**REPORT OF FORMAL THEORY AT IN2P3**
**D. Tsimpis, June 2021**

## What is *Formal Theory* ?

Already from the outset, the term *Formal Theoretical Physics* presents us with a methodological problem. A search in the literature reveals that this term is in fact hardly ever used. As an attempt do define it, one could postulate that it refers to those research activities on mathematical (*formal*) aspects of physical theories, whose relevance for experiment or other applications is not necessarily immediate. There are however a few problems with such a definition: first of all there is almost never a clear-cut distinction between what constitutes or not a formal research activity, as in most cases both aspects are potentially present in the same work. Secondly, research that may be classified as formal, can very well have immediate repercussions for experiments or applications. Finally it is often the case that the same researcher is involved in both applied and formal work.

For the purposes of the Conseil Scientifique, and bearing in mind the aforementioned caveats, we will assume that *Formal Theoretical Physics* comprises those activities that cannot always be grouped together with the rest of the identified research categories of IN2P3 (particle phenomenology; hadronic & nuclear physics; astrophysics and cosmology; interdisciplinary research in chemistry & health).

## Geographical breakdown

We have identified a total of 32 theorists (of which 7 are emeriti) in the institutes of IN2P3 whose activities can be labelled as partly, or primarily « formal ». More specifically, there are 20 enseignant-chercheurs (11 professeurs, 6 maîtres de conférence, 3 emeriti) and 12 chercheurs CNRS (5 directeurs de recherche, 3 chargés de recherche, 4 emeriti). Their geographical breakdown is as follows (*cf*. the appendix for the list of staff members):

Laboratoire AstroParticule et Cosmologie (APC): 6 EC, 2 CNRS, 2 Em
Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJLab): 4 EC, 4 CNRS, 3 Em
Insitut de Physique des 2 Infinis de Lyon (IP2I): 3 EC, 1 Em
Institut Pluridisciplinaire Hubert Curien (IPHC): 2 EC
Laboratoire de Physique Subatomique et Cosmologie (LPSC): 1 EC, 1 CNRS
Laboratoire de Physique de Clermont (LPC): 1 CNRS
Laboratoire de Physique Subatomique et Technologies Associées (SUBATECH): 1 EC
Laboratoire Univers et Particules de Montpellier (LUPM): 1 Em

## General presentation

The scientific output in the field is regular and of high quality: using iNSPIRE-HEP as a main source, we have counted a total of at least 372 articles and proceedings, published in some of the most prestigious journals over the past five years. In addition, several textbooks have been published by various editors.

There is an active participation in the organization of numerous international conferences and schools (usually financed by European programs such as Horizon, COST, etc, various national programs, or the different Labex). We have also counted one Advanced ERC grant: SM-GRAV (gravity, holography, and Standard Model), and one Masterprojet IN2P3: SlowSUGRA in relation with Particle Phenomenology and Cosmology.

Perhaps the most striking aspect of the field is the extent of its international network. Without exception, each and every researcher working in formal theory has built numerous international collaborations, as well as collaborations with French laboratories outside IN2P3 (*cf*. the appendix for the detailed list). As a whole, the extent of this network is impressive, spreading over five continents (North and South America, Europe, Africa, Asia), including well over a hundred institutes and even more collaborators. In addition, the national network includes over a dozen universities and grandes écoles.

Another striking aspect of formal theory is the extent of its thematic diversity, often present within the research interests of a single researcher. As a whole formal theory at IN2P3 covers a very large spectrum of high-energy theoretical physics including gravity, quantum field theory, and statistical physics. The formal publications in the past few years span about two dozen arXiv categories, with hep-th and gr-qc being the most numerous.

There are very often close links and collaborations between formal researchers and researchers in more applied fields, notably particle phenomenology and hadronic physics with numerous publications in [hep-ph], astrophysics and cosmology with several publications in [astro-ph.CO], nuclear physics with publications in [nucl-th], but also [nucl-ex] as well as a recent publication in [q-bio.PE]. In addition the statistical physics group at IJCLab has long-standing close links (common projects, student supervisions, etc) with research in interdisciplinary subjects (health and biology).

