

FROM THE EDITOR

Web at 30: celebrating a culture of openness



Matthew Chalmers
Editor

The articles in this issue show how far ahead our field is in the growing open-science movement

It is 30 years since Tim Berners-Lee, while working at CERN, released his proposal for a new information-management system. Two years and a lot of coding later, this vision of universal connectivity had become the World Wide Web. For those born too late to have enjoyed those first double-click hyperlinks, CERN has teamed up with developers to recreate the experience for you by emulating the NeXT browser on which the software was written (<https://worldwideweb.cern.ch>). This is part of a series of 30th anniversary celebrations worldwide taking place in March in partnership with the World Wide Web Consortium and the World Wide Web (WWW) Foundation.

Openness is the soul of the web, and CERN's 1993 agreement to place the software in the public domain shapes the web's character to this day (p39). It is part of a culture of sharing and collaboration that was set out in the CERN Convention 40 years earlier, and which is deeply engrained in the software and particle-physics worlds. The articles in this issue – from open-source software (p27), to open-access publishing (p29), open data (p31) and entirely open analysis procedures (p25) – show how far ahead our field is in the growing open-science movement.

Beyond science, the WWW Foundation, established by Berners-Lee a decade ago, advocates an "open web" as a means to build a just and thriving society. In November 2018 the foundation published a report that reflected on what the web has allowed humanity to accomplish over the past 30 years and outlined the threats that it now faces. The report notes that more than half of the world's population is still offline, with online take-up slowing dramatically, continuing: "The distributed power of the web has shifted to lay in the hands of just a few, online abuse is on the rise, and the content we see is increasingly susceptible to manipulation." This issue's Viewpoint, arguing for a "humanised internet" (p43), suggests that we have so far tapped only a fraction of the web's potential for good.



Happy anniversary The historic web logo created by CERN systems engineer Robert Cailliau, Berners-Lee's first partner on the WWW project.

Theoretical therapy

For anyone feeling down about the lack of discoveries of new elementary particles since the Higgs boson, redemption may be found in an extensive interview with theorist Nima Arkani-Hamed (p45). Known for his deep and original thinking, Arkani-Hamed explains why this is the most privileged time in centuries to be working in fundamental physics, and how the next collider after the LHC will guarantee progress. Elsewhere in this issue, the second in the *Courier's* redesigned format (do keep the feedback coming!): feast on 40 years of physics at the North Area (p34), learn about CERN's impact on your career (p55), get the latest on the search for the sterile neutrino (p7), delve into the weird world of supersymmetric lasers (p10), and more.

Reporting on international high-energy physics

CERN *Courier* is distributed to governments, institutes and laboratories affiliated with CERN, and to individual subscribers. It is published six times per year. The views expressed are not necessarily those of the CERN management.

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General distribution

Courier Addressage, CERN, 1211 Geneva 23, Switzerland; e-mail courier-addressage@cern.ch

