CURRICULUM VITAE

Personal data

Name/Surname: Zourab Berejiani (in passport), Zurab Berezhiani (english version, as in publications)

Date and Place of Birth: November 28, 1956, Tbilisi, Georgia

Nationality: Italian

Languages: Full handling of English, Italian, Russian and Georgian, basic level in German

Private address: Via Valle Partina 1/C, 67019 Scoppito, L'Aquila, Italy
Tel: (+39)-3355898420

Professional address: Full professor of Theoretical Physics, Dipartimento delle Scienze Fisiche e Chemiche, Università dell'Aquila, Via Vetoio, 67010 Coppito, L'Aquila

Tel: (+39)-0862-433058 Fax: (+39)-0862-433033
E-mail: zurab.berezhiani@aquila.infn.it

Education and Academic Degrees

1973-78: student at the Tbilisi State University (TSU), Department of Physics.
Graduated with *excellence* in 1978 and obtained the *M.S. degree in Theoretical and Mathematical Physics*, TSU, Tbilisi, presenting the thesis *"Could non-renormalizable field theories have asymptotically free behaviour?"*, Thesis advisor Prof. A. Ushveridze

1979-83: Ph.D student at the Institute of Physics of the Georgian Academy of Sciences (IPGAS), Particle Theory Division, supervisor Prof. O. Kancheli

1984: Ph.D. degree *(Kandidat Nauk)* in *Theoretical and Mathematical Physics* at the TSU, Tbilisi. Thesis: *"The quark and lepton charges, masses and mixing angles in L-R symmetric gauge models"*, Prof. J. Chkareuli thesis advisor

Employment

1998-pr.: Professor of Theoretical Physics (FIS/02), Università di L'Aquila, L'Aquila, and Theory Group staff at the INFN, Gran Sasso National Laboratories (LNGS), Assergi, Italy

1993-97: Senior Researcher *(Primo Ricercatore)* at the Ferrara Section of the INFN (Istituto Nazionale di Fisica Nucleare), Italy – *5 year contract under Art. 36*

1991-92: Alexander von Humboldt Fellow at the Physics Department, Ludwig-Maximillian University of Munich, Germany

1989-91: Visiting Senior Researcher in Theoretical Cosmology Group, Special Astrophysical Observatory of the Academy of Sciences of the USSR, Zelenchuck, Russia

1988-89: Visiting Scientific Researcher in Theory Division, Lebedev Physical Institute of the Academy of Sciences of the USSR, Theory Division, Moscow, Russia

1985-92: Senior Scientific Researcher in Particle Theory Division, Institute of Physics of the Georgian Academy of Sciences (IPGAS), Tbilisi, Georgia – *permanent staff member*

1979-85: Junior Scientific Researcher in Cosmic Ray Division, IPGAS, Tbilisi, Georgia

Teaching Experience

Regular teaching at the Department of Physics, L'Aquila University

In 1998 I entered the University of L'Aquila as a titular of the annual two-semester course of *Theoretical Physics (Quantum Field Theory)* and in 2001–2002 delivered also the course of *Cosmology*. Since MIUR reforms (Laurea Specialistica - Magistrale-Triennale) in different years since 2003 I covered several regular courses in Laurea Specialistica or Magistrale as *Quantum Field Theory, Gauge Theories, General Relativity and Cosmology, Classical Electrodynamics, Quantum Electrodynamics* and since academic year 2013–2014 also the course of *Mathematical Methods in Theoretical Physics* on Laurea Triennale. During a period 1998-17 I was a member of the Doctorate Council.

Below I list only the courses that I teach in last few years: [1]

A.A. 2020–2023

- QUANTUM ELECTRODYNAMICS (LM)
- ADVANCED QUANTUM FIELD THEORY (LM)
- METODI MATEMATICI DELLA FISICA I (LT)

A.A. 2019–2020

- QUANTUM ELECTRODYNAMICS (LM)
- PARTICLE PHYSICS (LM)
- METODI MATEMATICI DELLA FISICA I (LT)

A.A. 2018–2019

- QUANTUM ELECTRODYNAMICS (LM)
- METODI MATEMATICI DELLA FISICA I (LT)
- METODI MATEMATICI DELLA FISICA II (LT)

A.A. 2017–2018

- QUANTUM ELECTRODYNAMICS (LM)
- GENERAL RELATIVITY AND COSMOLOGY (LM)
- METODI MATEMATICI DELLA FISICA II (LT)

A.A. 2016–2017

- QUANTUM ELECTRODYNAMICS (LM)
- GENERAL RELATIVITY AND COSMOLOGY (LM)
- METODI MATEMATICI DELLA FISICA II (LT)

[1] LM=Laurea Magistrale (M.S. level), LT=Laurea Triennale (B.S. level)

Career Supervision

17 students of M.S. thesis:

