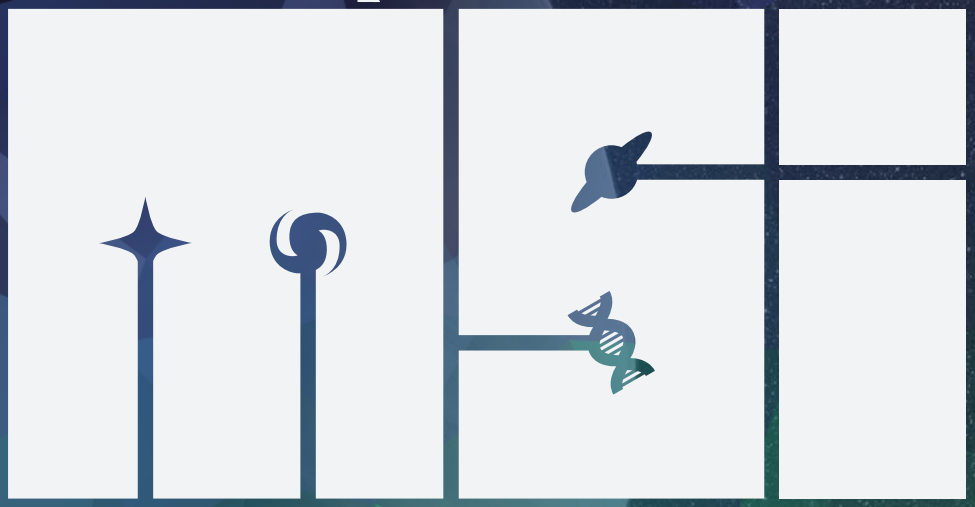
Institut Spatial de McGill



McGill Space Institute

Annual Report 2016-2017

Contents

About the McGill Space Institute

Mission

The McGill Space Institute advances the frontiers of space-related science by fostering world-class research, training, and community engagement.

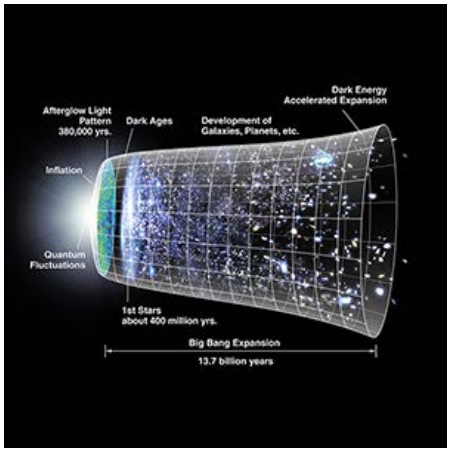
Vision

By 2022, MSI will be a world-renowned leader in space science research. This position will be built around the following components:

- Providing an intellectual home for faculty, research staff, and students engaged in space-related research at McGill, regardless of their home department;
- Supporting the development of technology and instrumentation for space-related research;
- Fostering cross-fertilization, interdisciplinary interactions and collaborations among Institute members in Institute-relevant research areas;
- Sharing with students, educators, and the public an understanding of and an appreciation for the goals, techniques and results of the Institute's research.

The intellectual hub of the Institute is at 3550 University, where many of the Institute members work, collaborate with visitors, and Institute events are held.

Research Areas



Early Universe and Theoretical Cosmology

Robert Brandenberger, Jim Cline

The theoretical cosmology group works to explain the history of the very early Universe and to provide an explanation of the large scale structure of the Universe. They create models using input from new fundamental physics such as superstring theory, dark matter particle theories and particle physics beyond the standard model. They also explore ways to test these new models with cutting-edge observations of the cosmic microwave background, large-scale structure, the neutral hydrogen 21-cm line, cosmic rays and data from the Large Hadron Collider.

Experimental and Observational Cosmology

Matt Dobbs

The McGill experimental cosmology group designs and builds new instrumentation for observational cosmology and develops analysis techniques for upcoming large cosmological surveys, including surveys of the cosmic microwave background and the 21 cm line of neutral hydrogen. They deploy and operate instruments wherever the observing conditions are best — from the geographic South Pole to the top of the Stratosphere to the South African desert, as well as analyze and interpret the data from these experiments to gain a better understanding of the origin, fate, and fundamental constituents of the Universe.

Galaxy and Supermassive Black Hole Co-Evolution

Tracy Webb, Daryl Haggard

The galaxy and black hole evolution group is interested in understanding when galaxies form the bulk of their stellar mass and what drives and later shuts down this process; how the local environments of galaxies affect their evolution and growth; how growing supermassive black holes interact with their host galaxies and galaxy clusters; and how our own supermassive black hole, Sgr A*, impacts the Milky Way galaxy.

Gamma Ray Astrophysics

David Hanna, Ken Ragan

The Gamma Ray Astrophysics group is part of the VERITAS collaboration which operates an array of four 12-m imaging atmospheric Cherenkov telescopes in southern Arizona. With this instrument they carry out a program of very-high-energy (VHE) gamma-ray astronomy, observing photons with energy in the range from 50 GeV to 50 TeV. Sources of such photons are among the most violent and exotic in the Universe and include supernova remnants and pulsar wind nebula in our galaxy, as well as blazar-class active galactic nuclei (AGNs) at cosmological distances. The group also develops instrumentation for the VERITAS detector including calibration and characterization devices.

Compact Objects

Andrew Cumming, Daryl Haggard, Vicky Kaspi

The observational pulsar and black hole groups are involved in several projects including: searches for radio pulsars, using pulsar timing arrays to detect gravitational waves (GW), detection of electromagnetic counterparts to GW sources, X-ray observations of both magnetars and accreting black holes, and development of pulsar instrumentation and algorithms for the CHIME telescope. The theory group studies the structure of neutron stars and how to use observations to constrain the physical processes operating in their interiors. They investigate the origin and evolution of neutron star's spin and magnetism, their interior structure, and the properties of neutron stars in close binary systems.

Radio Transients

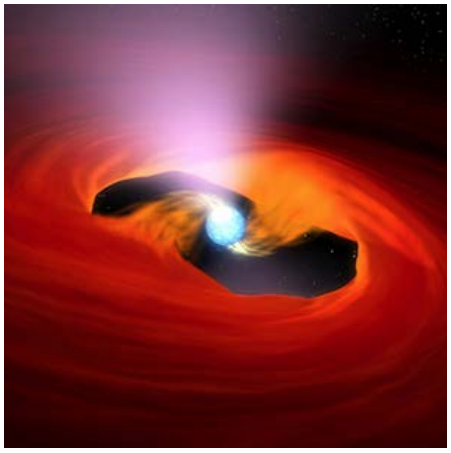
Vicky Kaspi, David Hanna, Matt Dobbs

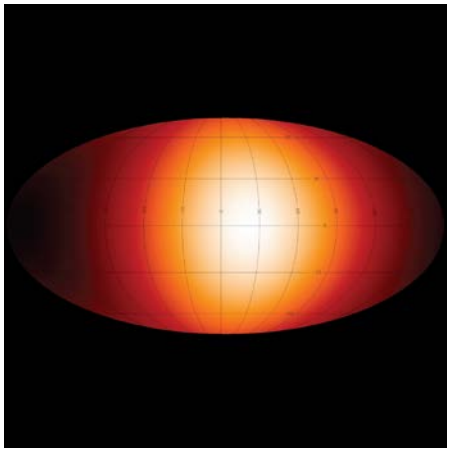
The radio transients group studies short-duration flashes of radio waves from new and unexpected astrophysical phenomena. Their most active area of research is in Fast Radio Bursts (FRBs), mysterious, powerful, millisecond-long flashes of radio waves that originate outside of the Milky Way galaxy. To study these phenomena, the group uses several world-class radio observatories, including the Arecibo Observatory, the Green Bank Telescope and the newly-built CHIME telescope.

Nuclear Astrophysics

Andrew Cumming

Nuclear astrophysics, at the intersection of astrophysics and nuclear physics, is study of the origin of the chemical elements in stars and supernovae, explosive events such as supernovae, classical novae, and X-ray bursts, and the properties of matter at high densities as found in the interiors of neutron stars. Nuclear astrophysics research at McGill is focused on developing connections between nuclear properties and astrophysical observations through the study of neutron stars, in particular by modelling the transient behavior of accreting neutron stars on timescales of seconds to years.





Climates and Atmospheres of Exoplanets

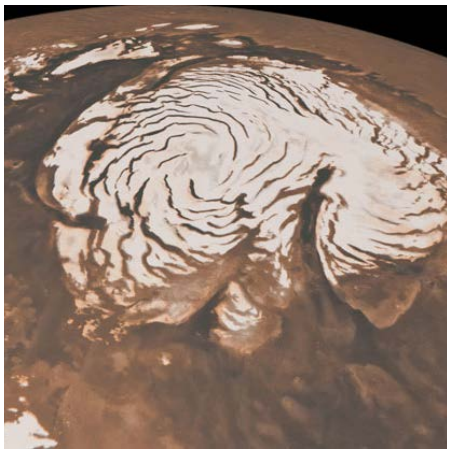
Nick Cowan, Andrew Cumming, Yi Huang, Tim Merlis

The extrasolar planet climate and atmosphere group works to characterize exoplanets using both observational evidence and climate modeling. Observations for exoplanetary atmospheres comes from a variety of sources including changes in brightness of the planet over time, spectroscopy, and upcoming next-generation direct-imaging experiments. Members also use computer models to expose the physical mechanisms of planet atmospheres by expanding climate models beyond the conditions found on Earth to simulate the wide range of possibilities of atmospheres on exoplanets. Much of this work is carried out as part of the Institute for Research on Exoplanets (iREx).

Formation and Evolution of Exoplanets

Andrew Cumming

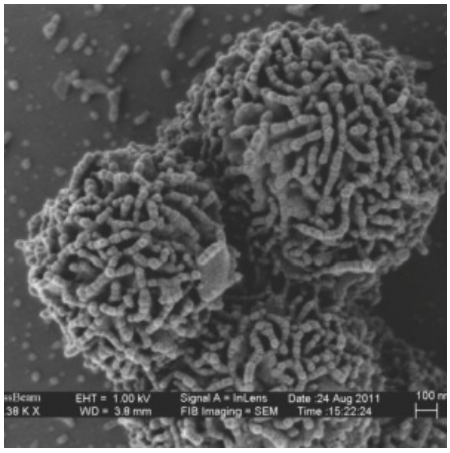
The large number and diversity of known exoplanets gives an opportunity to learn about how planets form and evolve, and the physical processes that operate in their atmospheres and interiors. The challenge is to draw connections between the observed properties of exoplanets or Solar System planets and theories of their formation, structure, and evolution. At McGill, we are working on several different aspects of the evolution of gas giant planets, including the role of magnetic fields in hot Jupiters, and models of gas giant formation with application to directly imaged planets.



Planetary Surfaces

Nick Cowan, Natalya Gomez

Members of the planetary surface group model the interactions between ice, water, climate and planetary interiors, and how these connections change planets surfaces through time. These models are applicable to both the Earth and other rocky, icy planets and moons in the Solar System. Members also remotely study the surfaces of exoplanets using current missions, and help design future missions that could map the surfaces of these distant worlds.



Astrobiology & Extraterrestrial Biosignatures

Lyle Whyte

Members of the Astrobiology and Extraterrestrial Biosignatures group focus on examining microbial biodiversity and ecology in the Canadian high Arctic and the Antarctic dry valleys where very unique habitats exist, using both classical microbiology and novel genomics-based molecular techniques for studying microbial communities. Understanding what types of microorganisms could survive or be active in these types of soils, as well as detecting biosignatures (in the form of dormant or dead cells, and nucleic acids, for example), is important to understanding what future missions could look for in near surface water ice on Mars in the north polar regions or other cold, rocky places in the solar system.

A Hot, Black Planet

Research lead by MSI master's student Taylor Bell, showed that an oddball planet, WASP-12b, reflects almost no light and may teach us about how clouds form on hot Jupiters, massive exoplanets that orbit extremely close to their host stars.

The planet originally discovered in 2008, is unlike anything that exists in our solar system. It is about 1.4 times Jupiter's mass and orbits its star every 1.1 days. This extremely close orbit means that the planet is probably tidally locked to its host star, with one side of the planet always facing the star and one side always facing away from the star. This creates a huge temperature difference between the permanent day- and nightside of the planet, 2500 degrees Celsius on the side facing the star and 1500 degrees Celsius on the side that faces away.

Bell's observations showed that WASP-12b reflects remarkably little light (less than 6%), making it as black as fresh asphalt. This very low reflectivity, or albedo, means there cannot be any clouds on the dayside of the planet, even though previous publications report evidence that there may be clouds along the boundary between day and night.

When Bell initially tried to model the atmosphere of WASP-12b using standard planetary atmosphere models, he got some puzzling results. "When my code spat out an extremely low value we were all pretty baffled" said Bell. "Later we considered another model based on stellar atmospheres, rather than Earth's atmosphere, which was able to explain this very low albedo."

It turns out that the dayside of Wasp 12-b behaves more like a star than a planet. The molecular hydrogen (along with other molecules with water) in the planet's extremely hot dayside is broken down into individual atoms, which means that different effects, typically seen only in stars, lower the planet's albedo.

