

**Memorandum of Understanding (LIGO-M050320-00-M)**  
**between the**  
**Northwestern University Gravitational Wave Astrophysics Group**  
**(NUGWAG)**  
**and the**  
**Laser Interferometer Gravitational Wave Observatory (LIGO)**

**August 15, 2005**

The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between the Northwestern University Gravitational Wave Astrophysics Group (NUGWAG) and the Laser Interferometer Gravitational-Wave Observatory (LIGO). Both parties to this agreement share the broad goals of developing the instruments and techniques for detecting and studying gravitational waves, and subsequently using them as an astrophysical probe. Under this MOU, the NUGWAG Group will be a member group of the LIGO Scientific Collaboration.

1. The Northwestern University Gravitational Wave Astrophysics Group (NUGWAG) consists of Professor Vassiliki Kalogera, who will serve as Principal Investigator for research in LIGO, and Richard O'Shaughnessy (postdoctoral associate), Chunglee Kim (graduate student), and Krzysztof Belczynski (Tombaugh postdoctoral fellow, NMSU). The focus of the work done by the NUGWAG Group under this agreement will be the theoretical astrophysics of gravitational wave sources for ground-based interferometers involving compact objects. Topics to be investigated include source formation rates, physical properties, and detectability; method development for interpretation of gravitational wave observations; method development for optimal and computationally efficient gravitational wave data analysis. This research will be conducted by NUGWAG members alone, or in collaboration with other LSC members, or in collaboration with researchers outside the LSC, as it may be necessary to maximize efficiency in project completion and publication/presentation of results.
2. LIGO comprises two parts: the LIGO Laboratory and the LIGO Scientific Collaboration. These two entities report to the LIGO Directorate, consisting of the LIGO Director, the LIGO Scientific Collaboration Spokesperson, and the LIGO Laboratory Deputy Director. The design and construction of the LIGO Observatories were carried out by California Institute of Technology (Caltech) and the Massachusetts Institute of Technology (MIT) under a Cooperative Agreement between the National Science Foundation (NSF) and Caltech. The LIGO Oversight Committee supervises the realization of LIGO.

- A. The LIGO Laboratory is responsible for the operation of the LIGO Observatories, the development and implementation of future detector systems, and participates in all aspects of the research with the LIGO detectors. LIGO is a system of three interferometric Fabry-Perot antennas, two of them 4 kilometers long and the third one 2 kilometers long, aimed at the simultaneous detection of gravitational waves in the frequency range 40-6000 Hz. LIGO Observatories are located in Hanford, Washington and in Livingston Parish, Louisiana (USA) and began observations in the year 2002. The LIGO Laboratory is funded through a Cooperative Agreement between the National Science Foundation and Caltech, with the portion of the LIGO Laboratory at MIT funded through a subcontract from Caltech.
  - B. The LIGO Scientific Collaboration (LSC) is organized as a separate entity from the LIGO Laboratory. It includes scientists from the LIGO Laboratory, and those from collaborating institutions, and has its own governance and leadership (which includes the LSC Spokesperson as a member of the LIGO Directorate). The Collaboration ensures equal scientific opportunity for individual participants and institutions. It organizes the research, publications, and all other scientific activities. The Collaboration reports to the LIGO Directorate for final approval of its research program, technical work, observational physics publications, and talks announcing new observations and physics results. This will be done through regular reports to the Directorate and its Program Advisory Committee. The organization of the LSC and its governance are defined in its Charter.
3. As a member group of the LSC, the NUGWAG Group will participate in the governance of the LSC and in setting its policies and procedures, as defined in the LSC charter. Similarly, it agrees to abide by the policies and procedures adopted by the LSC and posted on its website (<http://www.ligo.org/policies.html>), concerning publication, data access, software standards, and so on.
  4. Membership in more than one collaboration active in the same area of research may present complications. Members of the LSC contemplating joining other gravitational wave collaborations or participating in data analysis efforts with collaborations outside a framework established by the LSC should inform and consult with LSC and the LIGO Laboratory to ensure that no conflicts of interest exist.
  5. The LSC is the primary advocate of interferometric gravitational wave research in the U.S. To function effectively in this role, it needs to be informed in advance about major new initiatives. The NUGWAG Group agrees to inform the LSC of any major new proposals related to LIGO to be submitted to the NSF, and to consult with the LSC concerning the best approach to support the overall LIGO program. The final decision about the scope of any such proposal shall remain the prerogative of the NUGWAG Group.

