Paul Tiede | Curriculum Vitae

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Research Interests

black holes, AGN, computational imaging, statistics, machine learning, high-performance computing

Education

University of Waterloo/Perimeter Institute **Waterloo, ON**
Ph.D. Physics *2017–2021*

University of Waterloo **Waterloo, ON**
M.Sc Applied Mathematics (Mathematical Physics) *2015–2017*

University of Waterloo **Waterloo, ON**
B.Sc Mathematical Physics, Specialization: Astrophysics, Dean's Honors List *2010–2015*

Research Experience

Postdoctoral Fellow
Center for Astrophysics | Harvard & Smithsonian
Black Hole Initiative *2021–Present*

Graduate Research Assistant
Department of Physics and Astronomy, University of Waterloo *2017–2021*

Department of Applied Mathematics, University of Waterloo
Research Assistant (Master's) *2015–2017*

Department of Physics and Astronomy, University of Waterloo
Undergraduate Research Assistant *2012–2015*

Awards & Honours

Early Career Award
Event Horizon Telescope *2022*
Awarded for seminal contributions to developing innovative modeling frameworks to allow precise measurements from EHT observations of Sgr A*

Outstanding Thesis Award
Event Horizon Telescope *2021*
For his many contributions to EHT data analysis tools, particularly with respect to the study of variability

Bruno Rossi Prize
AAS High Energy Group (Shared with EHT Collaboration) *2020*

Breakthrough Prize in Fundamental Physics
Fundamental Physics Prize Foundation (Shared with EHT Collaboration) *2019*

Alexander Graham Bell Scholarship (CGS-D)
National Science Engineering Research Council (NSERC) *2017–2020*
Value: $ 35,000 per year

President's Graduate Scholarship (Doctorate)
University of Waterloo *2017–2020*
Value: $ 10,000 per year

Applied Mathematics Outstanding Teacher Assistant Award
University of Waterloo *2017*

Canada Graduate Scholarship (CSGS-M)
NSERC *2015–2016*
Value: $ 17,500 per year

President's Graduate Scholarship (Masters)
University of Waterloo *2015–2016*
Value: $ 10,000 per year

Undergraduate Student Research Award
NSERC *2015*

Helen Sawyer Hogg Scholarship
University of Waterloo *2014*
Value: $ 500

Undergraduate Student Research Award
NSERC *2013*

Undergraduate Student Research Award
NSERC *2012*

University of Waterloo
President's Scholarship *2010*
Value: $ 2,000

Outreach

Imaging Black Holes
Sq'éwquel Community School *2023*
Visited elementary and middle school indigenous students about Black Holes and what it is like being an astrophysicist.

The Quest to Image Black Holes
Center for Astrophysics YouTube *2022*
Participated in a panel discussion on YouTube about the first image of the black hole Sagittarius A*, with Ellen Stofan, the Under Secretary for Science and Research at The Smithsonian.

Let's Talk Science
Waterloo ON *2015–2017*
- Youth science education program focused on increasing STEM literacy and improving science education.
- Helped develop a physics lab day for high school students to learn about a variety of physics disciplines.

Teaching & Leadership

M87 2021 Coordinator
Event Horizon Telescope Collaboration *2023–*

CfA Seminar Organizing Committee Member
Center for Astrophysics | Harvard & Smithsonian *2022–*

Physics Graduate Teaching Assistant
University of Waterloo
- Physics 364 (Mathematical Physics I) Fall 2020
- Physics 115 (Physics for Engineering) Fall 2019
- Math 138 Calculus II (Physics based Section) Winter 2017
- Amath 473 Quantum Theory II Fall 2016
- Math 227 Calculus II for Science Fall 2016
- Amath 250 Introduction to Differential Equations Fall 2015

Elected Phys Club Member
University of Waterloo *2011 – 2013*

Students Mentored

Dominic Chang (Graduate, Harvard)
Erandi Chavez (Graduate, Harvard)
Rohan Dahale (Graduate IAA-CSIC, Spain)
Kathryn Hunter (Undergraduate MIT Haystack)
Dashon Jones (Rice, NBSP)
Uri Rolls (Undergraduate, Harvard)

Presentations

Computational Radio Astronomy with Julia Mini-symposium
JuliaCon 2023, Organizer and Speaker *2023*

