Astronomický ústav AV ČR

Michal Dovčiak
Tel.: (+420) 226 258 425
Fax: (+420) 226 258 499
dovciak@asu.cas.cz

Astronomical Institute of the Czech Academy of Sciences, Boční II 1401, CZ-14100, Praha 4, Czech Republic

REPORT ON PHD THESIS

Title: **Gravitational Lensing by Substructures in Dark Matter Halos**
Author: **Michal Karamazov**
Institution: **Institute of Theoretical Physics, Charles University, Prague**

Contents of the thesis

The main topic of the thesis is gravitational lensing in dark matter halos including substructures caused by individual galaxies. The thesis is divided into five chapters, starting with an introductory chapter (Chapter 1) where basics of gravitational lensing and dark matter halo properties are explained and ending by concise conclusions (Chapter 5). The core of the thesis consists of three chapters that contain original research, the critical curves and caustics in Navarro–Frenk–White (NFW) dark matter halo and in the main halo in combination with a point mass representing a substructure are studied (Chapter 2), properties of image geometry in terms of shear, phase and amplification in the same schemes are studied (Chapter 3), and an example of a more complex gravitational lensing in a galaxy cluster represented by an ellipsoidal NFW lens with substructures caused by individual galaxies represented by truncated ellipsoidal NFW lenses is investigated (Chapter 4).

Scientific impact

The theoretical research presented in the thesis is of high quality and the main original results include:

- extensive study of critical curves, caustics, shear and phase for gravitational lensing by NFW dark matter halo and NFW dark matter halo with a point mass – this shows an astounding number of different behaviours depending on the assumed parameters of the dark matter halo and point mass and will be very helpful in interpreting more complex situations with more substructures where many of these behaviours may occur,
- introducing the convergence-shear diagrams to represent the image geometry properties in a comprehensible way,
- creating a procedure and code to study more complex gravitational lensing in a galaxy cluster where both halo and its substructures are modelled by ellipsoidal NFW lenses in an efficient way (using CUDA for computations on GPUs),
- comparison of computed shear and phase with their weak limit in all studied cases including the complex full galaxy cluster scenario – this is interesting especially for the complex full galaxy cluster scenario where large discrepancies in the central part are visible and thus a weak-lensing limit is insufficient.

Chapters 2 and 3 comprise of two papers that have already been published in a very high impact factor journal, the Astrophysical Journal, which underlines the fact that very high quality scientific research is presented in the thesis. The results in Chapter 4 are not published yet, however, since they contain original interesting work where a gravitational lensing by a full cluster of galaxies is studied, one can expect that these will be published as well before too long. I expect that the presented results will have very high impact on the future development in this field of research.

Format of the thesis

As far as the style and language is concerned, the thesis is written in a very good scientific English with very few misprints. The typesetting of mathematical formulae, tables and figures are of standard quality expected in this type of document. Some mathematical formulae, however, would not fit into the text thus smaller font was used for them which is non-standard (mainly in Chapter 4) and feels strange when several different font sizes appear on one page (e.g. page 113). This happens especially when the term under square root is too long, one could avoid this by putting the term into brackets raised to the power of ½. Many of the figures might have been published in a larger size, maybe by dividing them onto two pages (the category B figures in Chapter 3

such as Fig. 3.7B, 3.8.B, 3.9.B, etc.).

Further comments

Few inconsistencies:

- page 6: while critical density has D_l in the denominator in its definition in the eq. (1.5) it should probably be in the numerator, see eq. (1.2),
- top of page 110: the distance in Mpc for the lens at cosmological redshift $z=0.4$ is larger than the distance to the source at $z=7$,
- top of page 118: the factor for the interpolated values should have another minus in front of 2 in the parenthesis

Questions

1. The convergence-shear diagram is a nice way to show the image properties especially since the convergence is somehow connected with the radius (it is monotonic for NFW dark halo).
   - Could you describe which parameters of the halo could shift or distort the green curve?
   - The location and/or shape of the green line will probably depend on the particular form of the halo inner profile – could you comment on that?
2. How much the real matter in and outside of galaxies (gas, stars, etc.) contributes to the gravitational lensing in comparison with dark matter?

Conclusion

I am persuaded that the research work done by Michal Karamazov that has lead to the publication of this thesis and to the two research papers published in the Astrophysical Journal, as well as the thesis itself demonstrate his capability of independent scientific research. I recommend the presented work to be accepted as a PhD thesis after its successful defence.

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Michal Dovčiak