WATERLOO CENTRE FOR ASTROPHYSICS

2018/19
ANNUAL REPORT

WATERLOO CENTRE FOR ASTROPHYSICS

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MESSAGE FROM THE DIRECTOR

Director Will Percival

The Waterloo Centre for Astrophysics (WCA) was formed to enable excellent research, and we have already seen many examples of such research being undertaken by WCA members during our first year. The biggest research highlight was the release of the image of the shadow of a black hole by the Event Horizon Telescope (EHT) collaboration in which Avery Broderick had a significant role. With the rest of the EHT team, Avery and his students will share the $3M 2019 Breakthrough Prize in Physics. This was clearly an outstanding achievement. We have also seen steady progress in many other fields of astrophysics, where breakthroughs are waiting to be discovered.

In particular, WCA members help to lead many international collaborations undertaking experiments in astrophysics. By using the Universe as a laboratory, we design and analyze experiments testing physical processes that are impossible to replicate on Earth. The Canadian Astronomical Society is currently creating a long-range plan for Canadian astronomy, something that happens every decade. Three WCA members are leading written contributions for this review highlighting forthcoming experiments and exciting research directions. Many other members of the Centre are contributing to these and to other submissions. We must make sure that we are as well placed to exploit this next generation of experiments as we can be.

The heart of the WCA is a group of aspirational young scientists, doctoral students and scientists working as post-doctoral researchers. I was very pleased when our first WCA Postdoctoral Fellows, Elena Massara and Go Ogiya joined us this September. These scholars are at key stages of their scientific careers and over the next few years we must continue to provide a creative, inspiring environment for these, and other researchers where lively research debate flourishes.

Getting to the stage we are at, as described in this annual report, has required dedicated and exceptional input from many, but especially from our administrative lead Donna Hayes, the Advancement team, and the members of the WCA. We have made great progress over the last year, and based on this and the current momentum, it should be clear that the Centre has a great future ahead of it.

MISSION STATEMENT

The Waterloo Centre for Astrophysics looks to the cosmos to solve the greatest mysteries of the universe. World-class researchers and students come here in an atmosphere of curiosity, creativity and collaboration; exploring our cosmic origin to truly understand the physical processes at work in the Universe. From black holes to cosmology, we aim to understand what lies beyond the Earth. The possibilities for new discoveries are limitless.

Our drive to explore propels our greatest achievements. Today there is no greater frontier of discovery than in the field of astrophysics. Using astronomical observations and theoretical reasoning the Waterloo Centre for Astrophysics will host aspiring young researchers and students, helping them to unlock the mysteries of the Universe. By designing and analyzing experiments we will test physical processes that are impossible to replicate on Earth.

The Waterloo Centre for Astrophysics (WCA) is an important addition to Waterloo's established global reputation in physics. The WCA builds on the Mike and Ophelia Lazaridis Distinguished Chair in Astrophysics. Under the leadership of the Chair, Prof. Will Percival, the Centre will collaborate with some of the top astrophysics agencies in the world. Moreover, the WCA will go beyond current research, developing sophisticated analysis methods and applying them to current data sets. Discoveries will be shared outside of the scientific community through public talks and events with the next generation of explorers — especially young people and communities currently under-represented within physics.

The breakthroughs made here will touch every aspect of life, business, and academia. They will have echo through history for generations to come. When we look at the skies, we stare into both our past, and our future. It challenges our imagination to its extremes, to think bigger, bolder, and farther beyond our earthly bounds. It teaches us how the Universe works, evidence that we can study and understand objectively, and then apply to our everyday lives and those of future generations.

What are the physical laws that govern the Universe? Do the rules that work on the Earth also work in extreme situations? Can the discoveries positively impact life on Earth? Let's find out together.

HISTORY

The Waterloo Centre for Astrophysics was approved by the University of Waterloo Senate at their November 19th meeting in 2018. Prior to this, the proposal was reviewed by the Senate grad & research council meeting (Oct 1), the Research Leaders Council (Sept 17), Science Faculty Council (Sept 12), and at a dedicated Physics and Astronomy department meeting (Aug 27). The WCA is an initiative conceived by members of the faculty specialising in astrophysics to build upon the generous donation by Mike Lazaridis, which enabled a Distinguished Research Chair in Astrophysics, currently held by the inaugural WCA Director, Will Percival.

After approval by the Senate, we were able to use the WCA name for the first time, and immediately advertised for our first Postdoctoral Fellows. The advert was posted Nov 23 2018 (following the Senate meeting), with a deadline of Jan 3, 2019. A call was made for members of the WCA to serve on the interview panel, and Mike Hudson stepped forwards to help Will Percival with shortlisting and interviews. We received 116 applications, interviewed 10, and were pleased when Elena Massara and Go Ogiya agreed to join the WCA. They both recently moved to Waterloo and have started work. This year, we will appointment a further postdoctoral fellow, with an advertising to start early in October.

Attempts were made to also hire a joint Postdoctoral Fellow with the Canadian Institute for Theoretical Astrophysics (CITA, based at the University of Toronto), and an offer was made for a CITA Canada Fellowship (2 years in Waterloo, 2 years in Toronto), but this was unfortunately turned down. The WCA will continue to actively pursue the options of hiring postdoctoral Fellows jointly with both CITA and the Perimeter Institute.

Our admin lead, Donna Hayes, was hired at the end of March 2019, after approval to hire was obtained. Donna started work mid-April, and this enabled administrative work to commence for Centre related activity: we now have a twitter account, logo, brochure, banner, merchandise (notebooks, pens, stickers), and an updated website, and were able to plan a launch event.

Our first major event is our launch, which will take place on October 4th 2019. This will feature a Scientific meeting focussed on the Future of Astronomy 10-4, followed by a reception and a public talk in the evening by Christine Forman on "Black Holes, Dark Matter and Dark Energy: Exploring the Invisible Universe". Hopefully these will be the first of many examples of meetings and public outreach events hosted by the WCA.

