

# B612

PROTECTING THE EARTH  
FROM ASTEROID IMPACTS

ANNUAL PROGRESS REPORT  
2017

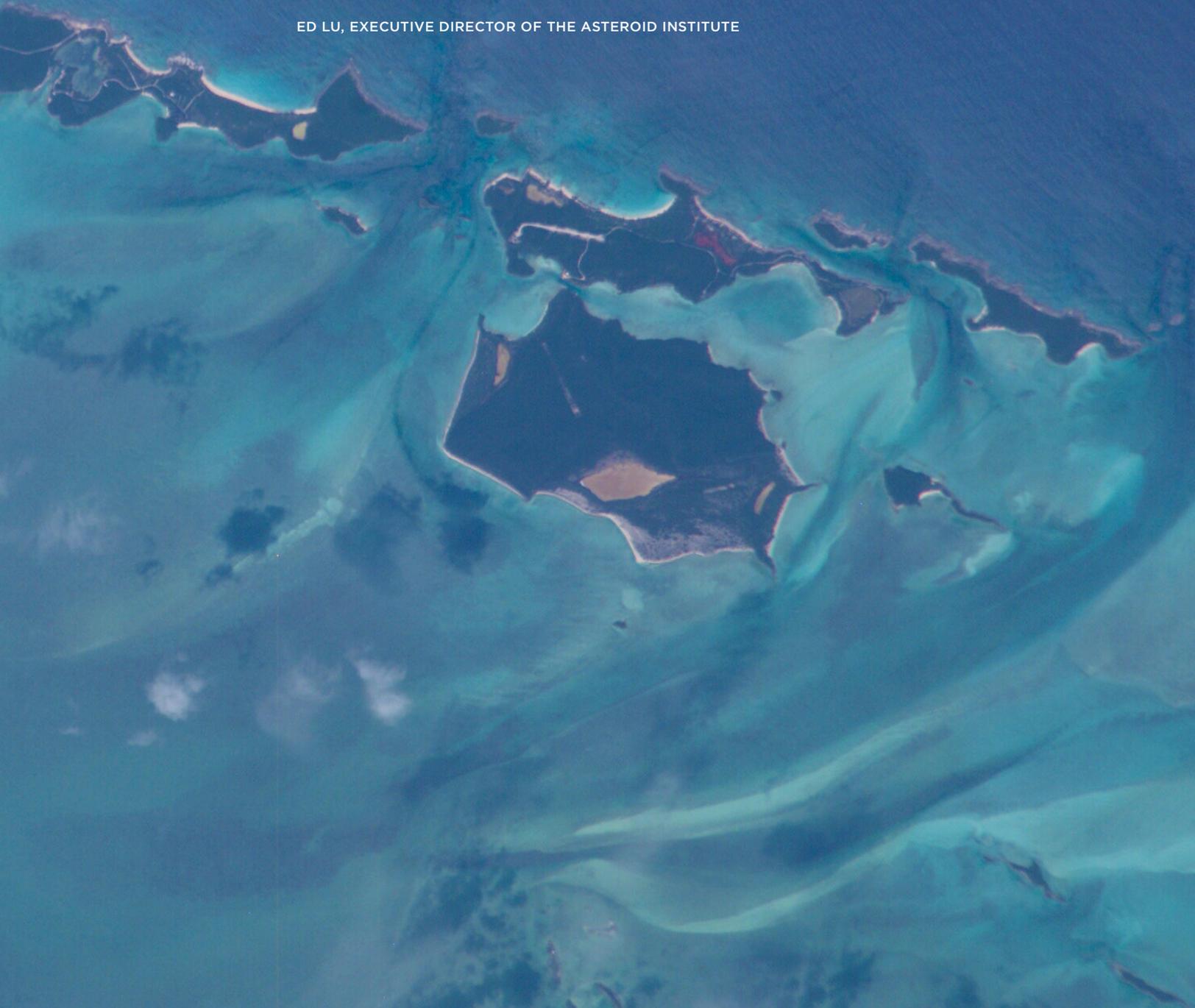


Cover: Photo by Ed Lu from the International Space Station

This Page: Photo by Ed Lu of islands in the Caribbean, from the International Space Station

**If you look at the history of our planet over 4.5 billion years, it has been struck by asteroids, large and small, thousands of times. And if you look at what we have the opportunity to do, it is to change the evolution of the entire solar system such that the third planet no longer gets hit by large asteroids. And that's actually within our capability.**

ED LU, EXECUTIVE DIRECTOR OF THE ASTEROID INSTITUTE



## LETTER FROM THE PRESIDENT

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In October we celebrated the anniversary of B612, which formally incorporated and elected officers fifteen years ago. Five forward-thinking individuals — Ed Lu, Piet Hut, Clark Chapman, Rusty Schweickart, and Geoff Baehr — were part of the organization’s founding. With your support the next fifteen years will be filled with asteroid discovery and global collaborations within the growing field of planetary defense.

