## External report on the PhD thesis of Mr. Michal Bilek entitled

### Galaxy Interactions: dark matter vs. Modified Newtonian dynamics (MOND)

I am reporting on the written thesis submit on June 19th, 2015, by Mr. Michal Bilek to the Faculy of Mathematics and Physics of Charles University in Prague for admission to the doctoral degree.

**Background**

The discovery of high and nearly constant galactic rotation curves by Rubin & Ford (1970) heralded a new era in astrophysics.

One possibility to explain this observation is based on extrapolating Newtonian/Einsteinian dynamics to be valid on all scales. This requires the existence of hitherto undetected (exotic) dark matter particles, which are not contained in the standard model of particle physics, to account for the departure from the originally predicted falling Newtonian rotation curves. This approach led to the development of the current standard model of cosmology. It has many problems, one of which is that it is entirely unable to allow predictions of the rotation curves around galaxies given a measurement of the visible mass distribution. Instead, rotation curves need to be observed in order to then calculate the distribution of dark matter around and within the galaxy.

Another possibility generalizes the effective equations of motion to be different from the Newtonian ones in the classical regime. Milgrom published in the early 1980s such an effective dynamical theory, and this theory has since been developed further including general relativistic versions and Lagrange formulations. Milgromian dynamics is fully predictive in that an observed distribution of matter within a galaxy yields a unique galactic rotation curve which can be tested by observation. Many other predictions have been made by this theory, and these have been most remarkably successful to date. One shortcoming of testing whether Milgromian dynamics is a correct classical description of gravity is that virtually all available significant tests have been restricted to data on rotationally supported galaxies. This is where Mr. Bilek's brilliant contributions enter the scene.

**Mr. Bilek's PhD thesis**

Before assessing Mr. Bileks research work and without knowing him well personally, I would like to stress that science usually progresses by rare individuals who leave the generally accepted framework to try new ways of looking at old problems. I count Mr. Bilek as a particularly excellent example of such an outstanding pioneer.

With his work he has rejuvenated a research field (shell galaxies), which was more or less stagnant since the late 1980s, by pointing out how valuable these systems are for testing gravitational theories. As Mr. Bilek emphasizes in his published work, shells allow tests of the theory of gravitation in systems which are not rotationally supported, thereby extending hitherto accessible tests on disk galaxies to spheroidal pressure-supported systems. *This is truly ground-breaking work on fundamental physics.* His work opens up, for the first time, tests of non-Newtonian gravitational theories even at distances $\gg 100\,\mathrm{kpc}$ from an elliptical galaxy, which corresponds to the ultra-weak-field classical regime for which such tests have barely been possible around galaxies until now.

The thesis of Mr. Bílek reports and summarises the contents of four first-author publications and one co-author publication of original research which appeared in leading astrophysical research journals. These papers are reprinted in the Appendix of Mr. Bílek's PhD thesis. Each of these research papers constitutes innovative and pioneering work (one of the listed papers, Bílek et al. 2015b, comprises a review of his work). Prior to discussing these papers (in Chapter 3), Mr. Bílek introduces, in Chapter 1 MOND (i.e. "Milgromian dynamics") and the many properties it implies galaxies ought to have (and are also observed to have). Chapter 2 introduces the various types of shell galaxies and the theories and models invoked to account for the shell features. Both introductory chapters are well written and are very useful as reviews. Concerning the actual PhD research:

In his first paper, Bílek et al. (2013) use the latest observational data on the previously much studied shell galaxy NGC 3923 thereby extending the number of known shells from 18 to 27. Therewith this already constitutes an important scientific discovery. Mr. Bílek uses archival observational data to discover the new shells and to measure the profile of the baryonic mass distribution in the main galaxy. In this work he developed a shell-identification method for testing whether a potential is consistent with the observed radial spacing of shells. With this method, Mr. Bílek can extract information such as when the individual pericenter passages of the minor galaxy occurred, the direction of the encounter and the shell ordering. He, for the first time, correctly applies Milgromian dynamics to model the shell system, since Hernquist & Quinn (1987) published their simplified study in which they erroneously concluded that MOND does not reproduce the then known shell system. Mr. Bílek thus uses stronger constraints, and shows that the shell system is well reproduced in MOND. One reason for the previously made erroneous conclusion is that the shell system is not a result of a single passage but of multiple orbital oscillations of the dwarf galaxy. As emphasized by Bílek et al., the potential is completely specified by the observed main galaxy (subject to uncertainties in the baryonic mass-to-light (M/L) ratio and the specific MOND theory employed), thus the model shell radii cannot be adjusted by arbitrarily changing the potential. Therefore Milgromian dynamics is successful in accounting for the shell radii.

In his second paper, Bílek et al. (2014) extend their previous study on NGC 3923 by investigating the range of MOND interpolating functions and M/L ratios. He also extends his previous made-by-hand approach by developing a highly efficient new automated shell identification method, which proved to be a major challenge but is now ready to be used for other shell systems. The most remarkable result, apart from the new algorithm and software, of this contribution is the prediction of a new shell at a distance of 230 kpc from the main galaxy thereby also predicting it surface brightness, if Milgromian dynamics is applicable.

