THEZA

TeraHertz Exploration and Zooming-in for Astrophysics

ESA Voyage 2050 White Paper

Contact Scientist (PI): Leonid Gurvits

Joint Institute for VLBI ERIC (EU/NL) and Delft University of Technology (NL)
Address: JIVE, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands
E-mail: lgurvits@jive.eu | Phone: +31 (0)521 596 500

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Executive summary

This ESA Voyage 2050 White Paper describes a concept of **TeraHertz Exploration and Zooming-in for Astrophysics (THEZA)**. The document addresses the science case and some engineering implementation issues of a space-borne radio inteferometric system for ultra-sharp imaging of celestial radio sources, at the level of angular resolution down to micro- and sub-micro-arcseconds. A system like that will operate at millimeter and sub-millimeter wavelengths (frequencies above $\sim$300 GHz), but might extend its observing bands to lower frequencies (e.g., down to 86 GHz) if deemed feasible at the detailed design study stage.

The THEZA concept science rationale is focused at the physics of spacetime in the vicinity of super-massive black holes as the leading science drive. The main aim of the concept – to facilitate a major leap forward in astronomical resolution and image quality, providing researchers with orders of magnitude improvements in the resolution and dynamic range in direct imaging studies of the most exotic objects in the Universe, black holes. The concept will open up a sizable range of hitherto unreachable parameters of observational astrophysics. This will result in creating a multi-disciplinary scientific facility for addressing the following science areas:

- Physics of the event horizon of the super-massive black hole (SMBH) in the center of Milky Way (the object Sgr A*);
- Astrophysical and cosmological studies of SMBH in other galaxies;
- Physics of inner jets in active galactic nuclei (AGN);
- Evolutionary properties of binary AGN – precursors to gravitational wave events;
- Synergistic studies of violent astrophysical processes (transients);
- Search for water maser emission in the interstellar medium and protoplanetary discs;
- Studies of exoplanets;
- Search for technosignatures – signals of extraterrestrial civilisations.

The concept unifies two major lines of development of space-borne radio astronomy of the past decades: Space VLBI (Very Long Baseline Interferometry) and mm- and sub-mm astrophysical studies with "single dish" instruments. It also builds up on the recent success of the Earth-based Event Horizon Telescope (EHT) – the first ever direct image of a shadow of the super-massive black hole in the center of the galaxy M87. As an amalgam of these three major areas of modern observational astrophysics, THEZA aims at facilitating a breakthrough in high-resolution high image quality studies in mm and sub-millimeter domain of the electromagnetic spectrum.

The THEZA concept is based on the ongoing study initiated in Europe (coordinated by the Radboud University, The Netherlands) in 2016. This study involves scientists and engineers from many European countries as well as experts from Australia, Canada, Chile, China, Japan, South Africa, and the USA. The THEZA concept carries a significant synergy with the topics submitted to the US Decadal Survey on Astronomy and Astrophysics (Astro2020). It would be natural to assume that implementation of the THEZA concept in a specific mission would benefit from a wide collaboration beyond ESA boundaries.

1 THEZA science rationale

Astronomical advances are typically driven by technological advances and expansion of the parameter space made available for observing the universe. Imaging has been and still is at the front line of astronomical research. There are two extreme ends one consider. One extreme frontier is covered by large survey telescopes which charter large areas of the entire sky to make ever-more complete inventories of cosmic sources. Gaia has measured billions of stars, revealing important aspects of Galactic structures. Euclid will map two billions galaxies to understand the structure of the universe and the nature of dark energy. On the ground telescopes like the Square Kilometre Array (SKA) promise to map billions of radio sources, including all powerful radio galaxies back to the beginning of the Universe.

However, the other extreme end of the astronomical parameter space is higher resolution, high quality imaging. Rather than understanding the entire Universe at once, individual objects are studied with ever sharper vision. In optics, the Hubble Space Telescope has certainly changed our view of the Universe and made a big impact not only on science as such, but also on its perception by the general public.

Both approaches are necessary. After all, we cannot understand the large scales of the Universe, if we do not understand the objects that populate it and we cannot understand cosmic processes, if we only look at them with blurred vision.

Here we argue that the time is ripe for a major leap forward in astronomical resolution and image quality, providing us with orders of magnitude improvements in both areas and a stunning view of the most exotic objects in the Universe: black holes.

One of the major challenges of fundamental physics in the coming decades will be understanding the nature of spacetime and gravity, and black holes are at the center piece of these challenges. Spacetime provides the underlying theater within which the entire drama of our Universe unfolds. Gravity and the geometry of space are in principle well-described by the theory of General Relativity (GR). Yet this theory is still one of the biggest mysteries in theoretical physics. The presence of dark energy in the cosmos tells us that our understanding of spacetime is not complete and may require quantum corrections, which can even affect the largest scales. Similarly, the notion of Hawking radiation suggests that quantum theory and classical black holes seem to be incompatible. However, after many decades of research the unification of GR and quantum theory is still a major problem and perhaps experiments may now need to lead the way.

Fortunately, we are now entering an era when experimental tests of gravity – even under the most extreme conditions – are becoming possible. The nature of dark energy is targeted by large scale surveys, as mentioned before. The Square Kilometre Array (SKA) will have the ability to detect and measure new pulsar systems to significantly improve on existing tests of GR. New X-ray missions like Athena will allow us to do spectroscopic measurements of hot gas orbiting black holes and gravitational wave experiments like LISA or the Einstein Telescope will provide detailed measurements of the dynamical nature of spacetime. Hence, one could claim that the past century was the century of particle physics and astrophysics, while this century promises to be the century of experimental spacetime physics - the ultimate synthesis of the two.

However, of all the techniques, there is only one that allows one to make actual images of black holes and the astrophysical processes surrounding them: interferometry. Optical interferometry with ESO's Gravity experiment has imaged the motion of gas around the Super-masive Black Hole (SMBH) in the center of Milky Way and Very Long Baseline Interferometry (VLBI) in the radio domain has imaged the innermost structures of jets and recently even the black hole shadow itself. These new results are quantum leaps and they only mark the beginning. By going into space, the imaging resolution and fidelity can be enhanced enormously, and we will be able to see black holes and their immediate environment in unprecedented detail and quality. Any physical and astrophysical theory of black holes and their activity will need to be able to predict in detail how they look.

In the following we will discuss the promises of space-based VLBI for the study of black holes within the concept dubbed **TeraHertz Exploration and Zooming-in for Astrophysics (THEZA)**. Of course, once one has access to the extreme resolution provided by VLBI other science cases will also become possible with the same technology, which we will also briefly touch upon. After all, what works for long baselines in space can also provide in principle interferometry at shorter baselines, if one chooses the right concept.

2 Science and technology heritage

2.1 Space VLBI

For more than half a century, since its first demonstrations in 1967, Very Long Baseline Interferometry (VLBI) holds the record in sharpness of studying astronomical phenomena. This record reaches angular resolutions of milliarcseconds and sub-milliarcseconds at centimetre and millimetre wavelengths owing to the ultimately long baselines, comparable to the Earth diameter. However, the hard limit of VLBI angular resolution defined by the size of Earth does not allow us to address astrophysical phenomena requiring an even sharper sight. Not surprisingly, soon after the demonstration of first VLBI fringes with global Earth-based systems, a push for baselines longer than the Earth diameter materialised in a number of design studies of Space VLBI (SVLBI) systems.

Over the past decades, several dozens of various SVLBI concepts have been presented with widely varying depth of development and level of detalisation (Gurvits, 2018, 2019b). They paved the way for the first SVLBI demonstration in the middle of the 1980s (TDRSS Orbital VLBI experiment, Levy et al. (1986)) and two dedicated SVLBI missions, VSOP/HALCA launched in 1997 (Hirabayashi et al., 1998) and RadioAstron launched in 2011 (Kardashev et al., 2013).

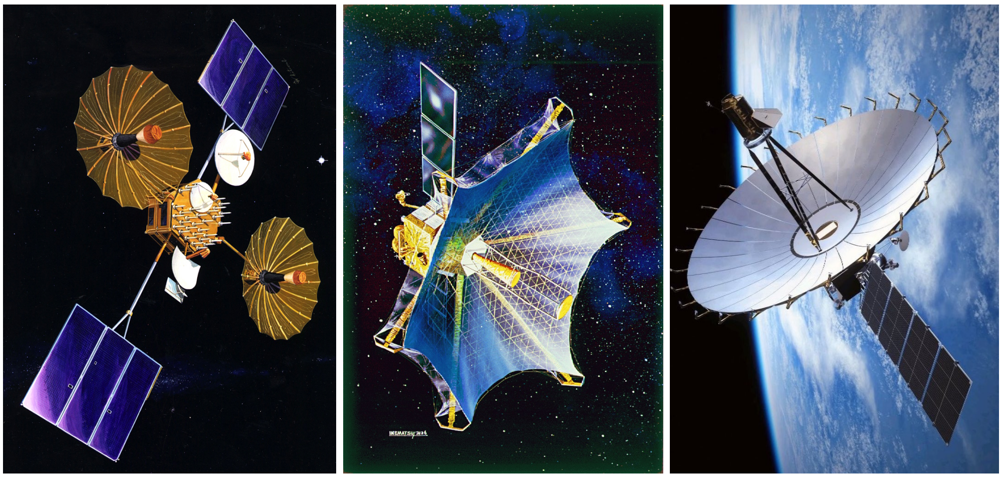

Figure 1: *Artist's impressions of (*left to right*): Tracking and Data Relay Satellite System (TDRSS) spacecraft, picture credit: NASA; Highly Advanced Laboratory for Communication and Astronomy (HALCA) of the VLBI Space Observatory Program (VSOP), picture credit: JAXA; Spektr-R spacecraft of the RadioAstron mission, picture credit: Lavochkin Scientific and Production Association.*

First VLBI "fringes" on baselines longer than the Earth diameter were obtained with the NASA's geostationary spacecraft of the Tracking and Data Relay Satellite System (TDRSS, shown in the left panel of Fig. 1) in 1986 (Levy et al., 1986). This was a very efficient example of ad hoc use of existing orbiting hardware not designed originally for conducting SVLBI observations. The main outcome of several TDRSS observing campaigns was two-fold. First, the very concept of getting coherent interferometric response (the so called interferometric "fringes") on baselines longer than the Earth diameter has been proved experimentally. Second, observations of two dozens of strongest AGN (Active Galactic Nuclei) at 2.3 GHz in 1986–87 (Levy et al., 1989; Linfield et al., 1989), and in a dual-frequency mode at 2.3 and 15 GHz in 1988 (Linfield et al., 1990) provided indications that at least some extragalactic sources of continuum radio emission were more compact and therefore brighter than expected. These milestones supported growing momentum for the first generation of dedicated Space VLBI missions.

