



A Search Using GEO600 for Gravitational Waves Coincident with Fast Radio Bursts from SGR 1935+2154

A. G. Abac¹ , R. Abbott², I. Abouelfettouh³, F. Acernese^{4,5}, K. Ackley⁶ , S. Adhicary⁷, N. Adhikari⁸ , R. X. Adhikari² , V. K. Adkins⁹, D. Agarwal^{10,11} , M. Agathos¹² , M. Aghaei Abchouyeh¹³ , O. D. Aguiar¹⁴ , I. Aguilar¹⁵, L. Aiello^{16,17,18} , A. Ain¹⁹ , P. Ajith²⁰ , T. Akutsu^{21,22} , S. Albanesi^{23,24,25} , R. A. Alfaiadi²⁶ , A. Al-Jodah²⁷ , C. Alléné²⁸, A. Allocca^{5,29} , S. Al-Shammari¹⁸, P. A. Altin³⁰ , S. Alvarez-Lopez³¹ , A. Amato^{32,33} , L. Amez-Droz³⁴, A. Amorosi³⁵, C. Amra³⁵, A. Ananyeva², S. B. Anderson² , W. G. Anderson² , M. Andia³⁶ , M. Ando³⁷, T. Andrade³⁸, N. Andres²⁸ , M. Andrés-Carcasona³⁹ , T. Andrić^{1,40,41,42} , J. Anglin⁴³, S. Ansoldi^{44,45} , J. M. Antelis⁴⁶ , S. Antier⁴⁷ , M. Aoumi⁴⁸, E. Z. Appavuravther^{49,50}, S. Appert², S. K. Apple⁵¹, K. Arai² , A. Araya³⁷ , M. C. Araya² , J. S. Areeda⁵² , L. Argianas⁵³, N. Aritomi³, F. Armato^{54,55} , N. Arnaud^{36,56} , M. Arogeti⁵⁷ , S. M. Aronson⁹ , G. Ashton⁵⁸ , Y. Aso^{21,59} , M. Assiduo^{60,61}, S. Assis de Souza Melo⁵⁶, S. M. Aston⁶², P. Astone⁶³ , F. Attadio^{63,64} , F. Aubin⁶⁵ , K. AultONeal⁶⁶ , G. Avallone⁶⁷ , D. Azrad⁶⁸, S. Babak⁶⁹, F. Badaracco⁵⁴ , C. Badger⁷⁰, S. Bae⁷¹ , S. Bagnasco²³ , E. Bagui⁷², J. G. Baier⁷³ , L. Baiotti⁷⁴ , R. Bajpai²¹ , T. Baka⁷⁵, M. Ball⁷⁶, G. Ballardín⁵⁶, S. W. Ballmer⁷⁷, S. Banagiri⁷⁸ , B. Banerjee⁴² , D. Bankar¹¹ , P. Baral⁸ , J. C. Barayoga², B. C. Barish², D. Barker³, P. Barneo^{38,79} , F. Barone^{5,80} , B. Barr²⁶ , L. Barsotti³¹ , M. Barsuglia⁶⁹ , D. Barta⁸¹ , A. M. Bartoletti⁸², M. A. Barton²⁶ , I. Bartos⁴³, S. Basak²⁰ , A. Basalae⁸³ , R. Bassiri¹⁵ , A. Basti^{84,85} , D. E. Bates¹⁸, M. Bawaj⁸⁶ , P. Baxi⁸⁷, J. C. Bayley²⁶ , A. C. Baylor⁸ , P. A. Baynard II⁵⁷, M. Bazzan^{88,89}, V. M. Bedakihale⁹⁰, F. Beirnaert⁹¹ , M. Beijger⁹² , D. Belardinelli¹⁷ , A. S. Bell²⁶ , V. Benedetto⁹³, W. Benoit⁹⁴ , J. D. Bentley⁸³ , M. Ben Yaala⁹⁵, S. Bera⁹⁶ , M. Berbel⁹⁷ , F. Bergamin^{40,41} , B. K. Berger¹⁵ , S. Bernuzzi²⁴ , M. Beroiz² , D. Bersanetti⁵⁴ , A. Bertolini³³, J. Betzwieser⁶² , D. Beveridge²⁷ , N. Bevin⁵³ , R. Bhandare⁹⁸, U. Bhardwaj^{33,99} , R. Bhatt², D. Bhattacharjee^{73,100} , S. Bhaumik⁴³ , S. Bhowmick¹⁰¹, A. Bianchi^{33,102}, I. A. Bilenko¹⁰³, G. Billingsley² , A. Binetti¹⁰⁴ , S. Bini^{105,106} , O. Birnholtz⁶⁸ , S. Biscoveanu⁷⁸ , A. Bisht⁴¹, M. Bitossi^{56,85} , M.-A. Bizouard⁴⁷ , J. K. Blackburn² , L. A. Blagg⁷⁶, C. D. Blair^{27,62}, D. G. Blair²⁷, F. Bobba^{67,107}, N. Bode^{40,41} , G. Boileau^{19,47} , M. Boldrini^{63,64} , G. N. Bolingbroke¹⁰⁸ , A. Bolliand^{35,109}, L. D. Bonavena⁸⁸ , R. Bondarescu³⁸ , F. Bondu¹¹⁰ , E. Bonilla¹⁵ , M. S. Bonilla⁵² , A. Bonino¹¹¹, R. Bonnard²⁸ , P. Booker^{40,41}, A. Borchers^{40,41}, V. Boschi⁸⁵ , S. Bose¹¹², V. Bossilkov⁶², V. Boudart¹¹³ , A. Boudon¹¹⁴, A. Bozzi⁵⁶, C. Bradaschia⁸⁵, P. R. Brady⁸ , M. Braglia¹¹⁵ , A. Branch⁶², M. Branchesi^{42,116} , J. Brandt⁵⁷, I. Braun⁷³, M. Breschi²⁴ , T. Briant¹¹⁷, A. Brillet⁴⁷, M. Brinkmann^{40,41}, P. Brockill⁸, E. Brockmueller^{40,41} , A. F. Brooks², B. C. Brown⁴³, D. D. Brown¹⁰⁸, M. L. Brozzetti^{49,86} , S. Brunet², G. Bruno¹⁰, R. Bruntz¹¹⁸ , J. Bryant¹¹¹, F. Bucci⁶¹, J. Buchanan¹¹⁸, O. Bulashenko^{38,79} , T. Bulik¹¹⁹, H. J. Bulten³³, A. Buonanno^{1,120} , K. Burtnyk³, R. Buscicchio^{121,122} , D. Buskulic²⁸, C. Buy¹²³ , R. L. Byer¹⁵, G. S. Cabourn Davies¹²⁴ , G. Cabras^{44,45} , R. Cabrera¹⁰, V. Cáceres-Barbosa⁷, L. Cadonati⁵⁷ , G. Cagnoli¹²⁵ , C. Cahillane⁷⁷ , J. Calderón Bustillo¹²⁶, T. A. Callister¹²⁷, E. Calloni^{5,29}, J. B. Camp¹²⁸, M. Canepa^{54,55}, G. Caneva Santoro³⁹ , K. C. Cannon³⁷ , H. Cao¹⁰⁸, L. A. Capistran¹²⁹, E. Capocasa⁶⁹ , E. Capote⁷⁷ , G. Carapella^{67,107}, F. Carbognani⁵⁶, M. Carlassara^{40,41}, J. B. Carlin¹³⁰ , M. Carpinelli^{56,121,131} , G. Carrillo⁷⁶, J. J. Carter^{40,41} , G. Carullo¹³² , J. Casanueva Diaz⁵⁶, C. Casentini^{16,17,133} , S. Y. Castro-Lucas¹⁰¹, S. Caudill^{33,75,134} , M. Cavaglià¹⁰⁰ , R. Cavaliere⁵⁶ , G. Cella⁸⁵ , P. Cerdá-Durán^{135,136} , E. Cesarini¹⁷ , W. Chaibi⁴⁷, P. Chakraborty^{40,41} , S. Chalahadka Subrahmanya⁸³ , J. C. L. Chan¹³⁷ , M. Chan¹³⁸, K. Chandra⁷, R.-J. Chang¹³⁹, S. Chao^{140,141} , E. L. Charlton¹¹⁸, P. Charlton¹⁴² , E. Chassande-Mottin⁶⁹ , C. Chatterjee¹⁴³ , Debarati Chatterjee¹¹ , Deep Chatterjee³¹ , M. Chaturvedi⁹⁸, S. Chaty⁶⁹ , A. Chen¹², A. H.-Y. Chen¹⁴⁴, D. Chen¹⁴⁵ , H. Chen¹⁴⁰, H. Y. Chen¹⁴⁶ , J. Chen³¹ , K. H. Chen¹⁴¹, Y. Chen¹⁴⁰, Yanbei Chen¹⁴⁷, Yitian Chen¹⁴⁸ , H. P. Cheng¹⁴⁹, P. Chessa^{49,86} , H. T. Cheung⁸⁷, S. Y. Cheung¹⁵⁰, F. Chiadini^{107,151} , G. Chiarini⁸⁹, R. Chierici¹¹⁴, A. Chincarini⁵⁴ , M. L. Chiofalo^{84,85} , A. Chiummo^{5,56} , C. Chou¹⁴⁴, S. Choudhary²⁷ , N. Christensen⁴⁷ , S. S. Y. Chua³⁰ , P. Chugh¹⁵⁰, G. Ciani^{88,89} , P. Cieciela⁹² , M. Cieřlar¹¹⁹ , M. Cifaldi¹⁷ , R. Ciolfi^{89,152} , F. Clara³, J. A. Clark^{2,57} , T. A. Clarke¹⁵⁰ , P. Clearwater¹⁵³, S. Clesse⁷², E. Coccia^{39,42,116}, E. Codazzo⁴² , P.-F. Cohadon¹¹⁷ , S. Colace⁵⁵ , M. Colleoni⁹⁶ , C. G. Collette³⁴, J. Collins⁶², S. Colloms²⁶, A. Colombo^{121,122,154} , M. Colpi^{121,122} , C. M. Compton³, G. Connolly⁷⁶, L. Conti⁸⁹ , T. R. Corbitt⁹ , I. Cordero-Carrión¹⁵⁵ , S. Corezzi^{49,86} , N. J. Cornish¹⁵⁶ , A. Corsi¹⁵⁷ , S. Cortese⁵⁶ , C. A. Costa¹⁴, R. Cottingham⁶², M. W. Coughlin⁹⁴ , A. Couineaux⁶³, J.-P. Coulon⁴⁷, S. T. Countryman¹⁵⁸ , J.-F. Coupechoux¹¹⁴, P. Couvares^{2,57} , D. M. Coward²⁷, M. J. Cowart⁶², R. Coyne¹⁵⁹ , K. Craig⁹⁵, R. Creed¹⁸, J. D. E. Creighton⁸ , T. D. Creighton¹⁶⁰, P. Cremonese⁹⁶ , A. W. Criswell⁹⁴ , J. C. G. Crockett-Gray⁹, S. Crook⁶², R. Crouch³, J. Csizmazia³, J. R. Cudell¹¹³ , T. J. Cullen² , A. Cumming²⁶ , E. Cuoco^{56,85} , M. Cusinato¹³⁵ , P. Dabadie¹²⁵, T. Dal Canton³⁶ , S. Dall'Osso⁶³ , S. Dal Pra⁶³ , G. Dálya¹²³ , B. D'Angelo⁵⁴ , S. Danilishin^{32,33} , S. D'Antonio¹⁷ , K. Danzmann^{40,41,41}, K. E. Darroch¹¹⁸, L. P. Dartez³, A. Dasgupta⁹⁰, S. Datta¹⁶¹ , V. Dattilo⁵⁶, A. Daumas⁶⁹, N. Davari^{131,162}, I. Dave⁹⁸, A. Davenport¹⁰¹, M. Davies³⁶, T. F. Davies²⁷, D. Davis² , L. Davis²⁷, M. C. Davis⁹⁴ , P. J. Davis^{163,164} , M. Dax¹ , J. De Bolle⁹¹ , M. Deenadayalan¹¹, J. Degallaix¹⁶⁵ , M. De Laurentis^{5,29} , S. Deléglise¹¹⁷ , F. De Lillo¹⁰ , D. Dell'Aquila^{131,162} , W. Del Pozzo^{84,85} , F. De Marco^{63,64} , F. De Matteis^{16,17} , V. D'Emilio² , N. Demos³¹, T. Dent¹²⁶ , A. Depasse¹⁰ , N. DePergola⁵³

- R. De Pietri^{166,167}, R. De Rosa^{5,29}, C. De Rossi⁵⁶, R. DeSalvo¹⁶⁸, R. De Simone¹⁵¹, A. Dhani¹, R. Diab⁴³, M. C. Díaz¹⁶⁰, M. Di Cesare²⁹, G. Dideron¹⁶⁹, N. A. Didio⁷⁷, T. Dietrich¹, L. Di Fiore⁵, C. Di Fronzo³⁴, M. Di Giovanni^{63,64}, T. Di Girolamo^{5,29}, D. Diksha^{32,33}, A. Di Michele⁸⁶, J. Ding^{69,170}, S. Di Pace^{63,64}, I. Di Palma^{63,64}, F. Di Renzo¹¹⁴, Divyajyoti¹¹⁴, A. Dmitriev¹¹¹, Z. Doctor⁷⁸, E. Dohmen³, P. P. Doleva¹¹⁸, D. Dominguez¹⁷², L. D’Onofrio⁶³, F. Donovan³¹, K. L. Dooley¹⁸, T. Dooney⁷⁵, S. Doravari¹¹, O. Dorosh¹⁷³, M. Drago^{63,64}, J. C. Driggers³, J.-G. Ducoin^{69,174}, L. Dunn¹³⁰, U. Dupletsa⁴², D. D’Urso^{131,162}, H. Duval¹⁷⁵, P.-A. Duverne³⁶, S. E. Dwyer³, C. Eassa³, M. Ebersold²⁸, T. Eckhardt⁸³, G. Eddolls⁷⁷, B. Edelman⁷⁶, T. B. Edo², O. Edy¹²⁴, A. Effler⁶², J. Eichholz³⁰, H. Einsle⁴⁷, M. Eisenmann²¹, R. A. Eisenstein³¹, A. Ejlli¹⁸, R. M. Eleveld¹⁷⁶, M. Emma⁵⁸, K. Endo¹⁷⁷, A. J. Engl¹⁵, E. Enloe⁵⁷, L. Errico^{5,29}, R. C. Essick¹⁷⁸, H. Estellés¹, D. Estevez⁶⁵, T. Etzel², M. Evans³¹, T. Evstafyeva¹⁷⁹, B. E. Ewing⁷, J. M. Ezquiaga¹³⁷, F. Fabrizi^{60,61}, F. Faedi^{60,61}, V. Fafone^{16,17}, S. Fairhurst¹⁸, A. M. Farah¹²⁷, B. Farr⁷⁶, W. M. Farr^{180,181}, G. Favaro⁸⁸, M. Favata¹⁸², M. Fays¹¹³, M. Fazio⁹⁵, J. Feicht², M. M. Fejer¹⁵, R. Felicitati¹⁸³, E. Fenyvesi^{81,184}, D. L. Ferguson¹⁴⁶, S. Ferraiuolo^{63,64,185}, I. Ferrante^{84,85}, T. A. Ferreira⁹, F. Fidecaro^{84,85}, P. Figura⁹², A. Fiori^{84,85}, I. Fiori⁵⁶, M. Fishbach¹⁷⁸, R. P. Fisher¹¹⁸, R. Fittipaldi^{107,186}, V. Fiumara^{107,187}, R. Flaminio²⁸, S. M. Fleischer¹⁸⁸, L. S. Fleming¹⁸⁹, E. Floden⁹⁴, E. M. Foley⁹⁴, H. Fong¹³⁸, J. A. Font^{135,136}, B. Fornal¹⁹⁰, P. W. F. Forsyth³⁰, K. Franceschetti¹⁶⁶, N. Franchini⁶⁹, S. Frasca^{63,64}, F. Frasconi⁸⁵, A. Frattale Mascioli^{63,64}, Z. Frei¹⁹¹, A. Freise^{33,102}, O. Freitas^{135,192}, R. Frey⁷⁶, W. Frischhertz⁶², P. Fritschel³¹, V. V. Frolov⁶², G. G. Fronzé²³, M. Fuentes-García², S. Fujii¹⁹³, T. Fujimori¹⁹⁴, P. Fulda⁴³, M. Fyffe⁶², B. Gadre⁷⁵, J. R. Gair¹, S. Galaudage¹⁹⁵, V. Galdi¹⁶⁸, H. Gallagher¹⁹⁶, S. Gallardo¹⁹⁷, B. Gallego¹⁹⁷, R. Gamba²⁴, A. Gamboa¹, D. Ganapathy³¹, A. Ganguly¹¹, B. Garaventa^{54,55}, J. García-Bellido¹¹⁵, C. García Núñez¹⁸⁹, C. García-Quirós¹⁹⁸, J. W. Gardner³⁰, K. A. Gardner¹³⁸, J. Gargiulo⁵⁶, A. Garron⁹⁶, F. Garufi^{5,29}, C. Gasbarra^{16,17}, B. Gateley³, V. Gayathri⁸, G. Gemme⁵⁴, A. Gennai⁸⁵, V. Gennari¹²³, J. George⁹⁸, R. George¹⁴⁶, O. Gerberding⁸³, L. Gergely¹⁹⁹, S. Ghonge⁵⁷, Archisman Ghosh⁹¹, Sayantan Ghosh²⁰⁰, Shaon Ghosh¹⁸², Shrobona Ghosh^{40,41}, Suprovo Ghosh¹¹, Tathagata Ghosh¹¹, L. Giacoppo^{63,64}, J. A. Giaime^{9,62}, K. D. Giardina⁶², D. R. Gibson¹⁸⁹, D. T. Gibson¹⁷⁹, C. Gier⁹⁵, P. Giri^{84,85}, F. Gissi⁹³, S. Gkaitatzis^{84,85}, J. Glanzer⁹, F. Glotin³⁶, J. Godfrey⁷⁶, P. Godwin², N. L. Goebbels⁸³, E. Goetz¹³⁸, J. Golomb², S. Gomez Lopez^{63,64}, B. Goncharov⁴², Y. Gong²⁰¹, G. González⁹, P. Goodarzi²⁰², S. Goode¹⁵⁰, A. W. Goodwin-Jones²⁷, M. Gosselin⁵⁶, A. S. Göttel¹⁸, R. Gouaty²⁸, D. W. Gould³⁰, K. Govorkova³¹, S. Goyal¹, B. Grace³⁰, A. Grado^{5,203}, V. Graham²⁶, A. E. Granados⁹⁴, M. Granata¹⁶⁵, V. Granata⁶⁷, S. Gras³¹, P. Grassia², A. Gray⁹⁴, C. Gray³, R. Gray²⁶, G. Greco⁴⁹, A. C. Green^{33,102}, S. M. Green¹²⁴, S. R. Green²⁰⁴, A. M. Gretarsson⁶⁶, E. M. Gretarsson⁶⁶, D. Griffith², W. L. Griffiths¹⁸, H. L. Griggs⁵⁷, G. Grignani^{49,86}, A. Grimaldi^{105,106}, C. Grimaud²⁸, H. Grote¹⁸, D. Guerra¹³⁵, D. Guetta^{63,205}, G. M. Guidi^{60,61}, A. R. Guimaraes⁹, H. K. Gulati⁹⁰, F. Gulminelli^{163,164}, A. M. Gunny³¹, H. Guo¹⁹⁰, W. Guo²⁷, Y. Guo^{32,33}, Anchal Gupta², Anuradha Gupta²⁰⁶, Ish Gupta⁷, N. C. Gupta⁹⁰, P. Gupta^{33,75}, S. K. Gupta⁴³, T. Gupta¹⁵⁶, N. Gupte¹, J. Gurs⁸³, N. Gutierrez¹⁶⁵, F. Guzman¹²⁹, H.-Y. H¹⁴⁰, D. Haba¹⁷², M. Haberland¹, S. Haino²⁰⁷, E. D. Hall³¹, E. Z. Hamilton⁹⁶, G. Hammond²⁶, W.-B. Han²⁰⁸, M. Haney³³, J. Hanks³, C. Hanna⁷, M. D. Hannam¹⁸, O. A. Hannuksela²⁰⁹, A. G. Hanselman¹²⁷, H. Hansen³, J. Hanson⁶², R. Harada³⁷, A. R. Hardison²¹⁰, K. Haris^{33,75}, T. Harmark¹³², J. Harms^{42,116}, G. M. Harry²¹¹, I. W. Harry¹²⁴, J. Hart⁷³, B. Haskell⁹², C.-J. Haster²¹², J. S. Hathaway¹⁹⁶, K. Haughian²⁶, H. Hayakawa⁴⁸, K. Hayama²¹³, R. Hayes¹⁸, A. Heffernan⁹⁶, A. Heidmann¹¹⁷, M. C. Heintze⁶², J. Heinze¹¹¹, J. Heinzl³¹, H. Heitmann⁴⁷, F. Hellman²¹⁴, P. Hello³⁶, A. F. Helmling-Cornell⁷⁶, G. Hemming⁵⁶, O. Henderson-Sapir¹⁰⁸, M. Hendry²⁶, I. S. Heng²⁶, E. Hennes³³, C. Henshaw⁵⁷, T. Hertog¹⁰⁴, M. Heurs^{40,41}, A. L. Hewitt^{179,215}, J. Heyns³¹, S. Higginbotham¹⁸, S. Hild^{32,33}, S. Hill²⁶, Y. Himemoto²¹⁶, N. Hirata²¹, C. Hirose²¹⁷, W. C. G. Ho²¹⁸, S. Hoang³⁶, S. Hochheim^{40,41}, D. Hofman¹⁶⁵, N. A. Holland^{33,102}, K. Holley-Bockelmann¹⁴³, Z. J. Holmes¹⁰⁸, D. E. Holz¹²⁷, L. Honet⁷², C. Hong¹⁵, J. Hornung⁷⁶, S. Hoshino²¹⁷, J. Hough²⁶, S. Hourihane², E. J. Howell²⁷, C. G. Hoy¹²⁴, C. A. Hrishikesh¹⁶, H.-F. Hsieh¹⁴⁰, C. Hsiung²¹⁹, H. C. Hsu¹⁴¹, W.-F. Hsu¹⁰⁴, P. Hu¹⁴³, Q. Hu²⁶, H. Y. Huang¹⁴¹, Y.-J. Huang⁷, A. D. Huddart²²⁰, B. Hughey⁶⁶, D. C. Y. Hui²²¹, V. Hui²⁸, S. Husa⁹⁶, R. Huxford⁷, T. Huynh-Dinh⁶², L. Iampieri^{63,64}, G. A. Iandolo³², M. Ianni^{16,17}, A. Iess^{85,222}, H. Imafuku³⁷, K. Inayoshi²²³, Y. Inoue¹⁴¹, G. Iorio⁸⁸, M. H. Iqbal³⁰, J. Irwin²⁶, R. Ishikawa²²⁴, M. Isi^{180,181}, M. A. Ismail¹⁴¹, Y. Itoh^{194,225}, H. Iwanaga¹⁹⁴, M. Iwaya¹⁹³, B. R. Iyer²⁰, V. JaberianHamedan²⁷, C. Jacquet¹²³, P.-E. Jacquet¹¹⁷, S. J. Jadhav²²⁶, S. P. Jadhav¹⁵³, T. Jain¹⁷⁹, A. L. James², P. A. James¹¹⁸, R. Jamshidi³⁴, J. Janquart^{33,75}, K. Janssens^{19,47}, N. N. Janthaler²²⁶, S. Jaraba¹¹⁵, P. Jaranowski²²⁷, R. Jaime⁹⁶, W. Javed¹⁸, A. Jennings³, W. Jia³¹, J. Jiang⁴³, J. Kubisz²²⁸, C. Johanson¹³⁴, G. R. Johns¹¹⁸, N. A. Johnson⁴³, M. C. Johnston²¹², R. Johnston²⁶, N. Johny^{40,41}, D. H. Jones³⁰, D. I. Jones²²⁹, R. Jones²⁶, S. Jose¹⁷¹, P. Joshi⁷, L. Ju²⁷, K. Jung²³⁰, J. Junker³⁰, V. Juste⁷², T. Kajita²³¹, I. Kaku¹⁹⁴, C. Kalaghatgi^{33,75,232}, V. Kalogera⁷⁸, M. Kamiizumi⁴⁸, N. Kanda^{194,225}, S. Kandhasamy¹¹, G. Kang²³³, J. B. Kanner², S. J. Kapadia¹¹, D. P. Kapasi³⁰, S. Karat², C. Karathanasis³⁹, R. Kashyap⁷, M. Kasprzak², W. Kastaun^{40,41}, T. Kato¹⁹³, E. Katsavounidis³¹, W. Katzman⁶², R. Kaushik⁹⁸, K. Kawabe³, R. Kawamoto¹⁹⁴, A. Kazemi⁹⁴, D. Keitel⁹⁶, J. Kelley-Derzon⁴³, J. Kennington⁷, R. Kesharwani¹¹, J. S. Key²³⁴, R. Khadela^{40,41}, S. Khadka¹⁵, F. Y. Khalili¹⁰³, F. Khan^{40,41}, I. Khan^{35,235}, T. Khanam¹⁵⁷, M. Khursheed⁹⁸, N. M. Khusid^{180,181}, W. Kiendrebeogo^{47,236}, N. Kijbunchoo¹⁰⁸, C. Kim²³⁷, J. C. Kim²³⁸, K. Kim²³⁹, M. H. Kim²⁴⁰, S. Kim²²¹, Y.-M. Kim²³⁹, C. Kimball⁷⁸, M. Kinley-Hanlon²⁶, M. Kinnear¹⁸, J. S. Kissel³,

