

# Hawking Radiation of Black Hole

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*A RUDN University physicist has developed a formula for calculating Hawking radiation on the event horizon of a black hole, which allows physicists to determine how this radiation would be changed with quantum corrections to Einstein's theory of gravity. [33]*

*Researchers at Weizmann Institute of Science and Cinvestav recently carried out a study testing the theory of Hawking radiation on laboratory analogues of black holes. [32]*

*One of the most cataclysmic events to occur in the cosmos involves the collision of two black holes. [31]*

*Black holes are known for their voracious appetites, binging on matter with such ferocity that not even light can escape once it's swallowed up. [30]*

*During the formation of a black hole, a bright burst of very energetic light in the form of gamma rays is produced, these events are called gamma ray bursts. [29]*

*A new Tel Aviv University-led study published today in Nature Astronomy finds that some supermassive black holes are triggered to grow, suddenly devouring a large amount of gas in their surroundings. [28]*

*Needless to say, we do not have the capability of performing real experiments in or near black holes yet, so scientists resort to theory and simulations to develop an understanding, by making predictions and new discoveries. [27]*

*Our first glimpses into the physics that exist near the center of a black hole are being made possible using "loop quantum gravity"—a theory that uses quantum mechanics to extend gravitational physics beyond Einstein's theory of general relativity. [26]*

*In the shadowy regions of black holes two fundamental theories describing our world collide. Can these problems be resolved and do black holes really exist? First, we may have to see one and scientists are trying to do just this. [25]*

*The authors suggest that this virtual reality simulation could be useful for studying black holes. [24]*

*Every galaxy is thought to harbor a supermassive black hole in the center, or nucleus, of the galaxy, and in active galaxies this black hole is fed by infalling matter. [23]*

*A new study by researchers at the University of Colorado Boulder finds that violent crashes may be more effective at activating black holes than more peaceful mergers. [22]*

*For the first time, a team of astronomers has observed several pairs of galaxies in the final stages of merging together into single, larger galaxies. [21]*

*In a cluster of some of the most massive and luminous [HYPERLINK](#) "https://phys.org/tags/stars/" stars in our galaxy, about 5,000 light years from Earth, astronomers detected particles being accelerated by a rapidly rotating neutron star as it passed by the massive star it orbits only once every 50 years. [20]*

*For the first time astronomers have detected gravitational waves from a merged, hyper-massive neutron star. [19]*

*A group of scientists from the Niels Bohr Institute (NBI) at the University of Copenhagen will soon start developing a new line of technical equipment in order to dramatically improve gravitational wave detectors. [18]*

*A global team of scientists, including two University of Mississippi physicists, has found that the same instruments used in the historic discovery of gravitational waves caused by colliding black holes could help unlock the secrets of dark matter, a mysterious and as-yet-unobserved component of the universe. [17]*

*The lack of so-called "dark photons" in electron-positron collision data rules out scenarios in which these hypothetical particles explain the muon's magnetic moment. [16]*

*By reproducing the complexity of the cosmos through unprecedented simulations, a new study highlights the importance of the possible behaviour of very high-energy photons. In their journey through intergalactic magnetic fields, such photons could be transformed into axions and thus avoid being absorbed. [15]*

*Scientists have detected a mysterious X-ray signal that could be caused by dark matter streaming out of our Sun's core.*

*Hidden photons are predicted in some extensions of the Standard Model of particle physics, and unlike WIMPs they would interact electromagnetically with normal matter.*

*In particle physics and astrophysics, weakly interacting massive particles, or WIMPs, are among the leading hypothetical particle physics candidates for dark matter.*

*The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.*

*There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.*

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## The Big Bang

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

## Calculating Hawking radiation at the event horizon of a black hole

A RUDN University physicist has developed a formula for calculating Hawking radiation on the event horizon of a black hole, which allows physicists to determine how this radiation would be changed with quantum corrections to Einstein's theory of gravity. This formula will allow researchers to test the accuracy of different versions of the quantum gravity theory by observing black holes, and comprises a step toward the long-sought "grand unification theory" that would connect quantum mechanics and relativity. The article is published in the journal *Physical Review D*.

Although Einstein's gravitation [theory](#) corresponds to the recent discovery of gravitation waves, it still leaves open some questions, including the nature of the singularity, dark matter, [dark](#)

[energy](#), and the question of quantum gravity. Also, even observations of gravity waves do not exclude that alternative gravitation theories may be accurate, and they can be used to describe [black holes](#). Such theories, which include additional quantum components, do not contradict the observed picture of black hole mergers. Calculations made following these theories predict the same behavior of black holes at a great distance from each other, but at the same time, demonstrate important features near the event horizon—the "border" of the black hole from beyond which there is no return.

It is believed impossible to look beyond the event horizon of a black hole because nothing can escape, including particles and radiation. However, Stephen Hawking proved that black holes can "evaporate" by emitting various elementary particles. This means that over time, all the information absorbed by a black hole can disappear, which is contrary to fundamental ideas about information—it is believed that information cannot disappear without a trace. Therefore, alternative gravitation theories, aimed at eliminating this paradox, have become more popular since they could contribute to a quantum gravitation theory.

One of the most promising approaches is the Einstein-dilaton-Gauss-Bonnet theory with dilaton—it applies quantum components as a correction to the Theory of General Relativity.

"The alternative theory we have considered is inspired by the low-energy limit of string theory, the so-called Einstein-dilaton-Gauss-Bonnet theory with dilaton. In addition to the Einstein part, it contains quadratic curvature terms and a scalar field," Roman Konoplya, a researcher at the Educational and Research Institute of Gravitation and Cosmology of the RUDN University, says.

To describe how a black hole responds to external gravitational perturbations, cosmologists use the concept of quasinormal modes. Modes are oscillations that occur when an external actions on a black hole, the characteristics of which depend on the force of the impact and the parameters of the black hole itself. They are called quasinormal because they fade over time and their amplitude can be measured only for a small period. Such oscillations are usually described using frequency as a complex number, the real part of which is the periodic oscillations, and the imaginary—the decay rate.

The RUDN University physicist, together with Czech Republic scientists Antonina Zinhailo and Zdeněk Stuchlík, studied classical (quasinormal) and quantum (Hawking's) radiation of test fields on the background of a four-dimensional, spherically symmetric and asymptotically flat black hole in the Einstein-dilaton-Gauss-Bonnet theory with dilaton. They obtained an analytical formula for the eikonal state of quasinormal modes and used it to calculate the quasinormal modes of the test scalar and Maxwell's fields and estimated the Hawking radiation intensity for the Einstein-dilaton-Gauss-Bonnet black hole.

Text fields are all fields in the vicinity of a black hole because they propagate on its background (for example, a Dirac field or an [electromagnetic field](#)). The intensity of the Hawking electromagnetic radiation and the Dirac field proved to be a significantly more sensitive characteristic than its quasinormal spectrum, showing an increase in the rate of energy emission by 57 percent and 48 percent respectively to the fields.

"We obtained an estimate of the intensity of the Hawking evaporation of black holes by taking into account quantum corrections to the geometry of the black hole," Roman Konoplya concludes.

"Classical radiation (e.g., electromagnetic or other waves) differ from Einstein's only a few percent, that is, Hawking radiation is a much more sensitive mechanism. Quasinormal modes are the frequencies of classical [radiation](#), which, unlike quantum modes, differ little from the Einstein case. In the future, perhaps by observing the primary black holes that appeared in the early universe, this may clarify our ideas about quantum corrections to gravity." [33]

## Testing Hawking radiation in laboratory black hole analogues

Researchers at Weizmann Institute of Science and Cinvestav recently carried out a study testing the theory of Hawking radiation on laboratory analogues of black holes. In their experiments, they used light pulses in nonlinear fiber optics to establish artificial event horizons.

Back in 1974, renowned physicist Stephen Hawking amazed the physics world with his theory of Hawking [radiation](#), which suggested that rather than being black, [black holes](#) should glow slightly due to [quantum effects](#) near the black hole's event horizon. According to Hawking's theory, the strong gravitational field around a black hole can affect the production of matching pairs of particles and anti-particles.

Should these particles be created just outside the event horizon, the positive member of this pair of particles could escape, resulting in an observed [thermal radiation](#) emitting from the black hole. This radiation, which was later termed Hawking radiation, would hence consist of photons, neutrinos and other subatomic particles. The theory of Hawking radiation was among the first to combine concepts from quantum mechanics with Albert Einstein's theory of General Relativity.

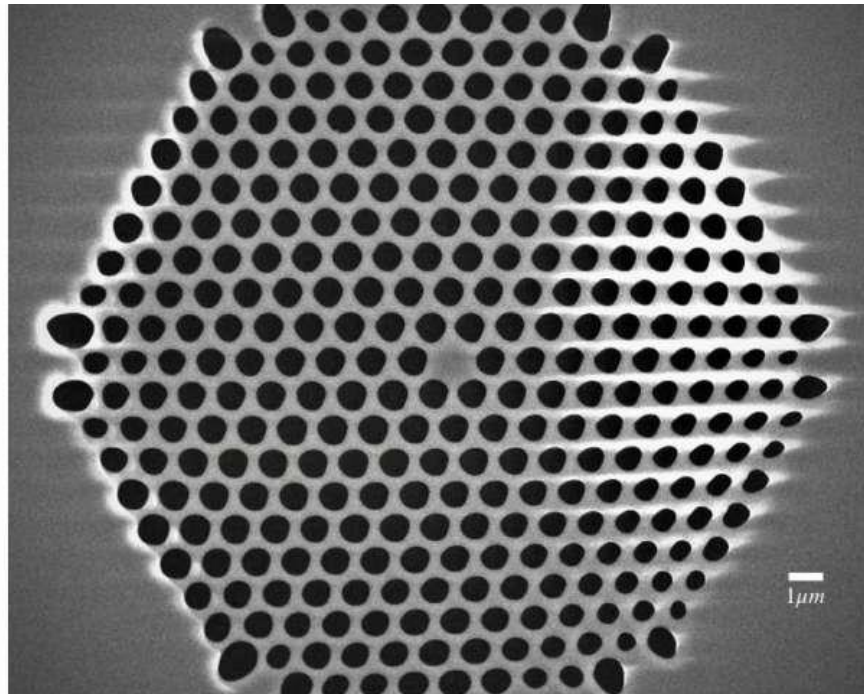
"I learned General Relativity in 1997 by lecturing a course, not by taking a course," Ulf Leonhardt, one of the researchers who carried out the recent study, told *Phys.org*. "This was a rather stressful experience where I was just a few weeks ahead of the students, but I really got to know General Relativity and fell in love with it. Fittingly, this also happened in Ulm, Einstein's birthplace. Since then, I have been looking for connections between my field of research, quantum optics and General Relativity. My main goal is to demystify General Relativity. If, as I and others have shown, ordinary optical materials like glass act like curved spaces, then the curved space-time of General Relativity becomes something tangible, without losing its charm."

In collaboration with his first Ph.D. student Paul Piwnicki, Leonhardt put together some initial ideas of how to create optical black holes, which were published in 1999 and 2000. In 2004, he finally achieved a method that actually worked, which is the one used in his recent study.

"Imagine, like in Einstein's gedanken experiments, light chasing after another [pulse](#) of light," Leonhardt explained. "Suppose that all the light travels inside an optical fiber. In the fiber glass, the pulse changes the speed of the light chasing it a little, such that the light cannot overtake the pulse. It experiences a white-hole horizon; a place it cannot enter. The front of the pulse acts like the exact opposite: a black-hole horizon, a place the light cannot leave. This is the idea in a nutshell."

Leonhardt and his colleagues published and demonstrated this idea in 2008. Subsequently, they tried to use it to demonstrate Hawking radiation.

Hawking radiation has never been directly observed in space, as this is not currently feasible. However, it can be demonstrated in laboratory environments, for instance, using Bose-Einstein condensates, water waves, polaritons or light. In the past, several researchers tried to test Hawking radiation in the lab using these techniques, yet most of their studies were, in fact, problematic and have thus been disputed.



This image shows an electron-microscope picture of the interior of one of the researchers' fibres. The fibres are sophisticated photonic-crystal fibres. They are as thin as a human hair and inside they carry hole structures that guide the light in the centre. Credit: Drori et al.

For instance, some [past findings](#) obtained with intense light pulses in optical media turned out to be inconsistent with theory. Rather than observing Hawking radiation made by horizons, as the authors themselves found out later, they had, in fact, observed horizon-less radiation created by their light pulses, as they exceeded the phase velocity of light for other frequencies. Other studies attempting to observe Hawking radiation [on water waves](#) and in [Bose-Einstein condensates](#) also turned out to be problematic.

Discussing the outcomes of these studies with *Physics World*, Leonhardt wrote, "I greatly admire the heroism of the people doing them, and their technical skills and expertise, but this is a difficult subject." He also wrote: "Horizons are perfect traps; it is easy to get trapped behind them without noticing, and this applies to horizon research, as well. We learn and become experts according to the classic definition: An expert is someone who has made all possible mistakes (and learned from them)."



As proven by previous efforts, observing Hawking radiation in the lab is a highly challenging task. The study carried out by Leonhardt and his colleagues could be the first valid demonstration of Hawking radiation in optics.

"Black holes are surrounded by their event horizons," Leonhardt explained. "The horizon marks the border where light can no longer escape. Hawking predicted that at the horizon light quanta—photons—are created. One photon appears outside the horizon and is able to get away, while its partner appears on the inside and falls into the black hole. According to quantum mechanics, particles are associated with waves. The photon on the outside belongs to a wave that oscillates with positive frequency, the wave of its partner on the inside oscillates with a negative frequency."

In their study, Leonhardt and his colleagues made light out of positive and negative frequencies. Their positive-frequency light was infrared, while the negative-frequency one was ultraviolet. The researchers detected both of them and then compared them with Hawking's theory.

The tiny bit of ultraviolet light that they managed to detect using sensitive equipment is the first clear sign of stimulated Hawking radiation in optics. This radiation is referred to as 'stimulated' because it is stimulated by the probe light that the researchers sent in to chase the pulses.

"Our most important finding, perhaps, is that black holes are not something out of the ordinary, but that they closely resemble what [light pulses](#) do to ordinary [light](#) in fibers," Leonhardt said.

"Demonstrating subtle quantum phenomena like Hawking radiation is not easy. It takes extremely short pulses, extraordinary fibers, sensitive equipment and, last but not least, the hard work of dedicated students. But even Hawking radiation is something one can actually understand."

The study carried out by Leonhardt and his colleagues is an important contribution to the physics field, as it provides the first laboratory demonstration of Hawking radiation in optics. The researchers also found the analogy to event horizons to be remarkably robust, despite pushing the optics to the extreme, which increased their confidence in the validity of their theories.

"We now need to improve our setup to get ready for the next big challenge: the observation of spontaneous Hawking radiation," Leonhardt said. "In this case, the radiation is not stimulated anymore, except by the inevitable fluctuations of the quantum vacuum. Our next goals are steps that improve the apparatus and test various aspects of stimulated Hawking radiation, before going all the way to spontaneous Hawking radiation." [32]

## **Physicists use supercomputers and AI to create the most accurate model yet of black hole mergers**

One of the most cataclysmic events to occur in the cosmos involves the collision of two black holes. Formed from the deathly collapse of massive stars, black holes are incredibly compact—a person standing near a stellar-mass black hole would feel gravity about a trillion times more strongly than they would on Earth. When two objects of this extreme density spiral together and merge, a fairly common occurrence in space, they radiate more power than all the stars in the universe.

