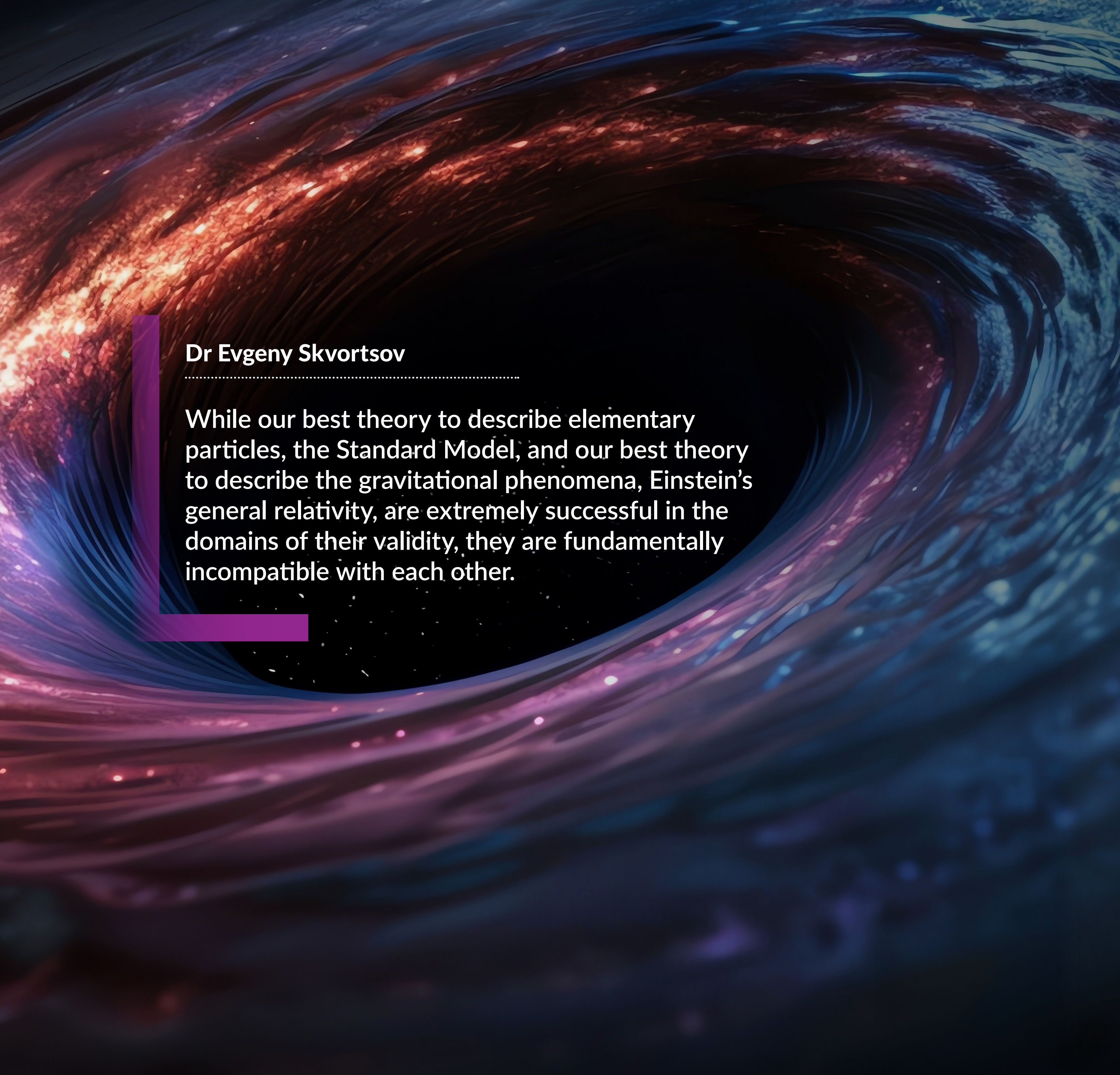
Left and right corners of quantum gravity



Dr Evgeny Skvortsov

While our best theory to describe elementary particles, the Standard Model, and our best theory to describe the gravitational phenomena, Einstein's general relativity, are extremely successful in the domains of their validity, they are fundamentally incompatible with each other.