Work in formal theory crucially involves the contribution of numerous PhD students and interns, and tends to attract the most academically accomplished among them. The exact calculation of the number of PhD students and interns involved has proven somewhat difficult to perform. Our estimate for the last few years is that there is, in any given academic year, about one PhD student per formal theorist on average, while the number of interns supervised is comparable or higher. The presence of postdocs is much more of an exception than a rule, financed by external funds (ERC, Labex, foreign institutions).

### Thematic breakdown

The breakdown of the formal research activities into different subcategories is not an easy problem to solve. We have opted for a classification according to three main categories: Gravity, Quantum Field Theory (QFT), and Statistical Physics. Each of these is further divided into several sub-categories which will be listed below. It is nevertheless important to bear in mind that this breakdown is necessarily artificial as the boundaries between different categories are almost never clear-cut. Often common methods are used to treat problems that belong to different categories (to give a recent example: the use of renormalization theory is of course used in QFT, but has also been used to study the spread of infectious diseases), at other times different methods are used to treat the same problem (for example the properties of black holes or cosmology in the context of string theory, loop quantum gravity, modified gravity, etc).

**Note:** in the following descriptions of the various research subjects we have freely used texts provided by our colleagues, from scientific publications available on the internet, or from the webpages of their institutions.

## GRAVITY

The gravitational force is famously the most mysterious of all forces in the universe. Most researchers share the conviction that the world is quantum, and thus gravity also ought to be quantized (although some have questioned this conclusion), however an attempt at quantizing Einstein's theory of gravity, using standard QFT methods, fails as the theory turns out to be non-renormalizable. Several alternative approaches to this problem have been developed over the years, including string theory, loop quantum gravity, group field theory, tensor field theory. Other approaches such as asymptotic safety, causal sets, causal dynamical triangulations, are not practiced within IN2P3, while non-commutative geometry, which also offers an alternative path to quantum gravity, will be examined below in the QFT section.

### String theory [Hohenegger, Kiritsis, Mourad, Nitti, Tsimpis]

String theory is a candidate "theory-of-everything". It features many unique and appealing properties. Replacing point particles by one-dimensional quantum objects leads to a completely new paradigm that has been built over the past five decades. Among many others, an important consequence of this fundamental shift is the natural appearance of a massless spin-2 particle, the graviton. In a sense, (quantum) gravity is therefore an unavoidable prediction of string theory. The long history of string theory went through several revolutions, from the discovery of superstrings – and the understanding that the theory might be capable of describing all elementary particles as well as all the interactions between them – to the unification of different versions of the model into the M-theory framework. The ideas of string theory have far reaching consequences in mathematical physics, particle physics, cosmology, black hole physics, condensed matter physics, nuclear physics. String theory, in the broad sense, is a rich and intricate framework made of many interconnected subfields.

The gauge/gravity duality, or *holographic correspondence*, is one of the deepest insights that have arisen from string theory, and has provided a new way of looking at QFT. It is a conjecture stating the equivalence between a QFT without gravity, and a gravitational theory (or string theory) that lives in a higher-dimensional, curved spacetime. The holographic correspondence provides a new link between QFT and geometry, and therefore lies at the interface between QFT, string theory and general relativity. At the same time, the holographic duality provides a valuable calculational tool: when the field theory side of the correspondence is strongly coupled and has a large number of degrees of freedom, the gravity side becomes classical and can be described with standard General Relativity. There is a large amount of ongoing research focused on applying the correspondence to strongly coupled field theories such as QCD, and applications have been suggested in the context of strongly interacting condensed-matter systems such as high-temperature superconductors and strongly correlated quantum Fermi systems. The gauge/gravity duality has also revealed an intriguing relation between the gravitational Einstein equations and the non-linear equations of fluid dynamics. In this context, dissipation in hydrodynamic systems have been related to the physics and geometry of black hole horizons.

According to string theory the effective description of our four-dimensional spacetime, and therefore the physical properties of our observable world, is encoded in the geometry of extra dimensions, whose existence is a prediction of the theory. The geometry of the internal space is therefore of paramount importance, as it has far-reaching qualitative and quantitative repercussions for every physical aspect of the theory. However, this internal geometry is far from being uniquely determined by the theory, and different possibilities arise. In the past years there has been enormous progress in our understanding of the internal geometry, the different classes of allowed internal spaces and their general properties.