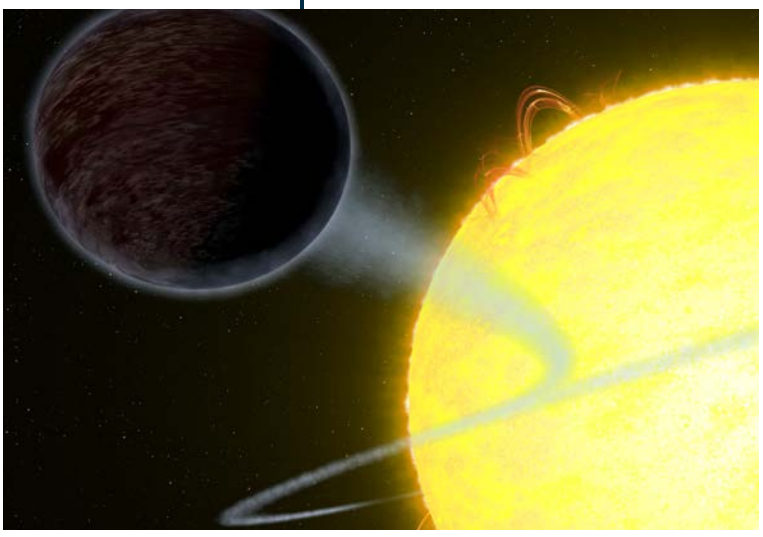
While the results from WASP-12b were unexpected, this is par for the course in the emerging field of modeling exoplanet atmospheres. According to Bell "there are a vast number of exoplanets that have been discovered, but we know little about most of them. Each planet that is characterized tends to surprise us."

Bell, T. J., Nikolov, N., **Cowan, N. B.**, et al. 2017, *The Very Low Albedo of WASP-12b from Spectral Eclipse Observations with Hubble*, ApJL, 847, L2

Why this is important

If hydrogen chemistry explains the very low albedo of WASP-12b, then all hot Jupiters with dayside temperatures as hot or hotter than WASP-12b should have equally low albedos. Currently there are only a few such planets known, but the upcoming TESS mission is expected to find hundreds more which could be easily characterized. The dissociation and recombination of molecular hydrogen should also have observable signatures in the orbital phase variations which will allow researchers to directly measure the wind strengths on the planet.

Taylor Bell *is a MSI graduate Fellow and Master's student under the supervision of Prof. Nicolas Cowan. His research focuses on better understanding the atmospheres of hot Jupiter-mass exoplanets using observations of thermal and reflected light.*



» Artist's impression of WASP-12b. NASA, ESA, and G. Bacon (STScI)

Merging Neutron Stars in X-rays and Gravitational Waves

Why this is important

The detection of X-rays from this gravitational wave event directly confirms that short gamma-ray bursts are produced in neutron star-neutron star mergers. Modeling of X-ray observations show that this is the first off-axis short gamma-ray burst ever detected. Detecting light (e.g. X-rays) from a gravitational wave event ushers in the long-awaited dawn of 'multi-messenger' astronomy, where both light and gravitational waves from a source can be studied together.

Prof. Daryl Haggard *is an Assistant Professor of Physics at McGill University in the McGill Space Institute. She studies the Galactic center and Sgr A*, electromagnetic counterparts to gravitational wave sources, accreting compact objects, supermassive black holes and their host galaxies, and multi-wavelength and time domain surveys.*

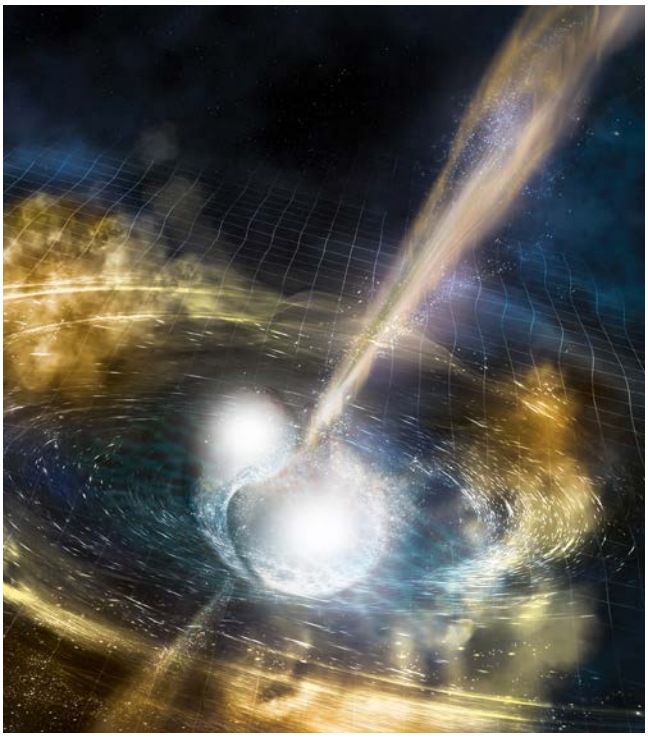
On the morning of August 17, 2017, MSI Professor Daryl Haggard was in her office when she received some exciting news — that LIGO (the Laser Interferometer Gravitational-Wave Observatory) had seen a new gravitational wave signal, ripples in spacetime made in the last seconds of the merger of massive, compact objects.

Attempts to observe an electromagnetic counterpart (a signal in some form of light) of the four previous mergers detected since LIGO came on line in 2015 had come up short, but those four mergers were pairs of black holes and were not expected to give off any light.

This time was different. Instead of colliding black holes, data from the fifth signal detected by LIGO pointed to a pair of merging neutron stars. Neutron stars, the corpses of massive stars, are extreme objects. They are about twice the mass of the Sun and about the size of the island of Montreal, making them incredibly dense.

The question that Haggard and her collaborators, including MSI postdocs Mel Nynka and John Ruan, had that August morning was: did they have enough evidence to "trigger" the space-based Chandra X-ray observatory to search for an X-ray signal from the gravitational wave source?

In the weeks that followed, "there was a world-wide collaboration of astronomers searching for electromagnetic emission from the neutron star merger, from those detecting neutrinos in the South Pole to astronomers using the



» Artist's impression of a neutron star-neutron star merger. National Science Foundation/LIGO/Sonoma State University/A. Simonnet

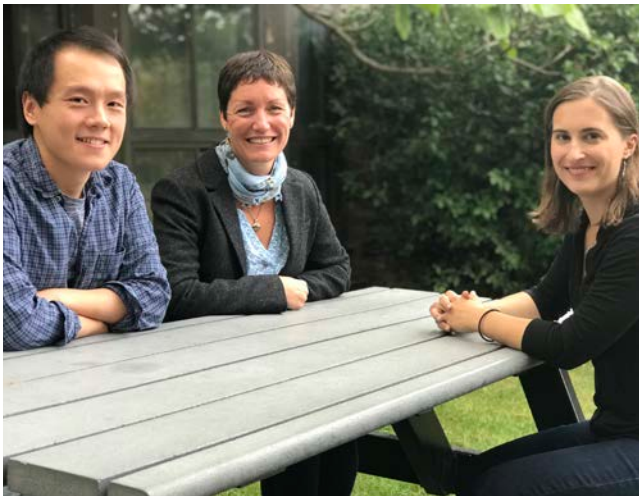
Hubble telescope to space-based gamma ray observatories," said Nynka, "It was both humbling and exciting to be a part of such an enthusiastic, global collection of scientists."

By August 19, observations detecting the merger in gamma-rays and visible light had pinpointed the location of the merger, giving Haggard's team enough information to initiate their Chandra observations. At first, their results were the same as those for previous studies of merging black holes — a non-detection in X-rays. However, observations taken 15 days later show a distinct X-ray source at the location of the merger.

"This was entirely unexpected," said Ruan, "our modeling [of the X-ray observations] showed that it is due to the jet from the gamma-ray burst produced in the neutron star-neutron star merger being off-axis (i.e. pointed away from the Earth)." This was the first confirmation that the cosmic explosions known as short gamma-ray bursts are the product of neutron star mergers and the first detection of an off-axis gamma-ray burst.

Haggard notes that "observations at other wavelengths also showed us that this merger led to a so-called kilonova. These explosions are crucial for making elements heavier than iron, like platinum, gold, silver, which make up almost half of our periodic table. So we've connected together gravitational waves, gamma-ray bursts, off-axis jets, and kilonova explosions, all in one exciting detection. That just doesn't happen every day."

Haggard's team is eagerly awaiting further observations in December, when the Chandra X-ray Observatory's orbit puts the location of the merger far enough away from the sun to safely observe it again. How the X-rays observed from the energetic jet change over time will give her team the additional pieces of information needed to understand the details of the merger and how the jet interacts with its surroundings.



« *from left to right: John Ruan, Daryl Haggard and Mel Nynka.*

Haggard, D., Nynka, M., Ruan, J. J., et al. 2017, *A Deep Chandra X-Ray Study of Neutron Star Coalescence GW170817*, ApJL, 848, L25

2017 Nobel Laureate Rai Weiss visits

Rai Weiss, professor emeritus at MIT, visited the McGill physics department in March of 2017 to give a public and scientific Anna I. McPherson Lecture about his work planning, developing and then making the first discoveries of black hole mergers in gravitational waves with LIGO. During his visit, he met with students from the MSI and the physics department.

Weiss along with Barry Barish, and Kip Thorne won the 2017 Nobel Prize in Physics "for decisive contributions to the LIGO detector and the observation of gravitational waves."

Latest news from the McGill Space Institute

First Light for the CHIME telescope

Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a new radio interferometer located at the Dominion Radio Astrophysical Observatory (DRAO) in British Columbia. At the McGilll Space Institute, ***Prof. Matt Dobbs****,* ***Prof. David Hanna*** *and* ***Prof. Vicky Kaspi*** *are involved with CHIME along with nearly two dozen McGill students, postdoctoral fellows and technicians*

CHIME, the $16M new Canadian radio telescope, saw its "First Light" on September 7th and was celebrated at a ceremony in Penticton, BC involving Federal Minister of Science, Kirsty Duncan.

The telescope is designed to simultaneously make unprecedented maps of the distant universe to understand the nature of dark energy, study pulsars, and help determine the origin of the mysterious phenomenon of Fast Radio Bursts.

Now that all the major components are in place, the first data from the instrument is starting to be collected. "After years of work it's fantastic to finally see the graphs showing real sky data coming through the system on all channels," said Nolan Denman, a graduate student at the University of Toronto, who produced the first light plots after an overnight session collecting data during the transit of Cygnus A (a nearby galaxy that is bright at radio wavelengths and is a useful source for calibrating the instrument).

Science

CHIME will probe the fundamental nature of dark energy, the mysterious agent that causes the accelerated expansion of the universe, by producing a three-dimensional map of the 21-cm emission from neutral hydrogen that covers the entire northern sky and spans redshifts 0.8 to 2.5. This will enable a measurement of Baryon Acoustic Oscillations (BAO) in the large scale distribution of neutral hydrogen — a relic that originates from sound waves propagating in the early universe. The size of the BAO feature will be used as a standard ruler to measure the expansion history of the universe during the epoch when dark energy generated the transition from decelerated to accelerated expansion.

Two further key science projects are currently under commissioning and will soon be conducted simultaneously alongside the cosmology experiment. These include a blind survey for Fast Radio Bursts (FRBs), energetic single pulses of radio emission arriving in

Future of CHIME

CHIME is now in its commissioning phase, in preparation for science operations. This new telescope will bring Canada to the forefront of an emerging important and technically challenging domain of radio astronomy. More information on CHIME can be found at chime-experiment.ca.

« CHIME at night: The telescope consists of four parabolic cylinders that are 20 m wide and 100 m long with a focal length of 5 m. It has no moving parts, instead relying on the earth's rotation to move the sky across its field of view.

random directions from unknown sources well beyond our galaxy. So far progress in resolving the mystery of their origin has been limited by the low survey efficiency of traditional single dish telescopes. With its huge field of view and broad frequency coverage, CHIME is a nearly ideal instrument for finding and studying many of these bursts. "It has taken almost 10 years to observe 25 FRBs with different telescopes" noted McGill postdoc Emmanuel Fonseca, adding, "CHIME is expected to detect 25 FRBs within one week of operation." Pinning down their rate will be crucial for determining the origin of FRBs.

The other project that CHIME will carry out is pulsar timing. CHIME will monitor the pulses from all known pulsars in the Northern hemisphere visible from Penticton, every day. Among other things, this information will aid in the search for gravitational waves — traveling ripples in space-time — passing through our galaxy.

Hardware

CHIME surveys the northern half of the sky every day as the earth rotates. It is composed of four cylindrical reflecting surfaces that resemble snowboard half-pipes and have a total collecting area equivalent to five hockey rinks (8,000 m^2). It records the information from all the radio waves that hit its surface with over a thousand antennas, made out of conventional low loss circuit boards that can be mass produced economically.

The CHIME correlator converts the massive amount of information that is contained in the radio waves incident on the cylinders into an image of the overhead sky. Measured in number of analog inputs (N=2048) squared times bandwidth (400 MHz), the CHIME correlator is the largest radio correlator in the world — and it was built for a comparatively low price. The correlator employs 128 field programmable gate arrays (FPGAs) to digitize the analog radio signals collected by the antennas and channelize their full bandwidth into 1024 narrow frequency bins. The FPGAs are interconnected through custom, full-mesh backplanes that enable a massive reorganization of 6.6 Terabit/second of data into the format required to compute the N^2 correlation matrix of the signals measured by the antennas. The data is then transmitted over more than a thousand fiber optic cables to a supercomputer.

