GW240925 and GW250207: Astrophysical Calibration of Gravitational-wave Detectors

A. G. Abac,[1] I. Abouelfettouh,[2] F. Acernese,[3,4] K. Ackley,[5] A. Adam,[6] C. Adamcewicz,[7] S. Adhicary,[8] D. Adhikari,[9,10] N. Adhikari,[11] R. X. Adhikari,[12] V. K. Adkins,[13] S. Afroz,[14] A. Agapito,[15] D. Agarwal,[16] M. Agathos,[17] N. Aggarwal,[18] S. Aggarwal,[19] O. D. Aguiar,[20] I.-L. Ahrend,[21] L. Aiello,[22,23] A. Ain,[24] P. Ajith,[25] T. Akutsu,[26,27] S. Albanesi,[28,29] L. Albers,[30] W. Ali,[31,32] S. Al-Kershi,[9,10] C. Alléné,[33] A. Allocca,[34,4] S. Al-Shammari,[35] P. A. Altin,[36] S. Alvarez-Lopez,[37] W. Amar,[33] O. Amarasinghe,[35] A. Amato,[38,39] F. Amicucci,[40,41] C. Amra,[42] C. Anand,[7] A. Ananyeva,[12] S. B. Anderson,[12] W. G. Anderson,[12] M. Andia,[43] M. Ando,[44,45] M. Andrés-Carcasona,[37] J. L. Andrey,[46] T. Andrić,[47,48] J. Anglin,[49] J. Anna,[50] S. Ansoldi,[51,52] J. M. Antelis,[53] S. Antier,[43] M. Aoumi,[54] E. Z. Appavuravther,[55,56] S. Appert,[12] S. K. Apple,[57] K. Arai,[12] A. Araya,[58] M. C. Araya,[12] M. Arca Sedda,[47,48] F. Arciprete,[22,23] J. S. Areeda,[59] N. Aritomi,[2] F. Armato,[31,32] S. Armstrong,[60] N. Arnaud,[61] M. Arogeti,[62] S. M. Aronson,[49] K. G. Arun,[63] G. Ashton,[64] Y. Aso,[54,65] L. Asprea,[29] M. Assiduo,[66,67] S. Assis de Souza Melo,[68] S. M. Aston,[69] P. Astone,[40] F. Attadio,[41,40] F. Aubin,[70] K. AultONeal,[50] G. Avallone,[71] E. A. Avila,[53] S. Babak,[21] C. Badger,[72] S. Bae,[73] S. Bagnasco,[29] L. Baiotti,[74] R. Bajpai,[75] T. Baka,[76,39] K. A. Baker,[6] T. Baker,[77] G. Balbi,[78] G. Baldi,[79,80] N. Baldicchi,[81,55] M. Ball,[82] G. Ballardin,[68] S. W. Ballmer,[83] S. Banagiri,[7] B. Banerjee,[47] D. Bankar,[84] T. M. Baptiste,[13] P. Baral,[11] M. Baratti,[85,86] J. C. Barayoga,[12] K. Baric,[12] B. C. Barish,[12] D. Barker,[2] N. Barman,[84] P. Barneo,[87,88,89] F. Barone,[90,4] B. Barr,[91] M. Barrios,[92] L. Barsotti,[37] M. Barsuglia,[21] D. Barta,[93] M. A. Barton,[91] I. Bartos,[49] A. Basalaev,[9,10] R. Bassiri,[94] A. Basti,[86,85] M. Bawaj,[81,55] P. Baxi,[95] J. C. Bayley,[91] A. C. Baylor,[11] P. A. Baynard II,[62] M. Bazzan,[96,97] V. M. Bedakihale,[98] F. Beirnaert,[99] M. Bejger,[100] D. Belardinelli,[23] A. S. Bell,[91] C. Bellani,[101] L. Bellizzi,[85,86] D. Beltran-Martinez,[102] W. Benoit,[19] I. Bentara,[61] M. Ben Yaala,[60] S. Bera,[103] F. Bergamin,[35] B. K. Berger,[94] S. Bernuzzi,[28] M. Beroiz,[12] C. P. L. Berry,[91] I. Berry,[104] D. Bersanetti,[31] T. Bertheas,[105] A. Bertolini,[39,38] J. Betzwieser,[69] D. Beveridge,[6] G. Bevilacqua,[106] N. Bevins,[107] R. Bhandare,[108] R. Bhatt,[12] A. Bhattacharjee,[109] D. Bhattacharjee,[110,111] S. Bhattacharyya,[112] S. Bhaumik,[49] V. Biancalana,[106] A. Bianchi,[39,113] F. Bianchi,[55] I. A. Bilenko,[114] G. Billingsley,[12] A. Binetti,[101] S. Bini,[79,80,12] C. Binu,[115] S. Biot,[116] O. Birnholtz,[117] S. Biscoveanu,[118,119] A. Bisht,[10] M. Bitossi,[68,85] M.-A. Bizouard,[120] S. Blaber,[121] J. K. Blackburn,[12] L. A. Blagg,[82] C. D. Blair,[6,69] D. G. Blair,[6] N. Bode,[9,10] N. Boettner,[30] P. Bogdan,[122] G. Boileau,[120] M. Boldrini,[40] G. N. Bolingbroke,[123] A. Bolliand,[124,42] L. D. Bonavena,[49] R. Bondarescu,[87] F. Bondu,[125] V. A. Bonhomme,[37] E. Bonilla,[94] M. S. Bonilla,[59] A. Bonino,[126] R. Bonnand,[33,124] A. Borchers,[9,10] N. Borghi,[127,78] V. Boschi,[85] S. Bose,[128] V. Bossilkov,[69] Y. Bothra,[39,113] A. Boudon,[61] M. Boyle,[129] A. Bozzi,[68] C. Bradaschia,[85] M. J. Brady,[130] P. R. Brady,[11] A. Branch,[69] M. Branchesi,[47,48] T. Briant,[131] A. Brillet,[120] M. Brinkmann,[9,10] P. Brockill,[11] E. Brockmueller,[9,10] A. F. Brooks,[12] B. C. Brown,[49] D. D. Brown,[123] M. L. Brozzetti,[81,55] S. Brunett,[12] G. Bruno,[16] R. Bruntz,[122] J. Bryant,[126] Y. Bu,[132] F. Bucci,[67] J. Buchanan,[122] O. Bulashenko,[87,88] T. Bulik,[133] H. J. Bulten,[39] A. Buonanno,[134,1] K. Burtnyk,[2] R. Buscicchio,[135,136] D. Buskulic,[33] C. Buy,[105] R. L. Byer,[94] R. Cabrita,[16] V. Cáceres-Barbosa,[8] L. Cadonati,[62] G. Cagnoli,[137] C. Cahillane,[83] A. Calafat,[138] T. A. Callister,[139] E. Calloni,[34,4] S. R. Callos,[82] M. Canepa,[32,31] G. Caneva Santoro,[140] K. C. Cannon,[45] H. Cao,[37] L. A. Capistran,[141] E. Capocasa,[21] G. Capoccia,[55] E. Capote,[2] G. Capurri,[86,85] G. Carapella,[71,142] F. Carbognani,[68] K. J. Cardona-Martínez,[13] M. Carlassara,[9,10] J. B. Carlin,[132] T. K. Carlson,[143] M. F. Carney,[110] M. Carpinelli,[135,68] G. Carrillo,[82] J. J. Carter,[9,10] G. Carullo,[126] A. Casallas-Lagos,[144] J. Casanueva Diaz,[68] C. Casentini,[145,23] S. Caudill,[143] M. Cavaglià,[111] R. Cavalieri,[68] G. Cella,[85] S. Cepic,[127] P. Cerdá-Durán,[146,147] E. Cesarini,[23] N. Chabbra,[36] W. Chaibi,[120] A. Chakraborty,[14] P. Chakraborty,[9,10] S. Chakraborty,[108] S. Chalathadka Subrahmanya,[30] R. Chalmers,[77] C. Chan,[148] J. C. L. Chan,[149] M. Chan,[121] K. Chang,[150] P. Charlton,[151] E. Chassande-Mottin,[21] C. Chatterjee,[152] Debarati Chatterjee,[84] Deep Chatterjee,[37] M. Chaturvedi,[108] S. Chaty,[21] K. Chatziioannou,[12] A. Chen,[153] A. H.-Y. Chen,[154] D. Chen,[155] H. Chen,[156] H. Y. Chen,[157] S. Chen,[152] Y. Chen,[158] G. Cheng,[153] H. P. Cheng,[104] P. Chessa,[81,55] T. Cheunchitra,[132] H. T. Cheung,[95] S. Y. Cheung,[7] F. Chiadini,[159,142] G. Chiarini,[9,10] A. Chiba,[160] A. Chincarini,[31] D. Chintala,[110] M. L. Chiofalo,[86,85] A. Chiummo,[4,68] C. Chou,[161] S. Choudhary,[6] N. Christensen,[120,162] S. S. Y. Chua,[36] G. Ciani,[79,80] P. Ciecielag,[100] M. Cieślar,[133] M. Cifaldi,[23] B. Cirok,[163] F. Clara,[2] J. A. Clark,[12,62] T. A. Clarke,[7] P. Clearwater,[148] S. Clesse,[116] F. Cleva,[120] S. M. Clyne,[130] E. Coccia,[47,48,140] E. Codazzo,[164] P.-F. Cohadon,[131] D. E. Cohen,[9,10] S. Colace,[32] E. Colangeli,[77] O. Cole,[148] M. Colleoni,[138] C. G. Collette,[165] J. Collins,[69] S. Colloms,[91] A. Colombo,[166,136] C. M. Compton,[2] G. Connolly,[82] L. Conti,[97] T. R. Corbitt,[13] I. Cordero-Carrión,[167] S. Corezzi,[81,55] N. J. Cornish,[168] I. Coronado,[169] A. Corsi,[170] L. A. Corubolo,[22,23] L. Cotnoir,[122] R. Cottingham,[69] M. W. Coughlin,[19] P. Couvares,[12,62] D. M. Coward,[6] D. C. Coyne,[12] R. Coyne,[130] A. Cozzumbo,[47] J. D. E. Creighton,[11] T. D. Creighton,[171] S. Crook,[69]

R. Crouch,[2] J. Csizmazia,[2] J. R. Cudell,[172] T. J. Cullen,[12] A. Cumming,[91] E. Cuoco,[127,78] M. Cusinato,[146] L. V. Da Conceição,[173] T. Dal Canton,[43] S. Dall'Osso,[174,78] S. Dal Pra,[175] G. Dálya,[105] O. Dan,[117] Y. Dang,[8] B. D'Angelo,[31] S. Danilishin,[38,39] S. D'Antonio,[40] K. Danzmann,[9,10] K. E. Darroch,[122] L. P. Dartez,[69] R. Das,[112] A. Dasgupta,[98] V. Dattilo,[68] A. Daumas,[21] I. Dave,[108] A. Davenport,[176] M. Davier,[43] T. F. Davies,[6] D. Davis,[12] L. Davis,[6] M. C. Davis,[19] P. Davis,[177,178] E. J. Daw,[179] M. Dax,[1] J. De Bolle,[99] M. Deenadayalan,[84] J. Degallaix,[180] M. De Laurentis,[34,4] C. J. Delgado Mendez,[102] F. De Lillo,[24] S. Della Torre,[136] W. Del Pozzo,[86,85] O. M. del Rio,[181] A. Demagny,[33] F. De Marco,[41,40] G. Demasi,[182,67] F. De Matteis,[22,23] N. Demos,[37] T. Dent,[183] A. Depasse,[16] N. DePergola,[107] R. De Pietri,[184,185] R. De Rosa,[34,4] C. De Rossi,[68] M. Desai,[37] V. Deshmukh,[91] R. De Simone,[159,142] S. Determan,[186] A. Dhani,[1] R. Dhurkunde,[77] R. Diab,[49] C. Diaz,[102] M. C. Díaz,[171] M. Di Cesare,[34,4] G. Dideron,[187] T. Dietrich,[1] L. Di Fiore,[4] C. Di Fronzo,[6] M. Di Giovanni,[188,85] T. Di Girolamo,[34,4] D. Diksha,[39,38] J. Ding,[37,21,189] S. Di Pace,[41,40] I. Di Palma,[41,40] D. Di Piero,[190,52] F. Di Renzo,[67,182] Divyajyoti,[35] A. Dmitriev,[126] J. P. Docherty,[91] Z. Doctor,[118] N. Doerksen,[173] E. Dohmen,[2] A. Doke,[143] A. Domiciano De Souza,[191] L. D'Onofrio,[4] F. Donovan,[37] K. L. Dooley,[35] T. Dooney,[76] S. Doravari,[84] O. Dorosh,[192] F. Dosopoulou,[35] W. J. D. Doyle,[122] M. Drago,[41,40] J. C. Driggers,[2] M. Dubois,[105] R. R. Dumbreck,[35] L. Dunn,[132] U. Dupletsa,[47] D. D'Urso,[193,164] P. Dutta Roy,[49] H. Duval,[194] P.-A. Duverne,[21] S. E. Dwyer,[2] C. Eassa,[2] M. Eberhardt,[186] M. Ebersold,[195,33] T. Eckhardt,[30] G. Eddolls,[83] A. Effler,[69] J. Eichholz,[36] H. Einsle,[120] M. Eisenmann,[26] R. A. Eisenstein,[37] M. Emma,[64] K. Endo,[160] R. Enficiaud,[1] L. Errico,[34,4] R. Espinosa,[171] M. Esposito,[4,34] R. C. Essick,[196] H. Estellés,[1] T. Etzel,[12] M. Evans,[37] T. Evstafyeva,[187] B. E. Ewing,[8] J. M. Ezquiaga,[149] F. Fabrizi,[66,67] V. Fafone,[22,23] S. Fairhurst,[35] X. Fan,[153] A. M. Farah,[139] B. Farr,[82] W. M. Farr,[197,198] M. Favata,[199] M. Fays,[172] M. Fazio,[60] J. Feicht,[12] M. M. Fejer,[94] J.-N. Feldhusen,[30] E. Fenyvesi,[93,200] J. Fernandes,[201] T. Fernandes,[202,146] D. Fernando,[115] S. Ferraiuolo,[203,41,40] T. A. Ferreira,[13] M. Ferrer,[138] F. Fidecaro,[86,85] P. Figura,[100] E. Finch,[12] A. Fiori,[85,86] I. Fiori,[68] M. Fishbach,[196] R. P. Fisher,[122] R. Fittipaldi,[204,142] V. Fiumara,[205,142] R. Flaminio,[33] S. M. Fleischer,[181] L. S. Fleming,[206] E. Floden,[19] H. Fong,[121] J. A. Font,[146,147] F. Fontinele-Nunes,[19] C. Foo,[1] B. Fornal,[207] P. W. F. Forsyth,[36] K. Franceschetti,[184] A. Franco-Ordovas,[12] F. Frappez,[33] S. Frasca,[41,40] F. Frasconi,[85] J. P. Freed,[50] Z. Frei,[208] A. Freise,[39,113] O. Freitas,[202,146] R. Frey,[82] W. Frischhertz,[69] P. Fritschel,[37] V. V. Frolov,[69] M. Fuentes-Garcia,[12] S. Fujii,[209] T. Fujimori,[210] P. Fulda,[49] M. Fyffe,[69] B. Gadre,[76] J. R. Gair,[1] S. Galaudage,[191] V. Galdi,[211] R. Gamba,[8] A. Gamboa,[1] S. Gamoji,[212] A. Ganguly,[84] B. Garaventa,[31] P. García Abia,[102] J. García-Bellido,[213] C. García-Quirós,[195] J. W. Gardner,[36] S. Garg,[45] J. Gargiulo,[68] X. Garrido,[43] A. Garron,[138] F. Garufi,[34,4] P. A. Garver,[94] C. Gasbarra,[214,23] B. Gateley,[2] F. Gautier,[215] V. Gayathri,[11] T. Gayer,[83] G. Gemme,[31] A. Gennai,[85] V. Gennari,[105] J. George,[108] R. George,[157] O. Gerberding,[30] L. Gergely,[163] Archisman Ghosh,[99] Sayantan Ghosh,[201] Shaon Ghosh,[199] Shrobana Ghosh,[9,10] Suprovo Ghosh,[216] Tathagata Ghosh,[84] J. A. Giaime,[13,69] K. D. Giardina,[69] D. R. Gibson,[206] C. Gier,[60] S. Gkaitatzis,[86,85] J. Glanzer,[12] F. Glotin,[43] J. Godfrey,[82] R. V. Godley,[9,10] P. Godwin,[12] A. S. Goettel,[35] E. Goetz,[121] J. Golomb,[12] S. Gomez Lopez,[41,40] G. González,[13] P. Goodarzi,[46] S. Goode,[7] A. Goodwin-Jones,[16] M. Gosselin,[68] C. Gostiaux,[70] R. Gouaty,[33] D. W. Gould,[36] K. Govorkova,[37] A. Grado,[81,55] A. E. Granados,[19] M. Granata,[180] V. Granata,[217,142] S. Gras,[37] P. Grassia,[12] C. Gray,[2] R. Gray,[91] G. Greco,[55] A. C. Green,[39,113] L. Green,[218] S. M. Green,[77] S. R. Green,[219] A. M. Gretarsson,[50] E. M. Gretarsson,[50] H. K. Griffin,[19] D. Griffith,[12] H. L. Griggs,[62] G. Grignani,[81,55] C. Grimaud,[33] H. Grote,[35] S. Grunewald,[1] D. Guerra,[146] A. G. Guerrero,[139] D. Guetta,[220] G. M. Guidi,[66,67] T. Guidry,[2] H. K. Gulati,[98] F. Gulminelli,[177,178] A. M. Gunny,[37] H. Guo,[153] W. Guo,[6] Y. Guo,[39,38] Anuradha Gupta,[221] I. Gupta,[8] N. C. Gupta,[98] S. K. Gupta,[49] V. Gupta,[19] N. Gupte,[1] J. Gurs,[30] N. Gutierrez,[180] N. Guttman,[7] F. Guzman,[141] D. Haba,[222] M. Haberland,[1] S. Haino,[223] E. D. Hall,[37] E. Z. Hamilton,[138] G. Hammond,[91] M. Haney,[39] J. Hanks,[2] C. Hanna,[8] M. D. Hannam,[35] O. A. Hannuksela,[224] H. Hansen,[2] J. Hanson,[69] R. Harada,[45] A. R. Hardison,[186] S. Harikumar,[100] K. Haris,[225] I. Harley-Trochimczyk,[141] T. Harmark,[226] J. Harms,[47,48] G. M. Harry,[227] I. W. Harry,[77] J. Hart,[110] M. T. Hartman,[21] B. Haskell,[100,228,229] C.-J. Haster,[218] K. Haughian,[91] H. Hayakawa,[54] K. Hayama,[230] A. Heffernan,[138] D. Hegde,[16] M. C. Heintze,[69] J. Heinze,[126] J. Heinzel,[37] H. Heitmann,[120] F. Hellman,[92] A. F. Helmling-Cornell,[82] G. Hemming,[68] O. Henderson-Sapir,[123] M. Hendry,[91] I. S. Heng,[91] M. H. Hennig,[91] C. Henshaw,[62] M. Heurs,[9,10] A. L. Hewitt,[231,232] J. Heynen,[16] J. Heyns,[37] S. Higginbotham,[35] S. Hild,[38,39] S. Hill,[91] Y. Himemoto,[233] N. Hirata,[26] C. Hirose,[234] D. Hofman,[180] B. E. Hogan,[50] N. A. Holland,[39,113] K. Holley-Bockelmann,[152] I. J. Hollows,[179] D. E. Holz,[139] L. Honet,[116] K. M. Hoops,[212] M. E. Hoque,[235] D. J. Horton-Bailey,[92] J. Hough,[91] S. Hourihane,[12] N. T. Howard,[152] E. J. Howell,[6] C. G. Hoy,[77] C. A. Hrishikesh,[22] P. Hsi,[37] H.-F. Hsieh,[156] H.-Y. Hsieh,[156] C. Hsiung,[236] S.-H. Hsu,[237] W.-F. Hsu,[101] Q. Hu,[91] H. Y. Huang,[150] Y. Huang,[8] Y. T. Huang,[83] A. D. Huddart,[238] B. Hughey,[50] V. Hui,[33]

