Tentative summary of the theoretical activities in astroparticle physics, cosmology, and gravitation, carried out at the IN2P3

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This document tries to shortly review the current functioning of theoretical and phenomenological activities in astroparticle physics, cosmology, and gravitation carried on by French groups of IN2P3 laboratories. This document is incomplete, sometimes very vague, and strongly lacks for balance due to the very limited preparation time, the number of topics covered, and the moderate level of response from colleagues. It is still meant to give a flavor of the expertise present within IN2P3 theoretical groups. Only the authors are to be blamed for the poor quality.

I. INTRODUCTION

In this introduction, after reviewing the main research topics discussed in the present document, we describe the broad picture of theoretical activities of IN2P3 groups, and how they insert themselves and articulate within the national landscape.

On the one hand, the research field of *Astroparticle Physics* (APP hereafter) can take several acceptions among theoretical physicists, depending on the specific community in which they were trained or in which they evolve. These acceptions do not necessarily overlap with each other. Tentative complementary and contemporary definitions could be:

- The study of astrophysical phenomena or processes in which (standard or exotic) particles or their interactions play a central role.
- The study of astrophysical phenomena or processes which can be traced by multimessenger astronomy (including gravitational waves).
- The building of (standard or exotic) theoretical scenarios or models thereof.

As a common practice in the whole field, the use of interdisciplinary approaches is one of the specificities of related research activities. The degree of transversality in the theoretical methodology or knowledge depends on the topic, but can sometimes be prominent. It varies among communities, as might be more striking as one goes through this document.

At the French level, interdisciplinarity is somewhat always related to transversality among the main research/funding institutes, beyond the CNRS-IN2P3. Most of the activities shortly described below are indeed often based upon collaborations between scientists from different CNRS institutes (IN2P3, INP, and INSU), and also from CEA (IPhT, IRFU). An additional layer of complexity that characterizes the organization of this research field is the way scientists are hired and their careers followed. Beside university positions that are ruled on local bases, CNRS positions in this field can be assigned by different sections of the CoNRS:[1] Section 01 (driven by IN2P3), Section 02 (driven by INP), and Section 17 (associated with INSU). It turns out that in IN2P3 laboratories, scientists working on theoretical APP can belong to (i.e. have their activities evaluated by) any of these three CoNRS sections. This mixing is much less prominent in laboratories driven by other institutes (except for Section 02-INP, which also used to appoint scientists in theoretical groups in INSU laboratories). This peculiar organization has some impact on the structuring and overall optimization of research activities, which significantly depend on the quality of connections between teams from different institutes.

Cosmology and Gravitation (Cosmo/Gr hereafter), on the other hand, are unambiguous topics in terms of definitions, even though they encompass a great variety of theoretical or phenomenological approaches, as well as observational probes. More specifically, cosmology is a discipline in which gravitation and high-energy physics can meet together. Gravitation mostly focuses on deepening the current understanding and proposing/investigating tests of General Relativity (GR) and its possible extensions (beyond GR). Typical objects of studies are black holes, and the expanding universe as a whole. Cosmology, as the study of the Universe, its content, and its dynamics over time, covers a broad spectrum of activities, from the study of phenomena or processes in the primordial Universe (pre-recombination), its current expansion and constituents, the formation and evolution of structures after recombination. Activities

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[1] The CoNRS coordinates national committees (or sections) with elected/nominated scientists responsible for the appointment and the evaluation of activities of scientists — .

in these research fields in France do not concentrate in CNRS-IN2P3 units neither, and receive strong contributions from CNRS-INSU or CEA groups (cosmology, structure formation, gravitation), as well as from CNRS-INP groups (in particular the early-universe, high-energy, particle physics, and/or formal aspects, in connection with early universe, compact objects). As for AAP scientists, researchers working in theoretical Cosmology and Gravitation in IN2P3 teams can depend on the same mixture of CoNRS Sections: 01, 02, and 17.

The main national tools for IN2P3 scientists to fund research activities in theoretical APP and Cosmo/Gr, which develop at the borders of different CNRS institutes, are *master projects* funded by IN2P3 (with some restrictions), national programs of INSU (*Programmes Nationaux*), and ANR or Labex grants. IN2P3 theoretical groups are also allocated, in principle, a yearly basis research grant which allows them to cover (fully or partly) regular internal scientific activities. This regular IN2P3 funding for theoretical physics has been generalized in the last 5 years, but was research unit-dependent before. More specific to IN2P3, research groups can be assigned postdoctoral and PhD grants to accompany project developments, a possibility that does not exists at INSU nor INP for example.

In the rest of this document, we summarize the main research activities carried out by IN2P3 groups. Since the AAP/Cosmo-Gr theoretical fields are characterized by a large diversity of topics, this review cannot claim to be exhaustive, nor precise. It will also be quite unbalanced as a consequence of the strong fluctuations in the material communicated by our colleagues. It is therefore meant to give only an overall flavor of what IN2P3 scientists mostly cover. Since influence in theoretical physics is not necessarily only measured in terms of number of researchers, but also in terms of quality and visibility of papers, trained students or research networks, the coverage of research activities will not be weighed by the number of participants. However, a tentative list of practitioners will be given at the end of this report, in A.

Two side remarks before engaging in the scientific review: (i) A specificity on the IN2P3 environment is the proximity of teams involved in the development of experimental or observational international projects, or data analyses thereof, whose data is or will be critical for theoretical progress, e.g.: Fermi-LAT, HESS, CTA, AMS-02, Auger, Antares, Km3, JUNO, Edelweiss, Xenon-1[n]t, Planck, LiteBIRD, Virgo, LISA, LSST, Euclid, etc. Exchanges with the relevant experimental or observational communities vary in degree among fields, but in some cases, they can be strong and regular. A few theoretical physicists or phenomenologists happen to be involved in international collaborations, and a few experimentalists or observers also make excursions in data interpretation and modeling. (ii) Several topics are actually transverse to both AAP and Cosmo/Gr. Examples are dark matter, primordial black holes, and the astrophysics/cosmology of neutrinos.

II. ASTROPARTICLE PHYSICS

As already said above, this field encompasses a great diversity of topics. We shall shortly review some of them below, starting with non-exotic or moderately exotic astrophysics, before moving to more speculative topics.

A. High-energy astrophysics and cosmic rays

Cosmic-ray physics is a very broad field of research. It includes the understanding of the cosmic-ray sources, comprising their progenitors, the mechanisms responsible for acceleration, internal diffusion, radiative processes, and then escape, transport and interactions in the interstellar or intergalactic medium for the most energetic cosmic rays. The physics involved includes gravitational dynamics, the physics of plasmas, magneto-hydrodynamics, radiative processes, diffusion, particle interactions, etc., with some aspects implying strongly non-linear physics, and/or sometimes extreme environments (highly magnetized, dense, strong gravity, etc.). Many of the physical processes or phenomena studied in this rich context often given rise to observational signatures, whose predictions constitute a significant part of the work. There are three main observables: the energy spectra per species, the composition, and the anisotropy of cosmic rays. Even though the transition between Galactic cosmic-ray and extragalactic domination is still to be understood more clearly, it turns out that the general physical mechanisms at the origin of cosmic ray production and transport may characterize (though in different regimes) both Galactic and extragalactic sources, even though the transport of cosmic rays depends on rigidity and on the properties of the interstellar or intergalactic magnetic fields, which have very different properties. Observations in multiwavelength emissions and in multimessenger channels play a central role in exploring this kind of physics, and in making progress. Phenomenological studies provide useful ingredients to theoretical developments, and vice versa. Finally, note that some topics are at the border of nuclear astrophysics, reviewed in another contribution.

