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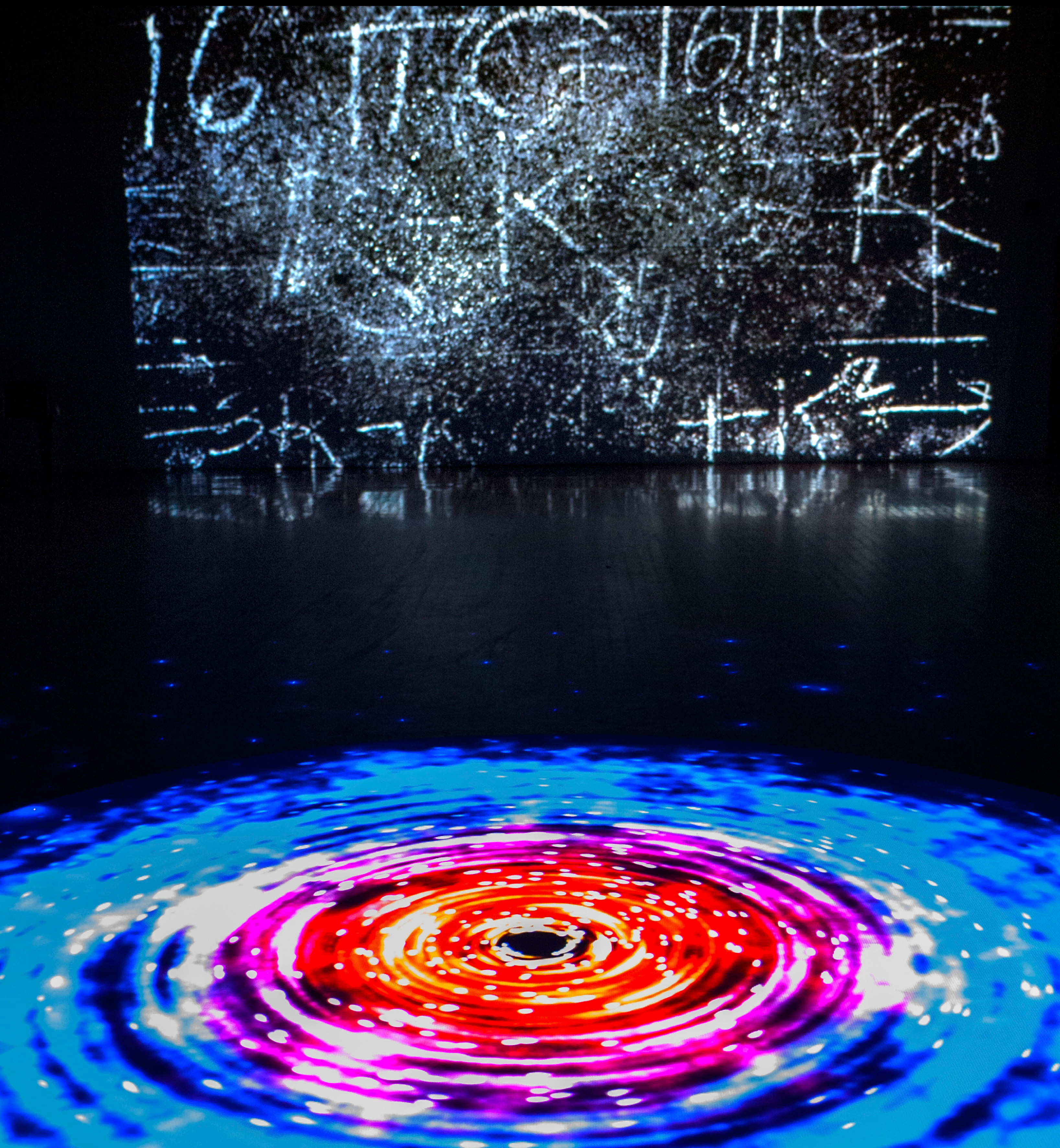