6. LSC Service Functions - Participation in the LSC brings with it responsibility for service functions to support the overall effort in achieving high detector sensitivity and high data quality. In particular, each LSC group is expected to assist in the staffing of scientific monitoring shifts during organized data runs. The staffing of these shifts is notable for both its importance and the travel burden it places on scientists. This burden makes an equitable shift allocation mechanism necessary.

A nominal guideline is that each LSC group should staff a fraction of the shifts comparable to its FTE fraction devoted to LSC activities. Vasiliki Kalogera (NUGWAG Group) will be responsible for interaction with the designated LSC Shift Organizer with respect to the NUGWAG Group's Service Function commitments.

Groups making extensive contributions to the LSC in other service efforts that involve a substantial travel burden may request a reduction in their nominal share of shift staffing. Those efforts can include:

- Commissioning and instrument improvement
  - Participation in on-site detector characterization investigations
  - Development/operation of analysis software/hardware infrastructure and validation of analysis software that requires travel away from the home institution.
7. Each party to this agreement continues to be responsible for all support of its staff including travel costs associated with the activities under this agreement. Exceptional support of travel by the other institution may be allowed for travel requested by that institution.
  8. Attachments to this MOU will be prepared annually to define the specific activities and responsibilities of the NUGWAG Group and to define any resources to be provided by the LIGO Laboratory to the NUGWAG Group in support of those activities.
  9. NUGWAG Group will provide an annual status report on its activities in support of LIGO. The report will consist of a summary status on research by topic as indicated in the Attachments for that period including progress against the milestones if any, significant accomplishments such as new insights/discoveries or publications, issues of concern if any, and an indication of invested time by each member of the group. The report will be due one month before the close of the period of performance under the Attachments in question.
  10. The LSC will review the progress report against the Attachments from the previous year and assess the Attachments for the up-coming year annually, under its established procedure, and recommend acceptance or rejection of each Attachment by the LIGO Director and the LSC Spokesperson.
  11. A list of NUGWAG Group members will be updated at least every six months. NUGWAG Group members and appropriate contact information will be provided in electronic form as Attachment Z to this Memorandum of Understanding. In cases

- where individuals who leave the group have had access to LIGO data and this access should be terminated, the NUGWAG Group Principal Investigator is responsible for timely notification to the Directorate and to the computing committee so access may be revoked.
12. The LIGO Laboratory is responsible for obtaining NSF approval of collaborative Memoranda of Understanding where required. All Memoranda of Understanding will be provided to NSF for their information.
  13. The rights to intellectual property developed under this Attachment using LIGO Laboratory resources will be subject to the National Science Foundation Grant Policy as indicated in Section 730, Intellectual Property.
    - A. In the event a patentable invention is conceived or first actually reduced to practice during the work of a member(s) of the NUGWAG Group at LIGO Laboratory facilities, he/she will:
      - i) make prompt disclosure of the invention to the Director of the LIGO Laboratory; and
      - ii) cooperate with LIGO Laboratory and supply all information and execute all papers including invention reports, records of invention, patent applications and powers of attorney, necessary and proper to fulfill the obligations of the LIGO Laboratory to the U.S. Government sponsor.
    - B. The ownership of inventions conceived solely by members of the NUGWAG Group at LIGO facilities shall be owned by the Northwestern University, although the LIGO Laboratory shall be granted a license to use such invention for noncommercial research purposes at LIGO facilities. Inventions that are conceived by both members of the NUGWAG Group and LIGO Laboratory staff as part of the LIGO project shall be jointly owned and any income from commercial licensing shall be shared in proportion to the number of joint inventors from each institution.

In all other regards, the rights to intellectual property developed by members of the NUGWAG Group under this Attachment will be in accordance with the policies of Northwestern University.

14. This MOU supersedes the previous MOU between the LIGO Laboratory and the NUGWAG group (LIGO-M020043-00-M) and its amendments and attachments. This MOU will remain in force until the parties mutually agree to terminate it, or until it is terminated in accordance with LSC procedures.

