

europhysicsnews

The magazine of the European Physical Society

The physics of **black holes**

Astrophotonics:
processing starlight

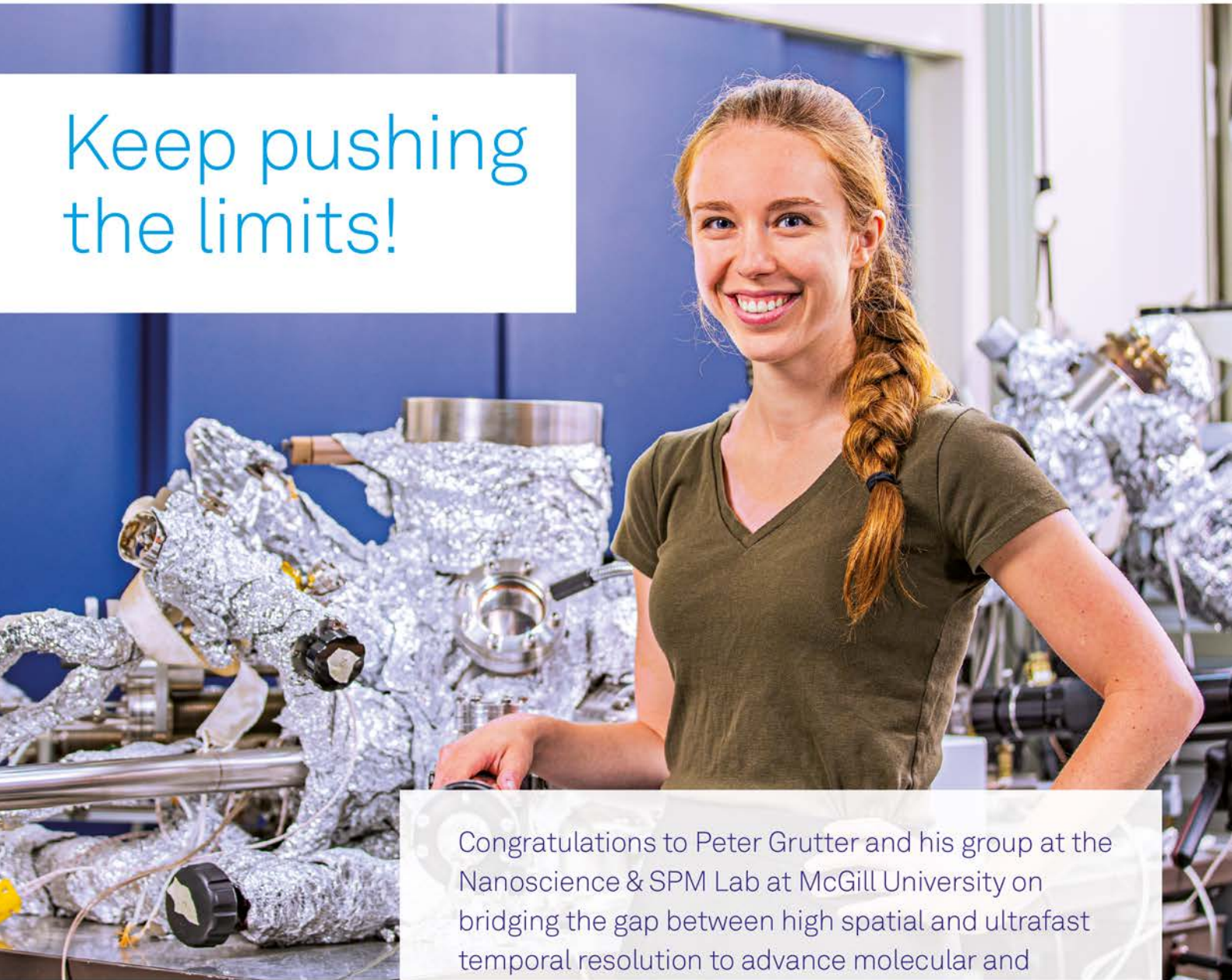
Probing the Earth
with neutrinos

Personal report
of a prize winner



edp sciences

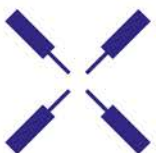
Keep pushing the limits!



Megan Cowie, Nanoscience & SPM Group,
McGill University

Congratulations to Peter Grutter and his group at the Nanoscience & SPM Lab at McGill University on bridging the gap between high spatial and ultrafast temporal resolution to advance molecular and quantum electronics. Observing 100 fs non-linear optical interactions and quantized vibration-modified electron transfer in single molecules with AFM are impressive achievements that set new standards at the forefront of scientific research.

We are excited to continue our collaboration and look forward to finding new ways of using lock-in amplifiers and boxcar averagers to push the limits of SPM applications.



Zurich
Instruments

www.zhinst.com

Your Application. Measured.



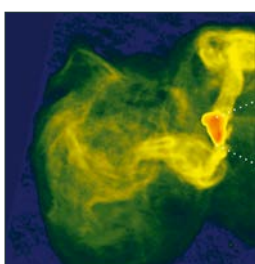
euromphysicsnews

Cover picture: an artist's concept of a distant galaxy with an active quasar at its center. A quasar emits exceptionally large amounts of energy generated by a supermassive black hole fueled by infalling matter.
© hubblesite.org, NASA and the Space Telescope Science Institute (STScI)



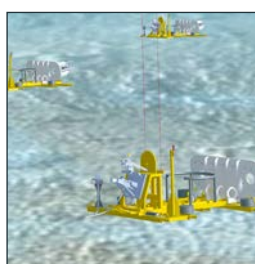
▲ PAGE 04

Personal report of a prize winner



▲ PAGE 12

Black hole astrophysics



▲ PAGE 19

Probing the Earth with neutrinos

EPS EDITORIAL

- 03 Diversity in Physics
P. Rudolf

IN THE SPOTLIGHTS

- 04 Personal report of a prize winner
06 Snapshot
07 In memoriam, Martinus Veltman
11 Physics faculty of TU/e awarded the 2020 NNV-Diversity prize

HIGHLIGHTS

- 08 Trapping nanoparticles with optical tweezers
Detecting solar neutrinos with the Borexino experiment
09 Can quarantine do more than just "flatten the curve"?
Automated symmetry adaption in nuclear many-body theory
School on Energy

YOUNG MINDS

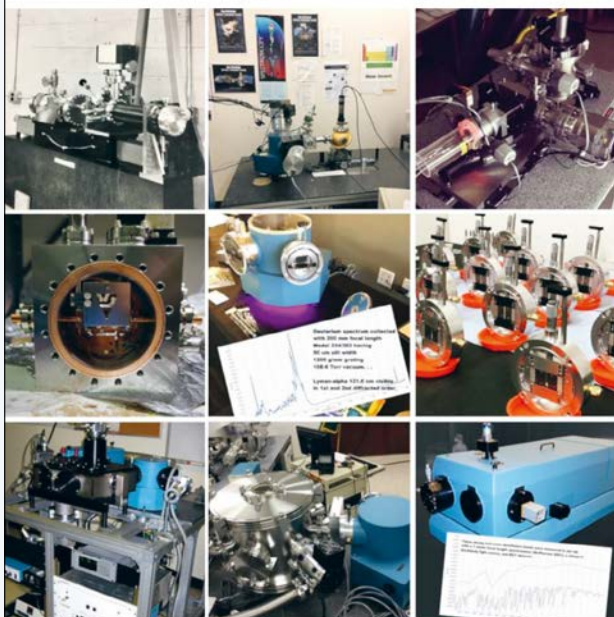
- 10 Strengthening the sense of belonging in a time of distancing
C. Martin, M. Ostinato, H. Mkrtchyan, R. Zeltner, T. Hernández Yanes, D. Pesina

FEATURES

- 12 New Horizons in black hole astrophysics
R. Blandford
16 Black holes
C. Rovelli
19 Probing the Earth's interior with neutrinos
V. Van Elewyck, J. Coelho, E. Kaminski and L. Maderer
22 Astrophotonics: processing starlight
A. N. Dinkelaker, A. Rahman
25 A very singular theorem
J. M. M. Senovilla
29 Modelling erosion and deposition in geophysical granular mass flows
S. Viroulet, C. Johnson and N. Gray

McPherson dispersive spectrometers
for best performance, at any
wavelength, from 1 nm to 20 microns

Good light throughput *and* high resolution



+1 (978) 256-4512, Sales@McPhersonInc.com

www.McPhersonInc.com

McPHERSON

Monochromators, Spectrometers & Optical systems

MBS

Do you do

ARPES measurements?

Analyse the **Spin** components?

Our state of the art ARPES System with

3D ARPES mapping

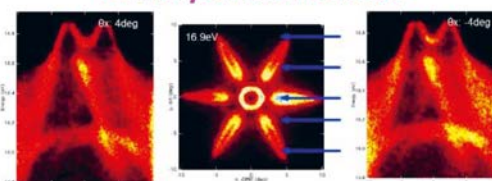
MBS A-1SYS + L4 lens*

(*: Patented by MB Scientific AB : US 9,997,346 B1, SE 539849, JP 3173552.)

ARPES System with **3D VLEED Spin Detector**

MBS A-1SYS + MBS 3D-VLEED

Gives you the results!



For more detailed information please contact us!

MB SCIENTIFIC AB

Address: Fålhagsleden 61, SE-753 23, Uppsala, SWEDEN

Tel: +46 18 290960, Fax: +46 18 572683

e-mail: info@mbscientific.se Homepage: mbscientific.se

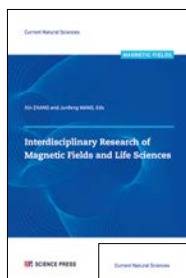
bookstore
edp sciences

Interdisciplinary Research of Magnetic Fields and Life Sciences

Scientific editor(s): Xin ZHANG and Junfeng WANG

January 2021 - 456 pages – 152€

This book mainly focuses on the progresses of inter-disciplinary researches of high magnetic fields and life sciences by researchers from mainland China. The topics covered can be roughly divided into two major categories.



Engineering Economy in Upstream Oil & Gas Field Development - A Concise Appraisal Technique for Investment Decision in Upstream Oil/Gas Projects

Authors: Menglan DUAN and Mac Darlington Uche ONUOHA

December 2020 - 284 pages color – 112€

This book guides the reader through these strategic processes, and presents the participants involved in the business of upstream oil and gas prospecting and the conditions that dictate the field development and investment decisions by investors.

Space Fault Tree Theory and System Reliability Analysis

Authors: Tiejun CUI and Shasha LI

December 2020 - 238 pages – 80€

Reliability is affected by factors, component properties and system structure, and its changes are complex. In order to solve this problem, the authors proposed the space fault tree theory in 2012. This book is the 1st time that the fundamental part of the theory has been presented internationally.

Order your copy from bookstore.edpsciences.com

[EDITORIAL]

Diversity in Physics

Awareness of the importance of diversity across all scientific disciplines has progressively increased in the last twenty years and some changes are visible: several European countries now boast twenty times more female physics and astronomy professors, while the numbers of current assistant professors imply that there will be three times more female full professors than now in the coming 10 years.

Unfortunately, the recent surveys on the impact of COVID-19 on the career development of researchers show that the effect on female researchers is more severe. This is mainly because childcare and domestic tasks are still not equally shared among partners. So we all have to stay alert and make our working environment more welcoming and supportive, also for parents.

The EPS is committed to support members, member societies, and physics research organisations in formulating and implementing strategies for improving equity, diversity, and inclusion. A few first examples of actions are described in the following. To counteract undesired behaviour of participants, the EPS introduced the code of conduct for all EPS-sponsored events and conferences. The EPS Equal Opportunities Committee started the monitoring project for Gender Fairness in Physics, in order to acquire statistics on the contribution of women physicists as invited/plenary speaker or as member of the scientific committees of EPS conferences. All Divisions and Groups are asked to consolidate the floor rate of 20% of women scientists in their various scientific and organisation committees, and in contributions as invited/plenary speakers, and to increase this rate in the coming years. All selection committees of prizes and awards are asked to avoid attributing any EPS award if not at least one woman is nominated. EPS invites all member societies to follow these examples for national events and prizes, where they do not already do so.

Another field of action is to provide an inspiration and a guideline in the path towards an inclusive work

environment. Here EPS recommends the website of the Gender Gap in Science project¹. The goals of this project were to conduct a survey and study publication patterns of women in mathematical, computing, and natural sciences to measure the gender gap. A data base with a collection of best practices can be accessed via the website. EPS plans to continue along the same line by listing resources of best practices on its website and cordially invites member societies to alert the EPS Equal Opportunities Committee to documents that can be highlighted by EPS like this Dutch one².

While these practical tips are precious as a start, other important questions inherent to the very nature of diversity are yet not, or only insufficiently addressed here. Diversity refers to differences across our social identities. These include, but are not limited to, race/ethnicity, gender, disability status, nationality, religious affiliation, socioeconomic background, and sexual orientation. In an inclusive environment these differences are not only welcomed and valued but supported and celebrated. Diversity and inclusiveness are crucially important for students and junior colleagues as well, for whom we strive to serve as role models. The EPS needs to support its member societies to also improve on issues of representation (How does a physicist look like?) and issues of diversification of the image of physics (What are careers in physics all about?). Exchange of best practices between member societies will be organised on these themes as well. Furthermore EPS aims to encourage outreach activities in socially disadvantaged neighbourhoods and activate EPS Young Minds in this sense.

Nobody can dream to be what they cannot see and nobody can love what they do not know. We know that it will take years to accomplish profound cultural change to create a truly inclusive environment in physics and we all have to work in synergy in a complex system comprising researchers, group leaders, colleagues, students, committees, the curriculum of BSc and MSc programmes, and organisational policies to achieve the goal. Our journey to recognise all talents in physics and make them feel that they belong is just at its start. ■

¹ <https://gender-gap-in-science.org>

² Improving diversity and inclusiveness, a collection of best practices: <https://www.dutchphysics.org/downloads>

europhysicsnews

2021 · Volume 52 · number 1

Europhysics news is the magazine of the European physics community. It is owned by the European Physical Society and produced in cooperation with EDP Sciences. The staff of EDP Sciences are involved in the production of the magazine and are not responsible for editorial content. Most contributors to Europhysics news are volunteers and their work is greatly appreciated by the Editor and the Editorial Advisory Board.

Europhysics news is also available online at:
www.europhysicsnews.org

General instructions to authors can be found at:
www.eps.org/?page=publications

Editor: Els de Wolf (NL)

Email: epn.editor@eps.org - **Twitter** @elsdewolf1

Science Editor: Ferenc Igloi (HU)

Email: igloi.ferenc@wigner.mta.hu

Executive Editor: David Lee

Email: david.lee@eps.org

Graphic designer: Xavier de Araujo

Email: xavier.dearaujo@eps.org

Director of Publication: Agnès Henri

Editorial Advisory Board:

Richard Zeltner (Young Minds), Tracey Clarke (UK), Gonçalo Figueira (PT), Zsolt Fülöp (HU), Manuel Güdel (A), Tero Heikkilä (FI), Agnès Henri (FR), Jo Hermans (NL), Christoph Keller (NL), Antigone Marino (IT), Arnulf Quadt (DE), Laurence Ramos (FR), Chris Rossel (CH), Victor R. Velasco (SP), Sylvain Viroulet (FR)

© European Physical Society and EDP Sciences

EPS Secretariat

Address: EPS · 6 rue des Frères Lumière
68200 Mulhouse · France

Tel: +33 389 32 94 40 · **fax:** +33 389 32 94 49
www.eps.org

Secretariat is open 09.00–12.00 / 13.30–17.30 CET
except weekends and French public holidays.

EDP Sciences

Managing & Publishing Director: Agnès Henri

Email: agnes.henri@edpsciences.org

Production: Sophie Hosotte

Advertising: Bernadette Dufour

Email: bernadette.dufour@edpsciences.org

Address: EDP Sciences

17 avenue du Hoggar · BP 112 · PA de Courtaboeuf
F-91944 Les Ulis Cedex A · France

Tel: +33 169 18 75 75 · **fax:** +33 169 28 84 91

www.edpsciences.org

Subscriptions

Individual Members of the European Physical Society receive Europhysics news free of charge.

Members of EPS National Member Societies receive Europhysics news through their society, except members of the Institute of Physics in the United Kingdom and the German Physical Society who have access to an e-version at www.europhysicsnews.org. The following are 2021 print version subscription prices available through EDP Sciences (Prices include postal delivery cost).

Institutions - European Union countries: 113 €
(VAT not included, 20%). **Rest of the world:** 136 €

Student - European Union countries: 54.17 €
(VAT not included, 20%). **Rest of the world:** 65 €

Contact: Europhysics News, EDP Sciences
17 avenue du Hoggar · Parc d'activités de Courtaboeuf
BP 112 · F-91944 Les Ulis CEDEX A, France

subscribers@edpsciences.org or visit www.edpsciences.org

ISSN 0531-7479 · ISSN 1432-1092 (electronic edition)

Printer: Fabrègue · Saint-Yrieix-la-Perche, France

Legal deposit: February 2021

The discovery of the Higgs boson was by no means "guaranteed"

The Royal Society of Science in Uppsala is the oldest academy of science in Sweden. The Bergstedt prize is the second oldest prize awarded by the Society. It was already established in 1827. In 2020, the prize was awarded to Rebeca Gonzalez Suarez of the Uppsala University "for her contribution to the discovery of the Higgs boson and to the precision studies of its properties". Here is her story.



My name is Rebeca Gonzalez Suarez and I am a particle physicist. I am a Researcher with the title of Associate Professor (Docent), at the Department of Physics and Astronomy in Uppsala University, where I also teach physics. Much like the Royal Society of Sciences, Uppsala University is also very old. Founded in 1477, it is the oldest university in the Nordic countries, and as such it is full of traditions and history.

My own history starts far away. I come from Spain, where I was born in Gijón, an industrial city in the north of Spain that opens to the Atlantic Ocean. In Spain I got a degree in fundamental physics and right after, in 2006, started my experimental particle physics career as a PhD student within the CMS collaboration, after obtaining a national grant to work with the Instituto de Física de Cantabria and Universidad de Oviedo in Spain.



It is encouraging that someone has been watching and values my scientific output”

Higgs to WW at CERN

The CMS experiment is, together with the ATLAS experiment, one of the two all-purpose LHC detectors at CERN, and when I started working there, it was under construction. In fact, both the LHC experiments and the physics analyses to be performed were being built at the same time. During my PhD-research I prepared and conducted with the early LHC data the first search for a Higgs boson produced via gluon-fusion, decaying into two W bosons and subsequently into two muons in CMS.