ARTISTS' NOTE

Black (W)hole

An Artscience and Education Collaboration

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ABSTRACT

Black (W)hole is an immersive art installation created collaboratively by artists and scientists utilizing data visualization of an extreme mass ratio inspiral (EMRI) and the sonification of its emitted gravitational waves in an experiential work of "artscience" and science education. The sensory-rich environment of the installation engages mind and body, expanding and enriching the participant's capacity to imagine and wonder about the beauty and meaning of this highly abstract astronomical object, the black hole. The work investigates both historical and current gravitational wave astronomy, illustrating our 21st-century understanding of the cosmos.

Albert Einstein is known for having said "Imagination is more important than knowledge" [1]. *Black (W)hole* asks participants to imagine themselves in space, standing on the edge of a black hole amongst the stars, as Einstein's historic equations, which led to the discovery of black holes, morph from chalk dust to star fields on the wall beyond (Fig. 1).

The two main visual elements of the installation are the black hole animation and an experimental film. Entering the installation, the viewer is surrounded by a laser field of stars and stands on the edge of an accretion disk, which swirls into a supermassive black hole in Newtonian trajectories. Suddenly, the animation zooms to the edge of the event horizon, as a much smaller black hole is captured and begins to orbit around the supermassive one. The sonic realization of the gravitational waves predicted to be produced in such an encounter surround the viewer [2].

A film of morphing images plays in a continuous loop on the back wall of the space, furthering the immersive experience [3]. The images are inspired by the solutions to Einstein's general relativity equations and represent work scrawled on a metaphorical blackboard. The solutions to Einstein's equations led to the prediction of the existence of black holes.

The electroacoustic sound environment of the installation is linked to the black hole animation. The visual and the aural combine to create a representation that is in essence a hyper-realization of human perception. We humans cannot "hear" gravitational waves, nor can we "see" black holes; we can only observe their effects, aided by scientific instruments. *Black (W)hole* allows the participant to see beyond human perceptual limitations.

Black (W)hole is one aspect of the larger "artscience" [4] event entitled *Celebrating Einstein*, a science outreach project designed to communicate the beauty and significance of Einstein's theory of general relativity to the public. Though artistic and scientific discovery propelled the process, *Black (W)hole*'s unique contribution to the project was the translation of accurate scientific data, giving the viewer a palpable experience of the visual and aural realities of black holes.

During *Celebrating Einstein*, *Black (W)hole* successfully engaged the imagination of 1,560 visitors in one week's time. Beyond the structured educational experiences for 120 K–12 students, community members were captivated by the piece. One prominent physicist and guest lecturer, Jim Gates, said: "I've studied black holes all my life, but now I'm actually standing on the edge of one!"

This collaboration began in August 2011, when Nicolás Yunes became a member of the Montana State University (MSU) physics faculty. This series of outreach events [5] was the first large-scale collaborative artscience project of its kind at MSU. The events, which also included *A Shout*

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Fig. 1. Enter *Black (W)hole*: A laser field of stars leads to the edge of a large-scale animation of a black hole projected onto the floor. The viewer stands at the edge of the accretion disk of a supermassive black hole as suddenly a much smaller black hole is captured and begins to spin around the larger one. The sounds that gravitational waves produce in such an encounter, presented in an audible frequency band, surround the viewer. (© The Einstein Collective [16]. Photo: Kelly Gorham.)

Across Time—a film/dance/orchestral work—as well as educational activities for both students and the general public, involved faculty from Princeton University, MIT, UCLA and MSU. Notable lecturers included Jim Gates, David Kaiser, Lisa Randall and Lawrence Krauss. As part of *Celebrating Einstein*, the team conducted assessments to determine the effectiveness of the event, testing both participants' prior knowledge and the new understandings they developed after attending one or more events. Learning gains were measured for various populations, with the final report concluding that there were significant learning gains, especially for participants who self identified as having a low level of expertise in physics [6].

