Statement of Recent Work (Sep/2014 - Sep/2019)

The applicant's interest in quantum chaos brought her to the United States to work as a postdoc at Yale University. What she learned about random matrix theory and signatures of quantum chaos left a mark in many of her future accomplishments. The research program that she established in her first years at Yeshiva University focused mostly on the properties of isolated many-body quantum systems that had already reached equilibrium, specially whether they had thermalized or not [1-6]. She had a prominent role in bridging the early researches on thermalization with the more recent studies that fall under the umbrella of the so-called "eigenstate thermalization hypothesis" (ETH). She demonstrated the relationship between chaotic states and correlated eigenvalues with the viability of thermalization in isolated quantum systems. Part of this work was summarized in her review article [6] and in a review article by her collaborators [7].

Since 2014, her research turned mainly to the properties of many-body quantum systems before reaching equilibrium. This is a highly interdisciplinary subject at the forefront of experimental and theoretical physics. Understanding, predicting, and controlling the behavior of many-body quantum systems out of equilibrium carry the potential for the discovery of new phases of matter, and for the development of efficient methods to reliably store and transfer many-body quantum coherences. The applicant's numerical and analytical studies focused on models employed in current experiments with nuclear magnetic resonance platforms, ion traps, and cold atoms, where long-time coherent dynamics can be achieved. The questions that have been addressed include the dependence of the dynamics on the initial states and observables [8]; the bounds in the spectrum [9]; the onset of chaos [10]; the range of the interactions [11]; and the proximity to a critical point, such as the metal-insulator transition in the presence of interactions [12,13] and excited state quantum phase transitions [14]. Main goals of these analyses have been to identify dynamical properties that are generic to realistic many-body quantum systems [15,16], to determine the conditions for self-averaging behavior [17], to extract the time scales involved in the relaxation process toward equilibrium [16,18], to provide analytical descriptions for the entire evolution of some observables [15-17], and to understand what defines many-body quantum chaos [19-21].

Many-body localization. The topic of localization in interacting quantum systems, now known as "many-body localization", became the theme of various workshops and special issues that have counted with the applicant's participation. She pioneered works on the subject [22] and used this background to investigate the dynamics of interacting quantum systems in the vicinity of the metal insulator transition. With her postdoc, they showed that as the onsite disorder strength of interacting spin models increases, the eigenstates become multifractal and affect the decay of the survival probability. This quantity develops a power-law behavior with an exponent that coincides with the multifractal dimension of the eigenstates [12], a result that inspired several related studies and supported the existence of extended nonergodic states in the intermediate region between the chaotic (thermal) and the many-body localized phase [13].

Dynamical manifestations of chaos. For one-body systems, quantum chaos refers to the well-established correspondence between chaos in the classical limit and level statistics as in random matrices in the quantum domain. The past few years have seen a burst of interest in the subject of quantum chaos, especially in the context of many-body physics, with new insights coming from fields as diverse as high energy physics, quantum information science, atomic and molecular physics, and condensed matter physics. The applicant has made important contributions to the fundamental question of what defines many-body quantum chaos.

Contrary to the widespread view that chaos causes the initial exponential decay of autocorrelation functions, the applicant's group showed that decays even faster than that can happen in isolated systems, and they are independent of spectral properties [8], depending instead on the strength of the perturbation that takes the system out of equilibrium. Furthermore, this behavior necessarily slows down at long times and becomes power law, due to the unavoidable presence of bounds in the spectrum [9]. Universal behaviors as in random matrix theory emerge only much later in time, when the dynamics resolve the discreteness of the spectrum and can finally detect the correlations between the eigenvalues [10]. The applicant's group has used these dynamical manifestations of spectral properties as detectors of integrable-chaos and metal-insulator transitions.

The search for the quantum counterpart of the exponential instability observed in chaotic classical systems has been pursued for many years. Recently, the subject has undergone intense investigation due to new studies that relate the exponential growth rate of out-of-time order correlators (OTOCs) with the classical Lyapunov exponent. This correspondence was indeed corroborated for one-body systems. Together with collaborators, the applicant made a step up towards an explicit quantum-classical correspondence for interacting many-body systems, by confirming the relationship for the Dicke model [19], which contains N atoms interacting with a quantized field. Yet, new results by this collaboration demonstrate that OTOCs can actually grow exponentially also in systems that are classically regular [21]. This finding is certain to shake the role that OTOCs have so far played in studies of many-body quantum chaos and to keep the debate about what defines many-body quantum chaos going on.

Time scales. Many-body quantum systems can hardly ever be treated analytically. The lack of analytical results and the difficulties involved in numerical simulations prevent us from reaching an agreement on some central questions, such as the time that it takes for these systems to reach equilibrium. Using techniques from random matrix theory, the applicant's group was able to obtain analytical expressions that describe the entire evolution of some observables, from perturbation to equilibrium [15-17]. They showed that the relaxation time grows exponentially with system size [16]. Using these analytical expressions and the notion of evolution in the many-body Hilbert space [18], instead of dynamics in real space, they also managed to generalize the concept of Thouless time to interacting disordered models and to show that it increases exponentially as the disorder strength increases and the system approaches a localized phase [16].

