ERC Advanced Grant 2022
Part B2

Sections (a) and (b) of Part B2 should not exceed 14 pages. References do not count towards the page limits.

Section a. State-of-the-art and objectives

The standard model of the fundamental interactions brought flourishing developments and astonishing discoveries. Confirmation after confirmation over the decades, the model defied all proposals to supersede it. The success of particle physics was also a success of quantum field theory and the basic theoretical principles that make the model so predictive. However, that successful framework did not incorporate quantum gravity. The fundamental principles lead to contradictions and/or absurdities when they were applied to gravity. Gravity is the only interaction of nature that permeates the whole universe, from the smallest distances to the largest ones. Due to this, the interplay among the quantum gravity, the standard model, particle phenomenology and primordial cosmology can offer a unique opportunity to advance our understanding of the laws of nature in an unprecedented manner.

The other side of the coin is that the incredible success of the standard model of particle physics and the lack of new experimental data have frustrated our hopes in the future. At present, the physics of fundamental interactions is going through a concerning, prolonged period of stagnation. On top of that, the scientific community shattered into a large number of isolated groups. Many mainstreams have consolidated, leaving not much room for the advancement of bright, original proposals. In frontier domains, like quantum gravity, most mainstreams have disavowed the inheritance of the glowing past and embarked on uncertain routes. A large number of antithetical proposals on quantum gravity are being pursued in this very moment, despite the lack of experimental data backing any of them: string theory, loop quantum gravity, the AdS/CFT correspondence, holography, asymptotic safety, nonlocal quantum gravity, causal dynamic triangulations, causal fermion systems, causal set theory, canonical quantum gravity, supergravity, twistor theory, non commutative quantum gravity, Regge calculus, double copy theory, preons... And so on and so forth. A large number of conferences are held every year, in each subdomain, and a huge number of papers are published, as well as volumes and special issues. Nevertheless, no tangible progress that might change the direction of fundamental physics has been made in decades.

This frustrating situation has lead to widespread sentiments of hopelessness and depression. The critical spirit has almost evaporated completely. Cross checking, questioning or hard challenging have basically disappeared. The situation is so serious that nowadays new, ambitious ideas are viewed suspiciously, when not ignored thoroughly. Instead of welcoming stimulating new challenges, people prefer to stick to much of the same and plunge into revivals of old things. Scientists are stressed everyday with multiple distractions and cannot find the rosebud. This is why I am urging the European Union to fund ERC grant projects that have the chance to revert the situation, with no further ado.

It is time to make room for approaches that are really out of the box and can truly trigger a renaissance of particle physics. Yet, they can only be believable if they are solidly rooted in the successes of the past. This ERC project pursues a research line that does stem from the achievements of the past, but is radically new and has the potential to take us out of the dark period. It is based on the notion of purely virtual particle, which is a crucial upgrade of the language that successfully describes the scattering processes tested in colliders. Its strength is validated by a key prediction, already achieved, in primordial cosmology, which could be confirmed experimentally within a decade. Moreover, the idea has so many ramifications and applications to potentially trigger the breakthroughs we need to activate a virtuous circle that can hopefully reunite the scientific community, by building bridges among quantum gravity, primordial cosmology and beyond the standard model physics, opening the door to unthinkable scenarios and involving every group in the new endeavour. Many more key predictions are probably around the corner, and maybe one of them will trigger the breakthrough that we need to make a U turn. It is imperative to act now, since another decade of meandering with no clue, like the recent ones, could have an extremely negative impact on the generations to come.

Particle physics taught us that experiments can advance enormously if a solid theoretical setup can anticipate where to aim and what to skip. Without data and without powerful guidelines similar to the ones that lead to the standard model, we may slide into disarray. Due to the difficulties of observations and data analysis, the risk of insisting along sterile paths, thereby missing chances, discoveries that may actually be around the corner, is very high. Discoveries could be delayed or even missed, if experimentalists do not search in the right directions. Establishing a close relationship between high-energy physics, cosmology and collider physics can be a first step to reunite the community and ultimately resolve the stalemate.

For example, the arbitrariness of classical theories can be overcome by the extremely selective constraints of quantum field theory. The principles of quantum field theory, which guided us through the successes of the past, can also help us get out of the present crisis by suggesting the missing hints. Indeed, the lack of new experimental data leaves us with only one possibility: that the answer has always been in front of our eyes and for some reason we just could not see it. We can find it if we stick to what has worked so well so far, and concentrate on that, search for the key clues there, instead of wondering forever in our own fantasies.

In this spirit, we must think that quantum gravity is just a step away from the standard model, a fairly guessable missing piece of the puzzle. To identify its solution, we need to go back to the basics and identify the major source of our knowledge in the whole of fundamental physics, which is electrodynamics. Electrodynamics has been an extremely precious guide for every further progress. At our scales of magnitude and the smaller ones, it provides a huge amount of data. The standard model of particle physics was built by mimicking quantum electrodynamics. Indeed, the intermediate bosons W and Z were introduced to replicate the diagrammatics of electrodynamics as close as possible. With one important novelty: the Higgs boson, which was necessary because the "photons" of the weak interactions have to be massive. Similarly, quantum chromodynamics is a set of "self-interacting photons", with another important novelty with respect to electrodynamics: asymptotic freedom.

At the quantum level, electrodynamics means interactions between light and electrons. Theoretically speaking, this means Feynman diagrams. Quantum electrodynamics and the standard model of particle physics, are indeed built on Feynman diagrams. The missing piece of the puzzle, quantum gravity, should be built along the same guideline. It is not wise to abandon the path that has worked so well so far, the route traced by Feynman diagrams, to embark on uncertain approaches bases on our personal or social inclinations.