The *Black (W)hole* installation team consisted of a group of artists and scientists with specialties in visual art, animation, architecture, experimental film, music composition and physics. Artist and painter Sara Mast served as team leader, with Nicolas Yunes and Joey Shapiro Key as science advisors. Over a period of 20 months, team members collaborated on the conception of *Black (W)hole*, which evolved from the use of 3D sculptural form to its ultimate form of two projections—a floor animation and an experimental film on the wall—all contained in a darkened, immersive electroacoustic sound environment. Guiding questions for the project were: How can we generate somatic and aesthetic participation in science outreach in a way that facts, mathematical formulas and on-screen visual simulations cannot? How can we integrate visual and aural scientific data in a large-scale installation to create a whole-brain experience that expresses the highly abstract, yet scientifically accurate, truths about black holes?

Beyond the trend to focus on STEM education, this project extends into another essential realm: science + technology + engineering + art + math = STEAM [7]. John Maeda, former Rhode Island School of Design president, has spearheaded the movement from STEM to STEAM. He states: "Research universities need excellent means to communicate and express their results to regular people" [8]. By adding art into the black hole equation and operating at the borders of our shared engagements of studio/lab research, experimentation, discovery and "living in the question," our aim is to enter the new singular vision of artscience, holistic understanding and shared meaning.

Science outreach must strike a delicate balance between public accessibility and scientific accuracy. On the one hand, science outreach must truly reach out, engaging and entertaining the general public. The most effective outreach impacts minority groups that are sometimes excluded by society from understanding the latest advances of science and experiencing current contemporary art. On the other hand, science outreach must also be deeply rooted in accurate scientific concepts. In particular, the all-too-common propagation of scientific misconceptions must be prevented and corrected.

The prejudice that "entertainment" and "education" are dissonant can be overcome through collaboration between educators, artists and scientists. A deep commitment that starts from the inception of a project and continues throughout is required from all parties to achieve success. Scientists must first describe in detail the underlying scientific concepts that one is trying to communicate. This "first contact" must be carefully delivered, so that all participants of the collaboration have a conceptual understanding of the science. Educators and artists must then work together to find creative new ways to effectively transmit the requisite scientific concepts. The scientists play a crucial role in ensuring that the creative process does not dilute or misrepresent the scientific concepts to be communicated.

This balance must be sustained throughout the collaboration between the scientists' desire to remain rigorous in scientific precepts, the educators' desire to enlighten and communicate "the facts," and the artists' desire to be rigorous in conceptual, visual, aural and aesthetic communication standards. A mutual understanding must be developed: Without a creative approach the science cannot be effectively communicated, yet without a certain level of rigor, the science simply does not make sense. Regular meetings, frequent communication and frank conversations are essential.

Celebrating Einstein and *Black (W)hole* demonstrated the importance of this philosophy in multidisciplinary collaborations. Owing to the magnitude of the full event, which encompassed an art installation, a musical performance, an original film and much more, the collective was divided into teams, each with one or two leaders. First contact was

Fig. 2. The *Black (W)hole* team worked through iterations of materials to create an immersive and impactful environment. (© The Einstein Collective [16]. Photo: Joey Shapiro Key.)

carried out with the entire team, and weekly meetings were conducted henceforth. During the meetings, team leaders reported on their progress and received input from the rest of the collaboration. The scientists continued to discuss the appropriate scientific concepts with each team separately, as the teams developed their individual pieces. Such a continuous interdisciplinary process was crucial to correct miscommunications and misconceptions that could have derailed the project.

INSTALLATION AND DESIGN PROCESS

In designing the *Black (W)hole* installation, the team's intention was to enhance student and general public understanding of black holes through an immersive, aesthetic experience. Throughout the entire process—including visualizations, material samples, test animations and films, sonic cues, trial installations and even the final installation—team members worked together, critiquing iterations both aesthetically and scientifically.

