



Search for Eccentric Black Hole Coalescences during the Third Observing Run of LIGO and Virgo

A. G. Abac¹, R. Abbott², H. Abe³, F. Acernese^{4,5}, K. Ackley⁶, C. Adamcewicz⁷, S. Adhicary⁸, N. Adhikari⁹, R. X. Adhikari², V. K. Adkins¹⁰, V. B. Adya¹¹, C. Affeldt^{12,13}, D. Agarwal¹⁴, M. Agathos¹⁵, O. D. Aguiar¹⁶, I. Aguilar¹⁷, L. Aiello¹⁸, A. Ain¹⁹, P. Ajith²⁰, T. Akutsu^{21,22}, S. Albanesi^{23,24}, R. A. Alford²⁵, A. Al-Jodah²⁶, C. Alléne²⁷, A. Allocca^{5,28}, M. Almualla²⁹, P. A. Altin¹¹, S. Álvarez-López³⁰, A. Amato^{31,32}, L. Amez-Droz³³, A. Amorosi³⁴, S. Anand², A. Ananyeva², R. Andersen³⁴, S. B. Anderson², W. G. Anderson², M. Andia³⁵, M. Ando^{36,37}, T. Andrade³⁸, N. Andres²⁷, M. Andrés-Carcasona³⁹, T. Andric^{1,40}, S. Ansoldi^{41,42}, J. M. Antelis⁴³, S. Antier⁴⁴, M. Aoumi⁴⁵, T. Apostolatos⁴⁶, E. Z. Appavuravther^{47,48}, S. Appert⁴⁹, S. K. Apple², K. Arai⁵⁰, A. Araya⁵¹, M. C. Araya⁵², J. S. Areeda⁵³, N. Aritomi⁵⁴, F. Armato⁵⁵, N. Arnaud⁵⁶, M. Arogeti⁵⁷, S. M. Aronson⁵⁸, K. G. Arun⁵⁹, G. Ashton⁶⁰, Y. Aso⁶¹, M. Assiduo⁶², S. Assis de Souza Melo⁶³, S. M. Aston⁶⁴, P. Astone⁶⁵, F. Aubin⁶⁶, K. AultONeal⁶⁷, S. Babak⁶⁸, A. Badalyan⁶⁹, F. Badaracco⁷⁰, C. Badger⁷¹, S. Bae⁷², S. Bagnasco⁷³, Y. Bai⁷⁴, J. G. Baier⁷⁵, R. Bajpai⁷⁶, T. Baka⁷⁷, M. Ball⁷⁸, G. Ballardini⁷⁹, S. W. Ballmer⁸⁰, G. Baltus⁸¹, S. Banagiri⁸², B. Banerjee⁸³, D. Bankar⁸⁴, P. Baral⁸⁵, J. C. Barayoga⁸⁶, J. Barber⁸⁷, B. C. Barish⁸⁸, D. Barker⁸⁹, P. Barneo⁹⁰, F. Barone⁹¹, B. Barr⁹², L. Barsotti⁹³, M. Barsuglia⁹⁴, D. Barta⁹⁵, S. D. Barthelmy⁹⁶, M. A. Barton⁹⁷, I. Bartos⁹⁸, S. Basak⁹⁹, A. Basalae¹⁰⁰, R. Bassiri¹⁰¹, A. Basti¹⁰², M. Bawaj¹⁰³, P. Baxi¹⁰⁴, J. C. Bayley¹⁰⁵, A. C. Baylor¹⁰⁶, M. Bazzan¹⁰⁷, B. Bécsy¹⁰⁸, V. M. Bedakihale¹⁰⁹, F. Beirnaert¹¹⁰, M. Bejger¹¹¹, A. S. Bell¹¹², V. Benedetto¹¹³, D. Beniwal¹¹⁴, W. Benoit¹¹⁵, J. D. Bentley¹¹⁶, M. Ben Yaala¹¹⁷, S. Bera¹¹⁸, M. Berbel¹¹⁹, F. Bergamin¹²⁰, B. K. Berger¹²¹, S. Bernuzzi¹²², M. Beroiz¹²³, C. P. L. Berry¹²⁴, D. Bersanetti¹²⁵, A. Bertolini¹²⁶, J. Betzwieser¹²⁷, D. Beveridge¹²⁸, N. Bevins¹²⁹, R. Bhandare¹³⁰, A. V. Bhandari¹³¹, U. Bhardwaj¹³², R. Bhatt¹³³, D. Bhattacharjee¹³⁴, S. Bhaumik¹³⁵, A. Bianchi¹³⁶, I. A. Bilenko¹³⁷, M. Bilicki¹³⁸, G. Billingsley¹³⁹, A. Binetti¹⁴⁰, S. Bini¹⁴¹, O. Birnholtz¹⁴², S. Biscans¹⁴³, M. Bisch¹⁴⁴, S. Biscoveanu¹⁴⁵, A. Bisht¹⁴⁶, M. Bitossi¹⁴⁷, M.-A. Bizouard¹⁴⁸, J. K. Blackburn¹⁴⁹, C. D. Blair¹⁵⁰, D. G. Blair¹⁵¹, F. Bobba¹⁵², N. Bode¹⁵³, M. Boër¹⁵⁴, G. Bogaert¹⁵⁵, G. Boileau¹⁵⁶, M. Boldrini¹⁵⁷, G. N. Bolingbroke¹⁵⁸, L. D. Bonavena¹⁵⁹, R. Bondarescu¹⁶⁰, F. Bondu¹⁶¹, E. Bonilla¹⁶², G. S. Bonilla¹⁶³, R. Bonnand¹⁶⁴, P. Booker¹⁶⁵, V. Boschi¹⁶⁶, S. Bose¹⁶⁷, V. Bossilkov¹⁶⁸, V. Boudart¹⁶⁹, A. Bozzi¹⁷⁰, C. Bradaschia¹⁷¹, P. R. Brady¹⁷², M. Braglia¹⁷³, A. Branch¹⁷⁴, M. Branchesi¹⁷⁵, M. Breschi¹⁷⁶, T. Briant¹⁷⁷, A. Brillet¹⁷⁸, M. Brinkmann¹⁷⁹, P. Brockill¹⁸⁰, A. F. Brooks¹⁸¹, D. D. Brown¹⁸², M. L. Brozzetti¹⁸³, S. Brunetti¹⁸⁴, G. Bruno¹⁸⁵, R. Bruntz¹⁸⁶, J. Bryant¹⁸⁷, F. Bucci¹⁸⁸, J. Buchanan¹⁸⁹, O. Bulashenko¹⁹⁰, T. Bulik¹⁹¹, H. J. Bulten¹⁹², A. Buonanno¹⁹³, K. Burtzyk¹⁹⁴, R. Buscicchio¹⁹⁵, D. Buskulic¹⁹⁶, C. Buy¹⁹⁷, G. S. Cabourn Davies¹⁹⁸, G. Cabras¹⁹⁹, R. Cabrita²⁰⁰, L. Cadonati²⁰¹, G. Cagnoli²⁰², C. Cahillane²⁰³, H. W. Cain III²⁰⁴, J. Calderón Bustillo²⁰⁵, J. D. Callaghan²⁰⁶, T. A. Callister²⁰⁷, E. Calloni²⁰⁸, J. B. Camp²⁰⁹, M. Canepa²¹⁰, G. Caneva Santoro²¹¹, M. Cannavacciuolo²¹², K. C. Cannon²¹³, H. Cao²¹⁴, Z. Cao²¹⁵, L. A. Capistran²¹⁶, E. Capocasa²¹⁷, E. Capote²¹⁸, G. Carapella²¹⁹, F. Carbognani²²⁰, M. Carlassara²²¹, J. B. Carlin²²², M. Carpinelli²²³, J. J. Carter²²⁴, G. Carullo²²⁵, J. Casanueva Diaz²²⁶, C. Casentini²²⁷, G. Castaldi²²⁸, S. Y. Castro-Lucas²²⁹, S. Caudill²³⁰, M. Cavaglia²³¹, R. Cavalieri²³², G. Cella²³³, P. Cerdá-Durán²³⁴, E. Cesarini²³⁵, W. Chaibi²³⁶, S. Chalathadka-Subrahmanya²³⁷, C. Chan²³⁸, J. C. L. Chan²³⁹, K. H. M. Chan²⁴⁰, M. Chan²⁴¹, W. L. Chan²⁴², K. Chandra²⁴³, I. P. Chang²⁴⁴, R.-J. Chang²⁴⁵, W. Chang²⁴⁶, P. Chanial²⁴⁷, S. Chao²⁴⁸, C. Chapman-Bird²⁴⁹, E. L. Charlton²⁵⁰, P. Charlton²⁵¹, E. Chassande-Mottin²⁵², L. Chastain²⁵³, C. Chatterjee²⁵⁴, Debarati Chatterjee²⁵⁵, Deep Chatterjee²⁵⁶, M. Chaturvedi²⁵⁷, S. Chaty²⁵⁸, K. Chatziioannou²⁵⁹, A. Chen²⁶⁰, A. H.-Y. Chen²⁶¹, D. Chen²⁶², H. Y. Chen²⁶³, H. Y. Chen²⁶⁴, J. Chen²⁶⁵, K. H. Chen²⁶⁶, X. Chen²⁶⁷, Y.-R. Chen²⁶⁸, Y. Chen²⁶⁹, H. Cheng²⁷⁰, P. Chessa²⁷¹, H. Y. Chia²⁷², F. Chiadini²⁷³, C. Chiang²⁷⁴, G. Chiarini²⁷⁵, A. Chiba²⁷⁶, R. Chiba²⁷⁷, R. Chierici²⁷⁸, A. Chincarini²⁷⁹, M. L. Chiofalo²⁸⁰, A. Chiummo²⁸¹, C. Chou²⁸², S. Choudhary²⁸³, N. Christensen²⁸⁴, S. S. Y. Chua²⁸⁵, K. W. Chung²⁸⁶, G. Ciani²⁸⁷, P. Cieciela²⁸⁸, M. Cieślak²⁸⁹, M. Cifaldi²⁹⁰, A. A. Ciobanu²⁹¹, R. Ciolfi²⁹², F. Clara²⁹³, J. A. Clark²⁹⁴, T. A. Clarke²⁹⁵, P. Clearwater²⁹⁶, S. Clesse²⁹⁷, F. Cleva²⁹⁸, E. Coccia²⁹⁹, E. Codazzo³⁰⁰, P.-F. Cohadon³⁰¹, M. Colleoni³⁰², C. G. Collette³⁰³, J. Collins³⁰⁴, A. Colombo³⁰⁵, M. Colpi³⁰⁶, C. M. Compton³⁰⁷, L. Conti³⁰⁸, S. J. Cooper³⁰⁹, T. R. Corbitt³¹⁰, I. Cordero-Carrión³¹¹, S. Corezzi³¹², N. J. Cornish³¹³, A. Corsi³¹⁴, S. Cortese³¹⁵, C. A. Costa³¹⁶, R. Cottingham³¹⁷, M. W. Coughlin³¹⁸, A. Couineaux³¹⁹, J.-P. Coulon³²⁰, S. T. Countryman³²¹, J.-F. Coupechoux³²², B. Cousins³²³, P. Couvares³²⁴, D. M. Coward³²⁵, M. J. Cowart³²⁶, B. D. Cowburn³²⁷, D. C. Coyne³²⁸, R. Coyne³²⁹, K. Craig³³⁰, J. D. E. Creighton³³¹, T. D. Creighton³³², A. W. Criswell³³³, J. C. G. Crockett-Gray³³⁴, M. Croquette³³⁵, R. Crouch³³⁶, S. G. Crowder³³⁷, J. R. Cudell³³⁸, T. J. Cullen³³⁹, A. Cumming³⁴⁰, E. Cuoco³⁴¹, M. Curylo³⁴², M. Cusinato³⁴³, P. Dabadie³⁴⁴, T. Dal Canton³⁴⁵, S. Dall'Osso³⁴⁶, G. Dálya³⁴⁷, B. D'Angelo³⁴⁸, S. Danilishin³⁴⁹, S. D'Antonio³⁵⁰, K. Danzmann³⁵¹, K. E. Darroch³⁵², C. Darsow-Fromm³⁵³, L. P. Darte³⁵⁴, A. Dasgupta³⁵⁵, S. Datta³⁵⁶, V. Dattilo³⁵⁷, A. Daumas³⁵⁸, I. Dave³⁵⁹, A. Davenport³⁶⁰, M. Davies³⁶¹, D. Davis³⁶², M. C. Davis³⁶³, E. J. Daw³⁶⁴, M. Dax³⁶⁵, M. Deenadayalan³⁶⁶, J. Degallaix³⁶⁷, M. De Laurentis³⁶⁸, S. Deléglise³⁶⁹, V. Del Favero³⁷⁰, F. De Lillo³⁷¹, D. Dell'Aquila³⁷², W. Del Pozzo³⁷³, F. De Marco³⁷⁴, F. De Matteis³⁷⁵, V. D'Emilio³⁷⁶, N. Demos³⁷⁷, T. Dent³⁷⁸, A. Depasse³⁷⁹, R. De Pietri³⁸⁰, R. De Rosa³⁸¹, C. De Rossi³⁸²

- R. De Simone¹⁵⁰, S. Dhurandhar¹⁴, R. Diab⁷⁸, P. Z. Diamond⁶⁷, M. C. Díaz¹⁶³, N. A. Didio⁷⁰, T. Dietrich¹, L. Di Fiore⁵, C. Di Fronzo³³, F. Di Giovanni¹³⁷, M. Di Giovanni⁴⁰, T. Di Girolamo^{5,28}, D. Diksha^{31,32}, A. Di Lieto^{19,80}, A. Di Michele⁸¹, J. Ding^{63,171}, S. Di Pace^{62,108}, I. Di Palma^{62,108}, F. Di Renzo¹⁵³, Divyajyoti¹⁷², A. Dmitriev¹¹⁵, Z. Doctor⁷², E. Dohmen⁵², P. P. Doleva¹¹⁴, L. Donahue¹⁷³, L. D’Onofrio^{5,28}, F. Donovan⁷⁵, K. L. Dooley¹⁸, T. Dooney⁶⁸, S. Doravari¹⁴, O. Dorosh¹⁷⁴, M. Drago^{62,108}, J. C. Driggers⁵², Y. Drori², H. Du³⁰, J.-G. Ducoin^{63,175}, L. Dunn¹²⁹, U. Dupletsa⁴⁰, D. D’Urso^{130,168}, H. Duval¹⁷⁶, P.-A. Duverne³⁵, S. E. Dwyer⁵², C. Eassa⁵², M. Ebersold^{27,177}, T. Eckhardt⁷⁹, G. Eddolls²⁵, B. Edelman⁶⁹, T. B. Edo², O. Edy¹²¹, A. Effler⁶¹, J. Eichholz¹¹, H. Einsle⁴⁴, M. Eisenmann²¹, R. A. Eisenstein⁷⁵, A. Ejlli¹⁸, E. Engelby⁵¹, A. J. Engl¹⁷, L. Errico^{5,28}, R. C. Essick¹⁷⁸, H. Estellés¹, D. Estevez¹⁷⁹, T. Etzel², C. R. Evans¹⁸, M. Evans⁷⁵, T. M. Evans⁶¹, T. Evstafyeva¹⁵, B. E. Ewing⁸, J. M. Ezquiaga¹²⁴, F. Fabrizi^{59,60}, F. Faedi^{59,60}, V. Fafone^{40,132,133}, H. Fair⁷⁰, S. Fairhurst¹⁸, P. C. Fan¹⁷³, A. M. Farah¹²⁴, B. Farr⁶⁹, W. M. Farr^{180,181}, E. J. Fauchon-Jones¹⁸, G. Favaro⁸³, M. Favata¹⁸², M. Fays⁷¹, J. Feicht², M. M. Fejer¹⁷, E. Fenyvesi^{76,183}, D. L. Ferguson¹⁴⁸, I. Ferrante^{19,80}, T. A. Ferreira¹⁶, F. Fidecaro^{19,80}, A. Fiori^{19,80}, I. Fiori⁵⁴, M. Fishbach¹⁷⁸, R. P. Fisher¹¹⁴, R. Fittipaldi^{106,184}, V. Fiumara^{106,185}, R. Flaminio²⁷, S. M. Fleischer¹⁸⁶, L. S. Fleming¹⁸⁷, E. Floden²⁹, H. Fong³⁰, J. A. Font^{137,138}, B. Fornal¹⁸⁸, P. W. F. Forsyth¹¹, K. Franceschetti¹⁶⁹, A. Franke⁷⁹, S. Frasca^{62,108}, F. Frasconi¹⁹, A. Frattale Mascioli^{62,108}, Z. Frei¹⁸⁹, A. Freise^{32,98}, O. Freitas^{137,190}, R. Frey⁶⁹, W. Frischhertz⁶¹, P. Fritschel⁷⁵, V. V. Frolov⁶¹, G. G. Fronze²⁴, S. Fujii¹⁵², I. Fukunaga¹⁹¹, P. Fulda⁷⁸, M. Fyffe⁶¹, W. E. Gabella¹⁹², B. Gadre⁶⁸, J. R. Gair¹, J. Gais¹³⁹, S. Galaudage⁷, S. Gallardo¹⁹³, R. Gamba⁹⁴, D. Ganapathy⁷⁵, A. Ganguly¹⁴, S. G. Gaonkar¹⁴, B. Garaventa^{53,125}, J. Garcia-Bellido¹¹⁰, C. García-Núñez¹⁸⁷, C. García-Quirós⁹², J. W. Gardner¹¹, K. A. Gardner³⁰, J. Gargiulo⁵⁴, F. Garufi^{5,28}, C. Gasbarra^{132,133}, B. Gateley⁵², V. Gayathri⁹, G. Gemme⁵³, A. Gennai¹⁹, J. George⁹⁶, O. Gerberding⁷⁹, L. Gergely¹⁹⁴, N. Ghadiri⁵¹, Abhirup Ghosh¹, Archisman Ghosh⁸⁷, Shaon Ghosh¹⁸², Shrobana Ghosh^{12,13}, Suprovo Ghosh¹⁴, Tathagata Ghosh¹⁴, L. Giaccoppo^{62,108}, J. A. Giaime^{10,61}, K. D. Giardina⁶¹, D. R. Gibson¹⁸⁷, C. Gier⁹¹, P. Giri^{19,80}, F. Gissi⁸⁹, S. Gkaitatzis⁸⁰, J. Glanzer¹⁰, A. E. Gleckl⁵¹, F. Glotin³⁵, J. Godfrey⁶⁹, P. Godwin², E. Goetz³⁰, R. Goetz⁷⁸, J. Golomb², S. Gomez Lopez^{62,108}, B. Goncharov⁴⁰, G. González¹⁰, A. W. Goodwin-Jones²⁶, M. Gosselin⁵⁴, R. Gouaty²⁷, D. W. Gould¹¹, S. Goyal²⁰, B. Grace¹¹, A. Grado^{5,195}, V. Graham²⁵, A. E. Granados²⁹, M. Granata¹⁶⁷, V. Granata¹⁰⁵, S. Gras⁷⁵, P. Grassia², C. Gray⁵², R. Gray²⁵, G. Greco⁴⁷, A. C. Green⁹⁸, S. M. Green¹²¹, S. R. Green¹, A. M. Gretarsson⁴³, E. M. Gretarsson⁴³, D. Griffith², W. L. Griffiths¹⁸, H. L. Griggs⁵⁵, G. Grignani^{47,81}, A. Grimaldi^{102,103}, C. Grimaud²⁷, H. Grote¹⁸, A. S. Gruson⁵¹, D. Guerra¹³⁷, D. Guetta⁶², G. M. Guidi^{59,60}, A. R. Guimaraes¹⁰, H. K. Gulati⁸⁶, F. Gulminelli^{196,197}, A. M. Gunny⁷⁵, H. Guo¹⁸⁸, Y. Guo^{31,32}, Anchal Gupta², Anuradha Gupta¹⁹⁸, Ish Gupta⁸, N. C. Gupta⁸⁶, P. Gupta^{32,68}, S. K. Gupta¹⁴⁰, N. Gupte¹, R. Gurav³⁴, J. Gurs⁷⁹, E. K. Gustafson², N. Gutierrez¹⁶⁷, F. Guzman¹²⁸, D. Haba³, L. Haegel⁶³, G. Hain¹¹⁴, S. Haino¹⁹⁹, O. Halim⁴², E. D. Hall⁷⁵, E. Z. Hamilton¹⁷⁷, G. Hammond²⁵, W.-B. Han²⁰⁰, M. Haney^{32,177}, J. Hanks⁵², C. Hanna⁸, M. D. Hannam¹⁸, O. A. Hannuksela¹³⁹, A. G. Hanselman¹²⁴, H. Hansen⁵², J. Hanson⁶¹, R. Harada¹²⁶, T. Harder⁴⁴, K. Haris^{32,68}, T. Harmark¹³¹, J. Harms^{40,111}, G. M. Harry⁴⁹, I. W. Harry¹²¹, D. Hartwig⁷⁹, B. Haskell⁸⁸, C.-J. Haster²⁰¹, J. S. Hathaway¹⁶¹, K. Haughian²⁵, H. Hayakawa⁴⁵, K. Hayama²⁰², F. J. Hayes²⁵, J. Healy¹⁶¹, A. Heffernan⁹², A. Heidmann¹¹², M. C. Heintze⁶¹, J. Heinze¹¹⁵, J. Heinzl⁷⁵, H. Heitmann⁴⁴, F. Hellman²⁰³, P. Hello³⁵, A. F. Helmling-Cornell⁶⁹, G. Hemming⁵⁴, M. Hendry²⁵, I. S. Heng²⁵, E. Hennes³², J.-S. Hennig^{31,32}, M. Hennig^{31,32}, C. Henshaw⁵⁵, A. Hernandez¹⁸², T. Hertog¹⁰¹, M. Heurs^{12,13}, A. L. Hewitt^{15,204}, S. Higginbotham¹⁸, S. Hild^{31,32}, P. Hill⁹¹, Y. Himemoto²⁰⁵, A. S. Hines¹²⁸, N. Hirata²¹, C. Hirose²⁰⁶, J. Ho¹⁴³, S. Hoang³⁵, S. Hochheim^{12,13}, D. Hofman¹⁶⁷, J. N. Hohmann⁷⁹, N. A. Holland^{32,98}, K. Holley-Bockelmann¹⁹², I. J. Hollows¹⁶⁶, Z. J. Holmes⁹⁰, D. E. Holz¹²⁴, C. Hong¹⁷, Q. Hong¹⁴¹, J. Hornung⁶⁹, S. Hoshino²⁰⁶, J. Hough²⁵, S. Hourihane², E. J. Howell²⁶, C. G. Hoy¹²¹, D. Hoyland¹¹⁵, H.-F. Hsieh¹⁴¹, C. Hsiung²⁰⁷, H. C. Hsu¹⁴³, S.-C. Hsu^{141,208}, W.-F. Hsu¹⁰¹, P. Hu¹⁹², Q. Hu²⁵, H. Y. Huang¹⁴³, Y.-J. Huang⁸, Y. Huang⁷⁵, Y. T. Huang²⁰⁸, M. T. Hübner¹²⁹, A. D. Huddart²⁰⁹, B. Hughey⁴³, D. C. Y. Hui²¹⁰, V. Hui²⁷, R. Hur⁶⁹, S. Husa⁹², R. Huxford⁸, T. Huynh-Dinh⁶¹, J. Hyland²⁵, A. Iakovlev²¹¹, G. A. Iandolo³¹, A. Iess^{19,165}, K. Inayoshi²¹², Y. Inoue¹⁴³, G. Iorio⁸³, P. Iosif²¹³, J. Irwin²⁵, M. Isi^{180,181}, M. A. Ismail¹⁴³, Y. Itoh^{191,214}, M. Iwaya¹⁵², B. R. Iyer²⁰, V. JaberianHamedan²⁶, T. Jacqmin¹¹², P.-E. Jacquet¹¹², S. J. Jadhav²¹⁵, S. P. Jadhav¹⁵⁵, D. Jain⁷, T. Jain¹⁵, A. L. James¹⁸, P. A. James¹¹⁴, R. Jamshidi³³, A. Z. Jan¹⁴⁸, K. Jani¹⁹², L. Janiurek²⁵, J. Janquart^{32,68}, K. Janssens^{44,107}, N. N. Janthaler²¹⁵, S. Jaraba¹¹⁰, P. Jaranowski²¹⁶, S. Jarov³⁰, P. Jasal³⁸, R. Jaime⁹², W. Javed¹⁸, K. Jenner⁹⁰, A. Jennings⁵², W. Jia⁷⁵, J. Jiang⁷⁸, H.-B. Jin^{217,218}, K. Johansmeyer¹⁸², G. R. Johns¹¹⁴, N. A. Johnson⁷⁸, R. Johnston²⁵, N. Johny^{12,13}, D. H. Jones¹¹, D. I. Jones²¹⁹, R. Jones²⁵, P. Joshi⁸, L. Ju²⁶, K. Jung²²⁰, J. Junker^{12,13}, V. Juste¹⁷⁹, T. Kajita¹⁵², C. Kalaghatgi^{32,68,221}, V. Kalogera⁷², M. Kamiizumi⁴⁵, N. Kanda^{191,214}, S. Kandhasamy¹⁴, G. Kang²²², J. B. Kanner², S. J. Kapadia¹⁴, D. P. Kapasi¹¹, S. Karat², C. Karathanasis³⁹, S. Karki¹³⁶, T. Karydas²⁷, Y. A. Kas-danouche⁶⁴, R. Kashyap⁸, M. Kasprzak², W. Kastaun^{12,13}, J. Kato¹⁵¹, T. Kato¹⁵², S. Katsanevas^{54,304}, E. Katsavounidis⁷⁵, J. K. Katsuren⁶⁴, W. Katzman⁶¹, T. Kaur²⁶, K. Kawabe⁵², F. Kéfélian⁴⁴, D. Keitel⁹², J. Kelley-Derzon⁷⁸, S. A. Kemper⁴³, J. Kennington⁸, R. Kesharwani¹⁴, J. S. Key²²³, S. Khadka¹⁷, F. Y. Khalili⁹⁹, T. Khanam¹⁵⁹, E. A. Khazanov²¹¹, M. Khursheed⁹⁶, N. Kijbunchoo¹¹, C. Kim²²⁴, J. C. Kim²²⁵, K. Kim²²⁴, M. H. Kim²²⁶, P. Kim²²⁶, S. Kim²¹⁰, W. S. Kim²²⁷, Y.-M. Kim²²⁸, C. Kimball⁷², N. Kimura⁴⁵, M. Kinley-Hanlon²⁵, R. Kirchhoff^{12,13}, J. S. Kissel⁵², T. Kiyota¹⁹¹, S. Klimenko⁷⁸, T. Klinger¹⁸, A. M. Knee³⁰, N. Knust^{12,13}, P. Koch^{12,13}, S. M. Koehlenbeck¹⁷