If the book of nature is written in mathematical language, quantum electrodynamics and the standard model of particle physics taught us that the language of particle physics is diagrammatic. Which means: scattering processes, particle collisions, resonance peaks: the ingredients that helped us build a one-century-long history of successes. Not strings, not the loops of loop quantum gravity, not holograms, triangulations, causal sets or preons, but just diagrams, like the ones that made us discover the Higgs boson at CERN in 2012, the top quark at Fermilab in 1995, the W and Z bosons at CERN in 1982-3, and all the other quarks before that. If there is any hope to trigger a renaissance of fundamental physics and build the future from there, we should examine carefully what has worked so far. With no new experimental data, with no new fresh hints, that is our only chance.

And there you find the answer, indeed, hidden in the diagrammatics, the last piece of the puzzle, the closure of the circle, the possibility that was missed: the purely virtual particle.

A usual elementary particle, such as the electron or the photon, can be real or virtual, depending on whether it is observed or not. A particle that is always real cannot exist. Nobody thought about a particle that is always virtual and can never become real. Such an entity must mediate interactions among other particles, but remain invisible to our detectors. In different words, it should be a particle of a purely quantum nature, which cannot be conceived by "quantizing" a classical system.

The idea of purely virtual particle has much in common with the idea that lead to the introduction of the intermediate W and Z bosons and the Higgs boson, and gave birth to the standard model of elementary particles: at that time, the goal was to make locality compatible with renormalizability and unitarity. This time, the goal is the same. In the case of gravity, the task requires the introduction of this radically new (yet, relatively simple) type of intermediate particle.

Such a particle is allowed by the mathematics of Feynman diagrams and can be identified by means of new diagrammatic rules [1]. Yet, the new diagrammatics is not a shot in the dark, because it is rooted in the usual one. Actually, it can be obtained from the usual one by means of surgical operations that remove degrees of freedom from crucial places. And such operations are simple enough that they can be implemented in existing software like FeynCalc, FormCalc, Looptools, Package-X, etc., to make physical predictions in model building of new physics beyond the standard model.

The idea of purely virtual particle, also called "fake particle", or "fakeon", allows us to formulate a sound proposal for quantum gravity that follows from principles similar to those that lead to the standard model of particle physics [2]. Unitarity of the new approach follows from the very definition, to all orders. Renormalizability is as usual, while locality must also be understood in a refined way.

The new theory is a "deformation" of the existing theories (standard model + general relativity), so its predictions match the present knowledge in a certain limit. Just one fake particle is necessary to solve the problems of quantum gravity. When that particle becomes infinitely heavy, we retrieve the previous knowledge. But when very high energies are involved, as in inflationary cosmology, the differences are crucial. What is of primary importance for this project is that the theory is able to make new, testable predictions, where nobody else thought it was even possible. And it shows that quantum gravity can be tested well below the Planck scale.

We cannot reach the energies required to test quantum gravity directly in laboratories, but primordial cosmology changes the perspective entirely. Solving a number of conceptual problems related to the fakeon projection on nontrivial backgrounds, Bianchi, Piva and I were able to work out the predictions of the theory for the basic inflationary parameters [4]. In [5,6] I derived the predictions for the runnings of the spectra to high orders. These recent developments point towards many more future results and possibly some breakthroughs.

The basic experiments that can test the theory within our lifetime are already on their ways. The crucial number of primordial cosmology to pay attention to is the "tensor-to-scalar ratio" r, which is the ratio between the two basic power spectra of the primordial quantum fluctuations, the tensor ones and the scalar ones. It will be measured in the incoming years, in experiments like LiteBird and Bicep/Keck. Its value will probably make big news no matter what. Why is it so important? Because, if nothing changes, it is the only quantity of fundamental physics that will be measured in our epoch.

The theory of quantum gravity built on the concept of purely virtual particle is so unique (thanks to the principles of particle physics it is built on), so constrained, and so predictive that it gives a very sharp prediction for r, a prediction that lies within less than one order of magnitude:

$$0.0004 < r < 0.0035$$

The present experimental bounds, based on the data collected so far, tell us that r must be smaller than about 0.035. We are not that far away afterall. In a few years (a decade at most) the theory could be spectacularly confirmed. This is a good starting point, to ensure that the present ERC proposal is solidly rooted.

Every popular model in primordial cosmology has a prediction for r. However, those predictions are model dependent. Only high-energy physics, through its extremely selective constraints, can make the prediction sharp and unique, because those constraints leave room for a very limited class of interactions. To the extent that the theory of quantum gravity emerging from the idea of fake particle is essentially unique (when matter is switched off) and contains just two independent parameters more than Einstein gravity, just one parameter more than the Starobinsky theory. The two parameters can be identified as the masses m_φ and m_χ of a scalar field φ (the inflaton) and the spin-2 fakeon $\chi_{\mu\nu}$ (the new particle that makes everything consistent). The triplet graviton-scalar-fakeon exhausts the set of degrees of freedom of the theory. From the cosmological point of view, the physical modes are the usual curvature perturbation and the tensor fluctuations.

Not only. The consistency of purely virtual particles in curved space leads to a crucial lower bound $m_\chi > m_\varphi/4$ on the mass m_χ of the fakeon with respect to the mass m_φ of the inflaton [4]. The bound narrows the window of allowed values of the tensor-to-scalar ratio r to the interval shown above, with a range that is less than one order of magnitude. This is what makes the predictions quite precise, even before knowing the actual values of m_φ and m_χ.

Theoretical and phenomenological exploration in the direction outlined here is needed now, with a particular attention to engaging bright, younger physicists, especially those with an inclination to think out of the box, and give them fair opportunities to grow.

