Lessons from the Local Group (and beyond) on dark matter

Pavel Kroupa

Helmholtz-Institut für Kern und Strahlenphysik, University of Bonn, Nussallee 14–16, 53115 Bonn, Germany; e-mail: pavel@astro.uni-bonn.de

Abstract. The existence of exotic dark matter particles outside the standard model of particle physics constitutes a central hypothesis of the current standard model of cosmology (SMoC). Using a wide range of observational data I outline why this hypothesis cannot be correct for the real Universe. Assuming the SMoC to hold, (i) the two types of dwarf galaxies, the primordial dwarfs with dark matter and the tidal dwarf galaxies without dark matter, ought to present clear observational differences. But in fact there is no observational evidence for two separate families of dwarfs, neither in terms of their location relative to the baryonic Tully-Fisher relation nor in terms of their radius–mass relation. This result is illuminated by the arrangements of the satellite galaxies around host galaxies for which we have data: the arrangements in rotating disk-of-satellites, in particular around the Milky Way and Andromeda, has been found to be only consistent with most if not all dwarf satellite galaxies being tidal dwarf galaxies. The predicted large numbers of independently or in-group accreted, dark-matter-dominated primordial dwarfs are most inconspicuously absent around the Milky Way in particular. The highly symmetric structure of the entire Local Group too is inconsistent with its galaxies stemming from a stochastic merger-driven hierarchical buildup over cosmic time. (ii) Dynamical friction on the expansive and massive dark matter halos is not evident in the data: the satellite galaxies of the Milky Way with proper motion measurements have no infall solutions as they would merge with the MW if they have dark matter halos, and galaxy groups such as the M81 group are found to not merge on the short time scales implied if each galaxy has a dark matter halo. Taking the various lines of evidence together, the hypothesis that dynamically relevant exotic dark matter exists needs to be firmly rejected.

1 Introduction

By applying Einstein’s general relativistic field equation, i.e. Newtonian dynamics, to galaxies and to the Universe as a whole, disagreements with observational data had been found that require the additional assumptions of inflation, exotic dark matter particles and dark energy. These may constitute major new physics components, but none have supporting experimental evidence independently of the observational astronomical data that are used to make the three postulates. For example, dark matter particles are not contained in the standard model of particle physics and have not been found in any of the experiments designed to search for them. If they do not exist, then a major pillar of the modern standard modell of cosmology (SMoC) collapses, such that the SMoC would be ruled out as a representation of the Universe and of the structures that develop within it over cosmic time. “Does dark matter exist?” is thus one of the most important questions of modern science. Direct searches for dark matter particles cannot falsify this question by design, since a non-detection may merely imply that the interaction cross section with baryons (e.g. via the weak force) is unmeasurably small. Direct
detection experiments thus speculate on receiving the Nobel Price, but they are not a well
designed experimental procedure in which a prediction can be falsified.

Here I argue that the astronomical observational data strongly, if not unequivocally, show
dark matter to not be present. I use three independent tests and many consistency checks.
While this goes against the perceived majority opinion with corresponding sociological and
possible career implications, the community does have to face a reality without dark matter,
as bleak and dark as it may appear.

Weighty evidence for this conclusion comes from the best data at hand, namely what we
learn from observing the galaxies and their star-formation processes in the Local Group. But
extragalactic evidence has also been crucial in refining the conclusions.

With this text I provide a synopsis of the arguments presented in more depth in [1] and
[2]. Fig. 1 outlines the structure of the argument.

There are three main reasons why cold or warm dark matter (DM) particles, collectively
referred to here as exotic DM particles, cannot be dynamically relevant on the scales of galax-
ies. These are discussed in Sec. 2. Secs. 3 and 4 contain consistency checks, and Sec. 5 de-
velops additional arguments to test the “no-DM” deduction based on galaxy populations over
cosmic time. The conclusions are provided in Sec. 6

2 Why can there be no cold or warm dark matter?

Assume the SMoC applies, and view the Universe through Newtonian eyes. By assuming
the SMoC applies, we accept the cosmological merger tree to be a description of how the DM
halos and the galaxies within them grow through many mergers due to dynamical friction
on the DM halos. The first structures begin to form before recombination and many of them
become primordial dwarf galaxies (PDGs). In the SMoC these are contained in DM halos.
Ignoring the well-known problem of downsizing, namely that dwarf galaxies are observed
to be younger but ought to be older than more massive galaxies [6,7,8], the evolution of the
galaxy population can be followed [9,8]. As the larger DM halos build up through coales-
ence, the galaxies within them merge. The gaseous and stellar matter that is expelled and
which carries away the angular momentum and energy from the merger in the form of tidal
arms often fragments and forms star clusters and new dwarf galaxies. These dwarf galaxies
are called tidal dwarf galaxies (TDGs), and they may contain captured previously existing
stars and they may form from pre-enriched gas, but this depends on the evolutionary stage of
the pre-merger galaxies.

Differently to PDGs, TDGs do not contain significant amounts of DM, because TDGs
have such small masses (~10^9 M_☉) that DM particles from the much more massive DM halos
of the pre-merger galaxies are rarely captured by them. Thus, in any realistic cosmological
theory in which galaxies can interact, TDGs and PDGs must exist. This is the “dual dwarf
galaxy theorem” [11]. In the SMoC, TDGs and PDGs differ in their DM content, and thus
can be distinguished observationally.