The vision and hard work of the founding and current board directors have laid the groundwork for us to create the Asteroid Institute earlier this year. The Asteroid Institute is a virtual collaboration rooted in science and technology programs. The Asteroid Institute team is working on hardware, new technologies, and applications that will help us accelerate our knowledge and understanding of asteroids.

The Asteroid Institute is building on the Asteroid Decision Analysis and Mapping project (ADAM) Cloud Platform (see pages 14-15). The ADAM project will provide a cloud-based infrastructure for large-scale orbital dynamics and related computations that will enable the science, policy, and business community to better understand and make sense of opportunities and threats coming from the asteroids in the solar system.

We continue to explore options to utilize synthetic tracking to increase the rate of asteroid discovery (see page 16). Our partners in the private sector and at CalTech, Southwest Research Institute, and other academic institutions are helping us advance these capabilities. As we have often stated, synthetic tracking technology could complement other telescopes by finding and tracking the large number of asteroids which will be missed by land-based telescopes — such as LSST — and infrared space telescopes such as NASA’s proposed NEOCam. Synthetic tracking technology will allow us to address asteroids less than 140 meters in size by using extremely fast data processing to compensate for the rapid motion of smaller asteroids.

B612's education and advocacy program accomplishments include our participation in Asteroid Day and its global broadcast. With the financial and in-kind support of corporate sponsors (see page 18), Asteroid Day delivered a 24-hour broadcast of educational asteroid programming around the world. Special thanks also goes to NASA, ESA, JAXA, the Large Synoptic Survey Telescope, as well as the University of Arizona's Lunar and Planetary Observatory whose participation in the live broadcast expanded the view of the many efforts to discover, observe and track asteroids.

But truly, the 1,200+ independently organized events taking place in over 200 countries by regional and local organizers were the heart of Asteroid Day. These coordinators and organizers invested their own time, dedication and passion to create their independent Asteroid Day events. Working with scientists, researchers and teachers in their communities, they shined a light on the experts who locally support the global conversation about asteroids.

In the past, this year and into the future, our work is only made possible through the generosity of our supporters and innovators in the field who partner with us. As we move towards the end of 2017, we will continue our strategy of leveraging our supporters' investments in the best possible way — for the maximum benefit to our field and to the world as a whole.

With appreciation to all our supporters around the world we look forward...



**Danica Remy**

President

B612 Foundation



Photograph of the Dumbarton Bridge and salt ponds,  
by Ed Lu from the International Space Station

## ABOUT US

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B612 is dedicated to protecting Earth from asteroid impacts. We do this through:

### Science & Technology

Driving forward the science and technologies needed to protect the Earth from asteroid impacts.

### Advocacy & Public Education

Educating the general public, the scientific community, and world governments about planetary defense against asteroid impacts.

Since the organization's inception in 2002, our work has been carried out entirely through the support of private donors.

What started in 2002 as a visionary idea to develop the technology to deflect an asteroid has grown into a world-renowned organization and scientific institute with a key role in the emerging field of planetary defense. For years, B612, our partners, and a global community of dedicated scientists and researchers have advocated for increased asteroid detection and many victories resulted from those efforts. Asteroid detection is now debated seriously in scientific, governmental, and public conversations. And now that conversation must advance further.

## IN THE LAST YEAR

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Last year we stated several objectives to support our work to advance the field of planetary defense. We are pleased to report we have made progress towards achieving those goals.

### Advance Cutting-Edge Technologies for Asteroid Detection

The first step in opening up a new frontier is to map it. A comprehensive map showing the location of geographic features, resources, and access routes has historically been the key to scientific discovery, economic expansion, and defense. The Asteroid Institute is advancing work to create a predictive dynamical map, which requires two things — multiple observations of the positions of each object over a long period of time, and the ability to calculate the future locations of those objects using the laws of orbital mechanics.

