INTEGRATING BLACK HOLES AND GRAVITATIONAL WAVES INTO SCHOOL PHYSICS

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Abstract

This article examines the incorporation of the topics "Black Holes" and "Gravitational Waves" into school physics education, highlighting their role in fostering student engagement and scientific competence. It highlights the significance of the LIGO project as a modern example of real-world applications in physics education. Through active exploration and collaboration, students can develop a deeper appreciation for the complexities of the universe while honing their analytical and communication skills. It presents a pyramid structure of constructivist teaching, emphasizing the importance of an active learning environment, scaffolding, and independent learning. The article outlines five principles of teacher-guided inquiry-based learning: active student engagement, the teacher as a facilitator, the use of real-world problems, effective classroom communication, and the gradual increase of student autonomy. By utilizing these principles, educators can create a dynamic learning atmosphere that encourages curiosity and collaboration among students.

Key words: black holes, gravitational waves, laser interferometer, science competence, constructivism, scaffolding, teacher-guided instruction.

Rezumat

Acest articol examinează integrarea temelor „Găurile negre" și „Undele gravitaționale" în predarea fizicii școlare, subliniind rolul lor în stimularea implicării elevilor și în dezvoltarea competenței științifice. De asemenea, evidențiază importanța proiectului LIGO ca exemplu modern de aplicare practică a fizicii în educație. Prin explorare activă și colaborare, elevii pot dezvolta înțelegerea mai profundă a complexității universului, în timp ce își perfecționează abilitățile analitice și de comunicare. Articolul prezintă o structură piramidală a predării constructiviste, accentuând importanța unui mediu activ de învățare, a scaffolding-ului și a învățării independente. Sunt conturate cinci principii ale învățării prin cercetare ghidată de profesor: implicarea activă a elevilor, profesorul ca facilitator, utilizarea problemelor din viața reală, o comunicare eficientă în clasă și creșterea treptată a autonomiei elevilor. Prin aplicarea acestor principii, profesorii pot crea un mediu de învățare dinamic, care încurajează curiozitatea și colaborarea între elevi.

Cuvinte cheie: găurile negre, undele gravitaționale, interferometrul laser, competența științifică, constructivism, eșafodaj, instruirea ghidată de profesor.

I. Introduction

Astrophysics and physics education intersect in powerful ways when topics like black holes and gravitational waves are introduced to the classroom. These cosmic phenomena, emblematic of the mysteries and wonders of the universe, not only capture students' imaginations but also serve as a rich framework for exploring core concepts in modern physics. Once reserved for researchers and astronomers, the study of black holes and gravitational waves is now making its way into school physics curricula. Integrating these topics not only aligns with the scientific goal of understanding the universe but also enriches educational experiences, offering students a gateway to contemporary scientific exploration.

This article examines effective approaches for teaching black holes and gravitational waves in school physics, covering the nature of black holes, fundamental characteristics of gravitational waves, and the operating principles of interferometers, with an emphasis on LIGO's pivotal role. It seeks to equip educators with strategies for creating interactive physics lessons that harness the allure of these cosmic phenomena to foster a deeper understanding of physics. By exploring LIGO's contribution to detecting gravitational waves and delving into the complex nature of black holes, the article presents a roadmap for making these advanced topics accessible and engaging within physics education.

In doing so, we aim to demonstrate how scientific competencies and lifelong learning skills can be developed through constructivist teaching methods that bring such extraordinary topics, like black holes and gravitational waves, into school physics. Integrating elements of astrophysics in this way not only nurtures students' conceptual understanding but also fosters a lasting interest in science by connecting them to the universe’s most compelling phenomena.

II. Characteristics of Black Holes

Black holes are among the universe's most enigmatic and captivating phenomena, marking regions of spacetime where gravitational forces are so intense that not even light can escape. Here’s an outline of the phases a star undergoes before transforming into a black hole [1]:

- **Main Sequence**: This is the star's stable, long-lived phase, much like our Sun. In this stage, the star primarily fuses hydrogen into helium in its core, where the outward radiation pressure from nuclear fusion perfectly counterbalances the inward pull of gravity.
- **Red Giant**: Once hydrogen in the core is mostly depleted, the star evolves into a red giant. In this phase, the core contracts and heats up, igniting the fusion of heavier elements like helium, while the outer layers expand dramatically, forming a giant, luminous sphere.
- **Supernova**: For stars with a mass at least eight times that of the Sun, the core eventually exhausts its nuclear fuel. Unable to counteract gravitational collapse, the core implodes, leading to a spectacular supernova explosion. This explosion ejects the star's outer layers into space with extraordinary force.
- **Black Hole Formation**: Following the supernova, if the remaining core's mass exceeds roughly 2.5-3 solar masses (the Tolman-Oppenheimer-Volkoff limit), it will continue collapsing under gravity until it forms a singularity—a point of infinite density surrounded by an event horizon. This final stage marks the birth of a black hole.

