

# Ilya Mandel

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## CONTACT INFORMATION

School of Physics and Astronomy, Monash University  
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## EDUCATION

**California Institute of Technology**, Pasadena, CA USA

Ph.D. in Physics (conferred June 2008)

- Dissertation Title: “The Three Ss of Gravitational Wave Astronomy: Sources, Signals, Searches”
- Advisor: Kip S. Thorne

M.S. in Physics, 2003

**Stanford University**, Stanford, CA USA

M.S. in Computer Science (Theory specialization), 2001

B.S. in Physics, with Distinction and Departmental Honors, 2000

## ACADEMIC EXPERIENCE

**Monash University, Australia**

*Professor of Astrophysics*

**2019 - present**

**University of Birmingham, UK**

*Honorary Professor*

**2019 - present**

*Professor of Theoretical Astrophysics*

**2016 - 2019**

*Senior Lecturer*

**2014 - 2016**

*Lecturer*

**2011 - 2014**

**NSF Astronomy & Astrophysics Postdoctoral Fellow**

**2009 - 2011**

At Northwestern 9/2009-6/2010; at MIT 7/2010-8/2011.

**Northwestern University**, Evanston, IL USA

*Postdoctoral Scholar in Theoretical Astrophysics*

**2007 - 2009**

Mentor: Vicky Kalogera

**California Institute of Technology**, Pasadena, CA USA

*Research Assistant*

**2006 - 2007**

*Teaching Assistant*

**2001 - 2006**

**Stanford University**, Stanford, CA USA

*Research Assistant, Gravity Probe B*

**1996 - 2003**

*Research and Teaching Assistant, Computer Science*

**1999**

## AWARDS

Australian Research Council Future Fellow, 2019-2023

Elected Patron of AstroSoc student society, 2017

Breakthrough Prize in Fundamental Physics (part of LIGO team), May 2016

SAMSI (Statistical and Applied Mathematical Science Institute) Research Fellow, 2016–2017

College of Engineering and Physical Sciences paper of the month award, February 2016

Classical and Quantum Gravity highlights – most cited article in 2 years (“Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors”), 2012

Head of School commendation letters for excellence in teaching (multiple years, 2013–2018)

Kevin Westfold Distinguished Visitor, Monash Center for Astrophysics, 2014

NSF Astronomy and Astrophysics Postdoctoral Fellowship  
Dean's Award for Academic Achievement (excellence in research), Stanford University  
Tau Beta Pi (engineering honor society) Member  
National Merit Scholar, National Advanced Placement Scholar

#### SERVICE

Reviewer for the Astrophysical Journal, Physical Review, Classical and Quantum Gravity, Monthly Notices of the Royal Astronomical Society, Philosophical Transactions of the Royal Society, Nature journals, Science (2008–current)  
Editorial Board member, Scientific Data; Advisory Board member, Universe  
Grant reviewer for NASA, NSF, Hungarian Scientific Research Fund, STFC, NWO (Netherlands Organisation for Scientific Research), European Research Council, CONICYT (Chile), ARC (2008–current)  
LIGO Scientific Collaboration member (2005–2016), LSC Council member (2012 – 2016)  
LSC internal reviewer (2009 – 2016), intermediate mass black hole source group co-chair (2012 – 2016)  
Mock LISA Data Challenge and Parameter Estimation Taskforce member  
Einstein Telescope Science Working Group member  
LOFT science team member  
University of Birmingham astrophysics seminar organizer (2012–2015)  
University of Birmingham physics and astronomy colloquium organizer (2015–current)  
University of Birmingham head of graduate admissions for astronomy (2012 – current)  
University of Birmingham Faculty Senate representative elected for Engineering and Physical Sciences (2016 – current)  
School and College Equality and Diversity Committee member, University of Birmingham (2014 – 2017)  
SOC member, inaugural South African GW workshop (2011)  
Convener of relativistic astrophysics session, GR-20 (2013)  
Co-organizer and SOC co-chair, “Science with the first gravitational-wave detections” (2013)  
Lead organizer, Aspen Physics Center Workshop on Ultra-compact Binaries as Laboratories for Fundamental Physics (2014)  
Main organizer and SOC chair, Gravitational-wave Astrophysics meeting at COSPAR (2014)  
Program Leader, SAMSI Program on Statistical, Mathematical and Computational Methods for Astronomy (2016–2017)  
Main organizer and SOC chair, Massive Binary Evolution meeting at COSPAR (2016 [cancelled because of current events in Turkey])  
International Society on General Relativity & Gravitation, Nominating Committee member (2016 – current)  
Aspen Center for Physics board member (2016 – current)  
Organizer, SAMSI workshop on Astrophysical Population Emulation and Uncertainty Quantification (2017)  
SOC member, Alpine Cosmology Workshop (2017 – current)  
Co-director, Kavli Summer Program in Astrophysics 2017: Astrophysics with gravitational wave detections (2017)  
Co-organizer and SOC co-chair, Lorentz Center Workshop “And then there was light: Electromagnetic signatures of stellar mass binary black hole mergers” (2017)  
Co-organizer, Munich Institute for Astro- and Particle Physics program “Precision gravity: from the LHC to LISA” (2019)  
Gravitational-Wave International Committee 3G Science Case team member, Binaries working group co-chair (2017 – current)  
Organising Committee Member, IAU Binary and Multiple Star Systems Commission (2018 – present)  
LISA Consortium Member  
SOC Member, EAS Symposium “What have we learned from the observed population of gravitational wave sources?” (2020)

SOC Member, COSPAR event “X- and Gamma-ray Counterparts of New Transients in the Multi-messenger Era” (2020)

Member of several electromagnetic transient surveys (e.g., ePESSTO) and multi-messenger consortia for following up gravitational-wave signals (e.g., ENGRAVE, where I co-chair the Populations theory group)

Deputy chair, steering committee of the Australian National Institute for Theoretical Astrophysics (ANITA; 2019 – current)

Councillor, Astronomical Society of Australia (2019 – current)

## MENTORING

### *Postdoctoral associates:*

Trevor Sidery (2011 – 2013, co-mentored with Alberto Vecchio), gravitational-wave data analysis  
Walter del Pozzo (2013 – 2016), tests of general relativity with compact binaries; now faculty at University of Pisa

Christopher Berry (2013 – 2017, co-mentored with Alberto Vecchio), astrostatistics; now faculty at Northwestern University