### Develop Tools for Analyzing and Assessing Asteroid Deflection Scenarios

The Asteroid Institute program started the Asteroid Detection Analysis Machine (ADAM) project last year, which will provide cloud-based infrastructure for large-scale orbital dynamics and related computations that will enable the science and business community to identify, track, analyze, understand, and react to opportunities and threats coming from the asteroids in the solar system. ADAM will provide openness and transparency, allowing others to use it as a baseline for comparison and collaboration.

### Demonstrate the Viability of Synthetic Tracking

For the past several years, B612 has supported the development of a technology for tracking asteroids called synthetic tracking, which we believe can revolutionize the discovery of asteroids by allowing us to track millions of asteroids too small to be seen by other means. Synthetic tracking compensates for the blurring effect caused by the motion of asteroids, allowing very long exposure times and the use of small inexpensive telescopes for finding these asteroids.

### Drive Global Conversation Around Asteroids

B612 is proud to be a founding partner of Asteroid Day, a global awareness campaign that teaches people about asteroids. Celebrated annually on June 30th, this year 1,200+ events were organized worldwide and a first-ever Asteroid Day LIVE 24-hour broadcast was held at the program's new global headquarters in Luxembourg.

**We space fliers have seen the cosmic scars on Earth, and our international collaboration in space is an example of how we should apply our joint skills in space technology to find rogue asteroids and divert them from a collision with Earth.** TOM JONES, ASTRONAUT

# PROGRAM EVOLUTION



2002

B612 founded with the goal of significantly altering the orbit of an asteroid in a controlled manner.

2004-2008

B612 leads the Apophis debate.

2005

B612 announces the invention of the Gravity Tractor in Nature.

2008-2009

B612 funds design study at JPL showing feasibility of the Gravity Tractor.

Congress gives NASA the goal of finding 90 percent of asteroids larger than 140 meters, called the George E. Brown Act.

2012

Open letter to NASA about deflection mission planning and discussions regarding potential impact of asteroid 2011 AG5.

B612 announces the Sentinel Space Telescope project.

B612 moves from a volunteer organization to staffed.

2013

Sentinel project passes its first major technical review.

Sentinel project design published in New Space.

2014

B612 releases asteroid impact video with data from the Nuclear Test Ban Treaty Organization.

UN Committee on Peaceful Uses of Outer Space and General Assembly pass resolution creating International Asteroid Warning Network.

B612 is Founding Sponsor of Asteroid Day project, a global asteroid-awareness campaign.

Construction project for Large Synoptic Survey Telescope (LSST) begins.

2015

B612's "Sentinel to Find 500,000 Near-Earth Asteroids," published in IEEE Spectrum.

B612 hosts Bay Area Asteroid Day event with California Academy of Science.

Asteroid Day project holds 150 events worldwide.

B612 begins work with Caltech on synthetic tracking research.

2016

NASA announces Planetary Defense Coordination Office. Asteroid Day is recognized by the United Nations and holds 500 events worldwide.

B612 issues pre-print "Sentinel Performance for Surveying the Near-Earth Object Population" describing optimization design.

B612 begins Asteroid Decision Analysis and Mapping project (ADAM) to improve ability to make decisions on potential asteroid threats.

B612 endorses NEOcam + LSST for 100M+ solution and stops fundraising for Sentinel project.

2017

B612 launches the Asteroid Institute program, a virtual organization comprised of planetary scientists and engineers around the world.

Asteroid Day project moves to Luxembourg and holds a 24-hour live asteroids broadcast. 1,200 events are held worldwide.

Asteroid Institute builds team for Asteroid Decision Analysis and Mapping project (ADAM) to provide analytical tools for asteroid defense scenarios.

Asteroid Institute program reports results from synthetic tracking stellar data collection.

B612 publishes call for shared solar system map in Financial Times.

## 15 YEARS OF PROGRESS IN THE FIELD

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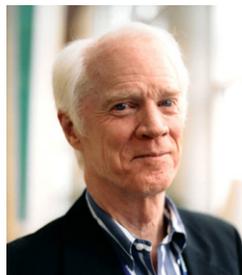
This year marks the 15 year anniversary of B612, which was started in 2002 by five forward-thinking individuals. Our five founding board members have shared their reflections on progress in the field, our role as a leading institution in the planetary defense community, and their thoughts on the future.