G. Koekoek^{31,32}, K. Kohri²²⁹, K. Kokeyama¹⁸, S. Koley⁴⁰, N. D. Koliadko⁶⁴, P. Kolitsidou¹⁸, M. Kolstein³⁹, K. Komori¹²⁶, V. Kondrashov², A. K. H. Kong¹⁴¹, A. Kontos²³⁰, M. Korobko⁷⁹, R. V. Kossak^{12,13}, N. Kouvatsos⁶⁵, M. Kovalam²⁶, N. Koyama²⁰⁶, D. B. Kozak², S. L. Kranzhoft^{12,13,31,32}, V. Kringel^{12,13}, N. V. Krishnendu²⁰, A. Królak^{174,231}, G. Kuehn^{12,13}, P. Kuijer³², S. Kulkarni¹⁹⁸, A. Kulur Ramamohan¹¹, A. Kumar²¹⁵, Praveen Kumar¹²³, Prayush Kumar²⁰, Rahul Kumar⁵², Rakesh Kumar⁸⁶, J. Kume¹²⁶, K. Kuns⁷⁵, S. Kuroyanagi^{110,232}, S. Kuwahara¹²⁶, K. Kwak²²⁰, K. Kwan¹¹, G. Lacaille²⁵, P. Lagabbe²⁷, D. Laghi¹²⁰, S. Lai¹⁴⁶, M. H. Lakkis³³, E. Lalande²³³, M. Lalleman¹⁰⁷, A. Lamberts^{44,234}, M. Landry⁵², B. B. Lane⁷⁵, R. N. Lang⁷⁵, J. Lange¹⁴⁸, B. Lantz¹⁷, A. La Rana⁶², I. L. Rosa^{27,108}, A. Lartaux-Vollard³⁵, P. D. Lasky⁷, J. Lawrence¹⁵⁹, M. Laxen⁶¹, A. Lazzarini², C. Lazzaro^{83,84}, P. Leaci^{62,108}, S. Leavey^{12,13}, S. LeBohec¹⁸⁸, Y. K. Lecoeuche³⁰, H. M. 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MacInnis⁷⁵, D. M. Macleod¹⁸, I. A. O. MacMillan², A. Macquet³⁹, K. Maeda¹⁵¹, S. Maenaut¹⁰¹, I. Magaña Hernandez⁹, C. Magazzù¹⁹, R. M. Magee², R. Maggiore^{32,98}, M. Magnozzi^{53,125}, M. Mahesh⁷⁹, S. Mahesh²⁴³, M. Maini¹⁶², S. Majhi¹⁴, E. Majorana^{62,108}, C. N. Makarem², S. Maliakal², A. Malik⁹⁶, N. Man⁴⁴, V. Mandic²⁹, V. Mangano^{62,108}, B. Mannix⁶⁹, G. L. Mansell^{70,75}, G. Mansingh⁴⁹, M. Manske⁹, M. Mantovani⁵⁴, M. Mapelli^{83,84}, F. Marchesoni^{47,48,244}, D. Marín Pina^{38,73,245}, F. Marion²⁷, S. Márka¹⁶⁰, Z. Márka¹⁶⁰, C. Markakis¹⁴⁵, A. S. Markosyan¹⁷, A. Markowitz², E. Maros², A. Marquina¹⁵⁸, S. Marsat¹²⁰, F. Martelli^{59,60}, I. W. Martin²⁵, R. M. Martin¹⁸², B. B. Martinez¹²⁸, M. Martinez^{39,246}, V. A. Martinez⁷⁸, V. Martinez¹²², K. Martinovic⁶⁵, D. V. Martynov¹¹⁵, E. J. Marx⁷⁵, H. Masalehdan⁷⁹, A. Masserot²⁷, M. Masso-Reid²⁵, M. Mastrodicasa⁶², S. Mastrogianni⁶², M. Mateu-Lucena⁹², M. Matiushechkin^{12,13}, M. Matsuyama¹⁹¹, N. Mavalvala⁷⁵, N. Maxwell⁵², G. 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- J. Petermann⁷⁹, C. Petrillo⁸¹, H. P. Pfeiffer¹, H. Pham⁶¹, K. A. Pham²⁹, K. S. Phukon^{32,221}, H. Phurailatpam¹³⁹, O. J. Piccinni³⁹, M. Pichot⁴⁴, M. Piendibene^{19,80}, F. Piergiovanni^{59,60}, L. Pierini^{62,108}, G. Pierra¹⁵³, V. Pierro^{89,106}, M. . Pietrzak⁸⁸, G. Pillant⁵⁴, M. Pillas³⁵, F. Pilo¹⁹, L. Pinard¹⁶⁷, C. Pineda-Bosque¹⁹³, I. M. Pinto^{28,54,89,106,270}, M. Pinto⁵⁴, B. J. Piotrkowski⁹, M. Pirello⁵², M. D. Pitkin^{15,25,204}, A. Placidi^{47,81}, E. Placidi^{62,108}, M. L. Planas⁹², W. Plastino^{271,272}, R. Poggiani^{19,80}, E. Polini²⁷, L. Pompili¹, S. Ponrathnam^{14,305}, J. Poon¹³⁹, E. Porcelli³², J. Portell^{38,73,245}, E. K. Porter⁶³, C. Posnansky⁸, R. Poulton⁵⁴, J. Powell¹⁵⁵, M. Pracchia²⁷, B. K. Pradhan¹⁴, T. Pradier¹⁷⁹, A. K. Prajapati⁸⁶, K. Prasai¹⁷, R. Prasanna²¹⁵, P. Prasia¹⁴, G. Pratten¹¹⁵, M. Principe^{89,106,134,270}, G. A. Prodi^{103,273}, L. Prokhorov¹¹⁵, P. Proposito^{132,133}, L. Prudenzi¹, A. Puecher^{32,68}, J. Pullin¹⁰, M. Punturo⁴⁷, F. 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Schouteden¹⁰¹, H. Schuler⁸, B. W. Schulte^{12,13}, B. F. Schutz^{1,18}, E. Schwartz¹⁸, J. Scott²⁵, S. M. Scott¹¹, T. C. Seetharamu²⁵, M. Seglar-Arroyo³⁹, Y. Sekiguchi²⁷⁹, D. Sellers⁶¹, A. S. Sengupta²⁸⁰, D. Sentenac⁵⁴, E. G. Seo²⁵, J. W. Seo¹⁰¹, V. Sequino^{5,28}, G. Servignat²⁶⁰, Y. Setyawati⁶⁸, T. Shaffer⁵², M. S. Shahriar⁷², M. A. Shaikh²²⁵, B. Shams¹⁸⁸, L. Shao²¹², P. Sharma⁹⁶, S. Sharma-Chaudhary¹³⁶, P. Shawhan¹¹⁷, N. S. Shcheblanov^{238,281}, A. Sheela¹⁷², B. Shen¹¹⁷, K. G. Shepard⁶⁴, Y. Shikano^{282,283}, M. Shikauchi¹²⁶, K. Shimode⁴⁵, H. Shinkai²⁸⁴, J. Shiota²⁵³, D. H. Shoemaker⁷⁵, D. M. Shoemaker¹⁴⁸, R. W. Short⁵², S. ShyamSundar⁹⁶, A. Sider³³, H. Siegel^{180,181}, M. Sieniawska¹¹³, D. Sigg⁵², L. Silenzi^{47,48}, M. Simmonds⁹⁰, L. P. Singer⁷⁷, A. Singh¹⁹⁸, D. Singh⁸, M. K. Singh²⁰, A. Singha^{31,32}, A. M. Sintes⁹², V. Sipala^{130,168}, V. Skliris¹⁸, B. J. J. Slagmolen¹¹, T. J. Slaven-Blair²⁶, J. Smetana¹¹⁵, J. R. Smith⁵¹, L. Smith²⁵, R. J. E. Smith⁷, J. Soldateschi^{60,239,285}, S. N. Somala²⁸⁶, K. Somiya³, K. Soni¹⁴, S. Soni⁷⁵, V. Sordini¹⁵³, F. Sorrentino⁵³, N. Sorrentino^{19,80}, R. Soulard⁴⁴, T. Souradeep^{14,287}, E. Sowell¹⁵⁹, V. Spagnuolo^{31,32}, A. P. Spencer²⁵, M. Spera^{83,84}, P. Spinicelli⁵⁴, A. K. Srivastava⁸⁶, V. Srivastava⁷⁰, C. Stachie⁴⁴, F. Stachurski²⁵, D. A. Steer⁶³, J. Steinlechner^{31,32}, S. Steinlechner^{31,32}, D. Stephens⁷², N. Stergioulas²¹³, P. Stevens³⁵, M. StPierre¹⁶², L. C. Strang¹²⁹, G. Stratta^{62,288,289,290}, M. D. Strong¹⁰, A. Strunk⁵², R. Sturani²⁹¹, A. L. Stuver⁹⁵, M. Suchenek⁸⁸, S. Sudhagar^{14,88}, N. Suelmann⁷⁹, H. G. Suh⁹, A. G. Sullivan¹⁶⁰, T. Z. Summerscales⁶⁴, L. Sun¹¹, S. Sunil⁸⁶, A. Sur⁸⁸, J. Suresh^{113,126}, P. J. Sutton¹⁸, Takamasa Suzuki²⁰⁶, Takanori Suzuki³, B. L. Swinkels³², A. Syx¹⁷⁹, M. J. Szczepańczyk⁷⁸, P. Szweczyk¹¹⁶, M. Tacca³², H. Tagoshi¹⁵², S. C. Tait²⁵, H. Takahashi²⁹², R. Takahashi²¹, A. Takamori⁵⁰, K. Takatani¹⁹¹, H. Takeda²⁹³, M. Takeda¹⁹¹, C. J. Talbot⁹¹, C. Talbot⁷⁵, M. Tamaki¹⁵², N. Tamanini¹²⁰, D. Tanabe¹⁴³, K. Tanaka¹⁵², S. J. Tanaka²⁵³, T. Tanaka²⁹³, A. J. Tanasijczuk¹¹³, S. Tanioka⁷⁰, D. B. Tanner⁷⁸, D. Tao², L. Tao⁷⁸, R. D. Tapia⁸, E. N. Tapia San Martín³², R. Tarafder², C. Taranto¹³², A. Taruya²⁹⁴, J. D. Tasson¹⁷³, M. Teloi³³, R. Tenorio⁹², L. Terkowski⁷⁹, H. Themann¹⁹³, M. P. Thirugnanasambandam¹⁴, L. M. Thomas¹¹⁵, M. Thomas⁶¹, P. Thomas⁵², J. E. Thompson¹⁸, S. R. Thondapu⁹⁶, K. A. Thorne⁶¹, E. Thrane⁷, J. Tissino⁴⁰, Shubhanshu Tiwari¹⁷⁷, Srishti Tiwari¹⁴, V. Tiwari¹⁸, A. M. Toivonen²⁹, A. E. Tolley¹²¹, T. Tomaru²¹, K. Tomita¹⁹¹, T. Tomura⁴⁵, M. Tonelli^{19,80}, A. Toriyama²⁵³, A. Torres-Forne^{137,138}, C. I. Torrie², M. Toscani¹²⁰, I. Tosta e Melo¹³⁰, E. Tournefier²⁷, A. A. Trani¹²⁶, A. Trapananti^{47,48}, F. Travasso^{47,48}, G. Traylor⁶¹, J. Trenado³⁸, M. Trevor¹¹⁷, M. C. Tringali⁵⁴, A. Tripathy⁸², L. Troiano^{106,295}, A. Trovato^{42,248}, L. Trozzo⁵, R. J. Trudeau², M. Tse⁷⁵, R. Tso¹⁴⁹, S. Tsuchida²⁹⁶, L. Tsukada⁸, T. Tsutsui¹²⁶, K. Turbang^{107,176}, M. Turconi⁴⁴, C. Turski⁸⁷, H. Ubach^{38,73}, A. S. Ubhi¹¹⁵, N. Uchikata¹⁵², T. Uchiyama⁴⁵, R. P. Udall², T. Uehara²⁹⁷, K. Ueno¹²⁶, C. S. Unnikrishnan²⁵², T. Ushiba⁴⁵, A. Utina^{31,32}, H. Vahlbruch^{12,13}, N. Vaidya², G. Vajente², A. Vajpeyi⁷, G. Valdes¹²⁸, M. Valentini^{32,98}, S. A. Vallejo-Peña²⁷⁵, S. Vallero²⁴, V. Valsan⁹, N. van Bakel³², M. van Beuzekom³², M. van Dael^{32,298}, J. F. J. van den Brand^{31,32,98}, C. Van Den Broeck^{32,68}, D. C. Vander-Hyde⁷⁰, M. van der Sluis^{32,68}, A. Van de Walle³⁵, J. van Dongen^{32,98}, H. van Haevermaet¹⁰⁷, J. V. van Heijningen¹¹³, J. Vanosky², M. H. P. M. van Putten²⁹⁹, Z. van Ranst^{31,32}, N. van Remortel¹⁰⁷, M. Vardaro^{31,32}, A. F. Vargas¹²⁹, V. Varma¹, M. Vasúth⁷⁶, A. Vecchio¹¹⁵, G. Vedovato⁸⁴, J. Veitch²⁵, P. J. Veitch⁹⁰, J. Venneberg^{12,13}, P. Verdier¹⁵³, D. Verkindt²⁷, P. Verma¹⁷⁴, Y. Verma⁹⁶

S. M. Vermeulen¹⁸, D. Veske¹⁶⁰, F. Vetrano⁵⁹, A. Veutro⁶², A. Viceré^{59,60}, S. Vidyant⁷⁰, A. D. Viets³⁰⁰,
A. Vijaykumar²⁰, V. Villa-Ortega¹²³, E. T. Vincent⁵⁵, J.-Y. Vinet⁴⁴, S. Viret¹⁵³, A. Virtuoso^{42,248}, S. Vitale⁷⁵,
H. Vocca^{47,81}, D. Voigt⁷⁹, E. R. G. von Reis⁵², J. S. A. von Wrangel^{12,13}, S. P. Vyatchanin⁹⁹, L. E. Wade⁶⁷, M. Wade⁶⁷,
K. J. Wagner¹⁶¹, R. C. Walet³², M. Walker¹¹⁴, G. S. Wallace⁹¹, L. Wallace², H. Wang²⁶⁶, J. Z. Wang⁸², W. H. Wang¹⁶³,
R. L. Ward¹¹, J. Warner⁵², M. Was²⁷, T. Washimi²¹, N. Y. Washington², K. Watada¹¹⁴, D. Watarai¹²⁶, K. E. Wayt⁶⁷,
B. Weaver⁵², C. R. Weaving¹²¹, S. A. Webster²⁵, M. Weinert^{12,13}, A. J. Weinstein², R. Weiss⁷⁵, C. M. Weller²⁰⁸,
R. A. Weller¹⁹², F. Wellmann^{12,13}, L. Wen²⁶, P. Weßels^{12,13}, K. Wette¹¹, J. T. Whelan¹⁶¹, D. D. White⁵¹, B. F. Whiting⁷⁸,
C. Whittle⁷⁵, J. B. Wildberger¹, O. S. Wilk⁶⁷, D. Wilken^{12,13,13}, K. Willetts¹⁸, D. Williams²⁵, M. J. Williams²⁵,
A. R. Williamson¹²¹, J. L. Willis², B. Willke^{12,13,13}, M. Wils¹⁰¹, C. C. Wipf², G. Woan²⁵, J. Woehler^{12,13},
J. K. Wofford¹⁶¹, D. Wong³⁰, H. T. Wong¹⁴³, I. C. F. Wong¹³⁹, M. Wright²⁵, C. Wu¹⁴¹, D. S. Wu^{12,13}, H. Wu¹⁴¹,
D. M. Wysocki⁹, L. Xiao², V. A. Xu⁷⁵, N. Yadav⁸⁸, H. Yamamoto², K. Yamamoto¹⁵¹, M. Yamamoto¹⁵¹,
T. S. Yamamoto²³², T. Yamamoto⁴⁵, S. Yamamura¹⁵², R. Yamazaki²⁵³, S. Yan¹⁷, F. W. Yang¹⁸⁸, K. Z. Yang²⁹,
L.-C. Yang¹⁴⁶, Y.-C. Yang¹⁴¹, Yang Yang⁷⁸, Yi Yang¹⁴⁶, M. J. Yap¹¹, Z. Yarbrough¹⁰, S.-W. Yeh¹⁴¹, A. B. Yelkar¹⁶¹,
S. M. C. Yeung⁹, T. Y. Yeung⁶⁴, J. Yokoyama^{36,37}, T. Yokozawa⁴⁵, J. Yoo³⁰¹, H. Yu¹⁴⁹, H. Yuzurihara⁴⁵,
A. Zadrożny¹⁷⁴, A. J. Zannelli¹¹⁴, M. Zanolin⁴³, M. Zeeshan¹⁶¹, T. Zelenova⁵⁴, J.-P. Zendri⁸⁴, M. Zevin¹²⁴, J. Zhang¹¹,
L. Zhang², R. Zhang⁷⁸, T. Zhang³⁰², Yanqi Zhang¹²⁸, Ya Zhang¹¹, C. Zhao²⁶, Yue Zhao¹⁸⁸, Yuhang Zhao^{21,63,152},
Y. Zheng¹³⁶, H. Zhong²⁹, R. Zhou²⁰³, Z.-H. Zhu^{127,303}, A. B. Zimmerman¹⁴⁸, M. E. Zucker^{2,75}, and J. Zweizig²

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 Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

³ Graduate School of Science, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan

⁴ Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy

⁵ INFN, Sezione di Napoli, I-80126 Napoli, Italy

⁶ University of Warwick, Coventry CV4 7AL, UK

⁷ OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia

⁸ The Pennsylvania State University, University Park, PA 16802, USA

⁹ University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

¹⁰ Louisiana State University, Baton Rouge, LA 70803, USA

¹¹ OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia

¹² Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany

¹³ Leibniz Universität Hannover, D-30167 Hannover, Germany

¹⁴ Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India

¹⁵ University of Cambridge, Cambridge CB2 1TN, UK

¹⁶ Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil

¹⁷ Stanford University, Stanford, CA 94305, USA

¹⁸ Cardiff University, Cardiff CF24 3AA, UK

¹⁹ INFN, Sezione di Pisa, I-56127 Pisa, Italy

²⁰ International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India

²¹ Gravitational Wave Science Project, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan

²² Advanced Technology Center, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan

²³ Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy

²⁴ INFN Sezione di Torino, I-10125 Torino, Italy

²⁵ SUPA, University of Glasgow, Glasgow G12 8QQ, UK

²⁶ OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia

²⁷ Univ. Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, F-74000 Annecy, France

²⁸ Università di Napoli "Federico II," I-80126 Napoli, Italy

²⁹ University of Minnesota, Minneapolis, MN 55455, USA

³⁰ University of British Columbia, Vancouver, BC V6T 1Z4, Canada

³¹ Maastricht University, 6200 MD Maastricht, The Netherlands

³² Nikhef, 1098 XG Amsterdam, The Netherlands

³³ Université Libre de Bruxelles, Brussels 1050, Belgium

³⁴ University of California Riverside, Riverside, CA 92521, USA

³⁵ Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

³⁶ Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

³⁷ Research Center for the Early Universe (RESCEU), University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan

³⁸ Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), c. Martí i Franquès, 1, 08028 Barcelona, Spain

³⁹ Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, E-08193 Bellaterra (Barcelona), Spain

⁴⁰ Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy

⁴¹ Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy

⁴² INFN, Sezione di Trieste, I-34127 Trieste, Italy

⁴³ Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA

⁴⁴ Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, Artemis, F-06304 Nice, France

⁴⁵ Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan

⁴⁶ Department of Physics, National and Kapodistrian University of Athens, 15771 Ilissia, Greece

⁴⁷ INFN, Sezione di Perugia, I-06123 Perugia, Italy

⁴⁸ Università di Camerino, I-62032 Camerino, Italy

⁴⁹ American University, Washington, DC 20016, USA

⁵⁰ Earthquake Research Institute, The University of Tokyo, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