Published by CERN, 1211 Geneva 23, Switzerland
Tel +41 (0) 22 767 61 11

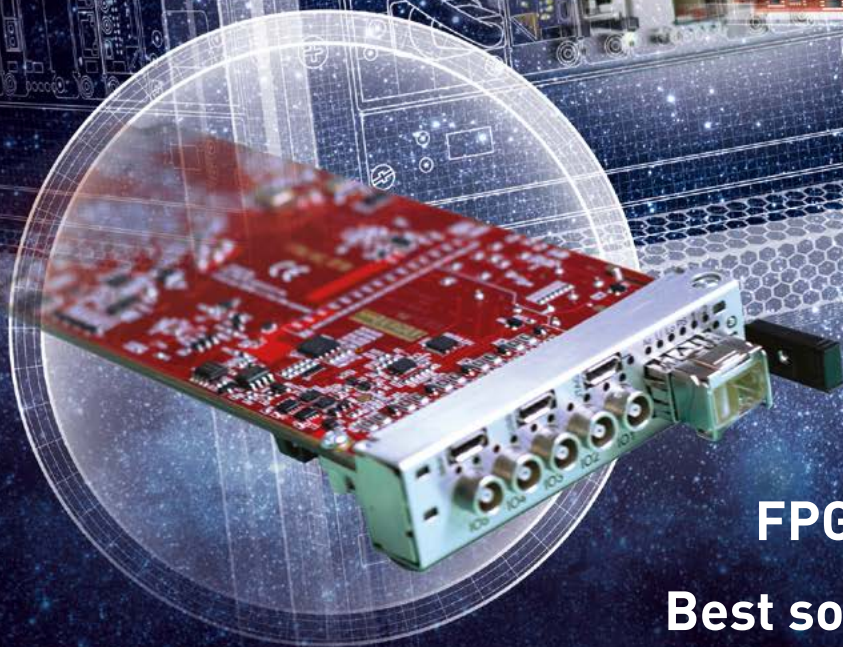
Printed by Warners (Midlands) plc, Bourne, Lincolnshire, UK

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ISSN 0304-288X



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Null result The MINOS+ experiment completed data taking in June 2016 and has since been dismantled, but much of its data remains to be analysed.

NEUTRINOS

MINOS squeezes sterile neutrino's hiding ground

Newly published results from the MINOS+ experiment at Fermilab in the US cast fresh doubts on the existence of the sterile neutrino – a hypothetical fourth neutrino flavour that would constitute physics beyond the Standard Model. MINOS+ studies how muon neutrinos oscillate into other neutrino flavours as a function of distance travelled, using magnetised-iron detectors located 1 and 735 km downstream from a neutrino beam produced at Fermilab.

Neutrino oscillations, predicted more than 60 years ago, and finally confirmed in 1998, explain the observed transmutation of neutrinos from one flavour to another as they travel. Tantalising hints of new-physics effects in short-baseline accelerator-neutrino experiments have persisted since 1995, when the Liquid Scintillator Neutrino Detector (LSND) at Los Alamos National Laboratory reported an 88 ± 23 excess in the number of electron antineutrinos emerging from a muon-antineutrino beam. This suggested that muon antineutrinos were oscillating into electron antineutrinos along the way, but not in the way expected if there are only

LSND, MiniBooNE and the reactor data are fairly compatible in terms of sterile neutrinos, but in stark conflict with the null results from MINOS+ and IceCube

three neutrino flavours.

The plot thickened in 2007 when another Fermilab experiment, MiniBooNE, an 818 tonne mineral-oil Cherenkov detector located 541m downstream from Fermilab's Booster neutrino beamline, began to see a similar effect. The excess grew, and last November the MiniBooNE collaboration reported a 4.5 σ deviation from the predicted event rate for the appearance of electron neutrinos in a muon neutrino beam. In the meantime, theoretical revisions in 2011 meant that measurements of neutrinos from nuclear reactors also show deviations suggestive of sterile-neutrino interference: the so-called "reactor anomaly".

Tensions have been running high. The latest results from MINOS+, first reported in 2017 and recently accepted for publication in *Physical Review Letters*, fail to confirm the MiniBooNE signal. The MINOS+ results are also consistent with those from a comparable analysis of atmospheric neutrinos in 2016 by the IceCube detector at the South Pole. "LSND, MiniBooNE and the reactor data are fairly compatible when interpreted

in terms of sterile neutrinos, but they are in stark conflict with the null results from MINOS+ and IceCube," says theorist Joachim Kopp of CERN. "It might be possible to come up with a model that allows compatibility, but the simplest sterile neutrino models do not allow this." In late February, the long-baseline T2K experiment in Japan joined the chorus of negative searches for the sterile neutrino, although excluding a different region of parameter space.

Whereas MiniBooNE and LSND sought to observe a second-order flavour transition (in which a muon neutrino morphs into a sterile and then electron neutrino), MINOS+ and IceCube are sensitive to a first-order muon-to-sterile transition that would reduce the expected flux of muon neutrinos. Such "disappearance" experiments are potentially more sensitive to sterile neutrinos, provided systematic errors are carefully modelled.

