Kyle Kremer | Curriculum Vitae

California Institute of Technology - 1216 E. California Blvd, Pasadena, CA 91125 kkremer@caltech.edu - www.kylekremer.com

Research Summary

My research program in computational astrophysics builds connections between the fields of stellar dynamics and compact objects. My areas of expertise include **N-body simulations** of dense star clusters, detection of compact object binaries via **gravitational waves** (e.g., LIGO & LISA), and **high-energy transient phenomena** such as tidal disruption events and fast radio bursts. I have also worked on binary star evolution, hydrodynamics of stellar mergers, radio pulsars, intermediate-mass black holes, white dwarf binaries, low-mass X-ray binaries, and observational searches for black holes in Milky Way globular clusters.

Academic Positions

California Institute of Technology	Pasadena, CA
NASA Einstein Fellow	2023–present
NSF Astronomy & Astrophysics Fellow	2020–2022
Carnegie Observatories	Pasadena, CA
NSF Astronomy & Astrophysics Fellow	2020–2022
Northwestern University	Evanston, IL
Research Associate	2020
NSF Graduate Research Fellow	2015-2019
Education	
Northwestern University Ph.D. in Astronomy – Thesis: The Role of Black Holes in Globular Cluster Dynamics – Advisor: Fred Rasio	Evanston, IL 2019
Master of Science in Physics & Astronomy	2017
Colburn Conservatory of Music	Los Angeles, CA
Master of Music	2015
Northwestern University	Evanston, IL
Bachelor of Music; Double Major in Physics and Music Performance	2012

Honors & Awards

NASA Einstein Fellowship	2022
NSF Astronomy & Astrophysics Postdoctoral Fellowship	2020
Carnegie Fellowship in Theoretical Astrophysics	2020
Caltech Burke Fellowship	2020
NSF Graduate Research Fellowship	2015
Winston Churchill Scholarship	2012
Barry M. Goldwater Scholarship	2011
National Undergraduate Fellowship, Princeton Plasma Physics Laboratory	2011
NASA Summer Research Program, Northwestern University	2009, 2010

 Modeling Black Hole Dynamics in Dense Star Clusters NASA Hubble Fellowship Program, \$400k 	2022
 Modeling Dense Star Clusters in the Era of LIGO, LISA, and LSST NSF Astronomy & Astrophysics Postdoctoral Fellowship Program, \$300k 	2020
• A KCWI Black Hole Search in Milky Way Globular Clusters	
Roughly 40 total hours awarded on Keck II through Caltech and Northwestern institutional calls	

Students Mentored

 Riya Shrivastava – Carnegie CASSI program; Caltech SURF program (1 publication) Fulya Kıroğlu – Grad student at NU (5 publications) Elena González Prieto – CIERA REU program; now grad student at NU (2 publications) Yanlong Shi – Grad student at Caltech (1 publication, 2 in prep) Devin Becker – CIERA REU program; now grad student at MIT (1 publication) Nicholas Rui – CIERA summer student; now grad student at Caltech (6 publications) 	2022-present 2021-present 2020-present 2020-present 2021-2023 2019 2019 2018
• Mitchell Lachat – CIERA REU program; now grad student at Univ of Rochester (1 publication)	2018