S. Husa,[138] L. Iampieri,[41,40] G. A. Iandolo,[38] M. Ianni,[23,22] G. Iannone,[142] J. Iascau,[82] K. Ide,[239] R. Iden,[222] A. Ierardi,[47,48] S. Ikeda,[155] H. Imafuku,[45] Y. Inoue,[150] G. Iorio,[96] P. Iosif,[190,52] J. Irwin,[91] R. Ishikawa,[239] T. Ishikawa,[240] M. Isi,[198] K. S. Isleif,[241] Y. Itoh,[210,242] S. Iwaguchi,[240] M. Iwaya,[209] B. R. Iyer,[25] C. D. Jackson,[49] C. Jacquet,[105] P.-E. Jacquet,[131] T. Jacquot,[43] S. J. Jadhav,[243] S. P. Jadhav,[148] M. Jain,[143] T. Jain,[231] A. L. James,[12] K. Jani,[152] J. Janquart,[16] N. N. Janthalur,[243] S. Jaraba,[244] P. Jaranowski,[245] R. Jaume,[138] W. Javed,[35] M. Jensen,[2] W. Jia,[37] J. Jiang,[104] H.-B. Jin,[246,247] G. R. Johns,[122] N. A. Johnson,[49] N. K. Johnson-McDaniel,[221] R. Johnston,[91] N. Johny,[9,10] D. H. Jones,[36] D. I. Jones,[216] R. Jones,[91] H. E. Jose,[82] P. Joshi,[62] S. K. Joshi,[84] G. Joubert,[61] J. Ju,[248] L. Ju,[6] I. L. Juarez-Reyes,[82] K. Jung,[249] J. Junker,[36] V. Juste,[116] H. B. Kabagoz,[37] T. Kajita,[209] I. Kaku,[210] V. Kalogera,[118] M. Kalomenopoulos,[218] M. Kamiizumi,[54] N. Kanda,[242,210] S. Kandhasamy,[84] G. Kang,[250] J. B. Kanner,[12] S. A. KantiMahanty,[19] S. J. Kapadia,[84] D. P. Kapasi,[59] M. Karthikeyan,[143] M. Kasprzack,[12] H. Kato,[160] T. Kato,[209] E. Katsavounidis,[37] W. Katzman,[69] R. Kaushik,[108] K. Kawabe,[2] R. Kawamoto,[210] D. Keitel,[138] S. A. Kemper,[57] L. J. Kemperman,[123] J. Kennington,[8] F. A. Kerkow,[19] R. Kesharwani,[84] J. S. Key,[251] R. Khadela,[9,10] S. Khadka,[94] S. S. Khadkikar,[8] F. Y. Khalili,[114] F. Khan,[9,10] T. Khanam,[170] M. Khursheed,[108] N. M. Khusid,[197,198] W. Kiendrebeogo,[120,252] N. Kijbunchoo,[123] C. Kim,[253] J. C. Kim,[254] K. Kim,[255] M. H. Kim,[248] S. Kim,[256] Y.-M. Kim,[255] C. Kimball,[118] K. Kimes,[59] M. Kinnear,[35] J. S. Kissel,[2] S. Klimenko,[49] A. M. Knee,[121] E. J. Knox,[82] N. Knust,[9,10] K. Kobayashi,[209] S. M. Koehlenbeck,[94] G. Koekoek,[39,38] K. Kohri,[257] K. Kokeyama,[35,240] S. Koley,[47,172] P. Kolitsidou,[126] A. E. Koloniari,[258] K. Komori,[44,45] K. Kompanets,[19] A. K. H. Kong,[156] A. Kontos,[259] K. Kopczuk,[110] L. M. Koponen,[126] M. Korobko,[30] X. Kou,[19] A. Koushik,[24] N. Kouvatsos,[72] M. Kovalam,[6] T. Koyama,[160] D. B. Kozak,[12] E. Kraja,[68] S. L. Kranzhoff,[38,39] V. Kringel,[9,10] N. V. Krishnendu,[126] S. Kroker,[260] A. Królak,[261,192] K. Kruska,[9,10] J. Kubisz,[262] G. Kuehn,[9,10] A. Kulur Ramamohan,[36] Achal Kumar,[49] Anil Kumar,[243] Praveen Kumar,[183] Prayush Kumar,[25] Rahul Kumar,[2] Rakesh Kumar,[98] Saurabh Kumar,[63] J. Kume,[263,264,45] K. Kuns,[37] N. Kuntimaddi,[35] S. Kuroyanagi,[265,266] S. Kuwahara,[45] K. Kwak,[249] K. Kwan,[36] S. Kwon,[45] G. Lacaille,[91] D. Laghi,[195] A. H. Laity,[130] A. Lakhal,[131] E. Lalande,[267] M. Lalleman,[24] S. Lalvani,[118] M. Landry,[2] R. N. Lang,[37] J. Lange,[157] R. Langgin,[218] B. Lantz,[94] I. La Rosa,[138] A. Lartaux-Vollard,[43] P. D. Lasky,[7] L. Lavezzi,[29] J. Lawrence,[171] M. Laxen,[69] C. Lazarte,[146] A. Lazzarini,[12] C. Lazzaro,[268,164] P. Leaci,[41,40] L. Leali,[19] Y. K. Lecoeuche,[121] H. W. Lee,[269] J. Lee,[83] K. Lee,[248] R.-K. Lee,[156] R. Lee,[37] Sungho Lee,[270] Sunjae Lee,[248] Y. Lee,[150] Y. S. C. Lee,[132] I. N. Legred,[12] J. Lehmann,[9,10] L. Lehner,[187] M. Le Jean,[180,124] A. Lemaître,[271] M. Lenti,[67,182] M. Leonardi,[79,80,272] M. Lequime,[42] N. Leroy,[43] M. Lesovsky,[12] N. Letendre,[33] M. Lethuillier,[61] S. E. Levin,[46] Y. Levin,[7] S. Lexmond,[113] K. Leyde,[77] K. L. Li,[273] T. G. F. Li,[101] X. Li,[158] Y. Li,[118] Z. Li,[91] Q. Liang,[153] A. Lihos,[122] E. T. Lin,[156] F. Lin,[150] L. C.-C. Lin,[273] Y.-C. Lin,[156] C. Lindsay,[206] S. D. Linker,[212] A. Liu,[224] G. C. Liu,[236] Jian Liu,[6] S. Liu,[153] F. Llamas Villarreal,[171] J. Llobera-Querol,[138] R. K. L. Lo,[149] J.-P. Locquet,[101] S. C. G. Loggins,[274] M. R. Loizou,[143] L. T. London,[72,37] A. Longo,[66,67] D. Lopez,[172] M. Lopez Portilla,[76] A. Lorenzo-Medina,[183] V. Loriette,[43] M. Lormand,[69] G. Losurdo,[188,85] E. Lotti,[143] T. P. Lott IV,[62] J. D. Lough,[9,10] H. A. Loughlin,[37] C. O. Lousto,[115] N. K. Y Low,[132] N. Lu,[36] L. Lucchesi,[85] H. Lück,[9,10] O. Lukina,[37] D. Lumaca,[23] A. P. Lundgren,[275,276] L. Lunghini,[68,34,4] A. W. Lussier,[267] S. Ma,[187] X. Ma,[46] D. M. Macleod,[35] I. A. O. MacMillan,[12] A. Macquet,[43] S. S. Madekar,[140] K. Maeda,[160] S. Maenaut,[101] S. S. Magare,[84] R. M. Magee,[12] E. Maggio,[1] R. Maggiore,[39,113] M. Magnozzi,[31,32] P. Mahapatra,[35] M. Mahesh,[30] S. Majhi,[84] E. Majorana,[41,40] C. N. Makarem,[12] E. Makelele,[110] D. Malakar,[111] J. A. Malaquias-Reis,[20] U. Mali,[196] S. Maliakal,[12] A. Malik,[108] L. Mallick,[173,196] A.-K. Malz,[64] N. Man,[120] M. Mancarella,[103] V. Mandic,[19] V. Mangano,[193,164] B. Mannix,[82] G. L. Mansell,[83,37] M. Manske,[11] M. Mantovani,[68] M. Mapelli,[96,97,277] S. Marchetti,[96,97] C. Marinelli,[106] F. Marion,[33] A. S. Markosyan,[94] A. Markowitz,[12] E. Maros,[12] S. Marsat,[105] F. Martelli,[66,67] I. W. Martin,[91] R. M. Martin,[199] B. B. Martinez,[141] D. A. Martinez,[59] M. Martinez,[140,278] V. Martinez,[137] A. Martini,[79,80] J. C. Martins,[20] D. V. Martynov,[126] E. J. Marx,[37] L. Massaro,[38,39] A. Masserot,[33] M. Masso-Reid,[91] T. Masters,[110] S. Mastrogiovanni,[40] G. Mastropasqua,[78] T. Matcovich,[55] M. Matiushechkina,[9,10] A. Matte-Landry,[267] L. Maurin,[215] N. Mavalvala,[37] N. Maxwell,[2] G. McCarrol,[69] R. McCarthy,[2] D. E. McClelland,[36] S. McCormick,[69] L. McCuller,[12] L. I. McDermott,[128] S. McEachin,[122] C. McElhenny,[122] G. I. McGhee,[91] K. B. M. McGowan,[152] J. McIver,[121] A. McLeod,[6] T. McRae,[36] R. McTeague,[91] D. Meacher,[11] B. N. Meagher,[83] R. Mechum,[115] Q. Meijer,[76] A. Melatos,[132] C. S. Menoni,[176] F. Mera,[2] R. A. Mercer,[11] L. Mereni,[180] K. Merfeld,[170] E. L. Merilh,[69] G. Merino,[102] J. R. Mérou,[138] J. D. Merritt,[82] M. Merzougui,[120] C. Messick,[11] B. Mestichelli,[47] M. Meyer-Conde,[279] F. Meylahn,[9,10] A. Mhaske,[84] A. Miani,[79,80] H. Miao,[280] I. Michaloliakos,[49] C. Michel,[180] Y. Michimura,[12,45] H. Middleton,[126] D. P. Mihaylov,[110] S. J. Miller,[12] M. Millhouse,[62] E. Milotti,[190,52] V. Milotti,[96] Y. Minenkov,[23] E. M. Minihan,[50] Ll. M. Mir,[140]

L. Mirasola,[164,268] C.-A. Miritescu,[140] A. Mishra,[25] C. Mishra,[112] T. Mishra,[49] A. L. Mitchell,[39,113] J. G. Mitchell,[50] O. Mitchem,[82] S. Mitra,[84] V. P. Mitrofanov,[114] K. Mitsuhashi,[26] R. Mittleman,[37] O. Miyakawa,[54] S. Miyoki,[54] G. Mo,[37] L. Mobilia,[66,67] S. R. P. Mohapatra,[12] S. R. Mohite,[8] M. Molina-Ruiz,[92] M. Mondin,[212] M. Montani,[66,67] C. J. Moore,[231] D. Moraru,[2] A. More,[84] S. More,[84] C. Moreno,[281] E. A. Moreno,[37] G. Moreno,[2] A. Moreso Serra,[87] C. Morgan,[35] S. Morisaki,[209] Y. Moriwaki,[160] G. Morras,[213] A. Moscatello,[96] M. Mould,[37] B. Mours,[70] C. M. Mow-Lowry,[39,113] L. Muccillo,[182,67] F. Muciaccia,[41,40] Arunava Mukherjee,[235] D. Mukherjee,[126] Samanwaya Mukherjee,[25] Soma Mukherjee,[171] Subroto Mukherjee,[98] Suvodip Mukherjee,[14] N. Mukund,[37] A. Mullavey,[69] A. R. Muller,[91] C. L. Mungioli,[6] M. Murakoshi,[239] P. G. Murray,[91] D. Nabari,[79,80] S. L. Nadji,[9,10] S. Nadji,[180] A. Nagar,[29,282] N. Nagarajan,[91] K. Nakagaki,[54] K. Nakamura,[26] H. Nakano,[283] M. Nakano,[12] D. Nanadoumgar-Lacroze,[140] D. Nandi,[13] V. Napolano,[68] S. U. Naqvi,[112] P. Narayan,[221] I. Nardecchia,[23] T. Narikawa,[209] H. Narola,[76] L. Naticchioni,[284,40] R. K. Nayak,[285] J. Neeson,[35] L. Negri,[76] A. Nela,[91] C. Nelle,[82] A. Nelson,[141] T. J. N. Nelson,[69] A. Nemmani,[100] M. Nery,[9,10] A. Neunzert,[2] M. Newell,[17] S. Ng,[59] L. Nguyen Quynh,[286] A. B. Nielsen,[287] Y. Nishino,[26,288] A. Nishizawa,[289] S. Nissanke,[290,39] W. Niu,[8] F. Nocera,[68] J. Noller,[291] M. Norman,[35] C. North,[35] J. Novak,[244,292] R. Nowicki,[152] J. F. Nuño Siles,[213] G. Nurbek,[171] L. K. Nuttall,[77] K. Obayashi,[239] J. Oberling,[2] C. E. Ochoa,[46] J. O'Dell,[238] M. Oertel,[244,292] G. Oganesyan,[47,48] T. O'Hanlon,[69] M. Ohashi,[54,279] F. Ohme,[9,10] I. Oke,[60] R. Omer,[19] B. O'Neal,[122] M. Onishi,[160] K. Oohara,[293,294] B. O'Reilly,[69] M. Orselli,[55,81] R. O'Shaughnessy,[115] S. Oshino,[54] C. Osthelder,[12] I. Ota,[13] G. Othman,[241] D. J. Ottaway,[123] A. Ouzriat,[61] H. Overmier,[69] B. J. Owen,[109] R. Ozaki,[239] A. E. Pace,[8] R. Pagano,[13] M. A. Page,[26] A. Pai,[201] L. Paiella,[47] A. Pal,[295] S. Pal,[285] M. A. Palaia,[85,86] M. Pálfi,[208] P. P. Palma,[41,22,23] C. Palomba,[40] P. Palud,[21] H. Pan,[156] J. Pan,[6] K.-C. Pan,[156,156] P. K. Panda,[243] Shiksha Pandey,[8] Swadha Pandey,[37] P. T. H. Pang,[39,76] F. Pannarale,[41,40] K. A. Pannone,[59] B. C. Pant,[108] F. H. Panther,[6] M. Panzeri,[66,67] F. Paoletti,[85] A. Paolone,[40,296] A. Papadopoulos,[91] E. E. Papalexakis,[46] L. Papalini,[85,86] G. Papigkiotis,[258] A. Paquis,[43] A. Parisi,[81,55] B.-J. Park,[270] J. Park,[297] W. Parker,[69] G. Pascale,[9,10] D. Pascucci,[99] A. Pasqualetti,[68] R. Passaquieti,[86,85] L. Passenger,[7] D. Passuello,[85] O. Patane,[2] A. V. Patel,[150] D. Pathak,[84] A. Patra,[35] B. Patricelli,[86,85] B. G. Patterson,[35] K. Paul,[112] S. Paul,[82] E. Payne,[12] T. Pearce,[35] M. Pedraza,[12] A. Pele,[12] F. E. Peña Arellano,[298] X. Peng,[126] Y. Peng,[62] S. Penn,[299,83] M. D. Penuliar,[59] A. Perego,[79,80] Z. Pereira,[143] C. Périgois,[300,97,96] G. Perna,[96] A. Perreca,[47,48] J. Perret,[21] S. Perriès,[61] J. W. Perry,[39,113] S. Peters,[172] S. Petracca,[211] C. Petrillo,[81] H. P. Pfeiffer,[1] H. Pham,[69] K. A. Pham,[19] K. S. Phukon,[126] H. Phurailatpam,[224] M. Piarulli,[105] L. Piccari,[41,40] O. J. Piccinni,[36] M. Pichot,[120] A. Pied,[91] M. Piendibene,[86,85] F. Piergiovanni,[66,67] L. Pierini,[40] G. Pierra,[40] V. Pierro,[301,142] M. Pietrzak,[100] M. Pillas,[302] L. Pinard,[180] I. M. Pinto,[301,142,303,34] M. Pinto,[68] B. J. Piotrzkowski,[11] M. Pirello,[2] M. D. Pitkin,[231,91] A. Placidi,[55] E. Placidi,[41,40] M. L. Planas,[138] W. Plastino,[217,23] C. Plunkett,[37] R. Poggiani,[86,85] E. Polini,[120] J. Pomper,[85,86] L. Pompili,[1] J. Poon,[224] E. Porcelli,[39] A. S. Porter,[109] E. K. Porter,[21] C. Posnansky,[8] R. Poulton,[68] J. Powell,[148] G. S. Prabhu,[84] M. Pracchia,[172] B. K. Pradhan,[84] T. Pradier,[70] A. K. Prajapati,[98] K. Prasai,[304] R. Prasanna,[243] P. Prasia,[305] G. Pratten,[126] A. Praveen,[196] G. Principe,[190,52] G. A. Prodi,[79,80] P. Prosperi,[85] P. Prosposito,[22,23] A. Puecher,[1] J. Pullin,[13] P. Puppo,[40] M. Pürrer,[130] H. Qi,[17] M. Qiao,[153] J. Qin,[36] G. Quéméner,[178,124] V. Quetschke,[171] P. J. Quinonez,[50] R. Rading,[241] I. Rainho,[146] S. Raja,[108] C. Rajan,[108] B. Rajbhandari,[115] K. E. Ramirez,[69] F. A. Ramis Vidal,[138] M. Ramos Arevalo,[171] A. Ramos-Buades,[138,39] S. Ranjan,[62] M. Ranjbar,[46] K. Ransom,[69] P. Rapagnani,[41,40] B. Ratto,[50] A. Ravichandran,[143] A. Ray,[118] V. Raymond,[35] M. Razzano,[86,85] J. Read,[59] J. Regan,[218] T. Regimbau,[33] T. Reichardt,[148] S. Reid,[60] C. Reissel,[37] D. H. Reitze,[12] A. I. Renzini,[12,135,136] B. Revenu,[306,43] A. Revilla Peña,[87] L. Ricca,[16] F. Ricci,[41,40] M. Ricci,[40,41] A. Ricciardone,[86,85] J. Rice,[83] J. W. Richardson,[46] M. L. Richardson,[123] A. Rijal,[50] K. Riles,[95] H. K. Riley,[35] S. Rinaldi,[277] J. Rittmeyer,[30] C. Robertson,[238] F. Robinet,[43] M. Robinson,[2] A. Rocchi,[23] L. Rolland,[33] J. G. Rollins,[12] A. E. Romano,[307] R. Romano,[3,4] A. Romero-Rodríguez,[33] I. M. Romero-Shaw,[231] J. H. Romie,[69] S. Ronchini,[8] T. J. Roocke,[123] L. Rosa,[4,34] T. J. Rosauer,[46] C. A. Rose,[62] D. Rosińska,[133] M. P. Ross,[57] M. Rossello-Sastre,[138] S. Rowan,[91] K. Rowlands,[186] S. K. Roy,[197,198] S. Roy,[16] D. Rozza,[135,136] P. Ruggi,[68] N. Ruhama,[249] G. H. Ruiz,[274] E. Ruiz Morales,[308,213] K. Ruiz-Rocha,[152] V. Russ,[181] S. Sachdev,[62] T. Sadecki,[2] P. Saffarieh,[39,113] S. Safi-Harb,[173] M. R. Sah,[14] S. Saha,[156] T. Sainrat,[70] S. Sajith Menon,[220,41,40] K. Sakai,[309] Y. Sakai,[279] M. Sakellariadou,[72] S. Sakon,[8] O. S. Salafia,[166,136,135] F. Salces-Carcoba,[12] L. Salconi,[68] M. Saleem,[157] F. Salemi,[41,40] M. Sallé,[39] S. U. Salunkhe,[84] S. Salvador,[178,177] A. Salvarese,[157] A. Samajdar,[76,39] A. Sanchez,[2] E. J. Sanchez,[12] N. Sanchis-Gual,[146] J. R. Sanders,[186] E. M. Sänger,[1] F. Santoliquido,[47,48] F. Sarandrea,[29] T. R. Saravanan,[84] N. Sarin,[7] P. Sarkar,[9,10] A. Sasli,[19,258] P. Sassi,[55,81] B. Sassolas,[180] B. S. Sathyaprakash,[8,35] R. Sato,[234] S. Sato,[160] Yukino Sato,[160] Yu Sato,[160] O. Sauter,[49]

