Gauging the inner mass power spectrum of early-type galaxies

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Chapter 7

Conclusions and future prospects

7.1 Conclusions chapter by chapter

In this thesis, I have investigated various aspects related to quantifying small-scale structure in the mass distribution of elliptical strong gravitational lens galaxies, from a statistical, numerical and observational perspective. First attempts were made to connect these results with galaxy formation scenarios, using the results of hydrodynamical galaxy-formation simulations from EAGLE. Besides this primary focus, I developed simulations and tools that have been applied to train Convolutional Neural Network (CNN) to find new strong lens candidates in the Kilo-Degree Survey (KiDS). These lens galaxies can be used in future studies of galaxy-formation scenarios.

In this concluding chapter, I summarise the results of this thesis, chapter by chapter, as well as conclude with a few noteworthy future prospects. Papers where I am the first author or co-author, and where I have contributed significantly, are indicated in bold.

- **Chapter 2 – Simulations of perturbed lens models and applications to machine learning**

  This chapter describes the construction of large numbers of mock string gravitational lenses used as training sets for Convolutional Neural Networks (CNNs). The CNNs were trained to recognise strong gravitational lens candidates in the 255 square degrees of the KiDS DR1 data. I developed the numerical framework and code to simulate of the order of $\sim 10^6$ mock lenses. From the two CNN lens-finders that were trained (one with single r-band images and another with g-r-i composite images), the results show that the accuracy and completeness of CNNs improve significantly by adding more complexity to the lens and source models rather than the addition of colour information of the images. Out of 21789 Luminous Red Galaxy (LRG) candidates selected from KiDS data, the single band CNN lens-finder retrieved 761 potential strong-lens candidates, which were down-selected to the 56 most promising lenses via visual-inspection. Further details of this search can be found in the companion papers by Petrillo, Tortora, **Chatterjee** et al (2017, 2018).

- **Chapter 3 – Power spectra analysis: statistical methodology and tests on simulated mock lenses**

  In this chapter, I mathematically established that lens-potential fluctuations present in the early-type galaxies can be well modelled by a stochastic field, which quantitatively is described by a two-parameter power-law model in power-spectrum space (**Chatterjee** & Koopmans 2018). These potential fluctuations, if present, give rise to the surface-brightness anomalies in strong galaxy-galaxy gravitational lensing. As a first order approximation, the statistical nature of this random field is assumed to be Gaussian. I show that the lens-potential or convergence perturbations can be inferred at the percentage level from e.g., *Hubble Space Telescope* (*HST*)-like single-orbit lens systems, and the inference is largely invariant to changes in the lensed-image topology of the lens system. The statistical prescription that I derived has subsequently been applied to the strong gravitational lens system SDSS J0252+0039 (Bayer, **Chatterjee** et al 2018).

- **Chapter 4 – Applications of a power spectrum analysis to HST observations of SDSS J0252+0039**

  In this Chapter, the statistical framework that I developed and tested on mock simulated lenses in Chapter 3 was applied to *HST* data of the strong gravitational lens SDSS J0252+0039, providing constraints on the matter-power spectrum on 1-10 kpc-scales. The pilot application of the statistical methodology (see Chapter 3) provides an upper limit on the fluctuation around the smooth potential, present in the lens plane, ($\delta\psi_{\mathrm{GRF}}$), as well as on the fluctuations of the differential deflection angle field ($\delta\alpha$) and the surface mass density ($\delta\kappa$). This lens galaxy has a matter power-spectrum models for which the convergence fluctuations $\sigma^2_{\delta\psi}$ do not exceed $\sim 10^{-2.5}$ at the 99 per cent confidence level. Within the studied field-of-view, this limit corresponds to $\sigma^2_{\delta\alpha} > 6 \times 10^{-3}$ when considering the differential deflection field, effectively independent of the value of the slope, β. The corresponding upper-limit constraints on the standard deviation of the convergence perturbation at three different scales were infered to be (0.5, 1 and 3-kpc): $\sigma_{\delta\kappa}(0.5\ \mathrm{kpc}) < 1$, $\sigma_{\delta\kappa}(1\ \mathrm{kpc}) < 0.3$ and $\sigma_{\delta\kappa}(3\ \mathrm{kpc}) < 0.1$. These upper limits on the small scale structure of (total) mass distribution, on all considered sub-galactic scales, however, are currently still above estimates from the cold dark matter substructure in the halo of this galaxy.

