordam & Smirnov 2010), initially developed for LOFAR and SKA, for mmVLBI (**D1.3.b**). Figure 4 shows simulated images of the BHs shadow generated with the CASA package. The model is based on numerical GRMHD simulations of Sgr A* by Mościbrodzka et al. (2011) and a telescope layout including ALMA and the above-mentioned telescopes. This indicates that even under pessimistic assumptions, i.e., the BH is maximally spinning and edge-on, the shadow of the BH is detectable with an array that can be operational during this project.

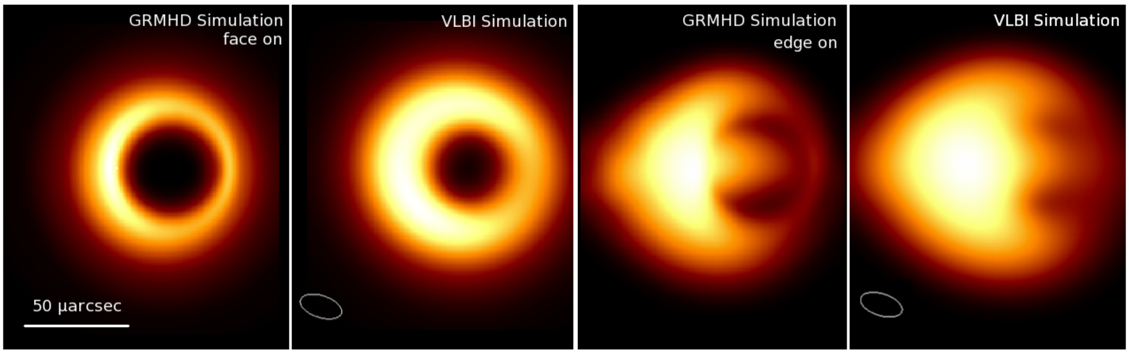

Figure 4: GRMHD simulation of the emission in an accretion flow around a rapidly spinning BH in Sgr A* (see **Figure 3**) blurred according to the expected interstellar scattering. This is compared to a reconstructed image from simulated submm-VLBI (Falcke et al. 2011, Mościbrodzka et al. 2011) for face-on and edge-on orientations of the accretion flow. In the optimal case, the shadow is easily visible, while in the most pessimistic one a still achievable dynamic range ~200:1 is needed to reveal the faint photon ring.

2.1.3 Pulsars with ALMA

Finally, we need to integrate the pulsar aspect into the BlackHoleCam system. Our team has a long track record in using phased-up interferometers for the observations of pulsars (see MK's LEAP project) and the observations of pulsars at the highest frequencies (see our record-holding observations at 32 GHz (Kramer et al. 1996), 43 GHz (Kramer et al. 1997), and 90 GHz (Morris et al. 1997).

As technology progresses, we see a convergence of the data acquisition needs of the VLBI and pulsar communities. Within the LEAP project, we have already developed such equipment for cm-wavelengths. High-bandwidth digital equipment and storage solutions for VLBI are also developed within the NEXPReS and RadioNet3 projects, led by JIVE and the MPIfR Bonn respectively. Based on this experience, we will design and build a unified recorder system that can serve both communities at mm-wavelengths. This will provide higher bandwidth, real-time processing, and independence from a single supplier (**D1.1.c**).

The recorder will thus also serve as the "pulsar machine" that can be installed at ALMA. Exactly the same data recorded to image the event horizon for VLBI can then be searched for pulsars in the Galactic Centre. However, pulsar observations can and will take place also simultaneously with standard interferometric Galactic Centre observations of ALMA, including those at lower frequencies.

An important product of this project will then be a standard pipeline searching the data from the phased ALMA (and potentially other telescopes in the VLBI networks) for pulsars, including a full acceleration search (**D1.3.c**), and providing the means of timing the discovered sources (**D1.3.d**).

