Nomination form for the 2021 Nishina Asia Award
(RENOMINATION from 2020)

Candidate (name, affiliation, curriculum vitae including the date of the degree of Ph.D., nationality, address, email and telephone)
Name: Parameswaran Ajith *Affiliation:* International Centre for Theoretical Sciences (Tata Institute of Fundamental Research) *Date of the degree of PhD:* Dec, 2007 *Nationality:* Indian *Address:* ICTS-TIFR, Shivakote, Hesaraghatta Hobli, Bengaluru North 560089, India. *Curriculum vitae:* Attached separately *E-mail:* *Tel.* +91 80 4653 6210, +91 91645 94474
Citation for the Award (within 30 words)
Description of the work

Key references (up to 3 key publications*)

*) Copy of one most significant publication should be attached.

Nominator (name, affiliation, email, telephone and relation to the candidate)

Spenta R. Wadia

Infosys Homi Bhabha Chair Professor, Professor Emeritus & Founding Director

International Centre for Theoretical Sciences (Tata Institute of Fundamental Research)

Bengaluru North 560089, India

E-mail:

Tel: +91 80 4653 6010

Relation to the candidate: Senior colleague

Signature Date 2 March 2021

Nomination form for the 2020 Nishina Asia Award

Candidate (name, affiliation, curriculum vitae including the date of the degree of Ph.D., nationality, address, email and telephone)

Name: Parameswaran Ajith
Affiliation: International Centre for Theoretical Sciences (Tata Institute of Fundamental Research)
Date of the degree of PhD: Dec, 2007
Nationality: Indian
Address: ICTS-TIFR, Shivakote, Hesaraghatta Hobli, Bengaluru North 560089, India.
Curriculum vitae: Attached separately
E-mail: ajith@icts.res.in
Tel. +91 80 4653 6210, +91 91645 94474

Citation for the Award (within 30 words)

For his pioneering contributions to the development of phenomenological models of gravitational-wave signals from coalescing binary black holes.

Description of the work

The recent discovery of gravitational waves (GWs) confirms a major prediction of Einstein's general theory of relativity (GR) and opens a fundamentally new observational window onto the Universe. Parameswaran Ajith has done impactful work on several aspects of GW physics and astronomy – in particular, in the modelling of GWs from binary black holes by combining analytical and numerical relativity, and probes of strong gravity using GW observations.

The detection of GWs from binary black holes, and the extraction of source parameters are performed by comparing the data with theoretical templates of the expected signal waveforms. Thus, the calculation of accurate theoretical templates plays a vital role in GW astronomy. Ajith pioneered one of the two existing approaches (the *phenomenological* method) for constructing waveform templates describing the full inspiral, merger and ringdown of binary black holes by combining analytical calculations in GR with large-scale numerical-relativity simulations[1 2 3 4 5]. Waveforms constructed using this method are widely used to extract the source parameters from the LIGO-Virgo events[6 17] and for testing the consistency of the observed signal with GR[7 8]. By coherently describing the entire coalescence (inspiral, merger and ringdown), such templates have significantly increased the sensitivity of GW searches and the accuracy and the precision of the parameter estimation. The extreme computational efficiency of the phenomenological waveforms has made them the standard workhorses in LIGO-Virgo data analysis.

Ajith was among the first to theoretically demonstrate the advantages of using inspiral-merger-ringdown templates in GW detection[2], parameter estimation[9], and tests of GR[10]. In addition, his work directly contributed to the implementation of inspiral-merger-ringdown templates in GW searches: He demonstrated the effectualness of templates modeling only non-precessing spins in detecting a significant fraction of black hole binaries with generic spins and identified an *effective spin* parameter that is well measured by observations[4 11]. He contributed to the construction of *template banks* employing non-precessing waveforms [12], to the demonstration of the improved efficiency of such searches in LIGO data[13], and finally to the actual searches for binary black holes in data from Initial LIGO's fifth and sixth scientific runs[14 15]. This body of work impactful on the design of current GW searches, which made the first detections.

Ajith's group at the International Centre for Theoretical Sciences (ICTS) made several direct contributions to deciphering the discovery of GWs. They formulated, developed an implemented a test of GR based on the consistency between the inspiral, merger and ringdown parts of observed GW signals from a binary black holes[16]. This was one among the handful of tests used to establish the consistency of the first LIGO event with a binary black hole system predicted by GR[7] and was one of the first tests of GR in the highly relativistic, strong-field regime of gravity[17]. Ajith and collaborators also proposed and implemented a method to infer the mass and spin of the remnant black hole in a binary merger, making use of full inspiral, merger, ringdown waveforms and fitting formulas calibrated to numerical relativity simulations[18]. This was used to infer the mass and spin of the final black hole in the LIGO events[6 19]. These are some of the best measurements of black-hole spin among all astronomical observations.

Ajith's group is one of the world-leading groups in the probes of strong gravity using GW observations. Their recent work include a test of the "no-hair" nature of binary black holes (i.e., to see if a binary black hole system in quasi-circular orbits is completely described by the masses and spin angular momenta of the black holes, as suggested by the uniqueness theorems in GR)[20] and a method for constraining the parameter space of exotic compact objects ("black hole mimickers") as potential sources of the GW events discovered by LIGO and Virgo[21]. Now that GW observations are becoming precision probes of gravity and astrophysics, it is important to characterize the systematic effects in our GR-based waveform models. Ajith's group characterized the systematic errors due to neglecting the higher order modes of the gravitational radiation from binary black holes [22] and constructed accurate waveform templates that include the effect of higher order modes[23]. Another exciting frontier of their research is the gravitational lensing of GWs. They developed a method for identifying strongly lensed binary black hole merger events in the LIGO-Virgo data[24] and performed the first search for lensing signatures[25]. Although no detection of lensing signatures has been made so far, the first detection is expected in the next few years.

Ajith is a recipient of the *NR Sen Young Researcher Award* by the Indian Association for General Relativity and Gravitation (2019), *CIFAR Azrieli Global Scholarship* by the Canadian Institute for Advanced Research (2017-19), is the Head of the *Max Planck Partner Group in Astrophysical Relativity* at ICTS-TIFR (2015-20) supported by the Max Planck Society and the PI of the *Indo-US Centre for the Exploration of Extreme Gravity* funded by the Indo-US Science and Technology Forum (2017-19).

Key references (up to 3 key publications*)

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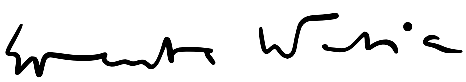
1. P.Ajith et al, *Inspiral-merger-ringdown gravitational-waveforms for black-hole binaries with non-precessing spins*, Phys. Rev. Lett. **106**, 241101 (2011).
2. P. Ajith, *Addressing the spin question in gravitational-wave searches: Waveform templates for inspiralling compact binaries with nonprecessing spins*, Phys. Rev. D **84** 084037 (2011).
3. Ab. Ghosh, Ar. Ghosh, N. K. Johnson-McDaniel, C. K. Mishra, P. Ajith, W. Del Pozzo, D. A. Nichols, Y. Chen, A. B. Nielsen, C. P. L. Berry, L. London, *Testing general relativity using golden black-hole binaries*, Phys. Rev. D **94**, 021101 (R) (2016).

Nominator (name, affiliation, email, telephone and relation to the candidate)

Spenta R. Wadia
Infosys Homi Bhabha Chair Professor, Professor Emeritus & Founding Director
International Centre for Theoretical Sciences (Tata Institute of Fundamental Research)
Bengaluru North 560089, India
E-mail: spenta.wadia@icts.res.in
Tel: +91 80 4653 6010
Relation to the candidate: Senior colleague

Signature  Date: 3 March 2020

References:

[1] P Ajith *et al*, Class Quantum Grav. **24** (2007) S689.
[2] P Ajith *et al*, Phys Rev D **77** (2008) 104017.
[3] P Ajith, Class Quantum Grav **25** (2008) 114033.
[4] P Ajith *et al*, Phys Rev Lett **106** (2011) 241101.
[5] L. Santamaria *et al*, Phys. Rev. D **82**, 064016 (2010).
[6] B P Abbott *et al* (LIGO-Virgo Collaboration), Phys Rev Lett **116**, 241102 (2016).
[7] B P Abbott *et al* (LIGO-Virgo Collaboration), Phys Rev Lett **116**, 221101 (2016).
[8] B P Abbott *et al* (LIGO-Virgo Collaboration), Phys Rev X **6** 041015 (2016).
[9] P Ajith, S Bose, Phys. Rev. D **79** (2009) 084032.
[10] D Keppel, P Ajith, Phys. Rev. D **82** (2010) 122001.
[11] P Ajith, Phys Rev D **84** 084037 (2011).
[12] P Ajith *et al*, Phys. Rev. D **89** 084041 (2014); S. Roy *et al* Phys. Rev. D **99**, 024048 (2019).
[13] S Privitera *et al*, Phys. Rev. D **89** 024003 (2014).
[14] J. Abadie *et al* (LIGO-Virgo Collaboration), Phys. Rev. D **83**, 122005 (2011)
[15] J. Aasi *et al* (LIGO-Virgo Collaboration), Phys. Rev. D **87**, 022002 (2013)
[16] A Ghosh *et al*, Phys Rev D **94**, 021101(R) (2016); Class. Quantum Grav. **35** 014002 (2017).
[17] B. P. Abbott et al. (LIGO-Virgo Collaboration), Phys. Rev. D **100**, 104036 (2019).
[18] A Ghosh, W Del Pozzo, P Ajith, Phys Rev D **94**, 104070 (2016).
[19] B P Abbott *et al* (LIGO-Virgo Collaboration), Phys Rev Lett **116,** 241103 (2016); Phys. Rev. X **9**, 031040
[20] S. Dhanpal *et al*, Phys. Rev. D **99**, 104056 (2019); T. Islam *et al*, Phys. Rev. D **101**, 024032 (2020).
[21] N. K. Johnson-McDaniel et al, arXiv:1804.08026 [gr-qc]
[22] V.Varma *et al* , Phys. Rev. D **90**, 124004 (2014); V. Varma & P. Ajith, Phys. Rev. D**96** 124024 (2017).
[23] A. K. Mehta *et al*, Phys. Rev. D **96**, 124010 (2017; A. K. Mehta *et al*, Phys. Rev. D **100**, 024032 (2019).
[24] K. Haris *et al,* arXiv:1807.07062 [gr-qc]
[25] O.A. Hannuksela *et al*, Astrophys. J. Lett. **874** L2, 10 (2019).

