1 The Universe as a laboratory for high-energy physics

Guillaume Dubus

Abstract Physics is validated through careful experimental work and its progress is punctuated by great experiments: Newton decomposing light with prisms, Thomson's discovery of the electron, Michelson's experiment on the speed of light through ether etc. Direct experimentation, whether ground-based or space-based, remains the method of choice. Yet, high-energy physics, the study of the fundamental constituents of matter and their interactions, has moved to the point where it can address conditions that cannot be tested by direct experimentation. Can the distant Universe then be used as a laboratory ? How have astronomical observations tested and expanded our knowledge of high-energy physics ? Is this affecting the way astrophysics is done ? These are the questions addressed in this contribution.

Key words: : Astroparticle physics; Relativistic processes; Gamma-ray burst: general; Cosmology

1 Can the Universe be used as a laboratory for physics ?

Using the Universe as a *laboratory* for physics may appear as wishful thinking, if not entirely preposterous. Laboratories are visualised as ordered spaces, controlled environments in which scientists with white coats design and carry out experiments, experiments that are analysed and refined until all of their parameters are understood, all of their uncertainties subdued. The outcome is an experimental protocol leading to results that can be repeated and verified by others. In contrast, "the Universe" conjures up images of something inaccessible, beyond our reach and our control, of something unintelligible of which we are only a passive spectator (Fig. 1). The two views would seem irreconcilable and this probably stems from the deeply

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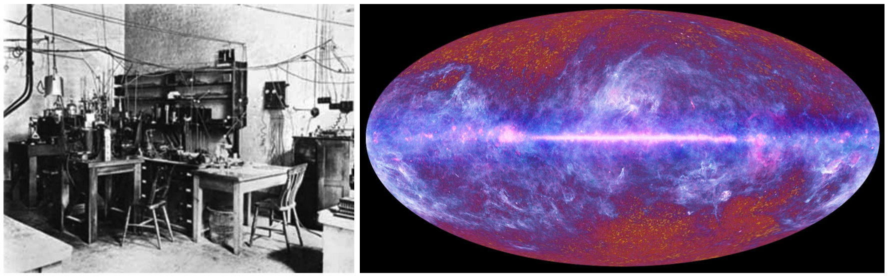

Fig. 1 Famous laboratories of physics: Rutherford's lab at the Cavendish in Cambridge *circa* 1920 and the microwave sky, showing foreground emission from the Milky Way and the Cosmic Microwave Background (CMB), as seen by ESA's *Planck* observatory *circa* 2010 (credits: AIP Emilio Segrè Visual Archive and ESA Planck LFI, HFI consortia [34]).

rooted preconception that the world populated by mankind and the heavens are distinct spheres governed by different rules.

Gravity: the historical showcase

Yet, one of the deepest foundations of science is that the laws derived on Earth should apply equally well anywhere else in the Universe. Indeed, the beginning of modern science is usually traced back to the discovery of the laws of gravitation and planetary motion. For the first time, laws divined on Earth are seen to apply up to the achievable accuracy to phenomena outside our realm. Confidence in the measurements can be increased by independent, repeated or simultaneous, observations. We have a clear experimental protocol to test a theory using space as our laboratory. Moreover, Newton's law unifies various phenomena under the same umbrella: from the fall of the apple to the movement of the Moon, tides, the shape of planets, the evolution of their orbits and spins can all be calculated to provide predictions amenable to tests via observations. The theory succeeds because it organises a large set of facts and because it proposes new observables.

Not only is the Universe accessible to the human mind but space provides a vast playground to test theories in the absence of other effects that can plague measurements or on scales impossible to realise on Earth. This is both enviable and delicate: we elaborate hypotheses as to the pertinent physics at work and improve the apparatus with which we observe but we have no control on the experimental setup. This can limit the precision to which a value can be derived. For instance, measuring the value of the gravitational constant – one of the least-well constrained fundamental constants – can be done only by careful direct experimentation [14]. This has not prevented astronomical observations from verifying predictions of general relativity, such as gravitational lensing, that are inaccessible to direct experimentation.

In verifying our knowledge of physics, we seek to match predictions from established theories with observations in novel environments. *Expanding* our knowledge of physics boils down to the search for disagreement. A subtle issue is then to decide if the mismatch represents a true deviation from known physics or a simply a deficiency in the observation or the interpretation. The explanation by general relativity of the advance of perihelion of Mercury, that differed significantly from the expectations from Newton's theory of gravity, was all the more compelling that the observational issues and several interpretations based on classical physics had been carefully considered and discarded. Even then, the decisive observation was that of the deviation of starlight near the Sun, an observation that stemmed from a distinctive prediction of general relativity that could not be accounted for by any classical interpretation.