2.2 Theory: How to model and interpret the observations

When a theory is already known to provide the correct interpretation of the observations, the latter can be used with confidence to refine the theory. However, the situation is far more complex when the theory itself, although well developed, is not necessarily the correct interpretation of the observations. The prospects become even more arduous if the observations cannot be translated easily into a set of prescriptions meant to improve the theory. To cope with these difficulties, the theoretical work on BlackHoleCam's observations will have to be flexible and wide, covering three distinct but interconnected aspects: *(i)* the modelling of the dynamics and emission from astrophysical plasmas (jets and accretion disks) around BHs; *(ii)* the classification and modelling of the signatures that different theories of gravity make on such dynamics and emission, and *(iii)* the production of observational predictions using detector simulations (Sec. 2.1.2). While we already have a considerable experience in the simulation of matter dynamics in strong gravitational fields, which we can exploit in the effort *(i)*, very little has been done so far worldwide within the effort *(ii)*. For example, no systematic parameterization exists yet for the predictions that different theories of gravity make about the emission near the event horizon of a BH, nor how these predictions differ in the case an event horizon is absent because the BH is replaced by an ultra-compact exotic object.

2.2.1 GRMHD simulations of BHs with particle acceleration

General relativistic magnetohydrodynamic (GRMHD) simulations have progressed rapidly over the last decade and a number of different codes are available. HF's group is working with *HARM(3D)* (Gammie et al. 2003, Noble et al. 2007), while LR's group uses *Whisky* (Rezzolla et al. 2010). These codes represent the state of the art in the modelling of MHD plasmas in 3D and curved spacetimes (either stationary or dynamic). In addition, *Whisky* has the ability of solving the Einstein equations and of simulating regimes as those of ideal-MHD, resistive MHD, and force-free (Rezzolla et al. 2011). Both codes are able to perform radiative-transfer calculations, either in post processing or in real time. While the heritage of *HARM(3D)* is that of the astrophysical community (mainly in the US) investigating accretion flows around BHs, *Whisky* has its origin from a team led by LR in a EU network of the GW community driven by fundamental-physics goals. Here, we bring together the expertise of these two communities to build a common powerful computational infrastructure for BlackHoleCam to successfully plan and interpret its observations.

Despite the maturity of the codes, a lot of additional work is still necessary. First of all, since numerical codes are not dissimilar from sophisticated instruments, a systematic effort will be dedicated to the testing and calibrating of the different codes across similar physical conditions; this stage will include also other auxiliary codes (e.g., Mignone et al. 2012) and libraries not mentioned above (**D2.1.a)**.

Secondly, once a common computational infrastructure will be readied, it will be used to investigate the large parameter space that could influence the dynamics of the matter, e.g., mass accretion rate, BH spin, inclination, magnetic-field properties, temperature distribution, and resistivity of the plasma (**D2.1.b**). All of these variables can influence the final physical observables and the appearance of accretion disks and jets.

Thirdly, new and more sophisticated techniques will be developed and added to the present codes to refine the comparison between the simulations and the astronomical observations. In this context, the evolution of relativistic particle distributions, including cooling and acceleration, represents by far the most important effort. While radiative cooling is relatively straightforward to implement, a good prescription of where and how particle acceleration takes place is still lacking. We will attack this problem with a parallel effort in which, on the one hand, we will implement semi-analytic prescriptions linking particle acceleration to local plasma properties (such as shocks and shear flows) and, on the other hand, couple our codes with particle-in-cell (PIC) simulations that can provide a much more faithful physical description on small scales. Finally, we will couple our general infrastructure to ray-tracing codes to include the emission and absorption of polarized light propagating in hybrid thermal and non-thermal electron (and/or positron) plasma, and with special-relativistic codes to follow the propagation of relativistic jets on large scales (**D2.1.c)**.

Once developed and tested, this computational infrastructure will represent a formidable tool with which we can predict observables to be confronted with the experiment, such as: spectra, variability, polarization, and VLBI structure of Sgr A and M87 and other supermassive BHs. The whole computational infrastructure will be made publicly available to foster research in this area at a much larger scale.*

2.2.2 Testing General Relativity and more

Together with the GRMHD simulations modelling the dynamics and emission of matter near the BH, we will build a theoretical framework for the measurement of the deviations from GR and other theories of gravity as deduced from BlackHoleCam's observations. This effort is much more innovative and challenging than the one pursued with GRMHD simulations, but it will have a tremendous impact on our understanding of both gravitation and the nature of BHs. Our approach will be based on two distinct but complementary strategies.

