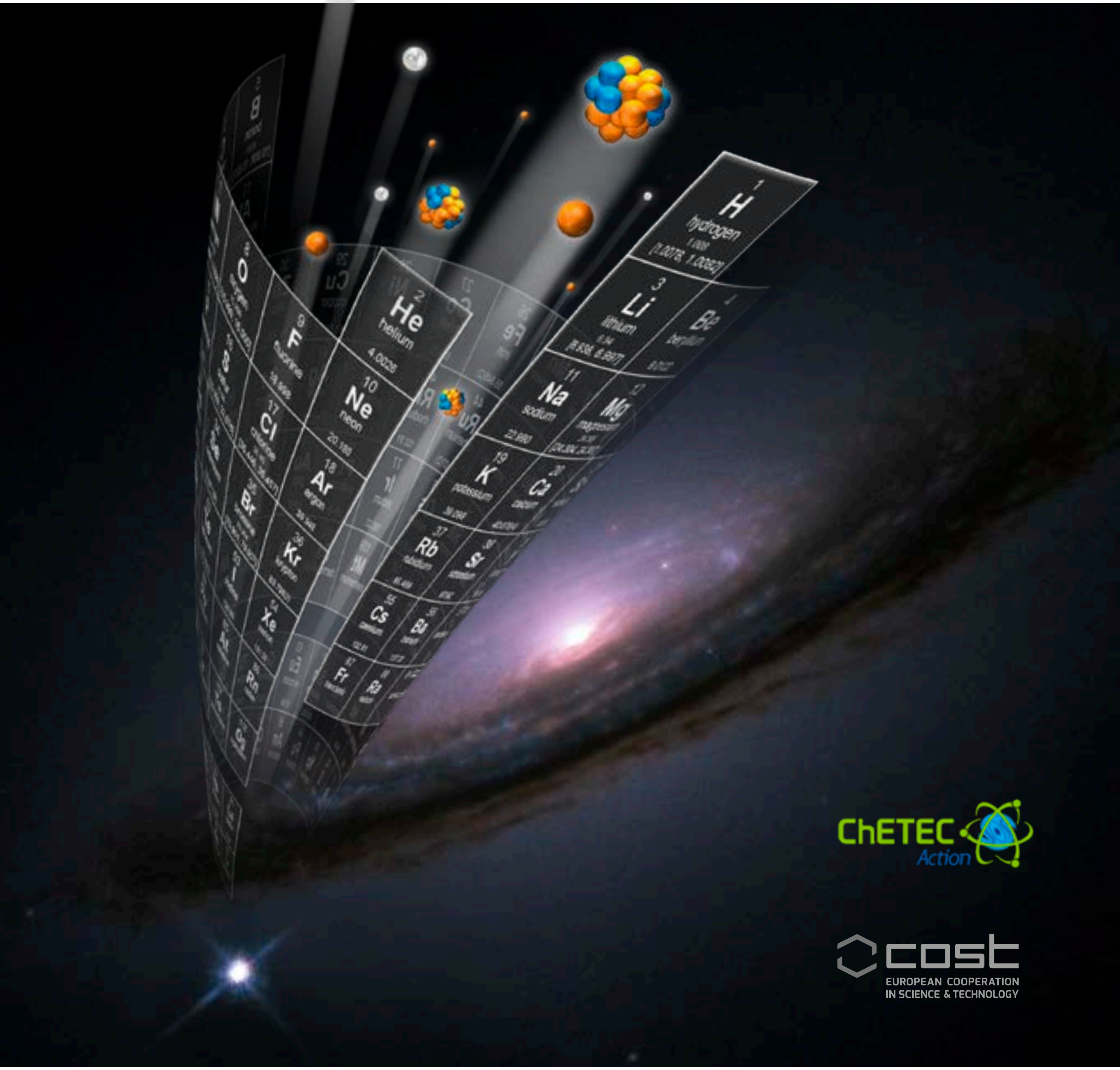
NUCLEAR ASTROPHYSICS:
COSMIC ORIGINS

How scientists explore the creation of all the elements that we find on Earth and across the Universe



STARS –
THE ORIGIN OF THE ELEMENTS AND US

Tracing the path from stars to life

All matter on Earth, including us, is composed of atoms.
Atoms in turn, are made up of subatomic particles. These include negatively charged electrons which surround the massive and extremely dense atomic nucleus. The nucleus itself is composed of further particles: positively charged protons and non-charged neutrons.

The number of constituent protons in a nucleus defines the chemical properties of each of the familiar elements, such as hydrogen, oxygen, carbon or iron. Atoms can then combine with others through their electronic 'glue', forming bonds to generate a rich diversity of molecules – from simple water (two atoms of hydrogen and one of oxygen) through to the complex DNA genetic code characterising individual humans.

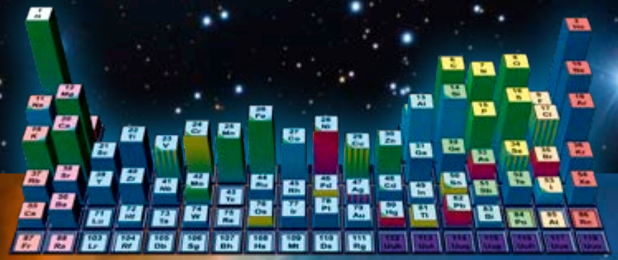
Elements, especially those with large numbers of protons, may have many 'isotopes', each with differing numbers of neutrons. The neutron number defines the particular isotope of an element. The various possible combinations of protons and neutrons define up to 10,000 different kinds of nuclei as 'nature's variety'. Indications are that most of these are realised in extreme cosmic objects under some special conditions. Yet everyday stable matter is built from not even 300 nuclear species. These include the 83 elements and their isotopes found on Earth.

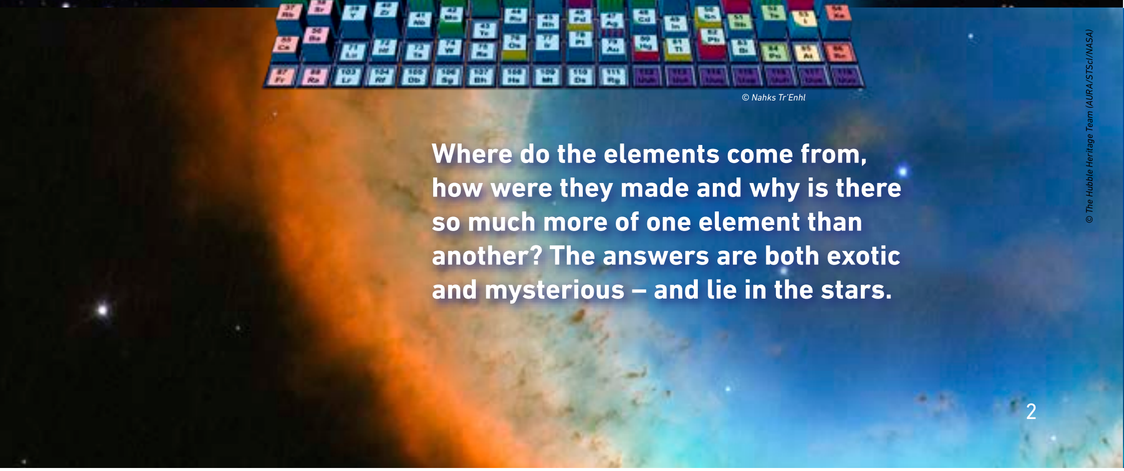
Essentially the same set of species is found in all cosmic material, however, in somewhat different relative proportions.

__Top image:__ These bright stars shining through what looks like a haze in the night sky are part of a young stellar grouping in one of the largest known star-forming regions of the Large Magellanic Cloud (LMC), a dwarf satellite galaxy of the Milky Way.

__Middle image:__ The relative abundances of the chemical elements in the Solar System.

__Bottom image:__ The ring nebula Messier 57 spectacularly displays the gaseous shroud of outer layers expelled from the dying, once sun-like star, now a tiny pinprick of light seen at the nebula's center.





Where do the elements come from, how were they made and why is there so much more of one element than another? The answers are both exotic and mysterious – and lie in the stars.

WHAT IS NUCLEAR ASTROPHYSICS
AND WHY DO WE NEED TO KNOW ABOUT IT?

Nuclear astrophysicists study nuclear reactions that fuel the Sun and other stars across the Universe, and how they create the variety of atomic nuclei. Almost all the elements found on Earth – except the very lightest ones – were exclusively made in stars and their explosions.

Understanding the underlying astrophysical processes gives us clues about:

- the origin of the elements and their abundances;
- the origin of the Earth and its composition;
- the evolution of life;
- the evolution of stars, galaxies and the Universe itself;
- the fundamental laws and building blocks of Nature.