The VSOP/HALCA (Fig. 1, middle) operated in orbit in the period 1997–2003. Its science heritage is summarised in Hirabayashi et al. (2000a), Hirabayashi et al. (2000b), Hagiwara et al. (2009, Parts 3-4). The RadioAstron mission (Fig. 1) was operational in the period 2011–2019. Its science outcome is still to be worked out; some preliminary summaries are presented in Kardashev & Kovalev (2017) and in the Spacial Issue of Advances in Space Research (Gurvits, 2019a). A very brief list of major legacy achievements of VSOP and RadioAstron missions with associated references is given in Gurvits (2018). The major qualitative result of the first generation SVLBI missions, VSOP and RadioAstron can be expressed as follows: sub-milliarcsecond angular scale in continuum (active galactic nuclei, pulsars) and spectral line (maser lines of hydroxyl and water molecules) sources is consistent with the current general understanding of the astrophysics of these sources, but various enigmatic details require further in-depth studies with similar or sharper resolution and higher sensitivity.

The first generation SVLBI era has come to the completion in 2019. It has provided a solid proof of concept of radio interferometers exceeding the size of Earth and serves as a stepping stone toward future advanced SVLBI systems presented in this White Paper.

2.2 Millimetre and sub-millimetre space-borne radio astronomy

Over the last three decades developments for ground and space-borne millimeter and sub-millimeter heterodyne detection instruments have generated important synergies. The SWAS (Melnick et al., 2000), ODIN (Frisk et al., 2003) and NASA Earth Observing System Microwave Limb Sounder (Waters et al., 2006) orbital missions were all equipped with room temperature or cooled Schottky receivers. One of the most important steps in advancing modern heterodyne instruments was the development of cryogenic systems with superconducting mixer elements (SIS). In particular such technology was essential for not only achieving the quantum limited noise but could also work with much lower local oscillator (LO) power, a condition permitting very compact and versatile solid state LO generators. The complex Herschel HIFI instrument adopted this technology for the on-board instrumentation enhanced by stringent quality insurance schemes (de Graauw et al., 2010). The success of HIFI showed that SIS and HEB technology is very well suited for space application.

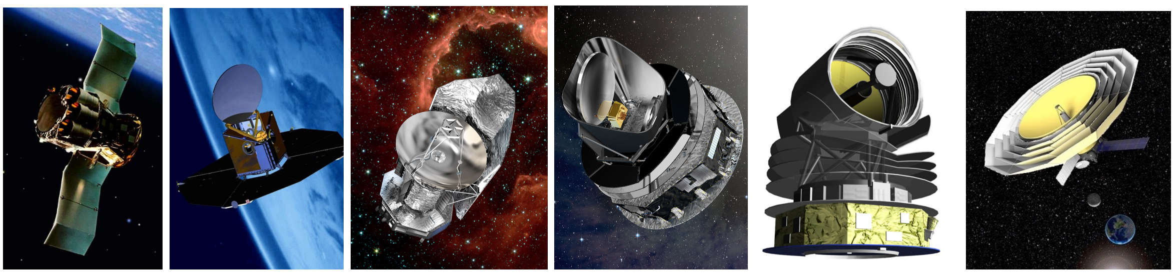

Figure 2: *Artist's impressions of (left to right): Sub-millimeter Wave Astronomy Satellite (SWAS), picture credit: NASA, USA; Odin satellite, picture credit: the Swedish National Space Agency, Sweden; Herschel spacecraft, picture credit: ESA; Planck spacecraft, picture credit: ESA; a concept of the SPace IR telescope for Cosmology and Astrophysics (SPICA), picture credit: SRON, The Netherlands; a concept of the Millimetron mission, picture credit: Astro Space Center, Russia.*

This technology path found its way into advanced mm/sub-mm systems both for Earth-based facilities (e.g., the ALMA and IRAM's NOEMA interferometers). The recent study for Origins (one of the four NASA's flagship candidates for the next decadal) included a thorough look at the heterodyne needs for the HERO (HEterodyne Receiver for Origins) onboard instrument (Wiedner et al., 2018). This study showed that achieving a high TRL sufficient for implementation within the timeframe of the 2020 US Decadal survey is possible and no showstoppers are foreseen. This also holds for direct detectors, as studied for SPICA and Origins, and in a different incarnation for the ESA's Cosmic Vision L2 mission

Athena (the XIFU instrument). The Transition Edge Sensors (TES) and Kinetic Induction Detectors (KID) devices provide ultimate sensitivity and, if needed, high multiplexing capabilities. The technology required for these detectors has been developed, in particular, at the SRON, The Netherlands. Finally very powerful broadband digital signal processing is now available which enables data processing with extreme efficiency, while power consumption for these digital operations is expected to decrease within the coming years to sufficiently low levels for space application.

Other important improvements in cryogenic heterodyne instruments have taken place and are still moving forward. Instantaneous bandwidth is now an orders of magnitude larger than 20 years ago also due to the greatly improved performance of cryogenic IF amplifiers. The Herschel instruments were passively cooled to 80 K and the instruments were kept cold through boiling of Helium gas in a large cryostat. With the developments of cryocoolers for Planck, the cryocoolers of Hitomi and the current developments for Athena and SPICA, we expect that any mission needing low temperatures can rely on closed cycle cryocooling rather than liquid Helium cryostats. Planck also showed the value of the V-groove system, currently employed in ARIEL and studied for the SPICA satellite. All in all, the available heritage of mm/sub-mm space missions and their instrumentation and ongoing developments assure beyond doubts that technical specifications for THEZA can be met within the Voyage-2050 timeframe. Fig. 2 presents artist's impressions of four completed missions (SAWS, Odin, Herschel and Planck) as well as two missions currently under development (SPICA and Millimetron) which can be seen as stepping stones toward a mission addressing the THEZA concept.

2.3 EVN, Global VLBI, GMVA, EHT

With a collecting area comparable to that of the first phase of the mid-frequency Square Kilometre Array (SKA1-MID), today the European VLBI Network (EVN[1]) is a joint facility of independent European, African, Asian and North American radio astronomy institutes with thirty-two radio telescopes throughout the world and operating in a range of frequencies going from 92 cm to 0.7 cm. The EVN offers (sub-)mas angular resolution with μJy sensitivity in those bands with best performances (21/18 cm and 6/5 cm). It is the most sensitive regular VLBI array adopting open sky policies. Since the start of its operations in the early 1980s, the EVN has been undergoing a continuous development to match the scientific requirements, the most relevant being: the increased recording rate at each telescope from the initial 4 Mbps to 2 Gbps at present; the increased number of member observatories, which has brought the number of antennas from 5 to the current 32, with an amazing jump in the image fidelity; and the real-time operations with a subset of the array through the e-VLBI, whereby the recorded signal is transferred to the EVN correlator at JIVE through fiber link connection, a feature which has made the e-EVN array an SKA pathfinder.

Owing to the broad frequency range and high sensitivity offered to the community, the EVN delivers outstanding science in almost any astrophysical area, from the distribution of dark matter through gravitational lensing, to the origin of relativistic jets in active galactic nuclei and their evolution with cosmic time, to stellar evolution – from the pre-main sequence stage to the post-asymptotic giant branch stage, to the successful detection of exoplanets. More recently, it has become clear that VLBI can uniquely contribute to what is now referred to as the *science of transient phenomena*, a broad range of very energetic phenomena covering fast radio bursts, gamma-ray bursts, tidal disruption events, and follow-up of electromagnetic counterparts to gravitational wave events, thanks to the combination of superb angular resolution and sensitivity, and micro-arcsecond precision localization.

While the EVN as such has no frequency overlap with the THEZA concept presented here, it is the vast area of complementary science that makes the EVN a highly synergistic to the THEZA science. Moreover, the most important synergy between EVN and THEZA is in human capital: most members of the THEZA Core Team (and many others who contributed to this White Paper but cannot be listed due to the authorship limit) are active EVN functionaries and users. In short, EVN is the major "breeding ground" for ideas, technologies and know-how behind the THEZA initiative.

[1]https://www.evlbi.org/home, EVN site accessed 2019.08.02.

The already superb angular resolution of the EVN can be sharpened by observing at shorter wavelengths, as it has been achieved by the Global Millimetre VLBI Array (GMVA[2]), another world array consisting of sixteen antennas operating at 3.5 mm (85–95 GHz band). The array may be further expanded with the addition of the phased Atacama Large Millimeter Array (ALMA) and the Korean VLBI Network. Further potential enlargement of the GMVA will involve the Greenland Telescope and the Mexican Large Millimetre Telescope. Exploration of the inner jet regions of nearby active galactic nuclei and blazars is one of the main scientific drivers for 3 mm GMVA observations.

The experience acquired with the GMVA, in operation since the early 2000s, for which observations, calibration and data analysis pose several challenges due to the weather dependence and the heterogeneity of antennas in the array, has paved the way to the Event Horizon Telescope (EHT[3]), which has pushed the angular resolution and observing frequencies to the limits of the current capabilities of ground-based VLBI. Imaging the black hole shadow of the nearby galaxy M 87 has been one of the most remarkable achievements of the VLBI technique to date (Event Horizon Telescope Collaboration et al. (2019a) and references therein), and this has been possible owing to 50 years of a worldwide collaborative effort based on scientific, technological, and human capital investment.

The EHT is the ultimate development of the Earth-based VLBI in terms of the wavelength and geometry of the array. It serves as a benchmark for the THEZA concept presented here. The next steps forward in development of VLBI at frequencies above 100 GHz and into the THz regime are necessitated by the astrophysical motivations. They promise transformational science results and require VLBI systems above the Earth's atmosphere. This is the essence of the THEZA concept.

3 THEZA science

3.1 Event horizon in SMBH: physics and cosmology

In 2019, after decades of developmental efforts from a global collaboration of scientists, the EHT collaboration presented the first image of a black hole (Event Horizon Telescope Collaboration et al., 2019a). The EHT image, revealing the supermassive black hole (SMBH) in M87, was captured using a global VLBI network operating at a wavelength of 1.3 mm. It is formed by light emitted near the black hole and lensed towards the photon orbit of the 6.5 billion solar mass black hole at the galaxy's core. The combination of light bending in curved space time and absorption by the event horizon leads to a characteristic black hole shadow embedded in a light ring that was predicted to be observable by mm-wave VLBI by Falcke et al. (2000). The results constrain the object to be more compact than the photon orbit, at a size $\leq 3/2R_{\rm S}$, where $R_{\rm S}$ is the Schwarzschild radius. This is comparable to the compactness currently probed by LIGO/VIRGO with gravitational waves, but on mass scales eight orders or magnitude larger.