"Imagine taking 30 suns and packing them into a region the size of Hawaii. Then take two such objects and accelerate them to half the speed of light and make them collide. This is one of the most violent events in nature," says Vijay Varma, a graduate student at Caltech.

In a new study in the January 11 issue of the journal *Physical Review Letters*, Varma and his colleagues report the most accurate computer model yet of the end stage of black hole mergers, a period when a new, more massive black hole has formed. The model, which was aided by supercomputers and machine-learning, or artificial intelligence (AI) tools, will ultimately help physicists perform more precise tests of Einstein's general theory of relativity.

"We can predict what's left after a black hole merger—properties of the final black hole such as its spin and mass—with an accuracy 10 to 100 times better than what was possible before," says co-author Davide Gerosa, an Einstein Postdoctoral Fellow in Theoretical Astrophysics at Caltech. "This is important because tests of general relativity depend on how well we can predict the end states of black hole mergers."

The research is related to a larger effort to study [black holes](#) with LIGO, the Laser Interferometer Gravitational-wave Observatory, which made history in 2015 by making the first direct detection of gravitational waves emitted by a black hole merger. Since then, LIGO has detected nine additional black hole mergers. Gravitational waves are ripples in space and time, first predicted by Einstein more than 100 years ago. Gravity itself, according to general relativity, is a warping of the fabric of spacetime. When massive objects like black holes accelerate through spacetime, they generate gravitational waves.

One of the goals of LIGO and the thousands of scientists analyzing its data is to better understand the physics of black hole collisions—and to use these data, in turn, to assess whether Einstein's [general theory of relativity](#) still holds true under these extreme conditions. A breakdown of the theory might open the door to new types of physics not yet imagined.

But creating models of colossal events like black hole collisions has proved to be a daunting task. As the colliding black holes become very close to one another, just seconds before the final merger, their gravitational fields and velocities become extreme and the math becomes far too complex for standard analytical approaches.

"When it comes to modeling these sources, one can use the pen-and-paper approach to solve Einstein's equations during the early stages of the merger when the black holes are spiraling toward each other," says Varma. "However, these schemes break down near the merger. Simulations using the equations of general relativity are the only means to predict the outcome of the merger process accurately."

That is where supercomputers help out. The team took advantage of nearly 900 black hole merger simulations previously run by the Simulating eXtreme Spacetimes (SXS) group using the Wheeler supercomputer at Caltech (supported by the Sherman Fairchild Foundation) and the Blue Waters supercomputer at the National Center for Supercomputing Applications (NCSA) at the University of Illinois at Urbana-Champaign. The simulations took 20,000 hours of computing time. The Caltech scientists' new machine-learning program, or algorithm, learned from the simulations and helped create the final model.

"Now that we have built the new model, you don't need to take months," says Varma. "The new model can give you answers about the end state of mergers in milliseconds."

The researchers say that their model will be of particular importance in a few years, as LIGO and other next-generation gravitational-wave detectors become more and more precise in their measurements. "Within the next few years or so, gravitational-wave detectors will have less noise," says Gerosa. "The current models of the final black hole properties won't be precise enough at that stage, and that's where our new [model](#) can really help out."

The *Physical Review Letters* study is titled "High-accuracy mass, spin, and recoil predictions of generic black-hole [merger](#) remnants." [31]

## How to escape a black hole: Simulations provide new clues about powerful plasma jets

Black holes are known for their voracious appetites, binging on matter with such ferocity that not even light can escape once it's swallowed up.

Less understood, though, is how [black holes](#) purge energy locked up in their rotation, jetting near-light-speed plasmas into space to opposite sides in one of the most powerful displays in the universe. These jets can extend outward for millions of light years.

New simulations led by researchers working at the Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) and UC Berkeley have combined decades-old theories to provide new insight about the driving mechanisms in the [plasma](#) jets that allows them to steal energy from black holes' powerful gravitational fields and propel it far from their gaping mouths.

The simulations could provide a useful comparison for high-resolution observations from the Event Horizon Telescope, an array that is designed to provide the first direct images of the regions where the [plasma jets](#) form.

The telescope will enable new views of the black hole at the center of our own Milky Way galaxy, as well as detailed views of other supermassive black holes.

"How can the energy in a black hole's rotation be extracted to make jets?" said Kyle Parfrey, who led the work on the simulations while he was an Einstein Postdoctoral Fellow affiliated with the Nuclear Science Division at Berkeley Lab. "This has been a question for a long time."

Now a senior fellow at NASA Goddard Space Flight Center in Maryland, Parfrey is the lead author of a study, published Jan. 23 in *Physical Review Letters*, that details the simulations research.

The simulations, for the first time, unite a theory that explains how electric currents around a black hole twist magnetic fields into forming jets, with a separate theory explaining how particles crossing through a black hole's point of no return—the event horizon—can appear to a distant observer to carry in negative energy and lower the black hole's overall rotational energy.

It's like eating a snack that causes you to lose calories rather than gaining them. The black hole actually loses mass as a result of slurping in these "negative-energy" particles.

Computer simulations have difficulty in modeling all of the complex physics involved in plasma-jet launching, which must account for the creation of pairs of electrons and positrons, the acceleration mechanism for particles, and the emission of light in the jets.

Berkeley Lab has contributed extensively to plasma simulations over its long history. Plasma is a gas-like mixture of charged particles that is the universe's most common state of matter.

Parfrey said he realized that more complex simulations to better describe the jets would require a combination of expertise in plasma physics and the general theory of relativity.

"I thought it would be a good time to try to bring these two things together," he said.

Performed at a supercomputing center at NASA Ames Research Center in Mountain View, California, the simulations incorporate new numerical techniques that provide the first model of a collisionless plasma—in which collisions between charged particles do not play a major role—in the presence of a strong gravitational field associated with a black hole.

The simulations naturally produce effects known as the Blandford-Znajek mechanism, which describes the twisting magnetic fields that form jets, and a separate Penrose process that describes what happens when negative-energy particles are gulped down by the black hole.

The Penrose process, "even though it doesn't necessarily contribute that much to extracting the black hole's rotation energy," Parfrey said, "is possibly directly linked to the electric currents that twist the jets' magnetic fields."

While more detailed than some earlier models, Parfrey noted that his team's simulations are still playing catch-up with observations, and are idealized in some ways to simplify the calculations needed to perform the simulations.

The team intends to better model the process by which electron-positron pairs are created in the jets in order to study the jets' plasma distribution and their emission of radiation more realistically for comparison to observations. They also plan to broaden the scope of the simulations to include the flow of infalling matter around the black hole's event horizon, known as its accretion flow.

"We hope to provide a more consistent picture of the whole problem," he said. [30]

## **The orderly chaos of black holes**

During the formation of a black hole, a bright burst of very energetic light in the form of gamma rays is produced, these events are called gamma ray bursts. The physics behind this phenomenon includes many of the least understood fields within physics today: general gravity, extreme temperatures and acceleration of particles far beyond the energy of the most powerful particle accelerators on Earth.

In order to analyse these gamma ray bursts, researchers from the University of Geneva (UNIGE), in collaboration with the Paul Scherrer Institute (PSI) of Villigen, Switzerland, the Institute of High Energy Physics in Beijing and the National Center for Nuclear Research of Swierk in Poland, built the POLAR instrument to analyze gamma ray bursts, which was sent in 2016 to the Chinese Tiangong-2 space laboratory. Contrary to prevailing theories, the first results of POLAR reveal that the high energy photons coming from gamma ray bursts are neither completely chaotic, nor completely organized, but a mixture of the two: Within short time intervals, the photons are found to oscillate in the same direction, but the oscillation direction changes with time. These unexpected results are reported in a recent issue of the journal *Nature Astronomy*.

When two neutron stars collide or a super-massive star collapses into itself, a black hole is created. This birth is accompanied by a gamma ray burst (GRB)—a very energetic light wavelength such as that emitted by radioactive sources.

### **Is the black hole birth environment organized or chaotic?**

How and where the gamma rays are produced is still a mystery, and there are two schools of thought on their origin. The first predicts that photons from GRBs are polarized, meaning the majority of them oscillate in the same direction. If this were the case, the source of the photons would likely be a strong and well-organized magnetic field formed during the violent aftermath of the black hole production. A second theory suggests that the photons are not polarized, implying a more chaotic emission environment. But how to check this?

"Our international teams have built the first powerful and dedicated detector, called POLAR, capable of measuring the polarization of gamma rays from GRBs. This instrument allows us to learn more about their source," said Xin Wu, professor in the Department of Nuclear and Particle Physics of the Faculty of Sciences of UNIGE. Its operation is simple. It is a square of 50 x 50 cm<sup>2</sup> consisting of 1600 scintillator bars in which the gamma rays collide with the atoms that make up these bars. When a photon collides in a bar, we can measure it. Afterwards, it can produce a second photon which can cause a second visible collision. "If the photons are polarized, we observe a directional dependency between the impact positions of the photons, continues Nicolas Produit, researcher at the Department of Astronomy of the Faculty of Sciences of UNIGE. On the contrary, if there is no polarization, the second photon resulting from the first collision will leave in a fully random direction."

### **Order within chaos**

In six months, POLAR has detected 55 gamma ray bursts, and scientist analyzed the polarization of gamma rays from the five brightest ones. The results are surprising, to say the least. "When we analyse the polarization of a gamma ray burst as a whole, we see at most a very weak polarization, which seems to clearly favour several theories," says Merlin Kole, a researcher at the Department of Nuclear and Particle Physics of the Faculty of Sciences of UNIGE and one of the main authors of the paper.

Faced with this first result, the scientists looked in more detail at a very powerful nine-second long gamma ray burst and cut it into time intervals of two seconds. "There, we discovered with surprise that, on the contrary, the photons are polarized in each slice, but the oscillation direction is different in each slice," Xin Wu says. It is this changing direction that makes the full GRB appear as very chaotic and unpolarized. "The results show that as the explosion takes place, something

happens that causes the photons to be emitted with a different polarization direction. What this could be, we really don't know," says Kole.

These first results confront the theorists with new information, requiring them to produce more detailed predictions. "We now want to build POLAR-2, which will be bigger and more precise. With that, we can dig deeper into these chaotic processes to discover the source of the [gamma](#) rays and unravel the mysteries of these highly energetic physical processes," explains Nicolas Produit. [29]

## **Team discovers new way supermassive black holes are 'fed'**

Supermassive black holes weigh millions to billions times more than our sun and lie at the center of most galaxies. A supermassive black hole several million times the mass of the sun is situated in the heart of our very own Milky Way.

Despite how commonplace supermassive [black holes](#) are, it remains unclear how they grow to such enormous proportions. Some black holes constantly swallow gas in their surroundings, some suddenly swallow whole stars. But neither theory independently explains how supermassive black holes can "switch on" so unexpectedly and keep growing so fast for a long period.

A new Tel Aviv University-led study published today in *Nature Astronomy* finds that some supermassive black holes are triggered to grow, suddenly devouring a large amount of gas in their surroundings.

In February 2017, the All Sky Automated Survey for Supernovae discovered an event known as AT 2017bgt. This event was initially believed to be a "star swallowing" event, or a "tidal disruption" event, because the radiation emitted around the black hole grew more than 50 times brighter than what had been observed in 2004.

However, after extensive observations using a multitude of telescopes, a team of researchers led by Dr. Benny Trakhtenbrot and Dr. Iair Arcavi, both of TAU's Raymond & Beverly Sackler School of Physics and Astronomy, concluded that AT 2017bgt represented a new way of "feeding" black holes.

"The sudden brightening of AT 2017bgt was reminiscent of a tidal disruption event," says Dr. Trakhtenbrot. "But we quickly realized that this time there was something unusual. The first clue was an additional component of light, which had never been seen in tidal disruption events."

Dr. Arcavi, who led the [data collection](#), adds, "We followed this event for more than a year with telescopes on Earth and in space, and what we saw did not match anything we had seen before."

The observations matched the theoretical predictions of another member of the research team, Prof. Hagai Netzer, also of Tel Aviv University.

"We had predicted back in the 1980s that a black hole swallowing gas from its surroundings could produce the elements of light seen here," says Prof. Netzer. "This new result is the first time the process was seen in practice."

Astronomers from the U.S., Chile, Poland and the U.K. took part in the observations and analysis effort, which used three different space telescopes, including the new NICER telescope installed on board the International Space Station.

One of the ultraviolet images obtained during the data acquisition frenzy turned out to be the millionth image taken by the Neil Gehrels Swift Observatory—an event celebrated by NASA, which operates this space mission.

The research team identified two additional recently reported events of black holes "switched on," which share the same emission properties as AT 2017bgt. These three events form a new and tantalizing class of black hole re-activation.

"We are not yet sure about the cause of this dramatic and sudden enhancement in the black holes' feeding rate," concludes Dr. Trakhtenbrot. "There are many known ways to speed up the growth of giant black holes, but they typically happen during much longer timescales."

"We hope to detect many more such events, and to follow them with several telescopes working in tandem," says Dr. Arcavi. "This is the only way to complete our picture of black hole growth, to understand what speeds it up, and perhaps finally solve the mystery of how these giant monsters form." [28]

## **Rotating black holes may serve as gentle portals for hyperspace travel**

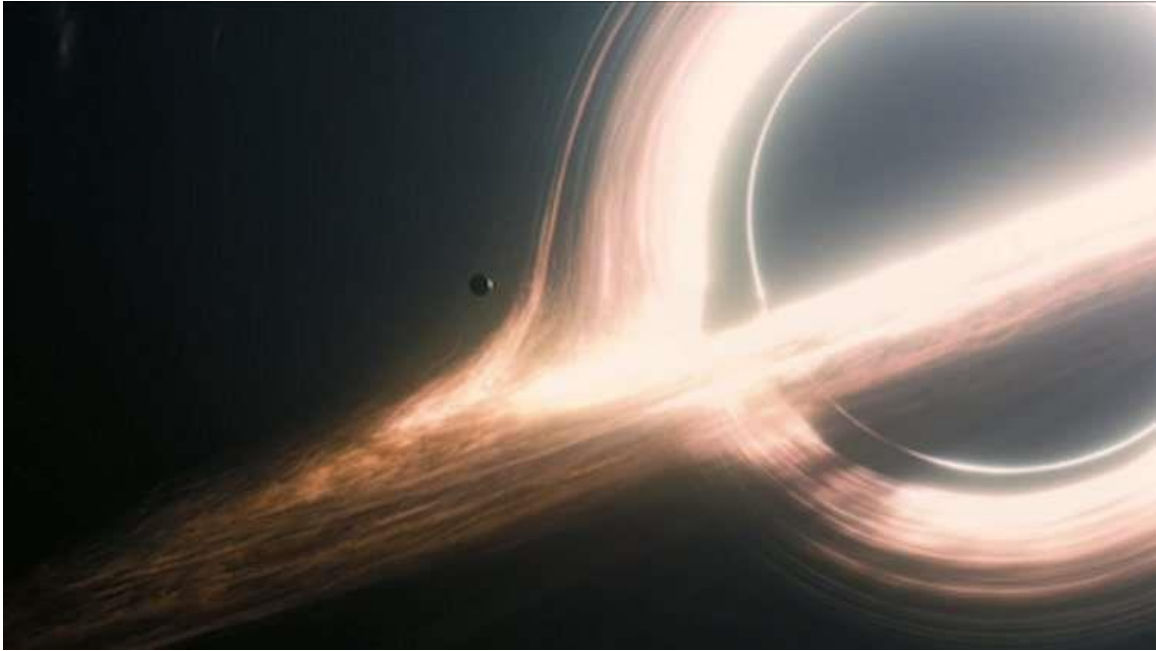
One of the most cherished science fiction scenarios is using a black hole as a portal to another dimension or time or universe. That fantasy may be closer to reality than previously imagined.

