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# A Quick Journey in the Universe in the Multimessenger Era

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Multifrequency Astrophysics is a pillar of an interdisciplinary approach to the knowledge of the physics of our Universe. Indeed, as clearly demonstrated in the last decades, only with the multifrequency observations of cosmic sources is it possible to get nearly the whole behaviour of a source and then to approach the physics governing the phenomena that originate such a behaviour. I regard a multidisciplinary approach in the study of each kind of phenomenon occurring in each kind of cosmic source as even more powerful than a simple "astrophysical approach".
Through the use of numerous space-based and ground-based experiments, our knowledge of the Universe has undergone a sharp acceleration. In this review I will try to carry out an imaginary journey into our Universe in order to highlight the progress that has been achieved in the last decades in the knowledge of the physics that governs it.
There are many problems in performing simultaneous nultifrequency, multisite, multiinstrument, multiplatform measurements due to: (i) objective technological difficulties; (ii) sharing common scientific objectives; (iii) problems of scheduling and budgets; and (iv) the political management of science. All these kinds of measurements converge in what is now called *Multimessenger Astrophysics*, this after the detection of gravitational wave events (GWEs) and the search for the electromagnetic counterparts of such events.
I will deal, without claiming to be complete, the leading topics of astrophysics with the aim of making the current knowledge of our Universe easier for the reader.

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## 1. Introduction

The astrophysics experiments carried out on board rockets contributed substantially to the advancement of knowledge of cosmic sources: for everyone it is necessary to remember the experiment by Giacconi et al. (1962) which detected for the first time X-ray emission from an extrasolar source (Sco X-1) which gave rise to the search for high energy sources through the preparation of experiments on board satellites with instruments sensitive to the UV, This is the period around the beginning of the 1970s which can be defined as the advent of the space age. From then on, a myriad of experiments sensitive to the bands of the electromagnetic spectrum not accessible from the ground due to the atmospheric barrier became the source of an immense quantity of data which in the space of just fifty years far exceeded the amount of data acquired until then with ground-based optical telescopes.

Figure 1 shows schematically the amount of data acquired along the electromagnetic spectrum versus time (updated from [1], after [2]).

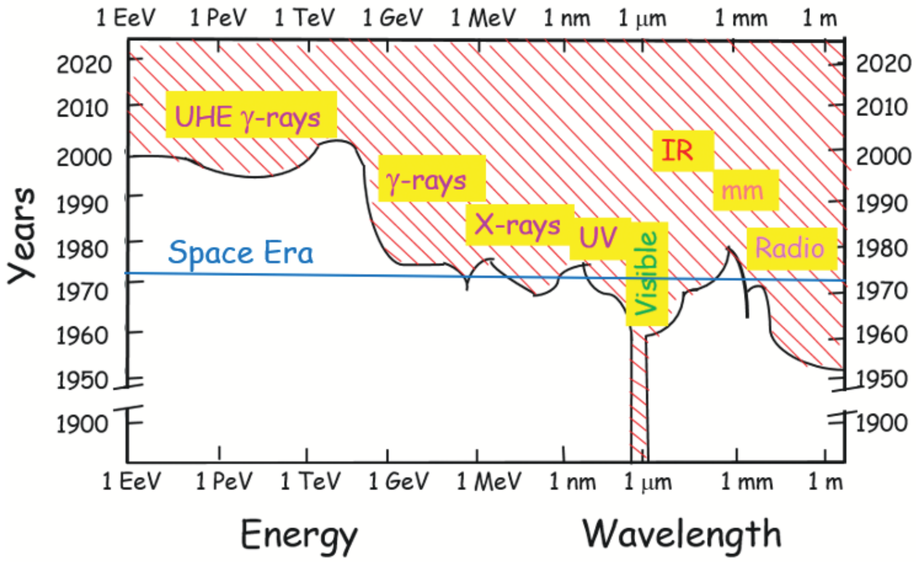



**Figure 1:** Sketch of the multifrequency data acquired after the beginning of the "Space Era" (updated from [1], after [2]).

Astrophysics is a branch of physics that in the last decade has produced important results that have given rise to several Nobel Prizes for Physics. In the following the short description of such prizes derived from astrophysical measurements:

- 2011: Saul Permutter, Adam Riess and Brian Schmidt for the discovery of the accelerating expansion of the Universe through observations of distant SNe.
- 2015: Takaaki Kajita and Artur McDonald for the discovery of neutrino oscillation, which show that neutrinos have mass.
- 2017: Kip Thorne, Rainer Weiss and Barry Barish for decisive contribution to the LIGO detector and the observations of Gravitational Waves (GWs).

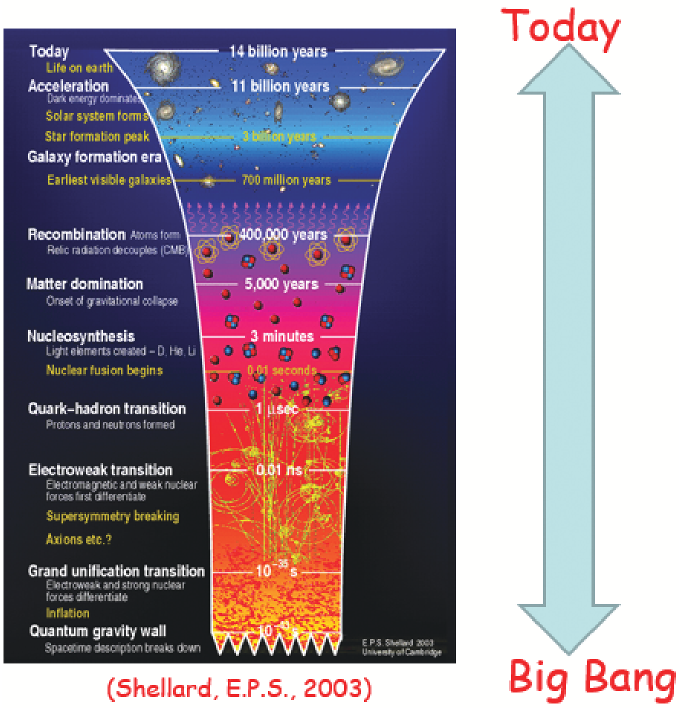



**Figure 2:** The history of the universe (adopted from [3]).

- 2019: James Peebles for theoretical discoveries in physical cosmology, and Didier Queloz and Michael Mayor for the discovery of an exoplanet orbiting a solar-type star.
- 2020: Roger Penrose for the discovery that black hole formation is a robust theory of general relativity, and Andrea Ghez and Reinhard Genzel for the discovery of a supermassive compact object at the center of our galaxy.

## 2. Our Universe

Independent of the origin of our Universe there is a bridge between such an origin and biology simply because we are here in our planet. However actually the most accepted origin of our Universe is the Big Bang occurred roughly 14 billion years ago. Figure 2 shows the history of the universe since the Big Bang up today [3].

What we can observe in the universe is limited to the surface of last scatter of the cosmic microwave background (CMB) radiation. It is analogous to the light coming through the clouds to our eyes on a cloudy day, as shown in Fig. 3 (Credit: NASA/WMAP Science Team - https://wmap.gsfc.nasa.gov/mission/sgoals_parameters_wmap.html).

### 2.1 Background Radiation in the Universe

Tiny inhomogeneities in the early Universe left their imprint on the microwave background in the form of small anisotropies in its temperature. These anisotropies contain information about basic cosmological parameters, particularly the total energy density and curvature of the universe.

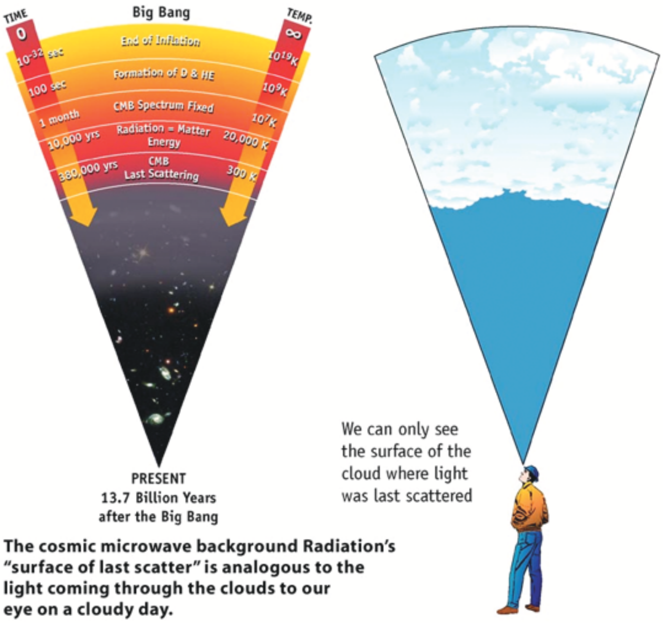



**Figure 3:** The surface of last scatter of the cosmic microwave background (CMB) radiation, analogous to the light coming through the clouds to our eyes on a cloudy day (Credit: NASA/WMAP Science Team).

On April 23, 1992, the COBE team announced the historical discovery of the anisotropies of cosmic microwave background radiation with characteristic anisotropy $\Delta T/T \approx 10^{-5}$ or $\Delta T \sim 30$ $\mu$K on angular scales larger than $\sim 7°$ at the annual meeting of American Physical Society in Washington, D.C. [3].

Observations of the cosmic microwave background temperature anisotropies have revolutionized and continue to revolutionize our understanding of the universe. The observation of the CMB anisotropies angular power spectrum with its plateau, acoustic peaks, and high frequency damping tail have established a standard cosmological model consisting of a flat – critical density – geometry, with contents being mainly dark energy (DE) and dark matter (DM) and a small amount of ordinary matter. In this successful model the dark and ordinary matter formed its structure through gravitational instability acting on the quantum fluctuations generated during the very early inflationary epoch. Current and future observations will test this model and determine its key cosmological parameters with spectacular precision and confidence (see the Nobel Lecture of George F. Smoot [4] for an exhaustive review about the Cosmic Background Radiation Anisotropies).

But the cosmic background radiation, although is peaked in the microwave region, permeates through the whole electromagnetic spectrum and is known as the Diffuse Extragalactic Background RAdiation (DEBRA). It is possible to consider the DEBRA as a radiation produced by a cosmic source: the whole Universe. Such a background radiation from radio to HE $\gamma$-ray energy bands has been deeply discussed by Ressell & Turner [5], and in GSG2004 [1] and the references therein. The analysis of the different components of DEBRA leads to the Grand Unified Photon Spectrum (GUPS), covering 29 orders of magnitude of the electromagnetic spectrum, from $10^{-9}$ to $10^{20}$ eV, as shown in Fig. 4 (after [5]). The light–red and the light–indico rectangles indicate the domains with energies less or greater than $\approx$ 10 GeV, respectively. The domain at higher energies is now

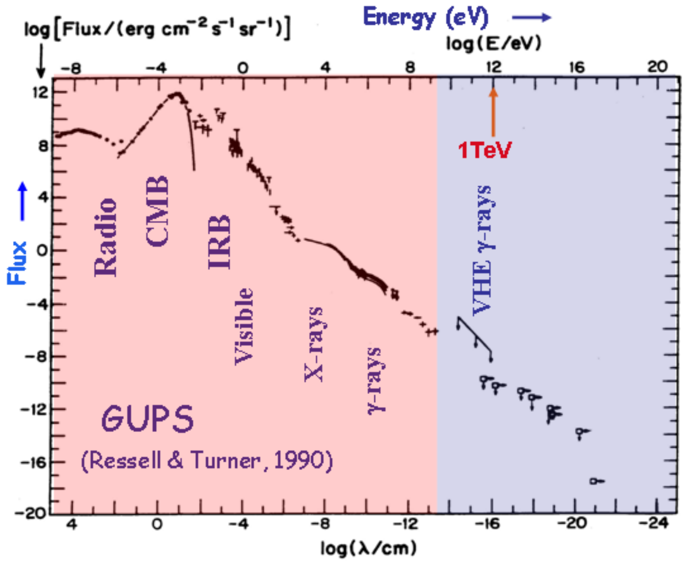



**Figure 4:** The Grand Unified Photon Spectrum of the Diffuse Extragalactic Background Radiation (after [5]).

explored by numerous experiments space–based, like Fermi LAT observatory (up to 300 GeV) and ground–based, like Whipple, Veritas, HESS, Magic, and the coming CTA (Cherenkov Telescopes Array). All these experiments will provide to fill the zone of the GUPS diagram prepared by Ressell & Turner [5] where only upper limits were reported. This paper was published in Communications in Astrophysics, a journal not present in all libraries of the universities and of research institutes. For this reason this important paper was ignored by most astrophysicists.

Henry [6,7] thoroughly discussed the experimental situation of the cosmic background till 2000.

### 2.2 Extragalactic Background Light

The intergalactic space is filled with the light produced by all the stars and accreting compact objects that populated the observable Universe throughout the whole cosmic history. This relic cosmic background from IR to UV is called the diffuse Extragalactic Background Light (EBL), long before known as DEBRA [5].

Direct measurements of the EBL are difficult due to bright local foregrounds. A powerful approach for probing these diffuse radiation fields in the UV to far-IR bands is through $\gamma$–$\gamma$ absorption of high-energy photons. Actually pair production ($e^+$ $e^-$) against EBL photons with wavelengths from ultraviolet to infrared is effective at attenuating $\gamma$–rays with energy above $\sim$ 10 GeV. This process introduces an attenuation in the spectra of $\gamma$–ray sources above a critical energy (e.g. [8,9]).

The last decade has been foreboding of a full coverage of the HE-VHE $\gamma$-ray energy band, thanks to the many ground– and space–based high sensitivity experiments. Thus it has been possible to collect a large amount of data from many extragalactic emitters at high redshift (e.g. [8]). Thanks to measurements of the quasar 3C 279 ($z \simeq 0.54$) obtained with the MAGIC experiment [12], and with the many sources at high redshift, including Gamma Ray Bursts (GRBs) measured with the

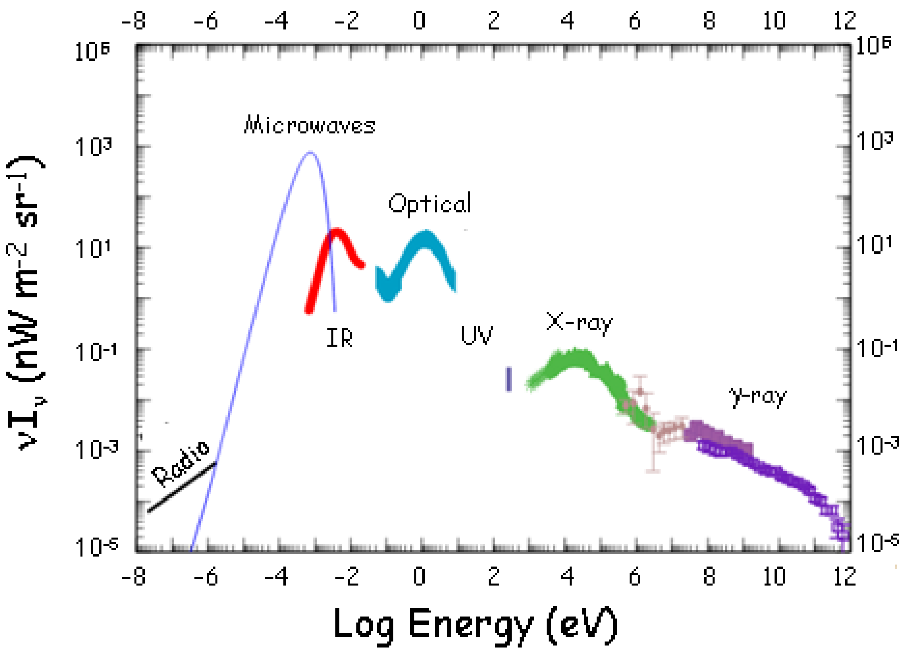



**Figure 5:** Intensity of the extragalactic background ($\nu I_\nu$ in units of nW m$^{-2}$ sr$^{-1}$) as a function of the energy (adopted from [10], after [11]).

FERMI observatory [13], it has been demonstrated that the Universe is more transparent to $\gamma$–rays than before believed [14].

Cooray [11] reviews the Extragalactic Background Light Measurements and Applications. This review covers the measurements related to the extragalactic background light intensity from $\gamma$-rays to radio in the electromagnetic spectrum over 20 decades in wavelength. Figure 5 shows such EBL measurements that updated those reported by Ressel & Turner [5]. It is important to remark that the numerous measurements in the range of the VHE $\gamma$-rays (Log E $\approx 9 - 13$ eV) have filled the zone where no measurements or only upper limits were available in the 1990-ies.

The CMB remains the best measured spectrum with an accuracy better than 1%. Durrer [15] in her interesting review describes the discovery of the cosmic microwave background radiation in 1965 and its impact on cosmology in the 50 years that followed.

Henry et al. [16] discussed the diffuse cosmic background radiation in the Galaxy Evolution Explorer far-ultraviolet (FUV, 1300-1700 Å. They deduced that the UV diffuse cosmic background radiation originates only partially in the dust-scattered radiation of FUV-emitting stars: the source of a substantial fraction of the FUV background radiation remains a mystery. They also discussed about our limited knowledge of the cosmic diffuse background at ultraviolet wavelengths shortward of Ly$\alpha$ - it could be that a "second component" of the diffuse FUV background persists shortward of the Lyman limit and is the cause of the reionization of the universe.

### 2.3 Confirmation of the Theory of General Relativity

In the last few years two further experimental results confirmed the validity of the theory of General Relativity (GR theory).

### 2.3.1 Gravitational lenses

Renn, Sauer & Stachel [17] published a historical reconstruction of some of Einstein's research notes dating back to 1912. These notes reveal that he explored the possibility of gravitational lensing 3 years before completing his general theory of relativity. On the basis of preliminary insights into this theory, Einstein had already derived the basic features of the lensing effect. When he finally published the very same results 24 years later, it was only in response to prodding by an amateur scientist.

Kochanek [18] discussed "The whys and hows of finding 10,000 lenses", mentioning the first radio lens survey – the MIT - Green Bank survey (MG) – that found lenses by obtaining Very Large Array (VLA) snapshot images of flux-limited samples of 5 GHz radio sources. The Hubble Space Telescope (HST), and Chandra observations (e.g. [19]) showed without any doubt that the gravitational lensing is operating.

Gravitational lensing is widely and successfully used to study a range of astronomical phenomena, from individual objects, like galaxies and clusters, to the mass distribution on various scales, to the overall geometry of the Universe (Williams & Schechter, [20]). They describe and assess the use of gravitational lensing as "gold standards" in addressing one of the fundamental problems in astronomy, the determination of the absolute distance scale to extragalactic objects, namely the Hubble constant.

Several papers have been published about the strong gravitational lensing (e.g. [21]; [22] and references therein), and the weak gravitational lensing [23]. A review on "Gravitational Lenses" have been published by Blandford & Kochanek [24]. A book on "Gravitational Lensing: Strong, Weak and Micro" was published by Meylan et al. [25]. Winn, Rusin & Kochanek [26] reported the most secure identification of a central image, based on radio observations of PMN J1632-0033.

Therefore, a further dowel supports the GR theory.

It is important to mention the paper *Resource Letter GL-1: Gravitational Lensing* by Treu, Marshall & Clowe [27]. This Resource Letter provides a guide to a selection of the literature on gravitational lensing and its applications. Journal articles, books, popular articles, and websites are cited for the following topics: foundations of gravitational lensing, foundations of cosmology, history of gravitational lensing, strong lensing, weak lensing, and microlensing.