The capability to image black holes on event horizon scales enables entirely new tests of General Relativity (GR) near a black hole (e.g., Johannsen & Psaltis, 2010a) and opens a direct window into the astrophysical processes that drive accretion onto a black hole and formation of relativistic jets (Mościbrodzka et al., 2016). Jets are a major source of energy output and high-energy emission for black holes across all mass scales. Their origin and formation is of fundamental importance to high-energy astrophysics and happens on event horizon scales.

For precise tests of GR and time-domain studies of accretion flows and jet formation, we therefore need sharper angular resolution, higher observing frequencies, and faster and more complete sampling of interferometric baselines.

The angular resolution of ground-based VLBI is approaching fundamental limits. Interferometer baseline lengths are currently limited to the diameter of the Earth, imposing a corresponding resolution limit for ground arrays of $\sim 22\mu$as at an observing frequency of 230 GHz. Observations at higher frequencies can improve the angular resolution but become increasingly challenging because of strong atmospheric absorption and rapid phase variations, severely limiting the number of suitable ground

[2]https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/, GMVA site accessed 2019.08.02.

[3] https://eventhorizontelescope.org, EHT site accessed 2019.08.02.

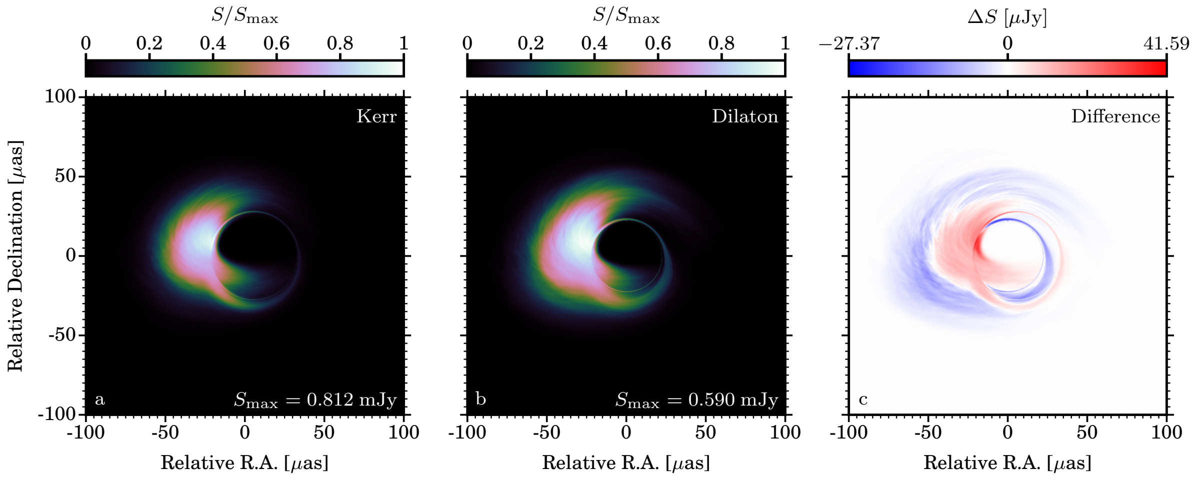

Figure 3: *Left: simulated image at 230 GHz from a GRMHD simulation of accretion onto a Kerr black hole. Middle: the same for a non-rotating dilaton black hole. Right: the difference between the two images. Figure from Mizuno et al. (2018).*

sites and the windows of simultaneous good weather at many global locations. The fixed telescope locations also limit the number of Fourier-components of the image that can be sampled and hence the image quality. Going into space would overcome these limitations and enable to open new scientific possibilities for horizon scale studies in SMBH.

Measuring the shape and size of the shadow and surrounding lensed photon ring in M87* and Sgr A* provides a null hypothesis test of GR (Psaltis et al., 2015). Better images allow one to measure spin, test the no-hair theorem, measure the structure of the spacetime and test for the possibilities for black hole alternatives (e.g., Mizuno et al., 2018).

The big advantage of SMBH imaging, with respect to Gravitational wave experiments, is that the sources are stable and their parameters can be determined independently with ever better accuracy. Extraction of parameters is achieved by comparing matched image templates from GRMHD simulations (Event Horizon Telescope Collaboration et al., 2019b,c). For example, in Sgr A*, the mass and distance are already well-measured within $\sim 1\%$ (Gravity Collaboration et al., 2018b). Therefore the precision of testing GR for Sgr A* is already limited by the fidelity of observing data and the ability to extract the emission corresponding to the black hole photon orbit and interior shadow. With the current resolution the sharply delineated lensed photon ring and more extended lensed emission structures are still blurred together, making detailed tests or spin measurements almost impossible.

Higher angular resolution by space VLBI will allow more precise measurement of the shadow size and shape and increased dynamic range will improve image fidelity. Space VLBI observation allows us to extract the thin, lensed photon ring feature from the more diffuse surrounding emission. Such high-resolution images of the black hole shadow will allow us to constrain the physics of the black hole itself. Figure 3 shows that the difference between accretion onto a Kerr black hole and a dilaton black hole, which is a modification of general relativity, becomes apparent in the size and shape of the photon ring at a resolution of 5-10 μas. The resolution of the ground-based EHT is not sufficient to distinguish between these cases based on reconstructed images (Mizuno et al., 2018), but Space VLBI concepts will be able to reach the required resolution (see also Section 4).

Another quantity that becomes measurable at this resolution is black hole spin. For a Kerr black hole, the effect of black hole spin on the shadow size is limited to about 4% (Johannsen & Psaltis, 2010b), which is impossible to measure with ground-based VLBI. Figure 4 shows that using machine learning techniques, the black hole spin starts becoming measurable at 5 μas resolution at 230 GHz (van der Gucht and other members of the THEZA Core Team, 2019, work in progress). High-frequency imaging at 690 GHz or higher will, therefore, allow for stronger constraints on the spin.

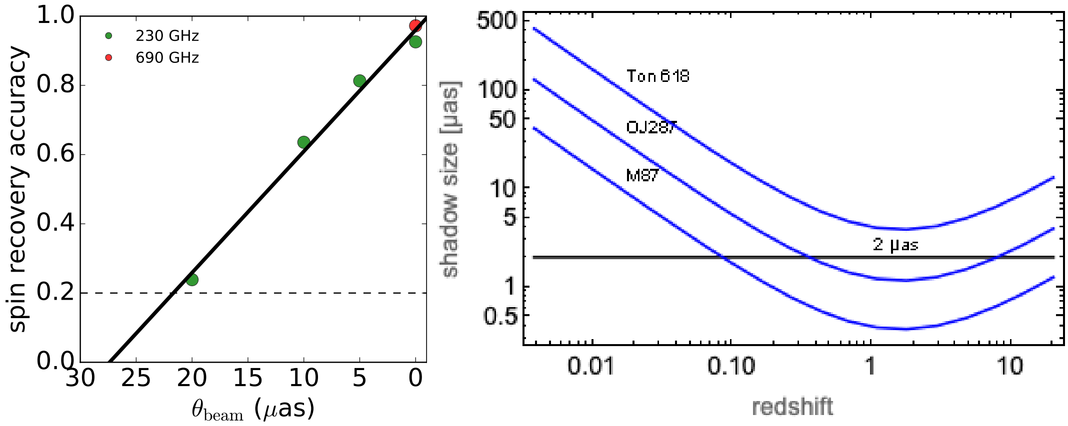

Figure 4: *Left: Black hole spin recovery accuracy from GRMHD simulations by a machine learning classifier network as a function of telescope beam size, where* 1 *means perfect accuracy and* 0.2 *means random guesses as five black hole spin values between -1 (maximal retrograde spin) and 1 (maximal prograde spin) were considered in this analysis. At the EHT resolution at 230 GHz (∼20 µas), the spin recovery accuracy is low. Only at high resolutions of around 5 µas, as could be attainable with Space VLBI, the classifier network is capable of recovering the correct spin value. Right: Size of black hole shadows for three different mass ranges of SMBHs as function of redshift. We use as as examples M87 ($6.4\times10^{9}M_{\odot}$), OJ287 ($2\times10^{10}M_{\odot}$) and TON618 ($6.6\times10^{10}M_{\odot}$), but allow them to be at any distance.*

The relatively small mass of Sgr A* ($4.1\times10^{6}\,\mathrm{M}_{\odot}$, Gravity Collaboration et al. (2018b)) results in correspondingly short dynamical timescales (of order ten minutes) for the system. The current EHT array lacks sufficient baseline coverage to form images on these timescales. The rapid baseline sampling of an orbiter is necessary to recover the complex structure in an evolving accretion flow. Movies of Sgr A* by multiple snapshot images will clarify the nature of coherent orbiting features such as "hotspots" (Gravity Collaboration et al., 2018a) and the origin of the flaring events observed in many wavebands (e.g., Marrone et al., 2008).

Magnetic fields play an important role in accretion and jet formation. The magnetorotational instability, (MRI, Balbus & Hawley, 1998) in accretion disk is thought to transport angular momentum and drive accretion onto the central black hole. Magnetic fields can also cause instabilities and flaring on horizon scale (Tchekhovskoy et al., 2011). Polarimetric imaging of polarized synchrotron radiation observed by space VLBI can reveal the structure and dynamics of magnetic fields near the horizon. It will allow to probe the magnetic field degree of ordering, orientation, and strength through Faraday rotation studies. Power spectral analysis will provide information of the turbulent accretion flow on very fine spatial scales, for the first time observationally testing our understanding of MRI and angular momentum transport in the inner part of accretion disk (Balbus & Hawley, 1998).

Finer angular resolution also provides access to additional targets with spatially resolved black hole shadows. At $\sim 5\,\mu$as angular resolution, the number of known nearby SMBHs that are expected to resolve the black hole shadow will increase also from two (Sgr A* and M87*) to six (M85, Cen A, M104, IC1459), allowing more robust tests. At $\sim 2\,\mu$as also IC4296 and M81 become accessible, but more importantly also large SMBHs at cosmological distances, e.g. something like OJ287 at $z = 0.3$ or SMBH monsters as TON618 at all redshifts.