These results recalled so far point towards several future developments. The **first main research line of this project** has the goal to work out other sharp, testable predictions of the fakeon approach in primordial cosmology. Indeed, other experiments are on their ways to measure the basic inflationary parameters and a powerful encouragement coming from theorists could motivate crucial upgrades and boost the key lines of research.

Moreover, the idea of purely virtual particle is not just for quantum gravity. It is far reaching and has ramification on the whole of fundamental physics. In the recent years, with the help of some collaborators at NICPB, Tallinn, new research avenues opened up, especially in phenomenology of collider physics, to study models of new physics beyond the standard model, which contain fake particles and so evade several constraints that limit the applicability of normal particles.

The second main research line of this project is to explore broadly new scenarios of phenomenology beyond the standard model, to derive testable predictions in collider physics. The basic assumption is that further, lighter fakeons, may exist besides the heavy one required to make sense of quantum gravity. It turns out that the fakeon phenomenology is very different from the one of ordinary particles and opens unforeseen possibilities of solving long standing problems. In 2021, the PI has explored scenarios of this type with other colleagues of NICPB/KBFI [9,10]. For example, the popular inert doublet model has new phenomenological properties if the second doublet is a fakeon [9]: since the fake doublet avoids the Z-pole constraints, regardless of the chosen mass scale, there is room for new effects below the electroweak scale. In addition, the absence of on-shell propagation prevents fakeons from inducing missing energy signatures in collider experiments. Other types of standard model extensions by means of fakeons predict measurable interactions at energy scales that are usually precluded. For example, the interactions between a fake scalar doublet and the muon can explain discrepancies concerning the measurement of the muon anomalous magnetic moment g-2 [10]. The experimental results can be matched for fakeon masses below the electroweak scale without contradicting precision data and collider bounds on new light degrees of freedom.

The third line of research revolves around the quantization of higher-spin massive multiplets, which are unitary and renormalizable if fakeons are used [15]. Among the other things, they allow us to quantize the Palatini version of quantum gravity consistently. These multiplets appear to have many interesting formal and physical properties. As shown recently by Piva [16], who will collaborate to this project, they can change the ultraviolet behaviour of quantum gravity and make it asymptotically free. Moreover, the masses of the particles that belong to the same multiplet are related by exact relations. For example, a spin 5/2 multiplet is made of two physical particles of spins 5/2 and 1/2, plus a fakeon of spin 3/2, with masses related in an exact way (to cancel their nonrenormalizable divergences). These relations could lead to spectacular discoveries of the multiplets, if they exist in nature. The purposes of the research on this domain are to: 1) search for other (free or interacting) fixed points and possibly open the way to (perturbative) asymptotic safety in quantum gravity; and 2) explore the phenomenological applications of the multiplets, their possible detection and their use as candidates for dark matter.

Forth line of research: fakeon techniques as mathematical tools for simplifying hard computations and compute quantities that have not been computed so far, like the physical absorptive parts of correlation functions. The main applications are in quantum chromodynamics. Normally, we think of the Faddeev-Popov ghosts as... ghosts, but it was shown in ref. [20] that it is more convenient to think of them as fakeons. This way, they can provide practical alternatives to the so called “physical gauges”. This allows us to define and compute the physical absorptive parts of the correlation functions of gauge fields and gravitons, solving the problem that these quantities, as normally defined, are gauge dependent or heavily nonlocal (see [23] for calculations in the quantum gravity theory of [2]).

Fifth line of research: reaching the wider public

On several occasions, the PI has been invited to give presentations on topics about quantum physics for the benefit of the general public. The positive reactions stimulated him to continue this endeavour, by means of videos and books. For example, the PI runs the well received YouTybe channel QuantumGravityTheory (around 2000 subscribers in 3 years). The goal is to explain the most advanced concepts of physics with no mathematics whatsoever, so as to make them accessible to literally everybody. So far, the experiment is working: most followers of the channel have little to no preparation in physics, yet they attend the videolessons every week and regularly interact with the PI through the comments that they leave below the videos. In the videos the PI explains the properties of quanta, the diagrammatics of the standard model, the key concepts of quantum gravity and how scientific discoveries emerge, going through the whole history of physics and also exploring the philosophical implications of the new ideas, and comparing them with the ideas of the past. Engaging the wider public in discussions on quantum physics can attract people from diverse groups and even contribute to reduce the gender gap in physics. To mention one thing, I receive by far more manifestations of interest from women than from men.

Research objectives

Cosmology

1. *Predictions of power spectra, spectral indices and running coefficients, along the lines traced in papers [4-8]*. This path needs to be pursued further and extended in several directions.
2. *Study of cosmic inflation as a renormalization-group flow*. This is a whole new sector opened up by paper [5] and deserves a thorough investigation in its own. It is expected to greatly increase our computational power, make it easier to suggest new experimental observations and move several steps ahead in the direction of turning primordial cosmology into an arena of precision tests of quantum gravity.
3. *Effects of the gravifakeon on the scalar power spectra and the running of power spectra. Corrections to the relation* $r + 8n_T = 0$ *and effects on the post-inflation eras*.
   A good amount of hard work is required to get to the bottom of this, although workarounds are available if the mass m_χ of the fakeon is larger than m_φ.

Phenomenology

4. *Study of Palatini quantum gravity with fakeons*. The objective is to study primordial inflation, the RG flow, its ultraviolet behaviour and its possible impact on particle phenomenology.
5. Search for Bank-Saks type *conformal fixed points* of the renormalization group flow in quantum gravity with fakeons coupled with higher-spin multiplets.
6. *Higher-spin particle production in phenomenology*. An interesting fact about higher-spin massive multiplets is that they have properties that could make them detectable in a relatively spectacular way.
7. *Dark matter with purely virtual particles*. A interesting possibility is that purely virtual particles may play a role to explain dark matter, as axions or higher-spin massive multiplets.

