Report on University of Szczecin Doctoral Thesis by Roberto Caroli

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I General assessment

The candidate presents his research on an extension of relativistic models of fluids in the cosmological context, proposing, in Chapter 4, five variants of "Ricci Cosmology" models, and presenting observational constraints for the simplest of these five models in Chapter 7. The theoretical presentation is well-presented and appears to be correct. The observational analysis is not easily reproducible in the state-of-the-art sense of Akhlaghi et al. (2021), but reproducibility is still an emerging standard of science that is currently only *recommended*, not *required*; a few weeks' work would likely be sufficient for a cosmologist to reproduce results similar to those of the candidate (see §II.G for more on this).

Overall this is a good PhD thesis presenting a substantial body of original research in cosmology.

There are several minor concerns that should be considered if revision of the thesis text is allowed, as follows.

II Concerns

II.A Relation to publication

I could not find where the candidate describes the relation between his thesis text and Caroli et al. (2021), except for a brief comment "Following (Caroli . . . 2021)" between Eqs (4.9) and (4.10).

Best would be a paragraph in the introduction describing which chapters or chapter sections overlap, and roughly to what degree there is text overlap, e.g. "are to a large degree an extension of" or similar. The relevant chapter introductions, presumably mainly Chapters 4 and 7, should have at least a sentence briefly commenting on this, so that the reader finds this information where s/he expects it.

II.B Chapter 2. Standard Cosmological Model

1. The description of Eq. (2.5) is incorrect in the sense that the value of $\mathrm{d}s^2$ is undefined at the equator in the spherical case, i.e. when $1 = Kr^2$, since division by zero is undefined. The candidate should redefine the second term, e.g. as a limit as $r' \to r$, where r' is an auxiliary variable for use in the limit, in order to remove the error.

2. Equations such as (2.6), (4.28)–(4.31), (4.63), (4.87)–(4.88), only make sense if $a(t)$ is dimensionless. This is inconsistent with K in Eq. (2.5) being dimensionless. The candidate should correct the inconsistent statement that "$K = +1, 0, -1$", since the reader should not be required to guess which formulae require rescaling and which do not.

II.C Chapter 3. Relativistic Fluid Dynamics

1. What appears to be a missing reference "(??)" is present in Eq. (3.20), although it would be odd to include an equation reference inside the equation itself;

2. The switch from (3.10) to (3.11) is key to defining the "isotropic" Ricci cosmology model; it would clarify the reasoning to the reader if this were recalled in Section 4.1

3. Missing reference "(??)" in the line just below Eq. (3.21).

4. In Eq. (3.20), only five terms are listed, not six; this is possibly related to the "(??)" error in the equation.

5. Section 3.2 — The sentence just after Eq. (3.23) should list the "coefficients multiplying each term", to make it easier for the reader to see that this is the point in the manuscript where these are introduced.

II.D Chapter 4. Ricci Cosmologies

1. The introductory part of this chapter should give a brief overview of the five models, explaining what they are and why they are relevant.

2. Section 4.1 — The fact that Eq. (4.1) is closely related to Eq. (3.24) should be stated and briefly commented in the presentation of Eq. (4.1) — e.g. that constants are assumed as a simple model.

3. In Eqs (4.6), (4.9), t_0 is used with a meaning different to the usual convention of being the current epoch; this should be stated as a warning to the reader, especially since Eq. (6.15) uses the $_0$ subscript in its usual meaning of the current epoch.

4. In Eq. (4.136) — mentioning the more modern term, "rapidity", for "hyperbolic tilt angle", would be useful here.

5. Figure 4.1 — this appears to be a copyright violation of Fig. 1 from King and Ellis (1973), since there is no documentation of permission from Springer–Verlag for reproduction of the figure. It should not be difficult for the candidate to draw an improved version of the figure, half a century after the original was drawn, while giving credit to King & Ellis (1973) for the original. Alternatively, the candidate should obtain permission from the copyright owner and then state that clearly.

II.E Chapter 5. Bayesian Inference and Monte Carlo methods

1. 5.1, p43, "have been using" – "have been used"

II.F Chapter 6. Cosmological Probes of Dark Energy

1. Eq. (6.1) — what the candidate has called l is not a luminosity; its physical dimensions differ from those of the luminosity L; l is usually called the "flux", without the adjective "apparent". All occurrences of "apparent luminosity" should be fixed.

