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Research Career

My research activity began in my last year of undergraduate studies at the University of Lisbon (1985). As part of my finals (exams) for a degree, I wrote an essay where I described in detail several features of particle creation in curved space-times. In particular, I studied the Rindler, Schwarzschild (black-hole) and de Sitter space-times, the latter as far as inflationary models were concerned. The connection between the presence of event horizons in such spaces and the production of particles with a thermal spectrum was emphasized and led to some publications in conference proceedings [1].

In 1986 I was given employment in the university system, but the conditions for research were not satisfactory. I decided in 1988 that I ought return to research in gravitation and cosmology. As a first step, I attended an M.Sc. course in Theoretical Physics, whose total duration was two years. After the first year, a research programme was established and I began working in several directions. I carried out my research at the Physics Department, Lisbon University, under the supervision of Prof. P. Crawford (DFFCL) and in collaboration with Prof. A. Barroso (then Head of Department), and Prof. J. Mourão (IST). My research was mainly focused on the two following issues.

- On the one hand, investigating Einstein-Yang-Mills-Higgs systems,
- On the other hand, analysing gravitational theories with a non-minimal coupling between matter and gravitation, their relation with particle physics and inflationary models.

My research activity was sucessfull and lead to satisfactory publications, one in a refereed journal [2] and also in conference proceedings [3]. My major contribution was to show how some features of spontaneous symmetry breaking features are affected when space-time curvature is present, which has important consequences at a particle physics level.

My next step was to read for a Ph.D. in Gravitation and Cosmology. I was awarded a JNICT ("Portuguese Research Council") Ph.D. Scholarship in 1990. My research was carried out under the supervision of Prof. P. Crawford (DFFCL) and Prof. J. Mourão (IST) in the Physics Department at the Lisbon University. I was given several problems to work on:

1. The analysis of Einstein-Yang-Mills-Higgs systems when the space-time geometry is Friedmann-Robertson-Walker (FRW).

   We proposed [4] and fully justify an adequate ansatz for gauge vector fields, so that they have non-zero spatial components, and induce a perfect fluid-type energy-momentum tensor. Usually a general vector field implies an energy-momentum tensor that is *not* compatible with a FRW geometry. The novelty of our approach was accomplished by defining vector fields which transform under a spatial coordinate transformation, and then are compensated by a non-Abelian gauge transformation.

   Moreover, such gauge fields were shown to enhance inflation [5]. In the massive case, a radiation to dust state transition occurs, with the mass of the vector field playing the role of transition scale [6].

2. Another problem was to study De Sitter space and find anisotropic foliations. The properties of a Kantowski-Sachs (KS) foliation were described [7], a Bianchi type-III foliation was found [8] and the validity of a De Sitter phase in KS Universes with a cosmological constant was also analysed [9].

3. Finally, I addressed the conditions for which an inflacionary scenario may occur in the early universe. This was done for the case of a non-minimal coupling between gravity and a massive scalar field (inflaton). It was found that inflation was indeed a general feature and even enhanced for some specific values of a negative coupling [10].

During my M.Sc. and Ph.D studies I was also a member of several research groups and centres, namely the gravitation groups of the Physics Department at the Lisbon University and the Physics Department of the Instituto Superior Técnico, the CFMC-INIC (Lisbon) and the CENTRA (Lisbon), participating in several seminars, collaborating in all their events and helping in conference organizations.

Before my Ph.D. examinations I was awarded a EU-HCM Post-Doctoral Fellowship at DAMTP, University of Cambridge, to develop my research in the gravitation group. My scientific officers were Dr. P.D'Eath and Prof. S.W. Hawking.

I worked then at Cambridge on the following research subjects:

- Quantum Cosmology, in particular on Supersymmetric Quantum Cosmology (derived from $d = 4, N = 1$ Supergravity):

    1. It was shown that supersymmetric Bianchi class A models with a cosmological constant have **no** physical states [12,13]. Nevertheless, in the Friedmann isotropic case a Hartle-Hawking type solution could be found. The reason was afterwards identified with a over-restrictive choice for the gravitino field [27].
    2. The canonical quantization of N=1 supergravity applied to more general models involving lower spin fields (supermatter), was accomplished in ref. [14,15,16].

