Panorama of Multi-messenger Astronomy

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Abstract. We discuss various aspects of multi-messenger astronomy from photonic astronomy to new branches of astronomy related to other particles and interactions, namely cosmic rays, neutrino, and gravitational waves, both in an astrophysical and cosmological context.

1. From Astronomy to Astrophysics to High Energy Astrophysics

High Energy (HE) astrophysics is the study of high energy phenomena in the Universe. Its stuff is mostly the cosmic rays (CR) of all kinds coming from celestial objects and reaching us on Earth. It comprises the electromagnetic radiation as UV, X rays and gamma rays, as well as charged particles, and other non conventional vectors like neutrinos and gravitational waves (GW).

Each wavelength and each messenger probes specific aspect of the cosmos and helps bring a more complete picture of its content and properties. HE astrophysics is thus closely related to particle physics, and the relatively recent blossoming of the field is a tribute to the usefulness of probing the Universe in a multi-messenger fashion while the high energy aspect is synonymous to studying violent most energetic processes which unravel new hitherto unknown facts of fundamental importance.

We shall review in this talk HE astrophysics particle by particle, including the recently christened GW-astrophysics, but we will focus mainly on standard CR-astrophysics and neutrino astrophysics. We will see that most of this new astrophysics deals with transient cosmic events, namely mergers of black holes or neutron stars, supernovae, gamma-ray bursts. Before dipping further into the subject, let us clarify the difference if any between astronomy and astrophysics. Astrophysics etymologically speaking comes from the juxtaposition of both astronomy and physics. In practice, it is putting the two disciplines into synergy and any attempt to disentangle astronomy from astrophysics is an impregnable challenge as both disciplines have become deeply intertwined. Furthermore, it is astronomy that has merged into this new discipline as astrophysics. Physics, the study of the material world, provides meaning to what is observed or detected. Without it, the pictures we obtain would be as meaningless as colorful mazes. On the other hand, astronomy provides the lifeline of physics, its Lebensraum: it opens up the range of investigations to the whole cosmos as most of the phenomena are taking place at the large scale and are not accessible in terrestrial labs. Think about degenerate matter in stars, the various hadronic forms of matter in collapsed objects, gravitational waves (GW), the ultra dilute forms of matter in the interstellar media...

As the Universe is mostly plasma, low energy plasma physics is required to describe the matter distributed in the vast expanse of diluted matter. As for the interiors of stars, hot plasma requires nuclear physics, and when it becomes so hot that nuclei are no more able to keep its nucleons together and reaches deconfinement regime nuclear matter turns into a quark-gluon plasma. Also as far as cosmology, the closer you get from instant zero and go through the various transition phases, the more
you will need the high energy branches of physics from nuclear physics all the way to particle physics, and even its speculative appendages.

In practice, the "Astronomie à papa" which was practiced roughly till the mid-fifties and which mainly consisted of localizing and cataloging celestial objects, is no more there and astronomers now go beyond measuring astrophysical quantities like spectra, light polarization... into interpreting and modeling and so have all become astrophysicists The nitty-gritty job of operating, calibrating organizing have eschewed to engineers, computer scientists and other specialists, even if some overlap remains!

High energy astrophysics can also be described as the study of the highly energetic electromagnetic radiation coming from celestial objects as well as of cosmic rays (CR), neutrinos and even gravitational waves (GW). Each wavelength and each messenger probes specific aspect of the cosmos and helps bring a more complete picture of its content and properties. HE astrophysics is thus closely related to particle physics, and the relatively recent blossoming of the field is a tribute to the usefulness of probing the Universe in a multi-messenger fashion while the high energy aspect is synonymous of studying violent most energetic processes which unravel new hitherto unknown facts of fundamental importance. To push further on the proximity of the field to particle physics, we may compare the acceleration mechanisms in sites like SNe, SNe remnants, quasars, accretion disks and the like, to the ones in colliders and synchrotrons machines, except that in the first case we are dealing with accelerator sites of cosmic size with un-collimated beams and highly complex environments while we are dealing in the second case with relatively clean collisions taking place in accelerator’s detectors. We shall review in this talk HE astrophysics particle by particle, including the recently christened GW-astrophysics, but we will focus mainly on CR-astrophysics and neutrino -astrophysics. But before that let us review briefly the basic constituents of matter and its modes of interactions.