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EDUCATION

Ph.D. Physics Max Planck Institute for Gravitational Physics (Albert Einstein Institute) and Leibniz University of Hannover, Hannover, Germany (December, 2007). With *Suma Kum Laude ('outstanding')*.

M.Sc. Physics (Astrophysics) School of Pure and Applied Physics, Mahatma Gandhi University, Kottayam, India. (January, 2003).

B.Sc. Physics (Mathematics, Computer Science) M. E. S. Kalladi College, Mannarkkad, University of Calicut, India. (March, 2000).

EMPLOYMENT

Associate Professor, International Centre for Theoretical Sciences, Bangalore, India (Since Jan 2017).

Reader, International Centre for Theoretical Sciences, Bangalore, India (Jan 2013 – Dec 2016) [1].

Senior postdoctoral scholar at California Institute of Technology, Pasadena, USA (Jan 2012 – Jan 2013). Mentors: Alan Weinstein, Yanbei Chen, Kip S. Thorne.

Postdoctoral scholar at California Institute of Technology, Pasadena, USA (Jan 2009 – Jan 2012) [2]. Mentors: Alan Weinstein, Yanbei Chen, Kip S. Thorne.

Postdoctoral scholar at Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Hannover, Germany (December 2007 – December 2008). Mentor: Bruce Allen.

Graduate student at Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Hannover, Germany (July 2004 – December 2007). Thesis: *On aspects of gravitational-wave detection: Detector characterisation, data analysis and source modelling for ground-based detectors*. Advisers: Bernard Schutz, Martin Hewitson.

Visiting student at Raman Research Institute, Bangalore, India (October 2003 – May 2004). Adviser: Bala R. Iyer.

PROFESSIONAL RECOGNITION

N. R. Sen Young Researcher Award by the Indian Association for General Relativity and Gravitation (2019).

CIFAR Azrieli Global Scholarship by the Canadian Institute for Advanced Research (2017-2019).

Special Breakthrough Prize in Fundamental Physics 2016 (as part of the LIGO-Virgo collaboration).

Gruber Cosmology Prize 2016 (as part of the LIGO-Virgo collaboration).

Head of the *Max Planck Partner Group in Astrophysical Relativity and Gravitational-Wave Astronomy* at ICTS-TIFR (2015-2020).

Associateship of the Indian Academy of Sciences (2014-2017).

Ramanujan Fellowship from the Department of Science and Technology, Govt. of India (2013-2018).

1 Had a concurrent offer from the Indian Institute of Science also (Assistant Professor).
2 Had concurrent postdoc offers from the Max Planck Institute for Gravitational Physics (Potsdam), University of Jena, Syracuse University, Cardiff University, University of Wisconsin - Milwaukee, and Penn State University.

Finalist, *Pappalardo Fellowships in Physics*, Massachusetts Institute of Technology, Cambridge MA, USA (2007).

Honorable mention in the PhD Thesis Prize competition by the Gravitational-Wave International Committee (2007).

International Max Planck Scholarship for Doctoral Students by Max Planck Institute for Gravitational Physics, Germany (2004 – 2007).

RESEARCH INTERESTS

Gravitational-wave source modelling using analytical and numerical relativity / Probing strong gravity and astrophysics using gravitational-wave observations / Gravitational-wave data analysis / Detector characterisation and veto development for gravitational-wave searches.

PUBLICATIONS

44 articles in peer-reviewed journals (over 2500 citations) + Co-author of over 100 publications by the LIGO Scientific Collaboration (over 47,000 citations) including the one announcing the discovery of gravitational waves. See the List of Publications (Page 7) for details. For additional metrics, see my publication profile in Google Scholar.

INVITED TALKS IN CONFERENCES (SELECTED)

Probes of strong gravity using gravitational waves, TMEX 2020 Conference, Quy Nhon, Vietnam (5-11 Jan 2020).

Probing strong gravity using gravitational wave observations, Grav19 Conference, Córdoba, Argentina (8-12 Apr 2019).

Gravitational-wave astronomy: A new frontier, BHU Frontiers of Sciences Symposium, Banaras Hindu University, Varanasi, India (8-12 March 2019).

Gravitational-waves from binary black holes: The interplay of theory and observation, 30th meeting of the Indian Association for General Relativity and Gravitation, BITS Hyderabad (4 Jan 2019).

Tests of general relativity and fundamental physics with gravitational waves, Gravitational Wave Physics and Astronomy Workshop, University of Maryland, USA (1-4 Dec 2018).

Einstein's messengers, 36th Annual Meeting of the Astronomical Society of India, Hyderabad, India, (5-9 Feb 2018)

Physics and astronomy from gravitational-wave observations, ICTS@10 Conference, Bangalore (4-6 Jan 2018).

Gravitational waves: The new frontier of Astrophysics, 29th Texas Symposium on Relativistic Astrophysics, Cape Town, South Africa, (3-8 Dec 2017).

LIGO: The new frontier of astrophysics, National Symposium on NSM Grid over NKN, Bangalore (10 Oct 2017).

Gravitational waves: The new frontier of Astrophysics, XXIX IUPAP Conference on Computational Physics, Paris, France (9-13 July 2017).

The discovery of gravitational waves, 104th Indian Science Congress, Tirupati, India (6 Jan 2017).

Testing General Relativity Using Gravitational-Wave Observations, 27th Mid-Year Meeting of the Indian Academy of Sciences, Bangalore, India (1 July 2016).

GW150914: The interface between theory and observation, Annual Meeting of the Astronomical Society of India, Srinagar, India (11 May 2016).

Towards gravitational-wave astronomy, 8th International Conference on Gravitation and Cosmology, IISER Mohali, India (14 December 2015).

Towards gravitational-wave astronomy, XXVII IUPAP Conference on Computational Physics, IIT Guwahati, India (4 December 2015).

Testing General Relativity using golden black-hole binaries, Astro-GR 2015 workshop, ICTP SAIFR, Sao Paulo, Brazil (14 Aug 2015).

Gravitational-wave observations and multi-messenger astronomy, Astronomical Society of India meeting, Pune, India (18 Feb 2015).

The gravitational-wave window to the Universe, XXI DAE-BRNS High Energy Physics Symposium 2014, Guwahati, India (2014 Dec 8–12).

The interface of theory and observation in gravitational-wave astronomy, India-UK Frontiers of Science meeting (organized by the Royal Society, UK and the Department of Science and Technology, India), Pune, India (2014 Oct 8).

Modeling of compact binary coalescence for gravitational-wave astronomy: Status, challenges and prospects, Gravitational-Wave Physics and Astronomy Workshop 2013, IUCAA, Pune, India. (2013 Dec 17).

Gravitational-wave- physics and astronomy: Status and prospects, 27th Meeting of the Indian Association of General Relativity and Gravitation, Srinagar (Garhwal), India. (2013 March 7).

Interfacing analytical- and numerical relativity for gravitational-wave astronomy, April Meeting of the American Physical Society, Atlanta, USA (2012 March 31).

Advances in phenomenological inspiral-merger-ringdown waveforms for binary black holes: GR 19 (parallel session on Analytic Approximation and Perturbation Methods and their Applications), Mexico City, Mexico (2010 July 5).

Interfacing numerical and analytical relativity for gravitational-wave astronomy: Status and prospects, "Theory Meets Data Analysis at Comparable and Extreme Mass Ratios" (NRDA + Capra Meetings), Perimeter Institute for Theoretical Physics, Waterloo, Canada (2010 June 24).

Network analysis using null-stream: Annual Meeting of the ILIAS-Gravitational Wave Antenna, Universitat de les Illes Balears, Palma de Mallorca, Spain (2005 Oct 25).

INVITED PEDAGOGICAL LECTURES (SELECTED)

Physics and astrophysics of black holes and neutron stars, HDM2017 : International Workshop on Hot and Dense Nuclear and Astrophysical Matter, Stellenbosch University, South Africa (26 Nov - 2 Dec, 2017).

On the physics and astronomy of Gravitational Waves, Popli Memorial Lecture series, St Stephens College Delhi (2017 Jan 16–18).

A first course in gravitational wave data analysis and applications, Advanced school on gravitational wave astronomy, Presidency University, Kolkata (2016 Dec 12-16).

Application of Fourier transforms in signal processing: A first course, Workshop on the application of Fourier Transforms in astrophysics, Mahatma Gandhi University, Kottayam, India (14-15 Feb 2013).

Introduction to approximation methods in General Relativity, 24th Chris Engelbrecht Summer School 2013 on Gravitational Wave Astronomy, Rhodes University, Grahamstown, South Africa (2013 January 15-24).

Interface between numerical relativity and gravitational-wave astronomy, 2010 International School on Numerical Relativity and Gravitational Waves, Asia-Pacific Center for Theoretical Physics, Pohang, Korea (July 26 – 30, 2010).

PUBLIC LECTURES (SELECTED)

Doubly Einstein! Gravitational lensing of gravitational waves, Public lecture part of the Vigyan Samagam Exhibition, Visvesvaraya Industrial & Technological Museum, Bangalore (17 Aug 2019).

Centenary of an Eclipse: Relatively speaking, Public lecture part of the Bangalore Science Collective's Science Lecture Series, Christ, Bangalore (29 June 2019).

One hundred years of gravitational lensing, Public lecture at Jawaharlal Nehru Planetarium, Bangalore (29 May 2019).

Four hundred years of the Telescope: From Galileo to Gravitational waves, Publc lecture in Malayalam organized by Amateur Astronomers Organization Kerala, Thiruvananthapuram (20 Apr 2019).

Astronomy's New Frontiers, Public Lecture as part of TIFR Hyderabad's Sawaal-Jawaab series, Phoenix Arena, Hyderabad (10 Nov 2018).

Einstein's messengers, Public lecture organized by the Applied Photonics Initiative, Indian Institute of Science, Bangalore (9 March 2018).

Undreamt by Einstein: The discovery of gravitational waves, Founders Day Colloquium, TIFR, Mumbai (30 Oct 2016).

The discovery of gravitational waves, Public lecture in Malayalam organized by the Galileo Science Center, Perintalmanna, India (2016 March 26).

Undreamt by Einstein: The discovery of gravitational waves, Inaugural lecture of the Physics festival BHOUTICS 2016, IIT Madras (2016 March 4).

