Institution: King's College London		
Unit of Assessment: 9 Physics		
Title of case study: Dark matter research changes Science Gallery's policy and practice		
Period when the underpinning research was undertaken: 2008 - 2019		
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:**
Malcolm Fairbairn	Professor in Physics	From 17/09/2007
Period when the claimed impact occurred: 2017 - 2020		
Is this case study continued from a case study submitted in 2014? N		

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

King's research into Dark Matter led by Professor Malcolm Fairbairn has enabled Science Gallery London (SGL) to produce DARK MATTER, their most complex and successful exhibition and events season to date. The close collaboration between Fairbairn and SGL resulted in a programme which raised awareness and understanding of dark matter and theoretical physics. The exhibition ran from 6 June to 26 August 2019, attracting 37,000 visitors consisting of members of the public, local communities, students, researchers, and artists. The success of the exhibition has meant that it has been recreated by Science Gallery Dublin in 2020, with broader impact across the international Science Gallery Network.

The collaboration with Fairbairn has significantly altered SGL's policy and practice. For example, SGL has changed its recruitment policy for mediators to include more specialist knowledge for future exhibitions, in order to deepen its engagement process with visitors. SGL has also gained a new methodology that has allowed them to tackle more complex and abstract scientific topics in their exhibitions and events which they were previously unequipped to deal with.

Three artists who collaborated with Fairbairn to create new works specifically for the exhibition have reported that their ongoing artistic practice has been impacted positively and that they have expanded their audience base. Inspired by the exhibition, a filmmaker also created a short film for the Channel 4 Random Acts platform, addressing the experience of women of colour in science.

2. Underpinning research (indicative maximum 500 words)

Over the past decade, Malcolm Fairbairn has carried out research on dark matter phenomenology. In particular he has explored axions, a candidate for bosonic dark matter.

Axions can have a very large range of masses, up to the point where they can form Bose-Einstein condensates on large scales. These condensates can become self-gravitating, and therefore form axion stars within dark matter halos. Under certain circumstances, these axion stars can collapse to form black holes [R1].

Fairbairn went on to explore the possibility of trying to find these compact axion clumps through gravitational lensing, first using old results to predict the distribution and density of these clumps over different mass ranges [R2] and subsequently investigating in more detail the distribution of these clumps [R3]. This work suggests that it might be possible to use gravitational lensing to look for axion stars and clumps.

If the axion is sufficiently light and forms the dark matter in the vicinity of Earth, it is possible that its slow oscillation would lead to a time periodic variation in the neutron electric dipole moment. Fairbairn and his co-authors therefore analysed data from two experimental collaborations which studied the neutron dipole moment for some years to see if there was any evidence of oscillation. They were able to place new constraints on a large region of parameter space which ruled out many axion models [R4].

Finally, Fairbairn's work on anomaly free extensions of the standard model represents a survey of minimal dark matter models which can be added to the standard model while satisfying the anomaly free condition of the standard model. This led to quite a particular range of models as opposed to the very large number of fields which can be added ad hoc. Having identified the minimal dark matter models which can be added whilst respecting anomaly cancellation, Fairbairn and his co-authors went on to analyse their phenomenology, including working out which combination of masses and couplings led to good relic abundance without violating constraints either from the LHC or from direct detection experiments [R5].

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

[R1] Helfer, T., Marsh, D. J. E., Clough, K., **Fairbairn, M**., Lim, E.A., & Becerril, R. (2017). Black hole formation from axion stars. *Journal of Cosmology and Astroparticle Physics*, 2017(3), [55]. DOI: 10.1088/1475-7516/2017/03/055

[R2] **Fairbairn, M.**, Marsh, D. J. E., & Quevillon, J. (2017). Searching for the QCD axion with gravitational microlensing. *Physical Review Letters*, 119(2), [021101]. DOI: 10.1103/PhysRevLett.119.021101