⁵¹ California State University Fullerton, Fullerton, CA 92831, USA

- ⁵² LIGO Hanford Observatory, Richland, WA 99352, USA
- ⁵³ INFN, Sezione di Genova, I-16146 Genova, Italy
- ⁵⁴ European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
- ⁵⁵ Georgia Institute of Technology, Atlanta, GA 30332, USA
- ⁵⁶ Chennai Mathematical Institute, Chennai 603103, India
- ⁵⁷ Royal Holloway, University of London, London TW20 0EX, UK
- ⁵⁸ The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan
- ⁵⁹ Università degli Studi di Urbino “Carlo Bo”, I-61029 Urbino, Italy
- ⁶⁰ INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
- ⁶¹ LIGO Livingston Observatory, Livingston, LA 70754, USA
- ⁶² INFN, Sezione di Roma, I-00185 Roma, Italy
- ⁶³ Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
- ⁶⁴ Andrews University, Berrien Springs, MI 49104, USA
- ⁶⁵ King’s College London, University of London, London WC2R 2LS, UK
- ⁶⁶ Korea Institute of Science and Technology Information, Daejeon 34141, Republic of Korea
- ⁶⁷ Kenyon College, Gambier, OH 43022, USA
- ⁶⁸ Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, 3584 CC Utrecht, The Netherlands
- ⁶⁹ University of Oregon, Eugene, OR 97403, USA
- ⁷⁰ Syracuse University, Syracuse, NY 13244, USA
- ⁷¹ Université de Liège, B-4000 Liège, Belgium
- ⁷² Northwestern University, Evanston, IL 60208, USA
- ⁷³ Departament de Física Quàntica i Astrofísica (FQA), Universitat de Barcelona (UB), c. Martí i Franqués, 1, 08028 Barcelona, Spain
- ⁷⁴ Dipartimento di Medicina, Chirurgia e Odontoiatria “Scuola Medica Salernitana,” Università di Salerno, I-84081 Baronissi, Salerno, Italy
- ⁷⁵ LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
- ⁷⁶ Wigner RCP, RMKI, H-1121 Budapest, Hungary
- ⁷⁷ NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
- ⁷⁸ University of Florida, Gainesville, FL 32611, USA
- ⁷⁹ Universität Hamburg, D-22761 Hamburg, Germany
- ⁸⁰ Università di Pisa, I-56127 Pisa, Italy
- ⁸¹ Università di Perugia, I-06123 Perugia, Italy
- ⁸² University of Michigan, Ann Arbor, MI 48109, USA
- ⁸³ Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
- ⁸⁴ INFN, Sezione di Padova, I-35131 Padova, Italy
- ⁸⁵ Montana State University, Bozeman, MT 59717, USA
- ⁸⁶ Institute for Plasma Research, Bhat, Gandhinagar 382428, India
- ⁸⁷ Universiteit Gent, B-9000 Gent, Belgium
- ⁸⁸ Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
- ⁸⁹ Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
- ⁹⁰ OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia
- ⁹¹ SUPA, University of Strathclyde, Glasgow G1 1XQ, UK
- ⁹² IAC3–IEEC, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain
- ⁹³ Departamento de Matemáticas, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain
- ⁹⁴ Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany
- ⁹⁵ Villanova University, Villanova, PA 19085, USA
- ⁹⁶ RRCAT, Indore, Madhya Pradesh 452013, India
- ⁹⁷ GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands
- ⁹⁸ Department of Physics and Astronomy, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, The Netherlands
- ⁹⁹ Lomonosov Moscow State University, Moscow 119991, Russia
- ¹⁰⁰ Center for Theoretical Physics, Polish Academy of Sciences, 02-668, Warsaw, Poland
- ¹⁰¹ Katholieke Universiteit Leuven, Oude Markt 13, 3000 Leuven, Belgium
- ¹⁰² Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
- ¹⁰³ INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
- ¹⁰⁴ Bar-Ilan University, Ramat Gan, 5290002, Israel
- ¹⁰⁵ Dipartimento di Fisica “E.R. Caianiello”, Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ¹⁰⁶ INFN, Sezione di Napoli, Gruppo Collegato di Salerno, I-80126 Napoli, Italy
- ¹⁰⁷ Universiteit Antwerpen, 2000 Antwerpen, Belgium
- ¹⁰⁸ Università di Roma “La Sapienza,” I-00185 Roma, Italy
- ¹⁰⁹ University Rennes, CNRS, Institut FOTON - UMR 6082, F-35000 Rennes, France
- ¹¹⁰ Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid, 28049 Madrid, Spain
- ¹¹¹ INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
- ¹¹² Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
- ¹¹³ Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
- ¹¹⁴ Christopher Newport University, Newport News, VA 23606, USA
- ¹¹⁵ University of Birmingham, Birmingham B15 2TT, UK
- ¹¹⁶ Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
- ¹¹⁷ University of Maryland, College Park, MD 20742, USA
- ¹¹⁸ Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy
- ¹¹⁹ INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
- ¹²⁰ L2IT, Laboratoire des 2 Infinis - Toulouse, Université de Toulouse, CNRS/IN2P3, UPS, F-31062 Toulouse Cedex 9, France
- ¹²¹ University of Portsmouth, Portsmouth, PO1 3FX, UK
- ¹²² Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France
- ¹²³ IGFAE, Universidade de Santiago de Compostela, 15782 Spain
- ¹²⁴ University of Chicago, Chicago, IL 60637, USA
- ¹²⁵ Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
- ¹²⁶ University of Tokyo, Tokyo, 113-0033, Japan
- ¹²⁷ Department of Astronomy, Beijing Normal University, Xijiekouwai Street 19, Haidian District, Beijing 100875, People’s Republic of China

- ¹²⁸ Texas A&M University, College Station, TX 77843, USA
- ¹²⁹ OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia
- ¹³⁰ INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy
- ¹³¹ Niels Bohr Institute, Copenhagen University, 2100 København, Denmark
- ¹³² Università di Roma Tor Vergata, I-00133 Roma, Italy
- ¹³³ INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
- ¹³⁴ University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy
- ¹³⁵ Colorado State University, Fort Collins, CO 80523, USA
- ¹³⁶ Missouri University of Science and Technology, Rolla, MO 65409, USA
- ¹³⁷ Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain
- ¹³⁸ Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
- ¹³⁹ The Chinese University of Hong Kong, Shatin, NT, Hong Kong
- ¹⁴⁰ Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
- ¹⁴¹ National Tsing Hua University, Hsinchu City 30013, Taiwan
- ¹⁴² Department of Physics, National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan
- ¹⁴³ National Central University, Taoyuan City 320317, Taiwan
- ¹⁴⁴ OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
- ¹⁴⁵ Queen Mary University of London, London E1 4NS, UK
- ¹⁴⁶ Department of Electrophysics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan
- ¹⁴⁷ Kamioka Branch, National Astronomical Observatory of Japan, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan
- ¹⁴⁸ University of Texas, Austin, TX 78712, USA
- ¹⁴⁹ CaRT, California Institute of Technology, Pasadena, CA 91125, USA
- ¹⁵⁰ Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ¹⁵¹ Faculty of Science, University of Toyama, 3190 Gofuku, Toyama City, Toyama 930-8555, Japan
- ¹⁵² Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan
- ¹⁵³ Université Lyon, Université Claude Bernard Lyon 1, CNRS, IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
- ¹⁵⁴ INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
- ¹⁵⁵ OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia
- ¹⁵⁶ Université libre de Bruxelles, 1050 Bruxelles, Belgium
- ¹⁵⁷ INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
- ¹⁵⁸ Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
- ¹⁵⁹ Texas Tech University, Lubbock, TX 79409, USA
- ¹⁶⁰ Columbia University, New York, NY 10027, USA
- ¹⁶¹ Rochester Institute of Technology, Rochester, NY 14623, USA
- ¹⁶² University of Rhode Island, Kingston, RI 02881, USA
- ¹⁶³ The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA
- ¹⁶⁴ Bellevue College, Bellevue, WA 98007, USA
- ¹⁶⁵ Scuola Normale Superiore, I-56126 Pisa, Italy
- ¹⁶⁶ The University of Sheffield, Sheffield S10 2TN, UK
- ¹⁶⁷ Université Lyon, Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
- ¹⁶⁸ Università degli Studi di Sassari, I-07100 Sassari, Italy
- ¹⁶⁹ Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
- ¹⁷⁰ INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
- ¹⁷¹ Corps des Mines, Mines Paris, Université PSL, 60 Bd Saint-Michel, 75272 Paris, France
- ¹⁷² Indian Institute of Technology Madras, Chennai 600036, India
- ¹⁷³ Carleton College, Northfield, MN 55057, USA
- ¹⁷⁴ National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland
- ¹⁷⁵ Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 75014 Paris, France
- ¹⁷⁶ Vrije Universiteit Brussel, 1050 Brussel, Belgium
- ¹⁷⁷ University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland
- ¹⁷⁸ Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada
- ¹⁷⁹ Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
- ¹⁸⁰ Stony Brook University, Stony Brook, NY 11794, USA
- ¹⁸¹ Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA
- ¹⁸² Montclair State University, Montclair, NJ 07043, USA
- ¹⁸³ Institute for Nuclear Research, H-4026 Debrecen, Hungary
- ¹⁸⁴ CNR-SPIN, I-84084 Fisciano, Salerno, Italy
- ¹⁸⁵ Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
- ¹⁸⁶ Western Washington University, Bellingham, WA 98225, USA
- ¹⁸⁷ SUPA, University of the West of Scotland, Paisley PA1 2BE, UK
- ¹⁸⁸ The University of Utah, Salt Lake City, UT 84112, USA
- ¹⁸⁹ Eötvös University, Budapest 1117, Hungary
- ¹⁹⁰ Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, PT-4710-057 Braga, Portugal
- ¹⁹¹ Department of Physics, Graduate School of Science, Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
- ¹⁹² Vanderbilt University, Nashville, TN 37235, USA
- ¹⁹³ California State University, Los Angeles, Los Angeles, CA 90032, USA
- ¹⁹⁴ University of Szeged, Dóm tér 9, Szeged 6720, Hungary
- ¹⁹⁵ INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
- ¹⁹⁶ Université de Normandie, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France
- ¹⁹⁷ Laboratoire de Physique Corpusculaire Caen, 6 boulevard du maréchal Juin, F-14050 Caen, France
- ¹⁹⁸ The University of Mississippi, University, MS 38677, USA
- ¹⁹⁹ Institute of Physics, Academia Sinica, 128 Sec. 2, Academia Road, Nankang, Taipei 11529, Taiwan
- ²⁰⁰ Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, People's Republic of China
- ²⁰¹ University of Nevada Las Vegas, Las Vegas, NV 89154, USA
- ²⁰² Department of Applied Physics, Fukuoka University, 8-19-1 Nanakuma, Jonan, Fukuoka City, Fukuoka 814-0180, Japan

- ²⁰³ University of California, Berkeley, CA 94720, USA
²⁰⁴ University of Lancaster, Lancaster LA1 4YW, UK
²⁰⁵ College of Industrial Technology, Nihon University, 1-2-1 Izumi, Narashino City, Chiba 275-8575, Japan
²⁰⁶ Faculty of Engineering, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan
²⁰⁷ Department of Physics, Tamkang University, No. 151, Yingzhuan Road, Danshui Dist., New Taipei City 25137, Taiwan
²⁰⁸ University of Washington, Seattle, WA 98195, USA
²⁰⁹ Rutherford Appleton Laboratory, Didcot OX11 0DE, UK
²¹⁰ Department of Astronomy and Space Science, Chungnam National University, 9 Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea
²¹¹ Institute of Applied Physics, Nizhny Novgorod, 603950, Russia
²¹² Kavli Institute for Astronomy and Astrophysics, Peking University, Yiheyuan Road 5, Haidian District, Beijing 100871, People's Republic of China
²¹³ Department of Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
²¹⁴ 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
²¹⁵ Directorate of Construction, Services & Estate Management, Mumbai 400094, India
²¹⁶ University of Białystok, 15-424 Białystok, Poland
²¹⁷ National Astronomical Observatories, Chinese Academic of Sciences, 20A Datun Road, Chaoyang District, Beijing, People's Republic of China
²¹⁸ School of Astronomy and Space Science, University of Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing, People's Republic of China
²¹⁹ University of Southampton, Southampton SO17 1BJ, UK
²²⁰ Department of Physics, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Ulju-gun, Ulsan 44919, Republic of Korea
²²¹ Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands
²²² Chung-Ang University, Seoul 06974, Republic of Korea
²²³ University of Washington Bothell, Bothell, WA 98011, USA
²²⁴ Ewha Womans University, Seoul 03760, Republic of Korea
²²⁵ Seoul National University, Seoul 08826, Republic of Korea
²²⁶ Sungkyunkwan University, Seoul 03063, Republic of Korea
²²⁷ National Institute for Mathematical Sciences, Daejeon 34047, Republic of Korea
²²⁸ Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea
²²⁹ Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba City, Ibaraki 305-0801, Japan
²³⁰ Bard College, Annandale-on-Hudson, NY 12504, USA
²³¹ Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland
²³² Department of Physics, Nagoya University, ES building, Furocho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
²³³ Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada
²³⁴ Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, Lagrange, F-06304 Nice, France
²³⁵ Inje University Gimhae, South Gyeongsang 50834, Republic of Korea
²³⁶ Technology Center for Astronomy and Space Science, Korea Astronomy and Space Science Institute (KASI), 776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea
²³⁷ Perimeter Institute, Waterloo, ON N2L 2Y5, Canada
²³⁸ NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS. Marne-la-Vallée, France
²³⁹ Università di Firenze, Sesto Fiorentino I-50019, Italy
²⁴⁰ Department of Physics, University of Trento, via Sommarive 14, Povo, 38123 TN, Italy
²⁴¹ National Center for High-performance Computing, National Applied Research Laboratories, No. 7, R&D 6th Road, Hsinchu Science Park, Hsinchu City 30076, Taiwan
²⁴² NAS. Marshall Space Flight Center, Huntsville, AL 35811, USA
²⁴³ West Virginia University, Morgantown, WV 26506, USA
²⁴⁴ School of Physics Science and Engineering, Tongji University, Shanghai 200092, People's Republic of China
²⁴⁵ Institut d'Estudis Espacials de Catalunya, c. Gran Capità, 2-4, 08034 Barcelona, Spain
²⁴⁶ Institució Catalana de Recerca i Estudis Avançats (ICREA), Passeig de Lluís Companys, 23, 08010 Barcelona, Spain
²⁴⁷ Tsinghua University, Beijing 100084, People's Republic of China
²⁴⁸ Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
²⁴⁹ Institute for Photon Science and Technology, The University of Tokyo, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-8656, Japan
²⁵⁰ INFN Cagliari, Physics Department, Università degli Studi di Cagliari, Cagliari 09042, Italy
²⁵¹ Saha Institute of Nuclear Physics, Bidhannagar, West Bengal 700064, India
²⁵² Tata Institute of Fundamental Research, Mumbai 400005, India
²⁵³ Department of Physical Sciences, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagami-hara City, Kanagawa 252-5258, Japan
²⁵⁴ Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France
²⁵⁵ Faculty of Law, Ryukoku University, 67 Fukakusa Tsukamoto-cho, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan
²⁵⁶ Indian Institute of Science Education and Research, Kolkata, Mohanpur, West Bengal 741252, India
²⁵⁷ Department of Physics and Astronomy, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556, USA
²⁵⁸ Department of Astronomy, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
²⁵⁹ Centre national de la recherche scientifique, 75016 Paris, France
²⁶⁰ Laboratoire Univers et Théories, Observatoire de Paris, 92190 Meudon, France
²⁶¹ Observatoire de Paris, 75014 Paris, France
²⁶² Université PSL, 75006 Paris, France
²⁶³ Université de Paris Cité, 75006 Paris, France
²⁶⁴ Graduate School of Science and Technology, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan
²⁶⁵ Niigata Study Center, The Open University of Japan, 754 Ichibancho, Asahimachi-dori, Chuo-ku, Niigata City, Niigata 951-8122, Japan
²⁶⁶ Department of Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan
²⁶⁷ CSIR—Central Glass and Ceramic Research Institute, Kolkata, West Bengal 700032, India
²⁶⁸ Consiglio Nazionale delle Ricerche—Istituto dei Sistemi Complessi, I-00185 Roma, Italy
²⁶⁹ Hobart and William Smith Colleges, Geneva, NY 14456, USA
²⁷⁰ Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi,” I-00184 Roma, Italy
²⁷¹ Dipartimento di Ingegneria Industriale, Elettronica e Meccanica, Università degli Studi Roma Tre, I-00146 Roma, Italy
²⁷² INFN, Sezione di Roma Tre, I-00146 Roma, Italy
²⁷³ Università di Trento, Dipartimento di Matematica, I-38123 Povo, Trento, Italy
²⁷⁴ Subatech, CNRS/IN2P3—Institut Mines-Télécom Atlantique—Université de Nantes, 4 rue Alfred Kastler BP 20722 44307 Nantes C'EDEX 03, France
²⁷⁵ Universidad de Antioquia, Medellín, Colombia

- ²⁷⁶ Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, 888 Nishikataai, Nagaoka City, Niigata 940-8532, Japan
- ²⁷⁷ Departamento de Matemática da Universidade de Aveiro, Centre for Research and Development in Mathematics and Applications, 3810-183 Aveiro, Portugal
- ²⁷⁸ Marquette University, Milwaukee, WI 53233, USA
- ²⁷⁹ Faculty of Science, Toho University, 2-2-1 Miyama, Funabashi City, Chiba 274-8510, Japan
- ²⁸⁰ Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India
- ²⁸¹ Laboratoire MSME, Cité Descartes, 5 Boulevard Descartes, Champs-sur-Marne, 77454 Marne-la-Vallée Cedex 2, France
- ²⁸² Graduate School of Science and Technology, Gunma University, 4-2 Aramaki, Maebashi, Gunma 371-8510, Japan
- ²⁸³ Institute for Quantum Studies, Chapman University, 1 University Drive, Orange, CA 92866, USA
- ²⁸⁴ Faculty of Information Science and Technology, Osaka Institute of Technology, 1-79-1 Kitayama, Hirakata City, Osaka 573-0196, Japan
- ²⁸⁵ INAF, Osservatorio Astrofisico di Arcetri, I-50125 Firenze, Italy
- ²⁸⁶ Indian Institute of Technology Hyderabad, Sangareddy, Khandi, Telangana 502285, India
- ²⁸⁷ Indian Institute of Science Education and Research, Pune, Maharashtra 411008, India
- ²⁸⁸ Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany
- ²⁸⁹ Istituto di Astrofisica e Planetologia Spaziali di Roma, 00133 Roma, Italy
- ²⁹⁰ INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy
- ²⁹¹ Universidade Estadual Paulista, 01140-070 Campinas, São Paulo, Brazil
- ²⁹² Research Center for Space Science, Advanced Research Laboratories, Tokyo City University, 8-15-1 Todoroki, Setagaya, Tokyo 158-0082, Japan
- ²⁹³ Department of Physics, Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan
- ²⁹⁴ Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan
- ²⁹⁵ Dipartimento di Scienze Aziendali—Management and Innovation Systems (DISA-MIS), Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ²⁹⁶ National Institute of Technology, Fukui College, Geshi-cho, Sabae-shi, Fukui 916-8507, Japan
- ²⁹⁷ Department of Communications Engineering, National Defense Academy of Japan, 1-10-20 Hashirimizu, Yokosuka City, Kanagawa 239-8686, Japan
- ²⁹⁸ Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands
- ²⁹⁹ Department of Physics and Astronomy, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 143-747, Republic of Korea
- ³⁰⁰ Concordia University Wisconsin, Mequon, WI 53097, USA
- ³⁰¹ Cornell University, Ithaca, NY 14850, USA
- ³⁰² Maastricht University, 6200 MD, Maastricht, The Netherlands
- ³⁰³ School of Physics and Technology, Wuhan University, Bayi Road 299, Wuchang District, Wuhan, Hubei, 430072, People's Republic of China

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Abstract

Despite the growing number of binary black hole coalescences confidently observed through gravitational waves so far, the astrophysical origin of these binaries remains uncertain. Orbital eccentricity is one of the clearest tracers of binary formation channels. Identifying binary eccentricity, however, remains challenging due to the limited availability of gravitational waveforms that include the effects of eccentricity. Here, we present observational results for a waveform-independent search sensitive to eccentric black hole coalescences, covering the third observing run (O3) of the LIGO and Virgo detectors. We identified no new high-significance candidates beyond those that have already been identified with searches focusing on quasi-circular binaries. We determine the sensitivity of our search to high-mass (total source-frame mass $M > 70 M_\odot$) binaries covering eccentricities up to 0.3 at 15 Hz emitted gravitational-wave frequency, and use this to compare model predictions to search results. Assuming all detections are indeed quasi-circular, for our fiducial population model, we place a conservative upper limit for the merger rate density of high-mass binaries with eccentricities $0 < e \leq 0.3$ at $16.9 \text{ Gpc}^{-3} \text{ yr}^{-1}$ at the 90% confidence level.

Unified Astronomy Thesaurus concepts: Gravitational wave astronomy (675); Eccentricity (441); Astrophysical black holes (98)

1. Introduction

The LIGO (Aasi et al. 2015) and Virgo (Acernese et al. 2015) gravitational-wave observatories have completed three observing runs thus far. During these runs, 90 compact binary merger candidates were identified that had a probability of astrophysical origin of $p_{\text{astro}} > 0.5$ (Abbott et al. 2023a, 2024). These discoveries opened previously inaccessible avenues to study the Universe, including the first direct information on binary black holes (Abbott et al. 2016a, 2016b), the multi-messenger observation of a binary neutron star coalescence (Abbott et al. 2017a, 2017; Margutti & Chornock 2021), a new type of constraint on cosmic expansion (Abbott et al.

2017b, 2023), and novel tests of general relativity (Abbott et al. 2016c, 2017c, 2021b).

Despite the growing number of candidates and the insight they have provided, the astrophysical sites and processes that produce the observed merging binaries remain uncertain. Multiple viable scenarios exist. The binary black holes could have formed from an isolated stellar binary (e.g., Bethe & Brown 1998; Dominik et al. 2015; de Mink & Mandel 2016; Marchant et al. 2016; Inayoshi et al. 2017; Gallegos-Garcia et al. 2021), via dynamical interactions in dense stellar clusters (e.g., Portegies Zwart & McMillan 2000; Banerjee et al. 2010; Ziosi et al. 2014; Morscher et al. 2015; Rodriguez et al. 2016a; Mapelli 2016; Askar et al. 2017), or triple systems (e.g., Antonini et al. 2017; Martinez et al. 2020; Vigna-Gómez et al. 2021), or via gas-driven capture in the disks of active galactic nuclei (AGN; e.g., McKernan et al. 2012; Bartos et al. 2017; Fragione et al. 2019; Tagawa et al. 2020). Furthermore, in addition to merging binary black holes formed from stars, there may also be merging binaries of primordial black holes

³⁰⁴ Deceased, November 2022.

³⁰⁵ Deceased, March 2022.



(e.g., Bird et al. 2016; Sasaki et al. 2016; Clesse & García-Bellido 2017).

