

Foreword

Training Schools of the COST Action CA18108 "Quantum gravity phenomenology in the multi-messenger approach" (QG-MM)

These lecture notes are one of the numerous results and legacies of the COST Action CA18108 "Quantum gravity phenomenology in the multi-messenger approach" (QG-MM). It was established at the confluence of two important scientific developments, namely quantum gravity phenomenology and multi-messenger astrophysics. Possibly unlike any other scientific pursuit, the search for the theory of quantum gravity was for a long time defined by a complete absence of experimental investigations. The principal reason was the expectation that the domain of quantum gravity, the energy scale at which it is manifested, is the Planck scale ($E_{\text{Pl}} \approx 10^{28}$ eV), so vastly beyond the direct reach of experimental facilities. The idea that astroparticles, i.e. cosmic rays, gamma rays, and neutrinos, emitted at ultra-high energies from astrophysical sources would be able to probe the microscopic structure of spacetime gave birth to the phenomenology of quantum gravity. These messengers traverse astronomical distances from their sources to our detectors, and the tiny effects of quantum gravity on their propagation can accumulate to become measurable. Astroparticles, together with gravitational waves, are often referred to as cosmic messengers. Quasi-simultaneous observations of the same astronomical event with different messengers marked the dawn of the multi-messenger era of astronomy, which is the second advancement on which the QG-MM project and community was established.

Main goals of QG-MM

QG-MM had two main goals. Firstly, to bring together and join forces of theorists, phenomenologists, and experimentalists in search of physical phenomena characteristic of quantum gravity. A second, although nonetheless important objective was to form a generation of scientists that will be competent in the interdisciplinary expertise that is needed in the effective search of quantum gravity footprints in the production, propagation and detection of cosmic messengers. The most important tool for achieving the second objective were training schools aimed at master and doctoral students and young postdocs. When selecting topics and lecturers, we sought to cover all the relevant topics on classical and quantum gravity and multi-messenger astronomy and astrophysics, while maintaining a balance between theoretical and experimental approaches.

The QG-MM Training Schools

There were three QG-MM Training Schools. The lecture notes of the First Training School were published under "School on Quantum Gravity Phenomenology in the Multi-Messenger Approach" as part of the Corfu Summer Institute 2021 "School and Workshops on Elementary Particle Physics and Gravity" edition¹. The lecture notes of the Second and Third Training schools are published

¹<https://pos.sissa.it/406/#session-4469>

in this issue of *PoS*. In addition to these lecture notes, the videos of lectures are available from the Action web site². All the events were organised as activities of the COST Action CA18108 and supported by COST. They served to establish a new research network.

First Training School (Corfu Summer Institute, Corfu, Greece, 27 Sep – 5 Oct 2021)³

Organising committee: José Manuel Carmona (University of Zaragoza, Spain), Armando di Matteo (INFN Turin, Italy), Goran Djordjević (University of Niš, Serbia), Giulia Gubitosi (University of Napoli "Federico II" & INFN, Italy), Nikolaos Mavromatos (NTU Athens, Grece & King's College London, UK), Flavio Mercati (University of Napoli "Federico II" & INFN, Italy), Carlos Pérez de los Heros (Uppsala University, Sweden), Christian Pfeifer (ZARM, University of Bremen, Germany), Emmanuel Saridakis (National Observatory of Athens (IAASARS), Grece), Tomislav Terzić (University of Rijeka, Croatia).

Lecturers and courses

- José Ignacio Illana (University of Granada, Spain)
Quantum field theory and the structure of the SM
- Tommaso Dorigo (Padua University, Italy)
Statistics
- Renate Loll (Nijmegen University, IMAPP, Netherlands)
Introduction to fundamental concepts in quantum gravity
- Gianluca Calcagni (Instituto de Estructura de la Materia, Madrid, Spain)
Cosmology
- Maurizio Spurio (Bologna University and INFN Bologna, Italy)
Astrophysical sources and acceleration mechanisms
- Elisa Prandini (INFN Padua, Italy)
High-energy photons: propagation and detection
- Denise Boncioli (L'Aquila University, Italy)
Cosmic rays: propagation and detection
- Mariam Tórtola (Valencia University and IFIC, Spain)
Neutrino physics
- Jerzy Kowalski-Glikman (Wroclaw University, Poland)
Doubly special relativity and relative locality

²<https://qg-mm.unizar.es/publications/>

³<https://indico.capa.unizar.es/event/17/>

Second Training School (Faculty of Physics, University of Belgrade, Serbia, 3 – 10 Sep 2022)⁴