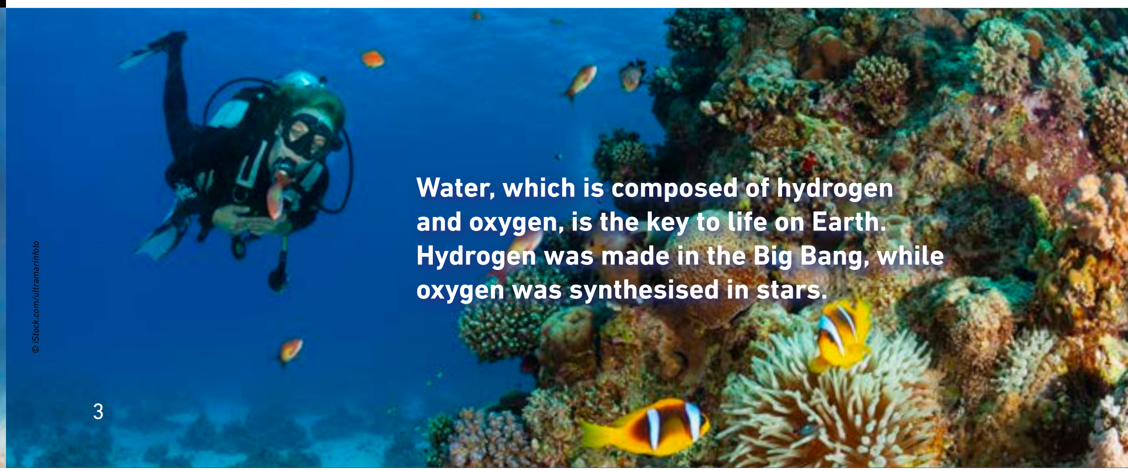
During their lives, stars generate many exotic, short-lived nuclei that do not exist on Earth, but are nevertheless significant in cosmic element creation, and also important puzzle pieces to understand the structure of all nuclear species and the fundamental forces governing them. In turn, this knowledge is essential in developing, for example, new types of safe energy and isotopes for industrial or medical use.

Nuclear astrophysicists pursue their research in several ways:

- by detecting and analysing emissions from stars and the hot or dusty remnants from exploded stars and from compact 'dead' stars e.g. with telescopes from radio to infrared, optical, and X-ray or gamma-ray light.
- by designing laboratory experiments that explore stellar nuclear reactions in the Big Bang, in stars and in supernova explosions.
- by analysing geological samples and those from extraterrestrial sources, such as meteorites with the 'stardust' grains they contain, or cosmic rays.
- by carrying out theoretical calculations on nuclear behaviour and its interplay with the stellar and explosive environments.

Nuclear astrophysics has recently been advanced through new generations of laboratory experiments, computations and astronomical instruments. But many mysteries remain to be solved.

The European astrophysics community is playing a key part in taking this work forward.



Water, which is composed of hydrogen and oxygen, is the key to life on Earth. Hydrogen was made in the Big Bang, while oxygen was synthesised in stars.

Sun image © NASA/SDO (AIA)

The Sun is an ordinary middle-aged star, one of 100+ billion stars in our Galaxy alone. The Sun consists largely of hydrogen (a nucleus made of one proton) and helium (two protons, two neutrons). These, the lightest elements, are thought to have been made in primordial processes just minutes after the Big Bang, nearly 14 billion years ago. Such primordial gas gradually condensed through gravity into massive incandescent balls of gas – the first stars.

In stars, tremendous pressure and heat drive the nuclear-fusion reactions of hydrogen nuclei to produce more helium, as well as carbon, oxygen, and other nuclei, with the release of huge amounts of energy – the 'nuclear binding energy'. We see the manifestation of this in the sunshine and warmth that sustains life, but also in the variety of elements around us – the oxygen we breathe, the carbon that is the basis of life as well as fossil fuel.

When the fuel of nuclear fusion in their cores runs out, stars like our Sun eventually blow off their outer envelopes, and their cores end up as inert and quiescent 'white dwarfs'. Stars that are much more massive, on the other hand, eventually collapse under their own gravity, and most of them explode as a supernova, throwing out material far into space.

Within the supernova, violent nuclear processes between transient exotic nuclei lead to the synthesis of more of the important elements that shape our life ('nucleosynthesis'). Such supernovae make the calcium in our bones, the oxygen we breathe, the iron in our blood, and rare and precious elements such as gold, platinum or uranium.

Eventually, the material dispersed by this catastrophic end of a star cools and condenses into new stars, perhaps with accompanying planets that could support life. We are, indeed, the children of stardust!

Nuclear astrophysicists investigate the processes underlying the creation of the elements and their influence on broader cosmic phenomena in gas, stars, galaxies, and in their evolution.

__Background:__ This image from the Wide Field Imager on the MPG/ESO 2.2-metre telescope at ESO's La Silla Observatory in Chile shows the bright open star cluster NGC 2547. Between the bright stars, far away in the background of the image, many remote galaxies can be seen, some with clearly spiral shapes.

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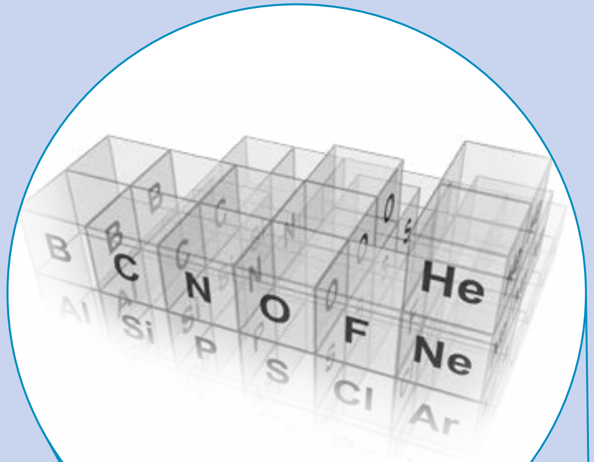
THE ELEMENTS AND THEIR ISOTOPES: MADE BY NUCLEAR REACTIONS

In atomic nuclei, protons and neutrons are bound together by the strong nuclear force against the electrostatic repulsion of the electric charge of protons. A nucleus is very compact, and ten thousand times smaller than the electron cloud that determines the size of the atom. The charge of the electron cloud determines the characteristic chemical properties of each element. The different number of neutrons that can be bound to the same number of protons make up the variety of isotopes, and these determine the characteristics of nuclear reactions. These reactions re-arrange the mix of protons and neutrons, thus creating new isotopes from existing ones. In cosmic environments, nuclear reactions often involve unstable and rare isotopes. Thus, from the primordial elements hydrogen and helium, elements such as carbon, oxygen, iron, and gold, and all their isotopes, are made.



A three-dimensional periodic table showing the various isotopes of the elements along the third axis.

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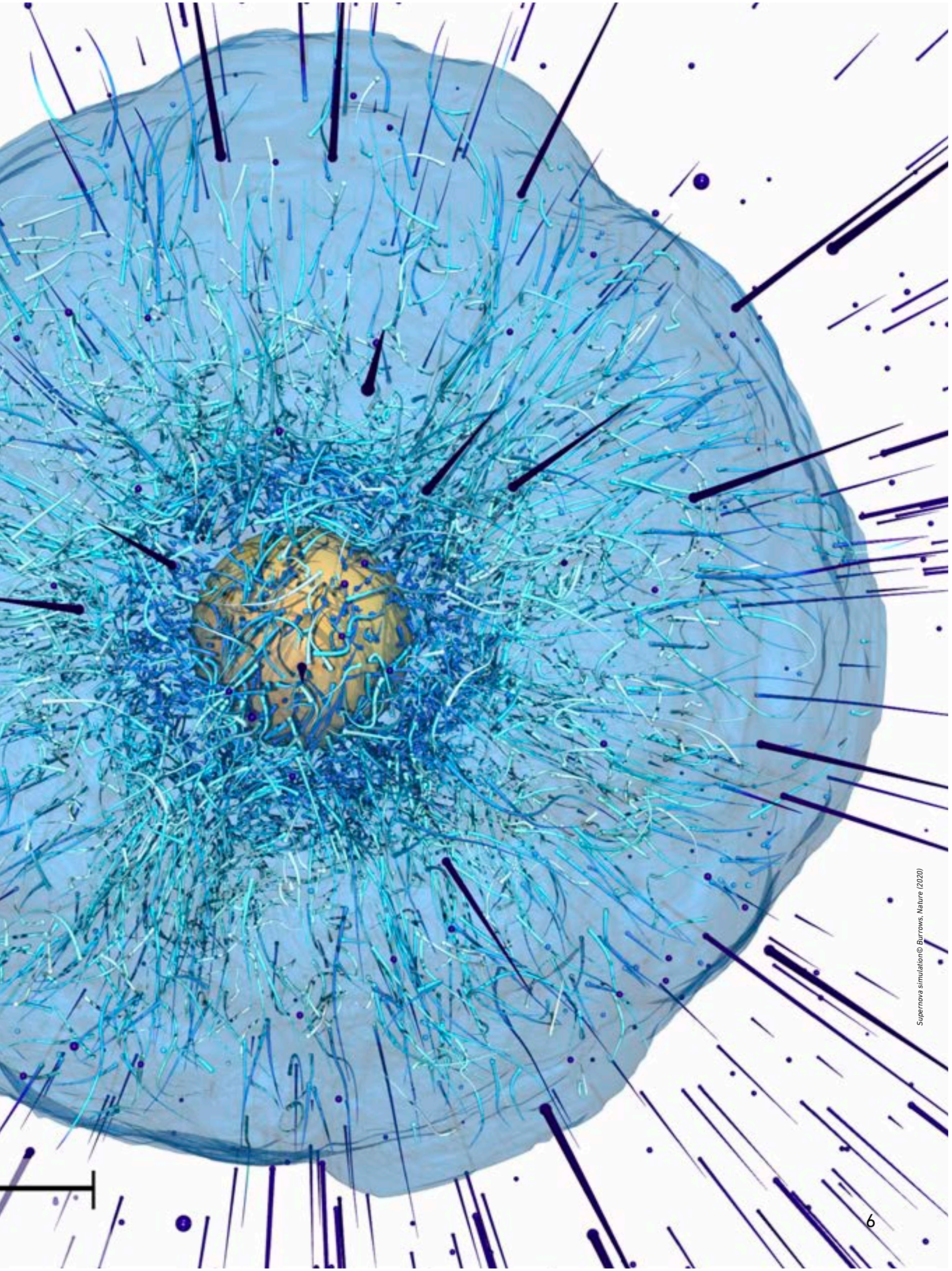
IUPAC Periodic table of the elements