Indeed, each Resource Letter focuses on a particular topic and intends to help teachers to improve course content in a specific field of physics or to introduce nonspecialists to this field.

### 2.3.2 Gravitational waves

The Universe that contains by definition all the matter or all the energy available showed one important event that was possible to be detected on the Earth. This event was a further direct experimental demonstration of the validity of the GR theory. Indeed, on September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory (LIGO) simultaneously observed a transient gravitational-wave signal. It matches the waveform predicted by GR theory for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a significance $\geq 5.1\sigma$ (Fig. 6). The source lies at a luminosity distance of $410^{+160}_{-180}$ Mpc corresponding to a redshift z = $0.090^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4}$ $M_{\odot}$ and $29 \pm 4$ $M_{\odot}$, and the final black hole mass is 62 ± 4 $M_\odot$ with 3.0 ± 0.5 $M_\odot$ $c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger [28].

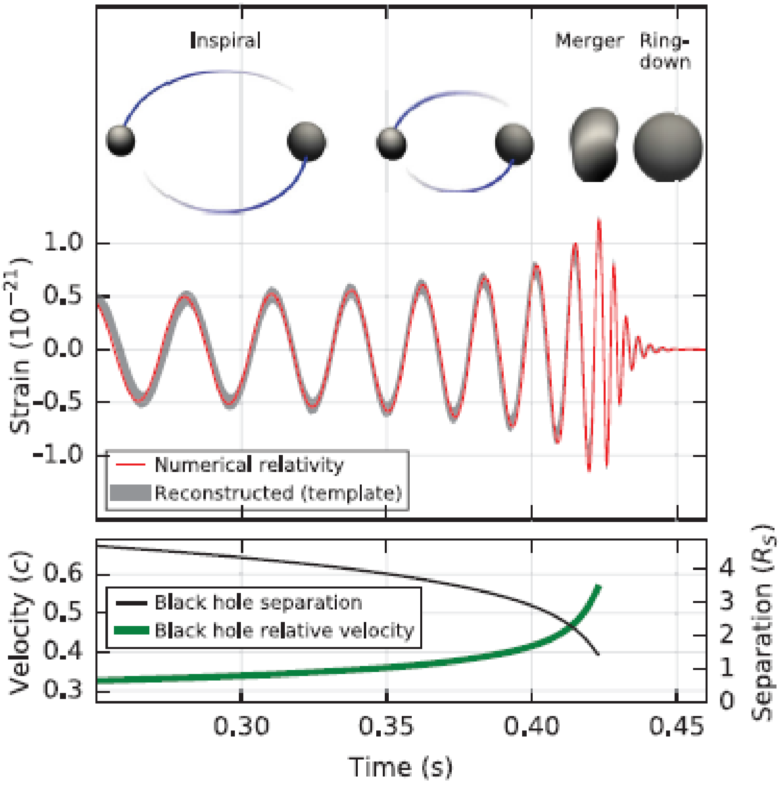



**Figure 6:** The GW150914 event. Top: estimated gravitational-wave strain amplitude. Bottom: the Keplerian effective black hole separation in units of Schwarzschild radii (adopted from [28]).

Abbott et al. [29] reported the second observation of a gravitational-wave signal produced by the coalescence of two stellar-mass black holes. The signal, GW151226, was observed by the twin detectors of the LIGO on December 26, 2015 at 03:38:53 UTC. The signal was detected at significance ≥ $5\sigma$. The inferred source-frame initial black hole masses are $14.2^{+8.3}_{-3.7}$ $M_\odot$ and 7.5±2.3 $M_\odot$, and the final black hole mass is $20.8^{+6.1}_{-1.7}$ $M_\odot$. One finds that at least one of the component black holes has spin greater than 0.2. This source is located at a luminosity distance of $440^{+180}_{-190}$ Mpc corresponding to a redshift z = $0.09^{+0.03}_{-0.04}$. All uncertainties define a 90% credible interval. This second gravitational-wave observation provides improved constraints on stellar populations and on deviations from the GR theory.

For these detections of gravitational waves – first predicted by Einstein 100 years ago – Rainer Weiss, Barry Barish & Kip Thorne have been awarded the 2017 Nobel prize in physics.

Abbott et al. [30] present a possible observing scenario for the Advanced LIGO (aLIGO) and Advanced Virgo gravitational-wave detectors over the next decade, with the intention of providing information to the astronomy community to facilitate planning for multimessenger astronomy with gravitational waves.

Gravitational waves provide a revolutionary tool to investigate yet unobserved astrophysical objects. Especially the first stars, which are believed to be more massive than present-day stars, might be indirectly observable via the merger of their compact remnants. An interesting paper by Hartwig et al. [31] developed a self-consistent, cosmologically representative, semi-analytical model to simulate the formation of the first stars. They estimated the contribution of primordial stars to the merger rate density and to the detection rate of the aLIGO. Owing to their higher masses, the remnants of primordial stars produce strong GW signals, even if their contribution in number is relatively small. They found a probability of $\geq 1\%$ that the current detection GW150914 is of primordial origin. The higher masses of the first stars boost their GW signal, and therefore their detection rate. Up to five detections per year with aLIGO at final design sensitivity originate from Pop III BH-BH mergers. Approximately once per decade, we should detect a BH-BH merger that can unambiguously be identified as a Pop III remnant.

On 2017 August 17 the merger of two compact objects with masses consistent with two neutron stars was discovered through gravitational-wave (GW170817), gamma-ray (GRB 170817A), and optical (SSS17a/AT2017gfo) observations. The optical source was associated with the early-type galaxy NGC 4993 at a distance of just $\sim$ 40 Mpc, consistent with the gravitational-wave measurement, and the merger was localized to be at a projected distance of $\sim$ 2 kpc away from the galaxy's center [32,33].

Lipunov et al. [34] predicted the NS-NS merger at a distance of $\leq$ 50 Mpc and the possibility of detecting GWs! They found the double neutron star merging rate as $R \approx 2 \times 10^{-4}$ yr$^{-1}$ $10^{-11}$ $M_\odot$ that is $10^7$ events yr$^{-1}$ for the entire Universe.

This prediction was born by the "Scenario Machine" that describes the evolution of gravimagnetic rotators [35,36], and commented by Giovannelli [37].

On August 17, 2017 Multimessenger Astrophysics was born! As pioneer of the Multifrequency Astrophysics, I am particularly happy!

Poggiani [38] published an extensive review about the GW170817 event, in which she discussed also the related multimessenger observations.

The LIGO and Virgo interferometers have now confidently detected gravitational waves from a total of 10 stellar-mass binary black hole mergers and one merger of neutron stars, which are the dense, spherical remains of stellar explosions. Table 1 shows the eleven events (adapted from [39]).

Figure 7 shows the Gravitational-Wave Transient Catalog-1 where the plots (frequency vs time) of the 11 events listed in Table 1 are reported together with the Einstein's theory predictions (Credit: LIGO Scientific Collaboration and Virgo Collaboration/Georgia Tech/S. Ghonge & K. Jani).

Figure 8 shows the localizations of the eleven gravitational-wave detections in the sky – listed in Table 1 (http://www.virgo-gw.eu/ (2018)).

The Advanced LIGO and Advanced Virgo detector network observed 90 binary-system mergers from 2015 to 2020. This is an updated version of the Gravitational-Wave Transient Catalog (https://www.ligo.org/detections/O3bcatalog.php).

Nitz et al. [40] present the fourth Open Gravitational-wave Catalog (4-OGC) of binary neutron star (BNS), binary black hole (BBH), and neutron star–black hole (NSBH) mergers. The catalog includes observations from 2015 to 2020 covering the first through third observing runs (O1, O2, O3a, and O3b) of Advanced LIGO and Advanced Virgo. The updated catalog includes seven

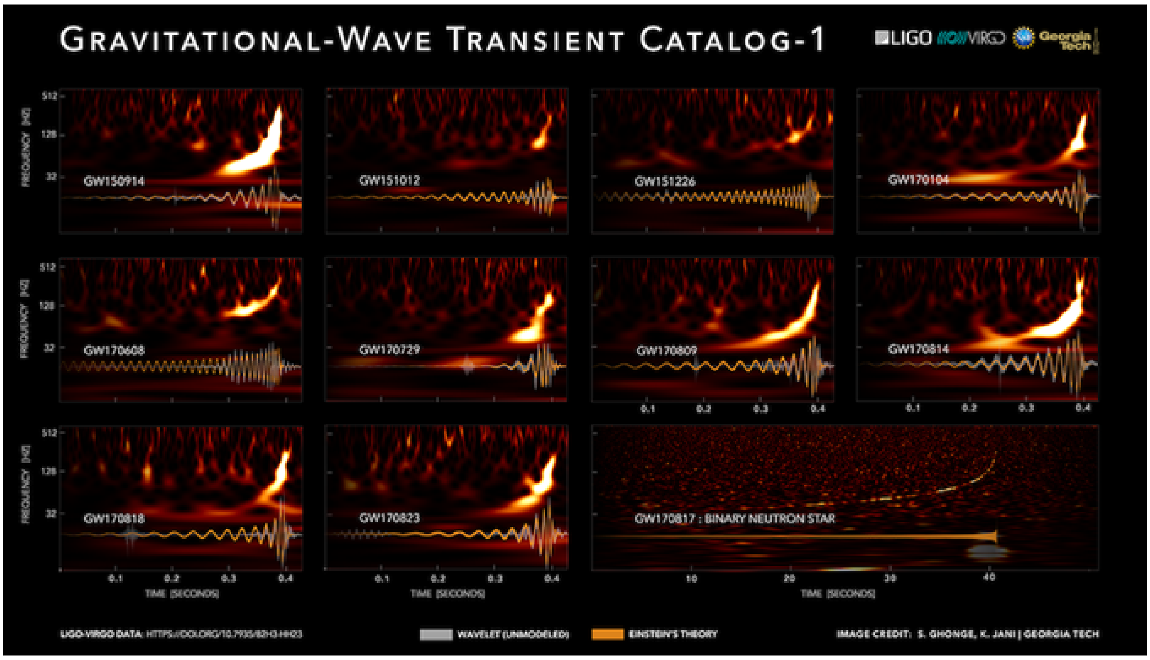



**Figure 7:** Gravitational Wave Transient Catalog-1. Credit: LIGO Scientific Collaboration and Virgo Collaboration/Georgia Tech/; Image Credit: S. Ghonge & K. Jani.

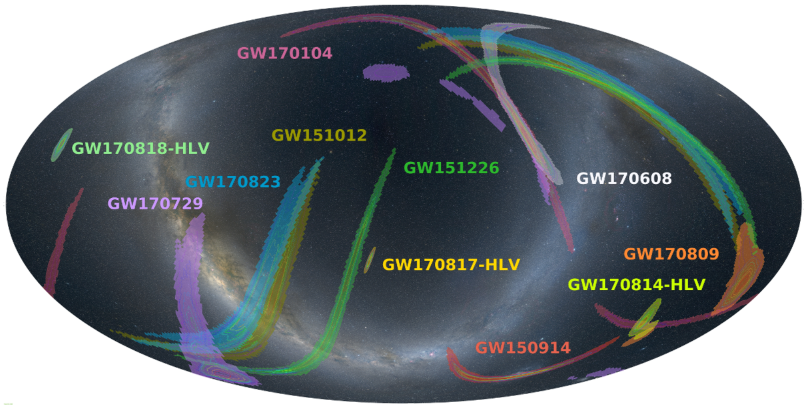



**Figure 8:** The localizations of the eleven gravitational-wave detections in the sky (http://www.virgo-gw.eu/ (2018)).

BBH mergers that were not previously reported with high significance during O3b for a total of 94 observations: 90 BBHs, 2 NSBHs, and 2 BNSs.

Barone et al. [41] analyzed the class of CVs as sources of Gravitational Radiation, basing their analysis only on known objects at that time (168 CVs) taken from the Catalog of Ritter [42].

From the analysis of GW emission from CVs, they derived that the emission frequencies are in the range $10^{-3}$ - $10^{-5}$ Hz and that the GW flux at Earth is in the range $10^{-10}$ - $10^{-13}$ erg $s^{-1}$ $cm^{-2}$ while the dimensionless amplitude is in the range $10^{-21}$ - $10^{-23}$. These results constituted a solid basis for planning the construction of GW detectors (especially space-borne GW antennas). Moreover, these results provided the possibility of experimentally proving the effectiveness of the

**Table 1:** Selected source parameters of the 11 confident detections. The columns show source-frame component masses $m_1$ and $m_2$, the chirp mass M, final source-frame mass $M_f$, luminosity distance $d_L$, and redshift z (adapted from Abbott et al., 2019).

| GW Event (name) | $m_1$ ($M_\odot$) | $m_2$ ($M_\odot$) | M ($M_\odot$) | $M_f$ ($M_\odot$) | $d_L$ (Mpc) | z (redshift) |
|---|---|---|---|---|---|---|
| GW 150914 | $35.6^{+4.7}_{-3.1}$ | $30.6^{+3.0}_{-4.4}$ | $28.6^{+1.7}_{-1.5}$ | $63.1^{+3.4}_{-3.0}$ | $440^{+150}_{-170}$ | $0.09^{+0.03}_{-0.03}$ |
| GW 151012 | $23.2^{+14.9}_{-5.5}$ | $13.6^{+4.1}_{-4.8}$ | $15.2^{+2.1}_{-1.2}$ | $35.6^{+10.8}_{-3.8}$ | $1080^{+550}_{-490}$ | $0.21^{+0.09}_{-0.09}$ |
| GW 151226 | $13.7^{+8.8}_{-3.2}$ | $7.7^{+2.2}_{-2.5}$ | $8.9^{+0.3}_{-0.3}$ | $20.5^{+6.4}_{-1.5}$ | $450^{+180}_{-190}$ | $0.09^{+0.04}_{-0.04}$ |
| GW 170104 | $30.8^{+7.3}_{-5.6}$ | $20.0^{+4.9}_{-4.6}$ | $21.4^{+2.2}_{-1.8}$ | $48.9^{+5.1}_{-4.0}$ | $990^{+440}_{-430}$ | $0.20^{+0.08}_{-0.08}$ |
| GW 170608 | $11.0^{+5.5}_{-1.7}$ | $7.6^{+1.4}_{-2.2}$ | $7.9^{+0.2}_{-0.2}$ | $17.8^{+3.4}_{-0.7}$ | $320^{+120}_{-110}$ | $0.07^{+0.02}_{-0.02}$ |
| GW 170729 | $50.2^{+16.2}_{-10.2}$ | $34.0^{+9.1}_{-10.1}$ | $35.4^{+6.5}_{-4.8}$ | $79.5^{+14.7}_{-10.2}$ | $2840^{+1400}_{-1360}$ | $0.49^{+0.19}_{-0.21}$ |
| GW 170809 | $35.0^{+8.3}_{-5.9}$ | $23.8^{+5.1}_{-5.2}$ | $24.9^{+2.1}_{-2.7}$ | $56.3^{+5.2}_{-3.8}$ | $1030^{+320}_{-390}$ | $0.20^{+0.05}_{-0.07}$ |
| GW 170814 | $30.6^{+5.6}_{-3.0}$ | $25.2^{+2,8}_{-4,0}$ | $24.1^{+1.4}_{-1.1}$ | $53.2^{+3.2}_{-2.4}$ | $600^{+150}_{-220}$ | $0.12^{+0.03}_{-0.04}$ |
| GW 170817 | $1.46^{+0.12}_{-0.10}$ | $1.27^{+0.09}_{-0.09}$ | $1.186^{+0.001}_{-0.001}$ | $\leq 2.8$ | $40^{+7}_{-15}$ | $0.01^{+0.00}_{-0.00}$ |
| GW 170818 | $35.4^{+7.5}_{-4.7}$ | $26.7^{+4.3}_{-5.2}$ | $26.5^{+2.1}_{-1.7}$ | $59.4^{+4.9}_{-3.8}$ | $1060^{+420}_{-380}$ | $0.21^{+0.07}_{-0.07}$ |
| GW 170823 | $39.5^{+11.2}_{-6.7}$ | $29.0^{+6.7}_{-7.8}$ | $29.2^{+4.6}_{-3.6}$ | $65.4^{+10.1}_{-7.4}$ | $1940^{+970}_{-900}$ | $0.35^{+0.15}_{-0.16}$ |

mechanism of Gravitational Radiation on CV evolution.

This important work was not sufficiently taken into account by the international community. However, now, after the detection of GWs coming from the fusion of black holes and neutron stars, the interest for that work has been rekindled in order to test the possibility of detecting GWs from CVs. Poggiani [43], and the references therein) discussed this possibility, reaching the conclusion that AM CVn systems and generally short-period systems are candidates for GW emission.

Amaro-Seoane et al. [44] in response to the ESA call for L3 mission concepts, presented the Laser Interferometer Space Antenna (LISA) that since 2030 will allow to observe Gravitational Waves from cosmic sources, then to explore a Universe inaccessible otherwise, a Universe where gravity takes on new and extreme manifestations. They concluded as follows: *The groundbreaking discovery of Gravitational Waves by ground-based laser interferometric detectors in 2015 has changed astronomy, by giving us access to the high-frequency regime of Gravitational Wave astronomy. By 2030 our understanding of the Universe will have been dramatically improved by new observations of cosmic sources through the detection of electromagnetic radiation and high-frequency Gravitational Waves. But in the low-frequency Gravitational Wave window, below one Hertz, we expect to observe the heaviest and most distant objects. Using our new sense to 'hear' the*

*Universe with LISA, we will complement our astrophysical knowledge, providing access to a part of the Universe that will forever remain invisible with light. LISA will be the first ever mission to survey the entire Universe with Gravitational Waves. It will allow us to investigate the formation of binary systems in the Milky Way, detect the guaranteed signals from the verification binaries, study the history of the Universe out to redshifts beyond 20, when the Universe was less than 200 million years old, test gravity in the dynamical sector and strong-field regime with unprecedented precision, and probe the early Universe at TeV energy scales. LISA will play a unique and prominent role in the scientific landscape of the 2030s.*

### 2.4 The most extreme objects in the Universe

The first image of a black hole, using Event Horizon Telescope (EHT) observations of the center of the galaxy M87 is shown in Fig. 9, left panel. The image shows a bright ring formed as light bends in the intense gravity around a black hole with $M_{BH} = 6.5 \times 10^9\ M_{\odot}$. This long-sought image provides the strongest evidence to date for the existence of supermassive black holes and opens a new window onto the study of black holes, their event horizons, and gravity [45,46].

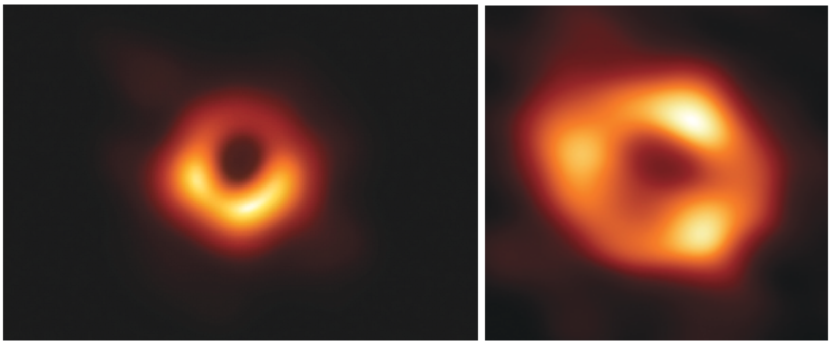


**Figure 9:** Left panel: Image of M 87 Black Hole (April 10, 2019) (Credit: Event Horizon Telescope Collaboration). Right panel: Image of Sgr A* Black Hole (Credit: Event Horizon Telescope Collaboration).