Black holes are perhaps the most mysterious objects in the universe. They are the consequence of gravity crushing a dying star without limit, leading to the formation of a true singularity – which happens when an entire star gets compressed down to a single point yielding an object with infinite density. This dense and hot singularity punches a hole in the fabric of spacetime itself, possibly opening up an opportunity for hyperspace travel. That is, a short cut through spacetime allowing for travel over cosmic scale distances in a short period.

Researchers previously thought that any spacecraft attempting to use a black hole as a portal of this type would have to reckon with nature at its worst. The hot and dense singularity would cause the spacecraft to endure a sequence of increasingly uncomfortable tidal stretching and squeezing before being completely vaporized.

## **Flying through a black hole**

My team at the University of Massachusetts Dartmouth and a colleague at Georgia Gwinnett College have shown that all black holes are not created equal. If the black hole like Sagittarius A\*, located at the center of our own galaxy, is large and rotating, then the outlook for a spacecraft changes dramatically. That's because the singularity that a spacecraft would have to contend with is very gentle and could allow for a very peaceful passage.



The fictional Miller's planet orbiting the black hole Gargantua, in the movie 'Interstellar.' Credit: [interstellarfilm.wikia.com](http://interstellarfilm.wikia.com)

The reason that this is possible is that the relevant singularity inside a rotating black hole is technically "weak," and thus does not damage objects that interact with it. At first, this fact may seem counter intuitive. But one can think of it as analogous to the common experience of quickly passing one's finger through a candle's near 2,000-degree flame, without getting burned.

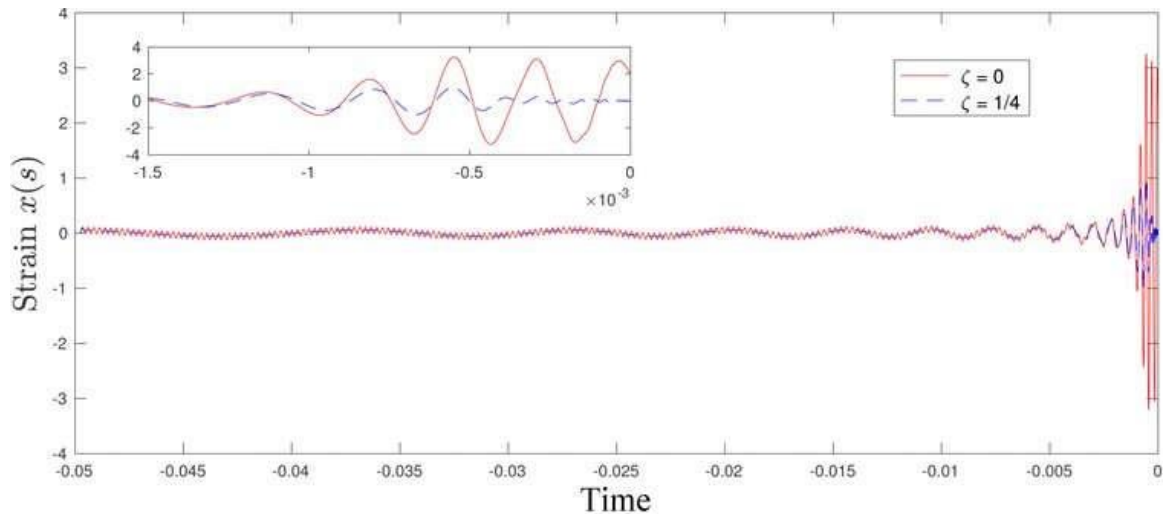
My colleague [Lior Burko](#) and I have been investigating the physics of black holes for over two decades. In 2016, my Ph.D. student, Caroline Mallary, inspired by Christopher Nolan's blockbuster film "[Interstellar](#)," set out to test if Cooper (Matthew McConaughey's character), could survive his fall deep into Gargantua – a fictional, supermassive, rapidly rotating black hole some 100 million times the mass of our sun. "Interstellar" was based on a book written by Nobel Prize-winning astrophysicist [Kip Thorne](#) and Gargantua's physical properties are central to the plot of this Hollywood movie.

Building on work done by physicist [Amos Ori](#) two decades prior, and armed with her strong computational skills, [Mallary built a computer model](#) that would capture most of the essential physical effects on a spacecraft, or any large object, falling into a large, rotating black hole like Sagittarius A\*.

### **Not even a bumpy ride?**

What she discovered is that under all conditions an object falling into a rotating black hole would not experience infinitely large effects upon passage through the hole's so-called inner horizon singularity. This is the singularity that an object entering a rotating black hole cannot maneuver around or avoid. Not only that, under the right circumstances, these effects may be negligibly small, allowing for a rather comfortable passage through the singularity. In fact, there may be no noticeable effects on the falling object at all. This increases the feasibility of using large, rotating black holes as portals for hyperspace travel.





This graph depicts the physical strain on the spacecraft's steel frame as it plummets into a rotating black hole. The inset shows a detailed zoom-in for very late times. The important thing to note is that the strain increases dramatically [...more](#)

Mallary also discovered a feature that was not fully appreciated before: the fact that the effects of the [singularity](#) in the context of a rotating black hole would result in rapidly increasing cycles of stretching and squeezing on the spacecraft. But for very large black holes like Gargantua, the strength of this effect would be very small. So, the spacecraft and any individuals on board would not detect it.

The crucial point is that these effects do not increase without bound; in fact, they stay finite, even though the stresses on the spacecraft tend to grow indefinitely as it approaches the black hole.

There are a few important simplifying assumptions and resulting caveats in the context of Mallary's model. The main assumption is that the black hole under consideration is completely isolated and thus not subject to constant disturbances by a source such as another star in its vicinity or even any falling radiation. While this assumption allows important simplifications, it is worth noting that most black holes are surrounded by cosmic material – dust, gas, radiation.

Therefore, a natural extension of [Mallary's work](#) would be to perform a similar study in the context of a more realistic astrophysical black hole.

Mallary's approach of using a computer simulation to examine the effects of a black hole on an object is very common in the field of black hole physics. Needless to say, we do not have the capability of performing real experiments in or near black holes yet, so scientists resort to theory and simulations to develop an understanding, by making predictions and new discoveries. [27]

## Beyond the black hole singularity

Our first glimpses into the physics that exist near the center of a black hole are being made possible using "loop quantum gravity"—a theory that uses quantum mechanics to extend gravitational physics beyond Einstein's theory of general relativity. Loop quantum gravity, originated at Penn State and subsequently developed by a large number of scientists worldwide, is opening up a new

paradigm in modern physics. The theory has emerged as a leading candidate to analyze extreme cosmological and astrophysical phenomena in parts of the universe, like black holes, where the equations of general relativity cease to be useful.

Previous work in loop quantum gravity that was highly influential in the field analyzed the quantum nature of the Big Bang, and now two new papers by Abhay Ashtekar and Javier Olmedo at Penn State and Parampreet Singh at Louisiana State University extend those results to black hole interiors. The papers appear as "Editors' suggestions" in the journals *Physical Review Letters* and *Physical Review* on December 10, 2018 and were also highlighted in a Viewpoint article in the journal *Physics*.

"The best theory of gravity that we have today is [general relativity](#), but it has limitations," said Ashtekar, Evan Pugh Professor of Physics, holder of the Eberly Family Chair in Physics, and director of the Penn State Institute for Gravitation and the Cosmos. "For example, [general relativity](#) predicts that there are places in the universe where gravity becomes infinite and [space-time](#) simply ends. We refer to these places as 'singularities.' But even Einstein agreed that this limitation of general relativity results from the fact that it ignores [quantum mechanics](#)."

At the center of a black hole the gravity is so strong that, according to general relativity, space-time becomes so extremely curved that ultimately the curvature becomes infinite. This results in space-time having a jagged edge, beyond which [physics](#) no longer exists—the singularity. Another example of a singularity is the Big Bang. Asking what happened before the Big Bang is a meaningless question in general relativity, because space-time ends, and there is no before. But modifications to Einstein's equations that incorporated quantum mechanics through loop quantum gravity allowed researchers to extend physics beyond the Big Bang and make new predictions. The two recent papers have accomplished the same thing for the black hole singularity.

"The basis of loop quantum gravity is Einstein's discovery that the geometry of space-time is not just a stage on which cosmological events are acted out, but it is itself a physical entity that can be bent," said Ashtekar. "As a physical entity the geometry of space-time is made up of some fundamental units, just as matter is made up of atoms. These units of geometry—called 'quantum excitations'—are orders of magnitude smaller than we can detect with today's technology, but we have precise quantum equations that predict their behavior, and one of the best places to look for their effects is at the center of a black hole." According to general relativity, at the center of a black hole gravity becomes infinite so everything that goes in, including the information needed for physical calculations, is lost. This leads to the celebrated 'information paradox' that theoretical physicists have been grappling with for over 40 years. However, the quantum corrections of loop quantum gravity allow for a repulsive force that can overwhelm even the strongest pull of classical [gravity](#) and therefore physics can continue to exist. This opens an avenue to show in detail that there is no loss of information at the center of a blackhole, which the researchers are now pursuing.

Interestingly, even though [loop quantum gravity](#) continues to work where general relativity breaks down—black hole singularities, the Big Bang—its predictions match those of general relativity quite precisely under less extreme circumstances away from the singularity. "It is highly non-trivial to achieve both," said Singh, associate professor of physics at Louisiana State. "Indeed, a number of investigators have explored the quantum nature of the black hole singularity over the past decade,

but either the singularity prevailed or the mechanisms that resolved it unleashed unnatural effects. Our new work is free of all such limitations." [26]

## **Will we ever see a black hole?**

In the shadowy regions of black holes two fundamental theories describing our world collide. Can these problems be resolved and do black holes really exist? First, we may have to see one and scientists are trying to do just this.

Of all the forces in physics there is one that we still do not understand at all: Gravity.

Gravity is where fundamental physics and astronomy meet, and where the two most fundamental theories describing our world—quantum theory and Einstein's theory of spacetime and gravity (aka. the theory of general relativity) – clash head on.

The two theories are seemingly incompatible. And for the most part this isn't a problem. They both live in distinct worlds, where quantum physics describes the very small, and general relativity describes the very largest scales.

Only when you get to very small scales and extreme gravity, do the two theories collide, and somehow, one of them gets it wrong. At least in theory.

But there is once place in the universe where we could actually witness this problem occurring in real life and perhaps even solve it: the edge of a black hole. Here, we find the most extreme gravity. There's just one issue – nobody has ever actually 'seen' a black hole.

## **So, what is a black hole?**

Imagine that the entire drama of the physical world unfolds in the theatre of spacetime, but gravity is the only 'force' that actually modifies the theatre in which it plays.

The force of gravity rules the universe, but it may not even be a force in the traditional sense. Einstein described it as a consequence of the deformation of spacetime. And perhaps it simply does not fit the standard model of particle physics.

When a very big star explodes at the end of its lifetime, its innermost part will collapse under its own gravity, since there is no longer enough fuel to sustain the pressure working against the force of gravity (yes, gravity feels like a force after all, doesn't it!).

The matter collapses and no force in nature is known to be able to stop that collapse, ever.

In an infinite time, the star will have collapsed into an infinitely small point: a singularity – or to give it another name, a black hole.

Of course, in a finite time the stellar core will have collapsed into something of a finite size and this would still be a huge amount of mass in an insanely small region and it still is called a black hole!

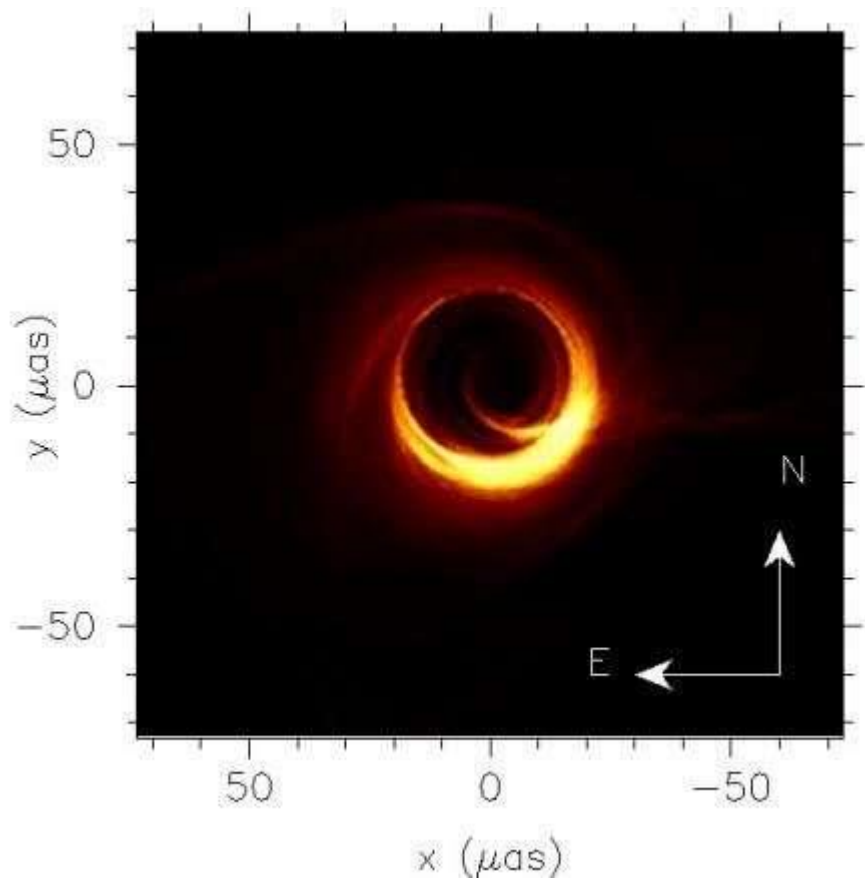
## **Black holes do not suck in everything around them**

Interestingly, it is not true that a black hole will inevitably draw everything in.

In fact, whether you are orbiting a star or a black hole that formed from a star, it does not make a difference, so long as the mass is the same. The good old centrifugal force and your angular momentum will keep you safe and stop you from falling in.

Only when you fire your giant rocket thrusters to brake your rotation, will you start falling inwards.