Early on, the team looked at a range of artists' works, including William Kentridge's film *Automatic Writing*, Raphael Lozano-Hemmer's *Solar Equation* and Olafur Eliasson's *Weather Project*. Though the original idea was to create sculptural objects, ultimately physical objects were abandoned for light, sound and film. Two projectors were used to display the visual components of the work, while a laser array mounted on the ceiling generated a star field around the black hole, allowing "starlight" to fall directly upon one's skin. Electroacoustic sound engulfed the participants in an audiovisual experience. All of this transpired within a darkened space, which was produced to create an impression of dislocation and disorientation.

The pedagogical model for this project is based in experiential education. As George Santayana once said, "The great difficulty of education is to get experience out of ideas" [9]. Astronomical ideas can be difficult to grasp due to problems with understanding the scale of objects and distances. In this artscience work, our aim is to engage the viewer in the idea of black holes on a multisensory level, bringing the vastness of this astronomical object down to human scale. Learning from experience, "learning by doing" [10], or "experience-based learning" [11] describe our educational model. Science education pioneer Robert Karplus [12] developed an experiential education process called the "learning cycle," and that model begins with the learner(s) encountering a discrepant or surprising event. Walking into the darkened space of the *Black (W)hole* installation, surrounded by sound and stars, the participant is somatically engaged in the concept of a black hole, so that he/she can generalize and apply this experiential understanding to new situations or combine that understanding with other concepts.

Mast initiated this installation with an invitation to Christopher O'Leary of UCLA to create an animation of a black hole. O'Leary worked on the installation long distance and