The involved community belongs to diverse institutes, and research activities are somewhat related to some *Programmes Nationaux*, in particular the PNHE, the PCMI, and the PNGRAM. Recently, part of this community has engaged some effort to structure itself or more practical bases. A series of workshops has been created, CFRCOS[2] (*Communauté Française du Rayonnement COSmique*). An IN2P3 project putting together cosmic-ray scientists from IN2P3 groups has also just been granted for 3 years, INTERCOS (APC, IJCLab, LPSC, LUPM), which articulates and structures collaborations between

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[2] CFRCOS1, CFRCOS2, CFRCOS3.

theoretical teams, but does not cover all of the topics discussed below.

1. *Accretion disks*

(APC)

Efforts are ongoing to understand and model the accretion disks forming around compact objects, which are natural sites for powerful mechanisms to take place and to accelerate photons up to gamma-ray energies. These theoretical developments apply to objects of different scales, *e.g.* black holes at the centers of radio-loud galaxies, X-ray binaries, etc., and one of the technical difficulties is to treat time-dependent magneto-hydrodynamic equations in the strong gravity regime. Although the physics at stake can be probed by multiwavelength observations, accurate predictions are challenging to make because of the intrinsic non-linearities and difficulties in handling the numerical calculations. Dedicated simulation codes have been developed recently allowing for a full embedding of magneto-hydrodynamic evolution equations in a general relativistic framework. An example is the NOVAs project [1], which led to the development of numerical simulation tools and allowed, among applications, to explore the impact of the Rossby wave instability in detail [2]. It actually turns out that part of these developments find also application in the understanding of the microphysics of cosmic-ray acceleration and transport [3, 4].

2. *Microphysics and phenomenology of cosmic rays*

(APC, LPSC, LUPM)

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Cosmic-ray microphysics is at the very center of several fields in astroparticle physics. It deals with the study of relativistic charge particle (Cosmic Rays) interaction with electromagnetic fluctuations present everywhere from solar, space plasmas to interstellar and intergalactic media. Progress in this topic is essential to understand the complex non-linear physics on-going at cosmic-ray sources, during the escape of cosmic rays from sources, and their journey to the Earth (or more generally throughout the Milky Way). Collisionless shocks, the generation and properties of magneto-hydrodynamic turbulences (*e.g.* [3]), the role of instabilities (*e.g.* [4, 5]), the back-reaction of cosmic rays themselves, are among the intricate aspects to study as self-consistently as possible in an evolving environment. These are usually difficult problems, non-linear and multiscale in space and time, an a self-consistent study would need to cover a dynamical range of almost 10 orders of magnitude [6]. Some of the current theoretical efforts are dedicated to adapting field theory calculations to non-linear turbulence models, and to further developing multi-scale numerical techniques run on super-calculators. Technical compromises have to be made, regarding either the number of spatial dimensions, the range of wavenumbers, or the time range of simulations. Promising developments include, for instance, the coupling of particle-in-cell with magneto-hydrodynamic codes [4]. Particle acceleration and transport microphysics are also more and more routinely studied in laboratory laser plasma experiments. This subject comprises about one-third of the activity in the next decadal survey of laser experiment physics (outside from IN2P3).

Regarding cosmic-ray acceleration, several topics have been addressed recently, for instance, acceleration at supernovae with transrelativistic outflows [7], at colliding shock waves [8], or acceleration in massive stars [9]. There is also attention paid to the escape of cosmic rays from their sources in the interstellar medium, which is still not fully understood [10–12]. In this context, multimessenger and multiwavelength observations are important to constrain production models [13]. A way to further probe the onset of diffusion at the vicinity of sources is to study the interaction of cosmic rays with molecular clouds [10, 12, 14]. This is particularly relevant to understand the origin of high-energy electrons and positrons, for which local sources like pulsars could be involved [15, 16].

Finally, there is expertise in the phenomenological analyses of Galactic cosmic-ray data (called "direct detection" of cosmic rays), in which interactions with the experimental community has been particularly fruitful. Such analyses try to infer the main phenomenological ingredients that describe the propagation of cosmic rays in the Milky Way from the data of several species of cosmic rays, in particular from the ratio of primary-to-secondary cosmic rays (*e.g.* B/C, sub-Fe/Fe, etc.). Some IN2P3 groups have developed cosmic-ray propagation codes to make such studies, such as the public code USINE [17]. The quality of the data collected by the AMS-02 space experiment has radically improved the constraints on propagation models, by reaching percent-level statistical uncertainties on the measurements of many cosmic-ray species (nuclei and leptons) from $\sim$ 0.1 GeV to $\sim$ 0.1 TeV. Systematic experimental uncertainties, and their correlation lengths, must therefore be modeled with care to make proper sense of these data, as they dominate over large parts of spectral measurements. This is where collaboration with inner experimental physicists becomes important. Another important source of theoretical errors is the still poor determination of relevant nuclear cross sections.[3] All this allowed to show that the spectral breaks observed in the proton and helium spectra could be associated to a spectral break in the diffusion coefficient [18]. Further studies could define classes of

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[3] This led to the organization of dedicated international workshops, for instance the XSCRC series at CERN.

propagation models linked to several possible microphysical interpretations, and exhibiting two spectral breaks in the the diffusion coefficient, both at low rigidity and high rigidity [19]. In this context, diffusive reacceleration models have become strongly constrained. Other consistency tests are for instance related to the compatibility of diffusion models with magnetic field models, as diffusion proceeds through scattering off magnetic turbulences [20]. Note that low-energy data provided by the Voyager spacecrafts, which crossed the heliopause, also allow to constrain diffusion models by limiting the effects of solar modulation.

The transition between Galactic and extragalactic cosmic rays can be inferred by simply scaling the Larmor radius with the intensity of galactic and intergalactic magnetic fields [21]. This does not prevent very high-energy cosmic rays to originate from the Milky Way, which could lead to anisotropies and be observed in gamma rays or neutrinos beyond TeV energies. Beside ultra high-energy cosmic rays, both diffuse gamma rays and neutrinos can be used to establish diagnoses on the transition from galactic to extragalactic domination, and also on the sources of extragalactic cosmic rays [22].

B. Astrophysics of neutrinos

(APC)

Neutrinos are studied in particle physics, astrophysics and cosmology. In particle physics, the goal is to understand the origin of their masses and their intimate properties, possibly arising from UV completions of the standard model (with sterile neutrinos possibly playing important roles in cosmology — there is expertise in leptogenesis/BSM leptonic flavors at IJCLab [23], LPC, LUPM). In astrophysics and cosmology, they can be both the messengers of physical processes in which they are produced, or at the deep origin of physical processes themselves [24]. They can also impact structure formation.

Two decades of atmospheric, reactor, accelerator and solar experiments have paved our knowledge of neutrino masses and mixing, since the oscillation discovery, and brought crucial observations for astrophysics and cosmology. Important open questions remain including the neutrino mass ordering and absolute mass, the (Dirac versus Majorana) neutrino nature, neutrino electromagnetic properties, the existence of sterile neutrinos and CP violation in the lepton sector. The neutrino oscillation discovery has deeply modified our understanding of neutrino propagation not only in vacuum, but also in cosmological and astrophysical environments — the Sun, core-collapse supernovae, accretion disks around compact objects (black holes, neutron star-black hole, and neutron star-neutron star) and kilonovae. Neutrinos are tightly connected to two longstanding key open issues in astrophysics: (i) What is the explosion mechanism of supernovae that undergo gravitational core-collapse? (ii) What are the sites where elements heavier than iron are made through r-process nucleosynthesis?