Laboratories in high energy physics

Newton's law of gravitation symbolises the first steps of a program that continues to this day, the endeavour to render intelligible the world around us through science. Modern high energy physics is a consecration of this vision with the explicit goal of achieving a *theory of everything* that would explain the fundamental constituents of our Universe and the basic laws governing their interactions. Progress is made through the extensive use of induction and falsification, a logical sequence that starts with the casting of hypotheses, continues by conceiving and designing apparatus to infirm these, by analysing their results, abandoning the dead branches of ideas not borne out by experiments and that concludes with the recast of new hypothesis as one progresses in the tree of knowledge. The story of the discovery of the neutrino epitomises this concerted effort balancing theory and experimentation [10]. Today, the *Large Hadron Collider* (LHC) at CERN (Fig. 2), the quintessential modern-day laboratory in high energy physics, involves thousands of scientists from around the world organised around its four detectors. The size and cost of the machine leave little place for hit and miss. It is designed to make specific measurements that will test quantitative theoretical predictions, most prominently to find evidence for the Higgs boson, a particle thought to be at the origin of mass. In 1964, J. R. Platt wrote of high energy physics that

> the theorists in this field take pride in trying to predict new properties or new particles explicitly enough so that if they are not found the theories will fall [24].

Platt was arguing that the astounding string of successes achieved by high energy physics compared to other branches of knowledge was due to the systematic use of strong inference. The LHC is undoubtedly a crowning achievement of this method.

Laboratories in astrophysics

Astrophysics also has its string of successes in the last century fueled by rapid technological advances that have vastly expanded the number of observables (low fluxes, wide fields, fast timing, multi-wavelength, etc [33]) and by a liberal application of inductive reasoning constantly challenged by these new observations. What hypotheses explain the widest set of observations ? Are they supported by new observations, anticipated or not ?

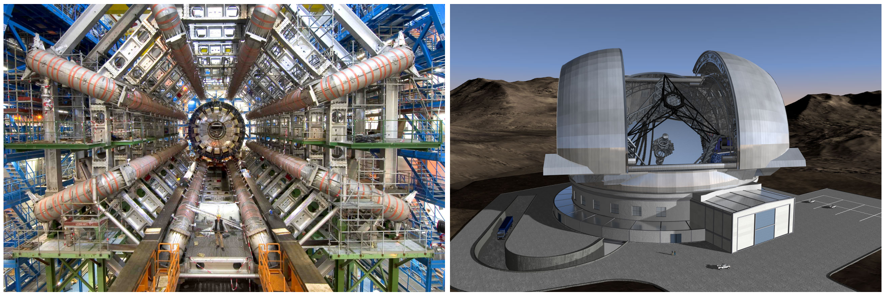

Fig. 2 Flagships of high-energy physics and astrophysics: the ATLAS detector at CERN's *Large Hadron Collider* (LHC) and ESO's planned *European Extremely Large Telescope* (E-ELT) (credits: ATLAS experiment at CERN and ESO, [35]).

A major point of intersection is cosmology where astronomical observations have been used to infer that the dominant constituents in the Universe are dark matter and dark energy. The evidence is all the more compelling that it comes from different independent sets of observations (for dark matter: big bang nucleosynthesis, the rotation curves of galaxies, confinement of hot gas in clusters etc). Hypotheses concerning their nature are formulated and then tested through the usual means of high energy physics (e.g. search for dark matter particles at the LHC or with sensitive detectors in underground laboratories) or by using astronomical observations (e.g. gamma-rays emitted when dark matter particles decay [5]). The method matters, observation replacing experimentation, not the means. Observations are a perfectly legitimate way of testing hypotheses and, in this sense, the Universe is indeed a laboratory for high energy physics.

Observatories, on the ground or in space, in ever greater sizes and with ever more sensitive detectors, mustering ever greater resources and investments, have become the focal points of an astrophysical community organised and structured increasingly like the high energy physics community. The *European Extremely Large Telescope* (E-ELT, Fig. 2), the quintessential modern-day laboratory in astrophysics and the future flagship of ESO, an organisation modelled on CERN, is representative of this evolution. One of its main objectives is the study of dark energy. This convergence of high energy physics and astrophysics has not gone unnoticed and the last section will come back to this.

2 How have astronomical observations tested and expanded our knowledge of high-energy physics ?

The theory of gravity and its tests using observations of the Universe has been mentioned. This section provides other examples of how data on astrophysical phenomena have been used to test and expand frontier knowledge in high energy physics.

2.1 High energy physics with the Sun

The link between high energy physics and astrophysics is, perhaps, most visible in cosmology. Yet, there is no need to look far to find several examples illustrating fruitful exchanges between astronomical observations and fundamental discoveries in high-energy physics. Our Sun has provided, and continues to provide, a useful laboratory from which major results have emerged.