Purely virtual particles as mathematical tools in gauge theories and gravity

Purely virtual particles can also be used as mere *mathematical tools* to simplify computations that are very hard if popular methods are used.

8. Compute the *physical absorptive parts* of the correlations of gauge fields and compare the results with those obtained by means of traditional methods.
9. Extend the computation to the *graviton correlation functions*.
10. *Conformal fixed points and a-theorem*. Explore the possibility of proving the irreversibility of the renormalization-group flow.
11. *Fake Faddeev-Popov fakeons instead of Faddeev-Popov ghosts* can provide good alternatives to the so called "physical gauges".

Interdisciplinarity

The project also aims at *disseminating knowledge about fundamental science* to the wider public, by investing part of the resources in science popularization. The goal will be achieved as follows.

12. *Regular YouTube videos on quantum physics*. This means about one 30-minute video per week.
13. *Articles on various aspects of quantum physic*s, to be submitted to popular science magazines. The PI expects to be able to complete two articles during the grant.

14. *Completion of three books covering the whole quantum physics* (from quantum mechanics to quantum field theory and quantum gravity), including its history and philosophical implications, explained in a way that (literally) everybody who can read can understand.

Back-up plan

All the investigations described above are sound and robust. 30 years of research experience allow the PI to guess which goals are realistic and can be achieved in due time and which cannot. It will be necessary to update the goals and the methodology every year, but no dramatic changes are expected during the grant. The work is expected to lead to a consistent number publications every year. In the best scenario, which is the ultimate goal of this project, the publications will lead to breakthroughs in our knowledge and shape the research of many other groups around the world for years to come.

If some of the projects listed above turn out to be too difficult to achieve in due time, a number of alternative investigations are ready, such as

15. *Non gaussianities:* theoretical understanding (conceptual issues related to the fakeon projection), phenomenological predictions, impact of the fakeons on the outcome.
16. *Effects of a nonzero curvature in the FLRW metric. Loop corrections. Corrections beyond the superhorizon limit.*
17. *Study of the reheating phase*. The many unconventional features of the new concept require a dedicated effort to understand this aspect conceptually and identify testable predictions.
18. *Baryogenesis*. Once quantum gravity is coupled to the standard model and extended to finite temperatures, purely virtual particles offer options that are not normally available, which may turn the electroweak symmetry breaking into a first order phase transition and solve long standing issues about baryogenesis.

My research experience makes me think that many more research lines will appear along the way, so there will be no problem to replace some research goals with new ones.

Section b. Methodology

Project structure

The research project will mainly consist in theoretical/phenomenological work devoted to extracting predictions from the theory, solving open conceptual problems, advancing our understanding in so far unexplored directions, analysing data from existing experiments and proposing new experiments. An important commitment of the team is to develop a net of contacts with experimentalists to better assess the last two goals just mentioned. The research work will produce a large number of publications in high-rank international journals and hopefully mark turning points in the future of particle physics, as well as in the careers of dynamic young physicists.

Specifically, the goal is to formulate new theories and models that are consistent with the basic principles of quantum field theory and can reshape the physics fundamental interactions for the generations to come, accompanying the scientific community out of its lethargy and the darkness of the past decades. The PI also plans to explore new ideas that challenge the basic principles in the most conservative ways, to maximize the ratio between the gain and the price to pay. Third, the PI commits to identify the potential practical applications, to extract predictions from the theories and inspire new experiments that can put them to a test. This work demands to analyze data from existing experiments and propose new experiments.

To carry out the project, the PI will rely on

1. four long term postdocs;
2. hosting high-profile guest researchers visiting NICPB;
3. organizing dedicated workshops;
4. disseminating the research results in conferences around the world;
5. computational tools and other equipment;
6. promote science dissemination.

Here are some colleagues who expressed interest in the project. They will be consulted about the progress made along the way and visit from time to time in person to share their views.

The research investigations will benefit from interactions and collaborations with senior researchers over the world. Interactions with the members of the theoretical group of NICPB/KBFI will be of key importance (in particular, Martti Raidal, Luca Marzola, Carlo Marzo, Kristjan Kannike, Alexandros Karam). The research members of the team will benefit from their expertise in the calculation of Feynman diagrams for phenomenological predictions at an advanced level, the use of advanced software for this purpose, and their knowledge in primordial cosmology. This may also lead to collaborations on fakeon phenomenology for collider physics.

Marco Piva, who was a PhD student under my supervision in Pisa and co-authored various of the papers published so far on the new ideas, will collaborate extensively. He is now a postdoc at NICPB and will continue to actively contribute to the project. Marco already gave several talks on the theory around the world. He received two awards: at the Bad Honnef 2018 conference "Quantum spacetime and the renormalization group" he won a prize for the best poster competition and got promoted to give a talk on the spot. Moreover, his 2019 PhD thesis got a special mention by INFN Group IV Director S. Piccinini in the context of the Fubini Prize.

Eugenio Bianchi, from Penn State University co-authored the pivotal paper on the cosmological predictions of the theory [4], together with Piva and myself. His work lies at the interface of general relativity, quantum field theory and quantum information. The main objective of his research is to understand the quantum nature of spacetime and a wide range of phenomena that include: the primordial state of the universe, the late stages of black hole evaporation, the thermalization of isolated quantum systems.

Emidio Gabrielli, a high-energy phenomenologist, former member of NICPB/KBFI, will be visiting NICPB for a number of months on sabbatical leave from his university. The PI has regular discussions with him through Skype on several overlapping projects. He is currently working on dark photons, but he is interested in working on fakeon phenomenology as well. Dark photons for dark matter can be an interesting arena to explore some applications of the idea of purely virtual particle.