Key: atomic number / **Symbol** / **name** / conventional atomic weight / standard atomic weight

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 **H** hydrogen 1.008 [1.0078, 1.0082]																	2 **He** helium 4.0026
3 **Li** lithium 6.94 [6.938, 6.997]	4 **Be** beryllium 9.0122											5 **B** boron 10.81 [10.806, 10.821]	6 **C** carbon 12.011 [12.009, 12.012]	7 **N** nitrogen 14.007 [14.006, 14.008]	8 **O** oxygen 15.999 [15.999, 16.000]	9 **F** fluorine 18.998	10 **Ne** neon 20.180
11 **Na** sodium 22.990	12 **Mg** magnesium 24.305 [24.304, 24.307]											13 **Al** aluminium 26.982	14 **Si** silicon 28.085 [28.084, 28.086]	15 **P** phosphorus 30.974	16 **S** sulfur 32.06 [32.059, 32.076]	17 **Cl** chlorine 35.45 [35.446, 35.457]	18 **Ar** argon 39.948
19 **K** potassium 39.098	20 **Ca** calcium 40.078(4)	21 **Sc** scandium 44.956	22 **Ti** titanium 47.867	23 **V** vanadium 50.942	24 **Cr** chromium 51.996	25 **Mn** manganese 54.938	26 **Fe** iron 55.845(2)	27 **Co** cobalt 58.933	28 **Ni** nickel 58.693	29 **Cu** copper 63.546(3)	30 **Zn** zinc 65.38(2)	31 **Ga** gallium 69.723	32 **Ge** germanium 72.630(8)	33 **As** arsenic 74.922	34 **Se** selenium 78.971(8)	35 **Br** bromine 79.904 [79.901, 79.907]	36 **Kr** krypton 83.798(2)
37 **Rb** rubidium 85.468	38 **Sr** strontium 87.62	39 **Y** yttrium 88.906	40 **Zr** zirconium 91.224(2)	41 **Nb** niobium 92.906	42 **Mo** molybdenum 95.95	43 **Tc** technetium	44 **Ru** ruthenium 101.07(2)	45 **Rh** rhodium 102.91	46 **Pd** palladium 106.42	47 **Ag** silver 107.87	48 **Cd** cadmium 112.41	49 **In** indium 114.82	50 **Sn** tin 118.71	51 **Sb** antimony 121.76	52 **Te** tellurium 127.60(3)	53 **I** iodine 126.90	54 **Xe** xenon 131.29
55 **Cs** caesium 132.91	56 **Ba** barium 137.33	57-71 lanthanoids	72 **Hf** hafnium 178.49(2)	73 **Ta** tantalum 180.95	74 **W** tungsten 183.84	75 **Re** rhenium 186.21	76 **Os** osmium 190.23(3)	77 **Ir** iridium 192.22	78 **Pt** platinum 195.08	79 **Au** gold 196.97	80 **Hg** mercury 200.59	81 **Tl** thallium 204.38 [204.38, 204.39]	82 **Pb** lead 207.2	83 **Bi** bismuth 208.98	84 **Po** polonium	85 **At** astatine	86 **Rn** radon
87 **Fr** francium	88 **Ra** radium	89-103 actinoids	104 **Rf** rutherfordium	105 **Db** dubnium	106 **Sg** seaborgium	107 **Bh** bohrium	108 **Hs** hassium	109 **Mt** meitnerium	110 **Ds** darmstadtium	111 **Rg** roentgenium	112 **Cn** copernicium	113 **Nh** nihonium	114 **Fl** flerovium	115 **Mc** moscovium	116 **Lv** livermorium	117 **Ts** tennessine	118 **Og** oganesson

57 **La** lanthanum 138.91	58 **Ce** cerium 140.12	59 **Pr** praseodymium 140.91	60 **Nd** neodymium 144.24	61 **Pm** promethium	62 **Sm** samarium 150.36(2)	63 **Eu** europium 151.96	64 **Gd** gadolinium 157.25(3)	65 **Tb** terbium 158.93	66 **Dy** dysprosium 162.50	67 **Ho** holmium 164.93	68 **Er** erbium 167.26	69 **Tm** thulium 168.93	70 **Yb** ytterbium 173.05	71 **Lu** lutetium 174.97
89 **Ac** actinium	90 **Th** thorium 232.04	91 **Pa** protactinium 231.04	92 **U** uranium 238.03	93 **Np** neptunium	94 **Pu** plutonium	95 **Am** americium	96 **Cm** curium	97 **Bk** berkelium	98 **Cf** californium	99 **Es** einsteinium	100 **Fm** fermium	101 **Md** mendelevium	102 **No** nobelium	103 **Lr** lawrencium

INTERNATIONAL UNION OF PURE AND APPLIED CHEMISTRY



Supernova simulation© Burrows, Nature (2020)

THE LONG JOURNEY OF UNRAVELING WHERE AND HOW ALL THE ELEMENTS IN THE UNIVERSE WERE CREATED

© Don Clayton

Margaret and Geoffrey Burbidge, Willy Fowler and Fred Hoyle in 1971

During the 19th century, physicists noted that the Sun's spectrum contained many dark 'absorption' lines that were also characteristically observed in the hot glow emitted from particular elements in the laboratory.

Spectroscopic studies showed that matter across the Cosmos was made from the same elemental building blocks. From this revelation, following the huge scientific progress made in the early 20th century – insights in basic physics (quantum physics and Einstein's relativity theories), and astrophysics (the Big Bang and the expansion of the Universe) – researchers began the long journey of unraveling where and how all the elements in the Universe were created.

First ideas

In the 1940s, Fred Hoyle had advocated the idea that stars produce all the elements in the Universe. The hydrogen-fusion reactions that make the Sun and most of the stars shine had been worked out in detail by Hans Bethe and Carl Friedrich von Weizsäcker in the late 1930s.

But many scientists remained sceptical at the time, because it was thought that stellar interiors never became hot enough for fusion reactions; and even if they did, it was not clear how the fusion products could ever get out of the stellar core.

This stimulated George Gamow and his student Ralph Alpher in 1948 to evaluate in detail previous ideas on the synthesis of all elements in the hot, early Universe of the Big Bang. Later studies concluded that only a handful of the lightest nuclei (specifically, deuterium, helium-3 and helium-4, and some lithium-7) can be produced in this early-Universe environment, while all other elements are synthesised in stellar or supernova interiors, involving a variety of complex nuclear processes. Most of these were defined and analysed in seminal papers of Al Cameron, and of Margaret and Geoffrey Burbidge, Willy Fowler and Fred Hoyle (above left to right) in 1957 (the latter now referred to as the B^2FH paper).

WHAT WE KNOW TODAY

- **The 'primordial' elements, hydrogen, helium and some lithium, were made shortly after the Big Bang.**
- **Our Sun and all stars are natural nuclear-fusion reactors that create most of the chemical elements.**
- **Through the ejection of energy and material, the processes in stars and their explosions mediate the evolution of galaxies and thus of the entire Universe.**
- **Such cosmic nucleosynthesis is key for the emergence of life. Intermediate-mass stars produce carbon; massive stars and supernovae synthesise the oxygen we breathe, the calcium in our bones, and the iron in our blood.**

THE CREATION OF
THE NUCLEI
AND THEIR ROLE IN THE UNIVERSE

Over the past century, we have built up a comprehensive picture of stars and their diverse and cyclic evolution, and how nucleosynthesis in stars has shaped the evolution of the entire Universe, including the formation of planets such as ours.

Today, we understand cosmic nucleosynthesis as the result of a complex series of reaction networks occurring at different stages in a star's evolution. These differ according to the star's overall mass. For most of their lives, stars 'burn' hydrogen to helium, but as the hydrogen is used up, helium starts burning to form carbon and oxygen.

This is what will happen in the Sun. When all the hydrogen fuel is used up, it will shrink under gravity to form a dense core, and the heat given off will cause the outer layers to swell, creating a red giant. Eventually, the outer gas layers puff off, leaving behind as dense remnant a white dwarf, consisting mostly of the products of helium burning: carbon and oxygen.

