Spacetime Physics

1. Analogue Gravity in Dielectric Media.

Analogue gravity consists in all those approaches whose aim is to reproduce in the laboratory, as faithfully as possible, some classical or quantum realisations of nontrivial phenomena involving gravity that usually cannot be tested in a real gravitational situation. Its origin can be identified with a paper by W. Unruh, who in 1981 proved that the linear perturbations of the steady flow of a perfect barotropic fluid are perfectly described by the relativistic wave equation of scalar field on a nontrivial curved spacetime background, whose precise geometry is determined by the exact unperturbed configuration. In particular, event horizons can be generated by allowing the fluid to pass from subluminal to superluminal regimes. Quantising the linearised perturbation one thus expects the analogue of the Hawking radiation phenomenon in the presence of horizons. Indeed, the Hawking effect is the prototype of the object of study in analogue gravity, since it has no hope of being detected in astrophysical observations. This is not however the only one, and a plethora of other possible effects can be considered, including classical and quantum effects in cosmological models. Moreover, from 1981 up to now, several different analogue systems have been introduced, for example in BEC, in condensed matter systems, and so on.

Reference papers

[1] F. Belgiorno, S. L. Cacciatori, F. Dalla Piazza and M. Doronzo, *Hopfield-Kerr model and analogue black hole radiation in dielectrics,* Phys. Rev. D **96** (2017) no.9, 096024.

[2] M. Tettamanti, S. L. Cacciatori and A. Parola, "Quantum quenches, sonic horizons and the Hawking radiation in a class of exactly solvable models," Phys. Rev. D **99** (2019) no.4, 045014.

2. Black Holes in Supergravity, Attractors and AdS/CFT.

Black holes in supergravity and in quantum gravity theories represent more than simply particular solutions of the (classical) equations of motion, since, at least as a residual supersymmetry is left unbroken, they provide perturbatively stable solutions around which testing quantum and/or stringy corrections, verifying the AdS/CFT correspondence, holography and so on. In this context, we are interested in looking for complete classifications of BPS solutions in $N = 2$, $D = 4$ supergravity theories, as well as studying the attractor mechanism for black holes in supergravity theories, including exceptional (magic) supergravities and gauged supergravities. In particular, we are interested in determining supersymmetric black holes in AdS_4, with non-constant scalar fields, for various choices of scalar potential. This is particularly interesting in relation to the attractor mechanism in gauged supergravity. In this case, indeed, one can show the presence of flat directions in the black hole potential so that, differently from the ungauged case, the moduli on the horizon are not completely specified by the charges. Still, the entropy remains fixed by the charges.

Reference papers

[1] D. Astesiano and S. L. Cacciatori, “De sitter magnetic black hole dipole with a supersymmetric horizon,” JHEP **12** (2021), 049

[2] D. Astesiano, S. L. Cacciatori and A. Marrani, “Black hole attractors and U(1) Fayet-Iliopoulos gaugings: analysis and classification,” JHEP **04** (2022), 099

3. Super geometry

A formulation of superstring theory based on first principles is still lacking. In particular, after several years of intensive effort, perturbative calculations in string theory have been systematically realised only up to genus two. The reason is that the geometry of the moduli space of super Riemann surfaces (underlying the stringy geometry) is far to be trivial, as it has been shown in a recent paper by R. Donagi and E. Witten. This has originated a new ferment in studying super geometry from a rigorous viewpoint. We are interested in this line of research.
We are particularly interested in the development of all mathematical tools necessary to overcome the problem of computation of super-string amplitudes at any genus. This involves developing a deep understanding of super geometry, the geometry of varieties involving fermionic coordinates, their cohomologies, and intersection theory, both in generic cases and for the specific case of moduli spaces of super Riemann surfaces with NS or R punctures. This includes the search for a satisfactory theory of pseudo-forms, and its possible connection to loop space geometry and cohomology.

