Institution: University College London (UCL)

Unit of Assessment: 9 - Physics

Title of case study: The use of black hole images to raise public awareness and interest in astrophysics

Period when the underpinning research was undertaken: 2012 - 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Dr. Ziri Younsi	Leverhulme Trust Early Career Fellow (UKRI Stephen Hawking Fellow)	2018 - 2020
Professor Kinwah Wu	Professor of Theoretical Astrophysics	2015 - 2020

Period when the claimed impact occurred: 2018 - 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact (indicative maximum 100 words)

UCL research into radiation transport in strong gravity has led to the development of physical frameworks and numerical techniques to study black hole systems. These were used to create the first-ever black hole image in 2019 by the Event Horizon Telescope (EHT). The release of the image has stimulated greater public awareness and interest in black holes research, which has been facilitated by UCL Mullard Space Science Laboratory (MSSL) staff in providing media contributions reaching millions of people. Furthermore, MSSL's staff have given over 50 talks to the public on their black holes research and to industry on research processes. These talks have inspired interest in astrophysics among the public and generated discussions about organisational change. Dr Younsi has also provided expert consultation to the Royal Mail and Mint for the production of commemorative stamps and coins stemming from an increase in public interest in this ground-breaking image and astrophysics.

2. Underpinning research (indicative maximum 500 words)

Until recently, the existence of black holes could only be demonstrated indirectly, for example by showing that the motion of stars at the centre of our own galaxy can only be understood if they are orbiting around an extremely high mass invisible object. To accelerate the understanding of black holes, an international consortium of over 60 institutes, including UCL, was established to link together existing telescopes using novel systems to create a fundamentally new instrument with angular resolving power that is the highest possible from the surface of the Earth. Through research and innovation, including unique contributions from UCL, the international EHT team were able to produce the first image of a black hole in 2019.

Black holes are so-called because their central regions are surrounded by a boundary, the "event horizon", from within which neither light nor matter can escape due to the extreme strength of the gravitational field produced by the central mass. Any material that is orbiting the black hole or falling into it is expected to be very hot and to be emitting electromagnetic radiation. In principle, light arriving at Earth from this hot material can reveal the "shadow" that the black hole casts by preventing light from sources behind the black hole travelling to Earth. However, the appearance of the light coming from the material orbiting the black hole will depend on how it is distributed; for example, the signature of an isolated orbiting clump of material will differ from that of a ring of hot material. The appearance of the system will also depend on the direction from which it is viewed.

The first direct image of a supermassive black hole (SMBH) made by the EHT team in 2019 was produced using data gathered by radio telescopes distributed across the Earth. Data from multiple sites was required to achieve the extremely fine angular resolution needed to see the

material orbiting the black hole at the centre of another galaxy, M87, about 53 million light years from Earth.

Studies performed by Professor Wu and Dr Younsi at MSSL played a key role in enabling the work that led to this first black hole image from the EHT collaboration. Between 2015-2020, MSSL staff members conducted research into radiative transfer through relativistic, polarised scattering media in strong-gravity environments with particular interest in physically realistic settings like turbulent accretion disks around black holes (**R1, R2, R3, R4**). Half of all the synthetic images used were made using the BHOSS code developed personally by Dr Younsi (**R5**). Numerical methods and techniques developed at MSSL underpinned all the other radiative transfer codes used throughout the EHT team.

To combine the data from multiple radio telescopes and produce candidate images, astronomers applied a variety of interferometric reconstruction techniques. Four different groups within the EHT consortium, used different approaches to generate a variety of non-identical images. It was also necessary, to generate a library of synthetic images based on a variety of possible distributions of material around the black hole, a variety of viewing directions and variety of possible black hole properties, and then to evaluate what each one would be expected to look like if viewed with the radio telescope network. The black hole image that was eventually released was defined by finding the best combination of image reconstruction assumptions and the best fit model of the system, hence also ensuring that a physically meaningful interpretation of the image was possible.

