Research Plan

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1 Introduction

There is much observational evidence that the ΛCDM model is extremely successful in explaining the structure formation on large scales in the Universe. However, the ΛCDM model still faces many challenges from observations of galaxies on small scales, for instance the missing satellites problem and the cusp-core problem. ΛCDM cosmological simulations predict that dark matter halos host thousands of dark matter subhalos, whereas only tens of satellites have been observed in the Milk Way and M31 up to the present. This is the so-called "missing satellites" problem. It is important to investigate the "missing satellites", since the properties of dark matter subhalos reflect not only the nature of dark matter, for example, the numbers of subhalos is one of the most significant differences between warm dark matter and cold dark matter[1, 2], but also the interaction of dark matter and baryons, for example, the dark matter substructures influence galaxy formation in galaxy clusters[3, 4]. The cusp-core problem is another great challenge to the ΛCDM model on small scales. A key result of cold dark matter from the numerical simulations is the formation of a central density cusp with a characteristic profile $\rho_{\rm DM} \propto r^{-1}$. Baryonic effects have been proposed to reduce the central concentration, even producing dark matter cores. The debate concerning the density slope in the inner parts of galaxies and galaxy clusters is far from being settled[5, 6]. Better observational data and new methods are required to solve this issue. Moreover, investigating the density profile of dark matter halos is important for direct dark matter searches, since the rate of gamma ray production from annihilation scales as $\rho_{\rm DM}^2$[7].

Gravitational lensing considers both multiple images, strong lensing, and image distortion, weak lensing, of background galaxies caused by the foreground gravitational field. It is considered to be one of the most promising tools to probe the dark matter mass distribution. The positions, magnifications and distortions of the images directly reflect the density structure of foreground lenses, independent of the dynamical state or the nature of matter. One can use flux ratio anomalies in strong lensing systems to detect dark matter substructures in lens galaxies[8, 9]. Strong lensing probability in the universe is a powerful tool to study the cusp-core problem statistically[10, 11]. There are probabilities for studying the inner slope of dark matter halos by combining the strong lensing, weak lensing shear and stellar dynamics [12, 13].

Gravitational lensing has become one of the most powerful tools available for investigating the dark side of the universe. Cosmological strong gravitational lensing, in particular, probes the properties of the dense cores of dark matter halos over decades in mass, offers the opportunity to study the distant universe at flux levels and spatial resolutions otherwise unavailable, and strongly lensed variable sources offer yet further scientific opportunities. One of the challenges in realising the potential of strong lensing is to understand the statistical context of both individual systems that recieve extensive follow-up study, and the larger samples of strong lenses that are now emerging from survey efforts. Motivated by these challenges, we have developed a image-simulation pipeline to generate realistic strong gravitational lensing signals from group and cluster-scale lenses.

2 Past and current research

2.1 Past research

My research begins with strong gravitational lensing. First, I have done some work about strong lensing probability in the universe [11]. As is well known, the probability of multiple images for a lensing system in a strong lensing survey, e.g. the Cosmic Lens All-Sky Survey (CLASS) or the Sloan Digital Sky Survey (SDSS), depends on the density profiles, mass function and redshift distribution of the lens galaxies, and the redshift distribution of sources. We investigated the effects of the inner structure of lenses on the lensing probability in the universe, and we found that core structure in the lens galaxies (e.g. Cored Isothermal Sphere model (CIS) and Burkert model) will decrease the cross section for a lens galaxy to generate multiple images. Cusp structure (e.g. Singular Isothermal Sphere model) is necessary for lens galaxies to generate such a probability as observations.

Second, I focused on the lensing effects of super-massive binary black holes (SMBBHs) in galaxy[18]. Recent observations indicate that many if not all galaxies host massive central black holes. Galaxies merge, and so we expect that SMBBHs exist. Our research shows that, for the lens galaxy with singular isothermal mass distribution model, the observational probability of the BH-images in the case of the lensing system as a galaxy with SMBBHs is about $10^{-4} \sim 10^{-3}$. However, high-contrast ($\gtrsim 10^6$) and high-resolution ($\lesssim 10^{-4}\mathrm{arcsec}$) are needed, because the BH-images are faint and close to each other. We are cautiously optimistic that SMBBHs can be independently discovered through careful observations of multiply-imaged systems, especially in the radio, e.g. with the Square Kilometer Array. For the galaxy with non-singular mass distribution model, the presence of SMBBHs can suppress the faint end of the cumulative distribution for the magnification of core images, while leaving the bright end largely unaffected. Such effects need to be accounted for in the constraint on the central mass profiles (e.g., core radius).

Third, I worked on weak lensing flexion and the mass distribution of galaxies and galaxy clusters. We investigate the potential of constraining the mass to light ratio of field galaxies using weak lensing shear and flexions. A suite of Monte Carlo simulations are used to generate weak lensing observations with different noise models. Using mock data, we find that the inclusion of flexions can improve the estimate of foreground halo parameters, but the details are strongly dependent on noise in the model. In the intrinsic noise limit, both shear and flexions are promising tools to study the mass to light ratio of galaxies. However, if the noise model of flexions follows the form described by Rowe et al., there is only 5% improvement in the constraints even with next generation lensing observations as LSST.

Fourth, I have written several codes for public science and uploaded them on my Github. E.g., one code is named **Gravitational Lensing Toy**, which is a software to demonstrate what gravitational lensing is. By using some combinations of mouse and keys, you can control sources and lenses. In this software, it not only shows sources and lensed images, but also caustic and critical curves of this lensing system. It is mainly written in python and boosted by using C and Cython. PyGame is applied to build the GUI and Interface. Another code is on illustrating the second order gravitational lensing phenomenon, i.e. Flexion, and measuring Flexion using a method named higher-order lensing image characteristics (HOLICs), which is in python only. It is translated from Goldberg's IDL HOLICs code[1]. These two programs both open source and can be found in my Github repositories[2][3].