The measurement of twenty-five electron anti-neutrinos events from SN1987A has brought key information on the supernova mechanism, favoring the delayed neutrino driven mechanism (Bethe-Wilson 1985) over the prompt explosion, as well as on unknown neutrino properties, non standard particles such as axions and interactions. If a core-collapse supernova blows up in our galaxy or nearby, an ensemble of observatories will precisely measure the time and energy signal for the three neutrino flavors. The precise measurement of the time signal can confirm/refute the delayed neutrino driven mechanism aided by SASI (Standing-Accretion-Shock Instability). The determination of the neutrino time signal and spectra gives the unique possibility to understand flavor evolution in dense environments, to learn about unknown neutrino properties, the properties of the newly born neutron star and new physics. For r-process nucleosynthesis, GW170817 has provided first evidence for the gravitational wave signal from a BNS in coincidence with a short Gamma-Ray-Burst and a kilonova. The electromagnetic signal gives the first evidence for ejecta with r-process elements (actinides and lanthanides) in a BNS. Ejecta are compatible with a dynamical pre-merger component and viscous and neutrino-driven winds ejecta from the post-merger phase. A second BNS event, without electromagnetic counterpart, has been measured recently. Comparison of the kilonova observations with predictions shows neutrinos impact ejecta composition in such environments.

The measurement of the two diffuse and never observed neutrino backgrounds will open new observational windows. The cosmological extremely cold one requires new concepts. Its detection represents currently a major challenge. On the contrary the discovery of the diffuse supernova neutrino background (DSNB, sensitive to the core-collapse supernova rate, the fraction of failed supernovae, to non-standard neutrino properties and new physics is around the corner, with the Superkamiokande+Gd experiment taking data, the JUNO experiment under construction and the now approved Hyper-Kamiokande experiment. Theoretical developments are essential to address these fundamental issues, and support the coming decade of crucial observations.

The impressive experimental progress in the field has triggered an in-depth investigation of flavor evolution in dense astrophysical and cosmological media. Beyond the well established Mikheev-Smirnow-Wolfenstein (MSW) effect, responsible for the deficit of high energy solar neutrinos, theoretical studies have shown shock waves, turbulence, neutrino self-interactions impact flavor evolution, the electron fraction and r-process nucleosynthetic abundances as well as the supernova neutrino time signals and spectra, important for observations.

In this overall context, several studies were performed in the last years:

- Exploring the role of contributions appearing at the mean-field level, so far neglected, in particular from the absolute neutrino mass that introduce a coupling between neutrinos and antineutrinos (helicity coherence). This could produce flavor modification and neutrino spectral swapping, influencing nucleosynthesis [25].

- Investigating the impact of flavor conversion phenomena due to standard and non-standard interactions in BNS that can influence the nucleosynthesis of heavy elements in neutrino driven winds (r-process) and are relevant in connection with the recent kilonova observation by the LIGO/Virgo Collaborations [26].

- Exploring the role of decoherence in a wave packet treatment of neutrino flavor evolution in strong gravitational fields and showing that decoherence can be significant on short distance scales, thus suppressing flavor conversion [27].

- Investigating conversion modes that occur on very short distance scales (referred to as "fast modes") and showing that contrarily to the current prejudice such modes do not produce flavor equilibration and degenerate neutrino fluxes [28]. The latter possibility would have greatly simplified simulations and the interpretation of future observations. Moreover the analysis of multi-dimensional simulations of supernovae neutrino fluxes has revealed that fast modes can occur in realistic simulations, contrarily to previous findings in one-dimensional simulations [29].

- First explicitly showing that the gravitational energy emitted of the newly born neutron star in a supernova explosion can be determined with a few percent precision, from the neutrino signal in Cherenkov detectors, giving mass and radius of the neutron star [30]. Nine degrees of freedom likelihood analyses of the neutrino spectra in Super-Kamiokande and Hyper-Kamiokande have also shown that the $\nu_e, \nu_\mu, \nu\tau$ spectral parameters can be precisely determined [31].

- Studying the possibility to precisely reconstruct the neutron star radius from the late time neutrino signal, in particular to explore the possibility to extract information on extended theories of gravity from total gravitational binding energy-neutron star radius relation. For the latter, the answer is, at least for the moment, not positive [32].

- Rederiving the neutrino quantum kinetic equations (νQKEs) based on the Born-Bogoliubov-Green-Kirkwood-Yvon (BBGKY) hierarchy that was used to go beyond the mean-field equations commonly employed in the astrophysical context [33]. In particular, this gives an alternative derivation of the full collision term, that includes both a diagonal and a non-diagonal contribution (due to the neutrino mixings), to the one based on the Closed-Time-Path (CTP) formalism. The numerical solution of the νQKEs, has given the currently most precise determination of ΔN_{eff} and the influence on the light primordial elements (BBN) has been obtained, for the first time, with the full collision integral.

C. Dark matter in astroparticle physics

Dark matter has long been studied in astroparticle physics. The particle physics aspects consist in finding new particles with the right properties to play the role of (cold) dark matter. Most of models used to be embedded in extensions of the standard model dedicated to solve problems inherent to particle physics. One of the most influencing framework in the last decades was that of the electroweak hierarchy problem, which led to expect new physics to show up around the TeV energy or mass scale. Sophisticated and promising theoretical scenarios were investigated very often in self-consistent UV-complete theories, resorting to supersymmetry, extra-dimensions, compositeness, or a mixing thereof. Rather generically, dark matter particles were predicted to be sorts of weakly-interacting massive particles (WIMPs), with weak cross sections arising from the right combinations of interaction couplings and mediator masses. WIMPs have been the leading candidates owing to their rather generic occurrence in extensions of the standard model, and also to the simplicity of their production mechanism in the early universe: thermal freeze out. They were also popular because they are associated with a rich phenomenology, and many detection strategies could be developed to probe them, from production at colliders to astrophysical searches of annihilation or decay signals. They have even led to dedicated searches in astroparticle physics: direct detection, which has reached the sensitivity to explore interesting parts of the parameter space for a decade.

However, the absence of signals of new physics at the LHC has somewhat changed the picture, with the usual top-down approach slowly reverting to a bottom-up one. Simplified (effective up to tree-level processes) particle physics models have been considered as prototypes to test more generic features that could be probed by observations, for which the main guiding principles are the production mechanisms (which could even imply a complex dark sector). On the other hand, other top-down scenarios that were previously less "fashion" in spite of their motivations originating in particle physics itself, for instance sterile neutrinos (neutrino masses and leptogenesis) or axions (strong CP problem), have been revisited with more attention. That change of hierarchy in the landscape has implications in the current developments. Other astrophysical or structure formation aspects (*e.g.* the CDM problems on small scale) have some interesting consequences that will be discussed in the cosmology section.

Model building in particle physics beyond the standard model:
(IJCLab, IP2I, IPHC, LPC, LPSC, LUPM)

French IN2P3 groups have been involved for a long time in particle model building, with expertise in supersymmetric (almost all of the "ino" candidates), extra-dimensional or composite, and great-unified extensions of the standard model of particle physics, and simplified models thereof [34–40]. Public codes have been developed to scan over the very large available parameter space, which include constraints from colliders (*e.g.* NMSSMTools, SuperISO). There is also expertise in the different production mechanisms that could lead to a cosmological abundance of dark matter consistent with current constraints: this consists in finding solutions to different moments of the Boltzmann equation in the early universe. For instance, thermal freeze-in is one of the mechanisms imported recently from neutrino cosmology in dark matter studies, which popped up some activity in the field [41–43]. Gravitational production has also been revisited [44]. Generic aspects of this kind of studies has been known for some time, but they have improved in the level of details included in recent analyses, or strengthened in the degree of speculation (number of processes considered, treatment of out-of equilibrium processes and evolution, dark sectors, etc.).