In the first one, we will set up *"null tests",* i.e., tests with either positive or negative outcomes, aimed at detecting deviations away from the Kerr solution. As mentioned above, the no-hair theorem shows that there is no regular axisymmetric isolated BH solution in GR that is different from Kerr. In such a metric, the quadrupole and higher order moments are fixed by a simple relation of the BH mass and spin. Therefore, a natural way of generalizing the Kerr metric has so far been to modify the quadrupole moment (and/or higher moments) of the geometry. This approach has led already to a number of modified theories, such as: the Manko-Novikov metric (Manko & Novikov 1992), the slowly rotating Hartle-Thorne metric (Glampedakis & Babak 2006), the formalism proposed by Ryan (Ryan 1995), the bumpy BHs (Collins & Hughes 2004), and the regular quadrupole-modified Kerr metric (Johannsen & Psaltis 2011). Our first task, therefore, will be that of building a generic numerical infrastructure able to produce the expected electromagnetic emission when the BH is considered in these and other arbitrary metric theories of gravity, including the spectral properties and the degree of polarization (**D2.2.a**). This unique computational platform will be coupled to the one discussed in Sec. 2.2.1 and will be used to build a catalogue of images and emission properties in alternative theories of gravity (**D2.2.b**).

Although straightforward, this "null-test" strategy is not without complications. All of the alternative metrics listed above, in fact, come with two basic problems. The first one is that any modification of the Kerr solution within GR (i.e., which does not modify the field equations) must involve a certain amount of exotic physics, either in terms of curvature singularities, or closed timelike curves (i.e., violations of causality) or exotic nonzero stress-energy tensor. Hence, when considering these metrics, great care must be paid to avoid exotic explanations to interpret a phenomenology introduced by classical, but poorly-modeled observational noise. The second complication is far more serious and is rooted in the fact that if a deviation from the Kerr geometry is detected, these alternative theories do not provide any information on what might be causing the deviation. The metrics mentioned above, in fact, are built "by hand" and are not consistent solutions of any theory of gravity alternative to GR. Because of this, their use to produce observables can only indicate whether GR is correct or not, but it cannot provide clues on what the correct "answer" actually is.

This is where our second strategy comes into action and which we will develop on a parallel track. In practice, we will construct a series of *"multi-answer tests"*, that is, develop a framework that provides quantitative measurements of the deviations from BH solutions in generic theories of gravity. Hence, we will not only assess the properties of BH solutions of plausible phenomenological alternatives to GR, but also investigate whether the observations can tell the difference from GR (**D2.2.c**). While the simplest theories, such as Brans-Dicke gravity or scalar-tensor theories without a potential, predict BHs that are identical to the Kerr solution, this is not the case for other phenomenological theories that may be expected to arise as low-energy limits of high-energy theories of gravity. In particular, we will focus on the following classes of theories, for which BH solutions are known to differ from GR: 1) theories with violation of Lorentz invariance in the gravity sector, such as Einstein-Aether gravity and Horava-Lifshitz gravity (Barausse et al. 2011); 2) theories with parity violation in the gravity sector, such as Cherns-Simons theory (Yunes & Stein 2011); 3) theories with higher-derivative terms in the gravity-scalar sector, such as Gauss-Bonnet dilatonic gravity (Pani & Cardoso 2009), Einstein-Gauss-Bonnet gravity, or Galileon gravity (Charmousis et al. 2012). It is important to remark that in some of these theories, e.g., in Einstein-Aether gravity, spinning black-hole solutions are yet to be found, while in others they are known, but only poorly.

Overall, the theoretical effort needed to explore these theories is far from being straightforward. We will tackle this by developing a unified and *parameterized framework* describing the properties of spinning black-hole solutions in generic metric theories of gravity. This framework will be similar in spirit to the one developed in the 1970ies with the parameterized post-Newtonian (PPN) framework describing the dynamics of compact binaries in theories alternatives to GR (Will 2006) and used in pulsar testing of GR. Also in this case, we will develop a general description in terms of dimensionless parameters translating our observations into a measure of the deviation from a given candidate theory of gravity, defining confidence areas in the parameter space (**D2.2.c**). This approach represents one of the major theoretical challenges of this project but it will be essential to assess, *in a quantitative manner*, how accurately GR is confirmed by our observations.

