# Research Statement

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## 1 Introduction

Gravitational lensing is the phenomenon of light deflection and delay when photons pass through a gravitational potential. The occurrence and morphology of lensed images reflect the properties of the gravitational potential of the lens. Lensing effects can be observed on all scales in the Universe: weak lensing on the scale of $\mathrm{Mpc}$, strong lensing on the scale of $\mathrm{kpc}$, and micro lensing on the scale of $\mathrm{pc}$. Applications of lensing in astrophysics and cosmology include a wide range of problems, e.g., reconstructing the lens mass distribution, identifying faint or dark substructures, detecting galaxies at high redshift, measuring the Hubble constant, and mapping the large-scale mass field. Thus, gravitational lensing is a universal tool, and can help greatly to understand the Universe both on large and small scales.

## 2 Past and Current Research

Cosmological strong gravitational lensing, in particular, probes the properties of the dense cores of dark matter halos over decades in mass and offers the opportunity to study the distant universe at flux levels and spatial resolutions that are otherwise unavailable. Strongly lensed variable sources offer yet further scientific opportunities. One of the challenges in realising the potential of strong lensing is in understanding the statistical context of both individual systems that receive extensive follow-up study, and the larger samples of strong lenses that are now emerging from survey efforts. Motivated by these challenges, my collaborators and I have developed a image-simulation pipeline to generate realistic strong gravitational lensing signals from group and cluster-scale lenses. This project has been the main focus of my work in the past two years.

### 2.1 Past Research

The research during my Ph.D. study led me to my current position and project. Firstly, I started with investigating the probability of cosmological lensed quasars in galaxies, where I found that core structure in the lens galaxies will decrease the cross section to generate multiple images. Second, I focused on the lensing effects of super-massive binary black holes (SMBBHs) in galaxies. The results showed that the observational probability of BH-images in the case of the lensing system being a galaxy with SMBBHs is about $10^{-4} \sim 10^{-3}$. Third, I investigated the feasibility of constraining the mass to light ratio of field galaxies using weak lensing shear and flexion. Using mock data, I found that the inclusion of flexion can improve the estimate of foreground halo parameters, but the details are strongly dependent on the noise models.

## 2.2 Current Research

Currently, I am focusing on developing a pipeline for simulations of strong gravitational lensing in galaxy clusters, which is named PICS — Pipeline for Images of Cosmological Strong-lensing (astro-ph/1511.03673). The goal is to produce simulated images that appear identical (to the eye, expert or otherwise) to real observations in various imaging surveys. The pipeline uses a low-noise and unbiased density estimator based on Delaunay Tessellations to calculate the density field from particle distributions from N-body simulations, and lensed images are produced by ray-tracing images of actual galaxies from deep Hubble Space Telescope observations. Other galaxies, similarly sampled, are added to fill in the light cone. The pipeline adds cluster member galaxies and foreground stars onto the lensed images. The entire image ensemble is then observed using a realistic point spread function, including bright stars with appropriate detector artifacts. Noise is then added, including non-gaussian elements such as noise window-paning from mosaiced observations, residual bad pixels and cosmic rays, and the like.

The priority application of the pipeline is strong lensing arc statistics. It is well known that the frequency of strongly lensed arcs on the sky reflects the abundance, concentration, and astrophysical properties of massive lenses. Thus, arc statistics help trace structure formation and can in principle constrain cosmological parameters. First, a full sky light cone is built based on the halos for which $M_{500} > 3 \times 10^{14} M_{\odot}$, from the Argonne Outer Rim simulation, one of the largest simulations currently available. Then the redshfit and positions of particles of a given halo can be obtained. By including these halos into the pipeline and setting the parameters for a given telescope, thousands of simulated images are produced. The statistical properties of simulated images can then be analyzed and compared to, in the first instance, optical follow-up results from the South Pole Telescope (SPT) cluster catalog (this last effort started in June 2015).

An auxiliary use for the pipeline is to test the preservation of morphological measurements, such as the Gini coefficient, under strong gravitational lensing. In particular, as the new generation of space-based large survey telescopes come online, such as the Wide-Field Infrared Survey Telescope (WFIRST), the number of observed strong lensing systems is expected to expand into the thousands. Such systems provide more detailed views of the internal structure of galaxies at higher redshift than would otherwise be possible, however the challenge is extracting useful morphological information from such data. It will be necessary to develop morphological measurements that are conserved under gravitational lensing and some elements of the pipeline described above have been used to test the reliability of image plane measurements of the Gini coefficient (astro-ph/1511.03617, astro-ph/1511.03594).

