PRESENTATION DE LA MISSION DU RÉSEAU THÉMATIQUE

Résumé en une dizaine de lignes

GDR on Cosmological Physics

Cosmology has entered an era of precision physics allowing us to tackle more and more deeply the very details of the physical processes that take place throughout the history of the Universe.

The GDR CoPhy will offer a way to bring together all the actors of this field in France, experimentalists, phenomenologists and theoreticians, and provide opportunities for joint meetings and discussion. It will help promote and give visibility to the younger researchers of the field, either through talks, flash talks, or poster sessions.

Today the main research topics in this field can be expressed by the three following science drivers :

- Initial conditions and primordial Universe
- Fundamental laws of the Universe
- Matter and energy content of the Universe

In the GDR, the activities will be organized around four main working groups (WG):

- CMB
- Dark Energy
- Theory, Universe and Gravitation
- Tools and Methodology

and completed by “Transverse Task forces” (TTF) that will be put in place as needed to meet the ad-hoc interests and needs of the GDR members. They aim at focusing on more narrow, dedicated topics, and will have a limited duration. Some examples could be non-linearities, cross-correlations or table-top experiments.

PROGRAMME ET PRINCIPAUX OBJECTIFS POUR LA DURÉE DU RÉSEAU THÉMATIQUE

1. Science Core topics

The main open questions in the field of cosmology today are:
- Initial conditions and primordial Universe
- Fundamental laws of the Universe
- Matter and energy content of the Universe

They define the CoPhy GDR scientific programme and are denoted Core Topics [1] (CT) in this document. They will be addressed as such during the GDR General meetings, therefore bridging gaps between experimentalists and theoreticians, but also: between the different experimental projects, between the experts of the various cosmological probes, and between the Working Groups (cf. Section 2) offering common grounds for exchange, discussion and collaboration.

1.1 Initial conditions and primordial Universe

The Inflation paradigm has been introduced as a possible solution to the hot Big Bang model problems. The last results from the Planck collaboration show that there is no evidence for dynamics beyond slow roll, while slow-roll inflationary models for large fields are already ruled-out. The remaining single-field models (including the simplest and well-motivated $R+R^2$ Starobinsky model) predict a tensor-to-scalar ratio of a few 10^{-3}. That corresponds to the sensitivity target of the future CMB projects. But the quest for a better understanding of the early phases of the Universe requires to go far beyond this result. If current observations are compatible with inflation predictions, they do not answer all the questions:

- What physical conditions prevailed in the very early universe? Can we test for the quantum origin of cosmological perturbations? What does it tell us about the nature of quantum mechanics in a gravitational context? Did the universe undergo a phase of contraction before expanding?
- In which cosmological contexts do quantum and gravitational physics both play a role? Can this help understand fine aspects of field theories on curved backgrounds, or even guide the construction of consistent theories of quantum gravity? How to use cosmology to test various candidates (string theory, loop quantum gravity, holographic approaches etc)?
- If we assume inflation: how did it start? How did inflation transfer energy to the standard-model particles? Is inflation (or any alternative) sensitive to ultraviolet (and even Planckian) degrees of freedom?
- About the physical processes that eventually occurred in the primordial Universe: how to probe the field content (if any) of the very early universe? did primordial black holes form?

There are different experimental ways to tackle these questions, some examples are given below :
- by measuring more precisely the tilt of the primordial spectrum (ns) and testing its running,
- by testing the Gaussian distribution of primordial fluctuations (predicted by slow rolling inflationary models), that can be assessed through the f_{NL} observables,
- by directly detecting the B modes of the polarization of the Cosmic Microwave Background (CMB), the so-called primordial gravitational waves, that should have been generated in the early phase of the Universe, as they would give insights into the shape of the inflationary potential at the time of inflation,

- by measuring the gravitational wave (GW) spectral energy density combining CMB, pulsar and GW direct detections, as a way to provide more insights on the inflation scenarios beyond the standard single-field slow-roll one, and on the (p)reheating periods.

Reinforced by the discovery of the Higgs boson (a scalar field) at the LHC, a high number of theoretical models, describing possible mechanisms to explain the origin of inflation, are based on the existence of (extra) scalar fields. But various other production process hypotheses are to be tested: cosmic strings, pre-big bang theories, phase transitions, ekpyrotic models...