G. Dvali and G. Devidze *(TSU 1987)*, R. Homeriki *(TSU 1988)*, G. Pola and L. Gianfagna *(Univ AQ 2000)*, N. Rossi *(Univ AQ 2004)*, A. Di Cecco and G. Di Panfilo *(Univ AQ 2006)*, P. Panci and A. Lepidi *(Univ AQ 2007)*, M. Babusci *(Univ AQ 2008)*, A. Addazi *(Univ Roma II 2013)*, B. Belfatto *(Univ AQ 2016)*, R. Beradze, I. Mantidze and T. Shengelia *(Univ AQ 2018)*, L. Pantskhava *(Univ AQ 2019)*

4 students of B.S. thesis:

G. D'Amico *(Univ AQ 2004)*, A. Maiezza and L. Di Luzio *(Univ AQ 2005)*, M. Crisostomi *(Univ AQ 2006)*

13 Doctorates Ph.D thesis:

A. Rossi *(Univ FE 1994)*, M. Giannotti *(Univ AQ 2002)*, P. Ciarcelluti *(Roma II 2003)*, L. Gianfagna and M. del Principe *(Univ AQ 2004)*, N. Rossi *(Univ AQ 2008)*, P. Panci *(Univ AQ 2011)*, G. Di Panfilo *(Univ AQ 2015)*, R. Biondi *(Univ AQ 2016)*, A. Addazi *(Univ AQ 2017)*, B. Belfatto *(GSSI – 2020)*, R. Beradze *(TSU – 2022)* M. di Giambattista *(Univ AQ – under preparation)*

12 Post-Doctoral Fellows:

Z. Tavartkiladze *(INFN FE 1996-97)*, D. Delepine *(LNGS 2000-01)*, A. Sakharov *(LNGS 2001-03)*, A. Galante *(Univ AQ 2001-05)*, P. Ciarcelluti *(Univ AQ 2004-06)*, F. Nesti *(Univ AQ 2004-09 and 2011-12)*, N. Rossi *(Univ AQ 2008-2011)*, D. Ejlli *(LNGS, 2014-16)*, A. Gazizov *(Univ AQ 2016-17, 2022-2023)*, R. Biondi *(Univ AQ 2016-19)* , P. Panci *(LNGS 2018)*, T. Vardanyan *(Univ AQ 2020-22), A. Maiezza (Univ AQ 2022-23)*

Among my ex-students most prominent is my first M.S. student and then collaborator – Gia Dvali – renowned world-class theorist, presently the Chair of the Particle Theory Division, Arnold Sommerfeld Centre in Ludwig-Maximlilians University of Munich, and Director of the Max-Planck Institute of Theoretical Physics, Germany.

Some of my former doctorates and postdocs are also well-known, as

Anna Rossi with a solid carrier and scientific record in Europe;
Maurizio Giannotti, presently full professor at the Barry Univ. (USA);
Fabrizio Nesti, presently associate professor at the Univ. L'Aquila;
Alexander Sakharov, presently researcher at CERN (Geneve);
Nicola Rossi, INFN researcher at LNGS (Italy);
Paolo Panci, presently associate professor at the Univ. Pisa;
Andrea Addazi presently associate professor at the Fudan Univ. (China);
Zurab Tavartkiladze, presently associate professor at the Ilia State Univ. (Georgia)

as well as younger rising researchers

Riccardo Biondi (presently post-doctoral fellow at Heidelberg and LNGS);
Benedetta Belfatto (presently-post doctoral fellow at SISSA).

Research activities

Coordination of Research Projects and Scientific Grants

PRIN: Research Projects of National Interest funded by MIUR

7 times winner of the PRIN grants as coordinator of the L'Aquila Unit:

- **PRIN 1999:** *biennal Grant No. 9902028315–004 "Astroparticle physics and supersymmetry" (26/11/1999 – 10/01/2002)*
- **PRIN 2002:** *biennial Grant No. 2002022592–006 "Phenomenology and particle astrophysics beyond the Standard Model" (16/12/2002 – 23/01/2005)*
- **PRIN 2004:** *biennial Grant No. 2004024710–002 "Particle phenomenology beyond the Standard Model and astroparticle physics" (30/11/2004 – 28/12/2006)*
- **PRIN 2006:** *biennial Grant No. 2006029094–003 "Theory and phenomenology of neutrinos and astroparticle physics" (09/02/2007 – 24/03/2009)*
- **PRIN 2008:** *biennial Grant No. 20084ZCK5J–004 "Astroparticle physics: neutrinos and dark side of the Universe" (22/03/2010 – 22/09/2013)*
- **PRIN 2012:** *triennial Grant No. 2012CPPYP7–007 "Theoretical Astroparticle Physics" (08/03/2014 – 03/05/2017)*
- **PRIN 2017:** *triennial Grant No. 2017X7X85K-004 "The Dark Universe: A Synergic Multimessenger Approach" – from Feb. 2019*