Gravitational waves carry information about the masses and spins of the merging black holes, which can be used to probe the binaries' origin (Abbott et al. 2016b; Mapelli 2021; Zevin et al. 2021a). Different formation channels have diverse predictions for the most common component masses, mass ratios, spin magnitudes, and spin orientations (Belczynski et al. 2002; Dominik et al. 2013; Vitale et al. 2017). For example, isolated stellar binaries are typically expected to produce black holes with spins mostly aligned with the binary's orbital axis with possible misalignments that could stem from recoil velocities imparted during supernova explosion (e.g., Rodriguez et al. 2016b; Gerosa et al. 2018; Wysocki et al. 2019). Dynamically formed binaries, on the other hand, generally have an isotropic spin distribution (e.g., Rodriguez et al. 2016b; Fishbach et al. 2017; Baibhav et al. 2020). However, while masses and spins provide crucial information about the binaries' origin, there is often overlap between their distributions for various formation channels. A catalog of binary black holes must therefore be considered to make statistical inferences about their origins using these properties alone.

Orbital eccentricity e is a unique signature that disfavors isolated binaries and favors triple systems, stellar clusters, or AGN-assisted mergers as the possible formation scenario of the binary. While isolated black hole binaries can be born with an initial eccentricity, gravitational-wave emission will circularize their orbit by the time their orbital frequency reaches the sensitive band of ground-based gravitational-wave observatories (Peters 1964). Dynamical encounters can form binaries closer to merger, leaving insufficient time for orbital circularization. In AGN disks, eccentricity can be enhanced for a significant fraction of mergers, e.g., via binary–single interactions (Tagawa et al. 2021; Samsing et al. 2022). Eccentricity can also be enhanced for field binaries by a nearby third object via the Kozai–Lidov mechanism (Kozai 1962; Lidov 1962; Naoz 2016; Antonini et al. 2017; Randall & Xianyu 2018; Bartos et al. 2023).

Despite the advantages that come with estimating the binary's orbital eccentricity, it has been difficult to probe this parameter through gravitational-wave observations for several reasons. (i) Eccentric orbits have a wider dynamical range than quasi-circular, or $e = 0$ orbits, making them more challenging to model semi-analytically (Huerta et al. 2014; Tanay et al. 2016). (ii) Eccentricity increases the dimension of the binary parameter space, requiring more gravitational waveform templates and substantially increasing the computational cost of both waveform computation (Cornish & Shapiro Key 2010) and running template-based searches (Lenon et al. 2021). (iii) Given these challenges and the lack of expected eccentricity in field binaries, the development of eccentric waveform models began with significant delay compared to circular waveform models (Junker & Schaefer 1992). Nonetheless, eccentric waveform development has been an active area recently, with several promising waveform models that could be useful in the future (e.g., Cao & Han 2017; Hinderer & Babak 2017; Albanesi et al. 2021; Islam et al. 2021; Khalil et al. 2021; Nagar et al. 2021; Setyawati & Ohme 2021; Liu et al. 2022; Ramos-Buades et al. 2022a; Wang et al. 2023).

While no comprehensive eccentric gravitational-wave template bank is currently available, indications of eccentricity may already exist within the catalog of detected gravitational

waves. The basis of such results is that standard gravitational-wave search algorithms developed to target circular binaries also have some sensitivity to eccentric binaries. For low masses, $\lesssim 10 M_{\odot}$, circular template-based searches show undiminished sensitivity for small residual eccentricities ($e \lesssim 0.05$ at 40 Hz). Here and throughout this work, we refer to eccentricity in the source frame. To detect signals with eccentricities beyond $e \gtrsim 0.1$, we would however require template banks that include eccentric waveforms (Brown & Zimmerman 2010). In contrast, for higher masses and eccentricities, it has been shown that eccentricities can be found without significant loss of signal-to-noise ratio (SNR) using model-agnostic searches (Abbott et al. 2019a).

To identify detected binaries as eccentric, two approaches have been carried out so far that circumvent the need for comprehensive template banks:

1. One approach is to employ Bayesian analyses using existing eccentric waveform models. An eccentric waveform model limited to eccentricities $e < 0.2$ was used to show that the binary merger that produced the signal GW190521 as well as two others are consistent with originating from eccentric binary black holes (eBBHs) and are poorly explained by the zero-eccentricity hypothesis (Romero-Shaw et al. 2020, 2021). Using a different waveform model that includes the full eccentricity range, Gamba et al. (2023) found strong support for the binary coalescence that produced GW190521 being highly eccentric. Both models were limited to waveforms with black hole spins aligned with the binary orbit. Orbital eccentricity and misaligned spins that induce precession of the orbital plane produce similar imprints in the gravitational-wave signal, and both of these effects should preferably be accounted for in order to accurately analyze the event (Calderón Bustillo et al. 2021; Romero-Shaw et al. 2023).
2. A different approach relies on numerical relativity simulations of eBBHs. Due to the computational cost, only a limited number of simulations can be carried out, which can only sparsely cover the parameter space. Gayathri et al. (2022) used such numerical relativity waveforms that discretely cover the full eccentricity space and include waveforms with both aligned and misaligned spin with the binary orbit. Interpolation methods and consistency checks were applied to recover the eccentricity and other parameters of the binary. They found that the signal GW190521 is most consistent with being produced by a highly eccentric ($e \sim 0.7$) binary.

The above approaches are similar as they rely on different approximations to accurate (numerical relativity) waveforms: in the first, waveform models are used to approximate numerical relativity waveforms, while in the second, the analysis results are interpolated. In this paper, we carry out a search focusing on eccentric black hole coalescences over the third observing run (O3) of the LIGO–Virgo network. We use a minimally modeled search algorithm (Klimenko et al. 2005; Tiwari et al. 2016; Salemi et al. 2019) that we optimize for sensitivity for a set of high-mass (total mass $M \geq 70 M_{\odot}$), eccentric gravitational waveforms (Hinder et al. 2018; Boyle et al. 2019). As methods to estimate the eccentricity of individual events are under development, we instead focus on potential detections that have not already been discovered by

other searches, and characterize the sensitivity of our search to eccentric binaries, relying on methods with well-understood performance.

This paper is organized as follows. In Section 2, we introduce our search algorithm and demonstrate its sensitivity to eccentric waveforms. In Section 3, we present our search results. In Section 4, we discuss constraints on astrophysical populations based on our search results. We conclude in Section 5.

Gravitational-wave strain data (Abbott et al. 2021c) and posterior samples (Abbott et al. 2021d) for all events from GWTC-3 are available from the Zenodo platform or the Gravitational Wave Open Science Center (Abbott et al. 2021e, 2023b).

2. Search Algorithm and Sensitivity

2.1. Characterization of Eccentricity

Due to the emission of gravitational waves, binary orbits have a gradually decreasing orbital separation. Eccentric binary orbits also circularize over time due to the emission of gravitational waves (Peters 1964). This makes the definition of eccentricity challenging. Determining eccentricity is particularly difficult at the late stages of the binary evolution when less than a full orbit separates the black holes from merger.

There have been various efforts to define eccentricity for binary compact object systems. These eccentricity definitions involve Keplerian orbit assumptions (Peters & Mathews 1963; Loutrel et al. 2018), angular frequencies at apocenter and pericenter (Mora & Will 2004), calculations using instantaneous radial acceleration (Healy et al. 2018), and using coordinate separations (Buonanno et al. 2011). A detailed list of the different eccentricity definitions that have been developed so far can be found in Loutrel et al. (2018).

For our analysis, we adopt the eccentricity definition following Ramos-Buades et al. (2022b), based on a calculation first developed by Mora & Will (2004) and later used by Lewis et al. (2017), Ramos-Buades et al. (2020a), and Shaikh et al. (2023). To compute eccentricity for each orbit, we used the gravitational-wave frequencies at apocenter (ω_a) and the consecutive pericenter (ω_p). With these, eccentricity for the given orbit is

$$e = \cos(\psi/3) - \sqrt{3} \sin(\psi/3) \quad (1)$$

with

$$\psi = \arctan\left(\frac{1 - e_{22}^2}{2e_{22}}\right), \quad (2)$$

where

$$e_{22} = \frac{\sqrt{\omega_p} - \sqrt{\omega_a}}{\sqrt{\omega_p} + \sqrt{\omega_a}}. \quad (3)$$

We used the orbital frequency of the $\ell = 2$, $m = 2$ multipole moments of the gravitational-wave signal.

In order to characterize the eccentricity as a function of time, we associate this eccentricity with a frequency that is an average of the pericenter and apocenter frequencies. This method of computing eccentricity using the waveform itself is advantageous because (i) it enables us to compute the evolution of eccentricity as a function of time (and frequency); (ii) it is gauge independent; and (iii) this definition can be uniformly

applied to all waveform models and can be computed during postprocessing.

Ultimately, we want to describe a waveform with a single eccentricity value. For this description, we choose 15 Hz gravitational-wave emission frequency. This selection is motivated by the typical eccentricity definition found in the literature (usually defined at a gravitational-wave emission frequency of ~ 10 –15 Hz; e.g., Fragione & Bromberg 2019; Zevin et al. 2021b).

2.2. Eccentric Waveforms

There are multiple ongoing efforts to develop a comprehensive set of eccentric binary coalescence waveforms. Multiple waveform families have been generated using the semi-analytical effective-one-body formalism, which is currently restricted to nonprecessing spins (Nagar et al. 2021; Ramos-Buades et al. 2022a). A suite of numerical relativity simulations has also been carried out that cover virtually the full eccentric and spin parameter space (Gayathri et al. 2022; Healy & Lousto 2022).

For our analysis, we adopted 12 state-of-the-art numerical relativity waveforms from the Simulating eXtreme Spacetimes (SXS) Collaboration (Hinder et al. 2018; Boyle et al. 2019), which were the only high-fidelity waveforms available to us at the time of this study. These waveforms cover the eccentricity space up to 0.3 defined at 15 Hz gravitational-wave frequency assuming a source total mass of $90 M_\odot$, and include a range of mass ratios: $q \equiv m_2/m_1 = \{1, 0.5, 0.33\}$, where m_2 and m_1 are the lighter and heavier masses, respectively. We list the properties of the waveforms in Table 1. In Figure 1, we show the corresponding eccentricity of these waveforms, assuming different source total masses.

As the numerical relativity simulations were carried out for the late stage of the binary coalescence, they cover the gravitational waveform for the full frequency band of the ground-based detectors only for total binary source masses $\gtrsim 70 M_\odot$. Above this mass limit, any binary mass can be obtained by a simple scaling of the simulated waveforms due to the scale invariance of general relativity (Tiglio & Villanueva 2021). The selected waveforms are nonspinning, which has a limited effect on the sensitivity estimates we compute below. When reconstructing the properties of detected gravitational-wave signals, it is important to include spins, as eccentricity and spin precession can mimic each other (Calderón Bustillo et al. 2021; Romero-Shaw et al. 2023). Since we do not use these waveforms to reconstruct the properties of signals in this analysis, this problem is not relevant here. Figure 2 shows the change in signal morphology as the orbital eccentricity is changed while keeping other source parameters fixed.

We used this set of 12 numerical relativity waveforms to quantify the search sensitivity to high-mass ($\gtrsim 70 M_\odot$) eccentric black hole mergers. However, with this limited set of waveforms we could not reconstruct the eccentricity of events.

2.3. Search Optimization and Sensitivity Improvement

Current template-based searches (Nitz et al. 2017; Aubin et al. 2021; Cannon et al. 2021; Chu et al. 2022) do not include eccentric gravitational waveforms. As a consequence, their sensitivity is limited for such events, in particular at high eccentricities and low masses (Brown & Zimmerman 2010),

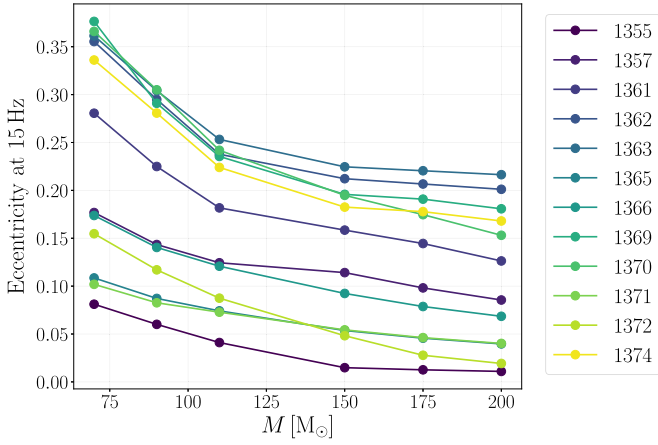


Figure 1. Variation in eccentricity at a fixed source-frame frequency of 15 Hz as a function of total mass for the 12 numerical relativity waveforms analyzed in this study. The identification numbers (IDs) in the legend correspond to the SXS:BBH:ID of each waveform.

Table 1

Parameters of the 12 Numerical Relativity Simulations Adopted from the SXS Binary Black Hole Simulations Catalog (Boyle et al. 2019)

q	e	Waveform ID
0.33	0.08	SXS:BBH:1371
0.33	0.12	SXS:BBH:1372
0.33	0.28	SXS:BBH:1374
0.5	0.09	SXS:BBH:1365
0.5	0.14	SXS:BBH:1366
0.5	0.29	SXS:BBH:1369
0.5	0.30	SXS:BBH:1370
1.0	0.06	SXS:BBH:1355
1.0	0.14	SXS:BBH:1357
1.0	0.22	SXS:BBH:1361
1.0	0.29	SXS:BBH:1362
1.0	0.30	SXS:BBH:1363

Note. Columns show the binary’s mass ratio q , and eccentricity e at a reference source-frame frequency of 15 Hz (Section 2.1) for a binary source total mass of $90 M_\odot$. Spin amplitudes χ_1 and χ_2 are zero for all considered models.

similarly to the effect of neglecting higher-order multipole moments (Capano et al. 2014). Eccentric searches can also be carried out using model-agnostic searches such as the coherent WaveBurst algorithm (cWB; Klimentko et al. 2005; Tiwari et al. 2016; Salemi et al. 2019), which uses minimal assumptions about the signal waveform and hence is expected to be sensitive to eccentric signals. The sensitivity of cWB and template-based searches are comparable for high-mass black hole mergers up to low eccentricities (Chandra et al. 2020; Ramos-Buades et al. 2020b; Abbott et al. 2023a). As the sensitivity of template-based searches drops with eccentricity (Zevin et al. 2021b), we rely on cWB for our search.

The cWB algorithm uses the Wilson–Daubechies–Meyer filter to transform time domain detector data to time-frequency representations (Necula et al. 2012). Excess power regions in the time-frequency representation of strain data that are obtained from the network of detectors are then identified by cWB using clustering algorithms. Selected clusters with excess energy above the expected detector noise are identified as events. The signal waveform, sky coordinates, and waveform

polarization of the source are then reconstructed for these events using maximum-likelihood analysis (Klimentko et al. 2016).

Once the search pipeline is run, thresholds are placed by cWB on the coherent statistics that it derives for each candidate event. These are used to better differentiate between astrophysical signals and noise artifacts (Gayathri et al. 2019). We will refer to these thresholds on cWB statistics as vetoes. Vetoes define a part of the parameter space over the coherent statistics that should be excluded from the analysis due to the high rate of non-Gaussian noise artifacts there. To maximize the sensitivity of cWB to eccentric binaries, we carried out an optimization of these vetoes applied by cWB to each event. The first two sets of vetoes that are common to the standard cWB pipeline and the eccentric search pipeline are summarized in the Appendix.

Transient non-Gaussian noise artifacts, also known as *glitches*, can limit the detector’s sensitivity to gravitational-wave signals. Targeted vetoes are placed by the standard cWB pipeline to mitigate this problem. These glitch-focused vetoes are derived using cWB summary statistics Q_a and TF . The waveform shape parameter derived by cWB is denoted by Q_a , and is a function of another cWB parameter Q_{veto} ($Q_a = \sqrt{Q_{veto}}$). This parameter quantifies how well the total energy of the signal is distributed across time (Vedovato 2018; Gayathri et al. 2019; Mishra et al. 2021). The threshold $Q_a > 0.3$ is placed to better distinguish between gravitational waves and a class of low-frequency transient noise artifacts called blip glitches (Cabero et al. 2019; Davis et al. 2021). Signals due to blip glitches, which have most of their energy localized to a small time segment, have low Q_a values as opposed to signals from binary coalescence, which have higher Q_a values as a consequence of signal energy being distributed over a longer duration. The TF parameter is a function of the signal bandwidth, duration, and power, which are additional statistics that cWB estimates for candidate events. A threshold on this parameter is placed to ensure that short-duration glitches that mimic gravitational-wave signals from intermediate-mass binary black hole systems are removed.

We injected simulated gravitational-wave signals from equal-mass, almost head-on systems (Healy & Lousto 2022) into real detector data to find the set of vetoes that do not remove highly eccentric signals while still rejecting most noise artifacts. To perform this optimization, the cWB algorithm was used to detect these injected signals and derive their properties. Vetoes were selected such that they maximized the number of detections at fixed false alarm rates.

We observed that Q_a and TF vetoes were prone to removing a significant fraction of highly eccentric simulated signals. We found that we could mitigate this problem if we removed these two thresholds, and instead introduced a new Q_a – Q_p veto to better distinguish between signals from highly eccentric binaries and short-duration glitches. This veto removes events identified by cWB that do not satisfy the condition $Q_a(Q_p - 0.8) > 0.07$. The summary statistic Q_p quantifies the number of cycles in the reconstructed signal. The Q_a – Q_p veto along with the first two sets of vetoes from the standard search, which are summarized in the Appendix were selected as the set of post-production vetoes for the eBBH search. We will refer to this version of cWB that is optimized for eccentric mergers as cWB-eBBH. While the vetoes were optimized using equal-mass waveforms, we confirmed that the optimized search

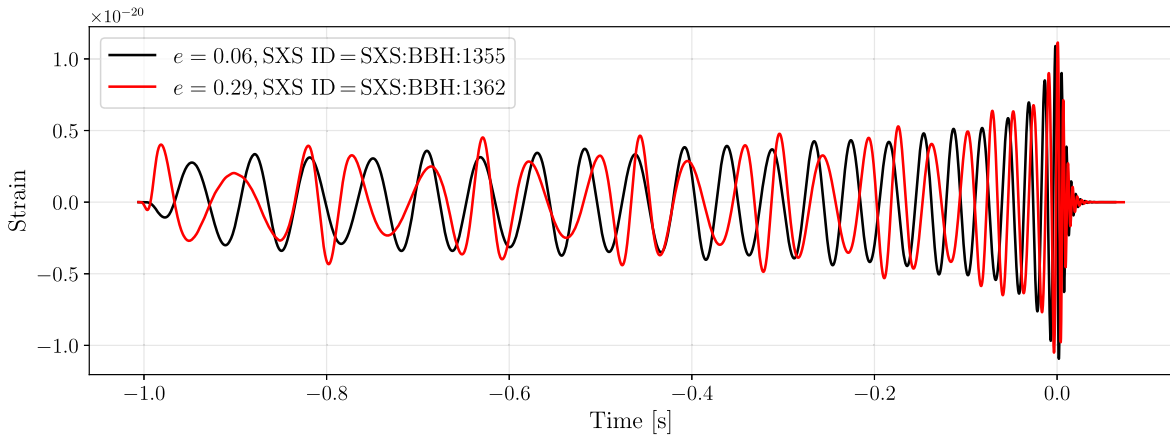


Figure 2. Examples of time domain waveforms with two different eccentricities (indicated in the legend) for equal-mass binary systems with a total source mass of $90 M_{\odot}$ at a distance of 100 Mpc. The simulations start at an orbital separation that translates to an orbital frequency $f_{\text{low}} = 15$ Hz. The eccentricity values indicated in the legend are defined at the same f_{low} .

improved eccentric event recovery for unequal mass injections as well.

Figure 3 shows an example of the standard cWB Q_a veto and the new cWB-eBBH $Q_a - Q_p$ veto for quasi-circular and highly eccentric systems. We also look at this veto’s performance with background events. To generate background events, data from one detector is time shifted relative to the other detector’s data by an amount greater than the maximum time for a gravitational-wave signal to travel between the detectors (Abbott et al. 2016d). The standard veto does well in removing background events and recovering the majority of quasi-circular simulation events. However, the distribution of simulation signals in the $Q_a - Q_p$ space changes for highly eccentric systems, and as a consequence, the standard cWB veto removes a significant fraction of simulation events.

We characterize the sensitivity improvement due to the optimization procedure by computing the number of injected gravitational waves detected by cWB-eBBH but not by standard cWB, divided by the total number of detections by standard cWB. Here, we consider a signal detected if it corresponds to an inverse false alarm rate (IFAR) of ≥ 1 yr. This IFAR threshold of ≥ 1 yr was only used to assess the improvement in sensitivity from the introduction of the cWB-eBBH veto, and not as a general detection threshold.

The fraction of events recovered with IFAR ≥ 1 yr by cWB-eBBH that are removed by the standard pipeline with respect to the total number of events recovered by the standard pipeline is $\sim 28\%$ for head-on collision (highly eccentric) equal-mass systems with a source total mass of $150 M_{\odot}$. Additionally, we see that this fraction is higher ($\sim 34\%$) for systems with more unequal mass. Therefore, our optimization is the most significant for highly eccentric binaries with unequal masses. The performance of cWB-eBBH for low-eccentricity signals remains comparable (within 5%) to the standard pipeline. We conclude that the cWB-eBBH veto does significantly better than the standard veto to improve sensitivity for highly eccentric systems without degrading sensitivity to less eccentric systems.

3. Results

3.1. Search Sensitivity

We carried out a search for simulated gravitational-wave signals to quantify the sensitivity of the cWB-eBBH search

algorithm. We performed injections in offline (high-latency) recalibrated O3 strain data with category 0, 1, 2, and 4 data quality vetoes (Davis et al. 2021; Abbott et al. 2023a). Category 0 vetoes are applied to ensure that the segments of data used in this analysis were collected when the detectors were in observing mode. Category 1 vetoes are used to discard data from periods in which the detectors were running in an improper configuration, data dropout, or on-site maintenance occurred at either detector, or when there are major problems with the operation of an instrument at the detectors. Category 2 vetoes flag data segments that likely contain non-Gaussian noise artifacts. Category 4 vetoes flag data segments that contain hardware injections.

The injected waveforms have source total mass $M \in [70 M_{\odot}, 200 M_{\odot}]$. We used six choices of total source mass. Waveforms with different masses were obtained by scaling the 12 numerical relativity waveforms listed in Table 1. The simulated signals for each waveform and choice of total mass were uniformly distributed in sky location (θ, ϕ) and inclination ι . They were also distributed uniformly in comoving volume up to a maximum redshift z_{max} .

Since each simulated waveform has a fixed initial eccentricity, our six choices of total mass will correspond to different eccentricities at an emitted gravitational-wave frequency of 15 Hz, as this frequency is reached at different points in the waveform. We computed the corresponding eccentricity values at 15 Hz in the source frame for each total mass and each waveform, as explained in Section 2.1. Below, we characterize the sensitive distance as a function of total source mass and eccentricity at 15 Hz.

For each waveform, we separately calculated z_{max} up to which they must be injected so that we do not make unnecessary injections that the search cannot detect. This was calculated with an optimal two-detector-network (Livingston-Hanford) SNR threshold of 5.0. We set the source to be directly overhead with a face-on configuration while calculating the optimal SNR. Since we observe signals with redshifted mass (Krolak & Schutz 1987), it is in principle possible to inject simulations with total source mass $< 70 M_{\odot}$ if we populate them at higher redshifts. This was however not performed in the presented analysis. Injections are spaced uniformly in time, approximately every 100 s in the O3 data set.