2. Basics of particle physics. Fundamental objects and ultimate laws
One of the most significant advance in physics is certainly its successful drive to find out about the intimate structure of the microscopic world. We can say in this early part of the XXIst century that we believe we know the fundamental constituents of matter and their various modes of interaction. So much so that this knowledge has now found its way even to High Schools’ textbooks.

2.1. The "stuff" and its rules
Our world is that of fermionic matter, conveniently classified in two kinds: the hadronic one and the leptonic one. The hadronic components which constitutes the bulk of matter and forms all the structures we see around including our bodies is made ultimately of quarks, two common ones the "u" and the "d" quarks, and four more found during fleeting instants in high energy processes like at colliders or when cosmic rays slam into matter. The leptonic matter is basically the electron, the only stable and massive one and two more massive ones namely the muon and the taon but unstable. Beside this, three chargeless and almost massless leptons exist, the neutrinos, but they are so weekly interacting that they are of no consequence in everyday life. All these matter particles interact through exchange of other particles of spin one and two, this time called bosons, namely the photon, the W and Z bosons, gluons and gravitons.

2. Figure 1: The basic components of matter: six quarks and six leptons. The four stables are: The "u" and "d" quarks forming the hadronic matter. The electron a non nuclear particle which reestablishes the overall electrical neutrality of matter. The neutrino which is an almost non interacting particle of no direct significance in daily life.

The picture we have drawn is very pleasing and strikes by its simplicity: matter particles called fermions of spin half-integer interacting among themselves through the exchange of "radiation"
particles of integer spin. All the complications arise in describing the dynamics since a different effective dynamics is at work at each energy scale. So, ultimately the world is simple but this simplicity is hidden. Does this not remind us of the realm of humans relations where pure sentiments are swamped by daily life complications?

3. Multi-messenger Astrophysics

Two shattering discoveries were made in the past few years which gave to the multi-messenger approach its letters of nobility as well as a new impetus. On the one hand, the discovery of the gravitational waves (GW) at the LIGO Observatory from merging black holes, and on the other hand, the discovery of the first astrophysical neutrinos at the cubic kilometer IceCube detector in the Antarctic ice [1]. Studying the Universe through various particle messengers allows each one of them to bring forth a unique perspective on some aspect of the Universe that other means separately can’t provide.

3.1. Powering cosmic emissions

Before going through the various astrophysical messengers and what each specifically brings to our understanding, it is useful to give an overall view of the mechanism which power the various observed emissions. A fact that came slowly to light during the past few decades is that the most extreme phenomena are powered by the weakest interaction, namely gravitation. This take place for compact objects when the potential energy is much higher than all the other forms of energy (atomic, nuclear...). Let us recall that according to today’s paradigm, all of SNe, AGN’s, GRB’s are actually resulting or related to the collapse of cosmic objects. Two basic characteristics of the gravitational interaction concurs to that fact, namely the $1/r^2$ dependency of the effective interaction, and its additive nature. Thus the energy liberated for the formation of a neutron star can be evaluated by subtracting the potential energy after collapse to that before collapse, which gives in Joules:

$$\Delta E \sim GM^2/R_{NS} \sim 3 \times 10^{46}(M/M_{\odot})^2$$

where $M$ is the neutron star mass while $R_{NS}$ is its final radius taken to be some 10km. The energy released is some 200 times larger than the nuclear fusion energy if all the collapsing mass was involved in that later process.

*Figure 2:* Graphic representation of a blazar sputtering accelerated protons (yellow lines) initiating a cascade made of various other particles. Image: © IceCube/NASA

The energy release is even larger if the end product is a black hole instead of a neutron star. Subsequent to that collapse, the in-falling matter will form an accretion disk, but having too much angular momentum, it will be unable to get rid of it, thus forming an accretion disk. Yet this matter will be slowly spiraling in by friction, which will enable that potential energy to be liberated as radiation. In view of the depth of the potential well, it will again lead to a tremendous energy release reaching up to some 40% of the rest mass energy. This same basic principle is also at work for super massive galactic black holes which power the Active Galactic Nuclei (AGN). In the same vein, colliding compact objects which are not as rare as one would think since they are the result of binary evolution, could radiate away the potential energy released from collapse.
It is in the environment of those compact objects, accretion disk, jets that particle processes take places for which subsequently the various multi-messengers disciplines need to be put into action.