Denis Comelli, a physicist from Ferrara who is well known among the NICPB group, plans to join the group for some months in 2024. He has been working on other topics, ovelapping with the research tasks of the grant, revolving around single field inflation and multifield inflation in primordial cosmology. The costs of his visit will partially covered by the research costs of this grant.

Giovanni Signorelli is an INFN experimental physicist from Pisa, currently working at LiteBird, a space observatory that is being built now and can measure the tensor-to-scalar ratio r of the primordial fluctuations (the key prediction so far of the theory of quantum gravity with fakeons). Remote consultations with him will be important throughout the duration of the grant.

A former collaborator of the PI is Ugo Aglietti, from Rome, la Sapienza, who is an expert in QCD phenomenology. He will be regularly engaged to give advice on aspects of phenomenology. The collaboration will occur only remotely, since he cannot travel for personal reasons.

The interactions with these collaborators will take place remotely or in person and will consist of discussions, critical exchanges and reciprocal advice. This background activity can in some cases lead to the development of new lines of research and new collaborations. Often, it will also lead to joint publications with the members of the team.

Nevertheless, the main focus of the ERC proposal is to raise younger generations who want to shape the future of research in Europe.

Estonia has become a state member of CERN recently. Having been a CERN fellow in the past and a CERN visitor multiple times, the PI will develop connections with people working in the CERN theory group, due to certain overlaps and common interests. Some staff members there are working on problems that revolve around key aspects of unitarity in quantum field theory. Purely virtual particles upgrade unitarity in an important way and offer a much better understanding of it. Moreover, the possibility of developing a phenomenology of fake particles for model building of new physics beyond the standard model can receive a great benefit from the interaction with the groups working there. The engagement of the PI with CERN is also part of the effort of disseminating the results and new ideas to field-specific researchers and engaging people from diverse domains and parts of the world.

A special attention will also be devoted to connections with experimental groups, in particular LiteBird for the part concerning the future developments of primordial cosmology and the possibility of measuring the tensor-to-scalar ratio r of the primordial fluctuations in the next years.

The PI commits to dedicate 67% of his working time and 100% of his research time to the project, stay at NICPB 67% of the time, spend 80% of working time in a EU MS or an AC.

Detailed outline

The goal of the research project is to develop theoretical and phenomenological models to address the open problems of quantum gravity, collider physics and primordial cosmology, and extract testable predictions, propose new experiments and advance our understanding in so far unexplored directions, to trigger the much awaited breakthroughs that can lead to revive the hope in the future of particle physics.

Here is the detailed work plan.

I. Primordial cosmology

1. Working out predictions in primordial cosmology along the lines of papers [4,5,6] for the power spectra of primordial fluctuations, spectral indices [4], running coefficients [5,6] and more. This includes extending the work along the following directions:
- Systematics of higher order corrections.

- Coupling to the standard model and exploring alternative phenomenological scenarios, within the constraints of the theoretical setup, as well as models of multifield inflation.
- Analyze data, refine predictions, propose new observations/experiments.

2. Inflation as a renormalization-group flow [5]. It is governed by a fine-structure constant with a value around 1/115. Various ramifications generated by this research are:
- Investigations of beta functions, anomalous dimensions and fixed points (in particular, the exact beta function is available and can be studied numerically).
- Extension to post-inflation eras.
- Extension to non gaussianities. This task requires to extend the cosmic RG flow to three-point functions and more complicated correlation functions and demands a considerable computational effort. I plan to develop ad hoc computational symbolic and numerical methods starting from the softwares commonly used in this research domain.

3. Deviations from the relation r + 8 nT ~ 0, where nT is the tilt of the power spectrum of the tensor fluctuations. The relation r + 8nT ~ 0 is known to be valid in most models, to the lowest degree of approximation. Experiments such as Plank, LiteBird etc., have already reported, or are expected to report, on its bounds. Deviations from this relation are allowed, as shown in [4,5,6,7]. A detailed study will be carried out to search for ways to improve the existing bounds and hopefully suggest how to measure the predicted value.

II. Phenomenology and collider physics

Since quantum gravity predicts the existence of one fakeon in nature, which is necessary to make it renormalizable and unitary, others might exist as well. Lighter fakeons inspire new models of physics beyond the standard model and may help us solve long-standing problems and discrepancies between theoretical predictions and data. Here is the research plan.

1. Fakeon phenomenology in beyond-standard-model (BSM) physics. The objective of this investigation is to study fakeon phenomenology in the following problems: the proton radius puzzle, the Z -> gamma gamma and H -> gamma gamma processes, the Z -> 4 muons and H -> 4 muons processed, the Higgs trilinear vertex, the Higgs couplings to fermions, the neutron lifetime anomaly. The presence of light fake particles in standard model extensions affects the physical predictions and may help us solve open problems by evading the phenomenological constraints that limit the applicability of normal particles, along the lines of papers [9,10].

2. Dark matter with purely virtual particles. A interesting possibility is that purely virtual particles may play a role in explaining dark matter, as axions or higher-spin massive multiplets (see below). The plan is to study their relic abundance to see how much dark matter they can explain today. This requires to understand fakeons at nonzero temperature.

III. Higher-spin RG flows and higher-spin phenomenology

1. Study of Palatini quantum gravity with fakeons. It consists of the theory of [2] coupled to a peculiar spin 3 massive multiplet (the Palatini multiplet), which is renormalizable and unitary if quantized as shown in [15]. The objective is to study primordial inflation, the RG flow and the ultraviolet behavior. This research line is just at the beginning.

2. Search for Bank-Saks type fixed points of the renormalization group flow in quantum gravity with fakeons coupled with higher-spin multiplets. The work of Piva [16] has opened the possibility of achieving asymptotic freedom in quantum gravity. Other investigations are the reduction of couplings à la Zimmermann-Oheme and the quest for asymptotic safety in the realm of perturbation theory.