The School was held within the broader framework of the program of the 11th Congress of the Balkan Physics Union (BPU11), with partial time and program overlaps with COST CA18108 Workshop on theoretical aspects of quantum gravity, SEENET-MTP Assessment Meeting and Workshop on Theoretical and Mathematical Physics 2022 – BWAM22, and CERN — SEENET-MTP — ICTP PhD School Gravitation, Cosmology and Astroparticle Physics (BS2022). This enabled positive synergistic, organizational and financial effects, and greatly contributed to the inclusive goals of the COST program and CA18108. The School was co-organized and by the Faculty of Physics, Belgrade and SEENET-MTP Centre, Niš, Serbia, and co-funded by the co-organizers and by the CERN-SEENET-ICTP PhD Training program.

Organising committee: José Manuel Carmona (University of Zaragoza, Spain), Armando di Matteo (INFN Turin, Italy), Marija Dimitrijević Ćirić (University of Belgrade, Serbia), Goran Djordjević (University of Niš, Serbia), Rodrigo Gracia Ruiz (IPHC Strasbourg, France), Giulia Gubitosi (University of Napoli "Federico II" & INFN, Italy), Nikola Konjik (University of Belgrade, Serbia), Milan Milošević (University of Niš, Serbia), Carlos Pérez de los Heros (Uppsala University, Sweden), Christian Pfeifer (ZARM, University of Bremen, Germany), Tomislav Terzić (University of Rijeka, Croatia).

Lecturers and courses

- Oleg Antipin (Ruđer Bošković Institute, Croatia)
Effective field theories and the standard model extension
- Enrico Barausse (SISSA, Italy)
Gravitational waves: theory and detectors
- Julien Bolmont (Sorbonne University, LPNHE, France)
Gamma-ray data collection, calibration and analysis for LIV studies
- Roberto Emparan (University of Barcelona, Spain)
Physics of black holes
- Antoine Kouchner (APC, Paris, France)
Detection and phenomenology of cosmic neutrinos
- Marko Simonovic (CERN, Switzerland)
Observational cosmology
- Patrizia Vitale (University of Naples Federico II, Italy)
Noncommutative field theory

⁴<https://indico.capa.unizar.es/event/23/>

Third Training School (Pałac Wojanów, Poland, 12 – 21 Feb 2023)⁵

This edition was held as a joint 59th Winter School of Theoretical Physics and Third COST Action CA18108 Training School in Pałac Wojanów, Poland from 12 to 21 February 2023. It was co-organised by the Institute of Theoretical Physics of the University of Wrocław, Poland, and co-funded from the state budget funds within the programme of Polish Ministry of Education and Science titled "Doskonała Nauka", project number DNK/SP/548521/2022. It was also organised under the auspices of the Polish Society on Relativity.

Organising committee: José Manuel Carmona (University of Zaragoza, Spain), Remigiusz Durka (University of Wrocław, Poland), Giulia Gubitosi (University of Napoli "Federico II" & INFN, Italy), Jerzy Kowalski-Glikman (University of Wrocław, Poland), Christian Pfeifer (ZARM, University of Bremen, Germany), Giacomo Rosati (University of Wrocław, Poland), Tomislav Terzić (University of Rijeka, Croatia), Tomasz Trzeźniewski (University of Wrocław, Poland).

Lecturers and courses

- Giovanni Amelino-Camelia (University of Naples "Federico II", Italy)
Quantum gravity phenomenology at the dawn of multi-messenger astronomy
- Sami Caroff (Laboratoire d'Annecy de Physique des Particules (LAPP), France)
Search for Lorentz Invariance Violation with time-lag on gamma-ray Cherenkov Telescope data: From the data to the time lag constraints
- Luca Ciambelli (Perimeter Institute, Canada)
Cornering quantum gravity
- Andrea Maselli (Gran Sasso Science Institute (GSSI), Italy)
Astrophysical black holes: theory and observations
- Emmanuel Saridakis (National Observatory of Athens (IAASARS), Greece)
Modified gravity theories
- Benjamin Wandelt (Institut d'Astrophysique de Paris (IAP), France)
Cosmology: observations

The future of QG-MM

The COST Action CA18108 ended on 13 September 2023. However, the activities within the quantum gravity phenomenology community are not stopping with the Action. A fifth Annual Conference and a fourth Training School, together with additional meetings and workshops, are already being organised. Therefore, these lecture notes are a result of the COST Action CA18108, but the true legacy thereof is still in the making.

⁵<https://indico.capa.unizar.es/event/30/>