"The MiniBooNE observations interpreted as a pure sterile neutrino oscillation signal are incompatible with the muon-neutrino disappearance data," says MINOS+ spokesperson Jenny ▸

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Thomas of University College London. "In the event that the most likely MiniBooNE signal were due to a sterile neutrino, the signal would be unmissable in the MINOS/MINOS+ neutral-current and charged-current data sets." Taking into account simple unitarity arguments, adds Thomas, the latest MINOS+ analysis is incompatible with the MiniBooNE result at the 2σ level and at 3σ sigma below a "mass-splitting" of 1eV^2 (see figure 1).

The sterile-neutrino hypothesis is also in tension with cosmological data, says theorist Silvia Pascoli of Durham University. "Sterile neutrinos with these masses and mixing angles would be copiously produced in the early universe and would make up a significant fraction of hot dark matter. This is somewhat at odds with cosmological observations."

One possibility for the surplus electron-neutrino-like events in MiniBooNE is insufficient accuracy in the way neutrino-nucleus interactions in the detector are modelled – a challenge for neutrino-oscillation experiments generally. According to MiniBooNE collaborator Teppei Katori, one effect proposed

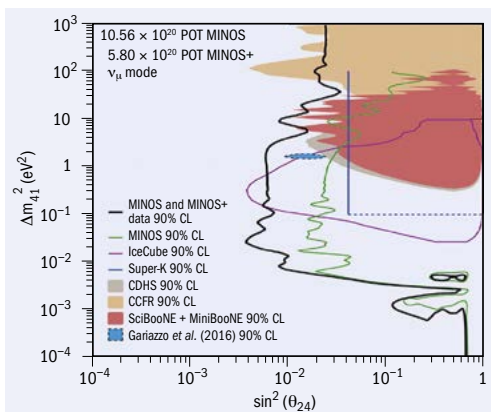


Fig. 1. New MINOS+ exclusion limits (black). The plot shows the coupling and mass splitting of sterile neutrinos with the established neutrinos. Parameter space to the right is excluded with 90% confidence.

to account for the MiniBooNE anomaly is neutral-current single-gamma production. "This rare process has many theoretical interests, both within and beyond the Standard Model, but the

calculations are not yet tractable at low energies (around 1 GeV) as they are in the non-perturbative QCD region," he says.

MINOS+ is now analysing its final dataset and working on a direct comparison with MiniBooNE to look for electron-neutrino appearance as well as the present study on muon-neutrino disappearance. Clarification could also come from other short-baseline experiments at Fermilab, in particular MicroBooNE, which has been operating since 2015, and two liquid-argon detectors ICARUS and SBND (CERN Courier June 2017 p25). The most exciting possibility is that new physics is at play. "One viable explanation requires a new neutral-current interaction mediated by a new GeV-scale vector boson and sterile neutrinos with masses in the hundreds of MeV," explains Pascoli. "So far this has not been excluded. And it is theoretically consistent. We have to wait and see."

Further reading

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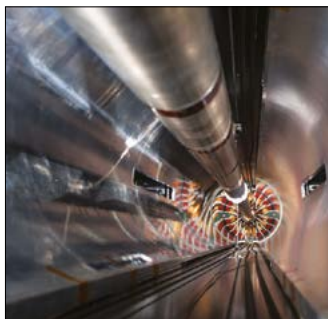
MONOPOLES

CMS beam pipe to be mined for monopoles

On 18 February the CMS and MoEDAL collaborations at CERN signed an agreement that will see a 6 m-long section of the CMS beam pipe cut into pieces and fed into a SQUID in the name of fundamental research. The 4 cm diameter beryllium tube – which was in place (right) from 2008 until its replacement by a new beam pipe for LHC Run 2 in 2013 – is now under the proud ownership of MoEDAL spokesperson Jim Pinfold and colleagues, who will use it to search for the existence of magnetic monopoles.

