FRONTIERS Project
Output 4: Evaluation and Dissemination Report

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Introduction:

The FRONTIERS consortium believe that the science classroom should provide challenging, open, authentic and higher-order learning experiences for students. There should be opportunities for students to participate in scientific practices and tasks, to use the discourse of science and work with scientific tools. Key to stimulating students and discovering the next generation of frontier science innovators is presenting frontier scientific ideas and activities that are closely related to new technological achievements and everyday life.

Under the unique circumstance of the Covid 19 pandemic, the consortium has been dynamic and innovative in delivering the project outcomes whilst overcoming unparalleled challenges. Despite the global lockdown of society, including in-person teaching & learning, the consortium has delivered high-quality teaching resources that blend frontier science with pedagogical thought, provided teacher training, facilitated virtual tours of research institutions to an international audience of teacher and students, and built a community of educators passionate about frontier physics.

The FRONTIERS project designed, developed, and evaluated 21 demonstrators. This series of innovative educational activities offer unique scientific resources to teachers and students organised under a systematic pedagogical framework. Teachers are supported on an ongoing basis through the FRONTIERS Community Support Environment, the online infrastructure that allows engagement and interaction between teachers, research institutes and project organisers.

A series of international e-schools, virtual visits, science contests, and teachers training activities were organised as part of the FRONTIERS project. Hundreds of teachers got involved in the design and development of innovative classroom activities in a collaborative way. Through the Frontiers network teachers collaborated with the outreach teams of large-scale research infrastructures. Being part of a professional network encouraged interaction and provided opportunities to enrich practices and professional context through cooperation within and between schools, universities, and frontier research institutions.

A series of virtual visits were organised for students where they were introduced to gravitational wave astronomy and guided by expert scientists in a remote tour to Virgo, Europe's advanced gravitational wave astronomy facility. This gave students a chance to witness first-hand how experiments are performed and how data acquired by these experiments are studied. This way of introducing science helps students overcome the idea of it being complex and too difficult for them to understand and helps them to see it as a tool to explore and understand nature.

The FRONTIERS Tool-Kit, "Effective Ways of Introducing Frontier Science in Schools", was developed and will be made available through the e-Twinning collaboration space to all European schools. The Tool Kit provides a set of recommendation for a pan European roadmap for the introduction of relevant activities in schools and how scientific work can be used to provide an engaging educational experience through the exploration of "real science".

Furthermore, by bringing together researchers from different fields of Science, including particle physics, astronomy and cosmology, this project promoted cooperation between managers of different infrastructures to achieve trans-national collaboration and the designing of effective and interdisciplinary educational activities.

The project partners are proud to present this evaluation of the Frontiers Project outputs.

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Project Overview

Aims and Objectives

The FRONTIERS project aimed to demonstrate how Nobel Prize winning science can be systematically integrated in the school curriculum. This is demonstrated through a monitored-for-impact use of innovative educational activities, the FRONTIERS Demonstrators, which provided feedback for the take-up of such interventions. The project consortium proposed the main ways that frontier science experiments can leverage educational activities are by:

a) Making scientific and educational resources available worldwide through advanced repositories and effective search mechanisms.
b) Supporting effective community building between researchers, teachers and students.
c) Creating virtual global classrooms by interconnecting the schools and the research centres.

The aim of the project was to mobilize 1,000 teachers and 10,000 students in the framework of the proposed activities. Building on the above ways that frontier science experiments could leverage educational activities, five project outputs were proposed as a means of achieving the main project objects.

1. Select a series of scientific research outreach programmes that successfully introduce the scientific methodology in school science education, by utilizing existing research infrastructures of frontier research institutions enriched with online tools (data analysis tools, simulations & games) and web-interactive educational material (O1).
2. Integrate these initiatives under a common educational approach and develop the FRONTIERS Demonstrators that could be exploited and widely used from the educational communities in Europe and beyond (O2).
3. Create virtual learning communities of educators, students and researchers and involve them in extended episodes of playful learning. The proposed project will involve teachers, students and researchers in collaborative learning activities. The development of the virtual learning community will be enhanced by the FRONTIERS Community Support Environment (O3).
4. Systematic validate the proposed approaches and activities in order to identify their impact in terms of the effectiveness and efficiency. The project will be implemented in schools, science teacher training centres, and research centres in different countries and a detailed evaluation report will be prepared (O4).
5. Design and implement a systematic raising awareness strategy that will contribute to the effective communication of the project's results and outcomes. A devoted Tool Kit (O5) will be developed that will be uploaded to the eTwinning collaboration space to act as a starting point for numerous collaborative projects between schools.

Impact of Covid 19

The FRONTIERS project set out to empower science teachers to affect change by enabling them to bring frontiers science into the classroom using an inquiry-based learning approach. This approach was adopted to increase students' interest and attainment in science.

A major challenge arising during the lifetime of the project was the Covid-19 pandemic. While the project achieved and even exceeded its stated objectives, the unprecedented societal lockdowns prevented elements of the proposed project activities from continuing as originally envisaged.

Instead, project partners successfully delivered project objectives through a range of dynamic and bespoke technical solutions.

A project objective was to provide face-to-face teacher professional development or multiplier events and practice reflection meetings at a local level in the different partner countries. These events took place face-to-face in 2019. Due to Covid-19 the project consortium could not continue with face-to-face events. In March 2020 a decision was made to continue offering the learning and teaching events using the online technologies available in the individual partner institutions or supported by project partners. An evaluation of the face-to-face and online professional development events was carried out using quantitative and qualitative methods. Feedback on the Demonstrators was also gleaned from the teachers and this led to further refinement and improvement of the Demonstrators ahead of final implementation.

The project planned to either map the process for the effective implementation of frontier science in school environments by integrating the Demonstrators into school practice or by extra-curriculum activities (e.g. masterclasses, summer schools, contests). A consequence of the Covid-19 pandemic and resulting societal lockdowns, was the closure of schools to students for long periods. This resulted in distance learning being adopted and heavily reduced in-person contact times on return. With normal laboratory-based classes not occurring, project partners decided that in-school implementation of FRONTIERS Demonstrators, was an unrealistic and unreasonable expectation of teachers and school authorities. Alternatively, priority was given to direct engagement and empowerment of teachers to implement the Demonstrators, through international e-school events. The project partners also focused on supporting teachers to engage students in a meaningful way through facilitated virtual visits to large research infrastructure such as CERN, Virgo and Pierre Auger.

Due to the covid-19 situation the one-week international summer schools planned for July 2020 and July 2021 and the one-week international winter school in February 2021 were redesigned to take place fully online. The planned one-week winter school took place over two consecutive weekends at the end of January and beginning of February and there were individual meetings with teachers between both weekends. The summer schools took place as fully online one-week schools.

Teachers were supported through online learning tools to participate in master classes, summer and winter schools, teacher networks and contests from March 2020 until July 2021. It is evident from the teacher feedback that the organisation and structure of these online events provided space for them to draw on the expertise of the project consortium and collaborate with teachers to gain a sound understanding of the Demonstrators and of the topics of Frontier science.

The alternative approach adopted by the project partners in a time of profound instability and change, facilitated the stated objectives of the FRONTIERS Project. Teachers were involved in the design and development of classroom activities in a collaborative way. An international professional community was established, allowing collaboration with not just other teachers, but also with the outreach teams of large-scale research infrastructures and universities. As documented in the report this objective exceeded our expectation as teachers created classroom activities based on the topics of the FRONTIERS Demonstrators. The teacher created resources are available on the Frontiers website and can be accessed by teachers across Europe and beyond.

Evaluation Plan

The project evaluation section of this report provides an overview of the evaluation process employed. This overview starts by revisiting the project aims and objectives, the delivered intellectual outputs and details of their intended impact. The section finishes with an account of the methodology employed to evaluate the effectiveness of the Frontier project deliverables.

Project Impact

The FRONTIERS approach aims to foster a culture of cooperation between research infrastructures and schools. By spreading good practices between outreach groups of large-scale research infrastructures and encouraging them to develop their activities in complementary ways the consortium aimed to demonstrate a vision of the science classroom of tomorrow. As far as the target groups are concerned the project is focusing on both students and teachers.

The FRONTIERS project aims to attract young people to science and pool talent to scientific careers

- By simulating the work of the researcher in the classroom
- By promoting a better understanding of how science works
- By enhancing students' science related career aspirations
- By promoting inquiry-based science teaching and learning

Key to achieving project aims is to empower science teachers to affect change. The consortium believe that the above actions can only be accomplished with the full collaboration and engagement of teachers and their schools.

With this in mind, the FRONTIERS project set out to expand opportunities for teachers' professional development, including occasions to interact with working scientists, to help stimulate and innovate their science classroom, and more generally think differently about their students' learning of and about science.

By offering teachers a large repertoire of tools and applications, along with a detailed school-based framework for their effective introduction, the FRONTIERS project sought to empower teachers. This is not only meant to change their teaching practice and introduce contemporary scientific issues in their lessons, but also to propose and initiate the necessary changes in their schools, to allow for a more seamless introduction of ICT innovations.

The challenge of professional development for science teachers is to create optimal collaborative learning situations in which the best sources of expertise are linked with the experiences and current needs of the teachers.

Measuring of Impact

This evaluation report aims to measure the impact and the effectiveness, both quantitatively and qualitatively, of the project at three levels; at teacher, student and institutional/school level.

The aim of the project was to mobilize 1,000 teachers and 10,000 students in the framework of the proposed activities. The development of the FRONTIERS users' community was based on the effective integration of already established strong educational communities with project consortium developed online resources and activities.

Teachers

With respect to participant teachers the project aimed to assess and estimate impact in the following areas:

a. the effectiveness of the training seminars and workshops
b. the extent participant teachers developed interdisciplinary educational activities
c. the extent participant teachers collaborated with other teachers

Students

The student target group of the project are aged 12-18 with a focus on the development of their content and concept knowledge, skills and attitudes. The project evaluation will mainly focus on estimating the impact of the project overall activities on the following distinct areas:

a. students' ability to operate experimental techniques to conduct a scientific inquiry
b. students' ability to monitor, record and analyse data
c. enhancement of students' problem-solving competence and interdisciplinary thinking
d. enhancement of a positive attitude towards STEM disciplines

Institutions and Schools

At institutional and school level, the project aims to assess and estimate impact at the following areas:

a. to what extent school authority encouraged or facilitated participation of its staff teachers in training and teacher development programmes
b. to what extent school authority encouraged or facilitated development of interdisciplinary educational activities e.g. by altering school's timetable so that teachers from different STEM disciplines can work together
c. to what extent schools collaborated or plan to collaborate in the future with other schools in their area/region/country or other countries
d. to what extent the participation of the schools in the FRONTIERS project was considered as recognition or distinction of achievement and further facilitated the participation in other projects and initiatives

Methodology

Given the broad range of project aims, intended impacts and participants involved, a mixed methods evaluation approach was adopted. Utilising both quantitative and qualitative data collection and analysis, partners set out to systematically and rigorously evaluate the impact of the project outputs have on integrating Nobel prize winning science into the classroom. The evaluation sets out to determine whether the project had achieved its intended impact and how it might be improved.

Multiple data collection methods and analysis were developed to evaluate the effectiveness of project outputs. To harness the multiple perspectives of relevant project stakeholders, a series of instruments and evaluation tools were developed to be more effective and user-friendly than the traditional. The expertise of the project partners has allowed for the development of a dynamic set of evaluation tools through quantitative and qualitative methods.

A mixed methods approach was adopted by project partners to evaluate the multiple stages and perspectives relevant to the FRONTIERS project outputs. According to Johnson, Onwuegbuzie and Turner (2007), the combining of elements of qualitative and quantitative research approaches in one study, has the benefit of providing breadth and depth of understanding and corroboration. Whilst gaining valuable insight into the lived experience of those closest to the phenomenon through the qualitative phase, the inclusion of the quantitative methods can make the study findings more generalisable and acceptable to quantitative-biased audiences.

Developing our evaluation plan for the FRONTIERS project, it was decided to employ a Convergent Mixed Methods Evaluation Design, as described by Creswell and Plano Clark (2018). The Convergent Mixed Methods Evaluation Design is appropriate for complex projects with multiple stages and objectives over several years. It allows for the evaluation of outcomes and activities undertaken in the cultural context with researchers undertaking several iterations of data collection, analysis, integration and implementation.

Onwuegbuzie and Hitchcock (2017) advocate conducting mixed methods impact evaluations of educational programmes, as the combination of qualitative and qualitative methods provides a rigorous impact evaluation that yields strong inferences with a focus on if and how the programmes have impacted society. While the quantitative approaches permit generalisation and test statistical difference, Bamberger, Vijayendra and Woolcock (2010) explain, the qualitative approaches allow in-depth description, process analysis and patterns of social interaction. It is also argued that a mixed method orientation to evaluation is critical to the three dimensions of transferability, generalisation and sustainability of evaluating an educational programme, as a “singular commitment to one paradigm might yield somewhat impoverished capacity to think about these concerns” (Onweugbuzie and Hitchcock, 2017, p. 59).

Evaluation Summary

The FRONTIERS project aimed to demonstrate how Nobel Prize winning science can be systematically integrated in the school curriculum. By fostering a culture of cooperation to spread Through the project activities and outputs the consortium sought to bring Nobel prize winning frontier physics to the classroom by:

a) Making scientific and educational resources available worldwide through advanced repositories and effective search mechanisms.
b) Supporting effective community building between researchers, teachers and students.
c) Creating virtual global classrooms by interconnecting the schools and the research centres.

Key to achieving the project aim is to empower science teachers to affect change. The consortium believe that the above actions can only be accomplished with the full collaboration and engagement of teachers and their schools. The Frontier project expanded the opportunities for teachers' professional development, providing occasions to interact with working scientists, helping them to introduce innovations in their science classroom, and think differently and more innovatively about their students' learning.

Project Impact

The evaluation report measured the impact and effectiveness of the FRONTIERS project outputs in bringing Nobel prize winning physics to the classroom. The impact was measured both qualitatively and quantitatively through a convergent mixed methods impact evaluation approach. This mixed methods approach allowed for the evaluation of outcomes and activities undertaken in the cultural context with researchers undertaking several iterations of data collection, analysis, integration and implementation.

Onwuegbuzie and Hitchcock (2017) advocate conducting mixed methods impact evaluations of educational programmes, as the combination of qualitative and qualitative methods provides a rigorous impact evaluation that yields strong inferences with a focus on if and how the programmes have impacted society.

This evaluation of the FRONTIERS project set out to measure the impact and effectiveness, both qualitatively and quantitatively, of the project at teacher, student and institutional level. The impact and effectiveness of the project at these three levels will be discussed below.

Teachers

Key to the success of the FRONTIERS project was empowering teachers to affect change and bring prize winning physics to the classroom. The consortium believed that the project aims can only be accomplished with the full collaboration and engagement of teachers and their schools. As a result, the Frontier project set out to expand opportunities for teachers' professional development.

In addition to the stated mobilisation target of 1,000 teachers, the project also aimed to assess and estimate impact at the following areas:

a) Effectiveness of the training seminars and workshops
b) Extent that participant teachers developed interdisciplinary educational activities
c) Extent that participant teachers collaborated with other teachers

Mobilisation Target

The first key performance indicator of the FRONTIERS project was to mobilise 1,000 teachers within the framework of the project. It has been demonstrated, through the range of activities and platforms employed by the project to engage and mobilise teachers, the consortium has mobilised well in excess of the target figure.

Project activities that were designed to engage and mobilise teachers included the project multiplier events and online community support. The multiplier events held by the project included the Initial Teacher Training, International e-Schools and Virtual Visits. The range of platforms used to engage teachers through the online community support involved Facebook, project website, OSOS platform and Google Classroom.

Teacher Mobilisation Figures	
Synchronous Engagement	
Initial Teacher Training	303
International e-Schools	277
Virtual Visits	192
Masterclasses	71
Total	843
Asynchronous Engagement	
Facebook	1,111
Project Website	8,305
OSOS Platform	174
Google Classroom	70
Total	9,660

Effectiveness of training seminars and workshops

The FRONTIERS project delivered a series of high-quality training seminars and workshops to science teachers, within the partner countries and beyond. Central to the effectiveness of these training events was the development of the 21 FRONTIERS Demonstrators. The purpose of these outputs was to empower science teachers in bringing Nobel prize winning physics to the classroom.

The selection and development of the Demonstrators, employing quality criteria and pedagogical framework selection consideration, ensured high quality resources to support bringing Nobel prize winning physics to the classroom.

The 15 initial teacher training events held across the project partner countries provided feedback on the quality and relevance of the demonstrators, and also the effectiveness of the training provided to teachers on how to effectively employ the resources in the classroom. The feedback from the 303 participants of the initial teacher training informed the development of the International e-School series. Using a 5-point scale, questionnaire responses indicated participants were interested and enjoyed the International e-Schools (M=4.25, SD=0.698). Participants also reported the e-School content was very valuable and useful to them (M=4.8, SD=0.48).

Key to measuring the effectiveness of the training events provided by the FRONTIERS project, was measuring the impact the training and resources had on the self-efficacy of the participating teachers. The evaluation methods used to measure the impact and effectiveness of project training events showed an increase in teacher confidence with the subject of Nobel prize winning physics, up 21%, as well as their ability to motivate students to learn about the topic, up 8%. Analysis of questionnaire data showed a statistically significant relationship between pre and post training levels of teacher confidence and ability to motivate students. These quantitative findings were also supported through the qualitative findings from focus group and round table discussion with participants.