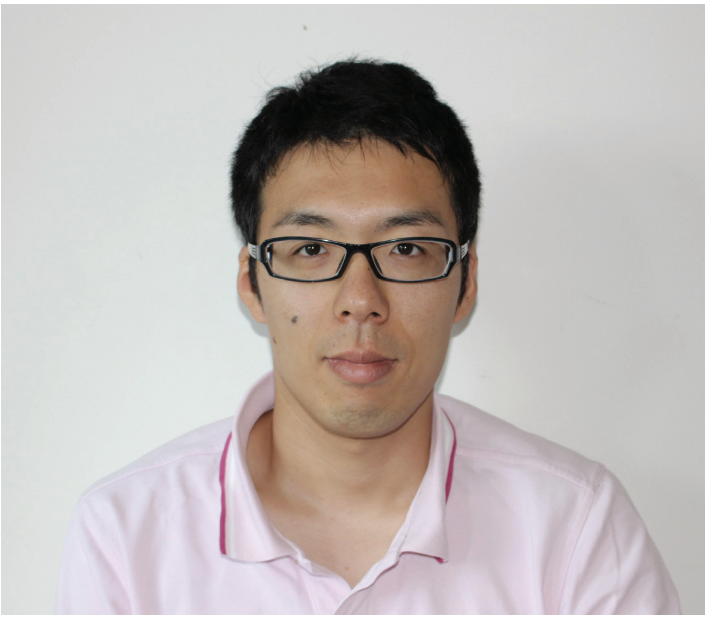
CURRENT WCA POSTDOCTORAL FELLOWS

ELENA MASSARA

Elena Massara earned her PhD from SISSA (Italy) in 2016 and she has previously held postdoctoral positions at the University of Berkeley (USA) and at the Flatiron Institute in New York (USA). Her research focuses on the study of the large-scale structure of the Universe with the aim of understanding the content and evolution of the Universe and studying the properties of neutrinos. Recently, she built a theory model to describe how matter distributes around cosmic voids, the almost empty regions of the Universe. This model represents an important step to enable cosmologists to use voids as a cosmological probe.

GO OGIYA

Before coming to Waterloo, Go Ogiya received his PhD from the University of Tsukuba (Japan) and held postdoctoral positions at the Max Planck Institute for Extraterrestrial Physics (Germany) and Observatoire de la Côte d'Azur (France). His research interest spans a wide range of astrophysics, from the smallest dark matter halos to the largest galaxy clusters, and of numerical computation, including developing high-performance simulation codes and machine learning. He is currently studying the orbital evolution of supermassive black hole binaries in dense star clusters and finds that they emit strong gravitational-waves within a time shorter than the age of the Universe, before the final coalescence. The results indicate that dense star clusters are likely promising sites of gravitational-wave emission and exciting targets for the upcoming observations.



ADVANCEMENT GOALS

Director Will Percival August 2018 Lecture

Mike Hudson August 2019 Lecture

The WCA Director is supported by a generous donation by Mike & Ophelia Lazaridis, which ensures sustainable funding for the first 5 years of the Centre, with extension for another 5 years. This is matched to the tenure of a Director (5+5 years). In order to make the Centre become self-sustaining over a longer term, we want to build up an endowment base.

As the heart of the research done within the Centre are Postdoctoral Fellows. Unfortunately, the situation in Canada is such that it is difficult to hire postdoctoral fellows using government funding - the basic support for many academics are NSERC Discovery grants, which are at a level being at a level that provides travel and graduate student support only. Consequently, our primary long-term goal for Advancement is to obtain an Endowment of $3M, which would allow a postdoctoral fellow to be hired in perpetuity. This could be named after a benefactor. In fact this adds prestige to a position, and works to attract the best talent. The approximate cost of such a fellow is $90k/annum, with $63k salary (matching the amount paid to CITA National Fellows), 24% benefits, and $10k research expenses. At the University of Waterloo, an Endowment pays ~3% per annum, and no matching funds are usually allowed for research fellow costs, giving the $3M requirement, Given three such named Fellowships, we would be able to hire one Postdoctoral Fellow per year, with three in residence at any one time.

A further goal is to use the WCA as a base for public outreach. At the moment, the WCA runs an annual event in August, jointly with the Kitchener-Waterloo branch of the Royal Astronomical Society of Canada which is timed to coincide with the Perseids meteor shower. In 2018, Will Percival gave a lecture on "Mapping the Universe", while in 2019, Mike Hudson gave a lecture on "Cosmic Mirages: seeing dark matter with gravitational lenses". Both were sold out. These were followed by a chance for the public to view the meteor shower. Unfortunately the weather was not great for this, this year. We also hosted a special public talk from Avery Broderick to coincide with the EHT image release. We wish to build on this and offer a more regular lecture series on astronomical stories of interest. In order to attract external speakers we would wish to offer travel, and estimate this could cost $500 per month. Setting this up in perpetuity, would require a $200k endowment.

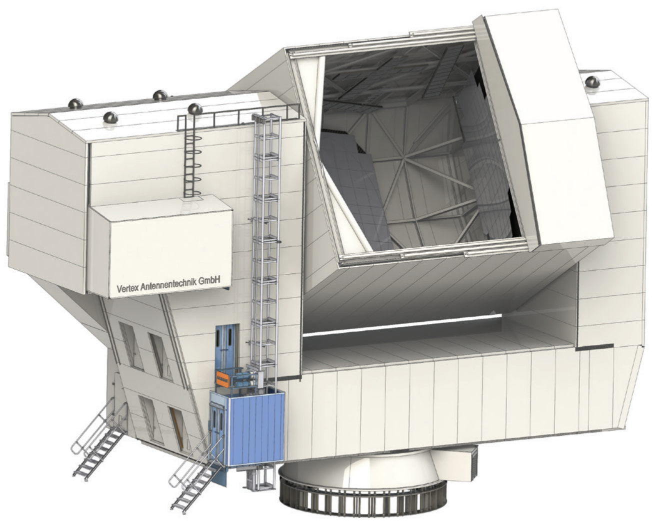
Further monies would allow graduate students to travel to conferences, and to go to telescopes around the world to undertake observing runs.

Over the past year, WCA members have worked closely with Meaghan Middleton (Associate Director, Development Faculty of Science), to understand and start Advancement activities for the WCA. On November 22 2018, Will Percival and Brian McNamara accompanied Meaghan Middleton on the Canadian Council for the Advancement of Education (CCAE) course "Development for Deans with Lorna Somers". This provided insight into the work of Advancement, and Advancement techniques. The University of Waterloo Advancement team also organised an event in Toronto that evening: "Four Chairs and a Beer: Alumni Reception" allowing Alumni to chat to Waterloo Professors about science and the University in an informal setting.

There have been a number of individual meetings with alumni and potential donors set up by the Advancement team within Waterloo. We also took the opportunity of both Will and Avery attending a conference on "Testing Gravity" in Vancouver in January 2019, to organise a public talk given by Avery "Images from the Edge of Spacetime: Resolving Black Holes" for Waterloo Alumni in the California region, and a number of meet-and-greet events for both Avery and Will in Vancouver.