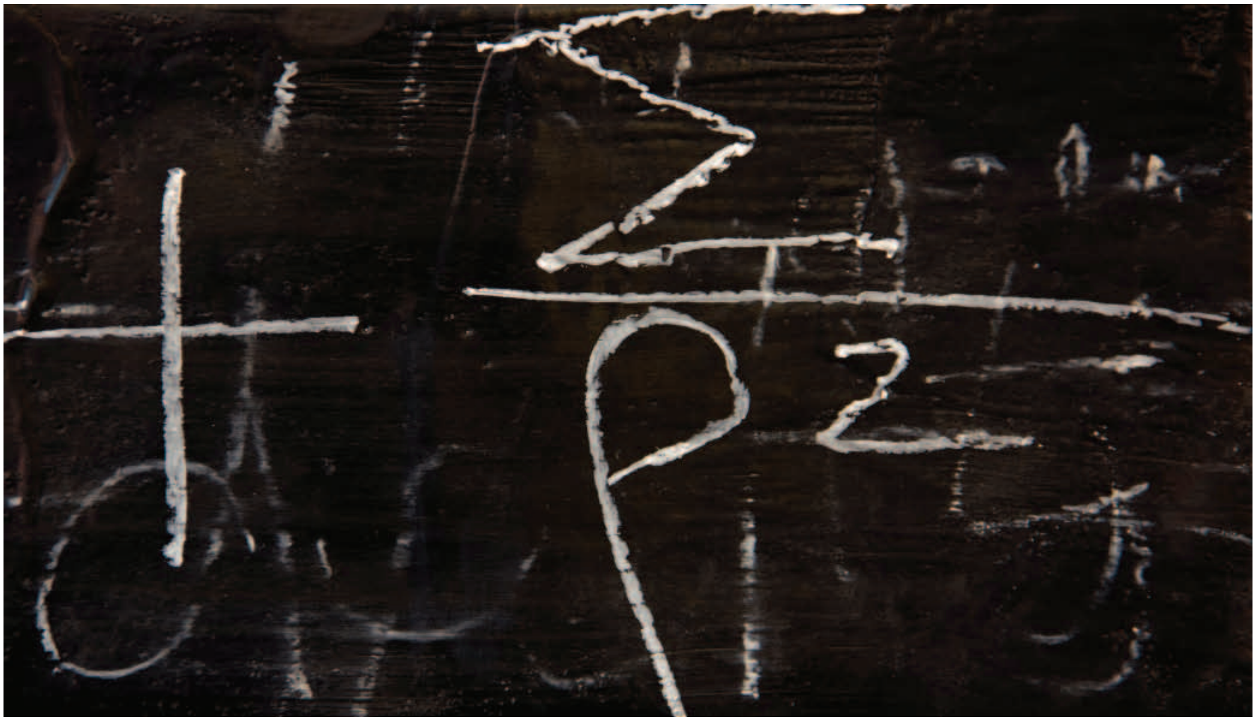

Fig. 3. A still image from the *Transmutations* film component of *Black (W)hole,* morphing the solutions to Einstein's general relativity equations in a continuous loop from scrawls on his blackboard to starfields of chalk dust (based on encaustic and mixed-media paintings by Sara Mast). (© The Einstein Collective [16]. Photo: Cindy Stillwell.)

in January 2013 met with Yunes. Together, they determined how the math would be used to create the generative animation. The team gave careful consideration to the aesthetic elements of the animation, including color, speed, transition and dramatic effect (Color Plate B).

Jessica Jellison, MSU School of Architecture, worked closely with Mast and the team on the vision and experience for the ballroom space at the Emerson Center for the Arts and Culture. Jellison generated several architectural floor plans and sections of the Emerson ballroom installation. Through a series of iterations, Mast and Jellison arrived at the final concept to project O'Leary's black hole animation on a large floor screen (Fig. 2). The decision to remove all physical objects and use light as a medium allowed viewers to imagine the vast and infinite without comparing their relative size and scale to that of the black hole.

Jason Bolte, MSU School of Music, composed an electroacoustic surround-sound environment in which participants are immersed in an aural realization of gravitational waves and material derived from other "space sounds" courtesy of NASA and Donald Gurnett of the University of Iowa [13]. The extreme mass ratio inspiral (EMRI) trajectories and associated gravitational waves were obtained by Steve Drasco's approximate solution to the Einstein equations, describing the predicted zoom-whirl orbit of EMRIs [14]. Yunes then up-converted Drasco's gravitational wave data in Matlab to produce a sonic realization that resides comfortably within the range of human hearing. The electroacoustic environment was designed to amplify the visual experience, thus engaging visitors through sight and sound.

Charles Kankelborg, MSU Physics Department, developed special armatures to send lasers through a series of lenses to distribute hundreds of light beams around the black hole, creating a star field. Careful calculations ensured that the laser stars were safe to project onto the entire surface of the viewer's body, a key component to the perception of being within a field of stars.

Cindy Stillwell, MSU Film and Photography, collaborated with Mast on a digital/analog-based film using equations that reflect black hole physics, using notes from a graduate class that Yunes teaches on General Relativity**.** Mast generated mixed-media paintings (encaustic, powdered pigment and oil stick) that Stillwell filmed one layer at a time. The images were subsequently altered with software and morphed into a unique, time-based film using the abstract language of physics as markmaking devices, which the viewer encounters in a large-scale moving image on the back wall of the installation (Fig. 3).

EDUCATION AND OUTREACH

Since *Celebrating Einstein* was truly an event for the whole family, the collaborators wanted to ensure that children could experience and enjoy the *Black (W)hole* installation. Jessica Raley, MSU Education Department, developed a Family Guide with Yunes's and Key's input to accompany the installation, providing an accessible, engaging explanation of the science behind the art. Using simple but scientifically accurate language, the Family Guide gave parents and children a way to learn together about the scientific concepts represented in the work: black holes, accretion discs,