2.2.3 Putting things together

The fundamental aspect of the project is, of course, the cross-comparison of the different predictions coming from the observations, in terms of stellar orbits, pulsar timing, and VLBI imaging (**D2.3.a**). This will represent the ultimate focus when both the theoretical framework and the observational work will have finally reached their complete maturation: Finding and monitoring pulsars or stars as they move around Sgr A*, we can measure the precession of their orbits and hence the spin of Sgr A*. This information, as well as the information of stellar orbits by GRAVITY can be used to determine the properties of the spacetime near Sgr A* in any metric theory of gravity. A potentially complicating factor can be the distortion of orbits by the central star cluster, but this will be assessed through the collaboration with experts in N-body simulations and observations of the cluster by the GRAVITY team.

The theoretical analysis will march on parallel tracks with a rigorous program of astronomical observations (**D2.3.b**). A main focus will be VLBI observations at mm-waves (43, 90, 220 GHz, and ultimately 350 GHz). Pulsar surveys with ALMA will mainly concentrate at the lower frequencies (90 GHz and 43 GHz once available, but also 220 GHz). Additional multi-wavelengths observations will be performed to further constrain the astrophysics of Sgr A* and M87 (e.g., monitoring). As stressed above, joined observing campaigns of GRAVITY and BlackHoleCam will be particularly important for our success.

Finally, we will undertake a vigorous plan of public outreach. BHs are eagerly followed on popular-science magazines and newspapers. All the PIs have a long track record in popularizing science and have produced a variety of animations and images that are diffused worldwide. We will intensify this effort by producing animations, web-contents, popular science articles, and contributions to public and social media (**WP 2.4**).

2.3 Synergy

2.3.1 The Team

Here the PIs join their expertise in the areas of astrophysical BHs and VLBI, pulsars, and GR/GW theory.

HF has pioneered the idea of imaging the BH shadow in the Galactic Centre. He is an expert in radio interferometry, BH theory, and astroparticle physics. As a long time leading proponent of the new LOFAR telescope he has ample experience in setting up large-scale astronomy consortia. A project manager, R. Tilanus, who was Head of operations at the JCMT mm-wave telescope in Hawai and who is directly involved in the 220 GHz VLBI experiments, will support him. A team of software developers and technicians at Radboud Univ. will support Falcke and Tilanus. E. Körding, an assistant professor at Radboud and expert in BH theory and radio interferometry, will coordinate astronomical observations and theory efforts together with M. Moscibrocka, an expert in numerical GRMHD simulations.

MK is an expert in the studies of pulsars as probes of fundamental physics and GR. He co-discovered the Double Pulsar, presenting the best strong-field test of GR, first detected pulsars as mm-waves, and is leading the European Pulsar Timing Array for the detection of GWs, organizing a network of telescopes. He will be supported by the LEAP team, as well as GR theoretician N. Wex and pulsar expert P. Freire. VLBI expert O. Wucknitz recently joined the group. Besides the fundamental radio astronomy group the MPIfR Bonn also has a VLBI group (A. Zensus) and a (sub)mm-wave group (K. Menten), collaborating closely with us. This includes, e.g., VLBI experts T. Krichbaum and A. Brunthaler, as well as technical staff in all areas relevant for radio astronomy. With such a large expertise intersecting, Bonn is an important backbone for the project.

LR has a long track record in the development and large-scale high-performance codes for the study of BHs and neutron stars under a variety of physical conditions. Some of his simulations have been at the core of the recent progress in computational relativistic astrophysics. The numerical-relativity group that he heads, and which will provide the logistic infrastructure for the code development and the running of simulations, will support him. He will collaborate with E. Barausse (his former student in SISSA), now researcher at the IAP/Paris and one of the world experts in alternative theories of gravity and their observational signatures.

HF and MK will jointly coordinate building the hard- and software components as well as organizing the observations. HF and LR will team up for the astrophysical modelling of Sgr A*, where HF brings in a detailed theoretical understanding of Sgr A* and LR the expertise in high-performance computing and numerical relativity. MK and LR will work together on the comparison of data with theories of gravity.

