Programmable Quantum Materials (Pro-QM)
EFRC Director: D.N. Basov
Lead Institution: Columbia University
Class: 2022 – 2026

Mission Statement*: To discover, characterize and deploy new forms of quantum matter controllable by light, gating, magnetic proximity electromagnetic environment, and nano-mechanical manipulation, effectively programming their quantum properties.*

Discovering quantum phases of matter and controlling their properties is an essential goal of the physical sciences. Quantum phases with controllable properties are required for new electronic, photonic, and clean energy applications needed to address mounting societal demands for fast and energy efficient sensing and information processing and transmission. *Quantum materials (QMs*) are appealing platforms for engineering "on-demand" quantum phases because they host interacting many-body electronic states born of the interplay between topology, reduced dimensionality, and correlations. The emergent "quantum matter" exhibits readily tunable quantum effects over a vast range of length, time, and energy scales.

The Pro-QM team is assembled of leading researchers with complementary skill sets who have pioneered some of the key advances in QMs. The effort will be led by Columbia University, in partnership with the University of Washington in Seattle, Brookhaven National Laboratory and the Flatiron Institute in New York City as an unfunded partner. The Pro-QM team is comprised of six female physicists, chemists and engineers with *Lipson* and *Velian* serving in leadership positions (Fig.1.1). One third of our co-PIs currently hold tenure track positions.

The scientific goals of the four-year program of Pro-QM are organized in two interdependent Research Thrusts (Fig. 1.1). Thrust 1 will create and image interacting topological states in van der Waals (vdW) quantum materials with emphasis on dynamic manipulation of band topology and on-demand topological spin textures. Thrust 2 will utilize interface phenomena for engineering correlated phases with new forms of electronic/magnetic order and will also create interacting light-matter interfaces in vdW structures hosting quantum effects down to the single-photon level required for robust and scalable quantum hardware. The two thrusts harness and rely on two cross-cutting research themes: Theme A, engineered materials, assemblies and architectures, and Theme B, transformative quantum nano-imaging. The concerted EFRC effort is therefore imperative to make the desired leaps in progress.

Programmable QMs are essential for realizing the revolutionary promise of quantum technology for disruptive advances in information transfer, processing, and sensing, because they enable currently inaccessible properties opening the door to new and, currently unimagined functions.

The Pro-QM team will investigate two-dimensional (2D) van der Waals QMs in view of their outstanding diversity of ultra-manipulatable properties. Realizing the potential for programmable quantum matter requires a three-pronged approach, combining *i)* the unique suite of controls and driving perturbations with *ii)* a transformative set of synthesis/device fabrication capabilities (Theme A) and *iii)* new nanoscale characterization techniques integrated in a single platform (Theme B). These strategies are particularly well-adapted to vdW materials. Our approach is to combine the three prongs into one cohesive team effort, expanding on already strong collaborations within the Pro-QM team.

Our chief scientific goals and tasks are outlined in Fig. 1 and closely aligned with the DOE Grand Challenges and Basic Research Needs Reports. A common thread underpinning these clear but ambitious goals and tasks is to develop strategies for transforming QMs into a desired state with tailored quantum properties not attainable in common metals or semiconductors. The present knowledge gaps remain immense but can be effectively addressed given the unique combined expertise of the Pro-QM team documented through a track record of breakthrough collaborative research.

Since the inception of the award, the Pro-QM team has published 89 collaborative works, including numerous articles in *Nature* and *Science*. Approximately 30% these papers acknowledge EFRC funding as the primary source of support. Many of these publications are highly collaborative, with up to nine co-authors. The Pro-QM team is therefore solidly on track toward meeting and surpassing its research targets pertaining to the mission of quantum phases on demand.

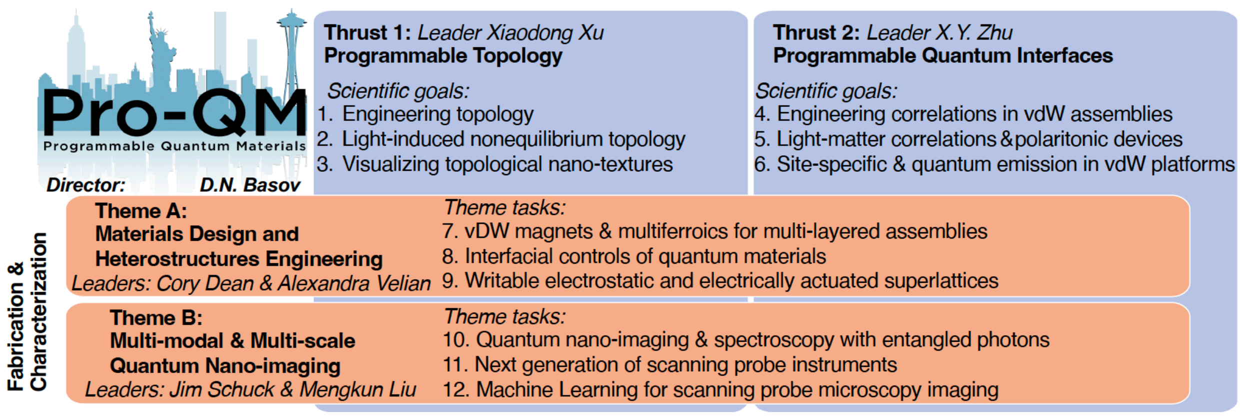

Figure 1: Energy Frontiers Research Center on Programmable Quantum Materials. Center activities are organized into two Thrusts and two cross-cutting Themes.

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