2 Astrophysics and General Relativity

R. Angèlil, S. Balmelli, R. Bondarescu, L. De Vittori, C. Huwyler, Ph. Jetzer, R. Küng, I. Mohammed, L. Philippoz, P. Saha and A. Schärer

2.1 Gravitational Lensing

2.1.1 Microlensing

We worked on different aspects of galactic gravitational microlensing. The PLAN (Pixel Lensing ANdromeda) Collaboration, of which we are a member, got observing time both at the 1.5 m Loiano telescope at the Osservatorio Astronomico di Bologna (2006 till 2010) and at the 2 m HCT (Himalayan Chandra Telescope) telescope in India (during 2010). Recently, we published our final results based on a fully automated pipeline for the search and the characterization of microlensing flux variations: altogether we detected 3 microlensing candidates. We evaluated the expected signal with the help of a Monte Carlo simulation of the experiment completed with an analysis of the reconstruction efficiency of our pipeline. We considered both “self lensing”and “MACHO lensing” lens populations, given by M31 stars and dark matter halo MACHOs, in the M31 and the Milky Way, respectively. The small number of events at disposal, did not allow us to put strong constraints on the nature of the events. Rather, the hypothesis, suggested by a previous analysis, on the MACHO nature of OAB-07-N2, one of the microlensing candidates, translated into a sizeable lower limit for the halo mass fraction in form of the would be MACHO population of about 15% for 0.5 $M_\odot$ MACHOs.

We completed an analysis of the results of the EROS-2, OGLE-II, and OGLE-III microlensing campaigns towards the Small Magellanic Cloud (SMC). Through a statistical analysis we addressed the issue of the nature of the reported microlensing candidate events, whether to be attributed to lenses belonging to known population (the SMC luminous components or the Milky Way disc, to which we broadly refer to as “self lensing”) or to the would be population of dark matter compact halo objects (MACHOs). Our analysis showed that in terms of number of events the expected self lensing signal may indeed explain the observed rate. However, the characteristics of the events, spatial distribution and duration (and for one event, the projected velocity) rather suggested a non-self lensing origin for a few of them [1, 2].

2.1.2 Cluster lensing

We developed a statistical strong lensing approach to probe the cosmological parameters exploiting multiple redshift image systems behind massive galaxy clusters [3]. Our method relies on free-form inversion of galaxy clusters by considering the statistical dispersion of the parameter space describing the mass distribution. This provides information about the assumed cosmological model and thus an estimate of the cosmological parameters, but requires to sample a high-dimensional convex polytope in 100 or more dimensions. Previous sampling strategies used for free-form reconstruction of gravitational lenses were unable to produce unbiased samples.

Another work was a new analysis of a strong-lensing cluster (ACO 3827), showing robust evidence for offsets of a few kiloparsecs between the galaxies and mass peaks [4]. Several possible explanations for this are considered, the most intriguing being interactions between baryons and dark matter.

2.2 Gravitational waves and LISA

Within our group we addressed various topics on gravitational wave physics. We studied gravitational waves emitted by compact binaries on unbound orbits (hyperbolic encounters). Since it is desirable to have ready-to-use search templates, consisting of the two GW polarization states h_+ and $h_\times$, in order to detect waves with the new generation ground-based and the proposed space-borne interferometric detectors, we developed an efficient and accurate prescription to find the explicit waveform radiated during such an encounter. We provided a semi-analytical approach using the traditional post-Newtonian expansion up to 1PN order in the dynamics, including leading order spin-orbit interaction, which has never been done before.

We studied the impact of alternative general relativistic (GR) theories on the parameter estimation for coalescing massive black holes as could be performed by a LISA-type detector, such as eLISA. This has been achieved by introducing correction parameters that account for modified gravity into the second post-Newtonian gravitational wave phase for circular, black hole binaries with precessing spins. In order to find LISA’s measurement accuracy for physical parameters of the binaries, we used the Fisher matrix approach and carried out Monte Carlo simulations for several black hole binary mass combinations. Moreover, we made a detailed study on the adopted criteria on the choice of a critical orbit at which the integrations need to be stopped. We found that the corrections can be measured with sufficient accuracy for total binary black hole masses up to a few $10^7\ M_\odot$ at redshift $z = 1$, errors increasing with redshift. The introduction of alternative theory parameters still leads to a reasonable accuracy of the binary parameters such as masses and spins.

Currently we are investigating more realistic scenarios. While in our previous study, theoretical estimates of the expected error distributions of suggested alternative theory parameters could be made, it is still uncertain whether eLISA will be able to actually recover such alternative theory parameters. We are working on a Markov Chain Monte Carlo framework which tests eLISA's ability to recover the alternative theory parameters of a gravitational wave signal injected into the expected noise background. This will allow us to see whether in practice eLISA will be able to distinguish the underlying theory from GR at all or whether some other spacecraft configuration could be more favorable.

Coalescing black hole binaries are expected to be one of the most relevant gravitational wave sources for the currently operating (LIGO, Virgo) and planned (eLISA) detectors. Up to now, the Effective-one-body (EOB) approach is the only (semi-)analytical method which has been able to reproduce the waveform of the full evolution (inspiral, merge and ringdown) of coalescing black holes. Our work has focused on improving the description of spinning black holes within the EOB formalism. The main motivation lies in the fact that black holes are generally expected to have a spin, and that gravitational wave signals from co-rotating black holes are stronger than in the non-spinning case. Moreover, the EOB approach is currently not sufficiently accurate to reproduce reliable waveforms if the black holes are rapidly spinning [5, 6].

2.2.1 LISA Pathfinder

We are member of the LISA and LISA Pathfinder science teams and of its consortium. LISA Pathfinder is a dedicated technology demonstrator for the joint ESA/NASA Laser Interferometer Space Antenna (LISA) mission. The technologies required for LISA are extremely challenging. LISA Pathfinder essentially mimics one arm of the LISA constellation by shrinking the 5 million kilometer arm length down to a few tens of centimeters, giving up the sensitivity to gravitational waves, but keeping the measurement technology: the distance between the two test masses is measured using a laser interferometric technique similar to one aspect of the LISA interferometry system. The scientific objective of the LISA Pathfinder mission consists then of the first in-flight test of low frequency gravitational wave detection metrology [7–9].

2.3 Space clocks and relativity

It is well known that GPS satellites are sensitive to general-relativistic effects (specifically gravitational time dilation). Clock technology has advanced greatly in recent years, and space-based clocks now being planned would be able to measure space curvature and frame dragging to a planet as well [10].

2.4 Further topics

Some further topics were explored, together with Masters students.

2.4.1 Lens Modeling

R. Küng in his MSc project developed a system for volunteers, who are not professionals but do have amateur expertise in the topic, to model gravitational lens candidates. This is part of the *Spacewarps* citizen-science project to discover new gravitational lenses.

2.4.2 Next-Generation Interferometry

T. Wentz in her MSc project studied the possibility of measuring phase in the Hanbury Brown and Twiss effect, following up on work involving our group suggesting three-point HBT interferometry for astronomical sources [11].

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