       Using an ansätze for the fields in consideration, a k=+1 Friedmann model was then studied in the case where just scalar fields and fermions were present, and also in the case where spin-1 fields were added. New solutions were found in the former [17] but in the latter more general case **no** physical states were found [18].

       Concerning the solutions in [17], "wormhole" (Hawking-Page) solutions were *not* found and the Hartle-Hawking solution could only be partially identified.
    3. The reason for the apparent absence of the wormhole state was latter identified with the choice of supersymmetric gauge and also of fermionic derivative ordering [19].
    4. Ref. [16] constitutes an analysis of a Bianchi-IX model in N=1 Supergravity with scalar matter field and supersymmetric partner. Unfortunately, neither the Hartle-Hawking or the wormhole could be found. It is suspected that the over-restrictive anasatz for the gravitino field is the cause [27].
    5. Finally, Bianchi class A models in N=2 supergravity were considered in ref. [21]. The most important feature is that the presence of the Maxwell field implies a

mixing in the several Lorentz invariant fermionic sectors that compose the wave function.

- Decoherence Processes with assive spin-1 fields within FRW cosmologies.

  1. It was found that the presence of a mass parameter results in the longitudinal modes of the spin-1 field being present in the Wheeler-DeWitt equation [11].
  2. Two cases (*global* Abelian - $U(1)$ - and non-Abelian - $SO(3)$ - symmetry) were studied in detail. The first is associated with a one-dimensional minisuperspace while the latter has a two-dimensional minusuperspace. Our results showed that although the quantum to classical transition for the gravitational degrees of freedom seemed to proceed as expected when the universe expands, the spin-1 matter field did not share this property [11]. This constitutes a major difference in contrast with scalar fields and allowed couplings.

After this fellowship, I received a *new one* from the Portuguese Research Council (JNICT/FCT) which gave me the opportunity to stay in DAMTP, University of Cambridge, for 3 more years. My scientific officer was still Prof. S.W. Hawking. My resarch activity could be summarized as follows

- I studied a multi-dimensional Einstein-Yang-Mills cosmological model, with a topology of the type $\mathbf{R} \times S^3 \times S^d$. As far as the literature in multi-dimensional quantum cosmological models is concerned, only scalar fields or Abelian spin-1 fields have been considered. In the latter case the only non zero components have been located in the extra dimensional spaces and usually restricted to a simple monopole configuration. Our approach consisted in introducing time-dependent spatial components in the 3 dimensional physical space for the gauge field modes. In such a way we created a more realistic model to help us to understand the behaviour of the very early universe: results include the Hartle-Hawking (no-boundary) wave function and the influence of both the extra dimensions and the components of the vector field in 4-dimensional physical space time on quantum solutions.
- In addition, I further investigated additional and different scenarios in supersymmetric quantum cosmology:

  1. The paradoxical situation found in [18] was subsequently addressed in [20]. The reasons for the results in [18] were an overly restricted Ansatz for the supermatter fermionic fields. The Hartle-Hawking and a wormhole-like solutions were eventualy obtained for a closed FRW model with only non-Abelian spin-1 fields and supersymmetric partners, but **no** scalar fields though. A discussion of the ansätze for the physical variables was also included in ref. [23].
  2. Investigated the possibility of constructing conserved currents in locally supersymmetric minisuperspaces. It was shown in [24] how conserved currents can be obtained and their limitations as well.
  3. Studying the canonical quantization of black holes in a N=2 supergravity scenario [26].

4. I also received an invitation from the Managing Editor of International Journal of Modern Physics **A** (World Scientific) to write an extensive review on the subject of supersymmetric quantum cosmology [25].
5. Continue to investigate the retrieval quantum fields in curved spaces and the origin of structure formation from supersymmetric quantum cosmology (SQC) [27]. Pertinent questions involved:Is it possible to establish whether a SQC formulation of the very early universe can lead to a scale-free spectrum of density perturbations? How does this compares to plain gravitational theories with matter fields but no supersymmetry? Is there an imprint of a supersymmetric quantum epoch into the observed Universe?