The study of supersymmetry-breaking mechanisms in string theory is inevitable if one wishes to construct physical models with realistic phenomenology. Among the tachyon-free ten-dimensional string theory models there is a unique class in which supersymmetry is either broken or is non-linearly realized. They are related to *brane supersymmetry breaking* a peculiar phenomenon that can occur in perturbative so-called orientifold vacua. The study of this class of models is not only of theoretical importance but also interesting for its potential applications to cosmology and particle physics.

The effective action of string (and its larger unifying framework usually referred to as M-theory) admits an infinite tower of higher-order derivative corrections, playing a crucial role in areas such as black holes, cosmology and the AdS/CFT duality. Superspace methods can be employed to determine the form of these M-theory corrections. The tools thereby developed have been used in order to determine the quartic fermion terms of IIA supergravity and their impact on cosmological models. A systematic investigation of the string effective action beyond lowest order, has also been performed using independent scattering amplitude techniques.

Little string theories are a class of interacting, non-local, ultraviolet-complete quantum theories in six dimensions (or lower). Often such theories lack a Lagrangian description and are therefore notoriously difficult to describe with purely field theoretic methods alone. However, their connection to string theory provides us with many new approaches and tools which allow to analyze non-perturbative aspects of these theories. In a series of works, it was shown that various incarnations of string U-duality lead to remarkable dualities and symmetries among these gauge theories, which are intrinsically non-perturbative in nature. These symmetries allow us a better understanding of the gauge theories, as well as the construction of new theories.

Compactifying string theory to lower dimensions reveals the presence of exceptional symmetries, which cannot be explained by Riemannian geometry of the internal manifold alone (or any other conventional symmetries). They are remnants of the so-called U-duality which is a nonperturbative symmetry of string (or M-) theory, hinting at more complex structures at higher energy scales. Since these exceptional symmetries are difficult to explain within the framework of standard field theories, it has been attempted to extend the higher dimensional versions of the latter in such a way as to make the appearance of the exceptional symmetries manifest upon compactification. The resulting theories are called exceptional field theories. The basic idea behind these constructions is an extended space-time, which allows for a geometric realization of the U-duality group.

**Loop quantum gravity and tensor group field theory** [Barrau, Martineau, Rivasseau]

Tensor group field theory (TGFT) is a background-independent formalism for quantum gravity. Using the powerful quantum field theory language, it offers both a tentative definition of the fundamental degrees of freedom of quantum spacetime and a precise encoding of their quantum dynamics. It combines the results of tensor models about the combinatorics of random discrete spaces and the insights of loop quantum gravity about quantum geometry. Specifically, TGFTs are QFTs on Lie groups, characterized by a peculiar non-local pairing of field arguments in their interactions, whose immediate consequence is that their Feynman diagrams are dual to cellular complexes rather than simple graphs. The quantum dynamics is thus defined, in perturbation theory, by a sum over such cellular complexes (interpreted as discrete spacetimes) weighted by model-dependent amplitudes, in turn functions of group-theoretic data.

Historically, group field theories (GFTs) grew out of tensor models of 3d and 4d gravity, themselves a generalization of the matrix model definition of 2d Riemannian quantum gravity. In tensor models, the dynamics of a quantum spacetime is given by a sum over equilateral d-dimensional triangulations, generated as the Feynman expansion of the partition function for a finite rank-d tensor, and weighted by (the equilateral restriction of) the Regge action for simplicial gravity. They are thus prototypical models of purely combinatorial random geometries. Soon it was realized that these group-theoretic data gave the boundary states of the same models the structure of loop quantum gravity states. Later GFTs were shown to provide a complete definition of the dynamics of the same quantum states as their Feynman amplitudes are given by spin foam models, a covariant definition of the dynamics of Loop Quantum gravity (LQG) spin networks, in turn dual to simplicial gravity path integrals. Currently they are understood as a second quantized formulation of LQG.

Loop Quantum gravity is a background free, nonperturbative Hamiltonian quantization of gravity whose starting point is the 3+1 foliation of the GR first order tetradic formulation. It is a modern canonical quantization that takes advantage of a new set of phase space variables – the Ashtekar variables – in order to cast the classical theory in a form close to the one of a local SU(2) gauge theory. The observable consequences of LQG in cosmology, when the full theory structure is taken into account, have been studied. This was done using a suitable gauge fixed version of the theory called quantum reduced loop gravity (QRLG). The study of QRLG was extended to address inflation and discuss features of the power spectrum for cosmological perturbations. It was shown that the number of inflationary e-folds is almost always higher than the observational lower bound.