The discovery of helium

Helium is the second most abundant chemical element in the Universe but it was discovered only in 1868 when Janssen and Lockyer noticed a strong line in solar spectra that corresponded to no known element. Wollaston and Fraunhofer had discovered absorption lines in spectra of the Sun in the early 1800s. Bunsen and Kirchhoff had established in the late 1850s that spectral lines in hot gases allow its elements to be identified and had found cesium in this way [8]. The interpretative framework for the observations of new lines in the Sun's spectrum was set. Yet, the attribution of the unidentified lines in the solar chromosphere to a new element was met with skepticism. It took 30 years before helium could be successfully isolated on Earth by Ramsay and others. This demonstrated that the constituents of the Universe can be determined remotely, provided the laws of physics are universal. There is a kinship between these observations and current work that shows baryonic matter accounts for less than 10% of the matter content of the Universe.

Nucleosynthesis

The source of the Sun's energy was a major puzzle until progress in nuclear physics made it possible to establish that this is provided by the fusion of hydrogen into helium in the core. The application to astrophysical objects also led to new discoveries for nuclear physics. Fusion opened up the possibility that elements up to iron could be manufactured by the stars, heavier elements being obtained by neutron capture. Whereas the paths involved in the fusion of hydrogen into helium were described by Bethe in 1939, it was not possible to go beyond and produce significant quantities of carbon from lighter elements in stars given the nuclear reaction rates known at the time. Hoyle conjectured in 1953 that synthesising carbon required the existence of an as-yet unknown resonance at 7.68 MeV in an excited nuclei of ^{12}C, a hypothesis that was quickly confirmed by direct experimentation [18]. Nowadays, nucleosynthesis intimately connects nuclear physics and astrophysics. The application of high energy physics theory to the big bang explains the abundances of light elements measured today. Our current understanding of the origin of everything we manipulate in daily life is entirely derived from the combination of high energy physics theory and astronomical observations. The theory and measurements are so delicately intertwined that it is possible to set upper limits on the density of exotic particles in the early universe because of the observable effects they would have on nucleosynthesis, thereby testing models for dark matter [16].

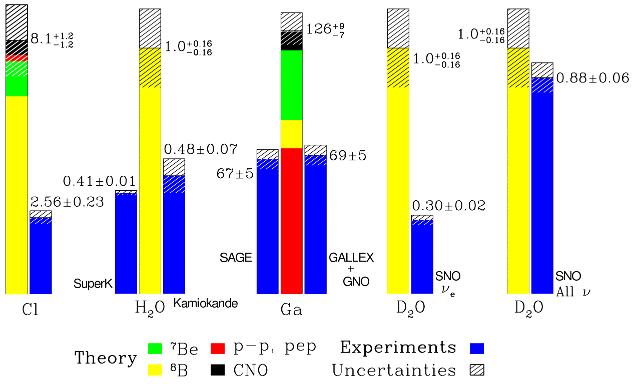

Fig. 3 Fusion in the Sun's core results in neutrino emission. This graph compares predicted and observed neutrino fluxes (in 2005) for several experiments (plot credit: J. Bahcall [3]). Each set of bars corresponds to a detection technique (Cl, water, etc). For each technique, the detected neutrino rate from various experiments is compared to the expected rate using the standard solar model and weak interaction model. The contribution to the neutrino rate from each nuclear fusion process ongoing in the Sun ($p-p$, ^{8}Be, etc) is detailed in the theoretical bar plot. The uncertainties in the expected and detected rates are also shown. Some of the detection techniques clearly led to large disagreements between expected and detected neutrino rates. The 40 year long effort to understand whether the discrepancies revealed problems with nuclear, solar or neutrino physics led to the discovery of neutrino oscillations. Solar neutrinos oscillate between flavours, not all of which are detectable by the experiments (only the *Sudbury Neutrino Observatory*, SNO, was sensitive to all neutrino types and has an observed flux matching predictions).

The standard solar model and neutrino oscillations

Knowledge of the nuclear reaction rates yield the energy input rate in the core of the Sun from which its structure may be derived using radiative transfer and hydrodynamics. Conditions vary with mass or composition, giving predictions of the radius, luminosity or colours for different stars that continue to be investigated in ever greater details by stellar astrophysicists. Using these stellar structures, astrophysicists can calculate how stars oscillate in response to perturbations. The observation of these oscillations in the Sun, heliosismology, brings exquisite constraints on the internal structure of our star: the sound speed in the Sun's interior derived from these measurements matches theory to within 0.1%.