RESEARCH GRANTS

The Physics and Astronomy and Applied Mathematics Department faculty members who are also members of the WCA, receive research funding from NSERC Discovery grants, summing to $470k/year. Through grants supporting the work on the Euclid and XRISM satellite missions, we also have two grants in place with the Canadian Space Agency, bringing in $76.4k/year. In addition, we have a grant from the "Asian Office of Aerospace R&D" of $53k/year awarded to Bob Mann to fund a postdoctoral fellow to work on a new approach to the celebrated Black Hole Information Paradox.



The **Cerro Chajnantor Atacama Telescope-prime (CCAT-p)** is a 6-meter aperture submillimeter wavelength telescope designed for very wide field observing. Construction began on November 1, 2018 and operations will start in 2022. CCAT-p will carry out several large-area surveys with a mapping speed unchallenged by any current or near-future facilities in the 150 to 1500 GHz telluric window. With CCAT-p, we will be poised to make new discoveries and grow our emerging leadership in key areas of observational cosmology and fundamental physics including:

1. What is the nature of dark energy and the sum of neutrino masses? The new frontier for cosmology is to utilize and extend the 6-parameter LCDM model to understand fundamental properties, e.g. the nature of dark energy and the sum of neutrino masses. The redshift-independent Sunyaev-Zeldovich (SZ) effects, which probe structure growth, provide a robust mechanism to make these measurements.

2. Trace the formation and large-scale, three-dimensional clustering of the first star-forming galaxies during the epoch of reionization through wide-field, broad-band spectroscopy.

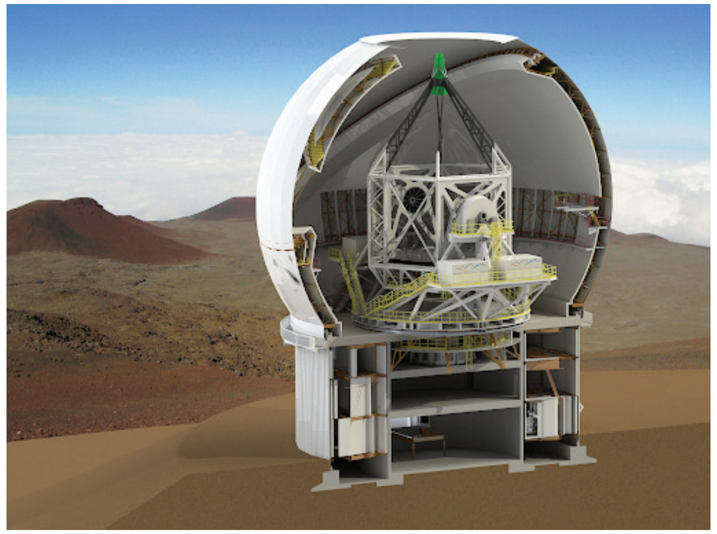
3. Enable more precise constraints on primordial inflationary gravity waves by characterizing dust foregrounds that dilute measurements of CMB polarization.

4. Directly trace the evolution of dust-obscured star formation in galaxies since the epoch of galaxy assembly, starting > 10 billion years ago

The Canadian Team for CCAT-p is led by WCA member Mich Fich and includes researchers at twelve other Canadian universities. Mike is leading an application to this year's call for Canada Foundation for Innovation (CFI) Innovation Fund 2020 grants to support the construction of CCAT-p. CFI calls for research infrastructure funding happen on a timescale of 24-36 months, and once approved within a University envelope (as the CCAT-p proposal has been), the success rate is 35%. This CFI grant, along with provincial grants associated with this federal funding would be the main source of new funding for the Canadian contribution to CCAT-prime construction. The total new Canadian funding requested is slightly over $8.9M. The largest expenditure required (slightly over $5M) will be for construction at the site of the observatory including assembly of the telescope, roads, power, and buildings. Other major expenses include a camera "module" for the main CCAT-prime instrument (prime-Cam) and software both for the observatory and for the instrument data reduction. Approximately $230k will be spent at the University of Waterloo for a number of CCAT functions including management costs, optics design work, and commissioning of the telescope and the prime-Cam instrument.

The **Large Synoptic Survey Telescope (LSST)** is an ambitious, US-led experiment to map most of the observable sky at optical wavelengths, revisiting each point on the sky approximately every three nights for ten years. Each visit will consist of multiple images spaced by about 15 seconds. This will provide an unprecedented look at the transient universe, discovering myriad phenomena that vary on timescales ranging from seconds to years. In addition, the cumulative exposures result in a very deep image of the night sky, providing optical characteristics for tens of billions of faint stars and galaxies. The University of Waterloo and the Faculty of Science have previously committed funding to allow five WCA members (Afshordi, Balogh, Hudson, McNamara, Taylor) to join the Large Synoptic Survey Telescope (LSST) collaboration, leveraging some funding support from the Dunlap Institute (for Balogh). However, the funding model for this collaboration has recently changed, and LSST cannot accept cash contributions toward operations. Instead, they will only consider in-kind contributions; the requirements and associated returns for in-kind support have not yet been provided, and hence it is unclear exactly how international partners can now join this US-led project. A CFI proposal being led out of Toronto will establish a data centre (CLASP) for integrating LSST data products with other survey data, and it is expected that this contribution will be of significant added value to LSST that they will consider it as a valid in-kind contribution. Percival and Balogh are participating in this proposal, and are negotiating with the Faculty and University to provide the previously committed funds toward this new model. These funds would now be used to fund five LSST fellows, and one Software Engineer, to reside at Waterloo and contribute to both the infrastructure development (i.e. the data centre) and LSST science. If successful, this will not only provide Waterloo researchers with access to LSST data, but will ensure close engagement in the project.

The **Maunakea Spectroscopic Explorer (MSE)** is an exciting, Canadian-led initiative to transform the existing CFHT into an 11-m wide field spectroscopic survey telescope. This capability has been identified by many international agencies (including ESO and AURA) as of critical importance to complement the ambitious imaging surveys (e.g. LSST, Euclid, WFIRST) of the next decades. A group of Canadians (including Balogh) are preparing a CFI proposal to support the preliminary design phase of this facility. The proposal (valued at $24M) explicitly notes that it is the first step toward a construction proposal (for around $40M) that will follow in the next CFI round. For this round, the University of Waterloo has committed $780k of CFI envelope (with a possible increase of up to $858k), and $82.5k of institutional cash, toward the project. These funds will go toward work on the software development, and fiber optic testing and characterization work. While MSE is the target, the design work will be generic and applicable to any 10-m class, highly multiplexed, fiber-fed spectroscopic facility. It is independent of site, and helps to ensure Canada (and Waterloo) will remain in the driver's seat of the first such facility, wherever it might be built.