Much more massive stars later burn carbon to build up heavier elements such as neon and silicon; finally, burning of silicon produces elements up to nickel and iron. The fusion stages become more speedy over time – hydrogen burns over millions of years or more, while the last stages happen in a matter of days. At the red-giant stage, elements heavier than iron are built up by a process in which a nucleus captures a stray neutron to form a heavier isotope. If this isotope is unstable, the subsequent transformation of a neutron into a proton (with the emission of an electron) creates the next heavier element. In this process, called the s-process for 'slow', significant amounts of elements up to lead and bismuth are made.

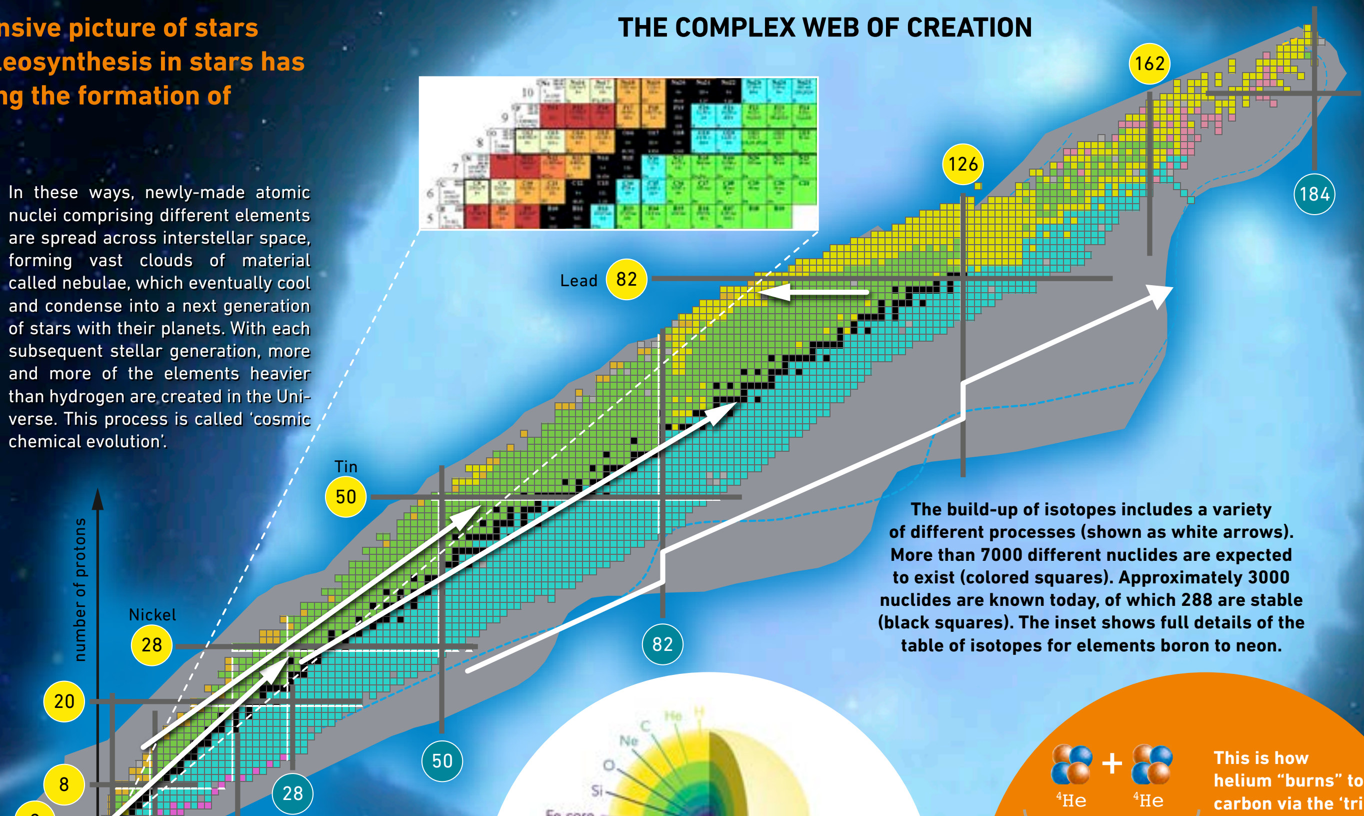
Many of the heavier elements are formed in a similar way, but in the wake of a spectacular explosion, which by some unknown mechanism creates a brief but intense flood of neutrons. Successive neutron-capture reactions within just a few seconds would generate a rapid (or r-) process, producing more of the rare, heaviest elements, up to gold and plutonium.

Such an explosion may happen when the nuclear fuel in a massive star runs out, and the central core collapses under gravity, which creates a gigantic shockwave that rushes outwards. The neutron-rich heavy elements may form in its wake in just a few seconds, together with lots of oxygen and other elements up to iron. We see this collapse as a supernova – an object shining millions of times brighter than the Sun, which leaves behind an ultradense remnant – a neutron star or a black hole. Another candidate type of explosion creating r-process elements is the collision and merger of two neutron stars. Such explosions have recently been detected by means of gravitational waves.

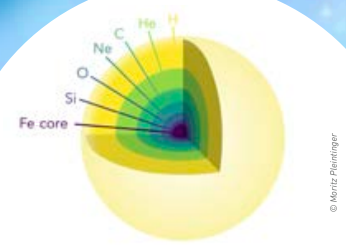
Other types of explosions can happen from a white dwarf that is part of a binary-star system – and most stars are. Re-ignition of nuclear burning may occur on the white dwarf from material drawn off its companion, triggering a 'nova' explosion. Within such systems, the white dwarf can be driven to self-destruct in a 'thermonuclear' or supernova explosion, also called 'type Ia'.

In these ways, newly-made atomic nuclei comprising different elements are spread across interstellar space, forming vast clouds of material called nebulae, which eventually cool and condense into a next generation of stars with their planets. With each subsequent stellar generation, more and more of the elements heavier than hydrogen are created in the Universe. This process is called 'cosmic chemical evolution'.

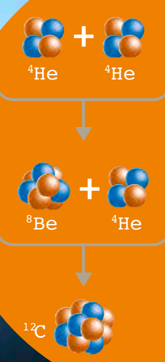
THE COMPLEX WEB OF CREATION



The build-up of isotopes includes a variety of different processes (shown as white arrows). More than 7000 different nuclides are expected to exist (colored squares). Approximately 3000 nuclides are known today, of which 288 are stable (black squares). The inset shows full details of the table of isotopes for elements boron to neon.



Schematic cut through a massive star soon to explode as a supernova (not to scale). Starting from hydrogen and helium, heavier elements are built up inside the star through chains of nuclear reactions.



This is how helium "burns" to carbon via the 'triple alpha' process, which is responsible for the amount of carbon created in stars. It is an unlikely reaction path, which is driven by subtle coincidental energy relationships between carbon, helium and beryllium nuclei.

The achievements:

NUCLEAR ASTROPHYSICS TODAY

The field of nuclear astrophysics has expanded – it has become truly multi-disciplinary

In contemporary nuclear astrophysicss, theorists, observational astronomers and experimental nuclear physicists work hand in hand in order to solve the mysteries of our Universe. Theorists have developed, and keep refining, the models of stellar interiors and supernova explosions with their nucleosynthesis reactions. Meanwhile observational astronomers scrutinise the abundances of elements and their isotopes across the galaxies, in stars, and in the dispersed material between the stars and galaxies – and across cosmic evolution. Complementing this, here on Earth, experimental nuclear physicists study the behaviour of the relevant nuclei in the laboratory, with help from nuclear theorists.

TOOLS OF NUCLEAR ASTROPHYSICS RESEARCH

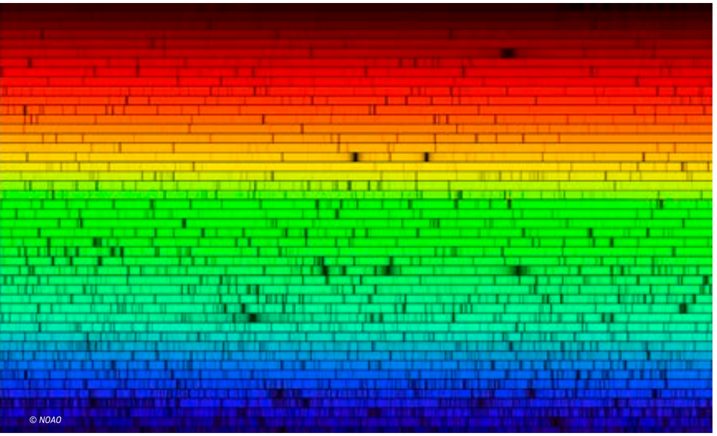
Accelerator experiments

A key approach to study nuclei and reactions of astrophysical significance is to re-create them in the laboratory. Nuclear physicists fire beams of subatomic particles or ions (atoms stripped of most of their electrons) at targets to create new nuclei through nuclear reactions. The nuclei are separated out into beams to study how they react. Mapping the secondary particles and gamma rays, they obtain clues to the structure and stability of such rare and unstable nuclei. Small, specialised accelerator laboratories, or dedicated units at large central facilities, employ such beams of both stable and radioactive ions and of protons, neutrons, also using lasers and sophisticated beam guides and filters. Experiments probing the very slow or rare reactions at the lowest energies, e.g. those that make the lightest elements, are studied in underground laboratories, to avoid interfering cosmic-ray background radiation.