So, an order of magnitude increase in resolution will provide at least an order of magnitude more sources for black hole shadow tests and access to the jet launching regions of hundreds to thousands of powerful AGN.

3.2 Physics of inner jets in AGN

The processes that govern the formation, acceleration, and collimation of powerful relativistic jets in active galactic nuclei (AGN) and X-ray binaries are a half-century old mystery in black hole physics.

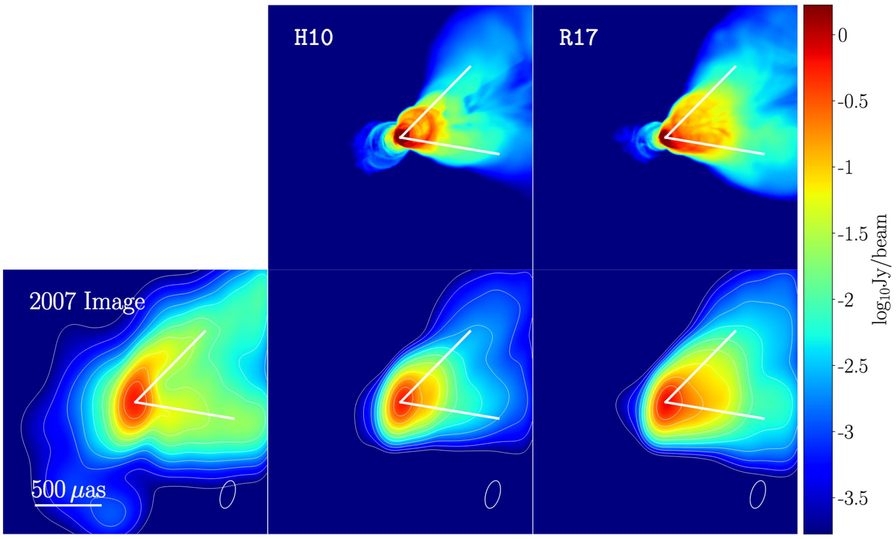

Figure 5: *VLBA image of M87 at 43 GHz (left), compared to simulations of the inner jet based on two models (right up), restored with the same beam as the original map (right bottom). Higher observing frequencies and space baselines are required to tell these apart. Figure from Chael et al. (2019).*

Without an instrument capable of resolving the accretion flow and eventual ejection of plasma in the immediate vicinity of the central black hole, most of the recent advances in our understanding of jet formation have resulted from the rapid development of three-dimensional general relativistic magneto-hydrodynamic (GRMHD) simulations (e.g., McKinney & Blandford, 2009; Tchekhovskoy et al., 2011; Liska et al., 2018). These simulations show that relativistic jets can be powered by magnetic extraction of rotational energy of either the central black hole itself, as originally proposed by Blandford & Znajek (1977), or the accretion disk (Blandford & Payne, 1982). However, we still do not understand the details of this process and cannot answer such basic questions as how the properties of the accretion flow and black hole are connected to the jet formation and why only a fraction of the actively accreting supermassive black holes produces powerful jets in the first place.

In these magnetically driven scenarios, the jet is initially triggered by magneto-centrifugal force, with further acceleration and collimation produced by magnetic pressure gradients and tension forces. In these regions the jet is expected to be characterized by a parabolic collimation profile and a gradual transition from a predominantly poloidal to a helical or toroidal magnetic field configuration. While the jet launching takes place in the innermost few Schwarzschild radii, it appears that the collimation and acceleration extends up to $\sim 10^{5\pm1}$ Schwarzschild radii from the black hole (Asada & Nakamura, 2012; Homan et al., 2015; Kovalev et al., 2019), with a bulk of acceleration taking place within the first $\sim 10^3$ Schwarzschild radii (Mertens et al., 2016). To test jet formation models with actual observations it is necessary to probe linear scales smaller than these. With the exception of M 87, the angular resolution required to resolve these structures is of the order of ten microarcseconds or better, and observations at short mm and sub-mm wavelengths are required to see through the self-absorbed synchrotron-emitting plasma at the jet base. This calls for space VLBI with orbiting antennas operating at mm and sub-mm wavelengths.

Space VLBI can provide the necessary angular resolution to study jet formation, collimation, and acceleration in other nearby AGN by directly resolving the sites of these physical processes (Meier, 2009). This would allow us to study what determines the jet power, and how this is related to the black hole spin, rate of accretion, and disk magnetization. Especially, polarization observations using space VLBI are fundamental to reconstruct the three-dimensional magnetic field structure of the jet as near as possible to the black hole, thus helping to understand the jet formation, conversion of the magnetic energy to the kinetic energy of the flow, and dissipation of this energy. The likely co-existence of relativistic, projection and other effects makes it challenging to reconstruct the intrinsic orientation and

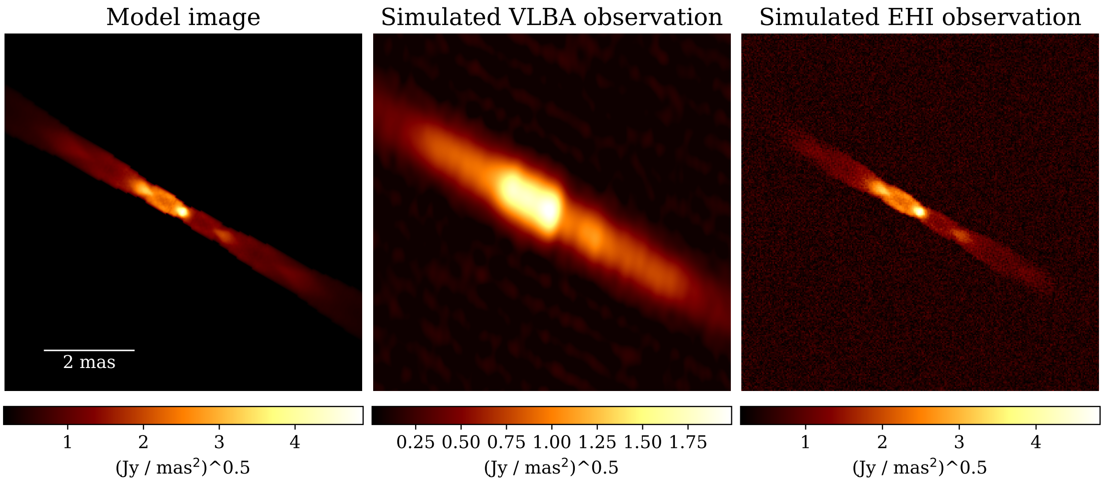

Figure 6: *Left: 43 GHz jet model with a recollimation shock (Fromm et al., 2016, 2018, 2019). The southwestern part is partly obscured by a dusty torus. The model is based on NGC1052 but can be used as a generic model for AGN jets. It was scaled to 8 Jy here to represent a typical bright AGN. Middle: simulated ground-based VLBA observation of this model. Right: simulated Space VLBI observation of this model with the Event Horizon Imager (EHI, see Sec. 4).*

strength of the magnetic fields along the jet where the very nature of these fields is still highly debated (see Boccardi et al., 2017, and references therein). In particular, it is unclear whether the observed polarization is due to compression in a shock of a random ambient magnetic field, or to the presence of a large-scale, ordered field permeating the plasma flow. Space VLBI polarization imaging, both along and transverse to the jet direction, at millimeter wavelengths of a significant number of jets will enable to reduce many of these uncertainties distinguishing between the different possible magnetic field configurations proposed (e.g., Gómez et al., 2016; Marscher et al., 2008, 2010).

Furthermore, multi-frequency space VLBI observations would allow measuring spatially resolved polarization spectrum near the black hole, which can be used to probe the line-of-sight component of the magnetic field and the low energy end of the electron energy distribution (e.g., Homan et al., 2009). Both of these are difficult to constrain by other ways.

To illustrate the jet imaging possibilities with space VLBI, we consider the jet model by Fromm et al. (2016, 2018, 2019). VLBI observations of radio galaxies reveal highly collimated jets surrounded by obscuring dusty tori. Detailed studies of the jet structure revealed several regions of enhanced emission. These regions could be interpreted as travelling shock waves compressing the underlying jet flow or as stationary recollimation shocks. Recollimation shocks are formed due to the mismatch between the pressure in the jet and in the surrounding medium. They cause a distinctive radiative signature in the form of an edge-brightened flow converging into a central bright region, as seen between the two brightest spots in the model image in Figure 6. The recollimation shock profile cannot be resolved by the Earth-based VLBA, but a simulated observation with the two-satellite Event Horizon Imager Space VLBI concept (Martin-Neira et al., 2017; Kudriashov et al., 2019; Roelofs et al., 2019, see Section 4 for details) shows that these features can be resolved with space VLBI.

Combining space VLBI with multi-wavelength observations that recover the complete spectral energy distribution (SED) from radio to gamma-rays will shed light on the mechanisms of energy dissipation in the innermost part of the jet, which is responsible for the spectacular flaring observed in blazars (e.g., Marscher et al., 2008, 2010). Correlated monitoring campaigns will help to localize emission features that fall outside the radio regime as we see structural changes related to flares at other wavelengths.

3.3 Binary AGN – GW precursors

The early growth of massive black holes is believed to go through intense phases of accretion and mergers, and to be tightly coupled to the evolution of their host galaxies (Hopkins et al., 2008; Kormendy & Ho, 2013). Since mergers drive both gas and the black holes to the nucleus, this should often lead to pairs of active galactic nuclei (AGN). On kpc scales these can be easily resolved from the radio to the X-rays, but well-established dual-AGN are still rare (Komossa & Zensus, 2016). Direct imaging of such dual-AGN on parsec to tens of parsec scales requires milliarcsecond angular resolution and therefore can only be done using the very long baseline technique (VLBI) in the radio. This means that a multi-band approach to confirm candidates is becoming problematic (An et al., 2018). The best established case with a projected separation of 7 pc is 0402+379 (Rodriguez et al., 2006).

Below about 10 parsec separation the dual black hole system becomes gravitationally bound, and we refer to these systems as massive black hole binaries (MBHB) (e.g. Bogdanović, 2015, and references therein). Over 100 MBHB candidates have been identified in optical quasar variability surveys (Graham et al., 2015b; Charisi et al., 2016; Liu et al., 2019), and orders of magnitude more is expected to be found in the first 5 years of operations of the much deeper all-sky time-domain survey by LSST. It is estimated that as much as 1% of the AGN below $z \sim 0.6$ could reside in massive binaries (Kelley et al., 2019). This regime is particularly important because the processes that lead to hardening of the binary are not well understood. The energy loss in mergers of black holes are initially dominated by dynamical friction on stars and dark matter, and subsequently by stellar scattering, but below about a few parsecs this becomes inefficient. In this sub-parsec regime, gas may play a role in promoting binary inspiral.