Magnetic monopoles with multiple magnetic charge, if produced in high-energy particle collisions at the LHC, are so highly ionising that they could stop in the material surrounding the collision points and bind there with the beryllium nuclei of the beam pipe. To detect the trapped monopoles, Pinfold and co-workers will pass the beam-pipe material through superconducting loops and look for a non-decaying current using highly precise SQUID-based magnetometers.

Materials from the CDF and Do detectors at the Tevatron and from the H1 detector at HERA were subjected to such searches during the 1990s, and the first pieces of beam pipe from the



Pipe dreams

The original CMS beam pipe, in use during LHC Run 1.

LHC experiments, taken from the CMS region, were tested in 2012. But these were from regions far from the collision point, whereas the new study will use material surrounding the CMS central-interaction region. "It's the most directly exposed piece of material of the experiment that the monopoles encounter when produced and moving away from the collision point," says Albert De Roeck of CMS and MoEDAL, who was involved in the previous LHC and HERA studies. "Although no signs of monopoles have shown up in data so far, this new study pushes the search for monopoles with magnetic charge well beyond the five Dirac charges currently achievable with the MoEDAL detector."

MoEDAL technical coordinator Richard Soluk and a small team of technicians will first cut the beam pipe into bite-sized

pieces at a special facility constructed at the Centre for Particle Physics at the University of Alberta, Canada, where they have to be especially careful because beryllium is highly toxic. The resulting pieces, carefully enshrined in plastic, will then be shipped back to Europe to the SQUID Magnetometer Laboratory at ETH Zurich, where the freshly sliced beam pipe will undergo a short measurement campaign planned for early summer. "On the analysis front we have to estimate how many monopoles would have been trapped in the beam pipe during its deployment at CMS as a function of monopole mass, spin, magnetic charge, kinetic energy and production mechanism," says Pinfold.

The latest search is complementary to general monopole searches that have already been carried out by the ATLAS and MoEDAL collaborations. Deployed at LHC Point 8, MoEDAL contains more than 100 m² of nuclear-track detectors that are sensitive only to new physics and has a dedicated trapping detector consisting of around one tonne of aluminum.

"Most modern theories such as GUTs and string theory require the existence of monopoles," says Pinfold. "The monopole is the most important particle not yet found."

Further reading

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HL-LHC

Report reveals full reach of LHC programme

The High-Luminosity LHC (HL-LHC), scheduled to operate from 2026, will increase the instantaneous luminosity of the LHC by at least a factor of five beyond its initial design luminosity. The analysis of a fraction of the data already delivered by the LHC – a mere 6% of what is expected by the end of HL-LHC in the late-2030s – led to the discovery of the Higgs boson and a diverse set of measurements and searches that have been documented in some 2000 physics papers published by the LHC experiments. “Although the HL-LHC is an approved and funded project, its physics programme evolves with scientific developments and also with the physics programmes planned at future colliders,” says Aleandro Nisati of ATLAS, who is a member of the steering group for a new report quantifying the HL-LHC physics potential.

The 1000+ page report, published in January, contains input from more than 1000 experts from the experimental and theory communities. It stems from an initial workshop at CERN held in late 2017 (CERN Courier January/February 2018 p44) and also addresses the physics opportunities at a proposed high-energy upgrade (HE-LHC). Working groups have carried out hundreds of projections for physics measurements within the extremely challenging HL-LHC collision environment, taking into account the expected evolution of the theoretical landscape in the years ahead. In addition to their experience with LHC data analysis, the report factors in the improvements expected from the newly upgraded detectors and the likelihood that new analysis techniques will be developed. “A key aspect of this report is the involvement of the whole LHC community, working closely together to ensure optimal scientific progress,” says theorist and steering-group member Michelangelo Mangano.