Also, in the SMoC encounters between galaxies lead to them merging, and therefore
to the emergence of the cosmological merger tree which drives galaxy evolution. Without
dark matter halos, the merger rate decreases most significantly [10,12], and there would be

1Noteworthy is that the evidence provided in the year 2012 which are claimed to falsify
the SMoC [11] have, to this date, not been countered by the community but have instead been
strengthened by recent progress [3,4,2].
Fig. 1. Structure of the falsification of dynamically relevant cold or warm dark matter. The dual dwarf galaxy (DDG) theorems and the tests using the baryonic Tully Fisher relation (BTFR), the radius-mass relation (R(M)R) of pressure supported dwarf galaxies and using dynamical friction (DF) are discussed in Sec. 2. The consistency checks based on the vast polar structure (VPOS) of the Milky Way and on the great plane of Andromeda (GPoA) are in Sec. 3 (see also Fig. 2). A high degree of self-consistency of the argument emerges by the VPOS and GPoA, which are mutually correlated rotating structures, ruling out the satellite galaxies being primordial dwarf galaxies (PDGs) with dark matter halos. Thus their observationally deduced high dynamical M/L ratios needs to be accounted for by effective non-Newtonian gravitation, which is the same conclusion reached using the BTFR test. This consistency is emphasized by the connected orange regions. If this conclusion is true then the SMoC cannot be a good description of the observed Universe. The theory confidence graph for the SMoC is discussed in Sec. 4 and indeed confirms the SMoC to not be an acceptable model; neither CDM nor WDM thus exists. This is further ascertained by the evidence for a lack of mergers in the observed galaxy population as covered in Sec. 5 whereby DM halo merger statistics are discussed in [25]. Other acronyms: TDGs=tidal dwarf galaxies (Sec. 2), C/WDM=cold or warm dark matter= exotic DM particles, i.e. particles outside the standard model of particle physics.
no cosmological merger tree which drives galaxy evolution. Our understanding of galaxy evolution is thus intimately connected to the existence of DM.

There are three tests which, independently of each other, rule out DM as a relevant physical aspect of galaxies, as long as the observational data remain undisputed. Two tests are based on the dual dwarf galaxy theorem, and one is based on the well-understood process of dynamical friction of the motions of galaxies through the DM halos of other galaxies.

1. Tidal dwarf galaxies cannot contain much DM and yet the three that have observed rotation curves show the same DM behavior as PDGs. Thus, the three TDGs lie on the observed baryonic Tully-Fisher relation (BTFR) but they should be displaced by a factor of 3 to 10 towards smaller velocities than the BTFR. Chance superposition of a TDG onto the DM-defined BTFR may occur if the velocity field of the gas in or around the TDG does not constitute a virialised (Keplerian) structure, but in such a case the TDG would be more likely placed elsewhere in the BTFR diagram. The rotational velocities of PDGs are assumed (but not understood) to be defined by the DM halos that are ten to hundred times more massive than the baryonic mass of the PDG [9,8]. That the baryonic masses do not correlate exactly one-to-one with the DM halo masses [11,12] comes from the stochastic and haphazard process of the mergers which build-up the DM halo, and the different modes of accretion (cold vs hot) in DM halos of different masses. Since TDGs and PDGs lie on the same BTFR, which is supposed to be defined by primordial galaxies that are DM dominated, it follows that DM is ruled out to be the origin for the BTFR. This deduction is sound, as long as the data remain unchallenged, because TDGs cannot contain much DM, even if it exists, such that they cannot lie on the BTFR. But their rotation velocities can be obtained in a non-Newtonian gravitational framework (e.g. in Milgromian dynamics [13]). PDGs can have DM, but their rotation curves can also be explained by non-Newtonian gravity. Thus, non-Newtonian gravitation is the only unifying concept concerning TDGs and PDGs.

2. Tidal dwarf galaxies must have different radii at the same mass than PDGs because they form without a DM halo, compared to pressure-supported PDGs which form within a substantial DM halo [11,12]. But TDGs are found to have, at a given mass, the same radii as PDGs [13]. Since TDGs cannot contain DM this implies that the morphological appearance needs to be driven by a physical process common to both, the TDGs and PDGs. Thus, only non-Newtonian gravitation can unify both types of dwarf galaxy.

3. Dynamical friction is a necessary and required property of DM halos [10,15]. Two similar galaxies that interact with relative velocities smaller than about the virial velocity dispersion of their DM halos and within a distance twice the virial radius of their DM halos will merge within an orbital time scale. A primordial satellite galaxy will merge with the main galaxy within a timescale given by Chandrasekhar’s friction time scale. The dynamical simulations of the M81 group of galaxies have shown them to merge within a group-crossing time such that the matter bridges that are observed between the galaxies cannot be reproduced [16,17]. Reproduction by models of the observed bridges and galaxy locations and line of sight velocities is only approximately successful in models without DM. Since galaxies do have flat rotation curves, it follows that these need to be explained without dark matter, i.e. with non-Newtonian dynamics. And, the satellite galaxies of the Galaxy with proper motion measurements cannot be traced back to pre-infall dwarf galaxies if they have DM halos [18].
3 Consistency of the deduction: The arrangement of galaxies in the Local Group and elsewhere

If the deduction reached in Sec. 2 that DM does not exist is correct such that the cosmological merger tree would need to be discarded, then what is the origin of the satellite galaxies that are observed around the Milky Way (MW), Andromeda and other nearby galaxies, and where do the dwarf galaxies, e.g. in the Local Group, stem from? The lack of evidence for the cosmological merger tree being active is also discussed in Sec. 5.