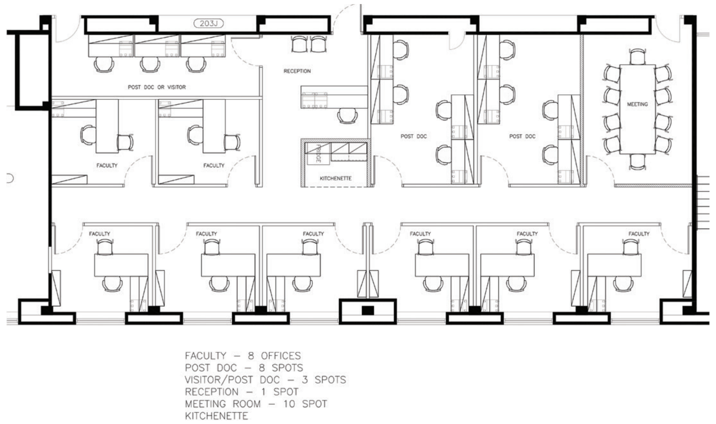


ACCOMMODATION FOR THE CENTRE

At the moment, the members of the Centre are mainly located within the Physics and Astronomy department on the University Campus. However, they are quite separated within the building and this does not help to foster a research environment. We have both a near-term and a long-term plan to rectify this situation: in the short-term, a space will be refurbished for our use in the physics lab wing. In the long-term, the WCA will occupy a floor in the new Physics and Astronomy building, part of the SCI-PHYS development.

Near-term: refurbished space within the physics lab wing

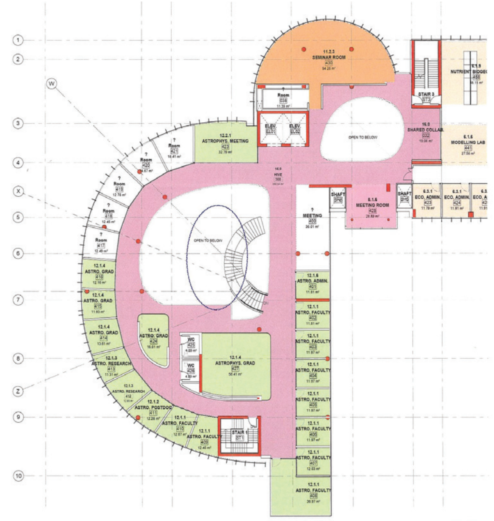
Before work starts on the SCI-PHYS development and possibly while construction is happening, we are working on a plan for accommodation where WCA researchers can interact. The plan for this is renovated an unused laboratory within the physics building to provide office and interaction space. This would host a small number of faculty members, the WCA postdocs and most of the graduate students. Costs for the refurbishment will be covered by the Science Faculty, with the aim of making the refurbishments have a long-term usability beyond the timescale of the SCI-PHYS development. The current plan is for construction to start in March 2020, and be completed by June 2020.



Long-term: the new SCI-PHYS development

The Department of Physics and Astronomy and the Dean's offices are working with HPA and ZAS Architects to develop plans for a new Physics research wing. The project began as a $5M upgrade to existing space for WCA, but has since evolved into a new Physics research space. Following inspections of both the west office wing and the physics laboratory wing, it was determined that the lab wing required substantial upgrades to the HVAC, thermal control systems, and cosmetic elements related to aging, but is otherwise in excellent shape. The office wing, built in 1959, was deemed to have exceeded its useful lifespan. The new $90M plan involves removing the current west office wing and the adjoining lecture hall, and replacing them with new research and interaction space. The space will include four floors and a below-ground Photonics laboratory. The concept, known colloquially as "the hive" will include open areas with black- and white-boards intended to promote collaboration and interactivity between research groups. The ground floor will include student and faculty activity spaces, conference rooms, restaurant and coffee services, and a 300 seat lecture theatre. Additional classrooms will be located on the upper floors. The building will feature an atrium and staircases rising throughout, with natural light permeating the building. Open sight-lines twill thread all floors, communicating the excitement of physics research to students and faculty alike. The plan includes bright faculty and staff office spaces that open out to science interaction areas and graduate student office spaces adjacent to faculty offices.

The WCA will occupy the fourth floor, and will feature a seminar theatre, open research areas, seminar rooms, and programmable flat screens with full connectivity to promote interaction with visitors and colleagues nearby at Perimeter Institute, and abroad. Realizing cost savings, the new physics research wing will adjoin the Science Centre for Innovation, sharing seminar space and the food court. The project, known as SCI-PHYS is the University's highest priority capital project, and is expected to break ground in the next year or two.