- S. Klimentko⁴³, A. M. Knee¹³⁸, N. Knust^{40,41}, K. Kobayashi¹⁹³, P. Koch^{40,41}, S. M. Koehlenbeck¹⁵, G. Koekoek^{32,33}, K. Kohri^{241,242}, K. Kokeyama¹⁸, S. Koley⁴², P. Kolitsidou¹¹¹, M. Kolstein³⁹, K. Komori³⁷, A. K. H. Kong¹⁴⁰, A. Kontos²⁴³, M. Korobko⁸³, R. V. Kossak^{40,41}, X. Kou⁹⁴, A. Koushik¹⁹, N. Kouvatsos⁷⁰, M. Kovalam²⁷, D. B. Kozak², S. L. Kranzhoft^{32,33}, V. Kringel^{40,41}, N. V. Krishnendu²⁰, A. Królak^{173,244}, K. Kruska^{40,41}, G. Kuehn^{40,41}, P. Kuijter³³, S. Kulkarni²⁰⁶, A. Kulur Ramamohan³⁰, A. Kumar²²⁶, Praveen Kumar¹²⁶, Prayush Kumar²⁰, Rahul Kumar³, Rakesh Kumar⁹⁰, J. Kume^{37,88,89}, K. Kuns³¹, N. Kuntimaddi¹⁸, S. Kuroyanagi^{115,245}, N. J. Kurth⁹, S. Kuwahara³⁷, K. Kwak²³⁰, K. Kwan³⁰, J. Kwok¹⁷⁹, G. Lacaille²⁶, P. Lagabbe²⁸, D. Laghi¹²³, S. Lai¹⁴⁴, A. H. Laity¹⁵⁹, M. H. Lakkis³⁴, E. Lalande²⁴⁶, M. Lalleman¹⁹, P. C. Lalremruati²⁴⁷, M. Landry³, B. B. Lane³¹, R. N. Lang³¹, J. Lange¹⁴⁶, B. Lantz¹⁵, A. La Rana⁶³, I. L. Rosa⁹⁶, A. Lartaux-Vollard³⁶, P. D. Lasky¹⁵⁰, J. Lawrence¹⁵⁷, M. N. Lawrence⁹, M. Laxen⁶², A. Lazzarini², C. Lazzaro^{88,89}, P. Leaci^{63,64}, Y. K. Lecoeuche¹³⁸, H. M. Lee²³⁸, H. W. Lee²⁴⁸, K. Lee²⁴⁰, R.-K. Lee¹⁴⁰, R. Lee³¹, S. Lee²³⁹, Y. Lee¹⁴¹, I. N. Legred², J. Lehmann^{40,41}, L. Lehner¹⁶⁹, M. Le Jean¹⁶⁵, A. Lemaître²⁴⁹, M. Lenti^{61,250}, M. Leonardi^{21,105,106}, M. Lequime⁵⁵, N. Leroy³⁶, M. Lesovsky², N. Letendre²⁸, M. Lethuillier¹¹⁴, S. E. Levin²⁰², Y. Levin¹⁵⁰, K. Leyde⁶⁹, A. K. Y. Li², K. L. Li¹³⁹, T. G. F. Li^{104,209}, X. Li¹⁴⁷, Z. Li²⁶, A. Lihos¹¹⁸, C.-Y. Lin²⁵¹, C.-Y. Lin¹⁴¹, E. T. Lin¹⁴⁰, F. Lin¹⁴¹, H. Lin¹⁴¹, L. C.-C. Lin¹³⁹, Y.-C. Lin¹⁴⁰, F. Linde^{33,232}, S. D. Linker¹⁹⁷, T. B. Littenberg²⁵², A. Liu²⁰⁹, G. C. Liu²¹⁹, Jian Liu²⁷, F. Llamas Villarreal¹⁶⁰, J. Llobera-Querol⁹⁶, R. K. L. Lo¹³⁷, J.-P. Locquet¹⁰⁴, L. T. London^{31,70,99}, A. Longo^{60,61}, D. Lopez¹¹³, M. Lopez Portilla⁷⁵, M. Lorenzini^{16,17}, A. Lorenzo-Medina¹²⁶, V. Lorette³⁶, M. Lormand⁶², G. Losurdo⁸⁵, T. P. Lott IV⁵⁷, J. D. Lough^{40,41}, H. A. Loughlin³¹, C. O. Lousto¹⁹⁶, M. J. Lowry¹¹⁸, N. Lu³⁰, H. Lück^{40,41,41}, D. Lumaca¹⁷, A. P. Lundgren¹²⁴, A. W. Lussier²⁴⁶, L.-T. Ma¹⁴⁰, S. Ma¹⁶⁹, M. Ma'arif¹⁴¹, R. Macas¹²⁴, A. Macedo⁵², M. MacInnis³¹, R. R. Macy^{40,41}, D. M. Macleod¹⁸, I. A. O. MacMillan², A. Macquet³⁶, D. Macri³¹, K. Maeda¹⁷⁷, S. Maenaut¹⁰⁴, I. Magaña Hernandez⁸, S. S. Magare¹¹, C. Magazzù⁸⁵, R. M. Magee², E. Maggio¹, R. Maggiore^{33,102}, M. Magnozzi^{54,55}, M. Mahesh⁸³, S. Mahesh²⁵³, M. Maini¹⁵⁹, S. Majhi¹¹, E. Majorana^{63,64}, C. N. Makarem², E. Makelele⁷³, J. A. Malaquias-Reis¹⁴, U. Mali¹⁷⁸, S. Maliakal², A. Malik⁹⁸, N. Man⁴⁷, V. Mandic⁹⁴, V. Mangano^{63,64}, B. Mannix⁷⁶, G. L. Mansell^{31,77}, G. Mansingh²¹¹, M. Manske⁸, M. Mantovani⁵⁶, M. Mapelli^{88,89,254}, F. Marchesoni^{49,50,255}, D. Marín Pina^{38,79,256}, F. Marion²⁸, S. Márka¹⁵⁸, Z. Márka¹⁵⁸, A. S. Markosyan¹⁵, A. Markowitz², E. Maros², S. Marsat¹²³, F. Martelli^{60,61}, I. W. Martin²⁶, R. M. Martin¹⁸², B. B. Martinez¹²⁹, M. Martinez^{39,257}, V. Martinez¹²⁵, A. Martini^{105,106}, K. Martinovic⁷⁰, J. C. Martins¹⁴, D. V. Martynov¹¹¹, E. J. Marx³¹, L. Massaro^{32,33}, A. Masserot²⁸, M. Masso-Reid²⁶, M. Mastrodicasa^{63,64}, S. Mastrogianni⁶³, T. Matcovich⁴⁹, M. Matiushechkin^{40,41}, M. Matsuyama¹⁹⁴, N. Mavalvala³¹, N. Maxwell³, G. McCarroll⁶², R. McCarthy³, S. McCormick⁶², L. McCuller², S. McEachin¹¹⁸, C. McElhenny¹¹⁸, G. I. McGhee²⁶, J. McGinn²⁶, K. B. M. McGowan¹⁴³, J. McIver¹³⁸, A. McLeod²⁷, T. McRae³⁰, D. Meacher⁸, Q. Meijer⁷⁵, A. Melatos¹³⁰, S. Mellaerts¹⁰⁴, A. Menendez-Vazquez³⁹, C. S. Menoni¹⁰¹, F. Mera³, R. A. Mercer⁸, L. Mereni¹⁶⁵, K. Merfeld¹⁵⁷, E. L. Merilh⁶², J. R. Mérou⁹⁶, J. D. Merritt⁷⁶, M. Merzougui⁴⁷, C. Messenger²⁶, C. Messick⁸, M. Meyer-Conde¹⁹⁴, F. Meylahn^{40,41}, A. Mhaske¹¹, A. Miani^{105,106}, H. Miao²⁵⁸, I. Michaloliakos⁴³, C. Michel¹⁶⁵, Y. Michimura^{2,37}, H. Middleton¹¹¹, A. L. Miller³³, S. Miller², M. Millhouse⁵⁷, E. Milotti^{45,183}, V. Milotti⁸⁸, Y. Minenkov¹⁷, N. Mio³⁷, LL. M. Mir³⁹, L. Mirasola^{63,259}, M. Miravet-Tenés¹³⁵, C.-A. Miritescu³⁹, A. K. Mishra²⁰, A. Mishra¹¹, C. Mishra¹⁷¹, T. Mishra⁴³, A. L. Mitchell^{33,102}, J. G. Mitchell⁶⁶, S. Mitra¹¹, V. P. Mitrofanov¹⁰³, R. Mittleman³¹, O. Miyakawa⁴⁸, S. Miyamoto¹⁹³, S. Miyoki⁴⁸, G. Mo³¹, L. Mobilia^{60,61}, S. R. P. Mohapatra², S. R. Mohite⁷, M. Molina-Ruiz²¹⁴, C. Mondal¹⁶³, M. Mondin¹⁹⁷, M. Montani^{60,61}, C. J. Moore¹⁷⁹, D. Moraru³, A. More¹¹, S. More¹¹, G. Moreno³, C. Morgan¹⁸, S. Morisaki^{37,193}, Y. Moriwaki¹⁷⁷, G. Morras¹¹⁵, A. Moscatello⁸⁸, P. Mourier⁹⁶, B. Mours⁶⁵, C. M. Mow-Lowry^{33,102}, F. Muciaccia^{63,64}, Arunava Mukherjee²⁶⁰, D. Mukherjee²⁵², Samanwaya Mukherjee¹¹, Soma Mukherjee¹⁶⁰, Subroto Mukherjee⁹⁰, Suvodip Mukherjee^{99,169,261}, N. Mukund³¹, A. Mullavey⁶², J. Munch¹⁰⁸, J. Mundi²¹¹, C. L. Mungoli²⁷, W. R. Munn Oberg²⁶², Y. Murakami¹⁹³, M. Murakoshi²²⁴, P. G. Murray²⁶, S. Muusse³⁰, D. Nabari^{105,106}, S. L. Nadjai^{40,41}, A. Nagar^{23,263}, N. Nagarajan²⁶, K. N. Nagler⁶⁶, K. Nakagaki⁴⁸, K. Nakamura²¹, H. Nakano²⁶⁴, M. Nakano², D. Nandi⁹, V. Napolano⁵⁶, P. Narayan²⁰⁶, I. Nardecchia¹⁷, H. Narola⁷⁵, L. Naticchioni⁶³, R. K. Nayak²⁴⁷, J. Neilson^{93,107}, A. Nelson¹²⁹, T. J. N. Nelson⁶², M. Nery^{40,41}, A. Neunzert³, S. Ng⁵², L. Nguyen Quynh²⁶⁵, S. A. Nichols⁹, A. B. Nielsen²⁶⁶, G. Nieradka⁹², A. Niko¹⁴¹, Y. Nishino^{21,37}, A. Nishizawa²⁶⁷, S. Nissanke^{33,99}, E. Nitoglia¹¹⁴, W. Niu⁷, F. Nocera⁵⁶, M. Norman¹⁸, C. North¹⁸, J. Novak^{109,268,269,270}, J. F. Nuño Siles¹¹⁵, L. K. Nuttall¹²⁴, K. Obayashi²²⁴, J. Oberling³, J. O'Dell²²⁰, M. Oertel^{109,268,269,270,271}, A. Offermans¹⁰⁴, G. Oganessian^{42,116}, J. J. Oh²⁷², K. Oh²²¹, T. O'Hanlon⁶², M. Ohashi⁴⁸, M. Ohkawa²¹⁷, F. Ohme^{40,41}, A. S. Oliveira¹⁵⁸, R. Oliveri^{109,268,269}, B. O'Neal¹¹⁸, K. Oohara^{273,274}, B. O'Reilly⁶², N. D. Ormsby¹¹⁸, M. Orselli^{49,86}, R. O'Shaughnessy¹⁹⁶, S. O'Shea²⁶, Y. Oshima³⁷, S. Oshino⁴⁸, S. Ossokine¹, C. Osthelder², I. Ota⁹, D. J. Ottaway¹⁰⁸, A. Ouzriat¹¹⁴, H. Overmire⁶², B. J. Owen¹⁵⁷, A. E. Pace⁷, R. Pagano⁹, M. A. Page²¹, A. Pai²⁰⁰, A. Pal²⁷⁵, S. Pal²⁴⁷, M. A. Palaia^{84,85}, M. Pálfi¹⁹¹, P. P. Palma^{16,17,64}, C. Palomba⁶³, P. Palud⁶⁹, H. Pan¹⁴⁰, J. Pan²⁷, K. C. Pan¹⁴⁰, R. Panai^{88,259}, P. K. Panda²²⁶, S. Pandey⁷, L. Panebianco^{60,61}, P. T. H. Pang^{33,75}, F. Pannarale^{63,64}, K. A. Pannone⁵², B. C. Pant⁹⁸, F. H. Panther²⁷, F. Paoletti⁸⁵, A. Paolone^{63,276}, E. E. Papalexakis²⁰², L. Papalini^{84,85}, G. Papigkiotis²⁷⁷, A. Paquis³⁶, A. Parisi^{49,86}, B.-J. Park²³⁹, J. Park²⁷⁸, W. Parker⁶², G. Pascale^{40,41}, D. Pascucci⁹¹, A. Pasqualetti⁵⁶, R. Passaquieti^{84,85}, L. Passenger¹⁵⁰, D. Passuello⁸⁵, O. Patane³, D. Pathak¹¹, M. Pathak¹⁰⁸, A. Patra¹⁸, B. Patricelli^{84,85}