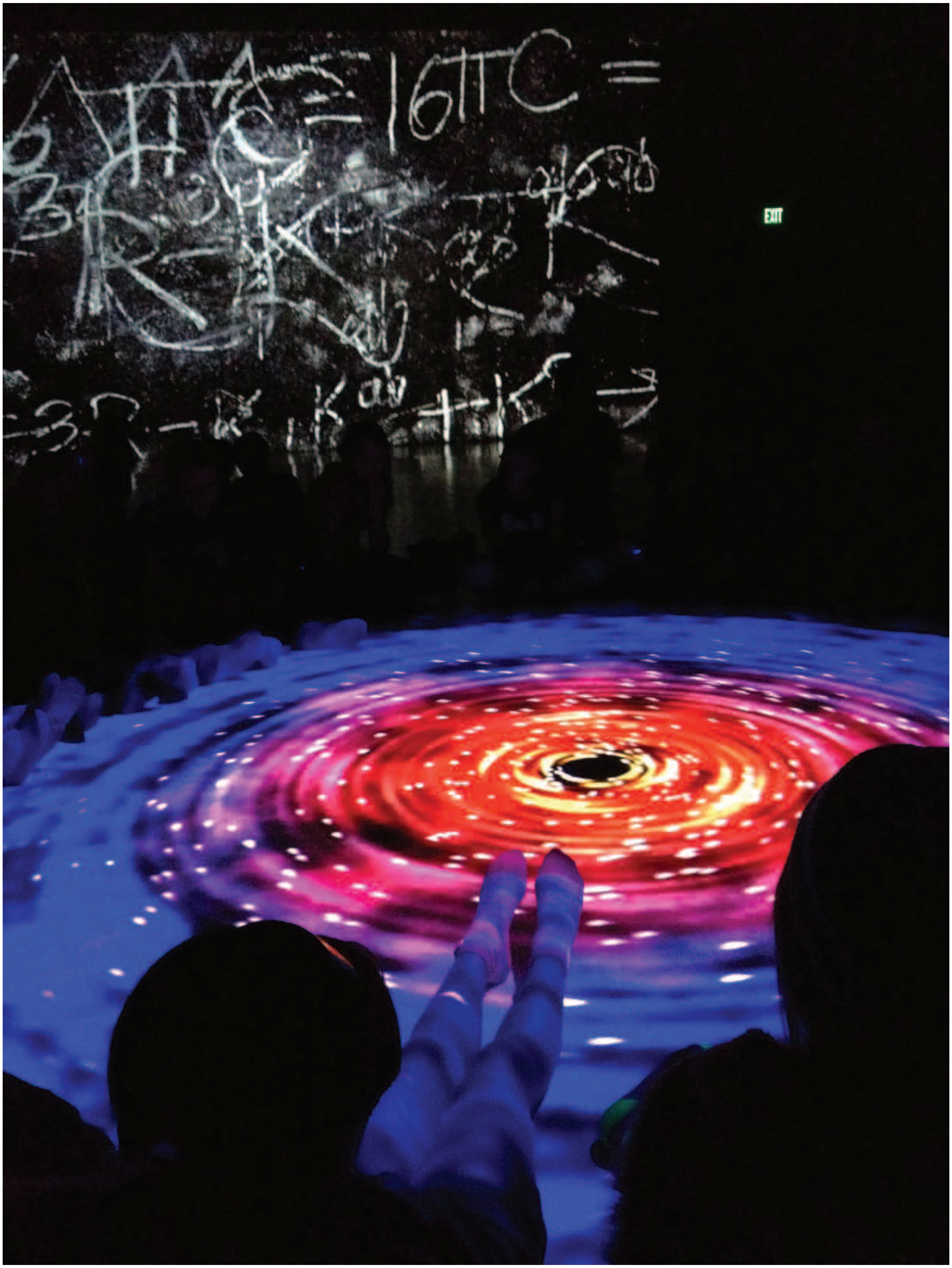

Fig. 4. Students interact with *Black (W)hole* as the artists and scientists encourage them to dip their feet into the projection. (© The Einstein Collective [16]. Photo: Jamie Cornish.)

gravitational waves and EMRIs. Visitors were able to step into the beauty and magic of the aesthetic experience, while also walking away with a better understanding of supermassive black holes.