R. L. Savage,[2] T. Sawada,[54] H. L. Sawant,[84] S. Sayah,[180] V. Scacco,[22,23] D. Schaetzl,[12] M. Scheel,[158] A. Schiebelbein,[196] M. G. Schiworski,[83] P. Schmidt,[126] S. Schmidt,[76] R. Schnabel,[30] M. Schneewind,[9,10] R. M. S. Schofield,[82,2] K. Schouteden,[101] B. W. Schulte,[9,10] M. Schulz,[47,48] B. F. Schutz,[35,9,10] E. Schwartz,[310] M. Scialpi,[311] J. Scott,[91] S. M. Scott,[36] R. M. Sedas,[69] T. C. Seetharamu,[91] M. Seglar-Arroyo,[140] Y. Sekiguchi,[312] D. Sellers,[69] N. Sembo,[210] A. S. Sengupta,[313] E. G. Seo,[91] J. W. Seo,[101] V. Sequino,[34,4] M. Serra,[40] A. Sevrin,[194] T. Shaffer,[2] U. S. Shah,[62] M. A. Shaikh,[314] L. Shao,[315] J. Sharkey,[91] A. K. Sharma,[138] Preeti Sharma,[13] Priyanka Sharma,[108] Ritwik Sharma,[19] Sushant Sharma-Chaudhary,[19] P. Shawhan,[134] N. S. Shcheblanov,[316,271] E. Sheridan,[152] Z.-H. Shi,[156] R. Shimomura,[317] H. Shinkai,[317] S. Shirke,[84] D. H. Shoemaker,[37] D. M. Shoemaker,[157] R. W. Short,[2] S. ShyamSundar,[108] A. Sider,[165] H. Siegel,[197,198] V. Sierra,[281] D. Sigg,[2] L. Silenzi,[38,39] L. Silvestri,[41,175] M. Simmonds,[123] L. P. Singer,[318] Amitesh Singh,[221] Anika Singh,[12] D. Singh,[92] M. K. Singh,[35] N. Singh,[138] S. Singh,[222,26] M. R. Sinha,[7] A. M. Sintes,[138] V. Sipala,[193,164] V. Skliris,[35] B. J. J. Slagmolen,[36] T. J. Slaven-Blair,[6] J. Smetana,[126] D. A. Smith,[69] J. R. Smith,[59] L. Smith,[190,52] R. J. E. Smith,[7] W. J. Smith,[152] S. Soares de Albuquerque Filho,[66] K. Somiya,[222] I. Song,[156] S. Soni,[37] V. Sordini,[61] F. Sorrentino,[31] H. Sotani,[319] F. Spada,[85] V. Spagnuolo,[39] A. P. Spencer,[91] P. Spinicelli,[68] A. K. Srivastava,[98] F. Stachurski,[91] C. J. Stark,[122] D. A. Steer,[320] N. Steinle,[173] J. Steinlechner,[38,39] S. Steinlechner,[38,39] N. Stergioulas,[258] P. Stevens,[43] M. StPierre,[130] M. D. Strong,[13] A. Strunk,[2] A. L. Stuver,[107,*] M. Suchenek,[100] S. Sudhagar,[100] Y. Sudo,[239] N. Sueltmann,[30] L. Suleiman,[59] K. D. Sullivan,[13] J. Sun,[254,250] L. Sun,[36] S. Sunil,[98] J. Suresh,[120] B. J. Sutton,[72] P. J. Sutton,[35] K. Suzuki,[222] M. Suzuki,[209] A. Svizzeretto,[81] S. Swain,[126] B. L. Swinkels,[39] A. Syx,[124] M. J. Szczepańczyk,[144] P. Szewczyk,[133] M. Tacca,[39] M. Tagliazucchi,[127,78] H. Tagoshi,[209] S. C. Tait,[12] K. Takada,[209] H. Takahashi,[279] R. Takahashi,[26] A. Takamori,[58] S. Takano,[9,10] H. Takeda,[321,322] K. Takeshita,[222] I. Takimoto Schmiegelow,[47,48] M. Takou-Ayaoh,[83] C. Talbot,[139] M. Tamaki,[209] N. Tamanini,[105] D. Tanabe,[150] K. Tanaka,[54] S. J. Tanaka,[239] S. Tanioka,[35] D. B. Tanner,[49] W. Tanner,[9,10] L. Tao,[46] R. D. Tapia,[8] E. N. Tapia San Martín,[39] C. Taranto,[22,23] A. Taruya,[323] J. D. Tasson,[162] J. G. Tau,[115] A. Tejera,[170] R. Tenorio,[138] H. Themann,[212] A. Theodoropoulos,[146] M. P. Thirugnanasambandam,[84] L. M. Thomas,[12] M. Thomas,[69] P. Thomas,[2] J. E. Thompson,[216] S. R. Thondapu,[108] K. A. Thorne,[69] E. Thrane,[7] J. Tissino,[47,48] A. Tiwari,[84] Pawan Tiwari,[47] Praveer Tiwari,[201] S. Tiwari,[195] V. Tiwari,[126] E. M. Todd,[91] M. R. Todd,[83] E. Tofani,[40] M. Toffano,[96] A. M. Toivonen,[19] K. Toland,[91] A. E. Tolley,[77] T. Tomaru,[26] V. Tommasini,[12] T. Tomura,[54] H. Tong,[7] C. Tong-Yu,[150] A. Torres-Forné,[146,147] C. I. Torrie,[12] I. Tosta e Melo,[324] E. Tournefier,[33] M. Trad Nery,[120] A. Trapananti,[56,55] R. Travaglini,[78] F. Travasso,[56,55] G. Traylor,[69] M. Trevor,[134] M. C. Tringali,[68] A. Tripathee,[95] G. Troian,[190,52] A. Trovato,[190,52] L. Trozzo,[4] R. J. Trudeau,[12] T. Tsang,[35] S. Tsuchida,[325] K. Tsuji,[240] L. Tsukada,[218] K. Turbang,[194,24] M. Turconi,[120] C. Turski,[99] H. Ubach,[87,88] A. S. Ubhi,[126] N. Uchikata,[209] T. Uchiyama,[54] R. P. Udall,[121] T. Uehara,[326] K. Ueno,[45] V. Undheim,[287] L. E. Uronen,[224] T. Ushiba,[54] M. Vacatello,[85,86] H. Vahlbruch,[9,10] G. Vajente,[12] J. Valencia,[138] M. Valentini,[113,39] E. Vallejo-Pagès,[140] S. A. Vallejo-Peña,[307] S. Vallero,[29] M. van Dael,[39,327] E. Van den Bossche,[194] J. F. J. van den Brand,[38,113,39] C. Van Den Broeck,[76,39] M. van der Kolk,[113] M. van der Sluys,[39,76] A. Van de Walle,[43] J. van Dongen,[39] K. Vandra,[107] M. VanDyke,[128] H. van Haevermaet,[24] J. V. van Heijningen,[39,113] P. Van Hove,[70] J. Vanier,[267] J. Vanosky,[2] N. van Remortel,[24] M. Vardaro,[38,39] A. F. Vargas,[132] V. Varma,[143] A. Vecchio,[126] G. Vedovato,[97] J. Veitch,[91] P. J. Veitch,[123] S. Venikoudis,[16] J. Venneberg,[37] R. C. Venterea,[19] P. Verdier,[61] M. Vereecken,[16] D. Verkindt,[33] B. Verma,[143] Y. Verma,[108] S. M. Vermeulen,[12] F. Vetrano,[66] A. Veutro,[40,41] A. Viceré,[66,67] S. Vidyant,[83] A. D. Viets,[328] A. Vijaykumar,[196] A. Vilkha,[115] N. Villanueva Espinosa,[146] V. Villa-Ortega,[183] E. T. Vincent,[62] J.-Y. Vinet,[120] S. Viret,[61] S. Vitale,[37] A. Vives,[82] L. Vizmeg,[181] H. Vocca,[81,55] D. Voigt,[30] E. R. G. von Reis,[2] J. S. A. von Wrangel,[9,10] W. E. Vossius,[241] L. Vujeva,[149] S. P. Vyatchanin,[114] J. Wack,[12] L. E. Wade,[110] M. Wade,[110] K. J. Wagner,[115] L. Wallace,[12] E. J. Wang,[94] H. Wang,[222] W. H. Wang,[171] Y. F. Wang,[1] Z. Wang,[153] G. Waratkar,[201] R. L. Ward,[36] J. Warner,[2] M. Was,[33] T. Washimi,[26] N. Y. Washington,[12] B. Weaver,[2] S. A. Webster,[91] N. L. Weickhardt,[30] M. Weinert,[9,10] A. J. Weinstein,[12] R. Weiss,[37,†] L. Wen,[6] K. Wette,[36] C. Wheeler,[69] J. T. Whelan,[115] B. F. Whiting,[49] C. Whittall,[126] E. G. Wickens,[77] D. Wilken,[9,10] B. M. Williams,[128] D. Williams,[91] M. J. Williams,[77] N. S. Williams,[1] J. L. Willis,[12] B. Willke,[9,10] M. Wils,[101] L. Wilson,[110] C. W. Winborn,[111] J. Winterflood,[6] C. C. Wipf,[12] G. Woan,[91] J. Woehler,[38,39] N. E. Wolfe,[37] H. T. Wong,[150] I. C. F. Wong,[101] K. Wong,[196] T. Wouters,[76,39] J. L. Wright,[2] M. Wright,[91,76] B. Wu,[83] C. Wu,[156] D. S. Wu,[9,10] H. Wu,[156] K. Wu,[128] Q. Wu,[57] Z. Wu,[105] E. Wuchner,[59] D. M. Wysocki,[11] V. A. Xu,[92] Y. Xu,[138] N. Yadav,[29] H. Yamamoto,[12] K. Yamamoto,[160] T. S. Yamamoto,[45] T. Yamamoto,[54] R. Yamazaki,[239] T. Yan,[126] H. Yang,[280] K. Z. Yang,[19] Y. Yang,[161] Z. Yarbrough,[13] J. Yebana,[138] S.-W. Yeh,[156] A. B. Yelikar,[152] X. Yin,[37] J. Yokoyama,[329,45,44] T. Yokozawa,[54] S. Yuan,[6] H. Yuzurihara,[54] M. Zanolin,[50]

M. Zeeshan,[115] T. Zelenova,[68] J.-P. Zendri,[97] M. Zeoli,[16] M. Zerrad,[42] M. Zevin,[118] H. Zhang,[153] L. Zhang,[12] N. Zhang,[62] R. Zhang,[104] T. Zhang,[126] C. Zhao,[6] Yue Zhao,[169] Yuhang Zhao,[21] Z.-C. Zhao,[330] Y. Zheng,[111] H. Zhong,[19] H. Zhou,[83] H. O. Zhu,[6] Z.-H. Zhu,[330, 331] Z. Zhu,[115] A. B. Zimmerman,[157] L. Zimmermann,[61] and M. E. Zucker[37, 12]

(The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration)

[1]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-14476 Potsdam, Germany*
[2]*LIGO Hanford Observatory, Richland, WA 99352, USA*
[3]*Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[4]*INFN, Sezione di Napoli, I-80126 Napoli, Italy*
[5]*University of Warwick, Coventry CV4 7AL, United Kingdom*
[6]*OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia*
[7]*OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia*
[8]*The Pennsylvania State University, University Park, PA 16802, USA*
[9]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany*
[10]*Leibniz Universität Hannover, D-30167 Hannover, Germany*
[11]*University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA*
[12]*LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*
[13]*Louisiana State University, Baton Rouge, LA 70803, USA*
[14]*Tata Institute of Fundamental Research, Mumbai 400005, India*
[15]*Centre de Physique Théorique, Aix-Marseille Université, Campus de Luminy, 163 Av. de Luminy, 13009 Marseille, France*
[16]*Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[17]*Queen Mary University of London, London E1 4NS, United Kingdom*
[18]*University of California, Davis, Davis, CA 95616, USA*
[19]*University of Minnesota, Minneapolis, MN 55455, USA*
[20]*Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil*
[21]*Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France*
[22]*Università di Roma Tor Vergata, I-00133 Roma, Italy*
[23]*INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy*
[24]*Universiteit Antwerpen, 2000 Antwerpen, Belgium*
[25]*International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India*
[26]*Gravitational Wave Science Project, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan*
[27]*Advanced Technology Center, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan*
[28]*Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany*
[29]*INFN Sezione di Torino, I-10125 Torino, Italy*
[30]*Universität Hamburg, D-22761 Hamburg, Germany*
[31]*INFN, Sezione di Genova, I-16146 Genova, Italy*
[32]*Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy*
[33]*Univ. Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, F-74000 Annecy, France*
[34]*Università di Napoli "Federico II", I-80126 Napoli, Italy*
[35]*Cardiff University, Cardiff CF24 3AA, United Kingdom*
[36]*OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia*
[37]*LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[38]*Maastricht University, 6200 MD Maastricht, Netherlands*
[39]*Nikhef, 1098 XG Amsterdam, Netherlands*
[40]*INFN, Sezione di Roma, I-00185 Roma, Italy*
[41]*Università di Roma "La Sapienza", I-00185 Roma, Italy*
[42]*Aix Marseille Univ, CNRS, Centrale Med, Institut Fresnel, F-13013 Marseille, France*
[43]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[44]*Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[45]*Research Center for the Early Universe (RESCEU), The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[46]*University of California, Riverside, Riverside, CA 92521, USA*
[47]*Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy*
[48]*INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy*
[49]*University of Florida, Gainesville, FL 32611, USA*
[50]*Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA*
[51]*Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy*
[52]*INFN, Sezione di Trieste, I-34127 Trieste, Italy*
[53]*Tecnologico de Monterrey, Escuela de Ingeniería y Ciencias, 64849 Monterrey, Nuevo León, Mexico*
[54]*Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan*
[55]*INFN, Sezione di Perugia, I-06123 Perugia, Italy*
[56]*Università di Camerino, I-62032 Camerino, Italy*

[57]*University of Washington, Seattle, WA 98195, USA*
[58]*Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan*
[59]*California State University Fullerton, Fullerton, CA 92831, USA*
[60]*SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom*
[61]*Université Claude Bernard Lyon 1, CNRS, IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France*
[62]*Georgia Institute of Technology, Atlanta, GA 30332, USA*
[63]*Chennai Mathematical Institute, Chennai 603103, India*
[64]*Royal Holloway, University of London, London TW20 0EX, United Kingdom*
[65]*Department of Astronomical Science, The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan*
[66]*Università degli Studi di Urbino "Carlo Bo", I-61029 Urbino, Italy*
[67]*INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy*
[68]*European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy*
[69]*LIGO Livingston Observatory, Livingston, LA 70754, USA*
[70]*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*
[71]*Dipartimento di Fisica "E.R. Caianiello", Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[72]*King's College London, University of London, London WC2R 2LS, United Kingdom*
[73]*Korea Institute of Science and Technology Information, Daejeon 34141, Republic of Korea*
[74]*International College, Osaka University, 1-1 Machikaneyama-cho, Toyonaka City, Osaka 560-0043, Japan*
[75]*Accelerator Laboratory, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba City, Ibaraki 305-0801, Japan*
[76]*Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, 3584 CC Utrecht, Netherlands*
[77]*University of Portsmouth, Portsmouth, PO1 3FX, United Kingdom*
[78]*Istituto Nazionale Di Fisica Nucleare - Sezione di Bologna, viale Carlo Berti Pichat 6/2 - 40127 Bologna, Italy*
[79]*Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy*
[80]*INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy*
[81]*Università di Perugia, I-06123 Perugia, Italy*
[82]*University of Oregon, Eugene, OR 97403, USA*
[83]*Syracuse University, Syracuse, NY 13244, USA*
[84]*Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India*
[85]*INFN, Sezione di Pisa, I-56127 Pisa, Italy*
[86]*Università di Pisa, I-56127 Pisa, Italy*
[87]*Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), c. Martí i Franquès, 1, 08028 Barcelona, Spain*
[88]*Departament de Física Quàntica i Astrofísica (FQA), Universitat de Barcelona (UB), c. Martí i Franqués, 1, 08028 Barcelona, Spain*
[89]*Institut d'Estudis Espacials de Catalunya, c. Gran Capità, 2-4, 08034 Barcelona, Spain*
[90]*Dipartimento di Medicina, Chirurgia e Odontoiatria "Scuola Medica Salernitana", Università di Salerno, I-84081 Baronissi, Salerno, Italy*
[91]*IGR, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[92]*University of California, Berkeley, CA 94720, USA*
[93]*HUN-REN Wigner Research Centre for Physics, H-1121 Budapest, Hungary*
[94]*Stanford University, Stanford, CA 94305, USA*
[95]*University of Michigan, Ann Arbor, MI 48109, USA*
[96]*Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy*
[97]*INFN, Sezione di Padova, I-35131 Padova, Italy*
[98]*Institute for Plasma Research, Bhat, Gandhinagar 382428, India*
[99]*Universiteit Gent, B-9000 Gent, Belgium*
[100]*Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland*
[101]*Katholieke Universiteit Leuven, Oude Markt 13, 3000 Leuven, Belgium*
[102]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, Avda. Complutense 40, 28040, Madrid, Spain*
[103]*Aix-Marseille Université, Université de Toulon, CNRS, CPT, Marseille, France*
[104]*Northeastern University, Boston, MA 02115, USA*
[105]*Laboratoire des 2 Infinis - Toulouse (L2IT-IN2P3), F-31062 Toulouse Cedex 9, France*
[106]*Università di Siena, Dipartimento di Scienze Fisiche, della Terra e dell'Ambiente, I-53100 Siena, Italy*
[107]*Villanova University, Villanova, PA 19085, USA*
[108]*RRCAT, Indore, Madhya Pradesh 452013, India*
[109]*University of Maryland, Baltimore County, Baltimore, MD 21250, USA*
[110]*Kenyon College, Gambier, OH 43022, USA*
[111]*Missouri University of Science and Technology, Rolla, MO 65409, USA*
[112]*Indian Institute of Technology Madras, Chennai 600036, India*
[113]*Department of Physics and Astronomy, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands*
[114]*Lomonosov Moscow State University, Moscow 119991, Russia*
[115]*Rochester Institute of Technology, Rochester, NY 14623, USA*
[116]*Université libre de Bruxelles, 1050 Bruxelles, Belgium*
[117]*Bar-Ilan University, Ramat Gan, 5290002, Israel*

[118]*Northwestern University, Evanston, IL 60208, USA*
[119]*Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[120]*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Artemis, F-06304 Nice, France*
[121]*University of British Columbia, Vancouver, BC V6T 1Z4, Canada*
[122]*Christopher Newport University, Newport News, VA 23606, USA*
[123]*OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia*
[124]*Centre national de la recherche scientifique, 75016 Paris, France*
[125]*Univ Rennes, CNRS, Institut FOTON - UMR 6082, F-35000 Rennes, France*
[126]*University of Birmingham, Birmingham B15 2TT, United Kingdom*
[127]*DIFA- Alma Mater Studiorum Università di Bologna, Via Zamboni, 33 - 40126 Bologna, Italy*
[128]*Washington State University, Pullman, WA 99164, USA*
[129]*Cornell University, Ithaca, NY 14850, USA*
[130]*University of Rhode Island, Kingston, RI 02881, USA*
[131]*Laboratoire Kastler Brossel, Sorbonne Université, CNRS,*
ENS-Université PSL, Collège de France, F-75005 Paris, France
[132]*OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia*
[133]*Astronomical Observatory, University of Warsaw, 00-478 Warsaw, Poland*
[134]*University of Maryland, College Park, MD 20742, USA*
[135]*Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy*
[136]*INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy*
[137]*Université de Lyon, Université Claude Bernard Lyon 1,*
CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France
[138]*IAC3–IEEC, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain*
[139]*University of Chicago, Chicago, IL 60637, USA*
[140]*Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of*
Science and Technology, Campus UAB, E-08193 Bellaterra (Barcelona), Spain
[141]*University of Arizona, Tucson, AZ 85721, USA*
[142]*INFN, Sezione di Napoli, Gruppo Collegato di Salerno, I-80126 Napoli, Italy*
[143]*University of Massachusetts Dartmouth, North Dartmouth, MA 02747, USA*
[144]*Faculty of Physics, University of Warsaw, Ludwika Pasteura 5, 02-093 Warszawa, Poland*
[145]*Istituto di Astrofisica e Planetologia Spaziali di Roma, 00133 Roma, Italy*
[146]*Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain*
[147]*Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain*
[148]*OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia*
[149]*Niels Bohr Institute, University of Copenhagen, 2100 Kóbenhavn, Denmark*
[150]*National Central University, Taoyuan City 320317, Taiwan*
[151]*OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia*
[152]*Vanderbilt University, Nashville, TN 37235, USA*
[153]*University of Chinese Academy of Sciences / International Centre for Theoretical Physics Asia-Pacific, Beijing 100190, China*
[154]*Institute of Physics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan*
[155]*Kamioka Branch, National Astronomical Observatory of Japan,*
238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan
[156]*National Tsing Hua University, Hsinchu City 30013, Taiwan*
[157]*University of Texas, Austin, TX 78712, USA*
[158]*CaRT, California Institute of Technology, Pasadena, CA 91125, USA*
[159]*Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy*
[160]*Faculty of Science, University of Toyama, 3190 Gofuku, Toyama City, Toyama 930-8555, Japan*
[161]*School of Physical Science and Technology, ShanghaiTech University,*
393 Middle Huaxia Road, Pudong, Shanghai, 201210, China
[162]*Carleton College, Northfield, MN 55057, USA*
[163]*University of Szeged, Dóm tér 9, Szeged 6720, Hungary*
[164]*INFN Cagliari, Physics Department, Università degli Studi di Cagliari, Cagliari 09042, Italy*
[165]*Université Libre de Bruxelles, Brussels 1050, Belgium*
[166]*INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy*
[167]*Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain*
[168]*Montana State University, Bozeman, MT 59717, USA*
[169]*The University of Utah, Salt Lake City, UT 84112, USA*
[170]*Johns Hopkins University, Baltimore, MD 21218, USA*
[171]*The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA*
[172]*Université de Liège, B-4000 Liège, Belgium*
[173]*University of Manitoba, Winnipeg, MB R3T 2N2, Canada*
[174]*INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy*
[175]*INFN-CNAF - Bologna, Viale Carlo Berti Pichat, 6/2, 40127 Bologna BO, Italy*
[176]*Colorado State University, Fort Collins, CO 80523, USA*