RESEARCH HIGHLIGHTS

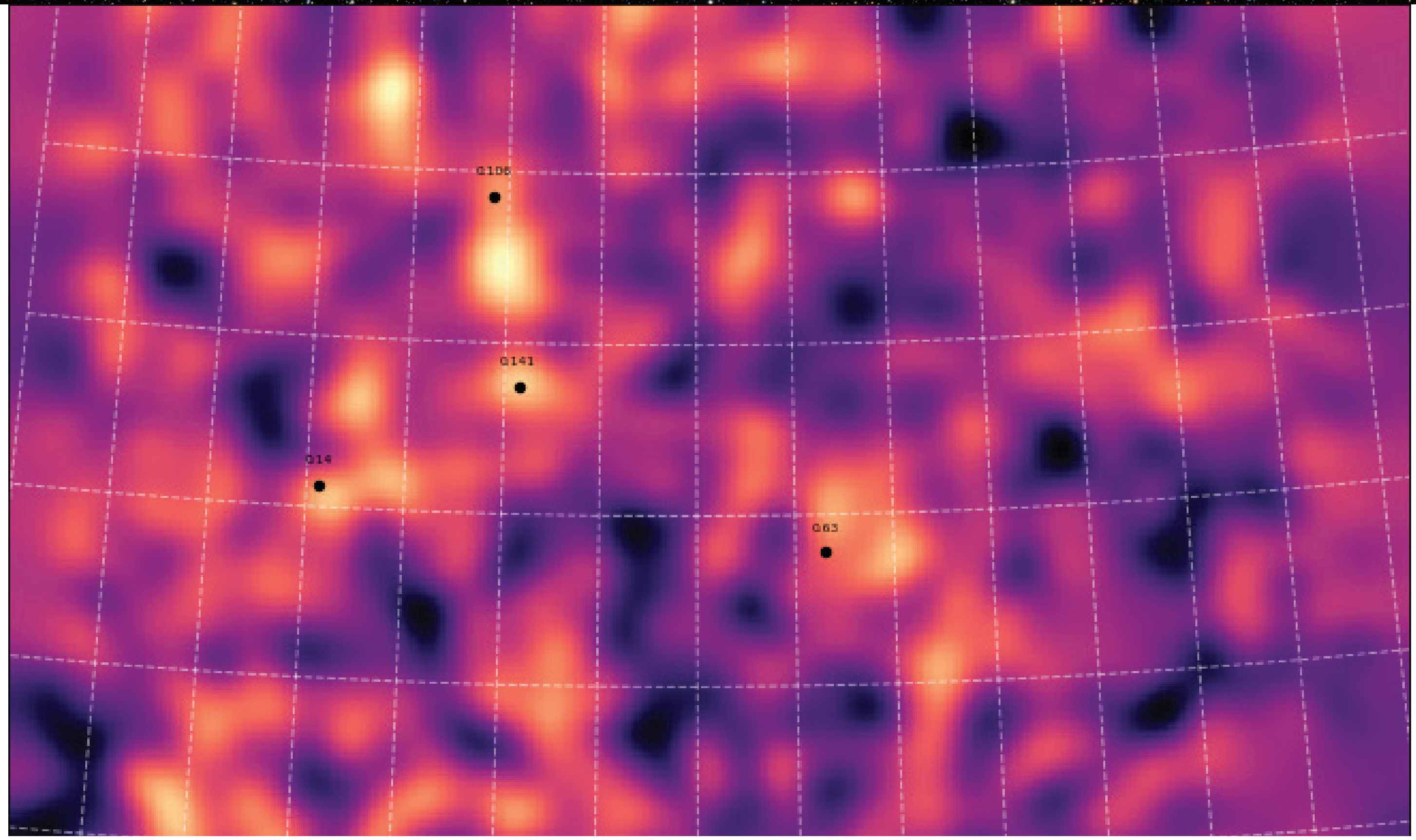
OBSERVING THE SHADOW OF A BLACK HOLE

WCA member Avery Broderick is also a member of the Event Horizon Telescope (EHT) Collaboration, a unique collaboration of eight ground-based radio telescopes spread over four continents. Avery and post doc supervisor Avi Loeb proposed 10 years ago that M87 (one of the most massive galaxies in the "local" Universe) was the best place for the EHT to focus its efforts. A layperson description of their proposal can be found in Scientific American in the December 2009 Issue. In the past years, Avery participates in the creation and interpretation of the first horizon-resolving images of astronomical black holes in the history of astronomy. Using large-scale computer simulations his group explores model images, looking for signatures of deviations from general relativity and the high-energy astrophysical processes responsible for the growth of black holes and the launching of outflows that extends their influence to intergalactic distances.

On April 10th this year, the (EHT) collaboration have reported the first ever image of a black hole. They used eight interconnected ground-based radio telescopes spread over four continents. These telescopes work together using a technique called very-long-baseline interferometry (VLBI). It synchronises facilities around the world and exploits the rotation of our planet to form one huge, Earth-size telescope. VLBI allows the EHT to achieve an astounding resolution of 10 to 20 micro-arcseconds — equivalent to reading a newspaper in New York from a sidewalk café in Paris. With these new cluster of powerful instruments, they have obtained images of the supermassive black hole M87, the first ever image of a black hole.

"This is a landmark in astronomy, an unprecedented scientific feat accomplished by more than 200 scientists", said EHT project director Sheperd S. Doeleman of the Center for Astrophysics | Harvard & Smithsonian. "This remarkable result has given humanity its first glimpse of the shadow of a supermassive black hole."

The EHT observations revealed a ring-like structure with a dark central region — the black hole's shadow. This ring appears in several observations using different imaging methods, making the scientists involved confident that they have indeed captured the shadow.



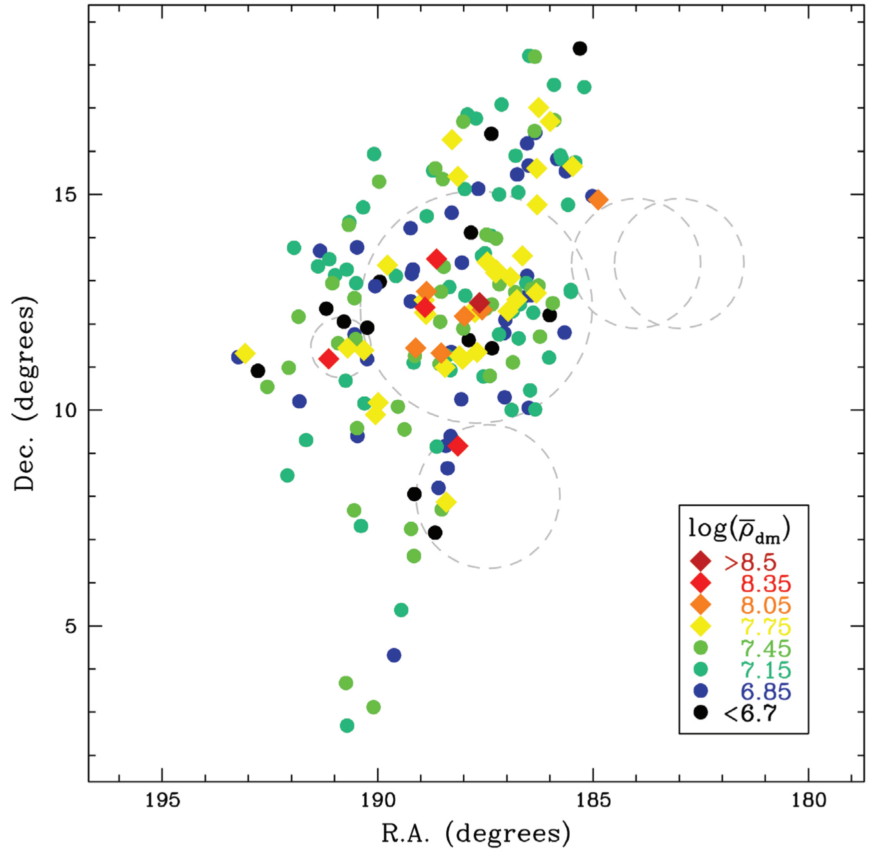
PROGRESS IN COSMOLOGICAL SURVEYS

WCA members Mike Hudson and Will Percival work on galaxy surveys. Mike coordinates the Weak Lensing Team of the Canada-France Imaging Survey – one of the world's imaging surveys. The survey will cover 4800 square degrees of the Northern Hemisphere, or about a tenth of the full sky, by taking digital images with the Megacam camera at the Canada-France-Hawaii Telescope over several years. Will works on the extended Baryon Oscillation Spectroscopic Survey, a survey taking spectra over 5800 square degrees. Using both of these surveys they will search for traces of Dark Energy, the physical mechanism causing the expansion of the Universe to accelerate in recent times.