There is still, however, strong interest in UV-complete model building (supersymmetric, or composite models), in which, beside dark matter, other phenomena in the early universe (inflation, phase transitions, etc.) are being explored motivated by ongoing and future observations of low-frequency gravitational waves. An example of funded IN2P3 Master projects is SlowSUGRA (IPHC, APC, LUPM), initiated from Ref. [45].

More recently, interest in the physics of axions has emerged in France from both astrophysical/cosmological [46, 47] and theoretical perspectives. This is again a top-down approach to dark matter model building, for which interest is growing owing to unsuccessful WIMP searches so far. Another source of motivation, beside the strong QCD problem, stems from the fact that axions or axion-like particles could participate in solutions to the electroweak hierarchy problem, and could lead to interesting signatures in cosmology. Besides, WIMP detectors (direct detection) are sensitive to axions, which allows to probe part of the parameter space with operating experiments. An IN2P3 master project has emerged recently on this topic (LPSC, LUPM), entitled *Axions: from particle physics to cosmology*, which could also help local experimental physicists to identify the most relevant parameter space to target with experiments (GrAHal, MIMAC, n2EDM).

Finally, another possibility is that of a stronger connection between the neutrino and dark matter sectors. Minimalistic scenarios to explain neutrino masses (and mixing) generation necessitate the extension of the SM via right-handed neutrinos, and depending on the model, their masses can lie in different energy scales. These heavy neutral fermions (HNL) mix with active neutrinos via Yukawa couplings to the SM Higgs boson, and can in principle be viable DM candidates: produced in the early Universe by active-sterile oscillations of the active neutrinos in thermal equilibrium (Dodelson-Widrow mechanism), or through resonant mixing (Shi-Fuller mechanism). Recent constraints restrict the DM neutrino mass at the keV scale, and may limit its relative abundance down to $\sim 30\%$ DM abundance. In specific scenarios, the Yukawa couplings are considered large enough such that the HNL thermalize in the early Universe, while the light sterile state does not. The freeze-in production mechanism (decay of heavy to light sterile neutrinos from mixing) partially decouples the DM abundance from the active-sterile mixing angle, thus complying with bounds from stability and indirect detection; the resulting DM spectrum is colder than the one obtained via the DW mechanism, relaxing structure formation bounds. Related model-buidling aspects combining solutions to dark matter and to leptogenesis are currently being explored [48].

Indirect and direct searches: The different searches for dark matter particle candidates are complementary to each other, as they probe different parts of the available parameter space (the velocity-dependence of interactions characterizes the constraining power of probes in astrophysical searches) — production at colliders, direct searches for collisions off target nuclei, indirect detection of induced astrophysical signals, gravitational probes, etc. Performing elementary particle physics process calculations is part of the expertise of particle physics theory. In direct WIMP or axion searches, one of the main uncertainties concerns the local distribution of dark matter particles, both in terms of number density and of velocity. For WIMPs, theoretical methods exist to self-consistently infer the velocity distribution from solutions to the collisionless Boltzmann equation [49], and theoretical errors can be estimated by applying them on cosmological simulations [50]. On the other hand, for both WIMPs and axions, it is important to figure out the level of local inhomogeneities, which are inherent to any cold dark matter scenarios [46, 51]. For indirect detection, there is also strong phenomenological expertise within IN2P3 groups, either in diffuse gamma rays or neutrinos [52, 53], in CMB, or in antimatter cosmic rays. For the latter, it was recently shown that a putative signal in the antiproton spectrum is very unlikely [54], or that the MeV e^+e- data collected by the Voyager spacecrafts could set strong constraints on MeV annihilating dark matter [55], complementary to CMB constraints, and still not constrained by direct searches (except for p-wave signals).

D. Intergalactic magnetic fields

(APC)

Magnetic fields in galaxies and galaxyclusters originate from seed magnetic fields of unknown nature that possibly pre-existed galaxies and have been produced by yet uncertain mechanism in the Early Universe. This seed magnetic field might reside in the intergalactic medium in its original form till present epoch. Such intergalactic magnetic field is detectable with the tools of gamma-ray, radio and ultra-high-energy cosmic ray astronomies. Complementary information on the mechanisms of generation of primordial magnetic fields in the Early Universe is accessible to gravitational wave detectors like LISA and EPTA. Finally, the primordial magnetic fields leave their imprint on the recombination process that is detectable with Cosmic Microwave Background probes. In particular, next generation gamma-ray and radio observatories CTA and SKA will have a possibility to explore previously inaccessible range of strengths and correlation lengths of intergalactic magnetic fields [56, 57].

III. GRAVITATION AND COSMOLOGY

(APC, IJCLab, IP2I, IPHC, L2IT, LAAP, LPNHE, LPSC, LUPM)

Theoretical developments in cosmology and gravitation within IN2P3 groups can be either very formal, model-building oriented, or phenomenological in spirit with significant connections with past, current, or future observational probes. Beside precision cosmology (CMB, LSS, supernovae, etc.), the gravitational wave window also appears as a promising probe of either early or late universe processes or dynamics. The high-frequency domain is particularly suited to probe modified gravity in the strong regime or exotic compact objects, while low frequencies may probe phase transitions, or primordial black hole production or evaporation in the early universe. The main topics studied in IN2P3 teams concern the dark components of the universe, gravity as a whole, and all processes (standard or exotic) that may take place in the early universe (inflation, phase transitions, magnetic fields, exotic particles or processes, etc.). The scientific coverage is impressive in spite of the moderate number of involved scientists.

A. Gravitation: GR, modified gravity, quantum gravity

(APC, IJCLab, LPSC)

Although General Relativity (GR) has received much interest from various groups over the last few decades, it seems that IN2P3 now focus more on beyond-GR theories.

1. Modified gravity

Although GR is compatible with all observations collected so far, in particular in the solar system, there are several motivations to go beyond GR. First, there are dark components in the universe that could be interpreted in terms of manifestations of modified gravity. A popular use of modified gravity arises in the quest for the origin of dark energy [58], and it may also be involved in the apparent dark matter. Second, singularities inherent to GR can be considered as theoretical pathologies, as well as our inability to formulate a quantum version of GR. Both might be cured with extensions of GR. Finally, building self-consistent extensions to GR can also be viewed as defining a sound theoretical framework to test GR itself.

Model building in modified gravity must meet three requirements: (i) the new theory must be internally consistent (e.g. no problematic instabilities), (ii) the theory must look like GR in all regimes where GR has been tested (laboratory tests, Solar system, Binary pulsars – and now binary black hole systems, etc.), which can be achieved via screening mechanisms, (iii) Hopefully (but not necessarily), the theory should account for the observed acceleration or exhibit some distinctive signatures, such as different waveforms for the gravitational waves emitted by binary mergers (this is approached via the calculation of black-hole quasi normal modes in modified gravity), speed of gravitational waves different from c (now constrained by GW170817, although the constraint only applies to wavelengths $\sim 10^3$ km [59]), evolution of cosmological perturbations different from Lambda-CDM predictions, etc.

Most models are based on scalar-tensor theories, and there has been a huge effort in the recent years to classify modified gravity models. In particular, IN2P3 groups have strongly influenced the field by their systematic analyses of degenerate higher-order scalar-tensor (DHOST) theories [60, 61].

Particular attention is given to cosmological consequences [62]. The strong gravity regime, and the study of compact objects or the impact of modified gravity on the properties of stars, are among the important tools to test gravity beyond GR [63, 64].

