Quantifying mass substructure in early-type galaxies
Vegetti, Simona

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2010

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.
Quantifying mass substructure in early-type galaxies

Proefschrift

ter verkrijging van het doctoraat in de Wiskunde en Natuurwetenschappen aan de Rijksuniversiteit Groningen op gezag van de Rector Magnificus, dr. F. Zwarts, in het openbaar te verdedigen op vrijdag 26 maart 2010 om 14:45 uur

door

Simona Vegetti

geboren op 25 januari 1980 te Aosta, Italië
# Contents

## Acknowledgments

1 **Introduction**

1.1 The missing satellite problem ................................. 2
1.2 Possible solutions to the missing satellite problem ................. 3
1.3 Gravitational lensing ........................................ 4
1.4 Probing mass substructure with gravitational lensing ............... 8
  1.4.1 Flux ratio anomalies ..................................... 8
  1.4.2 Astrometric perturbation .................................. 11
  1.4.3 Time delay millilensing .................................. 11
  1.4.4 Perturbations in highly magnified Einstein rings and arcs ....... 12
1.5 The SLACS survey ............................................. 12
  1.5.1 Motivation ................................................ 12
  1.5.2 Selection criteria ......................................... 13
  1.5.3 Major scientific results .................................. 13
1.6 This thesis .................................................... 14
  1.6.1 Outline of this Thesis .................................... 14

2 **Bayesian strong gravitational-lens modelling on adaptive grids** 15

2.1 Introduction .................................................. 16
2.2 Construction of the lensing operators .............................. 18
  2.2.1 The data, source and potential grids ........................ 18
  2.2.2 The source and potential operator .......................... 18
2.3 Inverting the data model ....................................... 21
  2.3.1 The penalty function ..................................... 21
  2.3.2 The optimization strategy .................................. 24
2.4 A Bayesian approach to data fitting and model selection .......... 25
  2.4.1 Model selection: smooth versus clumpy models ............... 29
  2.4.2 Model ranking: nested sampling ............................ 29
2.5 Testing and calibrating the method ................................ 31
  2.5.1 Mock data realisations .................................... 32
  2.5.2 Non-linear reconstruction of the main lens .................... 32
  2.5.3 Linear reconstruction: substructure detection ................ 33
  2.5.4 Non-linear reconstruction: main lens and substructure ......... 34
Statistics of mass substructure from strong gravitational lensing

Data realisation and analysis

Detection of a Dark Substructure through Gravitational Imaging

Error analysis and Model ranking

Quantifying dwarf satellites through gravitational imaging in SDSS J120602+514229
Stellingen
behorende bij het proefschrift

Quantifying mass substructure in early-type galaxies

1. Grid-based lens modelling techniques consistently embedded in the framework of Bayesian statistics provide a powerful tool to detect and quantify mass substructure in lens galaxies beyond the Local Universe.

2. A sample of 200 lenses observed with HST quality will allow to constrain the substructure mass fraction and mass function down to a few tenths of a percent error.

3. The detection of a substructure in the SLACS lens J0946+1006 implies a projected mass fraction in substructure of about 2 percent; this is high but consistent with the LCDM paradigm within the measurement errors.

4. Laser Guide Star Adaptive Optics data can under specific conditions be considered as a valid and complementary alternative to HST data in terms of sensitivity to mass substructure in lens galaxies.


6. Locally produced vegetables and fruits do not always have a lower carbon footprint than non-locally produced ones.

7. The real solution to the environmental issue is a deep reorganisation of society where the importance of sloth is strongly revalued.

8. Only thermoeconomics can be considered as a realistic economic theory.

9. “Forcing women to procreation every time they are pregnant means treating the woman’s body as a means of production. This is in conflict with the Kantian but also Christian imperative of treating humans as ends in themselves and not as means to an end.” - Umberto Galimberti.

10. Part of modern western society’s perception of freedom is based on the false illusion of a large choice between different products.