The image above shows a Dark Matter map from the CFIS survey. This false colour map shows a small piece of the Northern sky. Brighter colours indicate an excess of dark matter, whereas dark regions indicate a lower density. The black dots indicate the presence of known massive galaxy clusters. This maps are obtained by carefully measuring the shapes of very distant galaxies in order to measure their distorted appearance. This distortion of their shapes are caused by the gravitational lensing effect of dark matter that is located in between us and the distant galaxies. The map then represents a model of the distribution of dark matter necessary to explain the observed distortions. The scale of the map is approximately 7 degrees on a side, corresponding to 85 Megaparsecs or 280 million light years. The full CFIS survey will cover an area approximately 100 times larger. Credit: Axel Guinot (CEA Saclay and CFIS weak lensing team).

Both Mike and Will are helping to lead the Euclid Consortium, a team of 1500 scientists and engineers in theoretical physics, particle physics, astrophysics and space astronomy from around 200 laboratories in 14 European countries, Canada and the US. Using the Euclid satellite, this team will survey 15000deg2 of the sky, using both imaging and multi-object spectroscopy, in order to perform both weak-lensing and galaxy clustering observations. Via a phenomenon known as weak gravitational lensing, the appearance of distant galaxies is distorted by dark matter between us and the distant galaxies. Measuring this distortion accurately is an enormous technical challenge and over the past year the team has worked to overcome these challenges and has produced the world's largest data set usable for weak lensing.

In May 2019, Mike Hudson took over from Ray Carlberg (Toronto) as the Canadian Euclid Consortium Board representative. As a Founder of the project, Will Percival's contributions to the mission have already been acknowledged such that he has authorship rights on all future publications. He currently serves as a co-lead of the Galaxy Clustering science working group, and together with the equivalent scientists work in weak lensing, is one of four Science Coordinators for the consortium. Will also serves as a member of the Coordination Group, the Editorial Board, and the Science Publication Group, and contributes regularly to the Calibration and Survey working groups. Together with Euclid Consortium members Michael Balogh, and James Taylor they ensure that the WCA remains at the heart of the Euclid science.



OBSERVING THE BUILD-UP OF STRUCTURE

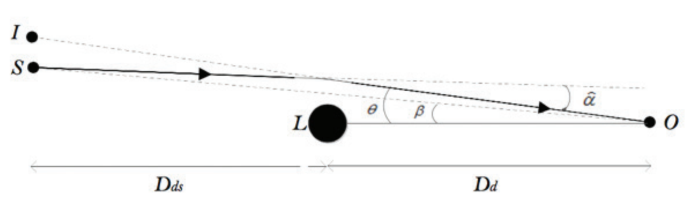
Theory predicts that the large structures we see around us in the universe - galaxies or groups and clusters of galaxies - should have assembled "hierarchically", from smaller pieces that formed earlier. While local structures such as the Virgo cluster certainly seem irregular, direct evidence for their hierarchical assembly from older components was lacking. In a recent publication, James Taylor, with collaborators J. Shin (Korea Astronomy and Space Science Institute), N. Ouellette (McGill) and S. Courteau (Queen's), James Taylor demonstrated that galaxies in the central regions of the cluster have higher dark matter densities than those on the edges of the cluster. This is the first direct evidence that these objects formed earlier, at a time when the background density of the universe was higher, and thus dark matter halos were denser.

In the attached figure, points represent individual galaxies whose mass distributions were determined by the SHIVir survey (Ouellette et al. 2017). The colour scale indicates average dark matter density within the optical extent of the galaxy. The dashed circles outline the main structural components of the cluster (note that SHIVir only covers the upper left half of the field). Galaxies with high dark matter densities (yellow, orange and red symbols) tend to reside at the centres of the structural components, showing that these regions formed earlier, whereas lower-density objects (green and blue symbols) are more widely dispersed.

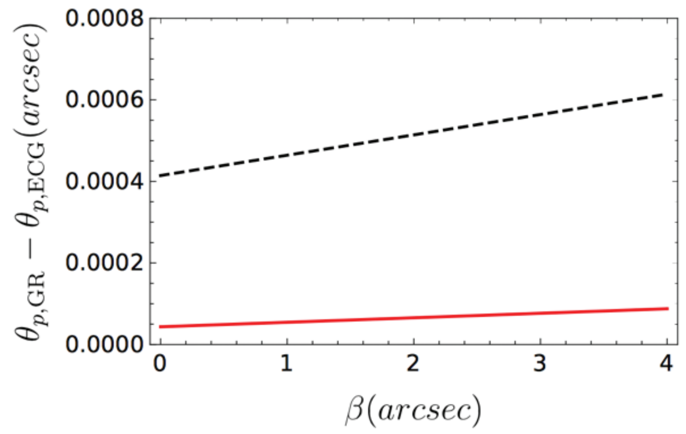
TESTING EINSTEIN’S THEORY OF GRAVITY

Finding competitors to Einstein’s theory of gravity is now quite commonplace. There are many ways of generalizing his original idea that gravity is manifest as spacetime curvature. However, finding generalizations that can agree with observation is considerably more difficult — observation continues to affirm Einstein’s original theory. However, one new competitor — known as Einstein Cubic Gravity — has recently been shown to be of interest. It modifies Einstein’s theory by adding a particular combination of terms cubic in curvature to the usual linear term in such a way that the thermodynamics of black holes is uniquely determined and that gravitational waves at large distances have behaviour identical to that in Einstein gravity. These 2 features make the theory an interesting competitor that can be tested by further observation. Last year, in a paper with PhD student Mohammad Poshteh, we showed that gravitational lensing effects due to black holes in Einstein Cubic Gravity differ in a small but distinct way from their counterparts in Einstein’s theory of general relativity. This means that Einstein Cubic Gravity can be tested by observation. Our paper came out in October 2018 and was published in Phys. Rev. D 99, 024035 (2019).