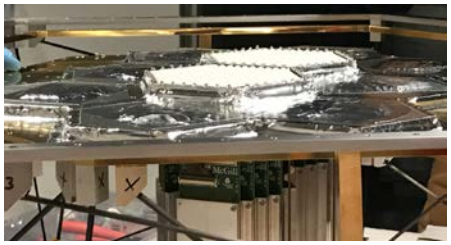
Using the data from the FPGAs, the CHIME supercomputer creates detailed sky maps and performs real-time beamforming which is used for the FRB and pulsar applications. This requires a huge amount of computing power, which was made possible thanks to the existence of low cost Graphics Processing Units (GPUs) from AMD, which were developed primarily for computer games, but are increasingly leveraged by scientists to perform complex calculations. In total CHIME has 1024 high end GPUs, spread out over 256 servers. Together they are able to perform over 7 quadrillion (a million billion) operations per second.

Undergraduate and graduate students played a key role in the assembly, testing, and on-site installation of the instrument. "My favourite part of working on CHIME has been interacting with all the wonderful people involved in this project. The team's enthusiasm and devotion is contagious" said Emilie Storer, an undergraduate student at McGill who helped test the FPGA motherboards.

» **Top:** *Minister of Science, Kirsty Duncan and Prof. Vicky Kaspi walk under the telescope at the CHIME first light ceremony.*

» **Below:** *Postdoc Cherry Ng connecting some of the 2048 50m-long coaxial cables; Postdoc Emmanuel Fonseca and summer intern Tristan Simmons raising feeds onto the focal line; Graduate student Nolan Denman assembling GPUs in the X-engine; Graduate student Juan Mena Parra installing FPGA motherboards.*

South Pole Telescope 3rd Generation Receiver



From November 2016 to February 2017 the McGill Cosmology Instrumentation Laboratory team from McGill installed the readout system for the new South Pole Telescope microwave receiver at the Amundsen-Scott research station in Antarctica.

This 3rd generation instrument represents a major upgrade for the South Pole Telescope, increasing the number of detectors by about an order of magnitude. The instrument is designed to measure the cosmic microwave background (CMB) B-mode polarization, exposing the signatures of gravitational lensing and, perhaps, evidence of gravitational waves from the early universe. The camera, like its predecessor, used readout electronics developed and built at McGill. Joshua Montgomery and Matt Dobbs were at the South Pole representing McGill, part of a much larger team that includes our partners from across the United States. Together, the team logged more than 1100 days at the South Pole, bringing this project to fruition.

The team is now preparing for its next polar mission, for maintenance and improvements to the camera. Graduate students Gavin Noble and Joshua Montgomery will journey to the South Pole, and Joshua plans to spend the dark, cold winter there operating the telescope.

The South Pole Telescope is also used as part of the Event Horizon Telescope (EHT), an ultra-long baseline interferometer that provides the resolution necessary to image the black hole at the center of our galaxy. During the austral summer, new interferometric observations were carried out with the South Pole Telescope providing an extreme southern baseline for the EHT.

« ***Top:*** *The focal plane of the South Pole Telescope 3g camera.*

Middle: *Amy Bender (Argonne National Lab, formerly a McGill postdoc) and Matt Dobbs (McGill) assembling the cryogenic wiring for the focal plane.*

Bottom: *The crew at the South Pole late night December 3 after closing the cryostat for its first cooldown.*

A possible dark origin of Matter

Why is there something, rather than nothing? While we know that there must have been more matter than antimatter created in the first moments after the Big Bang, we don't know why. One clue to the possible origin of this asymmetry between baryonic matter (protons and neutrons, normal matter that we are familiar with) and antimatter comes from a recent paper published by MSI professor Jim Cline and his collaborators.

According to Cline, this asymmetry, which is not predicted by current particle physics theory, "is one of nature's main clues to us that there must be new particles and interactions beyond those in the standard model of particle physics."

In a meeting with a colleague at the Aspen Center for Physics, a discussion lead to a novel idea — that bubbles in the Higgs field and a new dark matter particle play an important role in creating the baryonic matter/antimatter asymmetry.

Other theories of the origin of baryonic matter, or baryogenesis, work at energy scales that are too large to test with current laboratory experiments. Cline's theory of "electroweak baryogenesis", which works at energies associated with the electroweak interactions, is testable with current particle colliders. The theory makes a prediction of new interactions between standard matter particles, which could be observed by the Large Hadron Collider (LHC) at CERN.

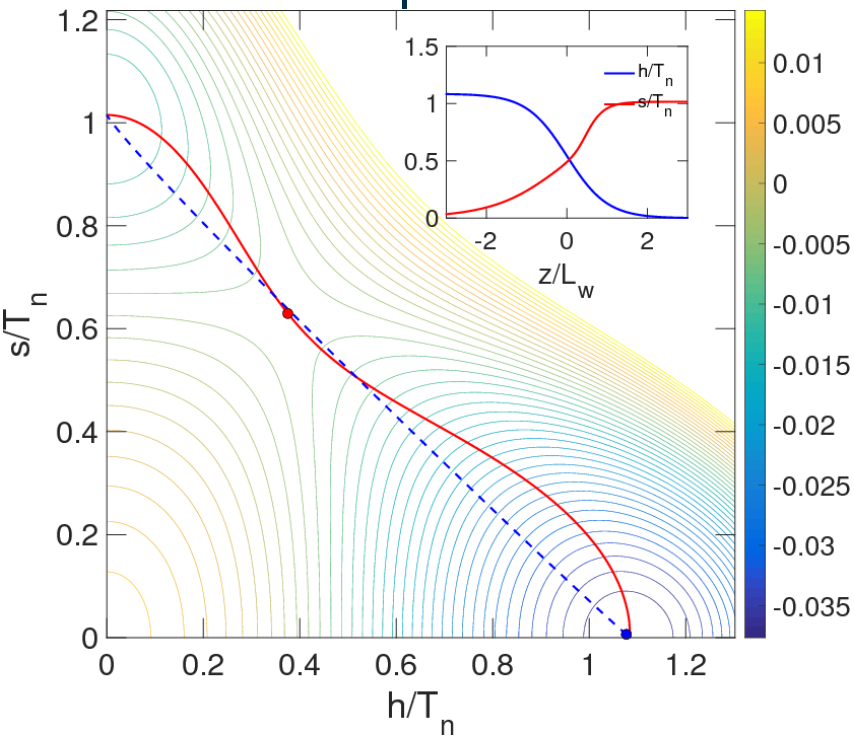
Cline emphasized the importance of working with his collaborators Kimmo Kainulainen, and David Tucker-Smith, "We had a few false starts, finding theories that seemed to work, then discovering that there was a problem. I almost convinced myself that the kind of theory we were seeking was impossible for various reasons, before we discovered one that worked."

Cline, J. M., Kainulainen, K., & Tucker-Smith, D. 2017b, *Electroweak baryogenesis from a dark sector*, PhRvD, 95, 115006

Why this is important

It opens up a new possibility, the idea that dark matter has interactions that don't respect the symmetry between particles and antiparticles, and this eventually leads to the baryon asymmetry at the electroweak scale. Even if our particular example turns out to be wrong, this more general idea could prove to be correct.

Prof . Jim Cline *is a professor of Physics at McGill University and CERN. His research focuses on the interface between particle physics and cosmology.*



» Shape of the bubble wall of the Higgs field used in Cline's electroweak baryogenesis model.

Research Highlight

The first host galaxy for a Fast Radio Burst

Why this is important

This was the first precise localization of a fast radio burst and the first direct distance measurement. This result allowed us to understand the energetics of FRBs, the type of environment in which it was formed and gave clues to what sort of objects could dwell there.

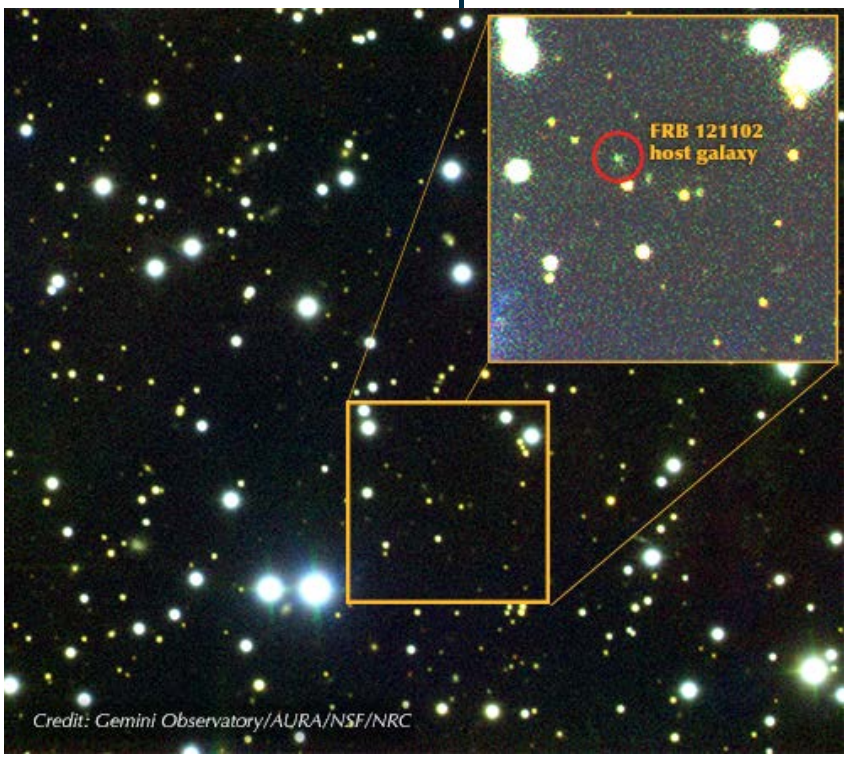
Dr. Shriharsh Tendulkar *is a Trottier postdoctoral fellow working under the supervision of Prof. Victoria Kaspi. His research interests include exploring the origins of fast radio bursts (FRBs) with CHIME and other telescopes and studying high energy phenomena in magnetars.*

Fast radio bursts (FRBs) are incredibly bright, mysterious flashes of radio light that last for only a few milliseconds and seem to be coming from all directions in the sky. Current observations suggest that these events are incredibly common — several thousand go off every day across the whole sky.

FRBs appear to come from extragalactic distances, suggesting that they are a trillion times brighter than the brightest radio pulses from pulsars, the rotating neutron stars typically associated with blips of radio light in our galaxy.

Since the first FRB was detected 10 years ago, their causes and their origins remained a mystery. One key step to solving this puzzle is to find the exact location on the sky of an FRB to see if they have counterparts at other wavelengths of light.

A group lead by MSI postdoc Shriharsh Tendulkar used the Very Large Array (VLA, multi-dish radio telescope array in New Mexico) to successfully pinpoint the exact location of a FRB for the first time. This observation was made possible because one FRB (FRB 121102, named after the date of the initial burst in 2012) was seen to burst more than once, a pattern first detected in late 2015 by former McGill Space Institute PhD student Paul Scholz.



While FRB 121102, sends out bursts on an unpredictable schedule, Tendulkar's team was able to use 83 hours VLA observations over six months to observe nine bursts from FRB 121102 and determine its exact location. At first, the only image the team had was a quick snapshot image taken by the Keck telescope in Hawai'i. It showed a small smudge at the location of the radio observations. While it was unclear whether the smudge was a star or a tiny galaxy, they found it puzzling that such a big flash of radio light could come from such a small, blurry object.