Dorottya Szécsi (2017 – 2018), stellar evolution; now Humboldt fellow in Cologne

Tyrone Woods (2018 – 2018), stellar and binary evolution; now Plaskett Fellow at the NRC Herzberg Astronomy and Astrophysics, Victoria, Canada

### *Post-graduate students:*

Vivien Raymond (2007 – 2012, co-advised with Vicky Kalogera), parameter estimation on spinning binaries; now faculty at Cardiff University via Albert Einstein Institute postdoc and Caltech postdoctoral prize fellowship

Ben Farr (2009 – 2014, co-advised with V. Kalogera), MCMC techniques in LIGO data analysis; now faculty at University of Oregon via McCormick postdoctoral fellow at U. Chicago

Carl Rodriguez (2010 – 2013, co-advised with V. Kalogera), signatures of deviations from Kerr spacetime; now Pappalardo prize postdoc at MIT

Rory Smith (2011 – 2013), intermediate-mass-ratio waveforms and rapid parameter estimation; now OzGrav postdoc at Monash via postdoc at Caltech

Will Vousden (2011 – 2015), astrophysics with multi-messenger gravitational-wave detections, now at Oxford Asset Management

Carl-Johan Haster (2012 – 2016), topics in gravitational-wave data analysis; now postdoc at CITA, winner of Springer PhD thesis award

Simon Stevenson (2013 – 2017), population synthesis of compact binaries; now OzGrav postdoc at Swinburne University

Ben Bradnick (2015 – 2017, co-advised with W. Farr), galactic center dynamics; now at Tesella

Serena Vinciguerra (2014 – 2018), advanced techniques for efficient parameter estimation; now postdoc at AEI Hannover

Alejandro Vigna Gomez (2015 – 2019), mass transfer in stellar binaries; now postdoc at DARK, Copenhagen

Jim Barrett (2015 – 2018, co-advised with W. Farr), emulators and machine learning; now in Stockholm

Coenraad Neijssel (2016 – present), formation of binary black holes across cosmic history

Reinhold Willcox (2019 – present), neutron star kicks and dynamics

Jeff Riley (2019 – present), massive stellar binary population synthesis

Mike Lau (2019 – present), low-frequency gravitational-wave sources

### *Undergraduate and masters students:*

Matthew Dodelson (2009) and Daniel Douglas (2010) testing GR with EMRIs

Frederick Robinson (2009 – 2010), Fisher matrix analysis

Luke Kelley (2010 – 2011, co-advised with Enrico Ramirez-Ruiz), electromagnetic counterparts to LIGO searches

Alex Mellus and Benjamin Hubbert (2012), investigation of numerical waveform accuracy and pa-

parameter estimation tests of convergence

Jason Tye (2012 – 2013), animations of gravitational waves, gravitational lensing of gravitational waves

Ben Bradnick and Hannah Middleton (2012 – 2013), progenitors of short gamma ray bursts; shared the Tesella Prize for best computational year 4 project, 2013

Zachary Hafen and Jenna Klemkowsky (2013), waveform accuracy requirements on hybrid waveforms and gravitational-wave event rate calculator

Kirsty Stroud and Chris Aldridge (2013 – 2014, co-advised with Will Farr), exoplanet properties in Kepler data

Hasini Janapriya and George King (2014 – 2015, co-advised with Will Farr), searching for exoplanets around red giants

Tom Riley, Ben Giblin (2014 – 2015, co-advised with Will Farr), short gamma ray bursts and time delays in binary mergers; Tom Riley earned prize for top 4th year project

Rajath Sathyaprakash and Morgan Brown (2015 – 2016), massive stellar evolution modeling

Andrea Colonna (2015 – 2016), clustering and inference, jointly with Computer Science

Kit Boyer and Fabian Gittins (2016 – 2017), modelling X-ray binaries

Gareth Thomas (2014 – 2017), searching for intermediate-mass-ratio inspirals

Dave Perkins (2016), analysis of population synthesis predictions

Kaila Nathaniel (2017), IREU student, chemically homogeneous evolution

Isobel Romero-Shaw (2017), impact of single stellar evolution on binary evolution

Luke Nugent (2017), mathematical modeling masters student, efficient population synthesis sampling

Alice Perry and Samuel Kingdon (2017– 2018), Be X-ray binaries as probes of supernovae and binary evolution

Nicholas Bennett and Samuel Ratcliff (2017– 2018, co-advised with Dorottya Szécsi), lithium abundances in globular clusters

Spencer Shortt and Ellen Butler (2018), chemically homogeneous evolution

Mike Lau (2018), compact binary observations with LISA

Floor Broekgaarden (2019, co-advised with Stephen Justham, Selma de Mink), adaptive importance sampling for population synthesis

Michelle Wassink (2019, co-advised with Gijs Nelemans), expansion of stars after the helium main sequence

COURSES TAUGHT	Classical Mechanics and Relativity (first-year, $\gtrsim 200$ students)
	Inference on Scientific Data (fourth year, $\sim 75$ students)
	Relativistic Astrophysics and Black Holes (third- and fourth-year, $\sim 50$ students)
	Introduction to Astrophysics (first-year, $\sim 50$ students)
	Introduction to Particle Physics and Cosmology (first-year, $\sim 50$ students)
	General Physics [back-of-the-envelope physics] (third-year, $\sim 150$ students)
	Group studies [research project] (third-year, 16 students)
	Observational Cosmology (third- and fourth-year, $\sim 30$ students)
	Gravitational-wave Astrophysics (graduate seminar, $\sim 10$ students)