Undreamt by Einstein: The discovery of gravitational waves, Science Day Lecture, Indian Institute of Astrophysics, India (2016 Feb 28).

LIGO Observation of Gravitational Waves from a Binary Black Hole Merger, Public lecture as part of the ICTS LIGO discovery event *The Universe in a New Light*, ICTS, Bangalore (2016 Feb 13).

See the List of Presentations (Page 11) for a more comprehensive list colloquia, seminars, public lectures and contributed talks.

PROJECTS & GRANTS

PI (along with B. S. Sathyaprakash, Penn State) of the *IndoUS Centre for the Exploration of Extreme Gravity* funded by the Indo-US Science and Technology Forum (2016-2018).

Head of the *Max Planck Partner Group in Astrophysical Relativity and Gravitational-Wave Astronomy* at ICTS-TIFR (2015-2020).

PI of the SERB FastTrack project "Gravitational-wave astronomy using astrophysical black-hole binaries", funded by the Department of Science & Technology (2013–2016).

Co-PI of the International Teaching and Research Chair "Mathematics of Complex Systems" at ICTS-TIFR and TIFR-CAM, funded by the EADS foundation (2013–2017)

Co-PI of the computational astrophysics project "Modeling gravitational wave signals from black hole binaries" (PI: Sascha Husa, Palma) which was awarded 37 million CPU hours on European supercomputers as part of the *Partnership for Advanced Computing in Europe* (PRACE) program (2012).

Co-PI of the "Indo-US Virtual Center for Gravitational-Wave Physics and Astronomy" (PIs: Tarun Souradeep, IUCAA and Rana Adhikari, Caltech) funded by the Indo-US Science and Technology Forum (2011–2013).

Co-PI of the computational astrophysics project "Modeling gravitational wave signals from black hole binaries" (PI: Sascha Husa, Palma) which was awarded 11 million CPU hours on European supercomputers as part of the PRACE program (2011).

Co-PI of the computational astrophysics project "General Relativity meets Astrophysics: Nonlinear Dynamics of Black Holes" (PI: Peter Diener, LSU) which was awarded 8.2 million CPU hours on the Teragrid supercomputer network (2011).

Co-PI of the computational astrophysics project "Computational Relativistic Astrophysics Models of Stellar Collapse and Binary Black Hole Coalescence" (PI: Christian Ott, Caltech) which was awarded 7.5 million CPU hours on the Teragrid supercomputer network (2010).

PROFESSIONAL MEMBERSHIPS

Member of LIGO Scientific Collaboration (2004 –), American Physical Society (2009 –), International Astronomical Union (2015 –), GEO Collaboration (2004 – 2008), American Association for the Advancement of Science (2010 – 2012), Indian Association of General Relativity & Gravitation (2007 –), IndIGO consortium (founding member) and Astronomical Society of India (2015 –).

SYNERGETIC ACTIVITIES

Member of the Program Committee, LIGO Scientific Collaboration (2019 –).

Member of the Executive Committee, Astronomical Society of India (2019 –).

Member of the editorial board, *Journal of Astrophysics and Astronomy* (2016 –).

Member of the Advisory Committee, Jawaharlal Nehru Planetarium, Bangalore (2018 –).

Member of the Scientific Organizing Committe, Gravitational-Wave Physics & Astronomy Workshop 2018 (University of Maryland), and 2019 (University of Tokyo).

Referee of *Physical Review Letters*, *Physical Review D*, *Classical and Quantum Gravity*, *International Journal of Modern Physics D*, *Advances in Space Research*.

External reviewer of proposals submitted to the US National Science Foundation, Swiss National Science Foundation and UK Research and Innovation.

Member of the *GWIC Thesis Prize* and *Stefano Braccini Thesis Prize* 2016, 2017 selection committees.

Organizer of the ICTS programs *The Future of Gravitational-Wave Astronomy*, *ICTS Einstein Lectures*, *ICTS Summer School on Gravitational-Wave Astronomy*, *ICTS Program on Numerical Relativity*, *ICTS Planck Day*, *ICTS Winter School on Experimental Gravitational-Wave Physics*. Co-organizer of the *GW@ASI2014: Satellite workshop on Gravitational Wave Astronomy at the ASI Meeting*, *First IndIGO School on Gravitational-Wave Astronomy*, *CMI Silver Jubilee Workshop on Astronomy, Cosmology & Fundamental Physics with GWs*.

Active involvement of the activities of the IndIGO consortium, including in the initial *project proposal* of *LIGO-India*.

Leadership in the establishment of the LIGO Tier-3 computing center at ICTS, Bangalore.

Internal reviewer for the technical papers authored by the members of the LIGO Scientific Collaboration, and for some of the codes used for LIGO data analysis.

Contact Person of the Numerical-Relativity Injection Analysis collaboration `https://www.ninja-project.org` (Nov 2009 – June 2010).

Member of the Executive Committee, Caltech-JPL Association for Gravitational-Wave Research `http://cajagwr.caltech.edu` (2009 – 2013).

STUDENT & POSTDOC MENTORING

Mentored/mentoring 10 postdocs, 4 graduate students, and 30 undergraduate/masters students during my tenure as a faculty member at ICTS-TIFR and a postdoc at Caltech.

SERVICE

Convener of the ICTS graduate cell (2020 –), Convener of the ICTS computing infrastructure committee (2015–19), Chair of the ICTS website redesigning committee (2015–17), Chair of the ICTS Purchase Committee (2017–), Member of the ICTS graduate cell (2015–17), Member of the ICTS childcare committee (2017–18).

TEACHING

Introduction to gravitational-wave physics & astrophysics, ICTS PhD Course (Spring 2020) [with Bala Iyer].

Mathematical methods for physics, ICTS Int-PhD Course (Spring 2019).

Numerical methods for physics and astrophysics, ICTS Graduate Course (Spring 2014, Spring 2015, Spring 2018, Spring 2018).

Reading course on gravitational-wave astronomy, ICTS Graduate Course (Fall 2014).

Reading course on astrophysical black boles, ICTS Graduate Course (Fall 2017).

PERSONAL PROFILE

Date of Birth	:	27 May 1980
Sex	:	Male
Marital Status	:	Married, with one child
Nationality	:	Indian
Language Proficiency	:	English and Malayalam

LIST OF PUBLICATIONS

PAPERS IN PEER-REVIEWED JOURNALS

44. T. Islam, A. K. Mehta, Ab. Ghosh, V. Varma, P. Ajith, B. S. Sathyaprakash, *Testing the"no-hair" nature of binary black holes using the consistency of multipolar gravitational radiation*, Phys. Rev. D **101**, 024032 (2020).

43. R. Kashyap, G. Raman, P. Ajith, *Can kilonova light curves be standardized?*, Astrophys. J. Lett., **886** L19, 5 (2019).

42. R. X. Adhikari, P. Ajith, Y. Chen, J. A. Clark, V. Dergachev, N. V. Fotopoulos, S. E. Gossan, I. Mandel, M. Okounkova, V. Raymond, J. S. Read, *Astrophysical science metrics for next-generation gravitational-wave detectors,* Class. Quantum Grav. **36**, 245010 (2019).

41. A. K. Mehta, P. Tiwari, N. K. Johnson-McDaniel, C. K. Mishra, V. Varma, P. Ajith, *Including mode mixing in a higher-multipole model for gravitational waveforms from nonspinning black-hole binaries*, Phys. Rev. D **100**, 024032 (2019).

40. O.A. Hannuksela, K. Haris, K.K.Y. Ng, S. Kumar, A.K. Mehta, D. Keitel, T.G.F. Li, P. Ajith, *Search for gravitational lensing signatures in LIGO-Virgo binary black hole events*, Astrophys. J. Lett. **874** L2, 10 (2019).

39. K. Haris, A. K. Mehta, S. Kumar, T. Venumadhav, P. Ajith, *Identifying strongly lensed gravitational wave signals from binary black hole mergers*, Submitted to Phys. Rev. D (2018). arXiv:1807.07062 [gr-qc]

38. N. K. Johnson-McDaniel, A. Mukherjee, R. Kashyap, P. Ajith, W. Del Pozzo, S. Vitale, *Constraining black hole mimickers with gravitational wave observations*, Submitted to Phys. Rev. Lett. (2018). arXiv:1804.08026 [gr-qc]

37. S. Dhanpal, Ab. Ghosh, A. K. Mehta, P. Ajith, B. S. Sathyaprakash, *A no-hair test for binary black holes*, Phys. Rev. D **99**, 104056 (2019).

36. S. Roy, A. S. Sengupta, P. Ajith, *Effectual gravitational-wave template banks for coalescing compact binaries using a hybrid placement algorithm*, Phys. Rev. D **99**, 024048 (2019).

35. A. K. Mehta, C. K. Mishra, V. Varma, P. Ajith, *Accurate inspiral-merger-ringdown gravitational waveforms for non-spinning black-hole binaries including the effect of subdominant modes*. Phys. Rev. D **96**, 124010 (2017).

34. Ab. Ghosh, N. K. Johnson-McDaniel, Ar. Ghosh, C. K. Mishra, P. Ajith, W. Del Pozzo, A. B. Nielsen, C. P. L. Berry, L. London, *Testing general relativity using gravitational wave signals from the inspiral, merger and ringdown of binary black holes*, Class. Quantum Grav. **35** 014002 (2017).

33. V. Varma, P. Ajith, *Effects of non-quadrupole modes in the detection and parameter estimation of black hole binaries with nonprecessing spins*, Phys. Rev. D**96** 124024 (2017).

32. Ab. Ghosh, Ar. Ghosh, N. K. Johnson-McDaniel, C. K. Mishra, P. Ajith, W. Del Pozzo, D. A. Nichols, Y. Chen, A. B. Nielsen, C. P. L. Berry, L. London, *Testing general relativity using golden black-hole binaries*, Phys. Rev. D **94**, 021101 (R) (2016).

31. S. J. Kapadia, N. K. Johnson-McDaniel and P. Ajith, *Estimating effective higher order terms in the post-Newtonian binding energy and gravitational-wave flux: Non-spinning compact binary inspiral*, Phys. Rev. D **93**, 024006 (2016).

30. A. Ghosh, W. Del Pozzo and P. Ajith, *Estimating parameters of binary black holes from gravitational-wave observations of their inspiral, merger and ringdown*, Phys. Rev. D **94**, 104070 (2016).

