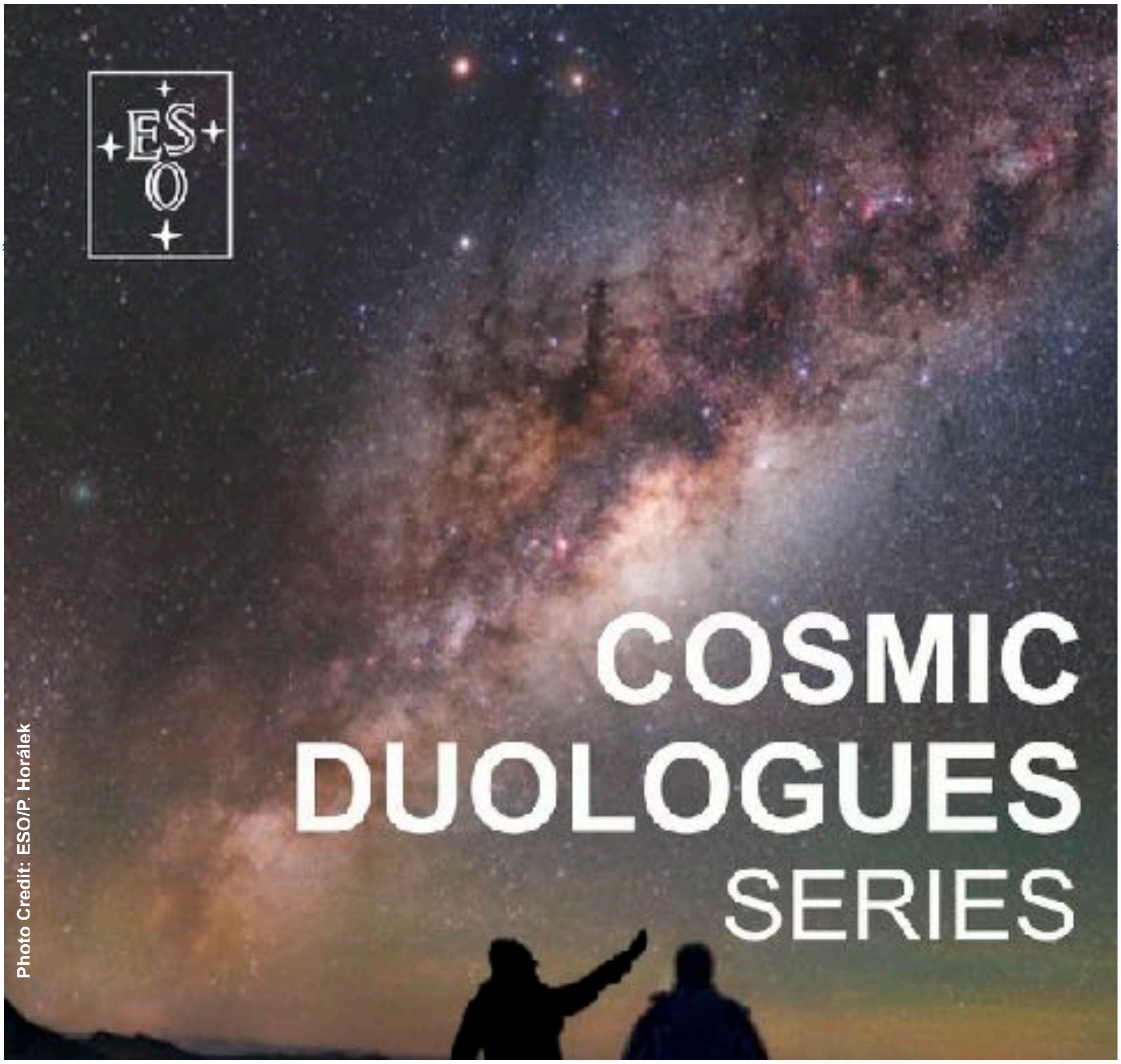

Dark Matter and MOND

ESO Cosmic Duologue 1 - Interview

27 April 2020

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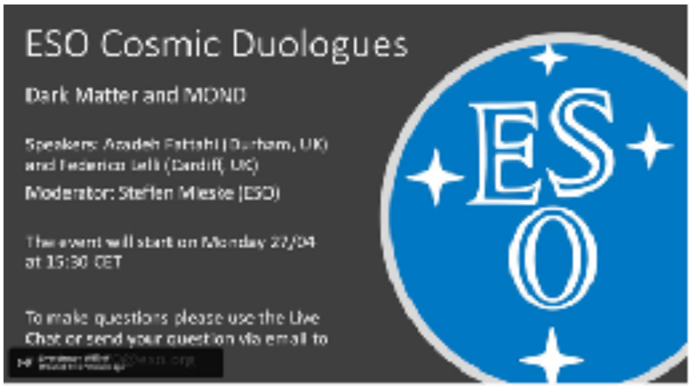
On Monday 27 April, 2020, the first ESO Cosmic Duologue took place. It consisted in a discussion between *Azadeh Fattahi* (Durham, UK) and *Federico Lelli* (Cardiff, UK) and chaired by *Steffen Mieske* (ESO), about MOND versus Dark Matter. Further information on this event, including a copy of the slides, the link to the video of the duologue, as well as to some background material, is available at *https://www.eso.org/sci/meetings/2020/Cosmic-Duologues/duologue1.html*.