GRANTS

2019–2024	Australian Research Council Future Fellowship (PI): <i>Shining gravitational waves on binary astrophysics</i> [AUD \$936k from ARC, AUD \$996k in matching Monash funds]
2017–2020	NERC grant (Co-I): <i>Reducing Greenhouse Climate Proxy Uncertainty</i> [total value of grant £434k]
2016–2019	STFC Consolidated grant (Co-I): <i>Searching for intermediate mass ratio coalescences in Advanced LIGO/Virgo data</i> [total value of grant £1,834k]
2016–2019	STFC grant supporting UK Involvement in the Operation of Advanced LIGO (co-I) [£244k to Birmingham]
2016	RAS Undergraduate Bursary <i>Black holes in globular clusters</i> (PI) [£1200]
2015	Kevin Westfold Distinguished Visitor to Monash University, Melbourne, Australia [\$12k support]
2015	RAS Undergraduate Bursary <i>Studying black holes with gravitational waves</i> (PI) [£1200]
2014	South African National Institute of Theoretical Physics (NITheP) long-term visitor grant [\$2k]
2013–2017	FP7 Marie Curie Initial Training Network (Co-I): <i>GraWIToN</i> [total value to Birmingham £481k]
2013–2016	Leverhulme Trust Research Project Grant (PI): <i>Testing general relativity with ground-based gravitational-wave observations</i> [£162k]
2013–2016	STFC Consolidated grant (Co-I): <i>Gravitational wave observations of compact binary systems</i> [total value of grant £1,876k]
2013–2016	ASPERA grant (Co-I): <i>Networking and R&amp;D for the Einstein Telescope</i> [salary and travel support, €59K]
2009–2011	NSF Astronomy and Astrophysics Postdoctoral Fellowship grant (PI): <i>Gravitational-wave astronomy: a new window on the universe</i> [\$249k]
2009–2002	NASA ATP grant (Co-I) <i>Binary White Dwarfs: Gravitational Wave Astrophysics and Data Analysis</i> [\$399k]

#### PROFESSIONAL SOCIETIES

Astronomical Society of Australia  
 International Society on General Relativity and Gravitation lifetime member  
 International Astrostatistics Association  
 International Astronomical Union

1. G. Howitt, S. Stevenson, A. Vigna-Gomez, S. Justham, N. Ivanova, T. E. Woods, C. J. Neijssel, I. Mandel. 2020. Luminous Red Novae: population models and future prospects. *MNRAS*, accepted. arXiv:1912.07771
2. P. Marchant, K. Breivik, C. P. L. Berry, I. Mandel, S. L. Larson. 2019. Eclipses of continuous gravitational waves as a probe of stellar structure. *Physical Review D*, accepted. arXiv:1912.04268
3. C. J. Neijssel, A. Vigna-Gomez, S. Stevenson, J. W. Barrett, S. M. Gaebel, F. Broekgaarden, S. E. de Mink, D. Szecsi, S. Vinciguerra, I. Mandel. 2019. The effect of the metallicity-specific star formation history on double compact object mergers. *MNRAS*, accepted. arXiv:1906.08136
4. F. S. Broekgaarden, S. Justham, S. E. de Mink, J. Gair, I. Mandel, S. Stevenson, J. W. Barrett, A. Vigna-Gomez, C. J. Neijssel. 2019. STROOPWAFEL: Simulating rare outcomes from astrophysical populations, with application to gravitational-wave sources. *MNRAS*, accepted. arXiv:1905.00910
5. R. X. Adhikari, P. Ajith, Y. Chen, J. A. Clark, V. Dergachev, N. V. Fotopoulos, S. E. Gossan, I. Mandel, M. Okounkova, V. Raymond, J. S. Read. 2019. Astrophysical science metrics for next-generation gravitational-wave detectors. *CQG*, accepted. arXiv:1905.02842
6. J. J. Andrews, I. Mandel. 2019. Double Neutron Star Populations and Formation Channels. 2019. *ApJ Letters* 880, L8. arXiv:1904.12745
7. J. Powell, S. Stevenson, I. Mandel, P. Tino. 2019. Unmodelled Clustering Methods for Gravitational Wave Populations of Compact Binary Mergers. *MNRAS* 488, 3810. arXiv:1905.04825
8. S. Stevenson, M. Sampson, J. Powell, A. Vigna-Gómez, C. J. Neijssel, D. Szécsi, I. Mandel. 2019. The impact of pair-instability mass loss on the binary black hole mass distribution. *ApJ*, accepted. arXiv:1904.02821
9. A. Vigna-Gomez, S. Justham, I. Mandel, S. E. de Mink, P. Podsiadlowski. 2019. Massive Stellar Mergers as Precursors of Hydrogen-rich Pulsational Pair Instability Supernovae. *ApJ Letters* 876, L29. arXiv:1903.02135
10. I. Mandel, W. M. Farr, J. R. Gair. 2019. Extracting distribution parameters from multiple uncertain observations with selection biases. *MNRAS*, accepted. arXiv:1809.02063
11. G. P. Lamb et al. 2019. The optical afterglow of GW170817 at one year post-merger. *ApJ Letters* 870, L15. arXiv:1811.11491
12. S. Vinciguerra, M. Branchesi, R. Ciolfi, I. Mandel, C. Neijssel, G. Stratta. 2019. saprEMo: a simplified algorithm for predicting detections of electromagnetic transients in surveys. *MNRAS* 484, 332. arXiv:1809.08641
13. G. P. Lamb, I. Mandel, L. Resmi. 2018. Late-time Evolution of Afterglows from Off-Axis Neutron-Star Mergers. *MNRAS* 481, 2581. arXiv:1806.03843
14. A. Vigna-Gómez, C.-J. Neijssel, S. Stevenson, J. W. Barrett, K. Belczynski, S. Justham, S.E. de Mink, B. Müller, P. Podsiadlowski, M. Renzo, D. Szécsi, I. Mandel. 2018. On the formation history of Galactic double neutron stars. *MNRAS* 481, 4009. arXiv:1805.07974
15. W. M. Farr, I. Mandel. 2018. Comment on “An excess of massive stars in the local 30 Doradus starburst”. *Science* 361, 6400. arXiv:1807.09772
16. J. D. Lyman, G. P. Lamb, A. J. Levan, I. Mandel, N. R. Tanvir et al. 2018. The optical afterglow of the short gamma-ray burst associated with GW170817. *Nature Astronomy*. arXiv:1801.02669
17. J. W. Barrett, S. M. Gaebel, C. J. Neijssel, A. Vigna-Gómez, S. Stevenson, C. P. L. Berry, W. M. Farr, I. Mandel. 2018. Accuracy of inference on the physics of binary evolution from gravitational-wave observations. *MNRAS* 477, 4685. arXiv:1711.06287
18. M. Cantiello et al. 2018. A precise distance to the host galaxy of the binary neutron star merger GW170817 using surface brightness fluctuations. *ApJL* 854, L31. arXiv:1801.06080

