Contents

Chapter 1

Astroparticle radio detection

Within this chapter, the reader will understand the reason behind the birth of astroparticle physics, and its main goals, with an important mention to the current scenario. The topic of this thesis requires focusing on the technique of radio detection for this cosmic particles, and an overview of the actual experimental landscape.

1.1 The astroparticle scenario

Astroparticle physics is a newborn field targeting the knowledge of fundamental physics, which involves the basic building blocks of matter, the fundamental forces, the origin and evolution of the universe, and the behavior of spacetime.
The first glance we had to the structure of matter was trough natural radioactivity, thanks to the discoveries of Henri Becquerel and Marie Curie. Because of the Heisenberg's principle, science needed higher energy to probe the smaller length scales:

$$\Delta x \simeq \frac{\hbar}{\Delta p}. \tag{1.1}$$

In this equation, $\hbar = h/2\pi = 10^{-34}$ Js is the so-called Plank constant. High energy physics was born in the late 1910's, with the discovery of extraterrestrial radioactivity, with the name, coniated by Victor Hess, of cosmic rays. In the mid-twentieth century accelerator physics brought huge developments in the field, conquering the TeV energy scale, which corresponds to distances down to 10^{-20} m (considering Eq. 1.1). Nevertheless, the way to a complete understanding of the fundamental constituents of the Universe is still long, despite the enormous progress of particle acceleration technology, the energies we can investigate on Earth are still lower than the most energetic cosmic rays. At these energies, phenomena predicted by theories beyond the Standard Model, such as quantum gravity effects, supersymmetry, or extra dimensions could become apparent.

The study of these high-energy beams can improve our knowledge of fundamental particle interactions, and of extreme astrophysical phenomena. While electromagnetic observations (traditional astronomy[1] covers from radio to γ-rays) reveal thermal and non-thermal emission processes, and gravitational waves probe bulk mass motions, astroparticles directly sample non-thermal acceleration sites. The synergy between these complementary information channels defines modern *multi-messenger* astronomy.

[1] Traditional astronomy here refers to the operation of direct-detection telescopes.

Astroparticle physics concerns not only cosmic rays, but also gamma rays, whose detection requires specialized technology to overcome atmospheric absorption. Finally, the discovery of the first cosmic neutrino in 2013, completed the astroparticle physics landscape.

At low energies, up until $\mathcal{O}(100\text{ MeV})$, the sources of extraterrestrial radiation are dominated by the Sun. Meanwhile, high-energy particles are mostly produced outside the Solar System.

The energy thresholds defining the "high-energy" regime are highly dependent on the astroparticle type, as evidenced by the diffuse intensity spectra in Figure 1.1. While gamma rays enter this regime around 1 GeV, the threshold rises to 1 TeV for neutrinos and 10 PeV for cosmic rays.