- A. S. Patron⁹, K. Paul¹⁷¹, S. Paul⁷⁶, E. Payne², T. Pearce¹⁸, M. Pedraza², R. Pegna⁸⁵, A. Pele², F. E. Peña Arellano⁴⁶, S. Penn²⁶², M. D. Penuliar⁵², A. Perego^{105,106}, Z. Pereira¹³⁴, J. J. Perez⁴³, C. Péroigis^{88,89,152}, G. Perna⁸⁸, A. Perreca^{105,106}, J. Perret⁶⁹, S. Perriès¹¹⁴, J. W. Perry^{33,102}, D. Pesios²⁷⁷, S. Petracca¹⁶⁸, C. Petrillo⁸⁶, H. P. Pfeiffer¹, H. Pham⁶², K. A. Pham⁹⁴, K. S. Phukon^{33,111,232}, H. Phurailatpam²⁰⁹, M. Piarulli¹²³, L. Piccari^{63,64}, O. J. Piccinni³⁹, M. Pichot⁴⁷, M. Piendibene^{84,85}, F. Piergiovanni^{60,61}, L. Pierini⁶³, G. Pierra¹¹⁴, V. Pierro^{93,107}, M. Pietrzak⁹², M. Pillas⁴⁷, F. Pilo⁸⁵, L. Pinard¹⁶⁵, I. M. Pinto^{29,93,107,279}, M. Pinto⁵⁶, B. J. Piotrkowski⁸, M. Pirello³, M. D. Pitkin^{179,215}, A. Placidi⁶¹, E. Placidi^{63,64}, M. L. Planas⁹⁶, W. Plastino^{17,280}, R. Poggiani^{84,85}, E. Polini²⁸, L. Pompili¹, J. Poon²⁰⁹, E. Porcelli³³, E. K. Porter⁶⁹, C. Posnansky⁷, R. Poulton⁵⁶, J. Powell¹⁵³, M. Pracchia¹¹³, B. K. Pradhan¹¹, T. Pradier⁶⁵, A. K. Prajapati⁹⁰, K. Prasai¹⁵, R. Prasanna²²⁶, P. Prasia¹¹, G. Pratten¹¹¹, G. Principe^{45,183}, M. Principe^{93,107,168,279}, G. A. Prodi^{105,106}, L. Prokhorov¹¹¹, P. Proposito^{16,17}, A. Puecher^{33,75}, J. Pullin⁹, M. Punturo⁴⁹, P. Puppo⁶³, M. Pürer¹⁵⁹, H. Qi¹², J. Qin³⁰, G. Quémener^{109,164}, V. Quetschke¹⁶⁰, C. Quigley¹⁸, P. J. Quinonez⁶⁶, R. Quitzow-James¹⁰⁰, F. J. Raab³, S. S. Raabith⁹, G. Raaijmakers^{33,99}, S. Raja⁹⁸, C. Rajan⁹⁸, B. Rajbhandari¹⁹⁶, K. E. Ramirez⁶², F. A. Ramis Vidal⁹⁶, A. Ramos-Buades³³, D. Rana¹¹, S. Ranjan⁵⁷, K. Ransom⁶², P. Rapagnani^{63,64}, B. Ratto⁶⁶, S. Rawat⁹⁴, A. Ray⁸, V. Raymond¹⁸, M. Razzano^{84,85}, J. Read⁵², M. Recaman Payo¹⁰⁴, T. Regimbau²⁸, L. Rei⁵⁴, S. Reid⁹⁵, D. H. Reitze², P. Relton¹⁸, A. I. Renzini², P. Rettegno²³, B. Revenu^{69,281}, R. Reyes¹⁹⁷, A. S. Rezaei^{63,64}, F. Ricci^{63,64}, M. Ricci^{63,64}, A. Ricciardone^{84,85}, J. W. Richardson²⁰², M. Richardson¹⁰⁸, A. Rijal⁶⁶, K. Riles⁸⁷, H. K. Riley¹⁸, S. Rinaldi^{88,254}, J. Rittmeyer⁸³, C. Robertson²²⁰, F. Robinet³⁶, M. Robinson³, A. Rocchi¹⁷, L. Rolland²⁸, J. G. Rollins², A. E. Romano²⁸², R. Romano^{4,5}, A. Romero¹⁷⁵, I. M. Romero-Shaw¹⁷⁹, J. H. Romie⁶², S. Ronchini^{42,116}, T. J. Rooke¹⁰⁸, L. Rosa^{5,29}, T. J. Rosauer²⁰², C. A. Rose⁸, D. Rosińska¹¹⁹, M. P. Ross⁵¹, M. Rossello⁹⁶, S. Rowan²⁶, S. K. Roy^{180,181}, S. Roy⁷⁵, D. Rozza^{121,122}, P. Ruggi⁵⁶, N. Ruhama²³⁰, E. Ruiz Morales^{115,283}, K. Ruiz-Rocha¹⁴³, S. Sachdev⁵⁷, T. Sadecki³, J. Sadiq¹²⁶, P. Saffarieh^{33,102}, M. R. Sah²⁶¹, S. S. Saha¹⁴⁰, S. Saha¹⁴⁰, T. Sainrat⁶⁵, S. Sajith Menon^{63,64,205}, K. Sakai²⁸⁴, M. Sakellariadou⁷⁰, S. Sakon⁷, O. S. Salafia^{121,122,154}, F. Salces-Carcoba², L. Salconi⁵⁶, M. Saleem⁹⁴, F. Salemi^{63,64}, M. Sallé³³, S. Salvador^{109,163,164}, A. Sanchez³, E. J. Sanchez², J. H. Sanchez⁷⁸, L. E. Sanchez², N. Sanchis-Gual¹³⁵, J. R. Sanders²¹⁰, E. M. Säger¹, F. Santoliquido⁴², T. R. Saravanan¹¹, N. Sarin¹⁵⁰, S. Sasaoka¹⁷², A. Sasli²⁷⁷, P. Sassi^{49,86}, B. Sassolas¹⁶⁵, H. Satari^{18,27}, R. Sato²¹⁷, Y. Sato¹⁷⁷, O. Sauter⁴³, R. L. Savage³, T. Sawada⁴⁸, H. L. Sawant¹¹, S. Sayah²⁸, V. Scacco^{16,17}, D. Schaetzl², M. Scheel¹⁴⁷, A. Schiebelbein¹⁷⁸, M. G. Schiowski¹⁰⁸, P. Schmidt¹¹¹, S. Schmidt⁷⁵, R. Schnabel⁸³, M. Schneewind^{40,41}, R. M. S. Schofield⁷⁶, K. Schouteden¹⁰⁴, B. W. Schulte^{40,41}, B. F. Schutz^{18,40,41}, E. Schwartz¹⁸, M. Scialpi²⁸⁵, J. Scott²⁶, S. M. Scott³⁰, T. C. Seetharamu²⁶, M. Seglar-Arroyo³⁹, Y. Sekiguchi²⁸⁶, D. Sellers⁶², A. S. Sengupta²⁸⁷, D. Sentenac⁵⁶, E. G. Seo²⁶, J. W. Seo¹⁰⁴, V. Sequino^{5,29}, M. Serra⁶³, G. Servignat²⁶⁸, A. Sevrin¹⁷⁵, T. Shaffer³, U. S. Shah⁵⁷, M. A. Shaikh²³⁸, L. Shao²²³, A. K. Sharma²⁰, P. Sharma⁹⁸, S. Sharma-Chaudhary¹⁰⁰, M. R. Shaw¹⁸, P. Shawhan¹²⁰, N. S. Shcheblanov^{249,288}, E. Sheridan¹⁴³, Y. Shikano^{289,290}, M. Shikauchi³⁷, K. Shimode⁴⁸, H. Shinkai²⁹¹, J. Shiota²²⁴, D. H. Shoemaker³¹, D. M. Shoemaker¹⁴⁶, R. W. Short³, S. ShyamSundar⁹⁸, A. Sider³⁴, H. Siegel^{180,181}, M. Sieniawska¹⁰, D. Sigg³, L. Silenzi^{49,50}, M. Simmonds¹⁰⁸, L. P. Singer¹²⁸, A. Singh²⁰⁶, D. Singh⁷, M. K. Singh²⁰, S. Singh^{21,59}, A. Singha^{32,33}, A. M. Sintes⁹⁶, V. Sipala^{131,162}, V. Skliris¹⁸, B. J. J. Slagmolen³⁰, T. J. Slaven-Blair²⁷, J. Smetana¹¹¹, J. R. Smith⁵², L. Smith²⁶, R. J. E. Smith¹⁵⁰, W. J. Smith¹⁴³, J. Soldateschi^{61,250,292}, K. Somiya¹⁷², I. Song¹⁴⁰, K. Soni¹¹, S. Soni³¹, V. Sordini¹¹⁴, F. Sorrentino⁵⁴, N. Sorrentino^{84,85}, H. Sotani²⁹³, R. Souldard⁴⁷, A. Southgate¹⁸, V. Spagnuolo^{32,33}, A. P. Spencer²⁶, M. Spera^{45,294}, P. Spinicelli⁵⁶, J. B. Spoon⁹, C. A. Sprague²⁶⁵, A. K. Srivastava⁹⁰, F. Stachurski²⁶, D. A. Steer⁶⁹, J. Steinlechner^{32,33}, S. Steinlechner^{32,33}, N. Stergioulas²⁷⁷, P. Stevens³⁶, M. StPierre¹⁵⁹, G. Stratta^{63,133,295,296}, M. D. Strong⁹, A. Strunk³, R. Sturani²⁹⁷, A. L. Stuver⁵³, M. Suchenek⁹², S. Sudhagar⁹², N. Suelmann⁸³, L. Suleiman⁵², K. D. Sullivan⁹, L. Sun³⁰, S. Sunil⁹⁰, J. Suresh¹⁰, P. J. Sutton¹⁸, T. Suzuki²¹⁷, Y. Suzuki²²⁴, B. L. Swinkels³³, A. Syx⁶⁵, M. J. Szczepańczyk^{43,298}, P. Szweczyk¹¹⁹, M. Tacca³³, H. Tagoshi¹⁹³, S. C. Tait², H. Takahashi²⁹⁹, R. Takahashi²¹, A. Takamori³⁷, T. Takase⁴⁸, K. Takatani¹⁹⁴, H. Takeda³⁰⁰, K. Takeshita¹⁷², C. Talbot¹²⁷, M. Tamaki¹⁹³, N. Tamanini¹²³, D. Tanabe¹⁴¹, K. Tanaka⁴⁸, S. J. Tanaka²²⁴, T. Tanaka³⁰⁰, D. Tang²⁷, S. Tanioka⁷⁷, D. B. Tanner⁴³, L. Tao⁴³, R. D. Tapia⁷, E. N. Tapia San Martín³³, R. Tarafder², C. Taranto^{16,17,64}, A. Taruya³⁰¹, J. D. Tasson¹⁷⁶, M. Teloi³⁴, R. Tenorio⁹⁶, H. Themann¹⁹⁷, A. Theodoropoulos¹³⁵, M. P. Thirugnanasambandam¹¹, L. M. Thomas², M. Thomas⁶², P. Thomas³, J. E. Thompson¹⁴⁷, S. R. Thondapu⁹⁸, K. A. Thorne⁶², E. Thrane¹⁵⁰, J. Tissino⁴², A. Tiwari¹¹, P. Tiwari⁴², S. Tiwari¹⁹⁸, V. Tiwari¹¹¹, M. R. Todd⁷⁷, A. M. Toivonen⁹⁴, K. Toland²⁶, A. E. Tolley¹²⁴, T. Tomaru²¹, K. Tomita¹⁹⁴, T. Tomura⁴⁸, C. Tong-Yu¹⁴¹, A. Toriyama²²⁴, N. Toropov¹¹¹, A. Torres-Forne^{135,136}, C. I. Torrie², M. Toscani¹²³, I. Tosta e Melo³⁰², E. Tournefier²⁸, A. Trapananti^{49,50}, F. Travasso^{49,50}, G. Traylor⁶², M. Trevor¹²⁰, M. C. Tringali⁵⁶, A. Tripathi⁸⁷, G. Troian¹⁸³, L. Troiano^{107,303}, A. Trovato^{45,183}, L. Trozzo⁵, R. J. Trudeau², T. T. L. Tsang¹⁸, R. Tso^{147,309}, S. Tsuchida³⁰⁴, L. Tsukada⁷, T. Tsutsui³⁷, K. Turbang^{19,175}, M. Turconi⁴⁷, C. Turski⁹¹, H. Ubach^{38,79}, T. Uchiyama⁴⁸, R. P. Udall², T. Uehara³⁰⁵, M. Uematsu¹⁹⁴, K. Ueno³⁷, S. Ueno²²⁴, V. Undheim²⁶⁶, T. Ushiba⁴⁸, M. Vacatello^{84,85}, H. Vahlbruch^{40,41}, N. Vaidya², G. Vajente², A. Vajpeyi¹⁵⁰, G. Valdes¹²⁹, J. Valencia⁹⁶, M. Valentini^{33,102,206}, S. A. Vallejo-Peña²⁸², S. Vallero²³, V. Valsan⁸, N. van Bakel³³, M. van Beuzekom³³, M. van Dael^{33,306}, J. F. J. van den Brand^{32,33,102}, C. Van Den Broeck^{33,75}, D. C. Vander-Hyde⁷⁷, M. van der Sluys^{33,75}

A. Van de Walle³⁶, J. van Dongen^{33,102}, K. Vandra⁵³, H. van Haevermaet¹⁹, J. V. van Heijningen^{33,102}, P. Van Hove⁶⁵, M. VanKeuren⁷³, J. Vanosky², M. H. P. M. van Putten¹³, Z. van Ranst^{32,33}, N. van Remortel¹⁹, M. Vardaro^{32,33}, A. F. Vargas¹³⁰, J. J. Varghese⁶⁶, V. Varma¹³⁴, M. Vasúth^{81,310}, A. Vecchio¹¹¹, G. Vedovato⁸⁹, J. Veitch²⁶, P. J. Veitch¹⁰⁸, S. Venikoudis¹⁰, J. Venneberg^{40,41}, P. Verrier¹¹⁴, D. Verkindt²⁸, B. Verma¹³⁴, P. Verma¹⁷³, Y. Verma⁹⁸, S. M. Vermeulen², F. Vetrano⁶⁰, A. Vetro^{63,64}, A. M. Vibhute³, A. Viceré^{60,61}, S. Vidyant⁷⁷, A. D. Viets⁸², A. Vijaykumar¹⁷⁸, A. Vilka¹⁹⁶, V. Villa-Ortega¹²⁶, E. T. Vincent⁵⁷, J.-Y. Vinet⁴⁷, S. Viret¹¹⁴, A. Virtuoso^{45,183}, S. Vitale³¹, A. Vives⁷⁶, H. Vocca^{49,86}, D. Voigt⁸³, E. R. G. von Reis³, J. S. A. von Wrangel^{40,41}, S. P. Vyatchanin¹⁰³, L. E. Wade⁷³, M. Wade⁷³, K. J. Wagner¹⁹⁶, A. Wajid^{54,55}, M. Walker¹¹⁸, G. S. Wallace⁹⁵, L. Wallace², H. Wang³⁷, J. Z. Wang⁸⁷, W. H. Wang¹⁶⁰, Z. Wang¹⁴¹, G. Waratkar²⁰⁰, J. Warner³, M. Was²⁸, T. Washimi²¹, N. Y. Washington², D. Watarai³⁷, K. E. Wayt⁷³, B. R. Weaver¹⁸, B. Weaver³, C. R. Weaving¹²⁴, S. A. Webster²⁶, M. Weinert^{40,41}, A. J. Weinstein², R. Weiss³¹, F. Wellmann^{40,41}, L. Wen²⁷, P. Weßels^{40,41}, K. Wette³⁰, J. T. Whelan¹⁹⁶, B. F. Whiting⁴³, C. Whittle², J. B. Wildberger¹, O. S. Wilk⁷³, D. Wilken^{40,41,41}, A. T. Wilkin²⁰², D. J. Willadsen⁸², K. Willetts¹⁸, D. Williams²⁶, M. J. Williams¹²⁴, N. S. Williams¹¹¹, J. L. Willis², B. Willke^{40,41,41}, M. Wils¹⁰⁴, J. Winterflood²⁷, C. C. Wipf², G. Woan²⁶, J. Woehler^{32,33}, J. K. Wofford¹⁹⁶, N. E. Wolfe³¹, H. T. Wong¹⁴¹, H. W. Y. Wong²⁰⁹, I. C. F. Wong²⁰⁹, J. L. Wright³⁰, M. Wright²⁶, C. Wu¹⁴⁰, D. S. Wu^{40,41}, H. Wu¹⁴⁰, E. Wuchner⁵², D. M. Wysocki⁸, V. A. Xu³¹, Y. Xu¹⁹⁸, N. Yadav⁹², H. Yamamoto², K. Yamamoto¹⁷⁷, T. S. Yamamoto²⁴⁵, T. Yamamoto⁴⁸, S. Yamamura¹⁹³, R. Yamazaki²²⁴, S. Yan¹⁵, T. Yan¹¹¹, F. W. Yang¹⁹⁰, F. Yang¹⁵⁸, K. Z. Yang⁹⁴, Y. Yang¹⁴⁴, Z. Yarbrough⁹, H. Yasui⁴⁸, S.-W. Yeh¹⁴⁰, A. B. Yelikar¹⁹⁶, X. Yin³¹, J. Yokoyama^{37,307}, T. Yokozawa⁴⁸, J. Yoo¹⁴⁸, H. Yu¹⁴⁷, S. Yuan²⁷, H. Yuzurihara⁴⁸, A. Zdrożny¹⁷³, M. Zanolin⁶⁶, M. Zeeshan¹⁹⁶, T. Zelenova⁵⁶, J.-P. Zendri⁸⁹, M. Zeoli^{10,113}, M. Zerrad³⁵, M. Zevin⁷⁸, A. C. Zhang¹⁵⁸, L. Zhang², R. Zhang⁴³, T. Zhang¹¹¹, Y. Zhang³⁰, C. Zhao²⁷, Yue Zhao¹⁹⁰, Yuhang Zhao⁶⁹, Y. Zheng¹⁰⁰, H. Zhong⁹⁴, R. Zhou²¹⁴, X.-J. Zhu³⁰⁸, Z.-H. Zhu^{201,308}, M. E. Zucker^{2,31}, J. Zweizig², and

The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration³¹¹

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 LIGO Hanford Observatory, Richland, WA 99352, USA

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

⁸ University of Wisconsin-Milwaukee, Milwaukee, WI 53201, USA

⁹ Louisiana State University, Baton Rouge, LA 70803, USA

¹⁰ Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium

¹¹ Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India

¹² Queen Mary University of London, London E1 4NS, UK

¹³ Department of Physics and Astronomy, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 143-747, Republic of Korea

¹⁴ Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil

¹⁵ Stanford University, Stanford, CA 94305, USA

¹⁶ Università di Roma Tor Vergata, I-00133 Roma, Italy

¹⁷ INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy

¹⁸ Cardiff University, Cardiff CF24 3AA, UK

¹⁹ Universiteit Antwerpen, 2000 Antwerpen, Belgium

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 INFN Sezione di Torino, I-10125 Torino, Italy

²⁴ Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany

²⁵ Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy

²⁶ SUPA, University of Glasgow, Glasgow G12 8QQ, UK

²⁷ OzGrav, University of Western Australia, Crawley, Western Australia 6009, Australia

²⁸ Univ. Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules—IN2P3, F-74000 Annecy, France

²⁹ Università di Napoli “Federico II,” I-80126 Napoli, Italy

³⁰ OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia

³¹ LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

³² Maastricht University, 6200 MD Maastricht, The Netherlands

³³ Nikhef, 1098 XG Amsterdam, The Netherlands

³⁴ Université Libre de Bruxelles, Brussels 1050, Belgium

³⁵ Aix Marseille Univ, CNRS, Centrale Med, Institut Fresnel, F-13013 Marseille, France

³⁶ Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

³⁷ University of Tokyo, 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 Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Germany