Bayesian Inference Algorithms for Imaging and Modeling with the EHT & ngEHT
EAS 2023, (*Invited*) *2023*

Simultaneous Imaging and and Prior Selection with Bayesian Imaging
Event Horizon Telescope Collaboration Meeting, (*Selected*) *2023*

A Black Hole Closeup: Enhancing Black Hole Science with the ngEHT and Space
Astrophysical Black Holes: A Rapidly Moving Field, (*Invited*) *2023*

Statistical Imaging of Black Holes Using the EHT
UBC Statistics Seminar, (*Invited*) *2023*

Accelerating Black Hole Imaging with Enzyme
Enzyme Conference 2023, (*Invited*) *2023*

Measuring the Variability, Morphology and Mass of Sgr A*
Black Hole Initiative Conference 2022, (*Invited*) *2022*

Modeling and Interpreting the Sgr A* Results
NERQUAM 2022, (*Invited*) *2022*

Variational Image Domain Feature Extraction and Modeling the Horizon
Black Hole Initiative (*BHI*) *Harvard University,* (*Invited*) *2021*

Spacetime Tomography with the Event Horizon Telescope
Event Horizon Telescope Collaboration Meeting 2019, (*Invited*) *2019*

Spacetime Tomography with the Event Horizon Telescope
Black Hole Initiative (*BHI*) *Harvard University,* (*Invited*) *2019*

Bow Ties in the Sky: Exploring the Fermi Gamma ray universe
University of Waterloo Applied Mathematics Graduate Colloquium *2016*

Modeling and Detecting Gamma Ray Halos from Active Galactic Nuclei
Canadian Undergraduate Physics Conference *2013*

Software

`Comrade.jl`
Primary Developer
- Bayesian Statistical Inference and Imaging Software for VLBI Imaging and Data Science
- Primary tool in EHT analysis from 2021–Present

`VIDA.jl`
Primary Developer

- Automated Feature Extraction Tool for Quantitative Science from the EHT
- Primary tool in EHT analysis from 2020–Present

Themis
Core Developer
- Bayesian Analysis Tool for EHT
- Used in first images of M87* and Sgr A*

Academic Service

Reviewer, The Astrophysics Journal
Reviewer, Astronomy & Astrophysics
Reviewer, Galaxies MDPI

Publications (ORCID ID: 0000-0003-3826-5648)

First Author and Primary Collaboration Constribution

[1] Event Horizon Telescope Collaboration and (**paper analysis**). First Sagittarius A* Event Horizon Telescope Results. VI. Testing the Black Hole Metric. *ApJl*, 930(2):L17, May 2022. doi:10.3847/2041-8213/ac6756.

[2] Event Horizon Telescope Collaboration and (**paper writing and analysis team**). First Sagittarius A* Event Horizon Telescope Results. IV. Variability, Morphology, and Black Hole Mass. *ApJl*, 930(2):L15, May 2022. doi:10.3847/2041-8213/ac6736.

[3] Event Horizon Telescope Collaboration and (**paper analysis**). First Sagittarius A* Event Horizon Telescope Results. V. Testing Astrophysical Models of the Galactic Center Black Hole. *ApJl*, 930(2):L16, May 2022. doi:10.3847/2041-8213/ac6672.

[4] Event Horizon Telescope Collaboration and (**paper writing and analysis**). First Sagittarius A* Event Horizon Telescope Results. III. Imaging of the Galactic Center Supermassive Black Hole. *ApJl*, 930(2):L14, May 2022. doi:10.3847/2041-8213/ac6429.

[5] **Paul Tiede**. Comrade: Composable Modeling of Radio Emission. *The Journal of Open Source Software*, 7(76):4457, August 2022. doi:10.21105/joss.04457.

[6] **Paul Tiede**, Avery E. Broderick, and Daniel C. M. Palumbo. Variational Image Feature Extraction for the Event Horizon Telescope. *ApJ*, 925(2):122, February 2022. doi:10.3847/1538-4357/ac3a6b.

[7] **Paul Tiede**, Avery E. Broderick, Daniel C. M. Palumbo, and Andrew Chael. Measuring the Ellipticity of M87* Images. *ApJ*, 940(2):182, December 2022. doi:10.3847/1538-4357/ac9cd2.