As a follow-up to this successful event, we have asked our two speakers to answer in more details some of the questions raised during the event. This is provided below, where the answers are identified by the initials of the speaker.



1. Was the power spectrum truly predicted? Is there a reference (prior to the data)?

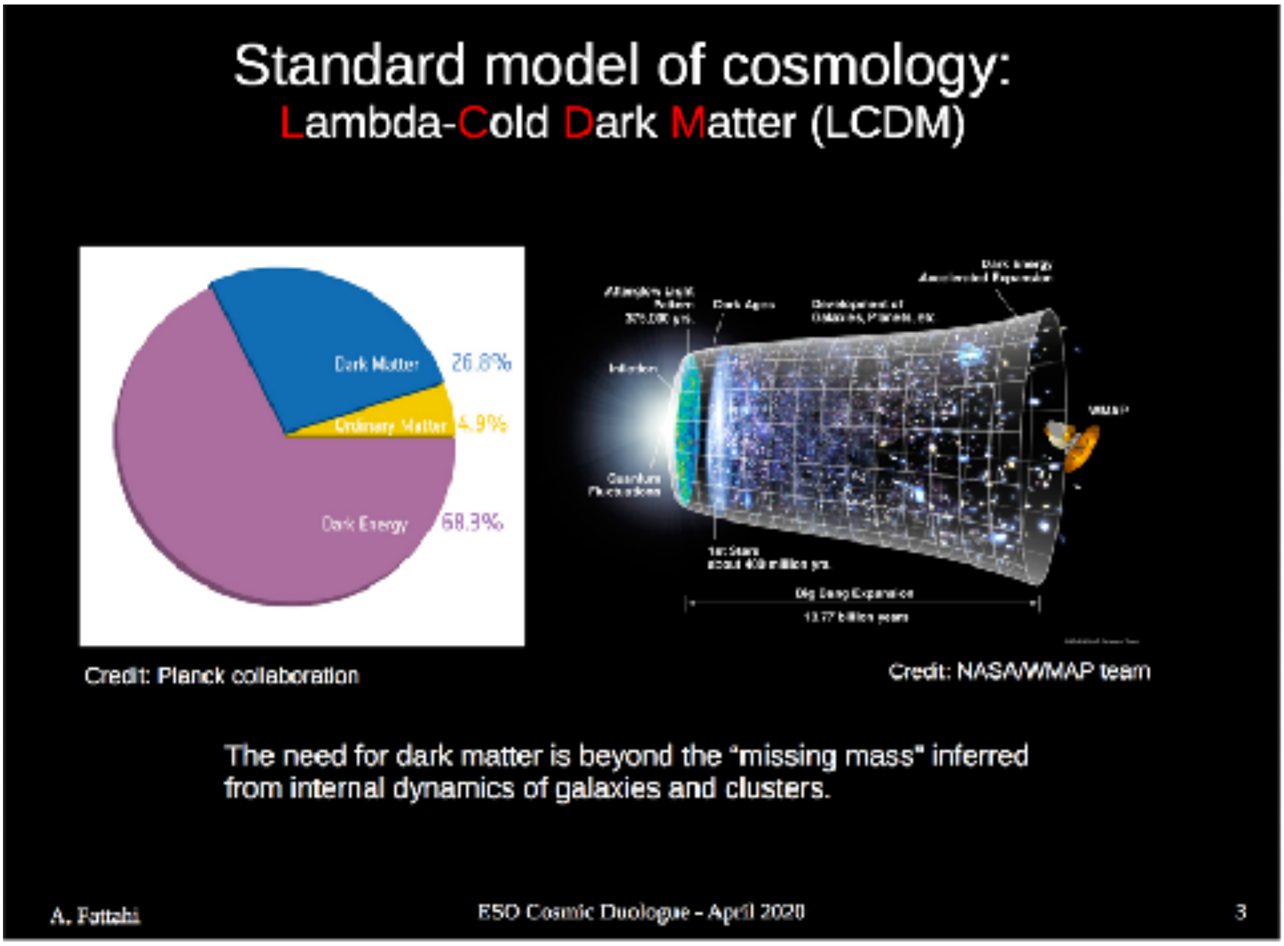
AF: The power spectrum is not a prediction of ΛCDM *per se*. What I meant as a “prediction” was the extrapolation of the power spectrum to smaller scales and the validation using independent observations. In the 2000s, the CMB was constraining power spectrum on scales larger than ~10 Mpc; extrapolating the relation to smaller scales assuming ΛCDM (power law at the small scale) was confirmed using other measurements such as weak lensing and Lyman-alpha forest. See, e.g., Tegmark et al. (2004).