3.1 Clues on their origin: spatially anisotropic satellite galaxy populations

The spatial arrangement of satellite galaxies around the MW gives a strong clue to their possible origin. All known stellar systems beyond about 10 kpc distance from the Galactic centre (classical dSph satellite galaxies found on photographic plates, ultra faint dwarf galaxies found with robots scanning the sky, globular clusters) and half of all gas and stellar streams are arranged independently of each other in a vast polar structure (VPOS, [23,19,4,24]). The proper motion measurements for the 11 brightest satellite galaxies show the VPOS to be rotating in one sense, the spin of the VPOS points into a direction which is close to the MW disk plane (let’s call it direction S). Viewing along the direction Galactic-centre—Sun, the VPOS lies approximately face-on. The VPOS can be described as a polar disk with diameter of about 500 kpc and thickness of about 50 kpc.

Halve of all satellite galaxies of Andromeda are in a vast thin disk of satellites (VTDS), i.e. in the great plane of Andromeda (GPoA, [21,3]). This GPoA is rotating, and its spin is directed only about 38 deg away from S. That is, the GPoA and the VPOS are impressively aligned, with the GPoA also being nearly perpendicular to the MW disk as is the VPOS (fig. 16 in [22]). Fig. 2 shows the VPOS, the Andromeda satellite galaxy system and their relative orientation and location, and the most remarkable and hitherto not noticed nor ever expected symmetric structure of the entire Local Group.

3.2 Other dwarf satellite galaxy populations

Beyond the Local Group, [25] discuss the dwarf galaxy population in the M81 group of galaxies, which is a sparse group comparable to the Local Group, and they find evidence that the faint satellite galaxies are distributed anisotropically. They write “In review, in the few instances around nearby major galaxies where we have information, in every case there is evidence that gas poor companions lie in flattened distributions.” [2] counts nine major galaxies with associated satellite systems which are anisotropic (see also [24]). It thus seems to be more the rule than the exception that satellite galaxies appear to be highly correlated in phase-space such that they appear arranged highly anisotropically about their hosts.

3.3 Satellite galaxies are tidal dwarf galaxies (TDGs)

How can the preponderance of such highly correlated satellite galaxies be explained? The occurrence of an anisotropic system of PDG satellites which is comparable to the VPOS or the GPoA is so unlikely that this possibility can be discarded safely, even if accretion of PDGs from cosmological filaments is considered [26,14]. The only known viable physical process which can generate such correlated structures is if the satellite galaxies are TDGs which
The distribution of all galaxies known today in the Local Group which is defined by the zero velocity sphere. Galaxies outside this sphere of radius about 1.5 Mpc recede from the Local Group, while within the sphere the galaxies fall towards us. The upper left and right panels depict all satellite galaxies within about 250 kpc around the MW and Andromeda, respectively. The galactic disks of the MW and of Andromeda are seen nearly edge-on, the north Galactic pole direction being upwards, and both galaxies are viewed from the same direction from infinity. MW satellites with known proper motions and radial velocities \([19,20]\), and Andromeda satellites that are in the GPoA \([21]\) are shown as colored circles. Red satellites are moving away from the observer, blue ones are approaching the observer. Thus the VPOS and GPoA are rotating in the same sense and the GPoA is seen edge-on from the MW as is evident in the lower-left panel. The VPOS and GPoA are statistically highly significant mutually correlated rotating structures inconsistent with being derived from accreted DM subhalos which host PDGs \([3,4]\). The VPOS and GPoA are inclined relative to each other by only about 38 degrees whereby the GPoA is oriented edge-on to the MW. This is seen in the lower left panel, which is a view from near the north Galactic pole downwards such that the VPOS and GPoA are seen approximately edge-on. Filled circles are dwarf galaxies in the disks of satellites of both major galaxies, while the crosses near M31 are satellite galaxies which are not in the GPoA. Viewing the Local Group along the line joining the MW and Andromeda it emerges that all non-satellite galaxies in the Local Group are arranged in two highly symmetrical equally thin planes (thickness about 50 kpc; diameters about 3 Mpc) equidistant from both, the MW and Andromeda, seen here edge on in the lower right panel. The crosses are as in the lower left panel; note the additional disk of satellite which lies in the equatorial plane of Andromeda and is here seen as a string of dwarfs (crosses) between the two major planes of the Local Group. The green and yellow filled circles show all non-satellite dwarf galaxies comprising the Local Group. They are all situated in one of two major symmetric planes. The short arrows depict the galaxy motions as given by the line-of-sight velocities. The Local Group is moving along the arrow towards the CMB. Evidently the Local Group is a highly structured symmetric distribution of galaxies which has never been predicted nor even hinted at as being a result of the structures forming through a SMoC merger tree. The upper two panels are according to \([2]\), while the two lower panels are according to \([22]\).
formed in tidal arms produced in a galaxy–galaxy encounter together with associated massive star clusters. Computer simulations of galaxy encounters show such structures to emerge readily (e.g. [27,28,29,30,31,32,33]), as shown by the pioneering work of Bruce Elmegreen et al. [34].