19. I. Mandel. 2018. The orbit of GW170817 was inclined by less than 28 degrees to the line of sight. *ApJL* 853, L1. arXiv:1712.03958
20. I. Mandel, A. Sesana, A. Vecchio. 2018. The astrophysical science case for a decihertz gravitational-wave detector. *Classical and Quantum Gravity* 35, 054004. arXiv:1710.11187
21. N. R. Tanvir, A. J. Levan, C. Gonzalez-Fernandez, O. Korobkin, I. Mandel et al. 2017. The Emergence of a Lanthanide-rich Kilonova Following the Merger of Two Neutron Stars. *ApJL* 848, L27. arXiv:1710.05455
22. A. J. Levan, J. D. Lyman, N. R. Tanvir, J. Hjorth, I. Mandel et al. 2017. The environment of the binary neutron star merger GW170817. *ApJL* 848, L28. arXiv:1710.05444
23. J. Hjorth et al. 2017. The Distance to NGC 4993: The Host Galaxy of the Gravitational-wave Event GW170817. *ApJL* 848, L31. arXiv:1710.05866
24. B. P. Abbott et al. 2017. A gravitational-wave standard siren measurement of the Hubble constant. *Nature*, accepted. arXiv:1710.05835
25. B. P. Abbott et al. 2017. Multi-messenger observations of a binary neutron star merger. *ApJL* 848, L12. arXiv:1710.05833
26. I. Mandel, A. Farmer. 2017. Gravitational waves: Stellar palaeontology. *Nature* 547, 284
27. W. M. Farr, S. Stevenson, M. C. Miller, I. Mandel, B. Farr, A. Vecchio. Distinguishing Spin-Aligned and Isotropic Black Hole Populations With Gravitational Waves. 2017. *Nature*, 548, 426. arXiv:1706.01385
28. P. Marchant, N. Langer, P. Podsiadlowski, T. Tauris, S. de Mink, I. Mandel, T. Moriya. 2017. Ultra-luminous X-ray sources and neutron-star-black-hole mergers from very massive close binaries at low metallicity. *A&A* 604, A55. arXiv:1705.04734
29. S. Stevenson, A. Vigna-Gómez, I. Mandel, D. Perkins, J. W. Barrett, S. E. de Mink. 2017. Forming GW151226 and LVT151012 through isolated binary evolution. *Nature Communications*, 8, 14906. arXiv:1704.01352
30. S. Stevenson, C. P. L. Berry, I. Mandel. 2017. Hierarchical analysis of gravitational-wave measurements of binary black hole spin-orbit misalignments. *MNRAS* 471, 2801. arXiv:1703.06873
31. B. Bradnick, I. Mandel, Y. Levin. 2017. Stellar binaries in galactic nuclei: tidally stimulated mergers followed by tidal disruptions. *MNRAS* 469, 2042. arXiv:1703.05796
32. S. Vinciguerra, J. Veitch, I. Mandel. 2017. Accelerating gravitational wave parameter estimation with multi-band template interpolation. *CQG*, 34, 115006. arXiv:1703.02062
33. I. Mandel, W. M. Farr, A. Colonna, S. Stevenson, P. Tiño, J. Veitch. 2017. Model-independent inference on compact-binary observations. *MNRAS* 465, 3254. arXiv:1608.08223
34. C.-J. Haster, F. Antonini, V. Kalogera, I. Mandel. 2016. N-body dynamics of intermediate mass-ratio inspirals in globular clusters. *ApJ* 832, 192. arXiv:1606.07097
35. L. P. Singer et al. 2016. Going the Distance: Mapping Host Galaxies of LIGO Sources in Three Dimensions Using Local Cosmography and Targeted Follow-up. *ApJL*, 829, L15. arXiv:1603.07333. Supplementary material in *ApJS*, 226, 10, arXiv:1605.04242
36. S. J. Smartt et al. 2016. A search for an optical counterpart to the gravitational wave event GW151226. *ApJL*, 827, L40. arXiv:1606.04795
37. T. Callister, L. Sammut, E. Thrane, S. Qiu, I. Mandel. 2016. The limits of astrophysics with gravitational wave backgrounds. *Phys. Rev. X* 6, 031018. arXiv:1604.02513
38. S. E. de Mink, I. Mandel. 2016. The Chemically Homogeneous Evolutionary Channel for Binary Black Hole Mergers: Rates and Properties of Gravitational-Wave Events Detectable by Advanced LIGO. *MNRAS* 460, 3545. arXiv:1603.02291
39. I. Mandel, S. E. de Mink. 2016. Merging binary black holes formed through chemically homogeneous evolution in short-period stellar binaries. *MNRAS* 458, 2634. arXiv:1601.00007