Further exploring techniques from random matrix theory, the applicant's group studied in detail the rather unchartered territory of self-averaging behavior in interacting many-body quantum systems out of equilibrium. An observable is self-averaging when its relative variance decreases with system size. This property is crucial in analysis of disordered systems. It implies that by increasing the system size, one can reduce the number of samples used in experiments and in statistical analysis. It also means that one can develop theoretical models to describe finite samples, since their properties are independent of the specific disorder realization. Lack of self-averaging, on the other hand, requires ensemble averages no matter how large the system is, which makes scaling analysis quite challenging. The group has shown analytically and confirmed numerically that self-averaging is not an intrinsic consequence of quantum chaos, as usually assumed. It depends on the quantity and on the time scale considered. Even in evolutions under full random matrices, one finds quantities that are not self-averaging at any time scale [17].

REFERENCES:

[1] L. F. Santos and M. Rigol, *Onset of Quantum Chaos in One-Dimensional Bosonic and Fermionic Systems and its Relation to Thermalization,* Phys. Rev. E **81**, 036206 (2010).
[2] M. Rigol and L. F. Santos, *Quantum chaos and thermalization in gapped systems,* Phys. Rev. A **82**, 011604 (R) (2010).
[3] L. F. Santos and M. Rigol, *Localization and the effects of symmetries in the thermalization properties of one-dimensional quantum systems*, Phys. Rev. E **82**, 031130 (2010).
[4] L. F. Santos, A. Polkovnikov, and M. Rigol, *On the entropy of isolated quantum systems after a quench*, Phys. Rev. Lett. **107**, 040601 (2011).
[5] L. F. Santos, F. Borgonovi and F. M. Izrailev, *Chaos and statistical relaxation in quantum systems of interacting particle*, Phys. Rev. Lett. **108**, 094102 (2012).
[6] F. Borgonovi, L. F. Santos, F. M. Izrailev, V. G. Zelevisnky, *Quantum chaos and thermalization in isolated systems of interacting particles*, Phys. Rep. **626**, 1 (2016).
[7] L. D'Alessio, Y. Kafri, A. Polkovnikov, and M. Rigol, *From quantum chaos and eigenstate thermalization to statistical mechanics and thermodynamics*, Adv. Phys. **65**, 239 (2016).
[8] E. J. Torres-Herrera, M. Vyas, and L. F. Santos, *General Features of the Relaxation Dynamics of Interacting Quantum Systems*, New J. Phys. **16**, 063010 (2014).
[9] M. Távora, E. J. Torres-Herrera, L. F. Santos, *Inevitable power-law behavior of isolated many-body quantum systems and how it anticipates thermalization,* Phys. Rev. A **94**, 041603 (R) (2016).
[10] E. J. Torres-Herrera, L. F. Santos, *Dynamical Manifestations of Quantum Chaos: Correlation Hole and Bulge*, Philos. Trans. R. Soc. Lond. A **375**, 20160434 (2017).
[11] L. F. Santos, F. Borgonovi, G. L. Celardo, *Cooperative shielding in many-body systems with longrange interaction: localization and light cone,* Phys. Rev. Lett. **116**, 250402 (2016).
[12] E. J. Torres-Herrera and L. F. Santos, *Dynamics at the Many-Body Localization Transition,* Phys. Rev. B **92**, 014208 (2015).
[13] E. J. Torres-Herrera and L. F. Santos, *Extended nonergodic states in disordered many-body quantum systems*, Ann. Phys. (Berlin) **529**, 1600284 (2017).
[14] L. F. Santos and F. Pérez-Bernal, *Structure of eigenstates and quench dynamics at an excited state quantum phase transition*, Phys. Rev. A **92**, 050101 (R) (2015).
[15] E. J. Torres-Herrera, A. García-García, L. F. Santos, *Generic dynamical features of quenched interacting quantum systems: survival probability, density imbalance and out-of-time-ordered correlator,* Phys. Rev. B **97**, 060303 (R) (2018).
[16] M. Schiulaz, E. J. Torres-Herrera, L. F. Santos, *Thouless and relaxation time scales in many-body quantum systems,* Phys. Rev. B **99**, 174313 (2019).
[17] M. Schiulaz, E. J. Torres-Herrera, F. Pérez-Bernal, L. F. Santos, *Self-averaging in many-body quantum systems out of equilibrium*, [arXiv: 1906.11856].
[18] F. Borgonovi, F. M. Izrailev, L. F. Santos, *Exponentially fast dynamics in chaotic many-body system,* Phys. Rev. E **99**, 010101 (R) (2019).
[19] J. Chávez-Carlos, B. López-del-Carpio, M. A. Bastarrachea-Magnani, Pavel Stránský, Sergio Lerma-Hernández, Lea F. Santos, Jorge G. Hirsch, *Quantum and classical Lyapunov exponents in atom-field interaction systems,* Phys. Rev. Lett. **122**, 024101 (2019).

[20] M. Niknam, L. F. Santos, D. G. Cory, *Sensitivity of quantum information to environment perturbations measured with the out-of-time-order correlation function*, [arXiv:1808.04375].
[21] S. Pilatowsky-Cameo, J. Chávez-Carlos, M. A. Bastarrachea-Magnani, Pavel Stránský, Sergio Lerma- Hernández, Lea F Santos, Jorge G Hirsch, *Positive quantum Lyapunov exponents in classically regular systems,* [arXiv:1909.02578].
[22] L. F. Santos, G. Rigolin, and C. O. Escobar, *Entanglement versus chaos in disordered spin chains*, Phys. Rev. A **69**, 042304 (2004).