This famous problem is known as the problem of quantum gravity. The article is devoted to the recent progress within higher-spin gravity that can be summarised as identifying 'the left and right corners of quantum gravity', and it would take some time to explain how quantum gravity can have left and right corners.

There are many different research lines devoted to the quantum gravity problem. The most developed one is, perhaps, string theory. There are many other ideas, such as asymptotic safety, canonical quantisation, tensor models, noncommutative geometry, loop quantum gravity, various modifications of general relativity and a few others. Another approach is higher-spin gravity, on which we concentrate here. While no approach can claim a complete victory, different research directions have different benefits and help to identify what the problem actually is by shedding light on it from various angles. Within the higher-spin gravity approach, a major progress has been to construct two twin theories that are 'left and right' corners of a yet elusive complete higher-spin gravity.

The most 'elementary' manifestation of the problem is in the so-called UV divergences that appear in the quantum corrections to general relativity. UV divergences—the infinities that appear when the energy of a process gets very large—are typical of quantum field theories, but the ones that appear in gravity are of the 'bad type'. At least within the usual particle/field paradigm, it does not seem possible to solve the problem without radical modifications of the theory by first introducing many more new degrees of freedom, as both string theory and higher-spin gravity do. This leads to the question of what can actually be added.

What nature (or a quantum gravity theory) is/can be made of?

What do we know about elementary particles in general? It is the famous result of Eugene Wigner from the early days of quantum field theory that the laws of special relativity, together with the postulates of quantum mechanics, imply that all elementary particles we can possibly observe can be described by just two numbers: mass and spin. The mass is a continuous parameter and is just the usual mass we are familiar with in our macroscopical world. On the contrary, spin is a truly quantum characteristic of matter, which can only take nonnegative integer and half-integer values. The closest classical analogue of spin would be the angular momentum, but it is difficult to imagine how it can come in discrete portions.

