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To Whom It May Concern
Center for Theoretical Physics
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Report on the dissertation by **Michele Grasso**
"Bigonlight: A new package for computing optical observables in numerical relativity"

Dear Colleagues,

I would like to say from the start that I consider that of Michele Grasso a well above average PhD thesis, and therefore I have absolutely no doubt that it is suitable for public defence. In addition, in my opinion this is a dissertation of very high scientific quality, it describes research work that has already led to three articles published in internationally renewed journals and it belongs to the best 20% of the many dissertations that I have examined over many many years. On this basis I am pleased to recommend a distinction. I will try to motivate this in the following.

The dissertation is very well written and organised, detailed but without excess, and it comprises of a short Introduction (Chapter 1), four main chapters, and a Summary (Chapter 6).

Chapter 2 is devoted to present *The standard cosmological model,* ΛCDM: the title however doesn't give justice to the content, which is much broader and introduces all the bases and provides the framework for the original work presented in the rest of the dissertation. It starts from introducing the three main observational pillars on which contemporary cosmology rests: the CMB, LSS, and Supernovae. In section two cosmological models are introduced, first providing a very well written and concise overview of General Relativity, then of FLRW models in general, then focusing on the spatially flat ΛCDM background solution that is at the basis of the standard model of contemporary cosmology. Section 2.2.1 gives a concise presentation of relativistic perturbation theory, starting form a standard introduction to the gauge dependence of perturbations that arises in comparing two spacetimes, the physical one and the background, then discussing the main gauges used in the literature. Section 2.2.2 briefly discusses the Newtonian approximation that is vastly used in analytical and semi-analytical approaches to structure formation in cosmology, in particular Lagrangian perturbation theory. Finally, Section 2.2.3 presents some exact solutions that are sometime used in cosmology for various purposes, such as spherically symmetric LTB model and Szekeres models; the motivation for presenting these models is that they can be used, as it is done later in the thesis, as testbeds for numerical codes. In Section 2.2.4 this chapter moves on numerical simulations, further broadening the content: this sections serves mostly to introduce the ADM or 3+1 formulation of General Relativity, which is at the basis of so-called numerical relativity, i.e. solving Einstein equations with an initial value problem approach on computers. Finally, Section 2.2.5 gives a concise summary of the state of the art for cosmological numerical relativity in relation to observations.

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Overall, my judgment of this chapter is extremely positive. Most PhD students struggle precisely on this part of their thesis, where they have to take a view of their subject that it is broader than the specific research project they have worked on. In my experience as a PhD theses examiner, this is the chapter for which I typically see most recommendations for rewriting and improving (so-called Minor Amendments in the context of British academia). In comparison with the similar part in the many theses that I have examined, this chapter is well above average. I found that it is very well written, a *tour de force* concisely introducing an unusually large set of topics, and I have found only very few and really minor weaknesses. 1) on page 11, the de Sitter spacetime could be introduced more broadly than just in its spatially flat representation; 2) the LCDM solution eq. (2.26) is certainly correct, but unnecessarily complicated; this is because conformal time is used; if proper time is used, the solutions is a simple power 2/3 of an hyperbolic sine; 3) on page 13, in the definition of the Lagrangian frame (AKA synchronous-comoving gauge) the condition for *comoving* is missing (this may well be a typo): what it is given is the condition for the synchronous class of gauges $B=\Psi=0$, but it should be $B=v=\Psi=0$, where v is the matter velocity perturbation; 4) before equation (2.57) there is typo: it should be γ_{ij} , not $\gamma_{i,j}$; 5) Ref. [169] is missing details.