[177]*Université de Normandie, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France*
[178]*Laboratoire de Physique Corpusculaire Caen, 6 boulevard du maréchal Juin, F-14050 Caen, France*
[179]*The University of Sheffield, Sheffield S10 2TN, United Kingdom*
[180]*Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France*
[181]*Western Washington University, Bellingham, WA 98225, USA*
[182]*Università di Firenze, Sesto Fiorentino I-50019, Italy*
[183]*IGFAE, Universidade de Santiago de Compostela, E-15782 Santiago de Compostela, Spain*
[184]*Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy*
[185]*INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy*
[186]*Marquette University, Milwaukee, WI 53233, USA*
[187]*Perimeter Institute, Waterloo, ON N2L 2Y5, Canada*
[188]*Scuola Normale Superiore, I-56126 Pisa, Italy*
[189]*Corps des Mines, Mines Paris, Université PSL, 60 Bd Saint-Michel, 75272 Paris, France*
[190]*Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
[191]*Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange, F-06304 Nice, France*
[192]*National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland*
[193]*Università degli Studi di Sassari, I-07100 Sassari, Italy*
[194]*Vrije Universiteit Brussel, 1050 Brussel, Belgium*
[195]*University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland*
[196]*Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada*
[197]*Stony Brook University, Stony Brook, NY 11794, USA*
[198]*Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*
[199]*Montclair State University, Montclair, NJ 07043, USA*
[200]*HUN-REN Institute for Nuclear Research, H-4026 Debrecen, Hungary*
[201]*Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India*
[202]*Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, PT-4710-057 Braga, Portugal*
[203]*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
[204]*CNR-SPIN, I-84084 Fisciano, Salerno, Italy*
[205]*Dipartimento di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy*
[206]*SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom*
[207]*Barry University, Miami Shores, FL 33168, USA*
[208]*Eötvös University, Budapest 1117, Hungary*
[209]*Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan*
[210]*Department of Physics, Graduate School of Science, Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan*
[211]*University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy*
[212]*California State University, Los Angeles, Los Angeles, CA 90032, USA*
[213]*Instituto de Fisica Teorica UAM-CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain*
[214]*Istituto Nazionale di Astrofisica - Osservatorio di Roma, Viale del Parco Mellini 84 - 00136 Roma, Italy*
[215]*Laboratoire d'Acoustique de l'Université du Mans, UMR CNRS 6613, F-72085 Le Mans, France*
[216]*University of Southampton, Southampton SO17 1BJ, United Kingdom*
[217]*Dipartimento di Ingegneria Industriale, Elettronica e Meccanica, Università degli Studi Roma Tre, I-00146 Roma, Italy*
[218]*University of Nevada, Las Vegas, Las Vegas, NV 89154, USA*
[219]*University of Nottingham NG7 2RD, UK*
[220]*Ariel University, Ramat HaGolan St 65, Ari'el, Israel*
[221]*The University of Mississippi, University, MS 38677, USA*
[222]*Graduate School of Science, Institute of Science Tokyo, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan*
[223]*Institute of Physics, Academia Sinica, 128 Sec. 2, Academia Rd., Nankang, Taipei 11529, Taiwan*
[224]*The Chinese University of Hong Kong, Shatin, NT, Hong Kong*
[225]*Nirula Institute of Technology, Kolkata, West Bengal 700109, India*
[226]*Niels Bohr Institute, Copenhagen University, 2100 København, Denmark*
[227]*American University, Washington, DC 20016, USA*
[228]*Dipartimento di Fisica, Università degli studi di Milano, Via Celoria 16, I-20133, Milano, Italy*
[229]*INFN, sezione di Milano, Via Celoria 16, I-20133, Milano, Italy*
[230]*Department of Applied Physics, Fukuoka University, 8-19-1 Nanakuma, Jonan, Fukuoka City, Fukuoka 814-0180, Japan*
[231]*University of Cambridge, Cambridge CB2 1TN, United Kingdom*
[232]*University of Lancaster, Lancaster LA1 4YW, United Kingdom*

[233]*College of Industrial Technology, Nihon University, 1-2-1 Izumi, Narashino City, Chiba 275-8575, Japan*
[234]*Faculty of Engineering, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan*
[235]*Saha Institute of Nuclear Physics, Bidhannagar, West Bengal 700064, India*
[236]*Department of Physics, Tamkang University, No. 151,*
Yingzhuan Rd., Danshui Dist., New Taipei City 25137, Taiwan
[237]*Department of Electrophysics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan*
[238]*Rutherford Appleton Laboratory, Didcot OX11 0DE, United Kingdom*
[239]*Department of Physical Sciences, Aoyama Gakuin University,*
5-10-1 Fuchinobe, Sagamihara City, Kanagawa 252-5258, Japan
[240]*Nagoya University, Nagoya, 464-8601, Japan*
[241]*Helmut Schmidt University, D-22043 Hamburg, Germany*
[242]*Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP),*
Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
[243]*Directorate of Construction, Services & Estate Management, Mumbai 400094, India*
[244]*Observatoire Astronomique de Strasbourg, Université de Strasbourg,*
CNRS, 11 rue de l'Université, 67000 Strasbourg, France
[245]*Faculty of Physics, University of Białystok, 15-245 Białystok, Poland*
[246]*National Astronomical Observatories, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing, China*
[247]*School of Astronomy and Space Science, University of Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing, China*
[248]*Sungkyunkwan University, Seoul 03063, Republic of Korea*
[249]*Department of Physics, Ulsan National Institute of Science and Technology (UNIST),*
50 UNIST-gil, Ulju-gun, Ulsan 44919, Republic of Korea
[250]*Chung-Ang University, Seoul 06974, Republic of Korea*
[251]*University of Washington Bothell, Bothell, WA 98011, USA*
[252]*Laboratoire de Physique et de Chimie de l'Environnement,*
Université Joseph KI-ZERBO, 9GH2+3V5, Ouagadougou, Burkina Faso
[253]*Ewha Womans University, Seoul 03760, Republic of Korea*
[254]*National Institute for Mathematical Sciences, Daejeon 34047, Republic of Korea*
[255]*Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea*
[256]*Department of Astronomy and Space Science, Chungnam National University,*
9 Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea
[257]*Division of Science, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan*
[258]*Department of Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece*
[259]*Bard College, Annandale-On-Hudson, NY 12504, USA*
[260]*Technical University of Braunschweig, D-38106 Braunschweig, Germany*
[261]*Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland*
[262]*Astronomical Observatory, Jagiellonian University, 31-007 Cracow, Poland*
[263]*Department of Physics and Astronomy, University of Padova, Via Marzolo, 8-35151 Padova, Italy*
[264]*Sezione di Padova, Istituto Nazionale di Fisica Nucleare (INFN), Via Marzolo, 8-35131 Padova, Italy*
[265]*Instituto de Fisica Teorica UAM-CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain*
[266]*Department of Physics, Nagoya University, ES building, Furocho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan*
[267]*Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada*
[268]*Università degli Studi di Cagliari, Via Università 40, 09124 Cagliari, Italy*
[269]*Department of Computer Simulation, Inje University,*
197 Inje-ro, Gimhae, Gyeongsangnam-do 50834, Republic of Korea
[270]*Korea Astronomy and Space Science Institute (KASI),*
776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea
[271]*NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France*
[272]*Gravitational Wave Science Project, National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan*
[273]*Department of Physics, National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan*
[274]*St. Thomas University, Miami Gardens, FL 33054, USA*
[275]*Institució Catalana de Recerca i Estudis Avançats, E-08010 Barcelona, Spain*
[276]*Institut de Física d'Altes Energies, E-08193 Barcelona, Spain*
[277]*Institut fuer Theoretische Astrophysik, Zentrum fuer Astronomie Heidelberg,*
Universitaet Heidelberg, Albert Ueberle Str. 2, 69120 Heidelberg, Germany
[278]*Institucio Catalana de Recerca i Estudis Avançats (ICREA),*
Passeig de Lluís Companys, 23, 08010 Barcelona, Spain
[279]*Research Center for Space Science, Advanced Research Laboratories, Tokyo City University,*
3-3-1 Ushikubo-Nishi, Tsuzuki-Ku, Yokohama, Kanagawa 224-8551, Japan
[280]*Tsinghua University, Beijing 100084, China*
[281]*Universidad de Guadalajara, 44430 Guadalajara, Jalisco, Mexico*
[282]*Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France*
[283]*Faculty of Law, Ryukoku University, 67 Fukakusa Tsukamoto-cho, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan*
[284]*Istituto Nazionale di Fisica Nucleare (INFN), Universita di Roma "La Sapienza", P.le A. Moro 2, 00185 Roma, Italy*

[285]*Indian Institute of Science Education and Research, Kolkata, Mohanpur, West Bengal 741252, India*
[286]*Phenikaa Institute for Advanced Study (PIAS), Phenikaa University, Yen Nghia, Ha Dong, Hanoi, Vietnam*
[287]*University of Stavanger, 4021 Stavanger, Norway*
[288]*Department of Astronomy, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[289]*Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 1-3-1 Kagamiyama, Higashihiroshima City, Hiroshima 739-8526, Japan*
[290]*GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, Netherlands*
[291]*University College London, London WC1E 6BT, United Kingdom*
[292]*Observatoire de Paris, 75014 Paris, France*
[293]*Graduate School of Science and Technology, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan*
[294]*Niigata Study Center, The Open University of Japan, 754 Ichibancho, Asahimachi-dori, Chuo-ku, Niigata City, Niigata 951-8122, Japan*
[295]*CSIR-Central Glass and Ceramic Research Institute, Kolkata, West Bengal 700032, India*
[296]*Consiglio Nazionale delle Ricerche - Istituto dei Sistemi Complessi, I-00185 Roma, Italy*
[297]*Department of Astronomy, Yonsei University, 50 Yonsei-Ro, Seodaemun-Gu, Seoul 03722, Republic of Korea*
[298]*Department of Physics, University of Guadalajara, Av. Revolucion 1500, Colonia Olimpica C.P. 44430, Guadalajara, Jalisco, Mexico*
[299]*Hobart and William Smith Colleges, Geneva, NY 14456, USA*
[300]*INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy*
[301]*Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy*
[302]*Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 75014 Paris, France*
[303]*Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", I-00184 Roma, Italy*
[304]*Kennesaw State University, Kennesaw, GA 30144, USA*
[305]*Government Victoria College, Palakkad, Kerala 678001, India*
[306]*Subatech, CNRS/IN2P3 - IMT Atlantique - Nantes Université, 4 rue Alfred Kastler BP 20722 44307 Nantes CÉDEX 03, France*
[307]*Universidad de Antioquia, Medellín, Colombia*
[308]*Departamento de Física - ETSIDI, Universidad Politécnica de Madrid, 28012 Madrid, Spain*
[309]*Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, 888 Nishikatakai, Nagaoka City, Niigata 940-8532, Japan*
[310]*Trinity College, Hartford, CT 06106, USA*
[311]*Dipartimento di Fisica e Scienze della Terra, Università Degli Studi di Ferrara, Via Saragat, 1, 44121 Ferrara FE, Italy*
[312]*Faculty of Science, Toho University, 2-2-1 Miyama, Funabashi City, Chiba 274-8510, Japan*
[313]*Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India*
[314]*Seoul National University, Seoul 08826, Republic of Korea*
[315]*Kavli Institute for Astronomy and Astrophysics, Peking University, Yiheyuan Road 5, Haidian District, Beijing 100871, China*
[316]*Laboratoire MSME, Cité Descartes, 5 Boulevard Descartes, Champs-sur-Marne, 77454 Marne-la-Vallée Cedex 2, France*
[317]*Faculty of Information Science and Technology, Osaka Institute of Technology, 1-79-1 Kitayama, Hirakata City, Osaka 573-0196, Japan*
[318]*NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[319]*Faculty of Science and Technology, Kochi University, 2-5-1 Akebono-cho, Kochi-shi, Kochi 780-8520, Japan*
[320]*Laboratoire de Physique de l'École Normale Supérieure, ENS, (CNRS, Université PSL, Sorbonne Université, Université Paris Cité), F-75005 Paris, France*
[321]*The Hakubi Center for Advanced Research, Kyoto University, Yoshida-honmachi, Sakyou-ku, Kyoto City, Kyoto 606-8501, Japan*
[322]*Department of Physics, Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
[323]*Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan*
[324]*University of Catania, Department of Physics and Astronomy, Via S. Sofia, 64, 95123 Catania CT, Italy*
[325]*National Institute of Technology, Fukui College, Geshi-cho, Sabae-shi, Fukui 916-8507, Japan*
[326]*Department of Communications Engineering, National Defense Academy of Japan, 1-10-20 Hashirimizu, Yokosuka City, Kanagawa 239-8686, Japan*
[327]*Eindhoven University of Technology, 5600 MB Eindhoven, Netherlands*
[328]*Concordia University Wisconsin, Mequon, WI 53097, USA*
[329]*Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), WPI, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8583, Japan*
[330]*Department of Astronomy, Beijing Normal University, Xinjiekouwai Street 19, Haidian District, Beijing 100875, China*

[331]*School of Physics and Technology, Wuhan University,*
Bayi Road 299, Wuchang District, Wuhan, Hubei, 430072, China
(Dated: August 13, 2026)

GW240925 and GW250207 are two loud gravitational-wave signals from binary black hole coalescences observed with network signal-to-noise ratios ∼ 32 and ∼ 69, respectively, by the LIGO Hanford–LIGO Livingston–Virgo network. Gravitational-wave signals from coalescing binaries have characteristic phase and amplitude evolution predicted by general relativity. These signal waveforms, together with measured instrumental calibration uncertainties, are used to infer source parameters. However, for sufficiently loud detections it is possible to constrain the calibration of the detectors directly using the signals themselves. We present the first informative astrophysical measurements of gravitational-wave detector calibration. For GW240925, we verify the inference of Hanford calibration from the astrophysical signal through cross-checks with known calibration errors obtained from in-situ measurements. At the time of GW250207, the Hanford detector was not fully stabilized, leading to elevated calibration uncertainties; thus, astrophysical calibration is essential to obtain accurate data and to enable source localization. These well-localized, high signal-to-noise observations have the potential to offer precise measurements of source properties, stringent tests of general relativity, and informative dark siren measurements, provided that calibration uncertainties are properly incorporated. As detector sensitivity improves, astrophysical calibration will become an increasingly valuable complement to in-situ calibration measurements. Obtaining accurate calibration will be essential for precision gravitational-wave science.

Introduction— We report the discovery of GW240925_005809 and GW250207_115645 (hereafter, GW240925 and GW250207), two loud gravitational-wave (GW) signals detected by the Laser Interferometer Gravitational-Wave Observatory (LIGO) Hanford, LIGO Livingston and Virgo during their fourth observing run (O4). Since the first direct observation of GWs in 2015 [1], the LIGO–Virgo–KAGRA (LVK) network [2–4] has undergone substantial upgrades, achieving a roughly tenfold increase in detection rate and facilitating high signal-to-noise ratio (SNR) observations of compact binary coalescences (CBCs) [5–10]. These advances mark a transition from an era of initial discoveries to one of precision GW astronomy. High-SNR observations enable precise measurements of signal properties [11–13], advancing our understanding of source astrophysics, the nature of gravity, and cosmology.

Interpreting GW signals requires accurate understanding of detector behavior [13]. GW240925 and GW250207 both coincide with times when the LIGO Hanford detector was not in its usual observational state with well-characterized calibration. The calibration process typically reconstructs the raw digitized output of each interferometer into an accurate and reliable measure of the dimensionless strain [14–17]. Its accuracy directly impacts signal-parameter estimation [18, 19]; miscalibrations can bias inferred source properties [20, 21], affect cosmological measurements [22] and even mimic or obscure deviations from general relativity (GR) [23, 24]. To take advantage of the small statistical uncertainties offered by high SNRs, we must ensure small systematic uncertainties.

Fortunately, GW signals can be used to constrain the detector response directly. This *astrophysical* calibration approach leverages accurate modeling of GW waveforms, allowing the astrophysical signal to serve as an independent reference for the frequency-dependent detector calibration [5, 25, 26]. Astrophysical calibration may be performed in a variety of ways: using the frequency and amplitude evolution of the (predicted) signal to infer calibration parameters together with source parameters [26–28]; using an electromagnetic counterpart (and assumed cosmology) to establish the distance to a source [29], which provides more information than using the GW signal alone [26]; combining data from multiple detectors so the signals should cancel out if the data are correctly calibrated [30], or using the population of detections to constrain the relative sensitivity of the detectors [31]. The sensitivity of the first years of observations was insufficient for astrophysical measurements to be informative compared to in-situ results [26–28], but with the improvements in the detector network, astrophysical calibration is now becoming feasible.

We present the first astrophysical calibrations of a GW detector used to enhance our understanding of the state of the instrument. We perform a coherent analysis of data from Hanford, Livingston and Virgo for GW240925 and GW250207, inferring calibration properties for Hanford at the times of the two observations using the GW signals.

For GW240925, there was a significant frequency-dependent calibration systematic error for Hanford at the time of the observation. The frequency-dependent error can be inferred using the signal, and cross-checked with the in-situ measurements. Agreement between results validates the GW-informed calibration measurements and demonstrates the utility of inferring calibration from an astrophysical signal.

At the time of GW250207, the Hanford detector response had not yet fully stabilized, leading to larger calibration uncertainties. Lacking in-situ measurements of the calibration, astrophysical calibration was essential to ensure the reliability of the Hanford data and accurate inference of source properties such as localization.

These results establish astrophysical calibration as a complementary cross-check and, when required, a critical input to GW analysis. While not yet as precise as typical in-situ measurements, astrophysical calibration will improve as detector sensitivity continues to be enhanced.

Detector calibration— GW detectors like LIGO [2], Virgo [3] and KAGRA [4] are enhanced Michelson interfer-

ometers that measure spacetime strain by detecting changes in light-travel time between their orthogonal arms [32, 33]. The detector output strain data d are defined as the free (uncontrolled) differential change in arm length $\Delta L_{\rm free}$ divided by arm length L, i.e., $d \equiv \Delta L_{\rm free}/L$; however, $\Delta L_{\rm free}$ is not directly measurable, as the detector actively suppresses differential motion via feedback control. A detailed *calibration* procedure is, therefore required to convert the raw digitized electrical output of the detector into the reconstructed strain data [14–16, 34, 35].

To reconstruct the strain, we need the frequency-dependent and time-varying detector response function $R(f;t)$ (detailed in Supplemental Material [36]); however, in the calibration procedure, the true response function is not perfectly known. The strain data are reconstructed using a *modeled* response function $R^{(\rm model)}(f;t)$ [14–16]. Calibration systematic errors arise from discrepancies between the true and modeled response functions; these errors and associated statistical uncertainties directly translate into the errors and uncertainties in the reconstructed d. In the absence of configuration changes (which are typically associated with updates to $R^{(\rm model)}$), $R(f;t)$ remains approximately stable, but it can vary on hour timescales during periods of evolving detector state, e.g., at the beginning of a lock stretch (see discussion of thermal lens below) [37]. For LIGO, we quantify calibration errors using a complex correction factor $\eta(f;t)$ [16, 38]:

$$\eta(f;t) = \frac{R(f;t)}{R^{(\rm model)}(f;t)} = \left[1 + \delta\mathcal{A}(f;t)\right] \exp\left[i\delta\phi(f;t)\right], \quad (1)$$

where $\delta\mathcal{A}(f;t)$ and $\delta\phi(f;t)$ denote amplitude and phase errors, respectively. A more accurate estimate of the true strain is obtained by multiplying the (frequency-domain) detector strain data by the correction factor η,

$$d^{(\rm corr)} = \eta d. \quad (2)$$

The probability distribution of $\eta(f;t)$ is evaluated using in-situ calibration measurements, primarily through excitations via photon calibrators [39–42] and quadruple-pendulum actuators [16, 43], and is used to construct the calibration prior for signal parameter estimation [44] (see Supplemental Material [36]).

The low-latency, online calibrated (C00) strain data produced during observing runs may contain systematic errors due to model inaccuracies that are not identified or corrected in real time. In previous observing runs, offline calibrated data (C01) were produced for the LIGO detectors as the standard final data product, incorporating all known corrections [14–16]. In O4, the photon calibrators were used to monitor the calibration accuracy at a discrete set of frequencies in real time [17, 43], and C01 data were generated when necessary, e.g., when the calibration error was known to exceed $\sim 10\%$ in amplitude or ~ 10 deg in phase (68% probability).

At the times of GW240925 and GW250207, Livingston and Virgo were observing normally, but the Hanford detector was either miscalibrated or still stabilizing, with a response deviating from the modeled behavior. KAGRA was not observing over this period of O4 [5]. Detailed real-time calibration monitoring measurements [43] at the Hanford detector around the times of these two observations are provided in Supplemental Material [36]. The Livingston and Virgo detectors had reliable calibration: in the most sensitive frequency band 20–2000 Hz, their frequency-dependent uncertainties (68% probability) were constrained to $\lesssim 2\%$ in amplitude and $\lesssim 2$ deg in phase for Livingston, and $\lesssim 2.5\%$ in amplitude and $\lesssim 6$ deg ($\lesssim 3$ deg below 500 Hz) in phase for Virgo [45].

For GW240925, a procedural inconsistency at Hanford resulted in a temporary mismatch between a calibration parameter used in the interferometer control system and the corresponding value adopted in the calibration model. The mismatch led to a mischaracterization of the detector response, introducing a frequency-dependent systematic error in the reconstructed strain data. The error reached up to $\sim 20\%$ in amplitude and ~ 12 deg in phase across the sensitive frequency band [46]. This large error in the C00 calibration, combined with GW240925's high SNR, provided a unique opportunity to cross-check signal-informed astrophysical calibration with in-situ measurements. C01 data were later generated around the time of GW240925, correcting the miscalibration.