The symmetric structure of the Local Group, and the mutually correlated disks of satellites around both, the MW and Andromeda, may have been created when the much younger Galaxy and Andromeda interacted closely (<55 kpc) about 7–11 Gyr ago [35]. This encounter would have thrown out gas rich tidal arms in which the dwarf galaxies of the Local Group formed. It would have thickened the then existing disk of the MW and of Andromeda and it may have led to the rapid buildup of a MW pseudo bulge through an induced radial-orbit instability ([35,2], see also the MSc thesis at Cambridge university: [36]).

Can TDGs, once formed, survive for a Hubble time? Yes they can. This has been shown by simulations that include star formation and feedback by [37] and [38]: self-consistent and thus self-regulated TDG formation implies that they do not blow themselves apart due to a star burst. TDGs may be destroyed on an orbital time scale if they are on highly plunging orbits. TDGs which have consumed their gas or have been partially stripped off it also do not dissolve easily. The simulations of gas free TDGs evolved dynamically over a Hubble time of tidal stressing have demonstrated them to survive [39,40]. Such satellite galaxies loose most of their stars but evolve into quasi-stable remnants which feign domination by DM although they do not contain any, as has been discovered by [39]. In that paper [39] a prediction of a satellite galaxy was made which was discovered ten years later and is today known as the Hercules satellite galaxy. The predicted model agrees with the radius, the velocity dispersion, the luminosity and dynamical $M/L$ ratio nearly exactly with the real Hercules satellite galaxy (fig. 6 in [41]). And, observations have led to the discovery of a few Gyr old TDGs [42].

Thus, many and perhaps a majority of TDGs appear to survive over many Gyr such that the MW and Andromeda dSph and ultra-faint dwarf satellite galaxies may be ancient TDGs.

### 3.4 If they are TDGs, then there is no cold or warm DM

The above then implies the following for the existence of exotic dark matter, independently of the arguments made in Sec. 2: Since the satellite galaxies that are in the GPoA have the same morphological properties and the same high dynamical mass to light ($M/L$) ratios as the Andromeda satellite galaxies not in the GPoA, the former and latter must be described by the same dynamics. If the former are ancient TDGs then they cannot contain dark matter. Thus, the “dark matter effect”, i.e. the elevated $M/L$ ratios, can only be due to non-Newtonian dynamics. Also, since the MW satellites are all in the VPOS and because they have high $M/L$ ratios, again non-Newtonian dynamics needs to be invoked. That Milgromian dynamics [43-44] accounts well for the properties of the Andromeda and the MW satellites has been shown by [45-46]. Tidal modulation and shaping of TDGs as they evolve on eccentric orbits over many Gyr additionally changes the stellar phase space distribution function such that even in Milgromian dynamics elevated apparent (but not true) dynamical $M/L$ ratios are expected to result which deviate from the pure-Milgromian values.²

²Although [39] suggested that the high $M/L$ ratios of the dSph satellite galaxies may be due to repeated tidal shaping of the stellar phase-space velocity distribution function in a Newtonian universe, this process is unlikely to account for all dSph satellite galaxies because they are on very different orbits. Consequently, non-Newtonian dynamics is required to account for the observed dynamical masses of all dwarf satellites.
Here the beautiful work by David Block et al. [48] becomes relevant as evidence: Block et al. have shown that the about 1 kpc sized dust ring near the centre of Andromeda may be explained by the compact and massive satellite M32 punching through the disk of Andromeda about 210 Myr ago. Given the present-day stellar mass of M32 (\(\approx 3 \times 10^9 M_\odot\)), it would have had a pre-infall DM halo mass >\(10^{11} M_\odot\) [11,12], such that dynamical friction on the massive DM halo of Andromeda would have significantly altered the orbit of M32. This problem thus needs to be studied further.

4 Consistency of the deduction: The performance of the SMoC and the theory confidence graph

If there is no dark matter, then the SMoC cannot be a realistic description of the Universe. How does the track-record of the SMoC in accounting for observational data fare? If it were to be good, i.e., if there is a long history of predictions which have been verified by observations performed after the prediction was published, then this would contradict the conclusion reached above that challenges the existence of exotic cold or warm dark matter. This has been studied using the theory confidence graph [1]. It turns out that the SMoC has a long history of failed predictions. If each failure or problem is associated with a reduction in confidence by 50 per cent in the fundamental theory (that Einstein’s general relativity is valid everywhere, and that all matter emerged at the big bang), then the SMoC would currently retain a probability of being a valid representation of the Universe of less than \(10^{-5}\) per cent [2]. This probability is further reduced taking into account the additionally failed predictions since 2012, such as the large-scale observational evidence against the cosmological principle [49], and the observed significant under-density of matter within the local volume of about 400 Mpc (fig. 7 in [2]). Thus, the present-day very low confidence in the SMoC is in agreement with the above no-DM conclusions. Consequently the SMoC is not a physical representation of the real Universe.

