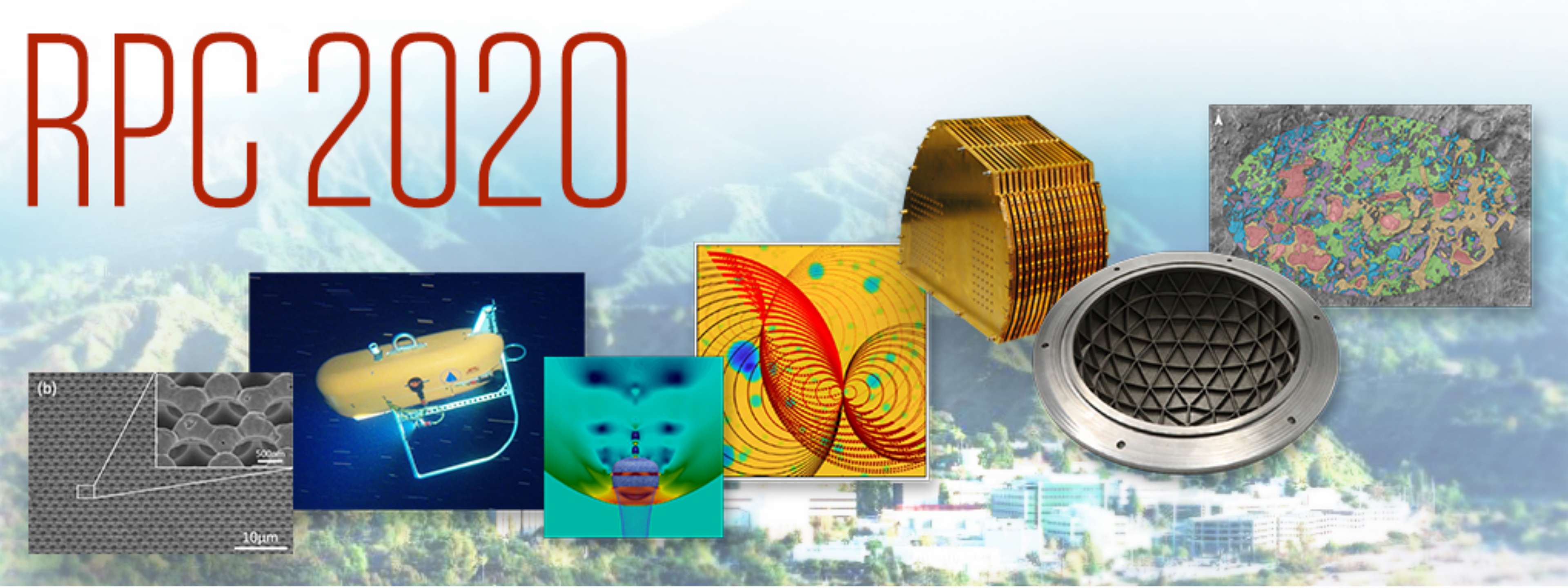


Virtual Research Presentation Conference

Gravitational-Wave Data Analysis From Earth to Space

Principal Investigator: Michele Vallisneri (335S)
Co-Is: Curt Cutler (3267)
Program: Strategic Initiative

RPC-003

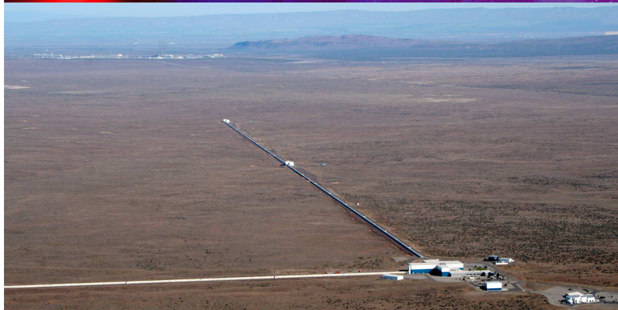
Jet Propulsion Laboratory
California Institute of Technology

Detecting gravitational waves from Earth to space

JPL has been a leader in the field of gravitational-wave detection, participating in **LIGO**'s 2016 discovery of merging stellar-mass black holes, creating crucial concepts and systems for the planned space-based gravitational-wave observatory **LISA**, and developing the statistical-inference framework for the gravitational-wave searches of the **NANOGrav** pulsar-timing-array consortium.