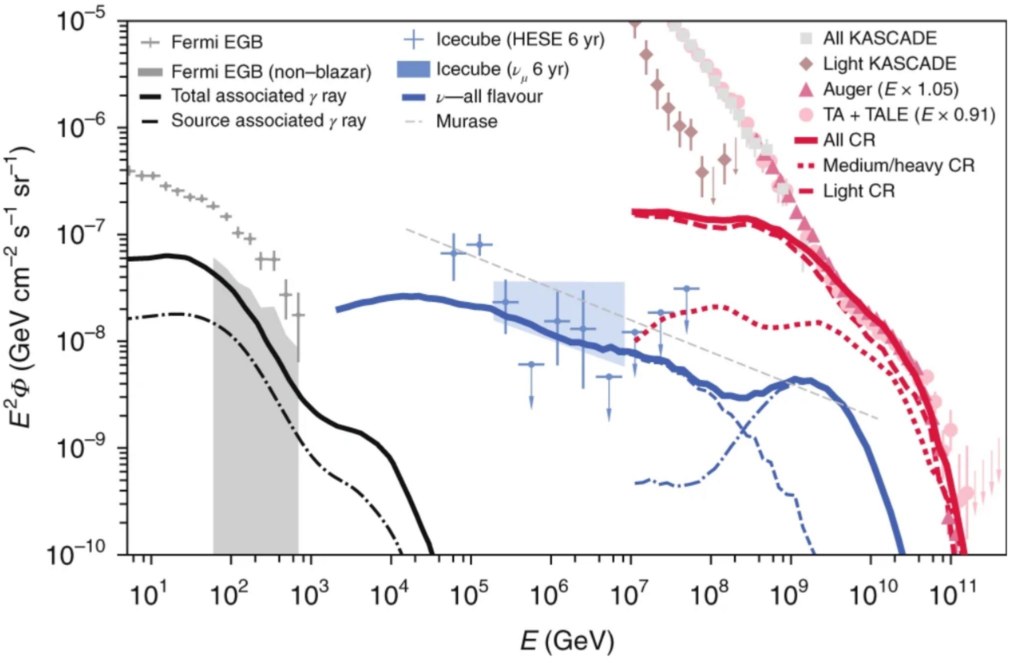

Figure 1.1: Comaprison of measured energy-corrected flux of high-energy astroparticles from ground-based and space-based observatories. [1]

1.1.1 Cosmic rays

Most of the energy in the cosmic ray flux is carried by protons, nuclei and electrons in the energy range of $10^9 - 10^{12}$ eV. Plausible models have been proposed to their acceleration (supernovae are a popular source). However, the energy spectrum extends up to 10^{20} eV, characterizing the so-called ultra-high-energy cosmic rays (UHECRs). This poses a challenge to theoretical models due to energy limitations of the acceleration processes and because particles with such energy cannot be retained in the Milky Way by its magnetic fields. [2]

The origin of UHECRs is still unknown. Measurements by the Pierre Auger Observatory (Auger) [3] find a power-law spectrum, $\Phi \propto E^{-2.6}$. The decline above 6×10^{10} GeV, is probably due to the interaction of UHECRs with cosmic radiation backgrounds such as the cosmic microwave background (CMB) or an upper limit of the particle energy reachable by the astrophysical accelerator.

In Figure 1.1, the total cosmic-ray spectrum (solid red) is decomposed into two composition groups: light (dashed red; H and He) and medium-heavy (dotted red; CNO, Si, Fe).

1.1.2 Cosmic neutrinos

The IceCube Observatory discovery of a diffuse flux of high-energy astrophysical neutrinos in 2013 revealed an isotropic distribution and flavour mix, indicating a predominantly extragalactic origin. The observation of equal neutrino flavors at IceCube is a direct test of neutrino oscillation physics over cosmological baselines. Any deviation could point to new physics, such as interactions with dark matter or sterile neutrinos.

Potential sources of cosmic neutrinos include violent environments capable of accelerating cosmic rays, such as active galactic nuclei, gamma-ray bursts, and starburst galaxies. [4]

The production mechanism in these sources is hadronic: cosmic rays accelerated therein interact with ambient matter or radiation fields to produce charged pions, which then decay to generate the observed neutrinos. This theoretical framework is illustrated in Fig. 1.1, where the PeV neutrino flux (solid blue) is modelled from two such processes: interactions of cosmic rays confined within galaxy clusters with the intracluster medium (dashed blue), and interactions of UHECRs with the cosmic microwave and extragalactic background light (CMB/EBL) during intergalactic propagation (dash-dotted blue).

1.1.3 Gamma ray astronomy

A γ-ray counterpart is a direct prediction of the hadronic processes responsible for neutrino production. When cosmic rays interact to produce charged pions (the parents of neutrinos), they simultaneously produce neutral pions, which decay into high-energy γ-rays. If the source environment is transparent to these γ-rays, they can escape directly. However, for distant extragalactic sources, these very-high-energy photons interact with the extragalactic background light (EBL), initiating electromagnetic cascades that degrade their energy. This process repopulates the GeV energy band, suggesting that a significant fraction of the Fermi-LAT extragalactic γ-ray background (EGB) could originate from the same population of sources responsible for the astrophysical neutrino flux.