29. V. Tiwari, S. Klimenko, N. Christensen, E.A. Huerta, S.R.P. Mohapatra, A. Gopakumar, M. Haney, P. Ajith, S.T. McWilliams, G. Vedovato, M. Drago, F. Salemi, G.A. Prodi, C. Lazzaro, S. Tiwari, G. Mitselmakher, and F. Da Silva, *Proposed search for the detection of gravitational waves from eccentric binary black holes*, Phys. Rev. D **93**, 043007 (2016).

28. C. Kalaghatgi, P. Ajith and K. G. Arun, *Template-space metric for searches for gravitational waves from the inspiral, merger and ringdown of binary black holes*, Phys. Rev. D **91**, 124042 (2015).

27. V. Varma, P. Ajith, S. Husa, J. C. Bustillo, M. Hannam and M. Pürrer, *Gravitational-wave observations of binary black holes: Effect of non-quadrupole modes*, Phys. Rev. D **90**, 124004 (2014).

26. P. Ajith, T. Isogai, N. Christensen, R. Adhikari, A. B. Pearlman, A. Wein, A. J. Weinstein, B. Yuan, *Instrumental vetoes for transient gravitational-wave triggers using noise-coupling models: The bilinear-coupling veto*, Phys. Rev. D **89**, 122001 (2014).

25. P. Ajith, N. Fotopoulos, S. Privitera, A. Neunzert, N. Mazumder, A. J. Weinstein, *An effectual template bank for the detection of gravitational waves from inspiralling compact binaries with generic spins*, Phys. Rev. D **89**, 084041 (2014).

24. S. Privitera, S.R.P. Mohapatra, P. Ajith, K. Cannon, N. Fotopoulos, M. A. Frei, C. Hanna, A. J. Weinstein, J. T. Whelan, *Improving the sensitivity of a search for coalescing binary black holes with non-precessing spins in gravitational wave data*, Phys. Rev. D **89**, 024003 (2014).

23. M. Pürrer, M. Hannam, P. Ajith, S. Husa, *Testing the validity of the single-spin approximation in inspiral-merger-ringdown waveforms*, Phys. Rev. D **88**, 064007 (2013).

22. P. Ajith *et al.* (NINJA Collaboration), *The NINJA-2 catalog of hybrid post-Newtonian/numerical-relativity waveforms for non-precessing black-hole binaries*, Class. Quantum Grav. **29** 124001 (2012).

21. P. Ajith, *Addressing the spin question in gravitational-wave searches: Waveform templates for inspiralling compact binaries with nonprecessing spins*, Phys. Rev. D **84** 084037 (2011).

20. P. Schmidt, M. Hannam, S. Husa and P. Ajith, *Tracking the precession of compact binaries from their gravitational-wave signal*, Phys. Rev. D **84** 024046 (2011).

19. P. Ajith, M. Hannam, S. Husa, Y. Chen, B. Brügmann, N. Dorband, D. Müller, F. Ohme, D. Pollney, C. Reisswig, L. Santamaría, and J. Seiler, *Inspiral-merger-ringdown gravitational-waveforms for black-hole binaries with non-precessing spins*, Phys. Rev. Lett. **106**, 241101 (2011).

18. M. Hannam, S. Husa, F. Ohme and P. Ajith, *Length requirements for numerical-relativity waveforms*, Phys. Rev. D **82** 124052 (2010).

17. L. Santamaria, F. Ohme, P. Ajith, B. Bruegmann, N. Dorband, M. Hannam, S. Husa, P. Moesta, D. Pollney, C. Reisswig, E. L. Robinson, J. Seiler, B. Krishnan, *Matching post-Newtonian and numerical relativity waveforms: systematic errors and a new phenomenological model for non-precessing black hole binaries*, Phys. Rev. D **82** 064016 (2010).

16. D. Keppel and P. Ajith, *Constraining the mass of the graviton using coalescing black-hole binaries*, Phys. Rev. D **82**, 122001 (2010).

15. S. Bose, S. Ghosh and P. Ajith, *Systematic errors in measuring parameters of non-spinning compact binary coalescences with post-Newtonian templates*, Class. Quantum Grav. **27** 114001 (2010).

14. C. Pankow, S. Klimenko, G. Mitselmakher, I. Yakushin, G. Vedovato, M. Drago, R. A. Mercer and P. Ajith, *A burst search for gravitational waves from binary black holes*, Class. Quantum Grav. **26** 204004 (2009).

13. P. Ajith and S. Bose, *Estimating the parameters of non-spinning binary black holes using ground-based gravitational-wave detectors: Statistical errors*, Phys. Rev. D **79** 084032 (2009).

12. P. Ajith, *Gravitational-wave data analysis using binary-black-hole waveforms*, Class. Quantum Grav. **27** 114033 (2008).

11. P. Ajith, S. Babak, Y. Chen, M. Hewitson, B. Krishnan, A. M. Sintes, J. T. Whelan, B. Bruegmann, P. Diener, N. Dorband, J. Gonzalez, M. Hannam, S. Husa, D. Pollney, L. Rezzolla, L. Santamaria, U. Sperhake, J. Thornburg, *Template bank for gravitational waveforms from coalescing binary black holes: non-spinning binaries*, Phys. Rev. D **77** 104017 (2008).

10. P. Ajith, M. Hewitson, J. R. Smith, H. Grote, S. Hild and K. A. Strain, *Physical instrumental vetoes for gravitational-wave burst triggers*, Phys. Rev. D **76** 042004 (2007).

9. P. Ajith, S. Babak, Y. Chen, M. Hewitson, B. Krishnan, J. T. Whelan, B. Bruegmann, P. Diener, J. Gonzalez, M. Hannam, S. Husa, M. Koppitz, D. Pollney, L. Rezzolla, L. Santamaria, A. M. Sintes, U. Sperhake, J. Thornburg, *Phenomenological template family for black-hole coalescence waveforms*, Class. Quantum Grav. **24** S689–S699 (2007).

8. S. Hild, P. Ajith, M. Hewitson, H. Grote and J. R. Smith, *A statistical veto method employing an amplitude consistency test*, Class. Quantum Grav. **24** 3783–3798 (2007).

7. P. Ajith, M. Hewitson, J. R. Smith and K. A. Strain, *Robust vetoes for gravitational-wave burst triggers using known instrumental couplings*, Class. Quantum Grav. **23** 5825-5837 (2006).

6. P. Ajith, M. Hewitson and I. S. Heng, *Null-stream veto for two co-located detectors: Implementation issues*, Class. Quantum Grav. **23** S741-S749 (2006).

5. J R Smith, P Ajith, H Grote, M Hewitson, S Hild, H Lück, K A Strain, B Willke, J Hough and K Danzmann, *Linear projection of technical noise for interferometric gravitational-wave detectors*, Class. Quantum Grav. **23** 527-537 (2006).

4. M. Hewitson and P. Ajith, *Using the null-stream of GEO 600 to veto transient events in the detector output*, Class. Quantum Grav. **22** 4903-4912 (2005).

3. M. Hewitson, H. Grote, S. Hild, H. Lück, P. Ajith, J. R. Smith, K. A. Strain, B. Wilke and G. Woan, *Optimal time-domain combination of the two calibrated output quadratures of GEO 600*, Class. Quantum Grav. **22** 4253-4261 (2005).

2. P. Ajith, B. R. Iyer, C. A. K. Robinson and B. S. Sathyaprakash, *Complete adiabatic waveform templates for a test-mass in the Schwarzschild spacetime: VIRGO and Advanced LIGO studies*, Class. Quantum Grav. **22** S1179-S1188 (2005).

1. P. Ajith, B. R. Iyer, C. A. K. Robinson and B. S. Sathyaprakash, *New class of post-Newtonian approximants to the waveform templates of inspiralling compact binaries: Test-mass in the Schwarzschild spacetime*, Phys. Rev. D **71** 044029 (2005).

SELECTED PUBLICATIONS FROM THE LIGO COLLABORATION WITH MY DIRECT CONTRIBUTION

1. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1,* Phys. Rev. D **100**, 104036 (2019).
2. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs,* Phys. Rev. X **9**, 031040
3. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *Observation of Gravitational Waves from a Binary Black Hole Merger*, Phys. Rev. Lett. **116**, 061102 (2016).
4. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *Tests of general relativity with GW150914*, Phys. Rev. Lett. **116**, 221101 (2016)
5. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *Properties of the binary black hole merger GW150914*, Phys. Rev. Lett. **116**, 241102 (2016).
6. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence*, Phys. Rev. Lett. **116**, 241103 (2016).
7. B. P. Abbott *et al.* [LIGO Scientific and VIRGO Collaborations], *GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2*, Phys. Rev. Lett. **118**, no. 22, 221101 (2017).
8. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence,* Phys. Rev. Lett. **119**, no. 14, 141101 (2017).
9. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral,* Phys. Rev. Lett. **119**, 161101 (2017).
10. B. P. Abbott *et al.* [LIGO Scientific Collaboration and Virgo Collaboration, Fermi Gamma-ray Burst Monitor, and INTEGRAL], *Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A*. Astrophys J Lett **848** L13 (27pp) (2017).
11. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *Binary Black Hole Mergers in the first Advanced LIGO Observing Run*, Phys. Rev. X **6**, 041015 (2016).
12. B. P. Abbott *et al.* [LIGO Scientific and Virgo Collaborations], *Effects of waveform model systematics on the interpretation of GW150914,* arXiv:1611.07531 [gr-qc].

13. J. Aasi *et al.* [LIGO Scientific and Virgo Collaborations], *Search for Gravitational Waves from Binary Black Hole Inspiral, Merger and Ringdown in LIGO-Virgo Data from 2009-2010*, Phys. Rev. D **87**, 022002 (2013)

14. J. Abadie *et al.* [LIGO Scientific and Virgo Collaborations], *Search for gravitational waves from binary black hole inspiral, merger and ringdown*, Phys. Rev. D **83**, 122005 (2011).

TECHNICAL DOCUMENTS & WHITE PAPERS

1. G. Gonzaléz, S. Fairhurst, P. Ajith, P. Brady, A. Buonanno, A. Corsi, P. Fritschel, B. Iyer, J. Key, S. Klimenko, B. Lantz, A. Lazzarini, D. McClelland, D. Reitze, K. Riles, S. Rowan, A. Sintes, J. Smith, *LIGO Scientific Collaboration Program 2019-2020*, LIGO Technical Document LIGO-M-1900084.