We used the fraction of detected and injected waveforms to compute the sensitive distance of the search for the given

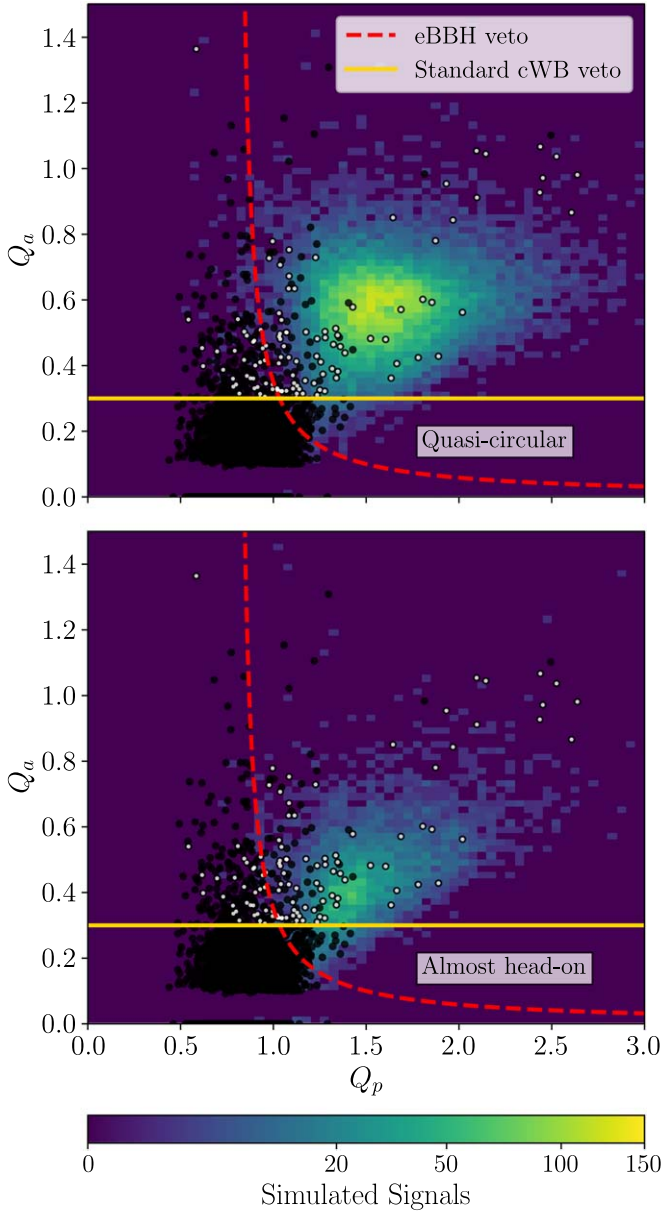


Figure 3. Distribution of Q_a and Q_p for simulated signals (shown as a two-dimensional histogram with a color bar denoting the number of events in each two-dimensional bin) and loud simulated background events (shown as black dots). The cWB statistics Q_a and Q_p describe the morphology of a signal. The yellow line represents the standard cWB Q_a veto and the red-dashed line denotes the eBBH Q_a - Q_p veto. The white dots correspond to loud background events that remain after all standard cWB vetoes (Lopez et al. 2022) are applied. Top: simulated signals correspond to equal mass, source total mass, $M = 150 M_\odot$, quasi-circular orbit systems. Bottom: simulated signals correspond to equal mass, $M = 150 M_\odot$, almost head-on (highly eccentric) systems.

waveform. Sensitive distance (Abbott et al. 2019b) is defined such that a detector that detects every event within the sensitive distance and no event beyond, it would have the same detection rate as our detector network.

A similar analysis was carried out with data from the first two observing runs of LIGO-Virgo using approximate eccentric waveform models (Abbott et al. 2019a). This analysis spanned the binary mass parameter space from $10 M_\odot$ to $100 M_\odot$ while the analysis described in this paper covers binary mass of $70 M_\odot$ to $200 M_\odot$. The sensitivities reported in this paper are higher than that analysis due to increased sensitivity

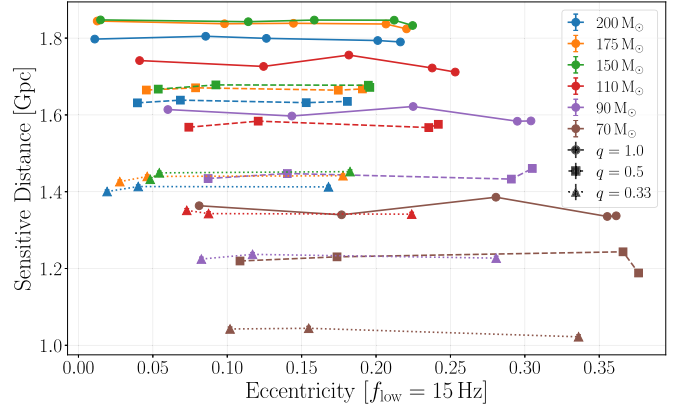


Figure 4. Sensitive distance as a function of orbital eccentricity for different binary total masses and mass ratios. Different marker shapes represent systems with different mass ratios and the different colors represent the various total masses considered here. We used an IFAR threshold of 1.32 yr, which was the loudest new candidate’s IFAR. The horizontal axis denotes the eccentricity of the binary at an orbital separation that corresponds to a source-frame frequency of 15 Hz. A given numerical relativity waveform corresponds to different eccentricities for the different total masses as it will reach 15 Hz at different points of its orbital evolution. The statistical error bars on the obtained sensitive distance are smaller than can be presented in this plot.

of the detector during the third observing run, and due to the higher masses considered here. There have also been studies to characterize the effect of eccentricity in the sensitivity of long-duration signals with unmodeled search pipelines using hybrid inspiral–merger–ringdown waveform models (Abbott et al. 2021f). However, these studies were targeted toward low-mass binary black holes and binary neutron stars as opposed to our search, which is targeted toward high-mass eccentric binaries. Therefore, the search sensitivities reported in Abbott et al. (2021f) are lower than what we obtain in this paper.

The obtained sensitive distance is shown in Figure 4, for different source total masses and mass ratios, as a function of binary eccentricity. The statistical error bars for the obtained sensitive distance range between 0.21 and 5.63 Mpc. The sensitivity at the considered high masses is mostly independent of the eccentricity up to our highest eccentricity of 0.3. We observe a sensitivity increase with total mass up to $175 M_\odot$ followed by a decline at $200 M_\odot$. This is because as the total mass of the source increases, the signal shifts toward lower frequencies where the detectors’ sensitivity decreases. Additionally, the in-band signals also become shorter in duration as the mass increases, making them more prone to being removed by the glitch-based vetoes. We also see, as expected, that sensitivity is highest for equal-mass binaries, and gradually drops as the difference between the two black hole masses increases.

3.2. Search and Loudest Event

We carried out the cWB-eBBH search over the O3 run of the LIGO and Virgo detectors. For most of the observing run, we used data from only the two LIGO detectors, as search sensitivity was not appreciably affected by the addition of Virgo data. For the 2020 January 4–22 period, we also incorporated Virgo in the search to analyze the candidate 200114_020818, which was found by the intermediate-mass black hole binary search (Abbott et al. 2022) in the three detector network configuration comprising the LIGO and Virgo detectors. Follow-up studies for this event (Abbott et al. 2022,

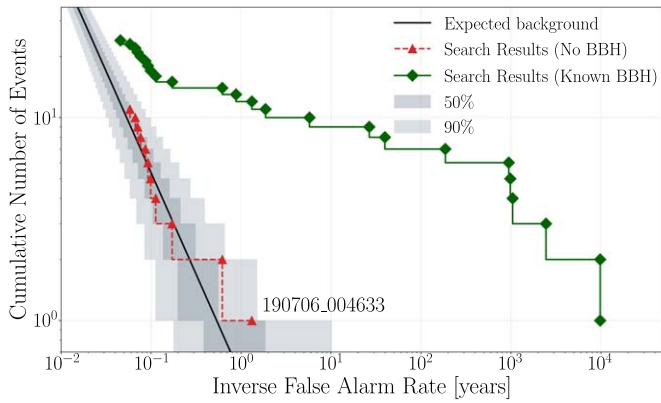


Figure 5. Cumulative number of events as a function of IFAR recovered by the cWB-eBBH search. The solid line represents the expected background for the O3 search, and the gray regions correspond to the 50% and 90% Poisson uncertainty regions. Green-filled squares denote previously reported gravitational-wave candidates (Abbott et al. 2022, 2023a) recovered by our search, and red-filled triangles show events that were not previously reported by other searches.

Appendix B) showed inconsistent results under a quasi-circular binary black hole hypothesis. We investigated if this candidate had higher significance under the eccentric hypothesis. However, this candidate was removed by the cWB-eBBH vetoes. The search and sensitivity results presented below were obtained using data from only the two LIGO detectors.

Our search recovered 28 gravitational-wave candidates with $\text{IFAR} > 1$ yr. By choosing this IFAR threshold, we eliminate low-significance candidates that could have been due to noise artifacts in the detector. All but one of these events have been identified previously by other searches as well (Abbott et al. 2022, 2023a).

The results of our search are summarized in Figure 5. The search results excluding previously found candidates are consistent with background noise.

We identified one event candidate with an $\text{IFAR} > 1$ yr that was not previously reported. This most significant new candidate, hereafter referred to as 190706_004633, was observed on 2019 July 6. It was recovered with an IFAR of 1.32 yr. It has an SNR of 12.2 and a central frequency of 74 Hz. Figure 6 shows the time–frequency map of this event candidate.

In order to better understand whether 190706_004633 is of astrophysical origin, we carried out a detailed study of the detector’s performance and characteristics at the time of the event. This study aims to uncover signs of instrumental or environmental artifacts that could have altered the gravitational-wave data and hence produced the candidate (Davis et al. 2021, Section 3.2.4). No such artifacts were found. However, the Gravity Spy machine learning classifier (Zevin et al. 2017; Soni et al. 2021) classified the excess power in LIGO-Livingston as a Tomte glitch. Tomtes are a common glitch class that are similar in morphology to high-mass binary coalescence signals (Ashton et al. 2022). No glitch or signal was identified in the LIGO-Hanford data by the same classifier. However, as the Gravity Spy machine learning model is not designed to search for astrophysical signals (Glanzer et al. 2023) or to differentiate eBBH merger signals from glitches, we cannot rule out an astrophysical origin.

To further investigate this event we carried out a standard parameter estimation analysis of the data using LALInference

(Veitch et al. 2015) with nested sampling assuming a quasi-circular waveform. We investigated the properties of this event using data from the two LIGO detectors as well as the Virgo detector. For this analysis, in lieu of an eccentric waveform that fully covers the necessary parameter space, we adopted the quasi-circular binary approximant IMRPhenomXPHM (Pratten et al. 2021). This estimation found that the estimated source total mass of 190706_004633 is $M \sim 320 M_{\odot}$, and its estimated redshift is $z \sim 0.3$. Studies have shown that the chirp mass of a binary with low to moderate eccentricity can be reconstructed with a bias of up to 4% using parameter estimation with quasi-circular waveforms (O’Shea & Kumar 2023). However, the reconstructed parameters would be considerably more inaccurate if the signal originated from a highly eccentric binary. Therefore, these results indicate that the signal, if astrophysical, would correspond to a high-mass binary, but should not be used to give precise indications of source properties.

The SNR obtained from the parameter estimation analysis is 14.9, which is higher than the SNR obtained by the search pipeline. We examined the Livingston and Hanford detector responses for the maximum-likelihood sky location that was obtained from parameter estimation. Livingston’s detector response was approximately 1.5 times greater than Hanford’s. This may explain the observed discrepancy in SNRs, which is highlighted in the caption of Figure 6. The parameter estimation study also yielded a Bayesian coherence ratio (BCR; Veitch & Vecchio 2010), with a corresponding value of $\ln(\text{BCR}) = -3.3$ for the candidate. This ratio characterizes the evidence for a coherent signal origin versus a random coincidence; the obtained value supports an incoherent noise origin over a circular binary origin.

Through these investigations, we were unable to conclusively determine if the event was in accordance with an astrophysical origin or an incoherent noise origin. This event was consistent with the expected background for O3 with a confidence level within 50% (Figure 5). In the following section, we therefore compute upper limits to merger rates assuming nondetection of any eccentric event.

4. Eccentric Binary Population Models

In order to understand the astrophysical implications of our results, we computed the expected number of detections for a fiducial source model. For this, we adopt the joint total mass and mass ratio probability density $p(M, q)$ that was inferred using LIGO-Virgo’s observations listed in the GWTC-3 (Abbott et al. 2023a, 2023c), assuming the power-law + peak model described in Abbott et al. (2021a). While this population model also incorporated the distribution of black hole spins, we did not include this in the presented analysis. As we have waveforms and simulations that are sparsely sampled in mass and mass ratio, we linearly interpolated the sensitivity of the existing waveforms to points in between the available points in order to obtain a sensitive distance for any source total mass and mass ratio within $70 M_{\odot} \leq M \leq 200 M_{\odot}$ and $0.33 < q < 1.0$. For a more general distribution, we considered a power-law black hole mass distribution of $M^{-2.3}$ (assuming a Salpeter initial mass function; Perna et al. 2019) and a uniform distribution in mass ratio. We further adopted an eccentricity distribution in which the probability density of the binaries’ eccentricity is $p(e) \propto 2(1 - e)$. This distribution is chosen to characterize a population that has a larger fraction of low eccentric binaries.

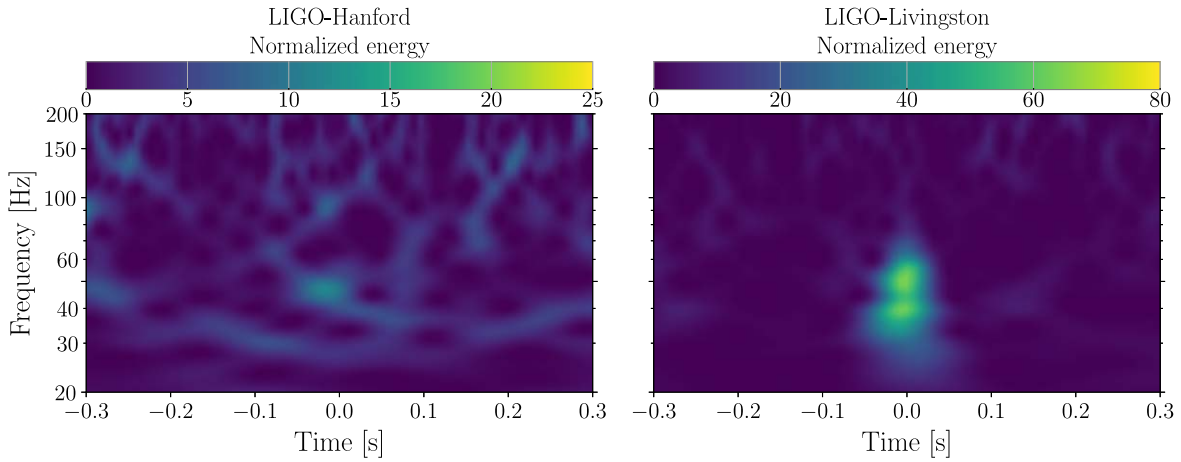


Figure 6. Time–frequency map (spectrogram) of the most significant new candidate identified by the cWB-eBBH search. We show the spectrogram for the LIGO-Hanford (left) and LIGO-Livingston (right) detectors. The individual detector SNRs in the LIGO-Hanford and LIGO-Livingston are 5.6 and 10.9, respectively. Since the energies in the two detectors are very different, we use different scales on the color bar. The Virgo detector was in observing mode during the time of this event. We used data from all three detectors for follow-up studies and observed that the SNR in the Virgo detector for this event was low (~ 2).

Having defined the probability density of our fiducial population with respect to the binary parameters, using the sensitive distance obtained over the considered parameter space (see Section 3.1), we computed the total volume–time (VT; Abbott et al. 2019b, the Appendix) covered by our search during O3, assuming an IFAR threshold of 1.32 yr, which is the IFAR of our search’s loudest new event. For our fiducial model, we obtained $VT = 6.88 \text{ Gpc}^3 \text{ yr}$ for eccentric binaries with $0 < e < 0.3$. Adopting a Jeffrey’s prior on the merger rate and assuming nondetection of any eccentric event, this would correspond to a constraint of $< 0.20 \text{ Gpc}^{-3} \text{ yr}^{-1}$ on the merger rate density at 90% confidence level in the $70 M_\odot \leq M \leq 200 M_\odot$ and $0.33 < q < 1.0$ parameter space.

We additionally computed the VT_e of events that are detected by the cWB-eBBH algorithm and are missed by the standard cWB algorithm. We used the same set of simulated signals that we used to compute the full search VT. The sensitive VT is computed using the number of events recovered by the cWB-eBBH pipeline that the standard pipeline misses. The goal of finding VT_e is to gauge the subpopulation of eccentric events that would be *detectable as eccentric* because of being missed by the standard pipeline, which has lower sensitivity to eccentric signals (Figure 3). We computed VT_e for the various distributions considered in Table 2. For our fiducial source population, we obtain $VT_e = 0.08 \text{ Gpc}^3 \text{ yr}$. Adopting a Jeffrey’s prior on the merger rate and assuming no eccentric events were detected by the cWB-eBBH search, this would correspond to a constraint of $< 16.9 \text{ Gpc}^{-3} \text{ yr}^{-1}$ on the merger rate density at 90% confidence level in the $70 M_\odot \leq M \leq 200 M_\odot$ and $0.33 < q < 1.0$ parameter space.

With the small number of available eccentric waveforms for this study, we cannot determine if the discovered binaries are eccentric. Therefore, we cannot discount the possibility that previously identified gravitational-wave candidates originate from eccentric binaries. In this case, the number of observed eccentric binaries is greater than zero, and so the merger rate could potentially be higher than our upper limits. Conversely, for some parts of the parameter space, template-based searches have better sensitivities, although we expect them to lose sensitivity at higher eccentricities. Hence, including the VT from these searches (Abbott et al. 2023a, 2024) would tighten our upper limits. For simplicity, we limit our results to those

Table 2

Total VT Covered by cWB-eBBH Search and VT Probed Exclusively by the cWB-eBBH Search (VT_e) Assuming Various Source Total Mass, Mass Ratio, and Eccentricity Probability Density Functions for the Different Illustrative Models Described in Section 4

$p(M)$	$p(q)$	$p(e)$	VT ($\text{Gpc}^3 \text{ yr}$)	VT_e ($\text{Gpc}^3 \text{ yr}$)
GWTC-3	GWTC-3	$2(1 - e)$	6.89	0.08
GWTC-3	GWTC-3	Uniform	6.93	0.08
$M^{-2.3}$	Uniform	$2(1 - e)$	8.22	0.14
$M^{-2.3}$	Uniform	Uniform	8.27	0.14
AGN	AGN	$2(1 - e)$	7.86	0.16
AGN	AGN	Uniform	7.91	0.17
DSC	DSC	DSC	6.69	0.08

from the cWB-eBBH analysis, assuming all previously identified candidates are from quasi-circular binaries.

Since binary mergers from dynamical formation channels can follow a mass distribution different from the one obtained from GWTC-3, we additionally computed VT, assuming other parameter distributions. We summarize our results in Table 2. Our focus on high-mass, eccentric events can be particularly interesting for astrophysical formation channels that favor the production of both high mass and high eccentricity, such as gas-driven capture in AGN disks. For this scenario, we adopted the AGN model of Gayathri et al. (2021) as an illustrative example. Our search sensitivity for this model is marginally higher than for the GWTC-3 distribution because this model favors higher masses that are more likely to fall in the mass interval that we are most sensitive to in this analysis. Assuming nondetection of any eccentric event, we place a constraint of $< 8.45 \text{ Gpc}^{-3} \text{ yr}^{-1}$ on the merger rate density at 90% confidence level for AGN-assisted mergers. Taking an estimated $\sim 70\%$ of mergers being eccentric (Samsing et al. 2022) and $\sim 4\%$ of mergers having $M > 70 M_\odot$ (Gayathri et al. 2021), we project the corresponding upper limit on the merger rate density to obtain upper limits on the overall AGN-assisted merger rate density as $\sim 8.45 \text{ Gpc}^{-3} \text{ yr}^{-1} / (0.7 \times 0.04) \sim 302 \text{ Gpc}^{-3} \text{ yr}^{-1}$. This is consistent with rate estimates in the literature (e.g., Yang et al. 2019; Gayathri et al. 2021).

As a second illustrative model we used the distribution expected in dense star clusters (DSC), adopted from Zevin et al.

(2021b). For this population, we are able to place a constraint of $<16.9 \text{ Gpc}^{-3} \text{ yr}^{-1}$ on the merger rate density at 90% confidence level assuming nondetection of any eccentric event. Taking an estimated $\sim 10\%$ being eccentric and $\sim 18\%$ of mergers having $M > 70 M_{\odot}$, we project the corresponding upper limit on the merger rate density to obtain upper limits on the overall DSC-assisted merger rate density as $\sim 16.9 \text{ Gpc}^{-3} \text{ yr}^{-1} / (0.1 \times 0.18) \sim 939 \text{ Gpc}^{-3} \text{ yr}^{-1}$. This is consistent with rate estimates in the literature (Kremer et al. 2020; Zevin et al. 2021b).

5. Conclusion

We carried out a search that does not rely on template banks, and optimized it to be sensitive to high-mass ($M > 70 M_{\odot}$) eBBH coalescences. We characterized the sensitivity of this search to understand our findings' implications for possible eccentric astrophysical populations. Our conclusions are:

1. We did not identify any high-significance candidates that had not already been detected by other searches. Our loudest and most significant new event has an IFAR of 1.32 yr. We performed detailed follow-up for this event, and concluded that astrophysical origin could not be ruled out. However, our search results are consistent with the expected background for O3.
2. For our fiducial model, we adopted a mass distribution that assumes a power-law + peak model that was inferred using GWTC-3 observations (Abbott et al. 2023c). We also chose an eccentricity distribution (defined in Section 4) that favors quasi-circular binaries. For this assumed population, our “differential” search sensitivity (that is beyond the sensitivity of the standard cWB search) is such that assuming nondetection of eccentric events, we can place a constraint of $<16.9 \text{ Gpc}^{-3} \text{ yr}^{-1}$ on the merger rate density at 90% confidence level. The obtained overall constraint is significantly above that of other searches for circular black hole mergers in a similar mass range (cf. inferred rate of $0.08^{+0.19}_{-0.07} \text{ Gpc}^{-3} \text{ yr}^{-1}$ of mergers similar to GW190521; Abbott et al. 2022).
3. As an illustrative example, we found that nondetection of any eccentric event corresponds to a constraint of $<302 \text{ Gpc}^{-3} \text{ yr}^{-1}$ on the AGN-assisted merger rate density, consistent with rate estimates in the literature (e.g., Yang et al. 2019; Gayathri et al. 2021).
4. As a second illustrative model, we computed our search sensitivity to mergers in dense star clusters, considering the model of Zevin et al. (2021b). The results are similar to the AGN channel and our expected sensitivity for a generic eccentric model. For this model, we found that nondetection of eccentric events corresponds to a constraint of $<939 \text{ Gpc}^{-3} \text{ yr}^{-1}$ on the merger rate density, consistent with rate estimates in the literature (Kremer et al. 2020; Zevin et al. 2021b).

The constraints we place on the rate of eccentric binary coalescences in this work are significantly improved over those computed with data obtained from the first and second observing runs (Abbott et al. 2019a). This improvement can be attributed to increased sensitivity of the detectors, progress in the development of highly accurate eccentric waveforms in the high-mass domain, and an optimized eccentric search. In view of the expected sensitivity of the fourth observing run by LIGO-Virgo-KAGRA (Abbott et al. 2018), we anticipate

seeing a significant rise in the number of binary black hole detections. This increases our prospects of detecting gravitational-wave signals from eccentric binary coalescences. Regardless, a nondetection would enable us to further constrain the binary black hole merger rates in astrophysical models favoring eccentric orbits.