**General Relativity and modified theories of gravity** [Babichev, Barrau, Charmoussis, Deruelle, Kiritsis, Langlois, Mourad, Steer, Zegers]

The study of possible infrared (long-distance) deformations of general relativity is of major theoretical and phenomenological importance. A number of questions can be put forward: is it possible to modify General Relativity in a mathematically consistent way (free of ghosts or other pathologies), and if so, can these theories be experimentally viable, i.e. consistent with GR at intermediate scales (ranging from about 1mm to solar system distances)? May they provide an alternative, and hopefully more natural, explanation for the observed late time acceleration of the universe today?

In recent years, there has been a lot of research on several theories of modified gravity. These include the so-called f(R) theories, Horndeski/Galileon theories, scalar-tensor theories, and massive gravity. The dynamics and problems of massive gravity have also been investigated using the holographic link to QFT. This same link makes massive gravity a model for studying momentum dissipation in finite density strongly coupled systems with potential applications to condensed matter physics. Various applications have been studied to cosmology, inflation, (p)reheating, CMB, LSS, dark energy, black hole physics, neutron stars, gravitational waves.

Solution generating methods in modified theories of gravity have been developed that led, for the first time, to regular black holes, i.e. black holes with no central singularity. Analytic exact rotating black hole solutions distinctively different from the Kerr solution have been constructed and their observational astrophysical constraints analyzed.

Various models of inflation have been examined, in particular those involving several scalar fields, and their detailed signatures (which are potentially detectable in present or future data) have been studied. Important specific signatures include non-Gaussianities and isocurvature perturbations. Moreover, the process of cosmological inflation is technically similar to approximate conformal invariance and scaling in Quantum Field Theory. This analogy is made precise by the gauge/gravity duality and points to a completely different view of the standard problems of inflation.

On a superficial level there are similarities between general relativity and hydrodynamics as they both rest on non linear partial differential equations depending on space and time. Interestingly, under some specific circumstances, this mere analogy is replaced by a precise correspondence. Attempts to model various phenomena of general relativity (such as black holes or cosmological geometries) using hydrodynamics or other physical systems, are known as analog models of gravity. This approach creates opportunities for practical experiments within the analog that might then be applied back to the original gravitational phenomena.

## QUANTUM FIELD THEORY

Quantum field theory (QFT) is a magnificent theory in its predictive power. QFT is the framework of the Standard Model which has provided us with some of the most stupendously accurate predictions to have ever been empirically tested. Nevertheless several theoretical issues remain unresolved: as is well-known the perturbative expansion is generally divergent, while a rigorous non-perturbative definition of QFT remains problematic. This is a matter of both great theoretical and practical importance, as many interesting phenomena occur in regimes where perturbation is not valid. Other open directions concern the choice of different renormalization schemes; the development of non-perturbative tools; the classical-quantum transition and the choice of quantization procedure. Defining QFT on a classical curved geometrical space is a way to take into account the effects of gravity, without having to quantize the latter: this is the subject of QFT on curved spacetimes. A lot of research has also been devoted to the important extension of QFT on non-commutative spacetimes. Finally, the gauge/gravity duality (examined in the string theory section) provides us with a novel non-perturbative tool of addressing different field theory phenomena, with applications to QCD, renormalization, condensed matter systems, non-equilibrium physics.

**QFT on curved spacetimes** [Gazeau, Huguet, Kiritsis, Nitti, Renaud, Serreau]

The study of quantum effects in strong gravitational backgrounds is a subject of topical interest in cosmology and astrophysics. Notable examples include the gravitational amplification of primordial density perturbations in inflationary cosmology or the Unruh-Hawking radiation from black holes which are cornerstones of modern cosmology and of the fundamental understanding of black hole physics. More generally, understanding situations where both quantum and gravitational effects come into play sheds a new light onto the laws of physics and may give insight concerning more fundamental laws.