2. Quantum gravity

The possible limitations of GR mentioned above may also be related to the lack of a quantum formulation of the theory. In quantum field theory on curved background, other issues may be pointing towards the same direction, such as the difficulty to control massless quantum theories in de Sitter space, for which it is not known whether this is due to the instabilities of the de Sitter space or to physics becoming non-perturbative.

Microphysical theories like string theory have received much consideration over the past few decades [65]. It provides a perturbative (and semiclassical) theory of quantum gravity.

Other approaches like holography give alternative hints on the (universal) nature of gravity, emerging from a class of quantum field theories, as an effective low-energy interaction. A study of its model-independent properties indicates that it has some important differences in the IR from standard gravity, that may be crucial in solving the cosmological constant problem and may have also implications, both for particle physics beyond the Standard Model and for inflation and dark matter [66].

Finally, one can also mention activity on loop quantum gravity approaches to cosmology or to singularity problems, that are being explored at IN2P3 also trying to discuss observation perspectives [67].

B. Dark matter in cosmology, primordial black holes

(APC, LPNHE, IP2I, LUPM)

Cosmological aspects of dark matter, beside production mechanisms (discussed earlier), may include structure formation. There is some interest to understand from theoretical grounds how robust results from cosmological N-body simulations are [68, 69]. There is also interest in modeling the cold dark matter subhalos down to the mass cutoff induced by free streaming in the early universe, as these subhalos could have consequences on dark matter searches [51]. Indeed, theoretical understanding of dark matter on small scales is important to further establish whether cold dark matter can be discarded from the so-called small-scale problems (mostly the cusp-core and diversity problems). The properties of dark matter subhalos are also closely related to the properties of the primordial power spectrum of fluctuations generated by inflation, and might give access to scales that cannot be probed by CMB nor Ly-α. Other probes of dark matter-related processes are the BBN, the CMB, and large-scale structures [70].

Also related to the primordial power spectrum, come the primordial black holes (PBHs), which are created from very large and rare density fluctuations entering the horizon in the early universe. These objects provide constraints on both the epoch during which large fluctuations were seeded (most often during inflation, although at a time that cannot be probed in the CMB, thus providing valuable information about parts of the inflationary sector that can hardly be constrained otherwise), and on the epoch at which they re-enter the Hubble radius, i.e. the epoch at which they form. The time of formation depends on the mass: primordial black holes with masses of order 10^5g would form immediately after inflation, those with masses 10^9g would form during reheating and evaporate at BBN, those with masses 10^{15}g would evaporate today, those with masses of the order of the solar mass (and which might thus be seen in LIGO/VIRGO detections) would form around the QCD phase transition, while those with masses 10^5 solar masses (and might thus provide seeds for supermassive black holes) would form just before BBN. This illustrates that PBHs offer a wide window into various epochs in the early universe.

Primordial black holes have actually been revived as serious dark matter candidates after the first direct observations of gravitational waves by Ligo/Virgo, and may also account for the existence of supermassive black holes at the center of galactic nuclei, or seed the large-scale structure formation early on in the universe. The interest of IN2P3 scientists in PBHs is actually not new [71–73], but it has taken new perspectives. Even though many constraints exist on the PBH dark matter scenario, PBHs might be the first dark matter candidate discovered so far (the mass window is constrained, in particular by microlensing and CMB, but the PBH mass function can be highly non-trivial and spread over several decades). Moreover, the predicted merging rate seems to be fully consistent with Ligo/Virgo measurements owing to the Poissonian clustering of PBHs in the early universe, that injects angular momentum on early binary systems of PBHs and make them longer-lived [74].

Several aspects are being covered by IN2P3 groups. It is usually considered that PBHs arise from large density fluctuations produced during inflation. Inflationary setups in which this occurs are such that these fluctuations backreact on the space-time dynamics (owing to their large amplitude), and since density fluctuations have a quantum mechanical origin during inflation, one has to deal with a quantum backreaction problem. Stochastic techniques are being developed to tackle this problem [75, 76]. They have proven the standard, perturbative techniques to vastly underestimate the abundance of primordial black holes, due to the presence of heavy tails in the distribution function of overdensities [77, 78]. Implications for various inflationary models are currently investigated [79].

Primordial black holes may also result from instabilities during preheating [80], phase transitions, or from the collapse of topological defects. They are predicted to evaporate in a timescale inversely proportional to their mass, making PBHs lightest than 10^{15} g fully evaporated today. However, this evaporation, if still ongoing, could lead to observational features. A code predicting the evaporation products has recently been released, BlackHawk [81]. PBHs could have stellar masses, and then distinguishing them from neutron stars is an issue [82]. Moreover, even those very light PBHs which have evaporated could have left traces that could be observed though low-frequency gravitational waves [83]. Finally, in a composite scenario of dark matter in which PBHs would co-exist with dark matter particles, the later would form extremely dense minihalos around PBHs, with strong consequences on constraints, in particular for annihilating dark matter particles [84].

C. Primordial universe

(APC, IJCLab, IP2I, LUPM)

The leading paradigm to describe the physics of the early universe is inflation, although alternatives exist and are also studied [85]. Inflation is a high-energy phase of accelerated expansion that was first introduced 40 years ago as a possible solution to the hot Big Bang model problems. During inflation, vacuum quantum fluctuations are stretched to astrophysical scales and parametrically amplified. This gives rise to primordial cosmological perturbations, leading to CMB fluctuations and large-scale structures in the universe. Inflation predicts that these perturbations should be almost Gaussian, close to scale invariance and phase coherent, predictions that have been remarkably well confirmed. Further, their detailed statistics allow one to constrain the microphysics of inflation and its dynamics. Inflation has thus become a very active field of research, since the energy scales involved during this early epoch are many orders of magnitude larger than those accessible in particle physics experiments.

Some IN2P3 groups have strong expertise in fundamental aspects of inflation, in particular using tools from quantum field theory [86] and the renormalization group equations [87, 88].

Inflation can proceed at energy scales as high as 10^{16} GeV, where particle physics remains elusive. This is why our ability to see through the inflationary window turns the early universe into a laboratory for ultra-high energy physics at energies entirely inaccessible to conventional experimentation. Various implementations of inflation have been proposed, embedded in different extensions of the standard model of particle physics. Even if one restricts to single-field models, which are the simplest scenarios compatible with observations, there are already hundreds of possibilities. When embedded in high-energy frameworks, single-field models further come with additional degrees of freedom, giving rise to possible multiple-field effects (entropic fluctuations, non Gaussianities, *etc.*). Given the vast landscape of inflationary models, Bayesian innovative methods have been developed to identify those models preferred by the data [89], and help identify the most pressing challenges for the inflationary paradigm [90]. Those tools are also used to prepare future CMB missions such as LiteBIRD, aiming at observing B-mode polarisation of the CMB anisotropies or, equivalently, primordial gravitational waves.

At a more fundamental level, quantum gravity effects may be accessible through inflation. Inflation can indeed occur at energies only three orders of magnitude below the Planck scale, so it is, in some sense, the closest mechanism to the scale of Quantum Gravity we can observe. Moreover, the inflationary mechanism for the production of cosmological perturbations explicitly makes use of General Relativity and Quantum Mechanics, two theories that are notoriously difficult to combine. Since this mechanism leads to theoretical predictions for the CMB anisotropies, inflation is one of the only case in Physics where, given our present-day technological capabilities, an effect based on GR and Quantum Mechanics can be tested experimentally. This makes inflation an ideal playground to discuss fundamental questions related to the interplay between these two theories. For example, it is still not clear whether a genuinely quantum signal can be seen in the CMB, and there is an ongoing effort to identify possible methods to prove or disprove the quantum origin of cosmic structures [91, 92], adapting and generalising recent developments in Quantum Information Theory. In this context, the role of quantum decoherence is also studied [93, 94]. This also implies that inflation may be used to test Quantum Mechanics itself, and alternatives to the standard formulation, such as dynamical collapse models of the wavefunction, are being applied to the generation of cosmological inhomogeneities during inflation to further understand their implications for cosmology [95].