Approved:

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Barry Barish  
LIGO Director

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Vassiliki Kalogera  
Principal Investigator  
Northwestern University Gravitational Wave  
Astrophysics Group

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Peter Saulson  
LSC Spokesperson

**Attachment ACF to the**  
**Memorandum of Understanding (LIGO-M050320-00-M)**  
**between the**  
**Northwestern University Gravitational Wave Astrophysics Group**  
**(NUGWAG)**  
**and the**  
**Laser Interferometer Gravitational Wave Observatory (LIGO)**  
**August 15, 2005**

This Attachment ACF to the Memorandum of Understanding LIGO-M050320-00-M defines the role of the Northwestern University Gravitational Wave Astrophysics Group (NUGWAG) as a Member of the LIGO Scientific Collaboration (LSC) and a member of the Advanced Detector Configurations Development Group (ADCDG). The period of performance for the activities in this Attachment is from August 15, 2005 to August 15, 2006.

1. Advanced Detector Configurations Development Group - The Advanced Detector Configurations Development Group (ADCDG) is the scientific collaboration for defining and developing entirely new advanced interferometers. It is expected that this development group will pursue research in dual recycling, resonant sideband extraction, Sagnac interferometers, systems with non-transmitting optics and other advanced configurations. MOU Attachments define the roles and responsibilities of groups in this development group.
2. During the period August 15, 2005 to August 15, 2006, the members of NUGWAG Group will participate in ADCDG in the following areas:
  - a) *Interferometer Configurations* – Richard O'Shaughnessy, most likely in collaboration with the Caltech group, will spend some of his time examining the potential uses and pitfalls of flat-topped beams in advanced interferometer configurations. He will first finish a long-delayed but thorough analysis of the advantages flat-topped beams offer for reducing coating thermal and thermoelastic noise in the pending fused-silica design. If time permits, he hopes to work with David Blair, Sergey Vyatchanin and others to examine the potential advantages flat-topped beams offer for reducing the impact of the tilt instability on advanced LIGO control.
3. Resource Sharing: The LIGO Laboratory will contribute resources including allocation of appropriate scientific and engineering personnel, research facilities and funding in support of the effort in Item No. 2, as indicated below.
  - a) Research accommodations for NUGWAG group members while on LIGO research assignment at any LIGO Laboratory site,
  - b) Access to LIGO data in support through established LSC channels in support of this work.

c) ...others...

4. Coordination and Reporting – NUGWAG Group will perform this research within the structures established by the LIGO Laboratory and the LSC where appropriate. In particular activities described in Item 2 will be carried out within the Advanced Detector Configurations Development Group of the LSC. Coordination will include keeping the Group leaders informed of activities and plans, reporting to the group at meetings and telecons, and through technical documents submitted to the LIGO Document Control Center.

In addition, an annual report will be submitted with the update to this Attachment, giving a summary status on research by topic as indicated in Item No. 2, including progress against the milestones if any, significant accomplishments such as new insights/discoveries or publications, issues of concern if any, and an indication of invested time. This Attachment will be updated at least annually with a plan of activities for the succeeding on-year period. These documents will be due one month before the close of the period of performance under this Attachment.

5. The research effort pursuant to this Attachment A will be coordinated by Vassiliki Kalogera (NUGWAG Group) and the leader(s) of the ADCDG.

Approved:

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Barry Barish  
LIGO Laboratory Director

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Vassiliki Kalogera  
NUGWAG Principal Investigator

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Peter Saulson  
LSC Spokesperson

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Ken Strain  
ADCDG Leader

**Attachment DAT to the**  
**Memorandum of Understanding (LIGO-M050320-00-M)**  
**between the**  
**Northwestern University Gravitational Wave Astrophysics Group**  
**(NUGWAG)**  
**and the**  
**Laser Interferometer Gravitational Wave Observatory (LIGO)**  
**August 15, 2005**

This Attachment DAT to the Memorandum of Understanding LIGO-M050320-00-M defines the role of the Northwestern University Astrophysics Group (NUGWAG) as a Member of the LIGO Scientific Collaboration (LSC), in particular, its activities in **theoretical astrophysics and data analysis and interpretation** in support of the initial LIGO interferometers. The period of performance for the activities in this Attachment is from August 15, 2005 to August 15, 2006.