Astronomical telescopes

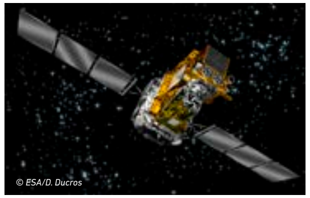
The spectra of stars and their explosions reveal the types and amounts of elements present. Large, ground-based observatories feature sophisticated spectrographs that can detect elements and their isotopes in stars, nebulae and galaxies, from radio through infrared to optical radiation.

To observe at ultraviolet/X-ray and gamma-ray wavelengths, instruments must be sent into space above the absorbing atmosphere. Such satellite observatories are able to map the distribution of isotopes in space, and home in on transient objects such as supernovae, novae, neutron-star collisions, and regions of intense current star formation, where nucleosynthesis reactions leave their observable traces.



__Above:__ The spectrum of our Sun in a high-resolution representation. This image was created from a digital atlas observed with the Fourier Transform Spectrometer at the McMath-Pierce Solar Facility at the National Solar Observatory on Kitt Peak, near Tucson, Arizona.

__Right:__ INTEGRAL is ESA's International Gamma- Ray Astrophysics Laboratory, launched in 2002, is helping to solve mysteries in high-energy astrophysics. Among its main tasks, it detects energetic radiation from newly-formed isotopes



Cosmic rays, stardust, neutrinos and gravitational waves

We do not only receive photons from celestial objects. Cosmic rays hit our Earth from interstellar space. These are nuclei with a wide range of (relativistic) energies, some well beyond what we can achieve in terrestrial particle accelerators such as the LHC. Their origin is still uncertain. They are particle messengers from Nature's most powerful particle accelerators.

Tiny grains of stardust left over from previous generations of stars or their explosions are included in meteorites. The isotopic composition of these 'pre-solar' grains are analysed by cosmochemists, using specialised mass spectrometers. These experiments provide important information about the nuclear ejecta of stars, and also the material that made the Solar System.

Neutrinos are ghostly subatomic particles with hardly any mass, which are widely and abundantly produced in nuclear astrophysical processes. Because they hardly interact with materials, they are difficult to detect, but also escape from deeply embedded nuclear reaction sites, such as the interior of our Sun or of supernovae. Large underground detectors have been built to record these evasive particles in sufficient numbers.

Gravitational waves have recently become a new branch of astronomy, allowing us to study the collisions and mergers of neutron stars and black holes, as they shake the very fabric of space-time. We have already learned that the mass spectrum of black holes is wider than expected from stellar-evolution theory, and that neutron-star mergers can produce r-process elements in significant amounts.

Combining any of these material probes, also including photons, is referred to as 'multi-messenger astronomy'.

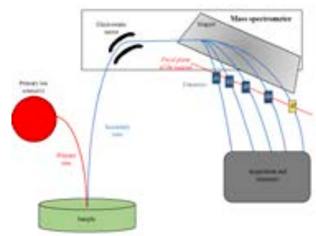
Computers and theory

The conditions in stars and their evolution, in the nuclear reactions, and how matter and energy is produced and transported to interstellar space, are explored by theorists, and results are used to compare with both astronomical observations and laboratory measurements.

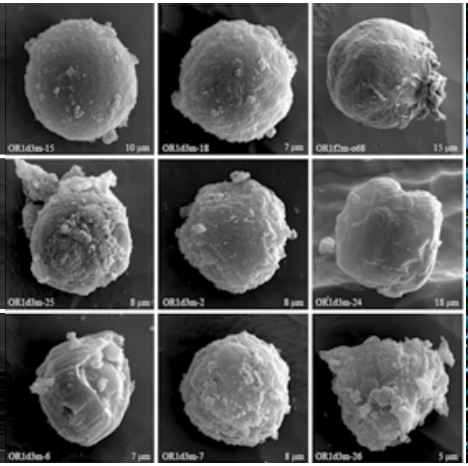
Supercomputers need to be employed to carry out three-dimensional simulations of stellar interiors and their sometimes fast evolution, and in outskirts of the nuclear landscape of many exotic and short-lived nuclei – conditions not possible to reproduce in the laboratory.

Theories of nuclear structure and stability, based on quantum descriptions of the fundamental strong and weak nuclear forces holding nuclei together, are essential to link stellar models to nuclei created there.

__Above:__ A nuclear particle accelerator experiment (INDRA and FAZIA detectors at GANIL, France). Modern particle detectors allow scientists to determine the number and composition of all products created in a particle collision.



__Right:__ A secondary-ion analyzer enables the study of small samples of precious cosmic materials such as micron-sized stardust grains.© Eden Camp



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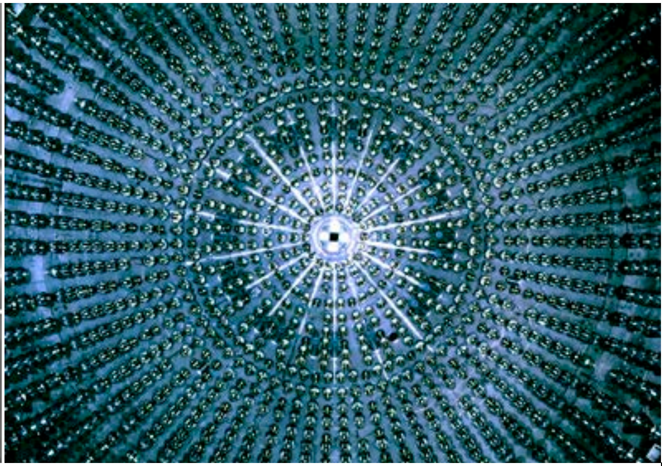


© Borexino Collaboration

SOME ACHIEVEMENTS AND THEIR IMPLICATIONS

Big-Bang nucleosynthesis

Measurements of the abundances of hydrogen, helium and lithium in various primitive sources confirm the theory of Big-Bang nucleosynthesis, also aided by nuclear reactions measured in underground laboratories.

How the Sun works

Earlier measurements of neutrinos emitted in solar nuclear reactions alarmingly indicated that our model of how the Sun works was wrong: far fewer than expected seemed to reach the Earth. This stimulated a new development in particle-physics theory and our understanding of the fundamental laws of Nature, which showed that neutrinos could change their form. Using this idea, improved neutrino measurements then confirmed the basics of the solar model. New precision tests of nuclear neutrino fluxes are being done, also utilising helio-seismic data to constrain the Sun's interior.

Making the lightest elements

Hydrogen-burning reactions leading to elements from helium to boron have been measured in the LUNA accelerator project at the Underground Gran Sasso National Laboratory in Italy. Fundamental calculations can be compared with these, and teach us about nuclear reactions at the lowest energies, as they are characteristic for stars.

Stars reveal their secrets in the laboratory

Neutron-capture reactions associated with the s-process in giant stars or the r-process in explosions are being measured by firing neutron beams at specific target materials. Using databases of those reactions, e.g., results from the analyses of pre-solar grains can be interpreted. Such dust grains can be found in meteorites, and analysed in the laboratory for their isotopic composition. They have also revealed extreme isotopic ratios of elements, such as for carbon, oxygen and silicon, that provide clues to the nucleosynthesis processes that made them.

Cosmic explosion probes

Supernova 1987A – the first such explosion to be close enough to us to study in detail – provided a test of theories of nucleosynthesis. Neutrino observatories detected 24 neutrinos at the time (February 1987), consistent with theoretical models of core collapse. Elements such as oxygen and calcium were detected early in ejecta through supernova spectroscopy, and after a few months, the heavier elements from deeper inside – nickel, cobalt and iron – were identified. The X rays and gamma rays from their radioactive decays are proof of their synthesis in the supernova. Since then, telescopes in space have measured directly the radioactive-decay gamma rays of freshly produced isotopes, such as nickel-56 and titanium-44, synthesized in different supernovae.

A rare type of explosion is required to make observed elements and isotopes heavier than iron, e.g. gold. Ideas range from jet-like supernova explosions to neutron-star mergers. The latter have been discovered recently through gravitational waves and gamma-ray bursts, triggering an impressive campaign in multi-messenger astronomy of cosmic explosions.

Gaia © ESA/ATG medialab; background: ESO/S. Brunier

Top left: *Stardust grains in electron microscope images. Their isotopic composition has been found to differ from Solar-System material.*

Top right: *Borexino is a particle-physics experiment which focuses on solar neutrinos. It has directly verified the hydrogen-fusion reactions in the Sun.*

Left: *Since 2014, the Gaia satellite has observed practically every object in the sky (down to a certain limiting magnitide). The resulting all-sky map is not a photo, but a star-density map.*

The challenges:

MYSTERIES TO UNCOVER

Understanding nuclear reactions and nuclei in a wide range of cosmic environments has far-reaching implications for our quest to answer the big questions: the nature of matter, the evolution of the Universe, and our own origins.

