Executice Summary of the MITP Topical Workshop/Scientific Program

The Mysterious Universe: Dark Matter – Dark Energy – Cosmic Magnetic Fields

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DATES 20.05.2019 – 07.06.2019

Goals of Topical Workshop/Scientific Program

Today's picture of the Universe suggests that classical large scale structures (galaxies, clusters, voids, filaments) grew from quantum fluctuations encoded in the initial state of the Universe. But details of how this may have come about are not understood, yet, and whether and how quantum mechanics enables one to describe the very early Universe remains unclear. Cosmological data, especially those extracted from the CMB show that only about 5% of the energy density in the Universe is made from visible matter (described by Standard-Model degrees of freedom), while about 95% of the energy density is of unknown nature and origin, and its evolution is not understood in a satisfactory way. Roughly 68% of the total energy density is contributed by Dark Energy and 27% by Dark Matter. Furthermore, the basic mechanisms underlying the formation of the observed large-scale magnetic fields remain mysterious, and the origin of matter-antimatter asymmetry remains quite mysterious, too. To this list we might add the problem of understanding whether General Relativity really describes the geometry of space-time on all scales and in the presence of very strong gravitational fields, or whether one should search for a modified theory of gravity.
In view of these basic puzzles and of tentative solutions proposed for some of them, we have identified the following seven topics for our workshop:

1. Quantum mechanics and gravity, quantum field theory on curved space-times

2. Nature, origin and amounts of Dark Matter and Dark Energy
3. Status, role and successes of Inflation
4. Matter-antimatter asymmetry in the Universe
5. Origin and growth of large-scale magnetic fields; their effects on cosmological/astronomical phenomena
6. Cosmological hints at Physics beyond the Standard Model
7. Tests of GR, extra dimensions; analogies to effects in condensed matter physics, (e.g., quantized Hall effect)

The goal of our program has been to come up with a concise (albeit coarse) survey of the present state of knowledge and understanding in cosmology, with special attention to the seven topics shown above, to identify key open problems and to initiate focused activities towards their solutions. It should be noted that, in spite of an intense flow of exciting observational data, much of theoretical cosmology remains a very speculative field with not entirely well defined standards, and it is not always easy to gauge the value of various ideas and proposals. By way of general and openly structured talks we have aimed at exposing some of the most important issues along the seven topics listed above and at summarizing the present ideas brought forward to clarify and resolve them. The material presented at the workshop (accessible on the Website) is intended to motivate participants and other researchers to pursue these issues and to contribute to progress in cosmology.

Scientific Program and Highlights of the Topical Workshop

Our workshop featured more than thirty talks, some lasting one and a half hours or longer, addressing relevant questions and sketching ideas of how to answer them. While in most, if not all of the lectures open problems, recent progress and food for thought were nicely exposed, the organizers have selected the following 'highlights' according to their personal taste:

Cosmic magnetic fields: The generation of primordial magnetic fields during and after inflation by non-conformal couplings was discussed, and various problems (back reaction, strong coupling) were pointed out. In several talks the interesting problem of evolution of magnetic fields in different epochs of the history of the Universe was addressed. Furthermore, an intriguing mechanism possibly responsible for the generation of baryon asymmetry accompanied by helical (hyper) magnetic fields was discussed. All these questions deserve to be pursued further.

Dark Matter: Apparently, it has become clear that the standard WIMP scenario of Dark Matter (DM) is ruled out by present data. As a consequence, more general ideas about the nature of the 'dark sector' have become the focus of present research in this area. In several talks effects of interacting Dark Matter have been explored, and limitations of current models have been discussed. For instance, it was argued that some models of the 'dark sector' may account for diverse forms of observed rotation curves, see Fig. 1 (at least at small radii), which may be detectable in new observations. Special properties of vector-DM caused by mixing with photons were discussed. Models of axions as the basic degrees of freedom underlying Dark Matter were presented. That dissipation of self interacting DM might modify the growth history of super massive black holes was discussed.

Beyond the Standard Model: It was shown that, even in very complicated models of high-scale supersymmetry breaking, there appear to be tachyons in the excitation spectrum, and the problem of breaking supersymmetry thus persists. Tentative models leading to a 'dark sector' or even addressing the cosmological constant problem were sketched.

Gravity and quantum theory: Alternative formulations of and alternatives to General Relativity were discussed, and generalizations aiming at replacing Dark Energy (DE) by infrared modifications of gravity were presented. In several lectures, the problem of a mathematically precise formulation of quantum field theories on general globally hyperbolic space-times (neglecting recoil) was addressed. The problem of incorporating the recoil of matter on space-time geometry was studied in a semi-classical approximation. Various approaches towards a full-fledged theory of quantum gravity were outlined. In particular, discussions of how to formulate a quantum theory of gravity in terms of true 'observables' were entertained. The problem of 'observables' in General Relativity (and other theories of gravity) and of their operational meaning also comes up in comparisons of classical relativistic computations in cosmology with observational data. Ways of testing General Relativity in a strong field regime in future observations were explored.