40. P. A. Rosado, P. D. Lasky, E. Thrane, X. Zhu, I. Mandel, A. Sesana. 2016. The most distant observable massive objects. *Phys. Rev. Lett.* 116, 101102. arXiv:1512.04950
41. B. Farr et al. 2016. Parameter estimation on gravitational waves from neutron-star binaries with spinning components. *ApJ* 825, 116. arXiv:1508.05336
42. S. A. L. Otaibi, P. Tino, J. Cuevas-Tello, I. Mandel, S. Raychaudhury. 2016. Kernel regression estimates of time delays between gravitationally lensed fluxes. *MNRAS* 459, 573. arXiv:1508.03439
43. C. Haster, Z. Wang, C. Berry, S. Stevenson, J. Veitch, I. Mandel. 2016. Inference on gravitational waves from coalescences of stellar-mass compact objects and intermediate-mass black holes. *MNRAS* 457, 4499. arXiv:1511.01431
44. I. Mandel. 2016. Estimates of black-hole natal kick velocities from observations of low-mass X-ray binaries. *MNRAS*, 456, 578. arXiv:1510.03871
45. I. Mandel and Y. Levin. 2015. Double tidal disruptions in galactic nuclei. *ApJ Letters*, 805, L4. arXiv:1504.02787
46. J. Veitch, M. Pürrer, I. Mandel. 2015. Measuring intermediate mass black hole binaries with advanced gravitational wave detectors. *PRL*, 115, 141101. arXiv:1503.05953
47. I. Mandel, C.-J. Haster, M. Dominik, K. Belczynski. 2015. Distinguishing types of compact-object binaries using the gravitational-wave signatures of their mergers. *MNRAS Letters*, 450, L85. arXiv:1503.03172
48. C. W. F. Everitt et al. 2015. The Gravity Probe B test of general relativity. *Classical and Quantum Gravity*, 32 224001.
49. A. S. Silbergleit, J. W. Conklin, M. I. Heifetz, T. Holmes, J. Li, I. Mandel, et al. 2015. Gravity Probe B data analysis: II. Science data and their handling prior to the final analysis. *Classical and Quantum Gravity*, 32 224019.
50. C.-J. Haster, I. Mandel, W. M. Farr. 2015. Efficient method for measuring the parameters encoded in a gravitational-wave signal. *Classical and Quantum Gravity*, 32, 235017. arXiv:1502.05407
51. W. Vousden, W. M. Farr, I. Mandel. 2016. Dynamic temperature selection for parallel-tempering in Markov chain Monte Carlo simulations. *MNRAS* 455, 1919. arXiv:1501.05823
52. C. Berry, I. Mandel, et al. 2015. Parameter estimation for binary neutron-star coalescences with realistic noise during the Advanced LIGO era. *ApJ*, 804, 114. arXiv:1411.6934
53. J. Veitch et al. 2015. Robust parameter estimation for compact binaries with ground-based gravitational-wave observations using LALInference. *Phys. Rev. D* 91, 042003. arXiv:1409.7215
54. W. Del Pozzo, K. Grover, I. Mandel, A. Vecchio. 2014. Testing general relativity with compact coalescing binaries: comparing exact and predictive methods to compute the Bayes factor. *Class. Quantum Grav.* 31, 205006. arXiv:1408.2356
55. M. Dominik, E. Berti, R. O’Shaughnessy, I. Mandel, K. Belczynski, C. Fryer, D. Holz, T. Bulik, F. Pannarale. 2015. Double Compact Objects III: Gravitational Wave Detection Rates. *ApJ*, 806, 263. arXiv:1405.7016
56. L. Singer et al. 2014. The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo. *ApJ*, 795, 105. arXiv:1404.5623
57. I. Mandel, C. P. L. Berry, F. Ohme, S. Fairhurst, W. Farr. 2014. Parameter estimation on compact binary coalescences with abruptly terminating gravitational waveforms. *Class. Quantum Grav.* 31 155005. arXiv:1404.2382
58. K. Belczynski, A. Buonanno, M. Cantiello, C. Fryer, D. Holz, I. Mandel, M. C. Miller, M. Walczak. 2014. The Formation and Gravitational-Wave Detection of Massive Stellar Black-Hole Binaries. *ApJ* 789, 120. arXiv:1403.0677



59. T. Sidery et al. 2014. Reconstructing the sky location of gravitational-wave detected compact binary systems: methodology for testing and comparison. *Phys. Rev. D* 89, 084060. arXiv:1312.6013
60. C. Hanna, I. Mandel, W. Vousden. 2014. Utility of galaxy catalogs for following up gravitational waves from binary neutron star mergers with wide-field telescopes. *ApJ*, 784, 8. arXiv:1312.2077
61. K. Grover, S. Fairhurst, B. F. Farr, I. Mandel, C. Rodriguez, T. Sidery, A. Vecchio. 2014. Comparison of Gravitational Wave Detector Network Sky Localization Approximations. *Phys. Rev. D* 89, 042004. arXiv:1310.7454
62. M. Dominik, K. Belczynski, C. Fryer, D. Holz, E. Berti, T. Bulik, I. Mandel, R. O’Shaughnessy. 2013. Double Compact Objects II: Cosmological Merger Rates. *ApJ* 779, 72. arXiv:1308.1546
63. C. L. Rodriguez, B. Farr, W. M. Farr, I. Mandel. 2013. Inadequacies of the Fisher Information Matrix in gravitational-wave parameter estimation. *Phys. Rev. D* 88, 084013. arXiv:1308.1397
64. C. M. F. Mingarelli, T. Sidery, I. Mandel, A. Vecchio. 2013. Characterising gravitational wave stochastic background anisotropy with Pulsar Timing Arrays. *Phys. Rev. D* 88, 062005. arXiv:1306.5394
65. R. J. E. Smith, C. Hanna, I. Mandel, A. Vecchio. 2014. Rapidly evaluating the compact binary likelihood function via interpolation. *Phys. Rev. D* 90, 044074. arXiv:1305.3798
66. N. Andersson et al. 2013. The Transient Gravitational-Wave Sky. arXiv:1305.0816
67. R. J. E. Smith, I. Mandel, A. Vecchio. 2013. Studies of waveform requirements for intermediate mass-ratio coalescence searches with advanced detectors. *Phys. Rev. D* 88, 044010. arXiv:1302.6049
68. W. M. Farr, J. R. Gair, I. Mandel, C. Cutler. 2015. Counting And Confusion: Bayesian Rate Estimation With Multiple Populations. *Phys. Rev. D* 91, 023005. arXiv:1302.5341
69. R. J. E. Smith, K. Cannon, C. Hanna, D. Keppel, I. Mandel. 2013. Towards Rapid Parameter Estimation on Gravitational Waves from Compact Binaries using Interpolated Waveforms. *Phys. Rev. D* 87, 122002. arXiv:1211.1254
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SELECTED  
PRESENTATIONS