This channel is one of the three that lead to the observation of the Higgs boson, together with Higgs to ZZ and Higgs to photons. From these channels, Higgs to WW is the one that happens more often, but it is tricky, since it does not offer the possibility of reconstructing a clear mass peak. The leptonic decays of W bosons contain neutrinos, which are invisible and cross the LHC detectors without leaving any trace, and we lose the information they carry. I laid the foundations of that search, carefully designing signal extraction strategies, and proposing the simultaneous estimation of the irreducible background coming from WW production.

Right in the middle of my PhD research, when I was already stationed at CERN, the LHC had technical problems and its schedule was delayed. As a consequence, the center-of-mass energy for the collisions became uncertain. We worked tirelessly then to produce the first Higgs boson cross sections used in CMS and ATLAS and prepared the first official estimations of the LHC sensitivity towards a Higgs boson discovery for different energy scenarios. Something that I keep telling the people is that, while we certainly had an idea about the energy scales where new physics could be found, the Higgs discovery was by no means a “guaranteed discovery”, and that was never the attitude of the Higgs group at the start of the LHC. We did not know if we were going to find anything at all, but we were fully ready to comb the available mass range to the greatest possible extent to find it.

Top quarks physics in Brussels and Nebraska

During my postdoc periods at the *Vrije Universiteit Brussel* (2010) and the University of Nebraska-Lincoln (2013) I shifted the focus of my work more and more towards top quark physics, but I always kept parallel Higgs boson projects. For example, I performed the first study of Higgs production in association with a Z boson in the WW channel and continued by studying the spin and parity of the Higgs boson in decays to vector-bosons and photons. This was an important step to understand if the Higgs boson has any obvious exotic behaviour, but what we found out was that it followed the predictions to a very high precision level. Thanks to this work I became the coordinator of the Higgs to WW subgroup within the CMS collaboration in 2014.

During the second running period of the LHC, I finally merged my interests in top quarks and Higgs bosons and investigated processes when they are produced together. These two particles have an interesting relationship which offers insights on the vacuum stability of the Universe. I participated in the first study of the production of single top quarks together with a Higgs boson and was a

part of the group that later achieved the first observation of a Higgs boson produced in association with a pair of top quarks. Managing the whole top quark physics group of the CMS Collaboration, however, pulled me away from the analysis in 2016.

Dark sector in Uppsala

In 2018, after 10 years based at CERN in Geneva, I moved to Uppsala with a starting grant from the Swedish Research Council to join the competition, the ATLAS Collaboration. Today I still study the interplay of the Higgs boson and the top quark, but in a different way, looking for a Higgs portal to a Dark Sector, that would explain Dark Matter, with top quarks in the final state.

The recognition that the Bergstedt Prize represents is especially meaningful when coming from a different country and a different experiment. Knowing that somebody has been watching and values my scientific output, is a very positive encouragement to keep pushing further and have a continuous impact in collider physics, today and in the future. ■

■ **Rebeca Gonzalez Suarez,**
Associate professor in the
Department of Physics and
Astronomy, Uppsala University



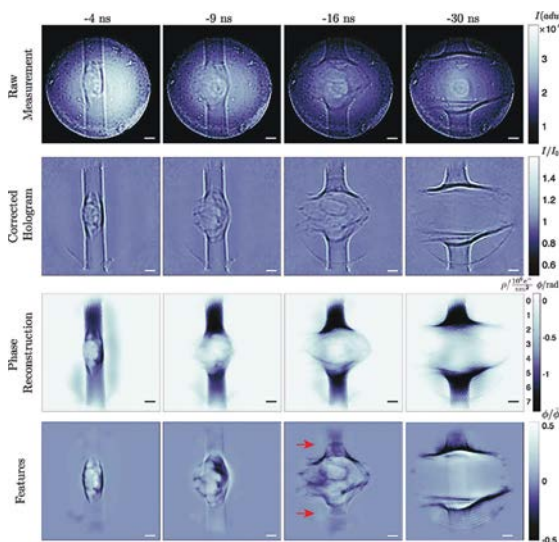
Snapshot

The intriguing title on the news site of DESY, Germany in the first week of 2021 referred to an experiment conducted at the European XFEL X-ray laser facility. Here, an international team of scientists made a X-ray image of an extremely rapidly exploding ultra-thin water jet. Johannes Hagemann from DESY is the lead author of the study that has been published in the *Journal of Synchrotron Radiation*.

At the free electron laser research facility European XFEL in Hamburg [1], ultrashort X-ray flashes are generated with unprecedented brilliance. The facility comprises multiple beamlines and scientific instrument areas each equipped with a series of mirrors and lenses for focusing and shaping the X-ray flashes and supporting devices for user experiments. In March 2019, the Materials Imaging & Dynamics (MID) instrument was opened for user operation. The MID is optimised for the investigation of materials and dynamics with nanoscale resolution both in space and time.

Probing structural dynamics of a sample system is an important step in complete and quantitative understanding of physical processes. In particular in the case of probing complex fluids or soft and biological matter, the application of for instance visible light or electron pulses is limited by optical refraction, multiple scattering and opacity in the sample. In this case, hard X-ray free electron lasers allow for high spatial and temporal resolution combined with a large penetration power.

To explore the probing opportunities of the new MID instrument at the European XFEL, the team of scientists designed an experiment to study and image the dynamics of a micro-fluidic water jet, which is commonly used as sample delivery system at XFELs. In the MID experimental environment they directed an infrared laser on a water jet which at the point of intersection had a diameter of about 0.04 mm. The infrared light from the laser heated the water causing it to evaporate at that point



▲ Pump-probe single-pulse imaging of an exploding water jet. From left to right the time delay is varied $\Delta t = -4$ ns, -9 ns, -16 ns and -30 ns. Top to bottom illustrates the workflow of data processing. Starting with the raw hologram, the flat-field corrected hologram and the retrieved phases. The two scales on the colorbar of the reconstructions indicate retrieved phase in radians on the right and electron area density in $10^6 \text{ e}^- \text{ nm}^{-2}$ on the left. The last row shows the reconstruction divided by the average phase. This highlights smaller structures present in individual images, which are otherwise hidden by large phase shifts. The red arrows in the -16 ns panel indicate shocks traveling along the jet in opposite directions. The scale bar indicates $20 \mu\text{m}$. (Fig. 9 in [2])

within about 20 ns. The X-ray pulses last only a few tens of femtoseconds, short enough for a sharp recording of the event, however, the pulses do not provide a steady illumination level. To solve this problem, the team applied the technique of single-pulse, phase contrast images. They recorded multiple empty holograms with fluctuating lighting levels from which they developed a model to describe the illumination. With this model the recorded raw holograms of the event were then processed to produce the actual snap shot image of the water jet and the explosion (see figure).

Fast evaporation by short laser pulses is already used for medical surgery. The experiment has shown that fine water jets are also suitable for carrying larger objects such as intact live cells into the X-ray beam in order to examine them. Thanks to the water, the cells remain in an aqueous environment as in the body and do not have to be immobilised or dried. In the future, with enhanced capabilities of the MID instrument, the Near Field Holography (NFH) approach to acquire sharp images applied in this experiment could also be useful for the study and imaging of more extreme cases such as the dynamics in plasma physics or hot dense matter physics.

Details of the experiment with the exploding water jet and the application of NFH in the imaging of the explosion are described in [2]. It is the first 'MID'-paper; the lead author is Johannes Hagemann, who works in the group of Christian Schroer, a lead scientist at DESY and one of the co-authors of the paper. ■

References

- [1] <https://www.xfel.eu>
- [2] Hagemann et al, *J. Synchrotron Rad.* **28**, 52 (2021). <https://doi.org/10.1107/S1600577520011557X>



The first paper of an experiment with the new Materials Imaging & Dynamics (MID) instrument of the European XFEL research facility. 🗨️

In memoriam Martinus Veltman

On 4 January 2021 Martinus Veltman who was awarded the 1999 Nobel Prize for Physics died at the age of 89.

He was a theoretical high-energy physicist from the Netherlands with a strong and remarkable personality and he was an honorary member of the Netherlands Physical Society NNV.

Like many other physicists, Martinus – Tini for intimi – was averse of boasting or bluffing. He always demanded that discoveries in theoretical physics could be verified experimentally. Indeed, his mantra was that you only discover new physics by developing mathematical equations and conducting many experiments. In that sense, he was a good friend of experimental particle physicists, while during his whole professional life and beyond he critically followed developments in physics and the research institutes he was working for.

As a true physicist he was convinced that nothing is more exciting than searching for the rules of nature. He did that not only by working very hard, but also by showing a strong will and by regularly deviating from main stream physics or even going in a transversal direction. Born in 1931, he studied mathematics and physics at the University of Utrecht in the Netherlands. After fulfilling the mandatory military service, he left the Netherlands in 1961 for CERN to conduct his PhD research. Here he wrote one of the first computer algebra systems for performing calculations for high-energy physics problems. Maple and Mathematica are the contemporary examples of such systems. The name “Schoonschip” refers to a Dutch expression for clearing things up. Among other reasons, Veltman chose the name to tease his colleagues who did not speak Dutch. It was his small guilty pleasure.

After his period at CERN, he was appointed professor at the University of Utrecht. Here, together with his PhD student Gerard 't Hooft, he developed the theoretical contributions to the Standard Model of particle

physics for which they were both awarded the Nobel Prize for Physics in 1999. In the sixties of the previous century, Glashow, Salam and Weinberg managed to unify the weak and electromagnetic interactions. Unfortunately, the theory seemed not to be renormalisable and generated infinite expressions. Consequently, it was not possible to use it to perform calculations. However, Veltman and 't Hooft showed how it was nonetheless possible to carry out renormalisation and used their theory to make precise calculations of particle properties. The predictions were confirmed when the W and Z particles were detected for the first time in 1983 at the Large Electron-Positron Collider at CERN.

In 1981 Veltman continued his work as a professor at the University of Michigan in the USA. After his retirement in 1996, he returned to the Netherlands, where he regularly gave lectures on physics and published a popular-science book on his work with the title *Facts and Mysteries in Particle Physics*. The University of Amsterdam awarded him an honorary professorship in 2001. He was also a regular guest at the annual Lindau Nobel Laureate



meeting in Germany.

The NNV is proud that Martinus became a member already at the age of 25 and remained a member of the society for the rest of his life. In 2009, the NNV awarded him honorary membership. During his 64 years of membership he regularly spoke at the annual NNV-conferences. In 1990 he received the prestigious Dutch Physica Prize. Typically for him, he gave his acceptance talk the title “*Quo Vadis High-Energy physics?*”.

Martinus Veltman was a brilliant, lauded and colourful Dutch physicist. We will miss him dearly. ■

■ **Diederik Jekel**

Chair of the Netherlands Physical Society NNV

Highlights from European journals

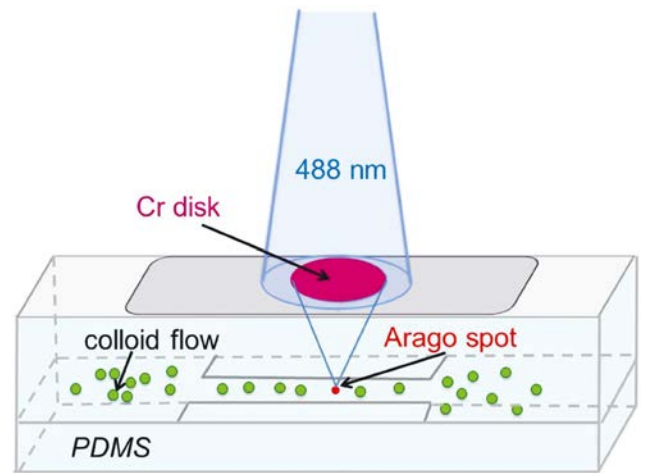
NANOPHYSICS

Trapping nanoparticles with optical tweezers

Optical tweezers are a rapidly growing technology, and have opened up a wide variety of research applications in recent years. The devices operate by trapping particles at the focal points of tightly focused laser beams, allowing researchers to manipulate the objects without any physical contact. So far, optical tweezers have been used to confine objects just micrometres across – yet there is now a growing desire to extend the technology to nanometre-scale particles. Janine Emile and Olivier Emile at the University of Rennes, France, demonstrate a novel tweezer design, which enabled them to trap fluorescent particles just 200 nanometres across for the first time. ■

■ **O. Emile, J. Emile,**

'Nanometre optical trap based on stimulated emission in evanescence of a totally reflected Arago spot', *Eur. Phys. J. E* **43**, 68 (2020). <https://doi.org/10.1140/epje/i2020-11991-6>



▲ Trapping fluorescent particles with Arago spots

NEUTRINO ASTROPHYSICS

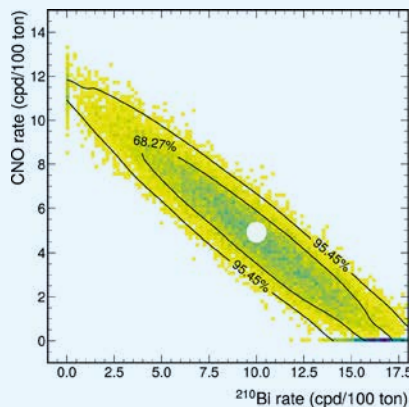
Detecting solar neutrinos with the Borexino experiment

Neutrinos produced by the CNO cycle within the core of the Sun are being hunted by the Borexino experiment so that we may learn more about this important nuclear process. A paper by the Borexino collaboration – including Xue Feng Ding,

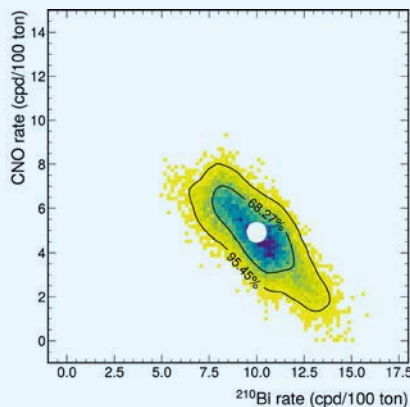
Postdoc Associate of Physics at Princeton University, United States – documents the attempts of the Borexino experiment to measure low-energy neutrinos from the Sun's carbon-nitrogen-oxygen (CNO) cycle for the first time. ■

■ **M. Agostini et al. (BOREXINO collaboration),**

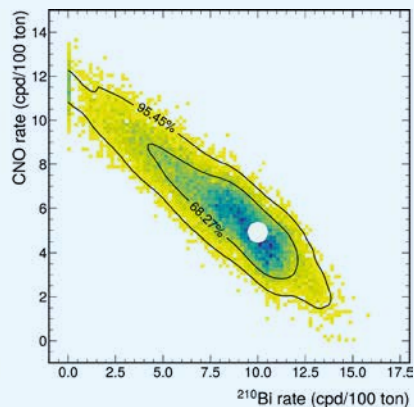
'Sensitivity to neutrinos from the solar CNO cycle in Borexino', *Eur. Phys. J. C* (2020)



(a) free



(b) symmetric Gaussian penalty



(c) upper limit

▲ Distribution of best-fit results of ^{210}Bi and CNO neutrinos interaction rates obtained fitting thousands of simulated datasets under different assumptions of ^{210}Bi backgrounds.

NUCLEAR PHYSICS

Automated symmetry adaption in nuclear many-body theory

The extreme cost of solving the A-nucleon Schrödinger equation can be minimised by leveraging rotational symmetry and, thus, enable the computation of observables in heavy nuclei and/or with high precision.

The associated reduction process, which amounts to re-expressing the working equations in terms of rotationally-invariant objects, requires lengthy symbolic manipulations of elaborate algebraic identities.

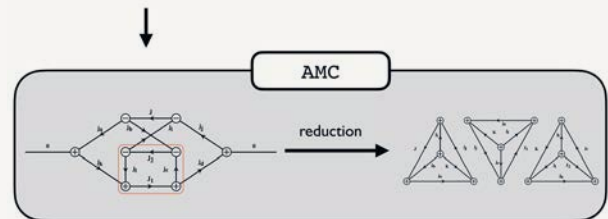
For the first time, this involved process is automated by a powerful graph-theory-based tool, the AMC code, which condenses months of error-prone derivations into a simple computational task performed within seconds.

The AMC program tightens the gap for a full automation of the many-body workflow, thereby lowering the time required to build and test novel quantum many-body formalisms. ■

■ **A. Tichai, R. Wirth, J. Ripoche and T. Duguet**, 'Symmetry reduction of tensor networks in many-body theory', *Eur. Phys. J. A* (2020) 56:272 <https://doi.org/10.1140/epja/s10050-020-00233-6>

Symmetry-unreduced Input:

$$D_{abij} \equiv \sum_{kl} \sum_{cd} H_{kicd} t_{aj}^k t_{ak}^l t_{cbil}$$



Symmetry-reduced Output:

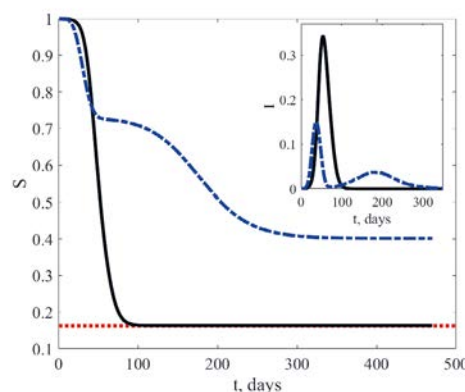
$$D_{abij}^J = \sum_{kl} \sum_{cd} \sum_{J_1 J_2 K} \frac{J_1^2 J_2^2 K^2}{a_j} \delta_{J_1 J_2} \delta_{J_1 J_2} \left\{ \begin{matrix} j_i & j_b & K \\ j_a & j_j & J \end{matrix} \right\} \left\{ \begin{matrix} j_c & j_i & K \\ j_a & j_j & J_1 \end{matrix} \right\} \left\{ \begin{matrix} j_i & j_i & J_2 \\ j_b & j_c & K \end{matrix} \right\} H_{kicd}^J t_{aj}^k t_{ak}^l t_{cbil}^J$$

▲ Symmetry reduction process of a prototypical many-body expression leading to an equivalent symmetry-reduced form. Recoupling coefficients arising from the AMC program are shown in red.

MODELLING

Can quarantine do more than just “flatten the curve”?

Our modelling of the epidemic shows that compared to a single-phase soft quarantine, a quarantine composed of a strict phase followed by a softer one results in a smaller overall number of infected individuals. This occurs if individuals with anomalously-many connections such as essential workers or store cashiers become immune before all others are allowed to come out of the strict quarantine. In this case, the most “socially connected” individuals, once recovered, act as efficient breaks in the network of disease transmission. ■



▲ The fraction of susceptible (main figure) and infected individuals (inset) for a single-phase soft quarantine (solid line) and a two-phase quarantine (dash-dot line).