OPEN QUESTIONS AND CHALLENGES

Although we now have a basic description of nuclear astrophysical processes, there are many open questions. Many nuclear reactions happen with very low probability. The exotic nuclei thought to be significant in nucleosynthesis mostly cannot be made in nuclear experiments. The reaction networks are extremely complicated and happen in extreme, complex environments that are challenging to simulate in computers and impossible to replicate on Earth.

© NuSTAR/ApJ

Above: *X- and gamma-ray image of the Cas A supernova remnant, showing for the first time radioactive titanium emission (blue) distributed in few clumps around the remnant's center. Titanium is created in the core of the supernova, along with iron. The pioneering Ti-44 measurement by the NuSTAR satellite is superimposed onto X-ray images in atomic lines from iron (red) and silicon (green) measured by the Chandra satellite.*

Lack of lithium in old stars

The amount of lithium-7 observed in old, pristine stars in the outer reaches of our Galaxy is, at face value, significantly less than predicted by calculations of Big-Bang nucleosynthesis. Once corrected for effects of stellar evolution which alter the surface composition of stars over time, the offset is diminished, but not entirely removed. What is more, the most pristine stars we can find seem to not converge on the Big-Bang nucleosynthesis value. It is still unclear what causes this effect. The nuclear history of the third lightest element in the Universe is surprisingly complicated!

Understanding our Sun

Even our Sun is poorly understood, as its core nuclear fusion creates the sunlight. Since the turn of the century, a refined description of solar surface convection has led to a sizable downward revision of, in particular, the solar oxygen abundance. However, this new value changes the modelling of the Sun's interior and does not tally with results from helio-seismology measurements.

Advanced stages of nuclear burning

The reaction paths leading to the heavier elements are of high complexity and full of gaps of our knowledge. They require much better theoretical models of nuclear structure and stability, to be supported by new experimental measurements using both stable and radioactive nuclear beams.

What determines the fate of a star?

We still do not understand the processes that determine whether a star becomes a red giant and then a white dwarf, or explodes as a supernova, leaving behind a neutron star or a black hole. Investigation of the underlying nuclear and transport processes in such very dynamic environments is vital. New insights from rare explosive events, stellar population details, stardust, and gravitational waves originating from compact-star mergers show that our understanding of stellar evolution is far from complete.

How and where are the heaviest elements made?

We know that large numbers of neutrons need to be present in a highly energetic environment to make the heaviest elements such as gold and uranium. Supernovae and neutron-star mergers seem likely candidates. The enormous number of rapid neutron-capture and possibly neutrino-induced reactions in these extreme environments needs theory combined with experiments constraining neutron binding in these complex-shaped exotic nuclei. Complex interplay between the burning shells of intermediate-mass stars also plays an important role in heavy-element synthesis. A variety of cosmic explosion models, each with specifics for nuclear reactions, needs exploration from theory and rare-event astronomy.

A physical model for supernovae

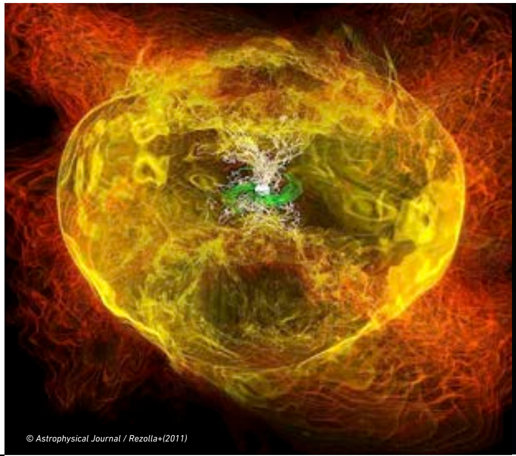
How do supernovae occur and what happens when the 'flames' of explosive nuclear burning zip through the entire object within a second or less? Precise understanding of the flame shapes, wrinkles and speeds in such exotic matter are key to a realistic model. Neutrinos streaming away from the newly-formed central neutron star, as well as amplified and thus strong magnetic fields as they are wound up by matter collapsing to the central object, are both believed to be essential in shaping conditions for creating elements and isotopes heavier than iron. To reach a satisfactory understanding, high-energy physics theory, experiments and astronomy need to be synthesised.

The nature of neutron stars

Neutron stars are extreme objects, thought to be composed of various kinds of exotic nuclear or quark matter. We need to explore this further through computer simulations, in high energy experiments, and observations of the rich variety of neutron-star phenomena in binary systems.

The role of binary systems

Many, if not most, stars are created as multiple systems, while current stellar-evolution theory primarily addresses single stars. The evolution of each star may be altered more or less by the presence of a close-by companion. For example, the gravitational pull of the companion star can strongly enhance mass loss, which in turn alters the star's interior structure and hence the conditions for nucleosynthesis and mixing. Then, once one of the stars has collapsed to a neutron star or black hole, material overflow can lead to a rich variety of transients, and collisions of neutron star or black-hole binaries are the ultimate extremes of such evolution. An interesting variety of nucleosynthesis conditions is inherent to such stellar multiplicity. We are just beginning to include such complexities into our concept of cosmic-material enrichments.



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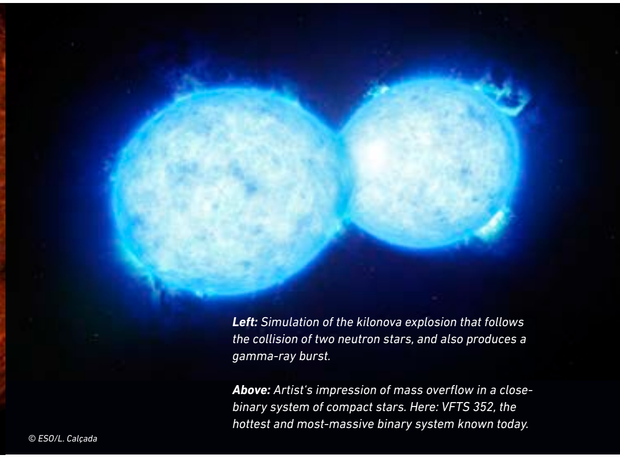

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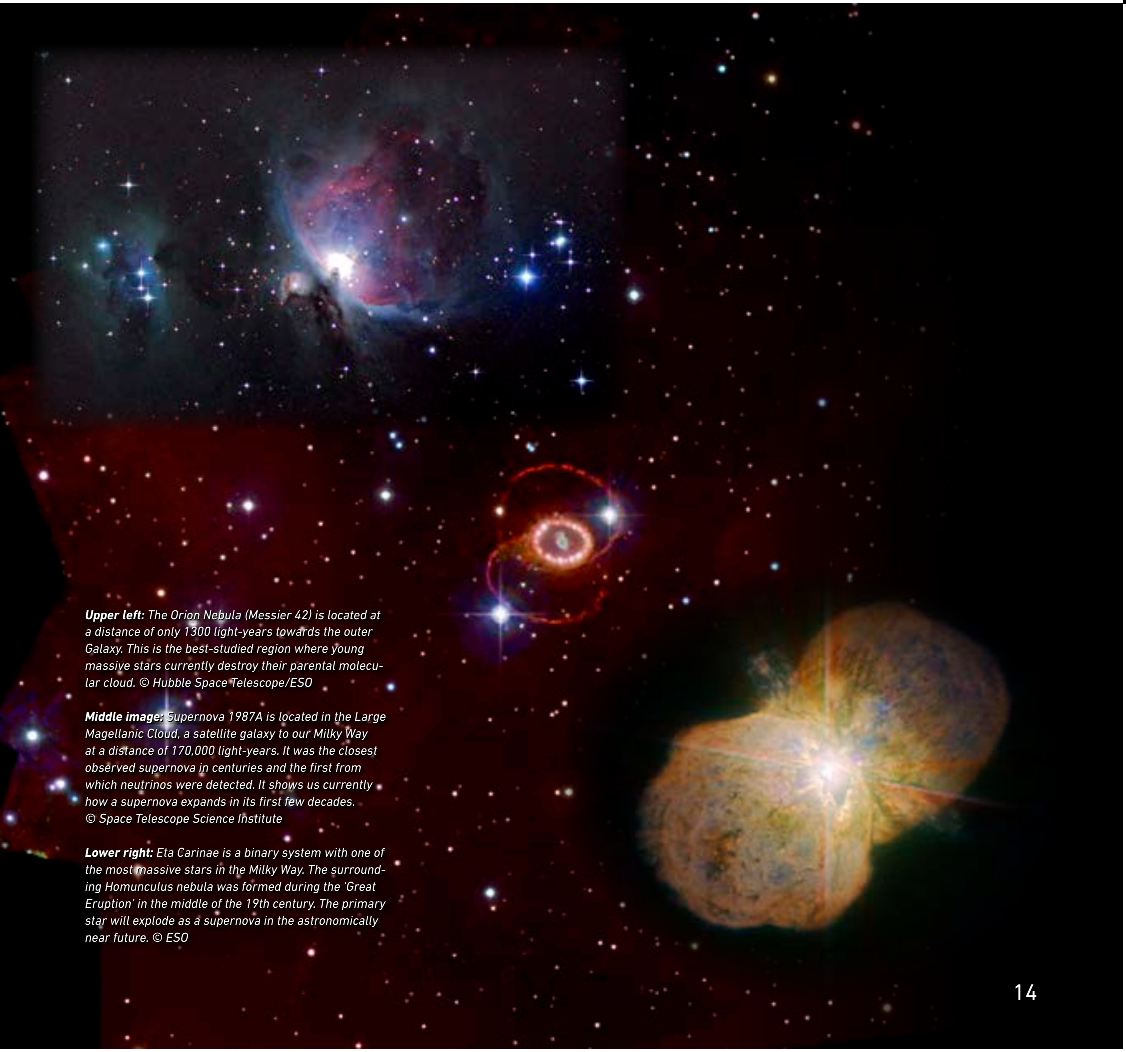
Left: *Simulation of the kilonova explosion that follows the collision of two neutron stars, and also produces a gamma-ray burst.*

