

**Request for Proposal: Interdisciplinary Cluster Hire  
Departments of Physics and Astronomy**

## **MULTI-MESSENGER EARLY UNIVERSE**

Laura Cadonati, Don Candela, John Donoghue, Krishna Kumar  
*Physics Department*

Daniela Calzetti, Mauro Giavalisco, Steven Schneider, Ron Snell,  
Daniel Wang, Martin Weinberg, Min Yun  
*Astronomy Department*

### **Introduction**

The Physics and Astronomy Department at UMass are natural partners in the quest to understand our Universe, the origin of galaxies and their evolutions, in the context of a new, multi-messenger astrophysics.

UMass has already played a pioneer role in this field. In 1974, UMass professor Joe Taylor and graduate student Russell Hulse discovered pulsar PSR 1913+16, in orbit around a neutron star. Over two decades, the orbit of this binary system was observed to shrink by the exact amount predicted by General Relativity, because it radiates energy through gravitational waves. The effect was small but the measurement robust, with a reduction of orbital period (7.75 hours) by about 75 millionths of a second per year. This discovery, which awarded the two UMass scientists a Nobel prize in 1993, was the first evidence of the existence of gravitational waves, and led to the current observational efforts of LIGO (Laser Interferometer Gravitational-wave Observatory) and LISA (Laser Interferometer Space Antenna) to directly measure gravity waves.

Within the next five years, LIGO promises to usher a new era of gravitational wave astronomy. Gravitational waves will become a new “messenger” and provide complementary information to electromagnetic radiation and neutrinos. Collaborations between gravitational wave experimentalists, relativists, particle physicists and astronomers are flourishing, and the interplay between gravitational waves and theoretical and observational astrophysics is a major part of the ongoing US Astronomy & Astrophysics Decadal Survey.

In this document, we propose to leverage on the current strengths in the Physics (LIGO gravitational wave observation) and Astronomy (multi-wavelength electromagnetic wave observation and computational astrophysics) departments and add one new faculty to each. This will establish a robust interdisciplinary program, spanning across our two departments, centered on the exploration of the Universe, with the complementary information from electromagnetic and gravitational waves.

### **The Science case**

Gravity wave science is a new frontier and the detection of gravitational waves will open up a completely new window to the universe. According to Einstein’s General Theory of relativity, when large masses accelerate, their gravitational fields change. These changes propagate as *gravitational waves*, tiny ripples in the fabric of space-time. Thus, gravity waves are the messengers from the most catastrophic events in our universe: the birth and death of a star, the collision of black holes and the Big Bang itself. While electromagnetic waves are produced by

the accelerated motion of charged particles, gravitational waves are produced by the accelerated motion of masses: they convey complementary information on their sources, like different “senses” for the universe.

It is only recently that we have the tools to measure gravity waves – this frontier is just starting. The best gravity wave sources are also the most dramatic. For example when a binary system such as the Hulse-Taylor pair sheds energy in gravitational waves, their orbit shrinks and the pair will eventually collapse into a black hole. The gravitational wave emission will be strongest, and detectable by LIGO, in those final instants. LIGO measures the passing wave by sensing a stretching and squeezing of space-time with the frequency of the wave. LIGO’s current sensitivity is to a strain ( $\Delta L/L$ ) of  $10^{-21}$ , equivalent to a change of Earth’s diameter by the size of an atom.

At this time, LIGO is the most sensitive gravitational wave detector. In its current configuration, it is a tremendous success, as it demonstrated the feasibility of such accurate measurements and explored new science. By 2014, Advanced LIGO will be 10 times more sensitive, and current prediction, based on source population studies, say it is poised to detect gravitational waves and open a new field of GW astronomy. We list here the most promising science targets for Advanced LIGO.