2. LIGO Scientific Collaboration, *Gravitational wave astronomy with LIGO and similar detectors in the next decade,* White Paper submitted to the 2020 Astronomy and Astrophysics Decadal Survey, arXiv:1904.03187 [gr-qc].

3. B.S. Sathyaprakash, A. Buonanno, L. Lehner, C. Van Den Broeck, P. Ajith , A. Ghosh, K. Chatziioannou, P. Pani, M. Puerrer , T. Sotiriou , S. Vitale, N. Yunes , K.G. Arun , E. Barausse, M. Baryakhtar , R. Brito, A. Maselli, T. Dietrich, W. East , I. Harry , T. Hinderer , G. Pratten , L. Shao , M. van de Meent , V. Varma, J. Vines , H. Yang , M. Zumalacarregui, *Extreme Gravity and Fundamental Physics,* White Paper submitted to the 2020 Astronomy and Astrophysics Decadal Survey by GWIC-3G Science Case Team, arXiv:1903.09221 [astro-ph.HE].

4. P. Ajith, M. Boyle, D. A. Brown, S. Fairhurst, M. Hannam, I. Hinder, S. Husa, B. Krishnan, R. A. Mercer, F. Ohme, C. D. Ott, J. S. Read, L. Santamaria, J. T. Whelan, *Data formats for numerical relativity waves*, arXiv:0709.0093 [gr-qc]

5. P. Ajith, S. Mohapatra, A. Pai, *A Gravitational-Wave Data Analysis Primer for the IndIGO Mock Data Challenge*, LIGO-T1100462-v1. link

THESES

1. P. Ajith, *On aspects of gravitational-wave detection: Detector characterisation, data analysis and source modelling for ground-based detectors*, Ph.D Thesis, Max Planck Institute for Gravitational Physics (Albert Einstein Institute) and Leibniz Universität Hannover (2007). link

POPULAR ARTICLES

1. P. Ajith and Bala R. Iyer, *Nobel for gravitational waves*, Current Science, Vol 113, No. 8 (25 Oct 2017).
2. P. Ajith, *Nobel for gravitational waves* (in Malayalam), Sasthrakeralam (Nov 2017).
3. P. Ajith, *Listening to black holes*, I Wonder, Issue 03, Feb 2017, pp 4.
4. P. Ajith, *Remembering C.V. Vishveshwara, the Quasimodo of Black Holes*, The Wire (20 Jan 2017).
5. P. Ajith and K. G. Arun, *The Indian role*, Frontline, March 18, 2016, pp 126.
6. P. Ajith, *Einsteins wavy messengers*, ICTS News Letter (Nov 2015).
7. P. Ajith, *Hundred years of General Relativity* (in Malayalam), Madhyamam Weekly (May 2015).
8. P. Ajith, *Imaginary planes* (in Malayalam), Mathrubhumi Online (Jan 2015).
9. P. Ajith, *The fear of the particle* (in Malayalam), Madhyamam Weekly (June 2014).
10. P. Ajith, *Science and Fundamentalism* (in Malayalam), Sasthragathi (March 2014).
11. P. Ajith, *Indian Neutrino Observatory: Science, Sociology and Politics* (in Mayalayam). Malayalam Weekly (Oct 2012).
12. P. Ajith and K. G. Arun, *Gravitational-Wave Astronomy: A new window to the Universe*, Resonance **16** 922-932 (October 2011).
13. P. Ajith, *Understanding the building blocks of the Universe* (in Malayalam), Grandhalokam Monthly (January 2009).

COLLOQUIA, PUBLIC LECTURES, SEMINARS, CONTRIBUTED TALKS

COLLOQUIA

1. *Gravitational-wave astronomy: A new frontier*, Physics Colloquium, Ashoka University, Sonipet (22 Jan 2020).
2. *Gravitational-wave astronomy: A new frontier*, Physics Colloquium, Jawaharlal Nehru University, New Delhi (21 Jan 2020).
3. *Einstein's Messengers*, Physics Colloquium, BITS Goa (20 Sep 2018).
4. *Einsteins messengers*, Colloquim, TIFR Hyderabad (9 Nov 2018).
5. *Gravitational waves: The new frontier of astrophysics*, Cochin University of Science & Technology (15 Oct 2018).
6. *The discovery of gravitational waves*, National Institute of Technology, Calicut (24 Feb 2017).
7. *Testing General Relativity using Gravitational-Wave Observations*, TIFR Theory Colloquium, Tata Institute of Fundamental Research, Mumbai, India (2016 Apr 18).
8. *LIGO Observation of Gravitational Waves from a Binary Black Hole Merger*, RRI Colloquium, Raman Research Institute, Bangalore, India (2016 Feb 25).
9. *The gravitational-wave window to the Universe*, IPR Colloquium, Institute for Plasma Research, Gandhinagar, India (2014 Nov 10).
10. *The gravitational-wave window to the Universe*, NCRA Colloquium, National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, Pune, India (2014 Feb 10).
11. *The gravitational-wave window to the Universe*, ICTS Colloquium, International Center for Theoretical Sciences, Bangalore, India (2012 June 11).
12. *Gravitational-wave astronomy: Opening a new window onto the Universe*: IRC Colloquium at Cochin University of Science and Technology, Cochin, India (2011 January 10).

PEDAGOGICAL LECTURES

1. *Gravitational waves: The new frontier of astronomy*, Feroke College, Kerala (21 Nov 2018).
2. *Gravitational-wave physics & astrophysics*, Assam University Silchar (11 Oct 2018).
3. *Gravitational-wave astronomy: Opportunities and challenges*, PES University, Bangalore (26 Sep 2018).
4. *Four hundred years of modern astronomy*, INSPIRE Camp, Mount Carmel College, Bangalore (25 Oct 2018).
5. *An introduction to gravitational-wave astronomy*, "An observational view of the Universe" –Indian Academy of Sciences-IIA Summer School, Bangalore (19 June 2018).
6. *Gravitational wave astronomy: A new window to the Universe*, INSPIRE Camp at Mount Carmel College Bangalore (21 Oct 2016).
7. *On the physics and astronomy of Gravitational Waves*, Orientation cum Selection camp for the International Astronomy Olympiad, Visvesvaraya Industrial & Technological Museum, Bangalore (27 Apr 2017).
8. *The discovery of gravitational waves*, IAU Winter School on Astronomy, Hyderabad (22 Feb 2017).
9. *Gravitational wave astronomy: A new window to the Universe*, INSPIRE Camp, Mount Carmel College, Bangalore (2016 Oct 21).

public/popular lectures

1. *LIGO-India: A gravitational-wave observatory in Indian soil*, Talk at the Science Communicators' meet, ASI meeting, Bangalore (17 Feb 2019).
2. *Einstein's Messengers*, Public lecture part of the Einstein Lectures series, IIT Mandi (14 June 2018).
3. *Science and Society*, Popular lecture in Malayalam, TRK Higher Secondary School, Vanikamkulam, Kerala (28 Apr 2018).
4. *Einstein's Messengers*, Lecture for school childrenon Yuris Night (remote talk), St. Xavier's Physics Council, Nepal (12 April 2018).
5. *Four centuries of the telescope*, Lecture for school children organized by the Bharat Gyan Vigyan Samiti, Bangalore (18 Nov 2017).
6. *Science and Fundamentalism*, Popular lecture in Malayalam, Govt Victoria College, Palakkad, Kerala (11 Nov 2017).
7. *Gravitational-wave astronomy: A new window onto the universe*, JNCASR, Bangalore (26 Oct 2017).
8. *Undreamt by Einstein: The discovery of gravitational waves*, Jain University, Bangalore (27 Sep 2017).
9. *The discovery of gravitational waves*, National Science Day Lecture, Mahatma Gandhi University, Kottayam (28 Feb 2017).
10. *Undreamt by Einstein: The discovery of gravitational waves*, Einstein Lecture, TKM College of Engineering, Kollam (28 Feb 2017).
11. *A new window to the Universe*, Public lecture in Malayalam as part of the Amature Astronomers Meet, Thirunavaya, Kerala (26 Feb 2017).
12. *Gravitational wave astronomy: A new window to the Universe*, ICTS-TIFR Bangalore (2016 June 29).
13. *A new window to the Universe*, TEDx talk at the TEDxBMSCE event, Bangalore (2016 April 23).
14. *The discovery of gravitational waves*, Public lecture in Malayalam organized by the Kerala Sasthra Sahithya Parishad, Vadakara, India (2016 April 16).
15. *Undreamt by Einstein: The discovery of gravitational waves*, MES Kalladi College Mannarkkad, Kerala, India (2016 March 23).
16. *LIGO Observation of Gravitational Waves from a Binary Black Hole Merger*, Presentation as part of the LIGO discovery event organized by the Indian team in LIGO, IUCAA, Pune (2016 Feb 11).
17. *The gravitational-wave window to the Universe*, Invited lecture as part of the Frontier Lecture Series in Physics, Mahatma Gandhi University, Kottayam , India (15 Feb 2013).
18. *Black holes, gravitational waves and other curved ideas of Dr. Einstein*: Christ College Irinjalakuda, Kerala, India (2008 Oct 21).
19. *Understanding the building blocks of our Universe*: Lecture for school children on the LHC experiment at three Higher Secondary Schools in Kerala, India (2008).
20. *A layman's introduction to gravitational waves*: MES Kalladi College Mannarkkad, India (2005 Jan).

workshop talks

1. *Gravitational lensing of gravitational waves*, Chennai Symposium on Gravitation and Cosmology, IIT Madras (23 Jan 2020).
2. *Gravitational-Wave Science and Statistics: Challenges and Opportunities*, International Indian Statistical Association Meeting, IIT Bombay (28 Dec 2019).
3. *Gravitational lensing of gravitational waves: A new frontier*, Transient astronomy: Current trends and upcoming frontiers ISRO Bengaluru (12 Nov 2019).
4. *Challenges in gravitational-wave template modelling*, PAX Meeting, IUCAA, Pune (Aug 2018).

5. *Physics & astronomy from gravitational-wave observations of binary black holes*, "Black Holes: From Classical to Quantum Gravity" Workshop, IIT Gandhinagar (18 Dec 2017).