■ **V. Nimmagadda, O. Kogan and E. Khain**

'Path-dependent course of epidemic: Are two phases of quarantine better than one?', *EPL* 132, 2 (2020), <https://doi.org/10.1209/0295-5075/132/28003>

CONFERENCE PROCEEDINGS

School on Energy

Since 2012, the European Physical Society and the Italian Physical Society jointly organise a biennial International School on Energy as part the training of young scientists working in the energy sector or intending to do so. The proceedings of the 5th Course with the title 'Energy: where we stand and where we go' are published in the EPJ Web of Conferences. Editors of the proceedings are L. Cifarelli and F. Wagner. ■

■ *EPJ/WoS* 246 (2020)



▲ Participants of the school at the Villa Monastero in Varenna, Lake Como, Italy



Strengthening the sense of belonging in a time of distancing

■ Carmen Martin, Mattia Ostinato, Hripsime Mkrtychyan, Richard Zeltner, Tanausú Hernández Yanes, Daryna Pesina

The Young Minds (YM) programme of the European Physical Society (EPS) was initiated eleven years ago, with the goal to connect young students and researchers all over Europe and to support their professional and personal growth. The programme now comprises more than 60 sections being active in over 30 countries. Ever since its foundations stimulating personal interaction among its members in the framework of the annual leadership meeting was one of the pillars of the programme. In 2020 the leadership meeting was cancelled due to the Corona pandemic. As many other organisations and professional institutions, the Young Minds Action Committee organised a series of webinars to stay connected with its members. In addition to the efforts of the committee, the overwhelming majority of the sections organised online events as well, covering topics ranging from scientific outreach talks to international networking events.

Providing opportunities for professional and personal growth

One of the major goals of the webinars was to provide opportunities for both professional and personal development, despite the cancelled annual meeting and the general restrictions regarding physical meetings. Accordingly, the Action Committee approached potential speakers, from vastly different professional backgrounds and with vastly different focus and topics, within its network that could deliver webinars for YM.

▼ Poster of the LaTeX webinar [1].

The first YM-webinar was given by Francesca di Franco, a former member of the Young Minds Section in Naples, who shared her experience and knowledge on creating appealing visual context during scientific outreach events. While this webinar addressed a topic very specific to the work in local sections, the speaker of the second webinar, Dr. Gregory Quarles, discussed how good decision-making could accelerate one's career. Finally, in the third webinar Dr. Marina Corradini, a former member of the Naples section as well, discussed why there is still a lot of work to do for

creating a scientific community that is truly diverse and inclusive and how each individual person can contribute to achieve this goal.

Considering the large spectrum of discussed topics, ranging from how to increase the impact of scientific outreach efforts over career development advice to the very essential question of diversity and inclusion, it is not too surprising that the webinars were well received: As summarised in Figure 1 attendees from at least 17 different countries, ranging from Egypt to Georgia as marked in blue, participated in the webinars, including representatives



Webinar series summary

- Topics: Scientific outreach, professional development, equality and diversity
- Participants from at least 17 countries and 17 different sections
- Reached an audience of almost 3000 people



from 17 different YM sections. The total reach of the series, e.g. the sum of participants who attended the ZOOM meeting and the people who followed the live stream on our social media presence, reached almost 3000. Among those were also people not associated with or in knowledge of the Young Minds programme yet, such that the series turned out to be not only a service to current members but also a tool to increase the overall visibility of the programme within the physics community in Europe and beyond.

Coming together online

In addition to the webinar series organised by the Action Committee, many sections quickly adapted to the new conditions and started to organise webinars, virtual lab tours, experiments, or other online events by themselves.

The scientific outreach series “Fisica in quarantena”, from the Naples Section, and “Fyzikální advent”, from the Prague section, are just two examples of the seemingly endless creativity of the sections when it comes to generating appealing content. What struck us the most, however, is the following: While initially many webinars were tailored and advertised to

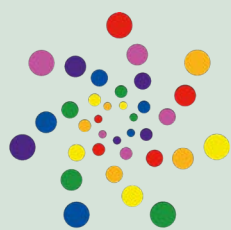


reach local communities, the sections opened their activities more and more to the international community of YM

and eventually reached out to other sections for collaboration and interaction. For instance, the “Zooming on Science” series, featuring scientific talks from different fields of physics, has been a joint collaboration of the Italian sections in Catania, Naples, and Trieste. Yet another example is the Kharkiv section that in early January 2020 hosted the Latex webinar “Using Latex in the preparation of scientific questions and not only!” on the Zoom platform and advertised it openly within the Young Minds community. Thanks to the online format, participants from other cities and countries could join the meeting, in particular, there were four applications from Yerevan State University (Armenia) and one from the University of Alcalá (Spain).

Finally, the Artsakh Young Minds section organised “section talks”: in this format representatives of other sections shared the experience they made within the YM programme and during their engagement in their local section. In total, Artsakh Young Minds launched three sessions featuring members from the sections in Cairo, Zagreb and Warsaw, which have been attended by several other sections as well. ■

PHYSICS FACULTY OF TU/e AWARDED THE 2020 NNV-DIVERSITY PRIZE

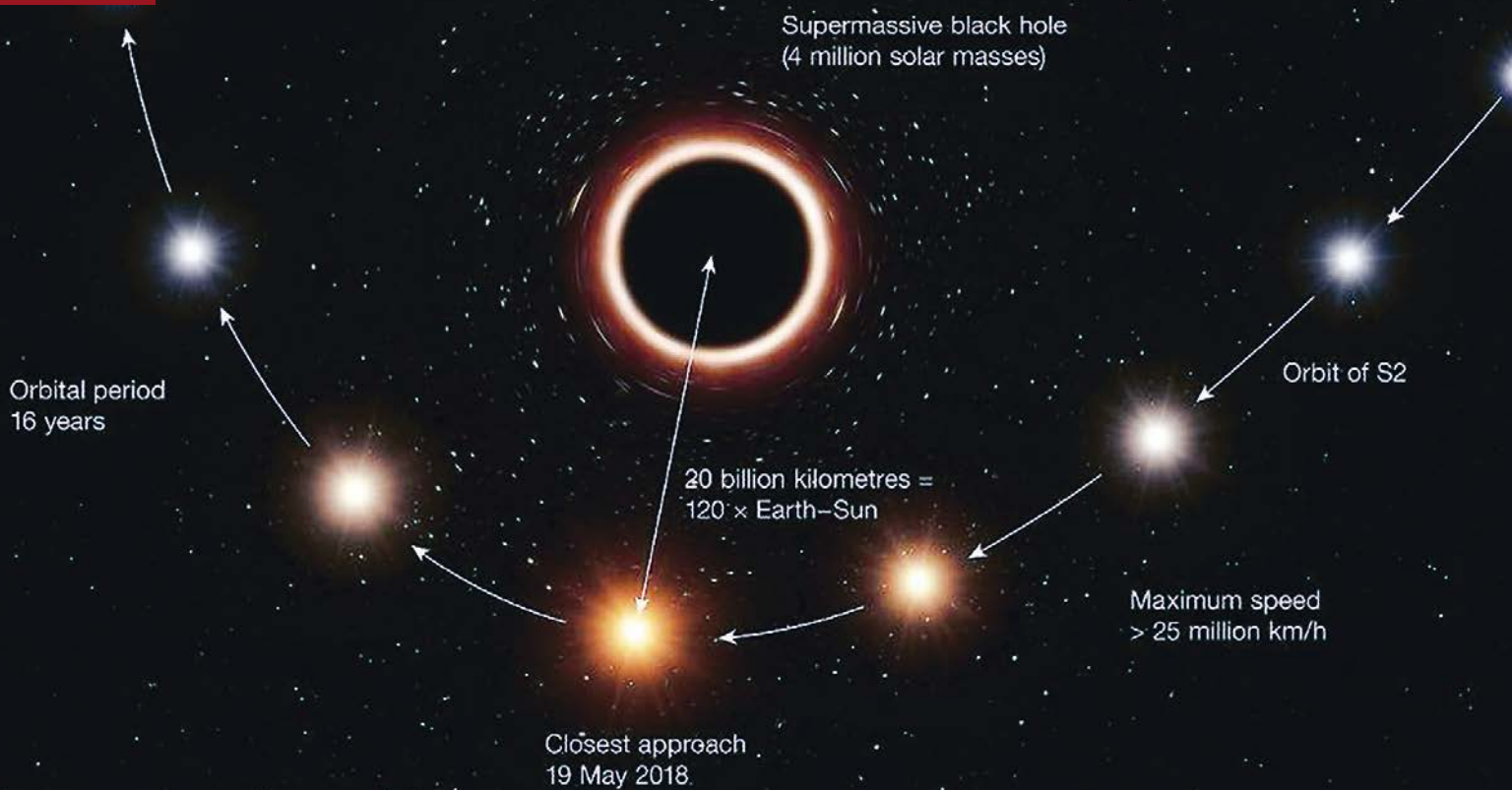


NNV-Diversiteitsprijs 2020

The Netherlands Physical Society NNV has awarded its Diversity Prize 2020 for physics institutions in the Netherlands to the Faculty Technical Physics of the Technical University of Eindhoven (TU/e). The biannual NNV Diversity Prize is given to a physics institution in the Netherlands that is making a real effort and is successful in bringing an open diversity to research and tuition. It is meant to be an inspiring prize for others to see how important and possible it is to make the field of physics inclusive and diverse. The jury assessed the applications for originality and concrete proof of success. It selected three institutions that excel above a policy that is already in place more generally for an on-line site visit to meet with the directorate and HR officers to discuss their diversity policy and the goals set. In a separate meeting with staff and students the experience with the policy was evaluated.

According to the jury, the awarded physics faculty of TU/e has made an impressive cultural change in a relatively short time. For this, the recently introduced PI system appeared to be instrumental and the faculty achieved more diversity in nationality and gender. It is also striking how important the role of the study association 'Johannes van der Waals' was and is in this transformation. Indeed, the latest generation is committed to and skilled in achieving this cultural change. The award ceremony took place on 18 January 2021, during the online version of the large annual Physics@Veldhoven conference of the whole physics community in the Netherlands. The ceremony was led by Diederik Jekel, Chair of the NNV (see <https://www.youtube.com/watch?v=ueWB5rYh4e4> or search on YouTube for 'NNV-Diversiteitsprijs')

The prize comprises a plaque that will be installed at the main entrance of the faculty in Eindhoven. ■



NEW HORIZONS IN BLACK HOLE ASTROPHYSICS

■ Roger Blandford – KIPAC, Stanford University – <https://doi.org/10.1051/epn/2021101>

Black holes, a seemingly inevitable consequence of Einstein’s general theory of relativity and stellar and galactic evolution are being observed in many new ways with masses ranging from roughly three to ten billion solar masses. Their masses and spins determine how they power the most luminous objects in the universe and impact their environments.

History

In 1916, just a few weeks after Albert Einstein published his general theory of relativity, Karl Schwarzschild, found a spherically symmetric solution to the field equations. Although this was not widely understood until the 1960s, this solution describes a non-spinning *black hole*, uniquely described by its mass [1]. It exhibits an event horizon, which can be thought of as a limiting, spherical surface in space from behind which light and material particles do not escape and, instead, as shown by Nobel Laureate Roger Penrose, proceeds towards a *singularity* where classical space and time come to an end [2]. The radius of the event horizon, measured by its circumference, is only 3 km for each solar mass in its total mass.

In parallel, astronomers realised that evolved, high mass stars were unlikely to escape ending their lives as black holes. They also discovered that the nuclei of galaxies could outshine the tens of billions of surrounding stars. One of the early interpretations of these sources, called quasars, was that they were due to gas accreting onto massive (millions to billions of solar masses) black holes and releasing gravitational energy as heat and radiation. This turned out to be correct.

Around this time, Roy Kerr generalised Schwarzschild’s solution introducing a second parameter, the spin, and this suffices to describe essentially all astrophysical black holes. In addition, Penrose demonstrated that rotational energy could be extracted from a Kerr black hole to provide a competitive power source to accretion.

Stellar Mass Black Holes

The first explicit demonstration that black holes really do exist, outside the febrile imaginings of theorists, came from observing X-ray sources in orbit around regular stars [3]. The sources have masses which were measured, using Kepler's laws, to exceed the maximum possible mass of a neutron star or a white dwarf and so, they had to be black holes. Gas is transferred from the regular star onto the black hole with sufficient angular momentum to form an *accretion disk*, within which magnetic “friction” allows gas to spiral inward, releasing energy and emitting X-rays. The luminosity is determined by the rate at which gas is supplied.

These disks can be very efficient radiators, in the sense that the energy that is radiated before gas plunges across the event horizon can be a much larger fraction of its rest mass, typically ten percent, than is released by the nuclear reactions inside stars (typically half a percent). Accretion disks are complicated, subject to instability on a variety of timescales and capable of driving powerful, *magnetised outflows*. When the mass supply is low, the gas is either expelled or ingested, before it can radiate, and so these disks are not so efficient. The manner in which disks radiate away the internal frictional heating and reflect incident radiation is also quite subtle but can be highly diagnostic of these complex flows and the black hole spin.

Massive Black Holes

Most normal galaxies have a massive black hole in their nucleus [3]. This is true of our galaxy which hosts a four million solar mass black hole (Fig. 1). However, it is almost dormant, emitting very weakly at radio through X-ray wavelengths because it is ill-fed. (We should not be upset. We would not want to live next to a quasar!) Our black hole is orbited by many stars, just like our sun is orbited by planets. These orbits have been followed using extremely careful infrared observations by teams led by Nobel Laureates Reinhard Genzel and Andrea Ghez and provide a compelling manifestation of the black hole [2].

Another important example is provided by the very massive (six billion solar masses) black hole in the nearby galaxy, M87 (Fig. 2). The moderate gas supply does not match the black hole's appetite and what it must have been in the past when M87 would have been one of the brightest “stars” on the sky. Recently, the Event Horizon Telescope collaboration has imaged gas orbiting close to the black hole, affirming its size as well as predictions from general relativity [4].

When a massive black hole is well-fed, the galaxy nucleus becomes “active”. This happened much more when the universe was younger. The accompanying accretion disks radiate in the ultraviolet, not X-ray bands and excite emission lines from nearby gas.

Relativistic Jets

Active galactic nuclei can also produce *jets* [5]. These are pairs of linear outflows launched perpendicular to the accretion disk along opposite directions. The outflow speeds are generally near to that of light and, as a consequence of special relativistic kinematics, they can exhibit “superluminal” expansion. In addition, the small minority of jets that are directed towards us will appear to be unusually luminous and dominate samples of such sources observed by astronomers. They comprise the majority of the powerful gamma-ray sources seen on the sky.

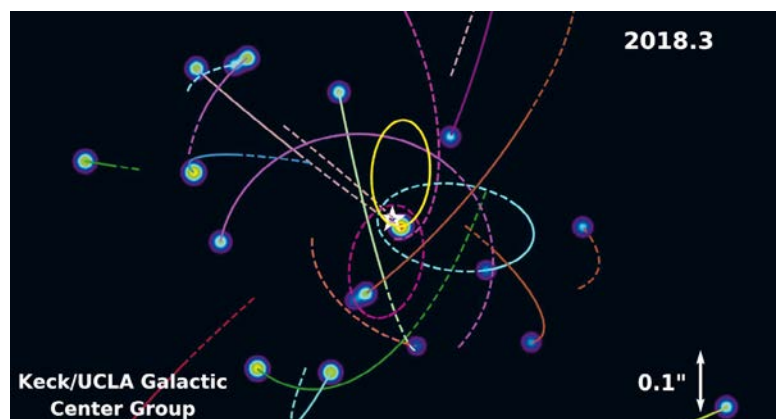
The power for these jets appears to derive from the spin of the black hole, extracted electromagnetically. The horizon of the black hole behaves like a rotating electrical conductor, similar to a Faraday wheel. In the most powerful cases, an EMF $\sim 10^{20}$ V is generated driving a current $\sim 10^{18}$ A, producing a power $\sim 10^{38}$ W again exceeding the total luminosity of a galaxy. If this is correct, then a magnetised, spinning massive black hole can plausibly accelerate an atomic nucleus to an energy more than 10^{20} eV and thereby account for the very highest energy cosmic rays that are observed hitting the earth's atmosphere.

Jet collimation is attributable to magnetised outflow from the accretion disk, an interaction which renders them visible. Despite this, jets can travel for millions of light years through the intergalactic medium. It is remarkable that a nuclear source, no larger than our solar system, can have a major, environmental impact on the gas far beyond the host galaxy.

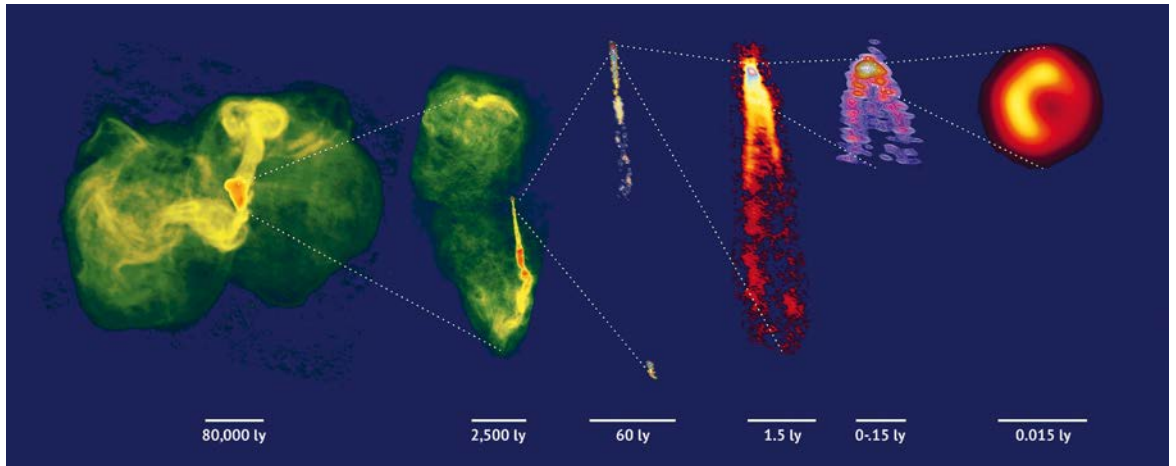
Formation of Black Holes

Stellar mass black holes form when the core of a sufficiently massive star runs out of nuclear fuel and is unable to withstand the weight of the surrounding gas, even at nuclear density [3]. The ensuing gravitational collapse is accompanied by a supernova, which can outshine the host galaxy for a few months. Many of these collapses appear to produce powerful, relativistic jets, analogous to those found in active galactic nuclei. The jets are so strong that, remarkably, they are able to punch two channels through the infalling stellar gas and expand into the interstellar medium with ultrarelativistic speed. These jets are associated with the

▼ FIG. 1: Observed stellar orbits around the four million solar mass black hole in the nucleus of our galaxy.