Let us also mention ongoing activities in primordial nucleosynthesis (BBN) [96, 97], primordial magnetic fields [98, 99] (also those potentially induced during inflation [100]), and topological defects [101]. Low-frequency gravitational waves are promising probes of some related phenomena in the primordial universe [102, 103].

D. Cosmological tensions

(LUPM)

Several tensions have emerged in the last decade as for the measurements of cosmological parameters through different probes, which triggered interest in the theoretical community. The most discussed are currently the H_0 tension, a tension in the determination of the present Hubble expansion rate based on distant (CMB) vs. local probes (supernovae), and the σ_8 tension (amplitude of the power spectrum of density fluctuations on large scales, discrepant between CMB and large scale structure measurements). Ongoing effort is carried out to interpret the H_0 tension in terms of early dark energy [104, 105]. It has also been noted that primordial magnetic fields could also be at the origin, at least partly, of this tension [106]. On the other hand, the σ_8 tension could be solved by decaying dark matter [107].

[1] P. Varnière, F. Casse, and F. H. Vincent, in *SF2A-2018: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics*, edited by P. Di Matteo, F. Billebaud, F. Herpin, N. Lagarde, J. B. Marquette, A. Robin, and O. Venot (2018) p. Di.

[2] F. Casse and P. Varnière, MNRAS **481**, 2736 (2018), arXiv:1809.02080 [astro-ph.HE].

[3] C. Demidem, M. Lemoine, and F. Casse, MNRAS **475**, 2713 (2018), arXiv:1710.08127 [astro-ph.HE].

[4] A. J. van Marle, F. Casse, and A. Marcowith, MNRAS **490**, 1156 (2019), arXiv:1909.06931 [astro-ph.HE].

[5] Y. Dubois, B. Commerçon, A. Marcowith, and L. Brahimi, A&A **631**, A121 (2019), arXiv:1907.04300 [astro-ph.GA].

[6] A. Marcowith, A. Bret, A. Bykov, M. E. Dieckman, L. O'C Drury, B. Lembège, M. Lemoine, G. Morlino, G. Murphy, G. Pelletier, I. Plotnikov, B. Reville, M. Riquelme, L. Sironi, and A. Stockem Novo, Reports on Progress in Physics **79**, 046901 (2016), arXiv:1604.00318 [astro-ph.HE].

[7] A. M. Bykov, D. C. Ellison, A. Marcowith, and S. M. Osipov, Space Sci. Rev. **214**, 41 (2018), arXiv:1801.08890 [astro-ph.HE].

[8] T. Vieu, S. Gabici, and V. Tatischeff, MNRAS **494**, 3166 (2020), arXiv:2003.03411 [astro-ph.HE].

[9] A. T. Araudo, M. Padovani, and A. Marcowith, MNRAS **504**, 2405 (2021), arXiv:2102.11583 [astro-ph.HE].

[10] L. Nava, S. Gabici, A. Marcowith, G. Morlino, and V. S. Ptuskin, MNRAS **461**, 3552 (2016), arXiv:1606.06902 [astro-ph.HE].

[11] L. Nava, S. Recchia, S. Gabici, A. Marcowith, L. Brahimi, and V. Ptuskin, MNRAS **484**, 2684 (2019), arXiv:1903.03193 [astro-ph.HE].

[12] L. Brahimi, A. Marcowith, and V. S. Ptuskin, A&A **633**, A72 (2020), arXiv:1909.04530 [astro-ph.HE].

[13] K. J. Andersen, M. Kachelriess, and D. V. Semikoz, ApJ **861**, L19 (2018), arXiv:1712.03153 [astro-ph.HE].

[14] V. H. M. Phan, G. Morlino, and S. Gabici, MNRAS **480**, 5167 (2018), arXiv:1804.10106 [astro-ph.HE].

[15] S. Recchia, S. Gabici, F. A. Aharonian, and J. Vink, Phys. Rev. D **99**, 103022 (2019), arXiv:1811.07551 [astro-ph.HE].

[16] S. Recchia, M. Di Mauro, F. A. Aharonian, F. Donato, S. Gabici, and S. Manconi, arXiv e-prints , arXiv:2106.02275 (2021), arXiv:2106.02275 [astro-ph.HE].

[17] D. Maurin, Computer Physics Communications **247**, 106942 (2020), arXiv:1807.02968 [astro-ph.IM].

[18] Y. Génolini, P. D. Serpico, M. Boudaud, S. Caroff, V. Poulin, L. Derome, J. Lavalle, D. Maurin, V. Poireau, S. Rosier, P. Salati, and M. Vecchi, Phys. Rev. Lett. **119**, 241101 (2017).

[19] Y. Génolini, M. Boudaud, P. I. Batista, S. Caroff, L. Derome, J. Lavalle, A. Marcowith, D. Maurin, V. Poireau, V. Poulin, S. Rosier, P. Salati, P. D. Serpico, and M. Vecchi, Phys. Rev. D **99**, 123028 (2019), arXiv:1904.08917 [astro-ph.HE].

[20] G. Giacinti, M. KachelrieSS, and D. V. Semikoz, J. Cosmology Astropart. Phys. **2018**, 051 (2018), arXiv:1710.08205 [astro-ph.HE].

[21] M. Kachelrieß and D. V. Semikoz, Progress in Particle and Nuclear Physics **109**, 103710 (2019), arXiv:1904.08160 [astro-ph.HE].

[22] A. Neronov and D. Semikoz, Soviet Journal of Experimental and Theoretical Physics **131**, 265 (2020), arXiv:1811.06356 [astro-ph.HE].

[23] A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric, and M. Lucente, Journal of High Energy Physics **2019**, 164 (2019), arXiv:1810.12463 [hep-ph].

[24] C. Volpe, arXiv e-prints , arXiv:1609.06747 (2016), arXiv:1609.06747 [astro-ph.HE].

[25] A. Chatelain and C. Volpe, Phys. Rev. D **95**, 043005 (2017), arXiv:1611.01862 [hep-ph].

[26] A. Chatelain and M. C. Volpe, Phys. Rev. D **97**, 023014 (2018), arXiv:1710.11518 [hep-ph].

[27] A. Chatelain and M. C. Volpe, Physics Letters B **801**, 135150 (2020), arXiv:1906.12152 [hep-ph].

[28] S. Abbar, H. Duan, K. Sumiyoshi, T. Takiwaki, and M. C. Volpe, Phys. Rev. D **101**, 043016 (2020), arXiv:1911.01983 [astro-ph.HE].

[29] S. Abbar, H. Duan, K. Sumiyoshi, T. Takiwaki, and M. C. Volpe, Phys. Rev. D **100**, 043004 (2019), arXiv:1812.06883 [astro-ph.HE].

[30] A. Gallo Rosso, F. Vissani, and M. C. Volpe, J. Cosmology Astropart. Phys. **2017**, 036 (2017), arXiv:1708.00760 [hep-ph].

[31] A. Gallo Rosso, F. Vissani, and M. C. Volpe, J. Cosmology Astropart. Phys. **2018**, 040 (2018), arXiv:1712.05584 [hep-ph].

[32] A. Gallo Rosso, S. Abbar, F. Vissani, and M. C. Volpe, J. Cosmology Astropart. Phys. **2018**, 006 (2018), arXiv:1809.09074 [hep-ph].