For a star to ultimately become a black hole, its initial mass must exceed about 8 solar masses. Stars below this threshold will instead end their lives as white dwarfs or neutron stars, lacking the necessary mass for gravitational collapse into a black hole.

If the stellar core remaining after a supernova has a mass between approximately 1.4 and 2.5-3 solar masses, it will collapse into a neutron star—a compact, incredibly dense object composed primarily of neutrons. Should the core mass fall below 1.4 solar masses, it will instead become a white dwarf, in line with the Chandrasekhar limit. As a result, our Sun, lacking sufficient mass, will ultimately pass through the red giant phase before settling into a white dwarf.

Two defining features of a black hole are its Schwarzschild radius—the critical boundary where gravity is so intense that not even light can escape—and its density, defined as the mass divided by volume. For a black hole with three times the Sun's mass, the Schwarzschild radius is approximately $r_S = 2GM/c^2 = 8{,}87\ km$, and the density is immense, $\rho = 3M/4\pi r_S^3 = 1{,}82 \times 10^{18}\ kg/m^3$, far surpassing that of any known material.

One of the most famous examples of black holes is Sagittarius A*, the supermassive black hole at the center of the Milky Way galaxy. It is estimated to have a mass equivalent to about 4 million suns. Another significant example is the black hole in the galaxy M87, which was imaged directly by the Event Horizon Telescope, providing the first visual proof of a black hole's existence. These two examples highlight the importance of black holes in understanding the dynamics of galaxies and the structure of the universe. Additionally, the nearest known black hole resides in the HR 6819 system within the constellation Telescopium (see Fig. 1), approximately 1,120 light-years from Earth.

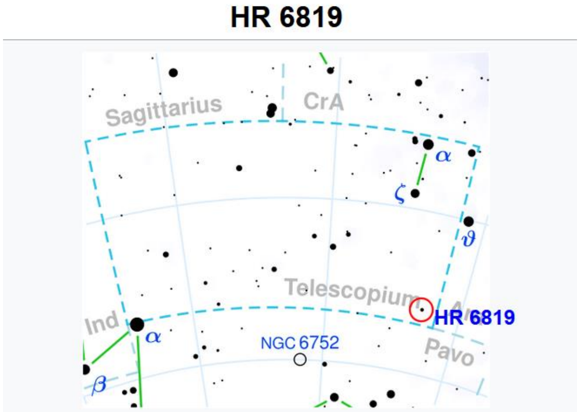

Fig. 1 The nearest black hole, marked with a red circle.

III. Characteristics of Gravitational Waves

The concept of gravitational waves was first predicted by Albert Einstein in 1916 as a part of his general theory of relativity. Einstein's theory suggested that massive accelerating objects would disturb spacetime, creating waves that propagate outward. Despite this prediction, Einstein himself doubted their detectability due to their minuscule effect.

Gravitational waves are ripples in the fabric of spacetime, traveling across the cosmos and caused by the rapid acceleration of massive objects, such as neutron stars or black holes. These waves resemble the ripples created when stones are thrown into water, yet they propagate through spacetime itself, altering distances between objects as they pass. Gravitational waves are typically generated by cataclysmic events involving enormous masses, such as:

- The fusion of two black holes,
- The collision of neutron stars, or
- Supernovae.

In essence, gravitational waves arise whenever two massive objects orbit each other, similar to figure skaters accelerating as they draw closer together, radiating energy outward in the form of spacetime distortions.

The fundamental characteristics of gravitational waves are as follows:

- **Amplitude**. The amplitude $A = 4GM_1M_2/c^4R = \Delta L/L \sim 10^{-21}m$, where R – detection distance, ΔL – the variation of the distance between two points in space, L – the initial distance between these two points. For example, the amplitude of the gravitational waves detected for the first time in 2015, for which the Nobel Prize was given in 2017, was $10^{-21}m$ [2].
- **Frequency**. The characteristic frequency is given by $f = c^3/GM$ (here c – speed of light, G – gravitational constant, M – the mass of the system producing gravitational waves). We have to mention that gravitational waves fall into two frequency categories: higher-frequency waves in the kilohertz range: $100\ Hz - kHz$, and lower-frequency waves in the nanohertz range: $nHz - \mu Hz$.