3. References to the research (indicative maximum of six references)

R1. Event Horizon Telescope Collaboration. Authors include **Younsi Z**, (2019) First M87 Event Horizon Telescope Results. I: The Shadow of the Supermassive Black Hole, *The Astrophysical Journal Letters*, 1, L1 doi:10/gfx8zm.
R2. **Younsi Z, Wu K**. (2015) Variations in emission from episodic plasmoid ejecta around black holes, , *Monthly Notices of the Royal Astronomical Society*, 454, 3 doi:10/f77hdv.
R3. Mizuno Y, **Younsi, Z**, Fromm CM, Porth O, De Laurentis M, Olivares H, Falcke H, Kramer M, Rezzolla L. (2018) The current ability to test theories of gravity with black hole shadows, *Nature Astronomy*, 2, 585 doi:10/gf4c55.
R4. Chatterjee K, **Younsi Z**, Liska M, Tchekhovskoy A, Markoff S, Yoon D, van Eijnatten, D, Hesp, C, Ingram, A, van der Klis, M. Observational signatures of disk and jet misalignment in images of accreting black holes *Monthly Notices of the Royal Astronomical Society,* 499, 362 (2020) doi:10.1093.
R5. **Younsi Z, Wu K**, Fuerst SV, (2012) General relativistic radiative transfer: formulation and emission from structured tori around black holes. *Astronomy and Astrophysics*, 545, A13 doi: 10.1051.

References (R1), (R3) and (R5) best indicate the quality of the underpinning research.

4. Details of the impact (indicative maximum 750 words)

Formulations and methods developed by MSSL's researchers were used alongside colleagues within the EHT to produce theoretical images and provide a scientific interpretation of the first image of a black hole (**R1**). The research underpinning this image was featured extensively in the media which stimulated public interest in black holes via news as well as popular culture programmes which have reached millions of people through print and visual media.
This resulted in the new depiction of black holes on special editions of UK coins and stamps. Dr Younsi has also given over 50 talks at schools and with industry on the work of MSSL, the EHT project, and research processes. These public engagement activities have raised the awareness of black hole research, its applications, and the importance of global collaboration. This has subsequently brought greater public attention to astrophysics and physics.

Enhancing public visibility of black hole research and astrophysics through media activity

Following the publication of the first image of a black hole by the EHT (**R1**) in April 2019, underpinned by UCL research described in Section 2, there was intense media coverage of this historic event **reaching diverse audiences and improving public awareness, knowledge and understanding of the field**. As UCL is the sole UK representative of the EHT project, Dr Younsi received media requests to provide expert scientific commentary on black holes and astrophysics to local and national newspapers, radio stations, entertainment magazines and television shows. This media engagement resulted in Dr Younsi establishing lasting relationships with several prominent science journalists at the BBC and *The Guardian*, leading to repeat interviews about black holes. For example, in April 2019 Dr Younsi appeared on both BBC Breakfast (2,000,000 viewers) and BBC News (468,000,000 global weekly reach) to provide expert commentary on the publication of the first images of the black hole (**S1**). Dr Younsi's underpinning research also garnered public interest from several other online news outlets, including *New Statesman* and Channel 4 News. Interviews on MSSL research and the EHT black hole project have also appeared in major national newspapers including *The Telegraph* (363,183 daily circulation), *The Times* (417,298 daily circulation), *Sun* (1,200,000 daily circulation), *Daily Mirror* (716,923 daily circulation), *Daily Express* (315,142 daily circulation), *iNews* (233,869 daily circulation), *Yorkshire Post* (18,534 daily circulation), *Scotsman* (16,349 daily circulation) (**S2**). As an example of the reach of Dr Younsi's black hole research [TEXT REDACTED FOR PUBLICATION].

Public interest in the science of **black hole research has also permeated into other cultural and entertainment-driven outlets reaching a wider breadth of audiences**. For instance, Dr Younsi's research has contributed to magazine articles for the BBC's *Sky at Night Magazine* (UK, circulation 23,453), *Computing* (UK circulation of 115,431), as well as lifestyle and cultural magazines such as the *Rolling Stone* (North America, circulation of 700,622) and *Vice* (North American based, circulation 900,000, worldwide) (**S3**). Dr Younsi also provided a quotation for the BBC's comedy quiz show *Have I Got News For You* (**S3**) and has given live expert commentary about his research to BBC radio stations, The Guardian's *Science Weekly* Podcast and Mark Dolan's *talkRADIO* show (**S4**).