1.2 Fundamental laws of the Universe

One of the key discoveries, at the turn of the century, has been the acceleration of the expansion of the Universe. Still, today, the underlying physical processes are yet to be understood. To go beyond the standard parameterisation through a cosmological constant or a fluid with a distinctive equation of state, one of the current hypotheses is the modification of General Relativity (GR) on cosmological scales. Such a modification could also solve the problem of the singularities inherent to GR as well as our inability to formulate a quantum version of GR. The big questions that are at the center of this Core Topic are, among others:

- Can General Relativity be extended to more general, internally consistent theories?
- Could modified gravity account for the dark sector of cosmology (dark matter / dark energy)?
- Can it incorporate quantum gravity effects?
- What are the distinctive signatures of these theories (early universe, structure formation, late-time acceleration etc)?
- Can they be used to further constrain General Relativity itself?

There are various ways to extend GR. Almost all new theories introduce new degrees of freedom beyond those of GR which participate in gravitational interactions. One of the most studied scenarios corresponds to the scalar-tensor theories, in which a single additional scalar field is introduced and yet offers a rich framework. Other paths include the presence of massive gravitons, or postulate a universe where higher dimensions are only visible to gravity while the standard model particles are confined to a 4D brane. These models easily explain the accelerated expansion. However, in most cases the cosmological constant problem remains unsolved. A radical idea may be then that at the fundamental level the gravitational interaction is emergent from a more fundamental theory, and accounts for dark matter.

There are several ways to test those theories at cosmological scales. On the observational side, once the initial conditions are set within a given background cosmology measurable at large scales, the formation of structures carries a unique signature of gravitational effects, limited at small scales by baryonic physics. Addressing this issue needs to combine not only results and data from projects operating at various wavelength and probing different redshift regimes (such as Euclid, Rubin, DESI and CMB projects), but also to address the small scale issue with the help of theoretical frameworks (either at the level of the equation of motions or based on an Effective Field Theory approach) and to rely on N-body simulations (mimic the impact of modified gravity on large scale structure formation).

To further constrain those models, it is mandatory that the theory can predict observables in a consistent way for all observational probes. Thus, bringing together the researchers working on LSS, on CMB (in addition to standard observables, one can mention the CMB lensing bi-spectrum), and on gravitational waves (as the constraints of the single GW170817 event have shown) is one of the key elements of the GDR to address this Core Topic. In a complementary way, Table-Top experiments can also explore alternative scenarios to the standard ΛCDM and probe key questions on the quantum nature of gravitation.

1.3 Matter and energy content of the Universe

The cosmological ΛCDM model is a concordance model which satisfies most of the current observational constraints. But the coming years will allow us to determine with an even higher accuracy its parameters. Still, its predictions must describe the observations from all probes in a unified way. The study of a (beyond-)ΛCDM model consistent with all cosmological measurements is at the core of this Core Topic.

Beyond the specific extensions of ΛCDM linked to the primordial Universe and those related to modified gravity, various extensions of the ΛCDM model need to be tested to further check the overall consistency of the model, and/or identify new sectors that require a finer description given the increasing accuracy of the data. In particular, we will keep an eye on the remaining "tensions" in our current interpretations of the data that are, today, not statistically significant enough, but which could be hints of New Physics. Among others, the H0 tension, the sigma_8 and the A_L consistency check which is not fully fulfilled, or the CMB large scale anomaly. Addressing these topics, theoretically and through an experimental program, is a route to further constrain or extend the ΛCDM model. This should help alleviate or increase the statistical significance of those observed discrepancies, and eventually pave the way to define new observables, or identify blind spots that need to be further studied.

Cosmology can also give insights on DM and neutrinos as different types of particles with different masses, interaction and decay properties do affect the power spectrum (or correlation function) at characteristic scales. Two main sectors are of specific interest for this GDR: namely the neutrino and the Dark Matter ones. Beyond the DM energy density, one could study various scenarios of energy injections, due to annihilation or dissipation of particles or field modes. This represents a unique opportunity to test the robustness of the model and look for new particles or fields beyond the HEP standard model. Last but not least one can also test parity conservation on cosmological scales by, for instance, observing the initial matter fluctuations (cosmic birefringence). The reionization era as seen by the 21cm line, even if poorly understood yet, could also offer a new window to detect a dark matter signal due to anomalous energy injection. On a radically different idea, testing for primordial black holes may provide a minimum way of explaining dark matter, alleviating the need for new particles. Interestingly, current direct GW observatories are sensitive in one of the mass ranges still open to explain a large fraction or even all dark matter. Last but not least the matter/anti-matter asymmetry is a puzzle that needs to be understood further.