Coordination of Internanational Grants

- *Coordinator of the LNGS extended team for the European FP6 Network MRTN-CT-2006-035863 UniverseNet: "The origin of our Universe: Seeking links between fundamental physics and cosmology", Gran Sasso National Laboratories (2006-10)*
- *Scientific Coordinator of Science Ministry biennal Grant No. 02.740.11.5220 "Neutrino Oscillations" at JINR (Joint Institute of Nuclear Research), Dubna (2010-11)*
- *Scientific Coordinator of Science Ministry biennal Grant No. 14.U02.21.0913 "Physics of solar, reactor and geo-neutrinos" at JINR, Dubna (2012-13)*
- *Scientific Coordinator of Rustaveli National Science Foundation (SRNSF) triennal Grant DI-8-6-100/12 Dark matter and extra dimensions at the Tbilisi State University (2013-15)*
- *Scientific Coordinator of SRNSF triennal Grant Grant DI-18-335 New Theoretical Models for Dark Matter Exploration at the Tbilisi State University – from 2019*

Coordination of the INFN projects

- *Coordinator of the LNGS node for the INFN Research Project (Iniziativa Specifica) PI21: "Field Theories and Model Building of Elementary Particles" (1999–2014)*
- *Coordinator of the LNGS node for the INFN Research Project (Iniziativa Specifica) AAE: "Astro-Alte Energies" (2015-2021)*
- *Coordinator of the LNGS node for the INFN Research Project (Iniziativa Specifica) TASP: "Theoretical Astro-Particle Physics" since 2021*

International Collaborations

- *PI of the experiment at Institut Laue-Langevin (ILL), Grenoble, France, performed by a team of scientists from L'Aquila Univ, ILL and PNPI (Petersburg Nuclear Physics Institute) at the EDM beam line of PF2 facility of the Grenoble Scientific Reactor, for searching* $n - n'$ *oscillation, 2014*
- *NNBAR Collaboration member projecting new large scale experiment for the neutron–antineutron oscillation search at the ESS (European Spallation Source), Lund, Sweden*
- *NNprime Collaboration member for the search of neutron–mirror neutron oscillation* $n \rightarrow n'$ *at the ORNL (Oak Ridge National Laboratory), USA*
- *nEDM Collaboration member conducting new large scale experiment for the neutron–mirror neutron oscillation search at the PSI (Paul Scherrer Institute), Villingen, Switzerland, 2020-22*

Participation in Grant Reviewing and Evaluation Committees

- *Reviewer of several research projects for II stage evaluation for ERC advanced grants and ERC starting grants (5 projects reviewed from 2015 to 2020)*
- *Reviewing of research projects for NSF (National Science Foundation) USA (since 2016)*
- *Reviewing of research projects for Swiss National Science Foundation*
- *Reviewing of research projects for National Science Foundation of Poland (2015 and 2018)*
- *Reviewer for Rita Levi-Montalcini programme for the brain return in Italy (2021)*

Participation in Selection Committees

Participated several times in selection committees for the posts of full, associate and assistant professorships (Univ. L'Aquila, Univ. Ferrara, SISSA, Univ. Manchester)

Participated several times in different selection committees for postdoc position (assegno di ricerca) and for the Ph.D. fellowships at the University of L'Aquila

Participated many times in final evaluation commissions for Ph D Theses (Univ. L'Aquila, Univ. Ferrara, Univ. Naples, Univ. Parma, Univ. Roma II, SISSA-Triest)

Scientific Awards

- *Alexander von Humboldt fellowship, 1991*
- *Research award from the University of Sydney, Australia, 2015*
- *Diaspora Medal 2019 in Science, Enigma-2 programme funded by EU and National Science Foundation of Georgia*

Editor and Reviewer Activities

Member of the editorial board of Physics mdpi (Switzerland)
Reviewer in the following high IF Scientific Journals (in alphabetic order):

- *Astronomy & Astrophysics*
- *Astrophysical Journal*
- *Astroparticle Physics*

- *European Physics Journal C: Particles and Fields (distinguished referee 2012 & 2017)*
- *Europhysics Letters*
- *Journal of High Energy Physics (JHEP)*
- *Journal of Cosmology and Astroparticle Physics (JCAP)*
- *Journal of Physics G: Nuclear and Particle Physics*
- *Journal of Experimental and Theoretical Physics (JETP)*
- *Int. Journal of Modern Physics*
- *Modern Physics Letters*
- *Monthly Notices of Royal Astronomical Society (MNRAS)*
- *Nuclear Physics B*
- *Physics Letters B*
- *Physical Review D*
- *Physical Review Letters*

Organization of Conferences

Organizing committee member of the Gran Sasso Summer Institutes:

- *"Low Energy Neutrinos in Physics and Astrophysics" (1992)*
- *"From Particle Physics to Cosmology" (1993)*

and Chair of the organising committee of subsequent Summer Institutes:

- *"Massive Neutrinos in Physics and Cosmology" (1999),*
- *"Dark Matter and Supersymmetry" (2000),*
- *"New Dimensions in Astroparticle Physics" (2002)*
- *"Particles, Gravity and Cosmology" (2004)*
- *"Particle Physics and Astrophysics beyond the TeV Scale" (2005),*
- *"Frontiers in Astroparticle Physics" (2006)*
- *"Dark Matter and Gravity" (2007),*
- *"Astroparticle Physics at the Age of LHC" (2008)*

One of the principal organizers of annual Spontaneous Workshops (SW) "Hot Topics in Modern Cosmology", IESC Cargese, France, with D. Comelli (INFN Ferrara), A. Dolgov (Novosibirsk Univ.) and R. Triay (Univ. Marseille) – **13** *workshops in a period from 2007 to 2019*

Chair of the organizing committee of the Topical Workshop "Hot Topics of Astroparticle Physics" in Gran Sasso National Laboratories, Sept. 2015, with invited lecturers as R. Barbieri (SNS Pisa, Italy), A. Dolgov (NSU, Russia), A. Vainshtein (TPI, USA) etc.

Organizer of the INFN "Astroscuola" in Otranto, Sept. 2001, with G.L. Fogli (Univ. Bari), A. Masiero (Univ. Padua) and G. Miele (Univ. Naples)

Principal organizer of Topical Workshop INT-17-69W "Neutron–antineutron oscillations: appearance, disappearance and baryogenesis", at the Institute of Nuclear Theory, Seattle (USA), Oct. 2017, with K.S. Babu (Univ. Oklahoma) and Y. Kamyshkov (Univ. Tennessee)

One of the principal organizers of the NORDITA Workshop "Particle Physics with Neutrons at the ESS", responsible for nn' programme, Stockholm, Sweden, 10-14 Dec. 2018

International Advisory Committee member of the following Conferences:

– *Int. Conference on Standard Model and Beyond (SMAB), Tbilisi, Georgia, 1996*
– *Int. Conference "Fundamental Physics with Neutrons", St.Petersburg, Russia, 2007*
– *Int. Conference TAUP 2009, Rome, Italy, 2009*
– *2nd Conference on Baryon and Lepton Violation (BLV 2011), Gatlinburg, USA, 2011*
– *Int. Conf. "Dark matter, dark energy and their detection", Novosibirsk, Russia, 2013*

Invited talks at International Conferences, Schools & Seminars

I presented invited talks at more than 150 international and more than 50 national schools and conferences, and delivered more than 300 invited colloquia and seminars at universities and scientific centres in Italy, US, UK, Germany, France, Switzerland, Spain, Austria, Australia, Denmark, Finland, Sweden, Portugal, Poland, Israel, Russia etc.

Main Areas of My Scientific Interests

Particle phenomenology: *Phenomenological aspects of electroweak symmetry breaking and Higgs sector, fermion masses and mixing, CP-violation, strong CP-problem and axion, neutrino mass models and neutrino oscillations, spontaneous lepton number violation, neutrinoless 2beta decay, neutrino propagation in medium, solar neutrinos and neutrinos from supernovae, astrophysical neutrinos, models of sterile neutrinos, dynamical symmetry breaking, radiative mass generation, supersymmetry and supersymmetric phenomenology, supersymmetry breaking mechanisms, supersymmetric Higgs, sparticle masses and flavor/CP problem, R-parity violation, grand unification and gauge hierarchy problem, grand unified models, baryon number nonconservation and proton decay, neutron–antineutron and neutron–mirror neutron oscillations, non-perturbative dynamics and dualities, string-inspired phenomenology, anomalous $U(1)$ symmetry and its applications, gauge theories in extra dimensions, gravity in extra dimensions and branes, bigravity/multigravity theories, Lorentz violation and large distance modification of gravity.*

Astroparticle physics: Cosmology and Astrophysics: *Cosmological evolution and inflation, baryogenesis and leptogenesis mechanisms, primordial nucleosynthesis and its implications for the particle phenomenology, dark matter candidates, decaying, self-interacting and dissipative dark matter, dark matter from parallel gauge sectors as e.g. mirror matter: dark matter and cosmological large scale structure, formation of galaxy halos, stellar formation and evolution, cosmological and astrophysical implications of light pseudoscalars: axion, majoron, etc., late decaying massive particles and cosmic photon background, particle propagation in medium, ultra high energy cosmic rays and cosmogenic neutrinos, solar and atmospheric neutrinos and neutrinos from supernovae, active-sterile neutrino oscillations, compact astrophysical objects as neutron stars and quark stars, gamma ray bursts, supernovae and gravitational waves, cosmological implications of the gravity modifcation at large distances.*