FL: The matter power spectrum does not classify as a true a-priori prediction of ΛCDM because one free parameter (at least) is always needed to relate the observed power spectrum (from galaxies or other tracers) to the underlying matter power spectrum due to the dark matter component. This is the so-called “bias factor”. Clearly, the bias factor can change depending on the observed tracer population and could potentially be scale dependent, introducing additional freedom in the comparison between data and theory. Reproducing the matter power spectrum with only one free parameter, however, is an important success of ΛCDM.

2. Is the existence of dark matter excluded by dynamical friction on the dark matter halos?

FL: Dynamical friction is a very interesting test for particle dark matter with many possible facets: the merger rates of galaxies, the merger rates of stellar-mass black holes, the existence and abundance of compact galaxy groups, the existence of globular cluster systems in low-mass galaxies, the pattern speed of stellar bars in disk galaxies, the possible existence of wide stellar binaries in diffuse low-mass galaxies, and more. Many good ideas have been put forward, but in my opinion the current observational evidence based on dynamical friction cannot unambiguously rule out the existence of dark matter.

AF: The question refers to the fact that dynamical friction caused by extended dark matter halos results in a short merging time scales for galaxy groups. We should note that in ΛCDM these groups merge quicker and at the same time new groups form; it is not readily obvious that the frequency of observed compact groups are in contradiction with ΛCDM. One should investigate this in, e.g., ΛCDM numerical simulations. The existence of substructures in the stellar halo of Milky Way, Andromeda and other nearby systems indicate the effect of dynamical friction. Moreover, Gaia measurements show the dynamics of the inner stellar halo of the Milky Way (the dominant population referred to as “Gaia-sausage” or “Gaia-Enceladus”) are consistent with the effect of dynamical friction on the orbit of a relatively massive dwarf galaxy.



3. How could the appearance of the acceleration scale a_0, both on cosmological and galactic scales, be explained in a ΛCDM context?

FL: In a ΛCDM context, a_0 should be an approximate scale emerging from the process of galaxy formation and evolution. In this case, the numerologies $a_0 \sim c \cdot H_0$, and $a_0 \sim c \cdot \Lambda^{0.5}$ are mere coincidences. Semi-empirical ΛCDM models can reproduce an approximate acceleration scale (Di Cintio & Lelli 2016, MNRAS; Navarro et al. 2017, MNRAS) but the expected galaxy-to-galaxy scatter seems uncomfortably large (Desmond 2017a, b, MNRAS). Full numerical simulations of galaxy formation have led to contradictory results, for example: Keller & Wadsley (2017) find an acceleration scale similar to the observed one; Ludlow et al. (2017) find an acceleration scale that is 70 sigma (random) and 7 sigma (systematics) higher than observed; Tenneti et al. (2018) find essentially no acceleration scale in simulated galaxies.