To try and determine what exactly the smudge was, the team took a spectrum of the object with the Gemini telescope. As they waited for data to download, Tendulkar

« Gemini telescope image showing the host galaxy of FRB 121102

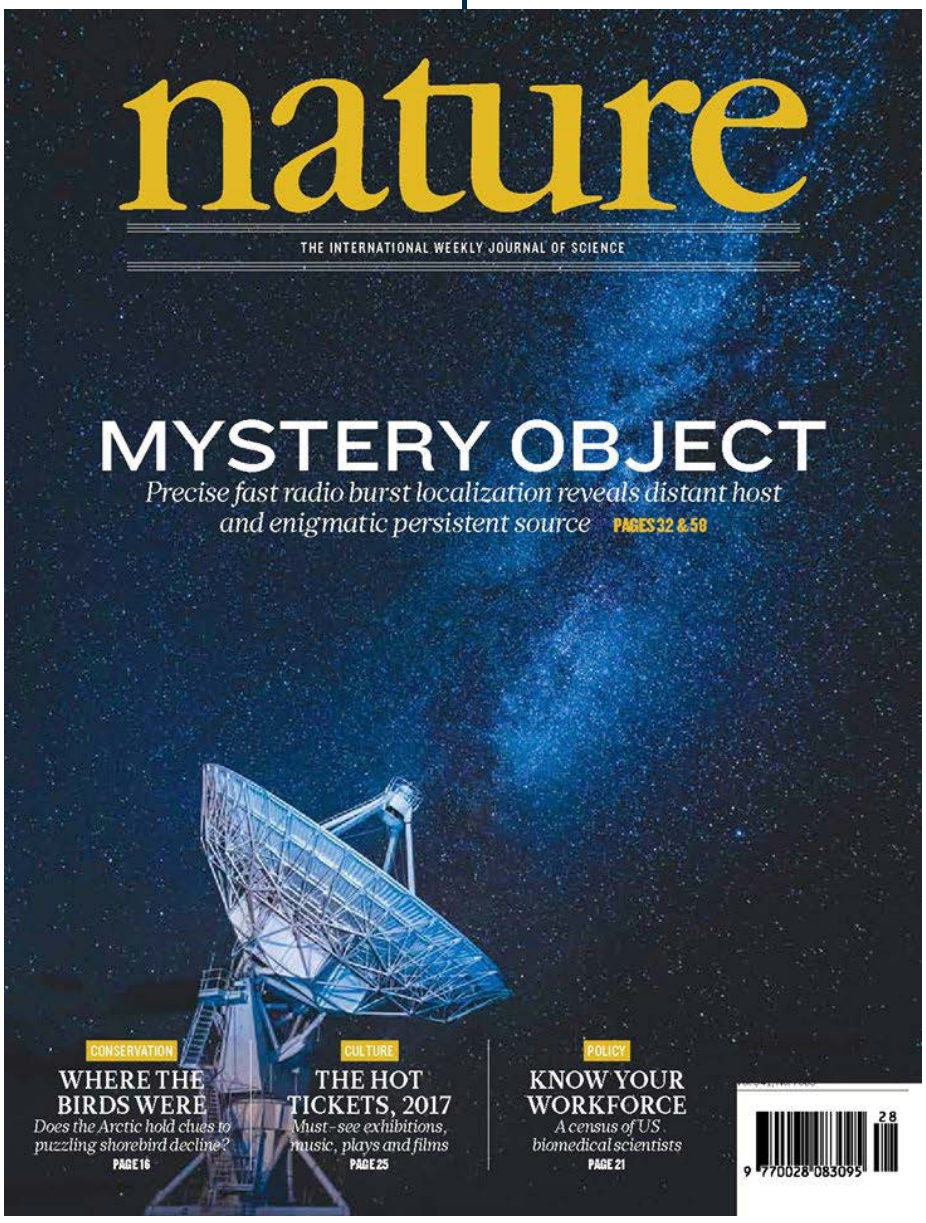
discussed the worst case scenarios with a collaborator, fearing that they might have to spend a considerable amount of effort over many days to make sense out of a faint signal.

However, they were pleasantly surprised, "As soon as we opened the files," Tendulkar said, "we just shouted in joy because it was clear from the extremely bright signatures of hydrogen and oxygen molecules that it was a galaxy that was forming stars at a rapid rate. Within 20 minutes, we were able to announce to the rest of the collaboration the distance to the FRB, and the type of galaxy it was in."

The host of the FRB was a dwarf galaxy with about a thousandth as many stars as the Milky Way, about 3 billion light years away from the Earth. While the discovery was able to definitively prove that FRBs come from distant galaxies (and not from within the Milky Way), the nature of the host galaxy poses additional questions.

"The host galaxy for this FRB appears to be a very humble and unassuming dwarf galaxy, which is less than 1% of the mass or our Milky Way galaxy," Tendulkar said. "That's surprising. One would generally expect most FRBs to come from large galaxies which have the largest numbers of stars and neutron stars — remnants of massive stars. This dwarf galaxy has fewer stars, but is forming stars at a high rate, which may suggest that FRBs are linked to young neutron stars. There are also two other classes of extreme events — long duration gamma-ray bursts and superluminous supernovae — that frequently occur in dwarf galaxies, as well. This discovery may hint at links between FRBs and those two kinds of events."

The newly-built Canadian Hydrogen Intensity Mapping Experiment (CHIME), an interferometric radio telescope in British Columbia, could help answer some of the remaining questions about FRBs. CHIME will survey half the sky each day, and may detect dozens of FRBs per day. MSI professor and FRB researcher Victoria Kaspi notes that "Once we understand the origin of this phenomenon, it could provide us with a new and valuable probe of the Universe."



Tendulkar, S. P., Bassa, C. G., **Cordes, J. M.**, et al. 2017b, *The Host Galaxy and Redshift of the Repeating Fast Radio Burst FRB 121102* ApJL, 834, L7

Chatterjee, S., Law, C. J., Wharton, R. S., **Tendulkar, S. P.**, **Kaspi, V. M.**, et al. 2017a, *A direct localization of a fast radio burst and its host*, Nature, 541, 58

Research Highlight

Muon Hunters: A Citizen Science Project

Why this is important

The VERITAS team received a phenomenal response from volunteers to the Muon Hunter project. The input from volunteers helped the collaboration gain insight into where the standard analysis is lacking, and train an updated machine learning model using convolutional neural networks. The Muon hunter project is an example of how citizen science is a great resource for both outreach and practical science, as well as an example of how advances in machine learning algorithms can be applied to astrophysics.

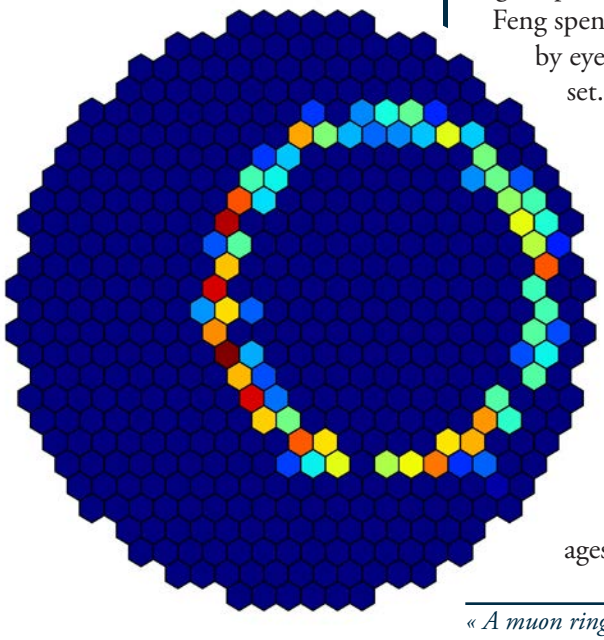
Dr. Qi Feng *was a postdoctoral fellow at the McGill Space Institute and a member of the VERITAS Collaboration. He is now a Postdoctoral Research Scientist at Columbia University.*

In southern Arizona, VERITAS (Very Energetic Radiation Imaging Telescope Array System) watches the nighttime desert sky for flashes of blue Cherenkov light with an array of four 12-meter telescopes.

When the high energy gamma-rays from astronomical objects hit the Earth's atmosphere, they make a shower of particles. Because these high-velocity particles move faster than the speed of light in air, but slower than the speed of light in a vacuum, they produce eerie blue light, called Cherenkov radiation, through a process similar to a sonic boom. VERITAS uses Cherenkov light to study the gamma-rays produced by some of the most extreme objects in the universe, including supernova remnants, active galactic nuclei and potentially even dark matter.

Unfortunately, cosmic rays — high energy particles from space, such as protons and electrons — also produce particle showers and Cherenkov light when they hit the Earth's atmosphere. One major challenge for the VERITAS team is to separate the Cherenkov light flashes made by Gamma-rays from the background events made by cosmic rays.

At a recent meeting of the VERITAS collaboration, MSI postdoc Qi Feng presented his work on the development of improved machine-learning algorithms to detect the signatures of one particular type of cosmic ray event, a shower of muons (the electron's fatter, shorter-lived cousin). Muons produce distinctive ring-shaped images in the VERITAS cameras. In order to train his algorithms, Feng spent a lot of time going through VERITAS data to pick out muon rings by eye, but had hard time finding enough images to make a proper data set.



« A muon ring as seen by the VERITAS telescope cameras.

Already on the lookout for a project using VERITAS data that would work on the Zooniverse citizen-science platform, collaborator Lucy Fortson wrote in a blog post that "it became immediately obvious that we should work with Qi to help him obtain the images he needed for his project."

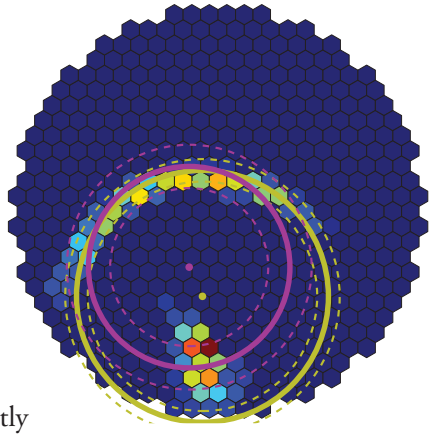
Several members of the VERITAS collaboration worked to build the Muon Hunter project on the Zooniverse, where volunteers without any specialised background, training, or expertise could identify muon rings by drawing circles on images from the VERITAS camera.

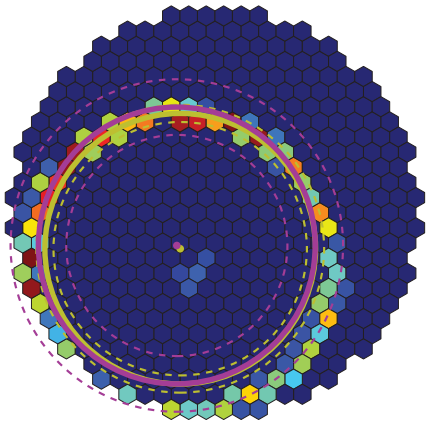
The project launched on 28th February, 2017 and ran out of images for volunteers to classify by April 20th. About 137,000

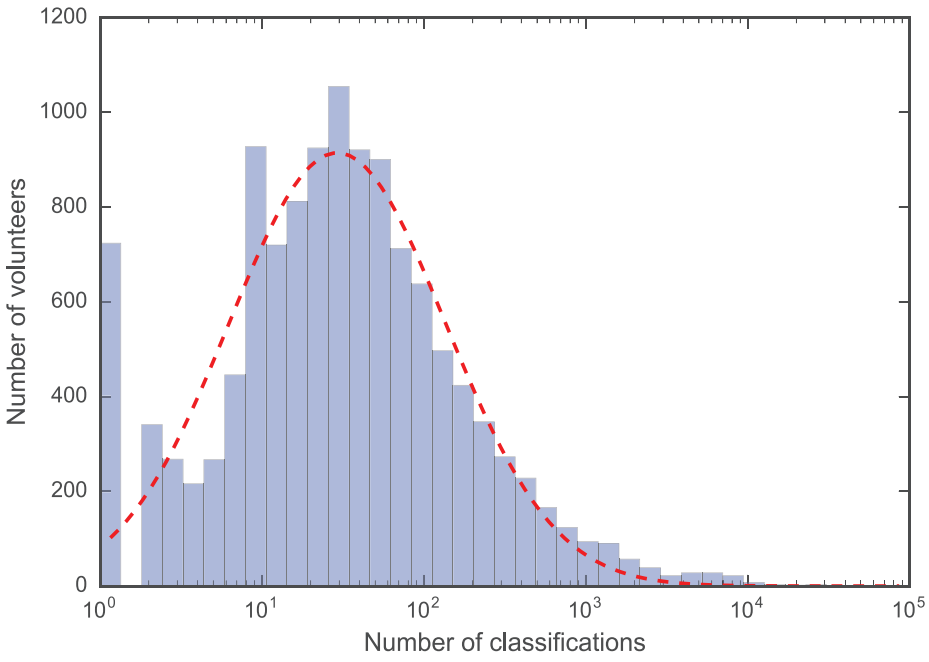
VERITAS single-telescope images were served on the Muon Hunter website. The project received about 2.1 million classifications, half within the first week after the official launch of the project, from 5,734 volunteers. While 724 volunteers only classified one image, 16 volunteers classified more than 10 thousand images each. Roughly 25 percent of the volunteers were under 18 years old.

Using the updated, larger data set provided by harnessing the pattern recognition power of the human brains of Muon Hunters volunteers, Feng was able to improve the accuracy of his model from ~95% to 97%. He was also able to demonstrate some flaws of the earlier model, which were due to the small number of images used in the original training.

Over 5,000 ordinary citizens were able to contribute meaningfully to cutting-edge research, as well as learn about the science behind the images that they classified. Thus, citizen science projects like Muon Hunters, are both a powerful way to sort through large data sets, and a unique outreach opportunity that allows the public to directly participate in the process of doing science.







Feng, Q. for the VERITAS Collaboration, Jarvis, J. 2017, *A citizen-science approach to muon events in imaging atmospheric Cherenkov telescope data: the Muon Hunter*, ArXiv e-prints, arXiv:1708.06393

» **Top:** *Muon rings identified by the older algorithm (magenta), and the Muon Hunter volunteers (yellow). solid lines and dashed lines show the mean and the standard deviation of the radius of the ring.*

» **Middle:** *Histogram showing the number of classifications each Muon Hunter volunteer made.*

» **Bottom:** *The VERITAS observatory in Arizona.*

Education and Public Outreach

AstroMcGill was founded in 2011 by an enthusiastic group of students and post-doctoral fellows. It serves as the education and public outreach (EPO) branch of the astrophysics group within the Physics Department at McGill University and the McGill Space Institute.