Invited Talks and Presentations

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	*Hubble Fellows Symposium, Cambridge, MA	September 2023	
	MODEST-23 Meeting, Evanston, IL	September 2023	
	*Aspen Summer Program (Stellar Interactions and the Transients they Cause), Aspen, CO	July 2023	
	*Las Cumbres Observatory Seminar Series, Goleta, CA	June 2023	
	*AAS HEAD Meeting (special session on intermediate-mass black holes), Waikoloa, HI	March 2023	
	GMT Community Science Meeting (Black Holes at All Scales), Sedona, AZ	September 2022	
	*Time Domain and Multimessenger Astrophysics NASA Workshop, Annapolis, MD	August 2022	
	AAS Summer Meeting, Pasadena, CA	June 2022	
	*TIFR Astronomy Seminar, Mumbai, IN	May 2022	
	IAU 361: Massive Stars Near & Far, Ballyconnell, IR	May 2022	
	Intermediate-mass Black Holes Meeting, San Juan, PR	April 2022	
	*AAS HEAD Meeting (special session on dynamical formation of GW sources), Pittsburgh,		
	Dynamical Formation of Gravitational Wave Sources, Aspen, CO	January 2022	
	*CIERA Science Happy Hour, Northwestern, Evanston, IL	September 2021	
	FRB 2021 Meeting (virtual)	July 2021	
	*Niels Bohr Institute, Copenhagen, DK	November 2020	
	*Michigan State Astro Seminar, East Lansing, MI	June 2020	
	*CGCA Seminar, UW-Milwaukee, Milwaukee, WI	February 2020	
24.	AAS Winter Meeting (dissertation talk), Honolulu, HI	January 2020	
23.	*Harvard–CfA, Cambridge, MA	December 2019	
22.	*Carnegie Obervatories Lunch Talk, Pasadena, CA	November 2019	
21.	*Caltech Tea Talk, Pasadena, CA	November 2019	
20.	*UCLA Astro Seminar, Los Angeles, CA	November 2019	
19.	*UC–Santa Barbara Astro Lunch, Santa Barbara, CA	October 2019	
18.	*UC–Santa Cruz FLASH Seminar, Santa Cruz, CA	October 2019	
17.	The Beginnings and Ends of Double White Dwarfs, Copenhagen, DK	July 2019	
16.	MODEST-19 Meeting, Bologna, IT	May 2019	
15.	*MODEST Meeting (Review talk), Bologna, IT	May 2019	
14.	LISA Astrophysics Working Group, Paris, FR	December 2018	
13.	*Caltech TAPIR Seminar, Pasadena, CA	November 2018	
12.	Midwest Relativity Meeting, Milwaukee, WI	October 2018	
	*University of Florida Theoretical Astrophysics Seminar, Gainesville, FL	September 2018	
	12th International LISA Symposium, Chicago, IL	July 2018	
	MODEST-18 Meeting, Santorini, GR	June 2018	

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Teaching Experience

Carnegie Astrophysics Summer Student Internship (CASSI) Co-instructor in annual series of lectures for roughly 20 summer undergraduate students. It scientific presentation/writing workshops, and research seminars	2021, 2022, 2023 ncludes python tutorials,
Guest Lecturer for Caltech graduate courses	
• Fluid Dynamics (taught by J. Fuller)	2023
• Seminar on Stellar Black Holes (taught by S.R. Kulkarni & M. Kasliwal)	2021
Guest Lecturer for undergraduate course at Northwestern University	2016, 2017
Developed curriculum and co-taught series of lectures for course "Engineering Improv	II: The Art of Applica-
tion." This course (for first-year undergraduates in the McCormick School of Engineeri	ng) studies how applied
improvisation can be a catalyst for creativity, innovation, and change in STEM fields.	
Teaching Assistant at Northwestern University	
• Introduction to Astrophysics (taught by G. Novak)	2018
Northwestern University Center for Talent Development	2016
Developed curriculum and co-taught two-day course on astronomy for class of 20 middle	e school students
Renaissance Arts Academy	2013-2014
Part-time (one day per week) instructor for G6-12 math/science courses at charter school	
Professional Service	
Departmental Service	
• Caltech Pizza Lunch co-organizer	2022-present
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Caltech Pizza Lunch co-organizer	2022-present
Caltech TAPIR Seminar co-organizer	2021-present
CIERA Seminar co-organizer	2019
Conferences Organized	
• MODEST-23: Star Clusters in the Post-Pandemic Era	2023
CIERA Workshop on Black Hole Dynamics in Clusters	2018
Panels Served	
• NASA Astrophysics Theory Program (Chair)	2023
• Five-hundred-meter Aperature Spherical Telescope (FAST) observing proposals	2023
Peer Reviewer (total ~ 25)	
• Nature Astronomy	
• Physical Review (PRD and PRL)	
• AAS Journals (ApJ and ApJL)	
Monthly Notices of the Royal Astronomical Society	

- Classical and Quantum GravityPublications of the Astronomical Society of Australia

Cosmos in Concert (www.cosmosinconcert.com)

Educational outreach program combining classical music with astronomy education. Presents multimedia shows featuring live music performance, astronomy visuals, and narration. 17 concerts in six states for audiences totaling over 6,000 people, including over 1,000 students from Chicago and Los Angeles public schools.

