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Assessment of the doctoral thesis presented by Michele Grasso

Michele Grasso presented a doctoral dissertation entitled `BIGONLight. A new package for computing optical observables in numerical relativity.' The thesis is 128 pages long; it consists of an extensive introduction that serves as a guide to the dissertation and the following two research articles:

1. Michele Grasso, Eleonora Villa, BiGONLight: light propagation with bilocal operators in numerical relativity, Class. Quantum Grav. 39, 015011 (2022).
2. Michele Grasso, Eleonora Villa, Mikołaj Korzyński, and Sabino Matarrese, Isolating nonlinearities of light propagation in inhomogeneous cosmologies, Phys. Rev. D 104, 043508 (2021).

The main achievement of the thesis is a public release of a numerical Wolfram Mathematica package called BIGONLight, implementing a formalism of the so-called bilocal geodesic operators (BGO) in General Relativity (GR). Bilocal geodesic operators constitute an elegant framework to describe the propagation of light in curved spacetimes within the geometrical optics, which in the context of GR amounts to an analysis of null geodesics. The BGO formalism maps local parameters of a congruence of null geodesics at the emitter location to corresponding parameters at the observer location. The formalism is developed with cosmological applications in mind. One of its main advantages is that it allows for a computation of important observable quantities, related to the propagation of light in cosmology. Such quantities include the redshift, the angular diameter distance, the luminosity distance, the parallax, the position drift, and the so-called redshift drift.

The BIGONLight package computes the BGO for a given metric, which can be provided either analytically or in a numerical form. The latter possibility seems to be especially important, as it allows for an analysis of light-propagation effects in spacetimes obtained as a result of numerical cosmological simulations. To allow for such applications, the implementation of the BIGONLight package works with metrics in the 3+1 split form --- probably the most common formalism of existing advanced numerical relativity codes. Let me point out that to allow for a smooth cooperation with such codes, the BGO formalism had to be rewritten in the 3+1 split form.

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The first of the papers has been published in Classical and Quantum Gravity (it was available as an accepted manuscript at the time the dissertation was written, and it is included in the thesis in such form). It presents the BIGONLight package and gives a derivation of the BGO formalism in the 3+1 split form. The remainder of the paper contains a discussion of several tests used to assess the correctness and precision of the BIGONLight. The tests are based on the ΛCDM model, a particular Szekerez model, and a dust universe model, evolved using the Einstein Toolkit (a well-known open-source numerical code in General Relativity). It is worth emphasizing that the last of these tests proves the ability of the presented package to work with real data obtained in numerical cosmological simulations. All tests are presented in terms of observable quantities (redshift, redshift drift, angular diameter distance). They all have been passed successfully.

The second paper has been published in Physical Review D. It reports an application of BIGONLight to a study of light propagation in inhomogeneous cosmological models. Since the idea behind this work was to test the impact of inhomogeneities on cosmological observables related to the propagation of light (the redshift and the angular diameter distance), the authors decided to use a toy-model solution, referred to as a wall universe. In this model density perturbations on the ΛCDM background are distributed along parallel planes. The general ansatz for the spacetime metric of the wall universe model allows for a solution using various approximations (they are referred to as Newtonian and post-Newtonian in the paper). In addition, light propagation can be solved either perturbatively or numerically, using BIGONLight. This allows for a comparison between the redshift and the angular diameter distance computed in various ways. Once again, results obtained using the above approximations agree with each other, but the redshift seems to be much more sensitive to the actual choice of the method than the angular diameter distance. In addition, the authors investigate the effects of the scale of perturbations on the differences between both observable quantities computed in different ways.

The quality of Michele Grasso's results can be also assessed by the prestige of journals in which they have been published --- both Classical and Quantum Gravity and Physical Review D belong to top ranking journals in GR. I understand, of course, that these papers have been prepared in collaboration with other authors, but I would say that this only shows the ability of the author to collaborate with other researchers in a fruitful way. On the other hand, in both papers constituting the presented thesis Michele Grasso is the first author; moreover Michele Grasso's contribution is clearly outlined in the thesis. In addition, both papers form a consistent mini cycle with a clear research programme, which is also a customary requirement for a good doctoral dissertation.

The subjects investigated in Michele Grasso's thesis are timely and important both from the observational and purely theoretical points of view. The idea of the BIGONLight package is clearly motivated by the existing and future numerical cosmological simulations obtained within GR. Some observables discussed in this thesis --- the redshift, the angular diameter distance, the luminosity distance --- belong to fundamental and well-known observable quantities in cosmology. Others, like the redshift drift, which expresses the change of the redshift due cosmic expansion and the proper motion of the source and the observer, remain (as I understand) beyond the reach of current cosmological observations. On the other hand, all these observables can be nicely incorporated in the BGO framework.

In his doctoral dissertation Michele Grasso has shown both analytical (mathematical) and numerical (programming) skills required to work with the modern geometric language of GR and to code a new Wolfram Mathematica package. I believe that both papers constituting Michele Grasso's thesis provide an important contribution to current research in GR and cosmology. Let me also point out that Michele Grasso is a co-author (with Mikołaj Korzyński and Julius Serbenta) of yet another paper, Geometric optics in general relativity using bilocal operators, Phys. Rev. D 99, 064038 (2019), introducing the BGO formalism and discussing related observable quantities.

It is hard to find truly critical remarks to the thesis. The errors I was able to find are basically typographical. I list them here basically as a form of fulfilling reviewer's tasks:

1. In section 2.1.1. the author writes: `...Einstein assumes that free particles move along geodesics in a four-dimensional Riemannian manifold M whose points represent physical locations in space and time.' I think what the author means are `free test particles.'
2. There is a typo in Eq. (23) of paper 1. The index *i* should be changed to *j*.
3. On page 111 the scale of 300 Mpc is unnecessarily repeated.

Perhaps my only critical remark (or a suggestion) concerns the presentation of the results in terms of the observable quantities in the second paper, where most of graphs show the variations of the redshift and the angular diameter distance obtained with different methods. It would be helpful to see the plots of absolute values of these quantities as well.

None of those remarks diminish my high opinion on the quality of the presented doctoral dissertation. **Therefore, I conclude that the presented dissertation meets the formal requirements for a Ph.D. thesis and recommend admission of the Candidate to the subsequent stages of the procedure, including the public defense.**

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