[8] **Paul Tiede**, Michael D. Johnson, Dominic W. Pesce, Daniel C. M. Palumbo, et al. Measuring Photon Rings with the ngEHT. *Galaxies*, 10(6):111, December 2022. doi:10.3390/galaxies10060111.

[9] **Paul Tiede**, Avery E. Broderick, Mohamad Shalaby, Christoph Pfrommer, et al. Constraints on the Intergalactic Magnetic Field from Bow Ties in the Gamma-Ray Sky. *ApJ*, 892(2):123, April 2020. doi:10.3847/1538-4357/ab737e.

[10] **Paul Tiede**, Hung-Yi Pu, Avery E. Broderick, Roman Gold, et al. Spacetime Tomography Using the Event Horizon Telescope. *ApJ*, 892(2):132, April 2020. doi:10.3847/1538-4357/ab744c.

[11] Event Horizon Telescope Collaboration and (**paper writing and analysis**). First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole. *ApJL*, 875(1):L6, April 2019. ISSN 2041-8205. doi:10.3847/2041-8213/ab1141. Publisher: IOP Publishing.

[12] **Paul Tiede**, Avery E. Broderick, Mohamad Shalaby, Christoph Pfrommer, et al. Bow Ties in the Sky. II. Searching for Gamma-Ray Halos in the Fermi Sky Using Anisotropy. *ApJ*, 850(2):157, December 2017. doi:10.3847/1538-4357/aa9375.

Other Selected Publications

[1] Koushik Chatterjee, Andrew Chael, **Paul Tiede**, Yosuke Mizuno, et al. Accretion Flow Morphology in Numerical Simulations of Black Holes from the ngEHT Model Library: The Impact of Radiation Physics. *Galaxies*, 11(2):38, February 2023. doi:10.3390/galaxies11020038.

[2] Sheperd S. Doeleman, John Barrett, Lindy Blackburn, Katherine Bouman, et al. Reference Array and Design Consideration for the next-generation Event Horizon Telescope. *arXiv e-prints*, arXiv:2306.08787, June 2023. doi:10.48550/arXiv.2306.08787.

[3] Razieh Emami, **Paul Tiede**, Sheperd S. Doeleman, Freek Roelofs, et al. Tracing Hot Spot Motion in Sagittarius A* Using the Next-Generation Event Horizon Telescope (ngEHT). *Galaxies*, 11(1):23, January 2023. doi:10.3390/galaxies11010023.

[4] Michael D. Johnson, Kazunori Akiyama, Lindy Blackburn, Katherine L. Bouman, et al. Key Science Goals for the Next-Generation Event Horizon Telescope. *Galaxies*, 11(3):61, April 2023. doi:10.3390/galaxies11030061.

[5] Svetlana Jorstad, Maciek Wielgus, Rocco Lico, Sara Issaoun, et al. The Event Horizon Telescope Image of the Quasar NRAO 530. *ApJ*, 943(2):170, February 2023. doi:10.3847/1538-4357/acaea8.

[6] Angelo Ricarte, **Paul Tiede**, Razieh Emami, Aditya Tamar, et al. The ngEHT's Role in Measuring Supermassive Black Hole Spins. *Galaxies*, 11(1):6, January 2023. doi:10.3390/galaxies11010006.

[7] Freek Roelofs, Lindy Blackburn, Greg Lindahl, Sheperd S. Doeleman, et al. The ngEHT Analysis Challenges. *Galaxies*, 11(1):12, January 2023. doi:10.3390/galaxies11010012.

[8] Nikola Surjanovic, Miguel Biron-Lattes, **Paul Tiede**, Saifuddin Syed, et al. Pigeons.jl: Distributed Sampling From Intractable Distributions. *arXiv e-prints*, arXiv:2308.09769, August 2023. doi:10.48550/arXiv.2308.09769.

[9] Avery E. Broderick, Roman Gold, Boris Georgiev, Dominic W. Pesce, et al. Characterizing and Mitigating Intraday Variability: Reconstructing Source Structure in Accreting Black Holes with mm-VLBI. *ApJl*, 930(2):L21, May 2022. doi:10.3847/2041-8213/ac6584.

