California Institute of Technology
Pasadena, CA
Scott Cushing
$1,100,00

The goal of this project is to create a first-of-its-kind ultrafast electron pump, ultrafast electron probe spectrometer, and, as a test case, to probe and dynamically tune the role of Coulomb interactions in strongly correlated superatomic materials. The all-electron approach offers significant advances compared to conventional ultrafast laser spectroscopy because it enables a more complete measurement of the longitudinal component of the dielectric function. While the optical (transverse) dielectric function controls light-based interactions, the longitudinal dielectric function controls electron type Coulomb interactions, such as those that lead to bond formation, charge transport, and screening in everything from molecules to complex many-body phenomena like superconductivity and correlated insulators. An ultrafast electron pump can replicate photoexcitation, but unlike a photon, can create finite momentum excitations to direct an electron across a material junction or a potential energy surface. Alternatively, if the electron pump is parallel to the sample, screening and bonding can be modulated without excitation to a higher lying state - similar to statically controlling screening and correlations by layering 2D materials for exotic quantum phases. The ultrafast electron energy loss spectroscopy (EELS) probe then decomposes the resultant excitations into their atomic contributions, or it can track finite momentum excitations across the multi-layer junctions that are prevalent in electronics, solar energy materials, and batteries. The ultrafast electron pump, ultrafast electron probe platform could have profound implications in quantum control of electron interactions relevant to developing new electrochemistry, creating transient quantum phases, and measuring quantum devices and ultrafast nanoscale electronics.

Michigan State University
East Lansing, MI
Elad Harel, Marcos Dantus
$1,300,000

Our understanding of cell biology has been greatly accelerated by our ability to peer directly into the cell with increasing spatial and temporal resolution. While incredible progress has been made in this realm, the ability to perform live cell imaging with molecular level resolution remains elusive. Super-resolution techniques offer relatively modest gains in spatial resolution and require complex fluorescent labeling methods that may interfere with natural cellular processes. Further, these methods have limited observation windows due to photobleaching. Non-optical methods such as electron microscopy may achieve the required spatial resolution but must be performed in vacuum environments, precluding observation in living systems. The PIs will pursue a new paradigm where spatial resolution is directly transformed into time to entirely avoid the diffraction limit. The method, which they call Gradient Reconstruction Imaging (GRI), achieves diffraction-less imaging with resolution approaching that of electron microscopy but on living systems. The approach, based on visible light, allows molecular ~5 nm resolution of living cells without risk of damage for unlimited observation times and without labeling. The work will deeply impact our understanding of complex biological processes through unprecedented access to the choreography of proteins in living systems. Critically, the tools developed will be designed upon a framework that is accessible to other researchers who may then develop the methods and applications further so that one day GRI will be a routine method of observation in biology and beyond.

University of California, Berkeley
Berkeley, CA
Ashok Ajoy
$1,000,000

Chemical reactions in micron-scale compartments, including droplets, films, and emulsions, proceed up to a million-fold faster than the same reactions in macroscopic beakers. Still unknown, however, is the mechanism of micro-confinement's substantial effects on the kinetics and equilibria of reactions, including those within biological cells. Insight into the contributing factors will have far-reaching fundamental and technological implications, but unraveling their mechanisms and interrelations requires an in-situ chemical probe deployable within microdroplets and capable of reporting on molecules therein with high specificity. A new probe will be developed using a completely reimagined form of nuclear magnetic resonance (NMR) spectroscopy, designed to provide high-resolution chemical information, on multiple analytes simultaneously, at micron length scales. Current NMR methods and instrumentation are restricted to macroscopic samples, preventing studies on scales of 10 μm or less, and precluding their use on vast array of problems. The approach will exploit the recent revelation that highly coherent hyperpolarized ^{13}C nuclear spins in nanodiamonds can serve as quantum sensors whose

own NMR output relays other vanishingly weak NMR signals from surrounding analytes, with fine spatial resolution set by the particle size. These NMR chemical probes will be used to uncover the origins of reaction acceleration under micro-confinement for a general class of condensation reactions that includes peptide bond formation. This advance will introduce novel deployable chemical imaging probes, enabling diverse applications that harness accelerated chemistry in microdroplet environments.