There are therefore issues that are at the core of the fundamental questions that we want to address in the GDR:

- What is the origin of the accelerated expansion of the universe? Is it a cosmological constant, a dark fluid such as dark energy or another component?
- Does dark matter point towards the existence of new degrees of freedom beyond the standard model? Do they resort to supersymmetry, grand-unified theories, sterile neutrinos, axions, extra dimensions, compositeness etc?
- How does the nature of dark energy and dark matter affect the formation and evolution of cosmological structures?
- How were dark and ordinary matter produced in the early universe?
- Are there interactions within the dark sector? Could primordial black holes account for (part of) the dark matter?

2 General meetings, Working Groups and Transverse Task forces

The scientific exchanges of the GDR will be made possible through general meetings, and thematic workshops. This will be a unique opportunity to develop a close synergy between experimentalists, phenomenologists and theorists. In order to better address the Core Topics, we propose to organize four working groups, so called WG ("CMB", "Dark Energy", "Theory Universe and Gravitation" and "Tools", as well as some Transverse Task Forces (TTFs).

The GDR working groups, as described below, build on existing initiatives (ADE, CMB France and TUG[1]). The structuration of the GDR will allow the theory content of ADE to develop a synergy within the WG "Theory Universe and Gravitation" in a coherent way with the other theoretical developments. Similarly the "Tools" WG of the current ADE initiative will evolve so that the tool WG of the GDR will be pertinent for both Dark Energy and the CMB. This will ensure a smooth transition between the current existing initiatives and the GDR. The GDR thus provides the French community with a common and coordinated structure and organization that allows the development of links between all WG, which were identified as missing in the pre-existing structures.

The GDR is committed to giving visibility to the younger actors involved in researches on cosmological physics in France: the coordinators of the various meetings are encouraged to give them priority to give talks, and to participate in the organization of all the meetings, and chair sessions.

2.1 General Meetings and e-seminars

General Meetings will be organized once or twice a year for a few days. They will be the place where a scientific watch will be carried out on the new results and developments in the field of cosmology at the international level. The outputs of the WG and the Transverse task forces will be presented and discussed during those meetings.

The General Meetings allow in particular to:

- bridge expertise between all the researchers involved in cosmology in France: from theory, to simulation, till observations
- propose and share new models and theories (quantum information theory, modified gravity...) and eventually develop new observables,
- develop phenomenological approaches to exploit at best the results to constrain the underlying theories (being motivated by string theories, QFT...and so on...)
- share the current ideas and develop new data analysis techniques to test and challenge the ΛCDM model using the various probes that we have at hands,
- share and compare the analysis methods to best address the systematic errors in the combination of the various datasets,
- share the latest scientific news from the experimental projects
- share the details of the analysis performed by the various experiments.

[1] The Dark Energy National Action (ADE) dedicated to dark energy studies, the CMB Colloque (CMB France), which aims at setting up a scientific animation around the CMB studies, and Théorie, Univers et Gravitation (TUG) which aims at bringing together theoreticians working in the field of cosmology and Gravitation.

To benefit from such gatherings, it is planned to dedicate some specific time for brainstorming through splinter hands-on sessions during the General Meetings. The topics will be chosen on the basis of the feedback of the participants, collected during the first part of the meeting

The General meetings will primarily offer young researchers a place to present their work, either through talks, flash talks or poster sessions: their participation could be encouraged through the awarding of prizes. Specific actions will also be set up for them: this could take, for example, the form of private sessions for PhD/postdoc/young recruits, or journal clubs.

The meetings will, in particular, help to identify the synergies and the lines of force of the field, to identify the means of action to ensure an optimal visibility for all the cosmologists working in France and to discuss the short-term priorities that could lead to the creation of "Transverse Task forces", as well as sharing the perspectives of the next generation of experiments. They will also be a place to invite and discuss with the HEP and GW communities working on direct and indirect searches in both the neutrino, the DM and the GW sectors.