Nuclear reactions in the core of the Sun produce neutrinos that can escape freely from the core (the dominant reaction in the Sun is the $p-p$ nuclear fusion chain $4p \rightarrow ^4\mathrm{He} + 2e^+ + 2\nu_e + 25$ MeV which occurs at temperatures $\approx 10^7$ K). In the 1960s, high energy physicists started programs to detect these solar neutrinos, which they did except there was a dearth of detections compared to predictions (Fig. 3). Inaccuracies in nuclear reaction rates and problems with the experimental setups were successively ruled out as the missing solar neutrino problem became acute [10]. Heliosismology then ruled out that the problem was due to inadequate astrophysical knowledge, leaving only neutrino oscillations as the solution [4]. Neutrinos propagating through vacuum or matter have a mixed probability of appearing as one of three flavours (ν_e, ν_μ, ν_τ; there are independent constraints on the number of neutrino families – three – including from big bang nucleosynthesis), which requires that neutrinos have a non-zero mass. Neutrinos of one type produced in the Sun's core are missed when they appear as another flavour to which the detector is not sensitive. This was confirmed in the past decade using neutrinos created when cosmic rays hit the atmosphere and with neutrinos produced in nuclear reactors. Neutrino oscillations are not part of the standard model of particle physics and measuring precisely how neutrino flavours mix is the focus of much activity.

Today, the same methodology is being used to constrain the properties of some dark matter particles using the Sun. Some (e.g. neutralinos) can be captured by the Sun's gravitational field, concentrate in its core and annihilate. Others (e.g. axions) can be created in the core and carry energy away from it. Constraints can be derived from the observable consequences on stellar models (including the solar neutrino flux !) or from the search on Earth for a flux of such particles from the Sun [5, 23].

2.2 High energy astrophysics

High energy astrophysics exemplifies the successful use of the Universe as a laboratory. The first *deliberate* attempts to constrain fundamental theories of high-energy physics from astrophysics can probably be traced back to the early 1960s and the beginnings of X-ray astronomy. This was all summed-up by Rees in 1974:

> The traditional kind of astrophysicist is, in a sense, an "applied" physicist, who computes models for stars and galaxies based on relatively well-understood properties of atoms and nuclei, Newtonian gravity, and other branches of classical physics. But recently radio and X-ray observations have revealed some fascinating cosmic objects and phenomena where the inferred energies, densities, and gravitation field strengths are so extreme that we cannot be confident that we know the relevant physics. The physical assumptions themselves, and not merely the astrophysical models, are then vulnerable to observational test; and the astrophysicist can feel that he has a symbiotic rather than a parasitic relationship with his physicist colleagues [26].

High energy astrophysics has since then sought to test and push theories to their limits or even beyond. Here are a few examples.

Neutron stars

The detection of steady, rapid radio pulsations from an astrophysical source by A. Hewish and J. Bell in 1967 can only be explained by the rotation of an extremely dense object. A normal star or even a white dwarf would be disrupted by centrifugal forces if forced to rotate on periods shorter than 1s. Stellar oscillations would not be expected to gradually slow down, as observed with pulsar periods. Gold and Pacini independently recognised in 1968 that magnetised neutron stars (pulsars) were the solution. White dwarfs were observationally known at the time but neutron stars, more compact objects supported by neutron degeneracy pressure and nuclear interactions instead of electron degeneracy pressure as in white dwarfs, were known only to theorists interested in highly condensed states of matter.

The existence of objects that squeeze a solar mass of material to super-nuclear densities offers the opportunity to constrain the behaviour of matter under the most extreme conditions [20]. Various hypotheses for the equation of state of matter at these densities can be distinguished through the measurement of the mass and radius of neutron stars. The accretion of material onto the neutron stars can lead to crustal heating and runaway nuclear fusion, which are used to constrain processes in nuclear physics (neutrino cooling, capture processes).

Many neutron stars are also inferred to possess huge magnetic field B resulting probably from the amplification of the star's field during collapse (conservation of magnetic flux $\propto BR^2$). Magnetars harbour fields of several 10^{15} G when the strongest man-made magnetic fields only reach 10^6 G. This is well above the critical field for which the Compton wavelength of an electron becomes equal to the radius of its gyration around magnetic field lines

$$B_{\rm crit} = \frac{(m_e c^2)^2}{e c \hbar} \approx 4\ 10^{13}\ G. \tag{1}$$

Quantum effects cannot be neglected at such extreme field intensities offering new prospects to test QED, the modern theory of electromagnetism [15]. For example, vacuum birefringence (never experimentally verified) means that photons travelling along or perpendicular to magnetic field lines will propagate differently. Neutron stars may also provide ways to constrain the coupling between photons and the hypothetical axion (the probability for a conversion of photon to axion is $\propto (BL)^2$ where L is the path length).