### Dr. Piet Hut, Astrophysicist



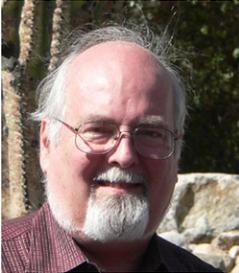
I met Ed Lu when he came to the Institute for Advanced Study in Princeton. In the middle of his talk, he made an off-hand remark about a new plasma engine being tested in the building where he worked, and how that could be used to visit asteroids and perhaps even nudge their orbit to prevent an impact on Earth. I immediately perked up upon hearing that line and asked him to go for a walk right after his presentation. While we took a stroll around the pond behind the Institute, we quickly realized that we had independently been thinking about ways to change the orbits of asteroids and ultimately protect the Earth from asteroid impacts. It didn't take long for us to conclude that the time had come to get a group of experts together to explore what could be done. Within a year, B612 was born.

### Rusty Schweickart, Apollo 9 Astronaut, Co-Founder, B612 Foundation



In the 15 years since co-founding B612, we've gotten a lot done and stimulated huge changes in the field. Today we have thousands of people working in this area. Early warning is one large category of work that's finding them, tracking them, being able to calculate their orbits, and predict whether or not they are going to hit the Earth. Then there's another set of people who are working on deflection. But then, we realized as we got into this that in fact if an asteroid is going to hit the Earth there are many, many political questions about who deflects it. So there's a whole community now of non-technical people — diplomats, lawyers, business people, and risk management people who are also involved in the planetary defense issue today. And now we need to have a map. Maps form the basis of the way in which we explore.

#### Dr. Clark Chapman, Planetary Scientist



Today, international interest in small solar system bodies and the hazard they pose is at an all-time high and funding has increased dramatically (if inadequately to fund a dedicated space mission). Professional papers on the topic are now published in prestigious, peer-reviewed scientific and engineering journals. The public is ever more aware of bolides exploding in the night skies and there are occasional network soap operas about a threatened asteroid apocalypse. The NEO hazard is now generally recognized as a significant element in the field of natural hazards and emergency management.

#### Geoff Baehr, Venture Capital



Collectively we're looking forward to the acceleration of asteroid discovery that will be brought to us by the emerging technology, telescopes and talent in the field. With the launch of the Asteroid Institute program this year and its work with the Asteroid Decision Analysis and Mapping project (ADAM) and the Synthetic Tracking project, our growing technical and scientific team, in collaboration with others in the field, should yield exciting results over the next decade.

#### Dr. Ed Lu, Executive Director, Asteroid Institute; Co-Founder, B612



We've come a long way in the last 15 years since the formation of B612. Prior to sitting down with my fellow co-founders, there was a lot of conversation about how we get politicians and the general public to take the issue of asteroids seriously. But now the idea of preventing asteroid impacts is somewhat mainstream. Just as important, we've made enormous progress in understanding the subtleties and nuances of deflecting asteroids from hitting Earth, and correspondingly great progress in finding and tracking asteroids. Not only have astronomers cataloged nearly all very large near-Earth asteroids (larger than 1 km in size), but we are making progress at finding and tracking smaller asteroids.

# ASTEROID INSTITUTE

## LETTER FROM THE EXECUTIVE DIRECTOR

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In June, we launched the Asteroid Institute, an academically focused program working to protect the Earth from asteroid impacts. B612 has consolidated all of our technical and scientific research into the Asteroid Institute program. The Asteroid Institute will continue to collaborate with major institutions such as Southwest Research Institute (SwRI), Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech), and the University of Washington. The Institute will also be an important non-governmental voice on planetary defense policy issues.

I am leading the Institute as Executive Director. Our team of planetary scientists and engineers is distributed at several locations. Recently recruited Asteroid Institute researchers will be based at the Data Intensive Research in Astrophysics and Cosmology Center (DIRAC) and the Department of Astronomy at the University of Washington. Our work includes collaboration with the Large Synoptic Survey Telescope (LSST) working on the asteroid data pipeline, the Asteroid Decision Analysis and Mapping project (ADAM), further development of synthetic tracking to improve our ability to discover small asteroids, and analysis of a future satellite constellation for detecting and tracking asteroids.

Our research can be broadly understood as working to develop an asteroid map of the solar system. Such a map is crucial to opening up the new space frontier because it enables future exploration and economic development of space, and of course it also allows us to protect our planet from asteroid impacts. Not only are we working on new technologies for finding and tracking asteroids like synthetic tracking, but we are building the tools and applications to allow us to use and understand these maps through the ADAM project. I believe our work at the Asteroid Institute is incredibly important to our future as a species, and that is why I am so excited we have made this step.