Future works will need to expand the study to eccentricities greater than 0.3, and to include masses below $70 M_{\odot}$ as well as black hole spins.

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Appendix Post-production Vetoes

In this appendix, we will describe in detail the post-production vetoes that are applied by the standard cWB pipeline (Gayathri et al. 2019; Lopez et al. 2022) to distinguish between true gravitational-wave signals and non-Gaussian noise artifacts that can mimic gravitational-wave signals.

The first set of vetoes is based on the morphology of the reconstructed signals. These vetoes are applied to the following cWB summary statistics: the energy-weighted central frequency of the signal f_0 ; the reconstructed chirp mass parameter, $\mathcal{M}^*$, which is obtained by fitting the signal with the characteristic time-frequency evolution for a quasi-circular

binary ($f \propto (t - t_c)^{-3/8}$), and Q_a , the waveform shape parameter introduced in Section 2.3. The parameter Q_a is a function of the cWB parameter Q_{veto} (Vedovato 2018; Gayathri et al. 2019; Mishra et al. 2021), which quantifies how well the total energy of the signal is distributed across time. The first set of vetoes removes events that do not satisfy $24 \text{ Hz} < f_0 < 100 \text{ Hz}$, $|\mathcal{M}^*/M_\odot| > 10$, $|(\mathcal{M}^*/M_\odot)/Q_a^2| > 15$, $\mathcal{M}^*/M_\odot > -100$.

The next set of vetoes is based on cWB reconstruction, and the correlation of the event across the network of detectors. The cWB summary statistics involved in this set are norm, defined as the ratio between the total energy over all wavelet resolution levels used for the analysis and the reconstructed energy of the event; χ^2 , a parameter that quantifies the quality of signal reconstruction by computing the residual noise energy that remains once the reconstructed signal is subtracted from data (Gayathri et al. 2019), and finally the $c_c[0]$ and $c_c[2]$ parameters that describe the correlation of the signal across the network of detectors in time domain and frequency domain, respectively (Tiwari et al. 2016). The second set of vetoes removes candidate events that do not satisfy $\text{norm} > 4$, $\log_{10}(\chi^2) < 0.4$, $c_c[0] > 0.8$, $c_c[2] > 0.7$.

The two sets of vetoes described above were optimized with gravitational waveforms for quasi-circular binary black hole coalescences for the standard cWB pipeline. We found that they performed optimally in recovering eBBH signals as well. Therefore, these vetoes along with the new eBBH veto introduced in Section 2.3 were chosen as the final set of vetoes for the cWB-eBBH search pipeline.

ORCID iDs

K. Ackley  <https://orcid.org/0000-0002-8648-0767>
 N. Adhikari  <https://orcid.org/0000-0002-4559-8427>
 R. X. Adhikari  <https://orcid.org/0000-0002-5731-5076>
 M. Agathos  <https://orcid.org/0000-0002-9072-1121>
 O. D. Aguiar  <https://orcid.org/0000-0002-2139-4390>
 L. Aiello  <https://orcid.org/0000-0003-2771-8816>
 A. Ain  <https://orcid.org/0000-0003-4534-4619>
 P. Ajith  <https://orcid.org/0000-0001-7519-2439>
 T. Akutsu  <https://orcid.org/0000-0003-0733-7530>
 R. A. Alfaidi  <https://orcid.org/0000-0002-6108-4979>
 A. Al-Jodah  <https://orcid.org/0000-0003-4536-1240>
 A. Allocca  <https://orcid.org/0000-0002-5288-1351>
 P. A. Altin  <https://orcid.org/0000-0001-8193-5825>
 A. Amato  <https://orcid.org/0000-0001-9557-651X>
 S. B. Anderson  <https://orcid.org/0000-0003-2219-9383>
 W. G. Anderson  <https://orcid.org/0000-0003-0482-5942>
 M. Andia  <https://orcid.org/0000-0003-3675-9126>
 N. Andres  <https://orcid.org/0000-0002-5360-943X>
 M. Andrés-Carcasona  <https://orcid.org/0000-0002-8738-1672>
 T. Andrić  <https://orcid.org/0000-0002-9277-9773>
 J. M. Antelis  <https://orcid.org/0000-0003-3377-0813>
 S. Antier  <https://orcid.org/0000-0002-7686-3334>
 K. Arai  <https://orcid.org/0000-0001-8916-8915>
 A. Araya  <https://orcid.org/0000-0002-6884-2875>
 M. C. Araya  <https://orcid.org/0000-0002-6018-6447>
 J. S. Areeda  <https://orcid.org/0000-0003-0266-7936>
 N. Aritomi  <https://orcid.org/0000-0003-4424-7657>
 N. Arnaud  <https://orcid.org/0000-0001-6589-8673>
 M. Arogeti  <https://orcid.org/0000-0001-5124-3350>
 S. M. Aronson  <https://orcid.org/0000-0001-7080-8177>

- K. G. Arun  <https://orcid.org/0000-0002-6960-8538>
 G. Ashton  <https://orcid.org/0000-0001-7288-2231>
 Y. Aso  <https://orcid.org/0000-0002-1902-6695>
 P. Astone  <https://orcid.org/0000-0003-4981-4120>
 F. Aubin  <https://orcid.org/0000-0003-1613-3142>
 K. AultONeal  <https://orcid.org/0000-0002-6645-4473>
 S. Babak  <https://orcid.org/0000-0001-7469-4250>
 F. Badaracco  <https://orcid.org/0000-0001-8553-7904>
 S. Bae  <https://orcid.org/0000-0003-2429-3357>
 S. Bagnasco  <https://orcid.org/0000-0001-6062-6505>
 J. G. Baier  <https://orcid.org/0000-0002-4972-1525>
 R. Bajpai  <https://orcid.org/0000-0003-0495-5720>
 G. Baltus  <https://orcid.org/0000-0002-0304-8152>
 S. Banagiri  <https://orcid.org/0000-0001-7852-7484>
 B. Banerjee  <https://orcid.org/0000-0002-8008-2485>
 D. Bankar  <https://orcid.org/0000-0002-6068-2993>
 P. Baral  <https://orcid.org/0000-0001-6308-211X>
 P. Barneo  <https://orcid.org/0000-0002-8883-7280>
 F. Barone  <https://orcid.org/0000-0002-8069-8490>
 B. Barr  <https://orcid.org/0000-0002-5232-2736>
 L. Barsotti  <https://orcid.org/0000-0001-9819-2562>
 M. Barsuglia  <https://orcid.org/0000-0002-1180-4050>
 D. Barta  <https://orcid.org/0000-0001-6841-550X>
 M. A. Barton  <https://orcid.org/0000-0002-9948-306X>
 S. Basak  <https://orcid.org/0000-0002-1824-3292>
 A. Basalaeu  <https://orcid.org/0000-0001-5623-2853>
 R. Bassiri  <https://orcid.org/0000-0001-8171-6833>
 A. Basti  <https://orcid.org/0000-0003-2895-9638>
 M. Bawaj  <https://orcid.org/0000-0003-3611-3042>
 J. C. Bayley  <https://orcid.org/0000-0003-2306-4106>
 A. C. Baylor  <https://orcid.org/0000-0003-0918-0864>
 B. Bécsy  <https://orcid.org/0000-0003-0909-5563>
 F. Beirnaert  <https://orcid.org/0000-0002-4003-7233>
 M. Bejger  <https://orcid.org/0000-0002-4991-8213>
 A. S. Bell  <https://orcid.org/0000-0003-1523-0821>
 W. Benoit  <https://orcid.org/0000-0003-4750-9413>
 J. D. Bentley  <https://orcid.org/0000-0002-4736-7403>
 S. Bera  <https://orcid.org/0000-0003-0907-6098>
 M. Berbel  <https://orcid.org/0000-0001-6345-1798>
 F. Bergamin  <https://orcid.org/0000-0002-1113-9644>
 B. K. Berger  <https://orcid.org/0000-0002-4845-8737>
 S. Bernuzzi  <https://orcid.org/0000-0002-2334-0935>
 M. Beroiz  <https://orcid.org/0000-0001-6486-9897>
 C. P. L. Berry  <https://orcid.org/0000-0003-3870-7215>
 D. Bersanetti  <https://orcid.org/0000-0002-7377-415X>
 J. Betzwieser  <https://orcid.org/0000-0003-1533-9229>
 D. Beveridge  <https://orcid.org/0000-0002-1481-1993>
 N. Bevens  <https://orcid.org/0000-0002-4312-4287>
 U. Bhardwaj  <https://orcid.org/0000-0003-1233-4174>
 D. Bhattacharjee  <https://orcid.org/0000-0001-6623-9506>
 S. Bhaumik  <https://orcid.org/0000-0001-8492-2202>
 M. Bilicki  <https://orcid.org/0000-0002-3910-5809>
 G. Billingsley  <https://orcid.org/0000-0002-4141-2744>
 A. Binetti  <https://orcid.org/0000-0001-6449-5493>
 S. Bini  <https://orcid.org/0000-0002-0267-3562>
 O. Birnholtz  <https://orcid.org/0000-0002-7562-9263>
 S. Biscoveanu  <https://orcid.org/0000-0001-7616-7366>
 M.-A. Bizouard  <https://orcid.org/0000-0002-4618-1674>
 J. K. Blackburn  <https://orcid.org/0000-0002-3838-2986>
 N. Bode  <https://orcid.org/0000-0002-7101-9396>
 G. Boileau  <https://orcid.org/0000-0002-3576-6968>
 M. Boldrini  <https://orcid.org/0000-0001-9861-821X>
 G. N. Bolingbroke  <https://orcid.org/0000-0002-7350-5291>
 L. D. Bonavena  <https://orcid.org/0000-0002-2630-6724>
 R. Bondarescu  <https://orcid.org/0000-0003-0330-2736>
 F. Bondu  <https://orcid.org/0000-0001-6487-5197>
 E. Bonilla  <https://orcid.org/0000-0002-6284-9769>
 R. Bonnand  <https://orcid.org/0000-0001-5013-5913>
 V. Boschi  <https://orcid.org/0000-0001-8665-2293>
 V. Boudart  <https://orcid.org/0000-0001-9923-4154>
 P. R. Brady  <https://orcid.org/0000-0002-4611-9387>
 M. Braglia  <https://orcid.org/0000-0003-3421-4069>
 M. Branchesi  <https://orcid.org/0000-0003-1643-0526>
 M. Breschi  <https://orcid.org/0000-0002-3327-3676>
 T. Briant  <https://orcid.org/0000-0002-6013-1729>
 A. F. Brooks  <https://orcid.org/0000-0003-4295-792X>
 M. L. Brozzetti  <https://orcid.org/0000-0002-5260-4979>
 R. Bruntz  <https://orcid.org/0000-0002-0840-8567>
 O. Bulashenko  <https://orcid.org/0000-0003-1720-4061>
 A. Buonanno  <https://orcid.org/0000-0002-5433-1409>
 R. Busicchio  <https://orcid.org/0000-0002-7387-6754>
 C. Buy  <https://orcid.org/0000-0003-2872-8186>
 G. S. Cabourn Davies  <https://orcid.org/0000-0002-4289-3439>
 G. Cabras  <https://orcid.org/0000-0002-6852-6856>
 R. Cabrera  <https://orcid.org/0000-0003-0133-1306>
 L. Cadonati  <https://orcid.org/0000-0002-9846-166X>
 G. Cagnoli  <https://orcid.org/0000-0002-7086-6550>
 C. Cahillane  <https://orcid.org/0000-0002-3888-314X>
 G. Caneva Santoro  <https://orcid.org/0000-0002-2935-1600>
 K. C. Cannon  <https://orcid.org/0000-0003-4068-6572>
 Z. Cao  <https://orcid.org/0000-0002-1932-7295>
 E. Capocasa  <https://orcid.org/0000-0003-3762-6958>
 J. B. Carlin  <https://orcid.org/0000-0001-5694-0809>
 M. Carpinelli  <https://orcid.org/0000-0002-8205-930X>
 J. J. Carter  <https://orcid.org/0000-0001-8845-0900>
 G. Carullo  <https://orcid.org/0000-0001-9090-1862>
 M. Cavaglia  <https://orcid.org/0000-0002-3835-6729>
 R. Cavallieri  <https://orcid.org/0000-0001-6064-0569>
 G. Cella  <https://orcid.org/0000-0002-0752-0338>
 P. Cerdá-Durán  <https://orcid.org/0000-0003-4293-340X>
 E. Cesarini  <https://orcid.org/0000-0001-9127-3167>
 S. Chalathadka-Subrahmanya  <https://orcid.org/0000-0002-9207-4669>
 J. C. L. Chan  <https://orcid.org/0000-0002-3377-4737>
 K. H. M. Chan  <https://orcid.org/0000-0002-2019-2025>
 P. Chanial  <https://orcid.org/0000-0003-1753-524X>
 S. Chao  <https://orcid.org/0000-0003-3853-3593>
 C. Chapman-Bird  <https://orcid.org/0000-0002-2728-9612>
 P. Charlton  <https://orcid.org/0000-0002-4263-2706>
 E. Chassande-Mottin  <https://orcid.org/0000-0003-3768-9908>
 C. Chatterjee  <https://orcid.org/0000-0001-8700-3455>
 Debarati Chatterjee  <https://orcid.org/0000-0002-0995-2329>
 Deep Chatterjee  <https://orcid.org/0000-0003-0038-5468>
 S. Chaty  <https://orcid.org/0000-0002-5769-8601>
 K. Chatziioannou  <https://orcid.org/0000-0002-5833-413X>
 D. Chen  <https://orcid.org/0000-0003-1433-0716>
 H. Y. Chen  <https://orcid.org/0000-0001-5403-3762>
 J. Chen  <https://orcid.org/0000-0001-5550-6592>
 P. Chessa  <https://orcid.org/0000-0001-9092-3965>
 F. Chiadini  <https://orcid.org/0000-0002-9339-8622>
 A. Chincarini  <https://orcid.org/0000-0003-4094-9942>
 A. Chiummo  <https://orcid.org/0000-0003-2165-2967>
 S. Choudhary  <https://orcid.org/0000-0003-0949-7298>

- N. Christensen  <https://orcid.org/0000-0002-6870-4202>
 S. S. Y. Chua  <https://orcid.org/0000-0001-8026-7597>
 G. Ciani  <https://orcid.org/0000-0003-4258-9338>
 P. Ciecielag  <https://orcid.org/0000-0002-5871-4730>
 M. Cieřlar  <https://orcid.org/0000-0001-8912-5587>
 R. Ciolfi  <https://orcid.org/0000-0003-3140-8933>
 J. A. Clark  <https://orcid.org/0000-0003-3243-1393>
 T. A. Clarke  <https://orcid.org/0000-0002-6714-5429>
 E. Codazzo  <https://orcid.org/0000-0001-7170-8733>
 P.-F. Cohadon  <https://orcid.org/0000-0003-3452-9415>
 M. Colleoni  <https://orcid.org/0000-0002-7214-9088>
 A. Colombo  <https://orcid.org/0000-0002-7439-4773>
 L. Conti  <https://orcid.org/0000-0003-2731-2656>
 S. J. Cooper  <https://orcid.org/0000-0001-8114-3596>
 T. R. Corbitt  <https://orcid.org/0000-0002-5520-8541>
 I. Cordero-Carrión  <https://orcid.org/0000-0002-1985-1361>
 N. J. Cornish  <https://orcid.org/0000-0002-7435-0869>
 A. Corsi  <https://orcid.org/0000-0001-8104-3536>
 S. Cortese  <https://orcid.org/0000-0002-6504-0973>
 M. W. Coughlin  <https://orcid.org/0000-0002-8262-2924>
 B. Cousins  <https://orcid.org/0000-0002-7026-1340>
 P. Couvares  <https://orcid.org/0000-0002-2823-3127>
 D. C. Coyne  <https://orcid.org/0000-0002-6427-3222>
 R. Coyne  <https://orcid.org/0000-0002-5243-5917>
 J. D. E. Creighton  <https://orcid.org/0000-0003-3600-2406>
 A. W. Criswell  <https://orcid.org/0000-0002-9225-7756>
 M. Croquette  <https://orcid.org/0000-0002-8581-5393>
 J. R. Cudell  <https://orcid.org/0000-0002-2003-4238>
 A. Cumming  <https://orcid.org/0000-0003-4096-7542>
 M. Cusinato  <https://orcid.org/0000-0003-4075-4539>
 T. Dal Canton  <https://orcid.org/0000-0001-5078-9044>
 S. Dall’Osso  <https://orcid.org/0000-0003-4366-8265>
 G. Dálya  <https://orcid.org/0000-0003-3258-5763>
 B. D’Angelo  <https://orcid.org/0000-0001-9143-8427>
 S. Danilshin  <https://orcid.org/0000-0001-7758-7493>
 C. Darsow-Fromm  <https://orcid.org/0000-0001-9602-0388>
 S. Datta  <https://orcid.org/0000-0001-9200-8867>
 D. Davis  <https://orcid.org/0000-0001-5620-6751>
 M. C. Davis  <https://orcid.org/0000-0001-7663-0808>
 E. J. Daw  <https://orcid.org/0000-0002-3780-5430>
 M. Dax  <https://orcid.org/0000-0001-8798-0627>
 J. Degallaix  <https://orcid.org/0000-0002-1019-6911>
 M. De Laurentis  <https://orcid.org/0000-0002-3815-4078>
 S. Deléglise  <https://orcid.org/0000-0002-8680-5170>
 V. Del Favero  <https://orcid.org/0000-0001-7099-765X>
 F. De Lillo  <https://orcid.org/0000-0003-4977-0789>
 D. Dell’Aquila  <https://orcid.org/0000-0001-5895-0664>
 F. De Marco  <https://orcid.org/0000-0002-5411-9424>
 V. D’Emilio  <https://orcid.org/0000-0001-6145-8187>
 T. Dent  <https://orcid.org/0000-0003-1354-7809>
 A. Depasse  <https://orcid.org/0000-0003-1014-8394>
 R. De Pietri  <https://orcid.org/0000-0003-1556-8304>
 R. De Rosa  <https://orcid.org/0000-0002-4004-947X>
 C. De Rossi  <https://orcid.org/0000-0002-5825-472X>
 M. C. Díaz  <https://orcid.org/0000-0002-7555-8856>
 T. Dietrich  <https://orcid.org/0000-0003-2374-307X>
 C. Di Fronzo  <https://orcid.org/0000-0002-2693-6769>
 F. Di Giovanni  <https://orcid.org/0000-0001-8568-9334>
 T. Di Girolamo  <https://orcid.org/0000-0003-2339-4471>
 A. Di Lieto  <https://orcid.org/0000-0002-4787-0754>
 A. Di Michele  <https://orcid.org/0000-0002-0357-2608>
 J. Ding  <https://orcid.org/0000-0003-1693-3828>
 S. Di Pace  <https://orcid.org/0000-0001-6759-5676>
 I. Di Palma  <https://orcid.org/0000-0003-1544-8943>
 F. Di Renzo  <https://orcid.org/0000-0002-5447-3810>
 Divyajyoti  <https://orcid.org/0000-0002-2787-1012>
 A. Dmitriev  <https://orcid.org/0000-0002-0314-956X>
 Z. Doctor  <https://orcid.org/0000-0002-2077-4914>
 L. D’Onofrio  <https://orcid.org/0000-0001-9546-5959>
 K. L. Dooley  <https://orcid.org/0000-0002-1636-0233>
 S. Doravari  <https://orcid.org/0000-0001-8750-8330>
 M. Drago  <https://orcid.org/0000-0002-3738-2431>
 J. C. Driggers  <https://orcid.org/0000-0002-6134-7628>
 L. Dunn  <https://orcid.org/0000-0002-1769-6097>
 D. D’Urso  <https://orcid.org/0000-0002-8215-4542>
 H. Duval  <https://orcid.org/0000-0002-2475-1728>
 M. Ebersold  <https://orcid.org/0000-0003-4631-1771>
 T. Eckhardt  <https://orcid.org/0000-0002-1224-4681>
 G. Eddolls  <https://orcid.org/0000-0002-5895-4523>
 B. Edelman  <https://orcid.org/0000-0001-7648-1689>
 O. Edy  <https://orcid.org/0000-0001-9617-8724>
 A. Effler  <https://orcid.org/0000-0001-8242-3944>
 J. Eichholz  <https://orcid.org/0000-0002-2643-163X>
 A. Ejlli  <https://orcid.org/0000-0002-4149-4532>
 R. C. Essick  <https://orcid.org/0000-0001-8196-9267>
 H. Estellés  <https://orcid.org/0000-0001-6143-5532>
 D. Estevez  <https://orcid.org/0000-0002-3021-5964>
 M. Evans  <https://orcid.org/0000-0001-8459-4499>
 J. M. Ezquiaga  <https://orcid.org/0000-0002-7213-3211>
 F. Fabrizi  <https://orcid.org/0000-0002-3809-065X>
 V. Fafone  <https://orcid.org/0000-0003-1314-1622>
 S. Fairhurst  <https://orcid.org/0000-0001-8480-1961>
 P. C. Fan  <https://orcid.org/0000-0003-3988-9022>
 A. M. Farah  <https://orcid.org/0000-0002-6121-0285>
 B. Farr  <https://orcid.org/0000-0002-2916-9200>
 W. M. Farr  <https://orcid.org/0000-0003-1540-8562>
 G. Favaro  <https://orcid.org/0000-0002-0351-6833>
 M. Favata  <https://orcid.org/0000-0001-8270-9512>
 M. Fays  <https://orcid.org/0000-0002-4390-9746>
 E. Fenyvesi  <https://orcid.org/0000-0003-2777-3719>
 D. L. Ferguson  <https://orcid.org/0000-0002-4406-591X>
 I. Ferrante  <https://orcid.org/0000-0002-0083-7228>
 F. Fidecaro  <https://orcid.org/0000-0002-6189-3311>
 A. Fiori  <https://orcid.org/0000-0003-3174-0688>
 I. Fiori  <https://orcid.org/0000-0002-0210-516X>
 M. Fishbach  <https://orcid.org/0000-0002-1980-5293>
 S. M. Fleischer  <https://orcid.org/0000-0001-7884-9993>
 J. A. Font  <https://orcid.org/0000-0001-6650-2634>
 B. Fornal  <https://orcid.org/0000-0003-3271-2080>
 F. Frasconi  <https://orcid.org/0000-0003-4204-6587>
 A. Frattale Mascioli  <https://orcid.org/0000-0002-0155-3833>
 Z. Frei  <https://orcid.org/0000-0002-0181-8491>
 A. Freise  <https://orcid.org/0000-0001-6586-9901>
 O. Freitas  <https://orcid.org/0000-0002-2898-1256>
 R. Frey  <https://orcid.org/0000-0003-0341-2636>
 G. G. Fronzé  <https://orcid.org/0000-0003-0966-4279>
 W. E. Gabella  <https://orcid.org/0000-0003-2954-512X>
 B. Gadre  <https://orcid.org/0000-0002-1534-9761>
 J. R. Gair  <https://orcid.org/0000-0002-1671-3668>
 R. Gamba  <https://orcid.org/0000-0001-7239-0659>
 D. Ganapathy  <https://orcid.org/0000-0003-3028-4174>
 A. Ganguly  <https://orcid.org/0000-0001-7394-0755>
 B. Garaventa  <https://orcid.org/0000-0003-2490-404X>
 J. Garcia-Bellido  <https://orcid.org/0000-0002-9370-8360>