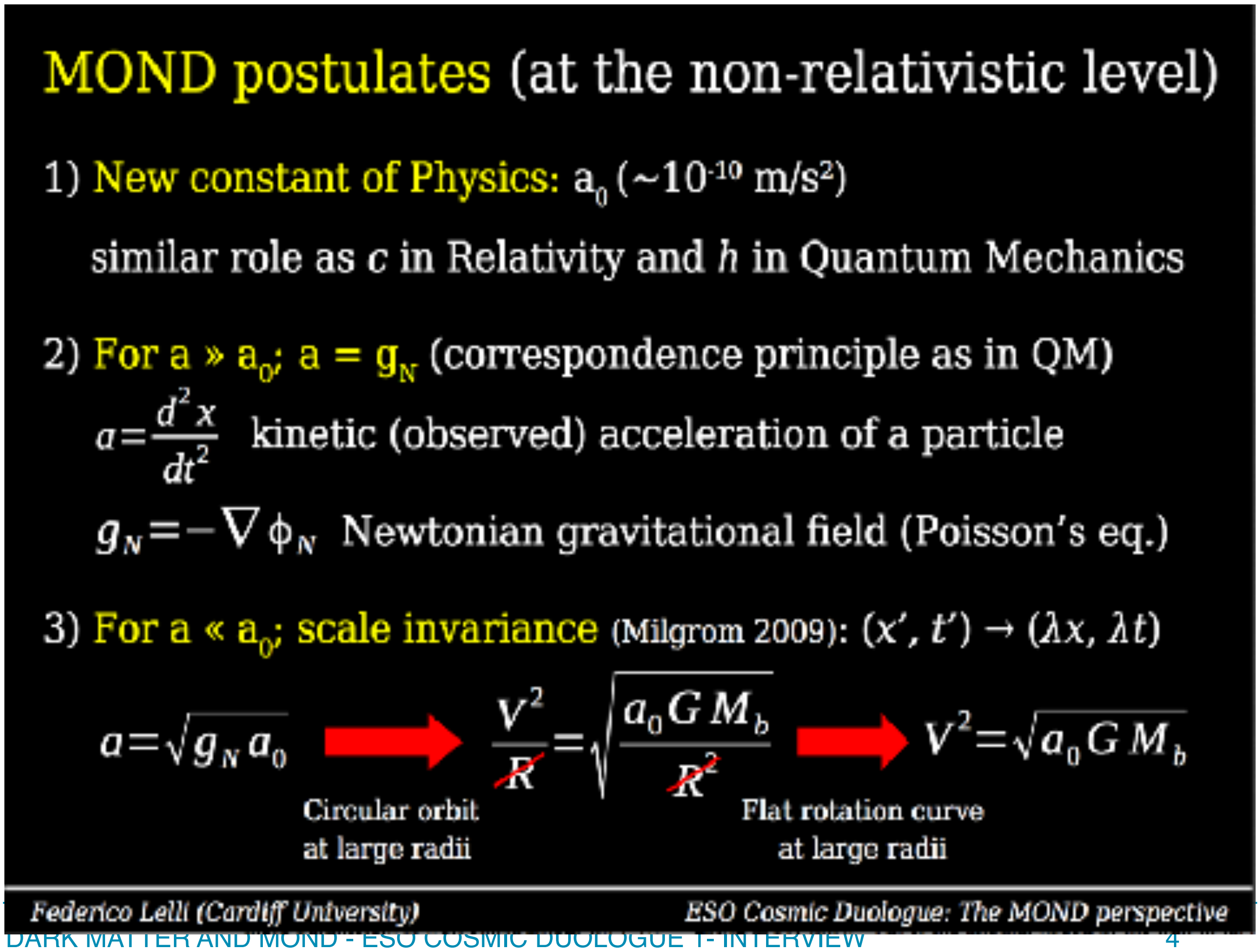
4. Does the existence of the Bullet cluster falsify both theories?

AF: The bullet cluster does *not* falsify ΛCDM. The claim that bullet cluster falsify ΛCDM is solely based on one assumption: the observed shock velocity is the same as the relative speed of the two clusters colliding. Springel & Farrar (2007) show that the shock velocity can be very different from the centre of mass velocity of the two components.