► FIG. 2: Observations of the jets associated with the nearby galaxy M87 on scales ranging from three hundred million light years to a three hundred times the radius of the Earth's orbit around the sun [2]. The leftmost image shows the bubbles being blown into the gas around the galaxy; the rightmost image shows synchrotron radio emission from electrons in orbit around the six million solar mass black hole.



most common type of *Gamma Ray Bursts* which are now seen at a rate of roughly one per day and typically last a few seconds. They were first discovered in the 1960s by satellites monitoring nuclear weapons.

A second type of Gamma Ray Burst has a shorter duration and is associated with the merger of two orbiting neutron stars to form a spinning black hole of roughly three solar masses. These mergers are due to the emission of gravitational radiation, that has been measured directly by the LIGO and Virgo *gravitational wave observatories*. These mergers also seem able to produce collimated relativistic jets as well. So, it appears that Gamma Ray Bursts are the “birth cries” of stellar mass black holes.

Most observed, gravitational wave signals, to date, are associated with the merger of black holes with masses in the ten to hundred solar mass range. The computation of the associated gravitational wave signals is a *tour de force* of numerical relativity and so far everything is compatible with the field equations, an impressive affirmation of general relativity in the strong gravity regime.

Similar collapses and mergers must occur with massive black holes. It is probably the case that the initial collapses make relatively low mass black holes. These then grow, up to masses that can exceed ten billion solar masses, radiating relatively efficiently, so as to account for the bright quasars. There ought to be occasional mergers of massive black holes following the mergers of the host galaxies.

New Horizons

The classical, general relativity theory of single and merging black holes is essentially complete and well-verified [6]. It provides a stage on which magnificent, high energy dramas can be watched by observational astronomers and simulated by astrophysicists.

However, the invisible kinematics of the collapse within the horizon and the extremely restrictive conditions, under which a wormhole might form, or a “naked” singularity may be viewed, still attract attention. Even more interest attends the interface with quantum mechanics - Hawking radiation, firewalls and string theory. However, none of this has been observed as yet.

Future observations hold great promise. The Event Horizon Telescope will study more sources with finer resolution informing more sophisticated simulations and may one day be deployed in space. LIGO-Virgo will continue to elaborate and inform the principles of advanced stellar evolution, including the provenance of the black hole binaries sources, and further test general relativity. The search for gravitational waves from massive black hole binaries, using accurate timing of radio pulsars, is on the threshold of discovering a background or establishing important upper limits. James Webb Space Telescope should flesh out the narrative history of galaxies and their active nuclei. However, most of all, this is a young and growing research field and one where great discoveries can still happen. ■

About the author



A native of England, **Roger Blandford** is a professor in the Physics Dept. at Stanford University and at the SLAC National Accelerator Laboratory. He has a long interest in the mechanisms through which black holes power some of the most luminous sources in the cosmos. He has also worked on neutron stars, cosmic ray physics, cosmology and gravitational lenses. Recently, he co-authored the graduate physics textbook “Modern Classical Physics” with Kip Thorne.

References

- [1] K. Thorne, *Black Holes and Time Warps*, New York: Norton (1994)
- [2] Royal Swedish Academy of Sciences, The Nobel Prize in Physics 2020 (2020)
- [3] M. Begelman, M. Rees, *Gravity's Fatal Attraction*, Cambridge: Cambridge University Press (2020)
- [4] Event Horizon Telescope Collaboration, *Astrophys. J.* **875**, L1 (2019)
- [5] R. Blandford, D. Meier, A. Readhead, *Ann. Rev. Astron. Astrophys.* **57**, 467 (2019)
- [6] R. Blandford, *Science* **347**, 1103 (2015)

COMPANY DIRECTORY

Highlight your expertise. Get your company listed in europhysicsnews company directory
For further information please contact bernadette.dufour@edpsciences.org

ADVANCED ENERGY

advancedenergy.com/trek

Advanced Energy designs and manufactures products for demanding applications in research and industry. High voltage amplifiers from our Trek product line utilize proprietary circuitry to provide a closed-loop amplifier system with exceptional DC stability and wideband performance for driving capacitive loads. Trek's non-contacting electrostatic voltmeters circumvent the charge transfer issues of traditional contacting technology.



BARTINGTON INSTRUMENTS

www.bartington.com

Bartington Instruments designs and manufactures high precision fluxgate magnetometers, Helmholtz coil systems, gradiometers, magnetic susceptibility instruments and associated data processing equipment, for the precise generation and measurement of magnetic fields around physics experiments, and for calibration of magnetometers in consumer electronics.



BLUEFORS OY

Bluefors.com

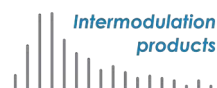
Bluefors manufactures cryogenic measurement systems and has a strong focus in the field of quantum technology. Our reliable and easy-to-operate systems can be customized to meet the special requirements of each experiment allowing the customer to get in direct contact with the scientists and engineers who design their system.



INTERMODULATION PRODUCTS AB

intermodulation-products.com

We develop and sell high-speed multichannel, multifrequency lock-in amplifiers with specialized signal processing capabilities for non-linear systems. In particular we have applications for determining the tip-surface force in tapping mode AFM, and an all-in-one measurement and control instrument for quantum computing.



MB SCIENTIFIC AB

www.mbscientific.se

MB Scientific AB is a Swedish company which develops and produces state of the art instruments for the photoelectron spectroscopy experiments. Our photoelectron energy analyser MBS A-1 gives you the opportunity to do world leading research together with MBSVUV photon sources, MBS L-1 and T-1, which produce the brightest and narrowest lines existing to be used for this type of experiments.



MCPHERSON

www.mcphersoninc.com

McPherson designs and manufactures scanning monochromators, flat-field imaging spectrographs, and vacuum monochromators and measurement systems for reflectance, transmittance, and absorbance testing. Its spectrometers and systems are built for soft x-ray, vacuum-ultraviolet, and UV/Vis and Infrared wavelengths. Applications range from lasers and lithography, solar, and energy to analytical life science and more.



PFEIFFER VACUUM

www.pfeiffer-vacuum.com/en/

Pfeiffer Vacuum stands for innovative and custom vacuum solutions worldwide, technological perfection, competent advice and reliable service. With the invention of the turbopump, the company paved the way for further development within the vacuum industry. Pfeiffer Vacuum offers a complete product portfolio: backing pumps, leak detectors, measurement and analysis devices, components as well as vacuum chambers and systems.



TOPTICA PHOTONICS

www.toptica.com

TOPTICA Photonics, founded in 1998 near Munich (Germany), develops and manufactures high-end laser systems for scientific and industrial applications. The portfolio includes diode lasers, ultrafast fiber lasers, terahertz systems and frequency combs. OEM customers, scientists, and over a dozen Nobel laureates all acknowledge the world-class exceptional specifications of TOPTICA's lasers, as well as their reliability and longevity.

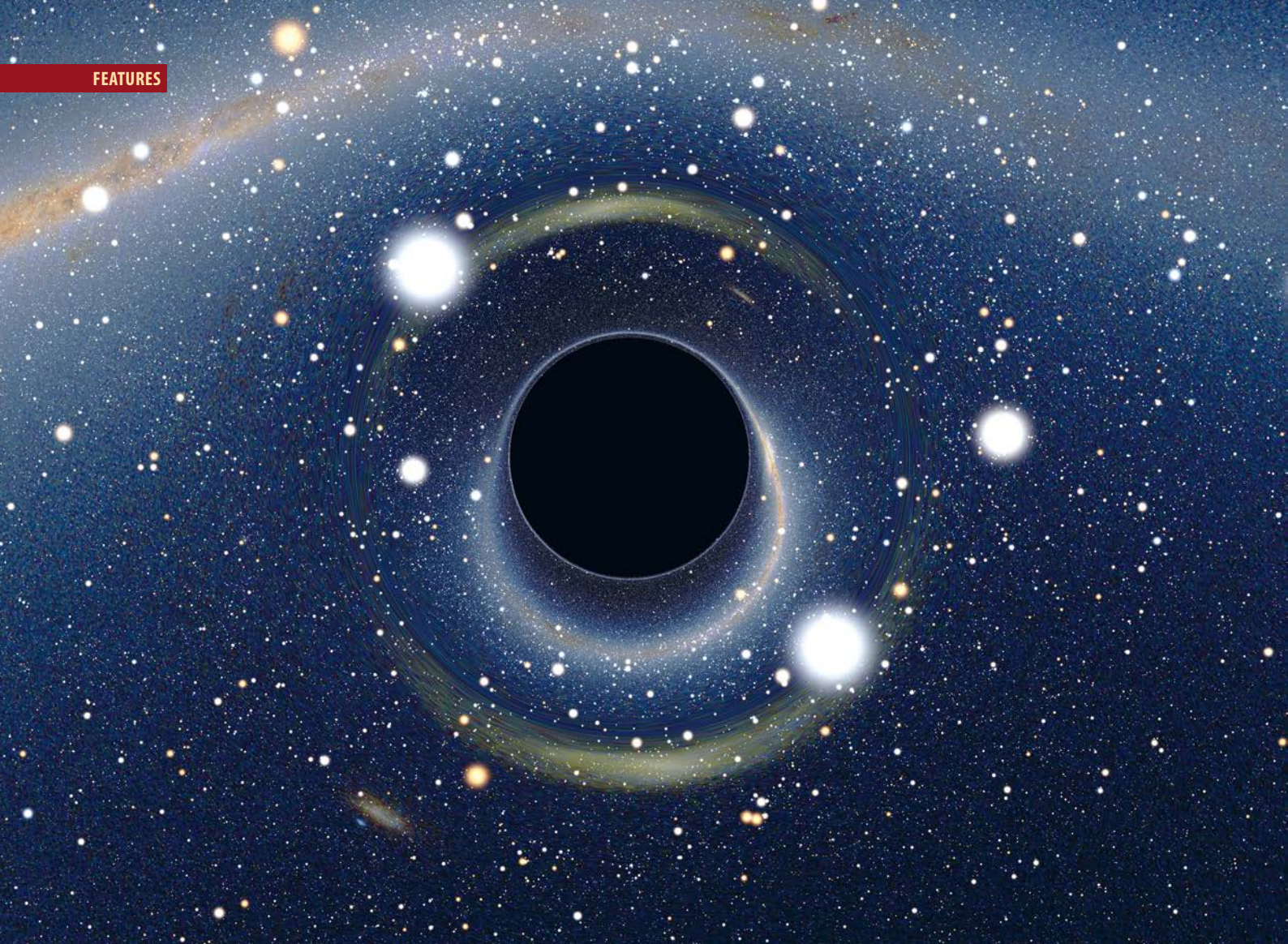


ZURICH INSTRUMENTS

www.zhinst.com

Zurich Instruments is a technology leader developing and selling advanced test & measurement instruments for dynamic signal analysis. These devices are used in many fields of application by high-technology research laboratories and industrial development sites. Zurich Instruments' vision is to revolutionize instrumentation in the high-frequency and ultra-high-frequency range by incorporating the latest analog and digital technology into powerful measurement systems.





BLACK HOLES

■ Carlo Rovelli – DOI: <https://doi.org/10.1051/epr/2021102>

■ Centre for Theoretical Physics, CNRS, Aix-Marseille Université and Université de Toulon, CNRS, France.

■ Rotmann Institute, Western Ontario University, Canada. Perimeter Institute, Canada.

They are out there in the sky in huge numbers. They are the most astonishing objects in the universe. Their existence was predicted and understood before we detected them. They behave precisely as the theory predicted. Yet, we do not know what happens at their center, nor in their future. But this confusion is our key towards what we most lack in fundamental physics: understanding quantum gravity.

▲ © Wikipedia Alain
r - Creative Commons
Attribution-Share
Alike 2.5 Generic

Albert Einstein was totally wrong about it. It was a mathematical solution of his equations that appeared to describe a funny perfectly round object surrounded by a surface where clocks appeared to slow down to stillness. Einstein thought that space would end at this surface: nothing behind it. The entire physical community was confused

about the nature of this solution. Ideas began to clear in the 1960s. But many viewed this solution just as a peculiar quirk of the equations, perhaps due to its unrealistic perfect symmetry.

It took Roger Penrose, recognised for this by the 2020 Nobel Prize, to develop mathematical tools showing that the strangeness of this solution was not a quirk: quite

generically, Einstein theory predicts that if a bunch of matter-energy is sufficiently compressed, it closes itself within a “trapping surface”, from which there is no escape: everything will inevitably sink into a locus where energy density becomes infinite and the theory becomes meaningless: a “singularity”. Einstein’s theory, that is, predicts that sufficiently compressed matter collapses into a black hole.

Still in the 1970s, people doubted all this could have anything to do with the real world. I studied general relativity -Einstein’s theory- in that decade, on the textbook by Steven Weinberg, Nobel in particle physics: it still presented black holes as mathematical objects probably irrelevant for reality. After all, to create a trapping surface we’d have to squeeze the entire the mass of the Earth into something like a centimetre cube, not an easy task, it seemed, even for the universe.

But all these doubts were misplaced. The evidence for the real existence of black holes in the Sky continued to pile up during the following decades. Examples are the radio observations of the accretion disks formed by matter that spirals around black holes before plunging in, the observations of gigantic jets emitted in the polar directions by these accretion disks, the detection of gravitational waves formed by two black holes merging that led to the 2017 Nobel Prize to Rainer Weiss, Barry C. Barish and Kip S. Thorne, and others. Perhaps the most spectacular is the direct observations of the Keplerian orbits of the stars orbiting the great black hole at the center of our galaxy: they show that a mass 4 million times our Sun is concentrated in a small region, which coincides with a strong radio source located within one Astronomical Unit (the distance between the Sun and the Earth). Nothing else that we can imagine could concentrate a similar immense mass in such a small space. These observations were awarded with the other half of the 2020 Nobel prize, given to Andrea Ghez and Reinhard Genzel. Today nobody doubts anymore that there are objects in the sky for which the best understanding we have is in terms of Einstein theory’s black holes.

We see in the sky black holes with stellar-size masses, clearly formed by star that have ended up their fuel and sank under their own weight, when the burning became insufficient to provide the pressure to keep them open. We see other black holes, much larger, at the centres of most galaxies. They can be millions or even billions times bigger than stars. They feed on matter and even stars falling in. Their origin, and the full relation between them and the galaxy that host them is under intense investigation and perhaps not completely clear yet. We also see other kinds of black holes, such as those whose merging has generated the gravitational waves we have detected, which are a few dozen of times larger than the stellar ones, and whose origin is not fully clear either. I would not be surprised if black holes of other

customized.

Innovative Laser Solutions tailored
by our experts to advance your research!



FemtoFiber Laser Solutions

Cutting-edge | Customized | Reliable | Simple & Turn-key

Your benefits:

- Advanced laser systems that unlock the full potential of your application
- Advise and support from our technology and application experts
- Simple, reliable, and turn-key fiberlaser technology

Contact our experts and
discuss your next laser system



sizes would soon add to this list. One likely possibility for instance is that smaller black holes formed in the very hot and dense environment of the early universe, and hang around in great numbers. A small black hole is not easily detectable: it interacts only gravitationally, while to see things we need them to interact with light, namely electromagnetically. As for myself, I have long suspected that the mysterious dark matter that we know fills the universe, and about which we have very little clue, could well be related to small black holes.



Our knowledge of black holes is a combination of understanding and ignorance. We understand well their observed behaviour; we are in the dark about what happens at their center and in their distant future. ¶¶

What is remarkable about our current knowledge about black holes is that it is a combination of nearly perfect understanding and total ignorance. On the one hand, general relativity appears capable to perfectly account for all the features of the black hole that we observe. For instance it shows that the reason a clock approaching the surface of a black hole slows down to zero is purely perspectival. That is, there is nothing particularly strange that happens on the black hole surface itself, if we look at a small enough portion of it. What is strange is the way all small regions of space and time are patched together: a short time for somebody staying put near the surface is viewed as a long time from somebody watching from outside. Beyond the horizon, contrary to what Einstein thought, space and time continue normally, except that everything irresistibly sinks towards the center. All this is clear.

On the other hand, however, we are totally in the dark about two aspects of the black hole. The first is what happens then at the center. At a moment of reflection, this is shocking: we literally see huge amount of matter sinking into the holes. Where does it go? We do not know. The second thing we do not know is what is going to happen to a black holes in the distant future. Steven Hawking as convincingly argued that because of a quantum mechanical effect energy can slowly leak out of a black hole and, as we say, the black hole slowly “evaporate”. Because of this a black hole, if left alone, will slowly loose mass until becoming very small. What happens next? Again, we do not know.

The reason we are in the dark about the center and the future of black holes is that their center and their life’s end belong to a physical regime that escapes our established

fundamental physical theories. This is the regime where quantum effects on the dynamics of space and time cannot be neglected. We need a quantum theory of gravity to figure out what goes on there.

There are few tentative theories of quantum gravity, but they are difficult to work with and we do not know if they are right. But this means that black holes are the perfect object to study if we hope to get some clarity about quantum gravity. Black holes are the perfect testing ground for quantum gravity.

Among the best developed tentative theories of quantum gravity are loop quantum gravity and string theory. The first appears to predict that spacetime continues beyond the center of the hole: matter falling-in can cross a central quantum region and find itself in a novel spacetime region which, using Penrose’s terminology, is not “trapped” but “anti-trapped”. There is a solution of Einstein theory describing such region, which is called “white hole”. The white hole solution to Einstein’s equations was long considered an unphysical mathematical quirk. But so were black holes, for that matter. At the end of the black hole’s life, the white hole would be found in its place, possibly emitting out some of what sank in the black hole.