The right panel of Fig. 9 shows the Sgr A* black hole at the center of the Milky Way. This is the second-ever direct image of a black hole having a mass $M_{BH} = (4.154 \pm 0.014) \times 10^6\ M_{\odot}$ [47].

A new image from the Event Horizon Telescope (EHT) collaboration has uncovered strong and organized magnetic fields spiraling from the edge of the supermassive black hole Sgr A* [48] is shown in left panel of Fig. 10. Seen in polarized light for the first time, this new view of the monster lurking at the heart of the Milky Way Galaxy has revealed a magnetic field structure strikingly similar to that of the black hole at the center of the M87 galaxy [45,49,50] - shown in the right panel of Fig. 10. The color scale traces the total intensity of the gravitationally lensed radio light emitted from around the black hole, and the streamlines indicate the polarization direction at each point in the image. A comparison of the two images of Fig. 10 suggest that strong magnetic fields may be common to all black holes. This similarity also hints toward a hidden jet in Sgr A*.

Important results were recently obtained by the Gaia mission [51]. Gaia's black holes at their positions in the sky are shown in the upper panel of Fig. 11. These black holes are also the closest ones to Earth that we know of. Lower panel of Fig. 11 reports the masses of known galactic black holes against their orbital periods, including those detected by the Gaia mission [52-54]. All of these black holes are part of a binary system. While black holes in X-ray binaries are typically detected due to the X-rays they emit when the matter of their neighbouring star is 'eaten', the black holes found by Gaia are all dormant. Gaia BH3 clearly stands out, both with its mass as well as with its orbital period.

Most black holes of stellar origin in our galaxy have a mass of about 10 $M_\odot$, with the record until now held by the black hole in Cyg X-1 with an estimated mass of about 20 $M_\odot$. Gaia BH3 goes way beyond and is the new record holder in our galaxy. Its mass is pinned down with unparalleled accuracy as well (32.7 ± 0.82 $M_\odot$), putting it firmly in the 30 solar mass range.

### 2.5 The accelerating Universe

The discovery of the accelerating expansion of the Universe is a milestone for cosmology. A very interesting paper about this argument has been published in 2011 by the "Class for Physics of the Royal Swedish Academy of Sciences" as Scientific Background on the Nobel Prize in Physics 2011. In this paper a historical journey about the last century development of cosmology is brilliantly presented.

The discovery in 1998 that the universe is speeding up and not slowing down [55,56] opened a question about the possibility of having different phases of acceleration and deceleration of the Universe along its life. Turner & Riess [57] from observations of SN 1997ff at $z \sim 1.7$ favor the accelerating universe interpretation and provide some direct evidence that the universe was once decelerating. They show that the strength of this conclusion depends upon the nature of the dark energy causing the present acceleration. Only for a cosmological constant is the SNe evidence definitive. Using a new test which is independent of the contents of the universe, they show that the SN data favor recent acceleration ($z < 0.5$) and past deceleration ($z > 0.5$).

Nielsen, Guffanti & Sarkar [58] found marginal evidence for cosmic acceleration from type Ia Supernovae. On the contrary, Haridasu et al. [59] found that the SN data alone indicate an accelerating Universe at more than $4.56\sigma$ confidence level.

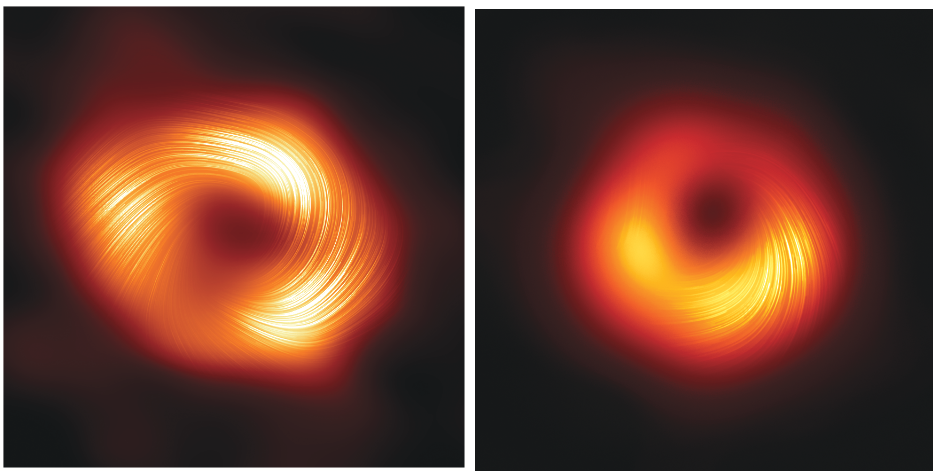
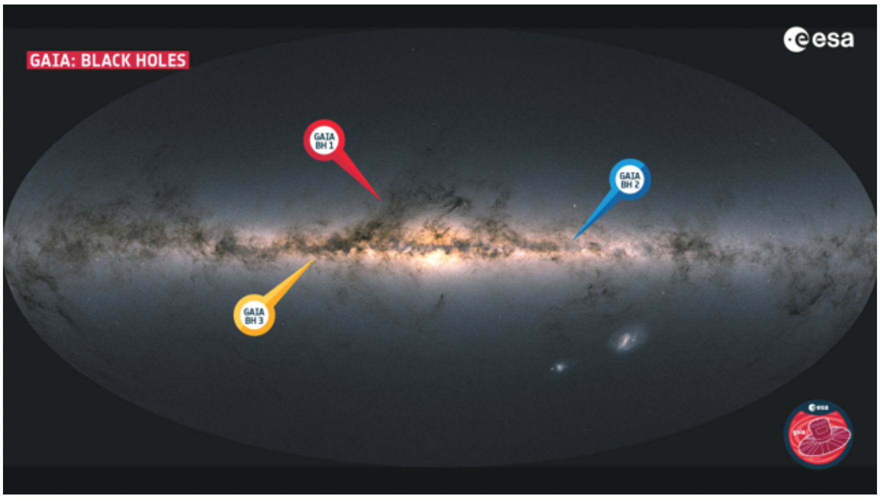


**Figure 10:** Left panel: polarized view of Sgr A* black hole [48]. Right panel: polarimetric average image of M 87 black hole [50].



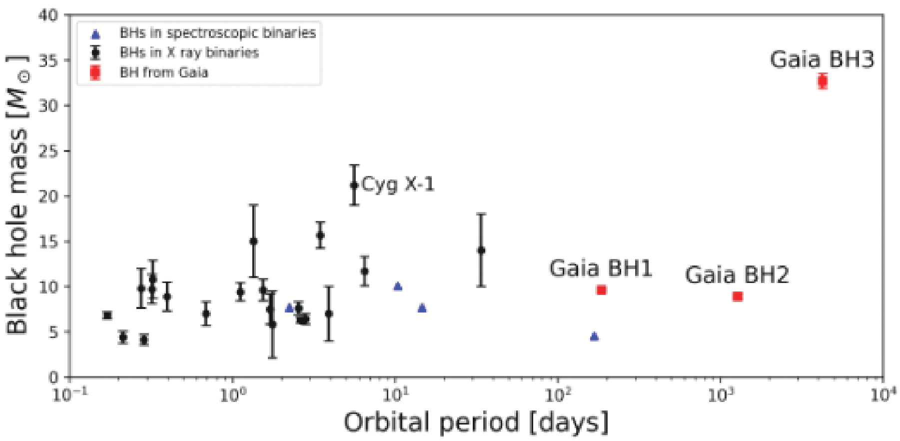




**Figure 11:** Upper panel: Gaia's black hole position (Credits: ESA/Gaia/DPAC- CC BY-SA 3.0 IGO). Lower panel: Galactic black hole mass vs orbital period (Credits: ESA/Gaia/DPAC - CC BY-SA 3.0 IGO. Acknowledgement: Created by Pasquale Panuzzo).

Considering that some divergent conclusions about cosmic acceleration were obtained using Type Ia supernovae (SNe Ia), with opposite assumptions on the intrinsic luminosity evolution, Tu, Hu & Wang [60] used strong gravitational lensing systems to probe the cosmic acceleration. They found that the flat ΛCDM is strongly supported by the combination of the data sets from 152 strong gravitational lensing systems.

### 2.6 The Big Bang Nucleosynthesis theory has been proved

The Big Bang Nucleosynthesis (BBN) theory predicts the presence of a fixed content of light elements, the temperature of the Universe inversely proportional to the typical distance between galaxy clusters: T = T(0) (1+z), and the CMB radiation temperature of ∼ 2.7 K.

In the last decade several experiments provided results confirming the validity of the BBN. In Fig. 12 one can see: i) (left panel): red star - the experimental confirmation of the content of the primordial light elements [61] superimposed to the theoretical curves [62]; ii) (middle panel): red line - the temperature of the Cosmic Microwave Background Radiation ($T_{CMBR}$) at redshift z =

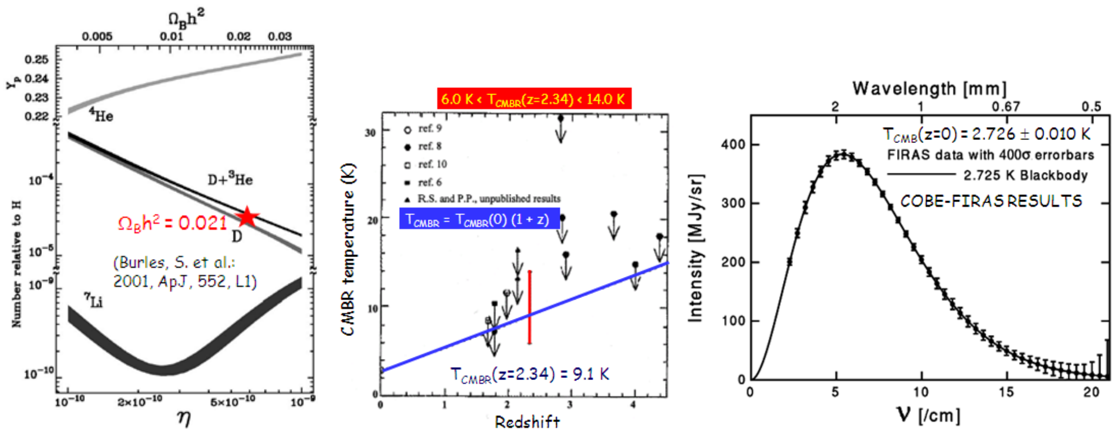



**Figure 12:** Three experimental results in favor of the BBN (see text for explanation).

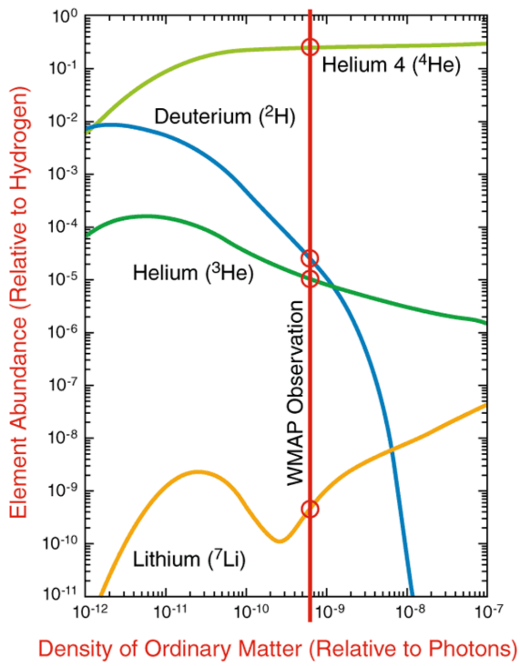



**Figure 13:** The experimental confirmation of the content of the primordial light elements from WMAP (https://map.gsfc.nasa.gov/universe/).

2.34, ranging between 6 and 14 K [63], in agreement with the theoretical temperature law $T_{CMBR}$= $T_{CMBR}(0)(1+z)$, which gives at z = 2.34 a temperature of 9 K; iii) (right panel): the CMB radiation temperature (2.726 ± 0.010 K) [64], after [65].

However, the Big Bang model can be tested further, thanks to the WMAP (Wilkinson Microwave Anisotropy Probe). Given a precise measurement of the abundance of ordinary matter, the predicted abundances of the other light elements becomes highly constrained. The WMAP satellite is able to directly measure the ordinary matter density and finds a value of 4.6% (± 0.2%), indicated by the vertical red line in Fig. 13 (https://map.gsfc.nasa.gov/universe/). This leads to predicted abundances shown by the circles in the graph, which are in good agreement with observed abundances. This is an important and detailed test of nucleosynthesis and is further evidence in support of the Big Bang theory.

However, in order to prove definitively the Big Bang theory it is necessary to measure the primordial B-mode polarization of the Cosmic Microwave Background (CMB) that until now, in spite of many attempts, it is still a chimera. B-mode polarization anisotropies in the CMB is a clear signature of the inflation. These anisotropies originate from tensor fluctuations of the metric produced during the inflationary phase. Their detection would therefore constitute a major step towards understanding the primordial Universe.

The theory of inflation is criticized by Ijjas, Steinhadt & Loeb [66]. They suggest that the origin of the Universe is not the Big Bang, but could be a "bouncing" Universe that does not need the inflation [67,68].

For this reason the measure of B-mode polarization anisotropies of CMB appears as the fundamental proof of the inflation.

For this purpose many experiments have been realized - but until now no one gave positive results - and others in preparation, e.g.:

- The QUBIC instrument based on the novel concept of bolometric interferometry, bringing together the sensitivity advantages of bolometric detectors with the systematics effects advantages of interferometry [69,70].

- The Large Scale Polarization Explorer (LSPE), a program dedicated to the measurement of the CMB polarization. LSPE is composed of two instruments: LSPE-Strip, a radiometer-based telescope on the ground in Tenerife-Teide observatory, and LSPE-SWIPE (Short-Wavelength Instrument for the Polarization Explorer) a bolometer-based instrument designed to fly on a winter arctic stratospheric long-duration balloon [71].

- The European Space Agency's Planck satellite was the third-generation space mission dedicated to measurements of CMB anisotropies. Planck satellite - dedicated to studying the early Universe and its subsequent evolution - was launched on 14 May 2009. It scanned the microwave and submillimetre sky continuously between 12 August 2009 and 23 October 2013, producing deep, high-resolution, all-sky maps in nine frequency bands from 30 to 857 GHz [72], and the references therein. The polarization data provided improved constraints on inflationary models that predict a small statistically anisotropic quadupolar modulation of the primordial fluctuations. However, the polarization data do not support physical models for a scale-dependent dipolar modulation. All these findings support the key predictions of the standard single-field inflationary models, which will be further tested by future cosmological observations [73].

- Bennett et al. [74] presented the final nine-year maps and basic results from the Wilkinson Microwave Anisotropy Probe (WMAP) mission. When WMAP data are combined with finer scale CMB, baryon acoustic oscillation, and Hubble constant measurements, they found that Big Bang nucleosynthesis is well supported and there is no compelling evidence for a non-standard number of neutrino species ($N_{eff}$ = 3.84 ± 0.40). The model fit also implies that the age of the universe is $t_0$ = 13.772 ± 0.059 Gyr, and the fit Hubble constant is $H_0$ = 69.32 ± 0.80 km $s^{-1}$ $Mpc^{-1}$. Inflation is also supported.

- The Bicep2 telescope is designed to measure the polarization of the cosmic microwave background on angular scales near 2-4 degrees, near the expected peak of the B-mode polarization signal induced by primordial gravitational waves from inflation [75].
- LiteBIRD "Lite satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection" is a space mission dedicated to the study of the CMB. LiteBIRD has been selected as a "Large Mission" by the Japanese Space Agency JAXA, who is the leader of a worldwide collaboration that includes Japan, USA, Europe and Canada. LiteBIRD, the next-generation CMB experiment, aims for a launch in Japan's fiscal year 2032, marking a major advancement in the exploration of primordial cosmology and fundamental physics. Orbiting the Sun-Earth Lagrangian point L2, this JAXA-led strategic L-class mission will conduct a comprehensive mapping of the CMB polarization across the entire sky [76]. LiteBIRD represents the fourth generation of satellites dedicated to the CMB following its predecessors COBE, WMAP and Planck and it will be the first completely dedicated to the CMB polarization.

### 2.7 Is the Universe Flat?

One of the most critical points about our Universe is the problem of its flatness. The present state of the cosmological tests is illustrated in Fig. 14.

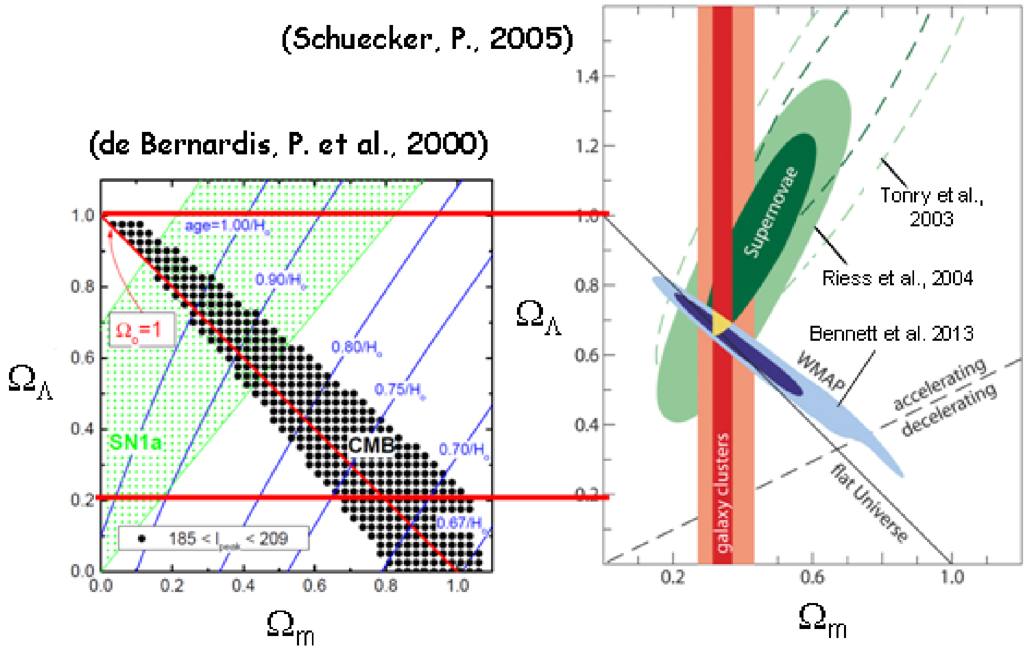



**Figure 14:** Constraints of cosmological parameters (after [61,74 77]).

The left panel of Fig. 14 shows the results obtained with the BOOMERanG (Balloon Observations Of Millimetric Extragalactic Radiation and Geomagnetics) experiment [61]. They are fully consistent with a spatially flat Universe. The right panel of Fig. 14 shows the combination of the likelihood contours obtained with three different observational approaches: i) type-Ia SNe [78,79]; ii) CMB [74,80]; iii) galaxy clusters [77,81]. One can see that the cosmic matter density is close to $\Omega_m$ = 0.3, and that the normalized cosmological constant is around $\Omega_\Lambda$ = 0.7. This sums up to unit total cosmic energy density and suggests a spatially flat universe. However, the density of cosmic matter growths with redshift like $(1 + z)^3$ whereas the density $\rho_\Lambda$ related to the cosmological constant $\Lambda$ is independent of z. The final results from WMAP [70] show a little misalignment with the line of "flat Universe". Thus it is necessary to be careful in the conclusions.