AstroNights

On the third Thursday of every month, AstroMcGill holds Public AstroNight. These events consist of a public talk given by a professional astronomer, usually a McGill student or professor, aimed at a broad audience. After the lecture, student volunteers lead night sky observations with portable telescopes (weather permitting).

Astronomy on Tap MTL

Astronomy on Tap events feature accessible, engaging presentations on topics in astronomy plus astronomy-themed trivia games and prizes, held in local Montreal bars. Events are held on the last Tuesday of the month and alternate between English and French nights.

AstroKids Night

AstroMcGill held an AstroKids Night event as part of the Quebec-wide science festival *24 Hours of Science* in May 2017. They welcomed kids of all ages to the Rutherford Physics building on the McGill campus for an evening of fun astronomy-themed hands-on activities, including exploring gravity, playing with light and colour, and building our own comets. Over 150 children attended the event with their parents.

McGill Teacher Inquiry Institute

Every year, AstroMcGill and Physics Matters organise the McGill Teacher Inquiry Institute. This one-day programme targets primary school teachers from the English-language Lester B. Pearson school board who self-identified as uncomfortable with teaching science in their classrooms. The Inquiry Institute gives teachers a safe space to address anxieties related to teaching science topics, allows them access to student volunteers who act as subject-matter experts, and gives teachers appropriate hands-on, inquiry-based lesson plans to use in their classrooms. In 2017 AstroMcGill lead an inquiry-based activity on the reason for the seasons.

Social Media

AstroMcGill is active on social media. The group has over 3,500 followers on Facebook and regularly have over 1000 people interested in AstroMcGill events. The AstroMcGill twitter account (@AstroMcGill), has over 2000 followers. There are also 950 people subscribed to the AstroMcGill mailing list.

Audience

AstroMcGill is notable not just for their enthusiasm and the breadth of the events that they organise, but also the diverse, young audience that they attract. Surveys of audience members done at AstroMcGill events found that 20-60% of all audience members were at their first Astronomy-themed event and a small contingent (10-20%) have come to 10 or more events. AstroMcGill is able to maintain a loyal fan base and attract hundreds of new people every month.

Surveys show that their audience is about 40/60 female/male, with a median age in the 25-35 age group. So while their audience is young, it extends beyond University students. About 55% of the audience members speak English at home, coming from either English-only, bilingual English/French or bilingual English/other language households. This suggests that although most talks are in English, their reach is beyond the Anglophone community in Montreal.

« **Left:** *MSI graduate student Robert Archibald leads a telescope observing session after a Public AstroNight talk.*

» **Top right:** *Teachers study yearly temperature observations in the Northern and Southern hemispheres at the McGill Teacher Inquiry Institute.*

» **Middle right:** *Over 450 people showed up to see The linguistics of Arrival: Aliens, fieldwork, and Universal Grammar by Prof. Jessica Coon.*

» **Bottom:** *MSI coordinator Kelly Lepo snaps a selfie with the AstroMcGill infrared camera.*

Solar Eclipse Watch MTL 2017

On August 21, 2017 a solar eclipse was visible from all of North America. The path of the total eclipse traveled across the United States, from Oregon to South Carolina. Observers in Canada were able to see a partial eclipse (from about 90 percent covered in Vancouver to about 20 percent in the Arctic). In Montreal, we saw a 58% eclipse.

Eclipse Glasses

AstroMcGill had 11,050 custom eclipse glasses printed by Rainbow Symphony, a leading US-manufacturer of eclipse glasses.

AstroMcGill distributed over 7,600 pairs of glasses at the Eclipse Watch MTL event and about 1,850 pairs of glasses were given to attendees of AstroMcGill events, including AstroNight lectures, Astronomy on Tap pub nights and sidewalk observing sessions on the McGill campus. In addition, about 1,500 pairs were given to various groups involved in education and community outreach, in partnership with the McGill Social Equity and Diversity Education (SEDE) Office. AstroMcGill also mailed about 100 pairs of eclipse glasses to Members of Parliament from the Montreal Island and surrounding areas.

Eclipse watching event at McGill

AstroMcGill began planning Solar Eclipse Watch MTL — an eclipse-watching party on the Lower Field of the McGill Campus — in September, 2016.

Before the event, about 19,500 people expressed interest in the event on Facebook. They had 2,100 people reserve eclipse glasses before the eclipse with another 900 people filling the wait list to capacity. They also had an additional 5500 eclipse glasses available on a first-come, first-served basis for people without reservations.

AstroMcGill also had solar telescopes (three Sunspotters and two H-alpha telescopes) available to observe the sun, hands on activities (including pinhole viewers, demonstrations of eclipse geometry and a scale model of the Earth/Moon/Sun system) as well as a live stream of the total eclipse.

The weather that afternoon was ideal for observing the Sun — 28 degrees and sunny. No clouds covered the Sun during the entire two and a half hours of the eclipse. The lower field began filling up as the first shift of volunteers arrived at 11:00 am.

The crowd was large and diverse: families with young children, the elderly, people from nearby offices in full business suits, McGill students in T-shirts and sandals, tourists visiting Montreal for the first time, as well as McGill researchers and staff members. Somewhere between 8,000 - 9,000 people stayed for at least part of the eclipse that afternoon.

Shortly after 1:30 pm, when the eclipse had just begun, the line for eclipse glasses snaked down the lower field to the Roddick gates and into Sherbrook street. As the supplies of eclipse glasses dwindled, volunteers gave out one pair of eclipse glasses per group — encouraging people to share them with as many people as possible. Although there were not quite enough eclipse glasses to go around, the relaxed positive mood of the attendees created a sense of community. Strangers shared glasses and took photos of each other. At 2:38, the point of maximum eclipse, spontaneous applause broke out in the gathered crowd.

After the maximum point, the crowd, hot from sitting in the full sun, began to slowly disperse, with a much smaller number staying until 3:50pm to see the last sliver of the Moon leave the Sun's disk.

Almost 50 volunteers helped us share the eclipse with the McGill and Montreal community. While most volunteers came from the McGill Space Institute and the McGill Department of Physics, there were also volunteers from other STEM fields at McGill as well as a few enthusiastic students from Concordia University.

Eclipse Glasses for Astronomers without Borders

After the event, AstroMcGill began an initiative to collect gently used eclipse glasses to send to the non-profit organization Astronomers without Borders. These glasses will be collected from many locations across North America, and then redistributed to children in developing countries in Asia and South America for eclipses in 2019.

AstroNights

L'astronomie gamma:
Lumière sur un universe d'extrêmes
June 16th, 2016
Étienne Bourbeau ✳ 100 people

Planets Near and Far
July 26th, 2016
Nicolas Cowan ✳ 400 people

Fast Radio Bursts:
Mysterious Explosions from Beyond the Milky Way
August 18th, 2016
Paul Scholz ✳ 300 people

Einstein's Waves:
New Cosmic Sounds
September 29th, 2016
Vicky Kalgera ✳ 450 people

How to find an inhabited planet
October 26th, 2016
David Charbonneau ✳ 450 people

Updating the Galactic Google Maps:
Measuring the motions and distances to 1 billion stars with GAIA
November 16, 2016
Shriharsh Tendulkar ✳ 200 people

Dark Matter Maps and Extreme Astrophysics:
Clues from the Cosmic Microwave Background
December 8, 2016
Joachim Harnois-Deraps ✳ 150 people

Mondes à découvrir:
lunes du système solaire
January 19, 2017
Emilie Parent ✳ 300 people

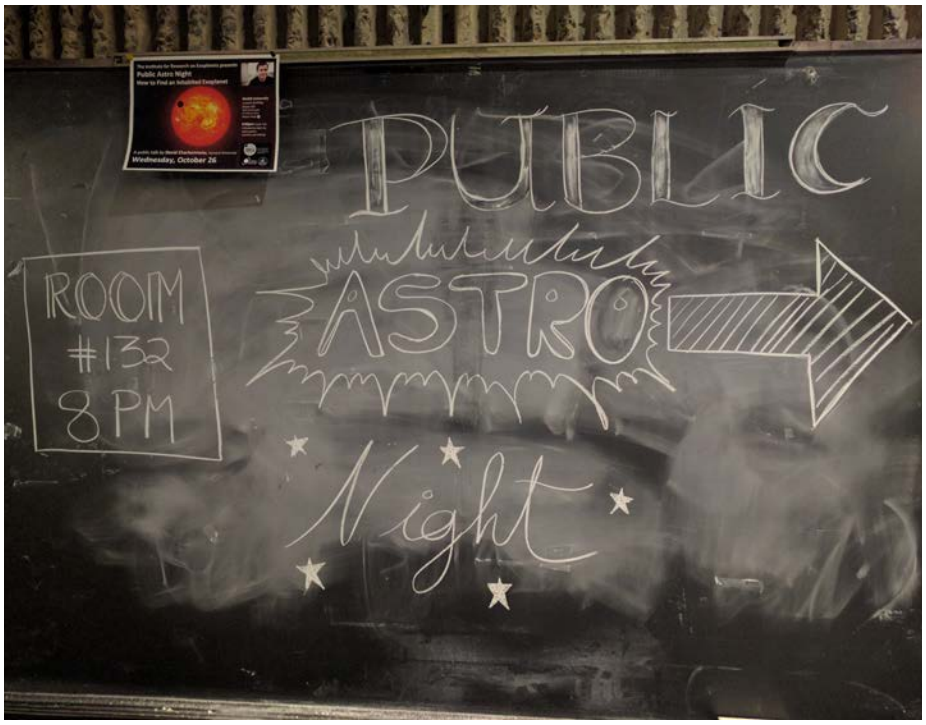
Exploring the X-ray Universe:
Satellites and Science
February 22, 2017
Melania Nynka ✳ 200 people

The linguistics of Arrival:
Aliens, fieldwork, and Universal Grammar
March 16, 2017
Jessica Coon ✳ 450 people

The Multiverse:
Fact or Fiction?
April 12, 2017
Robert Brandenberger ✳ 350 people

Strange New Worlds:
Kepler's Surprising Exoplanets
May 18, 2017
Holly Sheets ✳ 150 people


The Institute for Research on Exoplanets presents
Public Astro Night
How to Find an Inhabited Exoplanet
McGill University
McIntyre medical
Building, Room 504
3655 Promenade
Sir William Osler
Metro Peel
8:00pm Public Talk
Followed by night sky
observations
(weather permitting)
A public talk by David Charbonneau, Harvard University
Wednesday, October 26
iREx
Astro McGill


PUBLIC
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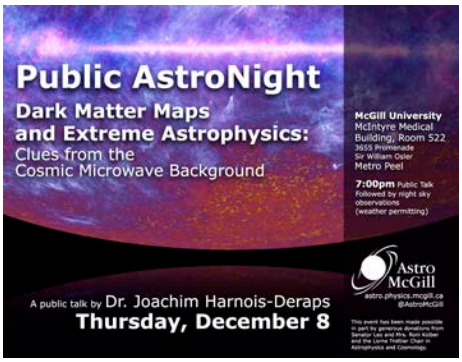
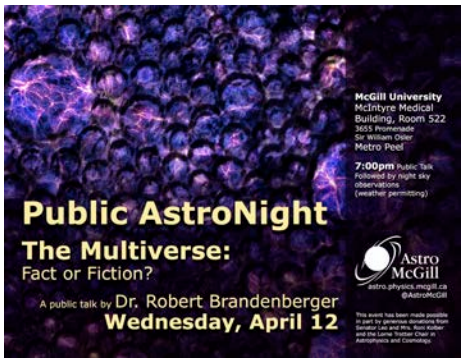
ASTRO
Night


Public AstroNight
Updating the Galactic Google Maps
Measuring the motions and distances to
1 billion stars with GAIA
McGill University
McIntyre Medical
Building, Room 522
3655 Promenade
Sir William Osler
Metro Peel
7:00pm Public Talk
Followed by night sky
observations
(weather permitting)
A public talk by Dr. Shriharsh Tendulkar
Wednesday, November 16
Astro McGill
astro.physics.mcgill.ca
@AstroMcGill


Public AstroNight
Dark Matter Maps
and Extreme Astrophysics:
Clues from the
Cosmic Microwave Background
McGill University
McIntyre Medical
Building, Room 522
3655 Promenade
Sir William Osler
Metro Peel
7:00pm Public Talk
Followed by night sky
observations
(weather permitting)
A public talk by Dr. Joachim Harnois-Deraps
Thursday, December 8
Astro McGill
astro.physics.mcgill.ca
@AstroMcGill


McGill University
McIntyre Medical
Building, Room 522
3655 Promenade
Sir William Osler
Metro Peel
7:00pm Public Talk
Followed by night sky
observations
(weather permitting)
Public AstroNight
The Multiverse:
Fact or Fiction?
A public talk by Dr. Robert Brandenberger
Wednesday, April 12
Astro McGill
astro.physics.mcgill.ca
@AstroMcGill


Public AstroNight
McGill University
McIntyre Medical
Building, Room 522
3655 Promenade
Sir William Osler
Metro Peel
7:00pm Public Talk
Followed by night sky
observations
(weather permitting)
Strange New Worlds:
Kepler's Surprising Exoplanets
A public talk by Dr. Holly Sheets
Thursday, May 18
Astro McGill
astro.physics.mcgill.ca
@AstroMcGill


Soirée publique d'astro
Mondes à découvrir:
lunes du système solaire
Université McGill
McIntyre Medical
Building, salle 522
3655 Promenade
Sir William Osler
metro Peel
19h00 Conférence
publique
Suivie d'observations
du ciel étoilé
(si la météo le permet)
Une conférence publique par Emilie Parent
jeudi, 19 janvier
Astro McGill
astro.physics.mcgill.ca
@AstroMcGill


McGill University
McIntyre Medical
Building, Room 522
3655 Promenade
Sir William Osler
Metro Peel
7:00pm Public Talk
Followed by night sky
observations
(weather permitting)
Public AstroNight
The linguistics of Arrival:
Aliens, fieldwork, and Universal Grammar
A public talk by Dr. Jessica Coon
Thursday, March 16
Astro McGill
astro.physics.mcgill.ca
@AstroMcGill
This event has been made possible
in part by generous donations from
Senator Leo and Mrs. Roni Kolber
and the Lorne Trottier Chair in
Astrophysics and Cosmology.


