Supersymmetry and the Early Universe
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Scientific Report

The research activities are summarised below under the headings of the main objectives of this network and the institution where the work was carried out. Collaborative work by members of different teams is emphasised and such publications are listed separately. A third list enumerates additional publications by the young researchers supported by the network.

(i) **Inflation**

Barcelona: Garriga calculated probabilities in eternal inflation [46] and discussed different proposed solutions to the cosmological constant problem [48].

Bonn: Groot-Nibelink calculated the density perturbation in multifield inflationary models [18, 19]. The possibility of Bose-Einstein condensation at reheating was addressed by Peloso [121]. Zucker [25] discussed the moduli problem in the braneworld picture.

Geneva: Giudice and Tkachev discussed the cosmological moduli problem and preheating [57]. Tkachev studied the possibility of inflation after preheating [60]. Veneziano continued his programme of pre-Big Bang string cosmology [62],

Helsinki: Enqvist, Kurku-Suonio and Valviita performed a fit to the recent CMB anisotropy data from Boomerang and Maxima, allowing the inflationary density perturbation to have both adiabatic and isocurvature components; in a spatially flat universe only a small isocurvature component is allowed by present data [1]. They also discussed the sensitivity of future observations by Planck [2].

Lancaster: Lyth continued his work on inflation and large-scale structure [68]. He discussed determination of the spectral index of the cosmological curvature perturbation from observations [69, 70] and developed a new approach to the evolution of cosmological perturbations on large scales [71,72]. He studied constraints on TeV-scale hybrid inflation [67,76, 77] as well as the production of gravitinos through vacuum fluctuations [73, 74].

Oxford: Davidson and Sarkar studied the time-scale for thermalisation of the decay products of the inflaton field [65]. Santos and Sarkar found evidence in large-scale structure and , CMB data for a feature in the primordial density perturbation, such as might arise due to symmetry breaking along a SUSY flat direction during inflation [75, 76]. Ross and Sarkar showed that the energy scale of inflation can be as low as the electroweak scale while still generating an acceptable primordial density perturbation; thus four-dimensional inflation is possible in the brane-world picture [77].

Nilles and Peloso (Bonn) and Sorbo (Trieste) clarified the important question of gravitino production during preheating following the end of inflation by doing the first explicit nonperturbative calculation in a model with broken SUS; they find that the production of gravitinos is not necessarily a disaster as was previously thought [112]. Their general formulation [113] for the calculation of particle production at preheating in the two-field case can be applied to hybrid inflation models as well.

Martin and Riazuelo (Meudon) collaborated with Sakellariadou (CERN) on the implications of non-vacuum initial states for inflation-generated perturbations [96].

A SUSY GUT model based on the Pati-Salam gauge group $SU(4)_c \times SU(2)_L \times SU(2)_R$ was presented by Jeannerot (Trieste) and Lazarides (Thessaloniki). This leads naturally to smooth hybrid inflation, avoiding the cosmological disaster encountered in the standard hybrid inflationary scenario from the overproduction of monopoles at the end of inflation; successful reheating is achieved satisfying the thermal gravitino constraint.

(ii) **Dark matter**

Annecy: Arbey, Lesgourgues and Salati examined whether the dark matter can be a scalar fieidTi7]. Concerning the search for SUSY dark matter, Donato analysed, in different SUSY frameworks, how detectability of relic neutralinos by direct and indirect means is related to their local and cosmological densities [8]. Donato, Maurin, Salati and Taillet completed a study on the cosmic $\bar{p}$ background from spallations on interstellar matter as a first step to study the observability of a neutralino-induced $\bar{p}$ signal [9, 10].

Bonn: The properties of neutralino dark matter in the presence of CP violating SUSY phases was studied by Nath [26, 27], and the consequences for neutralino properties from 9 -2 of the muon by Dedes [29] .Nilles disussed the consistency conditions for dark energy in extra dimensions and string theory [31].

Geneva: Ellis and collaborators continued their investigations of SUSY dark matter, focussing on the parameter space in the constrained MSSM at large tan.8 [52] and detection through elastic scattering [53], and also addressing the issue of fine tuning [54].