5 The galaxy population

If there is no dark matter, then the SMoC does not describe the Universe. The observed “dark matter effects” in galaxies then need to be explained by an effective non-Einsteinian/non-Newtonian theory of gravitation. In this case dynamical friction on DM would not occur and mergers would be much rarer despite galaxy–galaxy interactions. Can this be seen in the observed evolution of the galaxy population? A few important results:

- [9] construct semi analytically computed populations of galaxies based on a SMoC merger tree and star-formation recipes trimmed to agree with broad observed properties by discarding parameter ranges. The best final trimmed model leads to a curved BTFR in disagreement with the observed BTFR and to a much larger number of satellite galaxies than is observed, among other problems. The milestone Illustris project, which is the currently highest existing resolution calculation of structure formation of the Universe and includes gas dynamics and detailed star formation prescriptions [8], yields a Tully-Fisher relation in disagreement with the one obtained by [9]. But this is not discussed nor is the disagreement clarified by [8]. Both are steeper than the observed relation for galaxies with stellar masses larger than about \(10^{10} M_\odot\). That is, the model galaxies have larger rotational speeds at a given mass than the observed ones. An unphysical aspect of
such models is that they require stellar feedback to be a function of the hosting DM halo in order to have sufficient feedback energy to stop a sufficient amount of baryons making stars immediately such that they can be blown out and re-accreted slowly thereby helping to build-up galactic disks.\footnote{1}

In contrast, scale-invariant or Milgromian dynamics yields the observed Tully-Fisher relation exactly\footnote{2}.

- \cite{50} perform semi-analytical modelling of early-type galaxy formation. An interesting result from this work is that they need to suppress dynamical friction for improved agreement with the observational data. This is consistent with the independently deduced absence of evidence for dynamical friction noted in Sec. 2, Test 3.
- \cite{51} and \cite{52} find the fraction of disk galaxies with classical bulges to be very small. The small fraction (6 per cent) of disk galaxies with classical bulges is supported by \cite{53} for a sample of 189 isolated galaxies. \cite{53} point out that the small fraction of disk galaxies with classical bulges is incompatible with the merging history which would affect most galaxies if the SMoC were true. One deduction from this would be that mergers therefore cannot be a major aspect of galaxy evolution. The only way to suppress the occurrence of galactic mergers is to discard the massive DM halos made of particles.
- The population of galaxies is vastly dominated by late-type galaxies. According to \cite{54} only 3–4 per cent of all galaxies more massive in stars than about $10^{10} M_\odot$ are elliptical. This holds for the galaxy population about 6 Gyr ago and at the present epoch, and is in excellent agreement with the long-known result that disk galaxies are the by far dominant population in the field as well as in galaxy clusters (see fig. 4.14 in \cite{55}). It has never been successfully demonstrated that the merger-driven buildup of the galaxy population in the SMoC leads to the observed massive preponderance of rotationally supported, thin-disk star-forming late-type galaxies. Instead, galaxies that form in the SMoC are predominantly of early type, because angular momentum is ejected or cancelled-out during the many mergers. As emphasized by \cite{56}, the vast majority of galaxies appear to be a one-parameter family of objects, much simpler than expected with little variation (see also \cite{2}). Consequently, dark-matter-driven mergers cannot be a physically relevant process in galaxy formation.
- That this dominating population of late-type disk star-forming galaxies lie on a main sequence, is discussed by \cite{57}. These authors show that the main sequence of galaxies which corresponds to an approximately constant specific star-formation efficiency (star-formation rate per unit stellar mass) has a small dispersion and persists to high redshift. Galaxies are thus much simpler than expected from the haphazard buildup through a DM-driven merger tree in the SMoC, a view already arrived at by \cite{56} in their principle-component analysis of a large sample of galaxies.

The overall implication of this discussion is thus consistent with the above conclusions that DM-driven processes do not appear to play a role in the astrophysics of galaxies.

## 6 Conclusions

With exotic DM particles being ruled out by observation as being an important aspect of galactic dynamics, there would be no reason to consider the existence of such particles at

\footnote{3This would imply, essentially, that the table in my dining room would know it exists in the MW DM halo rather than in the DM halo of the Large Magellanic Cloud, in violation of the required fundamental property of DM particles which are supposed to not interact, apart maybe weakly, with the particles of the standard model of particle physics.}
all. Therewith the central pillar of the SMoC collapses, and the SMoC becomes irrelevant as a theoretical framework for the Universe. Probably most aspects of current cosmological understanding then collapse as well: the standard redshift–age and redshift–distance relations would probably be wrong, the inferred cosmological evolution of the star-formation rate density and of galaxy masses and of their ages would probably be wrong as well.

The failures of the SMoC thus require a new paradigm which comes by without exotic DM particles [58]. Important and successful hints have become available through the famous work of Milgrom [43,59]. The possible connections between the observed non-Newtonian but scale-invariant dynamics in the weak-field limit and cosmological parameters and the physics of the vacuum noted by Milgrom [60] may indicate a deep interrelation of both. Based on such ideas, a conservative cosmological model without exotic DM particles as described by [61,62,63] may be emerging [2]. As of very recently and thanks to special funding from the rectorate of the University of Bonn we have now, for the very first time, an adaptive mesh-refinement code, Phantom of Ramses (POR), which includes full treatment of baryonic processes [64]. With POR cosmological structure formation simulations of a universe consisting only of the constituents of the standard model of particle physics and with Milgromian dynamics have become possible.