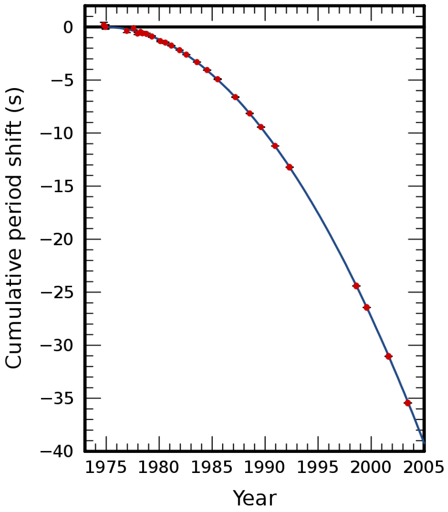

Fig. 4 Precise timing of radio pulsars allows many tests of general relativity. Here, the measured orbital decay of pulsar PSR B1913+16 is compared to the expected decay (solid line) due to gravitational wave emission over a timespan of 30 years [31]. The observation of this decay by Hulse and Taylor in 1978, using a fraction of the dataset shown here, constituted the first (indirect) proof for gravitational waves, a prediction of general relativity (plot credit: Wikipedia [31]).

The most emblematic use of neutron stars to test physics has been the determination by Hulse and Taylor in 1974 of the rate at which the 8 hour orbital period of the binary pulsar PSR B1913+16 decreased (Fig. 4). The binary parameters can be determined extremely precisely using the doppler shift of the 59 ms pulse as the neutron star moves in its orbit. Hulse and Taylor showed that the time of periastron passage gradually decreased. General relativity predicts that binary motion in tight orbits will generate gravitational waves carrying away orbital energy and angular momentum. The theoretical calculations match the observations so precisely that they are now used to constrain alternate theories of gravity. The discovery in 2003 of the binary system PSR J0737-3039 where pulses from each of the two neutron stars are detected brought even more possibilities to test general relativity. Pulsars make extremely accurate clocks. A daring proposal is to use very precise timing of an array of millisecond pulsars (old neutron stars with very stable pulsations) spread across the sky to search for slight deviations due to the passage of low-frequency gravitational waves. Big bang theory predicts a relic background of such gravitational waves.

Black holes

Black holes are one of the strongest links between fundamental theory and astrophysical observations. They are a clear prediction of general relativity, entirely and fully described by their mass, spin and charge. X-ray observations showed the existence of very compact objects in tight orbit around normal stars and with masses well above the maximum mass ($\approx 3\ M_\odot$) above which no known physical process can prevent a neutron star from collapsing onto itself. Only black holes fit the bill.

However, the best evidence for a black hole now comes from the observation of the movement of stars in our Galactic Centre. The orbit of the closest star approaches within 100 AU ($\sim$ the size of our Solar System) of an object with a mass of $4\ 10^6$ $M_\odot$, Sgr A* (Fig. 5). This mass and the density of matter it implies rule out every known alternative but a black hole [12].

Observations clearly favour the existence of black holes. For all practical purposes their presence in the hearts of galaxies and in some binaries is certain. *Proving* their existence is an extremely difficult task, underlining some of the difficulties that can arise when using the Universe as a lab. Even the stringiest constraints on the minimum density of matter enclosed by the stars at our Galaxy's centre will not prove that Sgr A* is a black hole rather instead of some exotic object not yet thought of. Proving an object is black hole requires finding evidence for its defining characteristic: the horizon beyond which light is trapped. Indirect evidence for horizons was inferred from the brighter X-ray emission from neutron stars compared to black holes, which is attributed to energy released at the surface of neutron stars but that disappears behind the horizon in black holes. High-resolution imaging of the region around Sgr A* at mm or infrared wavelength may lead to observing the black-hole's silhouette within the next decade [25] but the ultimate proof can be brought only by observations of merging black-holes (Buonanno).

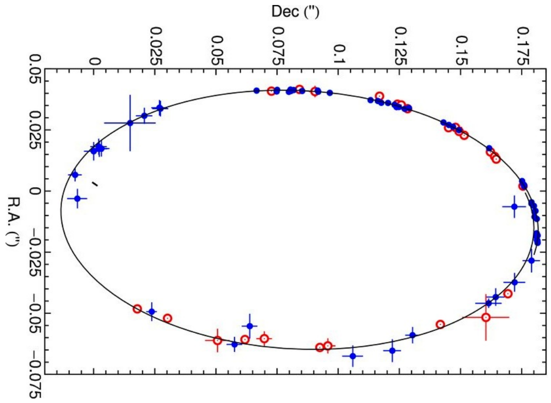

Fig. 5 Stellar and gas dynamics have revealed the presence of black holes in the Universe. The current best evidence is the 16-year long Keplerian orbit of a star (S2) in the centre of our Galaxy (at right, from [13], figure copyright 2009 reprinted with permission from the AAS). S2 passes within 18 light-hours from the derived center-of-mass (shown by a small line close to the origin). Only a 4 10^6 $M_\odot$ black hole can explain such a large mass enclosed by such a tight orbit.