Short summary of main scientific results

(More detailed description of some main results are given in **Appendix 1.***)*

- **1983:** *Universal seesaw mechanism for the fermion mass generation, today a principal tool in fermion mass model building*
- **1983:** *Concept of gauge family SU(3) symmetry; the role of flavon fields in the formation of fermion mass spectrum and mixing*
- **1987:** *Effect of matter induced neutrino decay*
- **1989:** *Higgs as Goldstone boson mechanism in SUSY GUT: SU(6) model*
- **1990:** *New axion being also a majoron and familon and cosmological effects*
- **1992:** *Inverse hierarchy model for fermion masses and mixing*
- **1992:** *Planck scale effects on neutrino masses, and origin of sterile neutrinos from a parallel dark sector*

- **1995:** *Natural origin of sterile neutrinos as neutrinos of parallel mirror sector*
- **1996:** *Minimal Flavor Violation in SUSY and the ways of its realization*
- **1996:** *Asymmetric mirror dark matter as a sort of dissipative atomic dark matter*
- **1998:** *Gamma Ray Bursts (GRB) & supernova explosions by heavy axion (Axidragon)*
- **2001:** *Solving strong CP-problem with heavy axion from mirror sector*
- **2001:** *Cosmology of mirror world from inflation to recombination; viability of mirror matter as dark matter*
- **2001:** *Cogenesis mechanism explaining baryon & dark matter fractions*
- **2002:** *LEP limits on non-standard neutrino interactions; proposal of their search with Borexino experiment*
- **2003:** *GRB–supernova association and conversion of neutron stars into quark stars*
- **2003:** *Viability of dissipative mirror dark matter in the light of CMB and LSS constraints*
- **2004:** *Generation of cosmological magnetic fields at recombination epoch*
- **2005:** *Supersymmetric Little Higgs and supersymmetric twin Higgs*
- **2005:** *Neutron-mirror neutron oscillation can be faster than the neutron decay*
- **2007:** *Lorentz-violation in bigravity and consistent picture of massive graviton*
- **2009:** *Resonant enhancement of neutron-mirror neutron oscillation by magnetic field*
- **2010:** *Mirror bigravity and rotation curves in galaxies*
- **2012:** *Evidence of* 5σ *magnetic anomaly in experiments on* $n-n'$ *conversion*
- **2012:** *Mirror dark matter and the origin of extreme energy cosmic rays*
- **2013:** *Generation of galactic magnetic fields by mini-charged dark matter*
- **2013:** *Decaying dark matter as the origin of high energy neutrinos (IceCube)*
- **2015:** *Decaying dark matter alleviates the cosmological tensions in* H_0 *and* σ_8
- **2015:** *Viability of SUSY at TeV scale in the light of Grand Unification*
- **2016:** *Mirror dark matter as the origin of cosmic antimatter*
- **2016:** *Baryonic Majoron and neutron–antineutron transition*
- **2016:** *Baryophotons vs. experimental limits on neutron–antineutron oscillations*
- **2017:** *DAMA anomaly and direct detection of mirror dark matter*
- **2018:** *New experimental bounds on* $n-n'$ *oscillation – results are included in PDG 2018*
- **2018:** *Neutron dark decay: explanation of neutron lifetime anomaly via* $n \to n'$ *decay*
- **2018:** *Explanation of neutron lifetime problem via* $n-n'$ *oscillations*
- **2019:** *Evidence of* 4σ *tension in the CKM unitarity and possible explanations*
- **2020:** *Possibility of neutron conversion into antineutron using mirror world as a shortcut*

Some of main scientific results, in more details

Family Symmetry, Flavon Fields and Fermion Masses and Mixing. *I developed the concept of chiral horizontal flavor symmetry, $SU(3)$ or $U(3)$, unifying the fermion families and studied the role of its breaking in the formation of fermion spectrum and mixing. Namely, I suggested that the quark and lepton mass spectrum and mixing pattern reflects the breaking pattern of the family symmetry via effective couplings that project the VEV structure and hierarchy of the horizontal scalars breaking the flavor symmetry (now coined as flavons) on the fermion Yukawa terms, opening a possibility for the predictive model building for fermion masses and mixing. In my first works [124, 121] these effective so called "projective couplings" were obtained by integrating out superheavy scalars in mixed representations. (In a particular realization in the context of $SU(5)$ grand unification, by special selection of representations of the latter scalars, a mass matrix pattern was obtained which was similar to the ansatz suggested an year after by B. Stech and coined after as "Stech mass matrix".) In the following works (refs. [117, 120] I have shown that it was more natural to obtain these effective operators via integrating out the superheavy fermions arguing that in this way one would avoid several (and severe) problems of naturality related to the gauge hierarchy, flavor changing in neutral currents, etc. Nowadays the flavor symmetry concept and mass generation mechanism are generally accepted for the flavor models and are widely used as a principal tool for the model building. N.B. A similar idea was independently suggested by H. Nielsen and C. Frogatt (before me) and S. Dimopoulos (after me). However, they used an abelian flavor symmetry $U(1)$ and related the fermion mass hierarchy to the different $U(1)$ charges between families rather than to the VEV hierarchy of the flavons breaking non-abelian $SU(3)$ symmetry.*