It was widely acknowledged that the *"hands-on"* and practical approach of the training workshops motivated teachers to participate more fully and enthusiastically. The inquiry-based learning approach adopted by the project was noted as being of great interest and benefit to teachers and students. The demonstrators in their content and design facilitated bringing the scientific approach to the classroom in both its content and pedagogical approach.

The age and experience of the teachers taking part in the training were important variables in relation to the impact the training had on the participants. A statistically significant relationship was found between participant age and the reported increase in confidence. While all age groups reported an increase in confidence in delivering Nobel prize winning physics, participants aged 34 and under had the highest average increase with more than 2 points on a 10-point scale.

Survey data collected from the International e-School participants found a significant increase was recorded in the average Self-Efficacy score from pre (M=3.8) and post (M=4.5) results on a 5-point scale. The confidence of the participant teachers with content knowledge of modern physics increased comparing pre (M=3.2) and post (M=4.0) training scores. The post training, participants reported feeling competent to design educational content relating to modern physics (M=4.2, SD 0.635).

The feeling that the FRONTIERS Demonstrators and International e-Schools would provide teachers with the tools, knowledge and confidence to bring frontier science to the classroom was held amongst participants. Following the completion of the International e-School, participants reported being very interested in implementing the FRONTIERS Demonstrators with their students (M=4.82, SD=0.39).

Extent that participant teachers developed interdisciplinary educational activities

The FRONTIERS project developed 21 Demonstrators to aid teachers in bringing Nobel Prize winning physics to the classroom. The range of physics categories covered through the Demonstrators and the training provided to participants, facilitated the teachers to engage with and develop a range of interdisciplinary educational activities in the field of physics.

The Demonstrators were organised according to categories of frontier physics, from basic physics to astronomy, cosmology and high energy physics. This interdisciplinary repository of resources and training were designed to encourage participant teachers to upskill and expand their teaching into other branches of physics that are less frequently delivered.

A key feature of the International e-School was establishing working groups of participating teacher to work collaboratively to create their own interdisciplinary resources based the FRONTIERS Demonstrators. This working group approach, supported by project facilitators and frontier physics researchers, was considered instrumental in participants reporting feeling competent to design educational content relating to modern physics in post training survey data (M=4.2, SD 0.635).

From the focus group findings, Teacher E explained that working with other colleagues to develop resources and *"meeting with mentors was very helpful to strengthen our confidence to talk to our own students about these topics…"* This supported development of professional confidence and self-efficacy was felt would be of great benefit to the teachers when delivering Nobel prize winning physics content in their classrooms.

The results of these interdisciplinary collaborations are hosted on the FRONTIERS website, as resources to be shared with other interested and motivated science teachers looking for inspiration.

Extent that participant teachers collaborated with other teachers

Highlighted through feedback from the initial teacher training events, a priority for the International e-Schools was to promote and facilitate participating teachers to work collaboratively with fellow professionals to explore the resources. The success of this was highlighted in the project focus group findings with participants. The focus group participants highlighted that the collaborative design of the Winter School helped the teacher develop a deeper understanding of the content and educational tool by allowing the professionals to explore and develop the resources together.

Survey data findings showed participants were satisfied with the level of collaboration with other teachers (M=4.18, SD=1.01), and very satisfied with the level of collaboration they experienced with course organisers (M=4.68, SD=0.72). In focus group discussion that reflected the general feeling of participants, Teacher C stated, *"I liked all things…but if had to choose one thing it would be the collaboration with colleagues far away from me."*

As the International e-Schools were held virtually, online collaborative tools had to be used to facilitate the teacher engaging with the content and each other. Several of the collaborative tools employed by the Frontier Project were subject to praise. The use of Zoom to host the live events and sharing of resources by email was functional and accessible to all participants. In the working groups, Google Slides received considerable praise.

In additional to working collaboratively with other participating teacher at the International e-School, the FRONTIERS project also set out to facilitate teachers working collaboratively with other professionals through the online community support and e-twinning projects. International e-School participants were very interested in collaborating with colleagues to create e-twinning projects (M=4.64, SD=0.73). The appetite of teachers to collaborate with other professional internationally was summed by Teacher C in the focus group discussion, who said, "*"The main reason I wanted to be part of the e-Winter school was it was very interesting and exciting to collaborate and to listen to what teachers from other countries had to say."*

Students

The student target group of the project was aged 12-18 years. The focus of the project was on the development of student content and concept knowledge and support the development of skills and attitudes towards frontier physics.

Mobilisation Target

The student mobilisation target for the FRONTIERS project was 10,000 within the framework of the proposed activities. The stated mobilisation target of 10,000 students was based on the given ratio that the mobilisation of 1 teacher would deliver the mobilisation of 10 students. This equivalence is arrived at as teachers employ resources and training with students in the classroom, at a minimum of 10:1. As the FRONTIERS project achieved its goal of mobilising over the stated goal of 1,000 teachers, it can be stated that the project also achieved its stated aim of mobilising over 10,000 students. In addition to indirect engagement of students through teachers, the FRONTIERS project also directly engagement students through virtual visits and masterclasses. The total number of students engaged in this in-person and online events was 1,505.

Student Skills Development

Through the collection of qualitative data from International e-School participants, teachers highlighted that the Demonstrator resources facilitated students working with real-life data using tools and techniques reflecting the work of physicists in the field. Despite the barriers presented by the Covid-19 pandemic and subsequent societal lockdowns, the FRONTIERS Demonstrators has been shown to be effective in promoting the prioritised student impact criteria as set out below.

a. students' ability to operate experimental techniques to conduct a scientific inquiry
b. students' ability to monitor, record and analyse data
c. enhancement of students' problem-solving competence and interdisciplinary thinking
d. enhancement of a positive attitude towards STEM disciplines

Integral to the development of the FRONTIERS Demonstrators was the inquiry-based pedagogical approach. Feedback from teachers that participating in the International e-School training events highlighted the approach was of great interest and benefit to both teachers and students. The internal evaluation criteria for development of the Demonstrators included the incorporation of student skills development. These included:

- **Learning and Innovation skills** include communication, collaboration, problem solving and thinking outside the box.
- **Literacy skills** involves the use of technology, ability to read statistics and graphs, access, evaluate and create media.
- **Life skills** is a term used to describe the ability to set goals, plan use of resources, respond to feedback, take responsibility for collecting, organizing and analysing data.

Through the voice of the teachers who undertook the training to implement the FRONTIERS Demonstrators in the classroom, the value and effectiveness of the resource in promoting student skills development was evident. Participant 4 of the focus group welcomed this way of engaging students with frontier physics, stating that, *"Physics is a nice subject but the blackboard is not enough to give the students the pleasure of intellectual discoveries."* Participant 4 felt that the *"practical aspect of FRONTIERS resources will instil in students the ability to ask questions and to explore."*

Participant 5 of the same focus group, had tried introducing frontier physics in a theoretical way, but since participating in the International e-School, they had started "*to introduce the topics in a practical way with the animations and videos that are part of the demonstrators".* As a result, she and her students feel they are *"working like a scientist."*

The blend of Nobel prize winning physics with inquiry-based pedagogical approach that speaks to the professional needs of teacher was highlighted for praise also. The development of the Demonstrators fulfilling both requirements meant *"students will be using scientific language and interpreting real graphs, using graphs in real life."* The inquiry-based learning approach to delivering content was identified as encouraging students to employ *"critical thinking, problem solving, justifying reasoning"* through *"practical investigation."*

In addition to the FRONTIERS Demonstrators as teaching and learning resource, the project partners facilitated virtual visits to large-scale research facilities to engage students directly. The evaluation results of these virtual visits delivered with the supporting Demonstrator resources, showed an increase in student confidence with subject of Nobel prize winning physics. Analysis of findings following virtual visits to the Virgo gravitational wave detector found students displayed a 22% increase in familiarity with vocabulary items related to Gravitational Wave production and detection principles as well as a 15.7% improved familiarity with items related to technical aspects of measurement.

Institutions/Schools

To assess and estimate the impact the project had at school and institution level, one of the identified measures was the extent to which school authorities encouraged and facilitated the participation of staff in the training provided by the FRONTIERS project.

During the 15 initial teacher training events hosted by partners, 303 science teachers attended. In addition, 277 teachers from an international audience attended the International e-School online training events. Each of these teachers was facilitated and encouraged to attend these training events as they were released by their schools and institutions to attend.

The FRONTIERS Project also facilitated the cross-sectional cooperative community building that say schools, universities and large-scale research institutions work collaboratively to promote Nobel prize winning physics. During the project lifetime, 15 virtual visits were undertaken to the four large-scale research facilities. Each of these visits was an opportunity for school communities to experience the frontier of modern physics that teachers and students rarely are given.

The virtual visits were also valuable opportunities for the large-scale research facilities to develop their out-reach programme networks, showcasing the important work being undertaken and encouraging the next generation of research scientists. The value of the virtual visits to research facilities is evident from the number of visits facilitated by the four locations; Virgo, CERN, Pierre Auger Observatory and the Faulkes Telescope.

The impact of the FRONTIERS Project on schools and institutions will be further built upon through the e-twinning opportunities supported through the Online Community Support.

Project Evaluation

Each of the relevant elements project outputs were evaluated in turn. Firstly, the FRONTIERS project demonstrators were evaluated, followed by the initial teacher training events. Next the International e-Schools were addressed, finishing with an evaluation of the Virtual Visits facilitated by the project partners.

Demonstrators

The project delivered 21 demonstrators following multiple phases of internal selection and evaluation criteria. Internal selection and evaluation by partners included best practice quality criteria and compatibility with the adopted pedagogical framework. A breakdown of the selection and evaluation criteria is included below, followed by scores for each selected demonstrator with a short description of content and activities.

Demonstrator Internal Selection and Evaluation

The first two phases of evaluation of the FRONTIERS project demonstrators were internal selection criteria. These criteria were developed to ensure project outputs would be effective in meeting key performance indicators and ensuring quality of deliverables. The internal evaluation and selection criteria of Quality Criteria and Pedagogical Framework are detailed below, followed by a summary of each of the final demonstrators selected.

Best Practice Quality Criteria

Possible demonstrators identified by partners were first evaluated using to the quality criteria outlined below to ensure that only proven best practice resources would be included. As a result, the outreach practices selected by the FRONTIERS consortium have not only been identified through bibliographic research but also through the project partners' hands-on experience.

To select the best outreach practices out of the 32 initially proposed by the project consortium, the criteria were applied using a Google form. A link to the Google form can be found here, as well as the feedback provided by partners.

Of the initial 32 outreach practices that were evaluated using the quality criteria, 25 were proposed as meeting the FRONTIERS best outreach practice criteria. The remainder of the outreach practices were not chosen for inclusion, with many being quite new having low levels of impact so far.

Pedagogical Framework

The developers of the National Science Education Standards (National Research Council, 1996) promoted the enactment of a science curriculum that embraced an inquiry-oriented approach to science teaching. They put forward the following essential features of inquiry-based teaching and learning:

- Learners are engaged by scientifically oriented questions.
- Learners give priority to evidence, which allows them to develop and evaluate explanations that address scientifically oriented questions.
- Learners formulate explanations from evidence to address scientifically oriented questions
- Learners evaluate their explanations in light of alternative explanations, particularly those reflecting scientific understanding.
- Learners communicate and justify their proposed explanations.

The continuum of inquiry-based learning in science education proposed by Banchi and Bell (2008) includes 4 types of inquiry; (i). Limited inquiry which is sometimes referred to as confirmation inquiry, (ii). structured inquiry, (iii). guided inquiry and (iv). open inquiry. The form of scientific inquiry embraced is determined by the level of teacher guidance. Meyer, Meyer et al. (2013) note that teachers can have strong conceptions of what inquiry requires, and still struggle to form instructional plans. Therefore, as suggested by Streich and Mayer (2020) guidance is pivotal in maximising the benefits of inquiry-based learning.

The Frontiers demonstrators were developed using 5 defined stages of inquiry.

1. Orienting and asking questions
2. Hypothesis generation and design
3. Planning and investigation
4. Analysis and interpretation
5. Conclusion and evaluation

A video was produced by DCU to support the inquiry process. The video can be accessed at https://youtu.be/aMjmowIBrOg

Those best-practice demonstrators that successfully passed the first evaluation criteria were then scored according to the pedagogical approach developed and adopted by the project. These evaluation criteria prioritised those demonstrators that adopted an inquiry-based approach to learning.

Scoring criteria under the above headings were developed for partners to evaluate each demonstrator. Each of the demonstrators was marked against the above criteria.

Other elements of the demonstrators were evaluated to enhance project impact and achievement of stated aims. To integrate the student skills development and promotion of a positive attitude towards STEM, the following areas were included at the initial evaluation stage.

- **Learning and Innovation skills** include communication, collaboration, problem solving and thinking outside the box.
- **Literacy skills** involves the use of technology, ability to read statistics and graphs, access, evaluate and create media.
- **Life skills** is a term used to describe the ability to set goals, plan use of resources, respond to feedback, take responsibility for collecting, organizing and analysing data.

Final Demonstrators

The final demonstrators selected for inclusion by the FRONTIERS project are listed below, organised according to categories of frontier physics. Following the table, a one-page description of each demonstrator is provided, with the Pedagogical Framework score and Student Skill Development score.

It should be noted that some demonstrators facilitating a virtual tour score relatively low on the pedagogical framework evaluation criteria. Although not aligning with the pedagogical framework adopted by the consortium, these demonstrators provide invaluable opportunity for students to witness and engage with the work of scientist in real world settings.

Each of the FRONTIERS Demonstrators is hosted on the Open Schools for Open Societies platform, reflecting the pedagogical framework adopted by the project and making them available to the wider community of teachers. This platform is explored further as part of the project Online Community Support.

Erasmus+

Non-accelerator physics
1. Cloud Chamber (EA)
2. Study cosmic rays using data from school detectors (IASA)

Gravitational Waves
3. Gravitational Wave Noise Hunting (EA)
4. Virtual Visit to the European Gravitational Observatory (EGO)
5. "Finding black-holes in a chirp": how to understand the first gravitational-wave detection (PCCP)
6. EGO Control (Class)room (EGO)
7. Earthquake Interferometer (EGO)

Special Relativity
8. Mass-Energy Equivalence (EA)
9. Relativistic muon time dilation (EA)

Astronomy
10. Discovering Alien Worlds - The discovery of an exoplanet (NUCLIO)
11. Black Holes in My School (NUCLIO)
12. Does the Sun rotate? (NUCLIO)
13. Exploring the Sun - Solar differential rotation (NUCLIO)

Cosmology
14. "Measuring the recess velocity of distant galaxies": calculating the age of the Universe (PCCP)

Optical Physics
15. From the Michelson-Morley experiment to the gravitational-wave detection - Discovering and building a Michelson interferometer (PCCP)

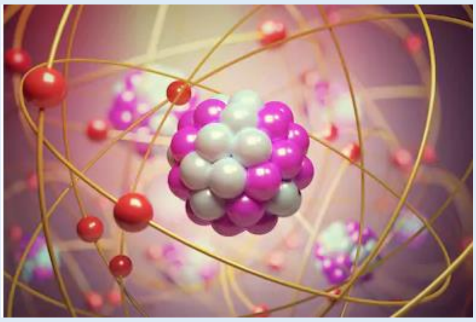
High Energy Physics
16. The ALICE experiment at CERN (EA)
17. Search for the Z and Higgs bosons (IASA)
18. How to accelerate particles (IASA)
19. Study data from the Large Hadron Collider (IASA)

Basic Physics
20. The magnetic field and its applications (IASA)
21. The Pendulum (PCCP)

Demonstrator 1: Build your own cloud chamber

Overview

This demonstrator introduces students to cloud chambers, the first experimental apparatus that enabled scientists to visualize elementary particles coming from the cosmos. Students are introduced to cosmic rays, they learn about the principles of operation of a diffusion cloud chamber, and with the help of their teacher they construct a simple diffusion cloud chamber in order to observe cosmic ray particle tracks in it.



OSOS Link Demonstrator 1

Metadata:
Age: 14-16
Duration: 3 hours
Equipment: Basic materials to build cloud chamber

Concepts introduced:
- Cosmic Rays:
- Muons
- Particle Detectors

Learning outcomes:
- To introduce students to the concept of particle detection.
- To have students build a simple cloud chamber detector.
- To teach students that invisible ionizing radiation can leave visible “footprints” and what these can be.
- To initiate a discussion about cosmic rays.

Prior knowledge:
- Thermodynamics: adiabatic expansion, condensation, vaporization
- Atomic Structure: Ionization
- Supersaturated solutions

Learning intentions:
- describe the principles of operation of a cloud chamber.
- explain what happens when ionizing radiation enters the cloud chamber.
- discuss qualitatively the properties of a muon track observed in a cloud chamber.
- explain what happens when overburden and altitude of the cloud chamber are changed

Key activities:
1. Construction of a diffusion cloud chamber with simple materials.
2. Observation of particle tracks due to cosmic ray interactions with the cloud chamber.