For GW250207, the Hanford detector had just reached its low-noise operational state but had not yet formally entered observing mode [46]. The detector was still settling; in particular, the changing thermal lens of the test masses affected the low-frequency response [10]. While real-time calibration monitoring can provide valuable information about the evolution of systematic errors during such transient periods [43], the monitoring lines had not yet stabilized, and several were not yet recording measurements. As a result, no reliable measurement of the real-time detector response is available for this period, and the associated calibration systematic errors and uncertainties in the Hanford strain data cannot be robustly quantified using in-situ measurements. Astrophysical calibration is essential to analyze Hanford data.

Detection— GW240925 and GW250207 were observed by the three-detector Hanford–Livingston–Virgo network. Time–frequency spectrograms of the data around the two signals are shown in Fig. 1. The characteristic chirps of CBC signals are visible sweeping up from low frequencies.

GW240925 was observed at 00:58:09 Coordinated Universal Time (UTC) on September 25, 2024 during the second part of O4 (O4b). It was identified in low latency in Hanford and Livingston data by the minimally modeled cWB [48–51] pipeline as well as the GstLAL [52–60], MBTA [61–63] and SPIIR [64] matched-filtering pipelines. The candidate was identified with SNRs of 17.3 and 25.8 in Hanford and Livingston, respectively, and a false alarm rate (FAR) of $< 1 \times 10^{-5}$ yr^{-1}. The Virgo detector was operating at the time, but the candidate's SNR of 2.7 was too small to contribute to the coincident detection. Nevertheless, the Virgo SNR time series was analyzed by BAYESTAR [65, 66] to infer the location. General Coordinate Network (GCN) Notices and Circulars about the detection were shared in low latency [67].

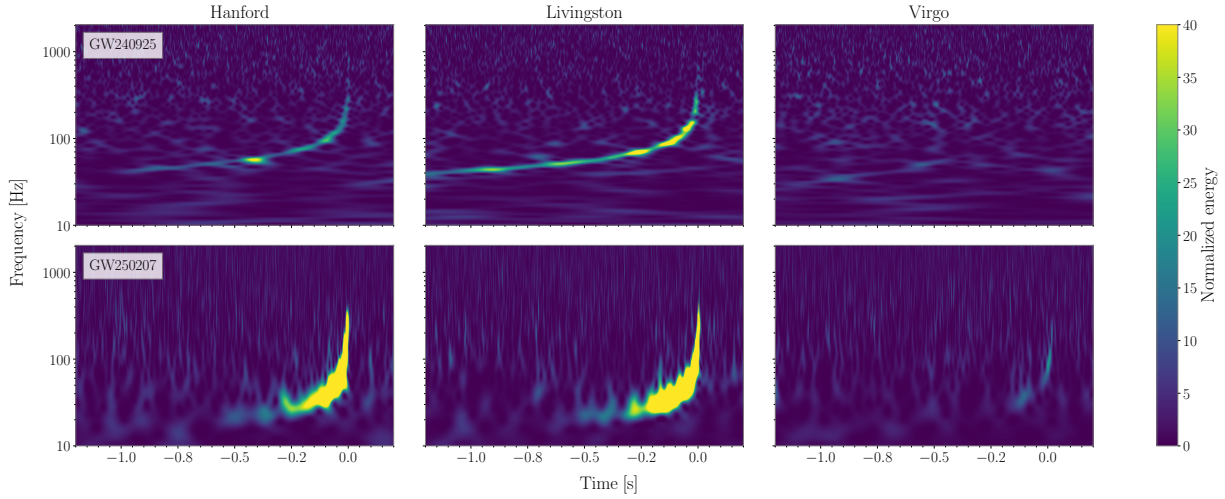

FIG. 1. Time–frequency spectrograms [47] showing data from LIGO Hanford (left), LIGO Livingston (middle) and Virgo (right) for GW240925 (top) and GW250207 (bottom). Times are relative to the times reported from the search algorithms for the two detections. We use C00 LIGO data. The data are whitened [13], and the scale bar shows the normalized energy.

Data quality (DQ) was scrutinized around GW240925 following established procedures [68]. We identified a burst of non-Gaussian noise (a *glitch* [69, 70]) in Livingston data, but this occurred sufficiently after the signal to not require mitigation [71]. No DQ issues impacting the analysis were found.

GW250207 was observed at 11:56:45 UTC on February 7, 2025 during the third part of O4 (O4c). It was identified in low latency in Livingston and Virgo data by the GstLAL and SPIIR search pipelines. The signal was measured with SNRs of 48.3 and 8.1 in the Livingston and Virgo detectors, respectively, and a FAR of $< 1 \times 10^{-5}$ yr^{-1}. DQ checks [68] revealed no issues impacting the detection. As Hanford was not in observing mode, its data were not used in low-latency, but they were later determined to be of good quality [46]. GCN Notices and Circulars were again shared in low latency [72].

Further DQ and search-analysis results for both detections are given in the Supplemental Material [36].

Inference of calibration errors and source properties— We analyze the detector data for each signal using Bilby [73, 74] to obtain posterior probability distributions on the parameters $\boldsymbol{\theta}$ characterizing the source binary and those describing the calibration of each detector [44]. We assume that a GR waveform $h(\boldsymbol{\theta})$ accurately describes the signal. To account for calibration uncertainty, the reciprocal of the correction factor $(1/\eta)$ is applied to the waveform. This reciprocal factor is parametrized using amplitude and phase deviations, derived from their counterparts in Eq. (1) [44, 75], which are modeled using splines and inferred from the data [44, 76, 77]. Further details on inferences are given in Supplemental Material [36].

The consistency of the signal across frequencies and between detectors provides information about the detector calibration. Typically, we use the in-situ measured calibration-uncertainty estimates from the time closest to the signal as priors in the analysis. As these are usually well constrained, the GW signal adds little information [6, 26]. However, for higher SNR signals or cases where calibration errors are significant, astrophysical calibration is expected to become informative.

We first demonstrate the measurement of the Hanford calibration error with GW240925, performing three analyses. For each, we use the usual calibration priors informed by in-situ measurements for Livingston and Virgo. We analyze LIGO C00 data, which contain the large Hanford calibration error, assuming two different priors for the Hanford calibration: one narrow, informed by in-situ measurements, and one wide across all frequencies. As the cause of the calibration error can be identified, we can directly compare the in-situ measured calibration error to the calibration independently inferred from the signal. We also analyze LIGO C01 data, where the calibration error has been corrected, assuming a narrow in-situ calibration prior.

In Fig. 2 (left), we plot the Hanford calibration parameters for GW240925 as a function of frequency. With the wide prior, the posterior provides the tightest constraints at frequencies where the signal is loud (below the peak of the dominant $\ell = |m| = 2$ multipole at a frequency $f_{22}^{\rm peak}$ of $\sim$ 680 Hz), and it tends toward the prior at higher frequencies where there is no signal to constrain the calibration (the oscillations reflect the discrete placement of spline nodes). To quantify the difference between the wide prior and the corresponding posterior, we use the Jensen–Shannon divergences (JSDs) [78] between the distributions, finding $0.06^{+0.09}_{-0.05}$ nat for amplitude and $0.05^{+0.13}_{-0.05}$ nat for phase, quoting the median and 90% range across the frequency nodes, where JSD $\lesssim 0.002$ nat is considered a negligible difference [74]. This indicates that the posterior is informed by the signal at various frequencies. The posterior obtained with the wide, uninformative prior agrees well with the results informed by the in-situ measurements, demonstrating that detector calibration can be inferred from an astrophysical signal. Although the signal-informed cali-

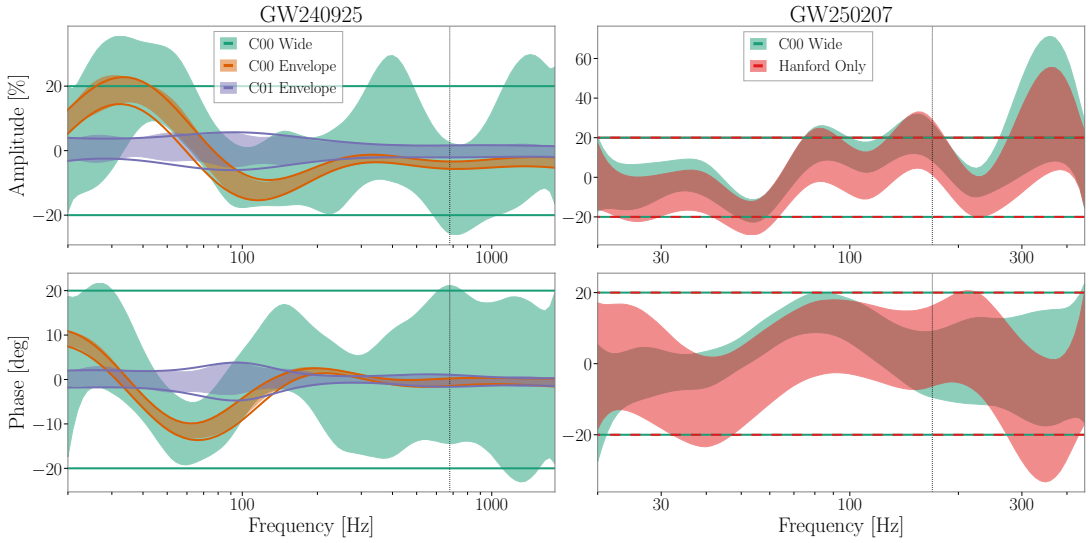

FIG. 2. LIGO Hanford calibration as a function of frequency over the analysis band for each signal. The top and bottom panels show the frequency-dependent amplitude error $\delta\mathcal{A}$ and phase error $\delta\phi$, respectively. Shaded regions indicate the 68% credible intervals of the posteriors, and the lines denote the 68% probability envelopes from which the priors are derived (see Supplemental Material [36]). GW240925 results (left) are from three analyses: one using a wide, uninformative prior on the miscalibrated C00 data (green), one using a narrow prior envelope based upon in-situ measurements on the same data (orange), and one using a narrow in-situ measured prior envelope for the recalibrated C01 data (purple). GW250207 results (right) are from two analyses, both using the same wide priors on the miscalibrated Hanford C00 data: one using data from all three detectors (green), with the in-situ priors applied to Livingston and Virgo data, and one using only Hanford data (red). Results are more informative for frequencies where there is more signal power (Fig. 1), and the dotted vertical lines indicate the approximate peak frequencies $f_{22}^{\rm peak}$ for the $\ell = |m| = 2$ multipole of the signals.

bration is less constrained than the in-situ measurements, it provides an independent cross-check and a valuable diagnostic for uncovering analysis inconsistencies. In this case, the direct comparison between constraints revealed (and led to the correction of) a long-standing convention mismatch in the analysis procedure for incorporating calibration uncertainties, which had only had a minor effect prior to O4 [44, 75]. Results from the C01 data for both LIGO detectors and Virgo are consistent with zero error, as expected after calibration correction.

We find that inferred source parameters are typically consistent between analyses. We adopt the C01 results as our default for interpretation, with medians and 90% symmetric credible intervals for the parameters listed in Table I.

The sky localization is illustrated in Fig. 3. Calibration uncertainty can have a significant impact on source localization [20, 27, 79], and using the wider calibration prior increases the localization area. Also shown in Fig. 3 is a medium-latency localization [80]; this did not use Hanford data because of the miscalibration. To leading order, the sky localization depends upon the time delay observed between detectors, and adding a third detector enables triangulation of the source [81–83]. The inclusion of the Hanford data significantly changes the inferred localization (the 90% localization volume shrinks from $\sim 1\times10^7$ Mpc^3 to $\sim 2\times10^5$ Mpc^3), as further discussed in the Supplemental Material [36], demonstrating the importance of using data from all detectors.

GW240925's source is inferred to be a low-mass binary black hole (BBH). The binary has a total mass of $M = 16.1^{+0.7}_{-0.4} M_\odot$ (median and 90% symmetric credible interval)

TABLE I. Inferred source properties [5] for GW240925 and GW250207. We report median values with 90% symmetric credible intervals. GW240925 results use C01 data and calibration uncertainties based upon in-situ measurements. GW250207 results use a wide prior for the Hanford calibration uncertainty, and a prior based upon in-situ measurements for Livingston and Virgo calibration. Quantities that evolve throughout the inspiral are quoted at a reference frequency of 20 Hz. Results are computed assuming a standard cosmology with $H_0 = 67.9\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [44, 84].

Parameter	GW240925	GW250207
Primary mass $m_1/M_\odot$	$9.0^{+2.0}_{-1.0}$	$35.2^{+1.7}_{-1.7}$
Secondary mass $m_2/M_\odot$	$7.0^{+0.8}_{-1.3}$	$30.6^{+1.5}_{-1.8}$
Total mass $M/M_\odot$	$16.1^{+0.7}_{-0.4}$	$65.9^{+1.0}_{-1.7}$
Chirp mass $\mathcal{M}/M_\odot$	$6.85^{+0.22}_{-0.08}$	$28.57^{+0.44}_{-0.77}$
Final mass $M_{\rm f}/M_\odot$	$15.3^{+0.7}_{-0.4}$	$62.7^{+1.0}_{-1.6}$
Effective inspiral spin $\chi_{\rm eff}$	$0.02^{+0.08}_{-0.02}$	$0.00^{+0.03}_{-0.04}$
Effective precession spin $\chi_{\rm p}$	$0.25^{+0.37}_{-0.20}$	$0.06^{+0.15}_{-0.05}$
Final spin $\chi_{\rm f}$	$0.69^{+0.02}_{-0.03}$	$0.69^{+0.01}_{-0.01}$
Luminosity distance $D_{\rm L}$/Mpc	356^{+61}_{-162}	187^{+121}_{-52}
Redshift z	$0.08^{+0.01}_{-0.03}$	$0.04^{+0.03}_{-0.01}$
Network SNR ρ	$31.96^{+0.11}_{-0.15}$	$68.91^{+0.08}_{-0.11}$

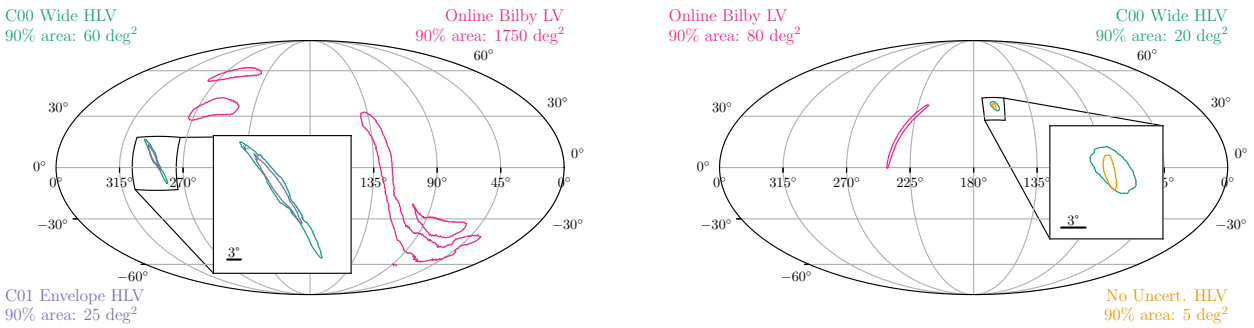

FIG. 3. Sky localization for GW240925 (left) and GW250207 (right) from analyses using data from all three detectors (HLV) and just Livingston and Virgo (LV). The contours show 90% credible areas. We show results using the wide calibration prior for Hanford (green), plus the result using the in-situ measured prior for GW240925 (purple), and the result neglecting calibration uncertainty for GW250207 (yellow). The medium-latency Online Bilby (magenta) analyses used only Livingston and Virgo data for both signals [80, 85]. Inclusion of the Hanford data, enabled by the simultaneous estimation of the calibration parameters, has a significant impact on both localizations.

and has support for equal-mass components, with mass ratio $q > 0.57$ (90% probability). The masses are consistent with the peak of the BBH mass distribution [86] and the masses of black holes in X-ray binaries [87–92]. The source is inferred to not have high spins ($\chi_1 < 0.53$ and $\chi_2 < 0.69$); the effective inspiral spin $\chi_{\rm eff}$ [93, 94] is small ($|\chi_{\rm eff}| < 0.08$), with positive values preferred, indicating a probable net alignment of the component spins with the orbital angular momentum.

Having demonstrated the efficacy of astrophysical calibration with GW240925, we turn to GW250207, where we must rely on signal-based inference to constrain the Hanford calibration. We analyze the C00 data using a wide prior across all frequencies for the Hanford calibration parameters, and in-situ measured priors for Livingston and Virgo. For comparison, we also perform (i) an analysis using only Hanford data, to show what can be inferred without constraints from other detectors, and (ii) an analysis assuming that the data from all three detectors are perfectly calibrated, to investigate the impact of neglecting calibration uncertainties.

The results in Fig. 2 (right) show that the astrophysical calibration posterior is informative and distinct from the prior across the frequency range of the signal ($f_{22}^{\rm peak}$ is ~ 170 Hz), similar to results for GW240925. For GW250207, we obtain JSDs between the posterior and prior of $0.15^{+0.11}_{-0.15}$ nat for amplitude and $0.14^{+0.13}_{-0.14}$ nat for phase. Some of the frequency-dependent structure reflects the discrete placement of spline nodes. The amplitude error near the 317.1 Hz node is only weakly constrained (likely by contributions from higher-order multipole moments); although the inferred error appears large, the posterior distribution is skewed and is still consistent with zero, with $\delta\mathcal{A} = 26^{+69}_{-32}\%$ (90% credible interval). The calibration is best constrained when using the in-situ measured priors for Livingston and Virgo, but the Hanford data alone remain informative. In the Hanford-only analysis, the overall (frequency-independent) calibration amplitude scale is fully degenerate with the source distance, since $h(\boldsymbol{\theta})$ scales inversely with distance, and the overall calibration phase scale is fully degenerate with the signal's reference phase. Therefore, the absolute scales of the Hanford-only constraints shown in Fig. 2 are prior driven: the prior favors $\delta\mathcal{A} \sim 0$ and $\delta\phi \sim 0$ deg. However, the *frequency-dependent* evolution of the calibration parameters can still be constrained using the signal morphology in the Hanford data alone.

Measurements of key astrophysical parameters for GW250207 are given in Table I. GW250207's source is similar to GW150914's [77, 95]. The BBH source has total mass of $M = 65.9^{+1.0}_{-1.7} M_\odot$ and a well-measured mass ratio of $q = 0.87^{+0.08}_{-0.08}$. The individual spins are small, with $\chi_1 < 0.15$ and $\chi_2 < 0.19$. These properties are consistent with the inferred BBH population, with component masses near the feature in the mass distribution at $\sim 35 M_\odot$ which contributes many observed binaries [86, 96]. With the inclusion of Hanford data, GW250207 has the second-highest network SNR published to date (after GW250114_082203 [7]), and its source is probably the closest BBH observed with $D_{\rm L} = 187^{+121}_{-52}$ Mpc [6, 95, 97, 98]. Such a high SNR facilitates more precise parameter estimation than for typical GW observations [6, 11].

GWs can be decomposed into spherical harmonics [99–102]. The $\ell = |m| = 2$ multipole moment dominates the signal. However, the high SNR of GW250207 means that other moments are observable; the signal probably has the highest $\ell = |m| = 4$ SNR found to date, $\rho_{44} = 5.1^{+0.5}_{-1.9}$ [6, 7, 103].

Comparing analysis results, we see that erroneously assuming perfect calibration for all detectors leads to narrower and, in some cases, biased posteriors for source parameters. The inferred distance becomes $D_{\rm L} = 175^{+42}_{-28}$ Mpc. The miscalibration at frequencies ~ 40–60 Hz is mistaken for a signature of spin precession: the constraint on the effective precession spin shifts from $\chi_{\rm p} = 0.06^{+0.15}_{-0.05}$, corresponding to a precessing SNR [104, 105] of $\rho_{\rm p} = 2.4^{+4.8}_{-1.9}$ (using the wide prior for Hanford and in-situ priors for Livingston and Virgo) to $\chi_{\rm p} = 0.13^{+0.17}_{-0.07}$, $\rho_{\rm p} = 5.8^{+6.8}_{-3.1}$ (neglecting calibration uncertainties). This demonstrates how miscalibration can mimic physical effects and impact astrophysical inferences.

The sky localization is shown in Fig. 3. Again, neglect-

ing calibration uncertainty leads to narrower posteriors. As for GW240925, and discussed in Supplemental Material [36], the inclusion of Hanford data shifts the sky-position posterior such that it lies outside of the two-detector 90% area [85]. This type of shift can happen in (infrequent) cases where the third detector adds information that strongly disfavors locations in the two-detector 90% area [106, 107]. The inclusion of the Hanford data reduces the volume localization from $\sim 2 \times 10^6$ Mpc^3 to $\sim 5 \times 10^4$ Mpc^3. Without using Hanford data and accounting for its uncertain calibration, it would be difficult to locate the source.

These results for GW240925 and GW250207 demonstrate that astrophysical signals can be used to infer detector calibration, providing both a practical fallback when in-situ measured calibration is incomplete or uncertain and a valuable cross-check of analysis procedures. Further results are provided in the Supplemental Material [36].