Irrespective of which cosmological model may be the next standard one, it will have to account for the time-dependent distribution and motion of matter on large-scales and on galaxy scales as well as for all properties of the microwave cosmic background.

7 Acknowledgments

I thank Ken Freeman for organizing this conference on the Seychelles. It will remain memorable for decades to come. I also thank David Block and Bruce Elmegreen for being around so actively and for so many years such that we could have this splendidly luxurious meeting to honor both of them.

References

1. P. Kroupa. The Dark Matter Crisis: Falsification of the Current Standard Model of Cosmology. PASA, 29:395–433, June 2012.
2. P. Kroupa. Galaxies as simple dynamical systems: observational data disfavor dark matter and stochastic star formation. Canadian Journal of Physics, in press, 2014.
3. R. A. Ibata, N. G. Ibata, G. F. Lewis, N. F. Martin, A. Conn, P. Elahi, V. Arias, and N. Fernando. A Thousand Shadows of Andromeda: Rotating Planes of Satellites in the Millennium-II Cosmological Simulation. ApJL, 784:L6, March 2014.
4. M. S. Pawlowski, B. Famaey, H. Jerjen, D. Merritt, P. Kroupa, J. Dabringhausen, F. Lüghausen, D. A. Forbes, G. Hensler, F. Hammer, M. Puech, S. Fouquet, H. Flores, and Y. Yang. Co-orbiting satellite galaxy structures are still in conflict with the distribution of primordial dwarf galaxies. MNRAS, in press, June 2014.
5. X. Wu and P. Kroupa. Galactic rotation curves, the baryon-to-dark-halo-mass relation and their space-time scale invariance. MNRAS, submitted, 2014.
6. S. Recchi, F. Calura, and P. Kroupa. The chemical evolution of galaxies within the IGIMF theory: the [$\alpha$/Fe] ratios and downsizing. A&A, 499:711–722, June 2009.
7. M. Vogelsberger, S. Genel, V. Springel, P. Torrey, D. Sijacki, D. Xu, G. F. Snyder, S. Bird, D. Nelson, and L. Hernquist. Properties of galaxies reproduced by a hydrodynamic simulation. ArXiv e-prints, May 2014.
8. M. Vogelsberger, S. Genel, V. Springel, P. Torrey, D. Sijacki, D. Xu, G. F. Snyder, D. Nelson, and L. Hernquist. Introducing the Illustris Project: Simulating the coevolution of dark and visible matter in the Universe. *ArXiv e-prints*, May 2014.

9. Y. Lu, H. J. Mo, N. Katz, and M. D. Weinberg. Bayesian inference of galaxy formation from the K-band luminosity function of galaxies: tensions between theory and observation. *MNRAS*, 421:1779–1796, April 2012.

10. A. Toomre. Mergers and Some Consequences. In B. M. Tinsley and R. B. G. Larson, D. Campbell, editors, *Evolution of Galaxies and Stellar Populations*, page 401, 1977.

11. P. S. Behroozi, R. H. Wechsler, and C. Conroy. The Average Star Formation Histories of Galaxies in Dark Matter Halos from $z = 0$–8. *ApJ*, 770:57, June 2013.

12. I. Ferrero, M. G. Abadi, J. F. Navarro, L. V. Sales, and S. Gurovich. The dark matter haloes of dwarf galaxies: a challenge for the $\Lambda$ cold dark matter paradigm? *MNRAS*, 425:2817–2823, October 2012.

13. G. Gentile, B. Famaey, F. Combes, P. Kroupa, H. S. Zhao, and O. Tret. Tidal dwarf galaxies as a test of fundamental physics. *A&A*, 472:L25–L28, September 2007.

14. J. Dabringhausen and P. Kroupa. Dwarf elliptical galaxies as ancient tidal dwarf galaxies. *MNRAS*, 429:1858–1871, March 2013.

15. J. E. Barnes. Dynamics of Galaxy Interactions. In R. C. Kennicutt, Jr., F. Schweizer, J. E. Barnes, D. Friedli, L. Martinet, and D. Pfenniger, editors, *Saas-Fee Advanced Course 26: Galaxies: Interactions and Induced Star Formation*, page 275, 1998.

16. R. C. Thomson, S. Laine, and A. Turnbull. Towards an Interaction Model of M81, M82 and NGC 3077. In J. E. Barnes and D. B. Sanders, editors, *Galaxy Interactions at Low and High Redshift*, volume 186 of *IAU Symposium*, page 135, 1999.

17. M. S. Yun. Tidal Interactions in M81 Group. In J. E. Barnes and D. B. Sanders, editors, *Galaxy Interactions at Low and High Redshift*, volume 186 of *IAU Symposium*, page 81, 1999.

18. G. W. Angus, A. Diaferio, and P. Kroupa. Using dwarf satellite proper motions to determine their origin. *MNRAS*, 416:1401–1409, September 2011.