⁴¹ Leibniz Universität Hannover, D-30167 Hannover, Germany

⁴² Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy

⁴³ University of Florida, Gainesville, FL 32611, USA

⁴⁴ Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy

⁴⁵ INFN, Sezione di Trieste, I-34127 Trieste, Italy

⁴⁶ Tecnológico de Monterrey Campus Guadalajara, 45201 Zapopan, Jalisco, Mexico

- ⁴⁷ Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Artemis, F-06304 Nice, France
- ⁴⁸ Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan
- ⁴⁹ INFN, Sezione di Perugia, I-06123 Perugia, Italy
- ⁵⁰ Università di Camerino, I-62032 Camerino, Italy
- ⁵¹ University of Washington, Seattle, WA 98195, USA
- ⁵² California State University Fullerton, Fullerton, CA 92831, USA
- ⁵³ Villanova University, Villanova, PA 19085, USA
- ⁵⁴ INFN, Sezione di Genova, I-16146 Genova, Italy
- ⁵⁵ Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
- ⁵⁶ European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
- ⁵⁷ Georgia Institute of Technology, Atlanta, GA 30332, USA
- ⁵⁸ Royal Holloway, University of London, London TW20 0EX, UK
- ⁵⁹ Astronomical course, The Graduate University for Advanced Studies (SOKENDAI), 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan
- ⁶⁰ Università degli Studi di Urbino “Carlo Bo,” I-61029 Urbino, Italy
- ⁶¹ INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
- ⁶² LIGO Livingston Observatory, Livingston, LA 70754, USA
- ⁶³ INFN, Sezione di Roma, I-00185 Roma, Italy
- ⁶⁴ Università di Roma “La Sapienza,” I-00185 Roma, Italy
- ⁶⁵ Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
- ⁶⁶ Embry-Riddle Aeronautical University, Prescott, AZ 86301, USA
- ⁶⁷ Dipartimento di Fisica “E.R. Caianiello,” Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ⁶⁸ Bar-Ilan University, Ramat Gan, 5290002, Israel
- ⁶⁹ Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
- ⁷⁰ King’s College London, University of London, London WC2R 2LS, UK
- ⁷¹ Korea Institute of Science and Technology Information, Daejeon 34141, Republic of Korea
- ⁷² Université libre de Bruxelles, 1050 Bruxelles, Belgium
- ⁷³ Kenyon College, Gambier, OH 43022, USA
- ⁷⁴ International College, Osaka University, I-1 Machikaneyama-cho, Toyonaka City, Osaka 560-0043, Japan
- ⁷⁵ Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, 3584 CC Utrecht, Netherlands
- ⁷⁶ University of Oregon, Eugene, OR 97403, USA
- ⁷⁷ Syracuse University, Syracuse, NY 13244, USA
- ⁷⁸ Northwestern University, Evanston, IL 60208, USA
- ⁷⁹ Departament de Física Quàntica i Astrofísica (FQA), Universitat de Barcelona (UB), c. Martí i Franqués, 1, 08028 Barcelona, Spain
- ⁸⁰ Dipartimento di Medicina, Chirurgia e Odontoiatria “Scuola Medica Salernitana,” Università di Salerno, I-84081 Baronissi, Salerno, Italy
- ⁸¹ HUN-REN Wigner Research Centre for Physics, H-1121 Budapest, Hungary
- ⁸² Concordia University Wisconsin, Mequon, WI 53097, USA
- ⁸³ Universität Hamburg, D-22761 Hamburg, Germany
- ⁸⁴ Università di Pisa, I-56127 Pisa, Italy
- ⁸⁵ INFN, Sezione di Pisa, I-56127 Pisa, Italy
- ⁸⁶ Università di Perugia, I-06123 Perugia, Italy
- ⁸⁷ University of Michigan, Ann Arbor, MI 48109, USA
- ⁸⁸ Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
- ⁸⁹ INFN, Sezione di Padova, I-35131 Padova, Italy
- ⁹⁰ Institute for Plasma Research, Bhat, Gandhinagar 382428, India
- ⁹¹ Universiteit Gent, B-9000 Gent, Belgium
- ⁹² Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
- ⁹³ Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
- ⁹⁴ University of Minnesota, Minneapolis, MN 55455, USA
- ⁹⁵ SUPA, University of Strathclyde, Glasgow G1 1XQ, UK
- ⁹⁶ IAC3–IEEC, Universitat de les Illes Balears, E-07122 Palma de Mallorca, Spain
- ⁹⁷ Departamento de Matemáticas, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain
- ⁹⁸ RRCAT, Indore, Madhya Pradesh 452013, India
- ⁹⁹ GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands
- ¹⁰⁰ Missouri University of Science and Technology, Rolla, MO 65409, USA
- ¹⁰¹ Colorado State University, Fort Collins, CO 80523, USA
- ¹⁰² Department of Physics and Astronomy, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, The Netherlands
- ¹⁰³ Lomonosov Moscow State University, Moscow 119991, Russia
- ¹⁰⁴ Katholieke Universiteit Leuven, Oude Markt 13, 3000 Leuven, Belgium
- ¹⁰⁵ Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
- ¹⁰⁶ INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
- ¹⁰⁷ INFN, Sezione di Napoli, Gruppo Collegato di Salerno, I-80126 Napoli, Italy
- ¹⁰⁸ OzGrav, University of Adelaide, Adelaide, South Australia 5005, Australia
- ¹⁰⁹ Centre national de la recherche scientifique, 75016 Paris, France
- ¹¹⁰ Univ Rennes, CNRS, Institut FOTON—UMR 6082, F-35000 Rennes, France
- ¹¹¹ University of Birmingham, Birmingham B15 2TT, UK
- ¹¹² Washington State University, Pullman, WA 99164, USA
- ¹¹³ Université de Liège, B-4000 Liège, Belgium
- ¹¹⁴ Université Claude Bernard Lyon 1, CNRS, IP2I Lyon/IN2P3, UMR 5822, F-69622 Villeurbanne, France
- ¹¹⁵ Instituto de Física Teórica UAM-CSIC, Universidad Autónoma de Madrid, 28049 Madrid, Spain
- ¹¹⁶ INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
- ¹¹⁷ Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS–Université PSL, Collège de France, F-75005 Paris, France
- ¹¹⁸ Christopher Newport University, Newport News, VA 23606, USA
- ¹¹⁹ Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland
- ¹²⁰ University of Maryland, College Park, MD 20742, USA
- ¹²¹ Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy
- ¹²² INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy

- ¹²³ L2IT, Laboratoire des 2 Infinis—Toulouse, Université de Toulouse, CNRS/IN2P3, UPS, F-31062 Toulouse Cedex 9, France
- ¹²⁴ University of Portsmouth, Portsmouth, PO1 3FX, UK
- ¹²⁵ Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France
- ¹²⁶ IGFAE, Universidade de Santiago de Compostela, 15782, Spain
- ¹²⁷ University of Chicago, Chicago, IL 60637, USA
- ¹²⁸ NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
- ¹²⁹ Texas A&M University, College Station, TX 77843, USA
- ¹³⁰ OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia
- ¹³¹ INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy
- ¹³² Niels Bohr Institute, Copenhagen University, 2100 København, Denmark
- ¹³³ Istituto di Astrofisica e Planetologia Spaziali di Roma, 00133 Roma, Italy
- ¹³⁴ University of Massachusetts Dartmouth, North Dartmouth, MA 02747, USA
- ¹³⁵ Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain
- ¹³⁶ Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
- ¹³⁷ Niels Bohr Institute, University of Copenhagen, 2100 København, Denmark
- ¹³⁸ University of British Columbia, Vancouver, BC V6T 1Z4, Canada
- ¹³⁹ Department of Physics, National Cheng Kung University, No.1, University Road, Tainan City 701, Taiwan
- ¹⁴⁰ National Tsing Hua University, Hsinchu City 30013, Taiwan
- ¹⁴¹ National Central University, Taoyuan City 320317, Taiwan
- ¹⁴² OzGrav, Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
- ¹⁴³ Vanderbilt University, Nashville, TN 37235, USA
- ¹⁴⁴ Department of Electrophysics, National Yang Ming Chiao Tung University, 101 Univ. Street, Hsinchu, Taiwan
- ¹⁴⁵ Kamioka Branch, National Astronomical Observatory of Japan, 238 Higashi-Mozumi, Kamioka-cho, Hida City, Gifu 506-1205, Japan
- ¹⁴⁶ University of Texas, Austin, TX 78712, USA
- ¹⁴⁷ CaRT, California Institute of Technology, Pasadena, CA 91125, USA
- ¹⁴⁸ Cornell University, Ithaca, NY 14850, USA
- ¹⁴⁹ Northeastern University, Boston, MA 02115, USA
- ¹⁵⁰ OzGrav, School of Physics & Astronomy, Monash University, Clayton 3800, Victoria, Australia
- ¹⁵¹ Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ¹⁵² INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
- ¹⁵³ OzGrav, Swinburne University of Technology, Hawthorn VIC 3122, Australia
- ¹⁵⁴ INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
- ¹⁵⁵ Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
- ¹⁵⁶ Montana State University, Bozeman, MT 59717, USA
- ¹⁵⁷ Texas Tech University, Lubbock, TX 79409, USA
- ¹⁵⁸ Columbia University, New York, NY 10027, USA
- ¹⁵⁹ University of Rhode Island, Kingston, RI 02881, USA
- ¹⁶⁰ The University of Texas Rio Grande Valley, Brownsville, TX 78520, USA
- ¹⁶¹ Chennai Mathematical Institute, Chennai 603103, India
- ¹⁶² Università degli Studi di Sassari, I-07100 Sassari, Italy
- ¹⁶³ Université de Normandie, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France
- ¹⁶⁴ Laboratoire de Physique Corpusculaire Caen, 6 boulevard du maréchal Juin, F-14050 Caen, France
- ¹⁶⁵ Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
- ¹⁶⁶ Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
- ¹⁶⁷ INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
- ¹⁶⁸ University of Sannio at Benevento, I-82100 Benevento, Italy and INFN, Sezione di Napoli, I-80100 Napoli, Italy
- ¹⁶⁹ Perimeter Institute, Waterloo, ON N2L 2Y5, Canada
- ¹⁷⁰ Corps des Mines, Mines Paris, Université PSL, 60 Bd Saint-Michel, 75272 Paris, France
- ¹⁷¹ Indian Institute of Technology Madras, Chennai 600036, India
- ¹⁷² Graduate School of Science, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
- ¹⁷³ National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland
- ¹⁷⁴ Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 75014 Paris, France
- ¹⁷⁵ Vrije Universiteit Brussel, 1050 Brussel, Belgium
- ¹⁷⁶ Carleton College, Northfield, MN 55057, USA
- ¹⁷⁷ Faculty of Science, University of Toyama, 3190 Gofuku, Toyama City, Toyama 930-8555, Japan
- ¹⁷⁸ Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada
- ¹⁷⁹ University of Cambridge, Cambridge CB2 1TN, UK
- 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 Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
- ¹⁸⁴ HUN-REN Institute for Nuclear Research, H-4026 Debrecen, Hungary
- ¹⁸⁵ Centre de Physique des Particules de Marseille, 163, avenue de Luminy, 13288 Marseille cedex 09, France
- ¹⁸⁶ CNR-SPIN, I-84084 Fisciano, Salerno, Italy
- ¹⁸⁷ Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
- ¹⁸⁸ Western Washington University, Bellingham, WA 98225, USA
- ¹⁸⁹ SUPA, University of the West of Scotland, Paisley PA1 2BE, UK
- ¹⁹⁰ The University of Utah, Salt Lake City, UT 84112, USA
- ¹⁹¹ Eötvös University, Budapest 1117, Hungary
- ¹⁹² Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, PT-4710-057 Braga, Portugal
- ¹⁹³ Institute for Cosmic Ray Research, KAGRA Observatory, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan
- ¹⁹⁴ Department of Physics, Graduate School of Science, Osaka Metropolitan University, 3-3-138 Sugimoto-cho, Sumiyoshi-ku, Osaka City, Osaka 558-8585, Japan
- ¹⁹⁵ Université Côte d'Azur, Observatoire de la Côte d'Azur, CNRS, Lagrange, F-06304 Nice, France
- ¹⁹⁶ Rochester Institute of Technology, Rochester, NY 14623, USA
- ¹⁹⁷ California State University, Los Angeles, Los Angeles, CA 90032, USA
- ¹⁹⁸ University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland

- ¹⁹⁹ University of Szeged, Dóm tér 9, Szeged 6720, Hungary
- ²⁰⁰ Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
- ²⁰¹ School of Physics and Technology, Wuhan University, Bayi Road 299, Wuchang District, Wuhan, Hubei, 430072, People's Republic of China
- ²⁰² University of California, Riverside, Riverside, CA 92521, USA
- ²⁰³ INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
- ²⁰⁴ University of Nottingham NG7 2RD, UK
- ²⁰⁵ Ariel University, Ramat HaGolan St 65, Ari'el, Israel
- ²⁰⁶ The University of Mississippi, University, MS 38677, USA
- ²⁰⁷ Institute of Physics, Academia Sinica, 128 Sec. 2, Academia Rd., Nankang, Taipei 11529, Taiwan
- ²⁰⁸ Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, People's Republic of China
- ²⁰⁹ The Chinese University of Hong Kong, Shatin, NT, Hong Kong
- ²¹⁰ Marquette University, Milwaukee, WI 53233, USA
- ²¹¹ American University, Washington, DC 20016, USA
- ²¹² University of Nevada, Las Vegas, Las Vegas, NV 89154, USA
- ²¹³ Department of Applied Physics, Fukuoka University, 8-19-1 Nanakuma, Jonan, Fukuoka City, Fukuoka 814-0180, Japan
- ²¹⁴ University of California, Berkeley, CA 94720, USA
- ²¹⁵ University of Lancaster, Lancaster LA1 4YW, UK
- ²¹⁶ College of Industrial Technology, Nihon University, 1-2-1 Izumi, Narashino City, Chiba 275-8575, Japan
- ²¹⁷ Faculty of Engineering, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan
- ²¹⁸ Department of Physics and Astronomy, Haverford College, 370 Lancaster Avenue, Haverford, PA 19041, USA
- ²¹⁹ Department of Physics, Tamkang University, No. 151, Yingzhuan Rd., Danshui Dist., New Taipei City 25137, Taiwan
- ²²⁰ Rutherford Appleton Laboratory, Didcot OX11 0DE, UK
- ²²¹ Department of Astronomy and Space Science, Chungnam National University, 9 Daehak-ro, Yuseong-gu, Daejeon 34134, Republic of Korea
- ²²² Scuola Normale Superiore, I-56126 Pisa, Italy
- ²²³ Kavli Institute for Astronomy and Astrophysics, Peking University, Yiheyuan Road 5, Haidian District, Beijing 100871, People's Republic of China
- ²²⁴ Department of Physical Sciences, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagami City, Kanagawa 252-5258, Japan
- ²²⁵ 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
- ²²⁶ Directorate of Construction, Services & Estate Management, Mumbai 400094, India
- ²²⁷ University of Białystok, 15-424 Białystok, Poland
- ²²⁸ Astronomical Observatory, Jagiellonian University, 31-007 Cracow, Poland
- ²²⁹ University of Southampton, Southampton SO17 1BJ, UK
- ²³⁰ Department of Physics, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Ulju-gun, Ulsan 44919, Republic of Korea
- ²³¹ Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8582, Japan
- ²³² Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, The Netherlands
- ²³³ Chung-Ang University, Seoul 06974, Republic of Korea
- ²³⁴ University of Washington Bothell, Bothell, WA 98011, USA
- ²³⁵ Aix Marseille Université, Jardin du Pharo, 58 Boulevard Charles Livon, 13007 Marseille, France
- ²³⁶ Laboratoire de Physique et de Chimie de l'Environnement, Université Joseph KI-ZERBO, 9GH2+3V5, Ouagadougou, Burkina Faso
- ²³⁷ Ewha Womans University, Seoul 03760, Republic of Korea
- ²³⁸ Seoul National University, Seoul 08826, Republic of Korea
- ²³⁹ Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea
- ²⁴⁰ Sungkyunkwan University, Seoul 03063, Republic of Korea
- ²⁴¹ Institute of Particle and Nuclear Studies (IPNS), High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba City, Ibaraki 305-0801, Japan
- ²⁴² Division of Science, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka City, Tokyo 181-8588, Japan
- ²⁴³ Bard College, Annandale-On-Hudson, NY 12504, USA
- ²⁴⁴ Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland
- ²⁴⁵ Department of Physics, Nagoya University, ES building, Furocho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan
- ²⁴⁶ Université de Montréal/Polytechnique, Montreal, Quebec H3T 1J4, Canada
- ²⁴⁷ Indian Institute of Science Education and Research, Kolkata, Mohanpur, West Bengal 741252, India
- ²⁴⁸ Inje University Gimhae, South Gyeongsang 50834, Republic of Korea
- ²⁴⁹ NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS. Marne-la-Vallée, France
- ²⁵⁰ Università di Firenze, Sesto Fiorentino I-50019, Italy
- ²⁵¹ National Center for High-performance Computing, National Applied Research Laboratories, No. 7, R&D 6th Rd., Hsinchu Science Park, Hsinchu City 30076, Taiwan
- ²⁵² NAS. Marshall Space Flight Center, Huntsville, AL 35811, USA
- ²⁵³ West Virginia University, Morgantown, WV 26506, USA
- ²⁵⁴ Institut fuer Theoretische Astrophysik, Zentrum fuer Astronomie Heidelberg, Universitaet Heidelberg, Albert Ueberle Str. 2, 69120 Heidelberg, Germany
- ²⁵⁵ School of Physics Science and Engineering, Tongji University, Shanghai 200092, People's Republic of China
- ²⁵⁶ Institut d'Estudis Espacials de Catalunya, c. Gran Capità, 2-4, 08034 Barcelona, Spain
- ²⁵⁷ Institutio Catalana de Recerca i Estudis Avançats (ICREA), Passeig de Lluís Companys, 23, 08010 Barcelona, Spain
- ²⁵⁸ Tsinghua University, Beijing 100084, People's Republic of China
- ²⁵⁹ INFN Cagliari, Physics Department, Università degli Studi di Cagliari, Cagliari 09042, Italy
- ²⁶⁰ Saha Institute of Nuclear Physics, Bidhannagar, West Bengal 700064, India
- ²⁶¹ Tata Institute of Fundamental Research, Mumbai 400005, India
- ²⁶² Hobart and William Smith Colleges, Geneva, NY 14456, USA
- ²⁶³ Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France
- ²⁶⁴ Faculty of Law, Ryukoku University, 67 Fukakusa Tsukamoto-cho, Fushimi-ku, Kyoto City, Kyoto 612-8577, Japan
- ²⁶⁵ Department of Physics and Astronomy, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556, USA
- ²⁶⁶ University of Stavanger, 4021 Stavanger, Norway
- ²⁶⁷ Physics Program, Graduate School of Advanced Science and Engineering, Hiroshima University, 1-3-1 Kagamiyama, Higashihiroshima City, Hiroshima 903-0213, Japan
- ²⁶⁸ Laboratoire Univers et Théories, Observatoire de Paris, 92190 Meudon, France
- ²⁶⁹ Observatoire de Paris, 75014 Paris, France
- ²⁷⁰ Université PSL, 75006 Paris, France
- ²⁷¹ Université de Paris Cité, 75006 Paris, France