3. Higher-spin particle production in phenomenology. An interesting fact about higher-spin multiplets is that the masses of the particles belonging to the same multiplet are related by exact formulas. So, if they exist in nature, they could be spotted experimentally in a relatively spectacular way.

IV. Purely virtual particles as mathematical tools to simplify and enhance hard computations in gauge theories and gravity

Purely virtual particles can be used as mere mathematical tools to simplify computations that are very hard when the most popular methods are used.

The goals of this research line are

1. Compute the physical absorptive parts of the correlation functions of gauge fields and compare the results with those obtained by means of traditional methods. Since the traditional methods involve nonlocal projectors and Wilson lines, the fakeon techniques simplify the task enormously.

2. Extend the computation to the graviton correlation functions, both in (nonrenormalizable) Einstein gravity and in the theory of quantum gravity with fakeons.

3. Conformal fixed points and a-theorem. Search for other physical quantities that can be computed by means of the fakeon technique along the same line of thinking, such as the "central charge a" of conformal fixed points. Explore the possibility of proving the so-called a-theorem, which is a key property of the renormalization-group flow and shows its irreversibility.

V. Interdisciplinarity

The project also aims at disseminating knowledge of fundamental science to the wider public, by investing part of the resources in science popularization. The goal will be achieved as follows.

1. Regular YouTube videos on quantum physics. This means about one 30-minute video per week. This goal is achievable, because the PI has already managed to achieve a similar goal throughout the past year. The videos will be in English, with the option to include (professionally translated) subtitles in several other European and non European languages. The possibility of adding automatically generated audios in such languages will be considered.

2. Articles on various aspects of quantum physics, to be submitted to popular science magazines. The PI expects to be able to complete two articles during the grant.

3. Completion of three books, in English, covering the whole quantum physics (from quantum mechanics to quantum field theory and quantum gravity), including its history and philosophical implications, explained in a way that literally everybody who can read can understand, with no mathematics and many illustrative figures. The books will be based on the Youtube videos of the PI's channel. Again, the goal is achievable, because the PI is already working at the first version of the first book. At present 200 pages are about ready. The PI can estimate, based on the YouTube videos of his channel, that the whole task will take 1000 pages, to be divided into three volumes. When the English books will be completed, the possibility of professional translations into other languages will be considered. This goal will take the whole 5 years (around 200 pages per year).

Equipment

The research tasks require a lot of computer and mental work to address the problems in an optimized way and achieve the goals in due time. No other particular resources are needed other than human skills and powerful computers to run Mathematica packages and other common software. Such resources are already available to the members of the team. Upgrades will be necessary during the 5 years of the grant, but the costs of such upgrades are very limited. The main part of the budget is the human cost, i.e. salaries for the implementation of the required work. The budget is optimized to fully support four long term post docs and one PhD student, besides the PI. The PI thinks that this is the minimum and optimal size of the research team needed to achieve the goals of the grant.

Dissemination

The dissemination of results to the field-specific researchers is achieved as follows.

a. As soon as a paper is completed, it is submitted the web repository arXiv.org, which is a daily meeting point for everybody working in the research domains involved in the project. The publication is almost automatic and takes one day, which ensures that everybody will have access to the results in due time.

b. Soon after that, the paper is submitted to a top international peer-reviewed journal , which can take three-four months for the publication. In addition, the PI will

c. Give talks on the results in international conferences, visits and invited seminars.

d. Write review papers, which will undergo the disseminations steps a) and b).

The seminars and lectures will be posted on the Youtube Channel "QuantumGravityTheory" (https://youtube.com/QuantumGravityTheory). Links to new papers are posted in the "Community tab" of the channel and on the PI's website "https://renormalization.com", on twitter and on facebook. The PI personal experience suggests that a YouTube channel is much more effective in disseminating results than a generic website.

Dissemination to the wider public

The dissemination of results to the wider public is achieved as follows.

On a regular basis, the PI will create and post videos for non experts on the channel "QuantumGravityTheory". Some videos will update the audience on the progress on the tasks of the research project.

The PI will also engage the wider public in lectures and discussions about the key ideas of quantum physics and, more broadly, modern physics, mainly through the publication of videos for non experts on the YouTube channel. The discussions with the people who watch the videos will unfold in the community tab of the channel and the comments section of each video. The PI has already a considerable experience on this type of engagement with the wider public and knows how fruitful it can be, both for the people who attend the lectures and for the PI himself, who can gradually improve and optimize the presentations.

While the language of the videos will be mainly English, a special effort will be devoted to reach each society specifically, by means of subtitles in other languages ad well as multiple versions of the videos, through professional translations and automated voices.

The PI will keep the public updated through the YouTube Channel about the hottest topics in primordial cosmology and beyond the Standard Model physics and their relations with the goals of the research project.

The importance of the project outside academia on society as a whole relies on the interest of common people for the physics discoveries of the past 120 years. For some reason, school education does not satisfy this high demand. Unfortunately, it appears that this is a common problem of all school systems. Numerous books are published regularly on physics dissemination, but they do not meet the demand either. The PI recently became aware of these facts through the engagement with the subscribers who regularly attend the videolessons of his Youtube Channel, most of whom have no degree in physics.

An advanced research project like the one submitted here may seem too far away from the wider public, but it is not so. Actually, to some extent, deeper concepts can stimulate the imagination and creativity of a science communicator more effectively than ordinary concepts, and allow him to better figure out how to explain the basic notions of physics in a way that literally anybody can understand. The reactions of the public to the YouTube presentations convinced the PI that he is on the right track towards sharing the core of physics with everybody, with no mathematics, but lots of drawings, images, metaphors, daily-life analogies and philosophical concepts.