- Organized, fundraised, and directed annual concert series at Northwestern University presenting multimedia shows for symphony orchestra. Past concerts include *Solar System Symphony* (Spring 2016), *A Shout Across Time* (Spring 2017), and *Celestial Suite* (Fall 2017).
- Collaborations with professional orchestras (Boulder Philharmonic Orchestra), top U.S. music conservatories (Bienen School of Music, Colburn School), leading composers (James Stephenson, Matthew Fuerst, Ira Mowitz), and Chicago-area science organizations (Fermi National Lab, Adler Planetarium).
- Presented concerts in Los Angeles in collaboration with the Colburn School as part of NSF Astronomy and Astrophysics Postdoctoral Fellowship.

Science Sonification Project

Developed and led a cross-disciplinary collaboration at Northwestern that brought together doctoral students in music composition and the sciences to create original science-inspired music compositions that showcase scientific innovation in the Northwestern research community.

- Facilitated collaboration between six scientists from various departments and six composers from the Bienen School of Music, with each pair creating a unique piece of music.
- As culmination of project, organized the Science Sonification Project Showcase in May 2017 featuring performances of these new compositions. Audience included Northwestern students, faculty, and staff as well as the general public.

The Nettelhorst School Astronomy Residency

Organized a six-week residency at The Nettelhorst School (a GK-8 Chicago Public School) to develop science curriculum.

- Led a team of ten Northwestern graduate students from various departments at Northwestern, including the School of Education and Social Policy, Materials Science, and Physics & Astronomy.
- Worked directly with middle school science teachers and students.
- \cdot Organized two live music performances presented by musicians from Northwestern's Bienen School of Music.
- In total, the residency reached approximately 500 GK-8 students at Nettelhorst.

Caltech Stargazing & Public Lecture Series

Served as lecturer, panelist, and/or telescope operator for monthly lecture series for general public in Pasadena.

Public Lectures

• Carnegie Lecture Series at Huntington Gardens; view here (San Marino, CA)	2023
• Pasadena City College (Pasadena, CA)	2023
• Pasadena Public Library (Pasadena, CA)	2023
• Caltech Astronomy Public Lecture Series (Pasadena, CA)	2022
• Colburn School (Los Angeles, CA)	2022
• Pasadena Senior Center (Pasadena, CA)	2022
• Wilmette Public Library (Wilmette, IL)	2017-2019
\cdot CIERA Astronomer Evenings at Dearborn Observatory (Evanston, IL)	2015 - 2019

2015-present

2015-2016

2022-present

2016-2017

Publications

Publication Metrics (as of October 2023):

- 70 total publications; 20 first-author, 43 co-author, and 7 research notes/proceedings/white papers
- $\cdot\,$ All publications 2703 citations, h-index of 30
- + First-author publications $861\ citations,\ h\text{-index of }15$

First-author publications:

- 20. Connecting the young pulsars in Milky Way globular clusters with white dwarf mergers and the M81 FRB Kremer, K., Fuller, J., Piro, A.L., Ransom, S.M. 2023, MNRAS, 525, L22
- Wind-reprocessed transients from stellar-mass black hole tidal disruption events Kremer, K., Mockler, B., Piro, A.L., Lombardi, J., 2023, MNRAS, 524, 6358
- Prospects for detecting fast radio bursts in globular clusters of nearby galaxies Kremer, K., Li, D., Lu, W., Piro, A.L., Zhang, B. 2023, ApJ, 944, 6
- 17. Formation of low-mass black holes and single millisecond pulsars in globular clusters Kremer, K., Ye, C.S., Kıroğlu, F., Lombardi, J., Ransom, S., Rasio, F.A. 2022, ApJL, 934, L1
- 16. Hydrodynamics of close encounters between main-sequence stars and black hole remnants Kremer, K., Lombardi, J., Lu, W., Piro, A.L., Rasio, F.A. 2022, ApJ, 933, 203
- 15. Dynamical formation channels for fast radio bursts in globular clusters Kremer, K., Piro, A.L., Li, D. 2021, ApJL, 917, L11
- 14. White dwarf subsystems in core-collapsed globular clusters Kremer, K. Rui, N.Z., et al. 2021, ApJ, 917, 28
- 13. Fast optical transients from stellar-mass black hole tidal disruption events in young star clusters **Kremer, K.,** Lu, W., Piro, A.L., et al. 2021, ApJ, 911, 104
- 12. Populating the upper black hole mass gap through stellar collisions in young star clusters **Kremer, K.,** Spera, M., Becker, D., Chatterjee, S., et al. 2020, ApJ, 903, 45
- 11. Modeling dense star clusters in the Milky Way and beyond with the CMC cluster catalog Kremer, K., Ye, C.S., Rui, N.Z., Weatherford, N.C., Chatterjee, S., et al. 2020, ApJS, 247, 48
- 10. Probing the survival of planetary systems in globular clusters with tidal disruption events Kremer, K., D'Orazio, D.J., Samsing, J., Chatterjee, S., Rasio, F.A. 2019, ApJ, 885, 2
- Tidal disruptions of stars by black hole remnants in dense star clusters Kremer, K., Lu, W., Rodriguez, C.L., Lachat, M., Rasio, F.A. 2019, ApJ, 881, 75
- Post-Newtonian dynamics in dense star clusters: Binary black holes in the LISA band Kremer, K., Rodriguez, C. L., Amaro-Seoane, P., Breivik, K., et al. 2019, PRD, 99, 063003
- How initial size governs core collapse in globular clusters
 Kremer, K., Chatterjee, S., Ye, C. S., Rodriguez, C. L., Rasio, F. A., 2019, ApJ, 871, 38
- 6. Low-mass X-ray binaries ejected from globular clusters
- Kremer, K., Chatterjee, S., Rodriguez, C.L., Rasio, F.A. 2019, submitted to ApJ, arXiv: 1802.04895
 5. How black holes shape globular clusters: Modeling NGC 3201
- Kremer, K., Ye, C. S., Chatterjee, S., Rodriguez, C.L., Rasio, F.A. 2018, ApJL, 855, L15 4. LISA sources in Milky Way globular clusters
- Kremer, K., Chatterjee, S., Breivik, K., Rodriguez, C.L., Larson, S.L., Rasio, F.A. 2018, PRL, 120, 191103
 3. Accreting black hole binaries in globular clusters
- Kremer, K., Chatterjee, S., Rodriguez, C.L., Rasio, F.A. 2018, ApJ, 852, 29
- Accreting double white dwarf binaries: Implications for LISA Kremer, K., Breivik, K., Larson, S.L., Kalogera, V. 2017, ApJ, 846, 95
- 1. Long-term evolution of double white dwarf binaries accreting through direct impact Kremer, K., Sepinsky, J., Kalogera, V. 2015, ApJ, 806, 76

Co-author publications:

- 43. Stellar Escape from Globular Clusters II: Clusters May Eat Their Own Tails Weatherford, N., Rasio, F.A., Chatterjee, S., Fragione, G., Kiroglu, F., Kremer, K. 2023, submitted to ApJ
- 42. An Analytic Model For Magnetically-Dominated Accretion Disks
 - Hopkins, P.F. et al. (including Kremer, K.) 2023, submitted to The Open Journal of Astrophysics, arXiv:2310.04507
- 41. FORGE'd in FIRE II: The Formation of Magnetically-Dominated Quasar Accretion Disks from Cosmological Initial Conditions

Hopkins, P.F. et al. (including Kremer, K.) 2023, submitted to The Open Journal of Astrophysics, arXiv:2309.13115