Two years after its start, the CoPhy GDR will organize a “return on experience” exercise to address the pros and cons of the general organization.

E-seminars will be proposed regularly on topics related to the scientific Core Topics.

2.2 CMB Working Group

The goal of this working group is to reinforce the scientific animation related to Cosmic Microwave Background studies in the post-Planck era.

This WG benefits from of a rich experimental program, in particular around the measurement of the polarization of the cosmic microwave background (advACT, SPT-3G, and Simons Observatory, and in a more distant future LiteBIRD and CMB-S4) but also on the future project on CMB spectroscopy (BISOU, Pixie or FOSSIL for instance).

It will be the right place to share the latest news on CMB related ground-based, balloon-borne experiments, and satellite missions. This WG will also cover specific CMB data analysis processes and methodologies such as foreground removal, dedicated instrumental systematics assessment, delensing, but also map making techniques, and high performance computing to handle the manipulation of large datasets.

It will allow to discuss further the constraints CMB can provide on the primordial Universe and its initial conditions (CT1), on the fundamental laws of the Universe (CT2), and the matter and energy content of the Universe (CT3). For this purpose, the WG will aim at increasing the links between theoreticians and experimentalists, to make a stronger link between the scientific interpretations and the theoretical studies on those topics.

The CMB Working Group will organize one or two workshops per year.

2.3 Dark Energy Working Group

The aim of this WG is to reinforce the scientific animation around the understanding of dark energy and its various interpretations: a cosmological constant, a new form of energy or a deviation from the standard theory of gravitation on cosmological scales. This WG is strongly connected to CT2 and CT3, at the heart of, among others, the Euclid, LSST, ZTF and DESI projects.

Multiple probes can address dark energy. Hence one of the goals of the Dark Energy WG is to gather together the corresponding experts to further compare the results, eventually combine them and best assess the underlying physics. For example, Type Ia supernovae and Baryon Acoustic Oscillations are the historical tools to probe the equation of state, while additional powerful constraints will come through the study of weak lensing. Dark energy can also be tested with lensing and clustering correlations, as well as cluster evolution and void statistics, not to mention the emerging probes such as peculiar velocities derived from Type Ia supernovae distances.

In parallel, the WG will give the opportunity to develop further collaborations between theoreticians and probe experts, in order to constrain further our understanding of dark energy.

The Dark Energy WG will organize an annual workshop, during which we will share the latest scientific news of the above-mentioned projects, enter into the details of the physics analyses of the various probes, and share discussions on theoretical models.

2.4 Theory Universe and Gravitation Working Group

The objective of this WG is to gather together the theoreticians working on the topics of cosmology and gravitation and to stimulate methodological exchanges. Investigations on fundamental aspects in cosmology and gravitation involve numerous theoretical tools and a growing number of strategies and expertises. While specialized meetings and working groups exist, a strong need has emerged for a common forum which could put periodically in contact the broader group of theoreticians working on both cosmology and gravitation, to update it with transversal developments, while allowing for some technical incursions in specific subjects undergoing a fast growth. The topics of interest range from approaches to quantum gravity (in string theory and loop quantum gravity, for instance) to strong-field tests of general relativity (with associated analytical and numerical tools), from new aspects of inflationary dynamics to gravitational waves probes of the early universe, from innovations in perturbative approaches to describe the large scale structures of the universe (including the production of public codes to deal with them) to new ideas concerning dark matter and dark energy, with potential impact on CMB, early or late universe physics, possibly shedding light on recent tensions in cosmological observables. As a consequence of its broad scope, all science core topics of the GDR are concerned. The WG will organize a yearly meeting almost exclusively dedicated to theoretical developments, while the GDR will provide the main arena for exchanges with experimental colleagues and the emergence of joint initiatives or teams to tackle specific subjects.

2.5 Tools and Methodology Working Group

This Working Group aims at sharing and helping the development of tools for which the needs are common to all the actors of the GDR. It includes:

- tools that are oriented toward the predictions of cosmological observables and their relative theoretical systematic uncertainties such as Boltzmann solvers, numerical simulations, approximate methods for the non-linear evolution, and forward modeling,
- development of estimators for data analysis which are for example based on power spectra, and higher order statistics,
- mathematical methods for inference such as the one based on MCMC, Machine Learning, and minimizers,
- production of validation data, such as mock galaxy catalog, mock CMB maps.
- tools for symbolic based computation in the cosmological context

The activities of this WG rely on specific mathematical technical developments, which will probably require developing links with colleagues in other institutes. Most of the issues addressed in this WG are also closely related to the increasing use of machine learning techniques and the need for specific computational methods and computing centers (high-performance computing, big data). All these topics will be at the heart of the WG, which will organize dedicated meetings once or twice a year.