[33] J. Froustey, C. Pitrou, and M. C. Volpe, J. Cosmology Astropart. Phys. **2020**, 015 (2020), arXiv:2008.01074 [hep-ph].

[34] A. Arbey, M. Battaglia, L. Covi, J. Hasenkamp, and F. Mahmoudi, Phys. Rev. D **92**, 115008 (2015), arXiv:1505.04595 [hep-ph].

[35] U. Ellwanger and C. Hugonie, European Physical Journal C **78**, 735 (2018), arXiv:1806.09478 [hep-ph].

[36] G. Arcadi, M. Dutra, P. Ghosh, M. Lindner, Y. Mambrini, M. Pierre, S. Profumo, and F. S. Queiroz, European Physical Journal C **78**, 203 (2018), arXiv:1703.07364 [hep-ph].

[37] M. A. G. Garcia, Y. Mambrini, K. A. Olive, and S. Verner, Phys. Rev. D **102**, 083533 (2020), arXiv:2006.03325 [hep-ph].

[38] H. Cai and G. Cacciapaglia, Phys. Rev. D **103**, 055002 (2021), arXiv:2007.04338 [hep-ph].

[39] G. Cacciapaglia, T. Ma, S. Vatani, and Y. Wu, European Physical Journal C **80**, 1088 (2020).

[40] G. Cacciapaglia, H. Cai, A. Deandrea, and A. Kushwaha, Journal of High Energy Physics **2019**, 35 (2019), arXiv:1904.09301 [hep-ph].

[41] L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, Journal of High Energy Physics **2010**, 80 (2010), arXiv:0911.1120 [hep-ph].

[42] A. Goudelis, K. A. Mohan, and D. Sengupta, Journal of High Energy Physics **2018**, 14 (2018), arXiv:1807.06642 [hep-ph].

[43] G. Bélanger, N. Desai, A. Goudelis, J. Harz, A. Lessa, J. M. No, A. Pukhov, S. Sekmen, D. Sengupta, B. Zal-

divar, and J. Zurita, Journal of High Energy Physics **2019**, 186 (2019), arXiv:1811.05478 [hep-ph].

[44] Y. Mambrini and K. A. Olive, arXiv e-prints , arXiv:2102.06214 (2021), arXiv:2102.06214 [hep-ph].

[45] G. Moultaka, M. Rausch de Traubenberg, and D. Tant, International Journal of Modern Physics A **34**, 1950004 (2019), 1611.10327 [hep-th].

[46] S. Davidson and T. Schwetz, Phys. Rev. D **93**, 123509 (2016), arXiv:1603.04249 [astro-ph.CO].

[47] A. Auriol, S. Davidson, and G. Raffelt, Phys. Rev. D **99**, 023013 (2019), arXiv:1808.09456 [hep-ph].

[48] A. Abada, G. Arcadi, V. Domcke, and M. Lucente, J. Cosmology Astropart. Phys. **2017**, 024 (2017), arXiv:1709.00415 [hep-ph].

[49] T. Lacroix, M. Stref, and J. Lavalle, J. Cosmology Astropart. Phys. **2018**, 040 (2018), arXiv:1805.02403 [astro-ph.GA].

[50] T. Lacroix, A. Núñez-Castiñeyra, M. Stref, J. Lavalle, and E. Nezri, J. Cosmology Astropart. Phys. **2020**, 031 (2020), arXiv:2005.03955 [astro-ph.GA].

[51] M. Stref and J. Lavalle, Phys. Rev. D **95**, 063003 (2017), arXiv:1610.02233 [astro-ph.CO].

[52] M. Hütten, C. Combet, and D. Maurin, Computer Physics Communications **235**, 336 (2019), arXiv:1806.08639 [astro-ph.CO].

[53] B. Eiteneuer, A. Goudelis, and J. Heisig, European Physical Journal C **77**, 624 (2017), arXiv:1705.01458 [hep-ph].

[54] M. Boudaud, Y. Génolini, L. Derome, J. Lavalle, D. Maurin, P. Salati, and P. D. Serpico, Physical Review Research **2**, 023022 (2020).

[55] M. Boudaud, J. Lavalle, and P. Salati, Phys. Rev. Lett. **119**, 021103 (2017), arXiv:1612.07698 [astro-ph.HE].

[56] A. Neronov and I. Vovk, Science **328**, 73 (2010), arXiv:1006.3504 [astro-ph.HE].

[57] R. Durrer and A. Neronov, A&A Rev. **21**, 62 (2013), arXiv:1303.7121 [astro-ph.CO].

[58] D. Langlois, International Journal of Modern Physics D **28**, 1942006-3287 (2019), arXiv:1811.06271 [gr-qc].

[59] D. Langlois, R. Saito, D. Yamauchi, and K. Noui, Phys. Rev. D **97**, 061501 (2018), arXiv:1711.07403 [gr-qc].

[60] D. Langlois and K. Noui, J. Cosmology Astropart. Phys. **2016**, 034 (2016), arXiv:1510.06930 [gr-qc].

[61] D. Langlois, K. Noui, and H. Roussille, Phys. Rev. D **103**, 084022 (2021).

[62] M. Crisostomi, K. Koyama, D. Langlois, K. Noui, and D. A. Steer, J. Cosmology Astropart. Phys. **2019**, 030 (2019), arXiv:1810.12070 [hep-th].

[63] E. Babichev, K. Koyama, D. Langlois, R. Saito, and J. Sakstein, Classical and Quantum Gravity **33**, 235014 (2016), arXiv:1606.06627 [gr-qc].

[64] E. Babichev, C. Charmousis, G. Esposito-Farèse, and A. Lehébel, Phys. Rev. Lett. **120**, 241101 (2018), arXiv:1712.04398 [gr-qc].

[65] E. Kiritsis, *String theory in a nutshell* (Princeton University Press, USA, 2019).

[66] P. Betzios, E. Kiritsis, and V. Niarchos, Journal of High Energy Physics **2021**, 202 (2021), arXiv:2010.04729 [hep-th].

[67] A. Barrau, Comptes Rendus Physique **18**, 189 (2017), arXiv:1705.01597 [gr-qc].

[68] L. H. Garrison, M. Joyce, and D. J. Eisenstein, MNRAS **504**, 3550 (2021), arXiv:2102.08972 [astro-ph.CO].

[69] F. Sylos Labini and M. Joyce, arXiv e-prints , arXiv:2106.02388 (2021), arXiv:2106.02388 [astro-ph.CO].

[70] V. Poulin, J. Lesgourgues, and P. D. Serpico, J. Cosmology Astropart. Phys. **2017**, 043 (2017), arXiv:1610.10051 [astro-ph.CO].

[71] K. Jedamzik, Phys. Rev. D **55**, R5871 (1997), arXiv:astro-ph/9605152 [astro-ph].

[72] J. C. Niemeyer and K. Jedamzik, Phys. Rev. Lett. **80**, 5481 (1998), arXiv:astro-ph/9709072 [astro-ph].

[73] K. Jedamzik and J. C. Niemeyer, Phys. Rev. D **59**, 124014 (1999), arXiv:astro-ph/9901293 [astro-ph].

[74] K. Jedamzik, Phys. Rev. Lett. **126**, 051302 (2021), arXiv:2007.03565 [astro-ph.CO].

[75] V. Vennin and A. A. Starobinsky, Eur. Phys. J. C **75**, 413 (2015), arXiv:1506.04732 [hep-th].

[76] K. Ando and V. Vennin, JCAP **04**, 057 (2021), arXiv:2012.02031 [astro-ph.CO].