- C. García-Quirós  <https://orcid.org/0000-0002-8059-2477>
J. W. Gardner  <https://orcid.org/0000-0002-8592-1452>
F. Garufi  <https://orcid.org/0000-0003-1391-6168>
C. Gasbarra  <https://orcid.org/0000-0001-8335-9614>
V. Gayathri  <https://orcid.org/0000-0002-7167-9888>
G. Gemme  <https://orcid.org/0000-0002-1127-7406>
A. Gennai  <https://orcid.org/0000-0003-0149-2089>
O. Gerberding  <https://orcid.org/0000-0001-7740-2698>
L. Gergely  <https://orcid.org/0000-0003-3146-6201>
Abhirup Ghosh  <https://orcid.org/0000-0002-2112-8578>
Archisman Ghosh  <https://orcid.org/0000-0003-0423-3533>
Shaon Ghosh  <https://orcid.org/0000-0001-9901-6253>
Suprovo Ghosh  <https://orcid.org/0000-0002-1656-9870>
Tathagata Ghosh  <https://orcid.org/0000-0001-9848-9905>
J. A. Giaime  <https://orcid.org/0000-0002-3531-817X>
P. Giri  <https://orcid.org/0000-0002-4628-2432>
S. Gkaitatzis  <https://orcid.org/0000-0001-9420-7499>
E. Goetz  <https://orcid.org/0000-0003-2666-721X>
R. Goetz  <https://orcid.org/0000-0002-9617-5520>
B. Goncharov  <https://orcid.org/0000-0003-3189-5807>
G. González  <https://orcid.org/0000-0003-0199-3158>
A. W. Goodwin-Jones  <https://orcid.org/0000-0002-0395-0680>
R. Gouaty  <https://orcid.org/0000-0001-5372-7084>
S. Goyal  <https://orcid.org/0000-0002-4225-010X>
A. Grado  <https://orcid.org/0000-0002-0501-8256>
A. E. Granados  <https://orcid.org/0000-0003-2099-9096>
M. Granata  <https://orcid.org/0000-0003-3275-1186>
V. Granata  <https://orcid.org/0000-0003-2246-6963>
R. Gray  <https://orcid.org/0000-0002-5556-9873>
A. C. Green  <https://orcid.org/0000-0002-6287-8746>
S. R. Green  <https://orcid.org/0000-0002-6987-6313>
W. L. Griffiths  <https://orcid.org/0000-0001-8366-0108>
H. L. Griggs  <https://orcid.org/0000-0001-5018-7908>
A. Grimaldi  <https://orcid.org/0000-0002-6956-4301>
H. Grote  <https://orcid.org/0000-0002-0797-3943>
D. Guerra  <https://orcid.org/0000-0003-0029-5390>
D. Guetta  <https://orcid.org/0000-0002-7349-1109>
G. M. Guidi  <https://orcid.org/0000-0002-3061-9870>
F. Gulminelli  <https://orcid.org/0000-0003-4354-2849>
H. Guo  <https://orcid.org/0000-0002-3777-3117>
Y. Guo  <https://orcid.org/0000-0002-6959-9870>
Anchal Gupta  <https://orcid.org/0000-0002-1762-9644>
Anuradha Gupta  <https://orcid.org/0000-0002-5441-9013>
Ish Gupta  <https://orcid.org/0000-0001-6932-8715>
F. Guzman  <https://orcid.org/0000-0001-9136-929X>
L. Haegel  <https://orcid.org/0000-0002-3680-5519>
O. Halim  <https://orcid.org/0000-0003-1326-5481>
E. D. Hall  <https://orcid.org/0000-0001-9018-666X>
G. Hammond  <https://orcid.org/0000-0002-1414-3622>
W.-B. Han  <https://orcid.org/0000-0002-2039-0726>
M. Haney  <https://orcid.org/0000-0001-7554-3665>
O. A. Hannuksela  <https://orcid.org/0000-0002-3887-7137>
A. G. Hanselman  <https://orcid.org/0000-0002-8304-0109>
T. Harnmark  <https://orcid.org/0000-0002-2795-7035>
J. Harms  <https://orcid.org/0000-0002-7332-9806>
G. M. Harry  <https://orcid.org/0000-0002-8905-7622>
I. W. Harry  <https://orcid.org/0000-0002-5304-9372>
D. Hartwig  <https://orcid.org/0000-0002-9742-0794>
C.-J. Haster  <https://orcid.org/0000-0001-8040-9807>
K. Haughian  <https://orcid.org/0000-0002-1223-7342>
F. J. Hayes  <https://orcid.org/0000-0001-7628-3826>
J. Healy  <https://orcid.org/0000-0002-5233-3320>
A. Heffernan  <https://orcid.org/0000-0003-3355-9671>
A. Heidmann  <https://orcid.org/0000-0002-0784-5175>
J. Heinze  <https://orcid.org/0000-0001-8692-2724>
H. Heitmann  <https://orcid.org/0000-0003-0625-5461>
F. Hellman  <https://orcid.org/0000-0002-9135-6330>
A. F. Helmling-Cornell  <https://orcid.org/0000-0002-7709-8638>
G. Hemming  <https://orcid.org/0000-0001-5268-4465>
M. Hendry  <https://orcid.org/0000-0001-8322-5405>
I. S. Heng  <https://orcid.org/0000-0002-1977-0019>
E. Hennes  <https://orcid.org/0000-0002-2246-5496>
C. Henshaw  <https://orcid.org/0000-0002-4206-3128>
M. Heurs  <https://orcid.org/0000-0002-5577-2273>
A. L. Hewitt  <https://orcid.org/0000-0002-1255-3492>
Y. Himemoto  <https://orcid.org/0000-0002-6856-3809>
I. J. Hollows  <https://orcid.org/0000-0002-3404-6459>
Z. J. Holmes  <https://orcid.org/0000-0003-1311-4691>
D. E. Holz  <https://orcid.org/0000-0002-0175-5064>
J. Hough  <https://orcid.org/0000-0003-3242-3123>
E. J. Howell  <https://orcid.org/0000-0001-7891-2817>
C. G. Hoy  <https://orcid.org/0000-0002-8843-6719>
H.-F. Hsieh  <https://orcid.org/0000-0002-8947-723X>
S.-C. Hsu  <https://orcid.org/0000-0001-6214-8500>
W.-F. Hsu  <https://orcid.org/0000-0001-5234-3804>
Q. Hu  <https://orcid.org/0000-0002-3033-6491>
H. Y. Huang  <https://orcid.org/0000-0002-1665-2383>
Y.-J. Huang  <https://orcid.org/0000-0002-2952-8429>
Y. Huang  <https://orcid.org/0000-0002-0937-7221>
M. T. Hübner  <https://orcid.org/0000-0002-9642-3029>
D. C. Y. Hui  <https://orcid.org/0000-0003-1753-1660>
V. Hui  <https://orcid.org/0000-0002-0233-2346>
S. Husa  <https://orcid.org/0000-0002-0445-1971>
J. Hyland  <https://orcid.org/0000-0003-3428-0090>
A. Iakovlev  <https://orcid.org/0000-0003-1576-2692>
A. Iess  <https://orcid.org/0000-0001-9658-6752>
K. Inayoshi  <https://orcid.org/0000-0001-9840-4959>
G. Iorio  <https://orcid.org/0000-0003-0293-503X>
P. Iosif  <https://orcid.org/0000-0003-1621-7709>
J. Irwin  <https://orcid.org/0000-0002-2364-2191>
M. Isi  <https://orcid.org/0000-0001-8830-8672>
M. A. Ismail  <https://orcid.org/0000-0001-9340-8838>
Y. Itoh  <https://orcid.org/0000-0003-2694-8935>
B. R. Iyer  <https://orcid.org/0000-0002-4141-5179>
V. JaberianHamedan  <https://orcid.org/0000-0003-3605-4169>
T. Jacqmin  <https://orcid.org/0000-0002-0693-4838>
P.-E. Jacquet  <https://orcid.org/0000-0001-9552-0057>
S. P. Jadhav  <https://orcid.org/0000-0003-0554-0084>
A. L. James  <https://orcid.org/0000-0001-9165-0807>
A. Z. Jan  <https://orcid.org/0000-0003-2050-7231>
K. Jani  <https://orcid.org/0000-0003-1007-8912>
K. Janssens  <https://orcid.org/0000-0001-8760-4429>
S. Jaraba  <https://orcid.org/0000-0002-4759-143X>
P. Jaranowski  <https://orcid.org/0000-0001-8085-3414>
R. Jaume  <https://orcid.org/0000-0001-8691-3166>
J. Jiang  <https://orcid.org/0000-0002-0154-3854>
H.-B. Jin  <https://orcid.org/0000-0002-6217-2428>
D. H. Jones  <https://orcid.org/0000-0003-3987-068X>
L. Ju  <https://orcid.org/0000-0002-7951-4295>
K. Jung  <https://orcid.org/0000-0003-4789-8893>
J. Junker  <https://orcid.org/0000-0002-3051-4374>

- T. Kajita <https://orcid.org/0000-0003-1207-6638>
V. Kalogera <https://orcid.org/0000-0001-9236-5469>
M. Kamiizumi <https://orcid.org/0000-0001-7216-1784>
N. Kanda <https://orcid.org/0000-0001-6291-0227>
S. Kandhasamy <https://orcid.org/0000-0002-4825-6764>
G. Kang <https://orcid.org/0000-0002-6072-8189>
S. J. Kapadia <https://orcid.org/0000-0001-5318-1253>
D. P. Kapasi <https://orcid.org/0000-0001-8189-4920>
C. Karathanasis <https://orcid.org/0000-0002-0642-5507>
S. Karki <https://orcid.org/0000-0001-9982-3661>
M. Kasprzak <https://orcid.org/0000-0003-4618-5939>
D. Keitel <https://orcid.org/0000-0002-2824-626X>
J. Kennington <https://orcid.org/0000-0002-6899-3833>
J. S. Key <https://orcid.org/0000-0003-0123-7600>
F. Y. Khalili <https://orcid.org/0000-0001-7068-2332>
N. Kijbunchoo <https://orcid.org/0000-0002-2874-1228>
K. Kim <https://orcid.org/0000-0003-1653-3795>
S. Kim <https://orcid.org/0000-0003-1437-4647>
Y.-M. Kim <https://orcid.org/0000-0001-8720-6113>
M. Kinley-Hanlon <https://orcid.org/0000-0002-7367-8002>
R. Kirchhoff <https://orcid.org/0000-0003-0224-8600>
J. S. Kissel <https://orcid.org/0000-0002-1702-9577>
A. M. Knee <https://orcid.org/0000-0003-0703-947X>
S. M. Koehlenbeck <https://orcid.org/0000-0002-3842-9051>
K. Kohri <https://orcid.org/0000-0003-3764-8612>
K. Kokeyama <https://orcid.org/0000-0002-2896-1992>
S. Koley <https://orcid.org/0000-0002-5793-6665>
P. Kolitsidou <https://orcid.org/0000-0002-6719-8686>
M. Kolstein <https://orcid.org/0000-0002-5482-6743>
K. Komori <https://orcid.org/0000-0002-4092-9602>
A. K. H. Kong <https://orcid.org/0000-0002-5105-344X>
A. Kontos <https://orcid.org/0000-0002-1347-0680>
M. Korobko <https://orcid.org/0000-0002-3839-3909>
N. Kouvatso <https://orcid.org/0000-0002-5497-3401>
N. V. Krishnendu <https://orcid.org/0000-0002-3483-7517>
A. Królak <https://orcid.org/0000-0003-4514-7690>
P. Kuijer <https://orcid.org/0000-0002-6987-2048>
S. Kulkarni <https://orcid.org/0000-0001-8057-0203>
Praveen Kumar <https://orcid.org/0000-0002-2288-4252>
Prayush Kumar <https://orcid.org/0000-0001-5523-4603>
J. Kume <https://orcid.org/0000-0003-3126-5100>
K. Kuns <https://orcid.org/0000-0003-0630-3902>
S. Kuroyanagi <https://orcid.org/0000-0001-6538-1447>
K. Kwak <https://orcid.org/0000-0002-2304-7798>
D. Laghi <https://orcid.org/0000-0001-7462-3794>
M. Lalleman <https://orcid.org/0000-0002-2254-010X>
R. N. Lang <https://orcid.org/0000-0002-4804-5537>
B. Lantz <https://orcid.org/0000-0002-7404-4845>
A. La Rana <https://orcid.org/0000-0001-8755-9322>
I. L. Rosa <https://orcid.org/0000-0003-0107-1540>
A. Lartaux-Vollard <https://orcid.org/0000-0003-1714-365X>
P. D. Lasky <https://orcid.org/0000-0003-3763-1386>
M. Laxen <https://orcid.org/0000-0001-7515-9639>
A. Lazzarini <https://orcid.org/0000-0002-5993-8808>
P. Leaci <https://orcid.org/0000-0002-3997-5046>
S. Leavey <https://orcid.org/0000-0001-8253-0272>
Y. K. Lecoche <https://orcid.org/0000-0002-9186-7034>
H. M. Lee <https://orcid.org/0000-0003-4412-7161>
H. W. Lee <https://orcid.org/0000-0002-1998-3209>
K. Lee <https://orcid.org/0000-0003-0470-3718>
R.-K. Lee <https://orcid.org/0000-0002-7171-7274>
S. Lee <https://orcid.org/0000-0001-6034-2238>
M. Lenti <https://orcid.org/0000-0002-2765-3955>
M. Leonardi <https://orcid.org/0000-0002-7641-0060>
E. Leonova <https://orcid.org/0000-0002-5757-4334>
N. Leroy <https://orcid.org/0000-0002-2321-1017>
M. Lethuillier <https://orcid.org/0000-0001-6185-2045>
K. L. Li <https://orcid.org/0000-0001-8229-2024>
X. Li <https://orcid.org/0000-0002-3780-7735>
Chun-Yu Lin <https://orcid.org/0000-0002-7489-7418>
E. T. Lin <https://orcid.org/0000-0002-0030-8051>
L. C.-C. Lin <https://orcid.org/0000-0003-4083-9567>
T. B. Littenberg <https://orcid.org/0000-0002-9574-578X>
A. Liu <https://orcid.org/0000-0003-1081-8722>
G. C. Liu <https://orcid.org/0000-0001-5663-3016>
Jian Liu <https://orcid.org/0000-0001-6726-3268>
R. K. L. Lo <https://orcid.org/0000-0003-1561-6716>
A. Longo <https://orcid.org/0000-0003-4254-8579>
M. Lorenzini <https://orcid.org/0000-0002-2765-7905>
G. Losurdo <https://orcid.org/0000-0003-0452-746X>
T. P. Lott <https://orcid.org/0009-0002-2864-162X>
J. D. Lough <https://orcid.org/0000-0002-5160-0239>
C. O. Lousto <https://orcid.org/0000-0002-6400-9640>
D. Lumaca <https://orcid.org/0000-0002-3628-1591>
A. W. Lussier <https://orcid.org/0000-0002-4507-1123>
M. Ma'arif <https://orcid.org/0000-0001-8472-7095>
R. Macas <https://orcid.org/0000-0002-6096-8297>
D. M. Macleod <https://orcid.org/0000-0002-1395-8694>
I. A. O. MacMillan <https://orcid.org/0000-0002-6927-1031>
A. Macquet <https://orcid.org/0000-0001-5955-6415>
S. Maenaut <https://orcid.org/0000-0003-1464-2605>
C. Magazzù <https://orcid.org/0000-0002-9913-381X>
R. M. Magee <https://orcid.org/0000-0001-9769-531X>
M. Magnozzi <https://orcid.org/0000-0003-4512-8430>
V. Mandic <https://orcid.org/0000-0001-6333-8621>
V. Mangano <https://orcid.org/0000-0001-7902-8505>
G. L. Mansell <https://orcid.org/0000-0003-4736-6678>
M. Manske <https://orcid.org/0000-0002-7778-1189>
M. Mantovani <https://orcid.org/0000-0002-4424-5726>
M. Mapelli <https://orcid.org/0000-0001-8799-2548>
D. Marín Pina <https://orcid.org/0000-0001-6482-1842>
F. Marion <https://orcid.org/0000-0002-8184-1017>
S. Márka <https://orcid.org/0000-0002-3957-1324>
Z. Márka <https://orcid.org/0000-0003-1306-5260>
C. Markakis <https://orcid.org/0000-0002-5524-0410>
A. Marquina <https://orcid.org/0000-0001-8767-4208>
S. Marsat <https://orcid.org/0000-0001-9449-1071>
F. Martelli <https://orcid.org/0000-0003-3761-8616>
I. W. Martin <https://orcid.org/0000-0001-7300-9151>
R. M. Martin <https://orcid.org/0000-0001-9664-2216>
V. Martinez <https://orcid.org/0000-0001-5852-2301>
H. Masalehdan <https://orcid.org/0000-0002-4589-0815>
M. Masso-Reid <https://orcid.org/0000-0001-6177-8105>
S. Mastrogianni <https://orcid.org/0000-0003-1606-4183>
M. Mateu-Lucena <https://orcid.org/0000-0003-4817-6913>
M. Matushechikina <https://orcid.org/0000-0002-9957-8720>
N. Mavalvala <https://orcid.org/0000-0003-0219-9706>
D. E. McClelland <https://orcid.org/0000-0001-6210-5842>
L. McCuller <https://orcid.org/0000-0003-0851-0593>
C. McIsaac <https://orcid.org/0000-0003-2484-2256>
J. McIver <https://orcid.org/0000-0003-0316-1355>
A. McLeod <https://orcid.org/0000-0001-5424-8368>
D. Meacher <https://orcid.org/0000-0001-5882-0368>
M. Mehmet <https://orcid.org/0000-0001-9432-7108>

- S. Mellaerts  <https://orcid.org/0000-0002-6715-3066>
A. Menendez-Vazquez  <https://orcid.org/0000-0002-0828-8219>
C. S. Menoni  <https://orcid.org/0000-0001-9185-2572>
R. A. Mercer  <https://orcid.org/0000-0001-8372-3914>
C. Messenger  <https://orcid.org/0000-0001-7488-5022>
M. Meyer-Conde  <https://orcid.org/0000-0003-2230-6310>
F. Meylahn  <https://orcid.org/0000-0002-9556-142X>
A. Miani  <https://orcid.org/0000-0001-7737-3129>
I. Michaloliakos  <https://orcid.org/0000-0003-2980-358X>
C. Michel  <https://orcid.org/0000-0003-0606-725X>
Y. Michimura  <https://orcid.org/0000-0002-2218-4002>
H. Middleton  <https://orcid.org/0000-0001-5532-3622>
D. P. Mihaylov  <https://orcid.org/0000-0002-8820-407X>
A. L. Miller  <https://orcid.org/0000-0002-4890-7627>
M. Millhouse  <https://orcid.org/0000-0002-8659-5898>
E. Milotti  <https://orcid.org/0000-0001-7348-9765>
Ll. M. Mir  <https://orcid.org/0000-0002-4276-715X>
M. Miravet-Tenés  <https://orcid.org/0000-0002-8766-1156>
C. . Miritescu  <https://orcid.org/0000-0002-7716-0569>
T. Mishra  <https://orcid.org/0000-0002-7881-1677>
S. Mitra  <https://orcid.org/0000-0002-0800-4626>
V. P. Mitrofanov  <https://orcid.org/0000-0002-6983-4981>
G. Mitselmakher  <https://orcid.org/0000-0001-5745-3658>
O. Miyakawa  <https://orcid.org/0000-0002-9085-7600>
S. Miyoki  <https://orcid.org/0000-0002-1213-8416>
G. Mo  <https://orcid.org/0000-0001-6331-112X>
L. M. Modafferi  <https://orcid.org/0000-0002-3422-6986>
S. R. Mohite  <https://orcid.org/0000-0003-1356-7156>
M. Molina-Ruiz  <https://orcid.org/0000-0003-4892-3042>
A. More  <https://orcid.org/0000-0001-7714-7076>
S. More  <https://orcid.org/0000-0002-2986-2371>
C. Moreno  <https://orcid.org/0000-0002-0496-032X>
S. Morisaki  <https://orcid.org/0000-0002-8445-6747>
Y. Moriwaki  <https://orcid.org/0000-0002-4497-6908>
G. Morras  <https://orcid.org/0000-0002-9977-8546>
A. Moscatello  <https://orcid.org/0000-0001-5480-7406>
B. Mours  <https://orcid.org/0000-0002-6444-6402>
C. M. Mow-Lowry  <https://orcid.org/0000-0002-0351-4555>
S. Mozzon  <https://orcid.org/0000-0002-8855-2509>
F. Muciaccia  <https://orcid.org/0000-0003-0850-2649>
D. Mukherjee  <https://orcid.org/0000-0001-7335-9418>
Suvodip Mukherjee  <https://orcid.org/0000-0002-3373-5236>
N. Mukund  <https://orcid.org/0000-0002-8666-9156>
E. A. Muñoz  <https://orcid.org/0000-0001-8844-421X>
P. G. Murray  <https://orcid.org/0000-0002-8218-2404>
T. Nagar  <https://orcid.org/0000-0002-2747-0497>
N. Nagarajan  <https://orcid.org/0000-0003-3695-0078>
K. Nakamura  <https://orcid.org/0000-0001-6148-4289>
H. Nakano  <https://orcid.org/0000-0001-7665-0796>
I. Nardecchia  <https://orcid.org/0000-0001-5558-2595>
L. Naticchioni  <https://orcid.org/0000-0003-2918-0730>
R. K. Nayak  <https://orcid.org/0000-0002-6814-7792>
S. Nesseris  <https://orcid.org/0000-0002-0567-0324>
S. W. S. Ng  <https://orcid.org/0000-0001-5843-1434>
C. Nguyen  <https://orcid.org/0000-0001-8623-0306>
L. Nguyen Quynh  <https://orcid.org/0000-0002-1828-3702>
A. Nishizawa  <https://orcid.org/0000-0003-3562-0990>
E. Nitoglia  <https://orcid.org/0000-0001-8906-9159>
J. Novak  <https://orcid.org/0000-0002-6029-4712>
J. F. Nuño Siles  <https://orcid.org/0000-0001-8304-8066>
L. K. Nuttall  <https://orcid.org/0000-0002-8599-8791>
M. Oertel  <https://orcid.org/0000-0002-1884-8654>
J. J. Oh  <https://orcid.org/0000-0001-5417-862X>
K. Oh  <https://orcid.org/0000-0002-9672-3742>
S. H. Oh  <https://orcid.org/0000-0003-1184-7453>
M. Ohashi  <https://orcid.org/0000-0001-8072-0304>
M. Ohkawa  <https://orcid.org/0000-0002-1380-1419>
F. Ohme  <https://orcid.org/0000-0003-0493-5607>
A. S. Oliveira  <https://orcid.org/0000-0001-5755-5865>
R. Oliveri  <https://orcid.org/0000-0002-7497-871X>
K. Oohara  <https://orcid.org/0000-0002-7518-6677>
B. O'Reilly  <https://orcid.org/0000-0002-3874-8335>
M. Orselli  <https://orcid.org/0000-0003-3563-8576>
R. O'Shaughnessy  <https://orcid.org/0000-0001-5832-8517>
Y. Oshima  <https://orcid.org/0000-0002-1868-2842>
S. Oshino  <https://orcid.org/0000-0002-2794-6029>
S. Ossokine  <https://orcid.org/0000-0002-2579-1246>
D. J. Ottaway  <https://orcid.org/0000-0001-6794-1591>
R. Pagano  <https://orcid.org/0000-0001-8362-0130>
M. A. Page  <https://orcid.org/0000-0002-5298-7914>
S. Pal  <https://orcid.org/0000-0003-2172-8589>
C. Palomba  <https://orcid.org/0000-0002-4450-9883>
K.-C. Pan  <https://orcid.org/0000-0002-1473-9880>
F. Pannarale  <https://orcid.org/0000-0002-7537-3210>
C. D. Panzer  <https://orcid.org/0000-0002-4536-5463>
F. Paoletti  <https://orcid.org/0000-0001-8898-1963>
L. Papalini  <https://orcid.org/0000-0002-5219-0454>
G. Pappas  <https://orcid.org/0000-0003-3344-3759>
A. Parisi  <https://orcid.org/0000-0003-0251-8914>
J. Park  <https://orcid.org/0000-0002-7510-0079>
W. Parker  <https://orcid.org/0000-0002-7711-4423>
D. Pascucci  <https://orcid.org/0000-0003-1907-0175>
R. Passaquieti  <https://orcid.org/0000-0003-4753-9428>
B. Patricelli  <https://orcid.org/0000-0001-6709-0969>
S. Paul  <https://orcid.org/0000-0002-4449-1732>
E. Payne  <https://orcid.org/0000-0003-4507-8373>
R. Pegna  <https://orcid.org/0000-0002-6532-671X>
A. Pele  <https://orcid.org/0000-0002-1873-3769>
F. E. Peña Arellano  <https://orcid.org/0000-0002-8516-5159>
S. Penn  <https://orcid.org/0000-0003-4956-0853>
A. Perego  <https://orcid.org/0000-0002-0936-8237>
C. Pérois  <https://orcid.org/0000-0002-9779-2838>
A. Perreca  <https://orcid.org/0000-0002-6269-2490>
S. Perriès  <https://orcid.org/0000-0003-2213-3579>
J. Petermann  <https://orcid.org/0000-0002-8949-3803>
H. P. Pfeiffer  <https://orcid.org/0000-0001-9288-519X>
K. A. Pham  <https://orcid.org/0000-0002-7650-1034>
K. S. Phukon  <https://orcid.org/0000-0003-1561-0760>
O. J. Piccinni  <https://orcid.org/0000-0001-5478-3950>
M. Pichot  <https://orcid.org/0000-0002-4439-8968>
F. Piergiovanni  <https://orcid.org/0000-0001-8063-828X>
L. Pierini  <https://orcid.org/0000-0003-0945-2196>
G. Pierra  <https://orcid.org/0000-0003-3970-7970>
V. Pierro  <https://orcid.org/0000-0002-6020-5521>
F. Pilo  <https://orcid.org/0000-0003-4967-7090>
I. M. Pinto  <https://orcid.org/0000-0002-2679-4457>
B. J. Piotrkowski  <https://orcid.org/0000-0001-8919-0899>
M. D. Pitkin  <https://orcid.org/0000-0003-4548-526X>
A. Placidi  <https://orcid.org/0000-0001-8032-4416>
E. Placidi  <https://orcid.org/0000-0002-3820-8451>
M. L. Planas  <https://orcid.org/0000-0001-8278-7406>
W. Plastino  <https://orcid.org/0000-0002-5737-6346>
R. Poggiani  <https://orcid.org/0000-0002-9968-2464>