Ioannina: Vergados studied the direct detection rate forSUSY dark matter predicted by the MSSM (with universal boundary conditions and large values for tan .8). Interesting rates were found for a region of parameter space consistent with the cosmological constraint on the relic abundance (taking coannihilations into account) and the experimental limits imposed by $b \to s\gamma$ and Higgs searches [32].

Lancaster: Roszkowski developed a new model independent method for extracting spin dependent (cross-section) limits from dark matter searches [78]. Chun and Lyth discussed the abundance of relativistic axions [80].

Oxford: Faraggi studied possible self-interacting dark matter candidates from hidden glueballs in realistic heterotic string models [64]. Sarkar reviewed the suggestion that metastable massive particles clustered in the halo are responsible for ultra-high energy cosmic rays; bound states in the hidden sector of SUSY have the required properties [79].

Brax (CERN) and Martin (Meudon) collaborated on studying the possible connection of quintessence to supergravity [95].

Sigl and Bertone (Meudon/IAP) studied with Silk (Oxford) how the massive black hole 'present at the center of our Galaxy accretes dark matter particles, thus creating a region of very high density where the dark matter annihilation rate is considerably increased, thus facilitating detection [90, 91].

Possible overproduction of dark matter in the braneworld picture was discussed by Falkowski (Warsaw), Lalak (Bonn & Warsaw) and Pokorski (Warsaw) [101].

Ferrer (Barcelona) and Evans and Sarkar (Oxford) calculated the expected anisotropy of ultra-high energy cosmic rays resulting from decays of metastable SUSY dark matter particles clustered in the Galactic halo [114].

Roszkowski (CERN & Lancaster) discussed, with Kim (Lancaster), the possibility that relic axinos.constitute the dark matter [106]. He also presented, with Nihei (Lancaster) and Ruiz de Austri (Lancaster), a more accurate calculation of the neutralino relic density [111]

(iii) **Cosmological phase transitions**

Bonn: The work on superhydrodynamics by Groot-Nibelink [20] is relevant to this issue.

Oxford: Kogan explored the formation of novel topological defects in the brane-world picture due to the breaking of isometries of the extra space dimension [87]. He also analysed the finite temperature deconfining phase transition in 2+1 dimensional Georgi-Glashow model [88].

Laine (CERN) and Rummukainen (Helsinki) collaborated on studying non-perturbative aspects of the electroweak phase transition in two-doublet models [108].

Tkachev (CERN) and Garcia-Bellido (Madrid) studied the dynamics of symmetry breaking and tachyonic preheating [116].

(iv) **Baryogenesis**

Helsinki: Enqvist, Jokinen and McDonald calculated numerically the fragmentation process of the Affieck-Dine condensate and pointed out that inflationary fluctuations would give rise to fluctuations in baryon number. If the condensate decay is the main source of both baryon number and dark matter in the form of neutralinos, there would also arise dark matter isocurvature perturbations at a level that is detectable by Planck [3]. The fragmentation itself is a complicated process with the condensate settling into the state of minimum energy, the Q-ball, by slowly radiating scalar waves and small Q-balls [4, 5].

Lancaster: Lyth studied baryogenesis following hybrid inflation at the TeV scale [67].

Madrid: Moreno and Quiros studied SUSY CP-violating currents in the bubble walls in the presence of a CP-violating background. A detailed calculation, using the Keldysh formalism, was performed in the framework of the MSSM, including the contributions from both squarks and charginos. The baryon asymmetry was evaluated and the region of MSSM parameter space consistent with all experimental data was established [44, 45].

Orsay: Joyce studied aspects of electroweak baryogenesis in the framework of SUSY theories[16].

Oxford: Plumacher discussed the influence that other chemical potentials can have on the generation of a baryon asymmetry [66].

Trieste: Masiero and Vives reviewed the possibilities for CP-violation, essential for baryogenesis, in extensions of the Standard Model [40].

Jeannerot (Trieste) and Lazarides (Thessaloniki) showed that in their SUSY GUT inflationary model, adequate baryogenesis via primordial leptogenesis occurs consistently with the Solar and atmospheric neutrino oscillation data [104].

(v) **String/M-theory cosmology**

Barcelona, Granada: Garriga studied the cosmology of brane-worlds [47]. Astrophysical implications of string/M-theory were examined by Cornet, Illana and Massip, specifically the neutrino-nucleon cross section at energies above the fundamental string scale, mediated by leptoquarks in the s-channel [43].