Potential for dark siren cosmology— CBCs act as dark sirens providing constraints on their source distances; cross-referencing the inferred localization volume with galaxy catalogs that provide redshift information then enables inference of the Hubble constant [25, 108, 109]. Localization of GW sources is best for high-SNR signals observed with at least three detectors [83, 107, 110–112].

Since the two signals have well-localized sources, they could be considered as potentially useful dark sirens. Unfortunately, GW240925 will not provide significant cosmological information from its localization as it is hidden by the Milky Way plane. However, GW250207 has a localization volume of $\sim 5 \times 10^4$ Mpc^3, similar to that of GW190814 ($\sim 5 \times 10^4$ Mpc^3 [95, 113]), far from the Milky Way plane, making it well suited for a dark siren cosmological analysis. The host galaxy of GW250207 has an estimated probability $\sim 74\%$ to be present in the extended version of the Galaxy List for the Advanced Detector Era (GLADE+) catalog [114, 115]. This probability is based on the K-band luminosity, assumes that the likelihood of hosting a CBC is proportional to the galaxy luminosity, and adopts a flat cosmological model with $H_0 = 67.9\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\Omega_\mathrm{m} = 0.3065$ [44, 84]. Both signals will be included in a comprehensive analysis of all detections up to the end of O4, which will be presented with a future version of the Gravitational-Wave Transient Catalog (GWTC), similar to the analysis for GWTC-4.0 [109]. This population analysis will allow information from multiple detections to be combined with a proper computation of selection effects across observing runs.

Consistency tests— We perform a suite of verification tests using the two observations, including general residual analyses, tests that constrain deviations of post-Newtonian (PN) parameters from the expected GR values, and quasinormal mode (QNM) spectroscopy tests of the remnant. These tests are often framed as tests of GR, but they are also sensitive to a variety of assumptions about the data. Failing to incorporate the calibration systematics in these analyses can lead to biased results, potentially mimicking or obscuring deviations from GR predictions [18, 23]. Here, we summarize results and provide additional details in Supplemental Material [36].

The residuals test evaluates the agreement between the data and the best-fit GR waveform by searching for excess coherent power remaining after subtracting the signal [116–118]. Residual power may indicate the presence of calibration errors, instrumental artifacts or waveform-modeling errors. We find no evidence of residual power.

The FTI [119], TIGER [120–123] and PCA [124, 125] analyses explore deviations of the PN coefficients from the GR value in the inspiral signal. TIGER also allows for deviations in the phenomenological coefficients of the postinspiral signal [123]. All analyses incorporate calibration uncertainties, like in the analyses to infer source properties, but now using waveform models that include the modeled deviations from GR. We find that neglecting calibration uncertainties can introduce mild biases in the inferred deviations, even though the results remain statistically consistent with GR. Using the wide, uninformative calibration priors mitigates the risk of falsely identifying GR violations. The GW250207 analyses for the PN deviation parameters give the tightest upper limits to date on the 2PN and higher-PN deviation parameters, surpassing GW250114_082203 [126]; at -1PN and 0.5PN, the constraints from GW170817 remain the best [127, 128].

For the ringdown signal, we use the pSEOBNR [129–133], QNMRF [134–137], and RINGDOWN [138–140] pipelines to perform QNM analyses. pSEOBNR can include calibration uncertainty with its parametrized waveform, but QNMRF and RINGDOWN do not currently support calibration marginalization, and instead, analyze Hanford and Livingston data separately to assess potential systematic errors. Figure 4 presents results from these analyses. These consistently show that neglecting calibration errors at Hanford leads to biased estimates for the $(2, 2, 0)$ QNM frequency and damping time relative to those inferred from the full inspiral–merger–ringdown (IMR) waveform. The 90% credible intervals on the $(2, 2, 0)$ QNM are compatible with GW230814_230901 [103], GW250114_082203 [7, 126], and other signals included in the GWTC-4.0 analysis [141].

Conclusion— Using the high-SNR BBH signals GW240925 and GW250207, observed during times of elevated calibration uncertainty, we have demonstrated that the information encoded within CBC signals can enable astrophysical calibration of GW detectors. With loud GW observations, we may cross-check in-situ calibration measurements. Furthermore, when we lack a complete set of calibration measurements, GW signals may be used to infer calibration properties: in such cases, signal-informed calibration is necessary and required to obtain precise and accurate source localization for multimessenger follow-up and cosmological measurements, along with unbiased tests of GR. Although astrophysical calibration has long been proposed as possible [19, 26, 29, 30], the ground-breaking higher SNRs found during O4 are now making it practical [26–28].

GW240925 and GW250207 were, fortunately, detected while multiple detectors were observing, allowing for a coherent analysis across the network. Having multiple observato-

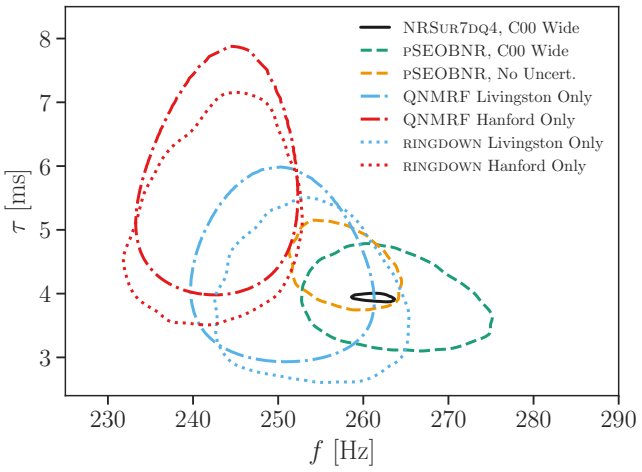

FIG. 4. Inferred $(2, 2, 0)$ QNM frequency and damping time from analyses of GW250207. The full IMR GR result, incorporating a wide prior for Hanford calibration, is indicated by the solid line. The pSEOBNR analysis (dashed) compares results obtained by either neglecting calibration uncertainties (yellow) or incorporating a wide prior for Hanford to marginalize over them (green). The QNMRF (dot–dashed) and ringdown (dotted) analyses analyze Hanford (red) and Livingston (light blue) data separately without calibration uncertainty to assess potential systematic errors. QNMRF and ringdown analyze the signal starting at $8t_{M_f}$ after the peak of the strain, where time is in units of the remnant mass in the detector frame (the maximum-likelihood estimate from the IMR analysis using the NRSur7dq4 waveform [142] and the wide calibration prior).

ries increases the probability of detection, improves source localization, and mitigates any adverse effects of detector noise on interpretation. Good source localization of GW250207 is possible only with the addition of LIGO Hanford data and the astrophysical inference of its calibration. Further expansion of the network [5, 83] with increasing sensitivity for KAGRA and the construction of LIGO India will enhance the opportunities for GW discovery and mitigate against cases where one observatory is adversely impacted by an instrumental problem, a glitch or a calibration issue. With a global observatory network, we are best prepared to fulfill the potential of GW astronomy and to make discoveries that advance our understanding of the Universe.

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Calibration of the LIGO strain data was performed with GstLAL-based calibration software pipeline [34], and calibration of the Virgo strain data is performed with C-based software [17]. DQ products and event-validation results were computed using the BRiSTOL [143], DMT [144], DQR [145], DQSEGDB [146], Glitchfind [147], GSpyNetTree [148], gwdetchar [149], Hveto [150], iDQ [151], LigoDV-web [152], OmegaOverlap [153], Omicron [154], PEMcheck [155], PythonVirgoTools [156] and Stationarity [157] software packages and contributing software tools. Analyses relied upon the LALSuite software library [158, 159]. The detection of the signals and subsequent significance evaluations were performed with the GstLAL-based inspiral software pipeline [52–55], with the MBTA pipeline [61, 62], the PyCBC package [160–162] and the cWB packages [50, 51, 163–165]. Estimates of the noise spectra and glitch models, as well as tests of residuals, were obtained using BayesWave [166–168]. Signal parameter estimation was performed with the Bilby library [73, 74] using the Dynesty nested-sampling package [169]. SEOBNRv5PHM waveforms used in parameter estimation were generated using pySEOBNR [170]. PESummary was used to postprocess and collate parameter-estimation results [171]. Tests of GR were performed with the FTI [119], TIGER [121–123] and pSEOBNR [129–133] tests implemented in BilbyTGR [172], as well as with the QNMRF [134–137] and ringdown [138–140] pipelines. Cosmological inference was performed with the gwcosmo [173–175] and icarogw [176, 177] codes. Some of the parameter-estimation analysis were managed with the Asimov library [178]. Plots were prepared with Matplotlib [179], seaborn [180] and GWpy [181]. NumPy [182] and SciPy [183] were used in the preparation of the manuscript.

C01 strain data for GW240925 and C00 strain data for GW250207 analysed as part of this study are publicly available through Gravitational Wave Open Science Center (GWOSC) [184–186]; the (miscalibrated) C00 strain data for GW240925 are available in a supplemental release from Zenodo. Data releases of inference results, together with example scripts, are available from Zenodo [187].

REFERENCES

* Deceased, September 2024.
† Deceased, August 2025.

[1] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. **116**, 061102 (2016), arXiv:1602.03837 [gr-qc].

[2] J. Aasi *et al.* (LIGO Scientific Collaboration), Advanced LIGO, Class. Quantum Gravity **32**, 074001 (2015), arXiv:1411.4547 [gr-qc].

[3] F. Acernese *et al.* (Virgo Collaboration), Advanced Virgo: a second-generation interferometric gravitational wave detector, Class. Quantum Gravity **32**, 024001 (2015), arXiv:1408.3978 [gr-qc].

[4] T. Akutsu *et al.* (KAGRA Collaboration), Overview of KAGRA: Detector design and construction history, PTEP **2021**, 05A101 (2021), arXiv:2005.05574 [physics.ins-det].

[5] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GWTC-4.0: An Introduction to Version 4.0 of the Gravitational-Wave Transient Catalog, Astrophys. J. Lett. **995**, L18 (2025), arXiv:2508.18080 [gr-qc].

[6] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GWTC-4.0: Updating the Gravitational-Wave Transient Catalog with Observations from the First Part of the Fourth LIGO-Virgo-KAGRA Observing Run, Astrophys. J. Lett. **1004**, L22 (2026), arXiv:2508.18082 [gr-qc].

[7] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GW250114: Testing Hawking's Area Law and the Kerr Nature of Black Holes, Phys. Rev. Lett. **135**, 111403 (2025), arXiv:2509.08054 [gr-qc].

[8] D. Ganapathy *et al.* (LIGO O4 Detector Collaboration), Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing, Phys. Rev. X **13**, 041021 (2023).

[9] W. Jia *et al.* (LIGO Instrument Science Collaboration), Squeezing the quantum noise of a gravitational-wave detector below the standard quantum limit, Science **385**, 1318 (2024), arXiv:2404.14569 [gr-qc].

[10] E. Capote *et al.*, Advanced LIGO detector performance in the fourth observing run, Phys. Rev. D **111**, 062002 (2025), arXiv:2411.14607 [gr-qc].

[11] C. Cutler and É. E. Flanagan, Gravitational waves from merging compact binaries: How accurately can one extract the binary's parameters from the inspiral waveform?, Phys. Rev. D **49**, 2658 (1994), arXiv:gr-qc/9402014.

[12] M. Pürrer and C.-J. Haster, Gravitational waveform accuracy

requirements for future ground-based detectors, Phys. Rev. Res. **2**, 023151 (2020), arXiv:1912.10055 [gr-qc].
[13] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), A guide to LIGO–Virgo detector noise and extraction of transient gravitational-wave signals, Class. Quantum Gravity **37**, 055002 (2020), arXiv:1908.11170 [gr-qc].
[14] B. P. Abbott *et al.* (LIGO Scientific Collaboration), Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914, Phys. Rev. D **95**, 062003 (2017), arXiv:1602.03845 [gr-qc].
[15] C. Cahillane *et al.* (LIGO Instrument Science Collaboration), Calibration uncertainty for Advanced LIGO's first and second observing runs, Phys. Rev. D **96**, 102001 (2017), arXiv:1708.03023 [astro-ph.IM].
[16] L. Sun *et al.*, Characterization of systematic error in Advanced LIGO calibration, Class. Quantum Gravity **37**, 225008 (2020), arXiv:2005.02531 [astro-ph.IM].
[17] F. Acernese *et al.* (Virgo Collaboration), Calibration of Advanced Virgo and reconstruction of the detector strain $h(t)$ during the Observing Run O3, Class. Quantum Gravity **39**, 045006 (2022), arXiv:2107.03294 [gr-qc].
[18] E. D. Hall, C. Cahillane, K. Izumi, R. J. E. Smith, and R. X. Adhikari, Systematic calibration error requirements for gravitational-wave detectors via the Cramér–Rao bound, Class. Quantum Gravity **36**, 205006 (2019), arXiv:1712.09719 [astro-ph.IM].
[19] R. Essick, Calibration uncertainty's impact on gravitational-wave observations, Phys. Rev. D **105**, 082002 (2022), arXiv:2202.00823 [astro-ph.IM].
[20] S. Vitale, W. Del Pozzo, T. G. F. Li, C. Van Den Broeck, I. Mandel, B. Aylott, and J. Veitch, Effect of calibration errors on Bayesian parameter estimation for gravitational wave signals from inspiral binary systems in the Advanced Detectors era, Phys. Rev. D **85**, 064034 (2012), arXiv:1111.3044 [gr-qc].
[21] S. Kumar, M. Melching, and F. Ohme, Accounting for the known unknowns: A parametric framework to incorporate systematic waveform errors in gravitational-wave parameter estimation, Phys. Rev. D **112**, 104071 (2025), arXiv:2502.17400 [gr-qc].
[22] Y. Huang, H.-Y. Chen, C.-J. Haster, L. Sun, S. Vitale, and J. S. Kissel, Impact of calibration uncertainties on Hubble constant measurements from gravitational-wave sources, Phys. Rev. D **111**, 063034 (2025), arXiv:2204.03614 [gr-qc].
[23] A. Gupta *et al.*, Possible causes of false general relativity violations in gravitational wave observations, SciPost Phys. Comm. Rep. 10.21468/SciPostPhysCommRep.5 (2024), arXiv:2405.02197 [gr-qc].
[24] M. R. Sinha, L. Sun, and S. Ma, Impact of Detector Calibration Accuracy on Black Hole Spectroscopy, Phys. Rev. D **112**, 084038 (2025), arXiv:2506.15979 [gr-qc].
[25] B. F. Schutz, Determining the Hubble Constant from Gravitational Wave Observations, Nature **323**, 310 (1986).
[26] R. Essick and D. E. Holz, Calibrating gravitational-wave detectors with GW170817, Class. Quantum Gravity **36**, 125002 (2019), arXiv:1902.08076 [astro-ph.IM].
[27] E. Payne, C. Talbot, P. D. Lasky, E. Thrane, and J. S. Kissel, Gravitational-wave astronomy with a physical calibration model, Phys. Rev. D **102**, 122004 (2020), arXiv:2009.10193 [astro-ph.IM].
[28] S. Vitale, C.-J. Haster, L. Sun, B. Farr, E. Goetz, J. Kissel, and C. Cahillane, Physical approach to the marginalization of LIGO calibration uncertainties, Phys. Rev. D **103**, 063016 (2021), arXiv:2009.10192 [gr-qc].
[29] M. Pitkin, C. Messenger, and L. Wright, Astrophysical calibration of gravitational-wave detectors, Phys. Rev. D **93**, 062002 (2016), arXiv:1511.02758 [astro-ph.IM].
[30] B. F. Schutz and B. S. Sathyaprakash, Self-calibration of Networks of Gravitational Wave Detectors, arXiv e-prints (2020), arXiv:2009.10212 [gr-qc].
[31] C. Alléné *et al.*, Relative calibration of the LIGO and Virgo detectors using astrophysical events from their third observing run, Class. Quantum Gravity **39**, 195019 (2022), arXiv:2204.00337 [gr-qc].
[32] C. Bond, D. Brown, A. Freise, and K. Strain, Interferometer Techniques for Gravitational-Wave Detection, Living Rev. Relativity **19**, 3 (2016), arXiv:0909.3661 [gr-qc].
[33] M. Pitkin, S. Reid, S. Rowan, and J. Hough, Gravitational Wave Detection by Interferometry (Ground and Space), Living Rev. Relativity **14**, 5 (2011), arXiv:1102.3355 [astro-ph.IM].
[34] A. D. Viets *et al.*, Reconstructing the calibrated strain signal in the Advanced LIGO detectors, Class. Quantum Gravity **35**, 095015 (2018), arXiv:1710.09973 [astro-ph.IM].
[35] T. Akutsu *et al.* (KAGRA Collaboration), Overview of KAGRA: Calibration, detector characterization, physical environmental monitors, and the geophysics interferometer, Prog. Theor. Exp. Phys. **2021**, 05A102 (2021), arXiv:2009.09305 [gr-qc].
[36] See Supplemental Material for details, which includes Refs. [188–238].
[37] LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration, *LIGO Virgo KAGRA Calibration Uncertainty (O4)*, Tech. Rep. DCC-T2500288 (LIGO, Virgo, and KAGRA, 2025).
[38] B. Allen, *LIGO calibration accuracy*, Tech. Rep. LIGO-T960189 (LIGO, 1996).
[39] S. Karki *et al.*, The Advanced LIGO Photon Calibrators, Rev. Sci. Instrum. **87**, 114503 (2016), arXiv:1608.05055 [astro-ph.IM].
[40] D. Estevez, P. Lagabbe, A. Masserot, L. Rolland, M. Seglar-Arroyo, and D. Verkindt, The Advanced Virgo Photon Calibrators, Class. Quantum Gravity **38**, 075007 (2021), arXiv:2009.08103 [astro-ph.IM].
[41] D. Bhattacharjee, Y. Lecoeuche, S. Karki, J. Betzwieser, V. Bossilkov, S. Kandhasamy, E. Payne, and R. L. Savage, Fiducial displacements with improved accuracy for the global network of gravitational wave detectors, Class. Quantum Gravity **38**, 015009 (2021), arXiv:2006.00130 [astro-ph.IM].
[42] D. Chen *et al.*, Performance of the KAGRA photon calibrators during the fourth joint observing run with LIGO and Virgo, Class. Quantum Gravity **42**, 185018 (2025), arXiv:2504.12657 [astro-ph.IM].
[43] M. Wade *et al.*, Toward low-latency, high-fidelity calibration of the LIGO detectors with enhanced monitoring tools, Class. Quantum Gravity **42**, 215016 (2025), arXiv:2508.08423 [gr-qc].
[44] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GWTC-4.0: Methods for Identifying and Characterizing Gravitational-wave Transients, Astrophys. J. Lett. **1004**, L21 (2026), arXiv:2508.18081 [gr-qc].
[45] F. Aubin, C. Grimaud, B. Mours, T. Pradier, L. Rolland, M. Seglar-Arroyo, H. Van Haevermaet, P. Van Hove, and D. Verkindt, From the Virgo interferometer calibration to the bias and uncertainty of the h(t) detector strain during the O4 run, J. Phys. Conf. Ser. **3177**, 012082 (2026), arXiv:2511.12566 [physics.ins-det].
[46] J. Betzwieser, *Calibration statements on OOOM requests*