However, once you fall towards a black hole you will be accelerated to higher and higher speeds, until you eventually reach the speed of light.



Simulated image as predicted for the supermassive black in the galaxy M87 at the frequencies observed with the Event Horizon Telescope (230 GHz). Credit: Moscibrodzka, Falcke, Shiokawa, *Astronomy & Astrophysics*, V. 586, p. 15, 2016, reproduced with permission © ESO

### **Why are quantum theory and general relativity incompatible?**

At this point everything goes wrong as, according to general relativity, nothing should move faster than the speed of light.

Light is the substrate used in the quantum world to exchange forces and to transport information in the macro world. Light determines how fast you can connect cause and consequences.

If you go faster than light, you could see events and change things before they happen. This has two consequences:

At the point where you reach the speed of light while falling inwards, you would also need to fly out at the [speed of light](#) to escape that point, which seems impossible. Hence, conventional physical wisdom will tell you that nothing can escape a black hole, once it has passed that point, which we call the "[event horizon](#)."

It also means that suddenly basic principles of quantum information preservation are brutally violated – conserved quantum quantities can simply disappear behind a wall of silence.

Whether that is true and whether and how the theory of gravity (or of quantum physics) needs to be modified is a question of intense debate among physicists, and none of us can say which way the argument will lead in the end.

### **Do black holes even exist?**

Of course, all this excitement would only be justified, if black holes really existed in this universe. So, do they?

In the last century strong evidence has mounted that certain binary stars with intense X-ray emissions are in fact stars collapsed into black holes.

Moreover, in the centres of galaxies we often find evidence for huge, dark concentrations of mass. These might be supermassive versions of black holes, possibly formed through the merger of many stars and gas clouds that have sunk into the centre of a galaxy.

The evidence is convincing, but circumstantial. At least [gravitational waves](#) have let us 'hear' the merger of black holes, but the signature of the event horizon is still elusive and so far, we have never actually 'seen' a black hole – they simply tend to be too small and too far and, in most cases, yes, black...

### **So, what would a black hole actually look like?**

If you could look straight into a black hole you would see the darkest dark, you can imagine.

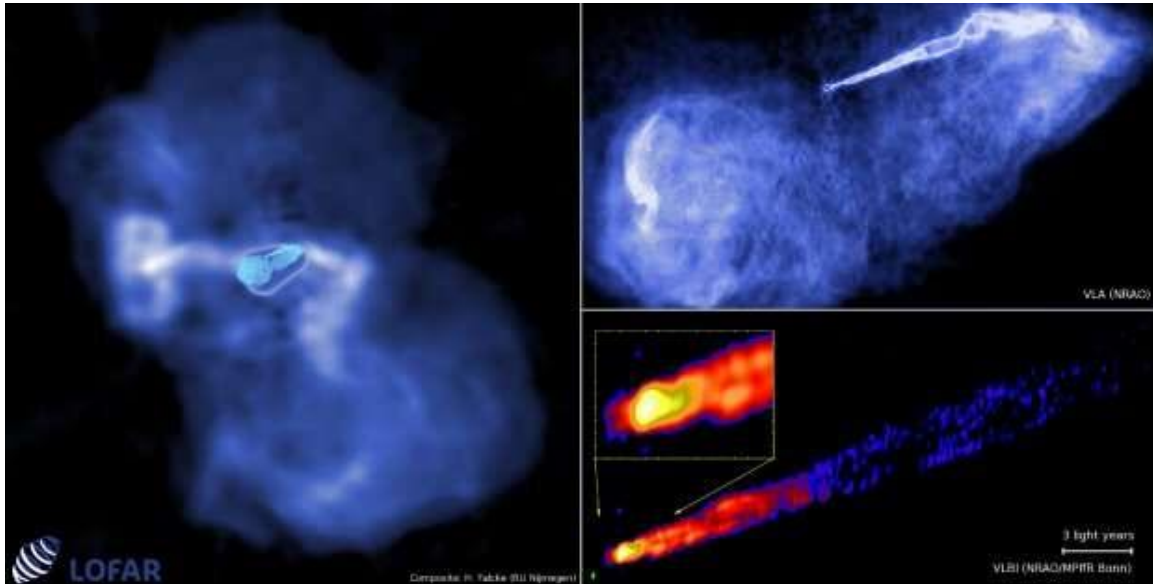
But, the immediate surroundings of a black hole could be bright as gasses spiral inwards –slowed down by the drag of magnetic fields they carry along.

Due to the magnetic friction the gas will heat up to enormous temperatures of up to several tens of billion degrees and start to radiate UV-light and X-rays.

Ultra-hot electrons interacting with the magnetic field in the gas will start producing intense radio emission. Thus, black holes can glow and could be surrounded by a ring of fire that radiates at many different wavelengths.

### **A ring of fire with a dark, dark centre**

In their very centre, however, the event horizon still lurks and like a bird of prey it catches every photon that gets too close.



Radio images of the jet in the radio galaxy M87 – observed at lower resolution. The left frame is roughly 250,000 light years across. Magnetic fields threading the supermassive black holes lead to the formation of a highly collimated jet ...[more](#)

Since space is bent by the enormous mass of a black hole, light paths will also be bent and even form into almost concentric circles around the black hole, like serpentines around a deep valley. This effect of circling light was calculated already in 1916 by the famous Mathematician David Hilbert only a few months after Albert Einstein finalised his theory of general relativity.

After orbiting the black hole multiple times, some of the light rays might escape while others will end up in the event horizon. Along this complicated light path, you can literally look into the black hole. The nothingness you see is the event horizon.

If you were to take a photo of a black hole, what you would see would be akin to a dark shadow in the middle of a glowing fog of light. Hence, we called this feature the shadow of a black hole .

Interestingly, the shadow appears larger than you might expect by simply taking the diameter of the event horizon. The reason is simply, that the black hole acts as a giant lens, amplifying itself.

Surrounding the shadow will be a thin 'photon ring' due to light circling the black hole almost forever. Further out, you would see more rings of light that arise from near the event horizon, but tend to be concentrated around the black hole shadow due to the lensing effect.

### **Fantasy or reality?**

Is this pure fantasy that can only be simulated in a computer? Or can it actually be seen in practice? The answer is that it probably can.

There are two relatively nearby supermassive black holes in the universe which are so large and close, that their shadows could be resolved with modern technology.

These are the black holes in the center of our own Milky Way at a distance of 26,000 lightyears with a mass of 4 million times the mass of the sun, and the black hole in the giant elliptical galaxy M87 (Messier 87) with a mass of 3 to 6 billion solar masses.

M87 is a thousand times further away, but also a thousand times more massive and a thousand times larger, so that both objects are expected to have roughly the same shadow diameter projected onto the sky.

### **Like seeing a grain of mustard in New York from Europe**

Coincidentally, simple theories of radiation also predict that for both objects the emission generated near the event horizon would be emitted at the same radio frequencies of 230 GHz and above.

Most of us come across these frequencies only when we have to pass through a modern airport scanner but some black holes are continuously bathed in them.

The radiation has a very short wavelength of about one millimetre and is easily absorbed by water. For a telescope to observe cosmic millimetre waves it will therefore have to be placed high up, on a dry mountain, to avoid absorption of the radiation in the Earth's troposphere.

Effectively, you need a millimetre-wave telescope that can see an object the size of a mustard seed in New York from as far away as Nijmegen in the Netherlands. That is a telescope a thousand times sharper than the Hubble Space Telescope and for millimetre-waves this requires a telescope the size of the Atlantic Ocean or larger.

### **A virtual Earth-sized telescope**

Fortunately, we do not need to cover the Earth with a single radio dish, but we can build a virtual telescope with the same resolution by combining data from telescopes on different mountains across the Earth.

The technique is called Earth rotation synthesis and very long baseline interferometry (VLBI). The idea is old and has been tested for decades already, but it is only now possible at high radio frequencies.

# The Event Horizon Telescope Network



Layout of the Event Horizon Telescope connecting radio telescopes around the world (JCMT & SMA in Hawaii, AMTO in Arizona, LMT in Mexico, ALMA & APEX in Chile, SPT on the South Pole, IRAM 30m in Spain). The red lines are to a proposed [...more](#)

The first successful experiments have already shown that event horizon structures can be probed at these frequencies. Now high-bandwidth digital equipment and large telescopes are available to do this experiment on a large scale.

## **Work is already underway**

I am one of the three Principal Investigators of the BlackHoleCam project. BlackHoleCam is an EU-funded project to finally image, measure and understand astrophysical black holes. Our European project is part of a global collaboration known as the Event Horizon Telescope consortium – a collaboration of over 200 scientists from Europe, the Americas, Asia, and Africa. Together we want to take the first picture of a black hole.

In April 2017 we observed the Galactic Center and M87 with eight telescopes on six different mountains in Spain, Arizona, Hawaii, Mexico, Chile, and the South Pole.

All telescopes were equipped with precise atomic clocks to accurately synchronise their data. We recorded multiple petabytes of raw data, thanks to surprisingly good weather conditions around the globe at the time.



We are all excited about working with this data. Of course, even in the best of all cases, the images will never look as pretty as the computer simulations. But, at least they will be real and whatever we see will be interesting in its own right.

To get even better images telescopes in Greenland and France are being added. Moreover, we have started raising funds for additional telescopes in Africa and perhaps elsewhere and we are even thinking about telescopes in space.

### **A 'photo' of a black hole**

If we actually succeed in seeing an event horizon, we will know that the problems we have in rhyming [quantum theory](#) and general relativity are not abstract problems, but are very real. And we can point to them in the very real shadowy regions of black holes in a clearly marked region of our universe.

This is perhaps also the place where these problems will eventually be solved.

We could do this by obtaining sharper images of the shadow, or maybe by tracing stars and pulsars as they orbit around black holes, through measuring spacetime ripples as black holes merge, or as is most likely, by using all of the techniques that we now have, together, to probe black holes.

### **A once exotic concept is now a real working laboratory**

As a student, I wondered what to study: particle physics or astrophysics? After reading many popular science articles, my impression was that particle physics had already reached its peak. This field had established an impressive standard model and was able to explain most of the forces and the particles governing our world.

Astronomy though, had just started to explore the depths of a fascinating universe. There was still a lot to be discovered. And I wanted to discover something.

In the end, I chose astrophysics as I wanted to understand gravity. And since you find the most extreme gravity near [black holes](#), I decided to stay as close to them as possible.

Today, what used to be an exotic concept when I started my studies, promises to become a very real and very much visible physics laboratory in the not too distant future. [25]

## **Researchers have created a virtual reality simulation of a supermassive black hole**

The black hole at the centre of our galaxy, Sagittarius A\*, has been visualised in virtual reality for the first time. The details are described in an article published in the open access journal *Computational Astrophysics and Cosmology*.

Scientists at Radboud University, The Netherlands and Goethe University, Germany used recent astrophysical models of Sagittarius A\* to create a series of images that were then put together to create a 360 degree [virtual reality](#) simulation of the black hole, that can be viewed on widely available VR consoles. The authors suggest that this virtual reality simulation could be useful for studying [black holes](#).

Jordy Davelaar, corresponding author, said: "Our virtual reality simulation creates one of the most realistic views of the direct surroundings of the black hole and will help us to learn more about how black holes behave. Traveling to a black hole in our lifetime is impossible, so immersive visualizations like this can help us understand more about these systems from where we are."

The authors also suggest that the virtual reality [simulation](#) could help encourage the general public, including children, to take an interest in astrophysics.

Davelaar said: "The visualisations that we produced have a great potential for outreach. We used them to introduce children to the phenomenon of black holes, and they really learned something from it. This suggests that immersive virtual reality visualizations are a great tool to show our work to a broader audience, even when it involves very complicated systems like black holes."

Heino Falcke, Professor at Radboud University adds: "We all have a picture in our head of how black holes supposedly look, but science has progressed and we can now make much more accurate renderings—and these black holes look quite different from what we are used to. These new visualisations are just the start, more to come in the future." [24]

## **Black holes play hide-and-peek in low-luminosity radio galaxies**

Every galaxy is thought to harbor a supermassive black hole in the center, or nucleus, of the galaxy, and in active galaxies this black hole is fed by infalling matter. This "central engine" is typically surrounded by dusty molecular gas in a doughnut configuration, which hides the black hole and the infalling material from our view along certain viewing directions. The picture of a central engine plus obscuring doughnut is thought to apply to all accreting supermassive black holes, explaining the apparent variety of active galaxies from the very brightest quasars to the lower-luminosity radio galaxies under a single "unified scheme."

However, it has long been known that the weaker [radio galaxies](#) have properties inconsistent with this model, lacking evidence for bright accretion structures and obscuring doughnuts, leading to suggestions that either their black holes or their gas infall mechanisms might be unique. New results from researchers at the University of Manitoba, presented today at the 2018 annual meeting of the Canadian Astronomical Society, show that up to one-third of weak radio [galaxies](#) may in fact have glowing infalling gas with their black holes hidden by dusty doughnuts that shine in the infrared.

To discern this, R. Gleisner, C. O'Dea, J. Gallimore, S. Baum, and S. Wykes fit the Infrared spectrum of a sample of weak radio galaxies with several components including stars, gas, dust, and a dusty torus using special techniques. They found that one-third of the radio galaxies show the classic central engines with accretion structures and doughnuts. They suggest that for the weaker [active galaxies](#), the properties of the central engine are changing dramatically and rapidly. While the [black holes](#) in these galaxies are typically on a diet with low feeding rates, they may periodically go on an occasional binge during which a much larger mass of gas flows into the central black hole causing the creation of the standard bright accretion structure and obscuring torus. [23]

## Tumultuous galaxy mergers better at switching on black holes

A new study by researchers at the University of Colorado Boulder finds that violent crashes may be more effective at activating black holes than more peaceful mergers.

When two galaxies collide, the supermassive black holes that sit at their centers also smash together. But before they do, these galaxies often flicker on, absorbing huge quantities of gas and dust and producing a bright display called an Active Galactic Nucleus (AGN).

But not all mergers are created equal. In some such marriages, only one black hole becomes active, while in others, both do.

The research team led by CU Boulder's Scott Barrows discovered that single activations seem to occur more often in mergers in which the galaxies are mismatched—or when one galaxy is huge and the other puny.

When lopsided galaxies join, "the merger is less violent, and that leads to less gas and dust falling onto the black holes," said Barrows, a postdoctoral research associate in the Center for Astrophysics and Space Astronomy (CASA). "And the less material you have falling onto the black holes, the less likely you are to have two of them become AGNs."

The researchers presented their findings today at a press briefing at the 232nd meeting of the American Astronomical Society, which runs from June 3-7 in Denver, Colorado.

Barrows and his colleagues used data collected by the Chandra X-ray Observatory to systematically scan the night sky for the signatures of AGNs. They spotted mergers in progress by looking for "offset galaxies," or galaxies with a single AGN that sits away from the center of the galaxy. Such a lack of symmetry suggests that a second supermassive black hole, which hasn't been turned on, might be hiding nearby.

Barrows and his colleagues next assembled a sample of 10 offset galaxies and compared that sample to galaxies with a pair of AGNs.