Gravitational waves: Possibilities of detecting a gravitational wave background arising from phase transitions in the early Universe were discussed. Modified signatures of gravitational waves in modified theories of gravity and their observational prospects were mentioned.

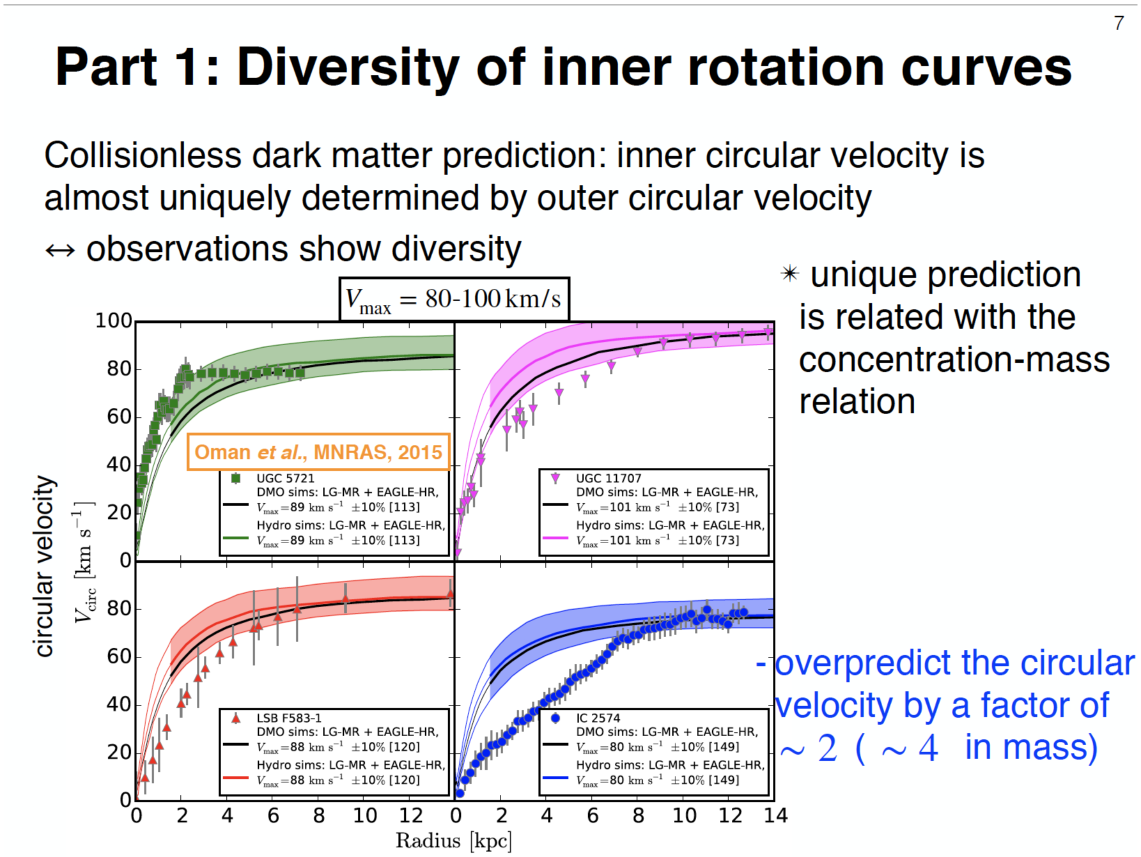

Figure 1: The diversity of rotation curves of dwarf galaxies (from the talk of A. Kamada).

Open problems

Although the range of questions and of ways to address them is vast, we have identified the following *open problems* as being particularly important and intriguing:

- *Dark Energy:* There is no clear way of distinguishing effects in modified theories of gravity from those caused by Dark Energy. Even if one might be able to rule out the ΛCDM paradigm with present and, more plausibly, with future clustering information, this will not enable one to distinguish phenomena arising in models of DE from phenomena predicted by modified theories of gravity. The nature of Dark Energy remains a mystery!

- *Dark Matter:* Abandoning the WIMP hypothesis has opened a Pandora's box of possible models of a 'dark sector'. Many models appear quite arbitrary and somewhat 'baroque' and are tuned to address but one specific observational problem. It is important to compare different models from a more holistic point of view, including both, observational and theoretical aspects. One must hope