As additional team members we include Robert Laing, European Instrument Scientist of ALMA (Garching), Huib-Jan van Langevelde, director of the Joint Institute for VLBI in Europe and associate professor at the Univ. of Leiden, and Frank Eisenhauer (MPE Garching), PI of the GRAVITY project.

ESO (European Southern Observatory) represents Europe within ALMA. Laing, a seasoned radio astronomer, ensures adequate recognition of the science interests of the European user community. He will work with a PostDoc on integrating BlackHoleCam into ALMA (**D1.2.a&b**) and on science exploitation (**D2.3.b).**

JIVE is located in Dwingeloo (NL) and provides the central services (e.g., correlator) for the European VLBI network (EVN), which includes the major radio observatories in Europe. JIVE leads the development for eVLBI (VLBI over Internet) and software in Europe, which they will adapt for our purposes here (**D1.1.d, D1.3.a**). Staff from Nijmegen is already almost weekly in Dwingeloo due to LOFAR.

Eisenhauer has pioneered and is leading many infrared observations of the Galactic Center BH, including the measurements of stellar orbits (Figure 1) and the discovery of IR flares from SgrA*. The group at MPE will work, with a PostDoc, on combined radio and near-infrared observations **(D2.3.b**) and the resulting joint constraints from all methods (mmVLBI, Pulsars, and stellar orbits**; D2.3.a**).

We will work with a substantial network of external experts that have agreed to collaborate on this project, including P. Strittmatter (director Steward Observatory, Az) and Lucy Ziurys (director SMTO telescope, Az), G. Bower (UC Berkeley, CARMA telescope and VLBI), M. Bremer (IRAM telescopes and VLBI), C. Gammie (Univ. Il, theory, author of *HARM*), O. Smirnov (SKA professor in South Africa, author MeqTrees simulation software). Thijs de Graauw, director of ALMA until spring 2013, will advise us as senior consultant. We collaborate with S. Portegies Zwart (U. Leiden) on N-body simulations of the central cluster.

With senior colleagues we are now writing a White Paper on mmVLBI to organize the broader EU community to realize a wider science case (Falcke et al. 2012). We will be open for our colleagues in the evolving EHT community for collaboration and make our data and methods open for the community.

2.3.2 Communication and management

International cooperation is standard in astronomy. Communication within the project will be through a combination of regular face-to-face meetings as well as Internet teleconferencing. Documents, minutes, slides, etc., will be collected centrally on a Wiki-page. This has been well tested, e.g., in LOFAR and LEAP.

The day-to-day management of the project will be handled by an *executive council* (EC) consisting of the three PIs. They will meet regularly (bi-weekly) either in person or via skype teleconference. A *project council* (PC) consisting of the PIs, the team members, and additional external team members will meet bi-monthly via teleconferencing. Each task and work package will be assigned to a task leader and a WP leader. Task leaders participate in the EC meetings, while WP leaders participate in the PC meetings. In between, there will be a one-hour bi-weekly status update meeting (alternating with the EC meetings) with short presentations of results and progress reports. This meeting will be conducted using teleconferencing tools for two-way communication with a large number of users (e.g., EVO/SeeVOGH or Vidyo).

To complete specific WPs, it has proven effective, to organize a co-location of several team members in one place. This will be achieved through “busy weeks”, where a few team members gather in one (sometimes remote) place to work exclusively on one project, starting and ending each day with a brief coordination meeting. The MPIfR will provide facilities at the Effelsberg Observatory near Bonn, which offers accommodation, catering, and amenities that ensure efficient and concentrated working sessions.

An international external *science advisory committee (SAC)*, consisting of senior scientists from inside and outside the EHT community, will be nominated to evaluate the overall project and to advise on its progress. An annual collaboration meeting will take place in a central location, where BlackHoleCam personnel present their science and technology results in the presence of members of the science advisory committee and the council. The meeting will be streamed via Internet and we may couple this to a public workshop.

Finally, we point out that HF lives in Cologne near Bonn and commutes daily to Nijmegen. He will continue to spend 1-2 days per week in Bonn, thereby increasing the face-to-face time. Moreover, the Cologne/Bonn area is well connected to Munich/Garching and Berlin/Potsdam (or Frankfurt in case LR moves there; see CV) by frequent flights and high-speed trains, making face-to-face meetings possible even at short notice.