- 40. Single millisecond pulsars from dynamical interaction processes in dense star clusters Ye, C.S., Kremer, K., Ransom, S.M., Rasio, F.A. 2023, accepted by ApJ, arXiv:2307.15740
- An elusive dark central mass in the globular cluster M4
 Vitral, E., Libraloto, M., Kremer, K., et al. 2023, MNRAS, 522, 5740
- 38. Growing Black Holes through Successive Mergers in Galactic Nuclei: I. Methods and First Results Atallah, D., Trani, A.A, Kremer, K., et al. 2023, MNRAS, 523, 4227
- Stellar Escape from Globular Clusters I: Escape Mechanisms and Properties at Ejection Weatherford, N.C., Kıroğlu, F., Fragione, G., Chatterjee, S., Kremer, K., Rasio, F.A. 2023, ApJ, 946, 104
- Tidal Disruption of Main-Sequence Stars by Intermediate-Mass Black Holes Kıroğlu, F., Lombardi, J., Kremer, K., et al. 2023, ApJ, 948, 89
- 35. Hyper-Eddington black hole growth in star-forming molecular clouds and galactic nuclei: Can it happen? Shi, Y., Kremer, K., Grudić, M.Y., Gerling-Dunsmore, H.J., Hopkins, P.F. 2023, MNRAS, 518, 3606
- 34. Constraining white dwarf tides from gravitational waves with LISA Biscoveanu, S., Kremer, K., Thrane, E. 2023, ApJ, 949, 95
- 33. Astrophysics with the Laser Interferometer Space Antenna Amaro-Seoane et al. (including **Kremer**, **K**.) 2023, LRR, 26, 2
- 32. Intermediate-mass Black Holes on the Run from Young Star Clusters González Prieto, E., Kremer, K., et al. 2022, ApJ, 940, 131
- 31. Radio detection of an elusive hidden millisecond pulsar in the globular cluster NGC 6397 Zhang, L. et al. (including Kremer, K.) 2022, ApJL, 934, L21
- 30. Stellar graveyards: Clustering of compact objects in globular clusters NGC 3201 and NGC 6397 Vitral, E., Kremer, K., Libralato, M., Mamon, G., Bellini, A. 2022, MNRAS, 514, 806
- 29. Compact Object Modeling in the Globular Cluster 47 Tucanae Ye, C.S., Kremer, K. et al. 2022, ApJ, 931, 84
- 28. Gravitational Microlensing Rates in Milky Way Globular Clusters Kıroğlu, F., Weatherford, N.C., Kremer, K. et al. 2022, ApJ, 928, 181
- 27. The Imprint of Superradiance on Hierarchical Black Hole Mergers Payne, E., Sun, L., **Kremer, K.**, Lasky, P.D., Thrane, E. 2022, ApJ, 931, 79
- 26. Implications of Eccentric Observations on Binary Black Hole Formation Channels Zevin, M., Romero-Shaw, I., **Kremer, K.** Thrane, E., Lasky, P.D. 2021, ApJ, 921, L43
- 25. Modeling Dense Star Clusters in the Milky Way and Beyond with the Cluster Monte Carlo Code Rodriguez, C.L. et al. (including **Kremer, K.**), 2021, ApJS, 258, 22
- 24. The Supersonic Project: SIGOs, a Proposed Progenitor to Globular Clusters, and their Connections to Gravitational Wave Anisotropies
 - Lake, W., Naoz, S., Chiou, Y.S., Burkhart, B., Marinacci, F., Vogelsberger, M., Kremer, K., 2021, ApJ, 922, 86
- Matching globular cluster models to observations
 Rui, N.Z., Kremer, K., Weatherford, N.C., Chatterjee, S., Rasio, F.A., Rodriguez, C.L., Ye., C.S., 2021, ApJ, 912, 102
- 22. Intermediate-mass Black Holes from High Massive-star Binary Fractions in Young Star Clusters González, E., Kremer, K., Chatterjee, S., Fragione, G., Roderiguez, C.L., et al. 2021, ApJ, 928, L29
- Gravitational Waves as a Probe of Globular Cluster Formation and Evolution Romero-Shaw, I., Kremer, K., Lasky, P., Thrane, E., Samsing, J. 2021, MNRAS, 506, 2362
- 20. Black hole mergers from star clusters with top-heavy initial mass functions Weatherford, N.C., Fragione, G., Kremer, K., Ye, C.S., Rasio, F. A., 2021, ApJ, 907, 25L
- 19. Joint constraints on the field-cluster mixing fraction, common envelope efficiency, and globular cluster radii from a population of binary hole mergers via deep learning
- Wong, K., Breivik, K., **Kremer, K.**, Callister, T. 2021, PRD, 103, 083021 18. Neutron Star-Black Hole Mergers from Gravitational Wave Captures
- Hoang, B.-M., Naoz, S., Kremer, K. 2020, ApJ, 903, 8
- Black Hole Mergers from Hierarchical Triples in Dense Star Clusters Martinez, M. A. S., Fragione, G., Kremer, K., et al. 2020, ApJ, 903, 67
- Demographics of triple systems in dense star clusters Fragione, G., Martinez, M. A. S., Kremer, K., et al. 2020, ApJ, 900, 16
- GW190412 as a third-generation black hole merger from a super star cluster Rodriguez, C. L., Kremer, K., Grudić, M., Hafen, Z., et al. 2020, ApJ, 896, L10
- 14. Illuminating black hole cusp populations in young star clusters Kaaz, N., **Kremer, K.**, Auchettl, K., Ramirez-Ruiz, E. 2020, ApJ, 917, 36