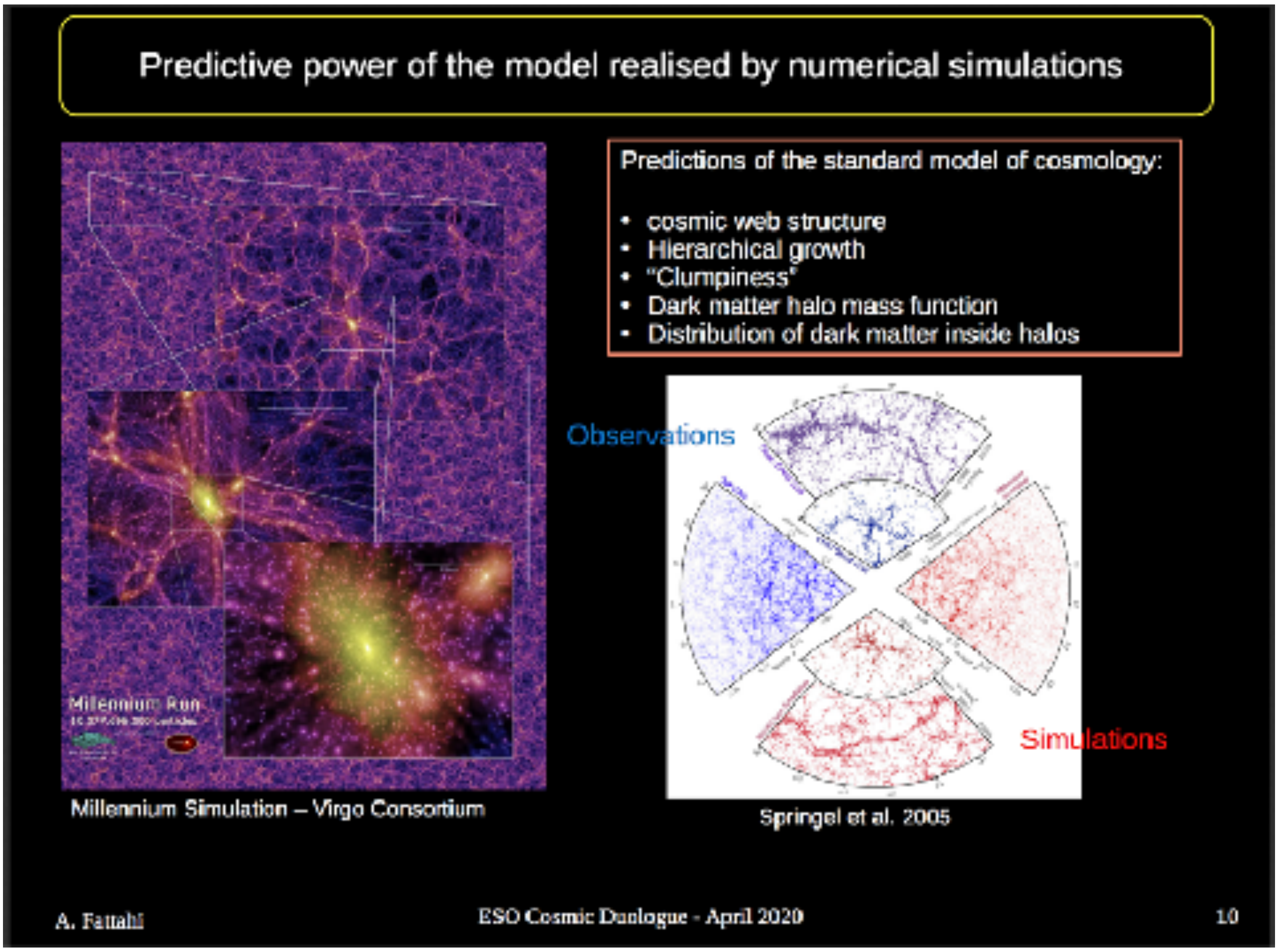
FL: The Bullet cluster is problematic for both theories for different reasons. The observed high collision speed of the two merging clusters occurs very rarely in ΛCDM simulations (Hayashi & White 2006; Farrar & Rosen 2006; Angus & McGaugh 2008). The amount of mass discrepancy is problematic for MOND (as in any other galaxy cluster in the Universe); the offset between the lensing peak and the hot gas distribution is not as problematic as often portrayed (Angus et al. 2006, 2007). Since plausible solutions have been suggested in both paradigms, the Bullet cluster does not strictly falsify neither of them, but does remain a controversial system. Clearly, the discovery and study of more systems like the Bullet cluster can shed new light on these issues.

5. Is the missing mass problem of galaxy clusters an important challenge for MOND?

FL: Yes: it is a key challenge for MOND that may potentially falsify the paradigm. The existing data shows that the discrepancy is a factor of 2–3 at most. Sensible solutions have been proposed, such as adding sterile neutrinos with masses of about 10 eV (Angus 2007) or