[10] Avery E. Broderick, Dominic W. Pesce, Roman Gold, **Paul Tiede**, et al. The Photon Ring in M87*. *ApJ*, 935(1):61, August 2022. doi:10.3847/1538-4357/ac7c1d.

[11] Avery E. Broderick, **Paul Tiede**, Dominic W. Pesce, and Roman Gold. Measuring Spin from Relative Photon-ring Sizes. *ApJ*, 927(1):6, March 2022. doi:10.3847/1538-4357/ac4970.

[12] Event Horizon Telescope Collaboration, Kazunori Akiyama, Antxon Alberdi, Walter Alef, et al. First Sagittarius A* Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way. *ApJl*, 930(2):L12, May 2022. doi:10.3847/2041-8213/ac6674.

[13] Event Horizon Telescope Collaboration, Kazunori Akiyama, Antxon Alberdi, Walter Alef, et al. First Sagittarius A* Event Horizon Telescope Results. II. EHT and Multiwavelength Observations, Data Processing, and Calibration. *ApJl*, 930(2):L13, May 2022. doi:10.3847/2041-8213/ac6675.

[14] Joseph Farah, Peter Galison, Kazunori Akiyama, Katherine L. Bouman, et al. Selective Dynamical Imaging of Interferometric Data. *ApJl*, 930(2):L18, May 2022. doi:10.3847/2041-8213/ac6615.

[15] Boris Georgiev, Dominic W. Pesce, Avery E. Broderick, George N. Wong, et al. A Universal Power-law Prescription for Variability from Synthetic Images of Black Hole Accretion Flows. *ApJl*, 930(2):L20, May 2022. doi:10.3847/2041-8213/ac65eb.

[16] Sara Issaoun, Maciek Wielgus, Svetlana Jorstad, Thomas P. Krichbaum, et al. Resolving the Inner Parsec of the Blazar J1924-2914 with the Event Horizon Telescope. *ApJ*, 934(2):145, August 2022. doi:10.3847/1538-4357/ac7a40.

[17] Peter Kurczynski, Michael D. Johnson, Sheperd S. Doeleman, Kari Haworth, et al. The Event Horizon Explorer mission concept. In Laura E. Coyle, Shuji Matsuura, and Marshall D. Perrin, editors, *Space Telescopes and Instrumentation 2022: Optical, Infrared, and Millimeter Wave*, volume 12180 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 121800M. August 2022. doi:10.1117/12.2630313.

[18] Astrid Lamberts, Ewald Puchwein, Christoph Pfrommer, Philip Chang, et al. Constraining blazar heating with the $2 \lesssim z \lesssim 3$ Lyman-α forest. *MNRAS*, 512(2):3045–3059, May 2022. doi:10.1093/mnras/stac553.

[19] Daniel C. M. Palumbo, Zachary Gelles, **Paul Tiede**, Dominic O. Chang, et al. Bayesian Accretion Modeling: Axisymmetric Equatorial Emission in the Kerr Spacetime. *ApJ*, 939(2):107, November 2022. doi:10.3847/1538-4357/ac9ab7.

[20] He Sun, Katherine L. Bouman, **Paul Tiede**, Jason J. Wang, et al. α-deep Probabilistic Inference (α-DPI): Efficient Uncertainty Quantification from Exoplanet Astrometry to Black Hole Feature Extraction. *ApJ*, 932(2):99, June 2022. doi:10.3847/1538-4357/ac6be9.

[21] Maciek Wielgus, Nicola Marchili, Iván Martí-Vidal, Garrett K. Keating, et al. Millimeter Light Curves of Sagittarius A* Observed during the 2017 Event Horizon Telescope Campaign. *ApJl*, 930(2):L19, May 2022. doi:10.3847/2041-8213/ac6428.

[22] Event Horizon Telescope Collaboration, Kazunori Akiyama, Juan Carlos Algaba, Antxon Alberdi, et al. First M87 Event Horizon Telescope Results. VII. Polarization of the Ring. *ApJl*, 910(1):L12, March 2021. doi:10.3847/2041-8213/abe71d.

[23] Event Horizon Telescope Collaboration, Kazunori Akiyama, Juan Carlos Algaba, Antxon Alberdi, et al. First M87 Event Horizon Telescope Results. VIII. Magnetic Field Structure near The Event Horizon. *ApJl*, 910(1):L13, March 2021. doi:10.3847/2041-8213/abe4de.