Moreover, I also initiated a line of research on the subjects of canonical quantization of black hole systems. In particular

1. I studied methods to retrieve a wave function for a Reissner-Nordström (RN) black hole which will be explicitely dependent on its mass *and* charge. This brings some light on the characteristics of quantum black-holes when $M > Q$ and $M = Q$. In particular, as the latter bears supersymmetric properties [29].
2. Deriving a quantum description of black strings/membranes configurations and their properties. We approached this quantization from a WKB approach as well as a phase space quantization. Both will bring relevant information concerning the partition function and entropy.

Since mid 1998 I was appointed a tenure track lecturer position at the Physics Department of Universidade da Beira Interior (UBI), Portugal. Research conditions for theoretical physics were literally inexistent. Moreover, lecture duties amount to circa 10-12h/week, to which administrative tasks are often added. During nearly one and half year I set up a research group (the GATC – Grupo de AsTrofisica e Cosmologia/Cosmology and AsTrophysics Group) with the assistance of a few other colleagues with similar interest and experiences in theoretical physics. From some grants awarded by the Portuguese Research Foundation (FCT) to research programmes I submitted, funds were assigned for the purchase of equipment (mainly PC's and laser printers), textbooks, and journal subscriptions. In mid 1999 and 2001, I also acquired funds from the FCT to offer a Post-Doctoral Programme in "Strings, Black Holes, Branes and Cosmology" as well as a Senior Fellowship in "Multidimensional Cosmology and Large Extra Dimensions". In addition, I have been recently collaborating with a M.Sc. student on "Quantization of Pre-Big-Bang Cosmologies from the perspective of a Broglie-Bohm formulation".

The lines of investigation described in the following paragraphs constitute a summary of my research work in the past 4-5 years. In particular, these lines continue and extend the programmes initiated 7 years ago at the University of Cambridge. My recent research career (see ref. [29]-[39]) has therefore been conducted along two quite fascinating directions:

- (Quantum) Cosmological Implications of String Theory;
- Black Holes in Quantum Gravity Theories.

The corresponding framework is Superstring Theory, which conveys one of the most promising foundations for an ultimate unified theory of the fundamental interactions, where the gravitational field would be consistently quantized. Five distinct string theories are known, such that all are related by fundamental duality relations. This attractive scenario has then led to the emergence of a novel understanding of our Universe. In fact, these 10-dimensional string theories constitute different realisations of a more fundamental 11-dimensional scenario called *M*-theory. The presence of duality transformations are at the basis of this achievement; Moreover, they brought 11-dimensional supergravity as another realisation of M-theory, which will embody the eagerly sought unification of all interactions.

A natural arena where the ideas previously mentioned should be enthusiastically tested is the very early Universe (ranging from a quantum origin up to structure formation, involving a crucial inflationary stage) and black hole properties. Indeed, the field equations in string theory have a different structure from Einstein equations, as important new symmetries provide a contrasting new picture. In addition, the presence of higher spatial dimensions, fermions and supersymmetry are mandatory. All these and many other features determine that there are plenty of open issues, reflecting primordial implications of string theory towards a quantum origin of the Universe and the final stages of gravitational collapse. To assert if superstring and M-theory sucessfully correspond to the emergence of a XXI century scientific revolution, more crucial investigations are needed. In particular, identifying whether string theory features could be present in the the observable universe and how quantization methods of the gravitational field may determine crucial properties for black holes.

Given the context above outlined, here is a description of my recent research work:

1. I have considered a scalar field and corresponding inhomogeneous perturbations on S^2 surfaces within a Schwarzschild black hole background. Upon canonically quantizing the black hole within the "*Apparent Horizon* approach", results implied that the black hole vacuum and particle states correspond to harmonic oscillators with time-dependent paramaters [34].