for GW240925 and GW250207, Tech. Rep. LIGO-T2500292 (LIGO, 2025).
[47] S. Chatterji, L. Blackburn, G. Martin, and E. Katsavounidis, Multiresolution techniques for the detection of gravitational-wave bursts, Class. Quantum Gravity **21**, S1809 (2004), arXiv:gr-qc/0412119.
[48] S. Klimenko, S. Mohanty, M. Rakhmanov, and G. Mitselmakher, Constraint likelihood analysis for a network of gravitational wave detectors, Phys. Rev. D **72**, 122002 (2005), arXiv:gr-qc/0508068.
[49] S. Klimenko, I. Yakushin, A. Mercer, and G. Mitselmakher, A coherent method for detection of gravitational wave bursts, Class. Quantum Gravity **25**, 114029 (2008), arXiv:0802.3232 [gr-qc].
[50] S. Klimenko *et al.*, Method for detection and reconstruction of gravitational wave transients with networks of advanced detectors, Phys. Rev. D **93**, 042004 (2016), arXiv:1511.05999 [gr-qc].
[51] T. Mishra, S. Bhaumik, V. Gayathri, M. J. Szczepańczyk, I. Bartos, and S. Klimenko, Gravitational waves detected by a burst search in LIGO/Virgo's third observing run, Phys. Rev. D **111**, 023054 (2025), arXiv:2410.15191 [astro-ph.HE].
[52] C. Messick *et al.*, Analysis Framework for the Prompt Discovery of Compact Binary Mergers in Gravitational-wave Data, Phys. Rev. D **95**, 042001 (2017), arXiv:1604.04324 [astro-ph.IM].
[53] S. Sachdev *et al.*, The GstLAL Search Analysis Methods for Compact Binary Mergers in Advanced LIGO's Second and Advanced Virgo's First Observing Runs, arXiv e-prints (2019), arXiv:1901.08580 [gr-qc].
[54] C. Hanna *et al.*, Fast evaluation of multidetector consistency for real-time gravitational wave searches, Phys. Rev. D **101**, 022003 (2020), arXiv:1901.02227 [gr-qc].
[55] K. Cannon *et al.*, GstLAL: A software framework for gravitational wave discovery, SoftwareX **14**, 100680 (2021), arXiv:2010.05082 [astro-ph.IM].
[56] S. Sakon *et al.*, Template bank for compact binary mergers in the fourth observing run of Advanced LIGO, Advanced Virgo, and KAGRA, Phys. Rev. D **109**, 044066 (2024), arXiv:2211.16674 [gr-qc].
[57] B. Ewing *et al.*, Performance of the low-latency GstLAL inspiral search towards LIGO, Virgo, and KAGRA's fourth observing run, Phys. Rev. D **109**, 042008 (2024), arXiv:2305.05625 [gr-qc].
[58] L. Tsukada *et al.*, Improved ranking statistics of the GstLAL inspiral search for compact binary coalescences, Phys. Rev. D **108**, 043004 (2023), arXiv:2305.06286 [astro-ph.IM].
[59] P. Joshi *et al.*, New Methods for Offline GstLAL Analyses, arXiv e-prints (2025), arXiv:2506.06497 [gr-qc].
[60] P. Joshi *et al.*, How Many Times Should We Matched Filter Gravitational Wave Data? A Comparison of GstLAL's Online and Offline Performance, arXiv e-prints (2025), arXiv:2505.23959 [gr-qc].
[61] T. Adams, D. Buskulic, V. Germain, G. M. Guidi, F. Marion, M. Montani, B. Mours, F. Piergiovanni, and G. Wang, Low-latency analysis pipeline for compact binary coalescences in the advanced gravitational wave detector era, Class. Quantum Gravity **33**, 175012 (2016), arXiv:1512.02864 [gr-qc].
[62] F. Aubin *et al.*, The MBTA pipeline for detecting compact binary coalescences in the third LIGO–Virgo observing run, Class. Quantum Gravity **38**, 095004 (2021), arXiv:2012.11512 [gr-qc].
[63] C. Alléné *et al.*, The MBTA pipeline for detecting compact binary coalescences in the fourth LIGO-Virgo-KAGRA observing run, Class. Quantum Gravity **42**, 105009 (2025), arXiv:2501.04598 [gr-qc].
[64] Q. Chu *et al.*, SPIIR online coherent pipeline to search for gravitational waves from compact binary coalescences, Phys. Rev. D **105**, 024023 (2022), arXiv:2011.06787 [gr-qc].
[65] L. P. Singer and L. R. Price, Rapid Bayesian position reconstruction for gravitational-wave transients, Phys. Rev. D **93**, 024013 (2016), arXiv:1508.03634 [gr-qc].
[66] L. P. Singer *et al.*, Going the Distance: Mapping Host Galaxies of LIGO and Virgo Sources in Three Dimensions Using Local Cosmography and Targeted Follow-up, Astrophys. J. Lett. **829**, L15 (2016), arXiv:1603.07333 [astro-ph.HE].
[67] GCN Circular archive for S240925n.
[68] S. Soni *et al.* (LIGO Instrument Science Collaboration), LIGO Detector Characterization in the first half of the fourth Observing run, Class. Quantum Gravity **42**, 085016 (2025), arXiv:2409.02831 [astro-ph.IM].
[69] L. K. Nuttall, Characterizing transient noise in the LIGO detectors, Phil. Trans. R. Soc. A **376**, 20170286 (2018), arXiv:1804.07592 [astro-ph.IM].
[70] J. Glanzer *et al.*, Data quality up to the third observing run of Advanced LIGO: Gravity Spy glitch classifications, Class. Quantum Gravity **40**, 065004 (2023), arXiv:2208.12849 [gr-qc].
[71] S. Hourihane and K. Chatziioannou, Glitches far from transient gravitational-wave events do not bias inference, Phys. Rev. D **112**, 084006 (2025), arXiv:2506.21869 [gr-qc].
[72] GCN Circular archive for S250207bg.
[73] G. Ashton *et al.*, BILBY: A user-friendly Bayesian inference library for gravitational-wave astronomy, Astrophys. J. Suppl. Ser. **241**, 27 (2019), arXiv:1811.02042 [astro-ph.IM].
[74] I. M. Romero-Shaw *et al.*, Bayesian inference for compact binary coalescences with BILBY: validation and application to the first LIGO–Virgo gravitational-wave transient catalogue, Mon. Not. R. Astron. Soc. **499**, 3295 (2020), arXiv:2006.00714 [astro-ph.IM].
[75] T. Baka *et al.*, *Correcting misspecification of calibration uncertainties in gravitational-wave data analysis with efficient reweighting*, Tech. Rep. LIGO-T2500295 (LIGO, 2025).
[76] W. Farr, B. Farr, and T. Littenberg, *Modelling calibration errors in CBC waveforms*, Tech. Rep. LIGO-T1400682 (LIGO, 2014).
[77] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), Properties of the Binary Black Hole Merger GW150914, Phys. Rev. Lett. **116**, 241102 (2016), arXiv:1602.03840 [gr-qc].
[78] J. Lin, Divergence measures based on the Shannon entropy, IEEE Trans. Info. Theor. **37**, 145 (1991).
[79] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), Binary Black Hole Mergers in the first Advanced LIGO Observing Run, Phys. Rev. X **6**, 041015 (2016), [Erratum: Phys. Rev. X 8, 039903 (2018)], arXiv:1606.04856 [gr-qc].
[80] LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration, LIGO/Virgo/KAGRA S240925n: Updated Sky localization and Source Classification, GCN **37607** (2024).
[81] L. Wen and Y. Chen, Geometrical Expression for the Angular Resolution of a Network of Gravitational-Wave Detectors, Phys. Rev. D **81**, 082001 (2010), arXiv:1003.2504 [astro-ph.CO].
[82] S. Fairhurst, Source localization with an advanced gravitational wave detector network, Class. Quantum Gravity **28**, 105021 (2011), arXiv:1010.6192 [gr-qc].

[83] B. P. Abbott *et al.* (KAGRA Collaboration, LIGO Scientific Collaboration, Virgo Collaboration), Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA, Living Rev. Relativity **23**, 3 (2020), arXiv:1304.0670 [gr-qc].

[84] P. A. R. Ade *et al.* (Planck Collaboration), Planck 2015 results. XIII. Cosmological parameters, Astron. Astrophys. **594**, A13 (2016), arXiv:1502.01589 [astro-ph.CO].

[85] LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration, LIGO/Virgo/KAGRA S250207bg: Updated Sky localization, GCN **39242** (2025).

[86] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GWTC-4.0: Population Properties of Merging Compact Binaries, arXiv e-prints (2025), arXiv:2508.18083 [astro-ph.HE].

[87] F. Özel, D. Psaltis, R. Narayan, and J. E. McClintock, The Black Hole Mass Distribution in the Galaxy, Astrophys. J. **725**, 1918 (2010), arXiv:1006.2834 [astro-ph.GA].

[88] W. M. Farr, N. Sravan, A. Cantrell, L. Kreidberg, C. D. Bailyn, I. Mandel, and V. Kalogera, The Mass Distribution of Stellar-Mass Black Holes, Astrophys. J. **741**, 103 (2011), arXiv:1011.1459 [astro-ph.GA].

[89] J. Casares and P. G. Jonker, Mass Measurements of Stellar and Intermediate Mass Black-Holes, Space Sci. Rev. **183**, 223 (2014), arXiv:1311.5118 [astro-ph.HE].

[90] J. Casares, I. Negueruela, M. Ribó, I. Ribas, J. M. Paredes, A. Herrero, and S. Simón-Díaz, A Be-type star with a black-hole companion, Nature **505**, 378 (2014), arXiv:1401.3711 [astro-ph.SR].

[91] J. M. Corral-Santana, J. Casares, T. Muñoz-Darias, F. E. Bauer, I. G. Martinez-Pais, and D. M. Russell, BlackCAT: A catalogue of stellar-mass black holes in X-ray transients, Astron. Astrophys. **587**, A61 (2016), arXiv:1510.08869 [astro-ph.HE].

[92] J. C. A. Miller-Jones *et al.*, Cygnus X-1 contains a 21–solar mass black hole—Implications for massive star winds, Science **371**, 1046 (2021), arXiv:2102.09091 [astro-ph.HE].

[93] P. Ajith *et al.*, Inspiral-merger-ringdown waveforms for black-hole binaries with non-precessing spins, Phys. Rev. Lett. **106**, 241101 (2011), arXiv:0909.2867 [gr-qc].

[94] L. Santamaria *et al.*, 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), arXiv:1005.3306 [gr-qc].

[95] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), GWTC-2.1: Deep extended catalog of compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run, Phys. Rev. D **109**, 022001 (2024), arXiv:2108.01045 [gr-qc].

[96] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), Population Properties of Compact Objects from the Second LIGO-Virgo Gravitational-Wave Transient Catalog, Astrophys. J. Lett. **913**, L7 (2021), arXiv:2010.14533 [astro-ph.HE].

[97] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo during the Second Part of the Third Observing Run, Phys. Rev. X **13**, 041039 (2023), arXiv:2111.03606 [gr-qc].

[98] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GW241011 and GW241110: Exploring Binary Formation and Fundamental Physics with Asymmetric, High-spin Black Hole Coalescences, Astrophys. J. Lett. **993**, L21 (2025), arXiv:2510.26931 [astro-ph.HE].

[99] K. S. Thorne, Multipole Expansions of Gravitational Radiation, Rev. Mod. Phys. **52**, 299 (1980).

[100] L. Blanchet, Gravitational Radiation from Post-Newtonian Sources and Inspiralling Compact Binaries, Living Rev. Relativity **17**, 2 (2014), arXiv:1310.1528 [gr-qc].

[101] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses, Phys. Rev. D **102**, 043015 (2020), arXiv:2004.08342 [astro-ph.HE].

[102] C. Mills and S. Fairhurst, Measuring gravitational-wave higher-order multipoles, Phys. Rev. D **103**, 024042 (2021), arXiv:2007.04313 [gr-qc].

[103] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GW230814: Investigation of a Loud Gravitational-wave Signal Observed with a Single Detector, Astrophys. J. Lett. **1004**, L23 (2026), arXiv:2509.07348 [gr-qc].

[104] S. Fairhurst, R. Green, C. Hoy, M. Hannam, and A. Muir, Two-harmonic approximation for gravitational waveforms from precessing binaries, Phys. Rev. D **102**, 024055 (2020), arXiv:1908.05707 [gr-qc].

[105] S. Fairhurst, R. Green, M. Hannam, and C. Hoy, When will we observe binary black holes precessing?, Phys. Rev. D **102**, 041302 (2020), arXiv:1908.00555 [gr-qc].

[106] L. P. Singer *et al.*, The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo, Astrophys. J. **795**, 105 (2014), arXiv:1404.5623 [astro-ph.HE].

[107] A. Ouzriat, V. Sordini, and F. Di Renzo, Characterizing Low-Latency Sky Localization in Multi-Detector Gravitational-Wave Networks, arXiv e-prints (2025), arXiv:2510.21930 [astro-ph.HE].

[108] J. R. Gair *et al.*, The Hitchhiker's Guide to the Galaxy Catalog Approach for Dark Siren Gravitational-wave Cosmology, Astron. J. **166**, 22 (2023), arXiv:2212.08694 [gr-qc].

[109] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GWTC-4.0: Constraints on the Cosmic Expansion Rate and Modified Gravitational-wave Propagation, arXiv e-prints (2025), arXiv:2509.04348 [astro-ph.CO].

[110] W. Del Pozzo, C. P. L. Berry, A. Ghosh, T. S. F. Haines, L. P. Singer, and A. Vecchio, Dirichlet Process Gaussian-mixture model: An application to localizing coalescing binary neutron stars with gravitational-wave observations, Mon. Not. R. Astron. Soc. **479**, 601 (2018), arXiv:1801.08009 [astro-ph.IM].

[111] C. Pankow, M. Rizzo, K. Rao, C. P. L. Berry, and V. Kalogera, Localization of Compact Binary Sources with Second Generation Gravitational-wave Interferometer Networks, Astrophys. J. **902**, 71 (2020), arXiv:1909.12961 [astro-ph.HE].

[112] M. Emma, T. F. de Nobrega, and G. Ashton, Comparing advanced-era interferometric gravitational-wave detector network configurations: Sky localization and source properties, Phys. Rev. D **110**, 064068 (2024), arXiv:2404.16949 [gr-qc].

[113] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object, Astrophys. J. Lett. **896**, L44 (2020), arXiv:2006.12611 [astro-ph.HE].

[114] G. Dálya, G. Galgóczi, L. Dobos, Z. Frei, I. S. Heng, R. Macas, C. Messenger, P. Raffai, and R. S. de Souza, GLADE: A galaxy catalogue for multimessenger searches in the advanced gravitational-wave detector era, Mon. Not. R. Astron. Soc. **479**, 2374 (2018), arXiv:1804.05709 [astro-ph.HE].

[115] G. Dálya *et al.*, GLADE+ : an extended galaxy catalogue for multimessenger searches with advanced gravitational-wave detectors, Mon. Not. R. Astron. Soc. **514**, 1403 (2022), arXiv:2110.06184 [astro-ph.CO].

[116] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), Tests of General Relativity with GWTC-3, Phys. Rev. D **112**, 084080 (2025), arXiv:2112.06861 [gr-qc].

[117] N. K. Johnson-McDaniel, A. Ghosh, S. Ghonge, M. Saleem, N. V. Krishnendu, and J. A. Clark, Investigating the relation between gravitational wave tests of general relativity, Phys. Rev. D **105**, 044020 (2022), arXiv:2109.06988 [gr-qc].

[118] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GWTC-4.0: Tests of General Relativity. I. Overview and General Tests, arXiv e-prints (2026), arXiv:2603.19019 [gr-qc].

[119] A. K. Mehta, A. Buonanno, R. Cotesta, A. Ghosh, N. Sennett, and J. Steinhoff, Tests of general relativity with gravitational-wave observations using a flexible theory-independent method, Phys. Rev. D **107**, 044020 (2023), arXiv:2203.13937 [gr-qc].

[120] T. G. F. Li, W. Del Pozzo, S. Vitale, C. Van Den Broeck, M. Agathos, J. Veitch, K. Grover, T. Sidery, R. Sturani, and A. Vecchio, Towards a generic test of the strong field dynamics of general relativity using compact binary coalescence, Phys. Rev. D **85**, 082003 (2012), arXiv:1110.0530 [gr-qc].

[121] M. Agathos, W. Del Pozzo, T. G. F. Li, C. Van Den Broeck, J. Veitch, and S. Vitale, TIGER: A data analysis pipeline for testing the strong-field dynamics of general relativity with gravitational wave signals from coalescing compact binaries, Phys. Rev. D **89**, 082001 (2014), arXiv:1311.0420 [gr-qc].

[122] J. Meidam *et al.*, Parametrized tests of the strong-field dynamics of general relativity using gravitational wave signals from coalescing binary black holes: Fast likelihood calculations and sensitivity of the method, Phys. Rev. D **97**, 044033 (2018), arXiv:1712.08772 [gr-qc].

[123] S. Roy, M. Haney, G. Pratten, P. T. H. Pang, and C. Van Den Broeck, Improved parametrized test of general relativity using the IMRPhenomX waveform family: Including higher harmonics and precession, Phys. Rev. D **113**, 024016 (2026), arXiv:2504.21147 [gr-qc].

[124] M. Saleem, S. Datta, K. G. Arun, and B. S. Sathyaprakash, Parametrized tests of post-Newtonian theory using principal component analysis, Phys. Rev. D **105**, 084062 (2022), arXiv:2110.10147 [gr-qc].

[125] P. Mahapatra *et al.*, Confronting General Relativity with Principal Component Analysis: Simulations and Results from GWTC-3 Events, Phys. Rev. D **112**, 104007 (2025), arXiv:2508.06862 [gr-qc].

[126] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), Black Hole Spectroscopy and Tests of General Relativity with GW250114, Phys. Rev. Lett. **136**, 041403 (2026), arXiv:2509.08099 [gr-qc].

[127] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), Tests of General Relativity with GW170817, Phys. Rev. Lett. **123**, 011102 (2019), arXiv:1811.00364 [gr-qc].

[128] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GWTC-4.0: Tests of General Relativity. II. Parameterized Tests, arXiv e-prints (2026), arXiv:2603.19020 [gr-qc].

[129] R. Brito, A. Buonanno, and V. Raymond, Black-hole Spectroscopy by Making Full Use of Gravitational-Wave Modeling, Phys. Rev. D **98**, 084038 (2018), arXiv:1805.00293 [gr-qc].

[130] A. Ghosh, R. Brito, and A. Buonanno, Constraints on quasinormal-mode frequencies with LIGO-Virgo binary–black-hole observations, Phys. Rev. D **103**, 124041 (2021), arXiv:2104.01906 [gr-qc].

[131] E. Maggio, H. O. Silva, A. Buonanno, and A. Ghosh, Tests of general relativity in the nonlinear regime: A parametrized plunge-merger-ringdown gravitational waveform model, Phys. Rev. D **108**, 024043 (2023), arXiv:2212.09655 [gr-qc].

[132] A. Toubiana, L. Pompili, A. Buonanno, J. R. Gair, and M. L. Katz, Measuring source properties and quasinormal mode frequencies of heavy massive black-hole binaries with LISA, Phys. Rev. D **109**, 104019 (2024), arXiv:2307.15086 [gr-qc].

[133] L. Pompili, E. Maggio, H. O. Silva, and A. Buonanno, Parametrized spin-precessing inspiral-merger-ringdown waveform model for tests of general relativity, Phys. Rev. D **111**, 124040 (2025), arXiv:2504.10130 [gr-qc].

[134] S. Ma, K. Mitman, L. Sun, N. Deppe, F. Hébert, L. E. Kidder, J. Moxon, W. Throwe, N. L. Vu, and Y. Chen, Quasinormal-mode filters: A new approach to analyze the gravitational-wave ringdown of binary black-hole mergers, Phys. Rev. D **106**, 084036 (2022), arXiv:2207.10870 [gr-qc].

[135] S. Ma, L. Sun, and Y. Chen, Using rational filters to uncover the first ringdown overtone in GW150914, Phys. Rev. D **107**, 084010 (2023), arXiv:2301.06639 [gr-qc].

[136] S. Ma, L. Sun, and Y. Chen, Black Hole Spectroscopy by Mode Cleaning, Phys. Rev. Lett. **130**, 141401 (2023), arXiv:2301.06705 [gr-qc].

[137] N. Lu, S. Ma, O. J. Piccinni, L. Sun, and E. Finch, Statistical identification of ringdown modes with rational filters, Phys. Rev. D **112**, 064047 (2025), arXiv:2505.18560 [gr-qc].

[138] M. Isi, M. Giesler, W. M. Farr, M. A. Scheel, and S. A. Teukolsky, Testing the no-hair theorem with GW150914, Phys. Rev. Lett. **123**, 111102 (2019), arXiv:1905.00869 [gr-qc].

[139] M. Isi and W. M. Farr, Analyzing black-hole ringdowns, arXiv e-prints (2021), arXiv:2107.05609 [gr-qc].

[140] H. Siegel, M. Isi, and W. M. Farr, Analyzing black-hole ringdowns. II. Data conditioning, Phys. Rev. D **111**, 044070 (2025), arXiv:2410.02704 [gr-qc].

[141] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), GWTC-4.0: Tests of General Relativity. III. Tests of the Remnants, arXiv e-prints (2026), arXiv:2603.19021 [gr-qc].

[142] V. Varma, S. E. Field, M. A. Scheel, J. Blackman, L. E. Kidder, and H. P. Pfeiffer, Surrogate model of hybridized numerical relativity binary black hole waveforms, Phys. Rev. D **99**, 064045 (2019), arXiv:1812.07865 [gr-qc].

[143] F. Di Renzo, F. Fidecaro, M. Razzano, and N. Sorrentino, BRiSTOL - a Band-limited RMS Stationarity Test Tool for Gravitational Wave Data, in *55th Rencontres de Moriond on Gravitation* (2024) arXiv:2401.15392 [gr-qc].

[144] John Zweizig, The Data Monitor Tool Project, labcit.ligo.caltech.edu/˜jzweizig/DMT-Project.html (2006).

[145] LIGO Scientific Collaboration and Virgo Collaboration, Data quality report user documentation, docs.ligo.org/detchar/data-quality-report/ (2018).

[146] R. P. Fisher, G. Hemming, M.-A. Bizouard, D. A. Brown, P. F. Couvares, F. Robinet, and D. Verkindt, DQSEGDB: A time-interval database for storing gravitational wave observatory metadata, SoftwareX **14**, 100677 (2021), arXiv:2008.11316 [astro-ph.IM].