Somewhere between $100 - 1000$ gravitational radii the dominant energy loss becomes gravitational wave radiation and MBHB become visible by LISA[4]. Revealing the rates at which various processes work at intermediate scales is possible in principle, given a large sample of MBHBs, via a measurement of the relative abundances of MBHBs for a range of separations (Haiman et al., 2009).

The possibility of directly resolving MBHB with mm-VLBI imaging was first discussed by D'Orazio & Loeb (2018). They focused on MBHBs that have orbital periods less than 10 years and are resolvable by ground-only baselines. They predict that 100 such systems might be detectable down to 1 mJy limit within $z < 0.5$ (their selection criteria for the tightest orbits and low Eddington rates for accretion biases towards the low-luminosity population). Studying the few hundred to few thousand gravitational radii regime for the most massive AGN ($\sim 10\%$ of which is radio-loud) at very high redshifts becomes feasible from space; estimates for the fraction of MBHBs in the AGN population range from 5% (D'Orazio & Loeb, 2018) to 30% (D'Orazio et al., 2015; Charisi et al., 2016).

The caveat is that space mm-VLBI observations require that both black holes are active, which is quite rare in SMBH pairs with kpc separations. There are good reasons to believe this is not the case for sub-pc MBHB. This is because the most common MBHB are likely formed in minor mergers that have unequal mass black holes; below about 0.1 pc the binary is embedded in an accretion disk and gas interaction becomes important (Armitage & Natarajan, 2002). Hydrodynamic simulations indicate that in unequal-mass binaries the secondary gets most of the accretion, and starves the primary (Farris et al., 2015). This will likely make the secondary super-Eddington, and the primary sub-Eddington (aka "hard state") – both of these $\dot{M}$ regimes are associated with jets and radio emission.

Depending on the configuration, a space mm-VLBI array operating at 230 GHz would have an angular resolution from 10 μas (few Earth radii) to 1 μas (~25 Earth radii) allowing direct imaging of a number of candidates (for reference, the diameter of the estimated orbit of the $z = 0.3$ periodic binary candidate quasar PG 1302−102 extends ≈10 μas (Graham et al., 2015a)).

3.4 Time- and X-ray-domain synergies

Radio transients are both the sites and signatures of the most extreme phenomena in our Universe: e.g. exploding stars, compact object mergers, black holes and ultra-relativistic flows. Essentially all explosive events in astrophysics are associated with incoherent synchrotron emission, resulting from ejections

[4] www.lisamission.org, LISA site accessed 2019.08.03.

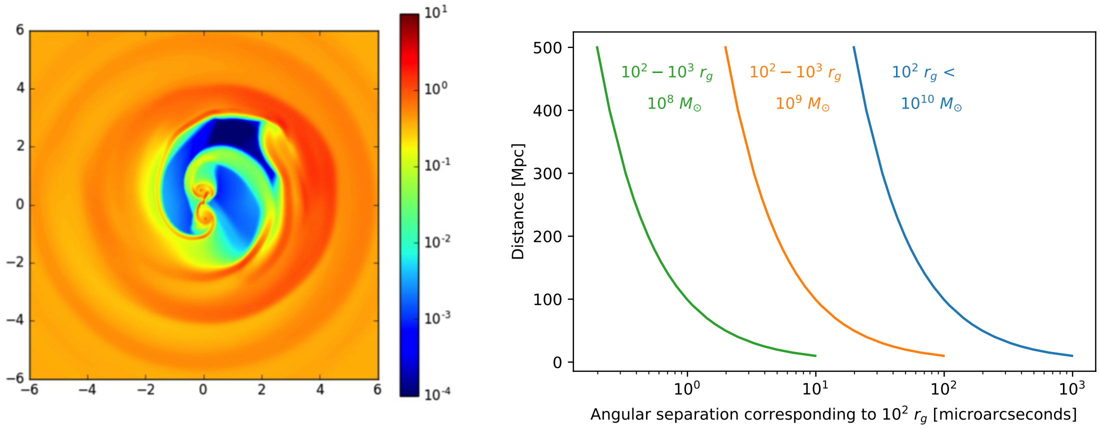

Figure 7: *Left: the surface density distribution in a sub-pc circumbinary gas disc (Tang et al., 2017), showing that tidal forces truncate mini discs in MBHBs, allowing to search for EM signatures of the binary . Right: apparent angular size of* $100 - 1000$ *gravitational radii separation – where GW radiation gradually becomes the dominant process in hardening the binary – for various SMBH masses, in the local Universe. Binaries are expected to be long-lived (spending ∼100,000 years) in this regime (Haiman et al., 2009) and can be directly probed by mm-VLBI for masses* $10^8 - 10^{10}\ M_\odot$*. The most massive sub-pc separation binaries as well as jet formation in LISA-detected SMBH mergers will be observable at cosmological distances by THESA (see also Fig. 4).*

at velocities in excess of the local sound speed that compress ambient magnetic fields and accelerate particles. These events range from relatively low-luminosity flares from stars, to the most powerful events in the universe, associated with gamma-ray bursts and relativistic jets from super-massive black holes in active galactic nuclei. Crucially, radio observations can act as a calorimeter for the kinetic feedback, probe the circumburst environment, and provide localisation/resolution unachievable at other wavelengths. Follow-up radio observations of high-energy astrophysical transients has a rich history of important discoveries, including the first galactic superluminal source (Mirabel & Rodríguez, 1994), the beamed-like nature of Gamma-Ray Bursts (GRBs) and their association with unusual supernovae (Kulkarni et al., 1998) and the association of highly relativistic jet-like flows with the tidal disruption and accretion of a star by a supermassive black hole (Zauderer et al., 2011). Most recently the LIGO-Virgo binary neutron star merger GW170817 was associated with a relativistic jet and associated radio afterglow (Mooley et al., 2018; Ghirlanda et al., 2019). Fig. 8 illustrates the luminosity – timescale space for all radio transients, including coherent sources (see below).

A prominent example of transient radio emission is accretion onto black holes, in which one of the most relativistic and energetic processes in the universe occurs on a range of spatial and time scales which extends over more than seven orders of magnitude. On the smallest scale is accretion on to stellar mass black holes in binary systems, in which we can track the full evolution of the radio jet and its connection to the varying accretion flow humanly-accessible timescales. Since these systems are typically at the same distance as Sgr A* (the closest know is about a factor of 8 closer), but they are 100,000 times less massive, we will never be able to image on scales comparable to their event horizons. However, we are able to test fundamental regions of the inner relativistic jet and, given the unique empirical coupling with the accretion flow we have established in such systems, probe the physics of time-variable jet formation in a way not really possible for AGN. Fig. 9 illustrates the spatial scales associated with a typical, nearby, black hole binary in our galaxy and shows how the innermost regions of the jet could be imaged by space-based mm VLBI. At these scales we would expect to see variations in the ∼ THz jet base occurring only *minutes* after X-ray variations, providing clues to the formation of jets in unprecedented detail. On larger physical scales, highly transient radio emission has been clearly associated with the transient accretion onto massive black holes resulting from tidal disruption

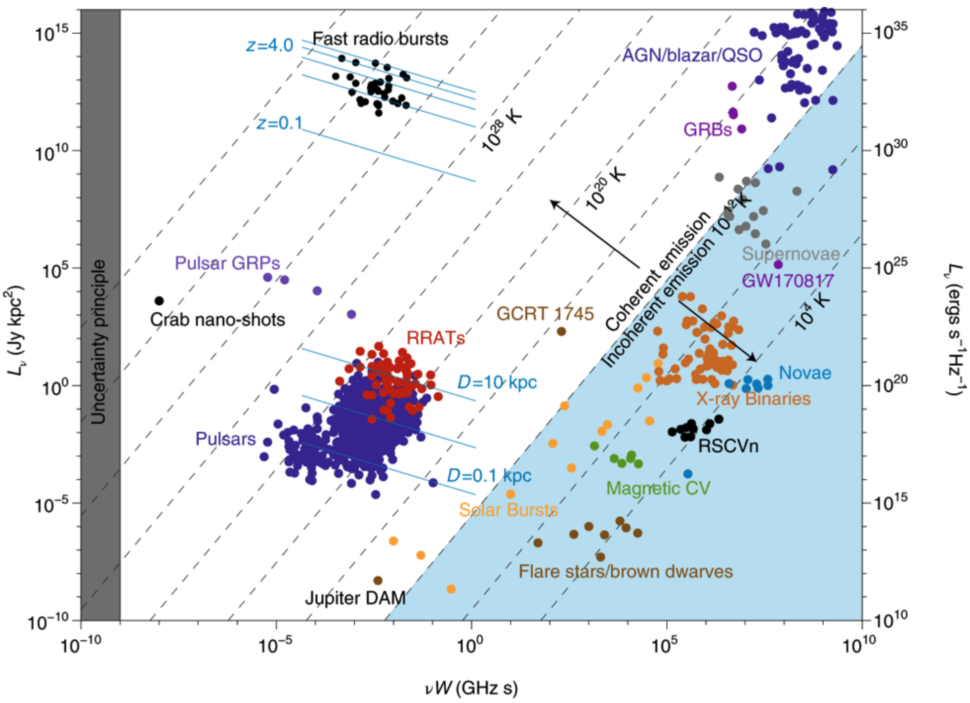

Figure 8: *Luminosity – timescale parameter space for radio transient and variables. The blue shaded region delimits a brightness temperature of* $10^{12}K$ *– source inside this region are likely to be incoherent synchrotron emitters, those in the white region coherent. From (Keane, 2018) and (Pietka et al., 2015).*

of a star. In non-thermal TDE this emission is likely to arise in a jet in most, if not all, cases, and VLBI offers a unique opportunity to see how accretion and jets evolve in pristine environments (rather than the very-long-timescale steady states associated with most AGN; see Yang et al., 2016; Mattila et al., 2018).

At the most explosive end of the stellar scale are gamma-ray bursts (GRB). The long variant is associated with the death of the most massive stars, while the short variant now appears quite clearly to be associated with the merger of two neutron stars. The end product in both cases can be stellar-mass black holes accreting at highly super-Eddington rates, and these are known to be powerful engines of relativistic jets. For a long time, long-GRBs have been known to produce relativistic jets that can be studied by ground-based VLBI (Taylor et al., 2004). Recently superluminal motion was detected in a jet associated with the late-peaking ($\sim$ 6 months) radio afterglow of the neutron star merger GW170818 (Mooley et al., 2018; Ghirlanda et al., 2019). In exceptional cases, we might be able to study the ultra-relativistic phase in "engine-driven" stellar jets by space VLBI, if these are nearby and beamed in our line of sight.