Physics streams

The physics programme has been distilled into five streams: Standard Model (SM), Higgs, beyond the SM, flavour and QCD matter at high density. The LHC results so far have confirmed the validity of the SM up to unprecedented energy scales and with great precision in the strong, electroweak and flavour sectors. Thanks to a 10-fold larger data set, the HL-LHC will probe the SM with even greater precision, give access to previously unseen rare processes,

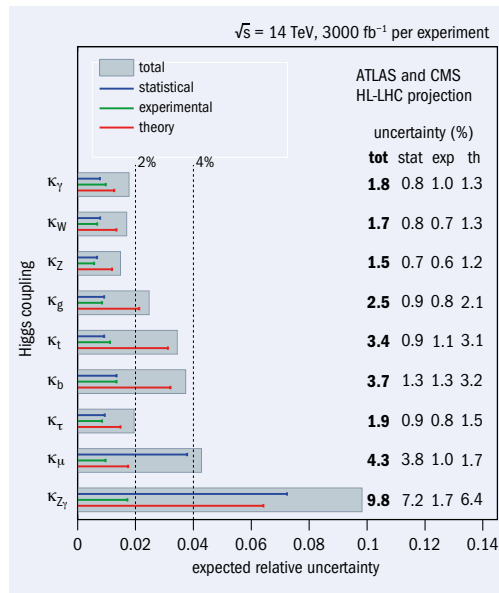


Fig. 1. Projected uncertainties on the Higgs-boson couplings to SM particles, within the so-called k -framework, with the full HL-LHC programme.

and will extend the experiments' sensitivity to new physics in direct and indirect searches for processes with low-production cross sections and more elusive signatures. The precision of key measurements, such as the coupling of the Higgs boson to SM particles, is expected to reach the percent level, where effects of new physics could be seen. The experimental uncertainty on the top-quark mass will be reduced to a few hundred MeV, and vector-boson scattering – recently observed in LHC data – will be studied with an accuracy of a few percent using various diboson processes.

The 2012 discovery of the Higgs boson opens brand-new studies of its properties, the SM in general, and of possible physics beyond the SM. Outstanding opportunities have emerged for measurements of fundamental importance at the HL-LHC, such as the first direct constraints on the Higgs trilinear self-coupling and the natural width. The experience of LHC Run 2 has led to an improved understanding of the HL-LHC's ability to probe Higgs pair production, a key measure of its self-interaction, with a projected combined ATLAS and CMS sensitivity of four standard deviations. In addition to significant improvements on the precision of Higgs-boson measurements (figure 1), the

HL-LHC will improve searches for heavier Higgs bosons motivated by theories beyond the SM and will be able to probe very rare exotic decay modes thanks to the huge dataset expected.

The new report considers a large variety of new-physics models that can be probed at HL-LHC. In addition to searches for new heavy resonances and supersymmetry models, it includes results on dark matter and dark sectors, long-lived particles, leptoquarks, sterile neutrinos, axion-like particles, heavy scalars, vector-like quarks, and more. “Particular attention is placed on the potential opened by the LHC detector upgrades, the assessment of future systematic uncertainties, and new experimental techniques,” says steering-group member Andreas Meyer of CMS. “In addition to extending the present LHC mass and coupling reach by 20–50% for most new-physics scenarios, the HL-LHC will be able to potentially discover, or constrain, new physics that is not in reach of the current LHC dataset.”

Pushing for precision

The flavour-physics programme at the HL-LHC comprises many different probes – the weak decays of beauty, charm, strange and top quarks, as well as of the τ lepton and the Higgs boson – in which the experiments can search for signs of new physics. ATLAS and CMS will push the measurement precision of Higgs couplings and search for rare top decays, while the proposed second phase of the LHCb upgrade will greatly enhance the sensitivity with a range of beauty-, charm-, and strange-hadron probes. “It's really exciting to see the full potential of the HL-LHC as a facility for precision flavour physics,” says steering-group member Mika Vesterinen of LHCb. “The projected experimental advances are also expected to be accompanied by improvements in theory, enhancing the current mass-reach on new physics by a factor as large as four.”