This strategic initiative supported theoretical studies and telescope observations to **identify supermassive black-hole binary candidates**; these systems are premier gravitational-wave sources for **LISA** and **NANOGrav**. New evidence was gathered for a few very promising candidates.

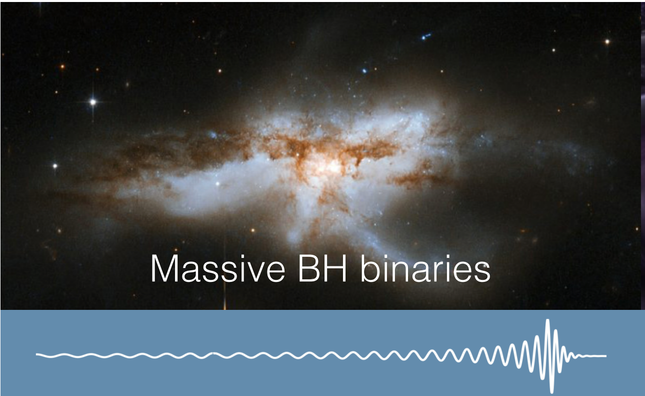
The initiative also supported the development of **novel statistical and computational techniques**, based on the current deep-learning paradigm, for **gravitational-wave data analysis** with **LISA** and **LIGO**, as well as improved computations of the gravitational waveforms expected from extreme-mass-ratio inspirals, a **LISA** source that will probe the spacetime around supermassive black holes.

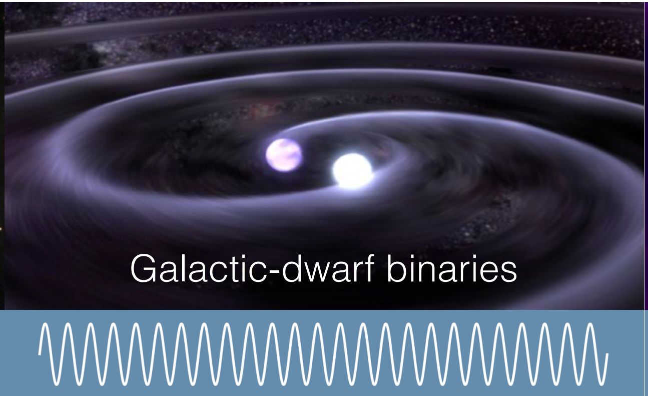


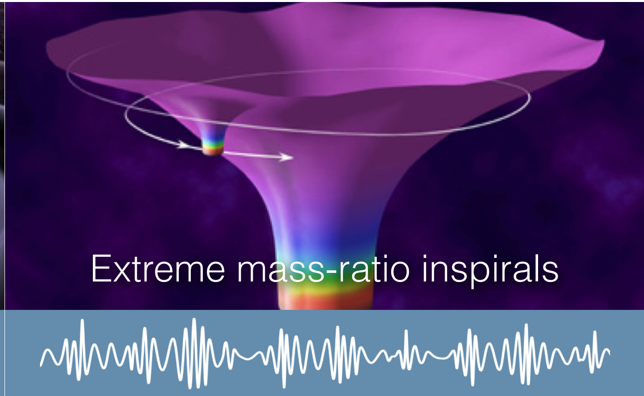
The **identification of supermassive black-hole binary candidates** is important to solidify the LISA science case and to prepare for the multimessenger observation of these systems in gravitational waves and in the electromagnetic spectrum.

Data-analysis is the “eyepiece” of gravitational-wave observatories, in that the astrophysical sources of the observed waveforms can only be understood by comparing those signals with large families of **theoretical templates** encompassing all possible source parameters. This is a challenging problem in both its waveform-generation and the statistical inference aspects.