- Gravitational-wave captures by intermediate-mass black holes in galactic nuclei Fragione, G., Loeb, A. Kremer, K., Rasio, F. A., 2020, ApJ, 897, 46
- A dynamical survey of stellar-mass black holes in 50 Milky Way globular clusters Weatherford, N.C., Chatterjee, S., Kremer, K., Rasio, F. A., 2020, ApJ, 898, 162
- COSMIC variance in binary population synthesis Breivik, K., Coughlin, S.C., Zevin, M., Rodriguez, C.L., Kremer, K., et al. 2020, ApJ, 898, 71
- 10. On the rate of binary neutron star mergers in globular clusters Ye, C.S., Fong, W.-F., Kremer, K., Rodriguez, C.L., Chatterjee, S., Fragione, G., Rasio, F.A., 2020, ApJ, 888, L10
- 9. Gravitational-wave captures of single black holes in globular clusters Samsing, J., D'Orazio, D.J., **Kremer, K.**, Rodriguez, C.L., Askar, A. 2019, PRD, 101, 123010
- 8. Can neutron-star mergers explain the r-process enrichment in globular clusters? Zevin, M., Kremer, K., Siegel, D.M., Coughlin, S., Tsang, B.T.-H., Berry, C.P.L., Kalogera, V. 2019, ApJ, 886, 4
- 7. Black holes: The next generation Repeated mergers in dense star clusters and their GW properties Rodriguez, C.L., Zevin, M., Amaro-Seoane, P., Chatterjee, S., Kremer, K., et al. 2019, PRD, 100, 043027
- 6. Probing the black hole merger history in clusters using stellar tidal disruptions Samsing, J. et al. (including **Kremer**, **K**.) 2019, PRD, 100, 043009
- In search of the thermal eccentricity distribution Geller, A.M., Leigh, N.W.C., Giersz, M., Kremer, K., Rasio, F.A., 2019, ApJ, 872, 165
- Millisecond pulsars and black holes in globular clusters
 Ye, C.S., Kremer, K., Chatterjee, S., Rodriguez, C.L., Rasio, F.A. 2019, ApJ, 877, 122
- 3. Post-Newtonian dynamics in dense star clusters: Formation, masses, and merger rates of highly-eccentric black hole binaries
- Rodriguez, C.L., Amaro-Seoane, P., Chatterjee, S., Kremer, K., et al. 2018, PRD, 98, 123005
- Characterizing accreting double white dwarf binaries with LISA and Gaia Breivik, K., Kremer, K., Bueno, M., Larson, S.L., Coughlin, S., Kalogera, V. 2018, ApJL, 854, L1
- Spin tilts in the double pulsar reveal supernova spin angular-momentum production Farr, W.M., Kremer, K., Lyutikov, M., Kalogera, V. 2011, ApJ, 742, 81

Research notes, proceedings, and white papers:

- Can LISA resolve black hole binaries in the M87 globular clusters? Evans, D. & Kremer, K. 2023, RNAAS, 7, 189
- 6. The effect of metallicity on the formation of massive black holes through stellar collisions in young massive star clusters

Shrivastava, R. & Kremer, K. 2022, RNAAS, 6, 157

- No black holes in NGC 6397
 Rui, N.Z., Weatherford, N.C., Kremer, K., et al. 2021, RNAAS, 5, 47
- 4. The Observed Rate of Binary Black Hole Mergers can be Entirely Explained by Globular Clusters Rodriguez, C.L., Kremer, K., et al. 2021, RNAAS, 5, 19
- 3. The role of "black hole burning" in the evolution of dense star clusters Kremer, K., Ye, C.S., Chatterjee, S., Rodriguez, C.L., Rasio, F.A. 2020, Proceedings of the IAU, 351, 357
- 2. Modeling pulsars in dense star clusters Ye, C.S., Kremer, K., et al. 2020, Proceedings of the IAU, 351, 357

Gravitational Wave Survey of Galactic Ultra Compact Binaries
 Littenberg, T.B., Breivik, K., Brown, W.R., Eracleous, M., Hermes, J.J., Holley-Bockelmann, K., Kremer, K., et al. 2019, BAAS, 51, 34 (Astro2020: Decadal Survey on Astronomy and Astrophysics)