The results were stark: Nine out of the 10 galaxies with only one active black hole came from lopsided mergers, or cases in which one galaxy was more than four times the size of the other. Two-thirds of the galaxies with two active black holes, in contrast, were experiencing clashes among near equals.

Barrows explained that when galaxies of roughly equal size meet, their black holes exert tremendous gravitational forces on each other. Those forces, in turn, send clouds of gas and dust raining onto the black holes.

"It's these torques that extract energy from the gas and dust, allowing it to fall into the nucleus of the black hole," Barrows said. In mismatched mergers, "you simply have smaller forces exerted on the gas and dust in each galaxy."

The team didn't find any rhyme or reason to which black hole activated during a mismatched merger. In some cases, Barrows said, it was the bigger black hole. In other cases, the smaller one.

Next up, he and his colleagues will focus on how the smashing together of two black holes affects the galaxies themselves, including how they create and destroy stars. [22]

## **Astronomers find pairs of black holes at the centers of merging galaxies**

For the first time, a team of astronomers has observed several pairs of galaxies in the final stages of merging together into single, larger galaxies. Peering through thick walls of gas and dust surrounding the merging galaxies' messy cores, the research team captured pairs of supermassive black holes—each of which once occupied the center of one of the two original smaller galaxies—drawing closer together before they coalesce into one giant black hole.

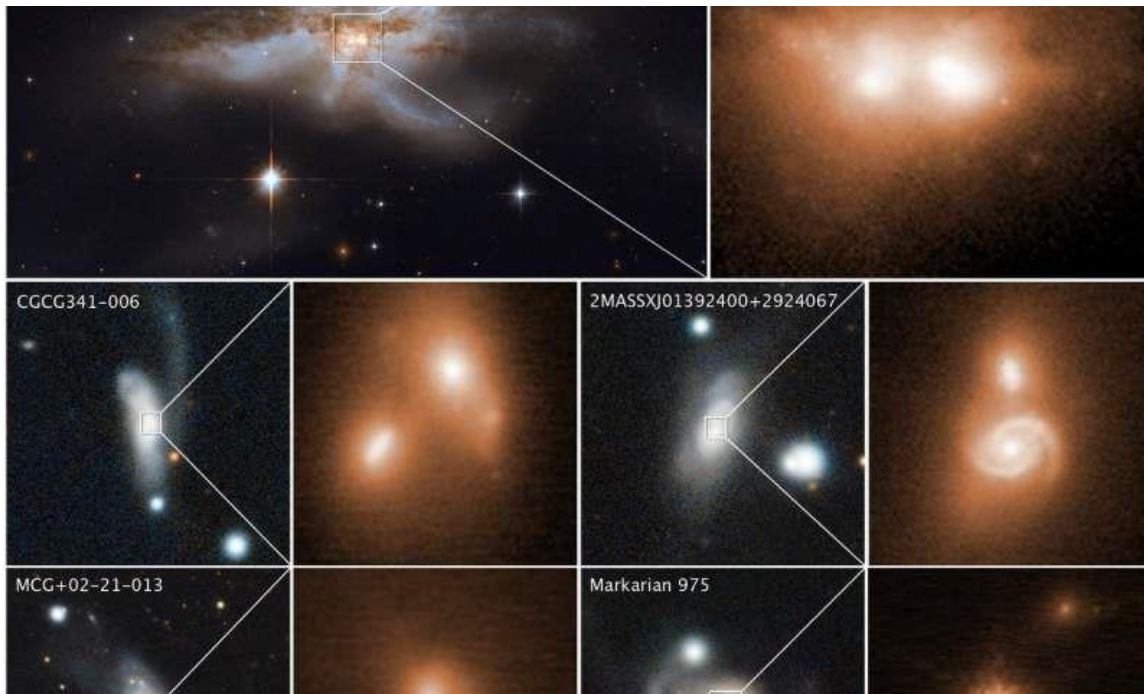
Led by University of Maryland alumnus Michael Koss (M.S. '07, Ph.D. '11, astronomy), a research scientist at Eureka Scientific, Inc., with contributions from UMD astronomers, the team surveyed hundreds of nearby [galaxies](#) using imagery from the W.M. Keck Observatory in Hawaii and NASA's Hubble Space Telescope. The Hubble observations represent more than 20 years' worth of images from the telescope's lengthy archive. The team described their findings in a research paper published on November 8, 2018, in the journal *Nature*.

"Seeing the pairs of merging galaxy nuclei associated with these huge black holes so close together was pretty amazing," Koss said. "In our study, we see two galaxy nuclei right when the images were taken. You can't argue with it; it's a very 'clean' result, which doesn't rely on interpretation."

The high-resolution images also provide a close-up preview of a phenomenon that astronomers suspect was more common in the early universe, when galaxy mergers were more frequent. When the black holes finally do collide, they will unleash powerful energy in the form of gravitational waves—ripples in space-time recently detected for the first time by the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors.

The images also presage what will likely happen in a few billion years, when our Milky Way galaxy merges with the neighboring Andromeda galaxy. Both galaxies host [supermassive black holes](#) at their center, which will eventually smash together and merge into one larger black hole.

The team was inspired by a Hubble image of two interacting galaxies collectively called NGC 6240, which later served as a prototype for the study. The team first searched for visually obscured, active black holes by sifting through 10 years' worth of X-ray data from the Burst Alert Telescope (BAT) aboard NASA's Neil Gehrels Swift Observatory.



These images reveal the final stage of a union between pairs of galactic nuclei in the messy cores of colliding galaxies. The image at top left, taken by Hubble's Wide Field Camera 3, shows the merging galaxy NGC 6240. A close-up of the two ...[more](#)"The advantage to using Swift's BAT is that it observes high-energy, 'hard' X-rays," said study co-author Richard Mushotzky, a professor of astronomy at UMD and a fellow of the Joint Space-Science Institute (JSI). "These X-rays penetrate through the thick clouds of dust and gas that surround [active galaxies](#), allowing the BAT to see things that are literally invisible in other wavelengths."

The researchers then combed through the Hubble archive, zeroing in on the [merging galaxies](#) they spotted in the X-ray data. They then used the Keck telescope's super-sharp, near-infrared vision to observe a larger sample of the X-ray-producing black holes not found in the Hubble archive.

The team targeted galaxies located an average of 330 million light-years from Earth—relatively close by in cosmic terms. Many of the galaxies are similar in size to the Milky Way and Andromeda galaxies. In total, the team analyzed 96 galaxies observed with the Keck telescope and 385 galaxies from the Hubble archive.

Their results suggest that more than 17 percent of these galaxies host a pair of black holes at their center, which are locked in the late stages of spiraling ever closer together before merging into a single, ultra-massive black hole. The researchers were surprised to find such a high fraction of late-stage mergers, because most simulations suggest that black hole pairs spend very little time in this phase.

To check their results, the researchers compared the survey galaxies with a control group of 176 other galaxies from the Hubble archive that lack actively growing black holes. In this group, only about one percent of the surveyed galaxies were suspected to host pairs of black holes in the later stages of merging together.

This last step helped the researchers confirm that the luminous galactic cores found in their census of dusty interacting galaxies are indeed a signature of rapidly-growing black hole pairs headed for a collision. According to the researchers, this finding is consistent with theoretical predictions, but until now, had not been verified by direct observations.

"People had conducted studies to look for these close interacting black holes before, but what really enabled this particular study were the X-rays that can break through the cocoon of dust," explained Koss. "We also looked a bit farther in the universe so that we could survey a larger volume of space, giving us a greater chance of finding more luminous, rapidly-growing black holes."

It is not easy to find galactic nuclei so close together. Most prior observations of merging galaxies have caught the coalescing black holes at earlier stages, when they were about 10 times farther away. The late stage of the merger process is so elusive because the interacting galaxies are encased in dense dust and gas, requiring very high-resolution observations that can see through the clouds and pinpoint the two merging nuclei.

"Computer simulations of galaxy smashups show us that black holes grow fastest during the final stages of mergers, near the time when the black holes interact, and that's what we have found in our survey," said Laura Blecha, an assistant professor of physics at the University of Florida and a co-author of the study. Blecha was a JSI Prize Postdoctoral Fellow in the UMD Department of Astronomy prior to joining UF's faculty in 2017. "The fact that [black holes](#) grow faster and faster as mergers progress tells us galaxy encounters are really important for our understanding of how these objects got to be so monstrously big."

Future infrared telescopes such as NASA's highly anticipated James Webb Space Telescope (JWST), slated for launch in 2021, will provide an even better view of mergers in dusty, heavily obscured galaxies. For nearby black hole pairs, JWST should also be capable of measuring the masses, growth rates and other physical parameters for each black hole.

"There might be other objects that we missed. Even with Hubble, many [nearby galaxies](#) at low redshift cannot be resolved—the two nuclei just merge into one," said study co-author Sylvain Veilleux, a professor of astronomy at UMD and a JSI Fellow. "With JWST's higher angular resolution and sensitivity to the infrared, which can pass through the dusty cores of these galaxies, searches for these nearby objects should be easy to do. Also with JWST, we will be able to push toward larger distances, to see objects at higher redshift. With these observations, we can begin to explore the fraction of objects that are merging in the youngest, most distant regions of the universe—which should be fairly frequent." [21]

## **Astronomers detect once-in-a-lifetime gamma rays**

Scientists have discovered something amazing.

In a cluster of some of the most massive and luminous [stars](#) in our galaxy, about 5,000 light years from Earth, astronomers detected particles being accelerated by a rapidly rotating neutron star as it passed by the massive star it orbits only once every 50 years.

The discovery is extremely rare, according to University of Delaware astrophysicist Jamie Holder and [doctoral student](#) Tyler Williamson, who were part of the international team that documented the occurrence.

Holder called this eccentric pair of gravitationally linked stars a "gamma-ray binary system" and likened the once-in-a-lifetime event to the arrival of Halley's comet or last year's U.S. solar eclipse.

Massive stars are among the brightest stars in our galaxy. Neutron stars are extremely dense and energetic stars that result when a massive star explodes.

This binary system is a massive star with a neutron star orbiting around it. Of the 100 billion stars in our galaxy, less than 10 are known to be this type of system.

Even fewer—only two systems, including this one—are known to have an identified neutron star, or pulsar, that emits pulses of radio waves that scientists can measure. This is important because it tells astronomers very accurately how much energy is available to accelerate particles, something scientists know little about.

"You couldn't ask for a better natural laboratory to study particle acceleration in a continually changing environment - at energies far beyond anything we can produce on the Earth," said Holder, a professor in UD's Department of Physics and Astronomy.

The project was led by a team of scientists, including Holder and Williamson, using the VERITAS [telescope](#) array at the Fred Lawrence Whipple Observatory in Arizona, in collaboration with scientists using the MAGIC telescopes at the Roque de los Muchachos Observatory located in La Palma, an island of the Canary Islands, Spain. (VERITAS stands for Very Energetic Radiation Imaging Telescope Array System and MAGIC stands for Major Atmospheric Gamma Imaging Cherenkov telescopes.)



One of the VERITAS telescopes at sunset. Credit: University of Delaware

The researchers recently reported their findings in the *Astrophysical Journal Letters*.

### **Hoping for fireworks**

The natural question, to many minds, is why do scientists care about accelerated particles?

"Because our galaxy is full of them. We call them cosmic rays and they carry as much energy as the light from all the stars," said Holder.

Astronomers discovered more than 100 years ago that accelerated particles exist, yet how or where these particles speed up remains a mystery. Pulsars are among the most extreme objects in the universe and they have magnetic fields around them that are millions of times stronger than anything scientists could hope to build on earth. When a pulsar encounters dust or gas close to a massive star, the particles nearby accelerate—to near speed of light velocities—and collide with what's around them. The result is a beam of high-energy light called gamma-radiation or [gamma rays](#).

Sophisticated telescopes, like those operated by VERITAS and MAGIC, can detect these gamma rays because they emit a blue flash of light when they reach the Earth's atmosphere. While our eyes can't see these flashes of light because they are too quick, only nanoseconds long, these telescopes can.



## Once-in-a-lifetime doctoral experience

Astronomers first discovered gamma rays coming from the pulsar in this unusual pair of stars in 2008. About the size of Newark, Delaware, the pulsar is spinning like the attachment on a kitchen blender, emitting little pulses of gamma rays and radio waves with every rotation.

By measuring these radio pulse frequencies, astronomers were able to tell how fast the pulsar was moving and calculate exactly when it would be closest to the massive star that it was orbiting— Nov. 13, 2017. It's a trip that took 50 years.



UD Professor Jamie Holder is dwarfed by one of the VERITAS cameras. Credit: University of Delaware

The VERITAS and MAGIC teams began monitoring the night sky and tracking the pulsar's orbit in September 2016. At first, they weren't even sure if they would see anything. But in September 2017 the astronomers began to detect a rapid increase in the number of gamma rays hitting the top of the earth's atmosphere.

As they monitored the data coming from the VERITAS telescopes, Holder and Williamson realized that the pulsar was doing something different each day.

"I would wake up every morning and check and see if we had new data, then analyze it as fast as I could, because there were times where the number of gamma rays we were seeing was changing rapidly over a day or two," said Williamson, a fourth-year doctoral student.

During the closest approach between the star and the pulsar in November 2017, Williamson noticed that the VERITAS telescopes had—overnight—recorded ten times the number of gamma rays detected only a few days before.

"I double checked everything before sending the data to our collaborators," Williamson said. "Then one of our partners, Ralph Bird at UCLA, confirmed he'd gotten the same results; that was exciting."

Even more interesting—this observational data did not match what predictive models had predicted.

Generally speaking, Holder said, existing models predicted that as the [pulsar](#) approached the massive star it was orbiting, the number of gamma rays produced would slowly accelerate, experience some volatility and then slowly decay over time.

"But our recorded data showed a huge spike in the number of gamma rays instead," Holder said. "This tells us that we need to revise the models of how this particle acceleration is happening."

What's more, according to Holder, while astrophysicists expected the National Aeronautics and Space Administration's (NASA) Fermi gamma-ray space telescope to record these gamma rays, it didn't. Holder said the reason for this is unclear, but that is part of what makes the VERITAS results so interesting.



UD doctoral student Tyler Williamson standing on one of the VERITAS telescope access platforms.  
Credit: University of Delaware

Astrophysicists want to learn just which particles are being accelerated, and what processes are pushing them up to these extreme speeds, in order to understand more about the Universe. Holder said that although gamma-ray binary systems probably don't accelerate a large portion of the

particles in our galaxy, they allow scientists to study the type of acceleration mechanisms which could produce them.

### Charting a promising future

Astronomers won't be able to see this binary system at work again until 2067 when the two stars are once again close together. By then, Williamson joked that he just might be an emeritus professor with time on his hands.

At the moment, Williamson is not worried about running out of things to do. He spent three months at the Arizona-based observatory earlier this year, taking measurements, performing hardware maintenance and devising a remote control to allow the researchers to turn on the telescope's cameras from a computer inside a control room.

"It was a great chance to spend hands-on time with the telescopes and get to know the instrument," said Williamson.