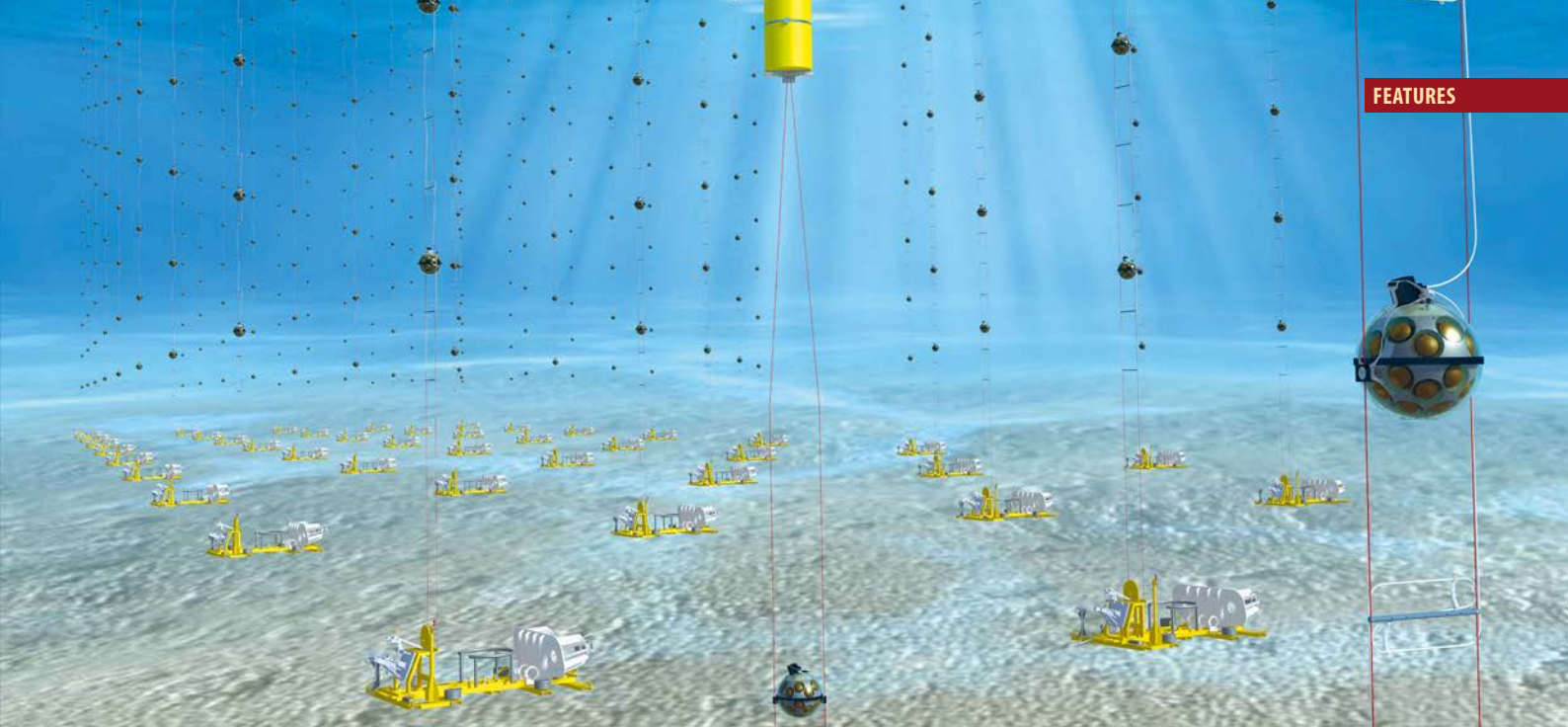
Many scientists trained in string theory, on the other hand, consider models where the black hole just disappears into nothing at the end of its evaporation, and try to find ways in which any information about matter sank in could be emitted mixed up with outgoing Hawking’s radiation. Who is right? One of the two? Both (this is possible)? Neither? We do not know. But given the huge amount of previous confusion that I have seen been clarified in the course of my life as a scientists, I trust that clarity will come also about this.

Contrary to some complains that we have heard, fundamental physics is not stagnant. To the opposite: it is a moment of vibrant development, especially in its gravitational sector, as testified by the string or recent Nobels in the field, and by the rapidity at which our understanding of these fantastic objects that fill the sky has evolved. ■

About the Author



Carlo Rovelli is theoretical physics known for his work in quantum gravity. He was born in Italy in 1956 and has worked in Italy, the Unites States and France. He directs the quantum gravity group of the Center for the Theoretical Physics of Luminy in France, holds a Distinguished Visiting Chair at the Perimeter Institute, and is affiliated with the Rotman Institute of Philosophy at the University of Western Ontario. He was awarded the Xanthopoulos Prize for his work on spacetime physics. He has written popularisation best sellers, translated in more than 40 languages and has been included in the 2019 list of the 100 most influential global thinkers by Foreign Policy magazine.



PROBING THE EARTH'S INTERIOR WITH NEUTRINOS

■ Véronique Van Elewyck^{1,2}, João Coelho³, Edouard Kaminski⁴ and Lukas Maderer¹
 DOI: <https://doi.org/10.1051/e3n/2021103>

■ ¹ Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France

■ ² Institut Universitaire de France, 75005 Paris, France

■ ³ Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

■ ⁴ Université de Paris, Institut de physique du globe de Paris, CNRS, F-75005 Paris, France

Neutrinos, the lightest entities of the Standard Model of particle physics, can traverse matter like no other known particle. The advent of a new generation of neutrino telescopes is turning these elusive messengers into a new probe to investigate the structure and composition of the deep Earth.

A virtual journey to the centre of the Earth

Geophysicists have been studying the Earth's interior since the early days of seismology more than a century ago. Seismic waves are a powerful probe that provide information on the Earth internal structures and identify large-scale variations in matter density and properties [1]. Combined with complementary measurements obtained from geodetic techniques, they led to a reference radial model of the Earth density (see Fig. 1).

But the real Earth is more complex, and seismic waves also reveal the presence of large-scale anomalies in the lower mantle, called super-plumes, whose nature, chemistry and origin are still uncertain. They can be remnants of deep primitive material or the product of the progressive recycling of subducted material - two hypotheses with very different consequences for the long-term dynamics of the planet.

Current models also do not univocally constrain the chemical composition of the deep Earth, because of a trade-off between the temperature and composition effect on geophysical observables. They must rely on indirect information provided by *e.g.* the study of meteorites or high-temperature/high-pressure laboratory experiments. All these constraints yield the current consensus of an Iron-Nickel alloy Core containing a few percent of light elements (Silicon, Oxygen, Sulphur, Carbon and/or Hydrogen). The exact nature of the light elements is however not precisely determined yet.

A renewed perspective on this question may come from a completely different branch of physics, dealing with the ghostliest elementary particles: neutrinos. Using these extremely penetrating messengers as a kind of X-ray, a new physical approach to Earth tomography is currently emerging, with the potential to bring original insights about our home planet.

▲ Artist's impression of the KM3NeT neutrino telescope. Credits: KM3NeT.

A new tool: the neutrino

In the Standard Model of particle physics, neutrinos are neutral and couple to matter only through the weak interaction, which explains their penetrating power. They exist in three “flavours”, each one associated to a companion charged particle: the electron, the muon or the tau. They are produced in a variety of terrestrial and extra-terrestrial sources, with energies ranging from the Mega electron-volt [MeV] up and above the Peta electron-volt [PeV].

Since the 80s, neutrino physicists have designed and run a wide range of experiments of ever-increasing dimensions aimed at compensating the small interaction probability of neutrinos with matter. Those patiently accumulated data samples have started unveiling the peculiar fundamental properties of neutrinos [3]. This endeavour recently culminated in the discovery of neutrino flavour oscillations, implying that neutrinos have mass – albeit so tiny that it has not been measured yet. This discovery, awarded the 2015 Nobel Prize in Physics [4], provides the first glimpses into physics beyond the Standard Model and might have far-reaching implications on our understanding of the laws of Nature.

A key contribution came from the study of the abundant and ubiquitous flux of neutrinos originating in the interaction of cosmic rays that continuously hit the Earth’s atmosphere and collide with air nuclei. Such collisions produce extended cascades of millions to billions of secondary particles, some of which decay into neutrinos. Most such neutrinos have energies in the range 100 MeV – 10 GeV; but their spectrum actually extends up to energies ten to hundred thousand times larger. The probability for a neutrino to interact with ordinary matter is so small that almost all neutrinos created in the atmosphere will simply traverse the Earth and emerge on the other side. A small fraction of them will nevertheless interact and leave a visible signal in one of the neutrino detectors located at the Earth’s surface.

Neutrino tomography: absorption and oscillation

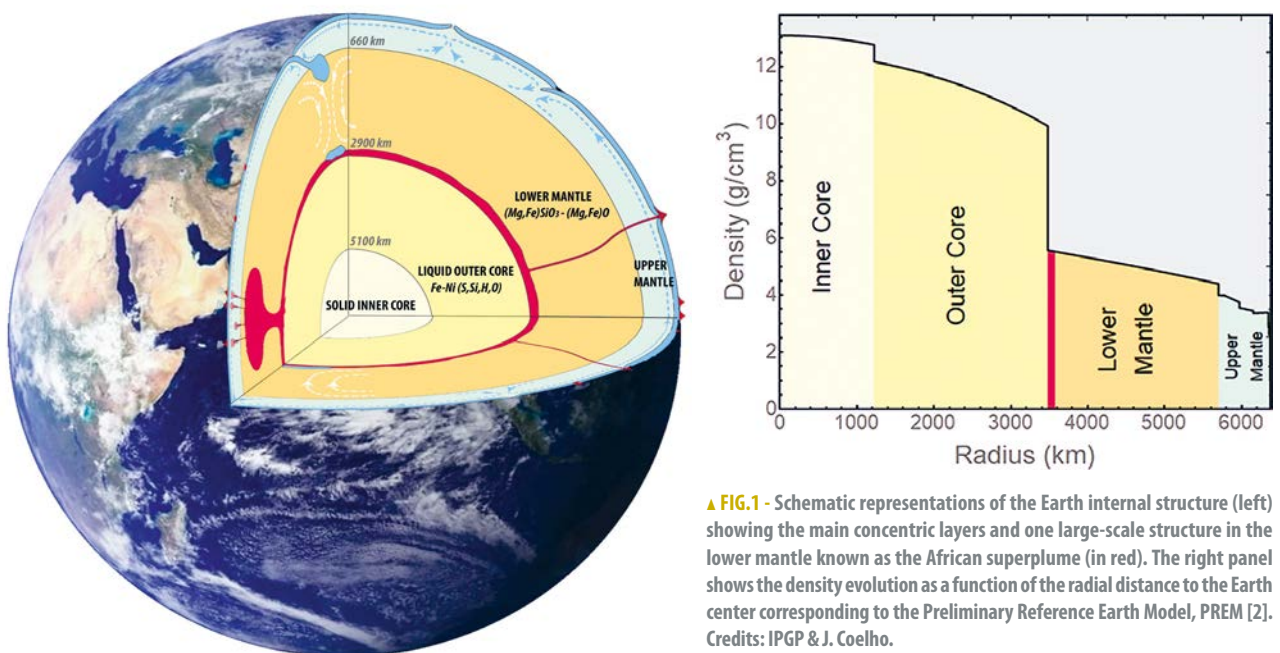
Now, how can these peculiar properties of the neutrino be used for retrieving information about the structure and composition of the Earth [5] ? Neutrino tomography can go along two different paths, depending on the mechanism involved – absorption or oscillation – and on the energy range under study.

At high (> 10 TeV) energies, the interaction probability of a neutrino with ordinary matter becomes large enough that absorption effects set in, leading to a progressive attenuation of the flux of through-going atmospheric neutrinos. The Earth becomes completely opaque to neutrinos with PeV-scale energy. The flux attenuation depends on the total amount of matter encountered along the neutrino path and can be inferred from its arrival direction at the detector. The angular distribution of neutrinos detected in different energy ranges will thus provide tomographic information on the matter density inside the Earth.

At lower energies (1 – 100 GeV), the presence of matter impacts the way neutrinos oscillate from one flavour to another along their path. Ordinary matter contains electrons but no muons nor taus, leading to a net effect on the electron flavour component of the neutrino flux. Depending on the electron density N_e , resonance effects may appear, which maximise the probability of oscillation. Typical electron densities inside the Earth will generate such resonances for neutrinos with energies of a few GeV. In this case, the angular and energy distributions of the observed neutrinos inform on the Earth electron content N_e , which is related to the matter density ρ_m as

$$N_e = (N_A/m_n) (Z/A) \rho_m$$

where N_A is the Avogadro number and m_n the nucleon mass. The Z/A parameter encodes the ratio of atomic-to-mass



▲ FIG.1 - Schematic representations of the Earth internal structure (left) showing the main concentric layers and one large-scale structure in the lower mantle known as the African superplume (in red). The right panel shows the density evolution as a function of the radial distance to the Earth center corresponding to the Preliminary Reference Earth Model, PREM [2]. Credits: IPGP & J. Coelho.

numbers, which depends on the chemical and isotopic composition of the medium. Assuming a known matter density profile ρ_m (such as the PREM shown in Fig. 1), one can then infer the value of Z/A in the distinct Earth layers, that will ultimately translate into compositional constraints. Such an approach can be relevant *e.g.* to constrain the nature and abundance of light elements in the outer core, in a complementary way to geophysical methods.

Imaging the Earth with neutrino telescopes

Both approaches to neutrino tomography require large samples of atmospheric neutrinos of different flavours, energies and arrival directions. Physicists therefore rely on Cherenkov telescopes, neutrino detectors that instrument huge volumes of water or ice with photosensors to detect the flash of light that accompanies a neutrino interaction. The IceCube detector [6], that continuously monitors about one cubic kilometer (equivalent to one Gigaton) of South Pole ice, has so far accumulated the largest sample of neutrinos in the TeV to PeV range, suitable for absorption tomography studies. Based on a one-year subset of IceCube data, it was possible to reconstruct a rough density profile of the Earth, and to infer its total mass and inertial momentum without relying on any geophysical input [7].

Another large-scale project is under construction on two abyssal sites in the Mediterranean Sea: the cubic-kilometer Neutrino Telescope KM3NeT [8], a distributed infrastructure which uses a novel photosensor design to exploit at best the excellent optical properties of seawater. The KM3NeT detectors consist of arrays of strings anchored to the seabed and supporting pressure-proof glass spheres equipped with multiple photosensors (see introductory illustration). The time and space distributions of the recorded light pulses are used to reconstruct the flavour, energy and direction of the incoming neutrinos. The spatial distribution of photosensors is optimised towards the scientific goal and specific neutrino energy range targeted by each detector. ORCA, off the coast of France, will monitor a few Megatons of seawater, focusing on atmospheric neutrinos in the 1 – 100 GeV range, with the aim of better understanding their fundamental properties (mass and oscillations). ARCA, close to Sicily, will instrument about 1 Gigaton of water and concentrate on high-energy (TeV-PeV) neutrino astronomy, with a sky coverage complementary to that of IceCube.

By combining the datasets from its two detectors ORCA and ARCA, KM3NeT could become the first neutrino telescope to simultaneously perform oscillation and absorption tomography of the Earth. Preliminary studies give promising perspectives for the determination of the electron density in the inner Earth with ORCA, although the final performance will also depend on the measurement of other parameters, such as the ordering of the neutrino masses (to be determined by ORCA itself and other neutrino experiments on a shorter timescale). Assuming normal mass ordering, after 10 years of operation ORCA will measure the Z/A parameter

to a precision of a few percent, both in the mantle and in the core [9]. Such information could help narrow down the allowed parameter space, and lead to new constraints on the primordial Earth composition, the type of convection (thermal vs thermo-chemical), and the long-term evolution of the planet. The stereoscopic combination of data from KM3NeT and IceCube also provides new perspectives to reconstruct full 3D density and composition profiles, allowing for a better insight into the mantle structure.

One thing is clear to physicists, however: exploiting the full potential of neutrino tomography will require yet another generation of detectors, combining huge instrumented volumes with unprecedented precision in the reconstruction and identification of neutrino events. The challenge of designing a detector fully optimised for Earth tomography might well take another decade; but that will certainly not frighten neutrino physicists who have made theirs the concept of *Festina lente*. ■

About the Authors



Véronique Van Elewyck is Assistant Professor at Université de Paris and member of Institut Universitaire de France. She leads the ANTARES/KM3NeT team at the APC Laboratory.



João Coelho, Associate Scientist at the IJC Laboratory, is a neutrino oscillation expert with a focus on atmospheric neutrinos.



Edouard Kaminski is an IPGP Professor of geophysics, specialized in geological fluid dynamics and currently Vice-President for Research at Université de Paris.

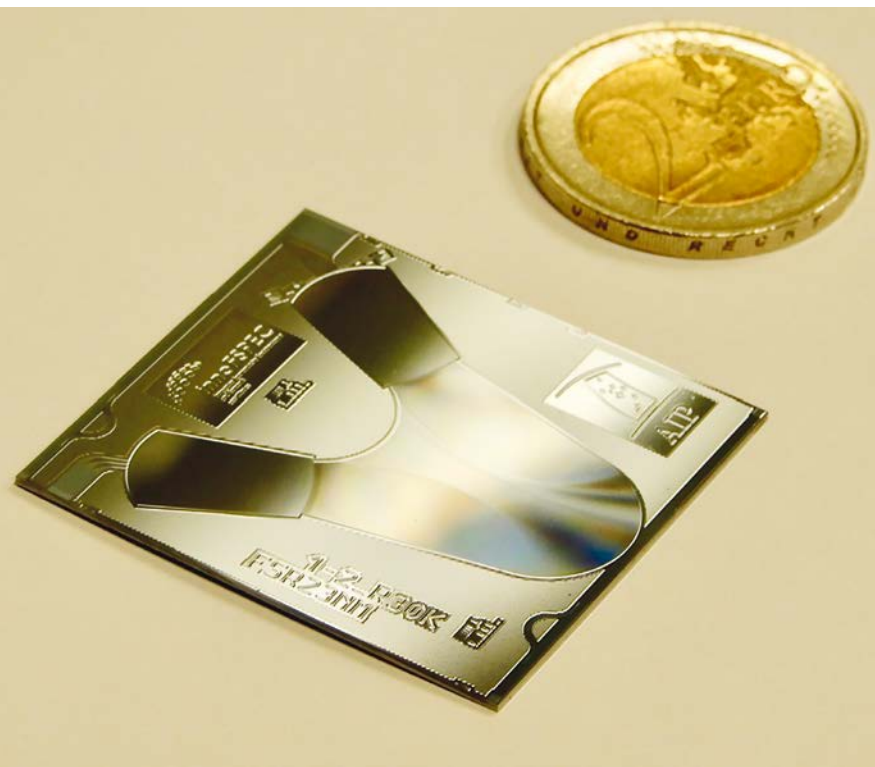


Lukas Maderer is a PhD grantee of the CNRS Interdisciplinary Program 80PRIME. The authors acknowledge the support of LabEx UnivEarthS (ANR-10-LABX-0023 and ANR-18-IDEX-0001) for their research.