3 Resources

Here we summarize the tasks, work packages (**WP**), and deliverables (**D**) we mentioned above and indicate the amount of full-time-equivalents (FTE) and hardware costs needed for each deliverable. One FTE will typically be on postdoctoral or student level. In square brackets, we give a very cursory timeline for each deliverable, by showing the percentage of total work performed in subsequent 2 year periods, i.e., [20,80,0] means that 20% of work is done in yr 1-2, 80% in yr 3-4, and nothing in yr 5-6.

3.1.1 Work packages and deliverables

Task 1 - The black hole camera system

WP 1.1: Develop a dynamically schedulable mmVLBI Camera System (***Sec. 2.1.1***)

- **D1.1.a**: Six BlackHoleCam units – an integrated modular system of clock (maser), recording equipment, interface cards, and necessary adapters that can be easily integrated with and adapted to existing mm-wave telescopes: 6 FTE Nijmegen, 4 FTE Bonn, 1.9M€ Hardware (3 Masers (3x280k€), 6 VLBI Recorders (6x100k€), housing, interfaces, cables etc. (6x75k€). We assume that we can use existing infrastructure (masers) at some telescopes. If more units are needed, we will use the telescope upgrade budget as contingency (see D1.2.b). **[60,30,10]**.
- **D1.1.b**: Software package for remote control and dynamical scheduling/alerting: 4 FTE Bonn (will also be responsible for coordinating observations) **[30,40,30]**.
- **D1.1.c**: Unified VLBI/pulsar backend for high-data rate storage (**Sec. 2.1.3**): 7 FTE Bonn plus 100k€ for a prototype recorder to be deployed at ALMA **[20,40,40]**.
- **D1.1.d**: Near real-time software correlator and eVLBI interface for testing of mmVLBI observations: 2 FTEs JIVE **[40,40,20].**

WP 1.2: System roll-out and installation at telescopes (***Sec. 2.1.1***)

- **D1.2.a**: Network of dynamically schedulable mmTelescopes, including ALMA: 18 FTE (3 FTE for 6 telescopes each) delegated from Bonn and Nijmegen to observatories (IRAM, ALMA, SMTO, etc.) to install and control hardware, perform observations, liaise with local staff, and do maintenance. **[33,33,33]**.
- **D1.2.b**: Telescope modification upgrade: We budget 1M€ for potential upgrades at telescopes – this allows for 1-2 new receivers to be built, plus 150k€ travel and material for ALMA. **[25,50,25].**

WP 1.3: Data Analysis and Simulation (***Sec. 2.1.1***)

- **D1.3.a**: automated VLBI software pipeline: 2 FTE Nijmegen, 3 FTE JIVE **[20,40,40]**.
- **D1.3.b**: mmVLBI simulation tool: 2 FTE Nijmegen (***Sec. 2.1.2***) **[50,50,0]**.
- **D1.3.c**: Pulsar search analysis pipeline for ALMA: 4 FTE Bonn (***Sec. 2.1.3)*** **[40,40,20]**.
- **D1.3.d**: Pulsar timing analysis pipeline working for ALMA: 1 FTE (***Sec. 2.1.3)*** **[0,100,0]**.

Task 2 - Theory and Science Analysis

WP 2.1: 3D GRMHD simulations of accretion/jets systems with ray tracing, radiation transport, and particle acceleration, predicting theoretical images, spectra, and variability (***Sec. 2.2.1***)

D2.1.a: Comparative study of GRMHD codes: 2 FTE Potsdam, 1 FTE Nijmegen **[100,0,0]**.

D2.1.b: Systematic investigation of BH model parameter space via full 3D GRMHD codes: 4 FTE Potsdam, 2 FTE Nijmegen **[50,50,0]**.

D2.1.c: Extending 3D GRMHD with particle acceleration and radiation codes (semi-analytic and PIC) for comparison with observations: 5 FTE Potsdam, 3 FTE Nijmegen **[33,33,33]**.