Above: *Artist's impression of mass overflow in a close-binary system of compact stars. Here: VFTS 352, the hottest and most-massive binary system known today.*



Upper left: *The Orion Nebula (Messier 42) is located at a distance of only 1300 light-years towards the outer Galaxy. This is the best-studied region where young massive stars currently destroy their parental molecular cloud. © Hubble Space Telescope/ESO*

Middle image: *Supernova 1987A is located in the Large Magellanic Cloud, a satellite galaxy to our Milky Way at a distance of 170,000 light-years. It was the closest observed supernova in centuries and the first from which neutrinos were detected. It shows us currently how a supernova expands in its first few decades. © Space Telescope Science Institute*

Lower right: *Eta Carinae is a binary system with one of the most massive stars in the Milky Way. The surrounding Homunculus nebula was formed during the 'Great Eruption' in the middle of the 19th century. The primary star will explode as a supernova in the astronomically near future. © ESO*

Supernova type-Ia explosions: standard candles?

The light of the 'standard candles' of supernovae type Ia in the early Universe has been the foundation of the idea that cosmic expansion is accelerated due to 'dark energy' pushing the Cosmos apart. However, in a young Universe, when the proportions of heavier elements – in particular, carbon and oxygen – were lower, the type-Ia supernova mechanism could have been slightly different, changing light output, and thus making these objects less reliable cosmic measuring sticks. Observed type-Ia explosions have also been attributed to colliding binaries composed of two white dwarfs, so that a variety of progenitors may follow different paths to create type-Ia supernovae. How can we extrapolate the different candidate supernova models to the early low-metal-content Universe if we do not understand each of them?

How do the elements become dispersed across space?

We do not know exactly how stellar winds and supernova ejecta spread over interstellar space within galaxies, forming gas clouds that give rise to a next generation of stars. Galactic archaeology – the structure and behaviour of galaxies across time as studied by the composition of the constituent stars – and the astronomy of ejecta in X rays and gamma rays, combined with suitable transport modeling, will help to clarify this picture.

A better understanding of fundamental theory

Atomic nuclei are tiny, complex 'many-body' systems, whose properties are mediated by electromagnetism, and the strong and weak nuclear forces. The daunting challenge for theorists is to describe nuclei in terms of these interactions, and how they may behave in extreme astrophysical environments. Atomic nuclei and their constituents are important quantum laboratories for exploring the fundamental laws of Nature.

The birth environment of our Sun and its planets

Was the Sun born together with a few tens or with many thousand siblings, and within a small or a giant stellar nursery? Is it possible to look back to 4.6 billion years ago to discover the birthplace of the Sun?

Yes, similarly to what archaeologists do with the radioactive nucleus carbon-14 to date human artefacts, we can use radioactive nuclei produced in stars and supernovae as clocks to determine the time of occurrence of astrophysical events before and around the birth of the Sun and determine properties of the birth environment. Meteorites contain key data in earliest condensations called chondrites; these are scrutinised with sensitive mass spectrometry. The inferred isotopic composition of Solar-System forming material is puzzling and suggests that the Sun's origin may be special.

Radioactivity generated in the interior of rocky bodies and planets, such as the Earth, would strongly influence their evolution, including their water content and habitability. Radioactive decay in the Earth's interior is the source of geothermal energy, and drives plate tectonics. In newly-forming planets, the ice mantles of dust grains provide the planet's water content; heating of such grains by radioactive isotopes within their composition is crucial for remaining versus evaporated ice. We still do not know where these nuclei come from, and need to explore if they are present in other planetary systems too.

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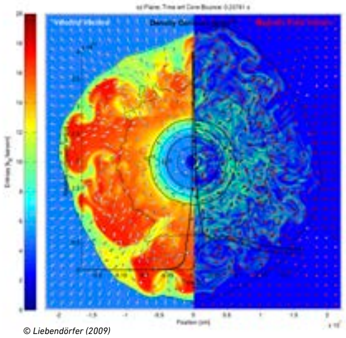

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Above top: *Dust sculptures of the Eagle Nebula (Messier 16). The powerful starlight illuminates and evaporates the dust that had formed earlier in the cold interstellar medium.*

Above: *Simulation of a massive star's core collapse, showing the complex and turbulent infall and ejection of matter as it follows gravity and is energized from neutrinos of the newly-forming neutron star.*

The future:

EXCITING FUTURE PROSPECTS

Although there have been tremendous advances in nuclear astrophysics, much more remains to be done

Progress in nuclear astrophysics is truly multi-disciplinary and multi-national: advances in astronomical instrumentation are generating ever-improving imaging and spectroscopy over both wider and deeper fields of view; high-precision analytical equipment increasingly allows us to measure minuscule amounts of rare isotopes in terrestrial rocks and meteorites; and sophisticated accelerator systems and detectors provide the tools to probe unusual, transient nuclei and reactions. All this research is brought together and complemented by work of theoreticians, often requiring high-performance computing.

Further progress can be achieved through enhanced synthesis of research efforts across the disciplines, based on focused collaboration between different expert groups. The education of young scientists needs to be enriched with specialised interdisciplinary courses and workshops. Along this line, initiatives have been set up by the European Programs for support of fundamental research collaborations and infrastructures under the umbrella of Horizon 2020.

Related to COST Action ChETEC "Chemical Elements as Tracers of the Elements of the Cosmos" (CA16117, 2017-2021), there is COST Action "The Multimessenger Physics and Astrophysics of Neutron Stars" (CA16214, 2017-2021), and an EU Research Infrastructures Network ChETEC-INFRA.

ChETEC-INFRA (2021-2025) is a Starting Community of Research Infrastructures and provides free access to 13 European research infrastructures (telescopes, nuclear laboratories and supercomputers) to researchers from any country, with proposals selected based on scientific excellence only. In addition, dedicated work packages improve the usability and accessibility of the three types of infrastructures and network them with each other, with the nuclear-astrophysics community, and with other scientific disciplines.

ChETEC-INFRA includes a strong outreach component, with support to both established and new nuclear-astrophysics scientific schools, outreach to high-school students, and to other stakeholders. The 32 ChETEC-INFRA partner institutions in 17 countries aim to serve both the European and international nuclear-astrophysics communities and are networked with related efforts on other continents.

CURRENT AND FUTURE PROJECTS

International projects that will benefit nuclear astrophysics are:

Astronomical observatories

Improved (multi-object) spectrometers at all wavelengths will provide extensive information on the origin of the elements:

ESA's Gaia satellite
An all-sky survey of 1.8 billion stars in the Milky Way. Primarily an astrometric mission measuring positions and motions in 3D with unprecedented accuracy, Gaia's instruments also measure colours for all of its targets and spectra for some 100 millions of them. These spectra provide line-of-sight velocities and individual stellar compositions.

WEAVE and 4MOST
Two ambitious multi-object spectrometers, one on the William Herschel Telescope on La Palma, The Canaries, the other on the VISTA telescope on Cerro Paranal, Chile. Together, they will provide chemical compositions for tens of millions of stars of all Galactic stellar populations. Both spectral resolution and wavelength coverage are larger than those of Gaia, thus giving access to more elements.

ALMA
The Atacama Large Millimeter Array in Chile is the most advanced radio interferometer in operation. It provides key observations of e.g. stellar nurseries and mass loss from giant stars. It also allows us to probe star formation in the early Universe.

ELT
ESO's Extremely Large Telescope, the successor of the VLT, with a segmented primary mirror of 39 meter diameter, will go into operation in the second half of the 2020s. It will be the largest optical and near-infrared telescope for many years to come and will e.g. observe exoplanet atmospheres (looking for tracers of life) and attempt to measure the expansion of the Universe in real time (the Sandage test).

INTEGRAL
ESA's International Gamma-Ray Astrophysics Laboratory is currently the only telescope which can measure the variety of gamma rays from cosmic radioactive nuclei. It was launched in 2002 and continues to be operational.

JWST
The 6.5-metre James Webb Space Telescope, to be launched in 2021, will complement ground-based telescopes to potentially observe the very first generation of stars and galaxies which lit up the universe 13.5 billion years ago. It is the long-awaited successor of the Hubble Space Telescope.

NuSTAR
The NASA Nuclear Spectroscopic Telescope Array mission maps in X rays newly synthesised titanium-44 in the debris of nearby young supernovae.