6. *Observation of gravitational waves from a binary neutron star inspiral*, *Cosmic Fireworks* ICTS Event on LIGO discovery of a binary neutron star merger, ICTS, Bangalore (19 Oct 2017).

7. *LIGO Observations of Binary Black Holes*, Workshop on gravitational waves, Aryabhatta Research Institute of Observational Sciences, Nainital (27 Oct 2016).

8. *LIGO Observations of Binary Black Holes*, ICTS Event on LIGO's second gravitational wave discovery, ICTS, Bangalore (17 June 2016).

9. *LIGO Observation of Gravitational Waves from a Binary Black Hole Merger*, Workshop: 750 GeV Excess @LHC Under Scrutiny, ICTS, Bangalore (5 May 2016).

10. *Gravitational-wave astronomy and cosmology*, Invited talk at the Workshop on Statistical Applications to Cosmology and Astrophysics, ISI Kolkata (13 Feb 2015).

11. *Fundamental physics, astronomy and cosmology from gravitational-wave observations*, Saha Theory Workshop: Cosmology at the Interface, Saha Institute, Kolkata, India (29 Jan 2015).

12. *Gravitational-wave observations and multi-messenger astronomy*, Invited talk at the India-China Workshop on Astronomy and Astrophysics, Indian Institute of Astrophysics, Bangalore (2014 Dec 3–5).

13. *Gravitational-wave astronomy: Opening a new window to the Universe*: Invited talk at the Workshop on Advances in Observational Astronomy, Mahatma Gandhi University, Kottayam, India (2008 Dec 1).

SEMINARS

1. *Was Einstein Right? Testing general relativity using gravitational wave observations*, Physics Seminar, BITS Goa (21 Sep 2018).

2. *Inferring the properties of astrophysical black holes from gravitational wave observations*, Cosmology & Astroparticle seminar, Tata Institute of Fundamental Research, Mumbai, India (19 April 2016).

3. *Observing gravitational waves from coalescing compact binaries*, Indian Institute of Science, Bangalore, India (3 March 2016).

4. *The gravitational-wave window to the Universe*, University of Hyderabad, India (27 Oct 2014).

5. *Detection template bank for gravitational waves from inspiralling compact binaries with spins*, LIGO Seminar at California Institute of Technology, Pasadena, USA (2012 Dec 7).

6. *Interfacing analytical- and numerical relativity for gravitational-wave astronomy*, International Center for Theoretical Sciences, Bangalore, India (2012 June 12).

7. *Interfacing analytical- and numerical relativity for gravitational-wave astronomy*, Raman Research Institute, Bangalore, India (2012 June 8).

8. *Interfacing analytical- and numerical relativity for gravitational-wave astronomy*, Indian Institute of Science, Bangalore, India (2012 Jan 10).

9. *Addressing the spin question in the search for gravitational waves from coalescing compact binaries*: LIGO Seminar at California Institute of Technology, Pasadena, USA (2011 Sep 20).

10. *Vetoes for transient gravitational-wave triggers using instrumental coupling models*: LIGO Seminar at California Institute of Technology, Pasadena, USA (2011 April 5).

11. *Interfacing analytical- and numerical relativity for gravitational-wave astronomy*: University of Delhi, India (2011 Feb 6).

12. *Coalescing compact binaries: From birth to death*: Indian Institute for Science Education and Research, Thiruvananthapuram, India (2011 January 6).

13. *Interfacing analytical- and numerical relativity for gravitational-wave astronomy*: Inter-University Center for Astronomy and Astrophysics, Pune, India (2010 Dec 9).

14. *Searching for gravitational waves from coalescing black hole binaries*: Universitat de les Illes Balears, Palma de Mallorca, Spain (2010 May 5).
15. *Identifying and subtracting noise transients in gravitational-wave detectors*: Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Hannover, Germany (2010 April 8).
16. *Gravitational-wave astronomy: Opening a new window onto the Universe*: Indian Institute for Science Education and Research, Thiruvananthapuram, India (2009 December 10).
17. *Searching for gravitational waves from coalescing binary black holes*: Inter-University Center for Astronomy and Astrophysics, Pune, India (2008 Nov 21).
18. *Searching for gravitational waves from coalescing binary black holes*: Institute of Mathematical Sciences, Chennai, India (2008 July 28).
19. *Gravitational-wave data analysis using binary black-hole waveforms*: Institut d'Astrophysique de Paris, France (2008 June 5).
20. *A template bank for gravitational waves from coalescing binary black holes*: Raman Research Institute, Bangalore, India (2008 Jan 23).
21. *A template bank for gravitational waves from coalescing binary black holes*: LIGO Seminar at California Institute of Technology, Pasadena, USA (2007 November 27).
22. *A template family for gravitational waves from coalescing binary black holes*: Albert Einstein Institute, Hannover, Germany (2007 May 9).
23. *Phenomenological template bank for black-hole coalescence waveforms*: Friedrich Schiller Universitaet, Jena, Germany (2007 Apr 16).
24. *Null-stream veto for the network analysis of gravitational-wave bursts*: Raman Research Institute, Bangalore, India (2006 Jan 2).
25. *New class of post-Newtonian approximants to the waveform templates of inspiralling compact binaries*: Raman Research Institute, Bangalore, India (2005 Jan 19).
26. *Looking for gravitational-wave bursts using a network of detectors*: Albert Einstein Institute, Hannover, Germany (2005 Oct 19).

CONTRIBUTED TALKS IN CONFERENCES

1. *Search for lensing signatures in LIGO-Virgo binary black hole events*, CIFAR Gravity & Extreme Universe Program Meeting, Kelowna, Canada (31 May 2019).
2. *Consistency test of general relativity using different multipoles of gravitational radiation from binary black holes*, CIFAR Gravity & Extreme Universe Program Meeting, Banff, Canada (2 Feb 2018).
3. *Getting a kick out of the short GRBs*, ASI meeting, IISER Mohali, India (2014 Mar 19).
4. *Addressing the spin question: Search templates for gravitational waves from spinning compact-binary coalescences*: International Conference on Gravitation and Cosmology, Goa, India (2011 Dec 15).
5. *Addressing the spin question in gravitational-wave searches: Waveform templates for inspiralling compact binaries with nonprecessing spins*: Amaldi+NRDA Meeting, Cardiff, UK (2011 July 11).
6. *"Complete" gravitational waveforms from black-hole binaries with non-precessing spins*: 12th Marcel Grossmann meeting, Paris, France (2009 July 16).
7. *Estimating parameters of non-spinning black-hole binaries using ground-based GW detectors: Statistical errors*: 12th Marcel Grossmann meeting, Paris, France (2009 July 17).
8. *"Complete" gravitational waveforms from black-hole binaries with non-precessing spins*: Numerical Relativity - Data Analysis (NRDA) meeting, Albert Einstein Institute, Potsdam, Germany (2009 July 8).
9. *Template bank for gravitational waves from coalescing binary black holes*: International Conference on Gravitation and Cosmology, IUCAA, Pune, India (2007 Dec 19).

10. *Gravitational-wave burst vetoes using known instrumental couplings*: Gravitational-wave Data Analysis Workshop 11, Albert Einstein Institute, Potsdam, Germany (2006 Dec 18).

11. *Phenomenological template family for black-hole coalescence waveforms*: 11th Marcel Grossmann Meeting, Frei Universitaet Berlin, Germany (2006 July 27).

12. *Implementing the Null-stream veto in the network analysis of gravitational-wave bursts*: Gravitational-wave Data Analysis Workshop 10, University of Texas at Brownsville, USA (2005 Dec 18).

Inspiral-Merger-Ringdown Waveforms for Black-Hole Binaries with Nonprecessing Spins

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We present the first analytical inspiral-merger-ringdown gravitational waveforms from binary black holes (BBHs) with nonprecessing spins, that is based on a description of the late-inspiral, merger and ringdown in full general relativity. By matching a post-Newtonian description of the inspiral to a set of numerical-relativity simulations, we obtain a waveform family with a conveniently small number of physical parameters. These waveforms will allow us to detect a larger parameter space of BBH coalescence, including a considerable fraction of precessing binaries in the comparable-mass regime, thus significantly improving the expected detection rates.

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Coalescing black-hole (BH) binaries are among the most promising candidate sources for the first detection of gravitational waves (GWs). Such observations will lead to precision tests of general relativity as well as provide a wealth of information relevant to fundamental physics, astrophysics, and cosmology. Computation of the expected waveforms from these sources is a key goal in current research in gravitation.

While the inspiral and ring-down stages of the BH coalescence are well-modeled by perturbative techniques, an accurate description of the merger requires numerical solutions of Einstein's equations. Although performing numerical simulations densely sampling the entire parameter space of BH coalescence is computationally prohibitive, waveform templates modeling all the three stages can now be constructed by combining analytical- and numerical- relativity results, dramatically improving the sensitivity of searches for GWs from BH binaries, and the accuracy of estimating the source parameters [1–4]. To date, inspiral-merger-ring-down (IMR) templates have been computed only for nonspinning BH binaries [1,3–6]. However, most BHs in nature are expected to be spinning [7], which necessitates the inclusion of spinning-binary waveforms in GW searches. But, spin adds six parameters (three components for each BH), and each additional parameter in a search template bank leads to a higher signal-to-noise-ratio (SNR) threshold for a confident detection [8]. Also, this requires accurate numerical simulations across this large parameter space, which are not yet available. Moreover, implementing a search covering the full spin parameter space has proven to be difficult.

In this Letter, we present an IMR waveform family modeling the dominant harmonic of binaries with nonprecessing spins, i.e., spins (anti-)aligned with the orbital angular momentum. Aligned-spin binaries are an astrophysically interesting population as such systems are expected from isolated binary evolution and in gas-rich mergers [9,10]. Nonprecessing binaries also exhibit interesting strong-gravity effects like the "orbital hang-up" [11] and "spin flips" [12]. We make use of the degeneracies in the system to parametrize our waveform family by only the total mass $M \equiv m_1 + m_2$ of the binary, the symmetric mass ratio $\eta \equiv m_1 m_2/M^2$, and a single spin parameter $\chi \equiv (1+\delta)\chi_1/2 + (1-\delta)\chi_2/2$, where $\delta \equiv (m_1 - m_2)/M$ and $\chi_i \equiv S_i/m_i^2$, S_i being the spin angular momentum of the ith BH. The last feature is motivated by the observation that the leading spin-orbit-coupling term in post-Newtonian (PN) waveforms is dominated by this parameter. We also show that this waveform family is able to capture a significant fraction of precessing binaries in the comparable-mass regime, providing an efficient and feasible way of searching for these systems [14].