Coherent transients and variables are amongst the most important sources in Astrophysics right now, in particular Fast Radio Bursts (FRBs) and pulsars. Often the broad-band nature of the phenomena is not well established (e.g. for FRB). Prominent counter-examples include pulsars and neutron stars, which are observed across the whole electromagnetic spectrum, but even in those cases, the TeraHertz window is mostly unexplored. Potential sources for this frequency range are, for instance, magnetars, which have been detected up to 291 GHz (Torne et al., 2017, MNRAS, 465, 242) with a rather flat flux density spectra spanning from a 1 GHz up to, now, 300 GHz. Whether this makes them prominent sources at THz frequencies will be interesting to see. The current status of the transient sky at radio frequencies is summarized in Fig. 8 as compiled by Keane (2018, Nature Astronomy, 2, 865). It is likely that THz frequencies will mostly probe the incoherent part but the magnetars detection at 300 GHz suggests that we should be open for surprises.

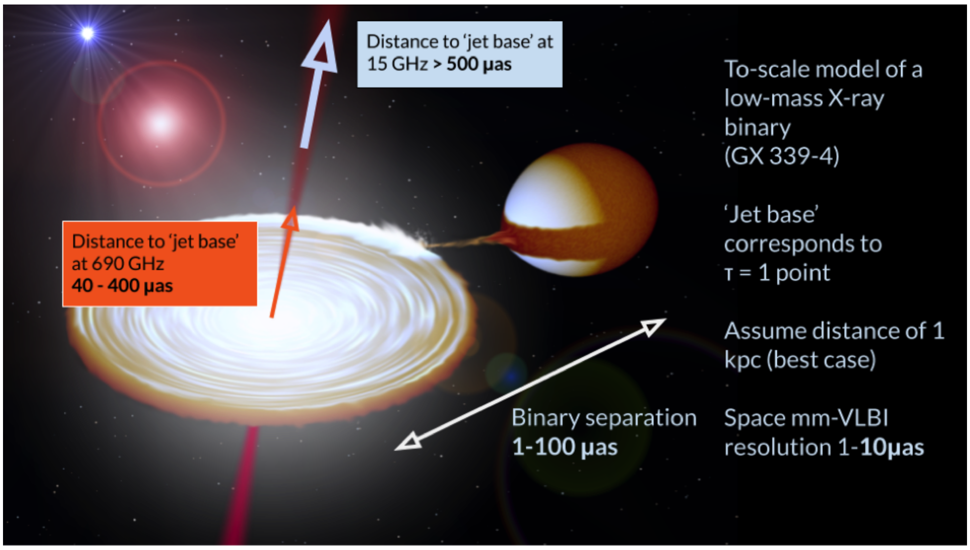

Figure 9: *Illustration of the angular scales associated with a low-mass black hole binary system at a distance of 1 kpc (equal to the smallest current distance know, typical distances are 8 kpc). For a space-VLBI resolution of 4 µas at 690 GHz both the jet base and binary separation are clearly resolvable. Coupled with X-ray (inner accretion flow) and infrared (innermost regions of the jet, close to launch zone) observations, we could achieve unprecedented understanding of how jets form and couple to accretion.*

3.5 Water maser science with space VLBI

Water vapour is found out to cosmic distances (e.g., Impellizzeri et al. 2008). It can emit thermally or through stimulated emission, masers. Because masers are compact and bright, they are excellent astrometry targets. Due to heavy atmospheric absorption the mm and sub-mm masers are much harder to observe from Earth than the well-studied 22 GHz transition: while bright water masers, e.g., 183 and 325 GHz, can be observed by dedicated ground-based telescopes (e.g., Humphreys et al. 2017), others have only been detected from above the atmosphere by the Kuiper Airborne Observatory and SOFIA. There are over a hundred predicted water maser transitions from GHz-THz frequencies (a few tens have been detected), mostly excited by collisional pumping under distinctive combinations of temperature, number density and other parameters (Gray et al. 2016). ALMA and RadioAstron observations found that mm and 22 GHz water and can have both extended and extremely compact, of a few solar radii, emission (Hirota et al. 2012; Sobolev et al. 2018). The mm water transitions are thus very suitable for space-space VLBI that would cover a range of baselines from hundreds of km to tens of Earth radii.

Typically, Galactic water masers arise from the disk-jet system of a young stellar object and in envelopes around evolved stars. Au-scale spatial distributions of a number of mm water masers transitions can put strong constrains on density, temperature and water distribution in gas surrounding the young stellar object that could be compared with current theories of star-formation (e.g., Klassen et al. 2016) and disk chemistry (Banzatti et al. 2015). Proper motions can trace the dynamics of the gas flow, and reveal the disk or jet origin of the emitting gas, as these have distinct kinematic signatures (Sanna et al. 2015). For evolved stars, various water transitions are observed at different stellar radii, see Fig. 10, tracing the change of physical conditions in the stellar envelope (Richards et al. 2014).

For nearby galaxies, bright mm-water maser emission will be an excellent tracer both of star formation and of the central engines of AGN. For example, in the interacting galaxy Arp 220, ALMA observations of mm-water masers find unresolved emission that is best modelled by a large number of pc-scale molecular clouds (König et al. 2017) - only space-space VLBI could provide images at these scales. On the other hand, towards Circinus and NGC 4945 the mm water maser emission is associated with the circumnuclear region (e.g. Hagiwara et al. 2013; Pesce et al. 2016). Water masers from cir-

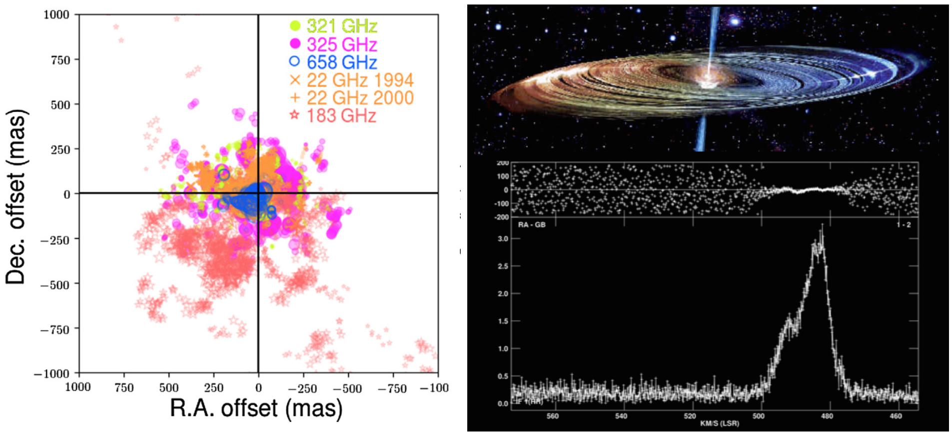

Figure 10: *Left: Various water maser transitions in the envelope of VY CMa (Richards et al. 2019). Right: Water masers in the circumnuclear disk of NGC4258 (artist impression: J. Kagoya, M. Inoue): RadioAstron satellite to Green Bank Telescope baseline of 1.9 earth diameters reveals the presence of compact, 790 AU, masing clouds (Baan et al. 2018).*

cumnuclear disks have been found to have extremely compact components on space-Earth baselines (see Fig 10). (Sub)mm water maser emission from the circumnuclear disks surrounding supermassive black holes holds the promise of one day yielding independent estimates of geometric distances, and perhaps even the Hubble constant.

One of the real benefits of space – space VLBI is bypassing the terrestrial atmosphere such that (sub)mm water masers which are currently difficult or even impossible to observe at most ground-based sites become accessible (see Gray et al. 2016 for model predictins of mm maser transitions). SOFIA observations have already detected THz water maser emission at 1.3 THz (Herpin et al. 2017). The more transitions of water that can be observed from the same volumes of gas, ideally quasi-simultaneously, the better constrained radiative transfer modelling to determine density and temperature become. Detecting the lines for the first time also provides a good test of the predictions of maser theory and models.

3.6 The quest for water in protoplanetary disks

Water is an important molecule in many astrophysical environments. In the case of protoplanetary disks, two key issues emerge from previous studies. On the one hand, water can freeze out on dust grains if conditions get sufficiently cold and shielded. In the heavily discussed core accretion scenarios of planet formation, the presence and location of such ice lines are essential ingredients for determining where and how efficiently the small dust grains can stick together and start the growth to larger agglomerates as a first step to planet formation (e.g., Birnstiel et al., 2016). Analysing the water vapour signals from the gas phase gives crucial constraints on the distribution of the water phases in a disk.

Secondly, water is intimately linked to the composition of exoplanets (e.g., Pontoppidan et al., 2019, and references therein). During the process of planet formation, the abundance and phase (solid or gas) of water traces the flow of volatile elements with implications for the bulk constitution of the planets, the composition of their early atmospheres, and the ultimate incorporation of such material into potential biospheres (e.g., Marty, 2012; Pearce et al., 2017). Furthermore, water as a simple molecule with high abundance is the dominant carrier of oxygen. Hence, its distribution in a disk can also steer the C/O ratio which can be a tell-tale connection between planet composition and the natal disk composition and location of the birth site (especially for giant planets).

After all, the complicated interplay between grain evolution, grain surface chemistry and freeze-out, photodesorption and photodissociation, and radial and vertical mixing processes will regulate the abundance of water in its different phases especially in the outer disk (e.g., Henning & Semenov, 2013). But integral models of these processes can only advance if we have observational access to all phases of water at all temperature regimes in a protoplanetary disk. Here, we will still have major deficits even in the 2030s. Though water vapour lines have been detected from the ground, such observations are mostly limited to high-excitation thermal lines ($E_{\rm up}/k \gtrsim 700$ K) that are not excited in the Earth atmosphere, or to certain maser lines. Water lines seen in the near-infrared just arise from the very inner hot gas disk. In the mid-infrared, one still probes very warm water gas of many hundred Kelvin. The MIRI instrument on JWST will make very sensitive observations of such warm water lines for many protoplanetary disks. But the spatial resolution of JWST in the mid-infrared towards longer wavelengths is limited, and typical disks of just 1–4 arcsec in size will just be moderately resolved. Furthermore, JWST does not offer sufficient spectral resolution to resolve the velocity structure of the detected lines. To get access to the bulk of the water vapour reservoir in a disk that contains the colder gas, one needs to include the far-infrared and sub-millimeter range. With the before-mentioned difficulties for sensitive observations of cooler water vapour from ground that severely hamper even ALMA with its good observing site, observations from space are pivotal to make progress in this field. To get spatially resolved information on such lines in a typical disk, one should aspire an angular resolution of 0.1". Thus, this field of research would demand short baselines on the order of several hundred meters to a kilometer.