2.6 Transverse Task forces

The GDR plans to create “Transverse Task forces” which aim at focusing on more narrow, dedicated topics, and may have a limited duration. They will be set up dynamically on the basis of the interests of those who will join the GDR meetings, to address a particular topic (and may concern a limited number of people). The GDR will organize dedicated meetings, either in association with the annual General Meeting (see Section 2.1), or independently for those Transverse Task forces.

Some examples of potential TFF are given below:

- the cross-correlations, in particular as a tool to reconstruct the growth rate of structures as a function of redshift (this TFF is therefore not only methodological),
- the non-linearities: from theory, simulations, to their impacts on predictions, and the derivation of related theoretical systematic errors for the inference of the cosmological information,
- the CMB spectral distortions, as a tool to further constrain the processes inducing energy injections, but also to probe primordial non-Gaussianity in particular at scales far beyond those accessible by CMB anisotropies and to better determine the role of baryonic feedback in structure formation,
- Table-top experiments as a way to explore alternative scenarios, test the quantum nature of gravity and search for hints of physics beyond ΛCDM.

Transverse Task Forces will be set up progressively, triggered by discussions during the General meetings, and fed by scientific breakthroughs, the need to gather certain expertise, or triggered by the scientific watch. In particular a dedicated discussion will be organized at the kick-off General meeting.

2.7 Relations with other (related) GDR, IRN, and INSU Programmes Nationaux

Joint ad-hoc meetings will be organized with other GDR and IRN, which encompass working groups (WG) that also tackle cosmological physics related topics such as :

- The Gravitational Waves GDR, through two of its WG - the cosmology WG and the Tests of General Relativity and alternative theories WG, whose goal is to use the gravitational waves as another cosmological probe.
- The Terascale IRN with its Dark Universe WG which aims at tackling the nature of dark matter and its interactions, combining the information coming from direct and indirect searches together with cosmological, astroparticle and astrophysical information.

The GDR will also maintain links with related INSU Programmes Nationaux such as the PNCG (Programme National Cosmologie et Galaxies).

3. GDR operations

The GDR CoPhy will convene one or two general meetings per year, during which hands-on splinter sessions will be set up on the basis of proposals from the audience. In between the WG and the general meetings, e-seminars will also be proposed.

For a period of 4 years, the GDR will be coordinated by Sophie Henrot-Versillé as director, and Vincent Vennin and Samuel Boissier acting as deputy directors.

A steering committee will be setup composed of the director, the two deputy directors and one representative per WG proposed by the WG coordinators and appointed by the directors of the GDR for a period of 2 years, renewable. Individuals that bring some special expertise to the discussions may be invited for a session. Once a year, representatives of the directions of the institutes involved should be invited to discuss the past activities and present the future plans of the GDR.

The steering committee will work to:

- Ensure and strengthen the scientific animation in cosmology in France
- Identify areas or topics on which new TFFs and WGs should be created, and create them when appropriate,
- Coordinate the scientific activities addressed during the WG meetings and the TFFs
- Organize the general meeting(s),
- Organize the "feedback" meeting planned after 2 years.
- Participate in roadmap exercises if and when required.
- Coordinate with other related GDR and IRN, such as the GDR Ondes Gravitationnelles, the GDR DuPhy, the IRN Terascale

A list of contact persons in each lab involved in cosmological physics will be setup in order to organize the interactions between the GDR direction and the members of the GDR.

At its beginning, the working groups will be coordinated by:

- Alain Blanchard, Philippe Brax and Pauline Zarrouk for the Dark Energy WG
- François Bouchet and Matthieu Tristram for the CMB WG
- Vivian Poulin and Pasquale Serpico for the TUG WG
- Guilhem Lavaux and Yann Rasera for the Tools and Methodology WG

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[1] While these questions are linked to astrophysical properties of the cosmological observations, the detailed astrophysical understanding of these probes and their foregrounds is beyond the scope of this GDR.