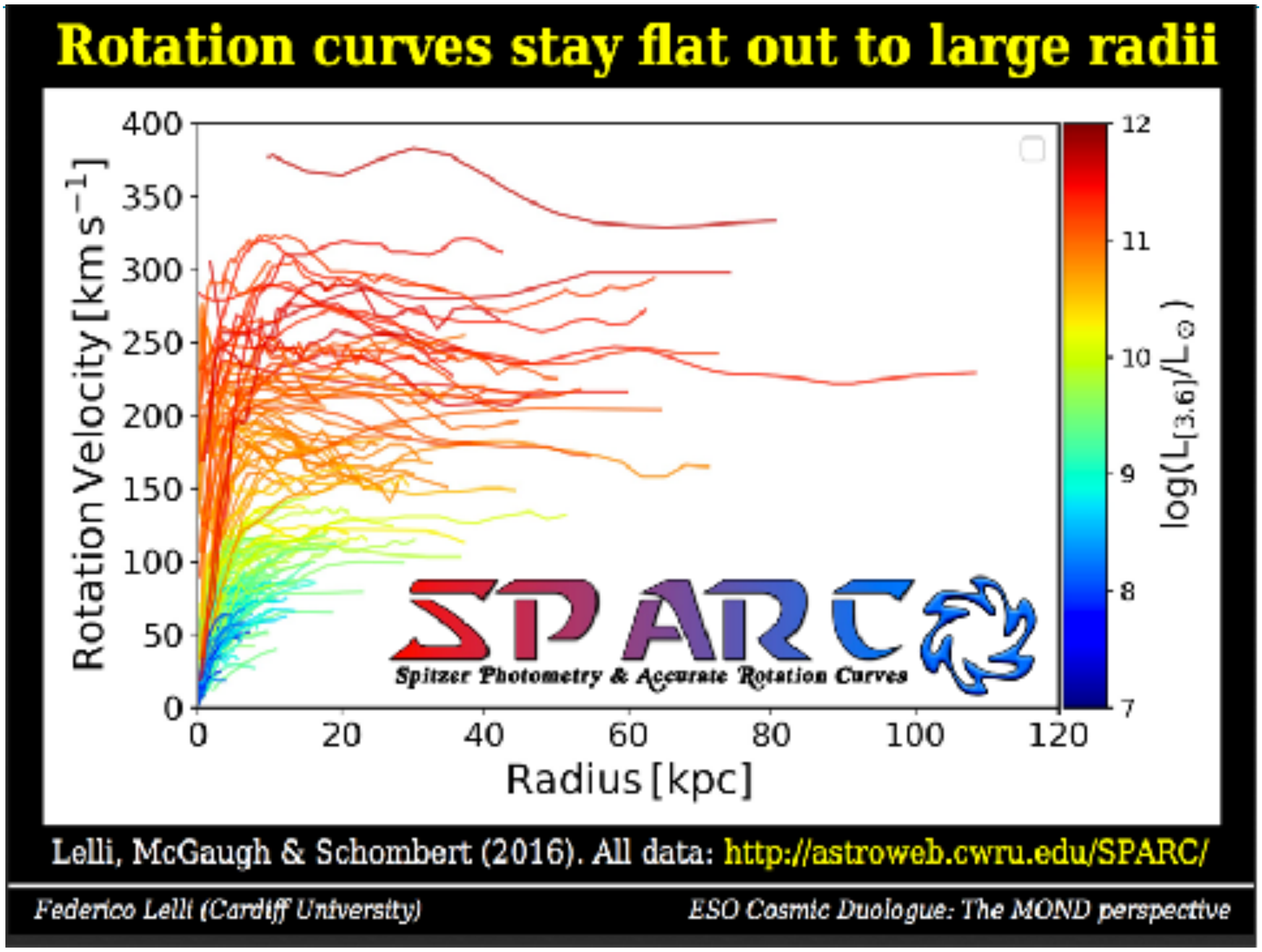
undetected baryons in some cold, dense phase (Milgrom 2008). The former proposal requires a minimal extension of the standard model of particle physics (SMoPP), which is nevertheless needed to explain the neutrino oscillations. In comparison, ΛCDM requires a deeper extension of the SMoPP, adding particles like WIMPs or Axions. The latter proposal can be thought as the "missing baryon problem" in MOND. ΛCDM has a missing baryon problem too but on galaxy scales, where the amount of missing baryons is on average 87% (e.g. Katz et al. 2018), much larger than the amount of missing baryons needed in galaxy clusters in MOND.



6. Every five years for the past thirty years I have heard "*we will know what the dark matter is in five years*." One can always come up with new flavors of WIMPs, and new flavors of others. The question is when to stop? Is it possible to falsify dark matter?

AF: Of course it is possible to falsify dark matter. For example, if mass distribution in clusters (non-linear regime) predicted by numerical simulation did not match observation, ΛCDM would be falsified already (see, e.g., Wang et al. 2016). Other important prediction is the existence of dark subhalos. Their discovery is almost a ready proof for dark matter; their non-existence will rule out certain flavours of DM.

FL: In theory, particle dark matter can be falsified with astrophysical arguments like dynamical friction. In practice, I think we will stop looking for particle dark matter only if we will be able to develop a proper alternative to ΛCDM cosmology, i.e., a new relativistic theory that can simultaneously explain the CMB, the large-scale structure, and the dynamics of galaxies and galaxy clusters. Clearly, this is a very tall order that requires a global effort from the Physics and Astronomy communities.



7. One of the less-discussed problems of ΛCDM is that of the Local Void – the Local Void seems to be too big and empty to be consistent with ΛCDM simulations. This seems hard to be solved by baryonic feedback. Has there recently been any progress in this issue?

FL: I am not aware of recent progress in this issue.