[R3] **Fairbairn, M.**, Marsh, D. J. E., Quevillon, J., & Rozier, S. (2018). Structure formation and microlensing with axion miniclusters. *Physical Review D*, 97(8), [083502]. DOI: 10.1103/PhysRevD.97.083502

[R4] Abel, C., […], **Fairbairn, M.**, et al. (2017). Search for axionlike dark matter through nuclear spin precession in electric and magnetic fields. *Physical Review X*, 7(4), [041034]. DOI: 10.1103/PhysRevX.7.041034

[R5] Ellis, J., **Fairbairn, M.**, & Tunney, P., (2018). Anomaly-free models for flavour anomalies. *European Physical Journal C*, 78(3), [238]. DOI: 10.1140/epjc/s10052-018-5725-0

DARKHORIZONS: Dark Matter and the Early Universe in the LHC Era, GBP1.5M grant, 2015-2021

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

Science Gallery is the world's only university network dedicated to public engagement with science and art. The Science Gallery Network comprises of eight members across four continents (Dublin, London, Melbourne, Bengaluru, Venice, Detroit, Rotterdam and Atlanta) with a mission to bring science, art, technology and design together to deliver world-class educational and cultural experiences for young people. Science Gallery programmes feature emerging research presented in connective, participative, and inspiring ways. [S1]

In 2016, Science Gallery London (SGL), based opposite the Shard in Central London, decided to produce a season (incorporating exhibitions, talks, performances, screenings, live experiments and open discussions) on dark matter. The season explored not only dark matter itself but also questions of how science aims to investigate and explain reality. The idea of dark matter can be challenging to explain to a non-specialist audience, but the overall concept of dark matter is an excellent way to help people understand how science works and how we can investigate aspects of the Universe that are seemingly impossible to understand. One of the key intentions was to help members of the public understand more about science and the scientific method, in order to build trust and open a dialogue between scientists and other members of society.

> *"Scientists' ongoing quest to understand dark matter is a lens through which to think about the human desire to reveal the unknown. The DARK MATTER season brings together scientific research, artistic expression, storytelling and philosophy to communicate and explore the limits of human knowledge and our fascination with the unknown."* – John O'Shea, SGL Associate Director [S2]

SGL approached Malcolm Fairbairn in 2016 and invited him to be involved as a season advisor. This is normally a light touch role, but in this case Fairbairn's involvement was unusually in-depth. He collaborated with the season curator on the narrative structure of the exhibition, selected art pieces, collaborated with commissioned artists, briefed the SGL team and oversaw exhibition text

and labels. This collaboration was deeply informed by the body of work outlined in sections 2 and 3 above. In particular, [R4] demonstrates the logic surrounding the methodology of Fairbairn's research, which fed into the conversations with artists and curators which took place during the formulation of this exhibition.

> *"He [Malcolm Fairbairn] was absolutely fundamental in shaping the show because his discussions weren't just about 'this is how Dark Matter is'; they did start going on a more exploratory and philosophical terrain and that helped me to find interesting ideas to explore the subject matter."* [Season Curator Sandra Ross in S3 p.7]

Fairbairn's involvement enabled SGL to tackle dark matter on a deeper level than they have for previous subjects and has directly resulted in them making changes to policy and practice. The resulting exhibition was SGL's most complex, successful and profitable exhibition and events season to date. The programme ran from 6 June to 26 August 2019, attracting 37,344 visitors. For 81% of visitors this was their first visit to SGL. These visitor numbers, combined with increased spend in the Science Gallery shop (GBP0.30 per head higher than the previous SGL exhibition), resulted in a GBP66,000 uplift in profit. [S3 p.4]

Following the success of the Dark Matter season at SGL, the exhibition was recreated by Science Gallery Dublin in March 2020 under a new title INVISIBLE, running as a free exhibition and events programme combining art, physics, and philosophy, and drawing on the latest research from King's College London [S4].