Chapter 3, *The BGO formalism for light propagation*, presents the results published in a first paper published in Physical Review D and co-authored by Michele, *Geometric optics in general relativity using bilocal operators*. The aim of this chapter is to introduce a new formulation for light propagation using the geometric optic approximation (totally standard and well motivated in cosmology) and based on bilocal geodesic operators. This work is based on a previous article by M. Korzyński and J. Kopiński (2018), of which it is an extension and generalization, as well as a re-derivation that allows a simple and more convenient geometrical formulation. Thus, although this chapter is not formally presented (Declaration, page iii) as one containing original work, as a matter of fact introduces research to which Michele Grasso has collaborated, co-authoring an original research paper. In other words, this chapter gives a well structured overview of some traditional material blended with the original research of the paper co-authored by Michele Grasso, presented in a more traditional fashion than Chapters 4 and 5, organising the content anew for the purpose of introducing the technical tools used in the following two chapters. This chapter is highly technical, but nonetheless very well written and illustrated with detailed figures, well organised, serving well its purpose. Very minor point: eq. (3.1) could be eliminated, given the more useful definition in eq. (3.4).

The fourth is the core chapter of this dissertation: it contains the published paper *Bigonlight: light propagation with bi-local operators in numerical relativity* presenting the Mathematica package written by Michele Grasso. The package implements the bi-local operator formalism as a series of Mathematica functions. These functions take as input the 3+1 ADM variables produced in a simulation in numerical relativity, or computed from an exact solutions, and use the bi-local formalism to compute any possible observable, as decided by the user, taking account observer and sources and their 4-velocities. The code is tested against two analytic spacetimes, the ΛCDM FLRW background and Sezekers-like models with a cosmological constant, and against simulations of a Einstein-de Sitter obtained using the Einstein Toolkit, a publicly available numerical relativity framework. The tests give excellent results. This is very promising in view of future applications of the code *Bigonlight* in more realistic situations, i.e. in cosmological simulations evolving realistic initial conditions obtained from a power spectrum of

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fluctuations at high redshift. One very good thing about *Bigonlight* is that it is designed to be completely flexible, i.e. adaptable to any gauge. This is excellent, because one of the major issues faced by cosmological numerical relativity simulations is that different codes use, for practical reasons, different gauges, hence it is crucial to offer users the flexibility of applying *Bigonlight* to different codes and the ability to compare results obtained with different codes. *Bingolight* has already been made public, and in my opinion it is a valuable tool offered to the scientific community.

Chapter 5 contains the published paper *Isolating nonlinearities of light propagation in inhomogeneous cosmologies*; the goal here is use the previously presented Mathematica package *Bigonlight* to understand the effects of non-linearities, in particular in the matter field, on observables. This is done in the context of a plane-symmetric spacetime. I agree with this approach: using a simplified framework that offers an analytical or semi-analytical counterpart serves well the purpose of applying a new code to isolate different effects. While such a simplified framework may not be general enough, it is reasonable to expect that the understanding gained in this contexts will be useful in future, when the code will be applied to realistic simulations. In particular, the work presented in this Chapter focuses on two cosmological observables, the redshift and the angular diameter distance, and looks at these in three different approximations: linear perturbation theory, Newtonian approximation, and post-Newtonian. While relativistic first-order perturbation theory is applicable to all cosmological scales, it is by definition limited to small-amplitude fluctuations; on the other hand, a Newtonian approximation is limited to scales smaller than the Hubble horizon, but can take fully into account large non-linearities in the matter distributions, and as such is used in N-body simulations in structure formations; the post-Newtonian approximation somehow bridges the two others. We are now in the era of so-called precision cosmology, where now the goal is to perform observations with 1% precision. In this context, current N-body Newtonian simulations of large scale structure that are performed in view of the upcoming galaxy surveys, e.g. Euclid, have a goal of 1% precision. Considering this, the question is if these simulations are equally accurate, or if there are relativistic effects of the order of ~percent that are missing. Thus the work presented in this chapter is very timely in my opinion, a first step to understand possible nonlinear relativistic effects in structure formation.

In summary, I consider the work presented in this PhD thesis highly valuable and well above average. The thesis itself is well written and in the top 20% of those that I have examined, and on this basis I recommend a distinction. I hope to have provided above my motivations for this recommendation.

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 defence.

Yours sincerely,

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