Finally, the report identifies four major scientific goals for future high-density QCD studies at the LHC, including detailed characterisation of the quark-gluon plasma and its underlying parton dynamics, the development of a unified picture of particle production, and QCD dynamics from small to large systems. To address these goals, high-luminosity lead-lead and proton-lead collision programmes are considered as priorities, >

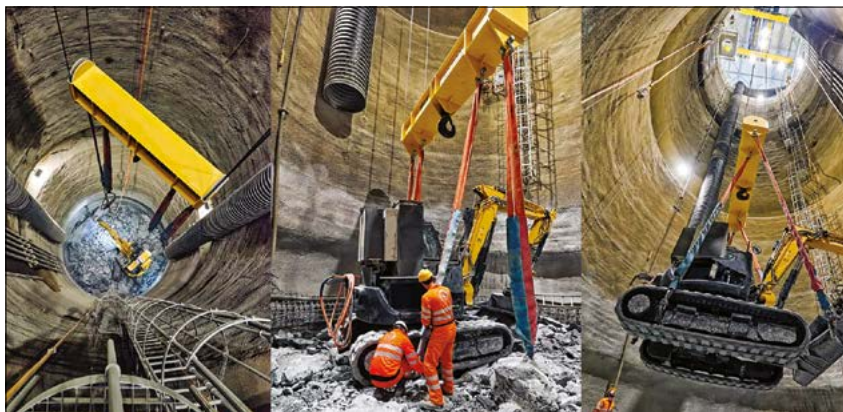
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while high-luminosity runs with intermediate-mass nuclei such as argon could extend the heavy-ion programme at the LHC into the HL-LHC phase.

High-energy considerations

One of the proposed options for a future collider at CERN is the HE-LHC, which would occupy the same tunnel but be built from advanced high-field dipole magnets that could support roughly double the LHC's energy. Such a machine would be expected to deliver an integrated proton-proton luminosity of $15,000 \text{ fb}^{-1}$ at a centre-of-mass energy of 27 TeV , increasing the discovery mass-reach beyond anything possible at the HL-LHC. The HE-LHC would provide precision access to rare Higgs boson (H) production modes, with approximately a 2% uncertainty on the $t\bar{t}H$ coupling, as well as an unambiguous observation of the HH signal and a precision of about 20% on the trilinear coupling. An HE-LHC would enable a heavy new Z' gauge boson discovered at the HL-LHC to be studied in detail, and in general double the discovery reach of the HL-LHC to beyond 10 TeV .

The HL/HE-LHC reports were submitted to the European Strategy for Particle Physics Update in December 2018, and



Digging for success The excavation of the two new shafts for the HL-LHC at points 1 and 5 of the accelerator has recently been completed.

are also intended to bring perspective to the physics potential of future projects beyond the LHC. “We now have a better sense of our potential to characterise the Higgs boson, hunt for new particles and make Standard Model measurements that restrict the opportunities for new physics to hide,” says Mangano. “This report has made it clear that these planned 3000 fb^{-1} of data from HL-LHC, and much more in

the case of a future HE-LHC, will play a central role in particle physics for decades to come.”

Further reading

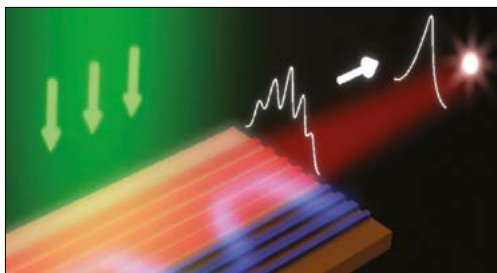
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OPTICS

First light for supersymmetry

Ideas from supersymmetry have been used to address a longstanding challenge in optics – how to suppress unwanted spatial modes that limit the beam quality of high-power lasers. Mercedes Khajavikhan at the University of Central Florida in the US and colleagues have created a first supersymmetric laser array, paving the way towards new schemes for scaling up the radiance of integrated semiconductor lasers.