References

- [1] C. M. R. Fowler, *The Solid Earth: An Introduction to Global Geophysics*, Cambridge University Press (2004)
- [2] A. Dziewonski and D. Anderson, *1981 Physics of the Earth and Planetary Interiors* **25**, 29 (356)
- [3] see <https://neutrino-history.in2p3.fr/> for a comprehensive history of neutrino physics
- [4] T. Kajita and A. MacDonald – Nobel Lectures 2015, NobelPrize.org
- [5] For a conceptual review on neutrino tomography, see W. Winter, *Earth Moon Planets* **99**, 285 (2006)
- [6] <https://icecube.wisc.edu/>
- [7] A. Donini, S. Palomares-Ruiz and J. Salvado, *Nature Phys.* **151**, 37 (2019)
- [8] <http://www.km3net.org>
- [9] The KM3NeT Collaboration (S. Bourret and V. Van Elewyck), *EPJ Web Conf.* **207**, 04008 (2019)

ASTROPHOTONICS: PROCESSING STARLIGHT



- Aline N. Dinkelaker*, Aashia Rahman*
- innoFSPEC, Leibniz Institute for Astrophysics Potsdam (AIP), Germany
- *both authors contributed equally
- DOI: <https://doi.org/10.1051/ePN/2021104>

The field of astrophotonics has been fostering photonic innovations critical and unique to astronomical applications for several years. As we are about to embark on the new era of extremely large telescopes, astrophotonics is poised to become an integral part of the next generation astronomical instruments.

◀ Astrophotonic chip developed at innoFSPEC (Image Credit: A. Stoll)

Astronomical observations enable a continuously increasing understanding of our universe, its evolution and our place within. To unravel its secrets, cutting-edge optical systems and instruments are required to guide, detect and analyze light. High resolution images of stars around the center of the Milky Way have confirmed the existence of a supermassive black hole in the center of our galaxy. This phenomenal discovery was honored by the 2020 Nobel prize in Physics. This groundbreaking work was contributed by GRAVITY [1], an instrument at ESO's Very Large Telescope (VLT). GRAVITY utilises an integrated photonic chip that combines light from four telescopes at the VLT. For future instruments, photonics in astronomy will play an increasingly important role along the beam path.

The next generation of large telescopes

Ground-based astronomy is just about to enter a very exciting era: the world's three largest telescopes (Extremely Large Telescope (ELT): 39 m, Thirty Meter Telescope (TMT): 30 m and Giant Magellan Telescope (GMT): seven 8.4 m diameter primary segments) are planned

to be commissioned in the coming decade. To keep up with these capabilities, astronomical instruments have to undergo a drastic transformation. Today's largest telescopes predominantly have instruments that consist of conventional optics. Upscaling these instruments and optics systems in line with future large telescopes, however, will be structurally and economically challenging and unsustainable. **The extraordinary demands on astronomical instruments can be approached with integrated photonics**, owing to their small footprint, flexibility to manipulate light, and ease of mass-fabrication. An additional technological enabler has been the demonstration of the successful coupling of light from Subaru extreme Adaptive Optics (AO) system to a single mode fiber [2]. As the large telescopes are pushing the limits of AO to the near-diffraction-limit, the AO-corrected light can be captured by these photonic devices efficiently using fibers.

Astrophotonics is an interface of photonics and astronomy. This rapidly growing field offers a broad range of optical solutions encompassing sky background filtering, high resolution imaging and spectroscopy. Over the last few decades, there have been promising developments in laboratory tests as well as several on-sky demonstrations

of a wide spectrum of fiber and on-chip photonic devices, such as photonic lanterns, complex Bragg gratings, pupil remappers, beam combiners / interferometers, photonic spectrographs, and frequency combs [3]. A possible device chain based on astrophotonics is shown in Figure 1.

Astrophotonics research at innoFSPEC

The astrophotonics group at the research and innovation center, innoFSPEC Potsdam, Germany, is dedicated to the research and development of photonics solutions for ground-based astronomical applications in the near-infrared (NIR). It is one of the few institutes worldwide specifically focusing on this topic.

Photonic Lanterns

AO has become an integral part of all modern ground-based telescopes to correct atmospheric effects in the science light from celestial objects, thus preventing image blurring. In order to correct the wavefront distortion, a conventional AO system consists of a wavefront sensor in an active control loop with a deformable mirror. The AO-corrected light is then either sent to a bulk optics system or fed to a multi-mode fiber for further processing. An interesting device that has emerged in astrophotonics is the photonic lantern (PL). This unique fiber-based photonic component exploits the modal properties of the fiber, allowing a low-loss transition from multi-mode to several single-mode fibers -and vice versa. At innoFSPEC, developments of 19 ports of PLs have already been accomplished. As it remains important to find a suitable combination of an AO system and a PL with a realistic number of outputs, innoFSPEC focuses on a low-order AO system in combination with PLs for efficient coupling of light into astrophotonic devices [4].

Complex Bragg Gratings

Ground-based NIR astronomy is adversely affected by the presence of more than 100 narrow hydroxyl (OH) emission lines originating in the Earth's atmosphere. Being several orders higher in intensity than the science light from a distant object, these OH emission lines contribute significantly to the stray light inside the spectrograph, making the measurement of the signals from faint galaxies or stars extremely challenging.

Due to the capability of filtering specific wavelengths with outstanding precision, complex fiber Bragg gratings (FBGs) were first introduced in astronomical applications by Bland-Hawthorn *et al.* [5] as a promising solution over existing technologies. For over three decades, a large number of designs of grating structures in fiber has been explored for many sensing and communication applications. However, the design of a complex FBG consisting of 100 narrow notches suitable for astronomical applications is unique. The fabrication process of these filters is critical, as it demands excellent repeatability in

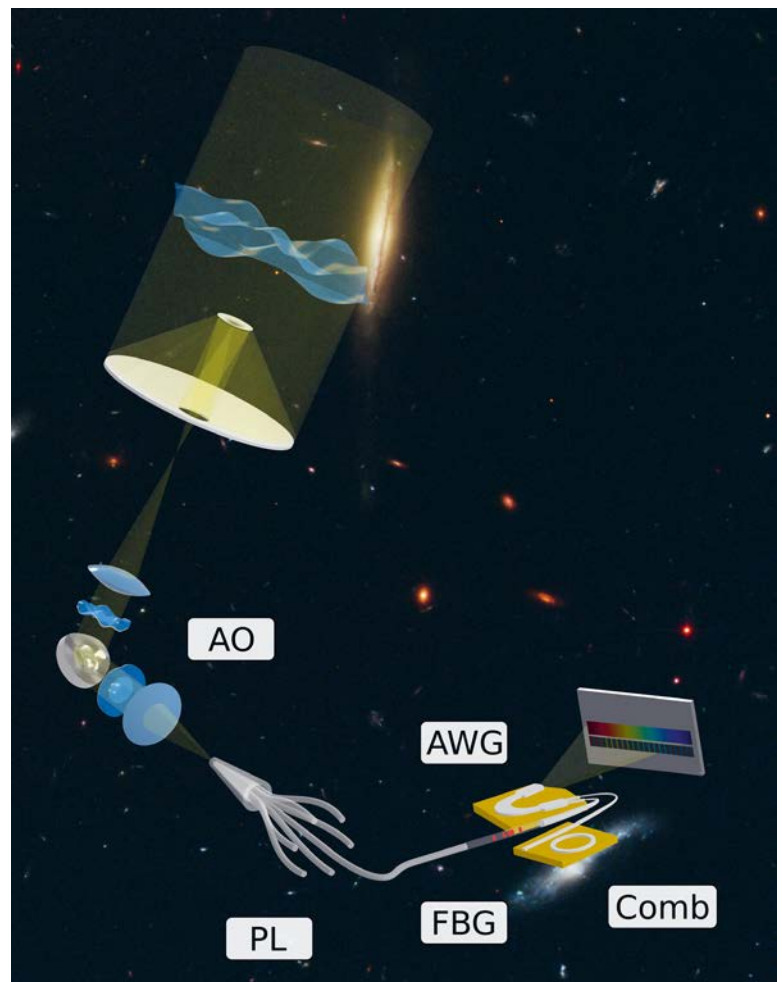
order to get integrated with PLs. In a joint project between innoFSPEC and their collaborators in Australia, the first on-sky demonstration of OH suppression in PRAXIS [6] -a high efficiency NIR spectrograph- has shown promising results. innoFSPEC is also exploring new ways of fabricating these filters using novel complex phase masks.

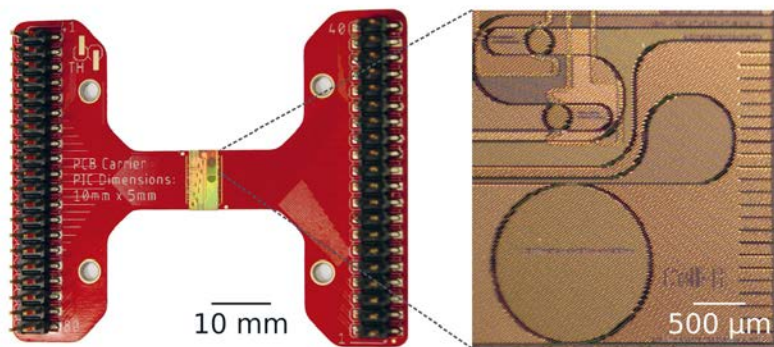
Spectrographs & Frequency Combs

A spectrograph is the heart of an astronomical observation. It allows to study the spectral composition of light or to measure a star's radial velocity, one of the key methods for Exoplanet detection. innoFSPEC is building a miniaturised spectrograph on-a-chip for astronomy based on an arrayed waveguide grating (AWG), a technology originating in the telecommunication industry. Scientists at innoFSPEC have optimised the design specifically for astronomy [7], by which they achieved extraordinarily high resolution (up to 30,000) and throughput (insertion loss of 2 dB). These fiber-fed devices could potentially replace free-space prism or grating optics. innoFSPEC is targeting an on-sky demonstration in 2021.

Frequency combs in astronomy can be used as absolute calibration of high resolution spectrographs. As a calibration source, a frequency comb must have a line spacing and wavelength coverage that matches the

▼ FIG. 1: Schematic showing an astrophotonics device chain for ground-based telescopes. (Image Credit: M. Diab (devices), using a background photo, credit: NASA/ESA, The Hubble Heritage Team and A. Riess (STScI))





▲ FIG. 2: A ring-resonator (developed at innoFSPEC) for frequency comb generation. (Image Credit: A.N. Dinkelaker)

requirements of the spectrograph, which is not easy to achieve. There are several technical realizations of frequency combs, and those based on microscopic ring resonators have suitable properties for astronomical calibration [8]. Such a chip-based device – an example is shown in Figure 2 – is currently tested in the lab for an upcoming on-sky test at the STELLA robotic telescope. An AWG in combination with a frequency comb could become key element for future compact spectrographs.

Beam Combiners for Interferometry

Using interferometric methods, high angular resolution astronomy can resolve incredibly small details, such as solar-type stars, interacting binaries, or the inner part of planet forming discs. Here, light from several independent telescopes *e.g.*, as part of telescope arrays, such as CHARA or VLTI, is combined interferometrically. Spatial information about the celestial object can be extracted from the interference fringes, thereby achieving the resolution of one large “virtual” telescope with an aperture size of tens to hundreds of meters. This technique has been very successful, from early measurements of star diameters to the position measurements of stars around a Black Hole [1]. The footprint of beam combining optics can be drastically reduced by replacing bulk optics with photonics. In addition to planar devices, 3D photonics are enabled by advances in the technique of laser inscription on glass substrates [9].

Designs from innoFSPEC have already been manufactured, characterised, and tested in collaboration with groups at Politecnico Milano and University of Cologne [10]. The same devices can be used to perform pupil remapping – a technique in which light at different points of the telescope is picked off. By interferometrically overlapping, atmospheric effects can be reduced. First on-sky tests of such a laser written pupil remapper and beam combiner have been performed in 2019.

Outlook

As astrophotonics continues to foster photonic innovations critical and unique to photon-starved astronomical applications, it is exciting to see how some of these devices have already started appealing to other fields of science and technology. In future, astrophotonics might find their

place in quantum technology, advanced communication systems, or space-based instruments.

Through laboratory characterization, iterative component developments and on-sky demonstrations, astrophotonics will continue to gain in performance and maturity. The continuous progress in manufacturing methods enables improved functionality and more innovations in the coming years. As the success of GRAVITY marks the importance for photonics in astronomy, we expect to see astrophotonics getting integrated in the design of future instruments, especially for the next generation of large telescopes, paving the way for new and exciting discoveries of our universe. ■

About the Authors



Aline N. Dinkelaker is a Senior Scientist in innoFSPEC at the Leibniz Institute for Astrophysics Potsdam (AIP), Germany. She is interested in optical systems, laser and space technology, with a research focus on astrophotonics, such as beam combiners for stellar interferometry.



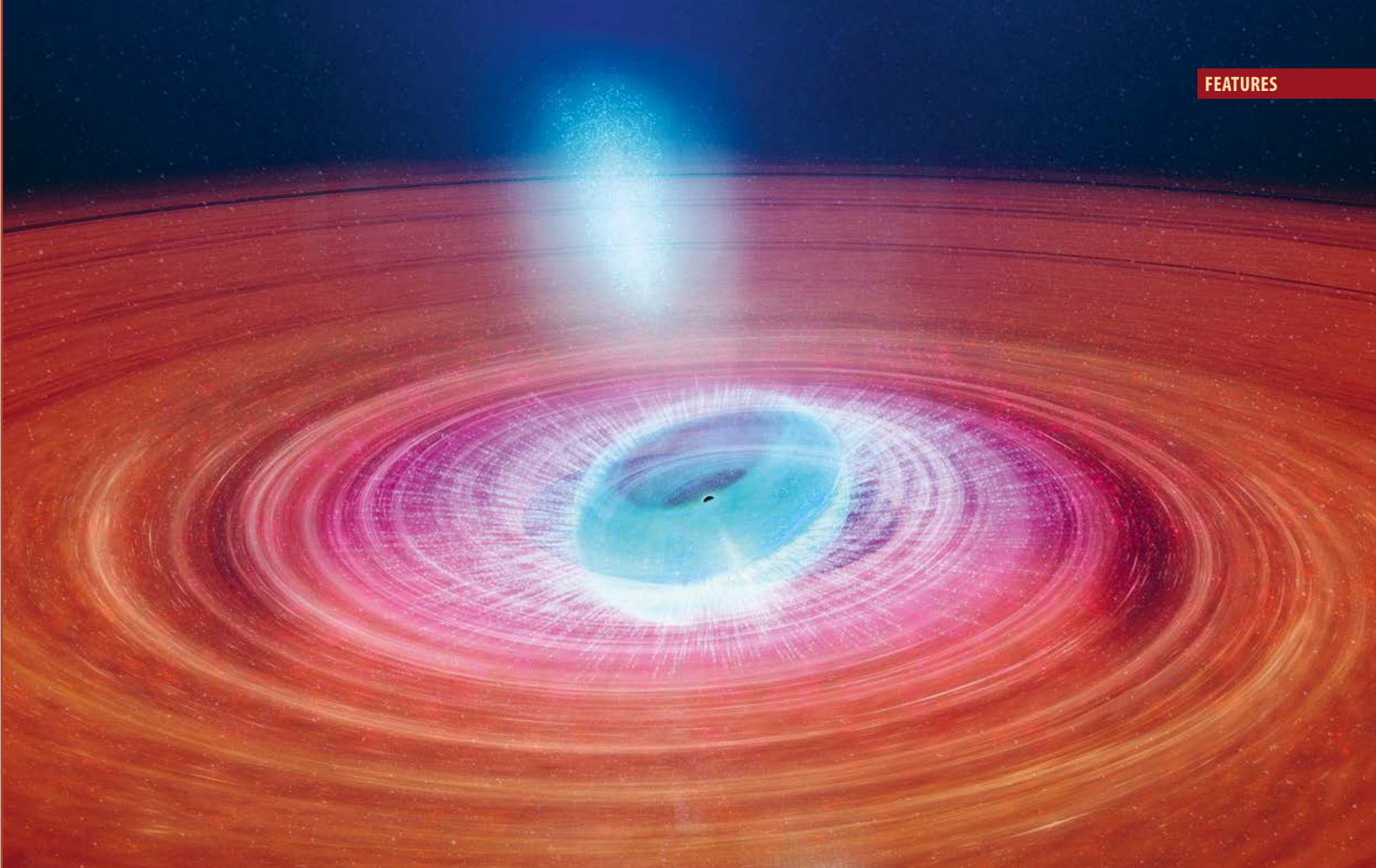
Aashia Rahman is a Senior Scientist in innoFSPEC at the Leibniz Institute for Astrophysics Potsdam (AIP), Germany. Her research experience includes photosensitivity in optical fibers, fiber Bragg gratings, ultra-fast laser inscription, and filters for astronomy.

Acknowledgements

This research has been funded by the BMBF grants no. 03Z22AN11, 03Z22A511, 03Z22AB1A, 03Z22AI1 and the Deutsche Forschungsgemeinschaft (DFG) project “Novel Astronomical Instrumentation through photonic Reformatting” (NAIR) (grant no. 326946494). The work presented here is carried out by the scientists at innoFSPEC Potsdam at the Leibniz Institute for Astrophysics Potsdam (AIP) and project partners. For more information, see <https://innofspec.de/en/>.

References

- [1] GRAVITY Collaboration, *Astronomy & Astrophysics* **615**, L15 (2018).
- [2] N. Jovanovic *et al.*, *Astronomy & Astrophysics* **604**, 122 (2017).
- [3] P. Gatkine *et al.*, *arXiv:1907.05904* (2019).
- [4] M. Diab *et al.*, *Mon. Not. R. Astron. Soc.*, staa3752 (2020).
- [5] J. Bland-Hawthorn, M. Englund, and G. Edvell, *Opt. Express* **12**, 5902 (2004).
- [6] S.C. Ellis *et al.*, *Mon. Not. R. Astron. Soc.* **492**, 2796 (2020).
- [7] A. Stoll, K. Madhav, and M. Roth, *Opt. Express* **28**, 39354 (2020).
- [8] E. Obrzud *et al.*, *Nat. Photon.* **13**, 31 (2019).
- [9] R.R. Thomson *et al.*, *Opt. Express* **19**, 5698 (2011).
- [10] A. Nayak *et al.*, *Opt. Express* **28**, 34346 (2020).



A VERY SINGULAR THEOREM

An elusive idea that emerged on a pedestrian crossing revealed some of the mysteries inside black holes. Announced in barely a couple of pages, it has been worth the 2020 Nobel Prize in Physics.

■ José M. M. Senovilla – DOI: <https://doi.org/10.1051/e pn/2021105>

■ Department of Physics at the University of the Basque Country (UPV/EHU)

Black holes (BHs) are the most prudish objects in the Universe. Born in tremendous collapses of dying stars, eventually they close themselves off from the exterior, disconnecting from the outside world. External inquisitive observers are not given access, by any method, to their intimacies. BHs are sealed zones delimited by an immaterial outer layer that cages everything there. Visitors are admitted, but not farewells: what gets into a BH is doomed to stay with these mysterious cosmic creatures.