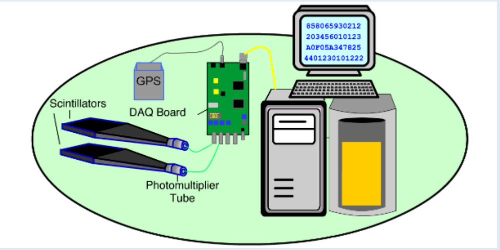
Pedagogical Framework Score:
17/18

Skills Development:
7/10

Learning Skills 4/4
Literacy Skills 0/3
Life Skills 3/3

Demonstrator 2: Study cosmic rays using data from school detectors

Overview



This scenario explains what cosmic rays are and how they interact with the earth's atmosphere. It talks about the different origins of cosmic rays in respect to their energy, what they are made of and how those particles end up producing others inside the atmosphere. It explains how time dilation works according to the special theory of relativity and how that helps muons reach the earth's surface. Then it explains how the students can use real data from cosmic ray detectors installed at schools all over the world make their own plots of muon lifetime.

Link OSOS Demonstrator 2

Metadata:	**Concepts introduced:**
Age: 14-17 Duration: 4 hours Equipment: PC with internet connection	● Relativity ● Particle collisions and interactions ● Particle lifetime

Learning outcomes:
1. Students learn about cosmic rays, what they are and where they come from
2. They learn about how they interact with the atmosphere
3. They learn how to use data and perform a simple analysis on them

Prior knowledge:

● Elementary particles	● Basic electromagnetism	● Basic astronomy: solar system, galaxies etc.

Learning intentions:
- Understand what cosmic rays are and where they come from
- Understand how relativity affects particle lifetime
- Use existing data to study muon lifetime

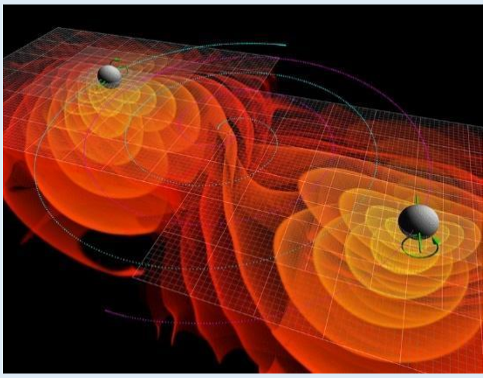
Key activities:
1. Videos and information to engage students
2. QuarkNET data and analysis tool for muon lifetime study
3. Student report and discussion

Pedagogical Framework Score:	**Skills Development:**	
16/18	9/10	Learning Skills: 4/4 Literacy Skills: 2/3 Life Skills: 3/3

Demonstrator 3: Gravitational Wave Noise Hunting

Overview

The discovery of Gravitational Waves provided humankind with a new window to the universe, allowing us to probe extreme cosmic phenomena and testing nature at its limits. This scenario provides a step-by-step introduction to gravitational waves and their detection, introduces the concept of detector sensitivity and through a game-based approach, introduces students to the different noise parameters that affect detector performance.



OSOS Link Demonstrator 3

Metadata:
Age: 16-18
Duration: 4 hours
Equipment: PC with internet connection

Concepts introduced:
- Gravitational wave
- Interferometer
- Sources of noise
- sensitivity
- reach

Learning outcomes:
1. To help students understand the meaning of noise.
2. To guide students to identify sources of noise for gravitational wave detectors.
3. To help students correlate the reach of a detector with its noise level.
4. To show how to compromise budget with performance.
5. To present how to estimate the most important sources of noise and make data driven decisions.

Prior knowledge:
- Waves: Definition and properties
- Newton’s law of gravitation
- Wave interference
- Signal and noise
- Orders of magnitude

Learning intentions:
- describe roughly what gravitational waves are.
- explain that detector noise deters us from exploring farther regions in the universe using gravitational waves as messengers.
- compare the significance of different sources of noise in a gravitational wave detector.
- explain that even though the effects of gravitational waves on earth are minuscule, these derive from very high energy processes.

Key activities:
1. Building a virtual gravitational wave detector
2. Identifying sources of noise and taking corrective actions to reduce it
3. Searching for glitches in a gravitational wave detector

Pedagogical Framework Score:
18/18

Skills Development:
10/10

Learning Skills: 4/4
Literacy Skills: 3/3
Life Skills: 3/3

Demonstrator 4: Virtual Visit to the European Gravitational Observatory

Overview

Virgo, based in Cascina, Pisa, Italy, is one of the three experiments in the world that is able to detect gravitational waves. Several thousands of high-school and university students visit the site every year since 2005. The demonstrator provides an interactive web-based environment for making a virtual visit of Virgo main experimental building. Students would need to understand the optical scheme of the detector in order to orientate themselves inside the labyrinth of vacuum pipes.

Supplementary materials about the discovery of gravitational waves, the birth of multi-messenger astronomy, the operating principle of the detector and its noises is also given.

OSOS Link Demonstrator 4

Metadata:	**Concepts introduced:**
Age: > 16 Duration: 3 hours Equipment: PC with internet connection	● Space-time ● Gravitational Wave ● Black-hole ● Interferometer ● Laser ● Seismic Noise

Learning outcomes:

1. Teach students about the discovery of gravitational waves and its importance to improve our understanding of the universe.
2. Give an idea of the experimental challenges of gravitational wave detection.
3. Introduce basic concepts of General Relativity and Astrophysics.

Prior knowledge:

● Newtonian Mechanics

Learning intentions:

- Have an idea of what are gravitational waves
- Have an idea of what is a laser interferometer and how it works

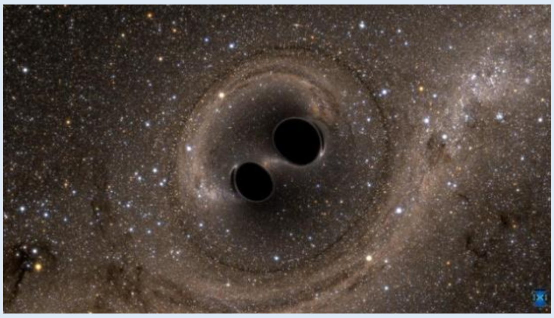
Key activities:

1. Slides with pictures and videos to engage
2. Understand Virgo optical scheme
3. Treasure hunting inside the interferometer experimental building
4. Impressions and discussion on exploration of the detector
5. Final report and discussion

Pedagogical Framework Score:	**Skills Development:**	
5/18	8/10	Learning Skills: 4/4 Literacy Skills: 3/3 Life Skills: 1/3

Demonstrator 5: Finding black holes in a chirp
How to understand the first gravitational-wave detection

Overview



This demonstrator introduces the concept of gravitational waves, their possible sources, and the way they have been detected. Students are introduced to the basics of data analysis using the real signal of the first gravitational wave ever detected, produced by the motion of two inspiralling masses.
Students will learn how to determine the masses and the radius of the binary system, to identify the two objects as black holes, and what are the fundamental properties and parameters of a black hole.

[OSOS Link Demonstrator 5]

Metadata:	Concepts introduced:
Age: >17 Duration: 3 hours Equipment: PC with internet connection	● Basics of general relativity ● Gravitational-wave emission ● Binary black holes systems ● Schwarzschild radius ● Chirp mass

Learning outcomes:
1. Learn the basics of general relativity, black holes, and gravitational-wave emission and detection.
2. understand the methodology and reproduce the analyses behind the discovery of gravitational waves.
3. Introduce basic concepts of astrophysics and gravitational-wave astronomy.

Prior knowledge:		
● Algebra ● Basic concept of calculus	● Wave properties	● Knowledge of Newton and Kepler laws

Learning intentions:
- Define a gravitational wave and interpret its signal
- Explain the gravitational waves observation method
- Calculate the Schwarzschild radius of an astrophysical object.
- Explain the merger of a binary system and draw a scheme of the gravitational signal emitted.

Key activities:
1. Videos to engage
2. Data analysis and explanation
3. Optional: python scripts for data analysis
4. Final report and discussion

Pedagogical Framework Score:	**Skills Development:**	
16/18	6/10	Learning Skills: 2/4 Literacy Skills: 2/3 Life Skills: 2/3

Demonstrator 6: Ego Control (Class)room

Overview

All big experiments like LHC or Virgo have a control room. It is there that all the magic happens! There all the troubles, successes, joy and despair of the experimental physicist life are concentrated. In this room tens of people workday and night together to improve the sensitivity of the detectors. The demonstrator allows the teacher to have in your class many of the screens present in the Virgo control room. This allows for several studies aimed at understanding the relationship between the detector and the environment. This activity is very close to the work done day by day by the physicists working on site. Supplementary materials about the discovery of gravitational waves, the birth of multi-messenger astronomy, the operating principle of the detector and its noises is also given.

OSOS Link Demonstrator 6

Metadata:	**Concepts introduced:**	
Age: >16	Gravitational Wave	Interferometer
Duration: 3 hours	Observing range (Parsec)	Fourier transform
Equipment: PC with internet connection	Seismic Noise	

Learning outcomes:

1. Give an idea of the experimental challenges of gravitational wave detection.
2. Give an idea of the work that physicists do in the Virgo control room.
3. Let students understand the strong interaction between the environment and the detector.

Prior knowledge:

- Newtonian Mechanics

Learning intentions:

- What are gravitational waves?
- What is a laser interferometer and how it works
- What are the noises that disturb the detector

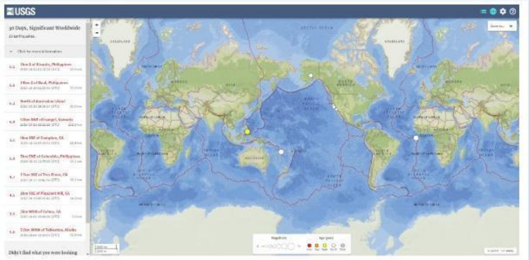
Key activities:

1. Slides with pictures and videos to engage
2. Configure the PC or RPi to show Virgo real time data
3. Familiarize with the Control Room tools (DMS, VIM, …)
4. Analysis of recent data in respect to the environment (Wind speed, Sea activit)
5. Final report and discussion

Pedagogical Framework Score:	**Skills Development:**	
13/18	8/10	Learning Skills: 4/4 Literacy Skills: 3/3 Life Skills: 1/3

Demonstrator 7: Earthquake Interferometer

Overview



Using the data shown in Control (Class)room demonstrator several studies aimed at understanding the relationship between the detector and the environment can be made. The correlation between the sensitivity of the detector and the arrival of strong remote earthquakes can be studied. This allows the students to understand both the nature and propagation speed of seismic waves and at the same time to experience directly how a gravitational interferometer work. Moreover, this activity is very close to the work done day by day by the physicists working on site.

OSOS Link Demonstrator 7

Metadata:

Age: >16

Duration: 3 hours

Equipment: PC with internet connection

Concepts introduced:

Gravitational Wave	Interferometer
Logarithmic scales	Fourier transform
Harmonic oscillator	Seismic Noise
Seismic waves & Earthquakes	

Learning outcomes:

1. Give an idea of the experimental challenges of gravitational wave detection.
2. Give an idea of the work that physicists do in the Virgo control room.
3. Let students understand the strong interaction between the environment and the detector.

Prior knowledge:

● Newtonian Mechanics

Learning intentions:

- What are gravitational waves
- What is a laser interferometer and how it works
- How earthquakes affect GW interferometers

Key activities:

1. Slides with pictures and videos to engage
2. Configure the PC or RPi to show Virgo real time data
3. Familiarize with the Control Room tools (DMS, VIM, …)
4. Analysis of the effect of recent earthquakes on the observing range of the detector
5. Final report and discussion

Pedagogical Framework Score:	Skills Development:	
15/18	8/10	Learning Skills: 4/4 Literacy Skills: 3/3 Life Skills: 1/3

Demonstrator 8: Mass-Energy Equivalence

Overview

This demonstrator introduces the most famous equation in Physics, E = mc2 to students. Students form a research question about the meaning of mass-energy equivalence, and they explore the equation and its applications. Students examine the units and calculations required to apply Einstein’s equation to real life. Students gain experience of completing calculations and compare their results to the experimentally collected data. Students understand that the law of conservation of energy and the law of conservation of mass don’t apply individually but together. They watch videos which explain this effect and its applications to real world phenomena.

OSOS Link Demonstrator 8

Metadata:	**Concepts introduced:**	
Age: 15-17	Mass-Energy	Nuclear power
Duration: 3 hours	Radioactivity	The electronvolt unit
Equipment: PC with internet connection	The atomic mass unit	

Learning outcomes:
1. Introduce students to the most famous equation in the history of Physics.
2. Introduction to the basic principles behind nuclear fission using mass-energy equivalence.
3. Demonstrate that energy and mass are not conserved separately in nature.

Prior knowledge:			
● Concept of mass	● Concept of energy	● Chemical formula	● Linear equations

Learning intentions:
- Identify the significance of Einstein’s equation
- List examples of processes where energy is created according to E=mc2
- Change the units of energy between eV and J
- Change the mass of a particle from amu to kg
- Calculate loss/gain in mass from a chemical reaction and calculate the energy created/required
- Explain the relationship between mass and energy

Key activities:
1. Matching activity of key words to images
2. Converting units’ calculations
3. Develop hypothesis and test using calculations
4. Summary presentation

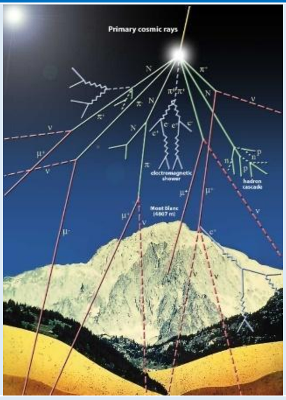
Pedagogical Framework Score:	**Skills Development:**	
17/18	6/10	Learning Skills: 3/4 Literacy Skills: 2/3 Life Skills: 1/3

Demonstrator 9: Relativistic Muon Time Dilation

Overview

This demonstrator introduces students to the phenomenon of relativistic time dilation, one of the most striking consequences of Einstein's Special Theory of Relativity. Utilizing a virtual simulation, students will investigate the rate of decay in flight of muons produced in elementary particle collisions in the atmosphere and will be guided to explain their findings using Einstein's theory of Special Relativity and the phenomenon of time dilation. This scenario is a follow-up from the educational scenario on cosmic muon decay.

OSOS Link Demonstrator 9



Metadata:	**Concepts introduced:**
Age: 16-18	Muon Decay in flight
Duration: 3 hours	Relativistic Time
Equipment: PC with internet connection	Dilation
	Flux

Learning outcomes:

- To introduce students to the concept of radioactive decay.
- To introduce students to cosmic ray muons.
- To introduce students to relativistic time dilation.
- To initiate a discussion about cosmic rays.

Prior knowledge: Exponential decay Radioactivity	Properties of muons, Exponential functions	The "eV" unit of energy and its multiples.

Learning intentions:

- Discuss the properties of muons.
- Discuss the phenomenon of radioactive decay.
- Explain the phenomenon of relativistic time dilation in simple terms.
- Plot data in excel and fit them with an exponential function.
- Explain the concept of flux and be able to calculate it for given parameters

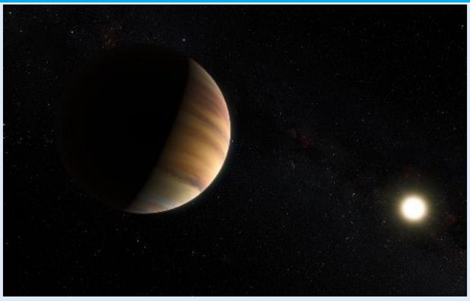
Key activities:

1. Performing simple kinematics calculations
2. Performing a simple counting experiment for different altitudes.
3. Collecting data, plotting them and fitting them
4. Develop hypothesis and test using calculations
5. Summary presentation

Pedagogical Framework Score:	**Skills Development:**	
17/18	7/10	Learning Skills: 3/4 Literacy Skills: 3/3 Life Skills: 1/3

Demonstrator 10: Discovering Alien Worlds - Discovery of an exoplanet

Overview



This demonstrator introduces the concept of an exoplanet and how they have been discovered in our universe. Students are introduced to the transit method of exoplanet detection. Real images will be used to look for changes in the starlight that might result due to the motion of an orbiting exoplanet. Students will be given real light images and learn how to use a specific image software to perform photometry and to analyse the graphs. The analysis of the light curve will allow students to estimate the rotational period of the exoplanet and its diameter. Students can present their work to the class and discuss how they compare with the most accurate results that astronomers have.

OSOS Link Demonstrator 10

Metadata:	**Concepts introduced:**
Age: 14-18 Duration: 3 hours Equipment: PC with internet connection, light sensor and basic lab equipment	● Exoplanets ● Luminosity ● Graphing

Learning outcomes:
1. Teach students about the discovery of exoplanets
2. Allow students to understand the science and methodology behind the discovery of alien worlds.
3. Introduce basic concepts of Astronomy and Image Processing

Prior knowledge:
- Basic Astronomy knowledge of a star and planet system

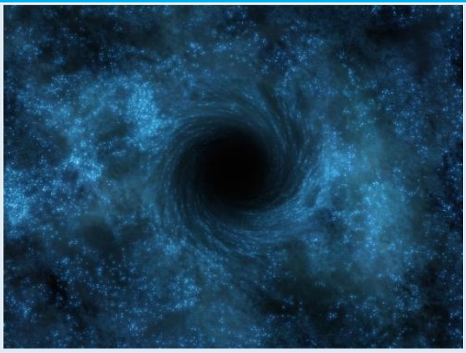
Learning intentions:
- Define an exoplanet
- Explain the transit method
- Describe a method to collect luminosity data
- Examine images using the salsa J software
- Form conclusions about a planet from a light graph

Key activities:
1. Videos to engage - possible edpuzzle
2. Explaining the light curve
3. Practical formation of a light curve
4. Salsa J - examination of 3 stars
5. Analysis and explanation
6. Final report

Pedagogical Framework Score:	**Skills Development:**	
16/18	9/10	Learning Skills: 4/4 Literacy Skills: 2/3 Life Skills:3/3

Demonstrator 11: Black Holes in My School

Overview



This demonstrator introduces the concept of black holes and how difficult it is to find them. Students are introduced to a method of detecting black holes in eclipsing binary systems – systems formed by a visible star and an eclipsing companion. Real images will be used to look for changes in the starlight that might result due to the presence of a companion. Students will learn how to use a specific image software to perform photometry on the images and will create a graph of brightness variation. The analysis of the light curve will allow students to estimate the orbital period of the companion and, given a relation between several parameters of the known star and the companion's mass, they will estimate the minimum mass of the unknown companion and decide if it is a strong candidate to be a black hole. Students can present their work to the class and discuss how they compare with the most accurate results that astronomers have.