Despite the fact that gravitational waves carry energy, they are extremely difficult to detect because the perturbations they cause in spacetime are very small.

IV. The Working Principle of the LIGO Interferometer

LIGO, or the Laser Interferometer Gravitational-wave Observatory, is a groundbreaking facility for gravitational wave detection, operating based on the principles of interferometry to identify these waves, which exist outside the electromagnetic spectrum. This sets LIGO apart from traditional observatories: rather than capturing light, LIGO detects the subtle distortions in spacetime created by massive cosmic events. It accomplishes this by using laser beams that travel through long, vacuum-sealed tubes arranged in an L shape, which makes it possible to detect gravitational waves by observing minute changes in the length of the tubes.

On September 14, 2015, the LIGO facilities in the United States, one in Hanford, Washington, and the other in Livingston, Louisiana, which are separated by 3,000 kilometers, detected the event GW150914—the merger of two black holes with masses of 29 and 36 solar masses [3]. The separation between these observatories is crucial, as it allows for:

- Precise triangulation of the gravitational wave source,
- Noise reduction, and
- Confirmation of detected events.

The collision resulted in the formation of a black hole with a mass of 62 solar masses, with a mass defect of 3 solar masses converted into gravitational wave energy. In interferometry, the interference pattern is produced by superposing two coherent waves that have a constant phase difference and nearly identical frequencies; if the frequencies differ, the interference pattern becomes unstable.

At LIGO, a laser beam is split into two perpendicular beams, each reflecting off a suspended mirror at the end of one arm. These beams are then recombined, and the resulting interference pattern is analyzed by a photodiode. In the absence of gravitational waves, the two beams cancel each other out at the photodiode. However, when a gravitational wave passes through, it slightly alters the length of one arm, modifying the interference pattern and allowing detection of the wave. LIGO is capable of detecting arm-length changes as small as $10^{-18}\ m$ −significantly smaller than the diameter of a proton.

In addition to the first two LIGO observatories, there is now a global network of facilities dedicated to gravitational wave detection [4]:

- **GEO 600**: Located near Hanover, Germany, this observatory features a 600-meter arm.
- **LIGO India**: This facility became operational in 2020 and expands the global detection capabilities.
- **VIRGO**: Situated in Pisa, Italy, this European observatory has a 3-kilometer arm and was launched in 2017. It boasts a sensitivity that is ten times greater than that of the LIGO facilities in the USA.
- **KAGRA**: The Kamioka Gravitational Wave Observatory in Japan is located underground in a mine. Its interferometer mirrors are cooled to 20 K to minimize thermal noise, which refers to the thermal agitation of the physical components. Other types of noise that can affect sensitivity include seismic, optical, and various environmental interferences.

This international network of observatories enhances the ability to detect and analyze gravitational waves, significantly contributing to our understanding of the universe.

V. Cosmic Complexity in the Classroom

The transition from advanced topics such as the detection of gravitational waves and black holes to teaching physics in schools may seem like a difficult leap. However, these themes offer unique opportunities to stimulate students' imagination and curiosity, motivating them to study physics. By exploring these captivating subjects, we can develop essential components of scientific competence [5] within the spectrum of lifelong learning competencies represented in Table 1.

Tab. 1 The components of scientific competence

Conceptual understanding	Interdisciplinarity
Application of knowledge	Scientific communication
Research skills	Collaboration
Inquiry-based learning	Curiosity
Data analysis	Lifelong learning

Let's describe how each of these ten components of scientific competence can be developed by studying black holes and gravitational waves.

- **Conceptual understanding.** Students can deepen their understanding of fundamental concepts such as mass, density, gravity, wave, energy, frequency, wavelength, and interference.
- **Application of knowledge.** Students can apply theoretical knowledge from chapters such as Interactions and Wave Optics in new and non-trivial contexts.
- **Research skills.** Students can develop research skills by learning how to organize a scientific experiment from hypothesis to application through case studies like LIGO.
- **Inquiry-based learning.** Students can engage in inquiry-based learning projects modeled after the LIGO project. Here, they will understand how school physics (in this case, coherent waves) can be used to address non-trivial research problems.
- **Data analysis.** The LIGO case provides a solid example and foundation for teaching students how to analyze real experimental data obtained in the school laboratory.
- **Interdisciplinarity.** Topics such as black holes and gravitational waves require an interdisciplinary approach, integrating knowledge from various scientific fields (physics, mathematics, astronomy), thereby developing students' ability to solve complex real-world problems.
- **Scientific communication.** Since scientific communication is a mandatory component of any constructivist teaching project [6], students not only learn to communicate the results of their experiments but also develop an active scientific vocabulary.
- **Collaboration.** Collaboration among members of the school research project team fosters the ability to work together, to be receptive to different opinions, and to explain complex phenomena in accessible language to peers [7].
- **Curiosity.** To nurture a research-oriented mindset and ensure the success of educational endeavors, curiosity must become an intrinsic trait of students. Mysterious phenomena like gravitational waves encourage the exploration of other

natural phenomena, stimulating curiosity and ultimately positioning the student as a researcher on a transcendental axis.