[147] L. Vazsonyi and D. Davis, Identifying glitches near gravitational-wave signals from compact binary coalescences using the Q-transform, Class. Quantum Gravity **40**, 035008

(2023), arXiv:2208.12338 [astro-ph.IM].
[148] S. Alvarez-Lopez, A. Liyanage, J. Ding, R. Ng, and J. McIver, GSpyNetTree: a signal-vs-glitch classifier for gravitational-wave event candidates, Class. Quantum Gravity **41**, 085007 (2024), arXiv:2304.09977 [gr-qc].
[149] A. L. Urban *et al.*, gwdetchar/gwdetchar, doi.org/10.5281/zenodo.2575786 (2021).
[150] J. R. Smith, T. Abbott, E. Hirose, N. Leroy, D. Macleod, J. McIver, P. Saulson, and P. Shawhan, A Hierarchical method for vetoing noise transients in gravitational-wave detectors, Class. Quantum Gravity **28**, 235005 (2011), arXiv:1107.2948 [gr-qc].
[151] R. Essick, P. Godwin, C. Hanna, L. Blackburn, and E. Katsavounidis, iDQ: Statistical Inference of Non-Gaussian Noise with Auxiliary Degrees of Freedom in Gravitational-Wave Detectors, Mach. Learn. Sci. Technol. **2**, 015004 (2020), arXiv:2005.12761 [astro-ph.IM].
[152] J. S. Areeda, J. R. Smith, A. P. Lundgren, E. Maros, D. M. Macleod, and J. Zweizig, LigoDV-web: Providing easy, secure and universal access to a large distributed scientific data store for the LIGO Scientific Collaboration, Astron. Comput. **18**, 27 (2017), arXiv:1611.01089 [astro-ph.IM].
[153] R. Macas and A. Lundgren, Sensitive test of non-Gaussianity in gravitational-wave detector data, Phys. Rev. D **108**, 063016 (2023), arXiv:2306.09019 [gr-qc].
[154] F. Robinet, N. Arnaud, N. Leroy, A. Lundgren, D. Macleod, and J. McIver, Omicron: a tool to characterize transient noise in gravitational-wave detectors, SoftwareX **12**, 100620 (2020), arXiv:2007.11374 [astro-ph.IM].
[155] A. Helmling-Cornell, P. Nguyen, R. Schofield, and R. Frey, Automated evaluation of environmental coupling for Advanced LIGO gravitational wave detections, Class. Quantum Gravity **41**, 145003 (2024), arXiv:2312.00735 [gr-qc].
[156] Virgo Collaboration, PythonVirgoTools, git.ligo.org/virgo/virgoapp/PythonVirgoTools (2021).
[157] S. Mozzon, L. K. Nuttall, A. Lundgren, T. Dent, S. Kumar, and A. H. Nitz, Dynamic Normalization for Compact Binary Coalescence Searches in Non-Stationary Noise, Class. Quantum Gravity **37**, 215014 (2020), arXiv:2002.09407 [astro-ph.IM].
[158] LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration, LVK Algorithm Library Suite, doi.org/10.7935/GT1W-FZ16 (2018).
[159] K. Wette, SWIGLAL: Python and Octave interfaces to the LALSuite gravitational-wave data analysis libraries, SoftwareX **12**, 100634 (2020), arXiv:2012.09552 [astro-ph.IM].
[160] S. A. Usman *et al.*, The PyCBC search for gravitational waves from compact binary coalescence, Class. Quantum Gravity **33**, 215004 (2016), arXiv:1508.02357 [gr-qc].
[161] A. H. Nitz, T. Dent, T. Dal Canton, S. Fairhurst, and D. A. Brown, Detecting binary compact-object mergers with gravitational waves: Understanding and Improving the sensitivity of the PyCBC search, Astrophys. J. **849**, 118 (2017), arXiv:1705.01513 [gr-qc].
[162] G. S. Davies, T. Dent, M. Tápai, I. Harry, C. McIsaac, and A. H. Nitz, Extending the PyCBC search for gravitational waves from compact binary mergers to a global network, Phys. Rev. D **102**, 022004 (2020), arXiv:2002.08291 [astro-ph.HE].
[163] S. Klimenko and G. Mitselmakher, A wavelet method for detection of gravitational wave bursts, Class. Quantum Gravity **21**, S1819 (2004).
[164] S. Klimenko, G. Vedovato, M. Drago, G. Mazzolo, G. Mitselmakher, C. Pankow, G. Prodi, V. Re, F. Salemi, and I. Yakushin, Localization of gravitational wave sources with networks of advanced detectors, Phys. Rev. D **83**, 102001 (2011), arXiv:1101.5408 [astro-ph.IM].
[165] M. Drago *et al.*, coherent WaveBurst, a pipeline for unmodeled gravitational-wave data analysis, SoftwareX **14**, 100678 (2021), arXiv:2006.12604 [gr-qc].
[166] N. J. Cornish and T. B. Littenberg, BayesWave: Bayesian Inference for Gravitational Wave Bursts and Instrument Glitches, Class. Quantum Gravity **32**, 135012 (2015), arXiv:1410.3835 [gr-qc].
[167] T. B. Littenberg, J. B. Kanner, N. J. Cornish, and M. Millhouse, Enabling high confidence detections of gravitational-wave bursts, Phys. Rev. D **94**, 044050 (2016), arXiv:1511.08752 [gr-qc].
[168] N. J. Cornish, T. B. Littenberg, B. Bécsy, K. Chatziioannou, J. A. Clark, S. Ghonge, and M. Millhouse, BayesWave analysis pipeline in the era of gravitational wave observations, Phys. Rev. D **103**, 044006 (2021), arXiv:2011.09494 [gr-qc].
[169] J. S. Speagle, dynesty: a dynamic nested sampling package for estimating Bayesian posteriors and evidences, Mon. Not. R. Astron. Soc. **493**, 3132 (2020), arXiv:1904.02180 [astro-ph.IM].
[170] D. P. Mihaylov, S. Ossokine, A. Buonanno, H. Estelles, L. Pompili, M. Pürrer, and A. Ramos-Buades, pySEOBNR: a software package for the next generation of effective-one-body multipolar waveform models, SoftwareX **30**, 102080 (2025), arXiv:2303.18203 [gr-qc].
[171] C. Hoy and V. Raymond, PESummary: the code agnostic Parameter Estimation Summary page builder, SoftwareX **15**, 100765 (2021), arXiv:2006.06639 [astro-ph.IM].
[172] G. Ashton *et al.*, Bilby TGR, doi.org/10.5281/zenodo.15676285 (2025).
[173] R. Gray *et al.*, Cosmological inference using gravitational wave standard sirens: A mock data analysis, Phys. Rev. D **101**, 122001 (2020), arXiv:1908.06050 [gr-qc].
[174] R. Gray, C. Messenger, and J. Veitch, A pixelated approach to galaxy catalogue incompleteness: improving the dark siren measurement of the Hubble constant, Mon. Not. Roy. Astron. Soc. **512**, 1127 (2022), arXiv:2111.04629 [astro-ph.CO].
[175] R. Gray *et al.*, Joint cosmological and gravitational-wave population inference using dark sirens and galaxy catalogues, J. Cosmol. Astropart. Phys. **12** (2023), 023, arXiv:2308.02281 [astro-ph.CO].
[176] S. Mastrogiovanni, D. Laghi, R. Gray, G. C. Santoro, A. Ghosh, C. Karathanasis, K. Leyde, D. A. Steer, S. Perries, and G. Pierra, Joint population and cosmological properties inference with gravitational waves standard sirens and galaxy surveys, Phys. Rev. D **108**, 042002 (2023), arXiv:2305.10488 [astro-ph.CO].
[177] S. Mastrogiovanni, G. Pierra, S. Perriès, D. Laghi, G. Caneva Santoro, A. Ghosh, R. Gray, C. Karathanasis, and K. Leyde, ICAROGW: A python package for inference of astrophysical population properties of noisy, heterogeneous, and incomplete observations, Astron. Astrophys. **682**, A167 (2024), arXiv:2305.17973 [astro-ph.CO].
[178] D. Williams, J. Veitch, M. L. Chiofalo, P. Schmidt, R. P. Udall, A. Vajpeji, and C. Hoy, Asimov: A framework for coordinating parameter estimation workflows, J. Open Source Softw. **8**, 4170 (2023), arXiv:2207.01468 [gr-qc].
[179] J. D. Hunter, Matplotlib: A 2D Graphics Environment, Comput. Sci. Eng. **9**, 90 (2007).
[180] M. L. Waskom, seaborn: statistical data visualization, J. Open Source Softw. **6**, 3021 (2021).
[181] D. Macleod *et al.*, gwpy/gwpy, doi.org/10.5281/zenodo.597016 (2021).
[182] C. R. Harris *et al.*, Array programming with NumPy, Nature

585, 357 (2020), arXiv:2006.10256 [cs.MS].
[183] P. Virtanen *et al.*, SciPy 1.0–Fundamental Algorithms for Scientific Computing in Python, Nat. Meth. **17**, 261 (2020), arXiv:1907.10121 [cs.MS].
[184] LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration, GW240925_005809, doi.org/10.7935/d2tg-qv58 (2026).
[185] LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration, GW250207_115645, doi.org/10.7935/k8et-b503 (2026).
[186] A. G. Abac *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration), Open Data from LIGO, Virgo, and KAGRA through the First Part of the Fourth Observing Run, Astrophys. J. **1004**, 232 (2026), arXiv:2508.18079 [gr-qc].
[187] LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration, Data Release for GW240925 and GW250207: Astrophysical Calibration of Gravitational-wave Detectors (2026).
[188] C. Grimaud, *Virgo interferometer calibration and h(t) strain reconstruction uncertainty during the O4 observing run*, Ph.D. thesis, Université Savoie Mont Blanc (2025).
[189] A. G. Sullivan *et al.*, Timing system of LIGO discoveries, Phys. Rev. D **108**, 022003 (2023), arXiv:2304.01188 [astro-ph.IM].
[190] F. Aubin, E. Dangelser, D. Estevez, A. Masserot, B. Mours, T. Pradier, A. Syx, and P. Van Hove, The Virgo Newtonian calibration system for the O4 observing run, Class. Quantum Gravity **41**, 235003 (2024), arXiv:2406.10028 [gr-qc].
[191] S. Soni *et al.* (LIGO Instrument Science Collaboration), Reducing scattered light in LIGO's third observing run, Class. Quantum Gravity **38**, 025016 (2021), arXiv:2007.14876 [astro-ph.IM].
[192] J. Glanzer, S. Soni, J. Spoon, A. Effler, and G. González, Noise in the LIGO livingston gravitational wave observatory due to trains, Class. Quantum Gravity **40**, 195015 (2023), arXiv:2304.07477 [astro-ph.IM].
[193] S. Soni, J. Glanzer, A. Effler, V. Frolov, G. González, A. Pele, and R. Schofield, Modeling and reduction of high frequency scatter noise at LIGO Livingston, Class. Quantum Gravity **41**, 135015 (2024), arXiv:2311.05730 [astro-ph.IM].
[194] P. B. Covas *et al.* (LIGO Instrument Science Collaboration), Identification and mitigation of narrow spectral artifacts that degrade searches for persistent gravitational waves in the first two observing runs of Advanced LIGO, Phys. Rev. D **97**, 082002 (2018), arXiv:1801.07204 [astro-ph.IM].
[195] D. Davis *et al.* (LIGO Instrument Science Collaboration), LIGO Detector Characterization in the Second and Third Observing Runs, Class. Quantum Gravity **38**, 135014 (2021), arXiv:2101.11673 [astro-ph.IM].
[196] F. Acernese *et al.* (Virgo Collaboration), Virgo detector characterization and data quality: tools, Class. Quantum Gravity **40**, 185005 (2023), arXiv:2210.15634 [gr-qc].
[197] G. Vajente, Y. Huang, M. Isi, J. C. Driggers, J. S. Kissel, M. J. Szczepańczyk, and S. Vitale, Machine-learning nonstationary noise out of gravitational-wave detectors, Phys. Rev. D **101**, 042003 (2020), arXiv:1911.09083 [gr-qc].
[198] S. Hourihane, K. Chatziioannou, M. Wijngaarden, D. Davis, T. Littenberg, and N. Cornish, Accurate modeling and mitigation of overlapping signals and glitches in gravitational-wave data, Phys. Rev. D **106**, 042006 (2022), arXiv:2205.13580 [gr-qc].
[199] D. Davis, T. B. Littenberg, I. M. Romero-Shaw, M. Millhouse, J. McIver, F. Di Renzo, and G. Ashton, Subtracting glitches from gravitational-wave detector data during the third LIGO-Virgo observing run, Class. Quantum Gravity **39**, 245013 (2022), arXiv:2207.03429 [astro-ph.IM].
[200] B. Allen, W. G. Anderson, P. R. Brady, D. A. Brown, and J. D. E. Creighton, FINDCHIRP: An Algorithm for detection of gravitational waves from inspiraling compact binaries, Phys. Rev. D **85**, 122006 (2012), arXiv:gr-qc/0509116.
[201] H.-Y. Chen, D. E. Holz, J. Miller, M. Evans, S. Vitale, and J. Creighton, Distance measures in gravitational-wave astrophysics and cosmology, Class. Quantum Gravity **38**, 055010 (2021), arXiv:1709.08079 [astro-ph.CO].
[202] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), Low-latency Gravitational-wave Alerts for Multimessenger Astronomy during the Second Advanced LIGO and Virgo Observing Run, Astrophys. J. **875**, 161 (2019), arXiv:1901.03310 [astro-ph.HE].
[203] T. Dal Canton, A. H. Nitz, B. Gadre, G. S. Cabourn Davies, V. Villa-Ortega, T. Dent, I. Harry, and L. Xiao, Real-time Search for Compact Binary Mergers in Advanced LIGO and Virgo's Third Observing Run Using PyCBC Live, Astrophys. J. **923**, 254 (2021), arXiv:2008.07494 [astro-ph.HE].
[204] T. Dal Canton *et al.*, Implementing a search for aligned-spin neutron star-black hole systems with advanced ground based gravitational wave detectors, Phys. Rev. D **90**, 082004 (2014), arXiv:1405.6731 [gr-qc].
[205] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), GW150914: First results from the search for binary black hole coalescence with Advanced LIGO, Phys. Rev. D **93**, 122003 (2016), arXiv:1602.03839 [gr-qc].
[206] R. Essick *et al.*, Compact binary coalescence sensitivity estimates with injection campaigns during the LIGO-Virgo-KAGRA Collaborations' fourth observing run, Phys. Rev. D **112**, 102001 (2025), arXiv:2508.10638 [gr-qc].
[207] L. Blanchet, T. Damour, B. R. Iyer, C. M. Will, and A. G. Wiseman, Gravitational radiation damping of compact binary systems to second postNewtonian order, Phys. Rev. Lett. **74**, 3515 (1995), arXiv:gr-qc/9501027.
[208] N. Christensen and R. Meyer, Parameter estimation with gravitational waves, Rev. Mod. Phys. **94**, 025001 (2022), arXiv:2204.04449 [gr-qc].
[209] T. B. Littenberg and N. J. Cornish, Bayesian inference for spectral estimation of gravitational wave detector noise, Phys. Rev. D **91**, 084034 (2015), arXiv:1410.3852 [gr-qc].
[210] G. Pratten *et al.*, Computationally efficient models for the dominant and subdominant harmonic modes of precessing binary black holes, Phys. Rev. D **103**, 104056 (2021), arXiv:2004.06503 [gr-qc].
[211] M. Colleoni, F. A. R. Vidal, C. García-Quirós, S. Akçay, and S. Bera, Fast frequency-domain gravitational waveforms for precessing binaries with a new twist, Phys. Rev. D **111**, 104019 (2025), arXiv:2412.16721 [gr-qc].
[212] E. Hamilton, L. London, J. E. Thompson, E. Fauchon-Jones, M. Hannam, C. Kalaghatgi, S. Khan, F. Pannarale, and A. Vano-Vinuales, Model of gravitational waves from precessing black-hole binaries through merger and ringdown, Phys. Rev. D **104**, 124027 (2021), arXiv:2107.08876 [gr-qc].
[213] E. Hamilton *et al.*, Improved gravitational wave model linking precessing inspirals and numerical-relativity-calibrated merger-ringdown, Phys. Rev. D **113**, 084055 (2026), arXiv:2507.02604 [gr-qc].
[214] A. Ramos-Buades, A. Buonanno, H. Estellés, M. Khalil, D. P. Mihaylov, S. Ossokine, L. Pompili, and M. Shiferaw, Next generation of accurate and efficient multipolar precessing-spin effective-one-body waveforms for binary black holes, Phys.

Rev. D **108**, 124037 (2023), arXiv:2303.18046 [gr-qc].
[215] H. Estellés, A. Buonanno, R. Enficiaud, C. Foo, and L. Pompili, Adding equatorial-asymmetric effects for spin-precessing binaries into the SEOBNRv5PHM waveform model, Phys. Rev. D **113**, 044049 (2026), arXiv:2506.19911 [gr-qc].
[216] G. Pratten, S. Husa, C. Garcia-Quiros, M. Colleoni, A. Ramos-Buades, H. Estelles, and R. Jaume, Setting the cornerstone for a family of models for gravitational waves from compact binaries: The dominant harmonic for nonprecessing quasicircular black holes, Phys. Rev. D **102**, 064001 (2020), arXiv:2001.11412 [gr-qc].
[217] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run, Phys. Rev. X **11**, 021053 (2021), arXiv:2010.14527 [gr-qc].
[218] LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration, LIGO/Virgo/KAGRA S240925n: Identification of a GW compact binary merger candidate, GCN **37604** (2024).
[219] A. Krolak and B. F. Schutz, Coalescing binaries — Probe of the universe, Gen. Relativ. Gravit. **19**, 1163 (1987).
[220] S. Nissanke, D. E. Holz, S. A. Hughes, N. Dalal, and J. L. Sievers, Exploring short gamma-ray bursts as gravitational-wave standard sirens, Astrophys. J. **725**, 496 (2010), arXiv:0904.1017 [astro-ph.CO].
[221] T. Narikawa, M. Kaneyama, and H. Tagoshi, Optimal follow-up observations of gravitational wave events with small optical telescopes, Phys. Rev. D **96**, 084067 (2017), arXiv:1705.04008 [gr-qc].
[222] S. A. Usman, J. C. Mills, and S. Fairhurst, Constraining the Inclinations of Binary Mergers from Gravitational-wave Observations, Astrophys. J. **877**, 82 (2019), arXiv:1809.10727 [gr-qc].
[223] B. S. Sathyaprakash and B. F. Schutz, Physics, Astrophysics and Cosmology with Gravitational Waves, Living Rev. Relativity **12**, 2 (2009), arXiv:0903.0338 [gr-qc].
[224] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), Effects of waveform model systematics on the interpretation of GW150914, Class. Quantum Gravity **34**, 104002 (2017), arXiv:1611.07531 [gr-qc].
[225] K. S. Thorne, Gravitational radiation, in *Three hundred years of gravitation*, edited by S. W. Hawking and W. Israel (Cambridge University Press, Cambridge, 1987) Chap. 9, pp. 330–458.
[226] L. S. Finn and D. F. Chernoff, Observing binary inspiral in gravitational radiation: One interferometer, Phys. Rev. D **47**, 2198 (1993), arXiv:gr-qc/9301003.
[227] B. F. Schutz, Networks of gravitational wave detectors and three figures of merit, Class. Quantum Gravity **28**, 125023 (2011), arXiv:1102.5421 [astro-ph.IM].
[228] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence, Phys. Rev. Lett. **119**, 141101 (2017), arXiv:1709.09660 [gr-qc].
[229] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Phys. Rev. Lett. **119**, 161101 (2017), arXiv:1710.05832 [gr-qc].
[230] K. Pearson, Note on regression and inheritance in the case of two parents, Proc. R. Soc. Lond. **58**, 240 (1895).
[231] R. Essick, S. Vitale, E. Katsavounidis, G. Vedovato, and S. Klimenko, Localization of short duration gravitational-wave transients with the early advanced LIGO and Virgo detectors, Astrophys. J. **800**, 81 (2015), arXiv:1409.2435 [astro-ph.HE].
[232] L. Sampson, N. Cornish, and N. Yunes, Gravitational Wave Tests of Strong Field General Relativity with Binary Inspirals: Realistic Injections and Optimal Model Selection, Phys. Rev. D **87**, 102001 (2013), arXiv:1303.1185 [gr-qc].
[233] B. Edelman *et al.*, Constraining unmodeled physics with compact binary mergers from GWTC-1, Phys. Rev. D **103**, 042004 (2021), arXiv:2008.06436 [gr-qc].
[234] L. Pompili *et al.*, Laying the foundation of the effective-one-body waveform models SEOBNRv5: Improved accuracy and efficiency for spinning nonprecessing binary black holes, Phys. Rev. D **108**, 124035 (2023), arXiv:2303.18039 [gr-qc].
[235] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration), Tests of general relativity with binary black holes from the second LIGO–Virgo gravitational-wave transient catalog, Phys. Rev. D **103**, 122002 (2021), arXiv:2010.14529 [gr-qc].
[236] E. M. Sänger *et al.*, Tests of general relativity with GW230529: A neutron star merging with a lower mass-gap compact object, Phys. Rev. D **113**, 084070 (2026), arXiv:2406.03568 [gr-qc].
[237] A. Pai and K. G. Arun, Singular value decomposition in parametrised tests of post-Newtonian theory, Class. Quantum Gravity **30**, 025011 (2013), arXiv:1207.1943 [gr-qc].
[238] A. A. Shoom, P. K. Gupta, B. Krishnan, A. B. Nielsen, and C. D. Capano, Testing the post-Newtonian expansion with GW170817, Gen. Rel. Grav. **55**, 55 (2023), arXiv:2105.02191 [gr-qc].