University of Minnesota, Twin Cities
Minneapolis, MN
Vlad Pribiag, Oleg Gang
$1,400,000

The main challenge toward developing practical quantum computers is the fragile nature of quantum states, which leads to rapid loss of quantum information. This huge obstacle could be mitigated by using topologically-protected quantum states, such as Majorana zero-modes (MZMs). MZMs can in principle protect quantum information against decoherence up to a threshold, in a manner analogous to the role of digital logic, which revolutionized conventional computing by departing from noisy analog schemes. Despite their great promise, the experimental demonstration of MZMs and MZM-based functional circuits using traditional approaches based on semiconductors has proven extremely challenging. This is primarily due to extremely demanding requirements on materials and nano-fabrication. The main goal of this project is to leverage recent advances in programmable DNA nano-assembly and inorganic nano-templating to demonstrate novel topological quantum structures that allow for the detection and control of MZMs. By relying on the high spatial precision, flexibility and speed of DNA nano-assembly, this team of researchers from the University of Minnesota and Columbia University will create topological structures with tailored properties from magnetic nanoparticles and nanoscale superconductors, without using semiconductors. The approach is also naturally suited for creating complex planar and three-dimensional architectures that can serve as a model for future high-density topological circuits. The quantum properties of the self-assembled nanostructures will be probed using low-temperature electronic transport measurements. The project has the potential to circumvent the challenges facing existing paradigms for quantum electronic device research, enabling the development of coherent, intrinsically stable quantum bits that combine scalability, high density, and rapid synthesis.

University of North Texas
Denton, TX
Elizabeth Skellam, Ana Alonso, Michael Carroll, Kent Chapman
$1,400,000

Conventional manufacturing of high-value pharmaceuticals relies on specialized industrial facilities that are energy and equipment-intensive and affect the environment irreversibly. For example, deep vat fermentation of fungal-derived medicines produces large amounts of pharmaceuticals in a short time but also generates high levels of chemical waste. Conversely, photosynthesis-driven pharmaceutical production in plants requires minimal inputs (sunlight, carbon dioxide, water, and mineral nutrients) that are easily scalable. The complete fungal metabolic pathways for the antibiotic, penicillin, and the immunosuppressive agent, mycophenolic acid, will be reconstituted within a plant host (Nicotiana benthamiana) in standard glasshouse conditions. The project includes parallel evaluation of the economic feasibility for this new manufacturing process using a cost-benefit analysis comparing deep vat fermentation-based technology to plant biotechnology-based production. This first-of-its-kind study will establish a new concept for producing valuable fungal products and may ultimately lead to medicines that can be delivered in plant seeds, eliminating downstream processing.

University of Oklahoma
Norman, OK
Doerte Blume, Grant Biedermann, Alberto Marino
$1,000,000

Classical self-organization, i.e., the dynamical emergence of order from an initially disordered state without an external drive, plays a pivotal role in the social sciences, engineering, and the fundamental sciences. This work aims to establish an array of ultracold atomic oscillators, coupled via entangling interactions and driven with classical and quantum light, as a novel, canonical table-top platform with which to theoretically and experimentally study different regimes of quantum self-organization. Leveraging the unique and complementary experimental and theoretical capabilities and know-how of the research team from the Homer L. Dodge Department of Physics and Astronomy and the Center for Quantum Research and Technology at The University of Oklahoma, the synchronization of a highly-tunable quantum network with distinct intra-unit and inter-unit couplings will be demonstrated using the spin and motional degrees of freedom of individual and Rydberg coupled, entangled atoms. This potentially transformative three-year research program will investigate the emergence of quantum analogs of classical synchronization, with the goal of identifying the minimal ingredients needed for the emergence of global quantum synchronization in multi-unit systems and developing a “standard model” of quantum self-organization and synchronization, including its transition from classical to quantum. Competing local and global orders will be quantified,

with the goal of formulating a quantum analog of the classical criticality hypothesis, which states that the dynamical regime between order and disorder achieves an optimal trade-off between robustness and flexibility. The anticipated outcomes of the proposed work will have fundamental importance for essentially all many-body quantum systems, with potentially disruptive long-term impact on quantum technology, including secure quantum communication, quantum networks, and distributed sensing.