- ²⁷² National Institute for Mathematical Sciences, Daejeon 34047, Republic of Korea
- ²⁷³ Graduate School of Science and Technology, Niigata University, 8050 Ikarashi-2-no-cho, Nishi-ku, Niigata City, Niigata 950-2181, Japan
- ²⁷⁴ Niigata Study Center, The Open University of Japan, 754 Ichibancho, Asahimachi-dori, Chuo-ku, Niigata City, Niigata 951-8122, Japan
- ²⁷⁵ CSIR-Central Glass and Ceramic Research Institute, Kolkata, West Bengal 700032, India
- ²⁷⁶ Consiglio Nazionale delle Ricerche—Istituto dei Sistemi Complessi, I-00185 Roma, Italy
- ²⁷⁷ Department of Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
- ²⁷⁸ Department of Astronomy, Yonsei University, 50 Yonsei-Ro, Seodaemun-Gu, Seoul 03722, Republic of Korea
- ²⁷⁹ Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi,” I-00184 Roma, Italy
- ²⁸⁰ Dipartimento di Ingegneria Industriale, Elettronica e Meccanica, Università degli Studi Roma Tre, I-00146 Roma, Italy
- ²⁸¹ Subatech, CNRS/IN2P3—IMT Atlantique—Nantes Université, 4 rue Alfred Kastler BP 20722 44307 Nantes CÉDEX 03, France
- ²⁸² Universidad de Antioquia, Medellín, Colombia
- ²⁸³ Departamento de Física—ETSIDI, Universidad Politécnica de Madrid, 28012 Madrid, Spain
- ²⁸⁴ Department of Electronic Control Engineering, National Institute of Technology, Nagaoka College, 888 Nishikataai, Nagaoka City, Niigata 940-8532, Japan
- ²⁸⁵ Università Degli Studi Di Ferrara, Via Savonarola, 9, 44121 Ferrara FE, Italy
- ²⁸⁶ Faculty of Science, Toho University, 2-2-1 Miyama, Funabashi City, Chiba 274-8510, Japan
- ²⁸⁷ Indian Institute of Technology, Palaj, Gandhinagar, Gujarat 382355, India
- ²⁸⁸ Laboratoire MSME, Cité Descartes, 5 Boulevard Descartes, Champs-sur-Marne, 77454 Marne-la-Vallée Cedex 2, France
- ²⁸⁹ Institute of Systems and Information Engineering, University of Tsukuba, 1-1-1, Tennodai, Tsukuba, Ibaraki 305-8573, Japan
- ²⁹⁰ Institute for Quantum Studies, Chapman University, 1 University Dr., Orange, CA 92866, USA
- ²⁹¹ Faculty of Information Science and Technology, Osaka Institute of Technology, 1-79-1 Kitayama, Hirakata City, Osaka 573-0196, Japan
- ²⁹² INAF, Osservatorio Astrofisico di Arcetri, I-50125 Firenze, Italy
- ²⁹³ iTHEMS (Interdisciplinary Theoretical and Mathematical Sciences Program), RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
- ²⁹⁴ Scuola Internazionale Superiore di Studi Avanzati, Via Bonomea, 265, I-34136, Trieste TS, Italy
- ²⁹⁵ Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany
- ²⁹⁶ INAF, Osservatorio di Astrofisica e Scienza dello Spazio, I-40129 Bologna, Italy
- ²⁹⁷ Universidade Estadual Paulista, 01140-070 São Paulo, Brazil
- ²⁹⁸ Faculty of Physics, University of Warsaw, Ludwika Pasteura 5, 02-093 Warszawa, Poland
- ²⁹⁹ Research Center for Space Science, Advanced Research Laboratories, Tokyo City University, 3-3-1 Ushikubo-Nishi, Tsuzuki-Ku, Yokohama, Kanagawa 224-8551, Japan
- ³⁰⁰ Department of Physics, Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan
- ³⁰¹ Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Kita-Shirakawa Oiwake-cho, Sakyou-ku, Kyoto City, Kyoto 606-8502, Japan
- ³⁰² University of Catania, Department of Physics and Astronomy, Via S. Sofia, 64, 95123 Catania CT, Italy
- ³⁰³ Dipartimento di Scienze Aziendali—Management and Innovation Systems (DISA-MIS), Università di Salerno, I-84084 Fisciano, Salerno, Italy
- ³⁰⁴ National Institute of Technology, Fukui College, Geshi-cho, Sabae-shi, Fukui 916-8507, Japan
- ³⁰⁵ Department of Communications Engineering, National Defense Academy of Japan, 1-10-20 Hashirimizu, Yokosuka City, Kanagawa 239-8686, Japan
- ³⁰⁶ Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands
- ³⁰⁷ Kavli Institute for the Physics and Mathematics of the Universe, WPI, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba 277-8583, Japan
- ³⁰⁸ Department of Astronomy, Beijing Normal University, Xijiekouwai Street 19, Haidian District, Beijing 100875, People’s Republic of China

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Abstract

The magnetar SGR 1935+2154 is the only known Galactic source of fast radio bursts (FRBs). FRBs from SGR 1935+2154 were first detected by the Canadian Hydrogen Intensity Mapping Experiment (CHIME)/FRB and the Survey for Transient Astronomical Radio Emission 2 in 2020 April, after the conclusion of the LIGO, Virgo, and KAGRA Collaborations’ O3 observing run. Here, we analyze four periods of gravitational wave (GW) data from the GEO600 detector coincident with four periods of FRB activity detected by CHIME/FRB, as well as X-ray glitches and X-ray bursts detected by NICER and NuSTAR close to the time of one of the FRBs. We do not detect any significant GW emission from any of the events. Instead, using a short-duration GW search (for bursts ≤ 1 s) we derive 50% (90%) upper limits of 10^{48} (10^{49}) erg for GWs at 300 Hz and 10^{49} (10^{50}) erg at 2 kHz, and constrain the GW-to-radio energy ratio to $\leq 10^{14}$ – 10^{16} . We also derive upper limits from a long-duration search for bursts with durations between 1 and 10 s. These represent the strictest upper limits on concurrent GW emission from FRBs.

Unified Astronomy Thesaurus concepts: Gravitational waves (678); Soft gamma-ray repeaters (1471); Magnetars (992); Radio transient sources (2008); X-ray sources (1822); Gravitational wave sources (677)

1. Introduction

Fast radio bursts (FRBs) are a class of extremely energetic radio transients that are theorized to be associated with neutron stars (D. Thornton et al. 2013; E. Petroff et al. 2019; E. Platts et al. 2019;

M. Bailes 2022; B. Zhang 2023). To date, thousands of fast radio bursts (FRBs) have been detected. The majority of these have been discovered using the Canadian Hydrogen Intensity Mapping Experiment (CHIME) telescope (M. Amiri et al. 2022) by the CHIME/FRB Collaboration (CHIME/FRB; CHIME/FRB Collaboration et al. 2018).³¹² Though the origins of FRBs remain unknown (D. R. Lorimer et al. 2024), their dispersion measure (DM) as observed by radio telescopes localizes them to extragalactic (and even cosmological) distances (D. R. Lorimer et al. 2007; S. Chatterjee et al. 2017; J. M. Cordes & S. Chatterjee 2019).

³⁰⁹ Deceased, November 2022.

³¹⁰ Deceased, February 2024.

³¹¹ lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.it and kscboard-chair@icrr.u-tokyo.ac.jp



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³¹² <https://www.chime-frb.ca/voevents>

The notable exceptions to this extragalactic consensus are the FRBs associated with FRB 20200428A. First detected in 2020 April by CHIME/FRB and the Survey for Transient Astronomical Radio Emission 2 (STARE2; C. D. Bochenek et al. 2020a), FRB 20200428A was quickly found to be associated with the Galactic magnetar SGR 1935+2154, which was undergoing an unusual period of flaring X-ray activity at that time (S. D. Barthelmy et al. 2020; C. D. Bochenek et al. 2020b; CHIME/FRB Collaboration et al. 2020; D. M. Palmer 2020). Simultaneous X-ray observations from Konus-Wind (D. Frederiks et al. 2022), INTEGRAL (S. Mereghetti et al. 2020), AGILE (M. Tavani et al. 2020), and Insight-HXMT (C. K. Li et al. 2022) led to the first coincident observation of both radio emission and X-rays from an FRB source. FRBs from SGR 1935+2154 were also observed during three other epochs by CHIME/FRB and others, on 2020 October 8, 2022 October 14, and 2022 December 1.³¹³ Additionally, X-ray glitches and bursts from SGR 1935+2154 were observed by NICER and NuSTAR during the nine hours surrounding the 2022 October 14 FRB (C.-P. Hu et al. 2024). The connection between these X-ray bursts and FRBs, even from the same magnetar, is not well understood—indeed, radio emission with no coincident X-rays has been detected from SGR 1935+2154 (W. Zhu et al. 2023), and vice versa (G. Younes et al. 2017).

The compact object nature of these powerful transients suggests that gravitational waves (GWs) could also be emitted by the same mechanisms that produce FRBs. The detection of GWs from an FRB source (or lack thereof) could help to elucidate the mechanisms behind FRBs (B. Zhang 2023), and potentially expand the realm of detected GWs beyond those with compact binary coalescence (CBC) origins.

Previous works by the LIGO, Virgo, and KAGRA Collaborations (LVK) have searched for GW emission coincident with FRBs (B. P. Abbott et al. 2016; R. Abbott et al. 2023), as well as for GWs from magnetar bursts (B. P. Abbott et al. 2019a, 2019b; A. Macquet et al. 2021a; R. Abbott et al. 2024) and pulsar glitches (J. Abadie et al. 2011; D. Keitel et al. 2019; R. Abbott et al. 2022a) using the Advanced LIGO and Advanced Virgo GW observatories (F. Acernese et al. 2015; J. Aasi et al. 2015). While no detections were found in these studies, the searches have established upper limits on GW energy that may have been emitted in association with these events. In particular, R. Abbott et al. (2023) performed a search for GW emission coincident with FRBs from CHIME/FRB during the O3a LIGO–Virgo observing run, with searches targeted at GWs from CBCs, as well as generic GW transients, setting an upper limit of 10^{51} – 10^{57} erg of GW energy within 70–3560 Hz. In addition, R. Abbott et al. (2024) placed upper limits on GW energy ($\sim 10^{43}$ erg) coincident with 11 X-ray and soft gamma-ray magnetar bursts from SGR 1935+2154.

SGR 1935+2154, as the first (and at the time of writing, only) FRB source to be confidently associated with a specific neutron-star progenitor, presents a unique opportunity to search for GWs when the source is localized to a particular compact object. Additionally, at ~ 6.6 kpc (P. Zhou et al. 2020), it is more than two orders of

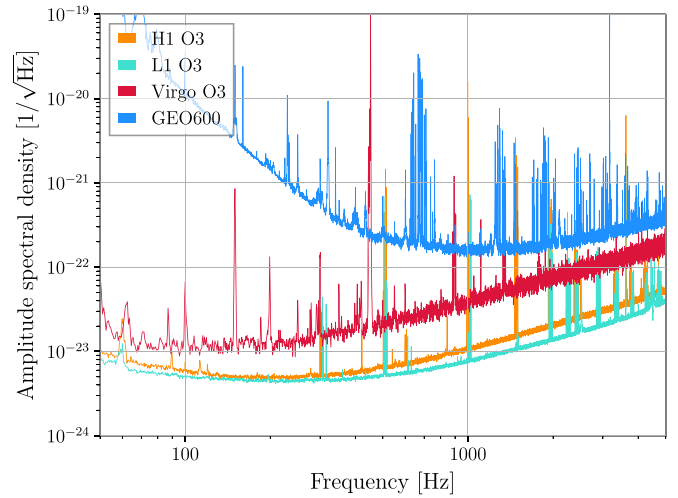


Figure 1. Amplitude spectral density of GEO600 on 2020 April 28 compared to those of LIGO Hanford, LIGO Livingston, and Virgo during O3 (B. P. Abbott et al. 2020). While at low frequencies GEO600’s sensitivity is substantially diminished compared to that of the larger detectors, the gap narrows at frequencies around 2 kHz, near the expected neutron-star f-mode frequency.

magnitude nearer to Earth than the next closest FRB, which has been localized to the nearby galaxy M81, 3.6 Mpc away (M. Bhardwaj et al. 2021; F. Kirsten et al. 2022).

The four periods of FRB activity from SGR 1935+2154 fell between the O3 and O4 observing runs of the LVK, when the LIGO and Virgo detectors were offline.³¹⁴ Fortunately, GEO600 (H. Grote et al. 2004; H. Lueck et al. 2010; C. Affeldt et al. 2014; K. L. Dooley et al. 2016), a GW detector in Hannover, Germany that is operated by members of the LIGO Scientific Collaboration, was observing in Astrowatch mode (H. Grote & the LIGO Scientific Collaboration 2010) and collecting GW data during all four periods. The CHIME/FRB events for three of the four periods occurred when GEO600 was in observing mode, while the fourth FRB occurred within minutes of when GEO600 was observing (see Section 3).

In this paper, we analyze GEO600 data to search for GW emission coincident with the four FRBs observed by CHIME/FRB from SGR 1935+2154. We conduct two searches for unmodeled GW transients: one targeted at short-duration bursts with $\mathcal{O}(\text{second})$ durations, and another aimed at long-duration bursts lasting from 1 to 10 s. Due to SGR 1935+2154’s proximity, the results constitute the most sensitive searches for GWs from FRB sources to date, despite GEO600’s lower sensitivity compared to LIGO and Virgo (see Figure 1). We also search for GWs coincident with the two X-ray glitches and the X-ray burst peak observed by NICER and NuSTAR in the hours around the FRB on 2022 October 14 (C.-P. Hu et al. 2024). This paper is organized as follows. In Section 2, we describe the electromagnetic (EM) observations of FRBs from SGR 1935+2154. Section 3 details our short- and long-duration searches for GWs, with results presented in Section 4. We discuss the implications of these findings and conclude in Section 5.

2. Fast Radio Bursts from SGR 1935+2154

The magnetar SGR 1935+2154 was discovered by Swift in 2014 (A. Y. Lien et al. 2014; M. Stamatikos et al. 2014). Since

³¹³ We note that the classification of these radio bursts as FRBs remains unclear: the SGR 1935+2154 radio bursts are a few orders of magnitude less luminous than typical extragalactic FRBs, but are still brighter than most giant radio pulses (U. Giri et al. 2023). C. D. Bochenek et al. (2020a) name them as FRBs while U. Giri et al. (2023) call them FRB-like. Here, we describe them as FRBs.

³¹⁴ <https://observing.docs.ligo.org/plan/>

then, it has been highly active, with periods of intense emission in the X-ray and radio (G. L. Israel et al. 2016; G. Younes et al. 2017).

On 2020 April 27, Swift observed multiple X-ray bursts from SGR 1935+2154, suggesting that the magnetar had entered a period of high activity (S. D. Barthelmy et al. 2020). Less than 24 hr later, CHIME/FRB and STARE2 detected an FRB from the location of SGR 1935+2154 (C. D. Bochenek et al. 2020b; CHIME/FRB Collaboration et al. 2020). Konus-Wind (D. Frederiks et al. 2022), INTEGRAL (S. Mereghetti et al. 2020), AGILE (M. Tavani et al. 2020), and Insight-HXMT (C. K. Li et al. 2022) observed hard X-rays arriving at the same time, serving as the first ever observation of simultaneous radio and X-ray emission from an FRB source. Follow-up radio observations during the same active period by the Five-hundred-meter Aperture Spherical Radio Telescope (C. F. Zhang et al. 2020) and radio telescopes from the European VLBI Network (F. Kirsten et al. 2021) identified additional radio bursts from SGR 1935+2154, though at lower energies. At higher energies, no gamma-ray emission has been observed from this source (H. Abdalla et al. 2021; G. Principe et al. 2023).

Since 2020 April, SGR 1935+2154 has had multiple periods of high activity leading to the emission of FRBs. On 2020 October 8, CHIME/FRB observed three FRBs from SGR 1935+2154 arriving within a few seconds (D. Good & CHIME/FRB Collaboration 2020; Z. Pleunis & CHIME/FRB Collaboration 2020; U. Giri et al. 2023). CHIME/FRB and the Green Bank Telescope (GBT) observed FRBs again two years later on 2022 October 14, with a CHIME/FRB event surrounded by five GBT FRBs within 1.5 s (F. A. Dong & CHIME/FRB Collaboration 2022; Y. Maan et al. 2022; U. Giri et al. 2023). During the days around the FRBs on 2022 October 14, SGR 1935+2154 was undergoing a period of intense X-ray burst activity. This burst storm began on October 10 (S. Mereghetti et al. 2022; D. M. Palmer 2022) and was monitored by various telescopes, such as NICER, NuSTAR, and XMM-Newton (see, e.g., C.-P. Hu et al. 2024; A. Y. Ibrahim et al. 2024), which detected hundreds of milliseconds to seconds-long bursts of high-energy photons. The X-ray burst rate peaked during a flare 2.5 hr (± 1 minute) before the FRB and then steadily decreased over the next hours (C.-P. Hu et al. 2024). In addition, the high-cadence monitoring observations allowed accurate measurements of the spin rate of SGR 1935+2154 (nominally 0.308 Hz; G. L. Israel et al. 2016). The evolution of the spin rate showed that SGR 1935+2154 underwent a spin-up glitch about 4.4 hr (± 30 minutes) before the FRB and another spin-up glitch about 4.4 hr (± 30 minutes) after the FRB, while the magnetar’s spin-down rate between these two glitches was about one hundred times higher than its normal rate (C.-P. Hu et al. 2024). X-ray bursts were also detected by GECAM and HEBS (C. W. Wang et al. 2022) and Konus-Wind (D. Frederiks et al. 2022) arriving within the expected FRB dispersion time. In addition to the NICER and NuSTAR observations mentioned above (T. Enoto et al. 2022), Insight-HXMT (C. K. Li et al. 2022) also observed X-rays from SGR 1935+2154 during this active period, though at the time of the FRB all three were occulted by the Earth. Finally, a fourth FRB was detected by CHIME/FRB on 2022 December 1 (A. B. Pearlman & CHIME/FRB Collaboration 2022; U. Giri et al. 2023), accompanied by a faint hard X-ray signal detected by Fermi-GBM (G. Younes et al. 2022).

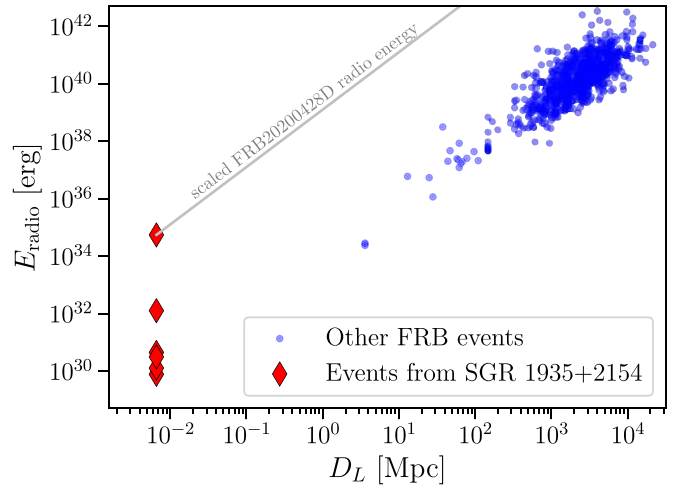


Figure 2. Radio energy versus luminosity distance for the SGR 1935+2154 FRBs investigated in this work (dark orange, U. Giri et al. 2023) and for 749 other public FRBs published by CHIME/FRB and others (E. Petroff et al. 2016; K. M. Rajwade et al. 2020; CHIME/FRB Collaboration et al. 2021) (blue). The FRB sample and the calculation of distances and radio energies is described in G. Principe et al. (2023) (with the exception of the FRBs studied in R. Abbott et al. 2023, for which we use the lower bound 90% distances from that analysis). Note that the radio energies from CHIME/FRB (derived from fluxes and fluences) should be interpreted as lower limits (CHIME/FRB Collaboration et al. 2021; B. C. Andersen et al. 2023). We show the radio energy required to produce a flare as bright as that of the brightest FRB from SGR 1935+2154, FRB20200428D, as a function of distance.

Most estimates and methods place the distance to SGR 1935+2154 between 1.5 and 15 kpc (G. Park et al. 2013; M. Z. Pavlovic et al. 2014; M. P. Surnis et al. 2016; R. Kothes et al. 2018; S. Ranasinghe et al. 2018; S.-Q. Zhong et al. 2020; P. Zhou et al. 2020; M. Bailes et al. 2021). We adopt the determination by P. Zhou et al. (2020) of 6.6 ± 0.7 kpc, falling near the mean of the measurements.

These SGR 1935+2154 FRBs are not quite like the rest of the population of FRBs, as mentioned in Section 1. As shown in K. Nimmo et al. (2022), they exhibit characteristics very similar to the extragalactic FRBs, but are a few orders of magnitude less luminous. Whether the SGR 1935+2154 FRBs are in the tail of the same population or truly occupy a different part of the phase space remains an open question. For example, while the 2020 April FRB from SGR 1935+2154 was several orders of magnitude less energetic than most FRBs, it was three orders of magnitude brighter than the next brightest previously observed radio flare from a magnetar (CHIME/FRB Collaboration et al. 2020). Figure 2 shows the radio energy as a function of distance for the FRBs from SGR 1935+2154, alongside a sample of 749 FRBs from CHIME/FRB³¹⁵ (CHIME/FRB Collaboration et al. 2021), the FRBCAT (E. Petroff et al. 2016), and the 76 m Lovell telescope (K. M. Rajwade et al. 2020), as collected and described in G. Principe et al. (2023). This could suggest that the emission mechanism which produces FRBs from SGR 1935+2154 may be different from that which results in FRBs from cosmological distances. Despite this reduced brightness compared to the typical FRB population, SGR 1935+2154’s proximity as the only known Galactic FRB source means that it presents the most promising opportunity to date for multiwavelength and multimessenger studies of FRB emitters.