- E. Polini  <https://orcid.org/0000-0003-4059-0765>
 L. Pompili  <https://orcid.org/0000-0002-0710-6778>
 J. Portell  <https://orcid.org/0000-0002-8886-8925>
 R. Poulton  <https://orcid.org/0000-0003-2049-520X>
 J. Powell  <https://orcid.org/0000-0002-1357-4164>
 B. K. Pradhan  <https://orcid.org/0000-0002-2526-1421>
 G. Pratten  <https://orcid.org/0000-0003-4984-0775>
 G. A. Prodi  <https://orcid.org/0000-0001-5256-915X>
 J. Pullin  <https://orcid.org/0000-0001-8248-603X>
 M. Punturo  <https://orcid.org/0000-0001-8722-4485>
 M. Pürrer  <https://orcid.org/0000-0002-3329-9788>
 H. Qi  <https://orcid.org/0000-0001-6339-1537>
 J. Qin  <https://orcid.org/0000-0002-7120-9026>
 P. Raffai  <https://orcid.org/0000-0001-7576-0141>
 K. E. Ramirez  <https://orcid.org/0000-0003-2194-7669>
 A. Ramos-Buades  <https://orcid.org/0000-0002-6874-7421>
 P. Rapagnani  <https://orcid.org/0000-0002-1865-6126>
 A. Ray  <https://orcid.org/0000-0002-7322-4748>
 V. Raymond  <https://orcid.org/0000-0003-0066-0095>
 N. Raza  <https://orcid.org/0000-0002-8549-9124>
 M. Razzano  <https://orcid.org/0000-0003-4825-1629>
 L. Rei  <https://orcid.org/0000-0002-8690-9180>
 D. H. Reitze  <https://orcid.org/0000-0002-5756-1111>
 P. Relton  <https://orcid.org/0000-0003-2756-3391>
 P. Rettegno  <https://orcid.org/0000-0001-8088-3517>
 B. Revenu  <https://orcid.org/0000-0002-7629-4805>
 A. S. Rezaei  <https://orcid.org/0000-0002-1674-1837>
 J. W. Richardson  <https://orcid.org/0000-0002-1472-4806>
 K. Riles  <https://orcid.org/0000-0002-6418-5812>
 S. Rinaldi  <https://orcid.org/0000-0001-5799-4155>
 A. Rocchi  <https://orcid.org/0000-0002-1382-9016>
 L. Rolland  <https://orcid.org/0000-0003-0589-9687>
 J. G. Rollins  <https://orcid.org/0000-0002-9388-2799>
 A. Romero  <https://orcid.org/0000-0003-2275-4164>
 S. Ronchini  <https://orcid.org/0000-0003-0020-687X>
 T. J. Rooke  <https://orcid.org/0000-0003-2640-9683>
 D. Rosińska  <https://orcid.org/0000-0002-3681-9304>
 M. P. Ross  <https://orcid.org/0000-0002-8955-5269>
 M. Rossello  <https://orcid.org/0000-0002-3341-3480>
 S. Rowan  <https://orcid.org/0000-0002-0666-9907>
 D. Rozza  <https://orcid.org/0000-0002-7378-6353>
 E. Ruiz Morales  <https://orcid.org/0000-0002-0995-595X>
 S. Sachdev  <https://orcid.org/0000-0002-0525-2317>
 J. Sadiq  <https://orcid.org/0000-0001-5931-3624>
 S. S. Saha  <https://orcid.org/0000-0002-3333-8070>
 M. Sakellariadou  <https://orcid.org/0000-0002-2715-1517>
 S. Sakon  <https://orcid.org/0000-0002-5861-3024>
 O. S. Salafia  <https://orcid.org/0000-0003-4924-7322>
 F. Salces-Carcoba  <https://orcid.org/0000-0001-7049-4438>
 M. Saleem  <https://orcid.org/0000-0002-3836-7751>
 F. Salemi  <https://orcid.org/0000-0002-9511-3846>
 M. Sallé  <https://orcid.org/0000-0002-6620-6672>
 S. Salvador  <https://orcid.org/0000-0003-3444-7807>
 N. Sanchis-Gual  <https://orcid.org/0000-0001-5375-7494>
 A. Sasli  <https://orcid.org/0000-0001-7357-0889>
 P. Sassi  <https://orcid.org/0000-0002-4920-2784>
 B. Sassolas  <https://orcid.org/0000-0002-3077-8951>
 O. Sauter  <https://orcid.org/0000-0003-2293-1554>
 R. L. Savage  <https://orcid.org/0000-0003-3317-1036>
 V. Savant  <https://orcid.org/0000-0002-4117-2269>
 T. Sawada  <https://orcid.org/0000-0001-5726-7150>
 M. G. Schiowski  <https://orcid.org/0000-0001-9298-004X>
 P. Schmidt  <https://orcid.org/0000-0003-1542-1791>
 S. Schmidt  <https://orcid.org/0000-0002-8206-8089>
 R. Schnabel  <https://orcid.org/0000-0003-2896-4218>
 E. Schwartz  <https://orcid.org/0000-0001-8922-7794>
 J. Scott  <https://orcid.org/0000-0001-6701-6515>
 S. M. Scott  <https://orcid.org/0000-0002-9875-7700>
 M. Seglar-Arroyo  <https://orcid.org/0000-0001-8654-409X>
 Y. Sekiguchi  <https://orcid.org/0000-0002-2648-3835>
 A. S. Sengupta  <https://orcid.org/0000-0002-3212-0475>
 E. G. Seo  <https://orcid.org/0000-0002-8588-4794>
 J. W. Seo  <https://orcid.org/0000-0003-4937-0769>
 G. Servignat  <https://orcid.org/0000-0003-0057-922X>
 Y. Setyawati  <https://orcid.org/0000-0003-3718-4491>
 M. S. Shahriar  <https://orcid.org/0000-0002-7981-954X>
 M. A. Shaikh  <https://orcid.org/0000-0003-0826-6164>
 L. Shao  <https://orcid.org/0000-0002-1334-8853>
 P. Shawhan  <https://orcid.org/0000-0002-8249-8070>
 N. S. Shcheblanov  <https://orcid.org/0000-0001-8696-2435>
 Y. Shikano  <https://orcid.org/0000-0003-2107-7536>
 K. Shimode  <https://orcid.org/0000-0002-5682-8750>
 H. Shinkai  <https://orcid.org/0000-0003-1082-2844>
 D. H. Shoemaker  <https://orcid.org/0000-0002-4147-2560>
 D. M. Shoemaker  <https://orcid.org/0000-0002-9899-6357>
 D. Sigg  <https://orcid.org/0000-0003-4606-6526>
 L. Silenzi  <https://orcid.org/0000-0001-7316-3239>
 L. P. Singer  <https://orcid.org/0000-0001-9898-5597>
 D. Singh  <https://orcid.org/0000-0001-9675-4584>
 M. K. Singh  <https://orcid.org/0000-0001-8081-4888>
 A. Singha  <https://orcid.org/0000-0002-9944-5573>
 A. M. Sintes  <https://orcid.org/0000-0001-9050-7515>
 V. Skliris  <https://orcid.org/0000-0003-0902-9216>
 B. J. J. Slagmolen  <https://orcid.org/0000-0002-2471-3828>
 J. R. Smith  <https://orcid.org/0000-0003-0638-9670>
 L. Smith  <https://orcid.org/0000-0002-3035-0947>
 R. J. E. Smith  <https://orcid.org/0000-0001-8516-3324>
 J. Soldateschi  <https://orcid.org/0000-0002-5458-5206>
 S. N. Somala  <https://orcid.org/0000-0003-2663-3351>
 K. Somiya  <https://orcid.org/0000-0003-2601-2264>
 K. Soni  <https://orcid.org/0000-0001-8051-7883>
 S. Soni  <https://orcid.org/0000-0003-3856-8534>
 N. Sorrentino  <https://orcid.org/0000-0002-1855-5966>
 A. P. Spencer  <https://orcid.org/0000-0003-4418-3366>
 M. Spera  <https://orcid.org/0000-0003-0930-6930>
 F. Stachurski  <https://orcid.org/0000-0002-8658-5753>
 D. A. Steer  <https://orcid.org/0000-0002-8781-1273>
 S. Steinlechner  <https://orcid.org/0000-0003-4710-8548>
 N. Stergioulas  <https://orcid.org/0000-0002-5490-5302>
 G. Stratta  <https://orcid.org/0000-0003-1055-7980>
 A. L. Stuver  <https://orcid.org/0000-0003-0324-5735>
 S. Sudhagar  <https://orcid.org/0000-0001-8578-4665>
 H. G. Suh  <https://orcid.org/0000-0003-2662-3903>
 A. G. Sullivan  <https://orcid.org/0000-0002-9545-7286>
 T. Z. Summerscales  <https://orcid.org/0000-0002-4522-5591>
 L. Sun  <https://orcid.org/0000-0001-7959-892X>
 A. Sur  <https://orcid.org/0000-0001-6635-5080>
 J. Suresh  <https://orcid.org/0000-0003-2389-6666>
 P. J. Sutton  <https://orcid.org/0000-0003-1614-3922>
 Takamasa Suzuki  <https://orcid.org/0000-0003-3030-6599>
 B. L. Swinkels  <https://orcid.org/0000-0002-3066-3601>
 M. J. Szczepańczyk  <https://orcid.org/0000-0002-6167-6149>
 P. Szewczyk  <https://orcid.org/0000-0002-1339-9167>
 M. Tacca  <https://orcid.org/0000-0003-1353-0441>

- H. Tagoshi  <https://orcid.org/0000-0001-8530-9178>
 S. C. Tait  <https://orcid.org/0000-0003-0327-953X>
 H. Takahashi  <https://orcid.org/0000-0003-0596-4397>
 R. Takahashi  <https://orcid.org/0000-0003-1367-5149>
 A. Takamori  <https://orcid.org/0000-0001-6032-1330>
 H. Takeda  <https://orcid.org/0000-0001-9937-2557>
 N. Tamanini  <https://orcid.org/0000-0001-8760-5421>
 S. J. Tanaka  <https://orcid.org/0000-0002-8796-1992>
 T. Tanaka  <https://orcid.org/0000-0001-8406-5183>
 S. Tanioka  <https://orcid.org/0000-0003-3321-1018>
 L. Tao  <https://orcid.org/0000-0003-4382-5507>
 E. N. Tapia San Martín  <https://orcid.org/0000-0002-4817-5606>
 A. Taruya  <https://orcid.org/0000-0002-4016-1955>
 J. D. Tasson  <https://orcid.org/0000-0002-4777-5087>
 R. Tenorio  <https://orcid.org/0000-0002-3582-2587>
 L. Terkowski  <https://orcid.org/0000-0003-4622-1215>
 L. M. Thomas  <https://orcid.org/0000-0003-3271-6436>
 J. E. Thompson  <https://orcid.org/0000-0002-0419-5517>
 J. Tissino  <https://orcid.org/0000-0003-2483-6710>
 Shubhanshu Tiwari  <https://orcid.org/0000-0003-1611-6625>
 Srishti Tiwari  <https://orcid.org/0000-0002-3284-6110>
 V. Tiwari  <https://orcid.org/0000-0002-1602-4176>
 A. E. Tolley  <https://orcid.org/0000-0001-9841-943X>
 T. Tomaru  <https://orcid.org/0000-0002-8927-9014>
 T. Tomura  <https://orcid.org/0000-0002-7504-8258>
 A. Torres-Forné  <https://orcid.org/0000-0001-8709-5118>
 M. Toscani  <https://orcid.org/0000-0001-5997-7148>
 I. Tosta e Melo  <https://orcid.org/0000-0001-5833-4052>
 E. Tournier  <https://orcid.org/0000-0002-5465-9607>
 A. A. Trani  <https://orcid.org/0000-0001-5371-3432>
 A. Trapananti  <https://orcid.org/0000-0001-7763-5758>
 F. Travasso  <https://orcid.org/0000-0002-4653-6156>
 J. Trenado  <https://orcid.org/0000-0002-0714-108X>
 M. C. Tringali  <https://orcid.org/0000-0001-5087-189X>
 A. Tripathi  <https://orcid.org/0000-0002-6976-5576>
 A. Trovato  <https://orcid.org/0000-0002-9714-1904>
 M. Tse  <https://orcid.org/0000-0003-1510-4921>
 S. Tsuchida  <https://orcid.org/0000-0001-8217-0764>
 T. Tsutsui  <https://orcid.org/0000-0002-2909-0471>
 K. Turbang  <https://orcid.org/0000-0002-9296-8603>
 H. Ubach  <https://orcid.org/0000-0002-0679-9074>
 N. Uchikata  <https://orcid.org/0000-0003-0030-3653>
 T. Uchiyama  <https://orcid.org/0000-0003-2148-1694>
 R. P. Udall  <https://orcid.org/0000-0001-6877-3278>
 T. Uehara  <https://orcid.org/0000-0003-4375-098X>
 K. Ueno  <https://orcid.org/0000-0003-3227-6055>
 T. Ushiba  <https://orcid.org/0000-0002-5059-4033>
 A. Utina  <https://orcid.org/0000-0003-2975-9208>
 H. Vahlbruch  <https://orcid.org/0000-0003-2357-2338>
 N. Vaidya  <https://orcid.org/0000-0003-1843-7545>
 G. Vajente  <https://orcid.org/0000-0002-7656-6882>
 G. Valdes  <https://orcid.org/0000-0001-5411-380X>
 M. Valentini  <https://orcid.org/0000-0003-1215-4552>
 V. Valsan  <https://orcid.org/0000-0003-0315-4091>
 M. van Beuzekom  <https://orcid.org/0000-0002-0500-1286>
 M. van Dael  <https://orcid.org/0000-0002-6061-8131>
 J. F. J. van den Brand  <https://orcid.org/0000-0003-4434-5353>
 J. van Dongen  <https://orcid.org/0000-0003-0964-2483>
 H. van Haevermaet  <https://orcid.org/0000-0003-2386-957X>
 J. V. van Heijningen  <https://orcid.org/0000-0002-8391-7513>
 M. H. P. M. van Putten  <https://orcid.org/0000-0002-9212-411X>
 Z. van Ranst  <https://orcid.org/0000-0002-0460-6224>
 N. van Remortel  <https://orcid.org/0000-0003-4180-8199>
 V. Varma  <https://orcid.org/0000-0002-9994-1761>
 M. Vasúth  <https://orcid.org/0000-0003-4573-8781>
 A. Vecchio  <https://orcid.org/0000-0002-6254-1617>
 J. Veitch  <https://orcid.org/0000-0002-6508-0713>
 P. J. Veitch  <https://orcid.org/0000-0002-2597-435X>
 J. Venneberg  <https://orcid.org/0000-0002-2508-2044>
 P. Verdier  <https://orcid.org/0000-0003-3090-2948>
 D. Verkindt  <https://orcid.org/0000-0003-4344-7227>
 Y. Verma  <https://orcid.org/0000-0003-4147-3173>
 S. M. Vermeulen  <https://orcid.org/0000-0003-4227-8214>
 D. Veske  <https://orcid.org/0000-0003-4225-0895>
 A. Viceré  <https://orcid.org/0000-0003-0624-6231>
 A. D. Viets  <https://orcid.org/0000-0002-4241-1428>
 A. Vijaykumar  <https://orcid.org/0000-0002-4103-0666>
 V. Villa-Ortega  <https://orcid.org/0000-0001-7983-1963>
 E. T. Vincent  <https://orcid.org/0000-0002-0442-1916>
 A. Virtuoso  <https://orcid.org/0000-0003-1837-1021>
 S. Vitale  <https://orcid.org/0000-0003-2700-0767>
 D. Voigt  <https://orcid.org/0000-0001-9075-6503>
 S. P. Vyatchanin  <https://orcid.org/0000-0002-6823-911X>
 M. Wade  <https://orcid.org/0000-0002-5703-4469>
 K. J. Wagner  <https://orcid.org/0000-0002-7255-4251>
 H. Wang  <https://orcid.org/0000-0002-6589-2738>
 M. Was  <https://orcid.org/0000-0002-1890-1128>
 T. Washimi  <https://orcid.org/0000-0001-5792-4907>
 A. J. Weinstein  <https://orcid.org/0000-0002-0928-6784>
 R. A. Weller  <https://orcid.org/0000-0002-2280-219X>
 K. Wette  <https://orcid.org/0000-0002-4394-7179>
 J. T. Whelan  <https://orcid.org/0000-0001-5710-6576>
 B. F. Whiting  <https://orcid.org/0000-0002-8501-8669>
 C. Whittle  <https://orcid.org/0000-0002-8833-7438>
 D. Wilken  <https://orcid.org/0000-0002-7290-9411>
 D. Williams  <https://orcid.org/0000-0003-3772-198X>
 M. J. Williams  <https://orcid.org/0000-0003-2198-2974>
 A. R. Williamson  <https://orcid.org/0000-0002-7627-8688>
 J. L. Willis  <https://orcid.org/0000-0002-9929-0225>
 B. Willke  <https://orcid.org/0000-0003-0524-2925>
 M. Wils  <https://orcid.org/0000-0002-1544-7193>
 G. Woan  <https://orcid.org/0000-0003-0381-0394>
 J. K. Wofford  <https://orcid.org/0000-0002-4301-2859>
 H. T. Wong  <https://orcid.org/0000-0003-4145-4394>
 I. C. F. Wong  <https://orcid.org/0000-0003-2166-0027>
 M. Wright  <https://orcid.org/0000-0003-1829-7482>
 C. Wu  <https://orcid.org/0000-0003-3191-8845>
 D. S. Wu  <https://orcid.org/0000-0003-2849-3751>
 H. Wu  <https://orcid.org/0000-0003-4813-3833>
 D. M. Wysocki  <https://orcid.org/0000-0001-9138-4078>
 L. Xiao  <https://orcid.org/0000-0003-2703-449X>
 V. A. Xu  <https://orcid.org/0000-0002-3020-3293>
 N. Yadav  <https://orcid.org/0000-0002-1423-8525>
 H. Yamamoto  <https://orcid.org/0000-0001-6919-9570>
 K. Yamamoto  <https://orcid.org/0000-0002-3033-2845>
 T. S. Yamamoto  <https://orcid.org/0000-0002-8181-924X>
 T. Yamamoto  <https://orcid.org/0000-0002-0808-4822>
 R. Yamazaki  <https://orcid.org/0000-0002-1251-7889>
 F. W. Yang  <https://orcid.org/0000-0001-9873-6259>

K. Z. Yang  <https://orcid.org/0000-0001-8083-4037>
 Yang Yang  <https://orcid.org/0000-0001-7254-219X>
 Yi Yang  <https://orcid.org/0000-0002-3780-1413>
 Z. Yarbrough  <https://orcid.org/0000-0002-9825-1136>
 A. B. Yelikar  <https://orcid.org/0000-0002-8065-1174>
 J. Yokoyama  <https://orcid.org/0000-0001-7127-4808>
 J. Yoo  <https://orcid.org/0000-0002-3251-0924>
 H. Yu  <https://orcid.org/0000-0002-6011-6190>
 H. Yuzurihara  <https://orcid.org/0000-0002-3710-6613>
 M. Zeeshan  <https://orcid.org/0000-0002-6494-7303>
 M. Zevin  <https://orcid.org/0000-0002-0147-0835>
 J. Zhang  <https://orcid.org/0000-0002-3931-3851>
 R. Zhang  <https://orcid.org/0000-0001-8095-483X>
 Ya Zhang  <https://orcid.org/0000-0002-5756-7900>
 C. Zhao  <https://orcid.org/0000-0001-5825-2401>
 Yuhang Zhao  <https://orcid.org/0000-0003-2542-4734>
 Y. Zheng  <https://orcid.org/0000-0002-5432-1331>
 H. Zhong  <https://orcid.org/0000-0001-8324-5158>
 Z.-H. Zhu  <https://orcid.org/0000-0002-3567-6743>
 A. B. Zimmerman  <https://orcid.org/0000-0002-7453-6372>
 J. Zweizig  <https://orcid.org/0000-0002-1521-3397>

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