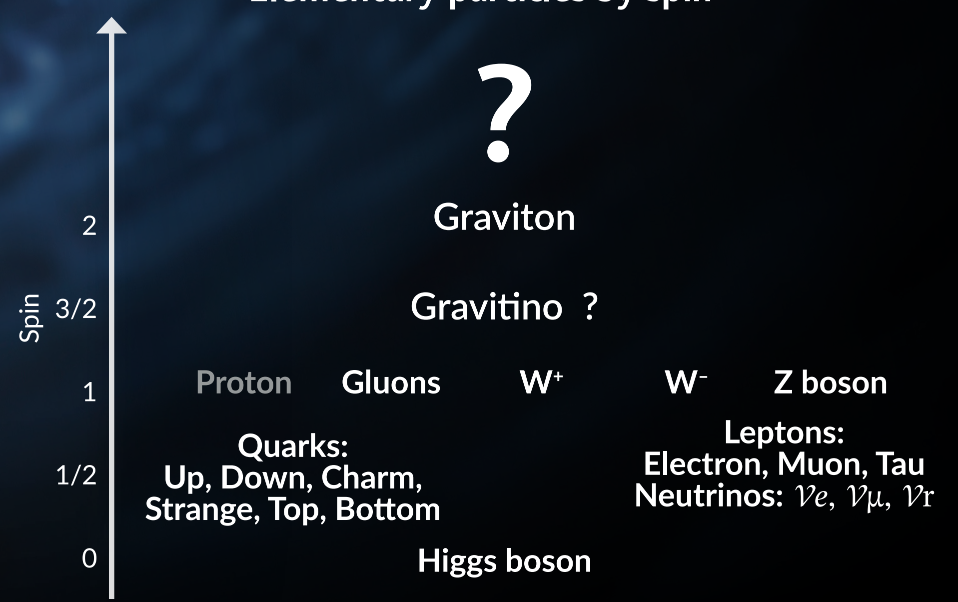


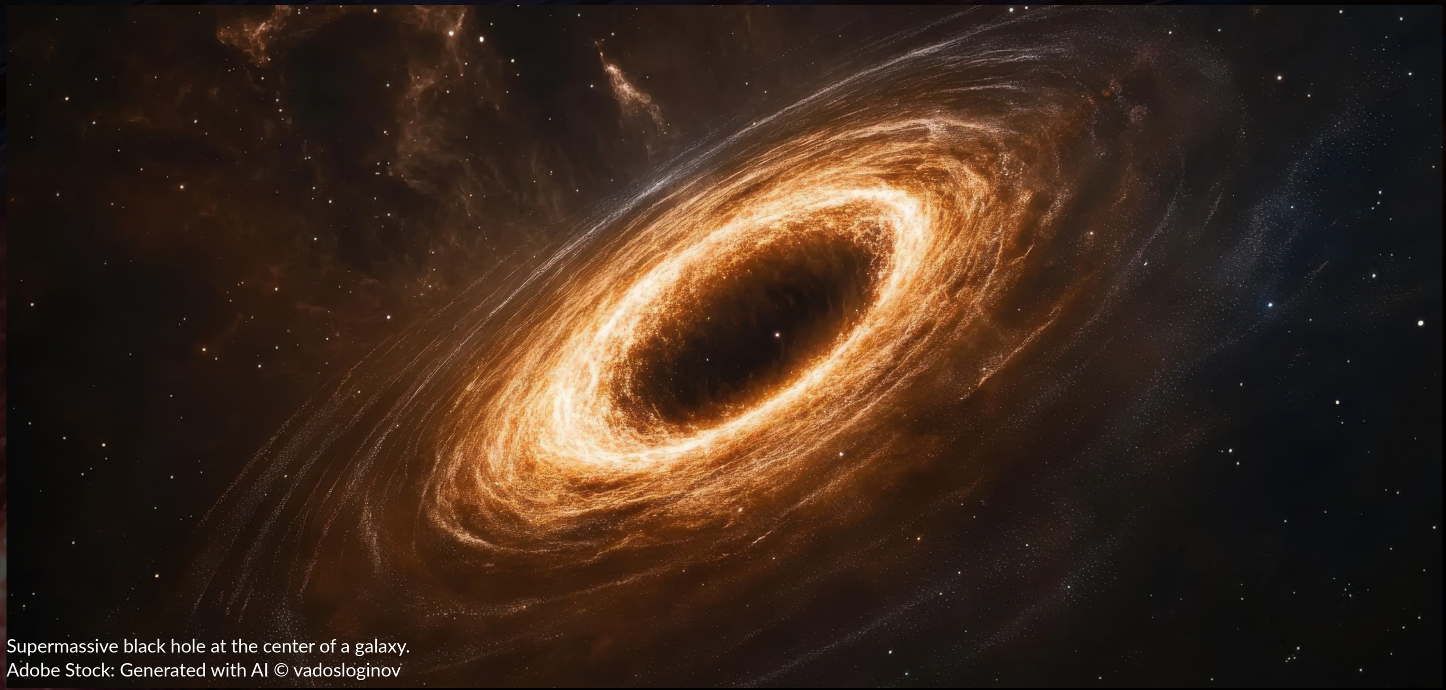
Figure 1:

For a particle to be characterised by the two numbers, spin and mass, it does not have to be truly elementary. Instead, it can be 'effectively elementary', that is, such that we cannot crack it open at the energies currently accessible to see what it is made of. In fact, we can never be sure that a given particle, such as an electron, is elementary. For what we know, electrons appear to be elementary, while protons behave as elementary particles at sufficiently low energies, but at some point their constituent quarks reveal their presence.

Particle approximation can give excellent results even in macroscopical situations. For example, in general relativity, the dynamics of compact objects, such as black holes, can be described by modelling black holes as elementary particles (massive particles with spin), see, e.g. Cangemi *et al.*, (2023).

