Overarching career goal: Push the frontier of multiphase flows in extreme conditions that are subjected to high speed, strong turbulence, and large mass loading*. For my graduate study, my aim is to unveil the underlying physical mechanisms of complex couplings between solid and gas phases in compressible particle-laden turbulence, which remains elusive for both industrial and astrophysical applications. The major challenge in this area is the lack of high-quality time-resolved experimental datasets that can illustrate the particle-gas and particle-particle interaction in extreme conditions. To address this issue, I plan to leverage a recently-developed ultra-high-speed diagnostic system to embark on understanding multiphase flows in this exciting new regime.*

Introduction and Background (Intellectual Merit):

From the atomization in internal combustion to collisions and growth of dust particles in protoplanetary disks (Fig. 1(left)), particles in high-speed compressible turbulent environments is ubiquitous in nature and engineering applications. This two-phase interaction produces some key issues: (i) **Multi-scale physics**: particles interact with compressible turbulence with many length scales and coherent structures. (ii) **The coupled interaction can lead to clusters of particles and droplets**, resulting in enhanced collision rates and fast growth[1]. This is important for rain droplet growth in turbulent clouds, a type of incompressible turbulence. In this well-known regime, particles preferentially cluster in regions of low vorticity and high strain rate[2], promoting collision but inhibiting mixing. This finding may have severe consequences in combustors, where mixing is desired for perfect combustion[2]. In compressible turbulence, there is a new structure – **shocklet**[3]. Rather than high vorticity or strain, it is a region of high pressure. Particles interacting with this new structure may alter the mean fields and turbulent characteristics of the flow[4]. A numerical study revealed that light particles cluster in very thin and long filaments on the shocklet surfaces[5] (Fig. 1(right)), while larger inertial particles form dense clouds downstream of the shocklet.

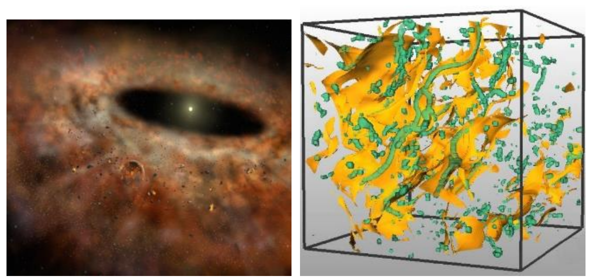

Fig. 1. (left) Artistic illustration of protoplanetary dust. (right) Numerical simulation iso-surface displaying light particles (green) and eddy shocklets (orange)[5].

Hypothesis: A new particle clustering mechanism will become important in compressible turbulence due to the unique coherent structure – shocklet. Since shocklets are intermittent spatially and temporally, particles will interact with other low-speed eddies as they would in incompressible turbulence. The dynamic competition between these two clustering mechanisms will pose an interesting new regime where the particle collision rate may be sensitive to small changes of the dimensionless groups, such as the turbulence Mach number, Stokes number, and Reynolds number.

Aim 1: Upgrade current 2D experimental facility to a supersonic turbulent environment

To generate a turbulent and supersonic environment, I will construct a facility to produce a 2D supersonic mixing layer using two opposing parallel supersonic streams, a method that has been used previously to visualize shocklets[3]. The two jets are separated by a vertical distance, enabling us to capture the interaction between the jets through the shear layer. Particles will be tracked using an in-house particle tracking code. I have access to different algorithms developed in the lab, which includes both 2D tracking and the 3D Shake-The-Box Method[6]. We have access to the **Shimadzu HPV-X2 camera, which captures images at 10 million frames per second at exposure times**

of 200 ns. With this camera I will take time-resolved measurements. We also own several Phantom high-speed cameras, which can take 40,000 images during one run. With this camera I can perform multi-scale measurements and conduct extensive statistical analysis of the flow. To obtain gas phase velocities, I will seed the flow with sub-micron sized particles and illuminate them with an in-house **burst-mode laser** (20 mJ per pulse at 100 kHz) and analyze the results using particle image velocimetry, a method I used previously both during my undergraduate research and at **Los Alamos National Laboratory** under the supervision of Dr. John J. Charonko. With this innovative experimental setup, I will obtain high-quality experimental images for further analysis.

<u>Aim 2: Investigate particle physics and its effect on the flow properties</u>

Because eddy shocklets are structures with strong compression regions, they can be visualized with either shadowgraph or Schlieren imaging methods. Thanks to the quasi-2D configuration of the proposed setup, shocklets will be visualized by the Schlieren method. I have already begun preliminary work to study particle motion using the underexpanded particle-laden jet facility in our lab. With the current experimental setup, I already visualized oblique and normal shocks using the Schlieren method. I also visualized the bow shocks that form around individual particles (like eddy shocklets) at high frame rates (Fig. 2). Finally, the statistics of particle clustering will be evaluated using the Voronoi analysis and the correlation between each of the particle's location.

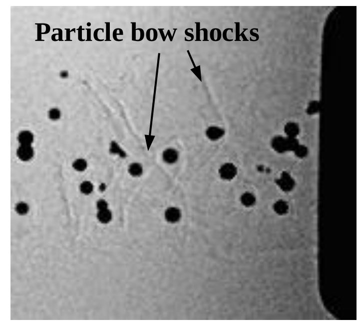

Fig. 2. Shadowgraph experiments using the compressible particle-laden jet facility at Johns Hopkins depicting particle bow shocks.

<u>Aim 3: Study the turbulence by characterizing coherent structures - shocklets</u>

The complex coupling covers a multi-dimensional space. Compressible turbulence can be quantified by both the Reynolds and Mach number, which includes both the free stream and fluctuation velocity. Small particles can be characterized by the Stokes number, particle Reynolds number, and particle Mach number. **I hypothesize that the particle Stokes number and particle Mach number are key parameters that may control the couplings between the two phases**. A large Stokes number results in a large particle inertia, which may induce a strong particle-based shocklet. In addition, the particle mass loading is important. As in the incompressible case, the low mass loading may be key in particle-turbulence interaction, but the particle-particle interaction or particle-turbulence two-way couplings will not be important when the mass loading becomes large. I will spend part of my thesis to understand the behavior of particles in different parameter regimes.

<u>Broader Impacts:</u>

Improving our understanding of particle-laden compressible turbulence will have significant impact in numerous areas of science and engineering. It may provide new insights as to how the universe formed. To aid researchers around the world, I will store our experimental data in an open source repository. *Outreach:* I will mentor underrepresented undergraduate students on a semester basis, provide them with the opportunity of assisting me with experiments, and enable them to co-author in research papers. Through the Johns Hopkins SABES program, I will perform simple experiments to show students the importance of particle behavior in the environment.

1. Pan, Liubin, *et al. The Astrophysical Journal* (2011). **2.** Squires, Kyle D., & John K. Eaton. *Physics of Fluids* (1991). **3.** Papamoschou, Dimitri. *Physics of Fluids* (1995). **4.** Chen, Chang H., & Diego Donzis. *Journal of Fluid Mechanics* (2019). **5.** Yang, Yantao, *et al. Physics of fluids* (2014). **6.** Schanz, Daniel, *et al. Experiments in fluids* (2016).