- **Lifelong learning.** This component focuses on cultivating a mindset for personal and professional development through continuous learning—the cornerstone of long-term success, well after graduating from school.

In order to develop these components of scientific competence, it is essential to create a learning environment that fosters students' cognitive effort, meaning a constructivist learning environment [8]. However, students' cognitive effort is not effective without appropriate guidance. In other words, for successful learning, in accordance with Visible Teaching and Learning, continuous feedback is necessary [9]. Thus, the pyramid structure of constructivist learning is illustrated in Fig. 2.

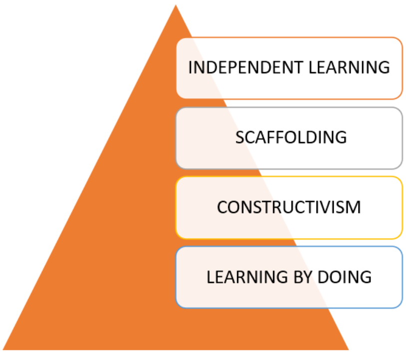

Fig. 2 Constructivist teaching and scaffolding within physics lesson

Firstly, the foundation for developing the components of scientific competence lies in an active learning environment — Learning by Doing — that supports students' cognitive efforts.

Secondly, constructivism, developed by Lev Vygotsky and other educational psychologists, posits that students construct their own knowledge based on their prior experiences and interactions.

Thirdly, scaffolding — a central concept in constructivist teaching — refers to the guidance provided by teachers as students strive to acquire new and complex knowledge and skills.

Finally, independent learning involves a gradual transfer of responsibility, representing the highest level of learning, where the teacher's objectives become the intrinsic goals of the students.

To design a constructivist teaching project, we will consider the following five principles of teacher-guided inquiry learning (see Fig. 3).

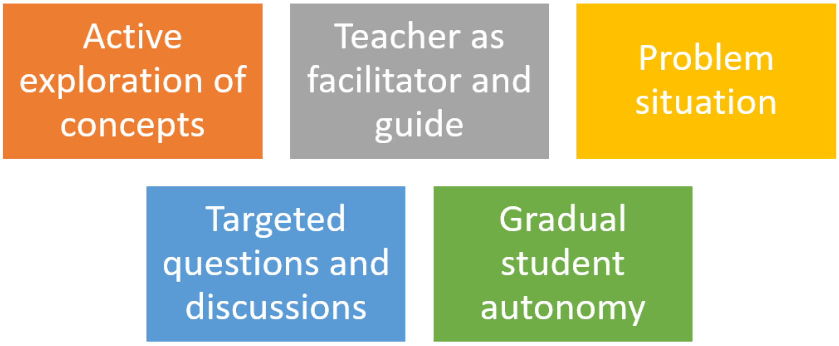

Fig. 3 The basic principles of teacher-guided inquiry-based learning lessons.

Principle One: The student is the active agent in learning. The foundation of the lesson rests on the student's effort in learning and investigation.

Principle Two: The student is not alone in their learning journey. Research indicates that greater autonomy in learning does not necessarily lead to academic success; the teacher's role as a guide is essential.

Principle Three: The teacher provides students with open-ended problems for research and analysis, addressing real-world issues.

Principle Four: Classroom communication and interaction are success factors. The success of the lesson is directly proportional to the level of classroom interaction.

Principle Five: As students develop research and analytical skills, a certain level of learning autonomy can emerge.

Finally, it is important to note that this model is effective only when two conditions are met:

- Systematic application in every lesson, and
- Early implementation, starting as early as primary school, so that students become accustomed to an inquiry-based classroom atmosphere.

VI. Conclusions

- Astrophysics topics such as black holes and gravitational waves make physics both relevant and engaging for students.

- LIGO provides a modern example for integrating recent discoveries into physics education.
- Constructivist teaching methods and scaffolding support the development of scientific competence components.
- The hierarchical structure of constructivist teaching includes: Learning by Doing, Constructivism, Scaffolding, and Independent Learning.
- The constructivist teaching project is based on five principles: active exploration of concepts, teacher as facilitator, real-life problems, focused class discussions, and a gradual increase in student autonomy.

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