3.2. Photonic / electromagnetic astronomy

Using photons has been for a long time the primary source of astronomical information, first in the optical band, then in the other bands of the spectrum as other means of observation became available. This gave the various branches of «photonic» astrophysics, from those involving harder photons as UV, X and gamma rays, to the ones with softer photons as infra red, microwave and radio. Spanning some twenty orders of magnitude, optical astronomy is the Swiss Army knife of astronomy, but any Swiss Army knife, it can’t be fully polyvalent and need more specific tools. Indeed many media are opaque to photons. Furthermore, other messengers could be more relevant to the photon for whole classes of phenomena. Thus for example, UHECR where particles -most probably protons- each carrying an energy of the order of the Joule, are unique probes of phenomena at the highest energy.

![Figure 3: Photons absorption versus distance horizon. While the Universe allows for neutrinos and GW as well as low energy photons to travel unimpeded basically across the Universe, harder photons are stopped at various distances due to the various media they encounter. It is clear from the figure that a sizeable part of the universe and energy range cannot be explored using photonic astronomy. Credit: IceCube Collaboration](image)

4. HE - Cosmic Rays astrophysics

Cosmic rays (CR) astronomy came to age in the early stage of the XXth century and is thus the oldest of the non-optical astronomy branches. It started with its discovery by Victor Hess in 1912 and got into serious business when Bruno Rossi and Pierre Auger discovered independently in 1934 the Extensive Air showers (EAS), that is the many kilometers wide cascade of ionized particles and electromagnetic radiation produced in the atmosphere when a primary cosmic ray hit the top of the atmosphere. For the larger EAS, billions of secondaries are produced that reach at ground level over areas of many square kilometers.

CR studies were not thought initially to have any great astronomical value as it was seen as mere atmospheric phenomena resulting from cosmic radiation. In fact it is as close as it can be from a misnomer since it is mostly not radiation but particles. The sources are, beside the copious but at
relatively low energy production from the Sun, the various cosmic accelerators in the Universe that we mentioned earlier, and which astrophysics started discovering in the past half a century like SNe, AGN’s, SNR’s... The astonishing fact about this field is that having being at the forefront of the advances in particle physics in the pre-accelerator era, then gone low key for many decades, it is now witnessing a strong revival due to its unique potential in probing high energy phenomena.

**Figure 4**: The galactic cosmic rays differential spectrum from various experiments. Notice the $E^{2.6}$ factor on the energy spectrum axis so as to amplify the various features of its high energy end [2].

When talking about High Energy CRs at energies beyond that resulting from the Sun’s activity, we quickly encounter the need to find its accelerating mechanisms, as we rapidly came to the conclusion that no known source or even potentially expected source could propel those particles to the stupendous energies of $10^{20}$J. Enrico Fermi was the first to describe an efficient mechanism to reach very high energy invoking a moving shock front propagating away from a source and for which the repeated shock encounters increase the energy of the charged particles within it in a characteristic power law. This is the essence of the Fermi mechanism which can provide the would be cosmic rays with energies far larger than the ones reached at terrestial particle colliders. Thus by analyzing the particles creating the showers we could go back to find the astronomical sources and their properties.

Let us acknowledge that the reality is less enchanting than what one could infer from the $10^7$ energy boost factor with respect to the terrestrial accelerators as it comes with a concomitantly rapidly falling rates which reaches a ridiculously one particle per km$^2$ per century when one reaches the highest energy of $\sim 10^{20}$ eV. Furthermore, cosmic rays are far from constituting a beam as they are highly non collimated and of unknown nature (although thought to be protons). Then the regions with appreciatively large magnetic field which could provide the accelerating mechanism are hard to found in the Universe. In any case, those accelerated particles then go through the Earth’s atmosphere leaving behind tracks and showers from which one then attempt to deduce the properties of the sources. It is indeed a long chain of inferences compared with the relatively straightforward analysis carried out at terrestrial accelerators.

At present time, the largest such CR detector is the Pierre Auger laboratory in the Argentina’s pampa with its 1660 water Cherenkov particle detector stations spread over 3000 km$^2$ overlooked by 24 air fluorescence telescopes is. It will be dwarfed by the JEM-EUSO space observatory with its look down capability of close to 200.000 km$^2$ which will «swamp» us with unique data on HE astrophysical objects.

So there is certainly HE cosmic rays in the future of astrophysics.

5. **GW Astrophysics**: The new GW window was opened in 2015, on time for the 100th anniversary of General Relativity, when the upgraded LIGO interferometer detected for the first time GW from the merger of two black
holes at the prodigious distance of nearly 1.3 billions light years away! It is called a new window because it allows to study phenomena not accessible otherwise, thus the detailed BH mergers for example can’t be observed easily by other means.