The pipeline can be also applied in weak lensing regime, for instance, we are investigating the essential properties of superclusters, which are observed in the Dark Energy Survey (DES). The mass of superclusters can be very large, in the regime of $5 \times 10^{16}\ M_{\odot}/h$. Using the data from a cosmological N-body simulation named the "Mira Universe" (astro-ph/1508.02654), we are producing a simulated convergence map that represents a DES-like observation. Weak lensing peak counting and the redmapper (astro-ph/1303.3562) galaxy finder are applied to identify superclusters — the same procedure as followed in the DES observation. Finally, going back to the simulation data, we can reveal the underlying structure of superclusters. This project is in progress.

I have written applications for public science and uploaded them on my *Github*. One such code is named *Bending Light*, which is an application to demonstrate gravitational lensed images and time delays. It is designed as an advanced tool, suitable for use in a classroom setting—or even in a research setting—to allow the rapid exploration of basic models for visualization purposes. By using the mouse and keyboard, one can build and explore a wide range of strong lensing scenarios. Extensive control of both the background sources and foreground lenses is offered. Another code illustrates the second-order gravitational lensing phenomenon, flexion. It also shows how to measure flexion using a method known as higher-order lensing image characteristics (HOLICs). The code is in python, and part of it is translated from Goldberg's IDL HOLICs code[1]. These two programs are both open source and can be found in my Github repositories[2,3].

[1] `http://www.physics.drexel.edu/~goldberg/flexion`
[2] `http://linan7788626.github.io/bending_light_cython`
[3] `http://linan7788626.github.io/flexion_holics_python`

# 3 Future Research

### Data Challenge of Lens Modeling

Lens modeling is a technique to reconstruct the mass distribution of lenses. It is a critical processing step for converting lensing signals to usable constraints for astrophysics and cosmology. At present, there are several tools for lens modeling, but the criteria for choosing the proper tools for specific applications is still unclear. The goal is to find this criteria using our simulations. Since I can produce identical simulated lensed images (to the human eye) for different telescopes, I plan to build a standard simulated database for lens modelers. They can model the mass distribution of the lens without knowing the correct input lens. By comparing the models and input mass distribution, lens modelers can assess the advantages and disadvantages of their methods. Simulations for different types of lensing systems and different telescopes are involved in this project. It will be started by mocking cluster scale lensing systems for space and ground-based telescopes.

### Machine Learning and Gravitational Lensing

So far, the majority of lens finding is based on human effort because human eyes are still the best tool to identify the subtle and complex shapes of lensed images of extended sources (galaxies). The number of observations is tolerably large ($100 \sim 1000$ lensing systems) for humans to look through, however, next-generation imaging surveys, e.g., LSST and WFRIST, will produce millions or even billions of images. It is impossible for several people to find all the lensing systems in these enormous datasets. There are two ways to deal with this situation. One is to ask help from citizen scientists, such as is done in SpaceWarps[4]. The alternative is to design an automated approach based on machine learning, a potentially powerful tool to perform pattern recognition. I am very interested in applying these techniques to improve algorithms for automated lens finding. Likewise, there is a similar problem of extremely large datasets in lens modeling, and I expect that machine learning can eventually lead to automated lens modeling as well.

### Simulations of Time Delay in Galaxy Scale Lensing

Simulations of galaxy scale lensing systems is one of my high-priority projects in the future, specifically the simulations of lensing time delays in galaxies. I am a member of the LSST Dark Energy Science Collaboration (LSST-DESC), and working on simulations with the LSST-DESC strong lensing work group. The **Twinkles**[5] project is one of my focus areas. My interests and responsibilities are: (a) Using CatSim and GalSim to produce the images of sources, line of sight galaxies and lenses. (b) Adding mass distributions of lenses and applying ray-tracing to produce multiple lensed images. (c) Adding PSF and photon noise using a photon ray-tracing code (PhoSim) to make the lensed images realistic. The purpose of this simulation is to test a number of software instruments that will be applied to make high accuracy cosmological measurements of type Ia supernovae and strong gravitational lensing time delays with LSST data, e.g., the pipeline for using strong lensing time delays to constrain the equation of state for dark energy.

# 4 Summary

In summary, in the near future my top priorities are the Twinkles simulation and the application of machine learning for automated arc finding. Moreover, with the capability of next-generation telescopes, e.g., LSST, WFIRST, and SKA, astrophysics and cosmology are stepping into the *big data* era. The application of machine learning for strong-lens finding is an attempt to take on one of the interesting challenges posed by *big data*. I am also interested in extending machine learning to other applications in astrophysics and cosmology.

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[4] `http://spacewarps.org`

[5] `https://github.com/DarkEnergyScienceCollaboration/Twinkles`