When COVID-19 and national lockdowns made physical visits unviable, the exhibition and events programme were transferred online. The Science Gallery Dublin team used the exhibition and its themes to trial online programmes (through Zoom/YouTube/Twitch/Instagram), from webinars and panel discussions, to a virtual 360° tour of the exhibition on their website along with calls with their mediators. By the end of 2020, INVISIBLE had become *"the longest running Science Gallery exhibition ever"* with almost 10,000 views and interactions (physical and online). [S5]

> *"There have been a number of learnings in taking DARK MATTER from Science Gallery London and adapting it to INVISIBLE. This was only the second time that an exhibition had toured from one Science Gallery to another and what has become evident is the importance of strong research underpinning the original exhibition in order to be able to build upon and adapt the theme. […] It is something that we have now discussed across the [Science Gallery] network as a potential new model for sharing exhibition themes. […] The ability to rely on the expertise and research in network universities is invaluable in communicating science to our audience."* - Aisling Murray, Head of Programming, Science Gallery Dublin [S5]

Impact on policy and practice of SGL

SGL had not previously collaborated in such a sustained way with just one season advisor: Fairbairn's involvement has given them experience of a new way of working, which will allow them to explore subjects more deeply and more effectively in future. Associate Director John O'Shea described this new style of collaboration as "360 involvement" where the season advisor interacts with everyone from front of house to curatorial and the artists themselves, giving the organisation multiple opportunities to understand and communicate their research from multiple perspectives [S3 p.11].

> *"It presented an opportunity that we hadn't previously anticipated. We had previously seen that it was valuable to get advice at specific points of a project, but we hadn't previously had a senior academic such as Malcolm working in parallel to a whole project from the first conversation through to being available at things like the press preview and being engaged as part of the project team all the way through."* [John O'Shea, SGL Associate Director in S3 p.11]

Through working with Fairbairn, SGL has established a new methodology for tackling more complex scientific topics by working closely with an expert academic.

> *"Through Malcolm's advice and work […] we think that we hit a sweet spot of the type of very ambitious art-science commissioning we have been aiming to do. This has given us a lot of confidence to approach subject matter that might be perceived as either complex,*

> *esoteric or specific, rather than areas of science which are more obviously tangible and immediately applicable to people's lives. We think now that in future planning we would be proactively seeking big profound questions to explore to contrast with scientific areas with more immediate applications. We also learnt a great deal more about how best to foster collaborations between artists and scientists."* - John O'Shea, SGL Associate Director [S6]

SGL has now commissioned a season on Artificial Intelligence (in Healthcare), which, in addition to the applications of AI technology in healthcare, will also address broader philosophical questions about the implications of AI for the human condition. This is the first post-Dark Matter season to employ the new knowledge and working methods that have emerged from the collaboration with Fairbairn. [S6, S7]

Previously, SGL used trained science communicators to act as mediators on the floor of the gallery. However, with guidance from Fairbairn, SGL's management decided to recruit PhD physics students for this role in the Dark Matter exhibition. They found that this higher level of subject-specific expertise in the mediators was of significant benefit to their public engagement. As a result, SGL has changed their recruitment policy, and now recruit students directly from relevant faculties to act as mediators. Furthermore, they have created an extra-curricular module in science communication for KCL students, which launched in October 2020. [S6]

Impact on visitors to the SGL exhibition

37,344 people, consisting of members of the public, local communities, students, researchers, and artists, visited the exhibition. Curiosity about the subject matter drew people in, with evaluation indicating that 49% were most motivated to attend by the subject of Dark Matter (as opposed to a general interest in art and science). [S3 p.4]

> *"Just at the entrance and then again at the end there is a big question about how you deal with the voids in your life. I thought differently on the way in and out – philosophical in, more concrete out. It became a broader question: how do I deal with the invisible?"* [Female visitor, aged 26 to 34 in S3 p.6]

Evaluation surveys showed that 58% had gained awareness, knowledge or understanding of dark matter (n=397), and 52% stated that their experience of the exhibition would inspire or support them to make a change in their life, work or interests (n=213). [S3 p.8-9]