WP 2.2: Investigation of alternative/expanded theories of gravity (***Sec. 2.2.2***)

D2.2.a: Imaging code for emission in arbitrary theories of gravity: 2 FTE Potsdam **[0,60,40]**.

D2.2.b: Catalogue of BH images and emission properties in alternative theories of gravity: 3 FTE Potsdam **[0,40,60]**.

D2.2.c: Framework for quantitative measurements of deviations from BH solutions in generic theories of gravity: 4 FTE Potsdam **[0,20,80]**.

WP 2.3: Putting things together: cross-validation of theory and observations (***Sec. 2.2.3***)

D2.3.a: Investigating constraints from combining pulsar, GRAVITY, and VLBI observations with theoretical predictions: 2 FTE Potsdam, 2 FTE Nijmegen, 2 FTE MPE Garching **[33,33,33]**.

D2.3.b: Astronomical observations of the Galactic Centre, M87, pulsars, and other sources with BlackHoleCam and other telescopes; comparison of the data with model predictions and analysis within our theoretical frame work: 3 FTE Nijmegen, 5 FTE Bonn, 3 FTE MPE Garching **[30,40,30]**.

WP 2.4: Outreach, education, and science communication (**Sec. 2.2.3**)

D2.4.a: Production of (3D) animations, popular science articles, and materials for textbooks, webpages, and social and other media: 1 FTE Nijmegen, 1 FTE Potsdam **[33,33,33]**.

For each FTE we calculate 5k€ Euro for travel and 1k€ Euro for computing per year. This will be sufficient for 2 overseas trips per year. For computing clusters we reserve 200k€ for Nijmegen and 800k€ for Potsdam. HF will dedicate 60%, LR will dedicate 50%, and MK 35% of their time to the project. MK does not need salary costs. There will be a scientific project manager and a secretary at Radboud University for 50% of their time for 6 years. For the costs of Internet communication, workshops, and team meetings we budget 10k€ per year per PI (=180k€ in total). Shipping of material (e.g., BHC units to telescopes, hard-disks to and from telescopes, etc.) is budgeted at 20k€ per year. The budget for team members ESO & MPE appear under Bonn, JIVE under Nijmegen. There is 20% overhead on eligible costs. Some limited contingency and in-kind contributions can be provided by the PIs from institutional funds.

3.2 Concluding remarks

This project fits right into the big questions of astrophysics, as formulated in the European Astronet Science Vision[2], ibid. Sec. 2.3 "Observing the extremes of the universes – can we see strong gravity in action?", where it explicitly recommends mmVLBI to detect the BH shadow, GW observations, and sensitive pulsar searches in the Galactic Centre – exactly the trio we propose here. Similarly, the US decadal review[3] on astronomy and astrophysics of the NRC stresses the promise of "the first discovery of GWs and imaging of the event horizon around a BH" and goes on to say: "*Ultra-high resolution at millimeter/submillimeter wavelengths tantalizes us with the possibility of imaging the event horizon of Sgr A*",* ending in a (not yet allocated) recommendation for funding of 15M$ for EHT – very similar to what we request here.

So, what can we possibly achieve within the 6 years of the program? When writing the final report, we should be able to present the first image of the event horizon of a BH and show that BHs exist. Maybe the BH shadow is easily visible right away; maybe it takes a while to get the right dynamic range. In any case, the image will have a great potential to enter many textbooks. It will certainly attract attention from the general public and further the support of fundamental science. We also should have found a pulsar around Sgr A* with our equipment at ALMA. Adding information from the stellar orbits measured with the VLTI, we will have nailed down the properties of Sgr A*: mass, spin, and orientation to decimals. Very likely, GWs will have been discovered as well – clearly, the coming years will mark the decade where extreme gravity becomes a precise experimental science. Maybe GR will turn out to be the ultimate theory of gravity, or maybe a new theory starts to emerge – we will see. *Clearly, each of the sub-projects proposed from the PI's fields of expertise can deliver fundamental results, but together they can transform our view of space and time.* After all, the entire structure of our universe depends on this little-understood force of gravity.

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[2] http://www.astronet-eu.org and http://www.eso.org/public/archives/oldpdfs/Astronet_ScienceVision.pdf

[3] http://www.nap.edu/catalog.php?record_id=12982

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