Public AstroNight
Exploring the X-ray Universe:
Satellites and Science
7:30pm Public Talk
Followed by night sky
observations
(weather permitting)
McGill University
McIntyre Medical
Building, Room 522
3655 Promenade
Sir William Osler
Metro Peel
A public talk by Dr. Melania Nynka
Wednesday, February 22
Astro McGill
astro.physics.mcgill.ca
@AstroMcGill

Astronomy on Tap

Science is even better with beer!

Starting in January 2017, Montreal became a "satellite" location of Astronomy on Tap, joining cities around the world that have astronomy outreach events in local bars. AstroMcGill joined the Institute for research on exoplanets (iREx) to organise Astronomy on Tap MTL (Astronomie en Fut MTL), a popular series of free, monthly events that feature short presentations on topics in astronomy, plus astronomy-themed trivia games and prizes. These events alternate between English nights at McLean's Pub and French nights at Pub l'Île Noire. Both venues are consistently at capacity (about 100 and 80 people, respectively) drawing praise from both the bar owners, who are happy to learn something while filling their venue on Tuesday nights, and patrons, who enjoy interacting with real astronomers in a casual setting.

Unlike more traditional astronomy outreach, which generally targets children or people who are interested enough in science to attend a lecture on a university campus, Astronomy on Tap reaches a more diverse audience of adults in a location where people already gather to socialize. Astronomy on Tap is also less formal and more accessible than traditional hour-long lectures, which helps AstroMcGill reach a wider audience, including people who know nothing about space or astronomy — or people who just think it sounds cool.

« **Top:** *Pint of beer with glow necklaces worn by volunteers so that they are easily visible.*

Bottom: *Over 100 people fill the bar at McLean's Pub during the September, 2017 Astronomy on Tap MTL.*

MSI in the News

Robert Brandenberger

14 December 2016 ✶ Did the Universe Start with a Bounce Instead of a Bang? ✶ PBS

17 January 2017 ✶ What happened before the Big Bang? ✶ McGill Tribune

Nick Cowan

25 August 2016 ✶ Planet Nine, Cosmic Front Next ✶ Japan Broadcasting Corporation

10 March 2017 ✶ What newly discovered planets can teach us ✶ CTV Montreal News

20 June 2017 ✶ Nasa Discovers 10 New Rocky' Planets like Earth — There is Probably Life Out There ✶ Natasha Hall Show, CJAD 800 AM

Natalya Gomez

2 March 2017 ✶ Faculty Feature: Dr. Natalya Gomez ✶ The Sandbox: Stories of Sustainability at McGill University

Daryl Haggard

1 June 2017 ✶ Bizarre Black Holes Revealed by New Spacetime Ripples ✶ National Geographic

19 May 2017 ✶ Strange signals from space and black holes: Astrophysicists in Canada tackle lingering mysteries ✶ National Post

Victoria Kaspi

17 November 2016 ✶ Long-sought signal deepens mystery of fast radio bursts ✶ Nature news

30 December 2016 ✶ Victoria Kaspi appointed to the Order of Canada ✶ Many publications including: CBC News, the Globe and Mail and the Montreal Gazette

5 January 2017 ✶ Astronomers discover two pulsars with an 'off' switch * Astronomy.com

5 January 2017 ✶ Part-Time Pulsars Perform 'Cosmic Vanishing Act' * Space.com

12 April 2017 ✶ Kaspi awarded FRQNT's 2017 Prix d'excellence * McGill Reporter

19 May 2017 ✶ Strange signals from space and black holes: Astrophysicists in Canada tackle lingering mysteries ✶ National Post

Michelle Kunimoto

7 June 2016 ✶ The Final Frontier: Recent College Grad Discovers Possible New Planets ✶ Mach - NBC News

Kelly Lepo

13 Nov 2016 ✶ Supermoon not so super after all ✶ CBC news Montreal

Richard Léveille

27 September 2016 ✶ Elon Musk reveals plan to get humans to Mars within 10 years ✶ CBC News

2 December 2016 ✶ Canadian scientists help prepare a path to Mars ✶ CBC News

12 December 2016 ✶ Canadian researchers lay groundwork for lava-tube living on Mars ✶ Global News

Paul Scholz

18 April 2017 ✶ A Cosmic Burst Repeats, Deepening a Mystery ✶ Quanta Magazine

Shriharsh Tendulkar

4 January 2017 ✶ Fast Radio Burst host galaxy found ✶ Many publications including: The New York Times, USA today, CNN, CBC, Radio Canada, Science and Nature News

MSI Fellowships

McGill Space Institute Fellowships are made possible by a generous $1 million donation from **the Trottier Family Foundation** to support MSI postdoctoral researchers and graduate students.

McGill Space Institute Fellowships are awarded by a committee of faculty members who span different fields of the MSI. They recognize excellence in research among the centre's PhD and MSc students, as well as support several postdoctoral researchers affiliated with the centre.

Graduate Fellows

Gavin Noble

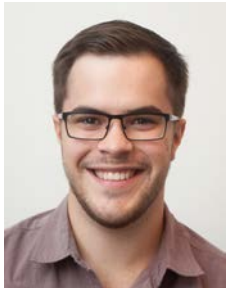
Physics ✶ *Supervisor: Matt Dobbs*

Gavin's research focuses on the development of microwave detector and readout technology in the McGill Cosmology Instrumentation Lab, but is also interested in the future of Canadian radio astronomy.

Jeremie Choquette

Physics ✶ *Supervisor: Jim Cline*

Jeremie's research focuses on self-interacting dark matter models, both on the particle physics scale and astrophysics scale.



Taylor Bell

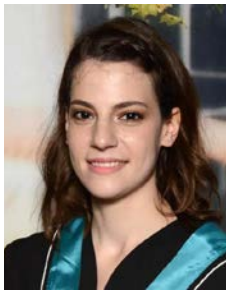
Physics ✶ *Supervisor: Prof. Nicolas Cowan*

Taylor's research focuses on better understanding the atmospheres of hot Jupiter-mass exoplanets using observations of thermal and reflected light.

Marie-Pier Labonté

Atmospheric and Oceanic Sciences ✶
Supervisor: Timothy Merlis

Marie-Pier's research interests include atmospheric hydrological cycle and Earth-Like exoplanets' climate.



Catherine Maggiori

Natural Resource Sciences ✶ *Supervisor: Lyle Whyte*

Catherine's research interests include astrobiology and the search for extraterrestrial life.

Postdoctoral Fellows

Vanessa Graber

Physics ✷ *Supervisor: Andrew Cumming and Vicky Kaspi*

Dr. Graber's research focuses on the interface between astrophysics and condensed matter physics, as she studies the influence of superfluid and superconducting components on neutron stars.

Eric Chan

Earth and Planetary Sciences ✷
Supervisor: Natalya Gomez

Dr. Chan's research topics include planetary structure, deformation, and rotational dynamics.

New Fellows 2017-18

Postdoctoral Fellows

John Ruan

Physics
Supervisor: Daryl Haggard

Dr. Ruan's research primarily focuses on supermassive black hole growth, and its effects on galaxy evolution over cosmic time.

Isabelle Raymond-Bouchard

Natural Resource Sciences
Supervisor: Lyle Whyte

Dr. Raymond-Bouchard's research interests include astrobiology, the development of novel methods for life detection, and the study of microbes and their adaptations to extreme environments.

Graduate Fellows

Bryce Cyr

Physics
Supervisor: Robert Brandenberger

David Purnell

Earth and Planetary Sciences
Supervisor: Natalya Gomez

Erin Gibbons

Earth and Planetary Sciences
Supervisors: Nicolas Cowan and Richard Leveille

Élie Bouffard

Physics
Supervisor: Daryl Haggard

Tristan Goodwill

Physics
Supervisor: Jim Cline

Matthew Muscat

Physics
Supervisor: Robert Brandenberger

Ariane Trudeau

Physics
Supervisor: Tracy Webb

MSI Seminars

MSI Faculty Jamboree
6 September 2016
Short presentations from all MSI faculty about their research

Michael Reid
University of Toronto
13 September, 2016
Defining and Reaching Outreach Audiences on a Budget

Jason Rowe
Université de Montréal
27 September, 2016
From Pixels to Planets: A history of transiting extrasolar planets and first hand account of the Kepler Mission

Mercedes López-Morales
CfA/Smithsonian
11 October, 2016
Breaking Through Exoplanetary Atmospheres

Allyson Brady
McMaster University
25 October, 2016
Packing for Mars: Integrating biomarker and exploration field science in Earth analogue environments

Blake Sherwin
University of California, Berkeley
8 November, 2016
CMB Lensing: Fundamental Physics from Maps of the Invisible

Christopher Lee
University of Toronto
22 November, 2016
Dust and water ice in the Martian atmosphere

Ue-li Pen
University of Toronto
10 January, 2017
Small Scale Structure of the Universe as seen by pulsars and FRBs

Diana Dragomir
MIT Kavli Institute
24 January, 2017
Looking At Super-Earths Through Their Atmospheres

Rita Parai
Washington University in St. Louis
25 February, 2017
Deep Earth volatile inventories and the formation of the Moon

Nia Imara
CfA/Smithsonian
15 March, 2017
A Story of Stellar Nurseries

Kristen Menou
University of Toronto, Scarborough
28 March, 2017
Exotic Climates on Exo-Earths

Workshops

Frontiers: Cosmos, Curiosity, Creativity
November 12-13, 2016
Centre for Research on Religion (CREOR) 2016 conference
An interdisciplinary conference with McGill's School of Religious Studies on how cosmologies inform culture and vice versa.

B-modes from SPACE
January 23-25, 2017
Cosmic Microwave Background workshop at McGill University, hosting 50 international scientists

McGill-Dartmouth Cosmology Day
May 25, 2017
Established closer contacts between the cosmology groups at McGill and Dartmouth

A Week at the MSI

Monday

MSI lunch Seminar (alternate weeks)	12:00 pm
Tea and Cookies	3:00 pm
French language discussion class	4:00 pm

Tuesday

Education, outreach and diversity discussion	*2:00 pm*
Tea and Cookies	*3:00 pm*
MSI or Astronomy Seminar	*3:30 pm*

Wednesday

Exoplanet Lunch	*12:00 pm*
Tea and Cookies	*3:00 pm*
Random Papers Discussion	*3:30 pm*

Thursday

iREx cafe (alternate weeks at UdeM)	*10:30 am*
Tea and Cookies	
Neutron Star Discussion	*3:00 pm*

Friday

Astronomy Journal Club	*10:30 am*

Planet Lunch

The Planet lunch series brings together 15-20 researchers from the Earth and Planetary Science, Atmospheric and Oceanic Science, and the McGill Space Institute for a weekly lunch discussion. These discussions take knowledge of geology and atmospheres taken from examples in our solar system and apply that knowledge to understanding exoplanets from the typically sparse data we have on them, and to understand what data would be best to acquire in the future.

Past topics include a discussion of lava ocean models, and the difficulties measuring properties of very hot lava "in the lab", on Earth, to calibrate what lava ocean planets might look like in spectra with things like JWST; Proxima Cen b and the TRAPPIST-1 planets, and how stellar activity could influence the habitability of those planets, since the "habitable zone" is so close to the star in those cases; as well as circulation patterns on tidally locked planets, and under what conditions water freeze out would on the night side, trapping it there.

Black Hole Lunch

The Black Hole Lunch series is an informal gathering and discussion that centers on supermassive black hole (SMBH) research. The group derives mostly from the research teams of Daryl Haggard (McGill), Julie Hlvacek-Larrondo (UdeM), and Tracy Webb (McGill), but is open to all researchers within McGill/MSI and the University of Montreal. They meet roughly once a month, alternating between McGill and UdeM, and tackle core concepts including growth, feeding, and feedback from SMBHs, they also discuss observational and theoretical challenges and share new discoveries and research findings. This gathering of black hole enthusiasts recently led to a more formal research collaboration between Profs Webb, Haggard and Hlvacek-Larrondo, The "Montréal Black Hole Collaboration" (MBH CoLAB), funded by Fonds de recherche du Québec – Nature et technologies.