### 2.8 Hubble Constant

The Hubble constant ($H_0$) is one of the most important numbers in cosmology because it is needed to estimate the size and age of the universe. The important problem of determination of $H_0$ value is one of the most exciting. Indeed, in the literature it is possible to find many determinations coming from different experiments using different methods. However, it is very complicated to obtain a true value for $H_0$. It is necessary to have two measurements: i) spectroscopic observations that reveal the galaxy's redshift, indicating its radial velocity; ii) the galaxy's precise distance from Earth (and this is the most difficult value to determine).

A large summary about the methods used for $H_0$ determination, and its derived values can be found in the Proceedings of the Fall 2004 Astronomy 233 Symposium on "*Measurements of the Hubble constant*" [82]. In this book, Teymourian [83], after a comparison of many constraints on the Hubble constant determinations, reports a value $H_0 = 68 \pm 6$ km s$^{-1}$ Mpc$^{-1}$.

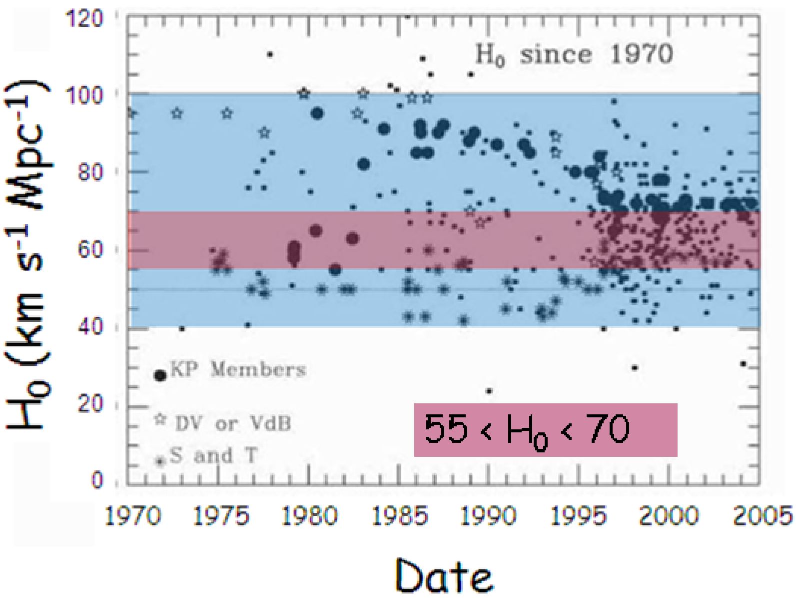



**Figure 15:** The Hubble constant determinations since 1970. The light-blue rectangle limits all the $H_0$ determinations. The light-red rectangle shows the narrow limits to to which the values of $H_0$ are converging (adopted from [86] after [87]).

Freedman & Madore [84] published a review about *The Hubble Constant* in which they discuss the considerable progress made in determining the Hubble constant over the past two decades. They discuss the cosmological context and importance of an accurate measurement of the Hubble constant, focusing on six high-precision distance-determination methods: Cepheids, tip of the red giant branch, maser galaxies, surface brightness fluctuations, the Tully-Fisher relation, and Type

Ia supernovae. Their best current estimate of the Hubble constant is $H_0$ = 73 ±2 (random) ±4 (systematic) km $s^{-1}$ $Mpc^{-1}$.

A discussion about the Hubble constant has been published by Giovannelli & Sabau-Graziati [85], where it is possible to find also a large number of references, reporting the many controversial evaluations of $H_0$.

Figure 15 shows the determinations of $H_0$ since 1970 (adopted from [86] after John Huchra [87]). Practically all the determinations lie in the range 40-100 km $s^{-1}$ $Mpc^{-1}$ (marked with light-blue rectangle), and most of them are converging in the range 55-70 km $s^{-1}$ $Mpc^{-1}$ (marked with light-red rectangle).

John Huchra [88] listed the last updated collection of data on October 7, 2010, just one day before his sudden death (https://www.cfa.harvard.edu/~dfab ricant/huchra/hubble.plot.dat). (*)

However, Riess et al. [89] with the HST determined a value of $H_0$ = 73.8 ± 2.4 km $s^{-1}$ $Mpc^{-1}$. This value agrees with the WMAP results: $H_0$ = 71.0 ± 2.5 km $s^{-1}$ $Mpc^{-1}$ [90]. Bennett et al. [91] discussed the progress occurred in recent years for determining the Hubble constant: results coming from the cosmic distance ladder measurements at low redshift and CMB measurements at high redshift.

(*) Professor John Huchra, died unexpectedly October 8th, 2010.

The CMB is used to predict the current expansion rate of the universe by best-fitting cosmological model. At low redshift baryon acoustic oscillation (BAO) measurements have been used – although they cannot independently determine $H_0$ – for constraining possible solutions and checks on cosmic consistency. Comparing these measurements they found $H_0$ = 69.6 ± 0.7 km $s^{-1}$ $Mpc^{-1}$.
Does this determination, finally, close the history about the search of the "true" value of $H_0$?

However, an important pioneer of science paper [92] reported how gravitational wave observations can be used to determine the Hubble constant. The nearly monochromatic gravitational waves emitted by the decaying orbit of an ultra-compact, two-neutron-star binary system just before the stars coalesce are very likely to be detected by the kilometer-sized interferometric gravitational wave antennas – at that time being designed. The signal is easily identified and contains enough information to determine the absolute distance to the binary, independently of any assumptions about the masses of the stars. Ten events out to 100 Mpc may suffice to measure the Hubble constant to 3% accuracy.

Fishbach et al. [93] performed a statistical standard siren analysis of GW170817. Their analysis did not utilize knowledge of NGC 4993 as the unique host galaxy of the optical counterpart to GW170817. Instead, they consider each galaxy within the GW170817 localization region as a potential host; combining the redshifts from all of the galaxies with the distance estimate from GW170817 provides an estimate of the Hubble constant as $H_0 = 77^{+37}_{-18}$ km $s^{-1}$ $Mpc^{-1}$.

Soares-Santos et al. [94] presented a multimessenger measurement of the Hubble constant using the binary-black-hole merger GW170814 as a standard siren, combined with a photometric redshift catalog from the Dark Energy Survey (DES). Their analysis results in $H_0 = 75^{+40}_{-32}$ km $s^{-1}$ $Mpc^{-1}$, which is consistent with both SN Ia and CMB measurements of the Hubble constant.

Independent estimation of the Hubble constant from the luminosity distance of GW signal (GW 170817) and the event association with NGC 4993 [95] gives a value $H_0 = 70.0^{+12.0}_{-8.0}$ km s$^{-1}$ Mpc$^{-1}$.

However, due to large errors, these values of Hubble constant do not add any significative information, but being obtained with independent methods provide a good support for the value of $H_0 = 69.6 \pm 0.7$ km s$^{-1}$ Mpc$^{-1}$, determined by Bennett et al. [91].

By using the SNe Ia Pantheon Sample, Dainotti et al. [208] derived a value $H_0 = 73.5$ km s$^{-1}$ Mpc$^{-1}$ compatible in $1\sigma$ with Planck measurements independent of the cosmological models. Poggiani [209] – and in the references therein – in her review on "*Estimating Hubble Constant with Gravitational Observations: A Concise Review*" concludes that the results from the bright siren GW 170817 and the associated electromagnetic counterpart have provided the first estimation of the Hubble constant independent of the astronomical distance ladder: $H_0 = 70.0^{+12.0}_{-8.0}$ km s$^{-1}$ Mpc$^{-1}$, as reported in [95].

### 2.9 Reionization Epoch

Ground-based observations of the CMB on subdegree angular scales suggest that the gas content of the universe was mostly neutral since recombination at z$\sim$ 1000 until about z$\sim$ 100 (Gnedin [96] and the references therein) because earlier reionization would have brought the last scattering surface to lower redshift, smoothing the intrinsic CMB anisotropy. At the same time, we know that the universe is highly ionized, since z$\approx$ 5, from observations of the spectra of quasars with the highest redshifts (e.g. [97]). This change of the ionization state of the universe from neutral to highly ionized is called "*reionization*". How large is the redshift to which the reionization started and stopped is object of strong debate.

The formation of the first stars and quasars marks the transformation of the universe from its smooth initial state to its clumpy current state. In current cosmological models, the first sources of light began to form at a redshift z $\sim$ 30 and reionized most of the hydrogen in the universe by z $\sim$ 7 (see review by Loeb & Barkana [98]).

A few years ago, Matsuoka et al. [99] reported the discovery of 15 QSOs and bright galaxies at $5.7 < z < 6.9$ from the Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs) project.

The argument for an extended period of reionization is now proved by measurements. Indeed, the WMAP has detected the correlation between temperature and polarization on large angular scales [100] that has an amplitude proportional to the total optical depth of CMB photons to Thomson scattering, $\tau$ [101-103].

Modeling reionization with a single sharp transition at $z_{ri}$, a multi–parameter fit to the WMAP data gives $z_{ri} = 17 \pm 5$ [80]. On the other hand, the evolution of quasar spectra from z$\approx$ 7 and z$\approx$ 6 shows a rapid decrease in the amount of neutral hydrogen, indicating the end of reionization [104]. A simple interpretation to explain these two very different datasets is that reionization started early, $z_{ri} \sim 20$, but did not conclude until much later (z$\sim$ 6) [105].

This was also confirmed by the results from Subaru Deep Field (SDF) [106,107]: the reionization of the universe has not been completed at z = 6.5. Also Ota et al. [108] in performing narrowband imaging of the SDF found two Ly$\alpha$ emitters (LAEs) at z = 7. This established a new redshift record, showing that galaxy formation was in progress just 750 Myr after the Big Bang.

They found that the attenuation of the Ly$\alpha$ photons from LAEs by the neutral hydrogen possibly left at the last stage of cosmic reionization at z ∼ 6 − 7.

Ouchi et al. [109] suggested an existence of a well-developed ionized bubble at z = 7. Ouchi et al. [110] reported the discovery of a giant LAE with a Spitzer/Infrared Array Camera (IRAC) counterpart near the reionization epoch at z = 6.595. Although the nature of this object is not yet clearly understood, this could be an important object for studying cooling clouds accreting onto a massive halo, or forming-massive galaxies with significant outflows contributing to cosmic reionization and metal enrichment of intergalactic medium.

Ouchi et al. [111] presented the Ly$\alpha$ luminosity function (LF), clustering measurements, and Ly$\alpha$ line profiles based on the largest sample to date of 207 LAEs at z = 6.6. The combination of various reionization models and their observational results about the LF, clustering, and line profile indicates that there would exist a small decrease of the intergalactic medium's (IGM's) Ly$\alpha$ transmission owing to reionization, but that the hydrogen IGM is not highly neutral at z = 6.6. Their neutral-hydrogen fraction constraint implies that the major reionization process took place at z ≥ 7.

Jiang et al. [112] presented Keck spectroscopic observations of z > 6 Lyman-break galaxy (LBG) candidates in the Subaru Deep Field (SDF). Their Ly$\alpha$ LF is also generally in agreement with the results of LAEs surveys at z ∼ 5.7 and 6.6. This study shows that deep spectroscopic observations of LBGs can provide unique constraints on both the UV and Ly$\alpha$ LFs at z > 6.

Ono et al. [113] presented the results of their ultra-deep Keck/DEIMOS spectroscopy of z-dropout galaxies in the SDF and Great Observatories Origins Deep Survey's northern field. The fractions of Ly$\alpha$-emitting galaxies drop from z ∼ 6 to 7 and the amplitude of the drop is larger for faint galaxies than for bright galaxies. These two pieces of evidence would indicate that the neutral hydrogen fraction of the IGM increases from z ∼ 6 to 7 and that the reionization proceeds from high- to low-density environments, as suggested by an inside-out reionization model.

The WMAP detection of reionization [100] implies the existence of an early generation of stars able to reionize the universe at z∼ 20. Panagia et al. [114] in deep HST/VLT/Spitzer images found that the source UDF 033238.7-274839.8 – a post–starburst galaxy with a mass $\sim 6 \times 10^{11}$ $M_\odot$ placed at z ≥ 6.5 – may be capable of reionizing its surrounding region of the universe, starting the process at a redshift as high as z = 15 ± 5.

The question about the end of the reionization is strongly disputed. However, in our opinion probably it is possible to put a reasonable limit to the epoch of the reionization end (z ∼ 6), looking at the paper by Toshikawa et al. [115]. They reported the discovery of a protocluster at z ∼ 6 containing at least eight cluster member galaxies with spectroscopic confirmations in the wide-field image of the SDF. They found no significant difference in the observed properties, such as Ly$\alpha$ luminosities and UV continuum magnitudes, between the eight protocluster members and the seven non-members. The velocity dispersion of the eight protocluster members is 647 ± 124 km $s^{-1}$, which is about three times higher than that predicted by the standard cold dark matter model. This discrepancy could be attributed to the distinguishing three-dimensional distribution of the eight protocluster members. They discussed two possible explanations for this discrepancy: either the protocluster is already mature, with old galaxies at the center, or it is still immature and composed of three subgroups merging to become a larger cluster. In either case, this concentration of z = 6.01 galaxies in the SDF may be one of the first sites of formation of a galaxy cluster in the universe.

Figure 16 shows schematically the updated experimental situation about cosmic sources (galax-

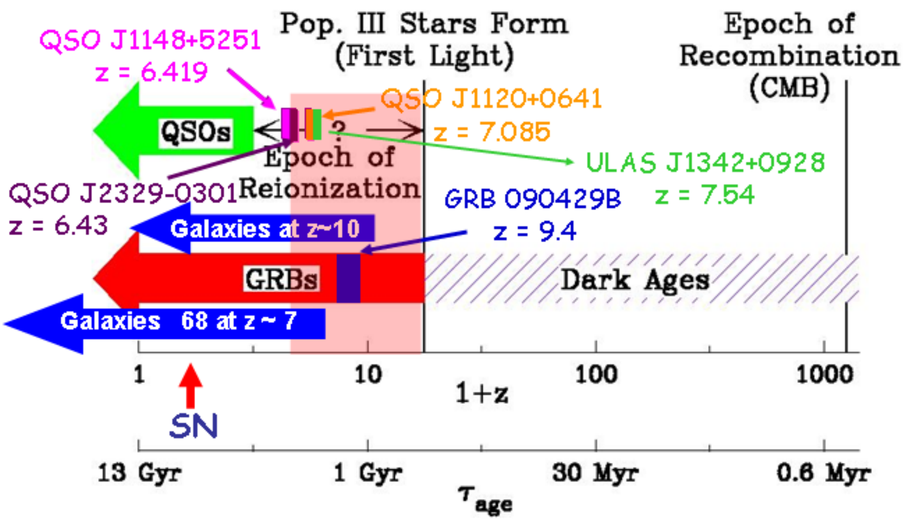



**Figure 16:** A sketch of reionization epoch (adapted from [116]).

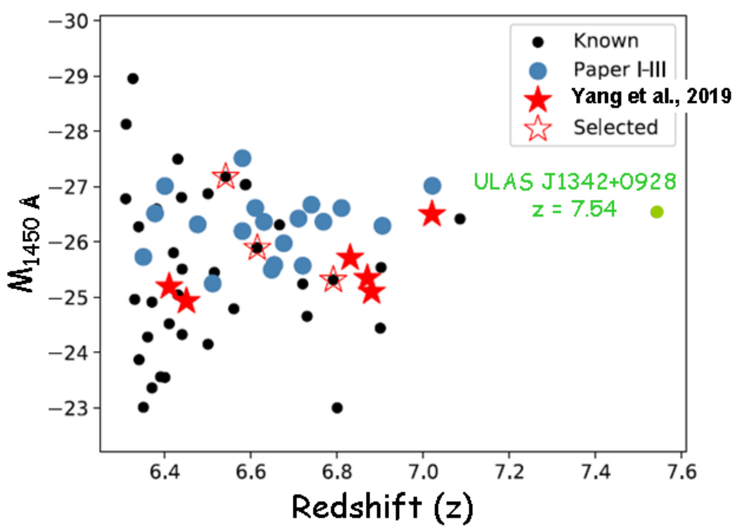



**Figure 17:** Redshift and $M_{1450}$ distribution of quasars at $z \gtrsim 6.3$ (adapted from Yang et al., 2019). The black filled circles are the previously known quasars. The blue filled circles denote quasars from surveys in the northern sky [117-119]. The red filled stars represent the six new quasars from Yang et al. [120] survey and the red open stars are the three known quasars in the Dark Energy Survey (DES) area that meet their selection criteria. The green dot represents the z = 7.54 quasar ULAS J1342+0928 [121].

ies, GRBs, QSOs, SNe) detected at high redshifts. The light–red rectangle marks the possible range of z during which the reionization occurred.

However, although there is rather good agreement about the epoch of reionization, how really reionization occurs is still object of debate. Indeed, Dopita et al. [122], considering that observations show that the measured rates of star formation in the early universe are insufficient to produce reionization, suggest the presence of another source of ionizing photons. This source could be the fast accretion shocks formed around the cores of the most massive haloes.

Interesting reviews about *The epoch of reionization*, and *An Introductory Review on Cosmic Reionization* have been published by Zaroubi [123] and Wise [124], respectively.

Yang et al. [120] announced the discovery of six new z ≥ 6.5 quasars. They plotted the positions of these new quasars in a diagram magnitude at 1450 Å versus redshift where also the known quasars at z ≥ 6.3 have been reported in Fig. 17. The meaning of the symbols are reported in the caption of Fig. 17. Note that the z = 7.54 quasar ULAS J1342+0928, hosted by a galaxy merger is also reported (green dot) [121].

A recent paper by Yan et al. [125] by using data coming from JWST suggests the possibility of having detected objects at z ≈ 11-20 in the supercluster SMACS 0723-73. They very probably are galaxies.

These works open a glimmer of light on the possibility of revealing in the future, with the advent of JWST, the presence of quasars immediately after the formation of the first Pop. III stars at z ≈ 25, as well as the possibility of detecting GRBs up to that redshift [126-128]. Indeed, the detection of the GRB 090429B at z ≃ 9.4 [129] is a good omen to think that future experiments can reveal GRBs up to the fateful threshold of z ≈ 25.

### 2.10 Star Formation

In his splendid review, Robert C. Kennicutt, Jr. [130] discussed the observations of star formation rates (SFRs) in galaxies that provide vital clues to the physical nature of the Hubble sequence and showing that these observations are key probes of the evolutionary histories of galaxies.

About the evolutionary history of galaxies, interesting results were discussed in the review paper "*Star-Formation Histories, Abundances, and Kinematics of Dwarf Galaxies in the Local Group*" by Tolstoy, Hill & Tosi [131]. They discussed the results of quantitative studies in nearby dwarf galaxies, since within the Local Universe, galaxies can be studied in great detail star by star. The color-magnitude diagram synthesis method is well established as the most accurate way to determine star-formation histories of galaxies back to the earliest times. These studies have shown how the properties of stellar populations can vary spatially and temporally. This leads to important constraints to theories of galaxy formation and evolution. The continuity of structural properties from dwarf galaxies to larger spheroidal and late-type systems is most likely dominated by physical processes that scale with mass, for example, the efficiency with which gas and/or metals can be lost from a system during its evolution through supernova winds and/or interactions.

