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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.

1 Introduction - State of the Art and Objectives

1.1 General Relativity (GR) – the fabric of space and time

Almost a century after its formulation, Einstein's theory of general relativity (GR) still gives the best description of gravity. *Black holes* (BHs) are its most extreme prediction and the event horizon is their defining and most intriguing feature. BHs are widely accepted and have become part of popular culture, but the event horizon represents a challenge for understanding gravity and its existence is not yet *proven*.

By definition, the event horizon is a surface through which photons (but also any particle) can enter but not leave. This "one-way" membrane in the fabric of spacetime is the border where time and space exchange their nature. The implications of the event horizon are far-reaching as it is through the entropy of the horizon that we hope to measure the quantum nature of BHs, or ultimately understand what happens to space and time when gravity dominates. The lack of direct observational evidence is made worse by the fact that plausible alternatives to BHs exist (Chirenti & Rezzolla 2007). Here we aim at providing the much-needed *proof* of BH existence by imaging the closest supermassive BH: the one in the centre of our Galaxy!

BHs come in two basic classes: as "*stellar BHs*", with masses of tens of solar masses and produced through supernova explosions, and as "*supermassive BHs*", with masses between 10^6-10^{10} solar masses residing in the nuclei of galaxies. The size of a BH is set by the Schwarzschild radius and is proportional to its mass. Stellar BHs have sizes of tens of kilometres and can be found in our Galaxy at distances of some kpc[1]. Supermassive BHs, instead, are intrinsically much bigger, but are also at much larger distances of some Mpc to Gpc. The angular sizes of both stellar and supermassive BHs are too small to be resolved by current technology. Fortunately, the putative supermassive BH at the heart of our Galaxy offers a notable exception.

By imaging and modelling the horizon of the supermassive BH in our Galactic Centre, we will open a laboratory to investigate the structure of spacetime in its most extreme limit. For this we will combine the distinct but overlapping expertise of the three PIs in BH astrophysics and radio interferometry, in pulsar observations and theory, and in GR and in gravitational-wave (GW) theory.

1.1.1 The Galactic Centre – imaging the closest supermassive BH

Of all supermassive BH candidates, the one in the centre of our Galaxy, Sgr A*, stands out (Genzel et al. 2010, Melia & Falcke 2001). Groups in Europe (Garching/Cologne) and the USA (UCLA) have determined the properties of Sgr A* by measuring the orbits of stars around it, revealing it has a mass of 4 million solar masses at a distance of only 8 kpc (Eisenhauer et al. 2005). This makes it a million times larger than any stellar BH in the Galaxy and at least a thousand times closer than any other supermassive BH. In other words, *this is the BH with the largest apparent size in the sky*.

After it was predicted that emission at higher radio frequencies would come from closer to the event horizon (e.g., Falcke et al. 1993), it was indeed shown that an emission peak at 350 GHz is due to optically-thin synchrotron radiation from near the horizon, suggesting that it is possible to image the horizon (Falcke et al. 1998). At low radio frequencies, scattering in the interstellar medium washes out all structures in Sgr A*. However, significant progress has been made in recent years to measure the size of Sgr A* with high-resolution radio interferometry at high frequencies (Bower et al. 2004, Doeleman et al. 2008), confirming this basic picture. Unfortunately, the data quality and array size is not yet sufficient to make a real image.

What would a BH actually look like? Falcke et al. (2000) showed that a BH embedded in an optically-thin emission region, as expected for Sgr A*, would lead to a sharp *"shadow"* cast by the event horizon, surrounded by a bright ring of light. The shadow is essentially a lensed image of the event horizon with a diameter of around 5 black hole radii. After many groups have confirmed this result (e.g., Broderick and Loeb 2006, Dexter et al. 2010), there is a general consensus that the horizon should be detectable.

The goal of this project is to take the first image of a BH horizon and compare it with the theoretical predictions of GR and of alternative theories of gravity.