³¹⁵ <https://www.chime-frb.ca/repeaters>

2.1. Models for Coincident GW-FRB Emission

Magnetars have long been theorized to be progenitors of FRBs (E. Platts et al. 2019). The detection of FRBs from SGR 1935+2154, a well-studied magnetar, has now confirmed this association for at least some FRBs, though the exact emission mechanism remains unclear (Y. Lyubarsky 2021; B. Zhang 2023).

Most models which predict GW emission from FRB progenitors assume a CBC association, such as during or after the final stages of the CBC inspiral (J.-S. Wang et al. 2016; S. Yamasaki et al. 2018), long before the CBC merger through interactions of magnetospheres (B. Zhang 2020), or other interactions of compact binaries with their environments (see E. Platts et al. 2019 for a review of FRB theory). Prior studies such as R. Abbott et al. (2023) have searched for GWs from these sources using targeted matched-filter analyses, aimed at CBC sources. Since SGR 1935+2154 is not in a compact binary (A. A. Chrimes et al. 2022) and has exhibited multiple periods of FRB activity, we do not expect CBC-like GW emission from this source. Instead, as a magnetar, we can focus on only a few possible emission mechanisms for GWs coincident with FRBs. In particular, because GWs are induced by time-varying quadrupole moments, we review models which predict EM magnetar activity associated with such moments.

Since at least some FRBs originate from magnetars, theories have drawn connections between them and magnetar giant flares (S. P. Tendulkar et al. 2016; B. Margalit et al. 2020; J. Cehula et al. 2024), which are thought to be powered by magnetic activity near the surface of a neutron star (C. Thompson & R. C. Duncan 1996; B. M. Gaensler et al. 2005). These giant flares are rare but so energetic that GW emission may be detectable due to hydromagnetic coupling of the magnetic dipole to the mass quadrupole (K. Ioka 2001; A. Corsi & B. J. Owen 2011). Quasi-periodic oscillations in the X-ray tails of giant flares may also create GWs through torsional or Alfvén modes which alter the star’s quadrupole moment (Y. Levin & M. van Hoven 2011; K. Glampedakis & D. I. Jones 2014; R. Quitzow-James et al. 2017). While no giant flares from SGR 1935+2154 were detected during its periods of FRB activity, the coincident X-ray activity suggests a potential link in the provenance of the high-energy EM emission.

Crustal f-modes are a possible source of transient GWs from isolated neutron stars (K. Glampedakis & L. Gualtieri 2018; W. C. G. Ho et al. 2020). These typically fall at around 2 kHz (N. Andersson & K. D. Kokkotas 1996), near the frequencies where GEO600 is most sensitive (see Figure 1).

Moreover, neutron-star glitches, such as those from SGR 1935+2154 in 2022 October investigated in this work, may emit GWs potentially observable by current GW detectors (R. Prix et al. 2011; L. Warszawski & A. Melatos 2012; A. Melatos et al. 2015). Previous limits were derived for the Vela pulsar (located at 290 pc; R. Dodson et al. 2003) glitch in 2006, providing limits on the emitted GW energy of the order of 10^{45} erg (J. Abadie et al. 2011).

3. Search for Gravitational Waves

Using data from GEO600, we search for generic GW transients from SGR 1935+2154 around the times of four FRBs detected by CHIME/FRB. GEO600 is a dual-recycled Michelson interferometer with folded arms and takes

astrophysical observations in the 40 Hz–6 kHz frequency band when operating in Astrowatch mode (H. Grote & the LIGO Scientific Collaboration 2010). Over the past two decades, it has pioneered several key technologies for GW detectors (C. Affeldt et al. 2014; J. Lough et al. 2021). GEO600 has lower sensitivity compared to the Advanced LIGO and Advanced Virgo detectors ($\sim 10^{-22}/\sqrt{\text{Hz}}$ at 1 kHz, see Figure 1), but has strengths in uptime. It continued taking observations during the initial period of the COVID-19 pandemic and subsequent LIGO and Virgo upgrades throughout 2020–2022, during which CHIME/FRB observed these FRBs from SGR 1935+2154.

Given the unknown nature of the emission mechanism of the FRBs, we search for generic transient gravitational-wave signals present in the GEO600 data using two unmodeled burst searches: PySTAMP (A. Macquet et al. 2021b), targeted at long-duration bursts with lengths from 1 to 10 s, and X-Pipeline (P. J. Sutton et al. 2010; M. Was et al. 2012), for short-duration bursts lasting less than 1 s. Previous searches for GWs coincident with FRBs, such as the ones presented in R. Abbott et al. (2023), also considered a possible CBC origin for the GW emission; the noncompact binary nature of SGR 1935+2154 precludes the use of CBC matched-filter searches. Given that SGR 1935+2154 is a magnetar, we follow the previous GW magnetar study presented in R. Abbott et al. (2024) and employ PySTAMP to perform a long-duration search, which has not previously been used for GW-FRB analyses. Additionally, prior searches have typically been restricted to coincidences with FRBs where data from at least two GW detectors is available. For these FRBs from SGR 1935+2154, only GEO600 was observing, so we employ a single-detector search. This limits our ability to veto candidates based on coherence between detectors and the amount of background that can be estimated, reducing the search sensitivity, but given the extraordinary nature of these FRBs, we determined that a single-detector search in GEO600 data was warranted.

For the 2020 April 28, 2020 October 8, and 2022 October 14 FRBs, we perform a search within an “on-source” time window starting at 1200 s before the infinite-frequency arrival time (i.e., the time accounting for the frequency-dependent delay introduced by the DM) of the FRB, t_0 , and ending 120 s after. This asymmetric window is motivated by the expectation that any potential GWs are likely generated from the interior of the magnetar, preceding FRB emission from the magnetosphere or beyond. On 2020 October 8, three bursts were detected by CHIME/FRB within 3 s; we use the first time, corresponding to the FRB with the highest fluence on that day, as our t_0 . The FRB on 2022 December 1 occurred during a time when GEO600 was not taking data, having exited observing mode approximately six minutes before the FRB, at 22:01:09 UTC. GEO600 returned to observing mode 23 minutes later, at 22:23:59 UTC. To be consistent with the on-source window for the other FRBs, we analyze the 800 s period of data beginning 1200 s before the FRB and ending shortly before GEO600 exited observing mode. Due to the large uncertainties in FRB–GW models (as described above in Section 2.1), we use a wide extended on-source window of $[-1200, 120]$ s. This allows us to probe a broad parameter space while keeping the detector behavior relatively stationary. We also employ a compact $[-4, 4]$ s search window in the short-duration search to probe the time immediately surrounding the FRB with higher sensitivity. In addition, we search for emission around the time of three

Table 1
Table of FRB and X-Ray Events for which we Perform GW Searches

FRB/X-Ray Event	Time (UTC)	Window for Long-duration Search (s)	Compact Window for Short-duration Search (s)	Extended Window for Short-duration Search (s)
2020 April 28	14:34:24	[−1200, 120]	[−4, 4]	[−1200, 120]
2020 October 08	02:23:33	[−1200, 120]	[−4, 4]	[−1200, 120]
2022 October 14 X-ray glitch 1	15:07:12	...	...	[−480, −240]*
2022 October 14 X-ray burst peak	16:55:12	...	...	[−1000, 1000]
2022 October 14	19:21:39	[−687, 120]*	[−4, 4]	[−600, 120]*
2022 October 14 X-ray glitch 2	23:45:36	...	...	[−500, 500]*
2022 December 01	22:06:59	...	...	[−1200, −400]*

Note. The long-duration `PySTAMP` search is performed with one time window, while the short-duration `X-Pipeline` search is performed with both a compact window and an extended window, where data availability and timing uncertainties permit. A dash (...) indicates that no search was performed, while an asterisk (*) denotes search windows that were necessarily truncated due to data availability.

X-ray events detected by NuSTAR and NICER on 2022 October 14. These events consisted of a spin-up glitch, a peak in the X-ray burst emission, and another spin-up glitch. Since the uncertainty in their times is greater than a minute, we only perform an extended-window search, targeting a symmetric [−1000, 1000] s window, subject to data availability. Table 1 summarizes the times and windows for which we perform searches.

We restrict our search to frequencies from 300 to 4096 Hz, with the lower cutoff set by the low frequency sensitivity of GEO600 and the upper cutoff aiming to capture neutron-star crustal f-modes, which are predicted to fall at approximately 2 kHz (N. Andersson & K. D. Kokkotas 1996).

3.1. Simulated Waveforms to Quantify Sensitivity

We measure the sensitivity of our search by inserting simulated waveforms (injections) into the off-source data and quantifying the pipeline’s ability to recover them. For the short-duration `X-Pipeline` search, these injections are largely the same as those used in R. Abbott et al. (2023). The waveforms include Sine-Gaussians and damped sinusoids and are summarized in Table 2. We briefly describe each waveform family below:

1. *Sine-Gaussians.* The majority of the simulated waveforms we use are Sine-Gaussians, which can model starquakes and certain neutron-star f-modes. They are described in Equation 1 of B. P. Abbott et al. (2017). Most of these injections are performed with inclinations chosen randomly, but we also employ some optimally inclined (circular polarization only, emitted face-on to the observer) waveforms near the expected f-modes at ~2000 Hz to better constrain our sensitivity to these models. In all the injected waveforms, we use a quality factor $Q = 9$ (the approximate number of cycles in the waveform) following R. Abbott et al. (2021, 2023), with central frequencies f_0 spanning from 300 to 3560 Hz, as shown in Table 2.
2. *Damped sinusoids.* We also use damped sinusoids to characterize any ringdown behavior in the magnetar. The waveform is described in Equation C12 of R. Abbott et al. (2024). These are placed at two frequencies, 1590 and 2020 Hz, to represent plausible f-mode signals. For each frequency, we use two damping timescales to probe a larger parameter space.

Table 2
Parameters for Waveforms Injected into Off-source Data for Recovery to Quantify each Search’s Sensitivity

Label	Frequency f_0 (Hz)	Duration Parameter (ms)
Short-duration Sine-Gaussian Chirplets		
SG-D	300	3.3
SG-E	500	0.20
SG-F	1100	0.91
SG-G	1600	0.63
SG-H	1995	0.50
SG-I	2600	0.38
SG-J	3100	0.32
SG-K	3560	0.28
SG-L ^c	1600	0.63
SG-M ^c	1995	0.50
Short-duration Ringdowns		
DS2P-A	1590	100
DS2P-B	1590	200
DS2P-C	2020	100
DS2P-D	2020	200
Long-duration Sine-Gaussian Chirplets		
...	520	10 ⁴
...	1020	10 ⁴
...	1520	10 ⁴
...	2020	10 ⁴

Note. For the generic short-duration transient search `X-Pipeline`, we follow the labeling convention in R. Abbott et al. (2023) for each waveform, where “SG” waveforms are sine-Gaussians and “DS2P” (damped sinusoid 2 polarizations) waveforms represent ringdowns. There are few enough long-duration waveforms that we did not assign labels to them. The duration parameter scales the width of the Gaussian envelope for the sine-Gaussian chirplets, and describes the damping time of the damped sinusoids used as ringdown waveforms. The ^c superscript denotes waveforms with circular polarizations.

The waveforms used by the long-duration `PySTAMP` analysis are also Sine-Gaussians, but with a duration parameter of 10 s. They are also described in Table 2.

3.2. Long-duration Search with `PySTAMP`

We use `PySTAMP` (A. Macquet et al. 2021b) to target GW signals with durations longer than 1 s around the three FRBs with coincident GEO600 data. The background distribution and

the detection efficiency of the search are characterized using an off-source window that consists of ~ 12 hr of data centered on the event time, excluding the on-source window described above. The workflow of the pipeline is as follows. The data are first down-sampled from 16384 to 8192 Hz, and then high-pass filtered with a frequency cutoff of 40 Hz to remove potential spectral leakage from lower frequencies. After these preprocessing steps, the resulting time series are split into 1 s Hann-windowed segments with 50% overlap. The fast Fourier transform is computed over each segment to build a time-frequency map (tf-map) with a resolution of $1\text{ s} \times 1\text{ Hz}$. For each frequency bin, the power spectral density (PSD) is estimated by taking the median of the squared modulus of the Fourier transform over 1320 s of adjacent data (similar to Welch’s method but using the median instead of the mean), and a signal-to-noise ratio (S/N) tf-map is built by dividing the value of the Fourier transform in each pixel by the square root of the PSD. To identify candidate GW events, a pattern recognition algorithm is run over the tf-map. We use the *burstegard* algorithm (T. Prestegard 2016), which identifies clusters of neighboring pixels whose S/N is above a threshold of 2.5. Clusters consisting of 5 or more pixels are saved as candidate GW events. Each cluster is then assessed a ranking statistic Λ that is the sum of the S/N of each of its pixels divided by the square root of the total number of pixels.

Clusters found in the off-source window form the background of the search and are used to estimate the false-alarm rate (FAR) of clusters found in the on-source window as a function of the ranking statistic Λ . *PySTAMP* is primarily intended to work on cross-correlated data from a pair of independent detectors, which allows for the simulation of an extended amount of background by shifting the time series of one detector with respect to the other. Such a method cannot be applied here in the single-detector GEO600 search. Hence, the background lifetime is limited to the duration of the off-source window, so the FAR of each cluster can only be estimated down to a minimum of ~ 1 per 12 hr (2.3×10^{-5} Hz). See Section 5 for further discussion of the limited FAR.

Noise from GW detectors typically features narrowband spectral artifacts that appear as horizontal lines in a time-frequency representation (or vertical lines in the amplitude spectral density; see Figure 1). Because the PSD is estimated for each frequency bin by taking the median over neighboring time segments, most of these lines are correctly factored into the PSD and do not generate high S/N pixels. However, we observe an excess of clusters in the off-source window around some specific frequencies, likely due to fluctuations of spectral lines around their central values. We therefore remove clusters for a narrow range of frequencies corresponding to known GEO600 spectral lines. In order to reject short, broadband noise transients (known as glitches), we also remove clusters for which more than 30% of the total energy is contained within a single 1 s time segment.

3.3. Short-duration Search with X-Pipeline

We perform a search for short-duration unmodeled GW transients using X-Pipeline (P. J. Sutton et al. 2010; M. Was et al. 2012). While typically run as a coherent search across multiple detector, such as in previous searches for GWs from FRBs (R. Abbott et al. 2023), gamma-ray bursts (R. Abbott et al. 2021, 2022b), and magnetars (R. Abbott et al. 2024), we use X-Pipeline in a single-detector mode

because GEO600 was the only GW detector collecting data at the time of the FRBs. X-Pipeline splits the PSD-whitened data into 64 s segments, then applies a Fourier transform to produce time-frequency maps. The time-frequency pixels with amplitudes in the highest 1% that neighbor each other are clustered into candidate detection events. Each event is then assigned a ranking statistic based on the summed energy contained in the pixels. To determine the significance of these candidate events, we compare them against a distribution of background energies empirically measured in an identical manner from an “off-source” period. This is chosen to fall around (but not including) the time of the on-source data and to be long enough to allow for meaningful significances to be calculated but not so long that the detector’s behavior is nonstationary. We employ a 24 hr off-source window, symmetric about each event’s time.

When X-Pipeline is run on data from multiple detectors as is typical, vetoes of problematic event candidates can be applied by utilizing the presumed coherence of any real GW event across detectors. This is unfortunately not an option in a single-detector search such as this, meaning that the search becomes more vulnerable to background noise. To improve the sensitivity of our search, we apply frequency-domain vetoes based on the distribution of time-frequency candidate events in the off-source window for each FRB search. We veto narrow frequency bands (~ 10 Hz bandwidth) where there is considerable excess noise; most of these vetoes corresponded to known spectral lines from the GEO600 detector.

4. Search Results and Limits on Coincident Emission

In this section, we present the results of the long and short-duration searches described above (see Table 1 for a summary).

We do not find any candidate GW events in either the long-duration or short-duration compact-window searches for any of the FRBs. For the long-duration *PySTAMP* search, no triggers survive the cuts described in Section 3.2 for the 2020 April and 2022 October FRBs. Five triggers survive for the 2020 October FRB, but the loudest trigger has a FAR of ~ 1 per 1000 s with a p -value of 0.76 and is thus not significant. In the short-duration X-Pipeline case, only the 2020 April, 2020 October, and 2022 October FRBs compact-window searches had enough background to be considered useful for GW searches, as described above. The only surviving trigger from these three searches is from the 2022 October FRB and has a p -value of 0.53, and thus is also not significant.

For the short-duration extended-window searches, long off-source windows are required to estimate the background, and the single-detector nature of this search prevents the use of “time-slides” between multiple detectors to artificially generate background. These limitations mean that for the extended-window short-duration searches, there are sometimes as few as six off-source background trials, limiting any potential detection’s maximum significance to a p -value of $1/6 \approx 0.17$ —which is insufficient for any meaningful statement about the astrophysical nature of any outlier in the data. Thus, instead of reporting potential GW candidates from the extended-window searches with inconsequential statements about significance, we decided to use the searches only to determine the loudest trigger within the on-source window for a given waveform model, thereby setting an upper limit on the corresponding GW energy. This is the “loudest event statistic” (R. Biswas et al. 2009, 2013).

Table 3
The 50% and 90% Upper Limits on GW Emission Energy in erg from the Long-duration PySTAMP Search

Event	520 Hz		1020 Hz		1520 Hz		2020 Hz	
	50%	90%	50%	90%	50%	90%	50%	90%
2020 April 28	2.0×10^{50}	5.7×10^{50}	7.4×10^{50}	2.7×10^{51}	3.3×10^{51}	1.1×10^{52}	2.3×10^{52}	7.3×10^{52}
2020 October 08	1.6×10^{51}	1.0×10^{52}	4.4×10^{51}	2.9×10^{52}	1.7×10^{52}	1.1×10^{53}	1.1×10^{53}	6.8×10^{53}
2022 October 14	8.6×10^{49}	3.0×10^{50}	4.3×10^{50}	1.4×10^{51}	2.4×10^{51}	8.1×10^{51}	1.5×10^{52}	4.6×10^{52}

Note. Each frequency corresponds to the central frequency f_0 of a Sine-Gaussian waveform with duration parameter equal to 10 s.