**Ed Lu**  
Executive Director, Asteroid Institute  
Co-Founder, B612

**The science of the next decade will be driven by data. With a new generation of telescopes and surveys coming online, providing the most detailed census of our universe ever undertaken, we have an unparalleled opportunity for new and fundamental discoveries about our solar system.**

ANDY CONNOLLY, DIRECTOR OF THE DATA INTENSIVE RESEARCH AND COSMOLOGY INSTITUTE (DIRAC), UNIVERSITY OF WASHINGTON



# ASTEROID INSTITUTE

## ASTEROID DECISION ANALYSIS AND MAPPING PROJECT

The ADAM project provides cloud-based infrastructure for large-scale orbital dynamics and related computations that will enable the science and business community to identify, track, analyze, understand, and react to opportunities and threats coming from the asteroids in the solar system.

ADAM is a project of the Asteroid Institute, and in layman's terms, the ADAM project is building the application and interface layer to access and make sense of the data comprising the asteroid map. A map is more than just a collection of data. For it to be truly useful, the data must be presented in a way that allows us to see the relationship amongst the elements and to calculate quantities of interest — for instance, a map of the probability distribution that a certain asteroid will impact the Earth on a particular date. An analogy would be the myriad of applications that use open APIs to access online map databases, making online maps so useful. The ADAM project will allow researchers worldwide to build applications that make use of the data in the asteroid map.

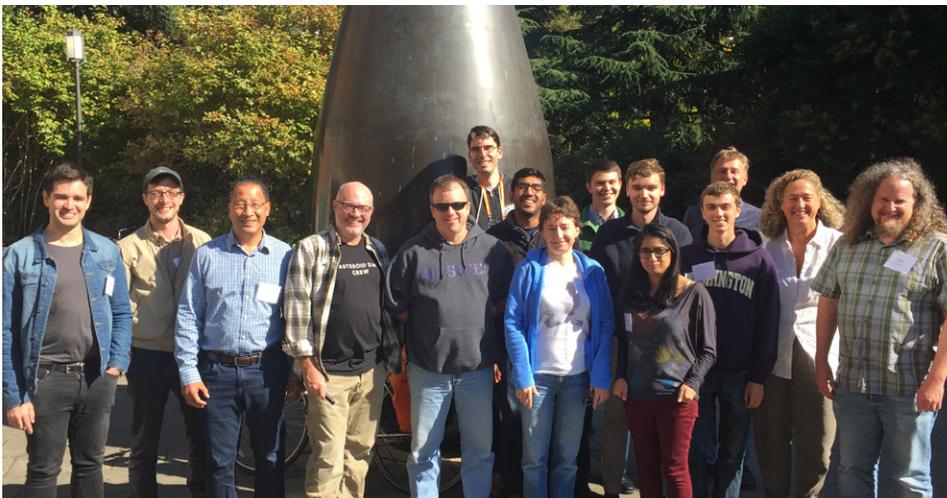
### The Case for Better Compute Resources

A goal of ADAM is greater openness and transparency with regards to analysis of asteroid threats. With open and published algorithms, ADAM will act as a baseline for comparison and collaboration. Researchers around the world will be able to use tools within ADAM to assess threatening situations, identify and trade-off possible realistic courses of action, and create actionable decision making data representations. A critical advantage of being hosted on the cloud is that it enables the astrodynamics algorithms to be run at an extremely large scale, with many runs being done simultaneously. This enables researchers to run computational problems that would be prohibitive on local workstations. Instead of making approximations and assumptions, thousands of highly accurate computations can be run simultaneously, yielding insight into the otherwise hidden effects of the nonlinearities of our solar system's chaotic dynamics. Furthermore, the rapid calculations enable researchers to see patterns more quickly, enabling iteration and improving understanding.

## Progress in the Last Year

With thanks to the generosity of our donors, we have built a world-class computational research group to support ADAM and to conduct original research. The team has developed a detailed project plan with project milestones and technical goals that dovetail with the LSST timeline. We have made progress on the computational tools and now have the capability to mathematically propagate an asteroid orbit over many decades to within an accuracy of a few kilometers. This required us to take into account such tiny effects as the curvature of space-time due to General Relativity, the non-sphericity of the Sun, the gravitational effects of each of the planets and of the larger asteroids, as well as the nonisotropic thermal re-radiation from rotation of the asteroid. One of the first questions we are investigating using ADAM is how much warning prior to an asteroid impact our current telescopes will be able to provide, and whether this is sufficient to be able to mount a deflection mission.