The study of interacting fields in de Sitter space is of notorious difficulty. The case of light fields in units of the inverse curvature, for which gravitational effects play a crucial role, is of particular interest, both theoretically and phenomenologically (e.g. for inflation). In that case, perturbative techniques are plagued by divergent contributions coming from low (physical) momenta or, equivalently, due to the gravitational redshift, late times. Such infrared/secular divergence signal important physical effects and must be resummed in order to get reliable answers. Resummation methods in de Sitter space and their application to questions of physical interest, e.g. in the context of inflationary physics, have been developed. Examples of such methods include the p-representation of correlators, large-N techniques, 2PI techniques borrowed from nonequilibrium quantum field theory, or renormalization group techniques. A still controversial question concerns the consequences of the secular terms (growing with time) which arise in perturbation theory of a massless scalar field in the cosmological patch of de Sitter: do these contributions indicate an instability of de Sitter space against quantum perturbations? Or is this conclusion an artifact of finite orders in perturbation theory, which is expected to disappear once an appropriate resummation is performed (as it is the case for infra-red effects in thermal perturbation theory)? In certain cases these questions have been answered using holographic techniques.

Integral quantization, which should be distinguished from path integral quantization (essentially based on canonical quantization), offers many ways to give a classical object a quantum version. It is a quantization of various geometries (such as symplectic manifolds) which is based on operator-valued measures. This approach emphasizes the probabilistic aspects of the procedure. The so-called Berezin or Klauder or yet Toeplitz quantization, or coherent state quantization, are particular cases thereof. Integral quantization is quite promising in view of its applications to various domains of physics, notably to quantum cosmology.

Conformal methods for fields in curved geometries have been developed within the general framework of quantum field theory on manifolds. To that end, a formalism has been developed, using the methods of differential geometry, which can be viewed as a generalization of the Dirac's six-cone formalism. One motivation is to obtain both exact and explicit expressions for quantities such as two-point functions, allowing for practical calculations and interpretations in quantum (and classical) field theory in curved backgrounds.

**QFT on non-commutative spacetimes** [Dubois-Violette, Gieres, Hohenegger, Rivasseau, Wallet]

There is by now a widespread belief among researchers, owing to theoretical evidence accumulated over the years, that the continuous description of spacetime as a Riemannian manifold ought to break down at the Planck scale. Non-commutative geometry (NCG) offers such a radical modification of our concept of spacetime, although the idea that the spacetime coordinates do not commute is quite old, and has its roots both in quantum physics and in pure mathematics. NCG has been studied both from a mathematical and a physical perspective, and the theory of operator algebras has been suggested as an appropriate framework for physics in non-commutative spacetime.

NCG has far reaching repercussions for QFT, as it modifies our standard intuition. Perhaps the most striking aspect of this modification is the so-called ultra-violet/infra-red mixing whereby the physics at low-energy scales is sensitive to the detailed features of the high-energy theory and vice-versa, contrary to Wilsonian renormalization intuition. Various associated technical and conceptual problems have been studied over the past years. We should also bear in mind that non-commutative geometry offers an alternative approach to quantum gravity, although for practical reasons we have included it in the QFT section of this document. Moreover it has been shown that non-commutative spaces appear in the context of string theory on certain backgrounds with magnetic fields. Gravitational and cosmological effects of NCG have also been investigated.

One possible attempt at reconciling gravity with quantum mechanics at the Planck scale, is to trade the continuous smooth manifold describing spacetime by a non-commutative (quantum) space. In this spirit, the κ-Minkowski space-time appears in the physics literature as one of the most studied non-commutative spaces with Lie algebra type non-commutativity, and is sometimes regarded as a good candidate for a quantum spacetime in a description of quantum gravity at least in some limit. The construction of the first physically suitable gauge theory on κ-Minkowski space-time solved a twenty-year old problem in the area of field theories on quantum spaces.

**The structure of QFT and its extensions** [Gieres, Grangé, Hohenegger, Mathiot, Rausch de Traubenberg, Rivasseau, Smilga, Tsimpis]

A lot of research concerns various structural aspects of QFT, including: Schwinger-Keldysh and

Taylor-Lagrange renormalization schemes; light-front quantization; covariant canonical quantization and Poisson structure, decoherence; general properties of the perturbation series, resummation and dispersion relations; constructive field theory; instanton solutions and vacuum structure; higher-spin theories; higher-derivative theories; supersymmetry, supergravity and superspace geometry.