Bonn: Forste [24] and Nilles [30] discussed the cosmological constant problem in M-theory and in the brane-world scenario. Explicit constructions of 4-dimensional string models in the D-brane scenario (D-branes at angles) and its properties for particle physics were given by Forste, Honecker and Schreyer [21, 22]; studies of the cosmological relevance are underway. Explicit constructions ofSUSY extensions of the Randall-Sundrum model were made [101]; this is interesting for the question of the moduli as dark matter [25]. The implications of extra dimensions for low energy phenomenology was discussed by Nath [28].

Geneva: March-Russell showed that if compactification occurs on a compact hyperbolic manifold, the spectrum of Kaluza-Klein modes is radically altered thus allowing an early universe cosmology with normal evolution [61].

Helsinki: Enqvist, Keski-Vakkuri and Rasanen considered the role of bulk matter in Randall-Sundrum cosmologies, with the conclusion that for a static two-brane configuration only stiff ideal fluid is admissible in the bulk; this condition is however relaxed if the branes are moving [6].

Ioannina: A new class of time-dependent solutions for the Randall-Sundrum model was derived by Kehagias and Tamvakis by patching together isometries broken by the brane. Solutions generated by generalized boosts along the fifth dimension are associated with localized gravity and lead to an effective Friedman equation on the brane with a scale factor exhibiting power law or exponential behaviour. The effective energy-density on the brane depends linearly on the brane tension [33, 34, 35].

Lancaster: Kim studied the cosmology of Randall-Sundrum models with an extra dimension [84, 85] and Nihei examined gravity localization with a domain wall junction [86].

Orsay + Meudon/IAP: Binetruy, Deffayet, Uzan, Bernardeau, Langlois and Carter were involved in studying brane cosmology, i.e. the consequences on the evolution of the early Universe of the possibility that there exists extra spatial dimensions only probed by gravity so that our world of quarks, leptons and gauge fields is localized on a surface or brane [12, 13, 14, 15]. They showed that the evolution of the Universe is generically non-conventional but standard evolution is recovered at late times in models where 4-dimensional gravity is localized on the brane. They also studied the dynamics of 2-brane system and the cosmological role of the radion field which identifies the interbrane distance.

Oxford: Kogan, Mouslopoulos, Papazoglou and Ross discussed multi-brane worlds and possible modification of gravity at large scales [81, 82, 89].

Warsaw: Falkowski, Lalak and Pokorski studied brane-world scenarios in theories with extra dimensions [41,117,118]. They proposed brane-bulk supersymmetry which correlates the brane and bulk Lagrangians. Then to each brane Lagrangian containing boundary projections of the bulk fields there corresponds a gauging of the five-dimensional supergravity; thus one can supersymmetrise the Randall-Sundrum model with the exponential warp factor. Brane-bulk supergravity was coupled to gauge sectors, containing chiral matter, living on the branes, and to hypermultiplets (moduli) living in the bulk. With this quasi-realistic theory the transmission of SUSY breakdown between branes was analysed; it was demonstrated how. the stabilization of the fifth dimension is related to SUSY breakdown and to the size of the four-dimensional cosmological constant. The effective 4d supergravity was derived for brane-bulk supergravities; moreover, the method was extended to deduce low 'energy supergravities corresponding to an arbitrary (BPS) warp factor in five dimensions. It was found that warped supergravities (not necessarily exponentially warped) very often lead to stabilization of the fifth dimension after SUSY breakdown. The 5D SUSY theory that was constructed is very likely to have a string or M-theory emedding, and is the only known example of a consistent locally superesymmetric brane world with chiral matter localized on branes. As such, it forms a natural basis for investigations of brane-world cosmology and phenomenology; work in this direction is in progress. Meissner and Olechow ski analyzed corrections of the form of Euler densities which appear in the a' limit of the string theory effective action [42]. Similar effective terms appear also in a semiclassical approach to quantum corrections in a nontrivial gravitational background. Such effects should in principle be taken into account in cosmological models especially for the early phases of the Universe evolution. The corresponding vacuum solutions have interesting properties. The space-time is a warped product of some (D- l)-dimensional Minkowski space-time and a line. It can be interpreted as a (D -2)-brane in a D-dimensional bulk. The cosmological evolution of backgrounds of this type is under investigation.