The technique needed to image the BH shadow is known as mm-wave very long baseline interferometry (mmVLBI) and has a strong heritage in Europe, as testified by the European VLBI Network and the Global mmVLBI Array, coordinated in Bonn. Indeed, the first VLBI detection of Sgr A* at 220 GHz was made in Europe (Krichbaum et al. 1998). What makes mmVLBI of Sgr A* so timely now is the availability of the

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

most sensitive mm-wave telescope ever built, the Atacama Large Millmetre Array (ALMA). The proposed experiment to image Sgr A* is supported in the European Astronet Science Vision and in the US decadal review on astronomy and astrophysics. Since 2009 various meetings were organized under the label "Event Horizon Telescope (EHT)" by groups in the USA (Doeleman, Marrone) and Europe (Falcke et al. 2012) to lay out plans for imaging Sgr A* with mmVLBI. At the moment, however, there is no sufficient funding and no formal international structure in place for EHT to say who will ultimately take the lead.

We propose to fund a European-led effort to build a "BH camera" targeted at imaging the event horizon of the BH in Sgr A. The camera will consist of the data-acquisition hardware, data analysis pipelines, and skilled personnel to provide a mmVLBI array at the highest frequencies with real imaging capabilities.*

1.2 More than just an image: stellar orbits, pulsars around Sgr A* with ALMA, and theory

To exploit the scientific impact of the image of the shadow we need to compare it with the theoretical predictions and to know the properties of Sgr A* as accurately as possible. To do this we will integrate expertise on pulsars, optical interferometry, and GR theory developed within the GW community. All these communities are very strong in Europe and are represented here by the Co-PIs and the team members.

The spacetime around BHs can be probed accurately using test masses orbiting them. Stars have been used to measure Sgr A*'s mass robustly. With ESO's new VLTI instrument GRAVITY (Eisenhauer et al. 2011), using optical interferometry, not only the BH mass will be determined more precisely, but also its spin.

Even more accurate probes would be pulsars. These are compact, rotating neutron stars that can be used as test-masses in a gravitational field with a precision clock attached (Lorimer & Kramer 2005). Pulsars provide tests of strong gravity with unrivalled precision (e.g., the Hulse-Taylor binary). Observations of a single pulsar around Sgr A* could determine with very high precision the BH properties (Liu et al. 2012). This can be compared with BH images for an effective proof of the existence of BHs and of the validity of GR.

So far, surveys of the Galactic Centre have not been successful, despite the expectation to find more than 1000 pulsars (e.g., Wharton et al. 2012). This is due to extreme scattering of radio waves in the turbulent interstellar medium in the Galactic Centre, which broadens any pulse. A pulsar cannot be detected as such if the pulse period is shorter than the scattering time. Fortunately, this obstacle can be removed by performing observations at the high radio frequencies our camera will operate on. Hence, although the signal becomes weaker at higher frequencies, observing there renders pulsars detectable with ALMA. A phased-up ALMA allows for the first time a sensible pulsar survey at frequencies ≳90 GHz. With 1 hour of integration time, about 3% of all known pulsars could be studied, and with 5 hours of integration nearly 10% of all known pulsars would be accessible, providing potentially dozens of pulsars at the Galactic Centre, including millisecond pulsars. It will then be sufficient to time a *single* normal pulsar, to measure the mass of Sgr A* with a precision of $<10^{-6}$, to test the cosmic censorship to about 0.1%, and the no-hair theorem to 1%.

An example is given in Figure 1, where we show projected precessing pulsar orbits and the resulting timing residuals together with the simulated shadow images for two BH orientations. Both methods produce clearly distinguishable signatures and independently provide information about Sgr A*'s mass, spin, and orientation.

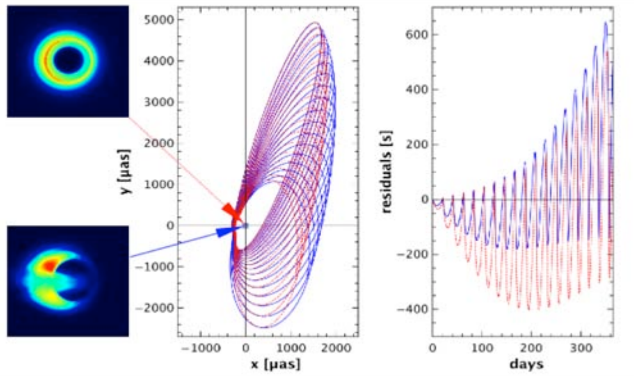

Figure 1: Simulated images of Sgr A* for two orientations (red/blue) of the spin axis (left) w/o instrumental effects, compared to potential pulsar orbits (middle) and timing signals (right) for these configurations. A rather extreme orbit has been chosen for display purposes.