Astrophysicists are also busy trying to find ways to measure the spin of black holes by the reddening it causes on emission or the space drag it imposes on accreting material. Measuring these properties through the observation of X-ray spectral lines and/or quasi-periodic oscillations is a major goal of the future *International X-ray Observatory*. Such measurements can lead to tests of general relativity in the strong field regime (when the curvature GM/R^3c^2 is high [25]). Mention should also be made of Hawking radiation from black holes, a prediction combining quantum mechanics and relativity, which is therefore at the frontiers of theoretical knowledge. However, Hawking temperatures of astrophysical black-holes are much lower than that of the CMB so instead of emitting they absorb radiation. Radiation from hypothetical primordial mini-black holes has still to be observed.

Cosmic-ray physics

There is every second, in a surface of a square meter, a proton or nucleus with an energy greater than 100 GeV impacting the Earth's atmosphere. The cosmic origin of these particles has been known since 1912 when Victor Hess showed that this ionising flux increases with altitude. Many ground-based or space-based particle detectors have measured the flux, composition, energy and arrival direction of cosmic rays. Their observed energies reach several 10^{20} eV. The collision of such a particle with a proton at rest in the atmosphere yields more than 10^{14} eV in the centre-of-mass frame, one order-of-magnitude above the energies reached with the LHC. The discovery of the positron (antimatter) by Anderson in 1932 (Fig. 6), of the muon (1936), the pion (1947) and other particles were made using observations of cosmic rays. Accelerators, with controlled injections and collisions, became the tool of choice after World War II. Observations of ultra-high energy cosmic rays (UHECR, $> 10^{18}$ eV, [22]) still push the limits of particle interaction models derived from accelerator data.

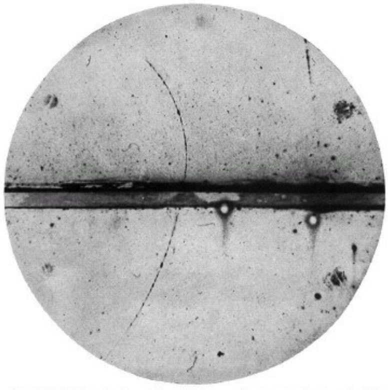

Fig. 6 Earth is bathed by a continuous flux of particles with energies greater than what can be achieved in man-made accelerators. The study of cosmic rays has led to the discovery of several fundamental particles, starting with the positron. This is C. D. Anderson's picture of a 63 MeV positron of cosmic origin going through his cloud chamber from his discovery article (figure copyright 1933 reprinted with permission of the APS from [2]).

One hundred years after their cosmic origin was established, we still do not understand where cosmic rays come from (see also Sigl, Waxman). In fact,

> at first [cosmic rays] were utilised mainly as a convenient source of energetic particles for particle physicists during the pre-accelerator days. Only in the early 50s was their astrophysical significance fully realized [33].

Cosmic rays are charged particles so their trajectories are scrambled by propagation and diffusion on Galactic magnetic fields. Up to $10^{15} - 10^{18}$ eV, cosmic rays probably get their energy from Fermi acceleration in the supernova remnants of our Galaxy. Accelerating particles to greater energies puts enormous requirements on the magnetic field and size of the astrophysical source (gamma-ray bursts are thought to be the most likely sources of UHECR). Because of this, UHECR have been suggested to be the product of the decay of exotic particles or topological defects. UHECR are not confined by Galactic magnetic fields and can have an extragalactic origin. If UHECR are protons, then they have enough energy to create e^-e^+ pairs and pions by interacting with photons from the 2.7K cosmic microwave background. There should be an observable diminution in the flux of UHECR due to this energy loss above $\approx 5\ 10^{19}$ eV (this is called the Greisen-Zatsepin-Kuzmin or GZK cutoff). The characteristic energy-loss length implies that protons with energies $> 3\ 10^{20}$ eV come from within ≈ 30 Mpc from us. The idea that UHECR hinted at new physics was entertained when the AGASA reported results inconsistent with a GZK cutoff. For instance, this could be due to a violation of Lorentz invariance (required by special relativity and that implies, for instance, the conservation of $E^2 - p^2c^4$ in any frame). The *Auger* collaboration operates a gigantic detector array in Argentina built largely for the purpose of settling this question. They have accumulated in the recent years a dataset superseding all others. The *Auger* dataset shows the expected GZK cutoff and also an anisotropy in the arrival directions of UHECR, firmly pointing to astrophysical sources.

Cosmic rays at lower energies are also being investigated for signatures of frontier physics. Reports of an excess of electrons and positrons with energies around

100 GeV and of an excess in the e^+/e^- ratio compared to the standard astrophysical model were interpreted as the contribution from the decay of dark matter particles. This has not been entirely corroborated by other measurements and our current knowledge of astrophysical sources and e^-e^+ propagation in the Galaxy are still too uncertain to rule out a conventional explanation [21]. The *Alpha Magnetic Spectrometer* (AMS), due for launch on the last space shuttle mission, will provide high quality measurements of the cosmic-ray spectrum at these energies as well as search for antimatter helium, which is not expected to occur in known astrophysical sources and, if detected, would require a revision of the role of antimatter in the evolution of the Universe.