One of the primary ways *Celebrating Einstein* reached children in the community was through school visits to the Emerson Center for the Arts and Culture. At the Emerson, students had an opportunity to playfully engage with the installation, before sitting down with some of the creators of *Black (W)hole* to learn about the science and the art (Fig. 4). A physicist was present for these visits to answer students' scientific questions. In a separate area, students met with two physics professors for a more in-depth lesson about gravity and black holes. An interactive spacetime model enhanced the lesson and provided another opportunity for students to explore some of the basic concepts represented in the art installation. Many of these same students later returned to the Emerson with their families and were able to share with their parents and siblings what they had learned.

FUTURE WORK

The excitement surrounding *Black (W)hole* and the *Celebrating Einstein* events in Montana have provided excellent preparation for the worldwide centennial celebration of Einstein's theory of general relativity in 2015 and 2016. The *Celebrating Einstein* team will continue to work with universities, science museums, art museums and planetariums to bring the beauty of *Black (W)hole* to communities across the world [15].

References and Notes

1 Albert Einstein, interviewed by George Sylvester Viereck in the 26 October 1929 issue of the *Saturday Evening Post*. Complete quote: "I am enough of an artist to draw freely upon my imagination. Imagination is more important than knowledge. Knowledge is limited. Imagination encircles the world."

2 See <https://vimeo.com/64747163>.

3 See <https://vimeo.com/9122099>.

4 *Artscience: Creativity in the Post-Google Generation*, David Edwards, Harvard Univ. Press, Cambridge, MA (2008).

5 See <www.celebratingeinstein.org>, <www.blackwhole.montana.edu>.

6 Grimberg, B.I., A Shout Across Time, Celebrating Einstein Final Report (2013). Available from the authors.

7 Meyer, A. "STEM to STEAM?"; <www.kuder.com>.

8 *And RISD's New President is . . . John Maeda—He answers our questions here*, Reena Jana, Businessweek Archives, 19 December 2007.

9 *Little Essays Drawn from the Writings of George Santayana (1920)* by Logan Pearsall Smith, p. 9.

10 Dewey and Dewey (1915), Schools of Tomorrow. New York: E.P. Dutton & Company, MW.8.255, 257, 258, 261, 265, 286 and 391.

11 Wolfe and Byrne (1975), "Research on Experiential Learning: Enhancing the Process," in *Simulation Games and Experiential Learning in Action,* Richard H. Buskirk (ed.), pp. 325–336.

12 Fuller, R.G. (2002), *A Love of Discovery: Science Education*, *The Second Career of Robert Karplus* (Springer).

13 Original space audio recordings provided courtesy of NASA and Donald Gurnett of the University of Iowa <www-pw.physics.uiowa.edu/space-audio>.

14 Drasco, S. (2012), One black hole is not like the other: Binary black holes with extreme mass ratios, <www.tapir.caltech.edu/~sdrasco/animations/>.

15 For more information: <www.celebratingeinstein.org>.

16 The Einstein Collective: Sara Mast, Jessica Jellison, Christopher O'Leary, Jason Bolte, Cindy Stillwell, Charles Kankelborg, Nicolás Yunes and Joey Shapiro Key. Co-author Jessica Raley serves as educational consultant.