- 9/2006 Talk at LISA Astro-GR@AEI, Golm, Germany. “Using EMRIs to probe bumpy black-hole spacetimes”
- 1/2007 Seminar at Leyden, Netherlands. “Gravitational waves from intermediate-mass-ratio inspirals in ground-based detectors”
- 4/2007 Talk at APS, Jacksonville, FL. “Intermediate-mass-ratio inspirals into intermediate-mass black holes”
- 7/2007 Talk at Amaldi 7, Sydney, Australia. “Time-Frequency Analysis of Extreme-Mass-Ratio Inspirational Signals: Mock LISA Data Challenge, Round 2”
- 10/2007 Astrophysics Seminar at Northwestern University, Evanston, IL. “Testing the No-Hair Theorem with Gravitational-Wave Observations”
- 11/2007 Talk at 17th Midwest Relativity Meeting, St Louis, MO. “Black-Hole Spins Following Minor Mergers”
- 12/2007 Talk at GWDAW-12, Boston, MA. “Extracting Extreme Mass Ratio Inspirational Parameters via Time-Frequency Methods”
- 2/2008 Seminar at Center for Gravitation and Cosmology, University of Wisconsin-Milwaukee. “Ground-based detection of gravitational waves from intermediate-mass-ratio inspirals”
- 3/2008 Talk at 24th Pacific-Coast Gravity Meeting, Santa Barbara, CA. “Extracting Extreme Mass Ratio Inspirational Parameters via Time-Frequency Methods”
- 6/2008 Talk at 7th LISA Symposium, Barcelona, Spain. “Can we detect IMRIs?”
- 9/2008 Short seminar at Institute of Astronomy, Cambridge, UK. “Ground-based detection of gravitational waves from intermediate-mass-ratio inspirals”
- 10/2008 Talk at 18th Midwest Relativity Meeting, Notre Dame, IN. “Can we detect intermediate-mass-ratio inspirals?”
- 12/2008 Seminar at HEP/Astrophysics Seminar, Purdue, West Lafayette, IN. “Prospects in Gravitational-Wave Astronomy”
- 2/2009 Seminar Southampton, UK “Compact binaries as sources for ground-based gravitational-wave detectors”
- 3/2009 Seminar KITP, UC Santa Barbara “Compact Binaries, Intermediate-Mass-Ratio Inspirals, and Other Prospects in Gravitational-Wave Astronomy”
- 4/2009 Talk at IMBH Workshop, UC Irvine. “Gravitational Waves from Binary Systems Containing Intermediate-Mass Black Holes”
- 6/2009 Talk at Amaldi-8 conference, Columbia University. “Compact binaries as sources for ground-based gravitational-wave detectors”
- 7/2009 Invited Talk at NRDA-2 at AEI, Golm, Germany. “Predictions for Detectable Coalescences of Compact Binaries Including Black Holes”
- 7/2009 Talk at Marcel Grossmann 12 in Paris, France. “Probing Light Seeds of Massive Black Holes”

with Gravitational Waves”

7/2009 Invited talk at MG-12, Paris. “Unravelling Binary Evolution from Gravitational-Wave Signals and Source Statistics”

10/2009 Invited talk at the CfA, Cambridge, MA. “Gravitational Waves from Binaries”

1/2010 Talk at NSF Fellows’ Symposium, AAS, Washington, DC. “Prospects in Gravitational-Wave Astronomy”

1/2010 Poster at GWDAW, Rome. “Parameter estimation on gravitational waves from multiple coalescing binaries”

2/2010 Talk at Aspen Winter School on Formation and Evolution of Black Holes, Aspen, CO. “Extracting the distribution of black-hole parameters from gravitational-wave observations”

3/2010 Seminar, University of California, Santa Cruz. “Prospects in Gravitational-Wave Astronomy”

5/2010 Seminar, Northwestern University. “Prospects in Gravitational-Wave Astronomy”

5/2010 Seminar, Rochester Institute of Technology. “Prospects in Gravitational-Wave Astronomy”

6/2010 Talk at NRDA at the Perimeter Institute, Waterloo, Canada. “Bayesian Inference on Numerical Injections”

6/2010 Poster at LISA Symposium, Stanford, CA. “Extracting the distribution of black-hole parameters from gravitational-wave observations”

7/2010 Invited talk at GR-19, Mexico City. “The Mock LISA Data Challenges”

7/2010 Seminar, University of Birmingham, UK. “GWastrophysics”

7/2010 Talk, COSPAR-2010, Bremen. “Testing General Relativity with Gravitational Waves from Extreme Mass Ratio Inspirals”

1/2011 Talk at NSF Fellows Symposium, Seattle. “Gravitational waves from compact binaries: Status and prospects”

1/2011 Talk at AAS, Seattle. “Searching For Gravitational-wave Signals From Compact Binaries With LIGO And Virgo”

1/2011 Talk at GWPAAW, Milwaukee, WI. “The Distribution of Coalescing Compact Binaries in the Local Universe: Prospects for Gravitational-Wave Observations”

2/2011 Seminar, West Virginia University, Morgantown, WV. “Markov Chain Monte Carlo techniques for parameter estimation”

2/2011 Seminar, University of Florida, Gainesville, FL. “GWastrophysics with compact binaries”

3/2011 Talk at Evolution of Compact Binaries, Valparaiso, Chile. “Compact Binary Coalescences: Connections to Gravitational-Wave Astronomy”

4/2011 Talk at MKI Postdoc Symposium, MIT. “Gravitational-wave Astrophysics with Compact

Binaries”

5/2011 Seminar at Princeton University. “GWastrophysics”

5/2011 Seminar at University of Maryland, College Park. “GW astrophysics with compact binaries”

5/2011 Talk at Aspen Center for Physics. “Why compact binaries are not boring”

9/2011 Poster at New Horizons in Time Domain Astronomy, Oxford, UK. “Electromagnetic transients as triggers in searches for gravitational waves from compact binary inspirals”

10/2011 Invited talk at LOFT Science Meeting, Amsterdam. “Gravitational wave observatories and LOFT”

11/2011 Seminar at Warsaw University, Poland. “Gravitational-wave Astrophysics of Compact Binaries”

12/2011 Seminar at Cardiff University. “GWastrophysics of Compact Binaries”

12/2011 Invited talk at LOFT and the Variable X-ray Sky, RAS, London. “LOFT and the EM counterparts to gravitational wave sources”

12/2011 Talk at Gravitation, Astrophysics and Cosmology conference, Quy Nhon, Vietnam. “Astrophysics, Cosmology and Fundamental Physics with ground-based gravitational-wave detectors”

3/2012 Invited talk at April APS Meeting, Atlanta, GA. “Intermediate-mass black holes: A theoretical perspective”

4/2012 Talk at April APS Meeting, Atlanta, GA. “What Waveforms do Data Analysts Want?, or the dangers of systematic errors in parameter estimation”

5/2012 Invited talk at Sackler conference: testing GR with astrophysical systems, Cambridge, MA. “Testing GR with Binary Coalescence Events”

6/2012 Talk at GWPAW, Hannover. “What Waveforms do Data Analysts Want?, or the dangers of systematic errors in parameter estimation”

6/2012 Invited talk at Exploring New Horizons with Gravitational Waves, Hannover. “Astrophysical Sources and Parameter Estimation”

7/2012 Invited course at Nijmegen Astroparticle summer school. “Gravitational Wave Astrophysics”

9/2012 Led discussion on parameter estimation for advanced detectors at KITP workshop, Santa Barbara

10/2012 Seminar at University of Nottingham. “GWastrophysics of Compact Binaries”

10/2012 Invited talk at Russian Young Scientists Conference on Physics and Astronomy, Saint Petersburg (in Russian)