However, any experiment is only useful as long as it can be interpreted. Over the last decade, the GW community has developed a deep theoretical understanding of GR and of BHs (Rezzolla 2009), and a multinational effort is building interferometers worldwide to detect GWs directly. To find a signal, gravitational theorists have launched a large-scale effort to produce a database of waveforms emitted by compact-object binaries to be compared with the noisy experimental data. These supercomputing numerical-relativity calculations have led to a much better understanding of GR and of the numerical techniques needed to model accurately BHs and their environment. However, so far this huge expertise in Europe has never been applied to Sgr A*! Moreover, the expectations of what a GW detector should see and of how the BH shadow should appear are based on the assumption GR is the correct description of gravity. This is not necessarily true and the observational evidence for so-called "dark matter" and "dark energy" in the universe has led to a number of alternative theories. In some of these theories, BHs have the same properties as in GR, but they differ in their response to perturbations (Barausse & Sotiriou 2008, Psaltis et al. 2008), complicating both the detection of GWs and the predictions of the imaging of the event horizon. Here, we will use this expertise to produce *quantitative tests of the validity of GR* from our data with the potential to open new theoretical avenues for understanding gravity.

Hence, our goal is to combine event-horizon imaging, pulsar dynamics, and BH modelling, in order to turn Sgr A into a laboratory that will test our understanding of spacetime.*

2 Methodology

2.1 Observations: A black hole camera for very long baseline interferometry

The methodology to obtain high-resolution radio images is well established and called very long baseline interferometry (VLBI). It correlates data recorded at widely separated radio telescopes to reconstruct an image of the source. The larger the observing frequency and the separation between the telescopes, the higher is the angular resolution. VLBI experiments use radio telescopes at arbitrary locations equipping them with recording instruments and atomic clocks. Using the clock's time stamps, signals are later correlated and turned into an image of the source. Low-frequency VLBI is routine, but high frequencies are a challenge, requiring broadband digital equipment and sensitive telescopes. Both challenges can be met now: the needed broadband is achievable and ALMA will improve the sensitivity of (sub)mmVLBI by an order of magnitude.

For the emission to become optically thin near the event horizon we will need to observe Sgr A* at 220 GHz and higher. So far this required a major effort. Often the scarce equipment needs to be shipped back and forth, setting-up of the equipment takes days, and post-processing takes many months. Also, scheduling of VLBI experiments is a major exercise, requiring block reservations at different telescopes. Our goal is a setup in which the *VLBI equipment is on standby and remote-controlled on all sites*, with a minimum burden on local operations. The first component of *BlackHoleCam* is to acquire and integrate hardware that can be provided to any participating radio telescope (**D1.1a**) and controled remotely (**D1.1b**). We will build a new recorder system that can serve the VLBI *and* pulsar communities at mm-wavelengths and can be installed at ALMA (**D1.1c**). Near real-time correlation via Internet will allow for system-readiness tests (**D1.1d**). Several telescopes in California, Hawaii, Arizona, Spain, France, and Chile have already participated in mmVLBI experiments of Sgr A* and have different needs. For smooth operation it may be beneficial to station scientists at participating sites to adapt, install, and maintain a stable VLBI network **(D1.2a).** New sites could come in Antarctica and Mexico and older sites may need upgrades, for which we make a provision (**D1.2b**). Our equipment can be shipped from one site to another, making us more flexible. Finally, a data-analysis pipeline will be developed (**D1.3a**), together with adequate VLBI simulation tools (see Figure 2; **D1.3b**).