Wigner's result enumerates all possible free particles, but it does not tell us how they can interact with each other. Free particles cannot even be seen; they have to interact with something that eventually interacts with the light we can see. Simple but important examples of interacting theories include the Yang-Mills theory and gravity. The Yang-Mills theory is one of the most important fundamental theories. In fact, it is a class of theories. From the fundamental point of view, it describes how massless particles of spin-one can interact with each other. The options/classes are parameterised by objects known as Lie algebras. The Yang-Mills theory is at the heart of the Standard Model, which describes all particles and forces except for graviton/gravity. Likewise, gravity is an interacting theory of the massless spin-two field, called the graviton.

Going to even smaller scales where the spacetime itself should no longer be understood as a passive spectator and reveal the quantum nature of its own, one cannot be sure that the concept of particles remains valid. Maybe the ultimate constituents are strings of string theory or something else. Nevertheless, the particle/field paradigm has been quite successful so far. Even elementary excitations of strings can be understood



Supermassive black hole at the center of a galaxy.
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as particles of certain spins and masses. Therefore, it makes sense to first try to attack the quantum gravity problem without abandoning the well-established concepts of particles and fields, which leads to the next question: which hypothetical particles might be needed?

Why higher spins?

The reason is quite simple: one can enumerate all options involving particles up to the spin-two graviton. The most promising theories of this kind are supergravities that enrich the symmetries of general relativity by so-called supersymmetry. The idea is that the more symmetry, the better (unless too much, of course). Indeed, the extended symmetry admits fewer quantities that are invariant under it. In particular, it reduces the number of possible divergences that are inherited from general relativity. However, all supergravities seem to suffer from UV divergences sooner or later.

The conclusion is that particles with spin greater than two have to be introduced. Now, it is time to decide whether they are massless or must have a certain mass. One argument in favour of massless states is that one should be able to neglect all masses for sufficiently high energies. Another argument is that massless particles seem more fundamental, since they can mediate long-range interactions, while the massive ones can only mediate short-range forces. Also, zero mass is a unique point, whereas massive states raise the question of why the masses are like this but not like that, which is a very interesting question under active investigation within the S-matrix programme.

However, string theory introduces many more higher-spin states and with masses growing up to infinity. Therefore, for an arbitrarily high energy, there are still infinitely many states whose masses are even higher. Nevertheless, one can choose the extra states to be massless to explore a route that looks different from string theory. Eventually, there are several points at which higher-spin gravities and string theory come close to each other, but that is a different story.

Higher-spin gravity?

At this point, we are looking for a theory that contains the graviton together with massless particles of various spins. Under quite general assumptions, it is easy to see that one needs infinitely many of them, roughly one particle of every spin.

Now, suppose we have such a theory, which can be called a higher-spin gravity: why might it solve the quantum gravity problem, and what subtleties could arise? Massless particles with spin are always associated with some symmetries and hence a higher-spin gravity would have a huge symmetry as compared to Yang-Mills and gravity theories. This symmetry can be powerful enough to forbid all possible UV divergences, for which there is now overwhelming evidence.

Therefore, the good news is that one may not even need to quantise anything directly since the symmetry can eliminate all problems. This sounds too good or too easy—indeed, in practice, it happens that the very presence of massless higher-spin particles does not want to fit into the very restrictive shoes of quantum field theory. There are clear signs that certain generalisations/extensions of the field theory paradigm are needed. These signs usually appear as interactions that tolerate this huge symmetry being too nonlocal (i.e. too long-range). This is why, at present, there is no example of a higher-spin gravity that would satisfy all the usual assumptions of field theory. What can be done before the right generalisation of the field theory approach is found?

Self-dual (left and right) corners?

Since it is very difficult to make exact calculations in complicated theories like Yang-Mills theory or gravity, physicists have been very creative in devising approximations that yield exact analytical results. The most generic expansion of this sort is to assume that particles are weakly-coupled and, hence, one can first consider their free propagation (essentially, plane waves, like gravitational waves) and, then, take the interactions into account order by order, i.e. to start with three-particles interaction, add one more particle to the process, and so on.

There are more intricate expansions. For example, quantum chromodynamics is a strongly coupled theory at the usual energies. A pioneering idea proposed by t' Hooft was to instead consider the expansion in the (inverse) number of colours of gluons.