3.7 Exoplanets

Thousands of exoplanets have been discovered in the last decades, showing the ubiquitous character of the planetary objects. The discovery of new worlds will continue in the next years even more efficiently with new and more sophisticated instruments, which will help to provide a complete knowledge of the formation and evolution processes of these objects. Observations are being carried out covering the complete electromagnetic spectrum from visible, IR to radio wavelengths. However, and despite the extraordinary contribution of the ALMA interferometer to protoplanetary disks, the observation of exoplanets at millimetre and sub-millimetre (sub-mm) wavelengths, covering to THz frequencies, is yet to be developed. Ground-based THz astronomy is heavily hampered by absorption features in the Earth's atmosphere, caused by the presence of molecules of oxygen and water. Although Earth's opacity can partially be alleviated by ground observatories built at high altitude, only space-based interferometers would definitely be free from Earth's atmospheric limitations, fully exploiting the science provided by sub-mm wavelengths.

Detection of exoplanets via astrometric monitoring of the reflex motion of the parent star can be successfully applied in the sub-mm range. The stellar photosphere is dominated by the permanent and more stable thermal, black body emission ($\propto \nu^2$), free from the on/off nature of stellar flares present in active stars at longer wavelengths. For the nearest stars, radio luminosities of normal, solar-like stars would correspond to tens of mJy at 100s GHz frequencies (Lestrade, 2008). An efficient monitoring of selected samples would solve the orbit inclination ambiguity inherent to the planetary masses determined by radial velocity (RV). Additionally, the population of planets on the outer side of the planetary systems, less sensible to RV techniques, can be characterized. Sub-milliarcsecond-precise astrometry would suffice to detect Jovian planets within 10 pc

Direct detection of exoplanets at sub-mm wavelengths would require μJy sensitivities. Most of the continuum exoplanet emission would correspond to thermal radiation, which at THz frequencies may reach 10-100 μJy from a Jupiter-like planet within 10 pc (Villadsen et al., 2014). This emission is 1-2 orders of magnitude larger than that measured by ground-based telescopes, showing that direct detection of exoplanets will necessarily require space missions. The importance of these measurements is fundamental as they will be able to bridge the gap between the far- mid-IR studies of exoplanets with the, so far elusive, emission at long radio wavelengths. Perspectives to detect exoplanets during their early stages of formation are particularly favoured at sub-mm wavelengths. Protoplanets still embedded in the circumstellar disks will radiate by reemission of the heated surrounding dust. Even modest millisecond resolution would discriminate between the emission of the disk and that of the circumplanetary material for a Jupiter at 1 AU within 100 pc. Measurements of non-Keplerian motions of the protoplanet would provide direct information of the density and viscosity of the disk (Wolf & D'Angelo, 2005; Pinte et al., 2018).

The sub-mm range of the spectrum (100—1000 GHz) is particularly rich in water lines which, with the adequate sensitivity and resolution, may not only characterize the atmosphere of newly discovered planets but unambiguously trace the signs of biological activity. Sub-mm spectroscopy of exoplanets highly irradiated by their host stars constitutes the best scenario to detect these absorption features. These studies are out of the capabilities of existing, or even planned, ground-based observatories as they are only doable for space-based missions with μJy sensitivities (Öberg et al., 2018). The characterization of the atmosphere of Earth-like planets by high-resolution sub-mm observations is of extraordinary relevance as the presence of water is anthropologically linked to the development of life.

3.8 SETI – search for technosignatures

Over the last few years, the field of SETI (Search for Extraterrestrial Intelligence) has undergone a major rejuvination, e.g., see Price et al. (2019); Siemion et al. (2013). The discovery by the Kepler mission that most stars host planetary systems, and that around 20% of these planets will be located within the traditional habitable zone, plus the continually growing evidence that the basic pre-biotic constituents and conditions we believe necessary for life are common and perhaps ubiquitous in the Galaxy, has brought new focus to one of the most important questions that human-kind can ask itself - Are We Alone?

A space-based mm-VLBI interferometer operating outside of the Earth's atmosphere would enable the first serious SETI searches to be conducted across the full mm and sub-mm domains of the e-m spectrum. The recent upsurge in interest in the search for "techno-signatures" (Wright, 2019) has a strong focus on covering as much of the e-m spectrum as is sensible. Searches at mm and sub-mm wavelengths are extremely well motivated. In particular, advanced civilisations will be well aware of the advantages of operating communication systems within this particular "high frequency" domain, especially for long distance communication systems that are likely to be associated with powerful interplanetary (and indeed interstellar) networks. Large bandwidth sub-mm systems offer significant carrying capacity, and yet continue to operate in a regime where scattering by ionised gas, and absorption by dust are usually negligible. This part of the high frequency radio spectrum is also relatively free of human-made radio frequency interference. Although this almost pristine environment is likely to change in the coming decades, a space-based, sub-mm long-baseline interferometer is largely immune to the effects that plague ground-based arrays of limited spatial extent.

The detection of "leakage" radiation or perhaps deliberately established beacons from another technical civilisation would be possible with a space-based sub-mm interferometer. In particular, such signals are likely to be entirely unresolved, even with resolutions approaching 10μ arcsecs. Narrow-band signals (like beacons) would probably exhibit very large Doppler accelerations and those transmitters associated with exoplanets located within 1 kpc of the Earth and with similar orbital periods ($\sim$ 1 yr), would show changes in proper motion to be detected that a space-based sub-mm interferometer would be sensitive to on timescales as short as a few days.

A space-based interferometer might also be able to detect non-coherent technosignatures. For example, the emission of waste heat from highly efficient mega-structures (such as Dyson spheres/swarms) could re-emerge as relatively cold black-body emission in the sub-mm. In particular, discontinous structures such as sharp edges or holes (as might be commonly associated with artificial mega-structures in general) would induce ringing in the uv-plane and a highly correlated response in the visibility data.

4 THEZA implementation options

The key capabilities of the THEZA concept require a space-borne VLBI system able to observe at frequencies above 200 GHz (1.5 mm wavelength) to at least 1 THz (300 μm wavelength) or even higher. Extension of the observing range toward lower frequencies, e.g., down to 86 GHz might be considered as an attractive broadening of the THEZA science scope. A design of the mission addressing the

THEZA science outlook will be subject of several major engineering trade-offs. One of them is between interferometers employing Space-Earth and Space-Space only baselines.

The former would have an enhanced baseline sensitivity due to a larger collecting area of Earth-based antennas, ultimately – a phased ALMA, just as demonstrated recently by the Event Horizon Telescope Collaboration et al. (2019a). However, such the system will be limited in frequency coverage by the atmosphere opacity thus likely operating efficiently at frequencies not higher than 350–400 GHz (practically – at 230 GHz, due to a foreseeable lack of Earth-based facilities able to operate at frequencies above 230 GHz simultaneously). That said, the ongoing design studies of several Earth-Space mm-VLBI mission concepts, such as Millimetron (Kardashev et al., 2014) should provide useful input into assessment of the feasibility of various models of THEZA implementation.

Interferometers with Space-only baselines offer a clear advantage in frequency coverage: they are not subjected to severe atmosphere limitations and can operate at frequencies above the practical for Earth-based VLBI cut-off of around 300 GHz. The further advantage is a principle possibility to cover the uv-plane efficiently by using free-flying spacecraft formations. However, these advantages come at a price: it is unrealistic to expect that on the timescale of the Voyage 2050 programme, large mm/sub-mm space-borne apertures comparable in size to Earth-based antennas can be deployed. Yet, by using receivers with system temperatures near the quantum limit and wide-band data acquisition systems, an acceptable baseline sensitivity can be achieved even with moderate in size space-borne antennas. This approach is pursued in several ongoing studies, including IRASSI (Infrared Astronomy Satellite Swarm Interferometry) for far-infra-red astronomy (Linz et al., 2019) and a concept of Event Horizon Imager (EHI), a step beyond the EHT requiring space-borne interferometric elements (Martin-Neira et al., 2017; Kudriashov et al., 2019; Roelofs et al., 2019).

4.1 Event Horizon Imager: a case study of space-only sub-mm aperture synthesis system

The EHI concept considers two or three satellites in circular Medium-Earth orbits (MEOs). By setting a small difference between the orbit radii, the satellites drift apart as they orbit Earth, increasing the baseline length as it constantly changes orientation. The resulting uv-plane coverage will have the shape of dense and isotropic spirals, which is especially suitable for high-fidelity and high-resolution imaging (Figure 11). In fact, the uv-coverage will be unlike that of any interferometer before and be almost like a filled aperture for integration times of weeks. Filling of the uv-plane is essentially done by Earth's gravity and happens in principle without any active orbital control during an observation.

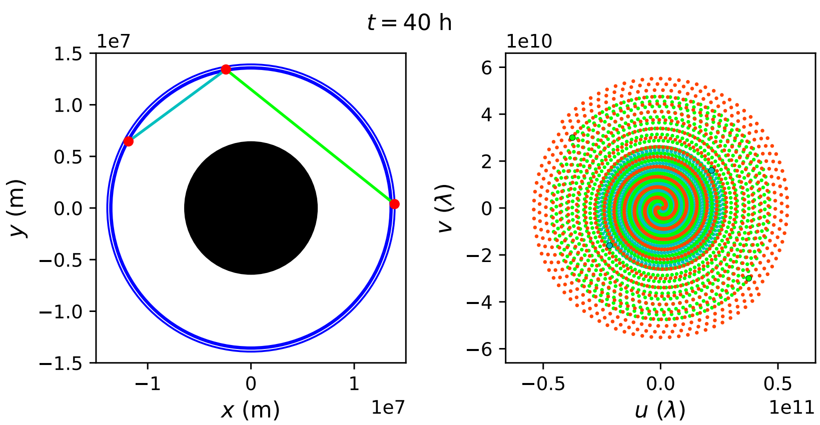

Figure 11: *Left: satellite orbits (blue) around Earth (black disk) with current satellite positions indicated in red and baselines indicated in green and blue. Right: corresponding uv-coverage. The maximum baseline length is set by the point where the Earth occults the intersatellite link between two satellites (orange baseline). Panels from Roelofs et al. (2019).*

Adjustments of the orbital height separation allow one to adjust the configuration to fill the uv-plane within a desired time scale from a few days to months, commensurate with the variability or integration time scale of the source to be observed. For small orbital height separations even a compact configuration with only a few hundreds of meters to hundreds of kilometers could be achieved and maintained for an extended period of time (i.e. to address ALMA science).