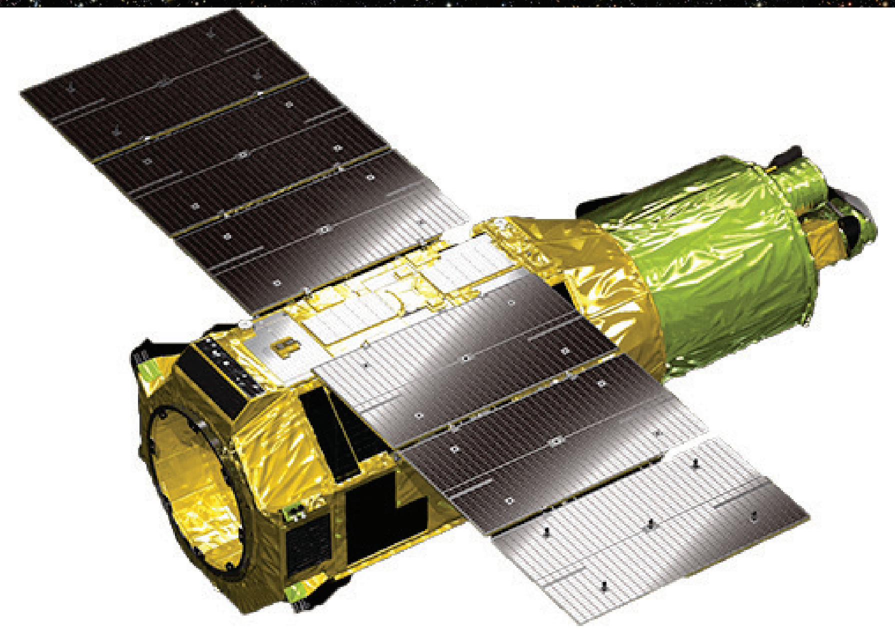
Figures:



Basic setup for gravitational lensing by a black hole. The observer is at O, the source at S, its image at I, and the black hole is located at L.



Deviation of primary image angular position in Einstein Cubic Gravity from General Relativity for the black hole Sgr A at the centre of our galaxy. The deviation increases with angular source position. The black dashed line is for the case D_ds/D_s=0.5 and the red line is for D_ds/D_s=0.05. For a fixed lens-observer distance, the deviation between the two theories for angular positions of primary images is larger for sources further away from the lens.*



X-RAY SATELLITES

In 2018-19 McNamara and colleagues continued ongoing studies of galaxy clusters, radio galaxies, and energetic feedback from supermassive black holes. McNamara serves as PI on a Canadian Space Agency’s contribution to developing the XRISM X-ray Observatory to be launched in 2022 (see artists concept opposite). The observatory features the Resolve microcalorimeter spectrometer that will deliver approximately 3 eV resolution at the 6 keV Iron K feature. The observatory is expected to enable major advances in our understanding of astrophysical plasmas and energetic feedback from massive black holes. McNamara is leading Canada’s effort to calibrate parts of Resolves’s optical system using the Canadian Light Source and other synchrotron facilities. McNamara is a member of the Resolve Instrument Team and the XRISM Science Team. McNamara serves as ex-officio member of the Science and Technology Definition Team for the Lynx X-ray Observatory and is coauthor of the Concept Study Report submitted to the National Academy of Sciences for consideration in the United States Decadal Survey. He is also Co-Lead for the European Athena X-ray Observatory panel on Clusters of Galaxies. This work follows from McNamara’s previous work with Chandra, and this year he co-wrote a review article with P. Nulsen entitled, ``Groups and Clusters of Galaxies’’ that will be included as a chapter in, ``The Chandra X-ray Observatory: Exploring the High Energy Universe.” The volume will be released for the celebration of the observatory’s 20 year anniversary celebration at Boston in December 2019, where McNamara will present an invited talk.

BUDGET

Given the youth of the WCA, we are not yet in "regular operation" mode, and consequently, our current outgoings for the Centre look very different from how they will look in subsequent years. In particular, the biggest expense expected will be for Postdoctoral Fellow salaries, and our two inaugural Postdoctoral Fellows only started in September 2019. For the first 5 years of the Centre, the income is $50k/annum from the Faculty of Science and $500k/annum from the Research stipend of the Director. The following table summarises the budget over the 11-month period Nov 1st 2018 - Sept 30 2019.

	Income $K	**Outgoings $K**	**Difference $K**
Operating budget	504.2		
Admin salary		23.1	
Postdoc salaries		1.2	
Postdoc travel/Moving		1.5	
Visitors program		2.8	
Operating		6.7	
TOTAL			468.9

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NIAYESH AFSHORDI

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MICHAEL BALOGH

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WILL PERCIVAL

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JAMES TAYLOR

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FACULTY MEMBERS, STUDENT AND POSTDOC REPRESENTATIVES

WILL PERCIVAL, DIRECTOR

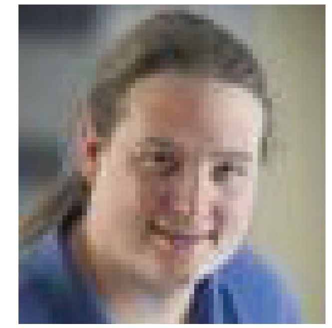
Professor Percival's research interests focus on the properties of the Universe on the largest scales. Surveys of three-dimensional galaxy positions provide a wealth of data both on the physics just after the Big-Bang when the seed fluctuations that will grow through gravity to become galaxies were created, and on the physics driving the evolution of the Universe today.

NIAYESH AFSHORDI

Dr. Afshordi dabbles in Astrophysics, Cosmology, and Physics of gravity and is obsessed with observational hints that could help address problems in fundamental physics.

MICHAEL BALOGH

Professor Balogh's research uses the world's largest telescopes to study the physical properties of distant galaxies. Through spectroscopy we can learn about the distances, ages, chemical composition and star formation histories of these galaxies. As the light we observe from more distant objects originated at earlier times, by observing ever more distant systems we can reconstruct the changes that occur over time to populations of galaxies. His particular expertise lies in trying to understand the source of the puzzling link between galaxy growth rates and surrounding large-scale structure, many orders of magnitude larger than the galaxies themselves.



AVERY BRODERICK

Dr. Broderick works to explain the fundamental physics of black holes and their observable characteristics. Black holes are sites where strong gravity dominates everything, from the dynamics of orbiting material to the shape of spacetime itself. As a result, they are the engines that power some of the brightest objects in the universe. Broderick works on scales spanning from the horizon to the cosmos, tied together by the unique physical conditions near black hole horizons.

RICHARD EPP

Current research interests: Geometrical, quasilocal frame approach to the problem of motion in general relativity. Ultimately, application to gravitational waveform prediction from compact, dynamic sources.

MICHEL FICH

Dr. Fich is an astronomer specializing in studies of star formation, the interstellar medium, and the structure of galaxies. His recent research activities have focused on "small scale" formation studies of low and intermediate mass stars, circumstellar disks, and the formation of proto-solar systems.

GHAZAL GESHNIZJANI

Prof. Geshnizjani's research has so far included tackling different aspects of theoretical cosmology such as investigating inflationary and bouncing scenarios, models of dark energy, modifications of general relativity, backreaction of metric perturbations, cosmic strings in extra dimensions and initial conditions for quantum fluctuations. While mathematically intertwined, these research topics aim at understanding the theoretical puzzles about our cosmos in different phases of its evolution.