1. Together, the LIGO Laboratory and the LIGO Scientific Collaboration are responsible for implementing and exploiting the initial LIGO detector through its science data runs. The LSC has organized the data analysis effort into search groups which coordinate the analyses, perform detailed reviews, and prepare publications on behalf of the collaboration. LSC groups are encouraged to participate in one or more of these groups. MOU Attachments define the contributions of each participating group to the data analysis groups.
2. During the period August 15, 2005 to August 15, 2006, the members of the NUGWAG Group will participate in the analysis **and interpretation** of initial LIGO data in the following areas:
  - a) *Binary Inspirals* – 1) Astrophysical and astronomical guidance needed in the development of data analysis pipelines; 2) Theoretical astrophysics calculations and predictions for binary inspiral source rates and properties needed for the development of data analysis and interpretation methods; 3) Development and testing of efficient data analysis methods; 4) Review and advising services. More specifically:
    - (i) Kalogera will provide advice and recommendations for signal hardware injections and Monte Carlo simulations for the determination of detection efficiencies and vetoes and upper limit calculations. This work will be based on the most current astronomical knowledge of galaxy distribution in space, physical properties and history in binary compact object formation, as well as current astrophysical predictions and knowledge of component masses, spins, and other relevant physical properties.
    - (ii) Kim and Kalogera (in collaboration with non-LSC member D. Lorimer) will continue their work on developing the first quantitative modeling of acceleration pulsar searches and their selection effects to estimate the binary inspiral rate contribution of a newly discovered double neutron star (the 4<sup>th</sup>

known in the Galactic field that will coalesce within a Hubble time) and other future discoveries through pulsar acceleration searches. This work is expected to be completed within the year upon Kim's PhD graduation in Summer 2006.

- (iii) Kim and Kalogera (in collaboration with non-LSC member D. Lorimer) will complete a publicly available web-based tool suite that will allow interested researchers to calculate inspiral rates based on binary pulsar discoveries.
- (iv) O'Shaughnessy, Kalogera, and Belczynski will continue their long-term work (presented in multiple completed and future publications) on constraining population synthesis models and binary black hole inspiral rate predictions by imposing empirical constraints. New constraints to be imposed include: empirical (from pulsar observations) rate constraints from eccentric and merging pulsar binaries with white dwarf companions, empirical supernova rates of different types, and empirical constraints on neutron star kicks.
- (v) O'Shaughnessy and Kalogera will address the issue of the contribution of elliptical galaxies and latent binary inspiral events to the total inspiral rate. The answer to this problem is crucial for the realistic population modeling needed for the analysis of S4 data, given the high instrument reach during S4.
- (vi) O'Shaughnessy and Kalogera will contribute to the population modeling needed in data analysis and searches for spinning black hole binaries, using their published results from last year's theoretical astrophysics studies of black hole spins.
- (vii) O'Shaughnessy will continue to explore the potential of genetic algorithms, as a means to more efficiently perform template inspiral searches. The expectation is that with proper tuning these methods will perform almost as reliably as a thorough study of any template bank, and compare very favorably with a conventional hierarchical search.
- (viii) O'Shaughnessy will complete the investigation of using generalized templates (e.g., "spiky" templates) to detect conventionally- and poorly-modelled signals in the presence of realistic detector noise.
- (ix) R. O'Shaughnessy will spend a limited amount of time developing and testing veto systems. Among others, he expects to test (i) one incorporating only the template scores themselves (i.e., the values of the overlap on various templates), in an effort to make use of the expected dependence of overlap with parameters; and (ii) one incorporating many control-channel signals, in an effort to use machine-learning and pattern-recognition algorithms to automate veto identification.
- (x) Kalogera will initiate the formulation and development of strategies for the interpretation first of astrophysically interesting upper limits, and later of inspiral detections under different assumed scenarios for circumstances (one or more detections of various signal-to-noise ratios, with or without parameter estimation, etc). Such upper limits and possibly detections could become available by the Inspiral group data analysis results this coming year.
- (xi) Kalogera will continue to serve as a Reviewer of the Inspiral Group analysis, publications, and presentations and as a Member of the LIGO-PAC committee.
- (xii) Kalogera will continue to provide advice and perform calculations promptly when requested on issues related to source detection expectations (signal-to-noise ratios, rates, etc) as a function of future detector noise characteristics. **This really belongs more into "support for future detector design", but**