19. M. S. Pawlowski, J. Pflamm-Altenburg, and P. Kroupa. The VPOS: a vast polar structure of satellite galaxies, globular clusters and streams around the Milky Way. *MNRAS*, 423:1109–1126, June 2012.

20. M. S. Pawlowski and P. Kroupa. The rotationally stabilized VPOS and predicted proper motions of the Milky Way satellite galaxies. *MNRAS*, 435:2116–2131, November 2013.

21. R. A. Ibata, G. F. Lewis, A. R. Conn, M. J. Irwin, A. W. McConnachie, S. C. Chapman, M. L. Collins, M. Fardal, A. M. N. Ferguson, N. G. Ibata, A. D. Mackey, N. F. Martin, J. Navarro, R. M. Rich, D. Valls-Gabaud, and L. M. Widrow. A vast, thin plane of corotating dwarf galaxies orbiting the Andromeda galaxy. *Nature*, 493:62–65, January 2013.

22. M. S. Pawlowski, P. Kroupa, and H. Jerjen. Dwarf galaxy planes: the discovery of symmetric structures in the Local Group. *MNRAS*, 435:1928–1957, November 2013.

23. P. Kroupa, C. Theis, and C. M. Boily. The great disk of Milky-Way satellites and cosmological sub-structures. *A&A*, 431:517–521, February 2005.

24. M. S. Pawlowski and P. Kroupa. The VPOS of the Milky Way Attains New Members. *ApJ, in press*, 2014.

25. K. Chiboucas, B. A. Jacobs, R. B. Tully, and I. D. Karachentsev. Confirmation of Faint Dwarf Galaxies in the M81 Group. *AJ*, 146:126, November 2013.