Multi-messenger astronomy

The detection of an anisotropy in UHECR arrival directions opens up the prospect of identifying the sources using images reconstructed from the cosmic-ray arrival directions. *Multi-messenger* astronomy using cosmic ray, neutrino and gravitational wave detectors brings new sources of information on the Universe complementing photon astronomy, exactly like radio, IR, X-ray and gamma-ray astronomy complement visible light. It is too early to tell exactly how observations by these instruments will challenge physics but there is no doubt that they will be used for this purpose.

The first (and only) astrophysical image of the sky in neutrinos shows the Sun [17]. The detection of an excess of neutrinos detected in coincidence with the collapse of supernova SN 1987A vindicated the standard supernova scenario but also triggered efforts towards building a neutrino detector capable of identifying other astrophysical sources. Neutrino emission must occur in the sources of cosmic rays since interactions with high-energy protons produce pions that decay into particles including high-energy neutrinos [11] (see also Waxman). The most advanced project is *ICECUBE* at the South Pole.

The *Virgo* and *LIGO* collaborations search for gravitational waves from phenomena involving masses of order of the mass of the Sun (e.g. binary neutron star coalescence). They use km-sized laser interferometers to measure the slight deviation in path length (smaller than the size of a nucleus) caused by the passage of a gravitational wave (see also Buonanno). The planned upgrades will make binary mergers observable within 100 Mpc. The merger rate in this volume is $\gtrsim$ 1/year and this should lead to the first direct detection of gravitational waves. This would be a tremendous intellectual and technological achievement [28]. A space mission, *LISA*, is also proposed. With arms of millions of km, the interferometer should be sensitive to the gravitational waves from merging massive black holes throughout the observable universe. The waveform detected during mergers provides an unrivalled means of seeing how the theory of gravity works at its extreme. The exact distance to the event can be deduced by comparison to theoretical waveforms so that, if an electromagnetic counterpart and a redshift are found, this will give a new, precise and independent way to calibrate the extragalactic distance scale.

3 Is this affecting the way astrophysics is done ?

Although the first use of the Universe as a laboratory is arguably the comparison of the movement of planets with the predictions of Newton's law of gravity, it is only in the last hundred years or so that astronomical observations have been increasingly used for insight and tests of physical theories. This has led to successes, some of which have been recapped above, and ambitious proposals to test the very foundations of physics. It has also led to pitfalls and has somewhat affected the way astrophysics is done.

Convergence

The equations of general relativity can be used to describe the evolution of the Universe as a whole and this introduced a significant qualitative change to the way astrophysics is perceived. From an effort to understand the workings of objects and phenomena in the sky, astrophysics becomes a path to fundamental insights into the nature of the world around us. Any initial skepticism that pertinent calculations or observations can be made on the Universe as a whole were blown away by the discovery of its expansion and the cosmic microwave background. Seemingly far-fetched hypotheses like inflation are actually being verified by precise measurements of the perturbations left on the CMB.

Cosmology has become such a fertile meeting ground between high energy physics and astrophysics that even the most basic tenets of physics are now thought to be within the realm of experimentation, including the universality of the laws of physics. For example, we can test whether the fundamental constants governing the laws of physics changed with time [30]. There are claims that the ratio of the frequencies of spectral lines changes with redshift, implying that the fine structure constant (the constant involved in the calculation of energy levels in atoms and molecules) had a different value in the early Universe. Even more ambitious ideas are that cosmological observations can test the Copernican principle [29] or constrain the existence of other universes, some of which may be governed by entirely different laws of physics [27]. How confident we have become in the use of the Universe as a laboratory (see Ellis) !

Nowadays, the Universe as a laboratory has become a pillar in the justification of the development and funding of astrophysics. Understanding *the extremes* or the *physics* of the Universe stands alongside the quest for the origins and the search for life in the top questions of both the 2007 European *ASTRONET* report (see Andersen) and the 2010 US Decadal Survey (see Trimble). Such is the perceived symbiosis that one could read in a *Science magazine* special issue on particle astrophysics

> researchers have begun explorations at the boundaries between particle physics, astrophysics, and astronomy [...] It's likely that in the next 10 years, one of these efforts will lead to a major discovery [7].

There is ground for optimism but this should not blind us to some difficulties discussed below.