Supersymmetry (SUSY) is a possible additional symmetry of space-time that would enable bosonic and fermionic degrees of freedom to be “rotated” between one another. Devised in the 1970s in the context of particle physics, it suggests the existence of a mirror-world of supersymmetric particles and promises a unified description of all fundamental interactions. “Even though the full ramification of SUSY in high-energy physics is still a matter of debate that awaits experimental validation, supersymmetric techniques have already found their way into low-energy physics, condensed matter, statistical mechanics, nonlinear dynamics and soliton theory as well as in



SUSY engineering Schematic representation of a supersymmetric laser array involving a primary active lattice (red) coupled to its lossy superpartner (blue), emitting exclusively in the fundamental in-phase mode.

stochastic processes and BCS-type theories, to mention a few,” write Khajavikhan and collaborators in *Science*.

The team applied the SUSY formalism first proposed by Ed Witten of the Institute for Advanced Study in Princeton to force a semiconductor laser array to operate exclusively in its fundamental transverse mode. In contrast to previous schemes developed to achieve this, such as common antenna-feedback methods, SUSY introduces a global and systematic method that applies to any type of integrated laser array, explains Khajavikhan. “Now that the proof of concept has been demonstrated, we are poised to develop

high-power electrically pumped laser arrays based on a SUSY design. This can be applicable to various wavelengths, ranging from visible to mid-infrared lasers.”

To demonstrate the concept, the Florida-based team paired the unwanted modes of the main laser array (comprising five coupled ridge-waveguide cavities etched from quantum wells on an InP wafer) with a lossy superpartner (an array of four waveguides left unpumped). Optical strategies were used to build a superpartner index profile with propagation constants matching those of the four higher-order modes associated with the main array, and the performance of the SUSY laser was assessed using a custom-made optical setup. The results indicated that the existence of an unbroken SUSY phase (in conjunction with a judicious pumping of the laser array) can promote the in-phase fundamental mode and produce high-radiance emission.

“This is a remarkable example of how a fundamental idea such as SUSY may have a practical application, here increasing the power of lasers,” says SUSY pioneer John Ellis of King’s College London. “The discovery of fundamental SUSY still eludes us, but SUSY engineering has now arrived.”

Further reading

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ASTROWATCH: MULTI-MESSENGER ASTRONOMY

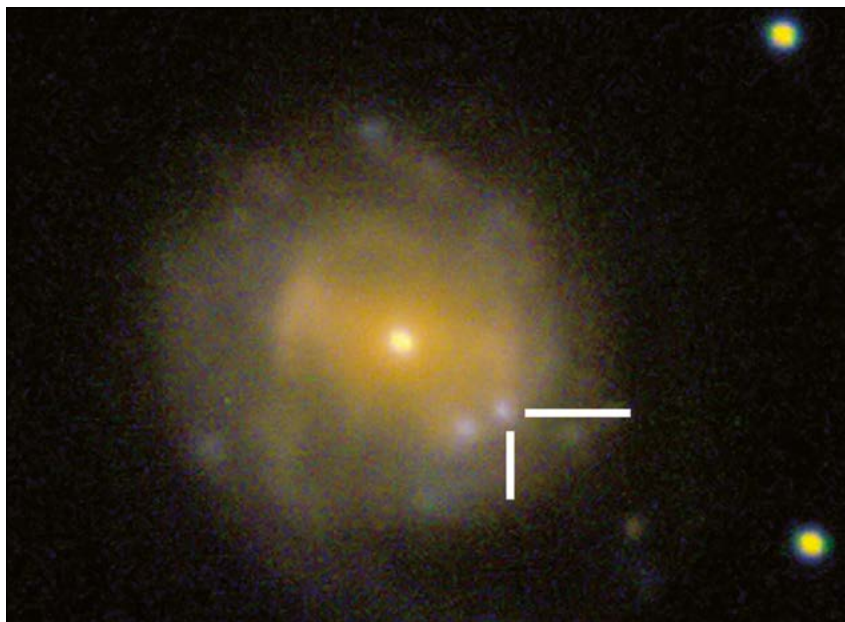
Mysterious burst confounds astrophysicists