**the Advanced detector template deals with real instrumentation development, so I put this here.**

3. Resource Sharing: The LIGO Laboratory will contribute resources including allocation of appropriate scientific and engineering personnel, research facilities and funding in support of the effort in Item No. 2, as indicated below.
  - a) Research accommodations for NUGWAG group members while on LIGO research assignment at any LIGO Laboratory site,
  - b) Access to LIGO data in support through established LSC channels in support of this work.
  - c) ...others...
4. Coordination and Reporting – NUGWAG Group will perform this research within the structures established by the LIGO Laboratory and the LSC where appropriate. In particular activities described in Item 2a) will be carried out within the LSC Inspiral Search Group, Item 2b) will be carried out within the LSC Burst Search Group, and Item 2c) will be carried out within the LSC Stochastic Search Group. Coordination will include keeping the Group leaders informed of activities and plans, reporting to the group at meetings and telecons, and through technical documents submitted to the LIGO Document Control Center.
 

In addition, an annual report will be submitted with the update to this Attachment, giving a summary status on research by topic as indicated in Item No. 2, including progress against the milestones if any, significant accomplishments such as new insights/discoveries or publications, issues of concern if any, and an indication of invested time. This Attachment will be updated at least annually with a plan of activities for the succeeding on-year period. These documents will be due one month before the close of the period of performance under this Attachment.
5. All computer code delivered to the LSC under this Attachment must be developed in consultation with the LSC Data Analysis Software Working Group (DASWG) and archived, documented and reviewed as determined by that group.
6. The research effort pursuant to this Attachment A will be coordinated by Vassiliki Kalogera (NUGWAG Group), Albert Lazzarini (LIGO Laboratory), Peter Shawhan (LSC Burst Search Group Leader), Patrick Brady (LSC Inspiral Search Group Leaders) and ....

Approved:

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Barry Barish  
LIGO Laboratory Director

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Vassiliki Kalogera  
NUGWAG Principal Investigator

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Peter Saulson  
LSC Spokesperson

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Peter Shawhan  
LSC Burst Search Group Leader

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Albert Lazzarini  
LIGO Laboratory Data and Computing  
Group Leader

**Attachment Number Z to the  
Memorandum of Understanding (LIGO-M050320-00-M)  
between the  
Northwestern University  
Gravitational Wave Astrophysics Group (NUGWAG)  
and the**

**Laser Interferometer Gravitational-Wave Observatory (LIGO) Laboratory**

**August 15, 2005**

This Attachment to the Memorandum of Understanding LIGO-M050320-00-M lists the coordinates of the NUGWAG members who will participate in the LIGO Scientific Collaboration (LSC) as members of LIGO Development Groups. The period of performance for the activities in this Attachment is from **August 15, 2005 to August 15, 2006**. This period may be modified by agreement to a revision of this Attachment.

<b>Name</b>	<b>Address</b>	<b>E-Mail</b>	<b>Phone Nos.</b>	<b>Begin Date</b>	<b>End Date</b>
Kalogera, Vassiliki LIGO I 40% AdLIGO 10% Faculty	Northwestern Univ. Dept. Of Physics & Astronomy 2131 Tech Drive, Evanston, IL 60208	vicky@ northwestern.edu	847-491-5669 Fax: 847-491-3135	Aug. 15, 2005	Aug. 15, 2006
Belczynski, Krzysztof LIGO I 10% AdLIGO 0% Tombaugh Postdoctoral Fellow	New Mexico State University Astronomy Dept., Las Cruces, NM	kbelczyn@ nmsu.edu	847-467-5076 Fax: 847-491-3135	Aug. 15, 2005	Aug. 15, 2006
O'Shaughnessy, Richard LIGO I 90% AdLIGO 10% Postdoctoral Associate	Northwestern Univ. Dept. Of Physics & Astronomy 2131 Tech Drive, Evanston, IL 60208	oshaughn@ northwestern.edu	847-491-5626 Fax: 847-491-3135	Aug. 15, 2005	Aug. 15, 2006

Kim, C. L. LIGO I 100% AdLIGO 0% Graduate Student	Northwestern Univ. Dept. Of Physics & Astronomy 2131 Tech Drive, Evanston, IL 60208	c-kim1@ northwestern.edu	847-467-5109 Fax: 847-491-3135	Aug. 15, 2005	Aug. 15, 2006
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Scientific Collaboration Council Delegate: Vassiliki Kalogera

Approved:

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Barry Barish  
LIGO Laboratory Director

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Vassiliki Kalogera  
NUGWAG Principal Investigator

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Peter Saulson  
LSC Spokesperson