[77] C. Pattison, V. Vennin, H. Assadullahi, and D. Wands, J. Cosmology Astropart. Phys. **2017**, 046 (2017), arXiv:1707.00537 [hep-th].

[78] J. M. Ezquiaga, J. García-Bellido, and V. Vennin, JCAP **03**, 029 (2020), arXiv:1912.05399 [astro-ph.CO].

[79] C. Pattison, V. Vennin, D. Wands, and H. Assadullahi, (2021), arXiv:2101.05741 [astro-ph.CO].

[80] P. Auclair and V. Vennin, J. Cosmology Astropart. Phys. **2021**, 038 (2021), arXiv:2011.05633 [astro-ph.CO].

[81] A. Arbey and J. Auffinger, European Physical Journal C **79**, 693 (2019), arXiv:1905.04268 [gr-qc].

[82] J. F. Coupechoux, A. Arbey, R. Chierici, H. Hansen, J. Margueron, and V. Sordini, arXiv e-prints , arXiv:2106.05805 (2021), arXiv:2106.05805 [gr-qc].

[83] T. Papanikolaou, V. Vennin, and D. Langlois, J. Cosmology Astropart. Phys. **2021**, 053 (2021), arXiv:2010.11573 [astro-ph.CO].

[84] M. Boudaud, T. Lacroix, M. Stref, J. Lavalle, and P. Salati, arXiv e-prints , arXiv:2106.07480 (2021), arXiv:2106.07480 [astro-ph.CO].

[85] J. Grain, A. Barrau, T. Cailleteau, and J. Mielczarek, Phys. Rev. D **82**, 123520 (2010), arXiv:1011.1811 [astro-ph.CO].

[86] G. Moreau and J. Serreau, Phys. Rev. D **101**, 045015 (2020), arXiv:1912.05358 [hep-th].

[87] P. Binétruy, E. Kiritsis, J. Mabillard, M. Pieroni, and C. Rosset, J. Cosmology Astropart. Phys. **2015**, 033 (2015), arXiv:1407.0820 [astro-ph.CO].

[88] G. Moreau and J. Serreau, Phys. Rev. D **99**, 025011 (2019), arXiv:1809.03969 [hep-th].

[89] J. Martin, C. Ringeval, and V. Vennin, Phys. Dark Univ. **5-6**, 75 (2014), arXiv:1303.3787 [astro-ph.CO].

[90] D. Chowdhury, J. Martin, C. Ringeval, and V. Vennin, Phys. Rev. D **100**, 083537 (2019), arXiv:1902.03951 [astro-ph.CO].

[91] J. Martin and V. Vennin, Phys. Rev. D **93**, 023505 (2016), arXiv:1510.04038 [astro-ph.CO].

[92] J. Martin and V. Vennin, Phys. Rev. D **96**, 063501 (2017), arXiv:1706.05001 [astro-ph.CO].

[93] A. Giraud and J. Serreau, Phys. Rev. Lett. **104**, 230405 (2010), arXiv:0910.2570 [hep-ph].

[94] J. Martin and V. Vennin, J. Cosmology Astropart. Phys. **2018**, 063 (2018), arXiv:1801.09949 [astro-ph.CO].

[95] J. Martin and V. Vennin, Phys. Rev. Lett. **124**, 080402 (2020), arXiv:1906.04405 [quant-ph].

[96] K. Jedamzik and M. Pospelov, New Journal of Physics **11**, 105028 (2009), arXiv:0906.2087 [hep-ph].

[97] A. Arbey, J. Auffinger, K. P. Hickerson, and E. S. Jenssen, Computer Physics Communications **248**, 106982 (2020).

[98] K. Jedamzik and A. Saveliev, Phys. Rev. Lett. **123**, 021301 (2019), arXiv:1804.06115 [astro-ph.CO].

[99] A. Neronov and D. Semikoz, arXiv e-prints , arXiv:2010.13571 (2020), arXiv:2010.13571 [hep-ph].

[100] C. Caprini, M. Chiara Guzzetti, and L. Sorbo, Classical and Quantum Gravity **35**, 124003 (2018), arXiv:1707.09750 [astro-ph.CO].

[101] P. Auclair, D. A. Steer, and T. Vachaspati, Phys. Rev. D **101**, 083511 (2020), arXiv:1911.12066 [hep-ph].

[102] C. Caprini and D. G. Figueroa, Classical and Quantum Gravity **35**, 163001 (2018), arXiv:1801.04268 [astro-ph.CO].

[103] A. Neronov, A. R. Pol, C. Caprini, and D. Semikoz, Phys. Rev. D **103**, L041302 (2021), arXiv:2009.14174 [astro-ph.CO].

[104] V. Poulin, T. L. Smith, T. Karwal, and M. Kamionkowski, Phys. Rev. Lett. **122**, 221301 (2019), arXiv:1811.04083 [astro-ph.CO].

[105] R. Murgia, G. F. Abellán, and V. Poulin, Phys. Rev. D **103**, 063502 (2021), arXiv:2009.10733 [astro-ph.CO].

[106] K. Jedamzik and L. Pogosian, Phys. Rev. Lett. **125**, 181302 (2020), arXiv:2004.09487 [astro-ph.CO].

[107] G. F. Abellan, R. Murgia, V. Poulin, and J. Lavalle, arXiv e-prints , arXiv:2008.09615 (2020), arXiv:2008.09615 [astro-ph.CO].

Appendix A: Groups in IN2P3 laboratories

Here we try to identify the scientists who work in APP or Cosmo/Gr ph/th ("inter" means in between or inside the two boxes). The list is very likely incomplete, and some colleagues might appear in wrong boxes. Some of the colleagues listed can be involved in experimental collaborations, but may contribute to phenomenological analyses or astrophysical modeling, either as plain ph/th experts or in tight collaboration with ph/th experts.

- APC (Paris):
  APP: Fabien Casse, Stefano Gabici, Andrii Neronov, Étienne Parizot, Dmitri Semikoz, Régis Terrier, Peguy Varnière
  Cosmo/Gr: Chiara Caprini, Nathalie Deruelle, Éric Huguet, Elias Kiritsis, David Langlois, Jihad Mourad, Francesco Nitti, Jacques Renaud, Julien Serreau, Danièle Steer, Vincent Vennin
  Inter: Cristina Volpe

- IJCLab (Orsay - theory groups joined IN2P3 in 2020):
  APP: Asmaa Abada, Ulrich Ellwanger, Yann Mambrini, Vincent Tatischeff
  Cosmo/Gr: Eugeny Babichev, Christos Charmousis, Karim Noui (from 09/2021), Bartjan Van Tent
- IP2I (Lyon):
  APP: Giacomo Cacciapaglia, Aldo Deandrea, Farvah Mahmoudi
  Cosmo/Gr: Hubert Hansen, Jérôme Margueron
  Inter: Alexandre Arbey

- IPHC (Strasbourg):
  APP/Cosmo: Michel Raush de Traubenberg

- L2IT (Toulouse):
  Cosmo/Gr: Nicola Tamanini

- LAPP (Annecy):
  Cosmo/Gr: Tania Regimbau

- LPC (Clermont-Ferrand): APP: Andreas Goudelis, Jean Orloff

- LPNHE (Paris):
  Cosmo: Michael Joyce

- LPSC (Grenoble):
  APP: Céline Combet, Jérémie Quevillon, David Maurin
  Cosmo/Gr: Aurélien Barrau, Killian Martineau

- LUPM (Montpellier):
  APP: Felix Brümmer, Sacha Davidson, Yves Gallant, Cyril Hugonie, Alexandre Marcowith
  Cosmo/Gr: Karsten Jedamzik, Julien Larena (from 09/2021)
  Inter: Julien Lavalle, Vivian Poulin