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Ph.D. DISSERTATION DEFENSE

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Title:	Physics-Informed Sparse Single Photon 3D Imaging
Chairperson:	Dr. Yuping Huang, Department of Physics, School of Engineering & Sciences
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ABSTRACT

Single-photon light detection and ranging (LiDAR) offers exceptional sensitivity for 3D imaging but faces fundamental barriers: sparse signal photons, high noise, and slow acquisition speeds due to point-by-point scanning. These limitations are especially severe in photon-starved environments or when imaging through scattering media. This dissertation overcomes these challenges through a unified hardware-software framework that co-designs physical data acquisition with computational reconstruction.

Our core innovation replaces conventional full-image capture with physical masking, where the imaging system intentionally measures only a small fraction of pixels (2-10%) by coordinating with a MEMS mirror during scanning. This approach is first embodied in the Physics-Informed Masked Autoencoder (PI-MAE), which reconstructs sparse single-photon scenes from as few as 9 photons per total pixel by conditioning the reconstruction on the known physical mask. We then extend this framework to complex real-world settings. Physics-Aware Transformers (PAT) disentangle occluded objects using time-of-flight histograms, enabling reconstruction of hidden background surfaces. For scenarios requiring real-time operation without training, we introduce biharmonic inpainting, a lightweight mathematical alternative that achieves comparable performance without machine learning. Finally, VideoPIMAE expands the paradigm to dynamic scenes, giving useful reconstructions in the 4-10x effective frame-rate regime and testing the limit at 50x.

Together, these contributions show that joint hardware and software design can overcome photon-budget limits in single-photon LiDAR. This work establishes a new path for active imaging when light is scarce or speed is critical.