Going forward, he'll spend the remainder of his doctoral studies combing through and analyzing in greater detail the nearly 175 hours of data the VERITAS telescopes collected in 2016 and 2017.

"Tyler is, without a doubt, the luckiest graduate student I've ever met because this event that happens only once every 50 years—one of the most exciting things we've seen with our telescopes in a decade—occurred right in the middle of his doctoral work," said Holder. [20]

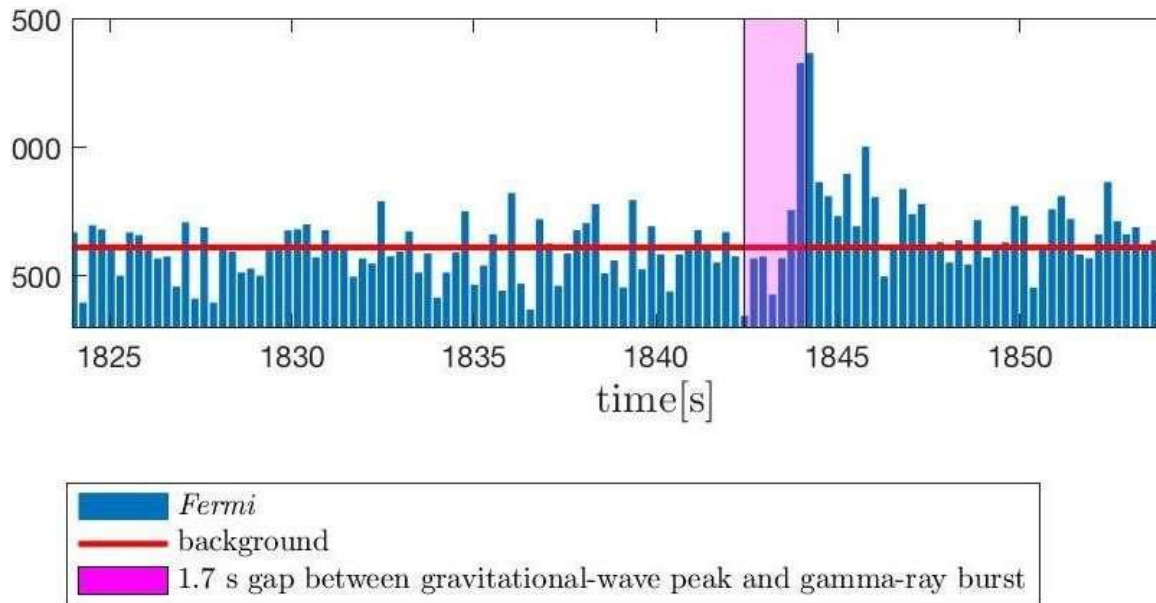
### Gravitational waves from a merged hyper-massive neutron star

For the first time astronomers have detected gravitational waves from a merged, hyper-massive neutron star. The scientists, Maurice van Putten of Sejong University in South Korea, and Massimo della Valle of the Osservatorio Astronomico de Capodimonte in Italy, publish their results in *Monthly Notices of the Royal Astronomical Society: Letters*.

Gravitational waves were predicted by Albert Einstein in his General Theory of Relativity in 1915. The waves are disturbances in space time generated by rapidly moving masses, which propagate out from the source. By the time the waves reach the Earth, they are incredibly weak and their detection requires extremely sensitive equipment. It took scientists until 2016 to announce the first observation of [gravitational waves](#) using the Laser Interferometer Gravitational Wave Observatory (LIGO) detector.

Since that seminal result, gravitational waves have been detected on a further six occasions. One of these, GW170817, resulted from the merger of two stellar remnants known as [neutron stars](#). These objects form after [stars](#) much more massive than the Sun explode as supernovae, leaving behind a core of material packed to extraordinary densities.

At the same time as the burst of gravitational waves from the merger, observatories detected emission in gamma rays, X-rays, ultraviolet, visible light, infrared and radio waves – an unprecedented observing campaign that confirmed the location and nature of the source.



A graph showing gamma-ray counts against time, whose initial peak is 1.7 seconds after the final coalescence of the two neutron stars. This short gamma-ray burst lasts for about three seconds during the period when the gravitational wave ...[more](#)

The initial observations of GW170817 suggested that the two neutron stars merged into a black hole, an object with a gravitational field so powerful that not even light can travel quickly enough to escape its grasp. Van Putten and della Valle set out to check this, using a novel technique to analyse the data from LIGO and the Virgo [gravitational wave detector](#) sited in Italy.

Their detailed analysis shows the H1 and L1 detectors in LIGO, which are separated by more than 3,000 kilometres, simultaneously picked up a descending 'chirp' lasting around 5 seconds. Significantly, this chirp started between the end of the initial burst of gravitational waves and a subsequent burst of gamma rays. Its low frequency (less than 1 KHz, reducing to 49 Hz) suggests the merged object spun down to instead become a larger neutron star, rather than a black hole.

There are other objects like this, with their total mass matching known neutron star binary pairs. But van Putten and della Valle have now confirmed their origin.

Van Putten comments: "We're still very much in the pioneering era of gravitational wave astronomy. So it pays to look at data in detail. For us this really paid off, and we've been able to confirm that two [neutron](#) stars merged to form a larger one."

Gravitational wave astronomy, and eking out the data from every detection, will take another step forward next year, when the Japanese Kamioka Gravitational Wave Detector (KAGRA) comes online. [19]

## Boosting gravitational wave detectors with quantum tricks

A group of scientists from the Niels Bohr Institute (NBI) at the University of Copenhagen will soon start developing a new line of technical equipment in order to dramatically improve gravitational wave detectors.

Gravitational wave detectors are extremely sensitive and can e.g. register colliding neutron stars in space. Yet even higher sensitivity is sought for in order to expand our knowledge about the Universe, and the NBI-scientists are convinced that their equipment can improve the detectors, says Professor Eugene Polzik: "And we should be able to show proof of concept within approximately three years."

If the NBI-scientists are able to improve the gravitational wave detectors as much as they "realistically expect can be done," the detectors will be able to monitor and carry out measurements in an eight times bigger volume of space than what is currently possible, explains Eugene Polzik: "This will represent a truly significant extension."

Polzik is head of Quantum Optics (Quantop) at NBI and he will spearhead the development of the tailor made equipment for gravitational wave detectors. The research – which is supported by the EU, the Eureka Network Projects and the US-based John Templeton Foundation with grants totaling DKK 10 million – will be carried out in Eugene Polzik's lab at NBI.

## A collision well noticed

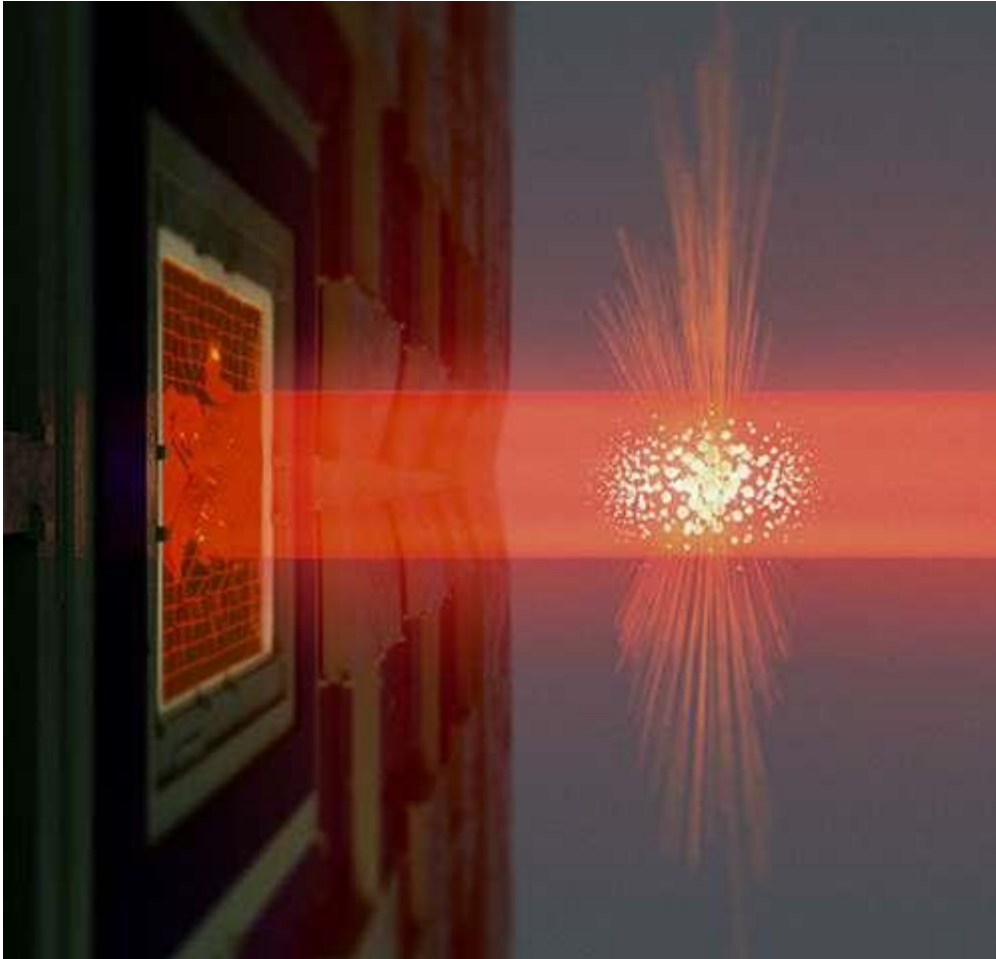
News media all over the world shifted into overdrive in October of 2017 when it was confirmed that a large international team of scientists had indeed measured the collision of two neutron stars; an event which took place 140 million [light](#) years from Earth and resulted in the formation of a kilonova.

The international team of scientists – which also included experts from NBI – was able to confirm the collision by measuring gravitational waves from space – waves in the fabric of spacetime itself, moving at the speed of light. The waves were registered by three gravitational wave detectors: the two US-based LIGO-detectors and the European Virgo-[detector](#) in Italy.

"These gravitational wave detectors represent by far the most sensitive measuring equipment man has yet manufactured – still the detectors are not as accurate as they could possibly be. And this is what we intend to improve," says Professor Eugene Polzik.

How this can be done is outlined in an article which Eugene Polzik and a colleague, Farid Khalili from LIGO collaboration and Moscow State University, have recently published in the scientific journal *Physical Review Letters*. And this is not merely a theoretical proposal, says Eugene Polzik:

"We are convinced this will work as intended. Our calculations show that we ought to be able to improve the precision of measurements carried out by the gravitational wave detectors by a factor of two. And if we succeed, this will result in an increase by a factor of eight of the volume in space which gravitational wave detectors are able to examine at present."



If laser light used to measure motion of a vibrating membrane (left) is first transmitted through an atom cloud (center) the measurement sensitivity can be better than standard quantum limits envisioned by Bohr and Heisenberg. Credit: Bastian Leonhardt Strube and Mads Vadsholt

### **A small glass cell**

In July of last year Eugene Polzik and his team at Quantop published a highly noticed article in *Nature* – and this work is actually the very foundation of their upcoming attempt to improve the gravitational wave detectors.

The article in *Nature* centered on 'fooling' Heisenberg's Uncertainty Principle, which basically says that you cannot simultaneously know the exact position and the exact speed of an object.

This has to do with the fact that observations conducted by shining light on an object inevitably will lead to the object being 'kicked' in random directions by photons, particles of light. This phenomenon is known as Quantum Back Action (QBA) and these random movements put a limit to the accuracy with which measurements can be carried out at the quantum level.

The article in *Nature* in the summer of 2017 made headlines because Eugene Polzik and his team were able to show that it is – to a large extent – actually possible to neutralize QBA.

And QBA is the very reason why gravitational wave detectors – that also operate with light, namely laser light—are not as accurate as they could possibly be," as professor Polzik says.

Put simply, it is possible to neutralize QBA if the light used to observe an object is initially sent through a 'filter.' This was what the article in Nature described – and the 'filter' which the NBI-scientists at Quantop had developed and described consisted of a cloud of 100 million caesium atoms locked-up in a hermetically closed glass cell just one centimeter long, 1/3 of a millimeter high and 1/3 of a millimeter wide.

The principle behind this 'filter' is exactly what Polzik and his team are aiming to incorporate in gravitational wave detectors.

In theory one can optimize measurements of gravitational waves by switching to stronger laser light than the detectors in both Europe and USA are operating with. However, according to quantum mechanics, that is not an option, says Eugene Polzik:

"Switching to stronger laser light will just make a set of mirrors in the detectors shake more because Quantum Back Action will be caused by more photons. These mirrors are absolutely crucial, and if they start shaking, it will in fact increase inaccuracy."

Instead, the NBI-scientists have come up with a plan based on the atomic 'filter' which they demonstrated in the Nature article: They will send the laser light by which the gravitational wave detectors operate through a tailor made version of the cell with the locked-up atoms, says Eugene Polzik: "And we hope that it will do the job." [18]

## **Gravitational wave detectors could shed light on dark matter**

A global team of scientists, including two University of Mississippi physicists, has found that the same instruments used in the historic discovery of gravitational waves caused by colliding black holes could help unlock the secrets of dark matter, a mysterious and as-yet-unobserved component of the universe.

The research findings by Emanuele Berti, UM associate professor of physics and astronomy, Shrobana Ghosh, a graduate student, and their colleagues appears in the September issue of Physical Review Letters, one of the most prestigious peer-reviewed academic journals in the field. "Stochastic and resolvable gravitational waves from ultralight bosons" is co-authored by fellow scientists Richard Brito, Enrico Barausse, Vitor Cardoso, Irina Dvorkin, Antoine Klein and Paolo Pani.

The nature of dark matter remains unknown, but scientists estimate that it is five times as abundant as ordinary matter throughout the universe.

"The nature of dark matter is one the greatest mysteries in physics," Berti said. "It is remarkable that we can now do particle physics – investigate the "very small" – by looking at gravitational-wave emission from black holes, the largest and simplest objects in the universe."

PRL is one of several publications produced by the American Physical Society and American Institute of Physics. It contains papers considered to represent significant advances in research, and therefore, published quickly in short, letter format for a broad audience of physicists.

This paper details calculations by the scientists, who work in Germany, France, Italy, Portugal and the U.S., show that gravitational-wave interferometers can be used to indirectly detect the presence of dark matter.

A companion paper by the team, "Gravitational wave searches for ultralight bosons with LIGO and LISA," also has been accepted and will appear in Physical Review D.

Calculations show that certain types of dark matter could form giant clouds around astrophysical black holes. If ultralight scalar particles exist in nature, fast-spinning black holes would trigger the growth of such scalar "condensates" at the expense of their rotational energy, producing a cloud that rotates around the black hole, now more slowly-spinning, and emits gravitational waves, pretty much like a giant lighthouse in the sky.

"One possibility is that dark matter consists of scalar fields similar to the Higgs boson, but much lighter than neutrinos," Pani said. "This type of dark matter is hard to study in particle accelerators, such as the Large Hadron Collider at CERN, but it may be accessible to gravitational-wave detectors."