In figures, the PI can manage to produce at least one 30-minute video per week and three books in the next five years. Some videos of the channel have already been viewed more than 4000 times (with 1000 hours of watchtime). Altogether, the channel has collected 123000 views so far, for a total of 20000 hours of watchtime (2000 hours per month) and 1630 subscribers. The number of subscribers grows at a pace of 100-120 per month.

The planned interdisciplinary lessons range from quantum mechanics to primordial cosmology, particle physics and quantum gravity. Topics include: electrodynamics, special and general relativity, the universe expansion, the law of the entropy explained with the help of Rubik's cube, quantum mechanics (the meaning of the wave function, entanglement, Schroedinger's cat, wave function collapse), the meaning of Feynman diagrams, quantum electrodynamics, standard model, quantum gravity, the fake particle and the fundamental principles of quantum field theory, like causality, unitarity, locality and renormalizability.

Interdisciplinarity

As said, the primary goal is to achieve breakthroughs that can shape the direction of future research in high energy physics for the next decade. The idea of purely virtual particle is very promising in this respect. Another important goal is to connect different research domains by means of new bridges. In the past two decades, the global scientific community experienced a dangerous tendency to fragment into many isolated, non communicating subcommunities, each devoted to the developments of very specific topics. An undesirable consequence of this involution is a lack of cross checks. Thus, many claimed results remain in doubt. The connection among different domains that I plan to develop with this research project can bring a great benefit to the scientific community as a whole and as a society. Being part of populated collaborations may not be good enough to solve this critical issue, if those collaborations belong to isolated subcommunities. Even a small research team, like the one of this project, can make the difference, because its purpose is to unify very diverse groups under the spell of new, ambitious ideas and results of high impact. The idea of purely virtual particle offers a remarkable chance to achieve this goal, since it has a broad range of applicability, as already shown by the PI in his past research activity.

References

This is the list the papers published so far by the PI and his collaborators on purely virtual particles, the theory of quantum gravity built on this idea, the applications to primordial cosmology, collider physics and other areas. You can retrieve the arXiv papers by clicking on the corresponding links. All the arXiv versions match the final, published journal versions.

THE NEW CONCEPT

The **diagrammatics** of purely virtual particles was developed to the fullest only recently, in the paper

[1] D. Anselmi, *Diagrammar of physical and fake particles and spectral optical theorem*, J. High Energy Phys. 11 (2021) 030 and arXiv :2109.06889 [hep-th].

This paper contains much more powerful and wide ranging results, which apply to all quantum field theories and reduce the key problem of unitarity to a set of merely algebraic operations, advancing our knowledge considerably in this field.

The theory of **quantum gravity** based on purely virtual particles (also called fakeons, or fake particles) was formulated in

[2] D. Anselmi, *On the quantum field theory of the gravitational interactions*, J. High Energy Phys. 06 (2017) 086 and arXiv: 1704.07728 [hep-th].

The concept of fakeon was first introduced in

[3] D. Anselmi, *Fakeons and Lee-Wick models,* J. High Energy Phys. 02 (2018) 141 and arXiv: 1801.00915 [hep-th].

THE IMPLICATIONS ON PRIMORDIAL COSMOLOGY

The first investigations on the implications of the theory on primordial cosmology and the **prediction about the tensor-to-scalar ratio *r*** can be found in

[4] D. Anselmi, E. Bianchi and M. Piva, *Predictions of quantum gravity in inflationary cosmology: effects of the Weyl-squared term*, J. High Energy Phys. 07 (2020) 211 and arXiv:2005.10293 [hep-th].

The **reformulation of primordial inflation as a renormalization-group flow** is in

[5] D. Anselmi, *Cosmic inflation as a renormalization-group flow: the running of power spectra in quantum gravity*, J. Cosmol. Astropart. Phys. 01 (2021) 048 and arXiv: 2007.15023 [hep-th]

The papers

[6] D. Anselmi, *High-order corrections to inflationary perturbation spectra in quantum gravity*, J. Cosmol. Astropart. Phys. 02 (2021) 029 and arXiv: 2010.04739 [hep-th]

[7] D. Anselmi, F. Fruzza and M. Piva, *Renormalization-group techniques for single-field inflation in primordial cosmology and quantum gravity*, Class. Quantum Grav. 38 (2021) 225011 and arXiv: 2103.01653 [hep-th]

[8] D. Anselmi, *Perturbation spectra and renormalization-group techniques in double-field inflation and quantum gravity cosmology*, J. Cosmol. Astropart. Phys. 07 (2021) 037 and arXiv: 2105.05864 [hep-th]

Have developed the analysis of inflation as a cosmic RG flow further, in single-field and double-field inflation.

The cosmological research line needs to be developed in several directions.

FIRST EXPLORATIONS OF THE IMPLICATIONS ON PARTICLE PHENOMENOLOGY AND COLLIDER PHYSICS

This research line is only at the beginning and has to be explored to the fullest, with enormous potential impact on the new experiments. The papers

[9] D. Anselmi, K. Kannike, C. Marzo, L. Marzola, A. Melis, K. Müürsepp, M. Piva and M. Raidal, *A fake doublet solution to the muon anomalous magnetic moment*, Phys. Rev. D 104 (2021) 035009 and arXiv:2104.03249 [hep-ph]

[10] D. Anselmi, K. Kannike, C. Marzo, L. Marzola, A. Melis, K. Müürsepp, M. Piva and M. Raidal,

Phenomenology of a Fake Inert Doublet Model, J. High Energy Phys. 10 (2021) 132 and arXiv:2104.02071 [hep-ph]

describe examples of applications and strategies for future investigations.