This connection is illustrated in Figure 1.1. The modelled γ-ray flux from the total cosmological population of neutrino sources (solid black) is comparable to the non-blazar component of the Fermi EGB. This agreement suggests that hadronic processes in these sources can explain most of the unresolved extragalactic γ-ray background. The separate contribution from cosmic-ray interactions in the intracluster medium alone (dash-dotted black) is subdominant, indicating that galaxy clusters are just one of several source classes contributing to this background [1].

1.1.4 Partial conclusions

The key takeaway is, despite the unknown origins of these astroparticle emissions, it is remarkable that over ten orders of magnitude in energy, the generation rates of UHECRs, IceCube neutrinos and Fermi extragalactic gamma-ray background (EGB) are all comparable, suggesting common physical processes. Unraveling these processes probes particle interactions at energies beyond terrestrial accelerators, maps the invisible non-thermal (dark) energy budget of the universe, tests the laws of physics over cosmological distances, and constrains the nature of dark matter.

1.2 The radio detection technique

With the advent of powerful digital processing, at the beginning of this century, the interest in detecting impulsive radio signals from the universe grew stronger then ever. Nowadays the radio tecnique brings to the field of multi-messenger astronomy high-precision measurement combined with a massive, cost-effective exposure, covering square kilometers of detection area. This feature is extremely valuable when searching the universe's rarest, highest-energy particles.

1.2.1 Traditional radiotelescopes

Traditional radio observatories study continuous or repetitive astronomical objects by analyzing their steady radio emission. These objects can be planets, satellites, asteroids, and comets as well as pulsars, radio galaxies, supernova remnants and the cosmic microwave backgorund. The latter being a more interesting science case. Because of the large distance of those radio sources from Earth, their signals are weak, so radiotelescopes require large antennas, and a sensitive recorder system.

An antenna in this field is a receiver that collects electromagnetic power in a specified bandwidth, polarization, and from a limited range of directions. They may be used individually or linked together electronically in an array, improving the covered area, sensitivity and directivity.

Radio observatories are preferentially located far from population centers to avoid radio frequency interference (RFI) form radio, television, radar and other anthropogenic devices.

The most straightfoward kind of telescope is the single dish. A large, parabolic reflector that collects radio waves from a specific region of the sky and focuses them onto an antenna (a "feed") at the dish's focal point. For a single dish, resolution is limited by diffraction:

$$\theta \simeq \frac{\lambda}{D}, \tag{1.2}$$

where λ is wavelength and D is the dish diameter. Since radio waves have long wavelengths, achieving sharp images requires impossibly large dishes. The larger the collecting area of the dish, the fainter the objects it can detect. Still, the observatory that discovered the first binary pulsar, providing the first indirect evidence for gravitational waves, was a single aperture telescope.

The radio interferometry technique is what revolutionized radio atsronomy. The same sharp signal can be detected with an enormously large dish than combining the signals from an array of smaller dishes spread over a large distance, but is much more feasible.

In this case, the distance between two telescopes in the array, is called the baseline. The maximum baseline acts as the effective diameter of a giant virtual telescope. The angular resolution becomes

$$\theta = \frac{\lambda}{B}. \tag{1.3}$$

By observing a source for many hours as the Earth rotates, the telescopes effectively fill in the "gaps" of the virtual giant dish. The correlator's data is then mathematically transformed (via a Fourier transform) into a detailed image of the sky.