- **Chapter 5 – A systematic testing in adaptive grid-based Bayesian lens modelling: The case of SDSS J0946+1006**

  In this Chapter, I have carried out the first *controlled experiments* on simulated lenses – mimicking the double ring system SDSS J0946+1006 – to quantify the impact of degeneracies and biases due to adaptive grid-based Bayesian lens modelling on the reconstruction of the lensed source, lensed images and the lens mass model, when Gaussian Random Fields perturb their lens potentials. I find that the lens reconstruction is nearly invariant against the choice of the size of the data mask and the type of source regularisation. The results, however, indicate a clear intrinsic mode-mixing, i.e., power redistribution, between the reconstructed source and the lens-potential fluctuations. In particular, much of the structure induced in the lensed images by small-scale potential fluctuations are removed by modifying the source model. Furthermore, if the smooth lens-model (an SIE in this case) parameters are kept fixed at the true parameters in the lens modelling, the image residuals induced by potential fluctuations retain more power on the large scales (small k values). This result indicates that the smooth lens model can also absorb large-scale fluctuations. The source model, however, can incorporate induced surface-brightness fluctuations on all scales.

- **Chapter 6 – Power spectrum analysis of varying galaxy evolution scenarios in EAGLE N-body hydrodynamic simulation**

  In this Chapter, I analysed nine galaxy formation scenarios from EAGLE N-body simulations using the power-spectrum analysis developed in Chapter 3. Four of these models were "calibrated", and depend on various stellar feedback descriptions (FBconst, FBσ, FBZ, FBZρ). The other five models were variations of the Reference model (*FBZ*ρ) and not calibrated. Two models have modified viscosity levels (ViscLo, ViscHi), and three models have varying levels of AGN activity, in particular, adjusted temperature increment rates of stochastic AGN heating (AGNdT8, AGNdT9 and No-AGN scenario). I determined the power spectra of the normalised mass maps of all massive elliptical galaxies ($M_\star \geq 1.76 \times 10^{10} M_\odot$), coming from these nine scenarios, after rotation them to a common position angle and taking the particle shot-noise and the Smooth Particle Hydrodynamics (SPH) smoothing kernel into account. I defined the estimator of the variance by subtracting the power spectrum of the average stacked galaxies, $P^{\langle\kappa\rangle}(k)$, from the average of the power spectrum, $\langle P^\kappa\rangle(k)$. Previous results have shown that three scenarios (i.e., FBconst, ViscHi and AGNdT8) and appear to match observed lenses the best in terms of their mass-size relation and density slope. These scenarios also produce the roundest galaxies and are therefore well-approximated by spherical models. Furthermore, the FBconst, NoAGN, FBσ and FBZ models generate the most compact galaxies, whereas ViscHi produces galaxies with the largest effective radii. Despite these difference, the variance in the mass-maps corresponding to all nine scenarios follow a power-law, $\sigma^2_\kappa(k) \propto k^{-4}$ within their respective errors.

7.2 Future prospects of this work

- **Extending to non-Gaussian fields**

  The statistical methodology, developed and tested in this thesis, to measure the lens-potential and convergence perturbations of lens galaxies, makes several strong assumptions. However, this method can be further extended to a more general framework. Currently we assume that the statistical nature of the lens-potential perturbations is that of a Gaussian random field. Although on the scales of interest (1-10 kpc) any possible non-Gaussianity present in the lensing galaxy will be observationally challenging to detect and quantify, from a theoretical standpoint, this could be a direct extension of the present theoretical framework.

- **Testing systematic biases**

  In addition, the covariance between the lens perturbations and the smooth lens model has been ignored or is assumed to be negligible. Also, the assimilating the surface-brightness fluctuations between the smooth lens-model and the source model has not yet been taken into account or mitigated. Some of these questions of bias and degeneracies in adaptive grid-based Bayesian lens modelling are investigated quantitatively in Chapter 5, but one should incorporate those results in the power-spectrum formalism of Chapter 3. Preliminary results of these effects were, however, presented in Chapter 5. We expect a considerable improvement in determining the smooth model parameters and source reconstruction, however, after incorporating mitigating correction for these biases in our methodology.

- **Analysing line-of-sight contributions and larger samples**

  The observational upper limits on the potential perturbations inferred from our study of the lens galaxy of the system SDSS J0252+0039 refer to the total mass distribution (both dark matter and baryonic matter). In reality, however, these perturbations are composed of matter in the lens galaxy *and* along the line-of-sight. Future research could investigate their respective contributions to the total matter-power spectra. Moreover, in our present Bayesian adaptive grid-based analysis, the degeneracies between the source model and the smooth lens model, regarding the suppression of the surface-brightness fluctuations, have not been mitigated yet. Finally, the upper-limits currently inferred are based on the analysis of only a single lens system, J0252+0039. Future work will show applications of this framework to the double lens system SDSS J0946+1006 and other SLACS lenses.

- **Comparing galaxy-formation and evolution scenarios from N-body simulations**

  The power-spectrum approach to analyse the galaxy mass maps inferred from hydrodynamical simulations, presented in Chapter 6, paves the way to a direct comparison to the results from the observational upper limits presented in Chapter 4. Furthermore, this formalism can be extended to apply to, and compare with, other numerical simulations (e.g. Illustris) to examine whether we find any significant deviations in the small-scale power spectra in galaxy mass distributions, as a function of their formation and evolution scenario, something that currently does not seem to be the case.