Since 2018, Dr Younsi has provided technical consultation on producing scientific images and movies for national and international scientific documentaries, which has been informed by the research outlined in Section 2. For example, Dr Younsi provided expert advice to Windfall Films (for the BBC) on "*How to see a black hole: the Universe's greatest mystery*", which tells the story of how the first-ever image of a black hole was captured by the EHT. Other documentaries in which UCL expertise on black hole imaging has contributed to includes TBS (Japan) "*TBS special program new space-age",* and TV Noe "*Through the depths of the Universe*" (Czech Republic). The total audience numbers reached by these television and newspaper activities is in the tens of millions.

Online programme productions include videos of research conducted at MSSL and has been included in documentaries on YouTube channels, such as *"skydivephil"* (34,000 subscribers) and Veritasium (6,800,000 subscribers). These videos have stimulated tens of thousands of comments and online discussions. Scientific videos of Dr Younsi's and Professor Wu's research have been viewed more than 6,000,000 times, with Dr Younsi's YouTube channel receiving more than 2,000 views per day from over 10,000 subscribers. Most visitors to the channel are from North and South America, Europe and East Asia. **Online viewer and subscriber numbers have grown significantly since the April 2019 black hole ima**ge from the EHT (**S5**).

The black hole image as a contributor to the commemoration of a learned society and an eminent scientist

As a result of the black hole image being of such historical significance and the wider public interest it has garnered, it was chosen to represent the field of astrophysics on memorabilia commissioned by the Royal Astronomical Society and the Royal Mint. Dr Younsi provided expert consultation to the Royal Mail and the creation of a black hole stamp by an artist, as part of a new collection: "Visions of the Universe" to commemorating the 200th anniversary of the Royal Astronomical Society. The new first class stamp, released in 2020 is an artist's depiction of a

black hole, informed by Dr Younsi's and Professor Wu's calculations at MSSL. The calculations and consultation with Dr Younsi were necessary to ensure the image depicted on the new black hole stamp was physically accurate and consistent with the EHT black hole image (**R4**), rather than purely providing an artist's impression. The black hole image was **one of eight images used to represent Britain's contribution to astronomy and astrophysics**. The black hole stamps were used by the Department of Physics at UCL to send offers of admission to prospective students, further **engaging UCAS applicants with black hole Physics** and the exciting, world-leading research opportunities available at UCL.

Dr Younsi's research work at MSSL also attracted the attention of the Royal Mint and led to him working alongside them to produce a coin cover for a limited edition 50p coin depicting a black hole. The "**brilliant uncirculated coin cover**" was limited to 7000 editions. The coin was struck by the Royal Mint to commemorate the life of Stephen Hawking, with black hole calculations (**R1-R4**) performed by Dr Younsi featuring as cover art throughout (**S6**). The sales and interest in both the black hole stamp and coin, resulting from research performed at MSSL demonstrated a growing public demand and curiosity to engage in black holes and astrophysics in general. According to the Royal Mail [TEXT REDACTED FOR PUBLICATION].

Increased awareness of MSSL black hole research and contributions to science education through public talks

Dr Younsi and Professor Wu have delivered more than 25 talks to thousands of secondary school students between 2015 and 2019 which has enhanced science education by demonstrating real-life applications of scientific theoretical concepts and frameworks to astrophysics (**R3-5**). Audiences ranged in size from 50 to 300 and these talks have covered MSSL research (**R3**) and have helped to stimulate interest and increase awareness of black hole research and astrophysics in general. Example feedback demonstrates that these talks have engaged students and stimulated their interest in astrophysics "[…], I just wanted to say many thanks for visiting our school. It was truly an **amazing experience** and one I'm sure my classmates won't forget. I hope you enjoyed delivering it as much as we did hearing it. The lecture **inspired a few questions from my own dissertation** which I hope you will be able to answer" (**S8**).