This form of vibration is unambiguously very different from the other kinds of vibrations since it is the very fabric of space-time which experiences these oscillations. Yet due to its intrinsic weakness, the signal will be strong enough to be detected only for very massive compact strongly accelerated objects. Detection at present time is restricted to BH and NS mergers. Thus, two black holes at an advanced stage of merging can rotate at a rate of up to 1000 times per second experiencing a huge acceleration which will suck up the remaining gravitational potential energy of the system while liberating in the form of powerful GW. Indeed the weakness of the effect is such that Einstein himself thought that its detection would be an impossible feat. Yet CR has the unique capability among the various other astronomies to reveal directly the evolution of compact objects.

![Black Holes of Known Mass](image)

*Figure 5: Chart of the masses for black holes detected through GW observations (blue). Source: LIGO collaboration.*

Beside those compact objects mergers, GW astronomy could possibly detect GW from asymmetric explosions of very massive stars as well as it has also some potential cosmological capability.

6. Neutrino Astrophysics

Neutrino astronomy is a somewhat late comer in multi-messenger astronomy. It all started with the detection of a handful of neutrinos in 1987 when SN 1987A situated in the Large Magellanic Cloud galaxy next to our Milky Way exploded, thus releasing most of its energy in neutrino form, some of which reached Earth on that fateful day of 23 February 1987. Solar neutrino astronomy started few years earlier when it was found a deficit on the number of solar neutrinos received in underground detectors. In addition, atmospheric neutrinos detection (Superkamiokande and Borexino detectors notably) coming from the decay of muons generated in cosmic rays air showers started in earnest. All this along with the various ongoing long baseline experiments has enabled us to determine most of the neutrino mixing matrix parameters. The first galactic neutrinos were detected in 2013 by the billion ton detector IceCube which is tracking neutrinos coming from below ground (And thus coming from the Northern hemisphere sky). At term, it should measure their flux and identify some of their sources which presumably are Active Galactic Nuclei (AGN) as well as Gamma-ray bursts and starburst galaxies. We can see displayed in Fig 6 the various neutrinos sources spanning a very large energy spectrum.
Figure 6. Neutrino fluxes from the various astrophysical and terrestrial sources.

In addition to all these astrophysical neutrino sources, there exists a neutrino cosmic background at slightly lower temperature and density than the photon CMB produced some 13.7 billion years ago, a little bit prior to the matter photons decoupling. Due to their extremely low energy, there is no foreseeable experiment which could detect them. Although they are only the second most abundant particles in the Universe after the photon, yet due their non-zero mass, they most likely give the largest contribution to the mass of ordinary matter.

Neutrino astronomy may also indirectly detect dark matter as dark matter candidates involves in many scenarios the weak interaction and thus very high energy neutrino pairs would be produced.

Beside cosmological neutrinos with its almost null possibility to be detected by any mean, the other neutrinos are by-products of the basic interactions occurring within the precincts of cosmic accelerators or from SNe. Indeed protons zipping through the matter of jets or in an accretion disk will interact through mostly neutral weak current to either directly producing neutrinos or through meson decay.

Here at few typical reactions taking place in those environments:
- Hadronic processes
- Photo-hadronic processes

In addition, since those particles have to be detected, one need the detectors to be placed in the bulk of the detector. Is should now be clear why the detector is made of water or of strongly packed transparent ice like for IceCube.

Figure 7: An illustration of what is involved in detecting an astrophysical neutrino at IceCube. Cosmic rays interact in the atmosphere at various locations w.r.t. the detector, and careful tracks directions allow to eliminate them as background to neutrino primaries sought [3].
Now due to its very weak interaction with matter, neutrinos need huge detectors to be seen. The largest such detector at present is IceCube under Antarctic ice, designed to look for point sources of neutrinos in the TeV range in order to explore the highest-energy astrophysical processes [4]. It can be described as a neutrino telescope as it aims at «imaging» in HE neutrinos far away cosmic sources. Yet, the fight against the background particles, whether they be neutrinos or muons is overarchingly and in fact is a bit like searching for needles in a haystack. Thus in a seven years period, IceCube has isolated some 100 high-energy astrophysical neutrinos, in the energy range between 100 TeV and 10 PeV, for more than a million atmospheric neutrinos and hundreds of billions of cosmic-ray muons.