Reference papers

[1] S. L. Cacciatori, S. Noja and R. Re, “Non-projected Calabi–Yau supermanifolds over $\mathbb{P}^2$,” Math. Res. Lett. **26** (2019) no.4, 1027-1058

[2] S. L. Cacciatori, S. Noja and R. Re, “The Unifying Double Complex on Supermanifolds,” Doc. Math. 27, 489-518 (2022)

[3] S. L. Cacciatori and B. Güneysu, “Odd characteristic classes in entire cyclic homology and equivariant loop space homology,” J. Noncommut. Geom. **15** (2021) no.2, 615-642

4. General relativistic dynamics of galaxies.

Most of the observational tests in the physics of Cosmo reveal important deviations from Newtonian dynamics applied to visible matter. This problem is usually solved by two main different approaches. One is the hypothesis of the existence of some very weakly interacting extra matter, dark matter, while the second involves modifications of the Newtonian/General relativistic dynamics. An estimation of linearised effects instead leads to the conclusion that General Relativity plays no role in such kinds of deviations. However, a systematic investigation of the full general relativistic equations in the description of the galactic dynamics, including non-linear effects, is still lacking. The goal of our investigations in Como is to fill this gap, in order to understand the true role of General Relativity in galactic dynamics, without any specific aim to prove or disprove the existence of dark matter or the necessity of novel dynamics.

Reference papers

[1] D. Astesiano, S. L. Cacciatori, V. Gorini and F. Re, "Towards a full general relativistic approach to galaxies," Eur. Phys. J. C **82** (2022) no.6, 554

[2] D. Astesiano, S. L. Cacciatori, M. Dotti, F. Haardt and F. Re, "Re-weighting dark matter in disc galaxies: a new general relativistic observational test," [arXiv:2204.05143 [astro-ph.GA]].

5. Non-perturbative methods in nuclear physics.

One of the most interesting and difficult problems in modern nuclear physics/QCD is related to the hadron/quark transition, the determination of the equation of state of superdense nuclear matter, and the determination of the phase-space of QCD. For the first problem, progress has been done thanks to the Maldacena conjecture, with the caveat that it works for supersymmetric theory, thus giving a qualitative description of the phenomenon but not a quantitative correct one, since it happens at energies very far from a possible supersymmetric regime. The second problem can hope to have strong hints from multimessenger gravitational way spectrometry. Finally, the last problem is tackled via numerical calculation in lattice QCD theory, with enormous computational efforts. In our research, we aim to use Skyrme theory as an effective nonperturbative tool for getting analytical results, in all such problems, as well as to understand its limits and possibly the improvement of such this model.

Reference papers

[1] P. D. Alvarez, S. L. Cacciatori, F. Canfora and B. L. Cerchiai, "Analytic SU(N) Skyrmions at finite Baryon density," Phys. Rev. D **101** (2020) no.12, 125011

[2] S. L. Cacciatori, F. Canfora, M. Lagos, F. Muscolino and A. Vera, "Analytic multi-Baryonic solutions in the SU(N)-Skyrme model at finite density," JHEP **12** (2021), 150

[3] S. L. Cacciatori, F. Canfora, M. Lagos, F. Muscolino and A. Vera, "Cooking pasta with Lie groups," Nucl. Phys. B **976** (2022), 115693

6. Feynman Amplitudes.

Feynman integrals are born as a tool for developing Quantum Field Theory, but nowadays appear as concrete tools also in other branches of physics, like the high order perturbative calculation in gravitational wave physics, fluid dynamics, and several other situations, no matter if quantum or classical, where one needs to solve nonlinear partial differential equations perturbatively. Recently, it is becoming more and more important to find new methods for explicitly solving Feynman integrals. The most powerful tools are integration by parts methods, differential equation systems, and intersection theory methods. We are working on the development of efficient combinations of such methods, and their improvements, for application to various specific physical problems.

Reference papers

[1] S. L. Cacciatori, M. Conti and S. Trevisan, "Co-Homology of Differential Forms and Feynman Diagrams," Universe **7** (2021) no.9, 328

[2] S. L. Cacciatori and P. Mastrolia, "Intersection Numbers in Quantum Mechanics and Field Theory," [arXiv:2211.03729 [hep-th]]

[3] S. L. Cacciatori, H. Epstein and U. Moschella, "Banana integrals in configuration space," [arXiv:2304.00624 [hep-th]].