MSI Lunch Talks

The Monday lunch talk series showcases the diverse research that goes on at the McGill Space Institute by inviting MSI grad students, postdoctoral fellows and faculty members to give short presentations about their work over lunch, followed by an extended, informal discussion about that research. These lunch discussions are held every other Monday, on weeks where there is not a MSI seminar, and have two speakers per week. Speakers are limited to three slides (with unlimited blackboard usage) and are asked to prepare 10 minutes of material for a 30 minute slot, with the remaining 20 minutes filled by questions from the audience.

The talks are an opportunity to introduce members of the MSI to research that others are doing, and provide an opportunity for students to practice conference talks or discuss an interesting finding in their field.

Awards

Faculty

Jim Cline

Outstanding Reviewer Award
Classical and Quantum Gravity

Daryl Haggard

Kavli Frontiers Fellow
National Academy of Sciences & Kavli Foundation

Vicky Kaspi

NSERC Herzberg Gold Medal for Science and Engineering

Companion to the Order of Canada

Prix d'excellence du FRQNT

Ken Ragan

Lifetime Achievement Award
SALTISE, a Montreal-area college and university community of science educators

Postdoctoral Fellows

Matt Kaplin

Dissertation Award in Nuclear Physics
American Physical Society

John Ruan

Dan David Scholarship

Students

Taylor Bell

McGill Physics Graduate Excellence Fellowship

Hope Boyce

Mary Louise Taylor Fellowship

Peter Crockford

Mitacs Globalink award

Agouron post-doctoral fellowship

Catherine Maggiori

McGill Graduate Excellence Scholarship

2016-2017 MSI Members

Faculty Members

Victoria Kaspi	Phys
MSI Director	
Andrew Cumming	Phys
MSI Associate Director	
Robert Brandenberger	Phys
James Cline	Phys
Nicolas Cowan	Phys & EPS
Matt Dobbs	Phys
René Doyon	Phys
Natalya Gomez	EPS
Daryl Haggard	Phys
David Hanna	Phys
Yi Huang	AOS
Timothy Merlis	AOS
Ken Ragan	Phys
Tracy Webb	Phys
Lyle Whyte	NRS

Postdoctoral Fellows

Dan Capellupo	Phys
Eric Chan	EPS
Jonathan Cornell	Phys
Qi Feng	Phys
Emmanuel Fonseca	Phys
Adam Gilbert	Phys
Vanessa Graber	Phys
Sean Griffin	Phys
Ryo Namba	Phys
Melania Nynka	Phys
Holly Sheets	Phys
Seth Siegel	Phys
Shriharsh Tendulkar	Phys
Ben Zitzer	Phys

Associate Members

Oscar Hernández	Phys
Richard Léveille	EPS

Graduate Students

Robert Archibald	Phys
Hossein Basrafshan	Phys
Taylor Bell	Phys
David Berardo	Phys
Nina Bonaventura	Phys
Étienne Bourbeau	Phys
Hope Boyce	Phys
Pragya Chawla	Phys
Gabriel Chernitsky	Phys
Jeremie Choquette	Phys
Ryan Chown	Phys
Peter Crockford	EPS
Disrael Cunha	Phys
Bryce Cyr	Phys
Lisa Dang	Phys
Anna Delahaye	Phys
Grace Dupuis	Phys
Elisa Ferreira	Phys
Guilherme Franzmann	Phys
Claire Guimond	EPS
Holly Han	EPS
Gilbert Hsyu	Phys
Alex Josephy	Phys
Dylan Keating	Phys
Marie-Pier Labonté	AOS
Tony Lin	Phys
Catherine Maggiori	NRS
Evan McDonough	Phys
Juan Mena	Phys
Joshua Montgomery	Phys
Gavin Noble	Phys
Yuuki Omori	Phys
Emilie Parent	Phys
Chitrang Patel	Phys
Ziggy Pleunis	Phys
Jerome Quintin	Phys
Elinore Roebber	Phys
Joel Schwartz	Phys
Gabrielle Simard	Phys
Jonathan Tyler	Phys

Undergraduate Students

Matthew Stubbs	Phys
Brayden Mon	Phys
Noelia de la Cruz Hernandez	Phys
Nicolas Choux	Phys
HanBaek Lee	Phys
David Borel	Phys
Camille Bergeron-Miron	Phys
Holly Marginson	Phys
Jackson Hoffart	Phys
Maximilien Lamberti	Phys
Veenu Suri	Phys
Elie Bouffard	Phys
Sudarsan Sundarajan	Phys
Diana Jovmir	Phys
Victoria Chayes	Phys
David Ittah	Phys
Emilie Storer	Phys
Natan Weinberger	Phys
Shihlung (Allen) Chen	Phys
Miles Cranmer	Phys
Stella Ocker	Phys
Mariya Krestiva	Phys
Senyang Huang	Phys
Gabriel Chernitsky	Phys

Staff

Kelly Lepo

MSI Coordinator

Phys: Physics
EPS: Earth and Planetary Sciences
AOS: Atmospheric and Oceanic Sciences
NRS: Natural Resource Sciences

2016-2017 MSI Board

External Members

Lorne Trottier

Co-founder of Matrox

Marc Guilbert

Director
Power Corporation of Canada

Vassiliki Kalogera

Director CIERA Institute at Northwestern University

McGill Internal Members

Chris Manfredi

Provost

Bruce Lennox

Dean of Science

Martha Crago

Vice-Principal (Research and Innovation)

MSI Internal Members

Victoria Kaspi

Director McGill Space Institute
Professor of Physics

Andrew Cumming

Associate Director
McGill Space Institute
Associate Professor of Physics

Matt Dobbs

Associate Professor of Physics

Robert Brandenberger

Professor of Physics

Timothy Merlis

Assistant Professor of Atmospheric and Oceanic Sciences

Isabelle Raymond-Bouchard

Postdoctoral Fellow

Emilie Parent

PhD Student

New Faculty 2018-19

Adrian Liu

The boundary between theory and observations in 21 cm cosmology.

Cynthia Chiang

Observational cosmology,cosmic microwave background.

Jonathan Sievers

Observational cosmology,cosmic microwave background

Visitors 2016-2017

Neil Cook

University of Hertfordshire
Hosted by Nick Cowan
M dwarfs, Brown dwarfs and exoplanets

Rodrigo Cuzinatto

Federal University of Alfenas
Hosted by Robert Brandenberge
Theoretical cosmology

Maxim Lyutikov

Purdue University
Hosted by Vicky Kaspi
Neutron stars and fast radio bursts

Lydia Philpott

University of British Columbia
Hosted by Nick Cowan
Messenger and OSIRIS-REx missions

Former MSI members

Postdoctoral fellows

Robert Ferdman

Now a lecturer at the University of East Anglia in the United Kingdom.

Alfonso Diaz Furlong

Now a research professor at Benemerita Universidad Autonoma de Puebla in Mexico.

Jackie Goordial

Now a postdoctoral fellow at at the Bigelow Laboratory for Ocean Sciences - studying deep sea ultra low energy sediment microbial ecology.

Leila Graef

Now a postdoctoral fellow at the Observatório Nacional in Brasil.

Andrew McCann

Now a Research Associate in the Earth Sciences Sector of Natural Resources Canada where he works on terrestrial gamma-ray detectors for safety and security applications.

Graduate students

Simon Archambault

Now a Research Associate at Chiba University in Japan.

Jesse Colangelo-Lillis

Now a Research Associate at University of Colorado Boulder.

Erik Madsen

Now an Actuarial Reporting and Analytics Lead at Manulife in Montreal, QC.

Paul Scholz

Now a Covington Postdoctoral fellow at the Dominion Radio Astrophysical Observatory in Pentiction, British Columbia.

MSI by the Numbers

96
Members of the MSI

24
Invited seminars or colloquia given by faculty members in
6
countries

33
Conferences attended by faculty members in
12
countries

3,036
Cups of afternoon tea

5,060
Cookies

18
Bottles of wine after seminars

Over **$3.7 Million**
Grants received by MSI faculty members

12
McGill Space Institute seminars

91
Journal articles published by MSI members

15
Faculty members

14
Postdoctoral fellows

24
PhD students

16
Masters' students

Facilities used by MSI members

Laboratory and Computing facilities

The McGill Stable Isotope Laboratory

Makes high precision measurements of natural abundance stable isotope ratios in earth and planetary materials.(Wing)

The McGill Cosmology Instrumentation Laboratory

Develops complex digital and ultra-low noise analog cryogenic electronics for astrophysics. Includes separate labs for radio instrumentation and mm-wave instrumentation. (Dobbs)

The Gamma-ray Astronomy Laboratory

Develops instrumentation for astroparticle and particle physics detectors. (Hanna, Ragan)

Prof. Whyte's laboratory

One of the few laboratories worldwide with the facilities to perform fundamental studies at subzero temperatures for molecular biology/microbiology and astrobiology-related investigations.

The McGill High Arctic Research Station (MARS)

Supports field research activities consisting of sample acquisition, some limited laboratory microbial and molecular analyses, and in situ analyses for microbial activity. (Whyte)

Guillimin supercomputer

Owned and administered by Compute Canada and Calcul Quebec (Cowan, Huang, Kaspi, Gomez)

Ground-based Telescope Facilities

The Canadian Hydrogen Intensity Mapping Experiment, CHIME (Dobbs, Hanna)

Pulsar backend recording and analysis system for CHIME (Kaspi, Dobbs)

VERITAS Gamma-ray Telescope (Hanna, Ragan)

South Pole Telescope, mm-wave, Cosmic Microwave Background (Dobbs)

POLARBEAR and the Simon's Array, mm-wave, Cosmic Microwave Background (Dobbs)

Atacama Large Millimeter Array (Webb)

Large Millimeter Telescope Alfonso Serrano (Webb)

Arecibo Observatory, Radio wavelengths (Kaspi)

Green Bank Telescope, Radio wavelengths (Kaspi)

Jansky Very Large Array, Radio wavelengths (Haggard, Kaspi, Webb)

Anglo-Australian Telescope (Webb)

Gemini Observatory (Haggard, Webb)

Canada France Hawaii Telescope (Webb)

Observatoire du Mont-Mégantic (Cowan)

W.M. Keck Observatory (Webb)

Space-based Telescope Facilities

EBEX stratospheric balloon telescope, Co-built in the McGill Cosmology Instrumentation Laboratory, funded by NASA and the CSA. (Dobbs)

NASA/Hubble Space Telescope (Cowan, Webb)

NASA/Kepler Mission (Cowan)

NASA/Swift X-ray Telescope (Cumming, Haggard, Kaspi)

NASA/Neutron Star Interior Composition Explorer, NICER (Kaspi)

NASA/NuSTAR X-ray Mission (Cumming, Kaspi)

NASA/Chandra X-ray Observatory (Haggard, Kaspi, Webb)

ESA/XMM-Newton X-ray Telescope (Cumming, Kaspi, Webb)

NASA Spitzer Space Telescope (Haggard, Cowan, Webb)

MSI Faculty Collaborations

McGill-lead collaborations

CHIME *The Canadian Hydrogen Intensity Mapping Experiment: Cosmology* **(Dobbs, Hanna)**
and Fast Radio Burst **(Kaspi, Dobbs)**
Other participating institutions: Dominion Radio Astrophysical Observatory ✶ University of British Columbia ✶ University of Toronto ✶ U.S. National Radio Astronomy Observatory

MBH CoLAB *Montréal Black Hole Collaboration* (**Haggard, Webb**)
Other participating institutions: Université de Montréal

PALFA *Pulsar Arecibo L-Band Feed Array survey* **(Kaspi)**
Other participating institutions: Albert Einstein Institute ✶ ASTRON ✶ Columbia University ✶ Cornell University ✶ Franklin and Marshall College ✶ Jodrell Bank Center for Astrophysics ✶ Lafayette College ✶ Max-Planck-Institut für Radioastronomie ✶ National Radio Astronomy Observatory ✶ National Radio Astronomy Observatory ✶ Naval Research Laboratory ✶ University of British Columbia ✶ University of East Anglia ✶ University of New Mexico ✶ University of Texas at Brownsville ✶ University of Wisconsin - Milwaukee ✶ West Virginia University

VERITAS **(Hanna, Ragan)**
Other participating institutions: Adler Planetarium and Astronomy Museum ✶ Argonne National Lab ✶ Barnard College ✶ Columbia University ✶ Cork Institute of Technology ✶ Georgia Institute of Technology ✶ Iowa State University ✶ National University of Ireland, Galway ✶ Purdue University ✶ Smithsonian Astrophysical Observatory ✶ University College Dublin ✶ University of California, Los Angeles ✶ University of California, Santa Cruz ✶ University of Chicago ✶ University of Delaware ✶ University of Iowa ✶ University of Minnesota ✶ University of Utah ✶ Washington University in St. Louis

Other collaborations

CASE *Contribution to ARIEL Spectroscopy of Exoplanets* **(Cowan)**
Other participating institutions: Jet Propulsion Laboratory, Arizona State University ✶ University of Arizona ✶ UC Santa Cruz, University of Chicago ✶ Smithsonian Astrophysical Observatory ✶ Penn State University, Space Science Institute ✶ Grinnell College ✶ INAF-Osservatorio Astronomico di Palermo, Space Telescope Science Institute

» Telescope T2 of the VERITAS array at sunset.