Another similar project at an advanced stage is the European neutrino telescope Cubic Kilometre Neutrino Telescope (KM3NeT)[5], which will be located at the bottom of the Mediterranean Sea. It is a five cubic kilometres water Cherenkov detector distributed over three locations.

Notice that due to its location, IceCube is more sensitive to point sources in the northern hemisphere than in the Southern Hemisphere. Indeed, it can observe astrophysical neutrino signals from any direction, but neutrinos coming from the direction of the southern hemisphere are swamped by the cosmic-ray muon background. KM3NeT could complete the map for the southern hemisphere.

**Figure 8**: Left: The IceCube neutrino observatory which has already started exploring our universe at energies at the PeV scale and above. Right: IceCube-Gen2, a ten-cubic-kilometer detector with extended version of surface which will allow vetoing unwanted CR. In brown is the «old» IceCube, and the extra arrays are the proposed extension. We see in addition to that, the PINGU detector as the Deep Core extension for high-energy neutrino oscillations and which might enables us to establish the right neutrino mass hierarchy. This extended IceCube should lead to a ten fold increase in detection rates and will provide an unprecedented view of the high-energy universe.

7. **The Two Dark Horses of Cosmology: DM & DE**
Modern astrophysics and cosmology has to their credit some great achievements, yet it is the source of the biggest actual physical puzzles. They are the ones like the GRB's which constitute by far the most powerful explosions in the Universe, the existence of the GZK limit[6] which may enable us to probe the limit on the validity of Lorentz transformation, or in other words of the validity of special relativity.

Another weird consequence of BigBang cosmology is the existence in addition to the CLB whose exploration in the past two decades has lead to the greatest advance in modern cosmology, is the existence of a similar background in neutrinos. Could one succeed one day in detecting the CνB (Cosmic Neutrino Background), that is the cosmic background of neutrinos instead of that of photons? It is actually unthinkable experimentally wise due to the extreme weakness of neutrino's interaction
with any form of matter, but perhaps we could find some unknown process in the future which would enable us to peek much farther in the history of the Universe.

\[\text{Figure 9 : The composition of the Universe circa 2018. We see that it is mostly made of substances unknown in terrestrial laboratories, namely DE and DM. As for neutrinos (0.5%), depending to what value its mass will turn out to have, it may compete with aggregated hadronic matter (0.3%) for which one is the most abundant ordinary matter in the Universe!}\]

Indeed this background, which is a strong prediction of the hot standard Big Bang model, appeared few seconds after the Big Bang when the Universe was at a temperature at this very early time that would allow one to probe the physics of the Universe and would constitute the ultimate looking back limit.

The existence of Dark Matter (DM) and Dark Energy (DE) has left perplexed the scientific community. What is this shadow matter which is everywhere but that we couldn't till now detect in any way? This is not as trivial as finding some traces of substance of unknown origin in some material object; we are talking about forms of matter making up some 96% of the energy content of the Cosmos!

Even in the context of the standard Big Bang cosmology (Friedmann - Lemaître models), DM & EE are game changing: geometry and fate of the Universe have become disentangled. Indeed, the Universe is flat only because of DE density, but then we don’t know the future evolution of the DE energy density and thus the Universe's ultimate fate is unknown; is it an indefinite expansion, a Big Rip or a Big Crunch? They are even higher theoretical speculations that may leave one in disarray: Visions where our Universe would be like a giant computer, or a Black Hole whose Schwarzschild radius is the Hubble's horizon, or a hologram. Even if we could determine its geometry, which at present time looks flat that is Euclidian, what is its topology or connectivity? When looking at it globally, is it simply connected space or multiply connected one? Does its structure has holes, handles, or is it crumpled? Then the most baffling speculation of all: Is the Universe single or multiple? In the latter case, it would be forming a so-called Multiverse[7] with causally disconnected bubble Universes, each one with its own specific set of laws, with our own Universe within its Hubble horizon constituting one single bubble.

So one may describe cosmology today as Trotsky’s physicalist version of permanent revolution, with indeed a fundamental conceptual revolution every decade or so.

8. Conclusions
Multi-messenger astronomy is the XXIst century’s way to study the Universe and in particular the objects and phenomena at the very high energy end of the spectra that XXth century astronomy has uncovered. To combine all of the information channels with all of the cosmic particles improves the search sensitivity and our confidence in our detected events. Multi-messenger astronomy has already lead to great successes and its potential when fully unleashed will certainly reveals a new unimagined picture of the Universe. Astronomy has never failed us in that respect.

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