The team led by Brito studied gravitational waves emitted by the "black hole plus cloud" system. Depending on the mass of the hypothetical particles, the signal is strong enough to be detected by the Laser Interferometer Gravitational-wave Observatory, with instruments in Louisiana and Washington, and its European counterpart Virgo, as well as by the future space mission Laser Interferometer Space Antenna.

"Surprisingly, gravitational waves from sources that are too weak to be individually detectable can produce a strong stochastic background," Brito said. "This work suggests that a careful analysis of the background in LIGO data may rule out – or detect – ultralight dark matter by gravitational-wave interferometers.

"This is a new, exciting frontier in astroparticle physics that could shed light on our understanding of the microscopic universe."

LIGO has been offline for a few months for upgrades. The team plans to announce new, exciting results from its second observing run soon.

"Our work shows that careful analysis of stochastic gravitational waves in the data they have already taken may be used to place interesting constraints on the nature of dark matter," Berti said.

This innovative work "confirms the high quality of the work in astroparticle physics and gravitationalwave astronomy done by members of the gravitational physics group at UM, widely recognized as one of the leaders in the field," said Luca Bombelli, chair and professor of physics and astronomy at Ole Miss. [17]



## Synopsis: Dark Photon Conjecture Fizzles

The lack of so-called “dark photons” in electron-positron collision data rules out scenarios in which these hypothetical particles explain the muon’s magnetic moment.

Dark photons sound like objects confused about their purpose, but in reality they are part of a comprehensive theory of dark matter. Researchers imagine that dark photons have photon-like interactions with other dark matter particles. And these hypothetical particles have recently gained interest because they might explain why the observed value of the muon’s anomalous magnetic moment disagrees slightly with predictions. However, this muon connection now appears to have been ruled out by the BaBar Collaboration at the SLAC National Accelerator Laboratory in California. The researchers found no signal of dark photons in their electron-positron collision data.

Like the normal photon, the dark photon would carry an electromagnetic-like force between dark matter particles. It could also potentially have a weak coupling to normal matter, implying that dark photons could be produced in high-energy collisions. Previous searches have failed to find a signature, but they have generally assumed that dark photons decay into electrons or some other type of visible particle.

For their new search, the BaBar Collaboration considered a scenario in which a dark photon is created with a normal photon in an electron-positron collision and then decays into invisible particles, such as other dark matter particles. In this case, only one particle—the normal photon—would be detected, and it would carry less than the full energy from the collision. Such missing-energy events can occur in other ways, so the team looked for a “bump” or increase in events at a specific energy that would correspond to the mass of the dark photon. They found no such bump up to masses of 8 GeV. The null result conflicts with models in which a dark photon contribution brings the predicted muon magnetic moment in line with observations. [16]

## Exchanges of identity in deep space

By reproducing the complexity of the cosmos through unprecedented simulations, a new study highlights the importance of the possible behaviour of very high-energy photons. In their journey through intergalactic magnetic fields, such photons could be transformed into axions and thus avoid being absorbed.

Like in a nail-biting thriller full of escapes and subterfuge, photons from far-off light sources such as blazars could experience a continuous exchange of identity in their journey through the universe. This would allow these very tiny particles to escape an enemy which, if encountered, would annihilate them. Normally, very high-energy photons (gamma rays) should “collide” with the background light emitted by galaxies and transform into pairs of matter and antimatter particles, as envisaged by the Theory of Relativity. For this reason, the sources of very high-energy gamma rays should appear significantly less bright than what is observed in many cases.

A possible explanation for this surprising anomaly is that light photons are transformed into hypothetical weakly interacting particles, “axions,” which, in turn, would change into photons, all due to the interaction with magnetic fields. A part of the photons would escape interaction with the intergalactic background light that would make them disappear. The importance of this process is emphasised by a study published in Physical Review Letters, which recreated an extremely

refined model of the cosmic web, a network of filaments composed of gas and dark matter present throughout the universe, and of its magnetic fields. These effects are now awaiting comparison with those obtained experimentally through Cherenkov Telescope Array new generation telescopes.

Through complex and unprecedented computer simulations made at the CSCS Supercomputing Centre in Lugano, scholars have reproduced the so-called cosmic web and its associated magnetic fields to investigate the theory that photons from a light source are transformed into axions, hypothetical elementary particles, on interacting with an extragalactic magnetic field. Axions could then be changed back into photons by interacting with other magnetic fields. Researchers Daniele Montanino, Franco Vazza, Alessandro Mirizzi and Matteo Viel write, "Photons from luminous bodies disappear when they encounter extragalactic background light (EBL). But if on their journey they head into these transformations as envisaged by these theories, it would explain why, in addition to giving very important information on processes that occur in the universe, distant celestial bodies are brighter than expected from an observation on Earth. These changes would, in fact, enable a greater number of photons to reach the Earth."

Thanks to the wealth of magnetic fields present in the cosmic web's filaments, which were recreated with the simulations, the conversion phenomenon would seem much more relevant than predicted by previous models: "Our simulations reproduce a very realistic picture of the cosmos' structure. From what we have observed, the distribution of the cosmic web envisaged by us would markedly increase the probability of these transformations." The next step in the research is to compare simulation results with the experimental data obtained through the use of the Cherenkov Telescope Array Observatories detectors, the new-generation astronomical observatories, one of which is positioned in the Canary Islands and the other in Chile. They will study the universe through very high-energy gamma rays. [15]

## **Astronomers may have detected the first direct evidence of dark matter**

Scientists have detected a mysterious X-ray signal that could be caused by dark matter streaming out of our Sun's core.

Now scientists at the University of Leicester have identified a signal on the X-ray spectrum which appears to be a signature of 'axions' - a hypothetical dark matter particle that's never been detected before.

While we can't get too excited just yet - it will take years to confirm whether this signal really is dark matter - the discovery would completely change our understanding of how the Universe works. After all, dark matter is the force that holds our galaxies together, so learning more about it is pretty important.

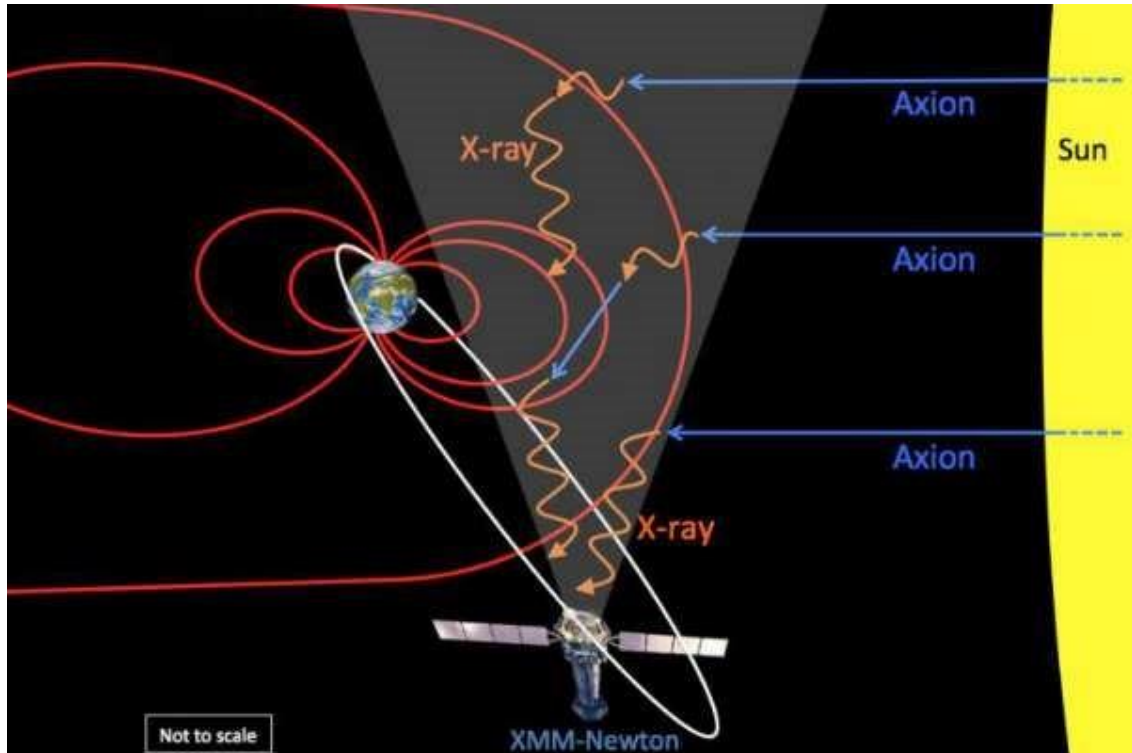
The researchers first detected the signal while searching through 15 years of measurements taking by the European Space Agency's orbiting XMM-Newton space observatory.

Unexpectedly, they noticed that the intensity of X-rays recorded by the spacecraft rose by about 10% whenever XMM-Newton was at the boundary of Earth's magnetic field facing the Sun - even once they removed all the bright X-ray sources from the sky. Usually, that X-ray background is stable. "The X-ray background - the sky, after the bright X-ray sources are removed - appears to be unchanged whenever you look at it," said Andy Read, from the University of Leicester, one of the lead authors on the paper, in a press release. "However, we have discovered a seasonal signal in

this X-ray background, which has no conventional explanation, but is consistent with the discovery of axions."

Researchers predict that axions, if they exist, would be produced invisibly by the Sun, but would convert to X-rays as they hit Earth's magnetic field. This X-ray signal should in theory be strongest when looking through the sunward side of the magnetic field, as this is where the Earth's magnetic field is strongest.

The next step is for the researchers to get a larger dataset from XMM-Newton and confirm the pattern they've seen in X-rays. Once they've done that, they can begin the long process of proving that they have, in fact, detecting dark matter streaming out of our Sun's core.



A sketch (not to scale) shows axions (blue) streaming out of the Sun and then converting into X-rays (orange) in the Earth's magnetic field (red). The X-rays are then detected by the XMM-Newton observatory. [13]

The axion is a hypothetical elementary particle postulated by the Peccei–Quinn theory in 1977 to resolve the strong CP problem in quantum chromodynamics (QCD). If axions exist and have low mass within a specific range, they are of interest as a possible component of cold dark matter. [14]

## Hidden photons

Hidden photons are predicted in some extensions of the Standard Model of particle physics, and unlike WIMPs they would interact electromagnetically with normal matter. Hidden photons also have a very small mass, and are expected to oscillate into normal photons in a process similar to neutrino oscillation. Observing such oscillations relies on detectors that are sensitive to extremely small electromagnetic signals, and a number of these extremely difficult experiments have been built or proposed.

A spherical mirror is ideal for detecting such light because the emitted photons would be concentrated at the sphere's centre, whereas any background light bouncing off the mirror would pass through a focus midway between the sphere's surface and centre. A receiver placed at the centre could then pick up the dark-matter-generated photons, if tuned to their frequency – which is related to the mass of the incoming hidden photons – with mirror and receiver shielded as much as possible from stray electromagnetic waves.

### **Ideal mirror at hand**

Fortunately for the team, an ideal mirror is at hand: a 13 m<sup>2</sup> aluminium mirror used in tests during the construction of the Pierre Auger Observatory and located at the Karlsruhe Institute of Technology. Döbrich and co-workers have got together with several researchers from Karlsruhe, and the collaboration is now readying the mirror by adjusting the position of each of its 36 segments to minimize the spot size of the focused waves. They are also measuring background radiation within the shielded room that will house the experiment. As for receivers, the most likely initial option is a set of low-noise photomultiplier tubes for measurements of visible light, which corresponds to hidden-photon masses of about 1 eV/c<sup>2</sup>. Another obvious choice is a receiver for gigahertz radiation, which corresponds to masses less than 0.001 eV/c<sup>2</sup>; however, this latter set-up would require more shielding.

### **Dark matter composition research - WIMP**

The WIMP (Weakly interactive massive particles) form a class of heavy particles, interacting slightly with matter, and constitute excellent candidates with the nonbaryonic dark matter. The neutralino postulated by the supersymmetric extensions of the standard model of particle physics. The idea of supersymmetry is to associate each boson to a fermion and vice versa. Each particle is then given a super-partner, having identical properties (mass, load), but with a spin which differs by 1/2. Thus, the number of particles is doubled. For example, the photon is accompanied by a photino, the graviton by a gravitino, the electron of a selectron, etc. Following the impossibility to detect a 511 keV boson (the electron partner), the physicists had to re-examine the idea of an exact symmetry. Symmetry is 'broken' and superpartners have a very important mass. One of these superparticles called LSP (Lightest Supersymmetric Particle) is the lightest of all. In most of the supersymmetric theories (without violation of the R-parity) the LSP is a stable particle because it cannot disintegrate in a lighter element. It is of neutral color and electric charge and is then only sensitive to weak interaction (weak nuclear force). It is then an excellent candidate for the not-baryonic dark matter. [11]

### **Weakly interacting massive particles**

In particle physics and astrophysics, weakly interacting massive particles, or WIMPs, are among the leading hypothetical particle physics candidates for dark matter. The term “WIMP” is given to a

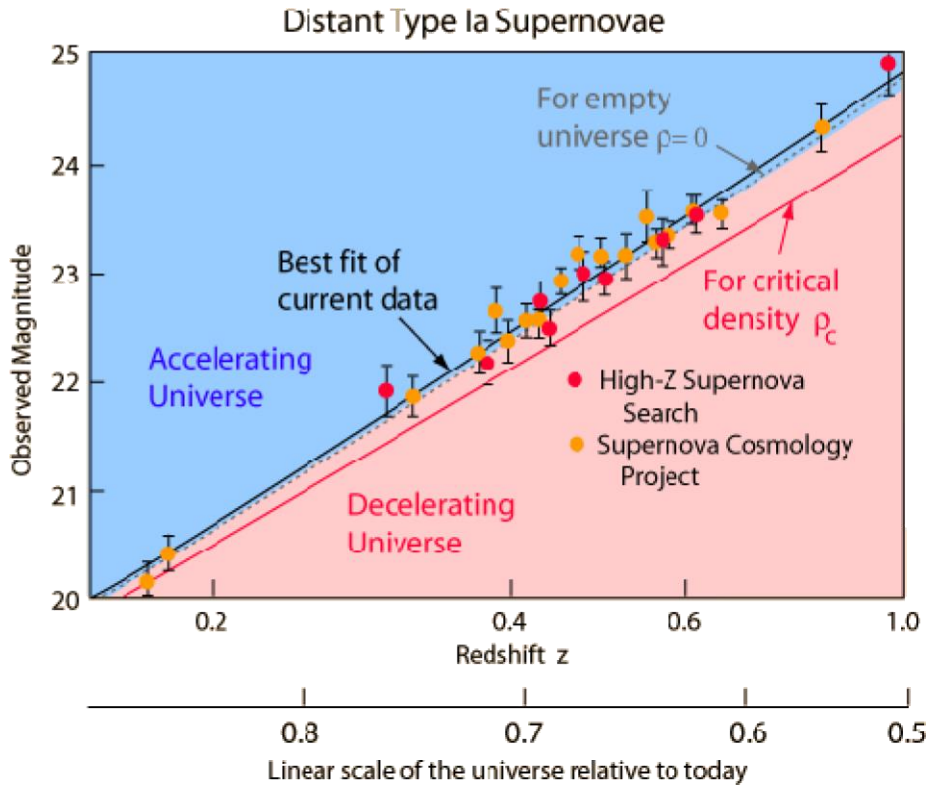
dark matter particle that was produced by falling out of thermal equilibrium with the hot dense plasma of the early universe, although it is often used to refer to any dark matter candidate that interacts with standard particles via a force similar in strength to the weak nuclear force. Its name comes from the fact that obtaining the correct abundance of dark matter today via thermal production requires a self-annihilation cross section, which is roughly what is expected for a new particle in the 100 GeV mass range that interacts via the electroweak force. This apparent coincidence is known as the "WIMP miracle". Because supersymmetric extensions of the standard model of particle physics readily predict a new particle with these properties, a stable supersymmetric partner has long been a prime WIMP candidate. However, recent null results from direct detection experiments including LUX and SuperCDMS, along with the failure to produce evidence of supersymmetry in the Large Hadron Collider (LHC) experiment has cast doubt on the simplest WIMP hypothesis. Experimental efforts to detect WIMPs include the search for products of WIMP annihilation, including gamma

rays, neutrinos and cosmic rays in nearby galaxies and galaxy clusters; direct detection experiments designed to measure the collision of WIMPs with nuclei in the laboratory, as well as attempts to directly produce WIMPs in colliders such as the LHC. [10]

## Evidence for an accelerating universe

One of the observational foundations for the big bang model of cosmology was the observed expansion of the universe. [9] Measurement of the expansion rate is a critical part of the study, and it has been found that the expansion rate is very nearly "flat". That is, the universe is very close to the critical density, above which it would slow down and collapse inward toward a future "big crunch". One of the great challenges of astronomy and astrophysics is distance measurement over the vast distances of the universe. Since the 1990s it has become apparent that type Ia supernovae offer a unique opportunity for the consistent measurement of distance out to perhaps 1000 Mpc. Measurement at these great distances provided the first data to suggest that the expansion rate of the universe is actually accelerating. That acceleration implies an energy density that acts in opposition to gravity which would cause the expansion to accelerate. This is an energy density which we have not directly detected observationally and it has been given the name "dark energy".