On 16 June 2018, a bright burst of light was observed by the Asteroid Terrestrial-impact Last Alert System (ATLAS) telescope in Hawaii, which automatically searches for optical transient events. The event, which received the automated catalogue name “AT2018cow”, immediately received a lot of attention and acquired a shorter name: “the Cow”. While transient objects are observed on the sky every day – caused, for example, by nearby asteroids or supernovae – two factors make the Cow intriguing. First, the very short time it took for the event to reach its extreme brightness and fade away again indicates that this event is nothing like anything observed before. Second, it took place relatively close to Earth, 200 million light years away in a star-forming arm of a galaxy in the Hercules constellation, making it possible to study the event in a wide range of wavelengths.

Soon after the ATLAS detection, the object was observed by more than 20 different telescopes around the world, revealing it to be 10–100 times brighter than a typical supernova. In addition to optical measurements, the object was observed for several days by space-based X- and gamma-ray telescopes such as NuSTAR, XMM-Newton, INTEGRAL and Swift, which also observed it in the UV energy range, as well as by radio telescopes on Earth. The IceCube observatory in Antarctica also identified two possible neutrinos coming from the Cow, although the detection is still compatible with a background fluctuation. The combination of all the data – demonstrating the power of multi-messenger astronomy – confirmed that this was not an ordinary supernova, but potentially something completely different.

Bright spark

While standard supernovae take several days to reach maximum brightness, the Cow did so in just 1.5 days, after which the brightness also started to decrease much faster than a typical supernova. Another notable feature was the lack of heavy-element decays. Normally, elements such as ^{60}Ni produced during the explosion are the main source of supernovae brightness, but the Cow only revealed signs of lighter elements such as hydrogen and helium. Furthering the event's mystique is the variability of the X-ray emission several days after its discovery, which



Holy cow! An optical image of “the Cow” (bottom right) and its host galaxy.

is a clear sign of an energy source at its centre. Half a year after its discovery, two opposing theories aim to explain these features.

The first theory states that an unlucky compact object was destroyed when coming too close to a black hole – a phenomenon called a tidal disruption event. The fast increase in brightness excludes normal stars. On the other hand, a smaller object (such as a neutron star, a very dense star consisting of neutron matter) cannot explain the hydrogen and helium observed in the remnant, since it contains no proper elements. The remaining possibility is a white dwarf, a dense star remaining after a normal star has ceased fusion but kept from gravitational collapse into a neutron star or black hole by the electron-degeneracy pressure in its core. The observed emission from the Cow could be explained if a white dwarf was torn apart by tidal forces in the vicinity of a massive black hole. One problem with this theory, however, is the event's location, since black holes with the sizes required for such an event are normally not found in the spiral arms of galaxies.

The opposing theory is that the Cow was a special type of supernova in which

either a black hole or a quickly rotating highly magnetic neutron star, a magnetar, is produced. While the bright emission in the optical and UV bands are produced by the supernova-like event, the variable X-ray emission is produced by radiating gas falling into the compact object. Normally the debris of a supernova blocks most of the light from reaching us, but the progenitor of the Cow was likely a relatively low-mass star that caused little debris. A hint of its low mass was also found in the X-ray data. If so, the observations would constitute the first observation of the birth of a compact object, making these data very valuable for further theoretical development. Such magnetar sources could also be responsible for ultra-high-energy cosmic rays as well as high-energy neutrinos, two of which might have been observed already. The debate on the nature of the Cow continues, but the wealth of information gathered so far indicates the growing importance of multi-messenger astronomy.

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The very short time it took for the event to reach its extreme brightness and fade away again indicates that this event is nothing like anything observed before



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