OSOS Link Demonstrator 11

Metadata: Age: 14-18 Duration: 3 hours Equipment: PC with internet connection	**Concepts introduced:** Black holes Luminosity Photometry Graph analysis

Learning outcomes:
1. Teach students about black holes and how to detect them.
2. Allow students to understand the science and methodology behind the detection of black holes.
3. Introduce basic concepts of Astronomy and Image Processing

Prior knowledge: Basic Astronomy knowledge Excel (charts)	Kinematic concepts: radial velocity, orbital period, Keppler's Law

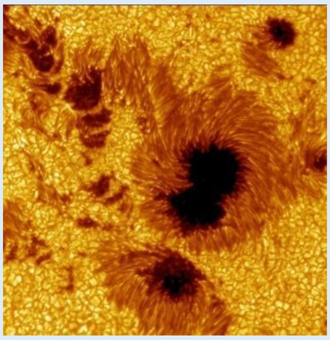
Learning intentions:
- Define a black hole
- Explain an eclipsing binary system
- Describe a method to collect luminosity data
- Examine images using the salsa J software

Key activities:
1. Videos to engage - possible edpuzzle
2. Explaining the light curve
3. Practical formation of a light curve
4. Salsa J - examination of 3 stars
5. Analysis and explanation
6. Final Report

Pedagogical Framework Score: 17/18	**Skills Development:** 9/10	Learning Skills: 4/4 Literacy Skills: 2/3 Life Skills: 3/3

Demonstrator 12: Exploring the Sun - Does the Sun rotate?

Overview



This demonstrator introduces the Sun as an active star with sunspots. Students will learn how to use a specific image software to explore sets of real images to understand better sunspots (they will measure sunspots and compare with Earth). The sets of images will lead students to say that the Sun rotates. But they are confronted with images of a transit of an inner planet. Students will have to find a way to argue that sunspots are not satellites - they belong to the Sun's surface and therefore show that the Sun rotates. Students can present their work to the class and discuss how Galileo Galilei solved this dilemma.

OSOS Link Demonstrator 12

Metadata:	Concepts introduced:
Age: 14-17 Duration: 2 hours Equipment: PC with internet connection	● Sun's activity ● sunspots

Learning outcomes:
1. Teach students about the Sun's activity and its influence on Earth.
2. Allow students to understand the evidence of the Sun's rotation movement.
3. Introduce basic concepts of Astronomy and Image Processing.
4. Recognize that sometimes the interpretation of the data analysis is not straightforward.

Prior knowledge:
- Basic Astronomy knowledge of the solar system (Sun, planets, satellites)
- Scales

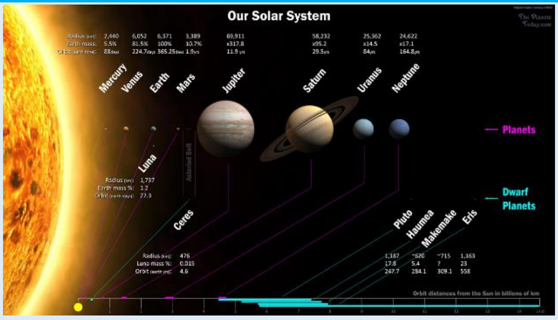
Learning intentions:
- Describe the Sun as an active star
- Explain what sunspots are
- Examine images using the salsa J software
- Form conclusions about evidences that the Sun rotates

Key activities:
1. Videos to engage
2. Salsa J - making movies and examining images
3. Analysis and explanation
4. Final report and discussion

Pedagogical Framework Score:	Skills Development:	
16/18	9/10	Learning Skills: 4/4 Literacy Skills: 2/3 Life Skills: 3/3

Demonstrator 13: Exploring the Sun - Solar differential rotation

Overview



This demonstrator introduces the Sun as an active star and how its activity can influence Earth. Students are questioned about its movements and led to realize that the Sun rotates. Real images will be used to determine the solar rotation period. Students will learn how to use a specific image software to track sunspots and calculate the Sun’s rotation period. Further analysis will show that the Sun doesn’t rotate as a rigid body: it exhibits differential rotation. Students can present their work to the class and discuss how they compare with the most accurate results that astronomers have.

OSOS Link Demonstrator 13

Metadata: Age: 14-17 Duration: 3 hours Equipment: PC with internet connection	**Concepts introduced:** ● Sun’s activity ● Sunspots

Learning outcomes:

1. Teach students about the Sun’s activity and its influence on Earth.
2. Allow students to understand the evidence of the Sun’s rotation movement.
3. Introduce basic concepts of Astronomy and Image Processing.

Prior knowledge: ● Basic Astronomy knowledge of the Sun as a star	● Excel (charts) ● Kinematic concepts such as: period

Learning intentions:

- Describe the Sun as an active star
- Explain what sunspots are
- Describe a method to measure the rotation period of the Sun
- Examine images using the salsa J software
- Form conclusions about the Sun’s differential rotation
-

Key activities:

1. Videos to engage
2. Salsa J - making movies and examining images
3. Different methods to measure the rotation period of the Sun
4. Analysis and explanation
5. Final report and discussion

Pedagogical Framework Score: 15/18	**Skills Development:** 9/10	Learning Skills: 4/4 Literacy Skills: 2/3 Life Skills: 3/3

Demonstrator 14: Measuring the Recess Velocity of Distant Galaxies

Overview

This demonstrator introduces the concept of the expansion of the Universe discovered by Edwin Hubble. Students will reproduce Hubble's measurements in order to obtain an estimate of the age of the Universe, thanks to real sky images and data taking. They will play the role of an observational astronomer and learn about some fundamental properties of astronomical sources, such as the magnitude and the luminosity distance. They will also learn about light spectra, absorption lines, redshift, and the Doppler effect. Students will reproduce the Hubble diagram and get a measurement of the Hubble constant and the age of the Universe. Students will present their work to the class and discuss how it compare with the most accurate results that astronomers have.

OSOS Link Demonstrator 14

Metadata:	**Concepts introduced:**
Age: > 16 Duration: 3 hours Equipment: PC with internet connection	● Spectral lines analysis ● Doppler effect ● Astronomical redshift ● Standard candles ● Universe's expansion and age ● Cosmic Microwave Background

Learning outcomes:

1. Teach students about the expansion of the Universe and the basics of Hubble observations.
2. Allow students to understand the daily work of an observational astronomer.
3. Introduce basic concepts of observational astronomy, cosmology, and image processing.

Prior knowledge:		
● Algebra	● Wave properties	● Basics of light spectrum

Learning intentions:

- Explain the expansion of the Universe and its observational discovery
- Remember the Doppler Effect and the interpretation of redshift.
- Describe a spectrum and interpret its absorption lines.
- Explain the idea of standard candles in astronomy.
- Interpret data evaluating signal/noise ratio.

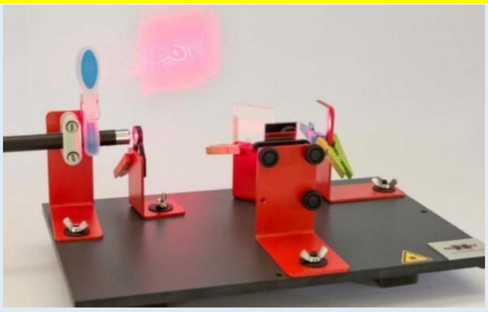
Key activities:

1. Videos to engage
2. Data taking, analysis, and interpretation
3. Final report and discussion

Pedagogical Framework Score:	**Skills Development:**	
15/18	9/10	Learning Skills: 3/4 Literacy Skills: 3/3 Life Skills: 3/3

Demonstrator 15: Discovering and Building a Michelson Interferometer

Overview



This demonstrator introduces the concept of waves, interference, and the wave nature of light. Students are introduced to the history of the Michelson interferometer and the Michelson-Morley experiment. They will learn how the same instrument was used to detect gravitational waves, thus confirming one of the main predictions of Einstein's general relativity. Students will experiment with a real small-scale Michelson interferometer, a powerful instrument that uses light interference to measure distances with high precision. They will learn about the basic properties of light interference and the working principle of an interferometer. Real images from the sites of the LIGO and Virgo instruments will be used to explain how modern-day interferometers are used to detect gravitational waves. Students will present their work to the class and discuss their results.

OSOS Link Demonstrator 15

Metadata:	**Concepts introduced:**
Age: > 16	● Light interference
Duration: 3 hours	● Gravitational-wave detection
Equipment: PC with internet connection	● Power of interferometry

Learning outcomes:

1. Give students an historical view of two Nobel Prize winning discoveries using the interferometer and its application to gravitational-wave detection.
2. Allow students to understand the methodology of experimental physics by building, calibrating, and operating an instrument such as a Michelson interferometer.
3. Introduce basic concepts of electromagnetism and light interferometry.

Prior knowledge:		
● Wave properties	● Basics of classical optics	

Learning intentions:

- Define the principles of light interference
- Explain how it can be used to measure distances
- Test and understand the response of an instrument

Key activities:

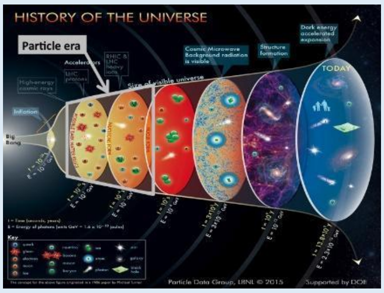
1. Michelson interferometer manipulation
2. Videos to engage
3. Data analysis and explanation
4. Final report and discussion

Pedagogical Framework Score:	**Skills Development:**	
17/18	10/10	Learning Skills: 4/4 Literacy Skills: 3/3 Life Skills: 3/3

Demonstrator 16: The ALICE experiment at CERN

Overview

The “ALICE Experiment at LHC” demonstrator, connects students with fundamental research taking place in one of the 4 large experiments of the LHC complex at CERN, ALICE, which reproduces and studies the state of the Universe at a tiny fraction of a second after the Big Bang: The Quark Gluon Plasma. Students learn about the research done at CERN and by working in teams, they explore and analyse real scientific data and search for the Signatures of Quark Gluon Plasma in the ALICE detector.



OSOS Link Demonstrator 16

Metadata:	**Concepts introduced:**
Age: 16 - 18	● Quark gluon plasma
Duration: 4 hours	● Strange particles
Equipment: PC with internet connection	● Invariant mass
	● Antimatter

Learning outcomes:

1. To demonstrate what Quark Gluon Plasma is.
2. To explain that through a high energy particle collision, students can study the Universe at its infancy.
3. To employ the conservation of momentum and energy to understand data produced by subatomic particle collisions.
4. To explain the internal structure of matter and the importance of fundamental particles such as strange particles, which are not part of our everyday world, in understanding the structure and the Laws of the Universe at its infancy.

Prior knowledge:

● Mass – energy equivalence ● Structure of the atom	● Conservation of momentum ● Conservation of energy	● What is a histogram

Learning intentions:

- Explain in general terms what Quark Gluon Plasma is and how we can detect it
- Explain in general terms what strangeness is
- Explain in general terms what is the mission of the ALICE experiment at CERN
- Understand that particles and their anti-particles are not the same but have equal masses.

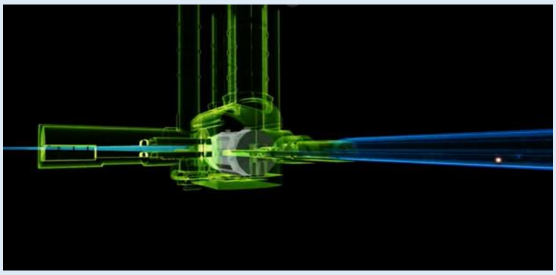
Key activities:

1. Observing histograms and extracting scientific information from them.
2. Identifying particles according to their properties in a virtual detector.
3. Creating histograms.
4. Summary presentation.

Pedagogical Framework Score:	**Skills Development:**	
16/18	7/10	Learning Skills: 3/4 Literacy Skills: 3/3 Life Skills: 1/3

Demonstrator 17: Search for the Z and Higgs bosons

Overview



This exercise introduces students to CERN, the LHC accelerator and the ATLAS experiment. It explains the basics of the standard model of particle physics and particle decays, more specifically Z and Higgs bosons. It explains how particles can be identified by their signatures and what invariant masses and histograms are. It gives instructions on how to use the HYPATIA event display to analyse data from ATLAS, specifically Z and Higgs boson decays. At the end through a series of questions and discussions directs students to present their findings.

OSOS Link Demonstrator 17

Metadata:	**Concepts introduced:**
Age: 14-17	● Particle decays
Duration: 4 hours	● Relativistic mass/invariant mass
Equipment: PC with internet connection	● Histograms

Learning outcomes:

1. Students learn about CERN, LHC and ATLAS
2. They become familiar with the standard model of particle physics and particle decays
3. They learn how to analyse data from the ATLAS experiment to look for specific particle signatures
4. They are asked to present their results and justify the outcome of their investigation

Prior knowledge:

● Fundamental forces	● Structure of matter	

Learning intentions:

- Understand the research being conducted at CERN and ATLAS
- Understand how the LHC works
- Learn how particle collisions can produce new particles
- Identify particles by their signature
- Understand and interpret the results of their investigation

Key activities:

1. Videos about CERN, LHC, ATLAS
2. Explanation about the standard model, particle collisions and decays
3. Investigation through the use of HYPATIA
4. Presentation of student investigation results

Pedagogical Framework Score:	**Skills Development:**	
17/18	8/10	Learning Skills: 4/4 Literacy Skills: 2/3 Life Skills: 2/3

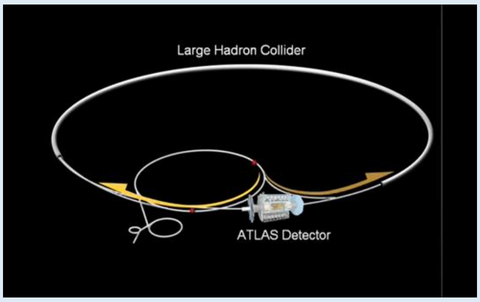
Erasmus+

Demonstrator 18: How to accelerate particles

Overview

This exercise in an introduction to particle accelerators and high energy physics. The focus of the exercise is the world's most powerful accelerator, the LHC, which is located at CERN. Students learn about how it accelerates, bends and focuses proton beams and how it makes sure that the protons collide inside one of the four detectors located on its circumference.

To emphasise what they've learned after the lesson, the students play a game in which they have to apply what they've learned in a 'virtual accelerator'.



OSOS Link Demonstrator 18

Metadata:	**Concepts introduced:**
Age: 6-12	● Fundamental Forces
Duration: 2 hours	● Magnetic and Electric Fields
Equipment: PC with internet connection	● Particle Accelerators

Learning outcomes:

1. To familiarise students with the basic concepts of particle accelerators
2. To introduce students to the high energy physics
3. To introduce students to CERN

Prior knowledge:		
● Fundamental forces	● Atom Structure and particles	● Basic electrostatics

Learning intentions:

- Explain the fundamental forces
- Explain how electric fields can be used to accelerate particles
- Explain how magnetic fields can direct particles in the LHC
- Describe how the LHC accelerates particles
- List practical uses of the LHC

Key activities:

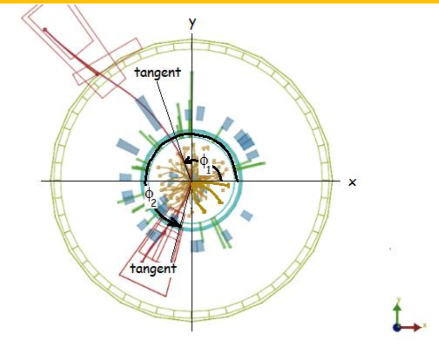
1. Videos to engage - possible edpuzzle
2. What is the LHC? (Possible student engaged jigsaw or research activity)
3. Online game to stimulate LHC
4. Student report

Pedagogical Framework Score:	**Skills Development:**	
14/18	5/10	Learning Skills: 4/4 Literacy Skills: 1/3 Life Skills: 0/3

Demonstrator 19: Study Data from the Large Hadron Collider

Overview:

This exercise introduces students to CERN, the LHC accelerator and the ATLAS and CMS experiments. It explains the basics of the standard model of particle physics and particle collisions. It explains what muons are and how their angles can be measured through the use of the HYPATIA event display or the CMS iSpy. It mentions what the expected distributions would look like and prompts students to study and explain their results and possible deviations for what is expected.