The type Ia supernova evidence for an accelerated universe has been discussed by Perlmutter and the diagram below follows his illustration in Physics Today.



The data summarized in the illustration above involve the measurement of the redshifts of the distant supernovae. The observed magnitudes are plotted against the redshift parameter  $z$ . Note that there are a number of Type Ia supernovae around  $z=0.6$ , which with a Hubble constant of 71 km/s/mbpc is a distance of about 5 billion light years.

### Equation

The cosmological constant  $\Lambda$  appears in Einstein's field equation [5] in the form of

$$R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu},$$

where  $R$  and  $g$  describe the structure of spacetime,  $T$  pertains to matter and energy affecting that structure, and  $G$  and  $c$  are conversion factors that arise from using traditional units of measurement. When  $\Lambda$  is zero, this reduces to the original field equation of general relativity. When  $T$  is zero, the field equation describes empty space (the vacuum).

The cosmological constant has the same effect as an intrinsic energy density of the vacuum,  $\rho_{vac}$  (and an associated pressure). In this context it is commonly moved onto the right-hand side of the equation, and defined with a proportionality factor of  $8\pi$ :  $\Lambda = 8\pi\rho_{vac}$ , where unit conventions of general relativity are used (otherwise factors of  $G$  and  $c$  would also appear). It is common to quote values of energy density directly, though still using the name "cosmological constant".

A positive vacuum energy density resulting from a cosmological constant implies a negative pressure, and vice versa. If the energy density is positive, the associated negative pressure will drive an accelerated expansion of the universe, as observed. (See dark energy and cosmic inflation for details.)

## Explanatory models

Models attempting to explain accelerating expansion include some form of dark energy, dark fluid or phantom energy. The most important property of dark energy is that it has negative pressure which is distributed relatively homogeneously in space. The simplest explanation for dark energy is that it is a cosmological constant or vacuum energy; this leads to the Lambda-CDM model, which is generally known as the Standard Model of Cosmology as of 2003-2013, since it is the simplest model in good agreement with a variety of recent observations.

## Dark Matter and Energy

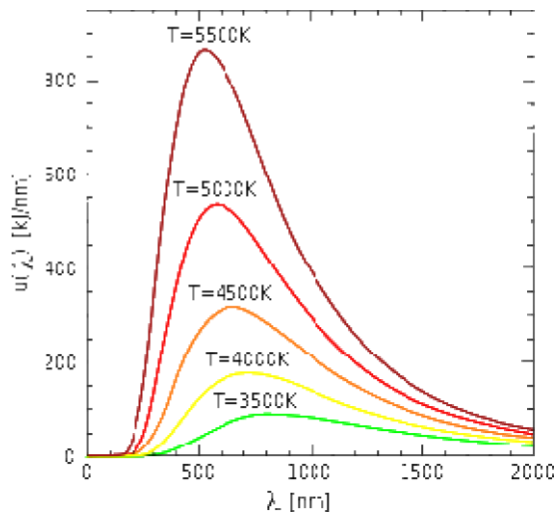
Dark matter is a type of matter hypothesized in astronomy and cosmology to account for a large part of the mass that appears to be missing from the universe. Dark matter cannot be seen directly with telescopes; evidently it neither emits nor absorbs light or other electromagnetic radiation at any significant level. It is otherwise hypothesized to simply be matter that is not reactant to light. Instead, the existence and properties of dark matter are inferred from its gravitational effects on visible matter, radiation, and the large-scale structure of the universe. According to the Planck mission team, and based on the standard model of cosmology, the total mass–energy of the known universe contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy. Thus, dark matter is estimated to constitute 84.5% of the total matter in the universe, while dark energy plus dark matter constitute 95.1% of the total content of the universe. [6]

## Cosmic microwave background

The cosmic microwave background (CMB) is the thermal radiation assumed to be left over from the "Big Bang" of cosmology. When the universe cooled enough, protons and electrons combined to form neutral atoms. These atoms could no longer absorb the thermal radiation, and so the universe became transparent instead of being an opaque fog. [7]

## Thermal radiation

Thermal radiation is electromagnetic radiation generated by the thermal motion of charged particles in matter. All matter with a temperature greater than absolute zero emits thermal radiation. When the temperature of the body is greater than absolute zero, interatomic collisions cause the kinetic energy of the atoms or molecules to change. This results in charge-acceleration and/or dipole oscillation which produces electromagnetic radiation, and the wide spectrum of radiation reflects the wide spectrum of energies and accelerations that occur even at a single temperature. [8]



## Electromagnetic Field and Quantum Theory

Needless to say that the accelerating electrons of the steady stationary current are a simple demystification of the magnetic field, by creating a decreasing charge distribution along the wire, maintaining the decreasing U potential and creating the  $\underline{A}$  vector potential experienced by the electrons moving by  $\underline{v}$  velocity relative to the wire. This way it is easier to understand also the time dependent changes of the electric current and the electromagnetic waves as the resulting fields moving by c velocity.

It could be possible something very important law of the nature behind the self maintaining  $\underline{E}$  accelerating force by the accelerated electrons. The accelerated electrons created electromagnetic fields are so natural that they occur as electromagnetic waves traveling with velocity c. It shows that the electric charges are the result of the electromagnetic waves diffraction.

One of the most important conclusions is that the electric charges are moving in an accelerated way and even if their velocity is constant, they have an intrinsic acceleration anyway, the so called spin, since they need at least an intrinsic acceleration to make possible they movement .

The bridge between the classical and quantum theory is based on this intrinsic acceleration of the spin, explaining also the Heisenberg Uncertainty Principle. The particle – wave duality of the electric charges and the photon makes certain that they are both sides of the same thing. Basing the gravitational force on the accelerating Universe caused magnetic force and the Planck Distribution

Law of the electromagnetic waves caused diffraction gives us the basis to build a Unified Theory of the physical interactions. [4]



## Lorentz transformation of the Special Relativity

In the referential frame of the accelerating electrons the charge density lowering linearly because of the linearly growing way they takes every next time period. From the referential frame of the wire there is a parabolic charge density lowering.

The difference between these two referential frames, namely the referential frame of the wire and the referential frame of the moving electrons gives the relativistic effect. Important to say that the moving electrons presenting the time coordinate, since the electrons are taking linearly increasing way every next time period, and the wire presenting the geometric coordinate. The Lorentz transformations are based on moving light sources of the Michelson - Morley experiment giving a practical method to transform time and geometric coordinates without explaining the source of this mystery.

The real mystery is that the accelerating charges are maintaining the accelerating force with their charge distribution locally. The resolution of this mystery that the charges are simply the results of the diffraction patterns, that is the charges and the electric field are two sides of the same thing. Otherwise the charges could exceed the velocity of the electromagnetic field.

The increasing mass of the electric charges the result of the increasing inductive electric force acting against the accelerating force. The decreasing mass of the decreasing acceleration is the result of the inductive electric force acting against the decreasing force. This is the relativistic mass change explanation, especially importantly explaining the mass reduction in case of velocity decrease.

## The Classical Relativistic effect

The moving charges are self maintain the electromagnetic field locally, causing their movement and this is the result of their acceleration under the force of this field.

In the classical physics the charges will distributed along the electric current so that the electric potential lowering along the current, by linearly increasing the way they take every next time period because this accelerated motion.

## Electromagnetic inertia and Gravitational attraction

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as an electromagnetic inertia, causing an electromagnetic mass.

It looks clear that the growing acceleration results the relativistic growing mass - limited also with the velocity of the electromagnetic wave.

Since  $E = hv$  and  $E = mc^2$ ,  $m = hv/c^2$  that is the  $m$  depends only on the  $v$  frequency. It means that the mass of the proton and electron are electromagnetic and the result of the electromagnetic induction, caused by the changing acceleration of the spinning and moving charge! It could be that the  $m_0$  inertial mass is the result of the spin, since this is the only accelerating motion of the electric charge. Since the accelerating motion has different frequency for the electron in the atom and the proton, they masses are different, also as the wavelengths on both sides of the diffraction pattern, giving equal intensity of radiation.

If the mass is electromagnetic, then the gravitation is also electromagnetic effect caused by the accelerating Universe! The same charges would attract each other if they are moving parallel by the magnetic effect.

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! Also since the particles are diffraction patterns they have some closeness to each other – can be seen as a gravitational force.

## Electromagnetic inertia and mass

### Electromagnetic Induction

Since the magnetic induction creates a negative electric field as a result of the changing acceleration, it works as an electromagnetic inertia, causing an electromagnetic mass. [1]

### Relativistic change of mass

The increasing mass of the electric charges the result of the increasing inductive electric force acting against the accelerating force. The decreasing mass of the decreasing acceleration is the result of the inductive electric force acting against the decreasing force. This is the relativistic mass change explanation, especially importantly explaining the mass reduction in case of velocity decrease.

### The frequency dependence of mass

Since  $E = h\nu$  and  $E = mc^2$ ,  $m = h\nu/c^2$  that is the  $m$  depends only on the  $\nu$  frequency. It means that the mass of the proton and electron are electromagnetic and the result of the electromagnetic induction, caused by the changing acceleration of the spinning and moving charge! It could be that the  $m_0$  inertial mass is the result of the spin, since this is the only accelerating motion of the electric charge. Since the accelerating motion has different frequency for the electron in the atom and the proton, they masses are different, also as the wavelengths on both sides of the diffraction pattern, giving equal intensity of radiation.

### Electron – Proton mass rate

The Planck distribution law explains the different frequencies of the proton and electron, giving equal intensity to different lambda wavelengths! Also since the particles are diffraction patterns they have some closeness to each other – can be seen as a gravitational force. [1]

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter.

## Gravity from the point of view of quantum physics

### The Gravitational force

The gravitational attractive force is basically a magnetic force.

The same electric charges can attract one another by the magnetic force if they are moving parallel in the same direction. Since the electrically neutral matter is composed of negative and positive charges they need 2 photons to mediate this attractive force, one per charges. The Big Bang caused parallel moving of the matter gives this magnetic force, experienced as gravitational force.

Since graviton is a tensor field, it has spin = 2, could be 2 photons with spin = 1 together.

You can think about photons as virtual electron – positron pairs, obtaining the necessary virtual mass for gravity.

The mass as seen before a result of the diffraction, for example the proton – electron mass ratio  $m_p/m_e=1840$ . In order to move one of these diffraction maximum (electron or proton) we need to intervene into the diffraction pattern with a force appropriate to the intensity of this diffraction maximum, means its intensity or mass.

The Big Bang caused acceleration created radial currents of the matter, and since the matter is composed of negative and positive charges, these currents are creating magnetic field and attracting forces between the parallel moving electric currents. This is the gravitational force experienced by the matter, and also the mass is result of the electromagnetic forces between the charged particles. The positive and negative charged currents attracts each other or by the magnetic forces or by the much stronger electrostatic forces!?

### The Graviton

In physics, the graviton is a hypothetical elementary particle that mediates the force of gravitation in the framework of quantum field theory. If it exists, the graviton is expected to be massless (because the gravitational force appears to have unlimited range) and must be a spin-2 boson. The spin follows from the fact that the source of gravitation is the stress-energy tensor, a second-rank tensor (compared to electromagnetism's spin-1 photon, the source of which is the four-current, a first-rank tensor). Additionally, it can be shown that any massless spin-2 field would give rise to a force indistinguishable from gravitation, because a massless spin-2 field must couple to (interact with) the stress-energy tensor in the same way that the gravitational field does. This result suggests that, if a massless spin-2 particle is discovered, it must be the graviton, so that the only experimental verification needed for the graviton may simply be the discovery of a massless spin-2 particle. [2]

### Conclusions

Researchers predict that axions, if they exist, would be produced invisibly by the Sun, but would convert to X-rays as they hit Earth's magnetic field. This X-ray signal should in theory be strongest when looking through the sunward side of the magnetic field, as this is where the Earth's magnetic

field is strongest. The high frequency of the X-ray and the uncompensated Planck distribution makes the axion a good candidate to be dark matter.

Hidden photons are predicted in some extensions of the Standard Model of particle physics, and unlike WIMPs they would interact electromagnetically with normal matter.

In particle physics and astrophysics, weakly interacting massive particles, or WIMPs, are among the leading hypothetical particle physics candidates for dark matter.

The gravitational force attracting the matter, causing concentration of the matter in a small space and leaving much space with low matter concentration: dark matter and energy.

There is an asymmetry between the mass of the electric charges, for example proton and electron, can understood by the asymmetrical Planck Distribution Law. This temperature dependent energy distribution is asymmetric around the maximum intensity, where the annihilation of matter and antimatter is a high probability event. The asymmetric sides are creating different frequencies of electromagnetic radiations being in the same intensity level and compensating each other. One of these compensating ratios is the electron – proton mass ratio. The lower energy side has no compensating intensity level, it is the dark energy and the corresponding matter is the dark matter. The electric currents causing self maintaining electric potential is the source of the special and general relativistic effects. The Higgs Field is the result of the electromagnetic induction. The Graviton is two photons together. [3]

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