Event Horizon Telescope:

Multiwavelength Coordination Team **(Haggard)**

Academia Sinica Institute of Astronomy and Astrophysics ✳ Barnard College ✳ Boston University ✳ Caltech Directory ✳ Chinese Academy of Sciences ✳ Columbia University ✳ Goethe University of Frankfurt ✳ Harvard University ✳ Harvard-Smithsonian Center for Astrophysics ✳ Instituto de Astrofísica de Andalucía ✳ Jagiellonian University ✳ Jet Propulsion Laboratory ✳ Kavli Institute for Astronomy and Astrophysics at Peking University ✳ Korea Astronomy and Space Science Institute ✳ Max Planck Institute for Extraterrestrial Physics ✳ Max Planck Institute for Radio Astronomy ✳ McGill University ✳ MIT ✳ MIT Haystack Observatory ✳ National Astronomical Observatory of Japan ✳ National Institute of Astrophysics, Rome ✳ National Radio Astronomy Observatory ✳ National Taiwan University ✳ Peking University ✳ Perimeter Institute ✳ Purdue University ✳ Purple Mountain Observatory ✳ Radboud University ✳ Shanghai Astronomical Observatory ✳ Steward Observatory ✳ The Pennsylvania State University ✳ Universidad de Concepción ✳ University of Amsterdam ✳ University of Arizona ✳ University of California, Los Angeles ✳ University of Heidelberg ✳ University of Köln ✳ University of Manchester ✳ University of Maryland ✳ University of Massachusetts ✳ University of Michigan ✳ University of Padova ✳ University of Tokyo ✳ University of Waterloo ✳ Villanova University ✳ Würzburg University

FINESSE *Fast Infrared Exoplanet Spectroscopy Survey Explorer* **(Cowan)**

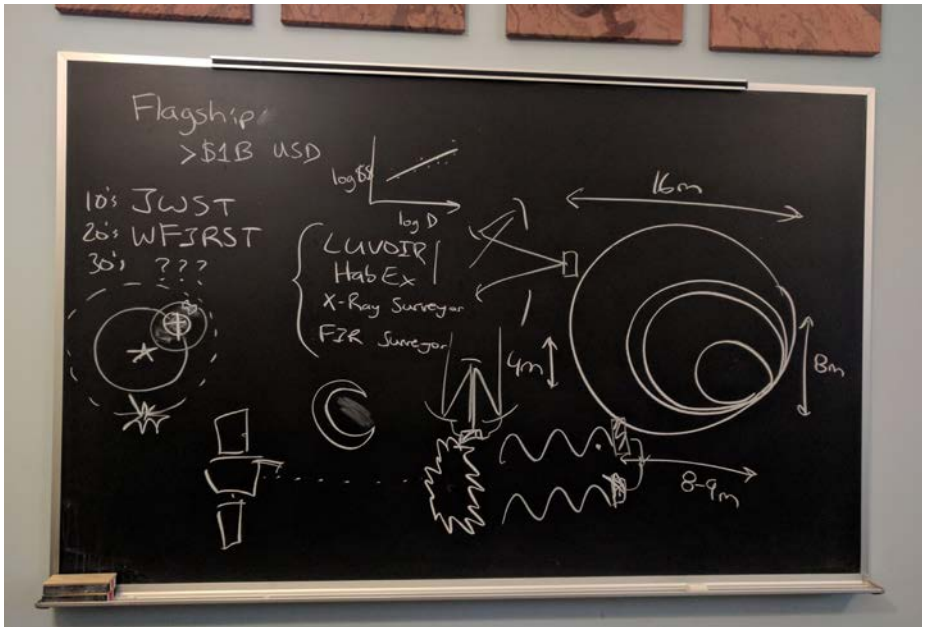
Other participating institutions:

California Institute of Technology ✳ INAF-Osservatorio Astronomico di Palermo ✳ Jet Propulsion Laboratory ✳ Max Planck Institute for Astronomy ✳ NASA Ames Research Center ✳ Princeton University ✳ Queen's University of Belfast ✳ University of Arizona ✳ University College London

GBNCC *The Green Bank North Celestial Cap pulsar survey* **(Kaspi)**

Other participating institutions:

ASTRON ✳ National Radio Astronomy Observatory ✳ Universiteit van Amsterdam ✳ University of British Columbia ✳ University of New Mexico ✳ University of Texas at Brownsville ✳ University of Virginia ✳ West Virginia University



« Notes on the chalkboard in the MSI lounge, the remnants of several discussions.

JINA/CEE *Joint Institute for Nuclear Astrophysics - Centre for Evolution of the Elements* **(Cumming)**

Other participating institutions:

Argonne National Laboratory ✳ Arizona State University ✳ Cluster of Excellence Origin and Structure of the Universe ✳ GSI Helmholtz Centre for Heavy Ion Research ✳ Florida State University ✳ Los Alamos National Laboratory ✳ Michigan State University ✳ Monash University ✳ North Carolina State University ✳ Nuclear Astrophysics Virtual Institute ✳ Nuclear Computational Low Energy Initiative ✳ Ohio State University ✳ Ohio University ✳ Princeton University ✳ Shanghai Jiao Tong University ✳ TRIUMF ✳ University of Chicago ✳ University of Minnesota ✳ University of Notre Dame ✳ University of Sao Paulo ✳ University of Victoria ✳ University of Washington ✳ Western Michigan University

NANOGrav *The search for gravitational waves using pulsars* **(Kaspi)**

Other participating institutions:

California Institute of Technology ✳ Cornell University ✳ Franklin and Marshall College ✳ Hillsdale College ✳ Huazhong University of Science and Technology ✳ Jet Propulsion Laboratory ✳ Lafayette College ✳ Montana State University ✳ NASA Goddard Space Flight Center ✳ National Radio Astronomy Observatory ✳ Naval Research Laboratory ✳ Notre Dame of Maryland University ✳ Oberlin College ✳ Penn State University ✳ University of Alabama ✳ University of British Columbia ✳ University of California, Berkeley ✳ University of East Anglia ✳ University of Maryland ✳ University of Texas Rio Grande Valley ✳ University of Vermont ✳ University of Washington Bothell ✳ University of Wisconsin Milwaukee ✳ West Virginia University

NICER *NASA's Neutron Star Interior*

Composition Explorer **(Kaspi)**
Other participating institutions:
MIT Kavli Institute for Astrophysics and Space Research ✶ NASA Goddard Space Flight Center ✶ Noqsi Aerospace

NIRISS *Near-InfraRed Imager and Slitless Spectrograph, James Webb Space Telescope* (Cowan)

Other participating institutions:
Cornell University ✶ COM DEV ✶ National Research Council Canada ✶ Saint Mary's University ✶ Space Telescope Science Institute (STScI) ✶ Swiss Federal Institute of Technology Zurich ✶ Université de Montréal ✶ University of Rochester ✶ University of Toronto ✶ York University

POLARBEAR (Dobbs)

Other participating institutions:
Cardiff University ✶ Imperial College ✶ KEK, High Energy Accelerator Research Organization ✶ Lawrence Berkeley National Lab ✶ Paris Diderot University ✶ University of California, Berkeley ✶ University of California, San Diego ✶ University of Colorado at Boulder

SpARCS *the Spitzer Adaptation of the Red-Sequence Cluster Method* (Webb)

Other participating institutions:
University of California - Riverside Irvine ✶ University of Toronto ✶ York University ✶ MIT ✶ University of Montreal ✶ Australian Astronomical Observatory ✶ University of Concepcion, Chile ✶ University of Waterloo ✶ Argelander-Instiut fur Astronomie, Bonn, Germany ✶ National Radio Astronomy Observatory ✶ Universidad Andrés Bello, Chile ✶ Spitzer Science Centre/Caltech, ✶ CEA Saclay, France, ✶ University Innsbruk, Austria

SPT *The South Pole Telescope* (Dobbs)

Other participating institutions:
Argonne National Lab ✶ Case-Western Reserve University ✶ Fermilab ✶ University of California, Berkeley ✶ University of Chicago ✶ University of Colorado, Boulder ✶ University of Illinois at Urbana-Champaign

The Simons Array (Dobbs)

Other participating institutions:
Cardiff University ✶ Dalhousie University ✶ High Energy Accelerator Research Organization, KEK ✶ Imperial College London ✶ Japan Aerospace Exploration Agency ✶ Lawrence Berkeley National Laboratory ✶ NASA Goddard Space Flight Center ✶ National Institute for Fusion Science ✶ Osaka University ✶ Princeton University ✶ The Graduate University for Advanced Studies ✶ Three-Speed Logic, Inc. ✶ University of California, Berkeley ✶ University of California, San Diego ✶ University of Chicago ✶ University of Colorado at Boulder ✶ University of Melbourne ✶ University of Paris Diderot ✶ University of Tokyo

The Simons Observatory (Dobbs)

Other participating institutions:
Lawrence Berkeley National Laboratory ✶ Princeton University ✶ University of California, San Diego ✶ University of California, Berkeley ✶ University of Pennsylvania

Thirty Meter Telescope

International Science Development Team for Supermassive Black Holes **(Haggard)**

Other participating institutions:
Caltech ✶ Institute of High Energy Physics ✶ IPAC ✶ Kavli Institute for Astronomy and Astrophysics, at Peking University ✶ Kyoto University ✶ National Astronomy Observatory of China ✶ National Astronomical Observatory of Japan ✶ National Optical Astronomy Observatory ✶ Shanghai Astronomical Observatory ✶ SOFIA Science Center ✶ Tata Institute of Fundamental Research ✶ Tohoku University ✶ Tokyo University of Science ✶ University of California, Irvine ✶ University of California, Riverside ✶ UC Santa Cruz ✶ University of California, Las Angeles ✶ University of Alaska, Anchorage ✶ University of Colorado, Boulder ✶ University of Illinois, Urbana-Champagne ✶ University of Manitoba ✶ University of Pennsylvania ✶ University of Science and Technology of China ✶ University of Waterloo ✶ University of Texas at San Antonio ✶ Virginia Tech ✶ Western University

» Green Bank Telescope (GBT) at the National Radio Astronomy Observatory (NRAO)

2016-2017 MSI Publications

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Abeysekara, A. U., **Archambault, S.**, Archer, A., **Feng, Q.**, **Hanna, D.**, **McCann, A.**, **Ragan, K.**, et al. 2016, *VERITAS and multiwavelength observations of the BL Lacertae object 1ES 1741+196*, MNRAS, 459, 2550

Abeysekara, A. U., **Archambault, S.**, Archer, A., **Feng, Q.**, **Hanna, D.**, **McCann, A.**, **Ragan, K.**, et al. 2017, *A Luminous and Isolated Gamma-Ray Flare from the Blazar B2 1215+30*, ApJ, 836, 205

Alexander, S., **Brandenberger, R.**, & Froehlich, J. 2016, *Dark Energy and Dark Matter in a Model of an Axion Coupled to a Non-Abelian Gauge Field*, ArXiv e-prints, arXiv:1609.06920

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Archambault, S., Archer, A., Benbow, W., **Feng, Q.**, **Griffin, S.**, **Hanna, D.**, **Ragan, K.**, **Zitzer, B.**, et al. 2017, *Search for Magnetically Broadened Cascade Emission from Blazars with VERITAS*, ApJ, 835, 288

Archer, A., Benbow, W., Bird, R., **Feng, Q.**, **Griffin, S.**, **Hanna, D.**, **Ragan, K.**, et al. 2016, *Very High Energy Observations of the Binaries V 404 Cyg and 4U 0115+634 during Giant X-Ray Outbursts*, ApJ, 831, 113

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Bender, A. N., Ade, P. A. R., Anderson, A. J., **Dobbs, M. A.**, **Gilbert, A.**, et al. 2016, *Integrated performance of a frequency domain multiplexing readout in the SPT-3G receiver*, in Proc. SPIE, Vol. 9914, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII, 99141D

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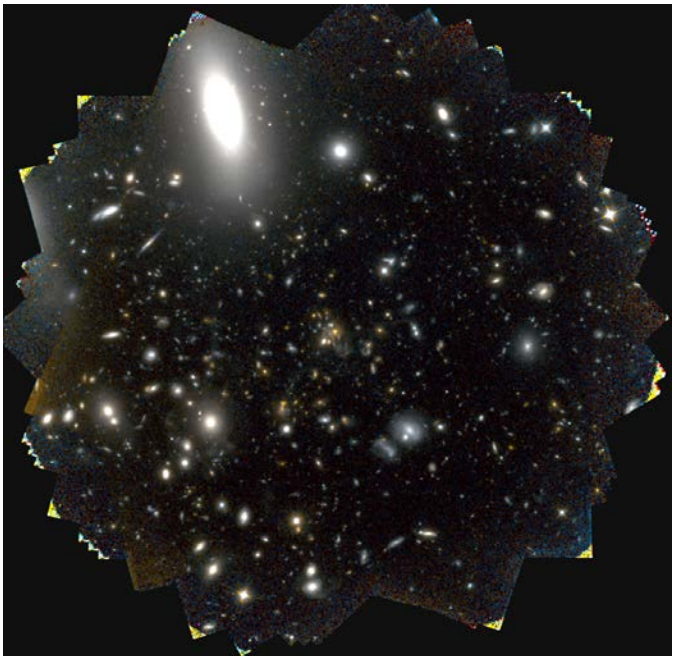

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