The gravitational field of the mother star persists, though. BHs are so watchful about their secrets that, strictly speaking, what they allow us to observe is the

final mass and spin of the progenitor just before it goes into isolation; if we are lucky, we can also perceive the stars and accretion disks that may orbit around them.

In 1964 Roger Penrose had a lucid yet fleeting thought. The idea emerged in the silence of a pedestrian crossing but, when he reached the other side, faded away. A diffuse feeling of elation remained that led him to review each moment of the day until, fortunately, the idea resurfaced [1]. The concept of *trapped surface* was born. He quickly scribbled the proof of a theorem that, in just two pages [2], uncovered internal properties of BHs. Fifty-five years later, the theorem has been worth the Nobel Prize in physics.

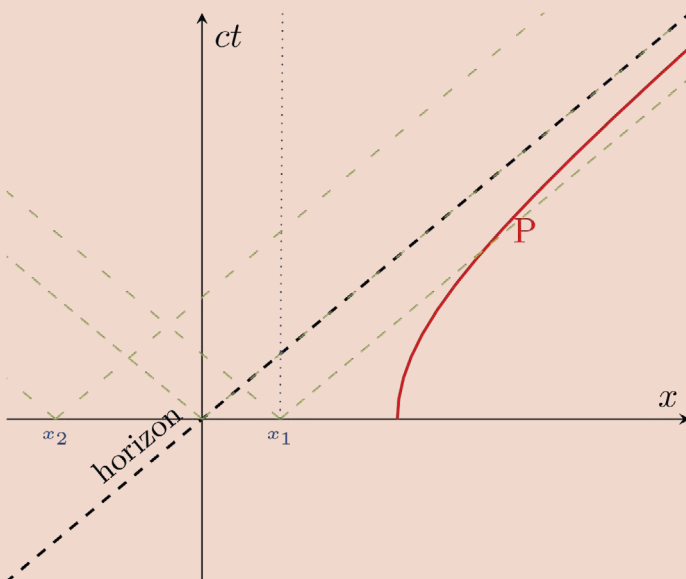
▲ Artist's impression of a black hole accretion disc.
© ICRAR - ESA



They concluded that the neutron degeneracy pressure (due to Pauli's exclusion principle) is unable to maintain equilibrium for large masses. Gravity ends up prevailing if there is enough mass. ””

HORIZONS

The (x, ct) plane, with c the speed of light. Nothing can travel faster than light, so no particle trajectory moving in the x -direction can exceed the 45° -slope with the vertical anywhere. This restriction defines, at each point, a future 'light cone', represented by green dashed lines for the points $(x_1, 0)$ and $(x_2, 0)$. A particle P starts from rest at $t = 0$ to move with constant acceleration, so its speed is always increasing. Thus, P describes a hyperbola — in red — with asymptote on the black, dashed, line. The P -trajectory crosses the $(x_1, 0)$ light-cone, but not that of $(x_2, 0)$. The border between these two situations is given by the asymptote line that acts as a **horizon** for P : no event above the horizon is ever observable by P , not even if P awaits infinite time. In fact, if P watches the trajectory of x_1 at rest (blue dotted line), from P 's point of view x_1 tends to be "frozen" without ever reaching the horizon. The region above the horizon and the zone observable by P are fully disconnected. A similar situation happens in black holes, which conceal themselves from the exterior by a cloaking horizon.



Historical context

In 1915 Einstein unified space, time, matter and geometry in the theory of general relativity (GR): the curved geometry of spacetime is a manifestation of the gravitational field created by matter and energy. Almost immediately K. Schwarzschild found the first exact solution of the GR field equations. It describes the gravitational field outside any spherically symmetric body and depends only on its mass M . The curvature was infinite at $r = 0$, where r is a variable such that the area of the spheres is $4\pi r^2$. This *singularity* was somehow expected, as the Newtonian central field behaves as M/r^2 . Yet, there was *another* problem at $r = r_g = 2GM/c^2$ — called gravitational radius — where G is the gravitational constant and c the speed of light in vacuum. Notice that r_g is approximately 9 mm for the mass of the Earth, and 10^{-25} m for a person weighing 75 kg. Schwarzschild concluded that such minuscule values of r would be unattainable in realistic situations. However, in 1933 G. Lemaître detected a discrepancy with some *dynamical* solutions found by A. Fridman, in which the area of spheres can be as *small as desired*. He showed that the supposed r_g -limit is fictitious and arises from having imposed a static solution: it can be eliminated by choosing coordinates that extend the spacetime to values of $r < r_g$, and $r = r_g$ simply describes a regular horizon. (Box.)

Still, are the *dynamical* regions with $r < r_g$ physically accessible in reality?

This brings me to the subject of gravitational collapse. In 1939 Oppenheimer and Volkoff analyzed the stability of *neutron stars* — predicted a little earlier but only observed in 1967 by J. Bell. They concluded that the neutron degeneracy pressure (due to Pauli's exclusion principle) is unable to maintain equilibrium for large masses. Gravity ends up prevailing if there is enough mass.

The same year Oppenheimer and Snyder (O-S) studied the collapse of a spherical dust ball shrinking by its own gravitational attraction. They found that (i) the contraction is unstoppable proceeding to values of $r < r_g$ and eventually to the $r = 0$ singularity, (ii) the star disconnects from any communication with the exterior so that (iii) surprisingly, outside observers never get to see the star crossing its gravitational radius, which thus becomes a horizon. The path to the black holes was thus cleared.

The decade of marvels (1955-64)

In 1955 A.K. Raychaudhuri published a fundamental formula that later became the basis of all singularity theorems. The *Raychaudhuri equation* describes the evolution of a pencil of world-lines in a gravitational field, allowing to prove that "caustics" generically develop: places where the curves intersect each other, analogous to the focus of a lens. This phenomenon is called the *gravitational focusing effect*. If the world-lines describe the motion of matter, a catastrophic singularity where the mass density becomes infinite is reached.

In 1962 M. Schmidt discovered that the radio-source 3C 273 is extra-galactic. This seemed “unbelievable” because 3C 273 looks pointlike, its redshift implied a distance of 2.5 billion light-years yet it emitted a gigantic amount of energy outshining entire galaxies! Subsequent observations of these “quasi-stellar radio-sources” (*quasars*) accumulated. At that time, no process capable of producing such powers was known — not even nuclear reactions. Agitation increased in 1963 with the discovery by R. Kerr of the spacetime that (now) we know describes the gravitational field of a rotating BH. It depends on the mass M and spin J of the BH. It was quickly understood that an accretion disk around a rotating BH could convert matter into radiation with up to 42% efficiency — truly amazing! In December of that year the “Texas Symposium on Relativistic Astrophysics” was devoted to quasars and GR [3].

J.A. Wheeler wanted to discern if singularities were actually an artifact of excessive idealizations, as in the O-S model that ignores the effects of pressure and rotation. He discussed it with Penrose. E.M. Lifshitz and I.M. Khalatnikov tackled the problem and concluded (erroneously) that singularities were just “problems of the coordinates”. In December 1964 A. G. Doroshkevich, Ya. B. Zel’dovich and I.D. Novikov submitted a paper where they argued that irregularities of non-spherical stellar collapse were either eventually suppressed by physical processes or negligible. The O-S picture looked like a reliable description of stellar collapse.

To close the decade Penrose entered the scene. He was not convinced by the Lifshitz-Khalatnikov conclusions. When he was crossing the street inspiration enlightened him; [2] was also submitted in December.

Penrose’s theorem and its legacy

Penrose proved that non-spherical irregularities were not capable of preventing the formation of singularities once a certain point of no return was reached. His theorem contained two revolutionary ideas, one of them brilliant, the other innovative.

The innovation was a clever way of avoiding the difficulties for a rigorous definition of singularities, because space-time itself breaks down at them. He decided to diagnose their existence if some hypothetical light rays (or other particle trajectories) come to a sudden end. If singularities were absent these paths would continue indefinitely. Their abrupt end, however, leaves the space-time *incomplete*. An unequivocal indication of the existence of a problem.

To characterise the “point of no return” in stellar collapse Penrose introduced the notion of trapped spheres, his genius idea from the crosswalk. As gravity is geometry, in dynamical situations geometrical quantities (such as area or volume) change with

LASERS FOR QUANTUM TECHNOLOGIES

Taking advantage of collective quantum effects has enabled the so-called first quantum revolution. Today, amid the second quantum revolution new sensing schemes offer higher sensitivities and better resolution thanks to the possibility to detect and control individual quantum states in microscopic systems like atoms, quantum dots, or color centers.



Read how the high performance lasers from HÜBNER Photonics are helping researchers in their quantum quest.



Scan the code to visit HÜBNER Photonics Quantum page (<https://hubner-photonics.com/applications/lasers-for-quantum-technologies/>)

About the company

HUBNER Photonics offer the full range of high performance Cobolt lasers, the CW tunable laser C-wave along, a full selection of C-FLEX laser combiners serving major instrument manufacturers and leading research labs for cutting-edge applications in the areas of fluorescence microscopy, flow cytometry, Raman spectroscopy, metrology, holography, nanophotonic and quantum research.

HÜBNER Photonics



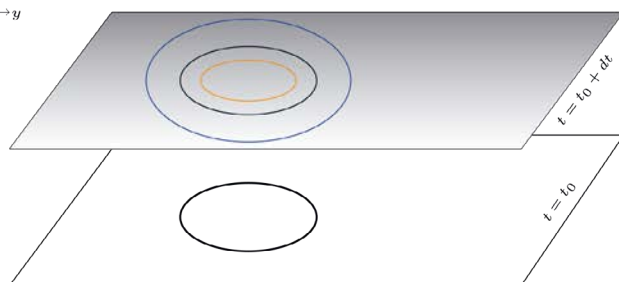


In short, they provide supporting evidence that GR is an incomplete theory and must be (possibly quantum) corrected in extreme situations. Wonder is that the theory shows its own limitations! 🔥

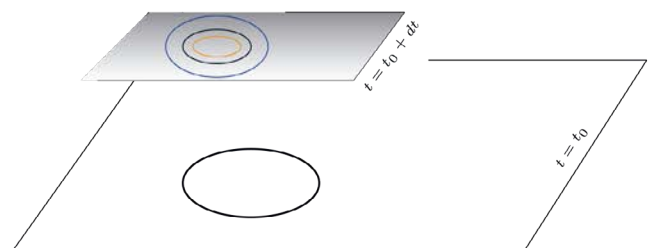
time. In extreme cases, the area of some spheroids may decrease with time *no matter how they evolve to the future* (see Fig.1). In this sense, they are *trapped*. Penrose proved that, when they form, singularities usually develop. Trapped surfaces are *stable against perturbations* and they arise in the O-S collapse, hence they must also form in asymmetrical but basically spheroidal collapses regardless of the particular details of the star. In conclusion, *singularities are not mere artifacts of coordinates or idealizations*. It is also known [4] that no trapped sphere sticks out the BH horizon. Therefore Penrose's theorem reveals (some of) the secrets inside BHs. There (i) trapped spheres reside ergo (ii) space-time becomes incomplete. This is the GR prediction.

This result shook the relativistic community. Its impact was deep and stimulating. A plethora of “singularity theorems” [4,5] with diverse application, particularly to cosmology, were rapidly developed. The list of after-effects incited by [2] is rather extensive. [2] was a synthesis containing many of the concepts conceived by Penrose in the 1960's which ultimately resulted in the modern, post-Einsteinian, era of GR [5,6]. In particular, he promoted the classical theory of BHs and devised a procedure to extract energy from them [7]. A refinement of this method, the Blandford – Znajek process, is the accepted explanation for the mechanisms powering quasars. As a conjecture (not proven yet), Penrose [7] proposed the existence of a “cosmic censor” in charge of surrounding all BH singularities with its cloak of concealment, its horizon, so that external observers are protected from any singularity-provoked hazards.

▼ **FIG. 1:** The concept of a *trapped sphere*. One dimension is suppressed. Time t goes up. A sphere S at $t = t_0$ is represented by the circle, the area of S by its length. An infinitesimal dt later flashes of light from S reach two new spheroids: the circles in red and blue. In a stationary situation (left) the area of the red (blue) sphere is smaller (greater) than the area of S . If the world is contracting (right), the blue circle may also have an area smaller than that of S at t_0 . Nothing can travel faster than light, ergo such an S is said to be future trapped.



Stationary situation



Spacetime in contraction

Concluding remarks

Gravitational configurations (planetary systems, stars, galaxies, clusters, ...) are free from singularities and effectively described by GR and its (post)-Newtonian limits. The only possible exceptions are the Universe and the interior of BHs, due to the singularity theorems. In short, they provide supporting evidence that GR is an incomplete theory and must be (possibly quantum) corrected in extreme situations. Wonder is that the theory shows its own limitations! .

The 2020 Nobel Prize in Physics is well deserved. Penrose's theorem has sheer beauty and important physical consequences. It spawned many fertile lines of research and uncovered intimacies of BHs that make them even more enigmatic. For more than twenty-five years stars have been observed at the centre of our galaxy orbiting something invisible, extremely compact and containing more than 4 million solar masses [6]. This hidden monster, most probably a BH, is called Sagittarius A*. For this discovery Andrea Ghez and Reinhard Genzel have received the other half of the Nobel prize.

A splendid, spectacular, grand finale for the scientific treasure initiated by the 1965 mathematical theorem. ■

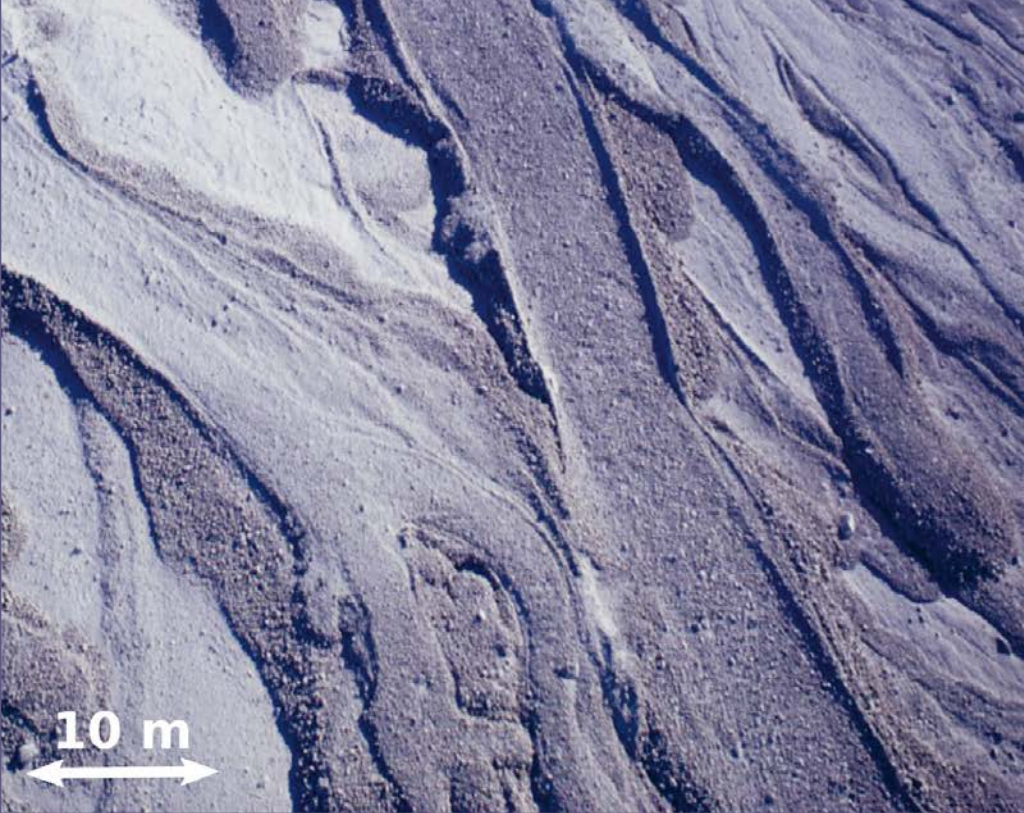
About the Author



Jose Senovilla is a Professor of theoretical physics in the Department of Physics at the University of the Basque Country (UPV/EHU) where he leads a research group on Gravitation and Cosmology.

References

- [1] R. Penrose, *The Emperor's new mind* (Oxford Univ. Press, Oxford, 1989)
- [2] R. Penrose, *Phys. Rev. Lett.* **14**, 57 (1965)
- [3] E. L. Schucking, *Physics Today* **42** **8**, 46 (1989)
- [4] S. W. Hawking and G. F. R. Ellis, *The large scale structure of space-time*, (Cambridge Univ. Press, Cambridge, 1973)
- [5] J. M. M. Senovilla and D. Garfinkle, *Class. Quantum Grav.* **32**, 124008 (2015)
- [6] Scientific Background on the Nobel Prize in Physics 2020: <https://www.nobelprize.org/uploads/2020/10/advanced-physicsprize2020.pdf>
- [7] R. Penrose, *Nuovo Cimento* **1**, 252 (1969).



MODELLING EROSION AND DEPOSITION IN GEOPHYSICAL GRANULAR MASS FLOWS

■ Sylvain Viroulet¹, Chris Johnson² and Nico Gray² – DOI: <https://doi.org/10.1051/epn/2021106>

■ ¹ Institut de Mécanique des Fluides de Toulouse, CNRS-Toulouse INP-UPS Université de Toulouse, Allée Camille Soula, 31400 Toulouse, France

■ ² Department of Mathematics and Manchester Centre for Nonlinear Dynamics, The University of Manchester, Manchester, UK

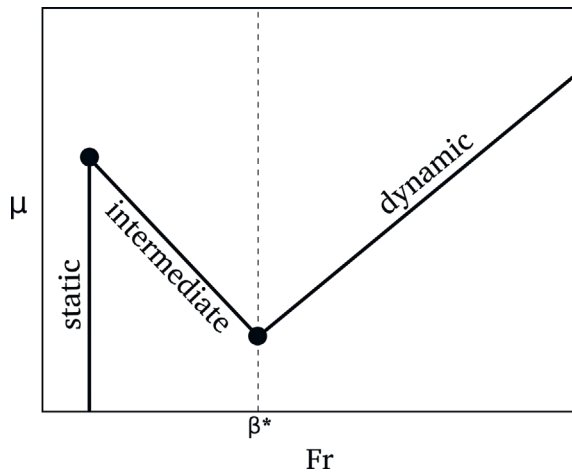
During hazardous geophysical mass flows, such as rock or snow avalanches, debris flows and volcanic pyroclastic flows, a continuous exchange of material can occur between the slide and the bed. The net balance between erosion and deposition of particles can drastically influence the behaviour of these flows. Recent advances in describing the non-monotonic effective basal friction and the internal granular rheology in depth averaged theories have enabled small scale laboratory experiments (see fig. 1) to be quantitatively reproduced and can also be implemented in large scale models to improve hazard mitigation.