Otherwise the baselines will be significantly longer than any ground-baselines and shorter than some of the longest baselines in past Space VLBI experiments, but ideally matched to the desired resolution with maximum image fidelity.

Space-space operation allows one to go to much higher frequencies than with Earth-based arrays or Space-Earth experiments, which increases resolution further.

The concept aims to exchange the data between the satellites via a laser-based intersatellite link and correlate the data on-board using an orbit model provided by, e.g., measurements with GNSS satellites. Circular MEOs allow for a relatively stable orbit to start with. Further processing of the data is then done on the ground using a refined orbit model based on, e.g., intersatellite ranging measurements and astronomical calibrators. The local oscillator signals may be shared between the satellites as well in order to increase phase stability. An on-going technological study is investigating the feasibility of this concept.

The laser-based intersatellite link provides high data rates over very large space-space distances and hence allows wide bandwidths and accordingly high sensitivity even with modest-sized dishes. The laser links could also be used to directly transport the IF signal down to Earth. That would allow one to perform Space-Earth VLBI during special campaigns, e.g. to do snap-shot observations of highly variable or very faint objects together with sensitive ground-arrays (e.g. EHT/ALMA or ngVLA). This is obviously only possible at longer wavelengths, e.g. 1.5 mm, as demonstrated by the EHT, or 3 mm, as done regularly by the Global mm-VLBI Array.

The concept of multi-element space-borne interferometer has been also considered by Fish et al. (2019). Their concept differs from the EHI in the choice of orbits, number of space-borne antennas and the overall interferometeric configuration of the system. These concepts have a lot in common and offer convenient starting points for further mission design studies.

4.2 Simulations of the Event Horizon Imager

Roelofs et al. (2019) performed imaging simulations of the EHI concept. Using GRMHD models of Sgr A* at 690 GHz from Mościbrodzka et al. (2014) as input, complex visibilities were sampled at the EHI uv-spiral points, and thermal noise was added based on preliminary system parameters. Orbit radii of 13,892 and 13,913 km were assumed for the two satellites, which gives a nominal resolution of 3.6 μas at 690 GHz. Each satellite was assumed to carry an antenna with a diameter of 4.4 m, which would fit in an ESA Ariane 6 spacecraft. Of course, larger dishes would yield even better results. Figure 12 shows a GRMHD model image and its reconstructions for two EHI system variants. The middle panel shows the case of a perfectly phase stable EHI configuration with two satellites, limited by thermal noise only. Because of the dense and isotropic uv-coverage, the visibilities could be gridded in the uv-plane and an image could be reconstructed by taking the FFT of the complex visibilities, which were averaged over six iterations of the uv-spiral to build up SNR on long baselines. The reconstructed image shows many of the detailed features that are present in the input GRMHD model. Roelofs et al. (2019) show that visibility averaging also helps mitigating source variability (which occurs on a timescale of minutes for Sgr A*), allowing to reconstruct an average image of a variable source. The basic reason is that averaging in Fourier space is the same as averaging in image space and the average structure is dominated by GR, which is not changing.

In practice, the EHI may not be phase stable over multiple months, depending on the attainable post-processing orbit reconstruction accuracy and clock stability. If the system is phase stable within an integration time (which is limited to timescales of minutes because of visibility smearing on arcs swept out in the uv-plane), a system consisting of three satellites would allow for the use of closure phase, which is the sum of the complex visibility phases on a triangle of baselines. Closure phases are robust against station-based phase errors such as those resulting from an inaccurate orbit model. The right panel

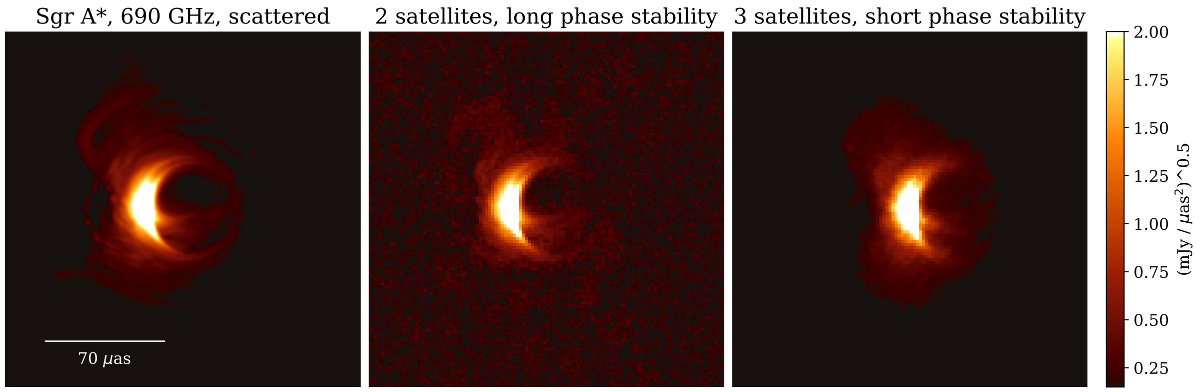

Figure 12: *Time-averaged GRMHD model of Sgr A* (left, Mościbrodzka et al., 2014), and image reconstructions with the EHI consisting of two satellites with long phase stability allowing for the use of complex visibilities for imaging (middle), and with the EHI consisting of three satellites with short phase stability relying only on the bispectrum for imaging (right). The total integration time is 6 months for both cases. EHI reconstructions from Roelofs et al. (2019).*

of Figure 12 shows a reconstructed image for such a system, made with the maximum entropy method implemented in the EHT-imaging library (Chael et al., 2016, 2018). The image quality is slightly less than for the idealized phase stable system, but the model features and size and shape of the black hole shadow are still recovered robustly.

5 Mission outlook and key technologies

The THEZA concept aims at addressing multi-disciplinary cutting edge topics of modern astrophysics. While many of these topics presented in Section 3 are complementary in their science contents and synergistic in terms of engineering implementation requirements, a single mission addressing them all would likely to be in the L-class category. However, optimisation of the mission science composition might lead to lowering some technical requirements (e.g., frequency band coverage, data acquisition rate, number of space-borne elements, etc,) and therefore shifting the mission toward the M-class envelope.

In general, all key engineering components required for THEZA implementation are well within the mainstream developments of relevant Earth-based and space-borne technologies. While we foresee a detailed analysis of the TRL figures for THEZA implementation at the stage of pre-design study of a specific mission, a preliminary evaluation conducted by the EHI study team has not identify insurmountable technological problems preventing a project with the launch well within the Voyage 2050 time frame.

VLBI is international and in fact global in its very nature. Obviously, this even more so for Space VLBI. Not surprisingly, all three implemented to date SVLBI experiments and missions described in subsection 2.1 have been widely international. We foresee that the THEZA concept implementation in a form of a specific mission would benefit greatly if involve more than one major space agency. Such the collaboration not only enhance the mission potential by choosing the best available technologies but also might help in fulfilling budgetary limitations of all parties involved. The THEZA Core Team is aware of several highly compatible initiatives prepared within the ongoing US Decadal Astronomy Survey. Close coordination and collaboration with respective projects in the US, as well as in other countries, will be highly beneficial for THEZA implementation.

This White Paper presents the concept developed within the framework of ongoing studies in Europe, the United States, Japan and Russia. In September 2018, a special workshop was held in Noordwijk, NL, to discuss scientific and technological issues of what is called here THEZA. The next workshop will be held at the National Radio Astronomy Observatory, USA, in January 2020. We expect that this next workshop will provide important contribution into advancing the THEZA concept.

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THEZA Core Proposing Team

Viviana Casasola,	INAF Institute of Radio Astronomy, Bologna, Italy
John Conway,	Onsala Space Observatory, Chalmers University, Sweden
Jordy Davelaar,	Radboud University, Nijmegen, The Netherlands
Heino Falcke,	Radboud University, Nijmegen, The Netherlands
Rob Fender,	Oxford University, UK
Christian M. Fromm,	Goethe-Universität Frankfurt, Germany
Michael Garrett,	Jodrell Bank Centre for Astrophysics, The University of Manchester, UK
Ciriaco Goddi,	Radboud University, Nijmegen, The Netherlands
José-Luis Gómez,	Instituto de Astrofísica de Andalucía – CSIC, Granada, Spain
Jeffrey van der Gucht,	Radboud University, Nijmegen, The Netherlands
Jose Carlos Guirado,	Observatorio Astronómico, University of Valencia, Spain
Zoltán Haiman,	Department of Astronomy, Columbia University, New York, USA
Frank Helmich,	SRON Netherlands Institute for Space Research and Kapteyn Institute, Univ. of Groningen, Groningen, The Netherlands
Elizabeth Humphreys,	ESO, Garching, Germany
Violette Impellizzeri,	Joint ALMA Observatory, Chile
Michael Kramer,	Max-Planck-Institut für Radioastronomie, Bonn, Germany
Michael Lindqvist,	Onsala Space Observatory, Chalmers University, Sweden
Hendrik Linz,	Max Planck Institute for Astronomy, Heidelberg, Germany
Andrei P. Lobanov,	Max-Planck-Institut für Radioastronomie, Bonn, Germany
Yosuke Mizuno,	Goethe-Universität Frankfurt, Germany
Zsolt Paragi (co-PI),	Joint Institute for VLBI ERIC, EU / The Netherlands
Luciano Rezzolla,	Goethe-Universität Frankfurt, Germany
Freek Roelofs,	Radboud University, Nijmegen, The Netherlands
Eduardo Ros,	Max-Planck-Institut für Radioastronomie, Bonn, Germany
Kazi L. J. Rygl,	INAF Institute of Radio Astronomy, Bologna, Italy
Tuomas Savolainen,	Aalto University Metsähovi Radio Observatory, Finland
Karl Schuster,	IRAM, Grenoble, France
Tiziana Venturi,	INAF Institute of Radio Astronomy, Bologna, Italy
Martina Wiedner,	Paris Observatory, Paris, France
J. Anton Zensus,	Max-Planck-Institut für Radioastronomie, Bonn, Germany