- **Coalescence of compact objects (neutron stars, black holes).** Advanced LIGO will be sensitive to the gravitational wave emitted in the last instants before coalescence of a system like the Hulse-Taylor binary out to 350 Mpc. Larger black holes at yet greater distances offer a probe for the star formation rate in the early Universe.
- **Core-collapse supernovae.** Violent supernova explosions also emit gravity waves. Detection of gravitational waves from supernovae will provide invaluable information as to how supernovae take place and what their rate is in the universe.
- **Gamma Ray Bursts:** These are some of the most violent and mysterious events in the visible universe. Gamma ray bursts are linked to the production of gravitational waves, and theories are being formulated to use them as a measurement standard for astrophysics and cosmology. Advanced LIGO should be able to observe many of these out to a distance of 500 Mpc.
- **Continuous waves.** The Universe is filled with other potential sources of gravity waves. Gravitational waves will teach us about the structure of neutron stars, both by looking at known pulsars and with an all-sky mapping. The consequences will be of interest not only for astronomy, but also for nuclear physics.
- **Stochastic Background.** This term refers to a continuous background of gravitational waves - the combined echo of a large collection of incoherent events. The nature of its sources could be cosmological (inflationary models, cosmic strings models etc) or astrophysical (relic gravitational waves from “old” black hole collisions and supernovae, rotating neutron stars, low-mass X-ray binaries, etc). The ultimate goal is to detect stochastic background from the Big Bang at the Planck Time: in the LIGO frequency band, produced  $10^{-22}$  s after the Big Bang, compared to cosmic microwave background which decoupled  $10^{12}$  sec later. Such challenging measurements, combined with studies of anisotropy, will be a key to unlock the secrets of the early universe.

While Advanced LIGO is poised to pioneer the science, we need more sensitive detectors to make statements about the early Universe: in space (for instance, with the Big Bang Observatory) or on the ground (with advanced techniques, such as squeezing, to beat the quantum noise limit). The third generation of gravitational wave experiments will have increased sensitivity to explore the origins of the universe with gravitational waves.

Astronomy also studies the physics of the developing early Universe, using observations with different wavelengths of electromagnetic radiation (optical, radio waves, gamma rays and X rays). Because of the finite speed of light, looking at distant objects means that one is looking at a past time – one sees directly the early Universe. The use of different wavelengths is key in understanding the evolution of cosmic sources, because the cosmic expansion shifts the observed wavelengths to the red: the same objects which are observed locally in one wave band are seen in a different wave band if observed at cosmological distances. This means that in order to observe the same physical processes at different distances and to carry out comparative studies one needs access to all available wavelengths.

The UMass Astronomy Department is a strong and leading presence in both observational and theoretical astrophysics and cosmology. The Department is completing construction of the Large Millimeter Telescope, the largest millimeter-wavelength telescope in the world, developed to understand the origin of structures in the early Universe. The telescope will be the most powerful probe of the coldest, densest and most-obscured environments in the Universe which are also often the sites of the earliest stages of structure formation and thus of gravitational wave sources. Related studies in the Department focus on complementary aspects of the galaxy and large-scale structure evolution, cosmic microwave background and on X-ray observations, which are all directly related to the astrophysics of gravitational wave sources. A strong theoretical and computational program adds further insights into structure formation and complements the observational program.

A joint Physics-Astronomy hire will strongly reinforce UMass' presence in the strategic research area of the cosmic origins. Investigating the formation and evolution of galaxies and structures in the Universe is one of the forefront quests in Astronomy, and one of NASA's strategic goals (NASA being a major source of funding for astronomical research). The nuclei of galaxies routinely host black holes, and the evolution of these compact objects across cosmic times naturally follows the evolution of galaxies. One of the major discoveries in recent times has been the so-called 'bulge -- black hole mass' relationship, i.e., the finding that the larger the mass of a galaxy, the larger the mass of the black hole in its center. It is now one of the fundamental, yet still not understood, scaling relations for galaxies. One of the puzzling characteristics is that the relation holds even if, in the current galaxy evolution paradigm, merging of galaxies should 'destroy' it! The gravitational waves given off by the merging black holes in merging galaxies represent the only probe available to Astronomers to investigate and solve this puzzle.

Sources of gravitational radiation are deeply related to the evolution of cosmic structures. Together with the bulge--black hole mass relation, gravitational waves will represent unique probes to investigate other aspects of the important, but elusive, collapsed objects that populate the centers of galaxies, including, but not limited to, the formation, evolution, and mass spectrum of central black holes, and the existence of the 'intermediate mass' black hole population.

All of these projects are truly interdisciplinary. Physicists, astronomers and engineers bring their diverse skills to the design and implementation of these experiments. The LIGO science team is a unique mix of theorists and experimenters. On the astronomy side, innovative receiver engineering has been one of the strengths of the UMass program. The teams are also multi-institutional, so that the infrastructure at one institution can complement that of another.

## **The Proposal**

The key point of this RFP is that development of the gravitational wave capabilities in the Physics Department complements the strengths and goals of the Astronomy Department. By adopting an interdisciplinary multiple messenger approach to this fundamental science, we can develop a new partnership in the study of the early Universe. This joint venture will greatly expand the visibility and leadership of UMass in these key research areas and attract funding and motivated students. The nascent field of graviton astronomy with complement future efforts in photon astronomy. It will also provide an ideal platform for future expansions of the scientific activities of both departments.