Universal Seesaw Mechanism. *In 1983 I suggested, in the context of $L-R$ symmetric model $SU(2)_L \times SU(2)_R \times U(1)$ the mass generation mechanism of the quarks and charged leptons via their mixing to the superheavy vector-like fermion species (ref. [120]), without involving Higgs bi-doublets and triplets but only Higgs doublets. In 1987 this mechanism was rediscovered in the independent works by D. Chang and R.N. Mohapatra, by A. Davidson and K. Wali, and by S. Rajpoot, after which it is known in the literature as "universal seesaw" mechanism while this type of $L-R$ models are named as minimal left-right symmetric models*

Natural axion from family symmetry. *The Peccei-Quinn symmetry $U(1)_{\rm PQ}$ can emerge in a natural way as accidental global symmetry associated with the horizontal gauge symmetry $SU(3)$ between fermion families. The axion emerging in this way, will have properties of familon (flavor changing couplings) and majoron (couplings with neutrinos). Properties of such axion was studied in several works with M. Khlopov in years 1990-1991. This particle, coined as archion in fact represents a 'trinity' of known Goldstone bosons (axion, familon, majoron) which before were considered in the literature as different particles originated from spontaneous breaking of different* ad hoc *global symmetries.*

Neutrino Decay in Matter. *In 1987, together with M. Vysotsky, I demonstrated that the matter effects could induce the decay of neutrino into antineutrino or vice versa, via emission of massless particle as e.g. majoron, even if the neutrino is stable in the vacuum [113].[2] Then in 1988 I studied implications of such matter induced decays for the supernova neutrinos in a work with A. Smirnov [111]. Along with the other effects in matter: neutrino oscillation (MSW effect) and the neutrino spin-flavor precession, the matter induced neutrino decay may be tested for the solar neutrinos or on the neutrinos of the astrophysical origin [83, 90, 94, 95] and could provide peculiar possibilities for testing the hidden features of the neutrino physics, and with some good luck, could shade a light on the origin of the lepton number breaking and*

[2] This work was also reprinted in Volume "Solar Neutrinos: The First Thirty Years", pp. 288-294. ed. J.N. Bahcall, Addison-Wesley, The Advanced Book Program, 1993.

the neutrino masses.

Goldstone Boson Mechanism and GIFT SU(6) Model. *In 1989, together with G. Dvali, I proposed natural "Higgs as Goldstone boson" mechanism for solving the grand hierarchy and doublet-triplet splitting problem in the context of supersymmetric grand unification, making use of the local $SU(6)$ symmetry for the GUT and accidental global symmetry $SU(6) \times SU(6)$ (ref. [110], see also ref. [80] which recovers its philosophy in more details). In fact, our model is a natural realization of the conjecture by K. Inoue, A. Kakuto, T. Takano (1987) and A.A. Anselm, A.A. Johansen (1988), coined by Anselm as GIFT (Goldstones Instead of Fine Tuning). However, at the level of the $SU(5)$ GUT this conjecture was equivalent to several fine tunings, and in addition it was controversial in the Yukawa sector. Our mechanism, instead, does not require any fine tuning, it solves naturally mu-problem and can be even rendered stable against the Planck scale corrections. Interestingly, the Goldstone character of the Higgs has far going consequences also for the Yukawa sector and fermion masses: it was demonstrated in ref. [84] that the only particle that can have an order 100 GeV mass can be Top quark while all other species must be at least order of magnitude lighter. Under some additional assumptions, the interesting mass relations can be obtained also between the masses of lighter quarks and leptons (ref. [78]) Without no doubt, if the concept of SUSY GUT will remain alive in the post LHC physics, than the GIFT mechanism will play a role as a most elegant and natural mechanism among the known solutions for the doublet-triplet splitting.*

Supersymmetric Little Higgs. *The Higgs as Goldstone boson mechanism can be very promising also in view of the Fine Tuning problem in the supersymmetric Standard Model, for solving of so called little hierarchy problem. In a work with A. Falkowski, S. Pokorski and P. Chakowski, we have shown, on the example of a minimal extension of the MSSM, that the supesymmetry and accidental global symmetry nicely collaborate to provide a double protection of the Higgs potential stability, and the electroweak symmetry breaking require practically no Fine Tuning (ref. [41]) After us, the same conclusions were reached in works by T.S. Roy, M. Schmalz, and by C. Csaki, M. Marandella, Y. Shirman, A. Strumia. In fact, this mechanism remains one of the few remaining possibilities for the supersymmetric Higgs naturality in the light of increasingly tight limits on the spectrum of superpartners.*