LOFAR (LOw Frequency ARray) is a good example of next-generation interferometers, instead of movable dishes, it uses thousands of simple, fixed dipole antennas spread across multiple countries in Europe. It uses sophisticated digital beamforming to "point" at different parts of the sky. Between the science cases of LOFAR we find: detecting solar bursts, conducting deep extragalactic surveys to understan galaxy formation and evolution. This also doubles as an astroparticle detector for cosmic rays, showing the tight link between the two fields. Low-frequency radio telescopes are the only instruments that can hunt for the faint signature of the burning of neutral hydrogen that filled the universe in its early stages, allowing us to study the universe's "first light". Similarly, OVRO-LWA (Owens Valley Radio Observatory - Long Wavelength Array) is also a digital low-frequency array. Despite being also employed to study the Sun and Jupiter's radio emissions, and the structure of our galaxy, it was specifically designed to be a cosmic ray and neutrino detector. OVRO-LWA dense core of antennas and its precise timing allow it to capture the extremely short radio pulses from UHECR air showers. It is one of the most sensitive instruments in the world for this kind of detection.

Moving to future observatories, LOFAR was also an important pathfinder for SKA (Square Kilometer Array), which will be the world's largest interferometer, with a collecting area of 1 square kilometer. SKA aims to tackle fundamental questions in cosmology: testing gravity, mapping cosmic structure, tracing the history of hydrogen, and searching for the origins of life. Its digital backbone will be so powerful it will also be capable of vast astroparticle physics searches.

1.2.2 Astroparticle radiotelescopes

Astroparticle radio detectors study single, ultra-high-energy events (such as cosmic rays and neutrinos) by capturing the brief, impulsive radio flash they generate. The energy threshod for radio detection of astroparticles is about 100 PeV, the signal produced by less energetic particles is buried under terrestrial radio interference and natural noise. This limit makes radio detectors useful to focus on the transition range (the so-called "knee" in the CR spectrum) between galactic and extragalactic astroparticle sources.

Ground-based experiments detect cosmic rays indirectly because of their interaction with the atmosphere, which generates particle showers, also called Cosmic Ray Extensive Air Showers (CREAS). Instead, neutrinos only interact with denser media, generating particle cascades. Neutrino detection experiments target this interaction in large ice or water volumes. As the name suggests, CREAS are much more extensive, with length scales of kilometers, while particle cascades in dense media develop within meters.

Radio emission

However produced, a particle shower, causes coherent radio emission generated by relativistic electrons and positrons in the electromagnetic component of the shower. Several mechanisms contribute to the total emission, the main ones are the geomagnetic deflection of charged particles and the Askaryan effect, radiation due to the time variation of the net charge excess (see Figure 1.2). The geomagnetic effect generally dominates in air showers and (bacause of the reduced length of the shower) is negligible in dense media where the Askaryan effect dominates. However, both the Askaryan and the geomagnetic effect are important in air. More about this in [5].