Table 4
The 50% Upper Limits on GW Emission Energy in erg from the Short-duration X-Pipeline Search

Event		SG-D	SG-E	SG-F	SG-G	SG-H	SG-I	SG-J
Date	Window	300 Hz	500 Hz	1100 Hz	1600 Hz	1995 Hz	2600 Hz	3100 Hz
2020 Apr 28	Compact	7.1×10^{48}	3.4×10^{48}	1.1×10^{49}	2.9×10^{49}	8.3×10^{49}	1.6×10^{50}	3.2×10^{50}
2020 Apr 28	Extended	2.0×10^{49}	9.2×10^{48}	3.0×10^{49}	7.9×10^{49}	2.1×10^{50}	4.2×10^{50}	8.3×10^{50}
2020 Oct 8	Compact	5.8×10^{49}	1.7×10^{49}	3.6×10^{49}	9.1×10^{49}	2.3×10^{50}	5.4×10^{50}	1.1×10^{51}
2020 Oct 8	Extended	1.7×10^{51}	3.4×10^{50}	7.6×10^{50}	1.8×10^{51}	4.4×10^{51}	8.9×10^{51}	1.7×10^{52}
2022 Oct 14 glitch 1	Extended	...	8.2×10^{49}	3.3×10^{50}	1.0×10^{51}	2.6×10^{51}	6.5×10^{51}	1.4×10^{52}
2022 Oct 14 X-ray peak	Extended	...	3.8×10^{49}	1.6×10^{50}	5.1×10^{50}	1.2×10^{51}	3.0×10^{51}	6.6×10^{51}
2022 Oct 14	Compact	...	1.3×10^{48}	6.4×10^{48}	2.0×10^{49}	4.4×10^{49}	1.2×10^{50}	2.6×10^{50}
2022 Oct 14	Extended	...	7.1×10^{48}	3.3×10^{49}	1.0×10^{50}	2.3×10^{50}	5.7×10^{50}	1.2×10^{51}
2022 Oct 14 glitch 2	Extended	4.8×10^{50}	1.6×10^{50}	7.4×10^{50}	2.5×10^{51}	6.8×10^{51}	2.0×10^{52}	4.5×10^{52}
2022 Dec 1	Extended	9.4×10^{49}	3.4×10^{49}	9.3×10^{49}	2.7×10^{50}	7.4×10^{50}	1.7×10^{51}	3.1×10^{51}
Event		SG-K	SG-L	SG-M	DS2P-A	DS2P-B	DS2P-C	DS2P-D
Date	Window	3560 Hz	1600 Hz	1995 Hz	1590 Hz	1590 Hz	2020 Hz	2020 Hz
2020 Apr 28	Compact	5.8×10^{50}	1.0×10^{49}	2.4×10^{49}	2.5×10^{49}	2.9×10^{49}	1.6×10^{50}	2.3×10^{50}
2020 Apr 28	Extended	1.5×10^{51}	2.5×10^{49}	6.0×10^{49}	7.8×10^{49}	7.5×10^{49}	3.6×10^{50}	6.6×10^{50}
2020 Oct 8	Compact	2.0×10^{51}	2.8×10^{49}	7.1×10^{49}	8.9×10^{49}	8.7×10^{49}	3.2×10^{50}	3.4×10^{50}
2020 Oct 8	Extended	3.5×10^{52}	4.7×10^{50}	1.0×10^{51}	1.8×10^{51}	2.0×10^{51}	6.7×10^{51}	6.7×10^{51}
2022 Oct 14 glitch 1	Extended	2.2×10^{52}	3.2×10^{50}	9.1×10^{50}	1.1×10^{51}	1.2×10^{51}	3.0×10^{51}	2.9×10^{51}
2022 Oct 14 X-ray peak	Extended	1.0×10^{52}	1.6×10^{50}	4.3×10^{50}	5.7×10^{50}	5.6×10^{50}	1.4×10^{51}	1.4×10^{51}
2022 Oct 14	Compact	4.3×10^{50}	6.3×10^{48}	1.6×10^{49}	1.7×10^{49}	1.7×10^{49}	4.1×10^{49}	4.7×10^{49}
2022 Oct 14	Extended	2.0×10^{51}	3.1×10^{49}	8.0×10^{49}	9.9×10^{49}	9.6×10^{49}	2.5×10^{50}	2.6×10^{50}
2022 Oct 14 glitch 2	Extended	1.0×10^{53}	8.8×10^{50}	2.2×10^{51}	2.8×10^{51}	2.7×10^{51}	8.8×10^{51}	8.9×10^{51}
2022 Dec 1	Extended	5.9×10^{51}	7.9×10^{49}	1.9×10^{50}	2.4×10^{50}	2.5×10^{50}	7.9×10^{50}	8.1×10^{50}

Note. Each injection waveform is defined as in Table 2. Dashes indicate that no limit was obtainable for this set of injections due to insufficient background or poor data quality.

For all searches and windows (listed in Table 1), we estimate the root-sum-square signal amplitude of the GW strain h_{rss} (see Equations (3) and (4) of P. J. Sutton 2013) at 50% and 90% detection efficiency to set upper limits on the GW energy emitted. To convert the h_{rss} values for each injection type that are output by the search pipelines to energy, we use (following P. J. Sutton 2013)

$$E_{\text{GW}} = \frac{2}{5} \frac{\pi^2 c^3}{G} D_L^2 f_0^2 h_{\text{rss}}^2, \quad (1)$$

with f_0 describing the central frequency of each injection and D_L set to the 6.6 kpc distance of SGR 1935+2154 (P. Zhou et al. 2020). The results of the long-duration search are shown in Table 3. The 50% and 90% limits from the short-duration analysis are shown in Table 4 and Table 5, respectively. We show in Figure 3 our 90% upper limits from both the long and short-duration analyses as a function of frequency, corresponding to the upper limits at which 90% of the injected signals were recovered. To be explicit, the $X\%$

h_{rss} value for a given waveform model (and corresponding GW energy) is calculated by finding the h_{rss} at which $X\%$ of the injected waveforms are recovered (i.e., found with a significance higher than the loudest noninjection event in the window).

For some injections in the short-duration search (mostly those at lower frequencies such as SG-D with $f_0 = 300$ Hz), limits could not be established because noise in the detector prevented sufficient recovery of the injected signals. Limited data availability and poor data quality around the time of the 2020 October 8 event meant that no injection reached 90% recovery, leading to the lack of 90% limits.

The nondetection of GW emission from our analyzed FRBs implies that the GW-to-radio energy ratio must be less than $E_{\text{GW}}/E_{\text{radio}} \sim 8 \times 10^{14}$ at the 90% level, for a time window from $[-4, 4]$ s at a GW frequency of approximately 300 Hz. At the ~ 2 kHz frequencies close to the neutron-star f-mode, $E_{\text{GW}}/E_{\text{radio}} \lesssim 1.7 \times 10^{16}$ at the 90% level. The GW and radio energies for our analyzed FRBs are shown in Figure 4,

Table 5
Same as Table 4 but with 90% Upper Limits

Event Date	Window	SG-D 300 Hz	SG-E 500 Hz	SG-F 1100 Hz	SG-G 1600 Hz	SG-H 1995 Hz	SG-I 2600 Hz	SG-J 3100 Hz
2020 Apr 28	Compact	4.2×10^{49}	2.0×10^{49}	5.6×10^{49}	1.5×10^{50}	9.3×10^{50}	1.1×10^{51}	2.2×10^{51}
2020 Apr 28	Extended	8.2×10^{49}	4.0×10^{49}	1.5×10^{50}	4.0×10^{50}	1.3×10^{51}	2.3×10^{51}	5.2×10^{51}
2020 Oct 8	Compact	-	-	-	-	-	-	-
2020 Oct 8	Extended	-	-	-	-	-	-	-
2022 Oct 14 glitch 1	Extended	-	5.7×10^{50}	1.9×10^{51}	6.6×10^{51}	-	4.1×10^{52}	-
2022 Oct 14 X-ray peak	Extended	-	1.6×10^{50}	6.8×10^{50}	2.2×10^{51}	4.6×10^{51}	1.1×10^{52}	2.9×10^{52}
2022 Oct 14	Compact	-	6.4×10^{48}	3.9×10^{49}	1.3×10^{50}	2.3×10^{50}	6.3×10^{50}	1.3×10^{51}
2022 Oct 14	Extended	-	3.0×10^{49}	1.3×10^{50}	3.9×10^{50}	1.0×10^{51}	2.2×10^{51}	5.1×10^{51}
2022 Oct 14 glitch 2	Extended	2.1×10^{51}	7.2×10^{50}	2.7×10^{51}	9.3×10^{51}	2.8×10^{52}	8.4×10^{52}	1.9×10^{53}
2022 Dec 1	Extended	-	-	-	-	-	2.1×10^{54}	6.0×10^{52}
Event Date	Window	SG-K 3560 Hz	SG-L 1600 Hz	SG-M 1995 Hz	DS2P-A 1590 Hz	DS2P-B 1590 Hz	DS2P-C 2020 Hz	DS2P-D 2020 Hz
2020 Apr 28	Compact	3.3×10^{51}	2.7×10^{49}	1.1×10^{50}	2.0×10^{50}	1.9×10^{50}	1.0×10^{52}	-
2020 Apr 28	Extended	9.3×10^{51}	7.4×10^{49}	2.5×10^{50}	4.5×10^{50}	4.3×10^{50}	-	-
2020 Oct 8	Compact	-	-	-	-	-	-	-
2020 Oct 8	Extended	-	-	-	-	-	-	-
2022 Oct 14 glitch 1	Extended	-	7.0×10^{50}	1.3×10^{51}	6.1×10^{51}	8.1×10^{51}	1.6×10^{52}	1.6×10^{52}
2022 Oct 14 X-ray peak	Extended	4.3×10^{52}	3.3×10^{50}	6.1×10^{50}	...	2.5×10^{51}	5.0×10^{51}	6.0×10^{51}
2022 Oct 14	Compact	2.1×10^{51}	1.6×10^{49}	3.8×10^{49}	9.5×10^{49}	9.6×10^{49}	2.0×10^{50}	2.6×10^{50}
2022 Oct 14	Extended	8.9×10^{51}	6.1×10^{49}	1.3×10^{50}	4.5×10^{50}	4.4×10^{50}	9.5×10^{50}	1.3×10^{51}
2022 Oct 14 glitch 2	Extended	3.9×10^{53}	1.5×10^{51}	4.5×10^{51}	1.3×10^{52}	1.1×10^{52}	3.2×10^{52}	4.1×10^{52}
2022 Dec 1	Extended	-	-	8.5×10^{50}	-	6.6×10^{51}	6.2×10^{52}	2.0×10^{53}

Note. For some injections (marked by a dash), fewer than 90% of the injections are recovered, preventing the calculation of 90% limits.

alongside the same quantities for FRBs from O3a analyzed in R. Abbott et al. (2023).

5. Discussion and Conclusion

The previous best limits on coincident GW emission with FRBs were set by R. Abbott et al. (2023) using extragalactic FRBs observed during the O3a LVK observing run, using SG waveforms and X-Pipeline. Figure 3 shows the 90% upper limits on the GW energy during our analyzed FRBs from SGR 1935+2154, we compared previous limits presented as a range spanning the best and worst 90% limits from R. Abbott et al. (2023). In the short-duration search at approximately 300 Hz, the best previous 90% upper limit on GW energy was set at 3.4×10^{51} erg; at approximately 2 kHz, the best previous 90% upper limit was 7.9×10^{54} erg. We improve on the 300 Hz constraint by about two orders of magnitude, and the 2 kHz constraint by over four orders of magnitude. No previous long-duration searches around FRB events have been performed, so the long-duration search results presented here represent the first constraints on such emission. Studies have predicted that magnetar flares can emit up to 10^{48} – 10^{49} erg in GW energy near the f-mode for ~ 200 ms (K. Ioka 2001; A. Corsi & B. J. Owen 2011)—a regime that is probed by our most stringent 50% short-duration constraints at approximately 2 kHz (see SG-H waveform in Table 4). We also slightly improve the upper limit on $E_{\text{GW}}/E_{\text{radio}}$, as shown in Figure 4.

We note that our results are not the most constraining limits on GW emission from the magnetar SGR 1935+2154, which are reported in R. Abbott et al. (2024) in a search for GW emission around times of magnetar X-ray and gamma-ray flares. The relationship between these magnetar bursts and FRBs is poorly understood, but are likely to be caused by

different physical processes, even if the underlying magnetar behavior may be related (Y. Tsuzuki et al. 2024). Hence, both GW limits are complementary and can help to better understand the emission mechanisms at play. Considering the X-ray spin-up glitches, our best limits on the emitted GW energy ($\sim 10^{51}$ erg at 300 Hz) are still far from the X-ray measured changes in rotational energy ($\sim 10^{42}$ erg from C.-P. Hu et al. 2024).

Since $E_{\text{GW}} \propto D_L^2$ in Equation (1), our constraints are heavily dependent on the distance to SGR 1935+2154. As mentioned in Section 2, estimates for SGR 1935+2154’s distance vary by almost an order of magnitude. If its true distance is as close as the 1.5 kpc measured by M. Bailes et al. (2021), our energy constraints would improve by a factor of almost 20. On the other hand, if SGR 1935+2154 is at almost 15 kpc, as suggested by M. P. Surnis et al. (2016), our constraints would worsen by a factor of 5.

As a single-detector search, the number of possible background trials (and thus the assessment of GW candidates via p -value or FAR) is limited by the time in which the detector behavior remains similar to that of the on-source window. For example, the minimum FAR for the long-duration PySTAMP search was limited to ~ 1 per 12 hr. Since we do not recover any candidates in the on-source windows which appear to differentiate themselves from the background, we did not have to assess any candidate’s significance beyond 1 per 12 hr, meaning that this limitation did not affect our results. However, future single-detector searches may encounter the problem where a candidate in the on-source window is unlike anything found in the background trials, complicating an accurate assessment of its significance. Some GW CBC searches have implemented techniques to improve single-detector significance estimation (S. Sachdev et al. 2019; G. S. Cabourn Davies

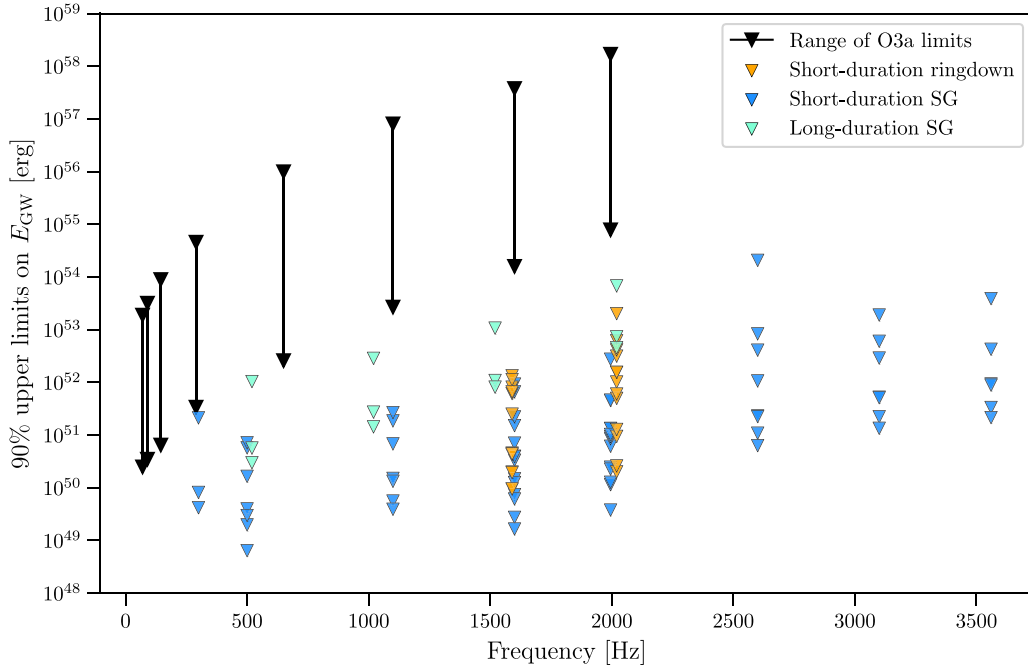


Figure 3. The 90% upper limits on the emitted GW energy from SGR 1935+2154 coincident with FRBs, alongside GW energy limits from FRBs during the O3a observing run as reported in R. Abbott et al. (2023). We plot the short-duration ringdown (orange) and Sine-Gaussian (SG; blue) waveforms from Table 5, and the long-duration SG waveforms (aquamarine) from Table 3. The previous range of 90% limits from R. Abbott et al. (2023), based on the lower bounds of the 90% credible distance as reported in their Table A1, are plotted in vertical black lines. These are for a short-duration search; R. Abbott et al. (2023) did not perform a long-duration analysis.

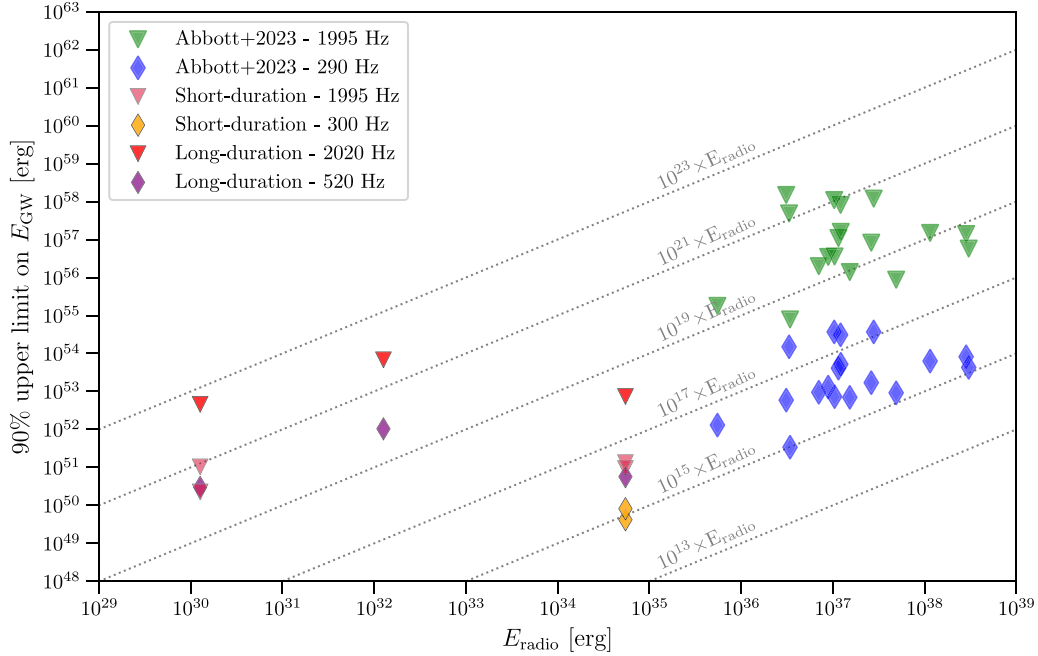


Figure 4. The 90% upper limits on the emitted GW energy from FRBs as a function of the FRB's radio energy. In the pink, orange, red, and purple, we show limits from FRBs emitted by SGR 1935+2154, for both our short- and long-duration searches. We plot limits for the Sine-Gaussian model at 300 Hz (SG-D) and 1995 Hz (SG-H) for the short-duration search and at 520 and 2020 Hz for the long-duration search. In the blue and green markers, we show the upper limits on GW energy and the corresponding radio energy for FRBs analyzed in R. Abbott et al. (2023), at 290 and 1995 Hz, for events with radio flux/fluence information from CHIME/FRB Collaboration et al. (2021) allowing for radio energy reconstruction. The estimated radio energies are calculated as described in G. Principe et al. (2023), scaled to the lower bound 90% distances as reported in R. Abbott et al. (2023). Note that the radio energies (derived from fluxes and fluences) should be interpreted as lower limits (CHIME/FRB Collaboration et al. 2021; B. C. Andersen et al. 2023). We also plot dotted lines representing different ratios of E_{GW} to E_{radio} , showing a slight improvement in $E_{\text{GW}}/E_{\text{radio}}$ compared to R. Abbott et al.'s (2023) results.

& I. W. Harry 2022); unmodeled searches such as PySTAMP and X-Pipeline may also benefit from such enhancements.

At the time of writing, no FRBs have been detected from SGR 1935+2154 since 2022. The O4 observing run of the

LVK, with participation from the LIGO, Virgo, and KAGRA detectors will continue until mid-2025. Given the increased sensitivity of these detectors compared to GEO600, any SGR 1935+2154 FRB during the remainder of O4

could provide another opportunity to probe the GW-FRB connection.