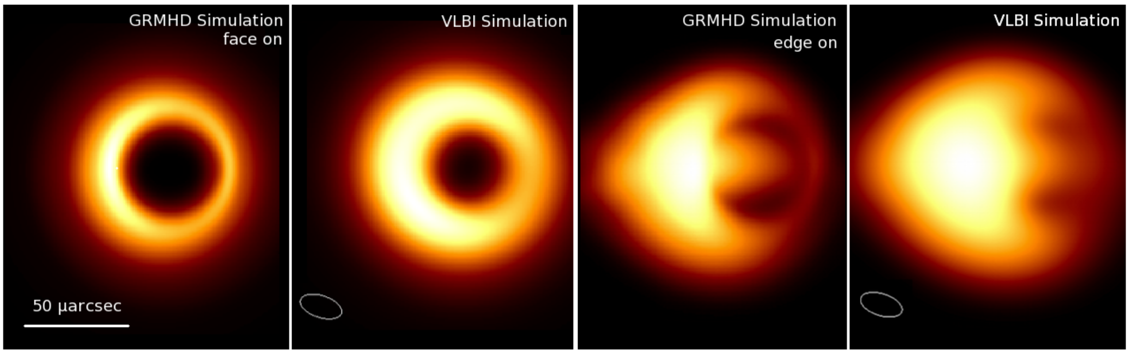

Figure 2: GRMHD simulation of the emission in an accretion flow around a rapidly spinning BH in Sgr A* (see **Figure 1**) blurred according to the expected interstellar scattering. This is compared to a reconstructed image from simulated submm-VLBI (Falcke et al. 2011, Mościbrodzka et al. 2011) for face-on 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.

Interestingly, by *using exactly the same data and equipment needed to image the event horizon, we can search for pulsars in the Galactic Centre* and conduct our measurements of the properties of Sgr A* in a powerful complimentary approach. Thus, we will produce a pipeline searching the ALMA VLBI (and other) data for pulsars, including a full-acceleration search (**D1.3c**) and tools to time them (**D1.3d**).

2.2 Theory: How to model and interpret the observations

The theoretical work of BlackHoleCam will cover two aspects: the modelling of the dynamics and emission from astrophysical plasmas around BHs, and the modelling of the signatures that different theories of gravity make on such dynamics and emission. The shadow shape depends solely on the spacetime properties, while the emission also on the astrophysical conditions. Our groups currently work with *HARM(3D)* (Noble et al. 2007) and *Whisky* (Rezzolla et al. 2011). These codes are state of the art in the modelling of MHD plasmas in three dimensions and curved spacetimes plus radiative-transfer. *Whisky*, developed in the GW community, also provides the ability of solving the Einstein equations and of simulating ideal-MHD, resistive MHD, and force-free conditions. The codes will be systematically compared and calibrated (**D2.1a**) and used to calculate the dynamics of the matter for different BH mass and spin, accretion rate and geometry, magnetic-field properties, and resistivity of the plasma (**D2.1b**). The heating and cooling of the particles producing the emission will be modelled via prescriptions that link particle acceleration to local plasma properties and by coupling the codes with particle-in-cell ones (**D2.1c)**. In addition to GRMHD simulations, we will build a theoretical framework for deviations from GR and other theories of gravity. We will set up *"null tests"* using generalized Kerr solutions with modified mass moments and simulate the emission in arbitrary theories of gravity (**D2.2a**), building a catalogue of images to be compared with observations (**D2.2b**).

Because these alternative theories do not reveal what might be causing a deviation from the Kerr geometry, we will also construct a series of *"multi-answer tests"*, *providing quantitative measurements of the deviations from BH solutions in generic theories of gravity* and assessing whether observations can tell the difference from GR **(D2.2c**). Focusing on theories for which BH solutions are known to differ from GR, we aim to develop a *parameterized framework* to quantify the deviation from GR and the Kerr solution.

Ultimately, we want to combine the information from all methods, i.e., compare the model predictions with pulsar timing, stellar orbits, and VLBI imaging **(D2.3a)**. The orbital distortion induced by the central cluster will be assessed using N-body simulations and observations of stellar orbits by our collaborators from the GRAVITY team in Garching. The theoretical analysis will march on parallel tracks with a rigorous program of astronomical observations (**D2.3b**): VLBI observations at mm-waves up to 350 GHz, pulsar surveys with ALMA, and multi-wavelengths campaigns including GRAVITY.

Last but definitely not least, we will undertake a vigorous plan of public outreach (**D2.4a**). BHs are popular indeed. All the PIs have a long track-record in popularizing scientific results and have produced a variety of animations and images that are diffused worldwide. We will further intensify this effort by producing web content, 3D animations, articles in popular science magazines, and giving presentations in public media.