Several members of the Asteroid Institute team are working alongside LSST researchers at the University of Washington.



Members of the Asteroid Institute team and ADAM Hackathon participants from left to right: Bryce Bolin, JP Carrico, Ed Lu, John Carrico, Mike Loucks, Mario Juric, Vivek Vittaldev, Tatiana Kichkaylo, Daniel Hawes, Joachim Moeyens, Samira Motiwala. Peter Whidden, Andy Connolly, Danica Remy, and Rory Barnes. For a full list of the team, see the back cover.

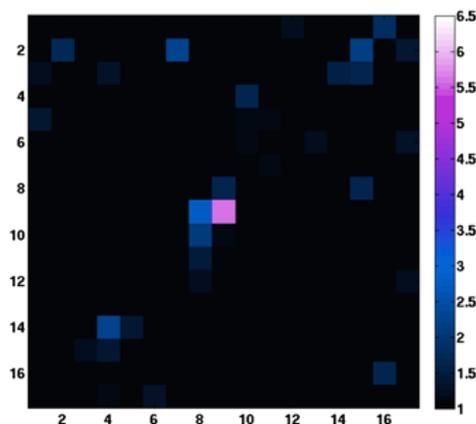
# ASTEROID INSTITUTE

## SYNTHETIC TRACKING

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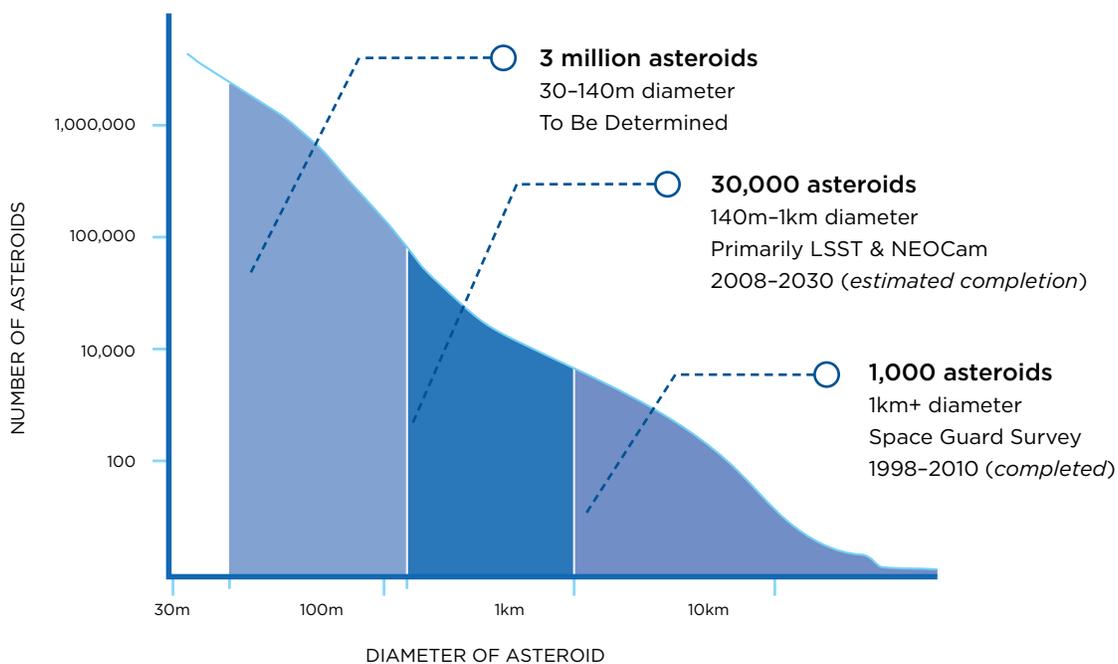
For the past several years, B612 has supported the development of a technology for tracking asteroids called synthetic tracking, which we believe can revolutionize the discovery of asteroids by allowing us to track millions of asteroids too small to be seen by other means. Synthetic tracking compensates for the blurring effect caused by the motion of asteroids, allowing very long exposure times and the use of small inexpensive telescopes for finding these asteroids.