2. Flat FRW (spatially homogenoeus and isotropic) cosmologies in superstring theory seem to induce N=2 supersymmetry, due to the presence of a scale-factor duality (inherited from T-duality in superstrings). Some (not all) anisotropic models (Bianchi) have other types of cosmological inherited dualities, adapted to the presence of spatial curvature. A spectrum of solutions holding N=2 supersymmetry has been found but not yet wholly complete [29, 30, 32].

3. Pre Big-Bang cosmologies (extracted from string inspired theories) have been quantized from the point of view of a Broglie-Bohm approach. It was found that quantum solutions (wave function of the Universe) only predict suitable classical scenarios for *small* values of the scale-factor, in contrast with conventional views of quantum cosmology [33].

4. I have also initiated the quantization of FRW models in the context of supergravity theories derived from M-theory. Investigation focused on invariant submanifolds in the phase space [31], corresponding to a type IIA superstring. In particular, I have analysed the canonical and quantum cosmological implications of a spatially flat, 4-D

Friedmann-Robertson-Walker (FRW) model that is derived from the M-theory effective action . Investigation was directed in studying how axions and form fields influence a four-dimensional FRW spacetime, first contracting from a strong coupling regime and then expanding to a weak coupling regime, while the internal space ever contracts.

5. I also became interested in issues relating (A)dS stability and large extra dimensions. For this purpose, a non-linear gravitational model with a multidimensional warped product geometry and quadratic scalar curvature terms (inspired in string corrections) was considered together with $p-$form fields. For certain parameter ranges, it was found that the extra dimensions are stabilized if the internal spaces have negative constant curvature. Susequently, the 4–dimensional effective cosmological constant as well as the bulk cosmological constant may become asymptotically negative or positive. In particular, the homogeneous and isotropic external space is asymptotically (A)dS$_4$. The connection between the D–dimensional and the 4–dimensional fundamental mass scales sets an additional restriction on the parameters of the considered non-linear models [35].

6. Actions of the Born-Infeld (BI) type have been the subject of wide interest in the context of M/string theory. This comes from the result that the effective action for the open string ending on D-branes can be written in a BI form. This action has also been used to investigate the physical behaviour of strings/branes from a gravitational perspective. In fact, solitonic degrees of freedom such as branes might be dominant towards the early universe. Hence, if either string or brane effects are present, it can be expected that may bring modifications and elucidate on current problems. Closed FRW models in the presence of a SO(N) gauge sector described by a non-Abelian Born-Infeld action were then investigated. Applications of Born-Infeld cosmology to early evolution [36,37], quintessence [38] and alpha-varying effects [39] were also discussed. It was shown that string or brane effects did change the physical scenario, bringing about new features that could solve a few issues within (quantum) cosmology.

Finally, I would like to stress I have received three prizes for research in three international competitions/events:

- Hounorable Mention for the work *"Is there a problem with quantum wormholes in N=1 Supergravity?"* (author: P.V. Moniz), DAMTP report R95/19, in the 1995 Gravity Research Foundation Awards for Essays in Gravitation

- Third Prize in the Poster competition at the 46-SUSSP NATO ASI – General Relativity – Aberdeen University, July 16-29 1995, for the work entitled *"Why Two makes it more exciting than One"* (authors: A.D.Y. Cheng and P. Moniz), DAMTP Report

- Hounorable Mention for the work *'Origin of Structure in Supersymmetric Quantum Cosmology"* (author: P.V. Moniz), in the 1997 Gravity Research Foundation Awards for Essays in Gravitation

As far as my research aspirations are concerned, I enclose information about my research projects separately. I would like to stress my total commitment to continue my research

in quantum gravity and cosmology, the physics of the very early universe and structure formation. These are indeed fascinating and active subjects with a plethora of open issues, and where I wish to contribute enthusiastically .

My aspirations also include establishing more contacts with other gravity groups, especially in Europe, and starting or participating in the formation of Research Networks

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