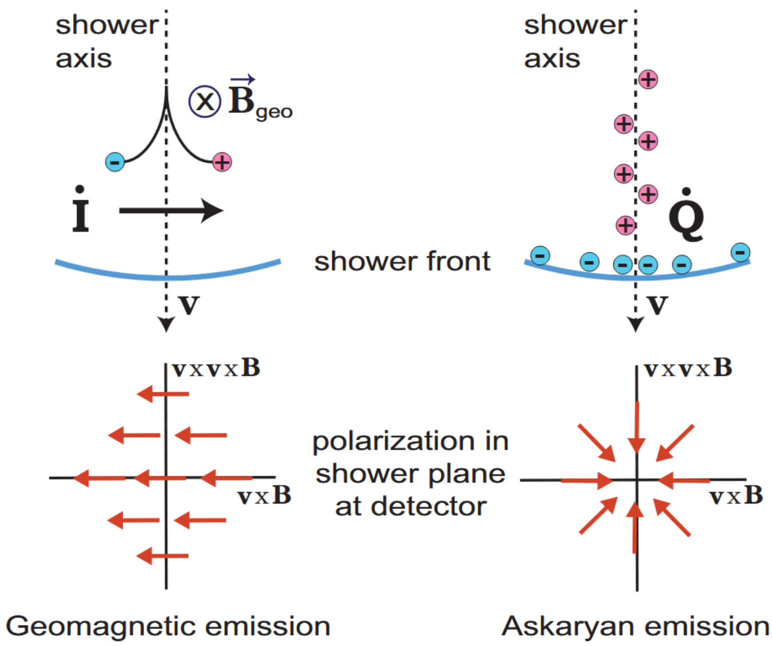

Figure 1.2: Two radio emission mechanisms are experimentally confirmed: on the left, the geomagnetic deflection of electrons and positrons causes linearly polarized radio emission. On the right, the time-variation of the charge excess in the shower front causes radially polarized radio emission, known as Askaryan effect.[6]

The emission is coherent if the wavelength is larger than the emission region. As a consequence of coherence the amplitude of the radio emission scales linearly and the power quadratically with the number of electrons in the shower. For this reason the total power in the radio signal scales quadratically with the energy of the primary particle [3], since the number of electrons in the shower is approximately proportional to the primary energy. Most of the radiation is produced where the electron density is highest (the shower front), since it's typical thickness is the order of one meter, the emission is coherent and strongly amplified at wavelengths of a meter or larger for air showers, and correspondingly at smaller wavelengths (about 10 cm) for the more compact showers in dense media. [5]

Moreover, Cherenkov-like effects appear in both cases. The typical electron in the shower is not necessarily slower than the speed of radio waves in air or whatever other medium. The propagation speed of the radio waves is defined by the refractive index n. At a certain angle, namely the Cherenkov angle of $\theta_c \simeq arccos(1/n) \simeq 1°$ in air, radio waves and ultra relativistic particles propagate roughly at the same speed. Thus, at this angle radiation

is coherent up to much smaller wavelengths, corresponding to several GHz. Therefore, a Cherenkov ring with a typical diameter of around 200 m (depending on observation level and shower inclination) is seen in the radio footprint of air showers on ground, in particular at higher frequencies (see figure 3 in [5]). For showers in dense media the refractive index is much larger and a significant emission strength is only observed close to the Cherenkov angle, which is about 56° in ice. The emission is also the strongest, and extends to highest frequencies of several GHz exactly at the Cherenkov angle. At lower frequencies, below 100 MHz the emission remains visible at a much wider angular range around the Cherenkov angle.
Whatever the medium, these Cherenkov-like features do not depend on the actual emission mechanism: the Cherenkov ring is not only expected for Cherenkov light emitted by particles faster than the speed of light in the medium, but for any kind of coherent electromagnetic emission. To say it clearly: radio emission by particle showers is *not* Cherenkov light at MHz and GHz frequencies, but caused by other emission mechanisms already discussed.

An important point is: corresponding to the broad frequency spectrum, radio pulses are short in time with typical pulse widths $\mathcal{O}(\mathrm{ns})$. This means that the radio pulse contains only a few oscillations at each frequency, which makes air-shower pulses very different to radio signals used for technical purposes like communication. Thus, one has to be careful when trying to apply general theorems of radio engineering on the radio signal emitted by air-showers. Due to the short nature of the radio pulse its measured shape does significantly depend on the bandwidth of the measurement device. Consequently, the main information contained in a measured radio pulse is only its amplitude and arrival time.