Soft Supersymmetry Breaking and Minimal Flavor Violation. *In 1996 I have shown that the concept of U(3) family symmetry can greatly help not only for understanding of quark and lepton mass/mixing spectrum, but also of the pattern of the soft SUSY breaking terms (refs. [67, 61, 71]). Namely, all 3×3 matrices of SSB parameters can be directly expressed in terms of 3×3 Yukawa matrices of respective fermions, so that all dangerous flavor-changing effects can be naturally suppressed. Such a situation was conjectured some years after by G. D'Ambrosio, G.F. Giudice, G. Isidori and A. Strumia (2002) and then the concept was coined in the literature as "minimal flavor violation". My model, to my knowledge, remains the one where the minimality of flavor violation can be consistently realized, and in addition it can still meet the Higgs naturality constraints strongly tightened after the LHC data.*

Natural and Predictive Grand Unified Models. *I tried to built consistent and complete SUSY GUT models which could lead to interesting predictions for the quark and lepton masses and mixing, including that of neutrinos. Some years ago this activity was in fashion, though now it is not clear what prospectives it will have if SUSY will not be discovered at the LHC. Nevertheless, I hope that fascinating predictive potential of the SUSY GUTs will not be lost in wain. In particular, suggested supersymmetric grand unification, based on $SU(5)$ or $SO(10)$, using discrete and $U(1)$ flavor symmetries as e.g. in refs. [69, 70, 77] or more interesting $SU(3)$ symmetry between families, as in e.g. refs. [42, 60, 64, 67]. My approach to built such models was complex, requiring that they must resolve the doublet-triplet splitting problem without Fine Tuning, must naturally suppress Triplet Higgsino mediated $D = 5$ operators for rendering* *proton long-lived enough, must provide the pattern of soft SUSY breaking terms satisfying the minimality of flavor violation, and finally, must be constructive in predicting relations between the fermion masses and mixing parameters.*

Gamma Ray Bursts and Supernova Explosions. *I suggested, with A. Drago, the model of the Gamma Ray Bursts and supernove explosions triggered by emission of heavy axion-like particle (Axidragon) at the gravitational core collapse of massive star or neutron star merger [62]. Consistent model of such a heavy axion was presented in ref. [58]. Interestingly, such an axidragon, with mass order MeV and Peccei-Quinn scale order thousand TeV cannot be excluded by astrophysical and cosmological limits and they are at the borderline of the experimental observability in the future reactor or beam dump experiments. Further, with A. Drago et al., we elaborated a consistent mechanism of the GRBs on the basis of delayed conversion of the neutron star to a quark star [48].*

Bi-Gravity and Spontaneous Lorentz-Breaking. *The picture of Lorentz symmetry breaking in bimetric theories where two metrics couple separately two systems of matter was studied in ref. [37] which, from the one hand, is an interesting tool for modelling the massive gravity in the limit when the second metric is static, and on the other hand can lead to interesting physical phenomena as propagation of the gavitational waves with speed different from speed of light. Spherically symmetric solutions in a certain class of these models were discussed in [36], and cosmological consequences of the respective large distance modification of gravity, in particular for the galactic rotational curves, were discussed in refs. [31, 32].*

Non-Standard Neutrino Interactions. *Surprisingly, the experimental data on the electron neutrino or antineutrino interactions with electron still allow large enough deviations from the Standard Model prediction and leave a large space for non-standard interactions – in fact their constants can be comparable to the Fermi constant. Together with A. Rossi, we have shown that the LEP data on nu-nu-gamma production in electron positron scattering can provide stronger limits than the direct measurements of $\nu_e - e$ cross sections [50]. In the following paper [51] we suggested that, in view of the mono-energetic character of the solar ^{7}Be neutrino fluxes, non-standard interactions of ν_e or ν_τ could provide a characteristic deformations of the recoil electron spectrum in the Borexino experiment, which renders it to be a competitive and promising tool for constraining the neutrino non-standard couplings.*