12/2012 Talk at Einstein Telescope Meeting, Hannover. “Challenges for source parameter estimation with the Einstein Telescope”

1/2013 Invited lectures on gravitational-wave astrophysics and parameter estimation at the Chris

Engelbrecht Gravitational-Wave Summer School, South Africa

2/2013 Seminars at Cambridge University and University of Warwick. “GWastrophysics of Compact Binaries”

2/2013 Invited overview talk at UK-India LIGO meeting. “Science Exploitation of advanced GW detectors: a provocation”

3/2013 Invited LIGO Academic Advisory Council lecture on “Astrophysics of binary black holes”

4/2013 Seminar at Hebrew University of Jerusalem. “GWastrophysics with Compact Binaries”

6/2013 Seminars at Guelph University and Perimeter Institute. “Exploring (astro)physics with gravitational waves”

6/2013 Invited talk at First UK LOFT Science meeting, London. “Gravitational Waves and LOFT”

7/2013 Invited lecture on LIGO and compact-binary astrophysics, Cracow School of Theoretical Physics, Zakopane, Poland

7/2013 Talk at GR-20, Warsaw. “BiG Waves: a different kind of gravitational-wave summer school”

8/2013 Invited lectures on gravitational-wave astrophysics at Beijing Normal University gravitational-wave summer school

9/2013 Talk at Numerical Relativity and Data Analysis workshop, Mallorca. “Waveform accuracy requirements for parameter estimation”

10/2013 Seminar at Imperial College, London. “LIGO and GWastrophysics of compact binaries”

12/2013 Talk at Gravitational-Wave Physics and Astronomy Workshop (GWPAW), Pune, India. “Parameter estimation, Fisher matrices, and abruptly terminating waveforms”. Invited panelist for discussion of multi-messenger astronomy

1,2/2014 Seminars at University of Kwa-Zulu Natal, University of Western Cape, and Stellenbosch University, South Africa, as part of a long-term National Institute of Theoretical Physics fellowship

3/2014 Seminars at Newcastle University, Florida Atlantic University

3/2014 Talk at “Stellar Tango in the Rockies” workshop, Lake Louise, Canada. “What can gravitational waves teach us about compact binary evolution?”

7/2014 Solicited talk at University of Washington INT workshop on “Binary Neutron Star Coalescence as a Fundamental Physics Laboratory”

8/2014 Seminar at University of California, San Diego. “Gravitational-wave astrophysics of compact binaries”

10/2014 Seminar at University of Southampton. “Adventures in Astrostatistics”

10/2014 Seminar (“Adventures in Astrostatistics”) and Tutorial (“All you wanted to know about Gravitational Wave Astrophysics and were afraid to ask”) at University of Amsterdam.

2/2015 Astronomy seminars at Melbourne and Monash Universities

4/2015 Physics colloquium at Monash University; astronomy seminar at Swinburne University: “Beautiful Binaries”

5/2015 Invited talk at Cardiff Black Hole Workshop: “Black-hole mass measurements”

6/2015 Invited talk at “GRG: A centennial perspective”, Penn State: “Overview of compact-binary merger rate predictions”

7/2015 Invited talks at Marcel Grossmann 14, Rome: “Intermediate-mass black holes: A theoretical perspective” and “Prospects for BNS Observations with Advanced GW Detectors”

7/2015 Talk at Alpine Cosmology Workshop: “Cosmology with gravitational waves”

11/2015 Invited talk, Jerusalem Tidal Disruption Workshop

2/2016 Invited talk, Aspen conference on Dynamics and accretion at the Galactic Center: “Tidal Disruptions of Binary Stars”

2/2016 Physics department colloquium, University of Florida; Astronomy seminar, Durham University: “Gravitational-wave astrophysics: the future is now”

3/2016 Invited talk at Workshop on Sampling in higher dimensions, Edinburgh: “Enhancing sampling efficiency: Inference on binary black holes with gravitational waves”

5/2016 Invited talk at The First Observations of a Binary Black Hole Merger, Hannover: “GW150914: Astrophysical implications of the discovery”

7/2016 Talk, Binary Stars in Cambridge, Cambridge, UK: “Massive Binary Paleontology with Gravitational Waves”

8/2016 Talk, GRavitational-wave Astronomy Meeting in Paris (GRAMPA): “Gravitational-wave Palaeontology”

9/2016 Colloquia, Leiden University and Center for Astrophysics, Harvard University: “Gravitational-wave astrophysics: The future is now” <https://www.youtube.com/watch?v=xXH-NBdhzk0>

10/2016 Invited talk at INTEGRAL conference, Amsterdam: “The astrophysics of LIGO gravitational-wave observations”

10/2016 Invited talk at Gravitational Waves & Cosmology meeting, DESY, Hamburg: “Astrophysical consequences of the LIGO discovery”

10/2016 Invited lectures at Marie Curie GraWIToN school, Rome

11/2016 Colloquium at the Geneva Observatory; Informal seminar at the Copernicus Center, Warsaw

12/2016 Colloquium at University of Nottingham

1/2017 Colloquium at Cardiff University

2/2017 Invited conference summary lecture, Aspen Center for Physics winter conference on “The Dawning Era of Gravitational-Wave Astrophysics”

2/2017 Colloquium at Lund University, Sweden

5/2017 Colloquium at Albert Einstein Institute (Max Planck Institute), Golm bei Potsdam

6/2017 Colloquium at University of Manchester

9/2017 Workshop summary talk at Lorentz Center, Leiden: “And then there was light: electromagnetic counterparts of binary black hole mergers”

9/2017 Invited talk at “Piercing the Sphere of Influence” conference, Cambridge: “Stellar binaries: tidal separations, mergers and disruptions”

9/2017 Plenary talk at DESY theory workshop “Fundamental physics in the cosmos”, Hamburg: “Astrophysical sources of GWs and future prospects for their detection”

10/2017 Seminar at Oxford University

11/2017 Invited discussion lead at Center for Computational Astrophysics (New York) special workshop on binary neutron stars

12/2017 Seminar at Keele University

2/2018 Seminars at University of California, Berkeley, and University of California, Santa Cruz, “The future of gravitational-wave astronomy”

4/2018 Seminar at St Petersburg Academic University (in Russian)

4/2018 Invited talk at “UQ for inverse problems in complex systems”, Isaac Newton Institute, Cambridge: “Studying black holes with gravitational waves: Why GW astronomy needs you!”