Based on this work, Mr. Bilek submitted an observing proposal with the 3.6 m CFHT, which was accepted being rated with the highest priority as "must-do".

In the third paper, Bilek et al. (2015c) study constraints on the circular velocity of the main galaxy and on the shell propagation velocity using future spectroscopic observations. This will uniquely allow measurements of the baryonic Tully-Fisher relation (BTFR) for elliptical galaxies. The BTFR is not expected to hold true in dark-matter frameworks, but it must hold in Milgromian dynamics. This paper therewith constitutes one of the most important research contributions in the past decade, as it identifies an entirely new observational strategy to test fundamental physics. He predicts, for an ensemble of shell systems, beyond which radius a measurement of the velocity field will test gravitational theory robustly. This is a completely new and original result.

His most recent research paper (Bilek et al. 2015a, arXiv) is currently under review. Here observations of NGC 3923 down to a hitherto unprecedented surface brightness level (29 mag/arcsec$^2$ in the g'-band) obtained by Mr. Bilek based on the above mentioned observing proposal using the CFHT are reported in order to test the previously made prediction. Invoking also archival HST observations, Bilek et al. discover 42 shells! This is the largest number of shells known for any galaxy. The probable progenitor of at least one of the shells is also discovered. These findings alone are most remarkable observational achievements, since with this project Bilek et al. have successfully and significantly advanced knowledge of the shell system of NGC 3923, and by implication of other shell systems. It was not thought that such a large number of shells could exist. The predicted shell is however not found, but these unprecedented fine data lead to the insight that the prediction had been done based on data of too poor quality (e.g. wrongly identified shell orders). Given the much improved new observational constraints, the previous calculations of the shell structure and the predictions change significantly, and this will be followed-up by Mr. Bilek's future work.

**In summary**

With his PhD research work, Mr. Bilek makes six major scientific contributions, each of which have advanced the field significantly:

1. He corrects a previously published wrong result by Hernquist & Quinn and demonstrates for the first time that MOND is consistent with the most-studied shell galaxy NGC 3923.

2. He invents an automated shell-analysis algorithm which will be very important for further research on shell galaxies.

3. He obtained new, hitherto unparalleled deep observations of the shell system of NGC 3923 with the CFHT reporting that this galaxy, which has been known thanks to Bilek's previous work to have 27 shells, to have 42 shells. Such a large number of shells has never been reported for any shell galaxy,

and this revolutionizes our understanding of such systems apart from posing increasingly severe constraints on theories of their origin.

4. He showed that the shell system of NGC 3923 was created most probably by two dwarf galaxies, one of which is still discernible.

5. He invents an entirely new empirical method to measure the shell propagation speed and the circular velocity at large distances from elliptical galaxies with shell systems therewith opening up a completely new approach to testing Milgromian dynamics in non-rotational systems and in the radial-velocity-anisotropy regime. This invention will not only allow tests of Milgromian dynamics, but will also allow testing different theories which underly Milgromian dynamics (modified-inertia theories vs modified gravity theories).

6. He demonstrates how explicit predictions can be made within Milgromian dynamics which are not possible in the dark-matter framework.

The thesis is well written, with a few minor grammatical errors. The figures and equations are well laid out. The thesis gives a good summary of the above four research papers.

**Queries**

As minor queries I have only the following: The explanation of Fig. 34 and its importance can be improved. I had to read the original paper to better understand the implications of this important result. Below equation 14 a small mistake implies the limit of the Newtonian potential, while the AQUAL potential ought to be written there. In Fig. 2 the colour scale is not explained. In the fourth point on p. 16 "strong external field" ought to be written instead of "strong internal field". The statement "where ΛCDM excels" on p. 21 is not understandable, because, on close scrutiny, this is a false statement to make. On p. 57 that "Potential wells of isolated objects are infinitely deep" ought to have been explained. And finally, in Section 1.1 he cites Ibata et al. (2013) as the original reference for brining up the "disk-of-satellites" problem, whereby he lists other previously found problems and the original papers that reported them. This is not correct, as the disk-of-satellites problem, which today stands unsolved within the dark matter framework and is probably the most significant failure of the dark-matter model, has been explicitly identified as such for the first time with the contribution by Kroupa et al. (2005).

**Recommendation**

I therefore certify that this thesis contains multiple new outstanding and original contributions with an impressive depth of analysis and thinking. It proves the ability of the author to conduct truly innovative and ground-breaking scientific research in the field of astronomy and astrophysics, and can unhesitatingly be recommended for the defense of the doctoral degree. Concerning the quality of the work, I would rate it of the highest in terms of originality and importance.

As a final comment I would like to emphasize that the choice by Mr. Bilek to work on MOND is a most remarkable and brave decision, given that the international research community does not reward such choices. Mr. Bilek therewith demonstrates the true scientific spirit, in terms of a deep desire to learn how nature works, which is evident only in the very rarest of young researchers today. Mr. Bilek has, to my mind, demonstrated a brilliance for doing pure research not usually evident amongst his peers.


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Bonn, July 24th, 2015

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