Zinnecker & Yorke [132] discussed in their review a basic description of the collapse of a massive molecular core and a critical discussion of the three competing concepts of massive star formation:

- monolithic collapse in isolated cores;
- competitive accretion in a protocluster environment;
- stellar collisions and mergers in very dense systems.

They concluded that high-mass star formation is not merely a scaled-up version of low-mass star formation with higher accretion rates, but partly a mechanism of its own, primarily owing to the role of stellar mass and radiation pressure in controlling the dynamics.

Kennicutt, Jr & Evans II [133] reviewed the progress over the previous decade in observations of large-scale star formation, with a focus on the interface between extragalactic and galactic studies. Methods of measuring gas contents and star-formation rates have been discussed, and updated prescriptions for calculating star-formation rates were provided. They reviewed relations between star formation and gas on scales ranging from entire galaxies to individual molecular clouds.

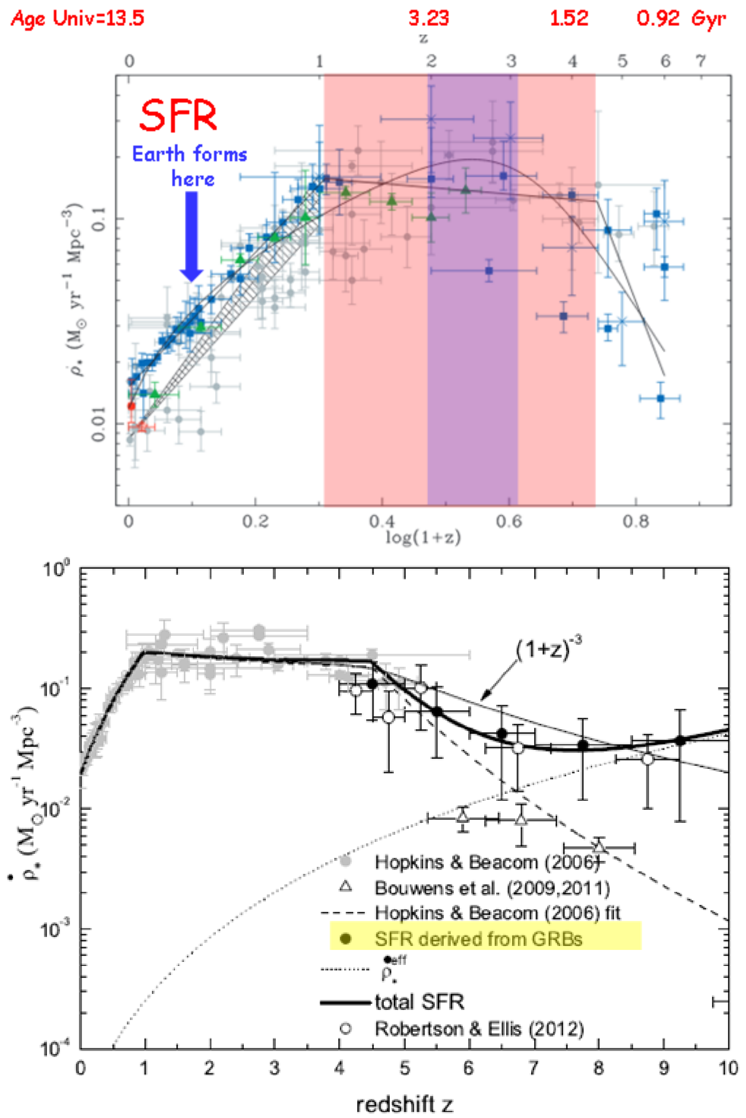



**Figure 18:** Upper panel: Evolution of SFR density with redshift (after [136]). Lower panel: Evolution of SFR density with redshift; black dots for z $\gtrsim$ 4.5 mark the values of SFR density derived from GRBs [138].

The key dynamical processes involved in star formation – turbulence, magnetic fields, and self-gravity – are highly nonlinear and multidimensional. Therefore, it is extremely difficult a complete quantitative description of the physics involved in the process of star formation. McKee & Ostriker [134] attempted to review the theory of star formation. For this reason they divided star formation into large-scale and small-scale regimes and reviewed each in turn. Large scales range from galaxies to giant molecular clouds (GMCs) and their substructures. Important problems include how GMCs form and evolve, what determines the star formation rate (SFR), and what determines the initial mass function (IMF) have been discussed. Small scales range from dense cores to the protostellar systems they beget. They discussed formation of both low– and high–mass stars, including ongoing accretion. The development of winds and outflows is increasingly well understood, as are the mechanisms governing angular momentum transport in disks. However, they concluded that a comprehensive theory of star formation will be tested by the next generation of telescopes.

Fumagalli et al. [135] investigated the evolution of the $H_\alpha$ equivalent width, EW($H_\alpha$), with redshift and its dependence on stellar mass, using the first data from the 3D-HST survey, a large spectroscopic Treasury program with the HST-WFC3. Combining these data with those from ground-based telescopes, they found that at all masses the characteristic EW($H_\alpha$) is decreasing towards the present epoch, and that at each redshift the EW($H_\alpha$) is lower for high-mass galaxies.

The cosmic history of star formation, heavy element production, and reionization of the Universe from the cosmic "dark ages" to the present epoch has been discussed in the review paper by Madau & Dickinson [136]. A consistent picture is emerging, whereby the star-formation rate density peaked approximately 3.5 Gyr after the Big Bang, at $z \approx 1.9$, and declined exponentially at later times, with an e-folding timescale of 3.9 Gyr. Half of the stellar mass observed today was formed before a redshift z = 1.3. About 25% formed before the peak of the cosmic star-formation rate density, and another 25% formed after z = 0.7. Less than $\sim$ 1% of today's stars formed during the epoch of reionization.

However, these results were already largely discussed and presented by Hopkins & Beacom [137], and later by Madau & Dickinson [136] and summarized in the Fig. 18 (upper panel). The light–red rectangle marks the range of redshift where the star formation density had the maximum ($1 \leq z \leq 4.5$) whose peak is between z = 2 and z = 3 and marked with the light violet rectangle. This will be better understood when the supernova rate density evolution, the ranges of stellar masses leading to core-collapse and type Ia supernovae, and the antineutrino and neutrino backgrounds from core-collapse supernovae will be known thanks to the next generation experiments both ground– and space–based. Figure 18 (lower panel) clearly show the values of SFR (black dots) derived from GRBs by Wang, Dai, & Liang [138] at redshifts $z \geq 4.5$.

A book about "*Star Formation in Galaxy Evolution: Connecting Numerical Models to Reality*" [139] reports an inventory of the physical processes related to the star formation involved at different scales and also to provide an overview of the major computational techniques used to solve the equations governing self-gravitating fluids, essential to galactic modeling. Together this provides a unique framework essential to developing and improving the simulation techniques used to understand the formation and evolution of galaxies.

### 2.11 Gamma Ray Bursts

Long discussions about Gamma-ray bursts (GRBs) can be found in numerous publications. A list of these can be found in GSG2004 [1] and in Giovannelli & Sabau-Graziati [86]. Recently Giovannelli [140] published an updated review on "*Gamma-Ray Bursts: The Energy Monsters of the Universe*".

Although big progress has been obtained in the last few years, GRBs theory needs further investigation in the light of the experimental data coming from old and new satellites, often



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coordinated, such as BeppoSAX or BATSE/RXTE or ASM/RXTE or IPN or HETE or INTEGRAL or SWIFT or AGILE or FERMI or MAXI. Indeed, in spite of thousands papers appeared in the literature since the discovery of GRBs, the problem of their energy emission is still elusive: i) what is jet's composition? (kinetic or magnetic?); ii) where is dissipation occurring? (photosphere? deceleration radius?); iii) how is radiation generated? (synchrotron, Inverse Compton, hadronic?) [210,211].

Kumar & Zhang [141] in a review paper *The Physics of Gamma-Ray Bursts & Relativistic Jets* discussed what we have learned about relativistic collisionless shocks and particle acceleration from GRB afterglow studies, and the current understanding of radiation mechanism during the prompt emission phase. They pointed out how these explosions may be used to study cosmology, e.g. star formation, metal enrichment, reionization history, as well as the formation of first stars and galaxies in the Universe.

The idea that GRBs could be associated to gravitational waves (GWs) emission is now popular. Indeed, short GRBs are believed to be produced by the mergers of either double NSs or NS-BH binaries [142] and the observation of a kilonova associated with GRB130603B [143,144] lends support to this hypothesis. In an interesting review, D'Avanzo [145] discussed the observational properties of short GRBs and showed how the study of these properties can be used as a tool to unveil their elusive progenitors and provide information on the nature of the central engine powering the observed emission. The increasing evidence for compact object binary progenitors makes short GRBs one of the most promising sources of gravitational waves for the Advanced LIGO/Virgo experiments. This idea obtained recently its experimental verification with the detection of GW 170817 event associated with the GRB 170817A [32,33].

Thanks to the NASA's Swift satellite we assisted to ten years of amazing discoveries in time domain astronomy. Its primary mission is to chase GRBs. The list of major discoveries in GRBs and other transients includes the long-lived X-ray afterglows and flares from GRBs, the first accurate localization of short GRBs, the discovery of GRBs at high redshift (z > 8) [146]. And essentially thanks to these discoveries we are now closer to understand the real nature of GRBs.

The review by Bernardini [147] discussed how the newly-born millisecond magnetars can compete with black holes as source of the GRB power, mainly with their rotational energy reservoir. They may be formed both in the core-collapse of massive stars, and in the merger of neutron star or white dwarf binaries, or in the accretion-induced collapse of a white dwarf, being thus a plausible progenitor for long and short GRBs, respectively.

Ghirlanda et al. [148] discussed about the apparent separation of short and long GRBs in the hardness ratio vs duration plot. This separation has been considered as a direct evidence of the difference between these two populations. The origin of this diversity, however, has been only confirmed with larger GRB samples but not fully understood. They concluded that short and long GRBs have similar luminosities and different energetics (i.e. proportional to the ratio of their average durations). Then, it seems that the results are pointing toward the possibility that short and long GRBs could be produced by different progenitors but the emission mechanism responsible for their prompt emission might be similar.

Piron [149] in his review discussed the updated knowledge of GRBs at very high energies. Their huge luminosities involve the presence of a newborn stellar-mass black hole emitting a relativistic collimated outflow, which accelerates particles and produces non-thermal emissions from the radio domain to the highest energies. He reviewed the progresses in the understanding of GRB jet physics above 100 MeV, based on Fermi observations of bright GRBs, and discussed the physical implications of these observations and their impact on GRB modeling.

More recently, Noda and Parsons [150] discussed GRBs as target of interest for very high energy gamma-ray observatories. The recent discovery of a number of bursts with photons reaching energies above 100 GeV invited them to write a review paper which summarize the GRB observational campaigns of the current generation of very high energy gamma-ray observatories as well as describing the observations and properties of the GRBs discovered so far. They compare the properties of the very high energy bursts to the total GRB distribution and make predictions for the next generation of very high energy gamma-ray observations. Figure 19 shows the X-ray light curve of the four VHE GRBs shown as flux (left) and luminosity (right) using data from the Swift-BAT (Burst Alert Telescope) and X-Ray Telescope (XRT).

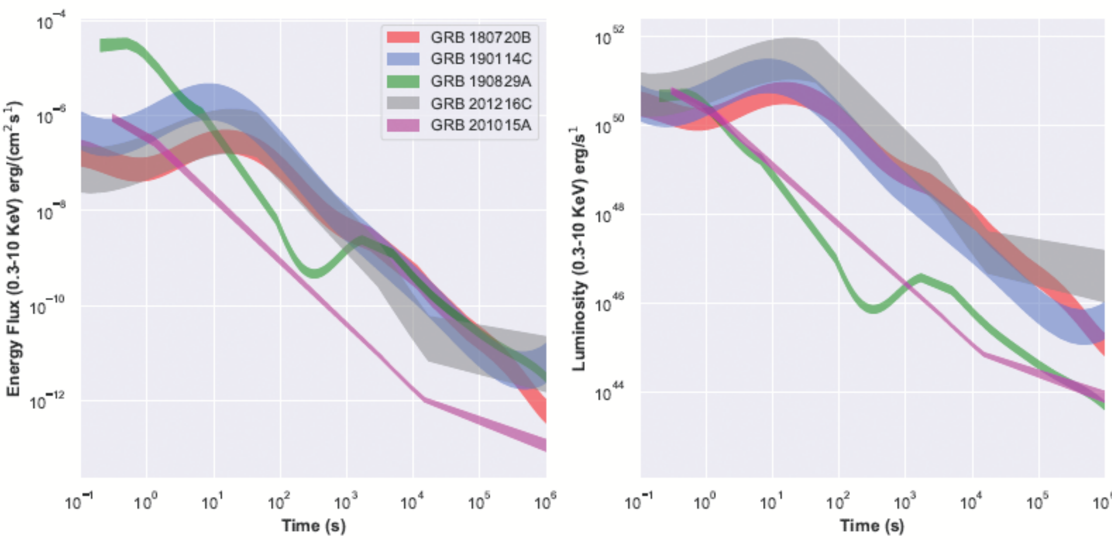


**Figure 19:** The X-ray light curve of the four VHE GRBs shown as flux (left) and luminosity (right) using data from the Swift-BAT (Burst Alert Telescope) and X-Ray Telescope (XRT) (adopted from [150]).

A few years ago Arnon Dar [151] proposed again to the attention of the international community his Cannonball (CB) model for explaining the physics of GRBs. In the CB model, GRBs and their afterglows are produced by the interaction of bipolar jets of highly relativistic plasmoids (CBs) of ordinary matter with the radiation and matter along their trajectory. Such jetted CBs are presumably ejected in accretion episodes of fall-back material on the newly formed compact stellar object in core-collapse supernovae (SNe) of Type Ic, in merger of compact stellar objects in close binary systems, and in phase transitions in compact stars [152-155]. Dado, Dar, and De Rújula [156] discussed a long series of different Swift GRBs, showing that the CB model fits all their broadband light curves. Dado and Dar [157] discussed the jet break in the X-ray afterglow of GRBs that appears to be correlated to other properties of the X-ray afterglow and the prompt gamma ray emission, but the correlations are at odds with those predicted by the conical fireball (FB) model of GRBs [158]. On the contrary they are in good agreement, however, with those predicted by the CB model of GRBs.

Dado and Dar [159,160] discussed on the *Critical test of gamma−ray bursts theories* and demonstrated definitively the validity of the CB model against the popular FB−model [158].

Figure 20 shows, as example, the fits of light curves of GRB 060729, GRB 061007, GRB 160625B, and GRB 130427A by using the CB model [159].

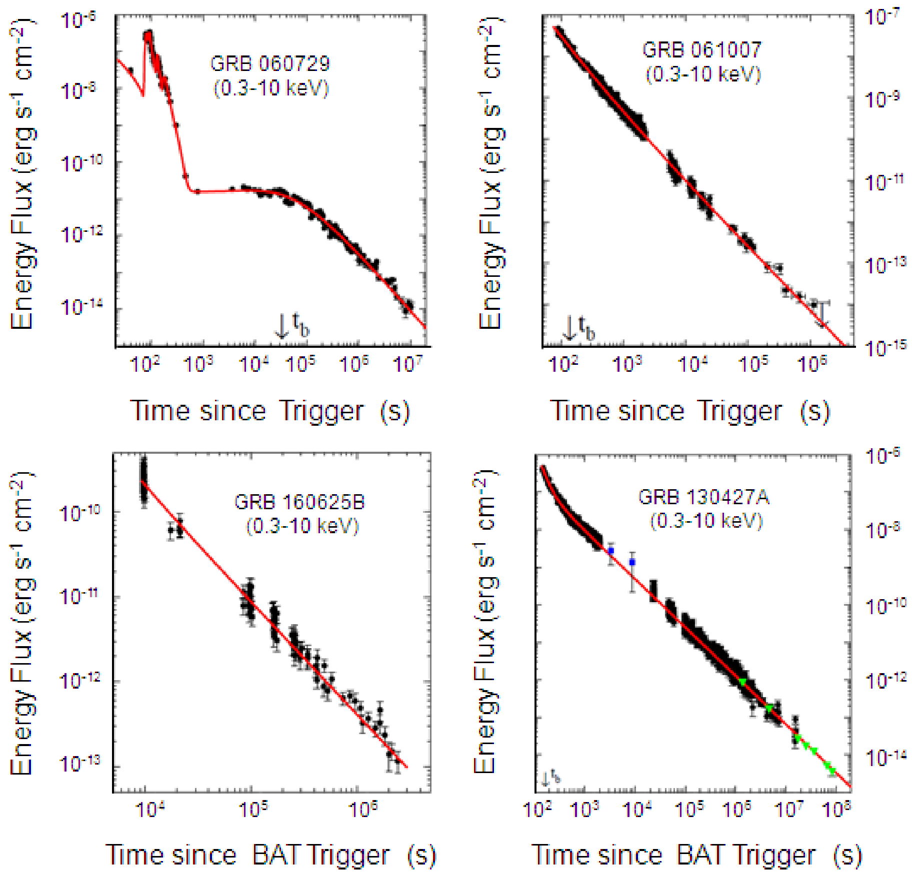


**Figure 20:** The 0.3−10keV X-ray light-curve measured with the Swift XRT [212], and the comparison between Swift observations and their CB-model description (adapted from [159]) for: **top left** GRB 060729, **top right** GRB 061007, **bottom left** GRB 160625B, **bottom right** GRB 130427A.

A larger sample of GRB light curves has been reproduced using the Cannon Ball model [156]. The fits to the data are extremely good. Figure 21 shows, as a further example of the goodness of CB model, the BATSE light-curve of GRB 990123 and its CB model description [161].

In my opinion, the problem of the models used for explaining the behavior of GRBs is still open. Indeed, as stated by Dar and De Rujula [162], the only obstacle still separating the CB model from a complete theory of GRBs is the theoretical understanding of the CBs' ejection mechanism in SN explosions. And this is true regardless of the model used to describe the behavior of GRBs.

Statistical studies of GRBs may ease the path to understanding the physics that govern these monstrous phenomena. Many papers have been published about statistical studies of GRBs.

Zhao et al. [163] performed an analysis for the shallow decay component of GRBs X-ray afterglow, in order to explore its physical origin with an updated sample of GRBs – data from

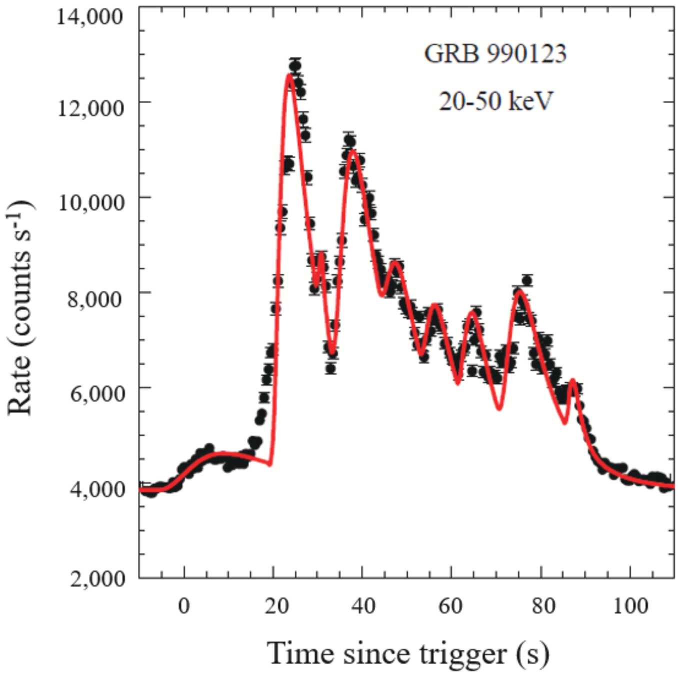


**Figure 21:** The BATSE light−curve of GRB 990123 and its CB model description (adopted from [161]).

Swift/XRT GRBs between February 2004 and July 2017 – with respect to that used by Liang et al. [164] based on the early-year observations from Neil Gehrels Swift Observatory.