MICHAEL HUDSON

Broadly speaking, Professor Hudson's research is in observational and theoretical cosmology, particularly Galaxy Formation, and measuring the properties of dark matter and dark energy through Gravitational Lensing, Cosmic Flows and Large-scale Structure.

ACHIM KEMPF

Prof. Kempf is currently particularly interested in opportunities for using cosmological observations to test theories that try to unite quantum theory and general relativity. The approach is based on the current understanding that, according to inflationary cosmology, all structure in the universe ultimately originated in tiny quantum fluctuations that were stretched to cosmological size during the initial very rapidly accelerated expansion of the universe. These virtual quantum fluctuations are thought to have become definite classical fluctuations when they were still almost as small as the Planck scale, which is where the laws of physics are dominated by quantum gravity effects. This provides opportunities to test quantum gravity theories by predicting and measuring possible modulations in the distribution of structure in the universe, included in the cosmic microwave background.

ROBERT MANN

Professor Mann works on gravitation, quantum physics, and the overlap between these two subjects. He is interested in questions that provide us with information about the foundations of physics, particularly those that could be tested by experiment.

BRIAN MCNAMARA

Giant black holes weighing upwards of one billion times the mass of the Sun are thought to lurk at the centers of all massive galaxies. Energy released by spin breaking and infalling matter onto such supermassive black holes may be regulating the growth of galaxies and clusters of galaxies.

JAMES TAYLOR

Dr. Taylor is using whatever tools he can, including numerical simulations, astrophysical theory and observational data, to try to figure what dark matter is, where it is, and how it behaves. His research includes gravitational lensing and dynamical studies of galaxy clusters, the properties of the smallest galaxies in the local universe, and the theory behind dark matter halos around galaxies and clusters.

STEVE WEINSTEIN

Prof. Weinstein's research is primarily in the foundations of physics, with special interests in the nature of time and the interpretation of quantum mechanics.

ANDREJ OBULJEN

Andrej Obuljen is a postdoctoral fellow at the University of Waterloo working with Prof. Will Percival. He has earned his PhD degree at SISSA (Italy). His main research interest is studying the Large-scale Structure of our Universe using either future 21cm Intensity Mapping or upcoming spectroscopic galaxy surveys (e.g. DESI) in order to better constrain main cosmological parameters. Andrej is the postdoc representative for the Waterloo Centre for Astrophysics.

KRISTI WEBB

Kristi is a second year PhD student at the University of Waterloo working with Dr. Michael Balogh. She is the graduate student representative for the Waterloo Centre for Astrophysics. Kristi earned her bachelor's degree from the University of Victoria. Her research interests are in galaxy evolution, and her project focuses on observations of galaxies in different environments.

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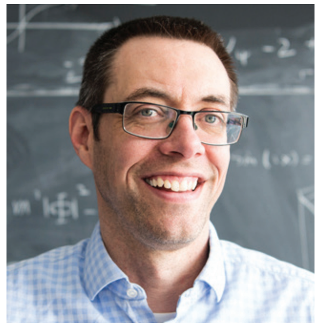

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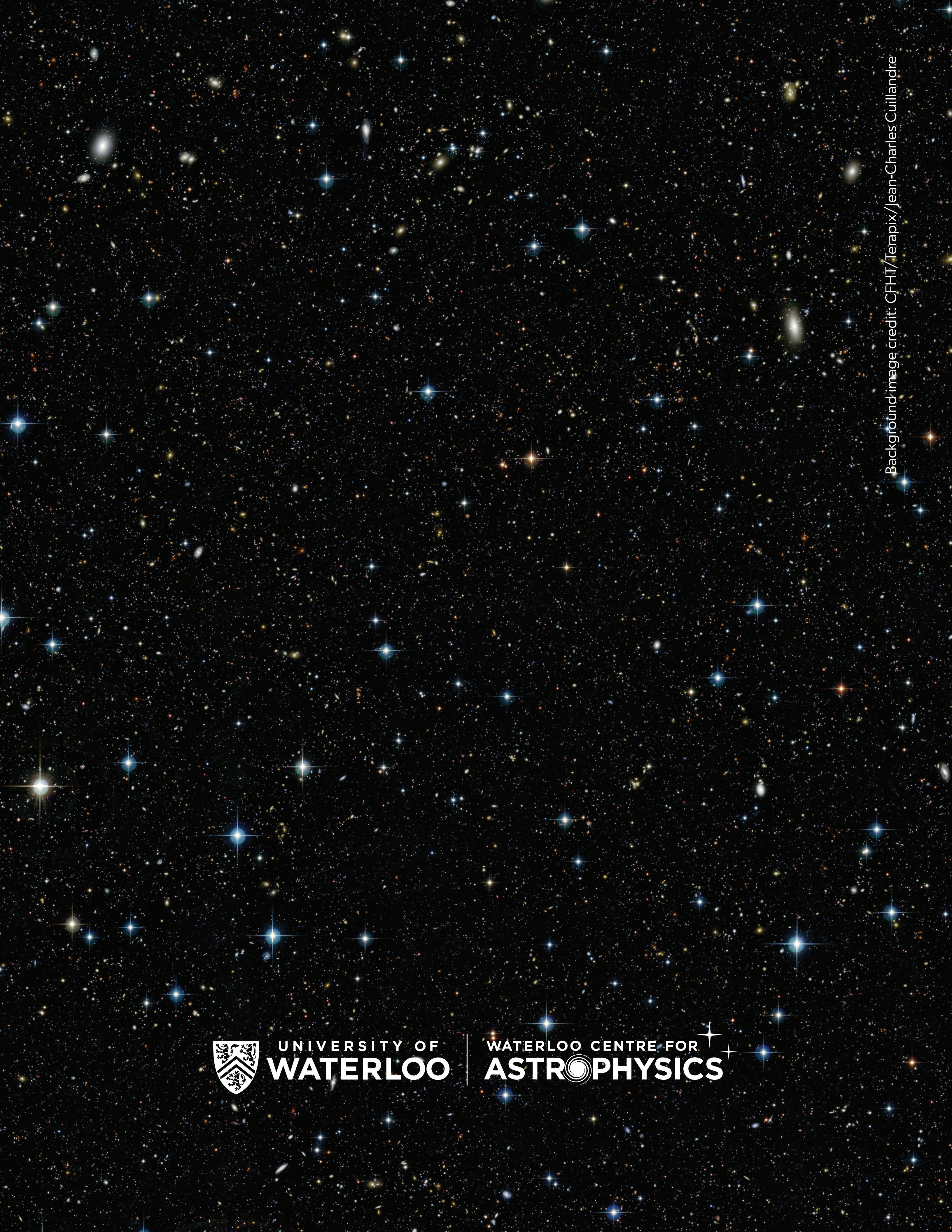
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