Pitfalls

With the increasing pace of research in physics, the pressure from funding agencies, are we sometimes going too far in wanting to identify new phenomena with new physics ? The detection of very high energy gamma rays from the vicinity of the Galactic Centre or of an excess in the positron fraction in the composition of cosmic rays were promptly interpreted as signatures of dark matter although explanations are readily found that involve no new physics or astrophysics (respectively: standard electromagnetic emission from the vicinity of the central black hole or a pulsar wind nebula, injection of positrons by nearby pulsars). The temptation to put forward ground-breaking hypotheses from experimental data is neither new nor condemnable in itself. After all, eminent physicists like Niels Bohr were prepared to abandon energy conservation to interpret β decay before Pauli hypothesised the existence of the neutrino. However, Bohr and Pauli were faced with a phenomenon that could not be satisfyingly explained by any theory at the time (unlike the examples above) and Pauli's conjecture actually led to verifiable consequences (the particle had to have such and such property that could be observed in such and such a way [10]).

Recently, the *Fermi Gamma-ray Space Telescope* observed an 31 GeV photon emitted in a distant ($z = 0.9$) gamma-ray burst (GRB 090510). Gamma-ray bursts are thought to be produced when a massive star collapses or a binary star merges to form a black hole. This photon, which had the highest energy ever observed in a GRB, arrived 0.8 seconds after the start of the event as measured with lower energy photons. The lag was used to place a lower limit on the energy scale at which Lorentz invariance may be broken. More prosaically, the question is whether light propagates at the same speed in vacuum regardless of its energy. Some theories of quantum gravity (theories thus going beyond standard physics) propose that this is not the case. A delay would arise in the arrival time of photons of different energies emitted at the same time. This delay can be written as

$$\Delta t \propto \frac{1}{H_0}\frac{\Delta E}{E_{\rm QG}}. \tag{2}$$

where $E_{\rm QG}$ is the energy scale at which this effect appears and H_0 is the Hubble parameter (≈ 70 km s^{-1} Mpc^{-1}). Assuming the delay due to quantum gravity is less than the observed $\approx$ 1s delay between the start of the burst and the detection of the 31 GeV photon sets a lower limit on $E_{\rm QG}$ slightly greater than the Planck energy scale $E_p = (\hbar c^5/G)^{1/2} \approx 10^{28}$ eV, as can easily be derived from the above equation [1].

Is there much to be derived from this exercise ? Some articles in the press hailed this as a test of Einstein's theory of relativity: it isn't since c is implicitly assumed to be constant when using the observed delay as an upper limit on Δt. The lower limit on $E_{\rm QG}$ excludes some theories of quantum gravity, a theory of which is required in the search for a theory of everything but which is not required at all to explain GRBs. In fact, delayed high energy emission in a GRB is much more likely to reflect the astrophysics of black hole formation than some fundamental property of our Universe. The observation of a delay is not a major puzzle in itself. Therefore, given our limited understanding of the astrophysics of the source, it is unlikely that observations of delayed emission will lead to the robust detection of some trick in the speed of light or that great insights into a quantum theory of gravity will be gained from these constraints.

Not all astrophysical results have fundamental consequences. In fact, few do and it would be a mistake to analyze them and judge their worth from the unique vantage point of high-energy physics [32]. Physics at the frontiers should also be no excuse for physics without limits. Anything goes in the Universe, who's there to check anyway? Astrophysics relies on a wide body of evidence continuously tested for consistency. Astronomical phenomena can rarely be studied in isolation so that assuming non-standard physics (e.g. a new particle) is never entirely without consequences on other subfields (e.g. stellar evolution). The relevant use of the Universe as a laboratory for high-energy physics, especially when it comes to finding evidence for new physics, requires well-identified astrophysics.

Divergence

Differences will and should remain between astrophysics and high energy physics. A recent CERN press release stated that

> as soon as they have ”re-discovered” the known Standard Model particles, a necessary precursor to looking for new physics, the LHC experiments will start the systematic search for the Higgs boson [6].

Whereas new particle accelerators redo measurements previously made before moving into new territory, astronomical observations are not all guaranteed to yield the same results because of changing conditions in the astrophysical source unbeknownst to us. New telescopes do check their results against previous measurements (if only for calibration purposes) but all astronomical observations are essentially unique with an importance for future work that cannot be assessed *a priori*. There is little hierarchy in the archival value of astrophysical data: observations taken in the 18th century can be as important as data taken yesterday with cutting-edge instrumentation (e.g. historical records that date supernovae remnants seen today).

The phenomena that can be observed, or are actually observed, are not decided by our understanding of physics and so care must be taken that we do not narrow our perspectives by focusing on specific measurements, leaving opportunities for the unexpected to be identified [9]. Accurate measurements in cosmology involve the processing of huge amounts of observational data into a few numbers like the acceleration of the expansion rate of the Universe with redshift. These same data might be used for many other studies, some we can imagine and others we cannot yet. Indeed,

> our celestial science seems to be primarily instrument-driven, guided by unanticipated discoveries with unique telescopes and novel detection equipment. With our current knowledge, we can be certain that the observed universe is just a modest fraction of what remains to be discovered [19].

Contingency and serendipity play major roles in the observation of the Universe and this should not be forgotten when we use it as a laboratory [32].

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