Overall, their results are generally consistent with Liang, Zhang & Zhang [165], confirming their suggestion that the shallow decay segment in most bursts is consistent with an external forward shock origin, probably due to a continuous energy injection from a long-lived central engine.

Tang et al. [166] considering that a plateau phase in the X-ray afterglow is observed in a significant fraction of GRBs performed a statistical study of this class. Previously, it has been found that there exists a correlation among three key parameters concerning the plateau phase, i.e., the end time of the plateau phase in the GRB rest frame ($T_a$), the corresponding X-ray luminosity at the end time ($L_X$) and the isotropic energy of the prompt GRB ($E_{\gamma,iso}$). They systematically searched through all the Swift GRBs with a plateau phase that occurred between 2005 May and 2018 August. They collected 174 GRBs, with redshifts available for all of them. They confirmed that a correlation exist and the best fit gives $L_X \propto T_a^{-1.01}\ E_{\gamma,iso}^{0.84}$. Such an updated three-parameter correlation still supports that the central leftover after GRBs is probably a millisecond magnetar. It is interesting to note that short GRBs with duration less than 2 s in their sample also follow the same correlation, which hints that the merger production of two neutron stars could be a high mass magnetar, but not necessarily a black hole. Moreover, GRBs having an "internal" plateau (i.e., with a following decay index being generally smaller than -3) also obey this correlation. It further strengthens the idea that the internal plateau is due to the delayed collapse of a high mass neutron star into a black hole. The updated three-parameter correlation indicates that GRBs with a plateau phase may act as a standard candle for cosmology study.

Wang et al. [167] performed a comprehensive statistical study using 6289 GRBs. They arrived to the conclusion that in order to reveal more physical principles one should try to classify the GRBs into more precise subgroups based on their physical origin, and the classification itself is a process to reveal the intrinsic properties of GRBs. With the detailed classifications, the correlations inside each group may be more tighter and more physical. The correlations are then can be used to study the radiation mechanism as well as the high energy radiation, to be indicators as standard candle or pseudo redshift, and to study the gravitational waves of compact binary mergers.

Thus also after this interesting paper, the answer to the real processes occurring in GRBs is still open.

## 3. Some key questions

Listing the crucial open questions is a difficult task [168]. However I will try to underline those that seem fundamental to me, namely:

- Are there deviations from general relativity, and on what scale?
- Are there deviations from the standard model of particle physics?
- Are there deviations from the standard cosmological model?
- What is the nature of dark matter?
- What is the origin of the accelerated expansion?
- Can we identify specific observational signatures of inflation?
- What can gravitational waves observations reveal about dark energy, dark matter and modifications of gravity on cosmological scales?
- How did galaxies obtain their gas?
- What are the properties of the first stars?
- What were the physical properties of early galaxies?
- Which sources caused reionization and how did it impact galaxy formation?
- What was the topology and history of reionization?
- What is the state of intergalactic gas?
- What DM halo properties (besides mass) determine the properties of a galaxy?
- What is the state of the gaseous halos that surround galaxies?
- How much material escapes from and cycles back to galaxies, and what drives these flows?
- How do stars form out of dense, molecular gas?
- What determines the star-formation history of individual galaxies?
- How does the structure of galaxies evolve?

- What is the role of the environment and large scale structure in galaxy evolution?
- How do supermassive black holes evolve with their host galaxies?
- The physics of supermassive black holes (SMBHs)
- Are collapsed objects in systems like Cyg X-1 really the black holes described by general relativity?
- How common are they, and how do they form?
- Do intermediate-mass black holes exist beyond the stellar mass range?
- Is there a mass gap between neutron stars and black holes (and within BHs)?
- What are the progenitors of type Ia supernovae?
- How does the Milky Way fit into the cosmological context?
- What is the underlying structure in the local group and its dark matter?
- What is the Milky Way's accretion history and how was the halo assembled?
- How much information is retained from the formation events?
- What are the abundance patterns of the first stars?
- Our very local (Solar) environment?
- What is the ultimate fate of planetary systems orbiting stellar remnants?
- Where do the highest energy cosmic rays come from and what are the acceleration sites?
- ..... and many more.

In order to answer to the key questions it is necessary the use of modern facilities both space- and Earth-based. A discussion about such facilities can be found in e.g. [168]. It is evident that in order to find satisfactory solutions it is necessary to use the technique of multi-messenger astrophysics.

An example of multi-messenger astrophysics is shown in an illustration (Fig. 22) which summarises the physical processes arising from the fusion of two neutron stars and which manifest themselves along the entire electromagnetic spectrum and with the emission of gravitational waves.

In addition to multi-wavelength observations that probe the generation and dissipation of energy within extreme events, the addition of non-photonic information in the form of gravitational waves, neutrinos or cosmic-rays enables a far more complete picture of the physics in a given event. The Fig. 22 shows a binary neutron star merger, but many systems will generate detectable multi-messenger signals in the next 10-15 years. Gravitational waves and neutrinos carry information from regions inaccessible to electromagnetic observations at any wavelength.

One example more about the use of many experiments for obtaining results as general as possible is that of the Cosmic-ray energy spectrum (Fig. 23).

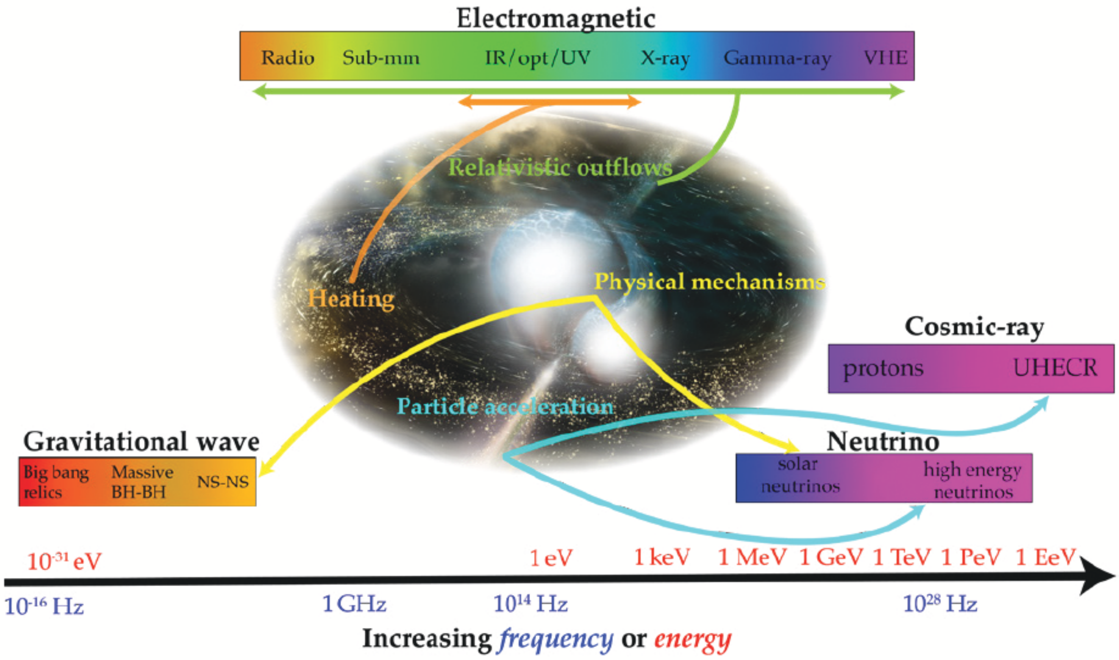


**Figure 22:** The spectrum of astrophysical messengers. The figure shows a binary neutron star merger (adopted from [168] (Credit: NSF/LIGO/Sonoma State University/A. Simonnet).

The spectrum, measured from multiple sources shows a complex morphology and is shaped by both intrinsic processes (e.g. the composition of the rays and their spectrum upon acceleration) and their propagation through the interstellar and sometimes intergalactic medium. Future work will improve the measurements of the spectrum, in particular at the highest energy end, determine the composition of the rays, and pinpoint the various physical sites in which acceleration may occur.

While everyone agrees on the existence of dark matter (e.g. [169]), there is no direct evidence of its existence, much less of what this matter is made of. An empirical proof of the existence of DM was published several years ago [170], and a new evidence for DM was discussed in [171].

However, thanks to images from the Hubble Space Telescope (HST), we can objectively state its existence. In fact, as shown in Fig. 24, the left panel shows the image of the galaxy cluster Cl 0024+17 (ZwCl 0024+1652) and the right panel shows the same image overlaid with a map of the cluster's mass distribution. The ring-like structure – discovered by Jee et al. [172] – evident in the map is one of the strongest pieces of evidence to date for the existence of dark matter.

## 4. Hunt for planets

The most important questions about the possible origin of life in our Universe became a real scientific question in the last couple decades when it appeared a near certainty that other planets must orbit other stars. And yet, it could not be proven, until the early 1990's. Then, radio and optical astronomers detected small changes in stellar emission which revealed the presence of first a few, and now many, planetary systems around other stars. We call these planets "exoplanets" to

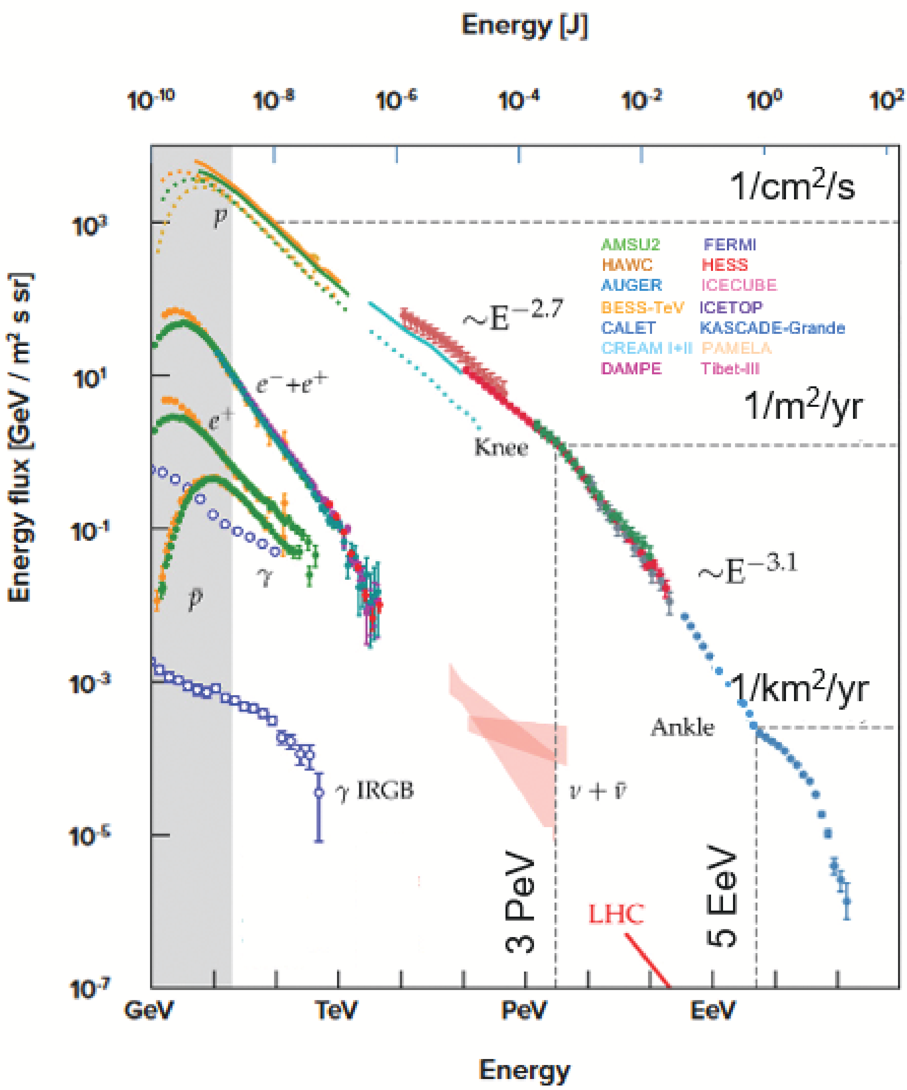


**Figure 23:** The cosmic-ray spectrum (adapted from [168]. Credit: https://zenodo.org/record/2360277).

distinguish them from our own solar system neighbors (http://science.nasa.gov/astrophysics/focus-areas/exoplanet-exploration/).

Figure 25 shows how fast is the discovery of new exoplanets, reporting the situation in 2010 and in 2020 [173].

Figure 26 shows the cumulative detection per year by using different techniques updated to April 24, 2025 (exoplanetarchive.ipac.caltech.edu).

From *The Open Exoplanet Catalogue* updated to Saturday April 26, 07:01:11 2025 (∗), we know 5,288 confirmed exoplanets, 5,414 planets (including Solar System objects and unconfirmed exoplanets), 4,081 planetary systems, 181 binary systems (http://www.openexoplanetcatalogue.com).

(∗) List of contributors: Hanno Rein, Andrew Tribick, Marc-Antoine Martinod, Ryan Varley, Cadenarmstrong, Miguel De Val-Borro, Christian Sturm, Marc-Antoine, Chrissy Teagan, Senger Hanno, Kenneth J Cott, Everett Schlawin, Landrok,

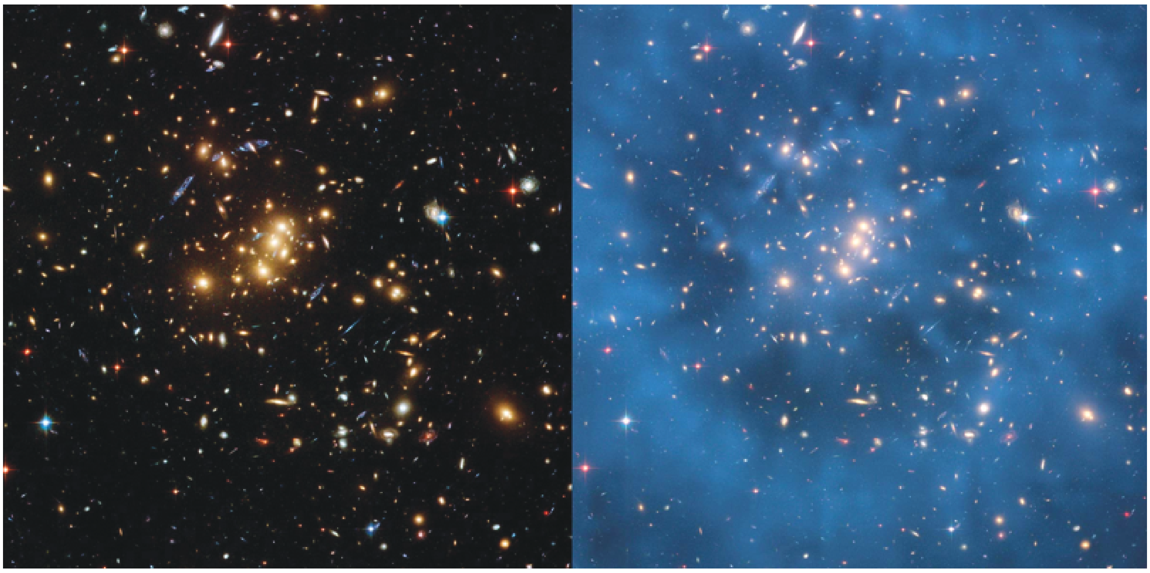

**Figure 24:** Left panel: Hubble Space Telescope image of the galaxy cluster Cl 0024+17. Right panel: the same image overlaid with a map of the cluster's mass distribution. The ring-like structure is evident [172] (Credit: NASA, ESA, M. J. Jee and H. Ford - Johns Hopkins University).

Sol-D, James Gregory, Daveshoszowski, Planetaryscience, Ewan Douglas, Rajeev-Jeyaraj, Sevenspheres, Jaroslav Merc, Claudionor Buzzo Raymundo, Dobb13, Knutover, Orome, Kevin Knittel, Allen Davis, Tobias Mueller, Florian Cabot, Allen B. Davis, Allen Davis, Paul Anthony Wilson, Diamondraph, Randomcoinforall, Darryl Hemsley, Dave, Callum Rodwell, Paul A. Wilson, Christian Sturm

We have gone from suspecting exoplanets existed to knowing that there are more exoplanets than stars in our galaxy.

Figure 27 shows the radius of planets versus their orbital period, including the solar system planets (https://exoplanetarchive.ipac.caltech.edu/).

One of the most exiting result of Kepler mission was the discovery of the planets orbiting around Kepler-62 star [174]. They present the detection of five planets – Kepler-62b, c, d, e, and f – of size 1.31, 0.54, 1.95, 1.61 and 1.41 Earth radii ($R_\oplus$), orbiting a K2V star at periods of 5.7, 12.4, 18.2, 122.4 and 267.3 days, respectively. The outermost planets (Kepler-62e & -62f) are super-Earth-size ($1.25 <$ planet radius $\leq 2.0\ R_\oplus$) planets in the habitable zone (HZ) of their host star, receiving $1.2 \pm 0.2$ and $0.41 \pm 0.05$ times the solar flux at Earth's orbit ($S_\odot$). Theoretical models of Kepler-62e and -62f for a stellar age of $\sim 7$ Gyr suggest that both planets could be solid: either with a rocky composition or composed of mostly solid water in their bulk.

Figure 28 shows an artistic picture of the comparison of the planetary system around the star Kepler-62 with our own Solar System (https://www.nasa.gov/content/kepler-62-and-the-solar-system – Image credit: NASA Ames/JPL-Caltech; Last Updated: Aug 7, 2017).

The research of potential habitable exoplanets has been strongly supported during last two decades. Indeed, this field of astrophysics is now probably the most exciting since the discovery of planets Earth-like could open a serious debate about the possibility of life outside of solar system.