Numerical simulations.—Binary BH (BBH) waveforms covering at least eight wave cycles before merger were produced by solving Einstein equations numerically, as written in the "moving-puncture" $3+1$ formulation [15,16]. The numerical solutions were calculated with the BAM [17,18], CCATIE [19] and LLAMA [20] codes. Initial momenta were chosen to give low-eccentricity inspiral, using either an extension of the method described in [21], or the quasicircular formula used in [22]. GWs were extracted at $R_{ex} = 90M$ with BAM, $R_{ex} = 160M$ with CCATIE and at future null infinity with LLAMA, using procedures discussed in [17,19,23]. In all simulations the GW amplitude is accurate to at least 10% and the phase to at least 1 rad. Most of the waveforms employed in the construction of the analytical templates are significantly longer (12–22 cycles) and more accurate [24].

We used seven sets of simulations: (i) Equal-mass binaries with equal, nonprecessing spins $\chi_i = \pm\{0.25, 0.5, 0.75, 0.85\}$, described in [24,25]. (ii) Nonprecessing, equal-spin binaries with $q \equiv m_1/m_2 = \{2, 2.5, 3\}$ and $\chi_i = \{\pm 0.5, 0.75\}$. (iii) Nonspinning binaries with $q = \{1, 1.5, 2, 2.5, 3, 3.5, 4\}$. (iv) Unequal-spin binaries with $q = \{2, 3\}$ and $(\chi_1, \chi_2) = (-0.75, 0.75)$. (v) Equal-mass, unequal-spin binaries with $\chi_i = \pm\{0.2, 0.3, 0.4, 0.6\}$. (vi) Equal-mass, precessing binaries with spin vectors (0.42, 0, 0.42), (0, 0, 0) and (0.15, 0, 0), (0, 0, 0). (vii) Precessing $q = 3$ binary with spins (0.75, 0, 0), (0, 0, 0) [26]. Simulation sets (i)–(iv) and (vii) were performed with BAM, set (v) with CCATIE, and set (vi) with LLAMA. The analytical waveform family is constructed employing only the equal-spin simulation sets (i)–(iii); sets (iv)–(vii) were used to test the efficacy of our model against more general spin/mass configurations. Two additional waveforms were used in these tests: the Caltech-Cornell equal-mass, nonspinning simulation [27], and the RIT $q = 1.25$ precessing binary simulation with $|\chi_1| = 0.6$, $|\chi_2| = 0.4$ [28].

Constructing hybrid waveforms.—We produce a set of "hybrid waveforms" [5] by matching PN and numerical-relativity (NR) waveforms in an overlapping time interval $[t_1, t_2]$. These hybrids are assumed to be the target signals that we want to detect. For the PN waveforms we choose the "TaylorT1" waveforms at 3.5PN [29] phase accuracy, with spin terms up to 2.5PN [13,30]. This is motivated by PN-NR comparisons of equal-mass spinning binaries, in which the accuracy of the TaylorT1 approximant was found to be the most robust [24,25]. We include the 3PN amplitude corrections to the dominant quadrupole mode [31] and the 2PN spin-dependent corrections [13], which greatly improved the agreement between PN and NR waveforms. For precessing waveforms, spin and angular momenta are evolved according to [30,32].

We match the PN and NR waveforms by a least-square fit over time- and phase shifts between the waveforms, and a scale factor a that reduces the PN-NR amplitude difference [5]. The NR waveforms are combined with the PN waveforms in the following way: $\mathsf{h}^{\rm hyb}(t) \equiv a\tau(t)\mathsf{h}^{\rm NR}(t) + (1-\tau(t))\mathsf{h}^{\rm PN}(t)$, where $\mathsf{h}(t) = h_+(t) - ih_\times(t)$ and τ ranges linearly from zero to one for $t \in [t_1, t_2]$.

Waveform templates for nonprecessing binaries.—The analytical waveforms that we construct are written in the Fourier domain as $h(f) \equiv A(f)e^{-i\Psi(f)}$, where

$$A(f) \equiv \mathcal{C} f_1^{-7/6} \begin{cases} f'^{-7/6}(1 + \sum_{i=2}^{3} \alpha_i v^i) & \text{if } f < f_1 \\ w_m f'^{-2/3}(1 + \sum_{i=1}^{2} \epsilon_i v^i) & \text{if } f_1 \le f < f_2 \\ w_r \mathcal{L}(f, f_2, \sigma) & \text{if } f_2 \le f < f_3, \end{cases}$$

$$\Psi(f) \equiv 2\pi f t_0 + \varphi_0 + \frac{3}{128\eta v^5}\left(1 + \sum_{k=2}^{7} v^k \psi_k\right). \tag{1}$$

Above, $f' \equiv f/f_1$, $v \equiv (\pi M f)^{1/3}$, $\epsilon_1 = 1.4547\chi - 1.8897$, $\epsilon_2 = -1.8153\chi + 1.6557$ (estimated from hybrid waveforms), $\mathcal{C}$ is a numerical constant whose value depends on the sky-location, orientation and the masses, $\alpha_2 = -323/224 + 451\eta/168$ and $\alpha_3 = (27/8 - 11\eta/6)\chi$ are the PN corrections to the Fourier domain amplitude of the ($\ell = 2$, $m = \pm 2$ mode) PN waveform [13], t_0 is the time of arrival of the signal at the detector and φ_0 the corresponding phase, $\mathcal{L}(f, f_2, \sigma)$ a Lorentzian function with width σ centered around the frequency f_2, w_m and w_r are normalization constants chosen so as to make $A(f)$ continuous across the "transition" frequencies f_2 and f_1, and f_3 is a convenient cutoff frequency such that the signal power above f_3 is negligible. The phenomenological parameters ψ_k and $\mu_k \equiv \{f_1, f_2, \sigma, f_3\}$ are written in terms of the physical parameters of the binary as

$$\psi_k = \psi_k^0 + \sum_{i=1}^{3}\sum_{j=0}^{N} x_k^{(ij)} \eta^i \chi^j,$$
$$\pi M \mu_k = \mu_k^0 + \sum_{i=1}^{3}\sum_{j=0}^{N} y_k^{(ij)} \eta^i \chi^j, \tag{2}$$

where $N \equiv \min(3 - i, 2)$ while $x_k^{(ij)}$ and $y_k^{(ij)}$ are tabulated in Table I.

We match these waveforms to 2PN accurate adiabatic inspiral waveforms in the test-mass ($\eta \to 0$) limit, where the phenomenological parameters reduce to

$$f_1 \to f^0_{\rm LSO}, \quad f_2 \to f^0_{\rm QNM}, \quad \sigma \to f^0_{\rm QNM}/Q^0, \quad \psi_k \to \psi_k^0. \tag{3}$$

Above, $f^0_{\rm LSO}$ and $f^0_{\rm QNM}$ are the frequencies of the last stable orbit [33] and the dominant quasinormal mode, and Q^0 is the ring-down quality factor [34] of a Kerr BH with mass M and spin χ, while ψ_k^0 are the (2PN) Fourier domain phasing coefficients of a test-particle inspiralling into the Kerr BH [13].

The test-mass-limit waveforms suffer from two limitations: (i) we assume that the evolution of the GW phase at the merger and ringdown is a continuation of the adiabatic inspiral phase, and (ii) in the absence of a reliable plunge model, we approximate the amplitude of the plunge with $f'^{-2/3}(1 + \sum_{i=1}^{2} \epsilon_i v^i)$. Nevertheless, in the test-mass limit, the signal is expected to be dominated by the inspiral, which is guaranteed to be well modeled by our waveforms. More importantly, the imposition of the appropriate test-mass limit in our fitting procedure ensures that the waveforms are well behaved even outside the parameter range where current NR data are available. Because of this, and the inclusion of the PN amplitude corrections, these waveforms are expected to be closer to the actual signals than the templates proposed in [1,6] in the nonspinning limit. However, since the parameter space covered by the NR simulations is limited, we recommend that these waveforms be used only in the regime $q \lesssim 10$ and $-0.85 \lesssim \chi \lesssim 0.85$. Also, these are meant to model only the

TABLE I. Phenomenological parameters describing the analytical waveforms. In test-mass limit, they reduce to the appropriate quantities given by perturbative calculations [13,33,34]. The test-mass limit of f_1 is a fit to the frequency of the last stable orbit [33].

	Test-mass limit (ψ_k^0)	$x^{(10)}$	$x^{(11)}$	$x^{(12)}$	$x^{(20)}$	$x^{(21)}$	$x^{(30)}$
ψ_2	$3715/756$	-920.9	492.1	135	6742	-1053	-1.34×10^4
ψ_3	$-16\pi + 113\chi/3$	1.702×10^4	-9566	-2182	-1.214×10^5	2.075×10^4	2.386×10^5
ψ_4	$15293365/508032 - 405\chi^2/8$	-1.254×10^5	7.507×10^4	1.338×10^4	8.735×10^5	-1.657×10^5	-1.694×10^6
ψ_6	0	-8.898×10^5	6.31×10^5	5.068×10^4	5.981×10^6	-1.415×10^6	-1.128×10^7
ψ_7	0	8.696×10^5	-6.71×10^5	-3.008×10^4	-5.838×10^6	1.514×10^6	1.089×10^7

	Test-mass limit (μ_k^0)	$y^{(10)}$	$y^{(11)}$	$y^{(12)}$	$y^{(20)}$	$y^{(21)}$	$y^{(30)}$
f_1	$1 - 4.455(1-\chi)^{0.217} + 3.521(1-\chi)^{0.26}$	0.6437	0.827	-0.2706	-0.05822	-3.935	-7.092
f_2	$[1 - 0.63(1-\chi)^{0.3}]/2$	0.1469	-0.1228	-0.02609	-0.0249	0.1701	2.325
σ	$[1 - 0.63(1-\chi)^{0.3}](1-\chi)^{0.45}/4$	-0.4098	-0.03523	0.1008	1.829	-0.02017	-2.87
f_3	$0.3236 + 0.04894\chi + 0.01346\chi^2$	-0.1331	-0.08172	0.1451	-0.2714	0.1279	4.922

late-inspiral, merger, and ringdown ($Mf_{\rm GW} > 10^{-3}$), i.e., binaries in the mass-range where merger ringdown also contribute to the SNR, apart from inspiral.