2. In the same equation: while L is related to the absolute magnitude, applying the adjective "absolute" to "luminosity" doesn't make sense. On the other hand, the adjective "bolometric" is necessary for the equation to be correct.

3. 6.7, p62, "put contraints" – "put constraints"

4. Figure 6.1 — the candidate has failed to satisfy the condition of the CC BY licence for the re-use of this figure; this can easily be rectified by inserting text such as "(C) CC BY" together with a link to `https://creativecommons.org/licenses/by/2.0`. The CC BY licence is designed to be easy to understand without requiring understanding of detailed legal terminology.

II.F.a 6.7 CMB

The claim that the CMB "has been discovered accidentally by American astronomers Arno Penzias and Robert Wilson in 1965" is misleading. While it is true that Penzias and Wilson were awarded a Nobel Prize for their rediscovery, access to the astronomical research literature has greatly improved since 1965; the claim that this was the first detection of the CMB is inconsistent with the easily verifiable historical record. The CMB was detected with an estimate of 2.3 K by McKellar (1941), based on observations by Adams (1941). This is acknowledged by Peebles (2014), who describes the Adams/McKellar 1941 detection as "the first measurement of the CMB left from the hot Big Bang". The fact that the CMB was detected in 1941 is uncontroversial and should be clearly stated. The rediscovery in 1965 should be retained, since it gained more community attention than the original detection, but should be described accurately.

II.G Chapter 7. Ricci Cosmology tested against astronomical data

The observational analysis presented in this chapter appears to be correct and gives interesting constraints.

The analysis does not satisfy state-of-the-art criteria for reproducible research (Akhlaghi et al., 2021) and open quantitative science[1]. For example, the reader is not informed about checksum-identified URLs (or more generically, URIs) of the input data files, and the precise versions of analysis software source code, software libraries, the detailed methods of compilation, and scripts for doing the analysis, are not known to the reader. In practical terms, another cosmologist than the candidate would require weeks or longer to reproduce roughly compatible results, or maybe months if doing this in ten years' time, while a reproducible research project should require typically a few hours or a day for full, detailed numerical verification by an independent cosmologist. Full

[1] `https://sorbonnedatadeclaration.eu`

documentation of data and software lineage and archiving of these are strongly encouraged by grant-giving organisations in Poland and much of Europe.

The candidate should consider doing the followup projects in line with state-of-the-art reproducibility criteria. Moreover, applications for grants will require that the candidate describe plans for reproducibility.

II.H Appendix A

1. title: "Priors derivation", using "priors" as an adjective, is unclear; a better title would be "Priors for the isotropic Ricci Cosmology parameters"

II.I Other minor flaws

1. Subscripts and superscripts that represent text labels rather than variables should be in roman font, e.g.
   (a) ^{eff}, not $^{eff} \equiv {}^{e\times f\times f}$;
   (b) $_{\mathrm{vac}}$, not $_{vac} \equiv {}_{v\times a\times c}$.
2. The candidate should choose to either:
   (a) use German strictly, and always write capitalised "Ansatz" in the singular and "Ansätze" for the plural; or
   (b) use unaccented English consistently, with "ansatz" as singular and "ansatzes" or "ansatze" as plural; or
   (c) use accented English consistently, with "ansätze" as singular and "ansätzes" as plural.
3. The candidate should remove the sarcastic term "so-called" throughout the thesis. (Alternatively, use of the adjective should, at least, be accompanied by a justification of why the candidate finds a piece of terminology dubious.)
4. There are numerous minor flaws in the English, but generally these do not prevent comprehension.

III Recommendation

This PhD thesis satisfies the current standards of scientific research in modern cosmology expected for a doctoral thesis. I recommend that the candidate proceed to the thesis defence, and that he be awarded the University of Szczecin doctoral degree, subject to satisfactory performance in the defence. Ideally, if the PhD procedure allows it, then the thesis text itself should be corrected, taking into account the above suggestions. (For the candidate's own reduction of the risks of identity theft, I recommend removal of the candidate's PESEL number from the document.)

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prof. dr hab. Boudewijn F. Roukema
13 September 2022, Toruń

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