26. M. S. Pawlowski, P. Kroupa, G. Angus, K. S. de Boer, B. Famaey, and G. Hensler. Filamentary accretion cannot explain the orbital poles of the Milky Way satellites. *MNRAS*, 424:80–92, July 2012.
27. J. E. Barnes and L. Hernquist. Formation of dwarf galaxies in tidal tails. *Nature*, 360:715–717, December 1992.
28. M. Wetzstein, T. Naab, and A. Burkert. Do dwarf galaxies form in tidal tails? *MNRAS*, 375:805–820, March 2007.
29. F. Bournaud, P.-A. Duc, and E. Emsellem. High-resolution simulations of galaxy mergers: resolving globular cluster formation. *MNRAS*, 389:L8–L12, September 2008.
30. F. Bournaud. Tidal Dwarf Galaxies and Missing Baryons. *Advances in Astronomy*, 2010, 2010.
31. M. S. Pawlowski, P. Kroupa, and K. S. de Boer. Making counter-orbiting tidal debris. The origin of the Milky Way disc of satellites? *A&A*, 532:A118, August 2011.
32. F. Hammer, Y. Yang, S. Fouquet, M. S. Pawlowski, P. Kroupa, M. Puech, H. Flores, and J. Wang. The vast thin plane of M31 corotating dwarfs: an additional fossil signature of the M31 merger and of its considerable impact in the whole Local Group. *MNRAS*, 431:3543–3549, June 2013.
33. Y. Yang, F. Hammer, S. Fouquet, H. Flores, M. Puech, M. S. Pawlowski, and P. Kroupa. Reproducing properties of MW dSphs as descendants of DM-free TDGs. *ArXiv e-prints*, May 2014.
34. B. G. Elmegreen, M. Kaufman, and M. Thomasson. An interaction model for the formation of dwarf galaxies and 10 exp 8 solar mass clouds in spiral disks. *ApJ*, 412:90–98, July 1993.
35. H. Zhao, B. Famaey, F. Lüghausen, and P. Kroupa. Local Group timing in Milgromian dynamics. A past Milky Way-Andromeda encounter at z > 0.8. *A&A*, 557:L3, September 2013.
36. I. Banik. Galactic Archaeology with RAVE: Clues to the Formation of the Thick Disk. *MSc thesis, Cambridge University, ArXiv e-prints*, June 2014.
37. S. Recchi, C. Theis, P. Kroupa, and G. Hensler. The early evolution of tidal dwarf galaxies. *A&A*, 470:L5–L8, July 2007.
38. S. Ploeckinger, G. Hensler, S. Recchi, N. Mitchell, and P. Kroupa. Chemo-dynamical evolution of tidal dwarf galaxies. I. Method and IMF dependence. *MNRAS*, 437:3980–3993, February 2014.
39. P. Kroupa. Dwarf spheroidal satellite galaxies without dark matter. *NA*, 2:139–164, July 1997.
40. R. A. Casas, V. Arias, K. Peña Ramírez, and P. Kroupa. Dwarf spheroidal satellites of the Milky Way from dark matter free tidal dwarf galaxy progenitors: maps of orbits. *MNRAS*, 424:1941–1951, August 2012.
41. P. Kroupa, B. Famaey, K. S. de Boer, J. Dabringhausen, M. S. Pawlowski, C. M. Boily, H. Jerjen, D. Forbes, G. Hensler, and M. Metz. Local-Group tests of dark-matter concordance cosmology. Towards a new paradigm for structure formation. *A&A*, 523:A32, November 2010.
42. P.-A. Duc, S. Paudel, R. M. McDermid, J.-C. Cuillandre, P. Serra, F. Bournaud, M. Capacciari, and E. Emsellem. Identification of old tidal dwarfs near early-type galaxies from deep imaging and HI observations. *MNRAS*, 440:1458–1469, March 2014.
43. M. Milgrom. A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *ApJ*, 270:365–370, July 1983.
44. B. Famaey and S. S. McGaugh. Modified Newtonian Dynamics (MOND): Observational Phenomenology and Relativistic Extensions. *Living Reviews in Relativity*, 15:10, September 2012.
45. S. S. McGaugh and J. Wolf. Local Group Dwarf Spheroidals: Correlated Deviations from the Baryonic Tully-Fisher Relation. *ApJ*, 722:248–261, October 2010.
46. S. McGaugh and M. Milgrom. Andromeda Dwarfs in Light of MOND. II. Testing Prior Predictions. ApJ, 775:139, October 2013.
47. F. Lüghausen, B. Famaey, and P. Kroupa. A census of the expected properties of classical Milky Way dwarfs in Milgromian dynamics. ArXiv e-prints, April 2014.
48. D. L. Block, F. Bournaud, F. Combes, R. Groess, P. Barnby, M. L. N. Ashby, G. G. Fazio, M. A. Ahre, and S. P. Willner. An almost head-on collision as the origin of two off-centre rings in the Andromeda galaxy. Nature, 443:832–834, October 2006.
49. R. G. Clowes, K. A. Harris, S. Raghunathan, L. E. Campusano, I. K. Söchting, and M. J. Graham. A structure in the early Universe at $z \sim 1.3$ that exceeds the homogeneity scale of the R-W concordance cosmology. MNRAS, 429:2910–2916, March 2013.
50. F. Shankar, S. Mei, M. Huertas-Company, J. Moreno, F. Fontanot, P. Monaco, M. Bernardi, A. Cattaneo, R. Sheth, R. Licitra, L. Delaye, and A. Raichoor. Environmental dependence of bulge-dominated galaxy sizes in hierarchical models of galaxy formation. Comparison with the local Universe. MNRAS, 439:3189–3212, February 2014.
51. T. Weinzierl, S. Jogee, S. Khocharf, A. Burkert, and J. Kormendy. Bulge n and B/T in High-Mass Galaxies: Constraints on the Origin of Bulges in Hierarchical Models. ApJ, 696:411–447, May 2009.
52. J. Kormendy, N. Drory, B. Bender, and M. E. Cornell. Bulgeless Giant Galaxies Challenge Our Picture of Galaxy Formation by Hierarchical Clustering. ApJ, 723:54–80, November 2010.
53. M. Fernández Lorenzo, J. Sulentic, L. Verdes-Montenegro, J. Blasco-Herrera, M. Argudo-Fernández, J. Garrido, P. Ramírez-Moreta, J. E. Ruiz, S. Sánchez-Expósito, and J. D. Santander-Vela. Are (pseudo)bulges in isolated galaxies actually primordial relics? ArXiv e-prints, May 2014.
54. R. Delgado-Serrano, F. Hammer, Y. B. Yang, M. Puech, H. Flores, and M. Rodrigues. How was the Hubble sequence 6 Gyr ago? A&A, 509:A78, January 2010.
55. J. Binney and M. Merrifield. Galactic Astronomy, Princeton University Press. 1998.
56. M. J. Disney, J. D. Romano, D. A. Garcia-Appadoo, A. A. West, J. J. Dalcanton, and L. Cortese. Galaxies appear simpler than expected. Nature, 455:1082–1084, October 2008.
57. J. S. Speagle, C. L. Steinhardt, P. L. Capak, and J. D. Silverman. A Highly Consistent Framework for the Evolution of the Star-Forming "Main Sequence" from $z \sim 0.6$. ArXiv e-prints, May 2014.
58. P. Kroupa, M. Pawlowski, and M. Milgrom. The Failures of the Standard Model of Cosmology Require a New Paradigm. International Journal of Modern Physics D, 21:30003, December 2012.
59. M. Milgrom. The Mond Limit from Spacetime Scale Invariance. ApJ, 698:1630–1638, June 2009.
60. M. Milgrom. The modified dynamics as a vacuum effect. Physics Letters A, 253:273–279, March 1999.
61. G. W. Angus. Is an 11eV sterile neutrino consistent with clusters, the cosmic microwave background and modified Newtonian dynamics? MNRAS, 394:527–532, March 2009.
62. G. W. Angus and A. Diaferio. The abundance of galaxy clusters in modified Newtonian dynamics: cosmological simulations with massive neutrinos. MNRAS, 417:941–949, October 2011.
63. G. W. Angus, A. Diaferio, B. Famaey, and K. J. van der Heyden. Cosmological simulations in MOND: the cluster scale halo mass function with light sterile neutrinos. MNRAS, 436:202–211, November 2013.
64. F. Lüghausen, B. Famaey, and P. Kroupa. Phantom of RAMSES (POR): A new Milgromian dynamics N-body code. ArXiv e-prints, May 2014.
This figure "Falsification_Logics_new.064.jpg" is available in "jpg" format from:

http://arxiv.org/ps/1409.6302v1
This figure "LocalGroup_structure.065.jpg" is available in "jpg" format from:

http://arxiv.org/ps/1409.6302v1