Origin of Sterile Neutrinos. *In 1992, I proposed a natural mechanism to have sterile neutrinos as light as the ordinary ones and with a substantial mixing with the latter, since the candidates Goldstino, axino or dilatino did not seem to me as natural candidates. Our scenario considers sterile neutrinos as neutrinos from a parallel shadow sector having the spontaneously broken electroweak-like symmetry similar to the Standard Model, but with the VEV of its Higgs H' different from the VEV of ordinary Higgs doublet H, and perhaps different number of families. Then such neutrinos must be massless by exactly the same reasons as ordinary ones – the mass terms of the latter emerge from effective operators $(1/M)LLHH$ with large cutoff scale M, bilinear in Higgs doublet H, while the ordinary-sterile neutrino mixing would emerge from the analogouls operators $(1/M)LL'HH'$ (ref. [92]). The idea was further developed in the context of parallel mirror sector in a paper with Mohapatra [76] where it was demonstrated that in such a frame one could naturally incorporate sterile mirror neutrinos for solving the existing puzzles in neutrino physics. In the next paper with A. Dolgov and R.N. Mohapatra [74] we have shown that the concept of mirror sectors, perhaps with different electroweak scale which transforms mirror sector to a shadow sector with predictable properties, can be cosmologically consistent (in agreement with the BBN limits) if one considers that after the inflation ordinary and mirror sectors are reheated in asymmetric way, with the different temperatures. We also discussed possible models of asymmetric reheating, discussed possible mass spectrum of shadow particles and several interesting cosmological implications of such a mirror/shadow sector:*

shadow neutrinos as warm dark matter, mirror/shadow baryons as (asymmetric) dark matter and mirror stars as MACHOs.

Dark Matter as Mirror Matter and Baryon - Dark Matter Cogenesis. *A considerable part of my research I devoted to a parallel mirror world which is an exact duplicate of our matter sector, with particle physics exactly identical to that of ordinary particles. This concept was put forward many years ago by Lee and Yang, and by Kobzarev, Okun and Pomeranchuk. I added two important points to this concept.*
(1) MIRROR BARYONS CAN BE A DARK MATTER. In a work with D. Comelli and F. Villante [59] we studied the whole time history of the mirror sector, starting from the inflation to epochs of baryogenesis, nucleosynthesis and recombination and demonstrated that mirror baryons can provide an interesting and testable candidate for dark matter if the mirror sector is few times colder than ordinary sector. Precise calculations of the effects of such kind of dark matter on the CMB and large scale structure were taken in ref. [45] and it was demonstrated that at the linear epoch of the perturbation growth mirror baryons behave perfectly as cold dark matter if mirror sector is colder at least by factor 3 so that photons in that sector decouple prior the matter-radiation equality epoch. On the other hand, such matter can also exhibit a Silk damping of small structures, with testable predictions, in particular for dark matter distribution features in the galaxies.
(2) CO-GENESIS OF BARYON AND DARK MATTER. I proposed *(with L. Bento) a new baryogenesis mechanism which is based the leptogenesis scenario via out-of-equilibrium, B-L and CP violating scattering processes $LH \to L'H'$ etc. that convert ordinary leptons into the hidden mirror sector leptons. This mechanism generates at the same time also baryon asymmetry in dark parallel sector so that mirror baryons appear to be a dark matter with a cosmological mass fraction equal or larger than that of ordinary baryons [53]. In the following paper [46] I solved the Boltzmann equations for the baryon and dark matter densities in such a co-genesis scenario of and calculated the mass ratio between the ordinary and mirror matter fractions as $1 < \Omega'_B/\Omega_B < 10$ for a realistic cosmological scenarios.*

Neutron – Mirror Neutron Oscillation. *I proposed (with L. Bento) that the neutron (n) oscillation phenomenon into its mass degenerate partner from parallel world, mirror neutron (n'). We have shown neither the present experimental limits nor astrophysical limits can exclude $n - n'$ oscillation with timescales order few seconds [40]. The possibility of such a fast process with baryon number violation, in fact faster than the neutron decay itself, is rather intriguing in itself, and it can have spectacular implications for the TeV scale Physics at the LHC, for the baryon matter and dark matter cogenesis in the Early Universe, for Big Bang nucleosynthesis, for neutron stars [40], and, rather interestingly, for the propagation of the ultra high energy cosmic rays at cosmological distances [30, 39]. On the other hand, this effect is testable in laboratory experiments with cold and ultra-cold neutrons which originated intensive experimental search conducted by several experimental groups at the Grenoble Research Reactor, Institute Laue-Langevin (France) and at the Munich Research Reactor (Germany). The data of first experiment (by the PSI group of Daum) have shown a surprising dependence of the neutron storage time on the direction of the magnetic field, with $B = 0.6$ Gauss, at about 3σ level. In ref. [29] I have shown that such effect is possible and it must have a resonant character, if also the mirror magnetic field is present in experimental site, which can be in principle generated by the rotation of dark mirror matter captured by the Earth. The last experiment, conducted by the group of A. Serebrov at the ILL, have shown a 5σ effect for measurements at $B = 0.2$ Gauss, and no deviation for $B = 0.4$ Gauss, as we observed by analyzing with F. Nesti in ref. [29] direct experimental records kindly provided to us by A. Serebrov. Needless to say, that if these results will be confirmed by the next experments, most remarkably via the effect of the neutron regeneration $n \to n' \to n$ [16], then its importance for the fundamental particle physics, astrophysics and cosmology hardly can be overestimated.*

Publications of Zurab Berezhiani in Peer Reviewed Journals

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