> *"I didn't study science at school because I felt like there's so much you have to learn about what other people have discovered that I felt there's not enough room to discover for yourself. Now I realise there's so much possibility and so many unknowns"* [Technology foresight strategist, female, aged 26 to 34 in S3 p.9]

> *"The experimental aspect really hit me; it was interesting to see how different researchers have found about it [dark matter] in different ways – different approaches mean different insights. It's interesting to think about how you might even begin to discover something you know nothing about."* [Medical Student, female, aged 19 to 25 in S3 p.10]

Impact on filmmaker

As a result of working with Fairbairn, who provided physics knowledge and details of several young female physicists and their work, SGL Young Leader and Mediator Laura Joy Pieters collaborated with film maker Adeyemi Michael to produce a film which uses Dark Matter as a metaphor for the marginalisation of black women in society [S3 pp.10-11]. This was screened on Channel 4's Random Acts platform in October 2019 and is available on YouTube, where it attracted 750 views in its first month, and over 2,000 views by October 2020. [S8]

This project gave Laura an opportunity to achieve her ambition to produce a film, and to address her own experience as a woman of colour in science.

> *"On the mediator team there are a few of us – women of colour who work in science. I chatted to them about what the film could be and how rare it is to see women of colour in science especially physics"* [Laura Pieters, SGL young leader and mediator in S3 p.11]

Impact on artists

As part of the exhibition, three new artist commissions were produced in collaboration with Fairbairn. Artists Yu-Chen Wang, Aura Satz and Agnieszka Kurant each worked with Fairbairn, who expanded their understanding of dark matter research and connected them to other experts in the field, including Chris McCabe, John Ellis, Mairi Sakellariadou, Diego Blas and David Marsh. The artists all reported that as a result they feel more able to work with scientists, and that the exhibition had expanded their audience base [S3 p.6-7].

Aura Satz, an audio-visual artist, found her work with Fairbairn, which incorporated his research, changed her understanding of music, and has informed her recent work on waves and transmission, commissioned for the Science Museum website. Her work incorporated Fairbairn's research on axions: in particular, the sounds created in the art piece are a sonification of a simulation of axion physics that was part of the research carried out in his papers [R1-R4].

> *"The process of producing the project with Malcolm has profoundly informed how I now approach both the creation and the analysis of structures evoked by music, and my appreciation, interaction and understanding of sound has become much deeper and more fundamental."* – Aura Satz, Artist [S9]

The exhibition allowed Satz to reach a younger and more diverse audience than in art galleries, and also led to her being featured in the New Scientist and on BBC Radio, which extended her usual audience reach. The piece she created is now touring as part of the exhibition with Science Gallery Dublin. [S9]

Agnieszka Kurant, working with Fairbairn, used liquid crystal to visualise ideas about the different phases of matter, using this to explore human society. This led to a successful art piece which has since been exhibited in Istanbul, with further shows in San Francisco and at Science Gallery Dublin. [S3 p.6]

Yu-Chen Wang stated that she had gained insight into her own practice through the similarity between Fairbairn's way of searching for answers and her own. She took part in a panel discussion at SGL and plans to do more work in her home country, Taiwan, around scientific discussions. She reported that her work has been seen by a wider range of people than is usual in art exhibitions. [S3 p.7]

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

[S1] Science Gallery International:

(a) Home page

(b) About the Network

[S2] DARK MATTER - 'Imagining the unseen and questioning the invisible'

[S3] Evaluation report produced by Flow Associates, November 2019

[S4] Replicating the Dark Matter season at Science Gallery Dublin:

(a) 2020 EXHIBITIONS (INVISIBLE) – Science Gallery Dublin

(b) INVISIBLE exhibition (online) - About; Exhibits

[S5] Testimonial from Aisling Murray (Head of Programming, Science Gallery Dublin)

[S6] Testimonial from John O'Shea (Associate Director, Science Gallery London)

[S7] Open call for AI & Ethics season at Science Gallery London

[S8] Short Film (Random Acts) - Dark Matter by Adeyemi Michael

[S9] Testimonial from Aura Satz (Artist)