Granular material is everywhere in our everyday life, from foodstuffs, industrial bulk materials and pharmaceuticals to the rings of Saturn and the surfaces of other planetary bodies. On Earth, geophysical mass flows are spectacular natural phenomena that pose a significant hazard to communities living in mountainous regions and on the flanks of volcanoes. They are composed of numerous grains of rock or ice of differing sizes and shapes, and

which may be mixed with interstitial water or hot air. As these complex mixtures flow down a mountainside they behave in a liquid-like way. While the relationship between stress and strain (the rheology) in a Newtonian liquid such as water is well understood, much about this relationship is still unknown for granular materials, making modelling of geophysical mass flows a challenging task. Moreover, when an avalanche flows over an erodible substrate, a continuous exchange of granular material

▲ FIG. 1: Deposits of the July 22nd 1980 eruption of Mount St Helens, USA (left) (from Kokelaar *et al.* 2014, Photo courtesy of Dan Miller and USGS). Erosion-deposition wave in the laboratory (right) (from Edwards *et al.*, 2017)

► FIG. 2: Evolution of the friction μ as a function of the Froude number Fr for a constant flow thickness. The vertical dashed line represents the transition between dynamic and intermediate regimes which occurs at $Fr = \beta^*$ (Edwards *et al.* 2019).



occurs between the avalanche and the bed as grains are eroded and deposited. When the avalanche erodes grains from the bed, its mass and run-out distance can be increased considerably, increasing the hazard posed.

In small scale experiments, when a granular material flowing steadily down a rough inclined plane is brought to rest by stopping the supply, it leaves a constant thickness static deposit on the plane. The deposited layer must, however, be inclined to a steeper angle before it begins to flow again. This exemplifies a key property of granular materials, namely hysteresis, where a layer of grains of a given thickness can exist in either a static or flowing equilibrium state. The origin of hysteresis is still not yet

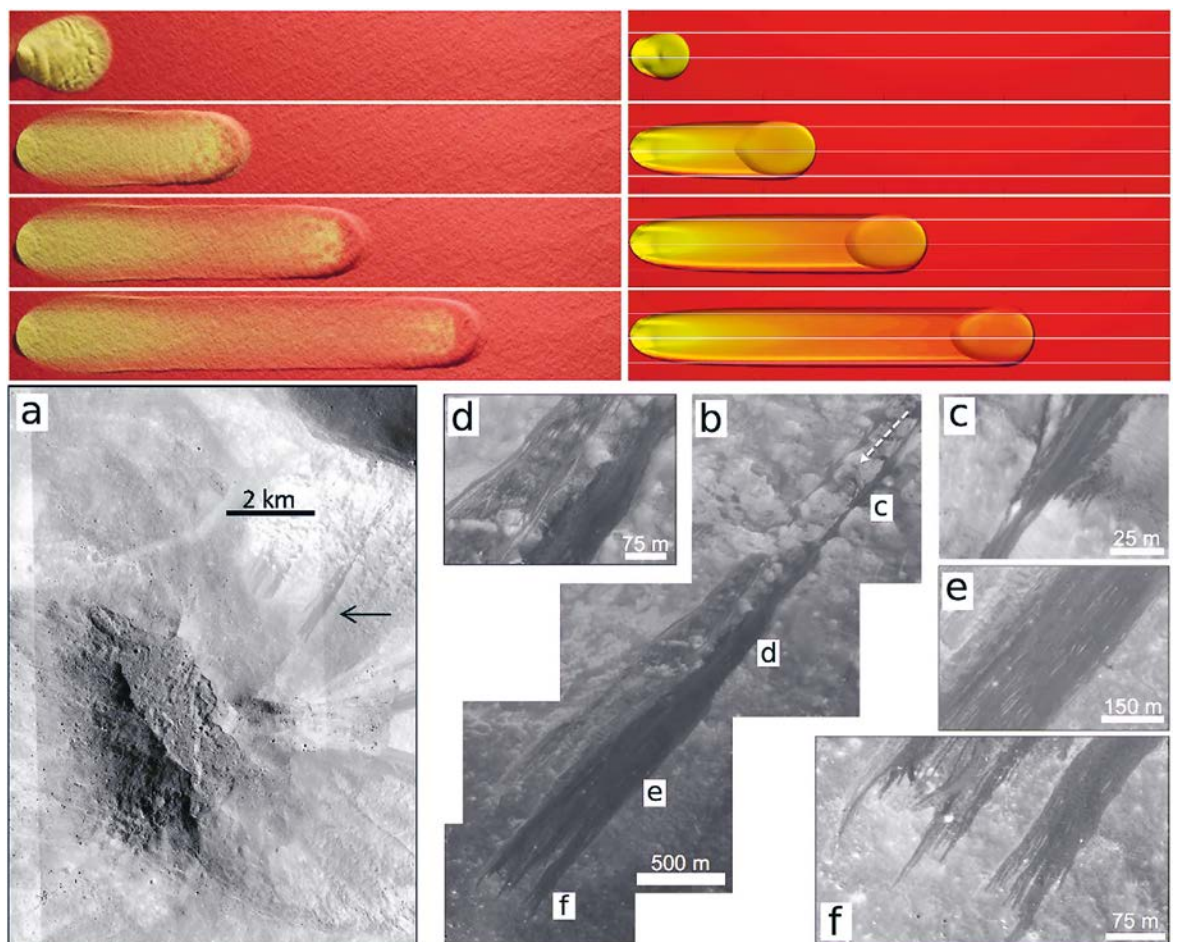
fully understood (Perrin *et al.* 2019), but it plays a key role in the transition between static and flowing regions of grains. Thus, an understanding of hysteresis is essential for modelling the exchange of mass between a flowing avalanche and its underlying substrate.

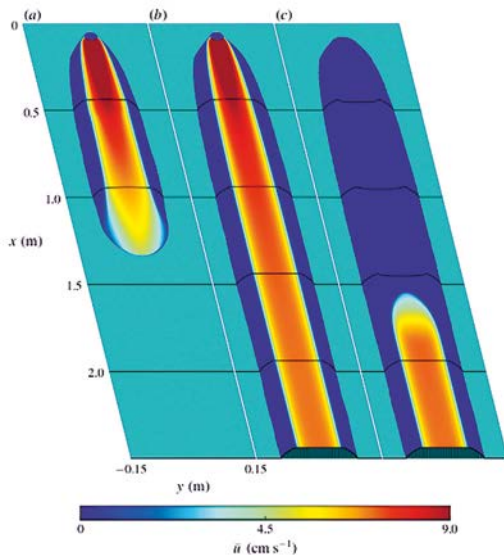
Is it a fluid, a solid or a gas?

The most visible aspect of powder snow avalanches and pyroclastic flows is a large cloud of dust and grains suspended by turbulent mixing in the surrounding air. Beneath this cloud, a rapid shallow dense granular flow moves in a liquid-like manner over a layer of static, but potentially erodible grains. It follows that grains in a single flow may behave as a gas, as a liquid, or as a solid, which complicates modelling.

Theoretical modelling of granular flow can be done via different methods depending on the size of the simulation and in a sense, how closely we look at the flow. When looking closely, each individual grain can be modelled as a solid sphere, where its motion is determined by Newton's laws and a contact model that describes the forces exerted by particles on one another. This discrete method is expensive in CPU time and consequently limited to a few million particles (about the number in half a cup of sand). A more macroscopic viewpoint treats granular material as a continuum, modelled as a fluid by solving the Navier-Stokes equations with a specific non-Newtonian granular rheology. Finally, at a large geophysical scale, a discrete

► FIG. 3: Steady travelling wave propagating on an erodible layer of constant thickness. Experiments (top left panel), corresponding numerical simulation via a depth-averaged model with viscous terms and a non-monotonic friction law (top right panel). Debris-flow deposit in the Virtanen F crater interpreted to result from the propagation of erosion-deposition waves (bottom panel) (from Viroulet *et al.* 2019).





◀ FIG. 4: (left) Numerical simulation of a granular flow from a constant inflow mass flux propagating steadily downslope and spontaneously forming static levees on either side of the central flowing channel. (right) Corresponding self-channelization experiment using monodisperse red sand on a non-erodible bed (Rocha *et al.* 2019).

simulation of every particle is far beyond today's computational resources, and even solving the Navier-Stokes equations for these complex three-dimensional flows would be a tremendous task. For these reasons, a depth-averaged approach was developed in the early 1990's (Savage & Hutter 1989). The shallowness of the flow enables the mass and momentum equations to be integrated through the flow depth assuming that the material is incompressible and the pressure is lithostatic. In doing this, the equations are reduced from three to two dimensions, which drastically simplifies their numerical solution.

This depth-averaged approach is widely exploited for modelling geophysical granular flows and is consequently used to calculate hazard maps and other operational tools for avalanche mitigation (Christen *et al.* 2010). Being able to include an accurate friction law in these models is of central importance to the predictions.

Rheology and granular hysteresis

Underneath the visible cloud of ash or snow in a geophysical event, a dense liquid-like granular flow rapidly propagates downslope. It is this part that is most destructive and therefore the most important to predict. The depth-averaged models still need to know about the effective basal friction and the depth-averaged viscosity, which are both dependent on the assumed rheology. In the early 2000's, a local rheology called the $\mu(I)$ -rheology was developed (Jop *et al.* 2006) which directly relates the shear-stress τ to the pressure p by the friction μ , *i.e.* $\tau = \mu p$. Unlike the classical Mohr-Coulomb relation the friction is not constant, but is a function of the non-dimensional inertial number $I = \dot{\gamma}d/\sqrt{p/\rho}$ where $\dot{\gamma}$ is the shear-rate, and d and ρ are the particle size and density, respectively. Using velocity and pressure profiles derived from a steady-uniform solution of the $\mu(I)$ -rheology, a depth-averaged viscous-like term can be constructed and included in the depth-averaged momentum equation (Gray & Edwards 2014; Baker *et al.* 2016). This new term introduces lateral variation in the downslope velocity across a flow in a channel and

provides an important mechanism for wavelength selection (Rocha *et al.* 2019).

Despite the major breakthrough of the $\mu(I)$ -rheology, this rheology alone cannot model the simultaneous presence of static and flowing layers on an incline, and therefore cannot be used to study erosion/deposition or the formation of static levees in geophysical flows. To cope with this issue, a non-monotonic effective basal friction law, first suggested by Pouliquen & Forterre (2002), has been modified and extended by Edwards *et al.* (2019). Depending on the thickness of the flow and the value of the Froude number, which represents the ratio of the depth-averaged velocity to the gravity wave speed, dynamic, static and intermediate regimes are defined each with an associated friction. The dynamic and static regimes can be interpreted as the friction when the material is flowing or at rest respectively. The static to flowing transition is modelled via the intermediate regime. A plot of the effective basal friction μ as a function of the Froude number Fr for a constant flow thickness is shown on figure 2. It consists of a multivalued static friction, a velocity decreasing intermediate friction and a velocity increasing dynamic friction.

Geophysical granular flows in the laboratory

Direct observations of geophysical granular flows are extremely difficult because of their inherent unpredictability and the risks of staying near the area during the event. Moreover, for snow avalanches or pyroclastic flows there is often no direct observation of the dense granular part of the flow due to the cloud of snow or ash in the air. The scale invariance of the underlying theory suggests, however, that small scale analogue experiments can be performed to shed light into the physical processes at work. Figure 3 shows a comparison between small scale experiment, depth-averaged numerical simulations and deposits of granular erosion-deposition waves on the Moon.

The experiment was performed by releasing a small amount of yellow sand on a static erodible layer of

identical red sand. Although the avalanche propagates steadily downslope, maintaining its shape and velocity, a continuous exchange occurs between the flow and the erodible layer. Yellow particles are progressively deposited along the flow path and the wave ends up completely composed of red particles (eroded from the bed) by the end of the chute. The exact balance between eroded and deposited particles allows the avalanche to propagate indefinitely, provided the slope angle and the erodible layer thickness is maintained. Depth-averaged numerical simulations that include both the viscous-like terms derived from the $\mu(I)$ -rheology and a non-monotonic friction law are in good qualitative and quantitative agreement with the experiments.

Dense granular flows also have the tendency to spontaneously self-channelise by forming static levees on each side of the flow (see fig. 1). This phenomenon appears regardless of whether an erodible layer is present and whether or not the flow is composed of a single grain size or particles of many different sizes. The ability of flows to self-channelise prevents lateral spreading and maintains flow depths for longer (Kokelaar *et al.* 2014) allowing avalanches to dramatically increase their overall runout. Figure 4 shows depth-averaged numerical simulations and small scale self-channelisation experiments, which are in very good quantitative agreement with each other, and with an exact solution for the height, width and velocity profile across the central channel (Rocha *et al.* 2019). The theory also predicts the transition to unsteady pulsing flow below a critical mass flux. These are just two examples of how depth-averaged models can very efficiently and effectively reproduce small scale experiments of dry granular flow with application to geophysical events.

Upscaling the models to a geophysical scale

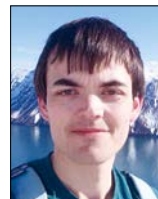
Although the new depth-averaged model with non-monotonic friction and viscous dissipation produces very good agreement with small scale experiments, quantitative prediction of flows at the geophysical scale remains a challenging issue. This is partly because the frictional parameters are more difficult to determine without being able to perform controlled experiments, but also because the depth-averaged theory implicitly assumes that the grains are either static or mobile throughout their entire depth. The theory is therefore much easier to apply to snow avalanches (where the maximum amount of entrainable snow may be defined by a clear horizon) than for a debris flow or rockfall. There are also other complications such as variable topography (Gray *et al.* 1999; Christen *et al.* 2010) and highly poly-disperse materials whose grains size distribution evolves as part of the flow (Gray 2018). Nevertheless there are very strong similarities between leveed flow deposits observed in the field (Felix & Thomas 2004) as well as observations of regularly pulsing debris-flows at Illgraben in

Switzerland (McArdell 2016), which suggest that the theory will be able to make useful predictions in situations of practical interest. ■

About the authors



Sylvain Viroulet is a “*Chargé de Recherche*” at CNRS working at l’Institut de Mécanique des Fluides de Toulouse. His major research topics are generation and propagation of tsunami waves and instabilities developing in dry granular flows with application to geophysical events.



Chris Johnson is a Senior Lecturer in Nonlinear Dynamics in the Department of Mathematics and the Manchester Centre for Nonlinear Dynamics at the University of Manchester, UK. His research focuses on modelling fluid and granular processes that occur in geophysical flows.



Nico Gray is a professor of Applied Mathematics in the Department of Mathematics and the Manchester Centre for Nonlinear Dynamics at the University of Manchester, UK. He is an expert on granular flows and the particle segregation that takes place within them.

References

- [1] J. L. Baker, T. Barker and J. M. N. T. Gray, *Journal of Fluid Mechanics* **787**, 367 (2016).
- [2] M. Christen, J. Kowalski and P. Bartelt, *Cold Reg. Sci. Technol.* **63**, 1 (2010).
- [3] A. N. Edwards, S. Viroulet, B. P. Kokelaar and J. M. N. T. Gray, *Journal of Fluid Mechanics* **823**, 5 (2017).
- [4] Edwards A. N., Russell A. S., Johnson C. G. and J. M. N. T. Gray, *Journal of Fluid Mechanics*, **875**, 1058 (2019).
- [5] G. Felix and N. Thomas, *Earth Planet. Sci. Lett.* **221**, 197 (2004).
- [6] J. M. N. T. Gray, *Annual Review of Fluid Mechanics* **50**, 407 (2018).
- [7] J. M. N. T. Gray and A. N. Edwards, *Journal of Fluid Mechanics* **755**, 503 (2014).
- [8] J. M. N. T. Gray, M. Wieland and K. Hutter, *Proc. R. Soc. A* **455**, 1841 (1999).
- [9] P. Jop, Y. Forterre and O. Pouliquen, *Nature* **44**, 727 (2006).
- [10] B. P. Kokelaar, R. L. Graham, J. M. N. T. Gray and J. W. Vallance, *Earth and Planetary Science Letters* **385**, 172 (2014).
- [11] B. W. McArdell, *Int'l J. Erosion Control Engng* **9** (4), 194 (2016).
- [12] H. Perrin, C. Clavaud, M. Wyart, B. Metzger and Y. Forterre, *Physical Review X* **9**, 031027 (2019).
- [13] O. Pouliquen and Y. Forterre, *Journal of Fluid Mechanics* **453**, 133 (2002).
- [14] F. M. Rocha, C. G. Johnson and J. M. N. T. Gray, *Journal of Fluid Mechanics* **876**, 591 (2019).
- [15] S. Savage and K. Hutter, *Journal of Fluid Mechanics* **199**, 177 (1989).
- [16] S. Viroulet, A. N. Edwards, C. G. Johnson, B. P. Kokelaar and J. M. N. T. Gray, *Earth and Planetary Science Letters* **523**, 115700 (2019).

Control your qubits with Vivace

An all-in-one platform from Intermodulation Products.
Reach microwaves without analog mixers!



ARBITRARY PULSES

Up to 256 templates with
500 ps resolution



QUANTUM EVENT ORGANIZER

Place pulses and readout
on a 2 ns event grid



TEMPLATE MATCHING

Match incoming pulses to stored
templates to trigger events



MULTIFREQUENCY

Continuous wave generation and
demodulation with 192
simultaneous frequencies



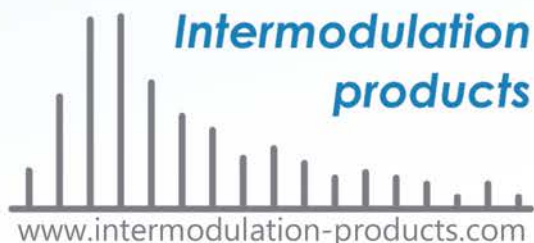
IQ MODULATION / DEMODULATION

Pair-wise length matched outputs
with DC-bias tuning, perfect for
driving external IQ-mixers



ALGORITHMS

Simple flexible interface for reset,
readout, Ramsey, Rabi or your
own custom algorithm



	Input	Output
Number of ports	8	8
Max frequency [GHz]	6	6
Sampling frequency [GHz]	4.096	6.554
Resolution [bit]	12	14
Lock-in frequencies	192	192

Cool for Progress.

[BLUEFORS.COM](https://bluefors.com)

High-density wiring

Our new high-density wiring is a modular option for the Bluefors side-loading XLDsl dilution refrigerator system that enables a large scale-up of the experimental wiring, especially for high-frequency signals. It is easy to install and to maintain.

 **BLUE
FORS**