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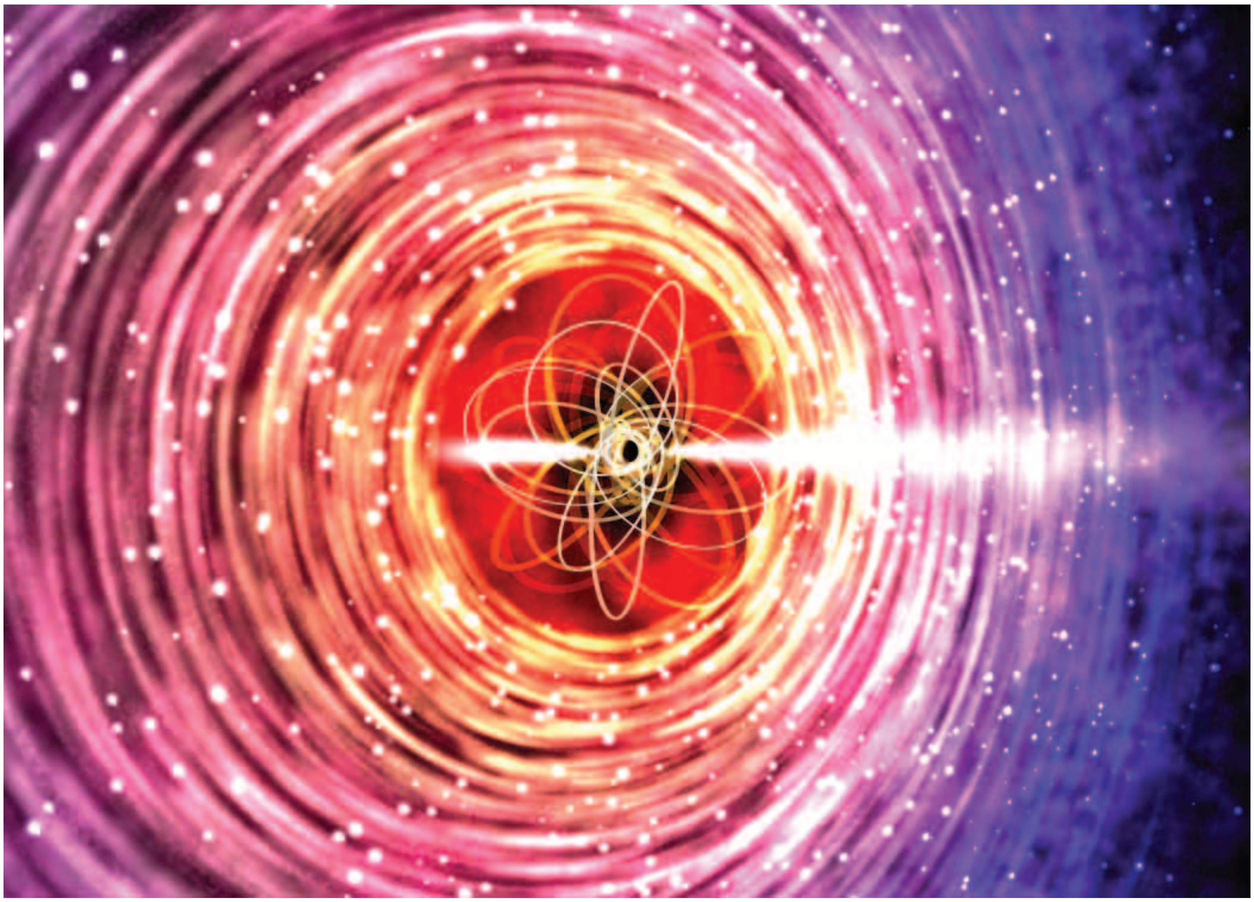
THE EINSTEIN COLLECTIVE *is a collaboration of artists, scientists and educators interested in sharing the beauty of Einstein's ideas with a broad audience.* Black (W)hole *was originally created as part of the* Celebrating Einstein *outreach events at Montana State University.*

COLOR PLATE B: ***BLACK (W)HOLE***



The *Black (W)hole* animation is a two-dimensional projection of a three-dimensional simulation, rotating the viewer's perspective from the plane of the accretion disk to view the three-dimensional sphere of the event horizon and the black hole jets streaming perpendicularly to the disk. (© The Einstein Collective. Photo: Christopher O'Leary.)