The Physics Department proposes to add a second faculty to the gravitational wave effort. The new faculty will join and complement Laura Cadonati, and her effort in LIGO data analysis (expertise on transient events: GRB, Supernovae, Mergers), and be involved in design and development of the next generation of gravitational wave detectors, either ground or space based.

A faculty hire in Astronomy will complement the Physics hire and will greatly increase the breath of astronomical research at UMass. In particular, this person will help to design and coordinate multi-wavelength follow-ups of GW sources, using space- and ground-based telescopes, especially the LMT. This Physical/Astronomy collaboration will provide an excellent opportunity for us to develop the expertise in the study of black holes --- a research area that is essential to our ongoing effort in understanding galaxy formation and evolution. This research in cosmic origins is also an important focus of other large telescope projects (e.g., GLAST, International X-ray Observatory, James Webb Space Telescope, and Atacama Large Millimeter Array) and is strongly supported by federal funding agencies (NASA, DOE, and NSF). Involvement in the research will also facilitate new opportunity of outreach to public and further our scientific leadership and visibility.

## **Support for this proposal**

Both the Physics and Astronomy Departments are well positioned to take advantage of this opportunity in the near future. Both departments have well defined plans for their future, and this joint RFP matches well with these plans. The completion of the LMT is a great accomplishment and UMass is about to reap the rewards for many years of hard work in its planning and construction. The new hires in both departments have reinforced the ‘multi-messenger’ theme that is needed for this science. All recently hired faculty members have become well funded.

Leadership is present in both departments to move this project forward. The senior scientists are committed to these directions. Mid-career faculty members are strong and are assuming leadership roles. Extremely promising junior hires have been made in the right areas and provide essential skills and enthusiasm for the success of the effort. The pieces are all in place to make this successful.

This initiative fits in well within the long-term vision for growth in the physics department. Several years ago, the faculty endorsed a plan to reach a steady-state level of nine faculty members pursuing the broad area of experimental microphysics, which can be loosely classified within three sub-areas: collider-based high energy physics, accelerator-based fixed target nuclear and particle physics, and particle astrophysics. The plan would use positions as they became available to reach a steady state level of three faculty members in each area. Currently, we are at eight faculty members, and the department has endorsed the view that the position proposed in

this initiative would be the ninth of these positions, completing the endorsed plan. If/when such a search is launched, we would anticipate support for a competitive startup package to be assembled together by the Dean of the college, with support from the Vice-Provost for research as well as the physics department.

The science goals of astronomy and physics have also co-mingled in recent years. The focus topic of this RFP – the early universe - is the area with the greatest overlap. The “multiple messenger” aspect of the field is a key to unravel the observational science. Because of the strengths existing within the UMass Astronomy and Physics department, we have a unique opportunity to play a leading role in the future of this exciting subject.

### **Educational aspects**

One of the exciting features of the study of the early Universe is that it provides a great way to educate students and the public about science. The subject is one that most people find fascinating and it can be presented well using different levels of sophistication. At UMass, both Astronomy and Physics offer general education courses which provide students with an entry into science. The LMT project also has an extensive outreach program. The discoveries from this science will provide the University with many opportunities to highlight the research accomplishments of UMass faculty.

The RFP is also supported by trends in graduate education in physics and astronomy. Besides basic courses such as in electromagnetic theory, there are advanced courses in general relativity and cosmology that are relevant for the present RFP. Previous plans for interdisciplinary computational science have led to a computational course offered by astronomy that is relevant for physics. These developments have taken place independent of the RFP, but support its mission and are evidence of the interdisciplinary collaboration which will be enhanced under the RFP.

### **Funding**

LIGO is a high priority for the NSF Gravity Program; advanced LIGO is fully funded (at a \$200M level) and grants are awarded for LIGO-related research. UMass/Physics holds one such single-PI grant, and the prospects are good for efforts that are well integrated in the LIGO science mission. In addition, gravitational astronomy ties extremely well with NASA's Cosmic Origin initiative, which several faculty of the Astronomy Department are involved with. Also, NASA is developing its own space-born gravitational observatory (LISA), and a joint activity of the Astronomy/Physics faculty will be a natural liaison at UMass between the space agency and the physics community.

The Astronomy 2010 decadal survey by the National Academy of Sciences, also supported by the DOE, NSF and NASA, is presently constructing the science case for the exploration of the Universe over the next ten years. This RFP has detailed the science topics that are the focus for the majority of the sub-panels for this survey. UMass is well positioned to be a major player in the future studies of the next generation of studies of the early Universe.