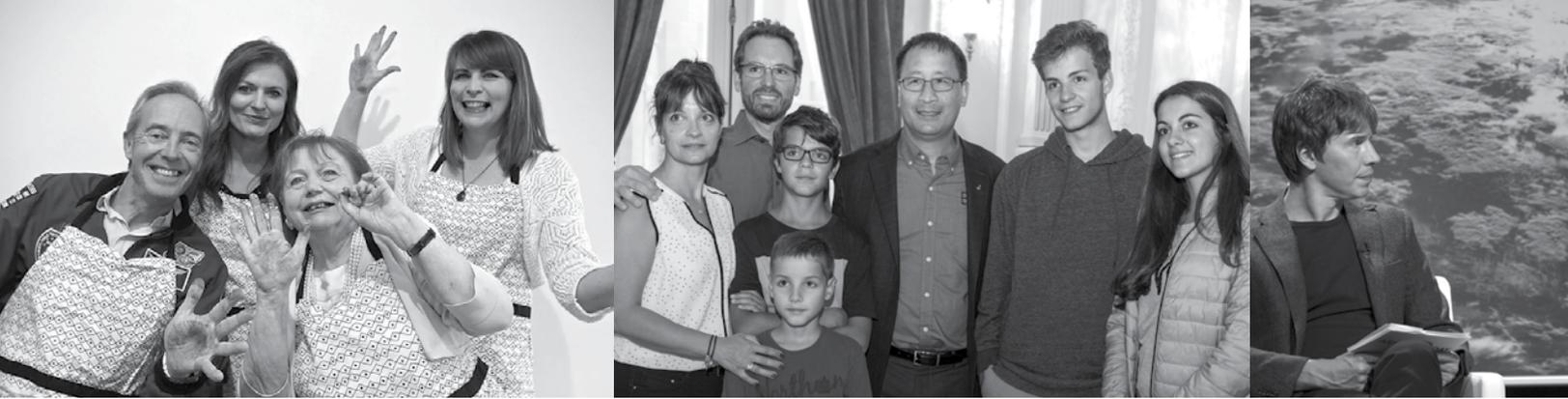
This year we demonstrated that the synthetic tracking process works on data from an Earth observation satellite that had been turned around to look away from Earth. The images were processed through our synthetic tracking algorithm after being downlinked to the ground. We were able to resolve asteroids which would have otherwise been too dim to be observed without synthetic tracking (see image below). Here we show the processed image of asteroid 1998 YP11 which appears as a violet pixel in the middle of the image. The synthetic tracking algorithm was able to resolve this asteroid and its motion even though the brightness of the asteroid in any particular image is less than the background sky noise level.



Asteroid 1998 YP11 observed on March 30, 2017, from Earth orbiting satellite using B612 Synthetic Tracking technology.

The next step is to demonstrate a full synthetic tracking system with onboard processing in Earth orbit as a precursor to an eventual constellation of solar orbiting telescopes. This will require a purpose-built small satellite with capability far in excess of the simple test shown above. Successful completion of this flight will then pave the way for the later deep space constellation and mapping of the bulk of asteroids in our inner solar system. Should all this prove successful, we will finally be able to complete the solar system map of asteroid trajectories, and with that be able to protect the Earth from asteroid impacts.





## ASTEROID DAY

30 JUNE

What began simply as a public information initiative and a scientifically-minded declaration of the need for rapid discovery of asteroids was transformed into a global movement. Three years after creating Asteroid Day, it is now based in beautiful Luxembourg. Asteroid Day has been declared an international day by the United Nations in December, 2016.

### Congratulations ASTEROID DAY — now at home in Luxembourg!

BRIAN MAY, ASTEROID DAY CO-FOUNDER,  
QUEEN GUITARIST, ASTEROID INSTITUTE  
ADVISOR, AND ASTROPHYSICIST



An unprecedented number of people tuned in to learn about asteroids during the very first curated 24-hour broadcast this year. Broadcasting from RTL City studios in Luxembourg would not have been possible without all of the organizations supporting the live broadcast. The support of Luxembourg, its citizens, companies, and especially Deputy Prime Minister Étienne Schneider and his team made this program a historic reality.

Deepest thanks goes to the premier sponsors: OHB, SES, BCE, and the Luxembourg Government — whose generous contributions were essential. Asteroid Day 2017 was also made possible thanks to the support of Discovery Science, BIL, Luxembourg's Chambre de Commerce, SNCI, GLAE, and B612 in the role as the founding partner.