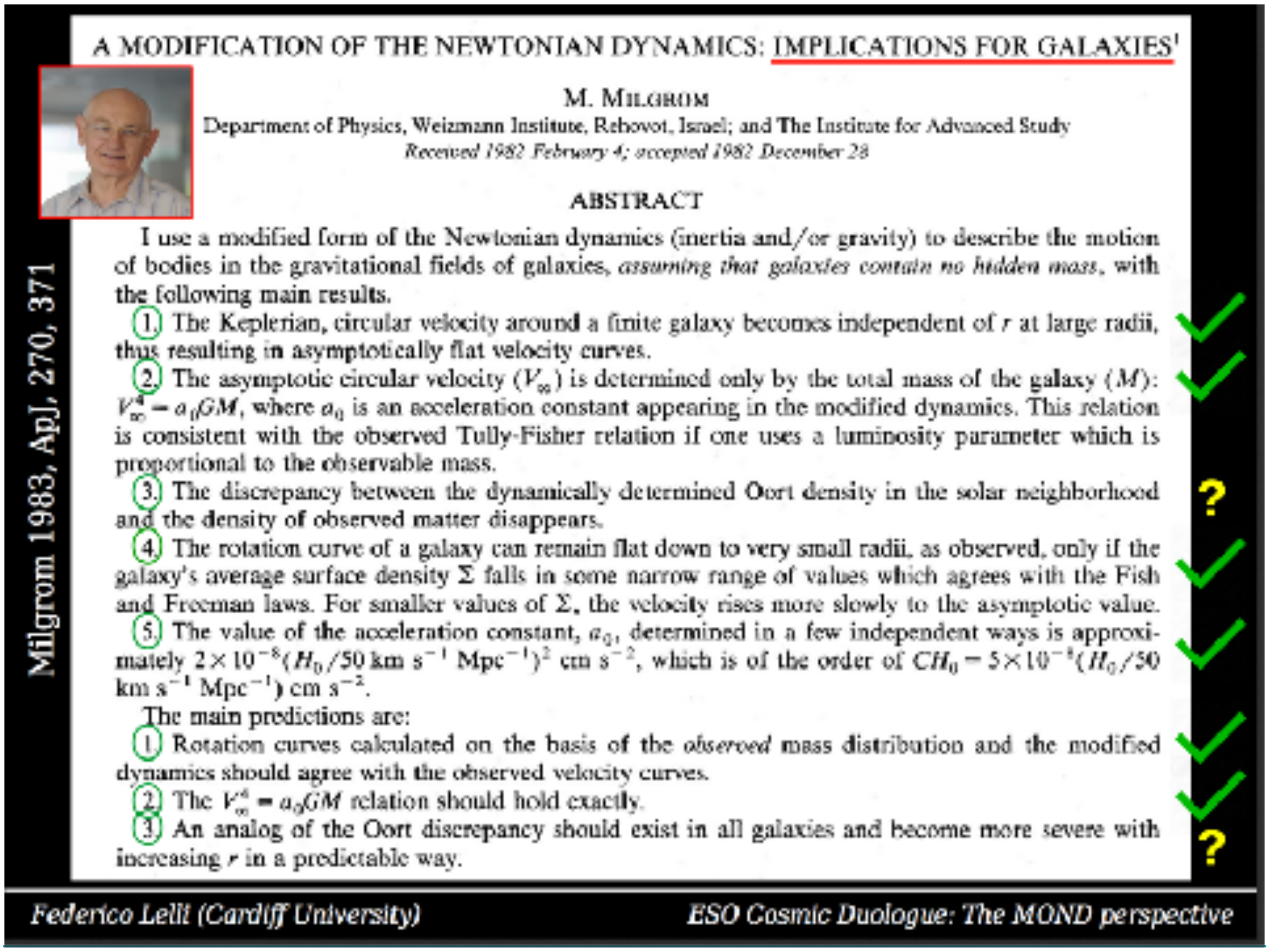
8. Is there any expectation for how MOND should work at higher redshift? If the proposed connection between a_0 and H_0 is not a coincidence, should we expect different behaviours across the cosmic time?