Accelerator-based research

New accelerator lab experiments throughout Europe will advance challenges in reaction-rate measurements among rare, unstable or exotic nuclei of cosmic importance:

ELI-NP in Romania determines cross sections of astrophysical interest by measuring inverse photo-disintegration reactions using intense and monochromatic gamma-ray beams.

ISOLDE at CERN in Switzerland investigates properties of neutron-rich nuclei in the vicinity of the doubly magic nuclei nickel-78 and zinc-132, close to the predicted path followed by the r-process. This effort helps to experimentally verify theoretical predictions used for the thousands of nuclei involved in the process, most of which are still unknown or at present too exotic to be produced experimentally.

NTOF at CERN in Switzerland investigates neutron-induced cross sections crucial for stellar models using the high neutron flux available. The facility is characterized by an excellent time resolution and very low background.

GSI FAIR in Germany will offer unique, unprecedented opportunities to investigate many of the important reactions of the p and rp process. The high yield of radioactive isotopes, even far away from the valley of stability, will allow the investigation of isotopes involved in these exotic processes.

GANIL in France can measure intrinsic properties (masses, half-lives...) of exotic nuclei in a systematic way through indirect measurements (transfer reactions, resonant elastic scattering, inelastic scattering...) at SPIRAL 1, and in the near future through direct measurements using radioactive beams in the framework of the SPIRAL2 phase-2 project.

LUNA/LUNA MV in Italy is a facility equipped with a 400 kV (LUNA) and a 3.5 MV (LUNA MV) accelerator, fully dedicated to nuclear astrophysics. Installed in the underground laboratory of Gran Sasso, it is characterized by a very low intrinsic background. LUNA MV has been installed in 2021 and will allow to directly measure cross sections crucial for He and C burning and the neutron-source reactions essential to provide the neutron flux for the s-process.

SPES in Italy is an ISOL-based facility where radioactive beams will be used to measure basic nuclear properties related to still unresolved issues in the chemical evolution of the Universe, shedding light on processes like supernova explosions or X-ray bursts.

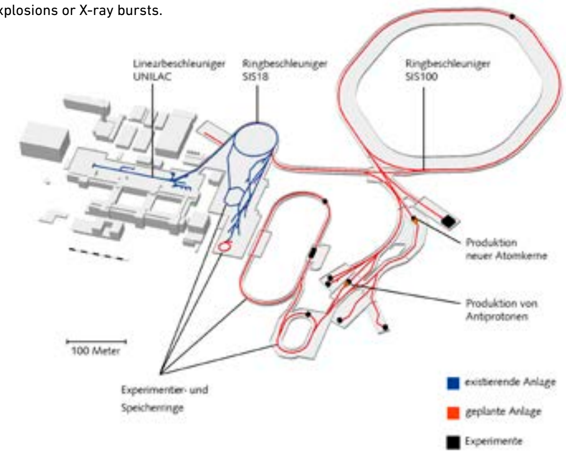
Laboratory analysis of cosmic materials

New generations of instruments called Nano-SIMS are capable of probing tiny samples of material with nanometer resolution. With these, we can measure the isotopic compositions of micrometer-sized pre-solar grains which are included in meteorites. Lasers are used in the RIMS variant of such experiments to measure the precise composition ratios of selected isotopes in very tiny material samples. Accelerator Mass Spectrometry (AMS) is used for separation of specific isotopes and their analysis; here, small material samples are accelerated in beam lines, and rare isotopes with abundance fractions down to 10^{-15} and below can be detected.

Computing and theory

Advances in computers are the key to developments of the complex theories of nuclear structure, supernova explosions, and cosmic evolution of the abundance of the elements: calculations on the latest hardware enable theories to be explored in a wide range of their parameters, and to guide experiments and compare their results with theoretical predictions. Databases of thousands of nuclei and their reactions, fast algorithms to adapt temporal and spatial resolution in dynamic modeling of, e.g., supernova explosions, and advanced graphics processing to visualise complex data or theories, are also key drivers of the field. New techniques such as artificial intelligence and deep learning have been developed within astrophysical applications and move our analyses into new territory.

Artist's impression of ESO's Extremely Large Telescope (ELT) on Cerro Armazones, Chile, will see "first light" in 2027. With its 39m primary mirror optimized for optical and infrared light, it will be the biggest eye on the sky for decades to come.



***Above:** The new Facility for Antiproton and Ion Research (FAIR) at GSI, Darmstadt, Germany. The existing GSI facility is shown on the left, in dark blue the existing GSI accelerator facilities and ion sources. The new FAIR complex is displayed in red.*

SPIN-OFFS

AND RELEVANCE FOR SOCIETY

The technology and skills developed for nuclear-astrophysics research are helping to find solutions to many of the challenges our society faces today.

HEALTH

Detectors developed for nuclear physics have been adapted for medical imaging and diagnosis: MRI (magnetic resonance imaging), PET (positron emission tomography) and CT (computer-aided tomography). Beams of atomic nuclei are also used to destroy cancerous tumours, and radiotherapy based on injections of radioactive substances is a part of cancer treatment.

Ionising and nuclear radiation is also used to sterilise medical equipment, household items and food, by utilising their lethal effects on microbes.

Applied benefits of nuclear astrophysics are also gained by harvesting and discovering new long-lived excited states of isotopes that play a key role in nuclear medicine, medical diagnostics and treatments of disease.

COMPUTING AND INFORMATION PROCESSING

The computational tools developed by researchers modelling stellar interiors and supernova explosions have inspired a variety of computing methods used in, for example, medical imaging and engineering, or simply to provide faster internet access and faster processors.

ENERGY

Solving mankind's energy supply is one of the biggest challenges for the next decades, and many countries will continue to rely on nuclear power. The techniques of nuclear astrophysics are used to improve the efficiency and safety of nuclear reactors, and technology is now available to 'clean' the radioactive waste so far generated. In the future, reactors employing fusion reactions like those in the Sun will generate safe nuclear energy.

ENVIRONMENT AND ANALYSIS

The evolving global climate and our effect on it is of great importance for mankind. Technologies from astronomy and nuclear physics have improved tools for satellite-based remote sensing. Radioactivity from both natural events, such as volcanoes, and man-made sources are monitored. Measurements of trace isotopes can track subsurface water flows. Detecting minute amounts of characteristic isotopes was pioneered in nuclear-astrophysics laboratories, and now allows us to identify art forgeries, determine the age of artefacts and materials, analyse geological samples, and monitor environmental pollution.

International trade and travel have been made more secure by detectors and analytical techniques from nuclear astrophysics that can track sensitive materials at national borders, and scan cargo and baggage for explosives, radioactive or fissile materials. Short-lived radioisotopes can probe manufacturing processes and analyse product performance, for example, wear and tear in engine components.

A SKILLED WORKFORCE

Understanding the puzzles of the Universe attracts talented students to study physics in an international and multi-disciplinary environment. This training produces highly-skilled individuals with the analytical and technical abilities needed by industry and the public sector to solve the problems faced by society today.

This brochure

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Community information

Throughout Europe, more than 100 research groups with several hundred senior scientists from 30 countries are actively involved in the science of nuclear astrophysics. Their work also relates to the largest nuclear experimental facilities such as CERN and FAIR, to astronomical observatories such as ESO's VLT and future ELT, observatories on space satellites such as ESA's Gaia and INTEGRAL, and to theoretical work connecting astrophysics with observations and experiments. Research groups are supported in their home countries – Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, The Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom – and by their home institutions, often through specific research grants.

The ChETEC community cooperates with many partners outside Europe via international research networks and organisations dedicated to this field (e.g., the IReNA NSF network of networks: URL: https://www.irenaweb.org/). International conferences of the field typically gather several hundred scientists, such as the "Nuclei in the Cosmos" and the European "Nuclear Physics in Astrophysics" bi-annual conference series, with a history of 15 and 9 incarnations, respectively, up to now.

www.chetec.eu

List of partner countries, their ChETEC institutions and relevant facilities

AUSTRIA
U Vienna - VERA

BELGIUM
ULB Brussels

BULGARIA
IANAO - RNAO

CROATIA
RBI Zagreb
U Zagreb

CZECH REPUBLIC
ASU - PEREK

DENMARK
Niels Bohr I, Copenhagen U
U Aarhus - NOT

FINLAND
U Jyväskylä - JYFL

FRANCE
CNRS - GANIL - SPIRAL2
CNRS - IPHC
CNRS- IPN - ALTO
IPGP

GERMANY
AIP Potsdam (Leibniz Gesellschaft)
ESO Garching
Excellence Clusters ORIGINS, UNIVERSE Garching
GSI Darmstadt (Helmholtz Gesellschaft)
H-ITS Heidelberg
HZDR Dresden - DREAMS - ELBE - Felsenkeller (Helmholtz Ges.)
ARI Heidelberg
LSW Heidelberg
MPE Garching (Max Planck Gesellschaft)
MPIA Heidelberg (Max Planck Gesellschaft)
MPICH Mainz (Max Planck Gesellschaft)
MPIK Heidelberg (Max Planck Gesellschaft)
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