The Habitable Worlds Catalog (HWC) lists up to 70 potentially habitable worlds out of over

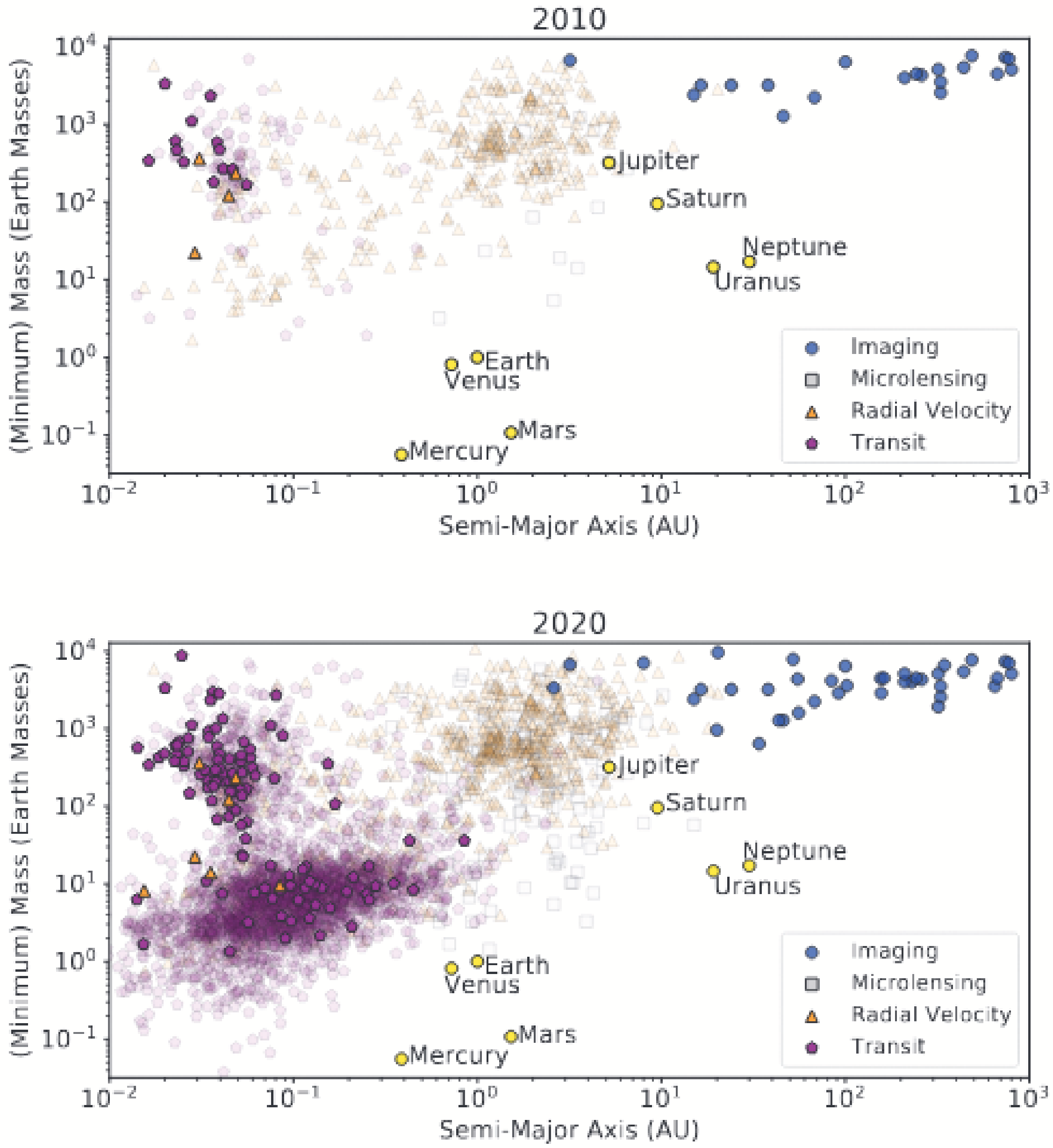


**Figure 25:** The population of known exoplanets in 2010 (top) and 2020 (bottom). Each symbol represents a known extra- solar planet, colored by initial discovery method. Open symbols are planets that have been discovered. Filled symbols are planets whose atmospheric composition has been characterized by measurements of its spectrum or brightness (adopted from [173], taken from the SOURCE: D. Savransky and B. Macintosh, with data from the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program).

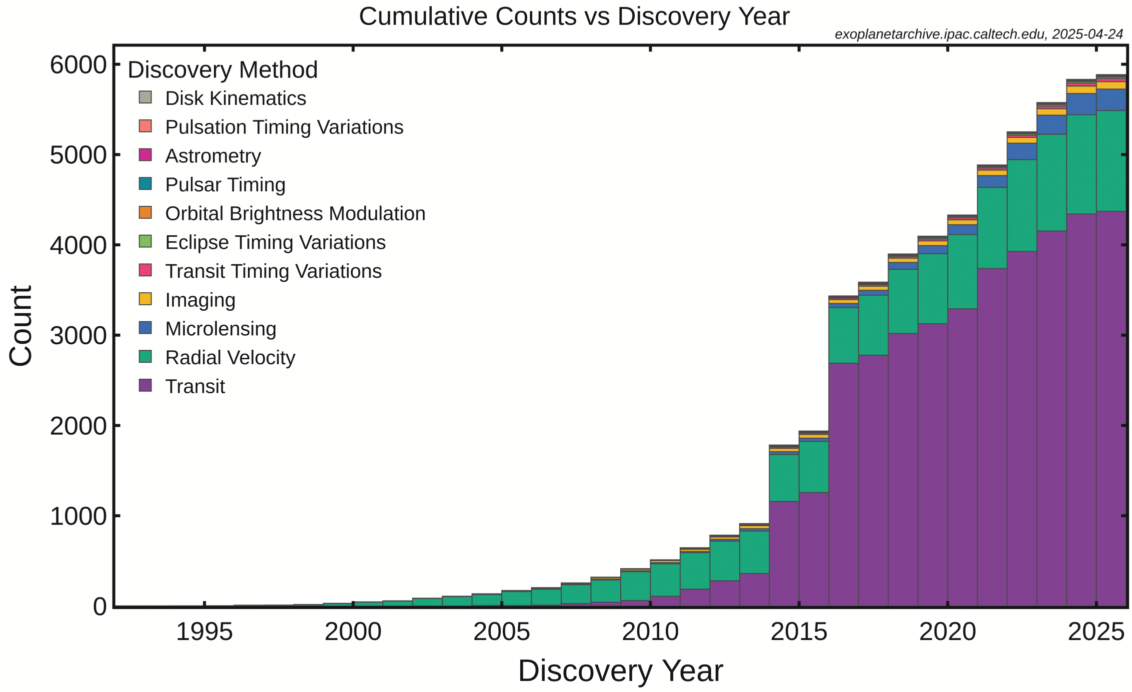


**Figure 26:** Cumulative number of detections of exoplanets per year, updated to April 24, 2025 (adopted from exoplanetarchive.ipac.caltech.edu)

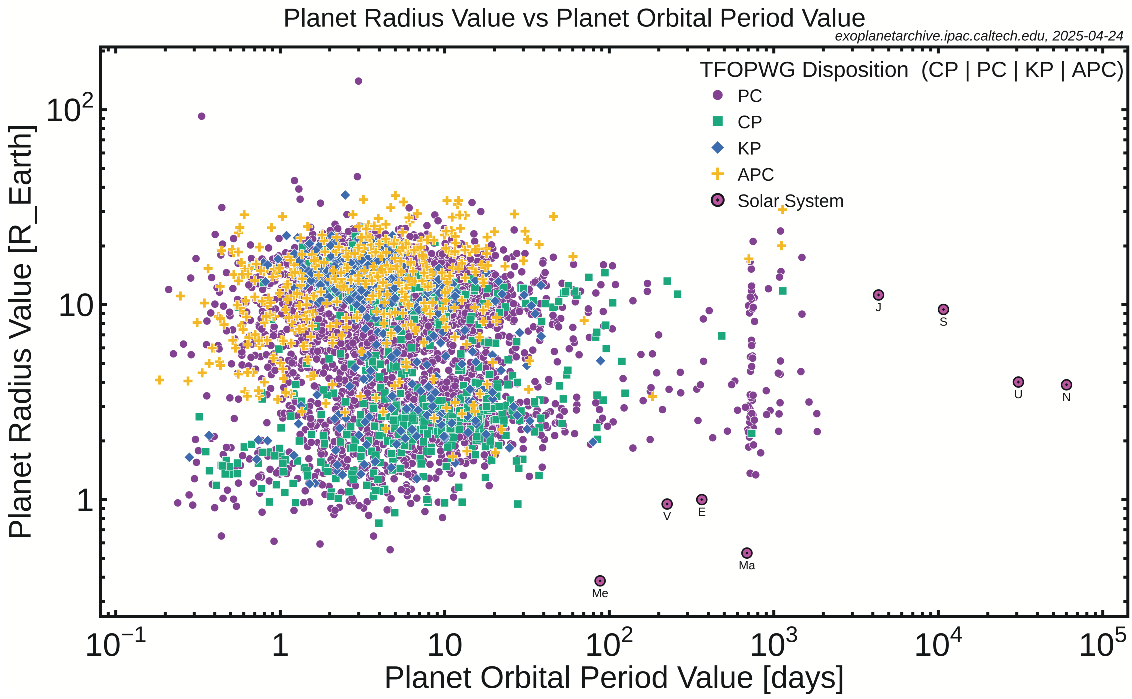


**Figure 27:** Planet radius value versus orbital period value, updated to April 24, 2025 (adopted from exoplanetarchive.ipac.caltech.edu). Solar system planets are clearly visible.

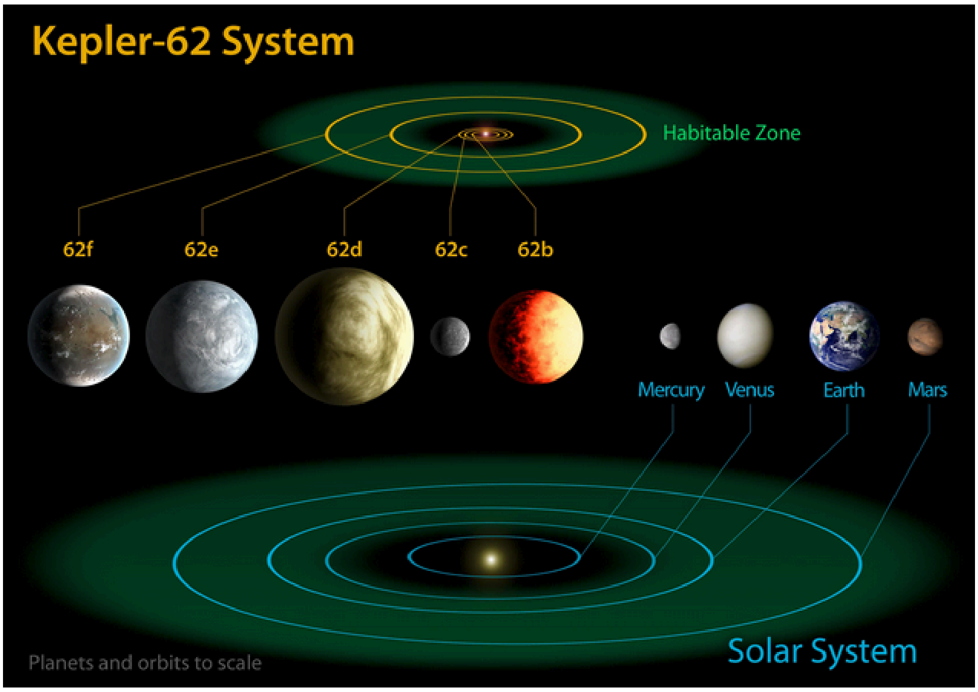


**Figure 28:** Comparison of the planetary system around the star Kepler-62 with our own Solar System. The relative size of the planetary orbits (top and bottom) is to scale. The planets (center) are also to scale, relative to each other. The habitable zone – the zone around the star that allows for liquid water on the surface of a planet orbiting at that distance – is shown in green. Kepler-62e and Kepler-62f are the best candidates yet for habitable planets: solid planets orbiting their host star in the habitable zone (credit: NASA Ames/JPL-Caltech; Last Updated: Aug 7, 2017).

five thousand known exoplanets. Of these, 29 are more likely to be rocky planets capable of surface liquid water (conservative sample). The other 41 might include water worlds or mini-Neptunes, with a lower likelihood of habitable conditions (optimistic sample).

The conservative sample is a list of exoplanets that are more likely to have a rocky composition and support surface liquid water (i.e., 0.5 < Planet Radius ≤ 1.6 Earth radii or 0.1 < Planet Minimum Mass ≤ 3 Earth masses). They are represented in Fig. 29, which artistically shows such potential habitable exoplanets (updated to 5th January 2023). This represents a list of the exoplanets that are more likely to have a rocky composition and maintain surface liquid water (i.e. 0.5 < Planet Radius ≤ 1.5 Earth radii or 0.1 < Planet Minimum Mass ≤ 5 Earth masses, and the planet is orbiting within the conservative habitable zone) (Credit: PHL@UPR Arecibo).

This list is continuously updated and the number of such exoplanets is rapidly increasing.

The Exoplanet Data Explorer is an interactive table and plotter for exploring and displaying data from the Exoplanet Orbit Database. The Exoplanet Orbit Database is a carefully constructed compilation of quality, spectroscopic orbital parameters of exoplanets orbiting normal stars from the peer-reviewed literature, and updates the Catalog of nearby exoplanets. A detailed description of the Exoplanet Orbit Database and Explorers was published by Han et al. [175]. The latest list in CSV format was updated on 2023, January 5 and is available at http://phl.upr.edu/hec.

Figure 30 (left panel) shows the orbital periods of the solar system planets versus their semi-

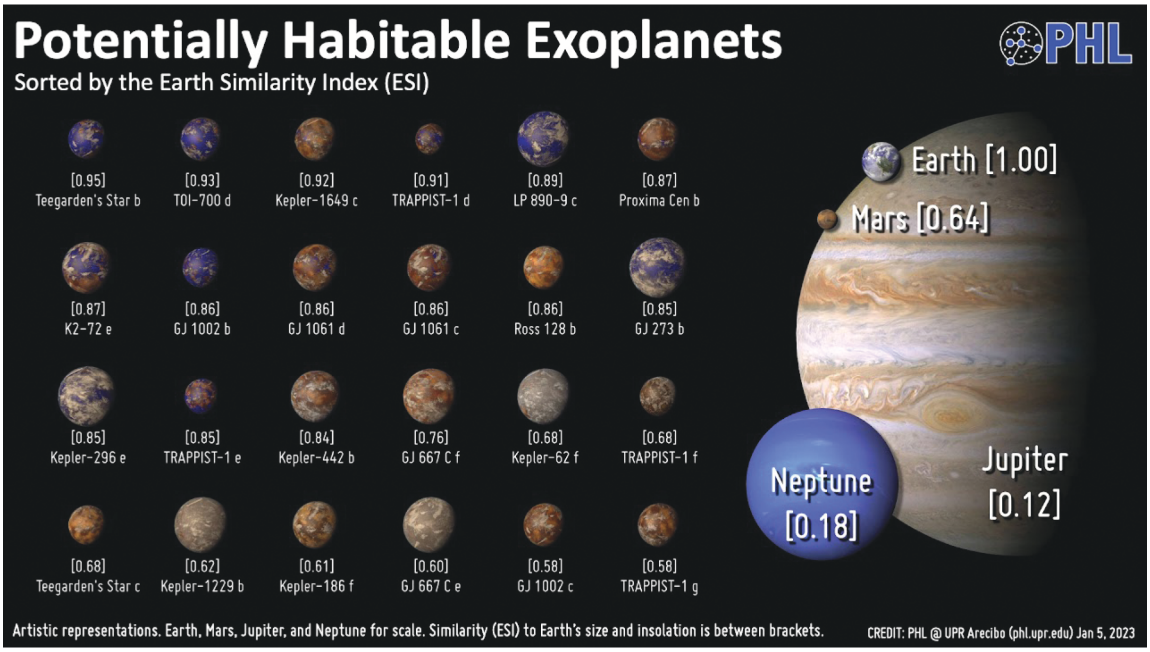


**Figure 29:** Current potential habitable exoplanets (2023, Credit: PHL@UPR Arecibo).

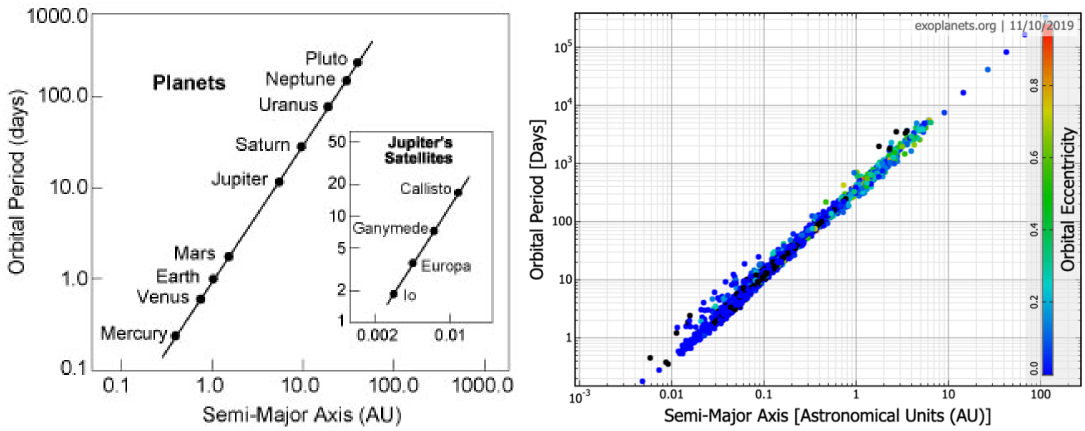


**Figure 30:** Left panel: the orbital periods of the planets versus their semi-major axes. The straight line has a slope of 3/2, thereby verifying Kepler's third law (NASA Cosmos). Right panel: the same for exoplanets discovered up to 11th October 2019 [176].

major axes (NASA Cosmos); Fig. 30 (right panel shows the same diagram for the exoplanets discovered up to 11th October 2019 [176]. We can note how all exoplanets are similar in terms of obeying the same laws of gravity and motion, leading us to conclude that rules of physics apply to every element in the universe. However, the orbits become more elliptical as the eccentricity increases. At low orbital eccentricity, it is harder to determine the semi-major axis correctly. The blue points therefore have a larger margin of error than the other points. Hence we can assume that these planets are either not exactly following Kepler's law due to their low eccentricity and extreme closeness to their star, or else they are indeed following the law but marginal errors in the measurement of the orbital period have been done.

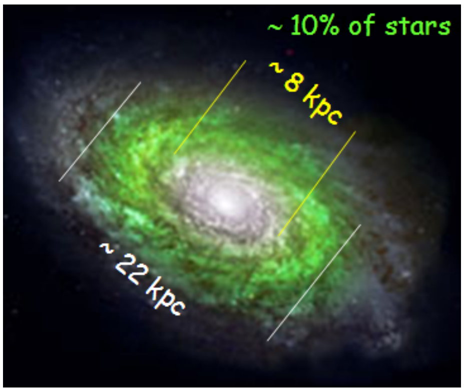


**Figure 31:** Habitable zone of a Milky Way-like galaxy ([86], after [177]; Image courtesy: Yeshe Fenner, Space Telescope Institute).

The presence of numerous exoplanets in the vicinity of solar system – within a distance of $\sim 0.9$ kpc, which is the range accessible by the Kepler mission – plays an important role in speculating about the possible number of such exoplanets within the whole habitable zone of our galaxy. Such habitable zone has an internal radius of $\sim 4$ kpc and an external radius of $\sim 11$ kpc, as shown in Fig. 31 (after [177]), where the habitable zone in a Milky Way-like galaxy is represented in green. The number of stars contained in this zone is $\approx 10\%$ of the total number of stars in the Galaxy. Taking into account that the thickness of the disk is $\approx 1$ kpc, as evaluated by the differential rotation of the Galaxy, the habitable volume is $\sim 330$ kpc$^3$. Therefore, if in a volume of $\approx 3.36$ kpc$^3$ there are 955 Earth-size planets detected, in the habitable zone of our Galaxy we could expect $\approx 9.4 \times 10^4$ Earth-size planets, as lower limit.