**Mathematical Physics** [Dubois-Violette, Friot, Hohenegger, Kibler, Rausch de Traubenberg, Rivasseau, Smilga, Tsimpis, Wallet, Zegers]

This includes works published in the mathematical physics category of the arXiv, as well the various mathematics sub-categories: differential and algebraic geometry, group theory, representation theory, number theory, quantum groups and algebras, spectral theory, geometric topology, combinatorics, etc. Researchers in this field have various motivations, typically originating in QFT and particle physics, as well as foundational aspects of quantum mechanics.

**STATISTICAL PHYSICS** [Appert-Rolland, Verley, Caillol, Hilhorst]

Statistical Physics is the study of systems with a great number of degrees of freedom. The research at IN2P3 focuses specifically on systems of charged particles, out of equilibrium systems, the reaction-diffusion process, granular systems, random geometry, complex networks and different phenomena associated with traffic (road, pedestrian, or intercellular). The research of the group can be divided in two main axes: the study of systems in and out of equilibrium, whether they are stationary or not.

Concerning equilibrium systems, whose properties are in principle derivable from microscopic interactions via the Boltzmann-Gibbs formalism, work has been done both at the fundamental level and in relation with concrete applications. The properties of different classes of systems have been studied analytically or with numerical simulations. Results include the phase diagrams of systems with long-range interactions, the effects of confined geometry (fusion transition of a two-dimensional crystal), forces created by thermal and/or quantum fluctuations between two atoms, or between an atom and a wall (van der Waals, Casimir-Polder, or Lifshitz forces). A recently developed activity concerns random geometry, e.g. the analytical description of the properties of Voronoi tessellation in two or three dimensions.

The research activity on out-of-equilibrium systems has greatly intensified since the beginning of the 21st century, thanks to theoretical breakthroughs and new experimental possibilities at the microscopic level (even at the level of a single molecule). A large variety of methods has been used to study stochastic processes, focusing both on models that might allow the determination of general principles, and on establishing "universal" relations (the so-called fluctuation relations for characteristic currents of stationary, out-of-equilibrium states). Recently a research activity has been developed with applications to road, pedestrian, or intercellular traffic. The aim is to construct realistic models inspired by data analysis, or toy models aiming at understanding the underlying mechanisms of these phenomena.

## Appendix

- **List of formal theorists at IN2P3**

Laboratoire AstroParticule et Cosmologie (APC): 6 EC, 2 CNRS, 2 Em

PR: F. Nitti, D. Steer, J. Mourad, J. Renaud
MCF: J. Serreau, E. Huguet
DR: E. Kiritsis, D. Langlois
Em: N. Deruelle, JP. Gazeau

Laboratoire de Physique des 2 Infinis Irène Joliot-Curie (IJLab): 4 EC, 4 CNRS, 3 Em

PR: V. Rivasseau
MCF: S. Friot, G. Verley, R. Zegers
DR: C. Appert-Rolland, C. Charmousis
CR: E. Babichev, JC. Wallet
Em: H. Hilhorst, M. Dubois-Violette, JM. Caillol

Insitut de Physique des 2 Infinis de Lyon (IP2I): 3 EC, 1 Em

PR: F. Gieres, D. Tsimpis
MCF: S. Hohenegger,
Em: M. Kibler

Institut Pluridisciplinaire Hubert Curien (IPHC): 2 EC

PR: J. Polonyi, M. Rausch de Trauenberg

Laboratoire de Physique Subatomique et Cosmologie (LPSC): 1 EC, 1 CNRS

PR: A. Barrau
CR: K. Martineau

Laboratoire de Physique de Clermont (LPC): 1 CNRS

DR: JF. Mathiot

Laboratoire de Physique Subatomique et Technologies Associées (SUBATECH): 1 EC

PR: A. Smilga

Laboratoire Univers et Particules de Montpellier (LUPM): 1 Em

Em: P. Grangé

- **List of national collaborations by institute**

Ecole Polytechnique, CPHT
ENS Paris
ENS Lyon
LAPTH Annecy
IHES

LUTH, Meudon
Paris VI
Paris XI
Paris XIII
IPhT, Saclay
Tours U.
Marseille CPT
Corsica U.
LPTMS Paris-Saclay
INRIA Rennes
ILM Lyon

- **List of international collaborations by institute**

**EUROPE**

Austria:
TU Vienna
University of Vienna

Belgium:
Université Libre de Brussels
Vrije U. Brussels
Leuven Un.
University of Namur

Bulgaria:
Institute for Nuclear Research and Nuclear Energy Sofia

Croatia:
Boskovic Inst. Zagreb

Czech Republic:
Prague, Inst. Phys.