The paper

[11] D. Anselmi, *On the nature of the Higgs boson,* Mod. Phys. Lett. A 34 (2019) 1950123 and arXiv: 1811.02600 [hep-th]

explores the possibility that the Higgs boson is a purely virtual particle, which is not ruled out by data, yet.

The paper

[12] D. Anselmi, *Dressed propagators, fakeon self-energy and peak uncertainty*, arXiv: 2201.00832 [hep-ph]

shows that the width of a purely virtual particle is associated with a new uncertainty principle, due to the fact that it is impossible to "approach the particle too closely", because it "refuses to be brought to reality".

UNIQUENESS AND UNIVERSALITY

Paper [2] shows that the quantum gravity theory based on purely virtual particles is unique. Aside from that, the concept of purely virtual particle is also unique. In the paper

[13] D. Anselmi, *The quest for purely virtual quanta: fakeons versus Feynman-Wheeler particles,* J. High Energy Phys. 03 (2020) 142 and arXiv:2001.01942 [hep-th]

it is shown that the option to define purely virtual particles by following an old approach by Feynman and Wheeler does not work, because its violates fundamental principles.

For different reasons, another alternative, which dates back to Lee and Wick, is unsatisfactory as a fundamental approach (but might work at the effective level), as shown in

[14] D. Anselmi, *Fakeons versus Lee-Wick models: physical Pauli-Villars fields, finite QED and quantum gravity*, arXiv: 2202.10483 [hep-th]

RG FLOW, CONFORMAL FIXED POINTS, THE A-THEOREM with purely virtual particles

In the paper

[15] D. Anselmi, *Quantum field theories of arbitrary-spin massive multiplets and Palatini quantum gravity*, J. High Energy Phys. 07 (2020) 176 and arXiv: 2006.01163 [hep-th]

I have shown that fakeons can be used to make sense of higher-spin massive particles (by embedding them into suitable multiplets). This opens the way to study Palatini quantum gravity and all its implications. Moreover, recently Piva in

[16] M. Piva, *Massive higher-spin multiplets and asymptotic freedom in quantum gravity*, Phys. Rev. D 105 (2022) 045006 and arXiv:2110.09649 [hep-th]

has shown that these multiplets can change the ultraviolet behaviour of quantum gravity, opening the way to the possibility of making it asymptotically free like quantum chromodynamics. These results lead to several new ramifications, from conformal fixed points to reductions of couplings, which could even let us understand the irreversibility of the RG flow (a-theorem).

THE VIOLATION OF MICROCAUSALITY

An important (expected) consequence of purely virtual particles is that causality is violated at very high energies. The first investigations of this property are in

[17] D. Anselmi, *Fakeons, microcausality and the classical limit of quantum gravity,* Class. and Quantum Grav. 36 (2019) 065010 and arXiv: 1809.05037 [hep-th].

[18] D. Anselmi, *Fakeons and the classicization of quantum gravity: the FLRW metric,* J. High Energy Phys. 04 (2019) 61 and arXiv: 1901.09273 [gr-qc]

[19] D. Anselmi and A. Marino, *Fakeons and microcausality: light cones, gravitational waves and the Hubble constant,* Class. And Quantum Grav. 37 (2020) 095003 and arXiv: 1909.12873 [hep-th].

This topic might lead to the identification of unforeseen ways to test the idea experimentally.

OTHER RAMIFICATIONS

A first example of methods to **use purely virtual particles as mathematical tools** was laid out in

[20] D. Anselmi, *Fakeons, unitarity, massive gravitons and the cosmological constant,* J. High Energy Phys. 12 (2019) 027 and arXiv: 1909.04955 [hep-th]

by using Faddeev-Popov fakeons, instead of Faddeev-Popov ghosts. However, this is a path that needs to be pursued along several other directions, because it has a potentially great impact.

The new concept of purely virtual particle was to some extent **inspired by the results of earlier investigations** on some related models, the Lee-Wick models (but note that the Lee-Wick models are not satisfactory, as explained above, and the theory of quantum gravity based on fakeons is not a Lee-Wick model):

[21] D. Anselmi and M. Piva, *Perturbative unitarity of Lee-Wick quantum field theory,* Phys. Rev. D 96 (2017) 045009 and arXiv: 1703.05563 [hep-th]

[22] D. Anselmi and M. Piva, *A new formulation of Lee-Wick quantum field theory,* J. High Energy Phys. 06 (2017) 066 and arXiv: 1703.04584 [hep-th].

The calculations of the **basic properties** of the theory of quantum gravity with fakeons (renormalization, absorptive part of the two-point function) can be found in

[23] D. Anselmi and M. Piva, *Quantum gravity, fakeons and microcausality,* J. High Energy Phys. 11 (2018) 21 and arXiv: 1806.03605 [hep-th].

[24] D. Anselmi and M. Piva, *The ultraviolet behavior of quantum gravity,* J. High Energy Phys. 05 (2018) 27 and arXiv: 1803.07777 [hep-th].

Reviews can be found in

[25] M. Piva, *On the behavior of gravitational force at small scales*, Int. J. Mod. Phys. D 28 (2019) 1944007 and arXiv: 1905.06516 [hep-th]

[26] D. Anselmi, *Purely virtual particles in quantum gravity, inflationary cosmology and collider physics,* Symmetry 2022, 14(3), 521 and arXiv: 2203.02516 [hep-th].

[27] D. Anselmi, *Fakeons, quantum gravity and the correspondence principle,* in "*Progress and Visions in Quantum Theory in View of Gravity: Bridging foundations of physics and mathematics*", F. Finster, D. Giulini, J. Kleiner and J. Tolksdorf editors, Birkhäuser Verlag (2019), arXiv:1911.10343 [hep-th]