We have examined the "faithfulness" [35] of the new templates in reproducing the hybrid waveforms by computing the match (noise-weighted inner product) with the hybrids. Loss of the SNR due to the "mismatch" between the template and the true signal is determined by the match maximized over the whole template bank—called fitting factor (FF). The standard criteria for templates used in searches is that FF >0.965, which corresponds to a loss of no more than 10% of signals.

Match and FF of the analytical waveforms with the equal- (unequal-) spin hybrid waveforms are plotted in Fig. 1 (Fig. 2), using the Initial LIGO design noise spectrum [36]. Note that the analytical waveform family is constructed employing only the equal-spin hybrids (Fig. 1). The PN-NR matching region used to construct the unequal-spin hybrids (Fig. 2) are also different from that used for equal-spin hybrids. These figures demonstrate the efficacy of the analytical templates in reproducing the target waveforms—templates are "faithful" (match >0.965) either when the masses or the spins are equal, while they are always "effectual" [35] in detection (FF >0.965). In contrast, the bottom left plot of Fig. 1 shows the FF of the nonspinning IMR template family proposed in [1,6] with the equal-spin hybrid waveforms. FFs as low as 0.8 suggest that up to 50% of binaries may go undetected if nonspinning IMR templates are employed to search for binaries with high (aligned) spins.

The bottom left plot of Fig. 2 shows the FF and match of the template family with four precessing hybrids. The high FFs are indicative of the effectualness of the templates in detecting precessing binaries. Since presently not enough NR simulations are available to make a quantitative statement, and since we expect the effect of precession will be predominant in the case of lower mass binaries (when large number of cycles are present in the detector band), we

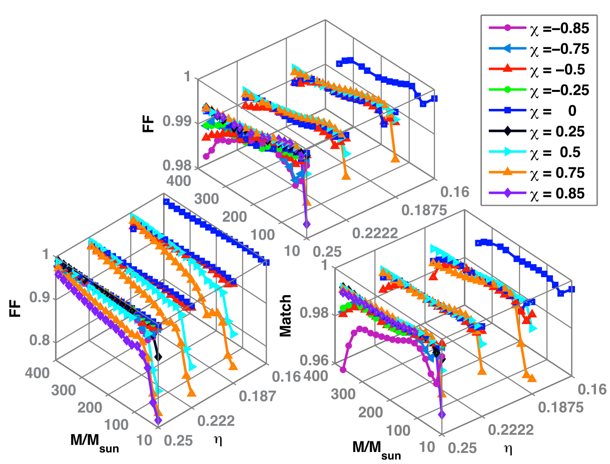

FIG. 1 (color online). Top and right plots: Match and FF of our IMR templates with equal-spin hybrid waveforms constructed from simulation sets (i)–(iii). Bottom left: FF of nonspinning IMR templates proposed in [1,6] with the same hybrids.

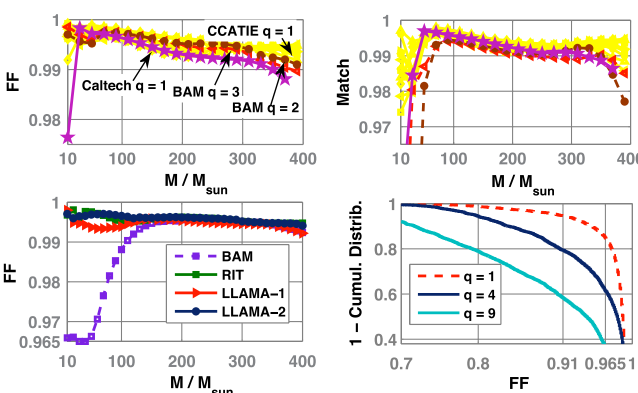

FIG. 2 (color online). Top panel: Match and FF of our templates with unequal-spin hybrid waveforms constructed from simulation sets (iv) and (v), and the Caltech-Cornell nonspinning simulation. Bottom left: FF with precessing hybrids constructed from sets (vi) and (vii), and the RIT simulation. Bottom right: Fraction of precessing PN waveforms ($M = 10M_\odot$) producing fitting factor FF with the IMR templates—85% (62%) 37% of the binaries with $q = 1(4)9$ produce FF >0.965.

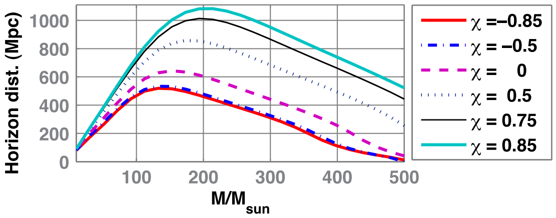

FIG. 3 (color online). Distance to optimally oriented equal-mass binaries with spin χ producing SNR 8 in Initial LIGO.

might be able to acquire some useful indication by studying precessing PN waveforms. We performed a Monte Carlo simulation where we generate precessing "restricted" PN waveforms with $M = 10M_\odot$, $q = \{1, 4, 9\}$, uniformly distributed spin magnitudes in the interval [0, 0.98] and isotropically distributed spin angles, and compute the FF with IMR templates. The relative inclination of the binary with the detector is also randomly chosen from $[0, \pi]$. The bottom right plot of Fig. 2 shows the cumulative distribution of the FF, strongly indicating the effectualness of the templates in detecting precessing binaries in the comparable-mass regime. These results indicate that a search employing nonprecessing templates described by a single spin parameter might be an attractive and feasible way of searching for generic spinning binaries.

Distance to optimally oriented BBHs producing SNR of 8 in Initial LIGO is shown in Fig. 2, which demonstrates the dramatic effect of spin for detection of high-mass binaries; if most BBHs are highly spinning, then LIGO will be able to detect coalescences up to 1 Gpc, thus increasing the event rates as much as 5 times compared to predictions based on nonspinning models. For Advanced LIGO, the distance reach is as high as 20 Gpc.

Conclusions.—We combine state-of-the-art results from analytical and numerical relativity to construct a family of analytical IMR waveforms for BBHs with nonprecessing spins. These waveforms are also able to detect a significant fraction of the precessing binaries in the comparable-mass regime, with spins represented by a single parameter. This will considerably simplify the use of our waveforms in GW searches in the near future, and will accelerate the incorporation of NR results into the current effort for the first detection of GWs. There are many other immediate applications of our waveforms: injections into detector data will help to put more realistic upper limits on the rate of BBH coalescences, and to compare the different algorithms employed in the search for BBHs, while employing these in population-synthesis studies will provide more accurate coalescence rates observable by the current and future detectors. Our method can readily be generalized to incorporate nonquadrupole harmonics, larger portions of the BBH parameter space and further information from analytical and numerical relativity.

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[1] P. Ajith *et al.*, Phys. Rev. D **77**, 104017 (2008).
[2] P. Ajith and S. Bose, Phys. Rev. D **79**, 084032 (2009).
[3] A. Buonanno *et al.*, Phys. Rev. D **76**, 104049 (2007).
[4] T. Damour and A. Nagar, Phys. Rev. D **79**, 081503 (2009).
[5] P. Ajith *et al.*, Classical Quantum Gravity **24**, S689 (2007).
[6] P. Ajith, Classical Quantum Gravity **25**, 114033 (2008).
[7] M. Volonteri *et al.*, Astrophys. J. **620**, 69 (2005).
[8] C. Van Den Broeck *et al.*, Phys. Rev. D **80**, 024009 (2009).
[9] V. Kalogera, Pramana **63**, 673 (2004).
[10] T. Bogdanović, C. S. Reynolds, and M. C. Miller, Astrophys. J. **661**, L147 (2007).
[11] M. Campanelli, C. O. Lousto, and Y. Zlochower, Phys. Rev. D **74**, 041501(R) (2006).
[12] A. Buonanno, L. E. Kidder, and L. Lehner, Phys. Rev. D **77**, 026004 (2008).
[13] K. G. Arun *et al.*, Phys. Rev. D **79**, 104023 (2009).
[14] The reason is that the (spin-dependent) phase evolution is primarily governed by the spin-orbit coupling, determined by the spin components along the angular momentum.
[15] M. Campanelli *et al.*, Phys. Rev. Lett. **96**, 111101 (2006).
[16] J. G. Baker *et al.*, Phys. Rev. Lett. **96**, 111102 (2006).
[17] B. Brügmann *et al.*, Phys. Rev. D **77**, 024027 (2008).
[18] S. Husa *et al.*, Classical Quantum Gravity **25**, 105006 (2008).
[19] D. Pollney *et al.*, Phys. Rev. D **76**, 124002 (2007).
[20] D. Pollney *et al.*, Phys. Rev. D **83**, 044045 (2011).
[21] S. Husa *et al.*, Phys. Rev. D **77**, 044037 (2008).
[22] B. Brügmann *et al.*, Phys. Rev. D **77**, 124047 (2008).
[23] C. Reisswig *et al.*, Phys. Rev. Lett. **103**, 221101 (2009).
[24] M. Hannam *et al.*, Phys. Rev. D **82**, 124008 (2010).
[25] M. Hannam *et al.*, Phys. Rev. D **78**, 104007 (2008).
[26] P. Schmidt *et al.*, arXiv:1012.2879.
[27] M. A. Scheel *et al.*, Phys. Rev. D **79**, 024003 (2009).
[28] M. Campanelli *et al.*, Phys. Rev. D **79**, 084010 (2009).
[29] L. Blanchet *et al.*, Phys. Rev. Lett. **93**, 091101 (2004).
[30] L. Blanchet, A. Buonanno, and G. Faye, Phys. Rev. D **74**, 104034 (2006).
[31] L. Blanchet *et al.*, Classical Quantum Gravity **25**, 165003 (2008).
[32] A. Buonanno, Y. Chen, and M. Vallisneri, Phys. Rev. D **67**, 104025 (2003).
[33] J. M. Bardeen *et al.*, Astrophys. J. **178**, 347 (1972).
[34] F. Echeverria, Phys. Rev. D **40**, 3194 (1989).
[35] T. Damour, B. R. Iyer, and B. S. Sathyaprakash, Phys. Rev. D **57**, 885 (1998).
[36] www.ligo.caltech.edu/~jzweizig/distribution/LSC_Data.