Yet another expansion that can be applied to the Yang-Mills theory and gravity is expansion over the self-dual subsector. It is not easy to describe what it is without going into gory mathematical details. One option is to say that each of these two theories has a smaller theory hidden inside. The latter are known as self-dual Yang-Mills theory and self-dual gravity. In fact, there are always two such sub-theories that are mirror images of each other: self-dual and anti-self-dual, which we can simply call left and right (or chiral), since their interactions discriminate between left and right.

The self-dual theories are still nontrivial and interacting. However, they have many remarkable properties that signify their simplicity. For example, they are integrable, which, in practice, means that any reasonable observable can be exactly computed in these theories, a luxury that is rarely available in quantum field theory. Solutions of self-dual theories are known as instantons and are very important in quantum theory, since they describe transitions that are classically forbidden (i.e., they correspond to the truly quantum evolution paths).

Left/right (chiral) higher-spin gravity

The main recent progress (Sharapov and Skvortsov, 2022; Sharapov, Skvortsov and Van Dongen, 2023; Sharapov *et al.*, 2023) in higher-spin gravity is thanks to the fact that such left/right corners were explicitly constructed under the name chiral higher-spin gravity. While its completion is yet beyond reach, it turned out that the chiral higher-spin gravity does not suffer from the main problem—nonlocality—while exhibiting the main expected features of higher-spin gravity, namely, the cancellation of UV divergences.

An additional bonus (Jain, Dhruva and Skvortsov, 2025) is that via AdS/CFT duality, the chiral higher-spin gravity is related to some theories that describe physics in the world around us, which is perhaps the only example of a quantum gravity model that is directly related to any kind of real-world physics at the moment.

References

Cangemi, L., Chiodaroli, M., Johansson, H., Ochirov, A., Pichini, P. and Skvortsov, E. (2023) 'Kerr black holes from massive higher-spin gauge symmetry', *Physical Review Letters*, 131(22), 221401. doi: 10.1103/PhysRevLett.131.221401.

Jain, S., Dhruva, K.S. and Skvortsov, E. (2025) 'Hidden sectors of Chern–Simons matter theories and exact holography', *Physical Review D*, 111(10), 106017. doi: 10.1103/PhysRevD.111.106017.

Sharapov, A. and Skvortsov, E. (2022) 'Chiral higher spin gravity in $(A)dS_4$ and secrets of Chern–Simons matter theories', *Nuclear Physics B*, 985, 115982. doi: 10.1016/j.nuclphysb.2022.115982.

Sharapov, A., Skvortsov, E. and Van Dongen, R. (2023) 'Chiral higher spin gravity and convex geometry', *SciPost Physics*, 14(6), 162. doi: 10.21468/SciPostPhys.14.6.162.

Sharapov, A., Skvortsov, E., Sukhanov, A. and Van Dongen, R. (2023) 'More on chiral higher spin gravity and convex geometry', *Nuclear Physics B*, 990, 116152. doi: 10.1016/j.nuclphysb.2023.116152.

HiSS

Higher Spin Symmetry in Quantum Gravity, Condensed Matter and Mathematics

PROJECT SUMMARY

The main goal of the HiSS project is to approach quantum gravity from a completely new direction—by providing the first working example of higher-spin gravity (HiSGRA). HiSS will construct new consistent models of quantum gravity along the higher-spin gravity lines, and explore and prove dualities in the condensed matter systems, which can be explained by higher-spin symmetry and deduced from HiSGRA.

PROJECT LEAD PROFILE

Dr Skvortsov is a research associate at Université de Mons, focusing on higher-spin gravities and applications thereof to the quantum gravity problem. Skvortsov graduated from Moscow Institute of Physics and Technology in 2005, obtained a PhD from Lebedev Institute of Physics in 2010 with a thesis on gauge fields in Minkowski and (anti)-de Sitter spaces within the unfolded formulation, and went on to spend time at Albert Einstein Institute (Max Planck Institute for Gravitational Physics), Potsdam and Ludwig Maximilian University of Munich.

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FUNDING

Funded by the European Union
European Research Council

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101002551.