OSOS Link Demonstrator 19

Metadata:	**Concepts introduced:**
Age: 12 - 16	● Particle decays
Duration: 2 hours	● Distributions
Equipment: PC with internet connection	● Histograms

Learning outcomes:

1. Students learn about CERN, LHC, ATLAS and CMS
2. They become familiar with the standard model of particle physics and particle collisions
3. They learn how to measure and analyse the angular distribution of muon tracks
4. They are asked to present their results and justify the outcome of their investigation

Prior knowledge:

● Structure of matter	● Fundamental forces	● Basic geometry

Learning intentions:

- Understand the research being conducted at CERN, ATLAS and CMS
- Understand how the LHC works
- Learn what happens when particles collide in the LHC experiments
- Study the distribution of muon track angles

Key activities:

1. Information about CERN, LHC, ATLAS, CMS
2. Explanation about the standard model and particle collisions
3. Investigation through the use of HYPATIA, iSpy
4. Presentation of student investigation results

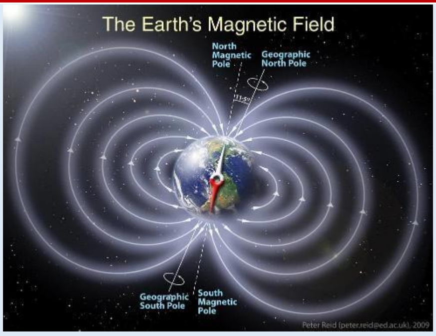
Pedagogical Framework Score:	**Skills Development:**	
17/18	8/10	Learning Skills: 4/4 Literacy Skills: 2/3 Life Skills: 2/3

Erasmus+

Demonstrator 20: The Magnetic Field and its Applications

Overview:

This exercise introduces students to CERN, the LHC accelerator and the ATLAS and CMS experiments. It explains the basics of the standard model of particle physics and particle collisions. It explains what muons are and how their angles can be measured through the use of the HYPATIA event display or the CMS iSpy. It mentions what the expected distributions would look like and prompts students to study and explain their results and possible deviations for what is expected.



OSOS Link Demonstrator 20

Metadata:	**Concepts introduced:**
Age: 12 - 16	● Particle decays
Duration: 2 hours	● Distributions
Equipment: PC with internet connection	● Histograms

Learning outcomes:

1. Students learn about CERN, LHC, ATLAS and CMS
2. They become familiar with the standard model of particle physics and particle collisions
3. They learn how to measure and analyse the angular distribution of muon tracks
4. They are asked to present their results and justify the outcome of their investigation

Prior knowledge:

● Structure of matter	● Fundamental forces	● Basic geometry

Learning intentions:

- o Understand the research being conducted at CERN, ATLAS and CMS
- o Understand how the LHC works
- o Learn what happens when particles collide in the LHC experiments
- o Study the distribution of muon track angles

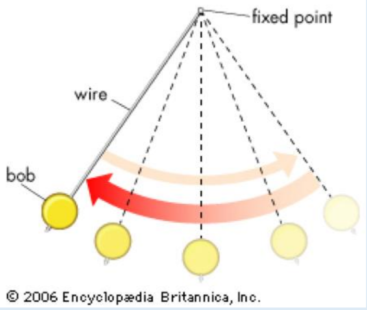
Key activities:

1. Information about CERN, LHC, ATLAS, CMS
2. Explanation about the standard model and particle collisions
3. Investigation through the use of HYPATIA, iSpy
4. Presentation of student investigation results

Pedagogical Framework Score:	**Skills Development:**	
16/18	5/10	Learning Skills: 3/4 Literacy Skills: 1/3 Life Skills: 1/3

Demonstrator 21: The Pendulum

Overview:



This demonstrator introduces the concept of the pendulum and the key concepts necessary to examine the properties of a pendulum. The demonstrator is inquiry based and supports students to develop controlled investigations on the different variables that affect the period of a pendulum. They will be looking at dependent and independent variables, and record data that they will display and analyse.
This demonstrator was designed as an introductory exercise for the gravitational-wave package of demonstrators, and it introduces the idea of a pendulum as a seismological filter for gravitational-wave detectors.

OSOS Link Demonstrator 21

Metadata:	**Concepts introduced:**
Age: > 12	● Pendulum
Duration: 2 hours	● Period
Equipment: PC with internet connection and basic lab equipment	● Frequency
	● Gravitational wave detector

Learning outcomes:
1. To introduce students to the concept of a pendulum.
2. To investigate the relationships between the variables that affect the period of a pendulum
3. To graph and analyse data and form conclusions about how a pendulum operates.

Prior knowledge:
- Types of variables
- Graphing

Learning intentions:
- o Define the following: pendulum, cycle/oscillation, frequency, period, variable
- o List examples of everyday pendulums
- o Develop a method for an investigation
- o Identify the types of variables
- o Graph the results of an investigation
- o Form conclusions based on the results collected

Key activities:
1. Pasta activity or alternative?
2. Design a basic pendulum
3. Plan and carryout investigation and collection of data
4. Graph results
5. Final Report

Pedagogical Framework Score:	**Skills Development:**	
16/18	10/10	Learning Skills: 4/4 Literacy Skills: 3/3 Life Skills: 3/3

Demonstrator Initial Teacher Training Workshops

Figure 1 Initial Teacher Training event in Ireland

A range of methodologies were employed at initial teacher training workshops to evaluate and further develop the final demonstrators. Through a series of pilot teacher training workshops delivered by project partners between September 2019 and March 2020, data was collected and analysed to evaluate the effectiveness of the demonstrators.

15 initial teacher training workshop events were held by the project partner countries (Ireland, Greece, Italy, France and Portugal). The general format of the workshops was an introduction to the project showing the FRONTIERS website and Facebook page, an overview of the project framework followed by an examination of at least two demonstrators. The workshop facilitators usually included a researcher in the field of physics pertinent to the demonstrators explored and an education and outreach expert with a physics background.

DCU produced guidelines for conducting the face-to-face training events, with partners delivering the presentations and workshop content in the native language of participants. The objective of the workshop /multiplier events was to ensure that teachers could implement at least one demonstrator in their classroom after the workshop.

There were slight variations in each workshop with regard to the duration as well as the mode of exploration of the demonstrators. The recommended workshop duration was 4 hours minimum.

The initial teacher training workshops were conducted with 303 science and physics teachers across the partner countries, with teachers from primary, secondary education as well as in-training teachers.

Figure 2 Initial teacher training participants in Greece

Pre and Post Workshop Questionnaire

The teachers completed a short pre-questionnaire in hard-copy at the start of the vision building workshop and a post-questionnaire in hard-copy was completed at the end of the workshop. The pre and post questionnaires, mainly addressed teachers' motivation and self-efficacy. All questions were answered through a 1-10 Likert scale. Likert scale questions encourage respondents to point to the extent to which they agree or disagree with a particular statement. The advantage of the Likert scale in this case was that it provided useful quantifiable data with regards teachers' opinions and perceptions around bringing Nobel Prize Physics topics into the classroom.

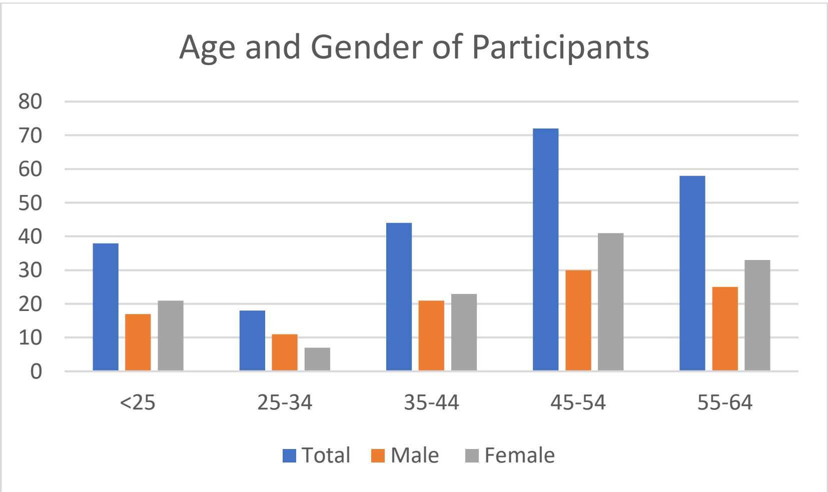
	Pre-Training Questions	Post-Training Questions
Question 1	I appreciate the value of teaching Nobel Prize Physics.	The content of the learning event was relevant/useful to my needs as a science teacher.
Question 2	I am confident with the subject content of Nobel Prize Physics.	I am confident of the subject content of Nobel Prize Physics.
Question 3	I am interested in integrating Nobel Prize Physics in my science classroom.	The learning event has motivated me to further explore Nobel Prize Physics with a view to integrating it into the science class.
Question 4	There are useful resources available (online) to teach about Nobel Prize Physics.	I can see the potential of applying Nobel Prize Physics in the teaching of science.
Question 5	I believe that I can motivate students to learn the topics of Nobel Prize Physics.	I believe that I can motivate students to learn the topics of Nobel Prize Physics.

The demographic data collected from teachers after following the proper consent procedures included: country, gender and age of teachers.

Questionnaire Findings

Of the 303 workshop participants, 230 (76%) completed both the pre and post training questionnaires.

Of the 230 participant who completed both the pre and post training questionnaire, 105 were male and 123 were female. Two participants did not indicate gender. The mean age of participants was 44 (SD=13), with the age of participants ranging from 19 to 64. The youngest of the participants were Initial Teacher Education students from DCU, Ireland. A breakdown of ages and gender can be found below.



Prior to undertaking the pilot training, participants were asked to complete a pre-questionnaire to explore the confidence and attitude of teachers with frontier science. From the data collected in the pre-questionnaire it is evident that prior to the workshops, teachers seemed to appreciate the value of teaching Nobel Prize Physics (Mean = 8.31, SD = 1.69), and they were interested in integrating Nobel Prize Physics in their science classroom (Mean = 8.34, SD = 1.57). Participants seemed marginally confident with the subject content of Nobel Prize Physics (Mean = 6.02, SD = 2.46), and were quite confident that they could motivate students to learn the topics of Nobel Prize Physics (Mean = 7.63, SD = 1.60). Finally, the sample identifies that they were marginally confident that there are useful resources available online to teach about Nobel Prize Physics (Mean = 6.25, SD = 1.95).

Following the workshop training, participants completed a post-intervention questionnaire to compare their confidence and attitudes, gauging the impact of the training. The pre and post questionnaires completed by each teacher were matched.

The results of the post-questionnaire indicate that the participants found the content of the workshops were relevant and useful to their needs as science teachers (Mean = 8.49, SD = 1.63). After the workshop participants were motivated to further explore Nobel Prize Physics with a view to integrating it into the classroom (Mean = 8.52, SD = 1.60) and they can see the potential of applying Nobel Prize Physics in the teaching of science (Mean = 8.34, SD = 1.51). Participants were quite confident with the subject content of Nobel Prize Physics (Mean = 7.30, SD = 1.93), and confident that they could motivate students to learn the topics of Nobel Prize Physics (Mean = 8.25, SD = 1.51).

Figure 3 Initial teacher training in Italy

It is evident that the teachers' confidence in the subject content as well as confidence that they could motivate students to learn the topics of Nobel Prize Physics had increased due to their participation in the training workshop. This increase will be further investigated in the following section.

Self-Efficacy

One of the stated aims of the FRONTIERS project was to empower teachers in delivering Nobel prize winning physics in the classroom. We set out to investigate whether the FRONTIERS workshops could improve teachers' self-efficacy in teaching Nobel prize Physics. This refers to their confidence with the subject content (Question 2) and their capability to motivate students (Question 5).

As the same variables are measured at two points in time with the same group (pre and post workshop), paired sample t-tests were conducted to discover whether there are statistically significant differences between means.

Question 2: I am confident with the subject content of Nobel Prize Physics.

Question 2 responses, referring to participant confidence with the subject content of Nobel prize physics, were found to have a statistically significant ($p<.01$) relationship between pre (Mean = 6.02) and post (Mean = 7.30) workshop mean scores. The 21.26% increase in mean scores had a positive strength in association considered large with a Pearson Correlation of 0.724.

Question 5: I believe that I can motivate students to learn the topics of Nobel Prize Physics.

Question 5 responses, referring to participant capability to motivate students to learn about Nobel prize physics, were also found to have a statistically significant ($p<.01$) relationship between pre (Mean = 7.63) and post (Mean = 8.25). The 8.12% increase in mean scores had a positive strength of association considered large with a Pearson Correlation of 0.614.

Self-Efficacy and Teacher Age

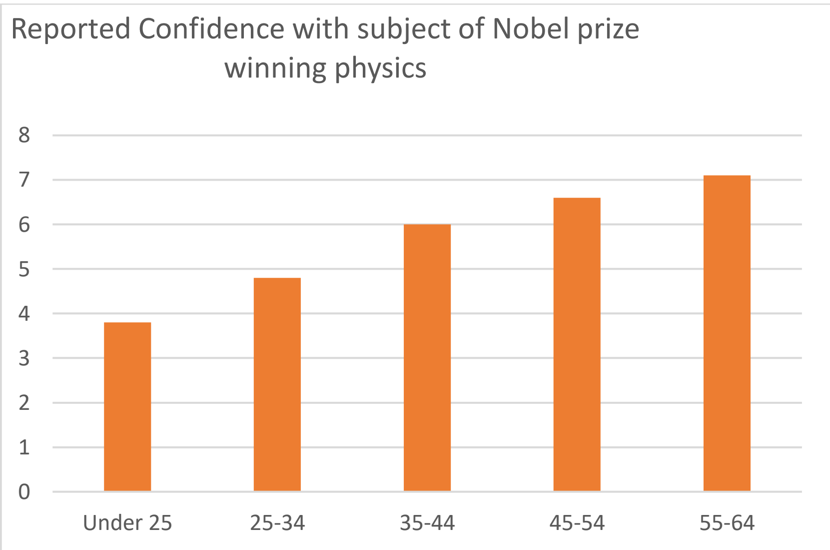
There was a broad distribution of ages in our sample; from pre-service science teachers to teachers with more than 30 years of experience. To explore possible relationship between age of participants and the impact of the training workshop on participants, a Single Factor ANOVA was undertaken of both question 2 and question 5 results, considered as relevant to teacher self-efficacy.

The participants were divided into five age categories: under 25, 25-34, 35-44, 45-54 and 55-64. The rationale for the inclusion of the 25 category was to measure the impact of the intervention with in-training and recently qualified teachers.

The score difference from the pre and post training workshop questionnaires were analysed for questions 2 and 5.

Teacher Confidence with subject of Nobel Prize winning physics

Question 2 of the pre and post training workshop questionnaire measured the confidence of participating teachers with the subject of Nobel prize winning physics. The initial ANOVA analysis of the reported confidence scores of teachers found a statistically significant relationship ($p<0.01$) between the age of teachers and their reported confidence with Nobel prize winning physics. The lowest average confidence scores were reported amongst the under 25 age category, while the highest was reported amongst the 55-64 category.



A second Single Factor ANOVA found a statistically significant (p<0.01) relationship between age and reported increase in confidence post workshop training. All age groups were found to have reported an average increase in confidence with the subject matter of Nobel prize winning physics. The Under 25 and 25-34 age groups saw the largest reported increase in confidence, with an average increase of more than 2 points on a 10-point scale (2.03 and 2.11 respectively). The group with the lowest reported increase in confidence following the training was the 55-64 category, with an average increase of less than 1 point on a 10-point scale.

Anova: Single Factor
Reported increase in teacher confidence with subject matter by age

SUMMARY

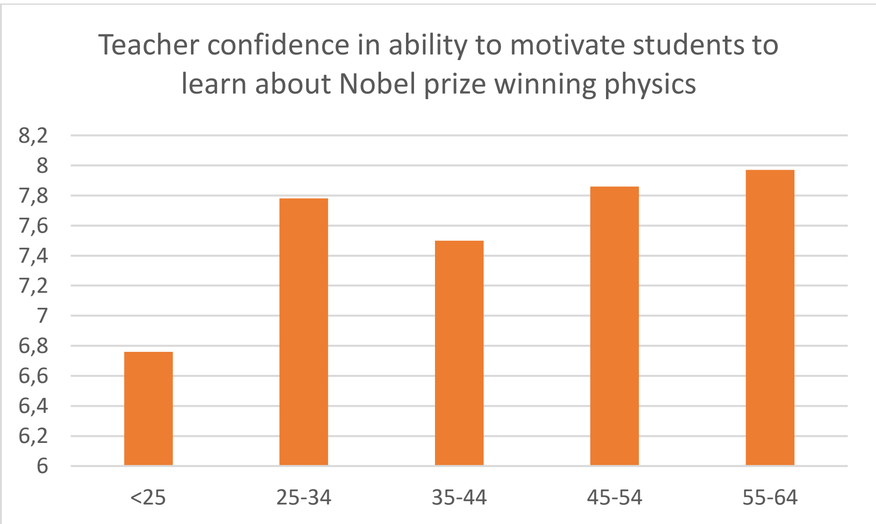
Groups	*Count*	*Average*	*Variance*
Under 25	38	2.0263	5.9182
25-34	18	2.1111	3.0457
35-44	44	1.3409	1.8113
45-54	72	1.1111	2.6071
55-64	58	0.7068	1.3336

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	54.864	4	13.716	5.0611	0.0006	2.4117
Within Groups	609.76	225	2.7100			

Teacher confidence motivating students to learn about Nobel Prize winning physics

Question 5 of the pre and post training workshop questionnaire measured the confidence that teachers had in their abilities to motivate students to learn about Nobel prize winning physics. An initial analysis of variance found a statistically significant relationship (p<0.01) between the age of the participants and their reported abilities to motivate students. The difference in average scores between age groups was far narrower than the previous analysis. The lowest average score by age group was the under 25s (6.76 on a 10-point scale), and the highest being the 55-64 age group (7.96 on a 10-point scale).