[24] S. Issaoun, M. D. Johnson, L. Blackburn, A. Broderick, et al. Persistent Non-Gaussian Structure in the Image of Sagittarius A* at 86 GHz. *ApJ*, 915(2):99, July 2021. doi:10.3847/1538-4357/ac00b0.

[25] Michael Janssen, Heino Falcke, Matthias Kadler, Eduardo Ros, et al. Event Horizon Telescope observations of the jet launching and collimation in Centaurus A. *Nature Astronomy*, 5:1017–1028, July 2021. doi:10.1038/s41550-021-01417-w.

[26] Avery E. Broderick, Roman Gold, Mansour Karami, Jorge A. Preciado-López, et al. THEMIS: A Parameter Estimation Framework for the Event Horizon Telescope. *ApJ*, 897(2):139, July 2020. doi:10.3847/1538-4357/ab91a4.

[27] Avery E. Broderick, Dominic W. Pesce, **Paul Tiede**, Hung-Yi Pu, et al. Hybrid Very Long Baseline Interferometry Imaging and Modeling with THEMIS. *ApJ*, 898(1):9, July 2020. doi:10.3847/1538-4357/ab9c1f.

[28] Jae-Young Kim, Thomas P. Krichbaum, Avery E. Broderick, Maciek Wielgus, et al. Event Horizon Telescope imaging of the archetypal blazar 3C 279 at an extreme 20 microarcsecond resolution. *A & A*, 640:A69, August 2020. doi:10.1051/0004-6361/202037493.

[29] Maciek Wielgus, Kazunori Akiyama, Lindy Blackburn, Chi-kwan Chan, et al. Monitoring the Morphology of M87* in 2009-2017 with the Event Horizon Telescope. *ApJ*, 901(1):67, September 2020. doi:10.3847/1538-4357/abac0d.

[30] Event Horizon Telescope Collaboration, Kazunori Akiyama, Antxon Alberdi, Walter Alef, et al. First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole. *ApJl*, 875(1):L1, April 2019. doi:10.3847/2041-8213/ab0ec7.

[31] Event Horizon Telescope Collaboration, Kazunori Akiyama, Antxon Alberdi, Walter Alef, et al. First M87 Event Horizon Telescope Results. II. Array and Instrumentation. *ApJl*, 875(1):L2, April 2019. doi:10.3847/2041-8213/ab0c96.

[32] Event Horizon Telescope Collaboration, Kazunori Akiyama, Antxon Alberdi, Walter Alef, et al. First M87 Event Horizon Telescope Results. III. Data Processing and Calibration. *ApJl*, 875(1):L3, April 2019. doi:10.3847/2041-8213/ab0c57.

[33] Event Horizon Telescope Collaboration, Kazunori Akiyama, Antxon Alberdi, Walter Alef, et al. First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole. *ApJl*, 875(1):L4, April 2019. doi:10.3847/2041-8213/ab0e85.

[34] Event Horizon Telescope Collaboration, Kazunori Akiyama, Antxon Alberdi, Walter Alef, et al. First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring. *ApJl*, 875(1):L5, April 2019. doi:10.3847/2041-8213/ab0f43.

[35] Event Horizon Telescope Collaboration, Kazunori Akiyama, Antxon Alberdi, Walter Alef, et al. First M87 Event Horizon Telescope Results. VI. The Shadow and Mass of the Central Black Hole. *ApJl*, 875(1):L6, April 2019. doi:10.3847/2041-8213/ab1141.

[36] Avery E. Broderick, **Paul Tiede**, Philip Chang, Astrid Lamberts, et al. Missing Gamma-Ray Halos and the Need for New Physics in the Gamma-Ray Sky. *ApJ*, 868(2):87, December 2018. doi:10.3847/1538-4357/aae5f2.

[37] Avery E. Broderick, **Paul Tiede**, Mohamad Shalaby, Christoph Pfrommer, et al. Bow Ties in the Sky. I: The Angular Structure of Inverse Compton Gamma-Ray Halos in the Fermi Sky. *ApJ*, 832(2):109, December 2016. doi:10.3847/0004-637X/832/2/109.