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ORCID iDs

A. G. Abac  <https://orcid.org/0000-0003-4786-2698>
 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>
 D. Agarwal  <https://orcid.org/0000-0002-8735-5554>
 M. Agathos  <https://orcid.org/0000-0002-9072-1121>
 M. Aghaei Abchouyeh  <https://orcid.org/0000-0002-1518-1946>
 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>
S. Albanesi  <https://orcid.org/0000-0001-7345-4415>
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>
S. Alvarez-Lopez  <https://orcid.org/0009-0003-8040-4936>
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-Carasona  <https://orcid.org/0000-0002-8738-1672>
T. Andrić  <https://orcid.org/0000-0002-9277-9773>
S. Ansoldi  <https://orcid.org/0000-0002-5613-7693>
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>
F. Armato  <https://orcid.org/0000-0002-8856-8877>
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>
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. Attadio  <https://orcid.org/0009-0008-8916-1658>
F. Aubin  <https://orcid.org/0000-0003-1613-3142>
K. AultONeal  <https://orcid.org/0000-0002-6645-4473>
G. Avallone  <https://orcid.org/0000-0001-5482-0299>
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>
L. Baiotti  <https://orcid.org/0000-0003-0458-4288>
R. Bajpai  <https://orcid.org/0000-0003-0495-5720>
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. Basalaev  <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>
F. Beirnaert  <https://orcid.org/0000-0002-4003-7233>
M. Bejger  <https://orcid.org/0000-0002-4991-8213>
D. Belardinelli  <https://orcid.org/0000-0001-9332-5733>
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>
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. Bevin  <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>
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. Bitossi  <https://orcid.org/0000-0002-9862-4668>
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>
M. S. Bonilla  <https://orcid.org/0000-0003-4502-528X>
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>
E. Brockmueller  <https://orcid.org/0000-0002-1489-942X>
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>
E. Capocasa  <https://orcid.org/0000-0003-3762-6958>
E. Capote  <https://orcid.org/0009-0007-0246-713X>
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>
 C. Casentini  <https://orcid.org/0000-0001-8100-0579>
 M. Cavaglià  <https://orcid.org/0000-0002-3835-6729>
 R. Cavalieri  <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>
 P. Chakraborty  <https://orcid.org/0000-0002-0994-7394>
 S. Chalathadka Subrahmanya  <https://orcid.org/0000-0002-9207-4669>
 J. C. L. Chan  <https://orcid.org/0000-0002-3377-4737>
 S. Chao  <https://orcid.org/0000-0003-3853-3593>
 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>
 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>
 Yitian Chen  <https://orcid.org/0000-0002-8664-9702>
 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>
 M. L. Chiofalo  <https://orcid.org/0000-0002-6992-5963>
 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>
 M. Cifaldi  <https://orcid.org/0009-0007-1566-7093>
 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>
 S. Colace  <https://orcid.org/0009-0007-9429-1847>
 M. Colleoni  <https://orcid.org/0000-0002-7214-9088>
 A. Colombo  <https://orcid.org/0000-0002-7439-4773>
 M. Colpi  <https://orcid.org/0000-0002-3370-6152>
 L. Conti  <https://orcid.org/0000-0003-2731-2656>
 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>
 S. T. Countryman  <https://orcid.org/0000-0003-0613-2760>
 P. Couvares  <https://orcid.org/0000-0002-2823-3127>
 R. Coyne  <https://orcid.org/0000-0002-5243-5917>
 J. D. E. Creighton  <https://orcid.org/0000-0003-3600-2406>
 P. Cremonese  <https://orcid.org/0000-0001-6472-8509>
 A. W. Criswell  <https://orcid.org/0000-0002-9225-7756>
 J. R. Cudell  <https://orcid.org/0000-0002-2003-4238>
 T. J. Cullen  <https://orcid.org/0000-0001-8075-4088>
 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>
 S. Dal Pra  <https://orcid.org/0000-0002-1057-2307>
 G. Dálya  <https://orcid.org/0000-0003-3258-5763>
 B. D’Angelo  <https://orcid.org/0000-0001-9143-8427>
 S. Danilishin  <https://orcid.org/0000-0001-7758-7493>
 S. D’Antonio  <https://orcid.org/0000-0003-0898-6030>
 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>
 P. J. Davis  <https://orcid.org/0009-0004-5008-5660>
 M. Dax  <https://orcid.org/0000-0001-8798-0627>
 J. De Bolle  <https://orcid.org/0000-0002-5179-1725>
 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>
 F. De Lillo  <https://orcid.org/0000-0003-4977-0789>
 D. Dell’Aquila  <https://orcid.org/0000-0001-5895-0664>
 W. Del Pozzo  <https://orcid.org/0000-0003-3978-2030>
 F. De Marco  <https://orcid.org/0000-0002-5411-9424>
 F. De Matteis  <https://orcid.org/0000-0001-7860-9754>
 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>
 R. DeSalvo  <https://orcid.org/0000-0002-4818-0296>
 M. C. Díaz  <https://orcid.org/0000-0002-7555-8856>
 M. Di Cesare  <https://orcid.org/0009-0003-0411-6043>
 T. Dietrich  <https://orcid.org/0000-0003-2374-307X>
 C. Di Fronzo  <https://orcid.org/0000-0002-2693-6769>
 M. Di Giovanni  <https://orcid.org/0000-0003-4049-8336>
 T. Di Girolamo  <https://orcid.org/0000-0003-2339-4471>
 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>
 M. Emma  <https://orcid.org/0000-0001-7943-0262>
 L. Errico  <https://orcid.org/0000-0003-2112-0653>
 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>
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>
R. . Felicetti  <https://orcid.org/0009-0005-6263-5604>
E. Fenyesi  <https://orcid.org/0000-0003-2777-3719>
D. L. Ferguson  <https://orcid.org/0000-0002-4406-591X>
S. Ferraiuolo  <https://orcid.org/0009-0005-5582-2989>
I. Ferrante  <https://orcid.org/0000-0002-0083-7228>
F. Fidecaro  <https://orcid.org/0000-0002-6189-3311>
P. Figura  <https://orcid.org/0000-0002-8925-0393>
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>
V. Fiumara  <https://orcid.org/0000-0003-3644-217X>
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>
M. Fuentes-García  <https://orcid.org/0000-0003-3390-8712>
B. Gadre  <https://orcid.org/0000-0002-1534-9761>
J. R. Gair  <https://orcid.org/0000-0002-1671-3668>
S. Galaudage  <https://orcid.org/0000-0002-1819-0215>
R. Gamba  <https://orcid.org/0000-0001-7239-0659>
A. Gamboa  <https://orcid.org/0000-0001-8391-5596>
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. García-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>
J. Gargiulo  <https://orcid.org/0000-0002-3507-6924>
A. Garron  <https://orcid.org/0000-0002-1601-797X>
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>
V. Gennari  <https://orcid.org/0000-0002-0190-9262>
R. George  <https://orcid.org/0000-0002-7797-7683>
O. Gerberding  <https://orcid.org/0000-0001-7740-2698>
L. Gergely  <https://orcid.org/0000-0003-3146-6201>
S. Ghonge  <https://orcid.org/0000-0002-5476-938X>
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>
C. Gier  <https://orcid.org/0000-0003-0897-7943>
P. Giri  <https://orcid.org/0000-0002-4628-2432>
S. Gkaitatzis  <https://orcid.org/0000-0001-9420-7499>
N. L. Goebbels  <https://orcid.org/0000-0002-3923-5806>
E. Goetz  <https://orcid.org/0000-0003-2666-721X>
S. Gomez Lopez  <https://orcid.org/0000-0002-9557-4706>
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>
A. S. Göttel  <https://orcid.org/0000-0002-6215-4641>
R. Gouaty  <https://orcid.org/0000-0001-5372-7084>
S. Goyal  <https://orcid.org/0000-0002-4225-010X>
B. Grace  <https://orcid.org/0009-0009-9349-9317>
A. Grado  <https://orcid.org/0000-0002-0501-8256>
V. Graham  <https://orcid.org/0000-0003-3633-0135>
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>
W. Guo  <https://orcid.org/0000-0002-4320-4420>
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>
T. Gupta  <https://orcid.org/0000-0003-2692-5442>
F. Guzman  <https://orcid.org/0000-0001-9136-929X>
M. Haberland  <https://orcid.org/0000-0001-9816-5660>
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. Harmark  <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>
C.-J. Haster  <https://orcid.org/0000-0001-8040-9807>
K. Haughian  <https://orcid.org/0000-0002-1223-7342>
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>
O. Henderson-Sapir  <https://orcid.org/0000-0002-1613-9985>
M. Hendry  <https://orcid.org/0000-0001-8322-5405>
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>
W. C. G. Ho  <https://orcid.org/0000-0002-6089-6836>
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>
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>
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>
L. Iampieri  <https://orcid.org/0009-0004-1161-2990>
G. A. Iandolo  <https://orcid.org/0000-0003-1155-4327>
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>
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>
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>
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>
J. Kubisz  <https://orcid.org/0000-0001-7258-8673>
M. C. Johnston  <https://orcid.org/0000-0002-0663-9193>
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>
R. Kashyap  <https://orcid.org/0000-0002-5700-282X>
M. Kasprzak  <https://orcid.org/0000-0003-4618-5939>
R. Kaushik  <https://orcid.org/0000-0003-4888-5154>
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>
F. Khan  <https://orcid.org/0000-0001-6176-853X>
W. Kiendrebeogo  <https://orcid.org/0000-0002-9108-5059>
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>
C. Kimball  <https://orcid.org/0000-0001-9879-6884>
M. Kinley-Hanlon  <https://orcid.org/0000-0002-7367-8002>
J. S. Kissel  <https://orcid.org/0000-0002-1702-9577>
A. M. Knee  <https://orcid.org/0000-0003-0703-947X>
N. Knust  <https://orcid.org/0000-0002-5984-5353>
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>
A. Kulur Ramamohan  <https://orcid.org/0000-0003-3681-1887>
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>
S. Kuwahara  <https://orcid.org/0009-0009-2249-8798>
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>
Y. K. Lecoeuche  <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. Le Jean  <https://orcid.org/0009-0003-8047-3958>
M. Lenti  <https://orcid.org/0000-0002-2765-3955>
M. Leonardi  <https://orcid.org/0000-0002-7641-0060>
N. Leroy  <https://orcid.org/0000-0002-2321-1017>
M. Lethuillier  <https://orcid.org/0000-0001-6185-2045>
K. Leyde  <https://orcid.org/0000-0001-7661-2810>
K. L. Li  <https://orcid.org/0000-0001-8229-2024>
X. Li  <https://orcid.org/0000-0002-3780-7735>
C.-Y. 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>
Y.-C. Lin  <https://orcid.org/0000-0003-4939-1404>

- 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>
J. Llobera-Querol  <https://orcid.org/0000-0003-3322-6850>
R. K. L. Lo  <https://orcid.org/0000-0003-1561-6716>
A. Longo  <https://orcid.org/0000-0003-4254-8579>
D. Lopez  <https://orcid.org/0000-0003-3342-9906>
M. Lorenzini  <https://orcid.org/0000-0002-2765-7905>
A. Lorenzo-Medina  <https://orcid.org/0009-0006-0860-5700>
G. Losurdo  <https://orcid.org/0000-0003-0452-746X>
T. P. Lott IV  <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>
N. Lu  <https://orcid.org/0000-0002-8861-9902>
D. Lumaca  <https://orcid.org/0000-0002-3628-1591>
A. W. Lussier  <https://orcid.org/0000-0002-4507-1123>
L.-T. Ma  <https://orcid.org/0009-0000-0674-7592>
M. Ma'arif  <https://orcid.org/0000-0001-8472-7095>
R. Macas  <https://orcid.org/0000-0002-6096-8297>
A. Macedo  <https://orcid.org/0009-0001-7671-6377>
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>
E. Maggio  <https://orcid.org/0000-0002-1960-8185>
M. Magnozzi  <https://orcid.org/0000-0003-4512-8430>
U. Mali  <https://orcid.org/0009-0003-1285-2788>
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>
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>
J. C. Martins  <https://orcid.org/0000-0002-6099-4831>
M. Masso-Reid  <https://orcid.org/0000-0001-6177-8105>
S. Mastrogianni  <https://orcid.org/0000-0003-1606-4183>
M. Matiushechkina  <https://orcid.org/0000-0002-9957-8720>
N. Mavalvala  <https://orcid.org/0000-0003-0219-9706>
L. McCuller  <https://orcid.org/0000-0003-0851-0593>
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>
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>
J. R. Mérou  <https://orcid.org/0000-0002-5776-6643>
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>
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>
V. Milotti  <https://orcid.org/0000-0003-4732-1226>
LL. M. Mir  <https://orcid.org/0000-0002-4276-715X>
L. Mirasola  <https://orcid.org/0009-0004-0174-1377>
M. Miravet-Tenés  <https://orcid.org/0000-0002-8766-1156>
C.-A. Miritescu  <https://orcid.org/0000-0002-7716-0569>
C. Mishra  <https://orcid.org/0000-0002-8115-8728>
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>
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>
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>
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>
P. Mourier  <https://orcid.org/0000-0001-8078-6901>
B. Mours  <https://orcid.org/0000-0002-6444-6402>
C. M. Mow-Lowry  <https://orcid.org/0000-0002-0351-4555>
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>
P. G. Murray  <https://orcid.org/0000-0002-8218-2404>
D. Nabari  <https://orcid.org/0009-0006-8500-7624>
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>
A. Neunert  <https://orcid.org/0000-0003-0323-0111>
L. Nguyen Quynh  <https://orcid.org/0000-0002-1828-3702>
A. B. Nielsen  <https://orcid.org/0000-0001-8694-4026>
A. Niko  <https://orcid.org/0009-0007-4502-9359>
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>
J. Oberling  <https://orcid.org/0009-0001-4174-3973>
M. Oertel  <https://orcid.org/0000-0002-1884-8654>
K. Oh  <https://orcid.org/0000-0002-9672-3742>
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. Orsell  <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>
I. Ota  <https://orcid.org/0000-0001-5045-2484>
D. J. Ottaway  <https://orcid.org/0000-0001-6794-1591>
B. J. Owen  <https://orcid.org/0000-0003-3919-0780>
R. Pagano  <https://orcid.org/0000-0001-8362-0130>
M. A. Page  <https://orcid.org/0000-0002-5298-7914>
A. Pai  <https://orcid.org/0000-0003-3476-4589>
S. Pal  <https://orcid.org/0000-0003-2172-8589>
M. A. Palaia  <https://orcid.org/0009-0007-3296-8648>
C. Palomba  <https://orcid.org/0000-0002-4450-9883>
P. Palud  <https://orcid.org/0000-0002-5850-6325>
K. C. Pan  <https://orcid.org/0000-0002-1473-9880>
R. Panai  <https://orcid.org/0009-0003-3282-1970>
F. Pannarale  <https://orcid.org/0000-0002-7537-3210>
F. Paoletti  <https://orcid.org/0000-0001-8898-1963>
L. Papalini  <https://orcid.org/0000-0002-5219-0454>
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>
O. Patane  <https://orcid.org/0000-0002-4850-2355>
B. Patricelli  <https://orcid.org/0000-0001-6709-0969>
K. Paul  <https://orcid.org/0000-0002-8406-6503>
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>
G. Perna  <https://orcid.org/0000-0002-7364-1904>
A. Perreca  <https://orcid.org/0000-0002-6269-2490>
S. Perriès  <https://orcid.org/0000-0003-2213-3579>
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>
L. Piccari  <https://orcid.org/0009-0000-0247-4339>
O. J. Piccinni  <https://orcid.org/0000-0001-5478-3950>
M. Pichot  <https://orcid.org/0000-0002-4439-8968>
M. Piendibene  <https://orcid.org/0000-0003-2434-488X>
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>
M. Pillas  <https://orcid.org/0000-0003-3224-2146>
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>
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. Principe  <https://orcid.org/0000-0003-0406-7387>
G. A. Prodi  <https://orcid.org/0000-0001-5256-915X>
L. Prokhorov  <https://orcid.org/0000-0002-0869-185X>
J. Pullin  <https://orcid.org/0000-0001-8248-603X>
M. Punturo  <https://orcid.org/0000-0001-8722-4485>
M. Pürner  <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>
G. Quémeré  <https://orcid.org/0000-0001-6703-6655>
F. J. Raab  <https://orcid.org/0009-0005-5872-9819>
B. Rajbhandari  <https://orcid.org/0000-0001-7568-1611>
K. E. Ramirez  <https://orcid.org/0000-0003-2194-7669>
F. A. Ramis Vidal  <https://orcid.org/0000-0001-6143-2104>
A. Ramos-Buades  <https://orcid.org/0000-0002-6874-7421>
S. Ranjan  <https://orcid.org/0000-0001-7480-9329>
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>
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. Rettengo  <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>
M. Ricci  <https://orcid.org/0009-0008-7421-4331>
A. Ricciardone  <https://orcid.org/0000-0002-5688-455X>
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. E. Romano  <https://orcid.org/0000-0002-0314-8698>
R. Romano  <https://orcid.org/0000-0002-0485-6936>
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>
S. K. Roy  <https://orcid.org/0000-0001-9295-5119>
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>
M. R. Sah  <https://orcid.org/0009-0005-9881-1788>
S. Saha  <https://orcid.org/0000-0002-3333-8070>
S. Sajith Menon  <https://orcid.org/0009-0008-4985-1320>
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>

- J. H. Sanchez  <https://orcid.org/0000-0001-7080-4176>
 N. Sanchis-Gual  <https://orcid.org/0000-0001-5375-7494>
 E. M. Sanger  <https://orcid.org/0009-0003-6642-8974>
 S. Sasaoka  <https://orcid.org/0000-0002-2155-8092>
 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>
 T. Sawada  <https://orcid.org/0000-0001-5726-7150>
 M. G. Schiworski  <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>
 M. Serra  <https://orcid.org/0000-0002-6093-8063>
 G. Servignat  <https://orcid.org/0000-0003-0057-922X>
 U. S. Shah  <https://orcid.org/0000-0001-8249-7425>
 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>
 H. Siegel  <https://orcid.org/0000-0001-5161-4617>
 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>
 W. J. Smith  <https://orcid.org/0009-0003-7949-4911>
 J. Soldateschi  <https://orcid.org/0000-0002-5458-5206>
 K. Somiya  <https://orcid.org/0000-0003-2601-2264>
 I. Song  <https://orcid.org/0000-0002-4301-8281>
 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>
 H. Sotani  <https://orcid.org/0000-0002-3239-2921>
 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>
 L. Suleiman  <https://orcid.org/0000-0003-3783-7448>
 L. Sun  <https://orcid.org/0000-0001-7959-892X>
 P. J. Sutton  <https://orcid.org/0000-0003-1614-3922>
 T. 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 Martn  <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. 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>
 S. Tiwari  <https://orcid.org/0000-0003-1611-6625>
 V. Tiwari  <https://orcid.org/0000-0002-1602-4176>
 A. M. Toivonen  <https://orcid.org/0009-0008-9546-2035>
 K. Toland  <https://orcid.org/0000-0001-9537-9698>
 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>
 N. Toropov  <https://orcid.org/0000-0002-0297-3661>
 A. Torres-Forne  <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. Tournefier  <https://orcid.org/0000-0002-5465-9607>
 A. Trapananti  <https://orcid.org/0000-0001-7763-5758>
 F. Travasso  <https://orcid.org/0000-0002-4653-6156>
 M. C. Tringali  <https://orcid.org/0000-0001-5087-189X>
 A. Tripathee  <https://orcid.org/0000-0002-6976-5576>
 A. Trovato  <https://orcid.org/0000-0002-9714-1904>
 T. T. L. Tsang  <https://orcid.org/0000-0003-3666-686X>
 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>
 M. Turconi  <https://orcid.org/0000-0001-9999-2027>
 H. Ubach  <https://orcid.org/0000-0002-0679-9074>
 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>
 V. Undheim  <https://orcid.org/0000-0003-4028-0054>
 T. Ushiba  <https://orcid.org/0000-0002-5059-4033>
 M. Vacatello  <https://orcid.org/0009-0006-0934-1014>
 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>
 J. Valencia  <https://orcid.org/0000-0003-2648-9759>
 M. Valentini  <https://orcid.org/0000-0003-1215-4552>
 S. A. Vallejo-Peña  <https://orcid.org/0000-0002-6827-9509>
 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>
 M. van der Sluys  <https://orcid.org/0000-0003-1231-0762>
 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>
 P. Van Hove  <https://orcid.org/0000-0002-2431-3381>
 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>
 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>
 A. Veutro  <https://orcid.org/0009-0002-9160-5808>
 A. M. Vibhute  <https://orcid.org/0000-0003-1501-6972>
 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>
 H. Vocca  <https://orcid.org/0000-0002-1200-3917>
 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>
 G. Waratkar  <https://orcid.org/0000-0003-3630-9440>
 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>
 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>
 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>
 H. W. Y. Wong  <https://orcid.org/0000-0002-4027-9160>
 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>
 V. A. Xu  <https://orcid.org/0000-0002-3020-3293>
 Y. Xu  <https://orcid.org/0000-0001-8697-3505>
 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>
 Y. Yang  <https://orcid.org/0000-0002-3780-1413>
 Z. Yarbrough  <https://orcid.org/0000-0002-9825-1136>
 A. B. Yelkar  <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>
 R. Zhang  <https://orcid.org/0000-0001-8095-483X>
 Y. 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>
 X.-J. Zhu  <https://orcid.org/0000-0001-7049-6468>
 Z.-H. Zhu  <https://orcid.org/0000-0002-3567-6743>
 J. Zweizig  <https://orcid.org/0000-0002-1521-3397>

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