2.2 Current research

Currently, I am focusing on developing a pipeline for simulations of strong gravitational lensing in galaxy clusters. Our aim is to produced 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, and lensed images are produced

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

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 further 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 suchs as noise window-paning from mosaiced observations, residual bad pixels and cosmic rays, and the like. The paper on this pipeline has been accepted by apj.

Strong lensing arc statistic is the most straightforward application of our pipeline.

An auxiliary use for this lensing code has been 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, e.g. WFIRST 4, come online, 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 infromation from such data. It will likely be necessary to develop morphological measurements that are conserved under gravitational lensing and some elements of the code described here have been used to test the the reliability of image plane measurements of the Gini coefficient (Florian et al. 2015).

For flexibility, we distribute our pipeline into series of modules, Calling different modules of this pipeline and input different sources, one can also investigate weak lensing in galaxy clusters, cluster CMB lensing, galaxy-galaxy lensing, etc.

3 Future research

3.1 Data challenge of lensing modeling

1– produce simulated images for different telescopes. 2– pass these data to challengers blindly. 3– reveal the input data later.

3.2 Machine learning and gravitational lensing

1– machine learning and arc finding. 2– machine learning and lensing modeling.

3.3 Simulations of time delay in galaxy scales lensing

1– Twinkles. 2– lensed supernova and quasar. 3– Constraining the cosmological parameters.

4 Summary

To sum up, the points mentioned above show my research plan in next two or three years. The application of big data and machine learning on lensing modeling and automatic arc finding will be my top priority in the near future, because, with the capability of the next generation telescopes, e.g. LSST, WFIRST and SKA, Astrophysics and cosmology are stepping in the big data era.

References

[1] C. J. Hogan and J. J. Dalcanton. New dark matter physics: Clues from halo structure. *Phys. Rev. D*, 62(6):063511, September 2000.

[2] A. V. Macciò, S. Paduroiu, D. Anderhalden, A. Schneider, and B. Moore. Cores in warm dark matter haloes: a Catch 22 problem. *MNRAS*, 424:1105–1112, August 2012.

[3] G. De Lucia, G. Kauffmann, V. Springel, S. D. M. White, B. Lanzoni, F. Stoehr, G. Tormen, and N. Yoshida. Substructures in cold dark matter haloes. *MNRAS*, 348:333–344, February 2004.

[4] J. E. Taylor and A. Babul. The evolution of substructure in galaxy, group and cluster haloes - II. Global properties. *MNRAS*, 364:515–534, December 2005.

[5] D. J. Sand, T. Treu, G. P. Smith, and R. S. Ellis. The Dark Matter Distribution in the Central Regions of Galaxy Clusters: Implications for Cold Dark Matter. *ApJ*, 604:88–107, March 2004.

[6] N. Okabe, M. Takada, K. Umetsu, T. Futamase, and G. P. Smith. LoCuSS: Subaru Weak Lensing Study of 30 Galaxy Clusters. *PASJ*, 62:811–, June 2010.

[7] V. Springel, S. D. M. White, C. S. Frenk, J. F. Navarro, A. Jenkins, M. Vogelsberger, J. Wang, A. Ludlow, and A. Helmi. Prospects for detecting supersymmetric dark matter in the Galactic halo. *Nature*, 456:73–76, November 2008.

[8] S. Mao and P. Schneider. Evidence for substructure in lens galaxies? *MNRAS*, 295:587, April 1998.

[9] N. Dalal and C. S. Kochanek. Direct Detection of Cold Dark Matter Substructure. *ApJ*, 572:25–33, June 2002.

[10] L.-X. Li and J. P. Ostriker. Semianalytical Models for Lensing by Dark Halos. I. Splitting Angles. *ApJ*, 566:652–666, February 2002.

[11] N. Li and D.-M. Chen. Cusp-core problem and strong gravitational lensing. *Research in Astronomy and Astrophysics*, 9:1173–1184, November 2009.

[12] D. J. Sand, T. Treu, and R. S. Ellis. The Dark Matter Density Profile of the Lensing Cluster MS 2137-23: A Test of the Cold Dark Matter Paradigm. *ApJ*, 574:L129–L133, August 2002.

[13] A. B. Newman, T. Treu, R. S. Ellis, D. J. Sand, J. Richard, P. J. Marshall, P. Capak, and S. Miyazaki. The Distribution of Dark Matter Over Three Decades in Radius in the Lensing Cluster Abell 611. *ApJ*, 706:1078–1094, December 2009.

[14] D. J. Bacon, D. M. Goldberg, B. T. P. Rowe, and A. N. Taylor. Weak gravitational flexion. *MNRAS*, 365:414–428, January 2006.

[15] X. Er and P. Schneider. Estimate of dark halo ellipticity by lensing flexion. *A&A*, 528:A52, April 2011.

[16] D. J. Bacon, A. Amara, and J. I. Read. Measuring dark matter substructure with galaxy-galaxy flexion statistics. *MNRAS*, 409:389–395, November 2010.

[17] M. Velander, K. Kuijken, and T. Schrabback. Probing galaxy dark matter haloes in COSMOS with weak lensing flexion. *MNRAS*, 412:2665–2677, April 2011.

[18] N. Li, S. Mao, L. Gao, A. Loeb, and R. di Stefano. Effects of supermassive binary black holes on gravitational lenses. *MNRAS*, 419:2424–2432, January 2012.