The Single Factor ANOVA of question 5, measuring the reported increase in confidence of teachers to motivate students to learn about Nobel prize winning physics, did not find a statistically significant relationship (p=0.57) between age and reported increase in confidence post workshop training. All age groups were found to have reported an average score increase between pre and post training questionnaires, although not as great as those responses to the previous question analysed.

Anova: Single Factor
Reported increase in teacher confidence to motivate students by age

SUMMARY

Groups	*Count*	*Average*	*Variance*
Under 25	38	0.3421	3.2581
25-34	18	0.7222	2.5653
35-44	44	0.6818	2.2219
45-54	72	0.7777	1.5273
55-64	58	0.5344	0.9549

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5.5066	4	1.3766	0.7329	0.57030	2.4117
Within Groups	422.58	225	1.8781			

Teacher and Facilitator Feedback

In addition to the quantitative data provided by the pre and post workshop questionnaires, qualitative data was collected by the workshop facilitators. Teacher feedback from post workshop discussions were reported as well as facilitator observations. This qualitative data was thematically analysed, with the major identified themes discussed below.

Motivation of Teachers

The high levels of motivation observed in teachers participating in the training workshops were noted by several facilitators. Discussions at training workshops in Greece showed that teachers' motivation was *"to receive training in order to enrich their educational practice and connect with cutting edge research in physics."* This eagerness to improve educational practice and knowledge of modern physics was evident in many workshop participants.

Despite the motivation and enthusiasm of teachers, it was reported at the beginning of one workshop in Greece that despite their efforts, students did not seem interested in physics.

Following workshops, many teachers reported that they could now see the potential of developing Nobel Prize Physics in the teaching of science. In Ireland it was stated by teachers that the training event had *"motivated them to further explore Nobel Prize Physics with a view to integrating it into the science lessons."*

Practical Nature of Workshops

The teachers appreciated the practical nature of the session as it gave them time to explore a few demonstrators during the session. It was widely acknowledged that the *"hands-on"* and practical approach of the training workshops motivated teachers to participate more fully and enthusiastically. It was also noted in Greece, the contrast in teacher engagement between the practical *"hands-on"* elements of the workshops compared to the more theoretical, with teachers seeming *"less interested in demonstrators that didn't follow a hands-on approach."*

Those workshops that incorporated a live virtual visit to a research facility also reported teachers improved engagement and enthusiasm.

Following workshops in Ireland, feedback from the participants indicated that the workshop was very relevant to their needs, and it helped to develop further confidence in the topic. In addition, participating teachers indicated that they "*felt much more confident after the online session about the subject content of Nobel Prize Physics."*

Demonstrators and Pedagogical Framework

The demonstrators were received very positively by participating teachers across the partnership workshop events. In France, the feedback was very positive with teachers *"convinced that demonstrators can be brought to the classroom."*

Figure 4 Initial teacher training in France

One of the most commonly reported benefits for teachers was that the demonstrators were designed using the language of educators and an enquiry-based learning approach. One Greek participant commented that other outreach activities that she had joined would *"just present content but don't speak the language of the educator and don't offer a means to do them in the classroom."*

The inquiry-based learning approach adopted by the project was noted as being of great interest and benefit to teachers and students. It was noted in Portugal that the "*inquiry methodology was very interesting because you feel that most teachers value such experience."* Teachers in France reported inquiry-based learning is not only suited for their teaching but encouraged by National Education. One participant at a workshop in France stated *"the most important point is to give a taste of the scientific method and approach, since science is very often taught in class in a non-scientific fashion."* The demonstrators in their content and design facilitated bringing the scientific approach to the classroom in both its content and pedagogical approach.

In Ireland, several participants commented on that the demonstrators encouraged students to undertake research in the classroom using scientific language through the inquiry-based learning model. One participant highlighted the demonstrator meant *"students will be using scientific language and interpreting real graphs, using graphs in real life."* The inquiry-based learning approach to delivering content was identified as encouraging students to employ *"critical thinking, problem solving, justifying reasoning"* through *"practical investigation."*

The demonstrators as a teaching resource were welcomed by teachers, with many reporting a lack of physics education resources available. In general, participating teachers were not aware of online ready-to-use tools and said that often they have to create their own material. The general concept of providing them with demonstrators was very welcome.

With the feedback being generally very positive, it was noted at several workshops a desire by teachers to engage in further detailed training in individual demonstrator. A workshop participant in Greece suggested *“systematic training one demonstrator at a time to have time to assimilate content.”* Some teachers also proposed additional training to improve their own knowledge in modern physics. This was evident in Portugal, where several teachers said that they would need help to implement the demonstrators as they “*aren’t at ease with modern physics.”*

Curriculum

There were mixed feelings reported by teachers participating in workshops on how the demonstrators could be incorporated into existing curriculums and within limited class contact times.

Teachers in Ireland stated that a number of the demonstrators could be used to support the existing Earth and Science strand of the science curriculum at Junior Cycle (14–15-year-olds).

In France, it was highlighted that cross curricular links could be made as school programmes now include mandatory computer programming classes. Teachers reported that it could interesting to be provided with data files and have to build some sort of analysis code in the classroom rather than use ready-to-use black-box apps.

Figure 5 Initial teacher training in Portugal

Some teachers in France also suggested that, rather than using the demonstrator during normal classes, they found it very suited for specific *"ateliers scientifiques"* (scientific workshops) that are already taking place in French high schools. It was explained that “during workshops there are no programme constraints and the students participating are already the most motivated.”

In other countries a common concern in implementing the demonstrators was the pressures and limitations of the curriculums of individual countries. In Italy it was raised that *“given the limited time available at school, would not be easy to dedicate 2 hours to a single demonstrator.”* This concern was echoed by participants in Greece, with teachers *“reluctant to implement scenarios that are outside the curriculum.”*

It was suggested that a support to teachers would be mapping each of the demonstrators to national curriculums. The ability of teachers to edit the demonstrators to their own needs was a major plus for their applicability.

The mapping of the demonstrators to target age groups was another topic of discussion across workshops. In Ireland it was felt that *“many of the demonstrators are more appropriate for the Leaving Certificate (17-18 year olds) syllabus.”* This was the feeling among participants in France too, who found that content may be *“too complicated for the average student (except maybe last year of high-school)”.*

Teachers in Ireland suggested that less able students may struggle with some of the more difficult concepts and *“abstract thinking”* covered in the demonstrators. It was suggested that *“less able students may need background lessons.”*

There was interest in participants to apply some of the demonstrators to younger school class groups, including primary school and early high school classes. In was suggested by participants in Portugal that demonstrators could be simplified for younger age groups.

Technology in the Classroom

Teachers generally felt that equipment and technology available in schools could be a barrier to engagement with the demonstrators. In Portugal, some teachers stated that *“the need for computers can be a drawback”* as they are not always accessible or available.

In France there was a concern that the demonstrators were strictly online, as good Wi-Fi connection seems to be an issue for some schools and educators.

Teacher Professional Development

The FRONTIERS Project undertook a range of teacher professional development events throughout the project lifetime. As per the original project proposal, multiplier events had been planned as FRONTIERS Visionary Workshops (E1-6) and FRONTIERS Practice Reflection Meetings (E7-12). As a result of adjustments made to the project activities due to the Covid-19 pandemic, project partners held professional development events that facilitated the quality engagement of teachers and students within the revised scope of the project. These events included Teacher Training workshops, Master Classes and Virtual Visits to large-scale research facilities.

A series of in-person FRONTIERS International Training Courses/Summer Schools (C1-3) and an International Symposium (E13) had also been outlined in the original project proposal. As international travel and in-person meetings were heavily restricted, a series of online International e-Schools were hosted by project partners. These International e-Schools facilitated hundreds of teachers to learn about the FRONTIERS Demonstrators, collaborate with other teachers as well as physics researchers to develop class plans, and join virtual visits to large-scale research facilities.

The impact and effectiveness of these teacher training events are evaluated in the following sections.

Initial Teacher Training Workshops

15 initial teacher training workshops were held by the project partner countries (Ireland, Greece, Italy, France and Portugal). The objective of these workshop multiplier events was to ensure that teachers could implement at least one demonstrator in their classroom after the workshop. The recommended workshop duration was 4 hours minimum. DCU produced guidelines for conducting the face-to-face training events, with partners delivering the presentations and workshop content in the native language of participants.

The workshops were offered in the teachers' native language. The general format of the workshops was an introduction to the project showing the FRONTIERS website and Facebook page, an overview of the project framework followed by an examination of at least two demonstrators. The workshop facilitators usually included a researcher in the field of Physics pertinent to the particular demonstrators explored and an education and outreach expert with a Physics background.

The initial teacher training workshops were conducted with 303 science and physics teachers across the partner countries, with teachers from primary, secondary education as well as in-training teachers. The evaluation findings of the initial teacher training events were explored in the previous section.

International e-Schools

The FRONTIERS Project ran three online training courses for science teachers in the form of International e-Schools. Hosted through Zoom, these synchronous online training events targeted science teachers who were motivated to introduce Nobel prize winning physics in their classroom. The lesson learned and insights gained from the initial teacher training workshops events informed the design of the International e-School series.

Due to the COVID 19 pandemic, the scale of implementation of the FRONTIERS Demonstrators initially envisaged for the project was not possible; school were closed to students for large periods and online learning meant drastic changes in teaching and learning activities. For this reason, the Frontier project partners decided to focus on engaging with, training and community building of motivated science teachers through online international training events.

The objectives of these online training events were:

- Introduce participants to the FRONTIERS pedagogical design and the proposed activities for bringing Nobel prize physics to the classroom.
- Visit to large scale research facilities in physics with the opportunity to interact with researchers.
- Discuss of the merits and barriers of introducing Nobel Prize Physics to the Classroom and presentation of the FRONTIERS methodology to achieve that.
- Provide hands on experience of using demonstrators and opportunities for teachers to develop lesson plans.

In response to the feedback gathered from teachers participating in the initial teacher training workshops, emphasis was given to:

- providing in-depth and detailed training to teachers on individual demonstrators
- facilitating teacher collaboration to adapt demonstrators to use with their students
- hosting participants on virtual visits to research facilities
- building a community of teachers motivated to bringing frontier physics to their students

Both quantitative and qualitative data was collected to facilitate the evaluation of the International e-School series. Quantitative data was collected using pre, and post questionnaires with participants. Round table discussions and focus groups were held with participants to gather qualitative data from the participant perspective. The 3 online training courses that comprised the International e-Schools are outlined below.

Summer School July 2020

The FRONTIERS Project International Summer School 2020 took place over ten days between for the 13th and 24th of July 2020. A link to the agenda and relevant presentations is here, with an agenda summary provided below. 50 teachers fully completed the Summer School 2020 receiving certification.

The first week of the Summer School 2020 included key-note speakers, introduction to the FRONTIERS Project, presentation of demonstrators to teachers and formation of module-oriented teacher working groups. The demonstrator modules explored each day included workshops on how to bring Gravitational Waves, Astrophysics, High Energy Physics and Cosmology to the classroom. Participants were also given a virtual tour of the Virgo Interferometer in Italy.

Monday	Tuesday	Wednesday	Thursday	Friday
Introduction to FRONTIERS Key Notes Speakers Virtual Visit to Virgo Interferometer	Astrophysics in the Classroom Module • Cloud Chamber • Relativistic Muons • Cosmic Rays	High Energy Physics in the Classroom Module • Accelerating Particles • Mass Energy Equivalence • Z and Higgs bosons	Astrophysics in the Classroom Module • Black holes • Alien Worlds • Exploring the Sun • Age of the galaxy	Gravitational Waves in the Classroom Module • Build an Interferometer • The Pendulum • Study Earthquakes • Discover Black Holes

		• Large Hadron Collider Data		

Table 1: Summer School 2020 week 1 agenda summary

Week 2 of the Summer School 2020 introduced participants to ways in which Nobel prize winning physics can be brought to life in the classroom and beyond, with working groups of participants collaborating to develop their own lesson plans based on FRONTIERS Demonstrators.

Table 2: Summer School week 2 agenda summary

Monday	Tuesday	Wednesday	Thursday	Friday
Introducing Nobel Prize Physics to the Primary School • Playing with Protons Initiative • Introduction to CERN • Particles and their Interactions • Q&A	REINFORCE Visionary Workshop Day 1 • Research Infrastructure for Citizens in Europe • Interactive Session • Zooniverse • Fishing for Neutrinos	REINFORCE Visionary Workshop Day 2 • Citizen science and school education • Gravitational Noise Hunting in the classroom	Working group activities and evaluation • Final rehearsal of working groups • Round Table Discussions • Evaluation • Future Outlook	Final Presentations • Working group presentation of class materials • Astrophysics • Gravitational Waves • High Energy Physics

Winter School 2020

The FRONTIERS Project Winter School 2021 took place over 6 days between the 29th of January and the 7th of February 2021. To facilitate teachers attending during the normal academic year and to avoid further class disruption, the Winter School took place over 2 weekends with meetings scheduled between both weekends. In total there were 203 participants in flexible attendance, with 30 teachers chosen to participate in workshops groups to develop teaching resources.

The Winter School followed a similar format as the previous Summer School. A link to the agenda and relevant presentations is available here, with an agenda summary provided below. The first weekend of the Winter School focused on introducing the participants to the FRONTIERS Project, establishing working groups of participants, workshops on demonstrators and visiting research facilities. The working groups used Google slides to collaborate on the development of lesson plans. There were scheduled times set aside between both weekends for participants to meet with experts if they had any questions around the content of the demonstrators.

Table 3: Winter School 2021 weekend 1 agenda summary

Friday	Saturday	Sunday

Welcome to the Winter School The FRONTIERS Project Inquiry Based Learning Establishing working groups Virtual Visit to CERN	Module 1: Gravitational Waves ● Introduction ● Demonstrators ● Working Groups Module 2: High Energy Physics ● Introduction ● Demonstrators ● Working Groups Virtual Visit to Virgo Interferometer	Module 3: Astrophysics and Cosmology ● Introduction ● Demonstrators ● Working Groups Module 4: Astroparticle Physics ● Introduction ● Demonstrators ● Working Groups Virtual visit to Pierre Auger Observatory

The second weekend of the Winter School showcased FRONTIERS best practice applications of Nobel prize winning physics in primary and high schools. Inspired by these educational experiences, participants were then given the opportunity to present their working group lesson plans developed from the FRONTIERS Demonstrators.

Table 4: Winter School 2021 weekend 2 agenda summary

Saturday	Sunday
FRONTIERS Best Practice Experience ● Primary Schools ● High Schools ● e-Twinning project Working groups with mentors	Working groups' presentation of educational materials adapted from FRONTIERS Demonstrators to being to the classroom. FRONTIERS Next Steps Presentation Winter School Final Remarks

Summer School 2021

The FRONTIERS Project International Summer School 2021 took place over five days between for the 12th and 16th of July 2021. A link to the agenda and relevant presentations is here, with an agenda summary provided below. 25 teachers fully completed the Summer School 2021 receiving certification.

The Summer School 2021 included key-note speakers, introduction to the FRONTIERS Project, presentation of demonstrators to teachers and visits to large research institutes in physics. The demonstrator modules explored each day included workshops on how to bring Gravitational Waves, Astrophysics, High Energy Physics and Cosmology to the classroom.

Table 5: Summer School 2021 agenda summary

Monday	Tuesday	Wednesday	Thursday	Friday
Introduction to FRONTIERS Muon Lifetime at rest and in flight Cosmic Rays, Muography and Citizen Science Virtual Visit to Pierre Auger Observatory	Virtual visit to Virgo The Pendulum and Gravitational Wave detection Investigating the Michelson Interferometer Gravitational Wave Noise Hunting	An introduction to High Energy Physics FRONTIERS Demonstrators on High Energy Physics Virtual Visit to ALICE Experiment at CERN Discussion	FRONTIERS Demonstrators on Astrophysics and Cosmology Introduction and live observation with the Faulkes Telescope Discussion	FRONTIERS Best Practices Developing the FRONTIERS Networks Round Table Discussion End of Summer School

Data and Analysis

The objectives of the evaluative analysis were threefold:

1. Had the FRONTIERS Project delivered high-quality online training on the demonstrators?
2. What impact had summer school on the development of teacher competencies and empowering implementation of FRONTIERS physics in the classroom?
3. Had the FRONTIERS Project established a community of teachers motivated to bringing frontier physics to the classroom?

Of the 50 teachers who successfully completed the Summer School 2020, 22 fully completed the pre, mid and post engagement questionnaires on whose data quantitative analysis was undertaken.

In addition to the questionnaire, qualitative data was collected from participants in the form of a focus group and round table discussions. These qualitative methods allowed the project partners to understand the participant experience in greater depth.