Asteroid Day would not have been possible without the speakers, astronauts, astrophysicists, asteroid experts, and industry professionals who travelled to Luxembourg. These individuals' expertise is the scientific foundation that the live programming was built upon. These scientists, technologists, and professionals are the true rock stars of Asteroid Day!





Special thanks also goes to NASA, ESA, JAXA, the Large Synoptic Survey Telescope, as well as the University of Arizona’s Lunar and Planetary Observatory whose participation in the live broadcast provided a more complete view of the many efforts to discover, observe and track asteroids.

Hundreds of independently organized events by regional and local organizers are the heart of Asteroid Day. These coordinators and organizers invested their own time, dedication and passion to create their own Asteroid Day events. Working with scientists, researchers and teachers in their communities, they shined a light on the experts locally who supported our global conversation about asteroids.

And finally the Asteroid Day team: Thomas Katucki, Pol Felten, Hailey Loucks and Manuel Bäuerle worked hard to deliver Asteroid Day LIVE from Luxembourg. Together, we are already looking forward to the next year.

(Left to right): Jean-Francois Clervoy (astronaut), Sabinje von Gaffke, Susan McKenna-Lawlor, and science center docent; Marc Serres & family with Ed Lu; Brian Cox & Rusty Schweickart; Danica Remy, Étienne Schneider, & Grig Richters; Bryce Bolin, Manuel Bauerle, Jean-Francois Clervoy (astronaut), Thomas Katucki, Maurice Heinz, Rusty Schweickart (astronaut), Dumitru-Dorin Prunariu (cosmonaut), Danica Remy, Hailey Loucks, Nicole Stott (astronaut), Ed Lu (astronaut), Philippine Griveaud, Pol Felten, & Grig Richters

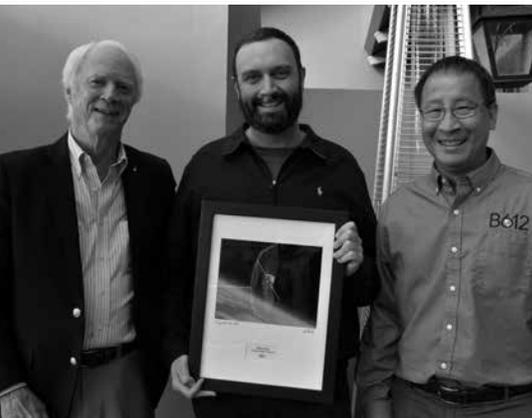
### 100X Declaration that Launched Asteroid Day

There are a million asteroids in our solar system that have the potential to strike Earth and destroy a city, yet we have discovered less than 10,000 — just one percent — of them. We have the technology to change that situation.

Therefore, we, the undersigned, call for the following action:

- Employ available technology to detect and track near-Earth asteroids that threaten human populations via governments and private and philanthropic organizations.
- A rapid hundred-fold acceleration of the discovery and tracking of near-Earth asteroids to 100,000 per year within the next ten years.

✓ **Global adoption of Asteroid Day, heightening awareness of the asteroid hazard and our efforts to prevent impacts, on June 30. [COMPLETED]**



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ANONYMOUS x 7

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Top Row (left to right): Crown Princess Stephanie of Luxembourg, Crown Prince Guillaume of Luxembourg, Rusty Schweickart, & Deputy Prime Minister Étienne Schneider; David & Cheryl Brin; Genevieve Lydstone, Erika Jurvetson, Leif Jurvetson, & Steve Jurvetson Bottom Row: Rusty Schweickart, Matthew Welty & Ed Lu; Astronaut Tom Jones at Lamplighter School in Texas; Film screening of "The Space Between Us"



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\*Leadership Gift (\$1M-\$5M)

Launched in 2017 as a follow-on  
to the Founding Circle

Jim Chervenak

Arthur Gleckler and Kristine Kelly

Jensen Huang

Top Row (left to right): Hillary Aiken, Scott Hubbard, Steve Grimm, & Julie Grimm;  
Garrett Gruener, Peter Leyden, Ed Lu, and Scott Manley; Dominik Kaiser, Danica Remy,  
Sarah Brightman, and Dumitru-Dorin Prunariu  
Bottom Row: B612 Technology Briefing event; Arthur Gleckler & Susan Hine; Crown  
Prince Guillaume of Luxembourg, Crown Princess Stephanie of Luxembourg, Steve  
Jurvetson, & Deputy Prime Minister Étienne Schneider



**We have donors from 46 countries.**

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**Moonrise, by Ed Lu from the  
International Space Station**



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