FL: To date there is no full-fledged relativistic MOND theory that can fit the CMB power spectrum, so there are no definitive MOND predictions about cosmology. At the moment, one can only proceed with reasonable *ansatz*. For example, the coincidence $a_0 \sim c \cdot H_0$ may be pushed further adopting $a(z) \sim c \cdot H(z)$. This would predict a significant evolution of the normalization of the Tully-Fisher relation, going as $a(z)$ G. To date there is no strong observational evidence for such evolution up to *z*~1 (e.g., Di Teodoro et al. 2016; Pelliccia et al. 2017), but the interpretation of the observations is very complex. I should also stress that the usually adopted relation between luminosity-distance and redshift, which sets galaxy luminosities and masses at high z, may be potentially different in a MOND cosmology. Keeping all these important caveats in mind, basic numerical simulations in MOND seems to predict that massive galaxies, the large-scale structure, and cosmic reionization should occurr earlier in MOND than in ΛCDM (see McGaugh 2015 for a review). The depth of the sky-averaged 21-cm absorption line at high *z* may also help distinguishing MOND from ΛCDM (McGaugh 2018).

9. Do the problems of MOND in dwarf spheroidals persist even if we exclude the galaxies out of equilibrium and take into account the effect of unresolved binaries?

FL: Observationally, it is very difficult to determine which dwarf satellites are really out-of-equilibrium: deep and wide photometry can identify outer disturbances and/or asymmetries due to tidal forces, but this approach is not feasible or expected to work in each and every system. Similarly, undetected binaries are very hard to identify: repeated spectroscopic observations during different epochs are needed to reveal at least some stellar binaries. The expected magnitude of these two combined effects, however, is consistent with the observed deviations of dwarf spheroidals from the MOND predictions for isolated galaxies. It is important to stress that the vast majority of the "classic satellites" of the Milky Way and Andromeda (the most massive and best studied systems) fully agree with the MOND predictions; the problem arises at the scale of the recently discovered "ultra-faint dwarfs", for which the observational situation is much more uncertain. Generally speaking, these non-isolated objects are simply not the best systems to test the general MOND predictions. Future surveys and facilities (like the *ESO ELT* and *SKA*) may potentially discover a galaxy population similar to the ultra-faint dwarfs in the Local Group but living in more isolated environments. These would represent better and cleaner tests for both MOND and ΛCDM.

AF: Essentially MOND underestimates the velocity dispersion of "all" ultra faint dwarf galaxies, at time by more than an order of magnitude (see, e.g. Fattahi et al. 2018). A large fraction of these faint dwarf galaxies have observed velocity dispersion of ~10 km/s, while MOND predicts <1km/s. Binaries are expected to affect velocity dispersion by no more than ~2-3 km/s; so not enough to bring the observed values down consistent with MOND.



10. From the observed matter distribution, it is possible to predict, by using the MOND theory, the expected rotation curve, i.e., this can then be tested by observation. Such a prediction is not possible in the dark matter paradigm, isn't it?

FL: I agree that this prediction is not possible in individual galaxies in the dark matter paradigm. It is possible, however, to obtain statistical expectations for different galaxy populations. These expectations are uncertain and model dependent due to the effects of baryon physics (gas flows, gas cooling, star formation, supernova and black-hole feedback, etc.). A common approach is to set the various free parameters describing baryon physics in order to reproduce the observed galaxy properties. Thus, the key question becomes "why should baryon physics work in such a way to mimic precisely the MOND predictions?"

11. There seems to be some Intriguing numerology: the acceleration scale in MOND is numerically close to that of the accelerated expansion. What do you think about this?

FL: There are two independent numerologies: $a_0 \sim c \bullet H_0$ and $a_0 \sim c \bullet \Lambda^{0.5}$. Both numerologies may suggest a connection between local galaxy dynamics and cosmology, or they may be mere numerical coincidences. Some facets of the first coincidence are discussed above to address a specific question. In general, I find the second coincidence more intriguing because it may relate the dark-matter problem to the dark-energy problem. Along these lines, Milgrom (1999) put forward heuristic ideas to explain the MOND phenomenology as a quantum-vacuum effect.

12. Is it correct to say that the optical rotation curves by Vera Rubin did not provide the compelling evidence for Dark Matter as they do not probe far out enough in the halo? Optical rotation curves can be plausibly explained by the distribution of baryonic matter.

FL: I agree. As far as I am aware of, this issue has been pointed out for the first time by Agris Kalnajs (1983) during the famous IAU-100 meeting. Given the luminosity profile of the galaxy, Kalnajs solved the Poisson's equation adopting the appropriate disk geometry rather than assuming Newton's shell theorem that only applies to spheres. He was able to reproduce four optical rotation curves from Rubin and collaborators with a constant stellar mass-to-light ratio and no dark matter. This has been later confirmed by Kent (1986) for more galaxies with optical rotation curves and improved surface photometry: only in a few exceptionally large spiral galaxies there was a significant dark-matter effect. The importance of using extended rotation curves from HI interferometric data (Bosma 1978, PhD thesis) was demonstrated by van Albada et al. (1985, ApJ), Begeman (1987, PhD thesis), and Kent (1987).

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