By supporting both, this initiative strengthened JPL’s intellectual leadership in GW science, as well as our readiness to compete for, develop, and operate the future LISA Science Center.







Approach

SMBH identification

Supermassive black-hole binaries (SMBHBs) are thought to be common in the nuclei of merged galaxies, and evolve into GW sources once they reach sub-parsec orbital separations.

Several binary candidates have been identified by selecting quasar spectra with Doppler-shifted broad emission lines, which could reflect orbital motion. JPL postdoc Simon (in collaboration with Caltech postdoc Charisi) has led a long-term observing campaign at Palomar Observatory, with the goal of detecting coherent modulation in the emission lines and periodicity in their intensity.

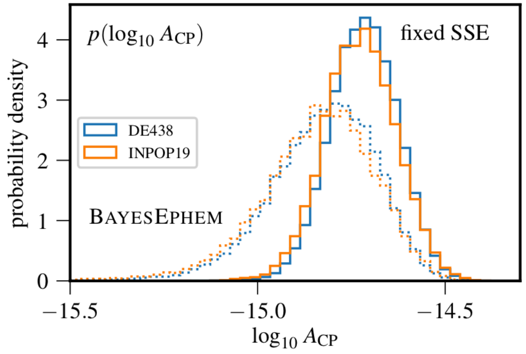
NANOGrav is already searching for GWs from these sources: postdoc Simon led the analysis of NANOGrav's 12.5yr dataset, which displays tantalizing clues (a common-amplitude process across pulsars) of a stochastic background from SMBHBs. More data is needed to detect the tell-tale GW quadrupolar pattern.

GW data analysis

JPL postdoc Chua and the PI developed cutting-edge deep-learning techniques to address the computational difficulty of relating astrophysics with GW observations, especially for LISA's extremely rich future dataset.

They pioneered efficient surrogates for the numerically intensive waveform models constructed from theory, and accelerated sampling algorithms for their high-dimensional posterior distributions. In FY20, he applied these tools and related techniques to LISA mock datasets and to data from ground-based GW observatories.

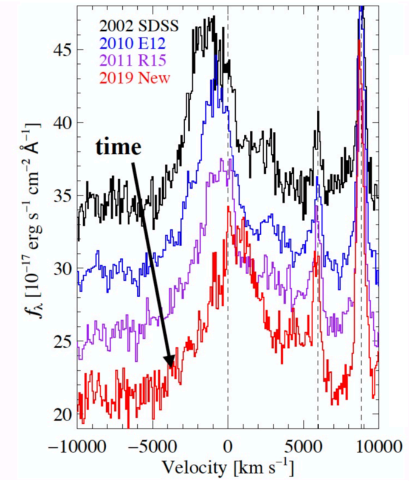
Amplitude of common stochastic process detected in NANOGrav data, as characterized with different solar-system ephemerides.



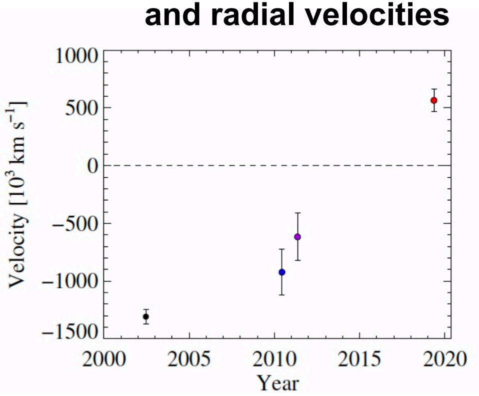
Results

SMBH identification

Simon and Charisi extended the spectroscopic monitoring of SMBHB candidates using Palomar, analyzing spectra and measuring velocity shifts. The most promising candidate is J0950+5128, whose evolving Hβ emission-line profiles imply changing radial velocities consistent with an orbital periods of order decades.