Denmark:
Bohr Inst, Un. of Copenhagen
CP3 Origins, University of Southern Denmark, Odense

Estonia:
NICPB National Institute for Chemical Physics and Biophysics, Tallinn
Tartu Inst. of Phys.

Finland:
Helsinki Inst. of Phys.

Germany:
Erlangen - Nuremberg U.
Regensburg U.
Humboldt U.
MPI Potsdam
LMU Munich
MPI Munich
TU Munich
Saarland University
Darmstadt Un.
Univ. Jena

Greece:
Crete U.
Aristotle U. Thessaloniki
Natl. Tech. U., Athens

Hungary:
Univ. of Debrecen

Italy:
Rome U.
Genoa U.
Florence Un.
ICTP, Trieste
Trieste Un.
SISSA Trieste
Pisa, Scuola Normale Superiore
Naples Un.
Milan Un.

Netherlands:
Nijmegen U., IMAPP
Utrecht Un.
Leiden Un.

Poland:
Jagiellonian University Cracow
Warsaw, Inst. Nucl. Studies
Warsaw Un.
Wroclaw Un.
University of Lodz

Portugal:
Instituto Superior Tecnico (IST), Lisbon
Lisbon Un.

Russia :
Dubna, JINR
Moscow Institute of Physics and Technology
Lebedev Phys. Inst. Moscow
Lomonosov Moscow State University
Institute for Nuclear Research (INR) Moscow

Slovakia:
Bratislava Inst. Phys.

Spain:
IEM Madrid
Un of Valladolid, Spain
UCM Madrid
Universitat Autonoma de Barcelona

Switzerland:
Zurich, ETH

United Kingdom:
Nottingham U.
Durham U.
Portsmouth U.
Southampton U.

Imperial Coll., London
Cambridge U.
King's College London
Oxford U.

Ukraine:
Kharkov Natl. U. Ukraine ;

## ASIA

China:
Zhejiang U. Tech.
Lanzhou University
Taiwan Un.
Fudan University, Shanghai

India:
Indian Institute of Sciences, Bangalore

Iran:
Islamic Azad University, Tehran

Japan:
Tokyo U., ICRR
Tokyo Institute of Technology
Kyoto U., Yukawa Inst.
Kyushu University, Fukuoka
Kanagawa University
Nagoya University
Saga University

Korea:
Asia Pacific Center for Theoretical Physics (APCTP) Korea ;
Seoul National University Korea ;
IBS Center for Theoretical Physics of the Universe Daejon Korea

Pakistan:
Abdus Salam School of Mathematical Sciences, Lahore

## NORTH AMERICA

Canada:
Montreal U.
Concordia University
McGill Un.
Univ. of Alberta
Perimeter Inst. Theor. Phys.

Mexico:
Universidad Nacional Autonoma de Mexico
Chiapas Univ.
Univ. of Michoacan;

United States of America:
Pennsylvania U.
Penn State U.
Baylor U.
Los Alamos NL

Kentucky U.
Chicago U., KICP
City Coll. N.Y.
Brown U.
Arizona State U.
Wisconsin U.
Michigan U.
Texas AM
University of Notre Dame, Indiana

## SOUTH AMERICA

Brasil:
Centro Brasileiro de Pesquisas Físicas (CBPF)
Rio de Janeiro Federal U.

Chile:
Universidad de Talca
Santiago de Chile U.
CECS, Valdivia
Pontificia Universidad Catolica de Valparaiso
Andres Bello Natl. U.
Adolfo Ibanez U.

Uruguay:
Universidad de la Republica, Montevideo

## AFRICA

Morocco:
Rabat Un.

Republic of Benin:
ICMPA University of Abomey-Calavi

Republic of South Africa:
U. Witwatersrand
Johannesburg U.