5/2018 Invited talk at Sackler conference on Gravitational-wave Astrophysics: “Formation of merging black holes through isolated binary evolution via the common envelope phase” <https://www.youtube.com/watch?v=QhPd1WvWnIO>

7/2018 Les Houches lecture series on astrophysical sources of gravitational waves

8/2018 Plenary talk, IAU General Assembly in Vienna (X-ray binary session), “Gravitational-wave astrophysics”

8/2018 Lecture at STFC summer school, Belfast

9/2018 Invited presentation at ULX meeting, ISSI, Bern

10/2018 Invited presentation at third-generation gravitational-wave detector science case planning meeting, Golm

2/2019 Seminar at Melbourne University

7/2019 Talk at ASA meeting

8/2019 Invited presentation at International Statistical Institute World Congress (Kuala-Lumpur, Malaysia), “Adventures in astrostatistics: Black holes and beyond”

8/2019 Talk at Munich Institute for Astro- and Particle Physics program “Precision gravity: from the LHC to LISA”

SELECTED  
OUTREACH  
ACTIVITIES

10/2019 Seminar at University of Western Australia

11/2008 LIGO Scientific Collaboration booth at the Society of Physics Students congress at Fermilab

12/2008 Co-presented *The Wonders of the Night Sky: The Life and Death of Stars* at the Theodore Roosevelt Elementary School's science fair in Park Ridge, Illinois

4/2009 Special event at Dearborn Observatory as part of the *100 Years of Astronomy* celebration of the International Year of Astronomy

5/2009 Science Club at Roosevelt elementary school

5/2009 Judging Meaningful Science Consortium *Project Showcase* for Chicago public high school students

7/2009 LIGO traveling exhibit at Adler Planetarium.

12/2009 Co-presented *The Wonders of the Night Sky: The Life and Death of Stars* at the Theodore Roosevelt Elementary School's science fair in Park Ridge, Illinois

3/2010 Co-organized the presentation of *Einstein's Cosmic Messengers*, a multimedia concert by Andrea Centazzo and Michele Vallisneri, at Northwestern University.

2/2011 Taught elementary school children at Anova school in Melrose, MA.

3/2012 Gravitational-wave presentation at the Big Bang Fair, Birmingham National Exhibition Center

2012–2016 Founder and lead organizer of the Birmingham Gravitational-wave summer school (BiG Waves)

6/2012 Presented and led interactive sessions at Physics Experience Week for local high school students

6-8/2012 Supervised a summer student in creating animations of gravitational-wave sights and sounds for public demonstrations

10/2012 Popular physics lecture to Birmingham Humanist society

2012 Edited chapters for Birmingham e-book on gravitational waves, <http://www.gwoptics.org/ebook/>

3/2013 Popular article on “Black Holes in Advanced LIGO: The observational payoff” (with Ben Farr), <http://www.ligo.org/magazine/LIGO-magazine-issue-2.pdf>

3/2014 National Science and Engineering Competition judge

3/2014 Source for March 2014 cover page National Geographic article on black holes, see <http://ngm.nationalgeographic.com/2014/03/black-holes/finkel-text>

9/2014 British Science Festival gravitational-wave hands-on exhibit

11/2014 National Science and Engineering Competition online judge

10/2012 — now Member of University of Birmingham HiSPARC team <http://www.hisparc.nl/en/>; advisor on data analysis strategies

3/2015 Popular article on “Where should I apply for grad school?”, LIGO magazine, <http://www.ligo.org/magazine/LIGO-magazine-issue-6.pdf#page=24>

5/2015 Public talk for Walsall Astronomical Society

1/2016 Public talk for the Association for Science Education annual conference (describing current research to school science teachers)

1/2016 School talk at Malvern College

1/2016 School talk at University of Birmingham School

1/2016 Institute of Physics public lecture

1/2016 Public talk as part of the “Astronomy in the City” series

2/2016 Source for Nature magazine news article, <http://www.nature.com/news/einstein-s-gravitational-waves-found-at-last-1.19361>

2/2016 Interviewed by Aspen public radio

3/2016 Public talk for Liberal Arts and Sciences

5/2016 “Pint of Science: Night with the stars” public talk

6/2016 Source for National Geographic news article, <http://news.nationalgeographic.com/2016/06/gravitational-waves-stars-ripples-space-time-origins-astronomy>

7/2016 Aspen public physics lecture: “Singing Binaries: Listening to the Chirps of Black Holes” <http://www.grassrootstv.org/view?showID=14164>

7/2016 Source for news article <http://www.birmingham.ac.uk/university/colleges/eps/news/college/2016/7/Merging-binary-black.aspx>

9/2016 In the press for proposing the chemically homogeneous evolution channel with Selma de Mink <https://www.quantamagazine.org/colliding-black-holes-tell-new-story-of-stars-20160906/>

12/2016 Talk at Wolverhampton Astronomical Society

1/2017 Talk for school children at Year 9 Big Quiz

3/2017 Invited talk at physics teachers conference, Santa Barbara

4/2017 In the press for Nature Communications article on binary black hole formation: including The Register, Physics World <http://physicsworld.com/cws/article/news/2017/apr/20/computer-model-helps-explain-how-ligo-s>

7/2017 Talk at King Edward’s VI Camp Hill School



7/2017 Talk for school children at university residential summer school

7/2017 Lecture at the Worshipful Company of Scientific Instrument Makers, London

8/2017 Authored article “Gravitational waves are helping us crack the mystery of how pairs of black holes form” in The Conversation,

<https://theconversation.com/gravitational-waves-are-helping-us-crack-the-mystery-of-how-pai>

9/2017 School talk at University of Birmingham School

3/2018 Radio interview on BBC West Midlands

4/2018 Source for Nature News Feature, <https://www.nature.com/articles/d41586-018-04157-6>

7/2018 Source for article in The Independent, <https://www.independent.co.uk/life-style/blood-moon-lunar-eclipse-mood-astronomy-astrology-sun-earth-a8464681.html>

<https://www.birmingham.ac.uk/schools/physics/news/2018/birmingham-professor-counters-myths-s.aspx>

4/2019 Source for Nature News Feature, <https://www.nature.com/articles/d41586-019-01064-2>

8/2019 School talk at LIDER Russian School, Melbourne

8/2019 Source for Quantum Magazine Article, <https://www.quantamagazine.org/to-make-two-black-holes>