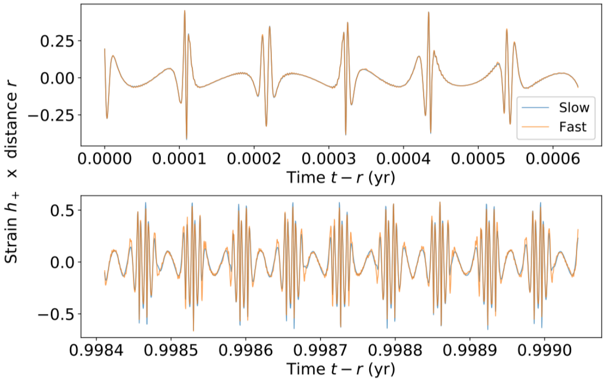


J0950+5128 emission-line profiles and radial velocities



GW data analysis

Chua worked on the rapid and accurate generation of the very complex waveforms from extreme-mass-ratio-inspirals (EMRIs), on GPU-accelerated parameter estimation for SMBHB signals, and on the application of his hyper-efficient Monte Carlo sampling method to LIGo-Virgo data. Chua and co-I Cutler investigated parameter degeneracy in the space of GW signals from EMRIs, proving the existence of degeneracy, and shedding light on its severity.



Six-hour EMRI snapshots: GPU-accelerated rapid waveforms track reference waveforms closely, but are computed in 1s vs hours

Publications and References

[A] A. J. K. Chua & M. Vallisneri, "ROMAN: Reduced-Order Modeling with Artificial Neurons," Phys. Rev. Lett. 122, 211101 (2019).

[B] A. J. K. Chua & M. Vallisneri, "Learning Bayes' theorem with a neural network for gravitational-wave inference," Phys. Rev. Lett. 124, 041102 (2020).

[C] A. J. K. Chua, "Sampling from manifold-restricted distributions using tangent bundle projections," Stat. Comput. 30, 587 (2020).

[D] NANOGrav collaboration, "The NANOGrav 11 yr Data Set: Astrophysical Implications of the Limits on Continuous Waves," in preparation.

[E] NANOGrav collaboration, "The NANOGrav 12.5-year Data Set: Observations and Narrowband Timing of 47 Millisecond Pulsars," in review, arXiv:2005.06490 (2020).

[F] NANOGrav collaboration, "The NANOGrav 12.5-year Data Set: Wideband Timing of 47 Millisecond Pulsars," in review, arXiv:2005.06495 (2020).

[G] NANOGrav collaboration, "The NANOGrav 12.5-year Data Set: Search for an Isotropic Stochastic Gravitational-Wave Background," in review, arXiv:2009.04496 (2020).

[H] M. Vallisneri, S. R. Taylor, J. Simon, et al., "Modeling the uncertainties of solar-system ephemerides for robust gravitational-wave searches with pulsar timing arrays," Astrophys. J. 893, (2020).

[I] A. J. K. Chua, M. L. Katz, N. Warburton & S. A. Hughes, "Rapid generation of fully relativistic extreme-mass-ratio-inspiral waveform templates for LISA data analysis," in review, arXiv:2008.06071 (2020).

[J] A. J. K. Chua, N. Korsakova, C. J. Moore, J. R. Gair & S. Babak, "Gaussian processes for the interpolation and marginalization of waveform error in extreme-mass-ratio-inspiral parameter estimation," Phys. Rev. D 101, 044027 (2020).

[K] M. L. Katz, S. Marsat, A. J. K. Chua, S. Babak & S. L. Larson. "GPU-accelerated massive black hole binary parameter estimation with LISA," Phys. Rev. D 102, 023033 (2020).

[L] A. J. K. Chua & C. J. Cutler, "Confusion and degeneracy of gravitational-wave signals from extreme-mass-ratio-inspiral sources for LISA," in preparation.

[M] A. J. K. Chua & M. Vallisneri, "On parametric tests of relativity with false degrees of freedom," in review, arXiv:2006.08918 (2020).