Dr Younsi has given 21 public talks since April 2019 on UCL-led research (**R1-4**) and the link between his research at MSSL on theoretical general-relativistic radiative-transfer calculations in strong gravity environments and how this was used to help create the first image of a black hole by the EHT. These have included repeat visits to scientific and astronomical societies, as well as at accessible science communication events such as the *International Pint of Science Festival* (2019) which is targeted at the general public and brings scientific research and discoveries to unusual venues such as pubs and cafés. Other events have included the *Bloomsbury Festival* in London (2019), Open Evenings at MSSL (2019), UCL's '*It's All Academic Festival*' (2019) and European *Astrofest* (2020), where Dr Younsi delivered talks to audiences of predominantly adults and families. The European Astrofest talk by Dr Younsi had an audience of one thousand people and improved the understanding of black hole research as evidence by the following comment from an attendee, "Your presentation was captivating and explained so much background to the audience, and **allowed them to understand so much more of what they were looking at"** (**S8**).

Dr Younsi's research talks at Physics Open Days at UCL (2019-2020) with full capacity auditoria of more than two hundred people and streaming to reach an online audience, inspired students to further their scientific education, "A quick thank you for taking the time to chat with my son at the UCL open day. He was most impressed and now **considering the extra year MSci** " (**S8**).

Stimulating discussion on the application of black hole imaging research processes and global collaborations to business

The EHT project is an example of unprecedented global teamwork, bringing together technical, and theoretical expertise from 60 institutions, working over 20 countries and regions. In recognition of the black hole image (**R1**) as one of the "finest examples of an achievement

resulting from close collaboration by researchers from around the world", the EHT was awarded the Group Achievement Award by the Royal Astrological Society. The award citation acknowledges that the EHT project "represents an important milestone in human ingenuity and scientific endeavour and is **opening new doorways to study the physics of accretion around super-massive black holes in completely unprecedented ways**" (**S9**). The operational processes of such large-scale, multi-national collaborations are of interest to industry and MSSL's research involvement (**R2**) and (**R3**) has gained the attention of the UK finance industry. As a result, Dr Younsi was invited in October 2019 as a Keynote speaker to the UBS Bank's annual Technology Conference [TEXT REDACTED FOR PUBLICATION]. Furthermore, Dr Younsi was invited to give a cross-government seminar on black hole physics [TEXT REDACTED FOR PUBLICATION].

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Recording of appearance on BBC Breakfast live: http://bitly.ws/9sHq

S2. Testimony from the Guardian to corroborate reach and compilation of scans of newspaper articles featuring quotes from Z. Younsi: 2019-2020 online quotes with the BBC and the Guardian

S3. Articles from BBC Sky at Night Magazine, UK Laboratory News, Viernes Chilean magazine interview (pg.16) and video from Have I Got News For You: http://bitly.ws/9sHm – corroborates the presence of black hole research in entertainment and accessible media as a vehicle to engage wider audiences with astrophysics.

S4. Black holes: seeing the unseeable - The Guardian Science Weekly podcast. Available online at: https://bit.ly/37Xep6Z. Interview on talkRADIO Mark Dolan show: http://bitly.ws/9sHv.

S5. Most viewed YouTube video: https://bit.ly/2w9VZ5K. Pdf file containing YouTube viewing and subscription numbers.

S6. UCL press release of Royal Mail stamp collection and Royal Mint coin. Royal Mail photoshoot with Z. Younsi on Twitter: http://bitly.ws/9sGe; and Facebook: http://bitly.ws/9sGa.

S7. Letter of support from Royal Mail.

S8. Compilation of feedback from attendees of talks – corroborates that attendees have been stimulated, interested and engaged.

S9. 2021 Royal Astronomical Society Group Achievement Award: https://bit.ly/3tjIZmB

S10. Compilation of feedback from organisers of the UBS Bank Technology Conference and DWP economist.