The scope of the focus group was to explore participant experience of the working group collaboration opportunities with other teachers facilitated by the FRONTIERS Winter School. The working group teacher collaborations had been run twice as part of the Summer School 2020 and the Winter School 2021. This qualitative data collection and analysis from the focus group provided a deeper understanding of the impact the project was having from the perspective of the teachers involved.

Five participants from the Winter School took part in the focus group which took place for 45 minutes over Zoom. Participants were from Poland, Romania, Italy and Greece, with two male and three female participants.

Round table discussions took place with participants at the end of each International e-School event. The purpose of these discussions was to capture data on the experience of participants through the voices of participants as soon as possible, ensuring an accuracy and detail of their account.

A joint analysis of these qualitative and quantitative findings was employed to evaluate the project impact guided by the above stated objectives.

1. Had the FRONTIERS Project delivered high-quality online training on the demonstrators?

The quality of the online training provided to participants was evaluated in part through the questionnaire response. Using a 5-point scale, questionnaire responses indicated participants were interested and enjoyed the summer school (M=4.25, SD=0.698) Participants also reported the training course was very valuable and useful to them (M=4.8, SD=0.48).

These quantitative findings were reinforced by the qualitative findings from the focus group of participants. The focus group participants also highlighted that the collaborative design of the Winter School helped the teacher develop a deeper understanding of the content and educational tool by allowing the professional explore and develop the resources together. Teacher C felt that they understood the demonstrators from the presentations, "*but after the collaboration I understood many things much better as the other teachers gave many ideas about things that I didn't notice /think about before.*"

As a priority of the Summer School was to provide teachers with the opportunity to collaborate with other teachers and the facilitators through the online platform, it was important to gather responses on this aspect of the course. Respondents reported being satisfied with the level of collaboration with other teachers (M=4.18, SD=1.01), and very satisfied with the level of collaboration they experienced with course organisers (M=4.68, SD=0.72).

From the focus group findings, the standout element that participants enjoyed and felt that they benefitted from most was the opportunity to collaborate with other teachers who share a passion for physics. This was reflected in the comments of most of the focus group participants.

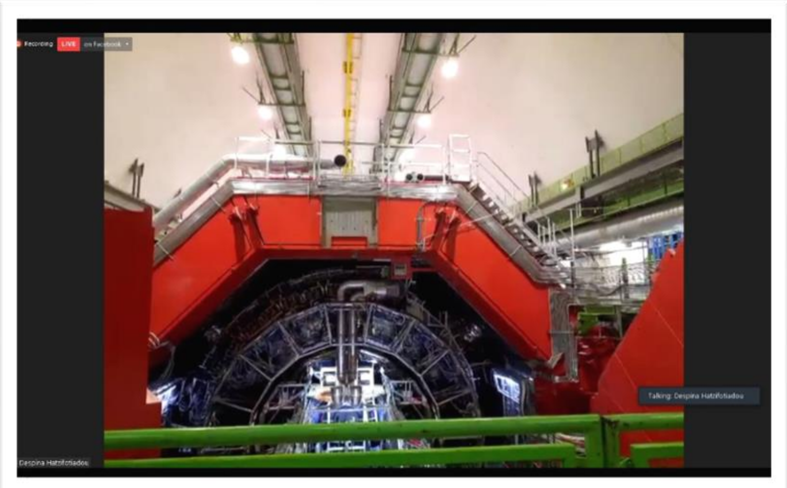


Figure 6 A screenshot from the virtual visit to CERN

Teacher C stated, *"I liked all things…but if had to choose one thing it would be the collaboration with colleagues far away from me."* The passion and motivation of the participants was summed up by Teacher B who also said that the sharing of ideas and collaboration with other physics teachers was the most important part of the Winter School *"as it shows that even in hard times we have the will and energy to create amazing things and to make this work."* Teacher C valued the collaborative nature of the Winter schools as *"we saw how our colleagues were thinking about these topics that we love."*

All the participants of the focus group felt that the collaboration with teachers and having the time to work through questions that they had to solve in the working groups was very useful as it would help them prepare for when their own students asked questions.

On average, participants experienced no difficulties in collaborating with other teachers during the summer school (M=1.91, SD=1.06).

As the International e-Schools were held virtually, online collaborative tools had to be used to facilitate the teacher engaging with the content and each other. This brought about several challenges but also opportunities to work differently yet effectively.

Although local internet connection issues for participants were mentioned, several of the collaborative tools employed by the Frontier Project were subject to praise. The use of Zoom to host the live events and sharing of resources by email was functional and accessible to all participants. In the working groups, Google Slides received considerable praise.

Teacher A explained how beneficial Google Slides was in helping with communication and collaboration. *"Google slides helped with the language barriers….. the use of chat in google slides was excellent as we could communicate even if we were not present at the same time, whereas in zoom the chat is all gone in chat but the chat on google slides was always there…"*

This praise was echoed by Teacher B when saying, *"we had the chance to write what we think and talk through the chat and express our ideas and organise collaboratively what we wanted to do. It was a very convenient and easy way to collaboration…It was easily accessible to everyone."*

The organisation of the International e-School was given much praise. Although it was generally felt that participants would have benefitted from having face-to-face engagement, there were a number of benefits to the online nature.

It was acknowledged that there were benefits to participants having a virtual event. Teacher A said, *"I think it was much better than a face to face meeting, collaboration was easy using chat from Google slides."* The online nature of the Winter School also facilitated virtual visits to research facilities that would not have been accessible otherwise. Teacher A commented on the benefit of the virtual visits, "*visiting all the sites that I may never be able to visit".*

Comparing the online Winter School to other face-to-face workshops and events that participants had attended, some benefits and drawbacks were identified. Teacher B recalled a European Space Agency workshop they attended and commented on how valuable it was *"to make things together, construct things and talk to each other and maybe talk to the other group at the next table."* Although Teacher B felt that the Winter School was really well organised, *"if face to face it would be awesome. All the demonstrators and we would have the chance to make the constructions and collaborate and to be closer to each other and communicate in a better way."*

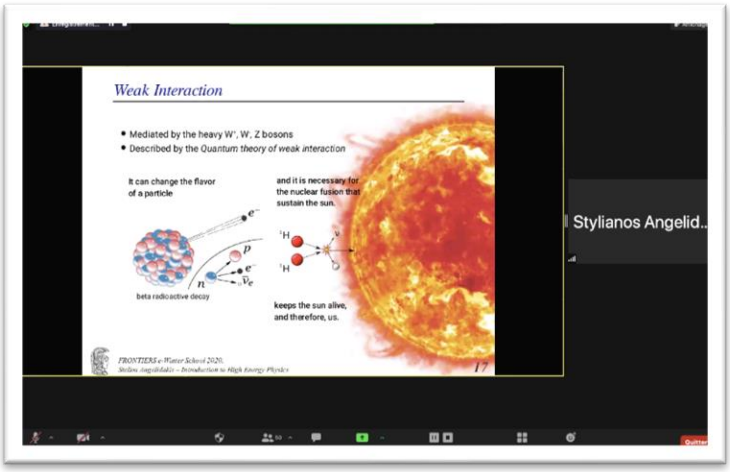


Figure 7 Screenshot from International e-School

The Winter School was the first time that Teacher B had taken part in a virtual workshop. While they said that the Winter School was *"great",* they suggested that it could be done *"blended"*. "*A mix of face to face and virtual would be better e.g. first part as virtual workshop but the second time after one or two months face to face."*

2. What impact had the International e-Schools had on the development of teacher competencies and empowering implementation of FRONTIERS physics in the classroom?

Self-Efficacy of participating teachers in teaching Nobel prise physic was measured in pre, mid and post summer school questionnaires. A significant increase was recorded in the average Self-Efficacy score from pre (M=3.8), mid (M=4.0) and post (M=4.5).

Respondents also reported being far more aware of resources available to them to support bringing Nobel prize winning physics to the classroom. This correlated with a measurable increase in the reported feasibility of implementing modern physics in the classroom.

In measuring the confidence and self-perceived competence of participating teachers, positive outcomes were recorded. The confidence of the participant teachers with content knowledge of modern physics increased comparing pre (M=3.2) and post (M=4.0) training scores. The post training, participants reported feeling competent to design educational content relating to modern physics (M=4.2, SD 0.635).

From the focus group findings, Teacher E explained that working with other colleagues to develop resources and *"meeting with mentors was very helpful to strengthen our confidence to talk to our* *own students about these topics…"* This supported development of professional confidence and self-efficacy was felt would be of great benefit to the teachers when delivering Nobel prize winning physics content in their classrooms.

All the participants of the focus group felt that the collaboration with teachers and having the time to work through questions that they had to solve in the working groups was very useful as it would help them prepare for implementing the demonstrator materials in their own lessons and better prepare them for when their own students asked questions in class.

Figure 8 International e-School participants

The participants at the round table discussion following Summer School 2021 revealed the training had improved the confidence of teachers in delivering frontier science in the classroom in a dynamic and meaningful way.

Participant 4 stated that, *"Physics is a nice subject but the blackboard is not enough to give the students the pleasure of intellectual discoveries."* They felt that the *"practical aspect of FRONTIERS resources will instil in students the ability to ask questions and to explore."*

The feeling that the FRONTIERS Demonstrators and International e-Schools would provide teachers with the tools, knowledge and confidence to bring frontier science to the classroom was held amongst many contributing participants. Participant 5, who had taken part in two of the International e-Schools, said *"some of the topics are very difficult for the teacher but these demonstrators help. I am starting to use the demonstrators in the classroom."* She had tried to introduce these topics previously but in a "theoretical way". Using what they had learned through the International e-Schools, they had started "*to introduce the topics in a practical way with the animations and videos that are part of the demonstrators".* As a result, she and her students *"feel like working like a scientist."*

The online nature of the International e-School provided Participant 7 with the knowledge, tools and opportunity to engage students with frontier science. They had attended the summer school event to help them *"introduce modern physics into the classroom".* They found great benefit from *"doing observation online and having a chance to visit CERN and other facilities. I will use all of these materials to teach my students."*

3. Has the FRONTIERS Project established a community of teachers motivated to bringing frontier physics to the classroom?

Following the completion of the summer school, participants on average reported being very interested in implementing the FRONTIERS Demonstrators with their students this year (M=4.82, SD=0.39). Participants were also very interested in collaborating with colleagues to create e-twinning projects (M=4.64, SD=0.73).

One of the main reasons given for taking part in the Winter School by some of the focus group participants, was that they wanted the opportunity to learn from teachers from other countries. Learning about different national physics curriculums was very valuable.

Teacher C stated *"The main reason I wanted to be part of the e-Winter school was it was very interesting and exciting to collaborate and to listen to what teachers from other countries had to say."* Teacher E echoed this, explaining that the opportunity to compare curriculums was an important learning experience. *"Working with teachers from other countries in the working group allowed us to … compare curriculums from different countries."* Teacher E was surprised to find how different each national curriculum was with areas seemingly developed to varying degrees.

Although there were a lot of differences discovered between national curriculums, the teachers found it interesting and exciting working to find common ground. Fertile creative ground was found between participants as Teacher B explained, *"we all found something in common and managed to collaborate and know that we can find ways if we want even if you have different curriculums and this is something we can expand through collaboration with schools from different countries…"*

The differences in national curriculums was overcome by the passion and motivation of the teachers involved, described Teacher A. *"We are all teachers, we have the same goals in all countries. We want to teach the students and help them to learn. It was interesting and very useful to see what levels of study there is in other countries."*

When asked if they would be interested in participating in follow-up meetings and/or activities, the response from participants were very positive (M=4.5, SD=0.80).

There was strong interest in participating in follow-up meeting and activities in focus group and round table discussions. Participant 9 of the round table discussion hoped that the *"collaboration continues as it was a great experience for me and my students."*

Virtual Visits

To directly engage students with Nobel prize winning physics and the FRONTIERS Project, a series of virtual visits to large-scale research facilities were facilitated by project partners. In total 1,100 students and 192 teachers took part in 11 virtual visits, allowing access to real-world physics experiments and the research scientists that work there.

Figure 9 Flyer for International e-School Summer 2021

The virtual visits undertaken included a visit to the ATLAS experiment at CERN in January 2021 organised by project partners IASA and EA. 150 students participated with it also broadcast live on Facebook. In May 2021, IASA organised 2 virtual visits were arranged to the ALICE experiment at CERN, in which 333 students from 13 schools took part. DCU organised a virtual visit to the ALICE experiment in May for 20 science teachers in Ireland. In addition, EA organised a series of 7 virtual visits to the VIRGO experiment, from which pre and post visit data was gathered from teachers and students. These visits and the analysis of data gathered from participated are discussed below.

The FRONTIERS Project invited teachers trained in Gravitational Wave Astronomy in the framework of FRONTIERS to perform virtual visits with their students. As part of this invitation, teachers were offered educational resources for an introduction of the topic to the classroom and an assessment framework and tools to assess the impact and educational merits of the visit. In total, 7 time slots were reserved for these virtual visits, in which more than 617 students and 24 teachers. The participants came from 24 schools in 8 countries (Greece (15); Italy (2); Romania (2); France (1); Pakistan (1); Portugal (1); Bangladesh (1); Austria (1)).

Virgo, the largest Gravitational Wave detector in Europe, has been designed and built by a collaboration between the French Centre National de la Recherche Scientifique (CNRS) and the Italian Instituto Nazionale di Fisica Nucleare (INFN). It is now operated and improved in Cascina, a small town near Pisa on the site of the European Gravitational Observatory (EGO), by an international collaboration of scientists from France, Italy, the Netherlands, Poland, and Hungary.

Virtual visits to Virgo were streamed to students live via Zoom. They were moderated by an education researcher of Ellinogermaniki Agogi and the field work was carried out by researchers and support staff of EGO/Virgo. They were filmed through a mobile phone streaming directly to the Zoom call which was led by an EGO/Virgo researcher, who accompanied the visitors through various areas of the Virgo experiment. The structure of the tour allowed the visitor to explore Virgo and find out about its mission: from the theory of how interferometry works and how it can be used to listen to the cosmos to the extraordinary experimental challenges that need to be overcome in order to accomplish that.

The visits lasted about 90-120 minutes and was composed of five parts:

- Introductory seminar
- Exhibits located in the hall of the EGO Main Building
- Virgo Tunnel
- Central Building
- Control Room

After each of these the visitors were encouraged to ask questions, with 5 minutes dedicated to the questions after each episode. To assess the episodes of the visit, a dedicated evaluation instrument was developed by the EA project partners.

A pre and post student questionnaire was developed to measure the effectiveness of the virtual visits in impacting on key performance indicators. A link to each of the questionnaires can be found here: Pre-Questionnaires and Post-Questionnaires.

617 students from 29 schools joined the visit, out of which a subsample of N=101 students from 24 schools offered matching pre – and post- questionnaires (response rate of16.8%). Out of the N=101 students, 50 were female and 47 male, with 4 not specifying. The majority of the respondents were high school students with age distribution: [12,15): 9 students; [15,19): 68 students; [19,20]: 20 students, while 4 students didn't answer the question.

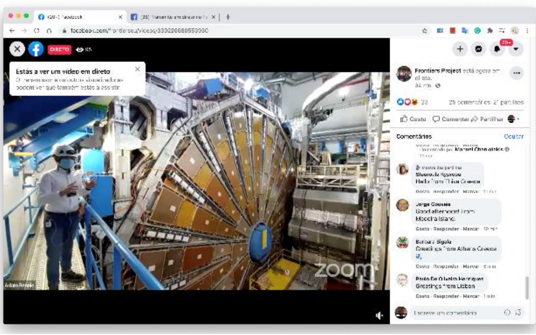
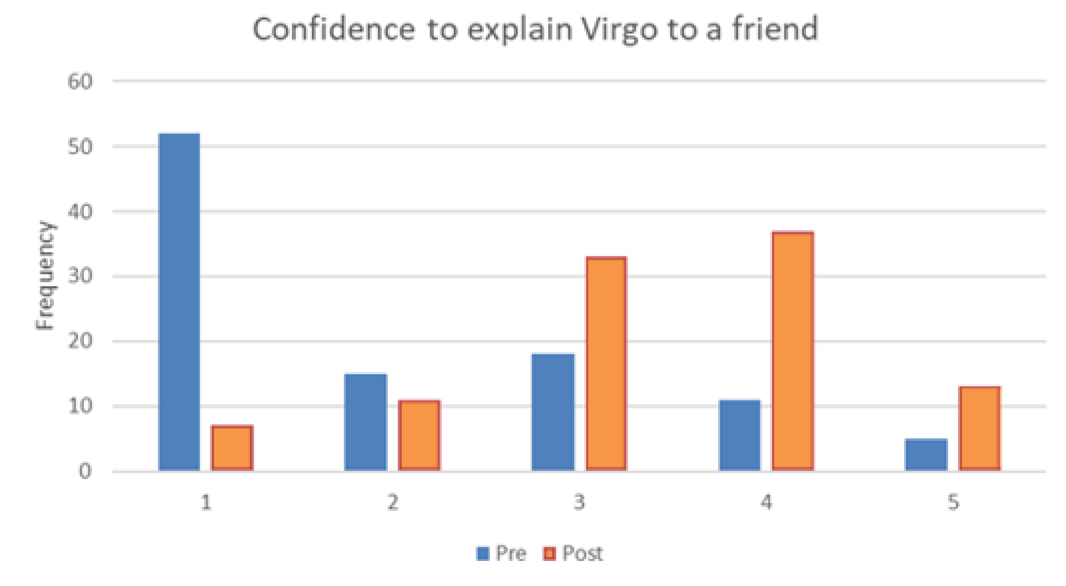


Figure 10: Screenshot from virtual visit to Virgo

Regarding the students' nationalities: 46 students came from Greece, 25 from Italy, 13 from Pakistan, 12 from Romania, 3 from Portugal, 1 from Austria and 1 from France. The students were offered an introductory presentation about Gravitational Waves by their teachers on average three days before the visit and answered the pre- questionnaires after that. The post questionnaires were delivered within 1 week from the completion of the visit.