Planets around other stars are the rule rather than the exception, and there are likely hundreds of billions of exoplanets in the Milky Way alone [178]. Therefore, it is evident that the probability of finding numerous habitable planets becomes very high. Next generation instruments ground– and space–based will provide valuable information about this intriguing problem.

Studies about exoplanet predictions around stars have been performed by Bovaird & Lineweaver [179]. They predict the existence of a low-radius ($R < 2.5\ R_\odot$) exoplanet within the habitable zone of KOI-812 and that the average number of planets in the habitable zone of a star is 1–2.

For life-forms like us, the most important feature of Earth is its habitability. Understanding habitability and using that knowledge to locate the nearest habitable planet may be crucial for our survival as a species. During the past decade, expectations that the universe could be filled with habitable planets have been bolstered by the increasingly large overlap between terrestrial environments known to harbor life and the variety of environments on newly detected rocky exoplanets. The inhabited and uninhabited regions on Earth tell us that temperature and the presence of water are the main constraints that can be used in a habitability classification scheme for rocky planets. Lineweaver & Chopra [180] compiled and reviewed the recent exoplanet detections suggesting that the fraction of stars with planets is $\sim 100\%$, and that the fraction with rocky planets may be comparably large. They reviewed extensions to the circumstellar habitable zone (HZ), including an abiogenesis habitable zone and the galactic habitable zone.

Earth is located in a dangerous part of the universe. Threats to life on Earth are manifold and range from asteroid impacts to supernova explosions and from supervolcano eruptions to human-induced disasters. If the survival of the human species is to be ensured for the long term, then life on Earth has to spread to other planetary bodies. Mars is the most Earth-like planet we currently know and is the second closest planet; further it possesses a moderate surface gravity, an atmosphere, abundant water and carbon dioxide, together with a range of essential minerals. Thus, Mars is ideally suited to be a first colonization target. Here we argue that the most practical way that this can be accomplished is via a series of initial one-way human missions [181].

However, we have interesting news about the presence of water in the universe. We knew that all the water found on Earth, has been transported by small bodies such as comets and asteroids. On the contrary, the work "*The ancient heritage of water ice in the solar system*" [182] has carried the knowledge one step further. It is understood that the water now present in Earth's oceans, and is present in other solar system bodies, has remained virtually unchanged with respect to that in the interstellar medium. This means that this water has not changed during the process of planet formation. This allows us to understand that the initial conditions that have favored the emergence of life are not unique, i.e. not dependent on the unique characteristics of our solar system. They can, however, be common in space.

Astrobiology is an interdisciplinary scientific field, recently born, not only focused on the search of extraterrestrial life, but also on deciphering the key environmental parameters that have enabled the emergence of life on Earth. Understanding these physical and chemical parameters is fundamental knowledge necessary not only for discovering life or signs of life on other planets, but also for understanding our own terrestrial environment. Two papers by Cottin et al. [183,184] presented an interdisciplinary review of current research in astrobiology, covering the major advances and main outlooks in the field. They reviewed the most recent discoveries, the new understanding of planetary system formation including the specificity of the Earth among the diversity of planets, the origin of water on Earth and its unique combined properties among solvents for the emergence of life, the idea that the Earth could have been habitable during the Hadean Era, the inventory of endogenous and exogenous sources of organic matter and new concepts about how chemistry could evolve towards biological molecules and biological systems. In addition, many new findings show the remarkable potential life has for adaptation and survival in extreme environments. All those results from different fields of science are guiding our perspectives and strategies to look for life in other Solar System objects as well as beyond, in extrasolar worlds.

An intriguing question about the probability of finding a number of civilization in the Galaxy arises. It is now evident that Drake's formula [185] must be object of a robust revision.

For years, the search for manifestations of extraterrestrial civilizations has been one of humanity's most ambitious projects. Major efforts are now focused on the interception of messages from extraterrestrial civilizations, and the millimeter range is promising for these purposes [186]. The Millimetron space observatory is aimed at conducting astronomical observations to probe a broad range of objects in the Universe in the wavelength range 20 $\mu$m to 20 mm, including the search for extraterrestrial life (Smirnov et al. [187]; Kardashev et al. [188], and the references therein).

Important news have been published by Anglada-Escudé et al. [189]. They reported observations that reveal the presence of a small planet with a minimum mass of about 1.3 Earth masses orbiting Proxima Centauri (d = 1.295 pc) with a period of $\approx$ 11.2 days at a semi-major-axis distance of $\sim$ 0.05 AU. Its equilibrium temperature is within the range where water could be liquid on its



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surface.

By using the European Southern Observatory's HARPS – a high precision instrument fitted to the 3.6-m telescope at the La Silla Observatory in Chile – 102 red dwarf stars neighbouring the sun over a period of six years have been studied. Red dwarfs are smaller and cooler than the Sun, however it's been found that 40% of red dwarf stars may have Earth-sized planets orbiting them that have the right conditions for life. New observations with Harps mean that about 40% of all red dwarf stars have a super-Earth orbiting in the habitable zone where liquid water can exist on the surface of the planet. Because red dwarfs are so common – there are about 160 billion of them in the Milky Way – this leads us to the astonishing result that there are tens of billions of these planets in our galaxy alone [190].

Therefore, planets around other stars are the rule rather than the exception, and there are likely hundreds of billions of exoplanets in the Milky Way alone. NASA's Kepler space telescope has found more than 2,400 alien worlds, including a new haul of 95 planets announced on Feb. 15, 2018.

A good help in finding and analyzing extrasolar planets can come from four recent "simple" programs:

- The TRAPPIST (TRAnsiting Planets and PlanetesImals Small Telescopes) consists in a network of two 60-cm robotic telescopes, one in Chile and one in Morocco, used by the Origins in Cosmology and Astrophysics (OrCA) researchers to contribute to the fields of astrobiology and planetology through two complementary approaches: the photometric detection and characterization of exoplanets transiting nearby stars (PI: Michael Gillon), and the photometric study of small bodies of our solar system (PI: Emmanuel Jehin) [191].

- The Search for habitable Planets EClipsing ULtra-cOOl Stars (SPECULOOS) Southern Observatory (SSO), a new facility of four 1-meter robotic telescopes at Cerro Paranal. The exquisite astronomical conditions at Cerro Paranal will enable SPECULOOS to detect exoplanets as small as Mars. It will explore approximately 1000 of the smallest ($\leq$ 0.15 $R_\odot$), brightest ($\leq$ 12.5 $K_{mag}$, and nearest (d $\leq$ 40 pc) very low mass stars and brown dwarfs. The ultimate goals of the project are to reveal the frequency of temperate terrestrial planets around the lowest-mass stars and brown dwarfs, to probe the diversity of their bulk compositions, atmospheres and surface conditions, and to assess their potential habitability [192,193].

  It is interesting to remark the importance of the book *SPECULOOS Exoplanet Search and Its Prototype on TRAPPIST* (Burdanov et al. [194]).

- ARIEL ESA mission [195] – scheduled for launch in 2029 – was conceived to observe a large number ($\sim$ 1000) of transiting planets for a chemical survey of exoplanets, including gas giants, Neptunes, super-Earths and Earth-size planets around a range of host star types using transit spectroscopy in the 1.25-7.8 $\mu$m spectral range and multiple narrow-band photometry in the optical. ARIEL will thus provide a representative picture of the chemical nature of the exoplanets and relate this directly to the type and chemical environment of the host star [196].

- The Transiting Exoplanet Survey Satellite (TESS) [197] is designed to discover thousands of exoplanets in orbit around the brightest dwarf stars in the sky. In its prime mission, a two-year survey of the solar neighborhood, TESS monitored the brightness of stars for periodic drops caused by planet transits. The prime mission ended on July 4, 2020 and TESS is now in an extended mission. TESS is finding planets ranging from small, rocky worlds to giant planets, showcasing the diversity of planets in the galaxy. TESS finished its primary mission by imaging about 75% of the starry sky as part of a two-year-long survey. In capturing this giant mosaic, TESS found 66 new exoplanets, or worlds beyond our solar system, as well as nearly 2,100 candidates to be confirmed. TESS has discovered its first Earth-size world. The planet, HD 21749c, is about 89% Earth's diameter. It orbits HD 21749, a K-type star with about 70% of the Sun's mass located 53 light-years away in the southern constellation Reticulum, and is the second planet TESS has identified in the system. The new world is likely rocky and circles very close to its star, completing one orbit in just under eight days. The planet is likely very hot, with surface temperatures perhaps as high as 800 °F (427 °C). The star that HD 21749c orbits is bright and relatively nearby, and therefore well suited to more detailed follow-up studies, which could provide critical information about the planet's properties, including potentially the first mass measurement of an Earth-size planet found by TESS [198].

Following the NASA Exoplanet Exploration page (https://exoplanets.nasa.gov/the-search-for-life/life-signs/) we can say that our early planet finding missions, such as NASA's Kepler and its new incarnation, K2, or the recently-launched James Webb Space Telescope, could yield bare bones evidence of the potentially habitable worlds. Perhaps K2's examination of nearer, brighter stars will stumble across an Earth-sized planet in its star's habitable zone, close enough for follow ups by other instruments to reveal oceans, blue skies and continents. Or James Webb, designed in part to investigate gas giants and super Earths, might find an outsized version of our planet. With a possible launch in the mid 2020s, WFIRST (Wide-Field Infrared Survey Telescope), could zero in on a distant planet's reflected light to detect the signatures of oxygen, water vapor, or some other powerful indication of possible life.

But unless we get lucky, the search for signs of life could take decades. Discovering another blue-white marble hidden in the star field, like a sand grain on the beach, will probably require an even larger imaging telescope. Designs are already underway for that next-generation planet finder, to be sent aloft in the 2030s or 2040s.

However, we are going to study $\sim$ 50,000 Clusters of Galaxies [199], and we have millions more. We know the lower limit of the extrapolated number of Earth-size planets in the habitable zone of our Galaxy. Thus a natural extrapolation can be reasonably thought. Thus, we can dare to say that we are approaching to the philosophical results obtained by two great free thinkers:

- Siddhartha Gautama also known as Shakyamuni (the sage of Shaka – between the VI and V century B.C.) who exposes a grandiose vision of the universe: through the concept of "**major system of worlds**", a concept on huge scale that implies both the existence of countless galaxies and the possibility of sentient life on other planets other than our own (from the Lotus Sutra – the central text of Mahayana Buddhism).

- About 2000 years later, Giordano Bruno (Nola 1548 – Roma 17th February 1600) who was burned alive in Campo dei Fiori by the "Saint Inquisition" because of his thought –


**Figure 32:** Left panel: Frontispiece of the original publication of *De l'infinito, universo et mondi* [200]. Right panel: Giordano Bruno [201].

summarized in *De l'infinito, universo e mondi* (Giordano Bruno [200]) (see Fig. 32) – that produced the same conclusions of Siddharta: **The Universe is infinite and is populated by a myriad of worlds**. Moreover he was saying that "*Whether we like it or not, we are the cause of ourselves. Being born in this world, we fall into the illusion of the senses: we believe in what appears. We ignore that we are blind and deaf. Then the fear attacks us and we forget that we are "divine". We can change the course of events*".

These philosophical lucubrations were not exactly in agreement with the position of the Roman (Catholic) Church!

Of course we must wait scientific confirmation for the "alien life". We must wait even more for the discovery of "intelligent life". But, the number of discovered planets is growing very fast. Thus, I can reasonably affirm that the **Universe is full of life**, hoping to avoid to be burned alive like Giordano Bruno.

A very important news, which could save me to be burned alive, is coming from the detection of a planet in an external galaxy M51 [202]. Indeed, many lines of reasoning suggest that external galaxies should host planetary systems, but detecting them by methods typically used in our own Galaxy is not possible. An alternative approach is to study the temporal behaviour of X-rays emitted by bright extragalactic X-ray sources, where an orbiting planet would temporarily block the X-rays and cause a brief eclipse. They report on such a potential event in the X-ray binary M51-ULS-1 in the galaxy M51. They examined a range of explanations for the observed X-ray dip, including a variety of transiting objects and enhancements in the density of gas and dust. The latter are ruled out by the absence of changes in X-ray colours, save any with sharp density gradients that cannot be probed with their data. Instead, the data are well fit by a planet transit model in which the eclipser is most likely to be the size of Saturn. They also find that the locations of possible orbits are consistent with the survival of a planet bound to a mass-transfer binary. With this fundamental paper, the search for **extroplanets**, planets in orbits located outside our galaxy, has now become a realistic and practical enterprise.

In my opinion we are witnessing a revolution similar to that of the discovery of a planet orbiting the star 51 Pegasi by Mayor & Queloz [203]. Until then, no planets were known rotating around a star outside the solar system, but the two planets orbiting the pulsar PSR 1257+12 announced by Wolszczan & Frail [204].

Sir Arthur C. Clarke (December 16, 1917 Minehead, UK - March 19, 2008 Colombo, Sri Lanka) – very famous professional fiction writer – said about the intelligent life in the Universe: "*Two possibilities exist: either we are alone in the Universe or we are not. Both are equally terrifying*".

It is important for me to close this section with the beautiful words full of hope of William Borucki – principal investigator for NASA's Kepler mission: *If we find lots of planets like ours... we'll know it's likely that we aren't alone, and that someday we might be able to join other intelligent life in the universe*.

## 5. Conclusions and perspectives

In this review I have tried to illustrate the salient points that have marked the evolution of our universe, underlining the great results obtained and at the same time the questions that have not yet been answered, from the Big Bang to the discovery of exoplanets. And all this obviously without the claim of completeness due to my limited knowledge and the reasonable length of this review.

In order to give some scientific perspectives for the next decade it is worth mentioning a few sentences of the preface, summary and the scientific opportunities of the book *Pathways to Discovery in Astronomy and Astrophysics for the 2020s* [173]. The great efforts in developing science in the most astounding field of modern physics (astrophysics) are evident. Indeed, we live in an extraordinary period of discovery in astronomy and astrophysics. Six Nobel Prizes have been awarded over the past decade alone for discoveries based on astronomical data (dark energy, gravitational waves, neutrino oscillations, the discovery of exoplanets, cosmology, supermassive black holes). Many of the ambitious scientific visions of the *2010 New Worlds New Horizons (NWNH)* [205]. NWNH decadal survey are being fulfilled, but momentum has only grown. We stand on the threshold of new endeavors that will transform not only our understanding of the universe and the processes and physical paradigms that govern it, but also humanity's place in it.

The National Academies of Sciences, Engineering, and Medicine shall convene an ad hoc survey committee and supporting study panels to carry out a decadal survey in astronomy and astrophysics. The study will generate consensus recommendations to implement a comprehensive strategy and vision for a decade of transformative science at the frontiers of astronomy and astrophysics.

The report of such a Committee for a *Decadal Survey on Astronomy and Astrophysics 2020 (Astro2020)* proposes a broad, integrated plan for space- and ground-based astronomy and astrophysics for the decade 2023-2032 [173].

The survey's scientific vision is framed around three broad themes that embrace some of the most exciting new discoveries and progress since the start of the millennium, and that promise to address some of the most fundamental and profound questions in our exploration of the cosmos. The first theme, Worlds and Suns in Context builds on revolutionary advances in our observations of exoplanets and stars and aims to understand their formation, evolution, and interconnected nature, and to characterize other solar-like systems, including potentially habitable analogs to our own. New Messengers and New Physics will exploit the new observational tools of gravitational waves



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and particles, along with temporal monitoring of the sky across the electromagnetic spectrum and wide-area surveys from the ultraviolet and visible to microwave and radio to probe some of the most energetic processes in the universe and also address the nature of dark matter, dark energy, and cosmological inflation. Research in the third theme, Cosmic Ecosystems, will link observations and modeling of the stars, galaxies, and the gas and energetic processes that couple their formation, evolution, and destinies. Within each of these broad and rich scientific themes, three priority areas motivate recommended investments over the coming decade. "Pathways to Habitable Worlds" is a step-by-step program to identify and characterize Earth-like extrasolar planets, with the ultimate goal of obtaining imaging and spectroscopy of potentially habitable worlds. "New Windows on the Dynamic Universe" is aimed at combining time-resolved multi-wavelength electromagnetic observations from space and the ground with non-electromagnetic signals to probe the nature of black holes, neutron stars, the explosive events and mergers that give rise to them, and to use signatures imprinted by gravitational waves to understand what happened in the earliest moments in the birth of the universe. "Unveiling the Drivers of Galaxy Growth" is aimed at revolutionizing our understanding of the origins and evolution of galaxies, from the nature of the tenuous cosmic webs of gas that feed them, to the nature of how this gas condenses and drives the formation of stars.

A very important news, I discussed, is the detection of a planet in an external galaxy M51 [202]. With this fundamental paper, the search for **extroplanets**, planets in orbits located outside our galaxy, has now become a realistic and practical enterprise.

Finally I can conclude with Fig. 33 that clearly explain all the mysteries of our Universe [206], or if you prefer the same attempt written in another language as shown in Fig. 34 [207]. People who are able to read these sentences can understand that "**The truth is written in the book of the Nature. We must learn to read this book**".

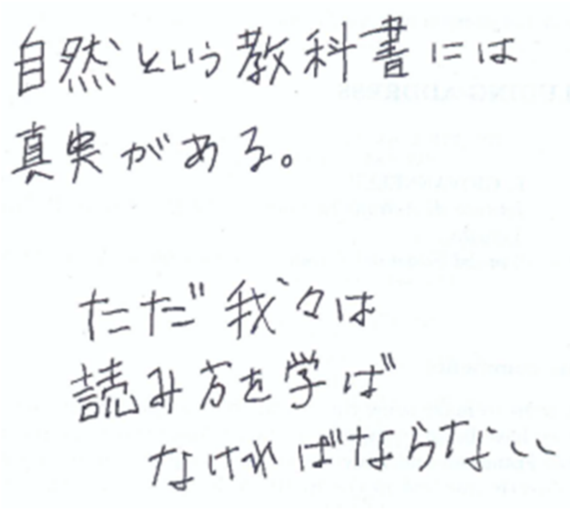


**Figure 33:** Understanding our Universe (Adopted from [206]).

The experiments provide the basic alphabet, immersed in an apparently chaotic soup, but necessary to understand the nature. From that soup we must extract words and phrases to compose the book of the nature. In other words, the data coming from the experiments constitute the basic alphabet that we use for constructing models that attempt to describe the nature. But we have a lot of

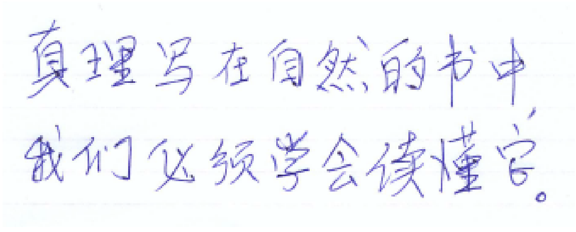


**Figure 34:** Understanding our Universe (Adopted from [207]).

models for interpreting the experimental data by the light of science. Depending on the hypotheses the results could run against the experiments. Then, in order to be acceptable, models can take into account and justify **ALL the available data**.

The same concept was expressed in much more incisive terms by Richard Phillips Feynman – Nobel laureate in Physics in 1965 – also known as *The Great Explainer*: **It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong**.

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- the Exoplanet Orbit Database and the Exoplanet Data Explorer at exoplanets.org.

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