Forste (Bonn), Lalak (Bonn & Warsaw), Lavignac (Bonn) and Nilles (Bonn) presented sum rules that have to be fulfilled by the bulk and brane tensions in order to obtain consistent solutions to the cosmological constant problem, and gave a critical evaluation of the mechanism of self-tuning [103]. Lalak (Bonn & Warsaw) and Falkowski and Pokorski (Warsaw) presented a five dimensional gauged supergravity which admits the Randall-Sundrum solution as a BPS vacuum with vanishing energy [118].

Ellis (CERN) and Mavromatos (KCL) studied the effects of quantum gravity induced space-time foam on particle interactions and the consequences for ultra-high energy cosmic ray propagation [98, 99], and also discussed the possible connection between string theory and cosmological vacuum energy [100]. Lalak (Warsaw & CERN) and Falkowski and Pokorski (Warsaw) discussed how to obtain four-dimensional supergravities from five-dimensional brane worlds[117].

Using conformal field theory methods, Leontaris (Ioannina) and Mavromatos (KCL) constructed a metric that describes the distortion of space-time surrounding a D(irichlet)-brane (solitonic) defect after being struck by another D-brane [109]. By viewing our four-dimensional universe as such a struck bran e, embedded in a five-dimensional space- time, the appearance of a band of massive Kaluza-Klein excitations for the bulk graviton (which is localized in a region of the fifth dimension determined by the inverse size of the band) was noted. The band incorporates the massless mode (ordinary graviton) and its thickness is determined essentially by'the width of the Gaussian distribution describing the (target-space) quantum fluctuations of the intersecting-brane configuration.

Mavromatos (KCL) and Rizos (Ioannina) considered [110] the $\mathcal{O}\alpha'$ string effective action, with Gauss-Bonnet curvature-squared and fourth-order dilaton-derivative terms, derived by a matching procedure with string amplitudes in five space-time dimensions. They showed that a non-factorizable metric of the Randall-Sundrum' (RS) type, with four- dimensional conformal factor $e^{-2k|z|}$, can be a solution of the pertinent equations of mo- tion. The parameter k is found proportional to the string coupling g_s and thus the solution appears to be non-perturbative. The general solution for the dilaton and metric functions was studied. In the case of an anti-de-Sitter bulk, there exists a continuous interpolation between (part of) the RS solution at $z = \infty$ and an (integrable) naked singularity at $z = 0$. This implies the dynamical formation of domain walls (separated by an infinite distance), thus restricting the physical bulk space-time to the positive z axis.

Kortals-Altes (Marseille) collaborated with Laine (CERN) on the fate of discrete symmetries when gauge degrees offreedom are located on a topological defects (as in the case of branes) [107].

Kachelreiss (CERN) and Plumacher (Oxford) showed that the enhanced neutrino scattering cross-section (through exchange of Kaluza-Klein gravitons) in TeV-scale quantum gravity models is inadequate to enable cosmic neutrinos to be the primaries for ultra-high energy cosmic rays [105].

Binetruy (Orsay) and Silk (Oxford) studied the constraints imposed by the CMB and gravitational lensing on brane models where gravity at very large (cosmological) distances is 5-dimensional[92]. Abel (Orsay) and Kogan (Oxford) examined the cosmological effects of the Hagedorn phase in brane-world models; even in the absence of a cosmological constant, winding modes cause a negative 'pressure' that can drive brane inflation [115].

Pokorski (Warsaw) and Quiros (Madrid) collaborated on studying brane effects on extra dimensional scenarios [97].

(vi) **Cosmological constraints**

Annecy: Lesgourgues is carrying out a program on accurate cosmological parameter extraction from the CMB and large-scale structure data. Relevant codes were developed leading to a first publication on cosmological models with large lepton asymmetry [11].

Barcelona: Masso and Rota studied high energy neutrino-photon interactions [49] and Masso also examined pseudoscalar production in electromagnetic fields [50] -both caclculations being of relevance to the extraction of cosmological constraints. Ferrer and Grifols discussed the effects of Bose-Einstein condensation on forces among bodies in a boson heat bath [51].