In order to investigate students' familiarity with related concepts we performed a non-parametric Related Samples Wilcoxon Signed Rank test for each vocabulary item to compare the pre and post answers with the null hypothesis that the medians of the pre and post-test are similar. The null hypothesis was rejected in all cases with $p<0.05$.

Students display a statistically significant increase in familiarity with vocabulary items related to Gravitational Wave (GW) production and detection principles (22% increase; $p<0.05$) as well as familiarity with items related to technical aspects of GW measurement (15.7% increase; $p<0.05$). Furthermore, students' answers to an open-ended question regarding how they would explain Gravitational Waves to a friend demonstrate a significant increase in their fluency (29.7% increase of scientifically correct answers; $p<0.05$).



The findings of the present study indicate that students demonstrate a statistically significant increase in confidence to explain Virgo to a friend (33.3% increase; $p<0.05$).

Students displayed an increase in their understanding of wave interference and interferometry (77% increase; $p<0.05$), something that can be explained taking into account that the visit's main theme was the detection of gravitational waves, the principle of which is based on the phenomenon of wave interference. As this phenomenon was discussed in detail in the introductory presentation, the visit to the Michelson interferometer exhibit as well as the visit to the Virgo interferometer itself, it is understood that students' understanding of destructive interference of light is improved, however, not adequately taking into account that less than 50% of the students answered correctly in the pre and post questionnaire respectively. It is proposed that students who attend the visit do prior preparation in the classroom regarding the phenomenon of wave interference.

Masterclasses

A series of Masterclasses were organised by project partners IASA with school students and their teachers being given the opportunity to learn about Nobel prize winning physics. Facilitated by the

Universities of Athens and Crete, students were given a hands-on experience of using the HYPATIA event display to look for Z and Higgs bosons, as used in the FRONTIERS demonstrators. Teachers were introduced to the FRONTIERS Project with the Demonstrators presented.

Over 8 Masterclass events, held both in-person and virtually, 405 students and 71 teachers took part. These events further supported and promoted the engagement of teachers and students in the FRONTIERS Demonstrators and the meaningful engagement with frontier physics.

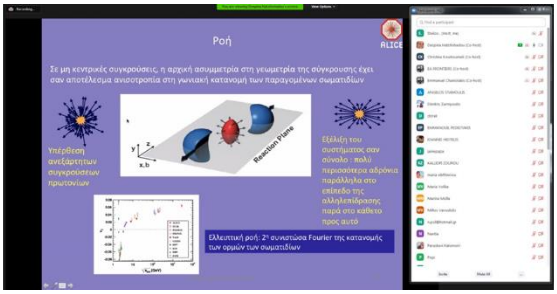


Figure 11: A screenshot from an online Masterclass event.

Community Support Environment

A central aim of the FRONTIERS project was to create a sustainable and expanding network of teachers to collaborate with researchers and students to introduce Nobel Prize Physics in education. This was provided through the FRONTIERS Community Support Environment.

One of the main messages coming from teachers who have participated in outreach activities regarding frontier science is that they need systematic and professional support to be able to effectively teach these issues to their students. This means that they need to feel part of a community of practice, and to have regular interaction with experts. A forum for the exchange of ideas and practices with their peers was seen to facilitate teachers feeling confident enough to teach complex scientific issues in an understandable and systematic fashion.

In the FRONTIERS community support environment, the participants can discuss with their peers and interact with researchers in the fields of frontier Physics and Science Education in a systematic fashion. The community environment also allows members to explore the project's resources, participate in debates, share projects, upload their own resources, and participate in online activities such as webinars. Furthermore, members of the FRONTIERS online community can receive continuous support by the project partners.

The desired characteristics of the FRONTIERS Community were:

a. Provide opportunities for sustainable engagement and networking:
    - Systematic interaction with experts in the fields of frontier physics.
    - Collaboration with peers sharing the same vision and facing the same challenges, from all over the world.
b. Offer continuous professional support:
    - Provide teachers with training materials and model educational activities for their classroom.
    - Organize participatory engagement activities for teachers' professional development.
    - Encourage teachers to become content creators.
c. Offer appreciation and recognition
    - Offer teachers tangible appreciation and recognition for their achievements.
    - Encourages teacher discussion and pay attention to their needs and concerns.
    - Boost the self-confidence of teachers in teaching frontier physics.
    - Offer teachers an active role and give them opportunities to increase their status.
d. Offer tools for online community building
    - Offer a platform for text-based and multimedia interaction between community members.
    - Offer a repository of unique educational resources, scientific and educational tools as well as authoring tools for content creation.
    - Offer a platform for the organization of virtual participatory engagement and training activities.

To develop and facilitate the FRONTIERS Community and realise the above-mentioned desired characteristics, the following online FRONTIERS Project resources have been utilised.

1. Facebook
2. Website
3. Open Schools for Open Societies Platform
4. Summer and Winter Schools
5. Google Classroom

Each of the FRONTIERS Project online resources will be examined and evaluated as contributing towards the FRONTIERS Project Community.

Facebook

The Facebook platform has been utilised by the FRONTIERS Project to engage with physics teachers and the wider public.

The platform has been used to share FRONTIERS project news, upcoming events and live streaming events such as virtual visits to research facilities. It has also been used to share teacher and student generated material adapted from the FRONTIERS Demonstrators, as well as other physics related content.

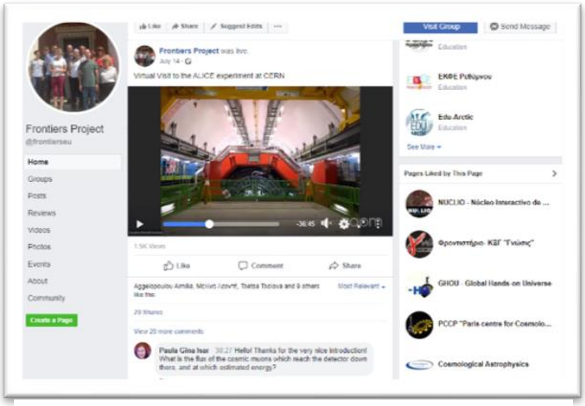
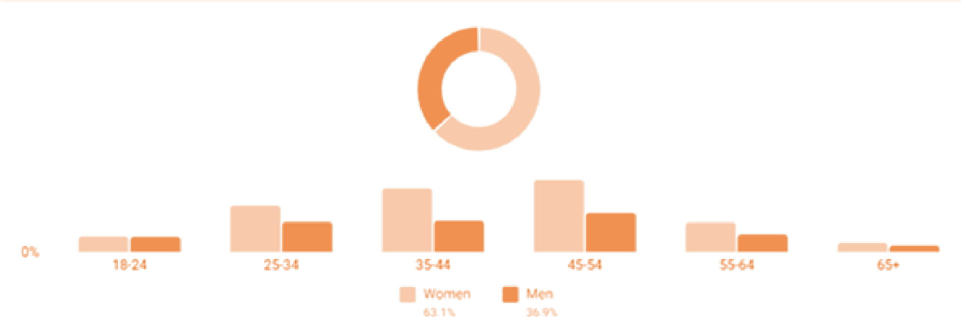


Figure 12: The FRONTIERS Project Facebook page

The FRONTIERS Facebook page has a total reach of 155,129 Facebook users. The page has 1,111 likes, with 1,227 people actively following the page. Of the Facebook users that like the FRONTIERS page, 63% are female and the largest cohort aged between 45 and 54 years.



The FRONTIERS project Facebook page has a broad international reach. Of the Facebook users that liked the Frontiers page, most users came from Greece, Portugal and Italy. Also in the top ten countries that users came from included Turkey, Bulgaria, the United Kingdom and India.

Website

[FRONTIERS Project website](#) has been developed as an online presence for all relevant information and updates relating to the project. This includes details of project partners, outputs and community.

The website hosts regular news updates as well as access to the developed Nobel prize winning physics demonstrators.

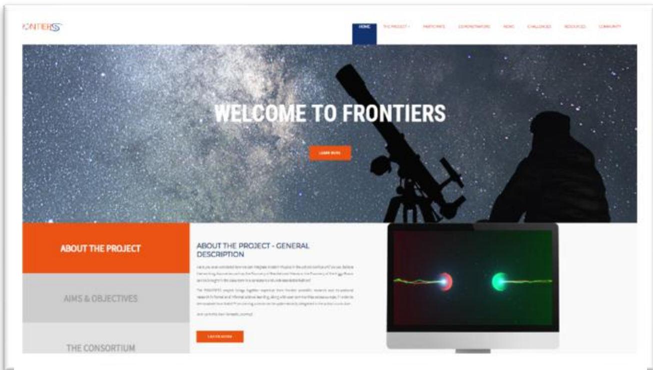


Figure 13: The FRONTIERS website homepage

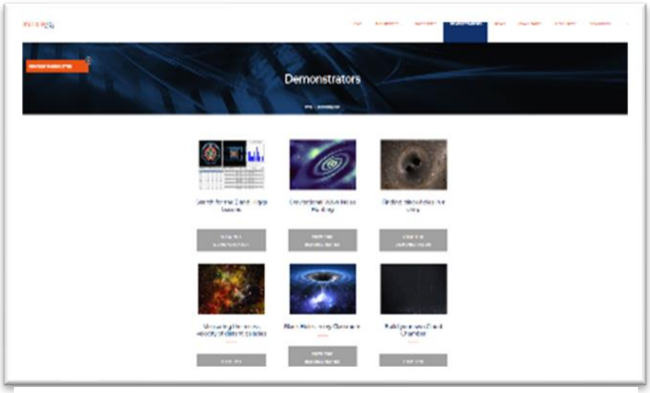
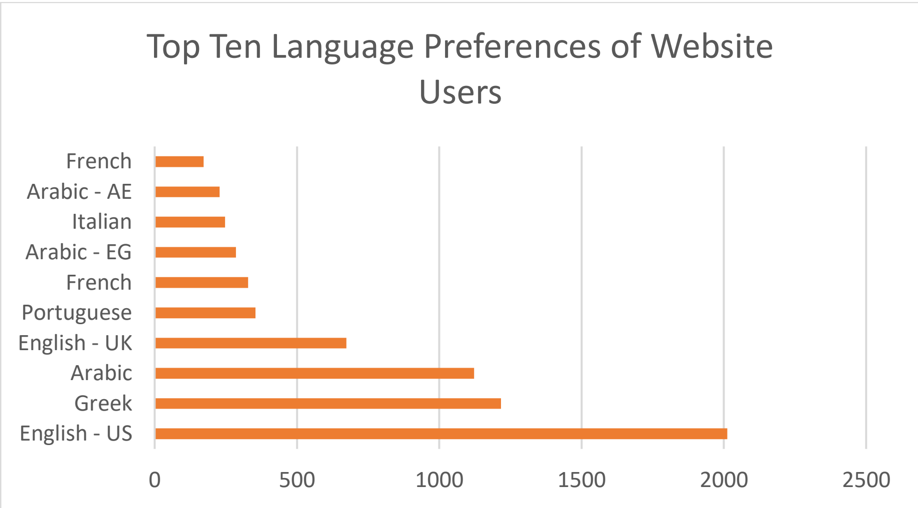


Figure 14: The FRONTIERS Demonstrators hosted on the project website

Also hosted on the website are best-practice examples of developed resources from the FRONTIERS Community Teachers for other teachers to engage with and use in their own classrooms.

The FRONTIERS website had 8,305 visitors between January 2019 and August 2021. These users accounted for 12,305 sessions on the websites, giving an average of 1.48 visits per user. During these sessions each user visited an average of 2.15 pages on the website.

Similar to the FRONTIERS Facebook page, the project website had a broad international audience. The top 10 preferred languages of the website users included English, Greek and Arabic.



Open Schools for Open Societies

The FRONTIERS Community aimed to encourage the cooperation between teachers, students and researchers and create an online experience that engages educators in sharing their best science teaching practices.

Following detailed comparative research of the available online platforms, the project consortium chose Open Schools for Open Societies (OSOS) platform to host the project Demonstrators and other community building activities. The OSOS portal is the online educational portal for Open Schooling in

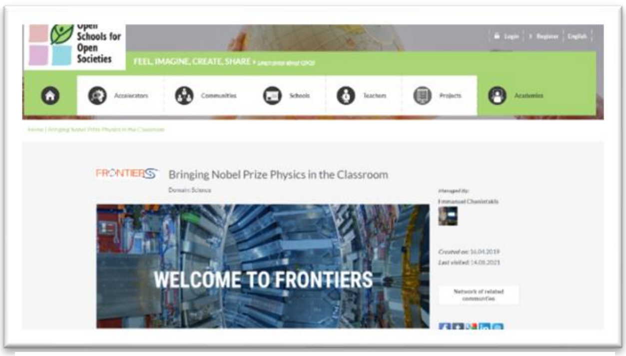


Figure 15: The Frontiers Demonstrators hosted on OSOS platform

Europe, hosting 100 vibrant online communities of 1000 schools and engaging more than 1500 teachers.

The OSOS platform provided the opportunity to create educational resources using a dedicated authoring environment, the ISE authoring tool. This tool facilitated the hosting of the FRONTIERS Demonstrators following the inquiry based pedagogical approach adopted by the project partners.

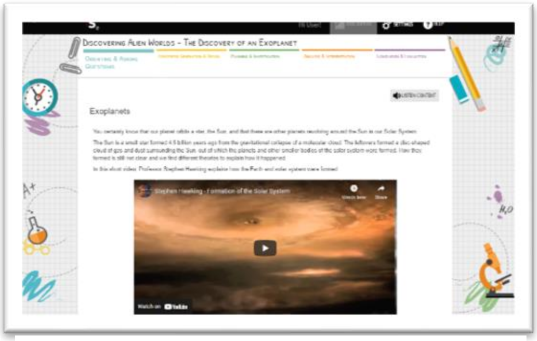


Figure 16: The inquiry-based pedagogical framework support by the OSOS platform

Educational scenarios using the ISE authoring tool allowed partners to embed multimedia (videos, photos) as well as virtual labs and datasets in an educational scenario. This allowed FRONTIERS teachers and their students to engage with the Demonstrators and the Nobel prize winning physics behind them in a more meaningful and real way.

Embedding the multimedia resources and virtual lab facilities with the Demonstrators on the OSOS platform, facilitated the teacher and student to undertake real-world scientific work using the tools and language of researchers.

All 21 FRONTIERS Demonstrators and associated resources are hosted on the OSOS platform.

The OSOS platform also hosts communities of educators in each of the partner countries with resources in their native language. There are six communities hosted on the OSOS; International, Greek, Irish, French, Italian and Portuguese. There are 174 active members across these virtual communities.

International e-Schools

In addition to the initial training of teachers across the project partner countries, three online International e-Schools have taken place. The training provided to these FRONTIERS Community members was designed and implemented systematically upon the finalisation of the project's demonstrators.

Training activities offered teachers an in-depth view of the project's pedagogical framework; proposed educational activities helping teachers to enhance their content knowledge. Furthermore, connections from FRONTIERS resources with the school curricula were highlighted and developed. Teachers were given the opportunity to take part in virtual visits to research facilities and encouraged to bring them to the classroom. Finally, the training activities aimed to empower teachers to adapt and create their own content.

Participating teachers to the International e-Schools were able to interact synchronously or asynchronously with the content of the training, interact with their trainers and peers, and complete given tasks provided by the FRONTIERS community environment.

277 participants have fully completed the International e-Schools so far, with many others joining for virtual visits hosted as part of the e-School events. This group of teachers who have been engaged, trained and supported in integrating Nobel prize winning physics into their classes, is evidence of the active FRONTIERS Community of motivated teachers of physics across the EU and beyond.

Google Classroom

Google Classroom offers teachers the potential for organising focus groups online, uploading exercises, receiving students' answers and initiating dedicated discussions.

There are 70 teachers actively enrolled in the FRONTIERS Google Classroom.

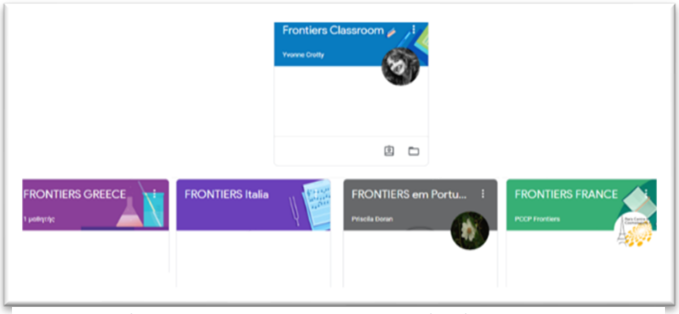


Figure 17: The FRONTIERS Project on Google Classroom

An international google classroom has been developed alongside each national Frontiers Google classroom. These classrooms are used to engage with FRONTIERS Teachers who join, communicating FRONTIERS Project updates, upcoming training events, relevant other materials, as well as an opportunity for the community to engage and support each other.

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