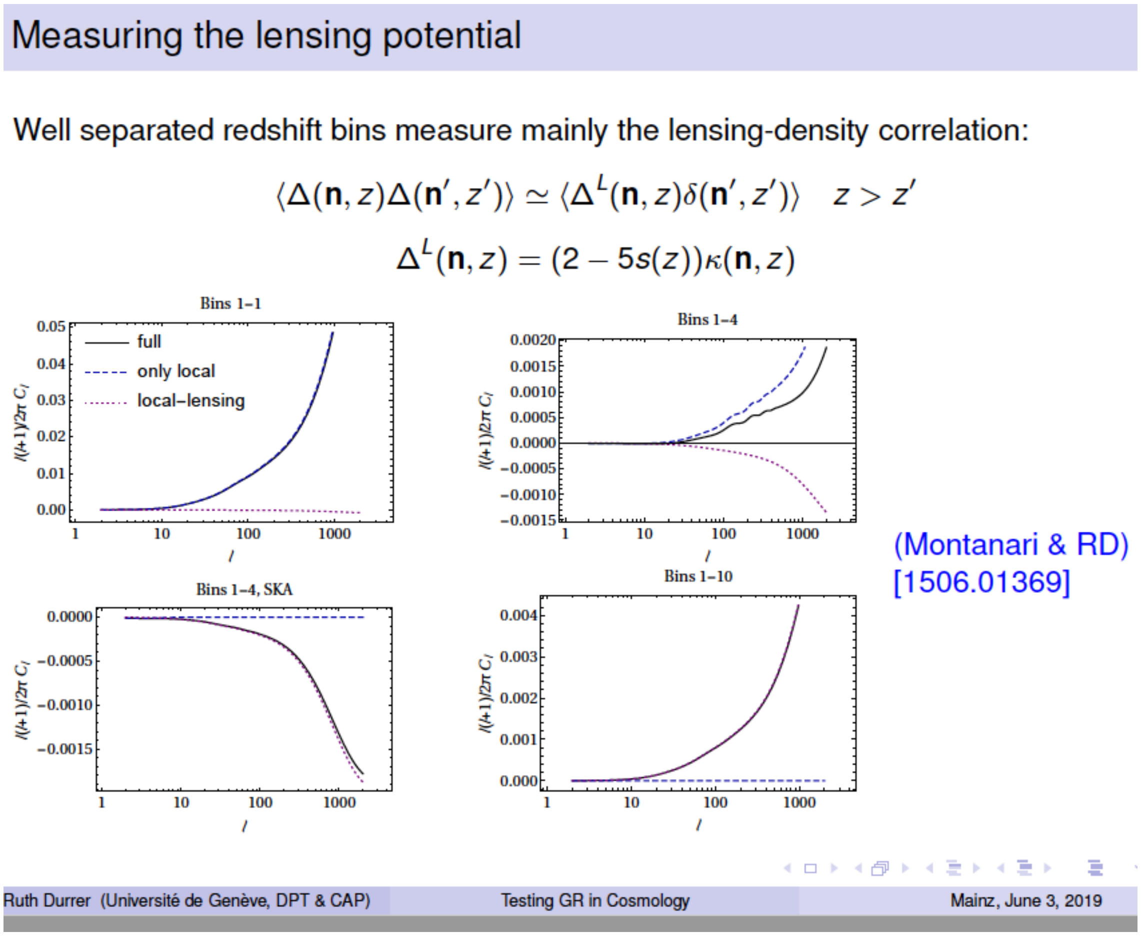

Figure 2: Lensing of large scale structure is an important new contribution which will be measured in future redshift surveys of galaxy number counts (from the talk of R. Durrer).

that future observational data will provide a clearer direction and more focus to theoretical speculation.

- Understanding the origin and evolution of *large-scale primordial magnetic fields* is a persistent and intriguing open problem in cosmology. The chiral anomaly may be relevant to understand their evolution in the very early Universe.
- The challenge of searching for a *unified theoretical explanation* of Dark Matter, Dark Energy, matter-antimatter asymmetry and the presence of large-scale magnetic fields should be taken seriously.
- Processes evolving in the early Universe might offer the most promising (if not the only!) way to test ideas about *quantum gravity* observationally.

- *Future observations:* Possible future observations that could test general relativity have been discussed. This direction of research looks promising.

Some lessons learned at this workshop

- The interdisciplinary composition of the field of participants was perceived as very stimulating and appears to have resulted in certain adjustments of research directions and a number of new research initiatives. Comments from outsiders are sometimes very interesting and may lead to truly new ideas.
- For a relatively interdisciplinary community of researchers like the one of this workshop, it is most important that every talk be opened with a clear and perspicuous introduction. This serves to overcome certain 'language barriers' and to eliminate terminology issues that often hinder enriching discussions.
- Talks often went on for significantly more than one hour, and it proved very important to let people interrupt the speaker and ask questions during the talks, with the aim of optimizing communication and understanding.
- The coffee breaks are a welcome and important complement to the talks and serve to continue discussions. Long intermissions between talks serve to stimulate interactions and collaboration between participants.
- Inviting the physics students to a pizza-and-beer event and offering them a glimpse of an exciting area of physics is a very rewarding activity for both sides. We recommend that such an event become a regular feature of programs at the MITP.
- In view of the extensive nature of the scientific program, a duration of three weeks of our workshop was appropriate.
- In rapidly evolving fields, such as cosmology, it may be appropriate to schedule a series of several workshops taking place in intervals of one or a few years.

Acknowledgements

All in all, we have enjoyed a very dynamic, stimulating and successful workshop in Mainz. We wish to thank the MITP and its director for offering us hospitality in an excellent infrastructure. We are especially indebted to *Heidi Stein* for her efficient, enduring and friendly support.