Geneva: Giudice discussed the cosmological constraints for neutralino and neutrino masses if the reheat temperature of the universe is low [58]; in particular standard model neutrinos can then be candidates for warm dark matter [59].

Lancaster: Chun and Kim studied cosmological constraints on a Peccei-Quinn fiatino as the lightest supersymmetric particle [81].

Brax (CERN) and Martin and Riazuelo (Meudon) collaborated on the constraints on quintessence models from the CMB [94].

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Other Publications by Young Researchers (with non-network collaborators)

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Young Researchers

The hiring of young researchers to fill post-doctoral positions for the first year of the project was hampered by the delay in obtaining funds from the EC (which were received by the co-ordinating node only in November 2000). Consequently, there were only 2 Network Fellows appointed in October 2000 (Dr Michael Plumacher at Oxford and Dr Marco Peloso at Bonn). The majority of the remaining appointments will be made in Autumn 2001. All positions were advertised widely by email as well on the RTN webpage.

Meetings

We were committed to hold a Meeting Of Team Leaders to fix research tasks, collaborations, appointment of young researchers, education and outreach activities within 1 month of Start Date. This was held at CERN (during the SUSV'01 conference) on 28 June 2001, with the participation of about 30 network members. The Team Leaders presented overviews of the activities in their respective teams to the entire group, followed by a closed meeting at which administrative issues were discussed. The programme and participants are listed on: `www-thphys.physics.ox.ac.uk/users/SubirSarkar/eunetwork/rneetings/2000`.

We were also committed to hold the First Network School/Meeting, with lectures by both Network Scientists and invited outside experts, as well as seminars by young researchers and reports from the Team Leaders, *within 1 year of the Start Date.* This was also held at CERN, 18-22 April 2001 and attended by about 70 people. The programme consisted of topical lectures in

the mornings and specialised seminars in the afternoons. Copies of the lectures were distributed to all participants and a Discussion Forum set up on the network's webpage. The list of participants and meeting programme can be seen on:
`www-thphys.physics.ox.ac.uk/users/SubirSarkar/eunetwork/meetings/2001`.

The following scientific meetings, both regional and international, were organised under the aegis of the network:

International workshop on Physics and Astrophysics of Extra Dimensions,
College de France, Paris, 9 May-22 Jun 2001 (`www.iap.fr/users/sigl/extradim.html`)
- Organised by the Orsay and Meudon/IAP nodes. The idea was to host a two-month long meeting in Paris where world experts could be present for periods of time ranging from one week to one month to discuss the most recent issues in the field. This attracted 180 registered participants. The first period was concluded by a three-day meeting (28 May-l June) on Ultra High Energy Cosmic Rays, while the second period (June) was concluded by a week (18-22 June) devoted to Cosmology.

Journee des Lacs Alpins de Cosmologie (`wwwlapp.in2p3.fr/lesgourg/JLAC/jlac.html`)
▷ 1ère Journe (Université de Geneve, 16 January 2001)
▷ 2ième Journe (LAPP, Annecy, 22 May 2001)
- In order to reinforce the cohesion of the network members at the CERN and Annecy nodes, Annecy started to organise regular meetings (every four months) intended mainly for CERN, Annecy and University of Geneva cosmologists (with participation also from Lausanne and Grenoble). Two meetings have been held so far.

Other important meetings which network members organised and/or participated in were:

- International Workshop on Strong and Electroweak Matter, Marseilles, 14-17 Jun 2000
- SUSY 2K, Geneva, 26 Jun-1 Jul 2000
  (`wwwth.cern.ch/susy2k/susy2k.html`)
- Conference on Cosmology and Particle Physics, Verbier, 17-28 Jul 2000
  (`mpej.unige.ch/ kunze/capp2000/final/capp2000.html`)
- Thirty Years of SUSY, Minneapolis, 13-15 Oct 2000
  (`www.tpi.umn.edu/susy30.html`)
- Planck'01, La Londe les Maures, 1-16 May 2001
  (`www.esf.org/euresco/01/pc01141a.htm`)
- 37th Karpacz Winter School, 6-15 Feb 2001
  (`www.ift.uni.wroc.pl/karp37/`)
- SUSY'01, Dubna, 11-17 Jun 2001
  (`susy.dubna.ru/`)