2.3 Synergy

H. Falcke has pioneered the idea of imaging the BH shadow in the Galactic Centre and is an expert in radio interferometry, BH theory, and astroparticle physics. R. Tilanus, former head of operations at a mm-wave telescope in Hawaii, and who is directly involved in recent 220 GHz VLBI experiments, is project manager. M. Kramer is an expert in the studies of pulsars as probes of fundamental physics and GR. He has a long track record in pulsar observations at mm-wavelengths and in using phased-up interferometers. VLBI expert O. Wucknitz recently joined the group. Besides the pulsar group, the MPIfR in Bonn also has a VLBI group (A. Zensus), and a (sub)mm-wave group (K. Menten), which will collaborate closely with us. This includes VLBI experts T. Krichbaum and A. Brunthaler, as well as technical staff in all relevant areas. L. Rezzolla is a gravitational theorist with a track record in the development of parallel codes for the study of BHs and neutron stars under a variety of physical conditions. The numerical-relativity group that he heads will provide the logistic infrastructure for the code development and the running of the simulations. We will work in pairs: HF and MK oversee instrumentation, HF and LR the theory, and LK and MK the fundamental tests.

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, Frank Eisenhauer (MPE Garching), PI of the Gravity project. Laing will work on integrating ALMA into the VLBI network, van Langevelde will work on software and near-real time correlation, Eisenhauer will work on stellar orbits and combined radio and near-infrared observations.

We will benefit from several external experts including: T. de Graauw (ALMA director), P. Strittmatter (director Steward Observatory, AZ), Lucy Ziurys (director SMTO telescope, AZ), G. Bower (UC Berkeley, CARMA telescope and VLBI), M. Bremer (IRAM telescopes and VLBI), C. Gammie (Univ. of IL, author of *HARM*), O. Smirnov (ASTRON, NL, MeqTrees software), S. Portegies Zwart (U. Leiden, NL, N-body sim.).

Communication within the project will be through a combination of regular face-to-face meetings, telecons, and a Wiki for documents. HF lives near Bonn and commutes daily to Nijmegen. He will spend 1-2 days per week in Bonn as core time. The Bonn area is well connected to Garching and Potsdam by several daily flights and high-speed trains. The PIs will meet bi-weekly, either in person or via skype teleconference. In between, there will be a one-hour bi-weekly status update meeting for all team members. "Busy weeks" will be held regularly, where a few team members gather to concentrate on a specific goal. All team members will meet at a annual collaboration meetings, which will be audited by a senior science advisory committee.

3 Project structure and Resources

Here we summarize the tasks and work packages indicating the full-time equivalents (FTE; one year of salary on a postdoctoral or engineer level) and hardware costs needed for each work packages. Details can be found in Part B1. Deliverables (**D**) corresponding do each Work Package (**WP**) are given in the text above.

Task 1	**The Black Hole Camera system**	
WP 1.1	Develop a dynamically schedulable mmVLBI Camera System	23 FTE + €2M
WP 1.2	System roll-out and installation at telescopes	18 FTE + €1.2M
WP 1.3	Data Analysis and Simulation	12 FTE
Task 2	**Theory and Science Analysis**	
WP 2.1	3D GRMHD simulations of accretion/jets systems	17 FTE + €1M
WP 2.2	Investigation of alternative/expanded theories of gravity	9 FTE
WP 2.3	Putting things together: observing and cross-validation with theory	17 FTE
WP 2.4	Public outreach and educational material	3 FTE

With overhead, salaries for PIs, travel, and computing (incl. compute cluster) we arrive at close to 15 M€.

4 Summary

Do BHs exist? Our current thinking is they do. But despite the fact that most people, children included, have heard about them, we honestly do not know. We have not seen a BH yet, but only inferred their existence through theory and indirect observational evidence alone. Could we be wrong? If we are not, does Einstein's theory of gravity describe these most extreme objects correctly? Do BHs indeed have an event horizon that "saves our physics" from being applied to a naked singularity at the centre? And, is it true that BH don't have hairs, ie., are they so simple that they are only described by their mass and spin? Answering these questions may have fundamental consequences for our understanding of gravity and for the whole universe as governed by this little-understood force. The answers may surprise us and it is foremost our human curiosity that drives us to venture into this as yet unexplored regime of physics. Hence, we are deeply convinced that the first-ever image of a black hole will not just be hard fundamental science but also an inspiration for the curious mind of all ages, thereby opening up new horizons.

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