Modern experiments

The first generation of digital radio experiments for cosmic rays successfully demonstrated the feasibility of the technique. Two pioneering arrays were LOPES (LOFAR PrototypE Station), located in Karlsruhe, Germany, and CODALEMA (COsmic-ray Detection Array with Logarithmic Electro-Magnetic Antennas), located in a radio-quiet site, in France. Triggered by the KASCADE and Grande particle detector arrays, LOPES was operated from 2003 to 2013, in the 40-80 MHz band, proving that digital radio interferometry could detect air showers even at a site with high radio-frequency interference. In contrast, CODALEMA was built in a radio-quiet zone. Since the co-located particle detector array was limited in accuracy, in later stages, dedicated antenna stations with self-triggering capability were installed, and the triggered events were cross-checked with the coincident measurements of an array of 13 scintillators detecting air-shower particles. With these measurements CODALEMA provided evidence for the geomagnetic and Askaryan emission mechanisms [7]. Currently CODALEMA consists of a 1 km^2 large, sparse array autonomous antenna stations operating in the frequency band of 20 - 200 MHz, and a compact array of cabled antennas triggered by the scintillator array.

Among the second generation of cosmic ray detectors, AERA (Auger Engineering Radio Array) is one of the enhancements of the Pierre Auger Observatory in Argentina. It's technical mission is to demonstrate that the radio technique can be applied to large-scale arrays.

LOFAR detailed measurements of air showers have been exploited to gain deeper insight in the radio emission, and the change of the radio signal during thunderstorms [8]. Moreover, LOFAR so far yields the most precise radio measurements of the shower maximum position, which was exploited to estimate the mass composition of cosmic rays in the energy range around 10^{17} eV [9].

Finally, Tunka-Rex (Tunka Radio Extension) is the radio extension of the Tunka-133, and Tunka-Grande arrays, all located in Siberia. The main goals of Tunka-Rex have been a cross-calibration of radio and air-Cherenkov measurements and the demonstration that an economic design of the antenna stations does not hamper the performance as cosmic-ray detector.

By combining the radio technique with particle detectors, these experiments acquired higher accuracy on air-shower measurements, which allows for better separation of the cosmic rays' primary particles.

Even when optimizing for cosmic-ray detection, neutrino searches can be continued in parallel, where neutrinos would be distinguishable from cosmic rays by the arrival direction and polarization characteristics. Experiments that implement this dual targeting: TREND (Tianshan Radio Experiment for Neutrino Detection) and GRAND (Giant Radio Array for neutrino detection), both located in a radio-quiet Chinese valley. TREND successfully demonstrated that self-triggering on cosmic-ray air showers is possible [10] and revealed itself as a pathfinder for GRAND [11]. The latter will be the largest cosmic-ray detector on Earth, covering an area of 200.000 km^2. Its main scientific goal will be the detection of neutrinos interacting in the surrounding mountains and initiating air showers, which generate radio pulses. One of the key technological questions for this experiment is how to achieve efficient self-triggering and robust discrimination against background pulses over such vast areas. As proof-of-principle, smaller prototype arrays (GRANDproto) are currently in operation.

Finally, TAROGE (Taiwan Astroparticle Radiowave Observatory for Geo-synchrotron Emissions) is a new experiment consisting of two sites in Taiwan [12]. It aims at the detection of near horizontal showers, the receiver is placed on top of a mountain. Depending on the observation angle, the radio signal can be measured directly or after reflection on the ocean. In principle also neutrino-initiated showers should be detectable provided sufficient discrimination against background pulses, e.g., caused by ships. The clear advantage of TAROGE is its large area covered with only few antennas. A potential disadvantage is the missing knowledge on how exactly the radio signal is affected by the reflection on the ocean, since water waves could have structures of similar size as the radio wavelengths, which may cause interference effects limiting the measurement accuracy.

Apparently, huge exposure is the future to study the highest-energy CR and neutrinos, however, this pursuit introduces formidable technical challenges. Together with GRAND, the proposed SWORD (Synoptic Wideband Orbiting Radio Detector) project [13] and the EVA (ExaVolt Antenna) [14] balloon concept are examples of this prospect.
SWORD will be a satellite mission observing cosmic-ray and neutrino-induced showers from space. This setup might complicate the reconstruction of both energy and arrival direction, since the radio signal from the air showers will be distorted by the ionosphere.

1.2.3 Partial conclusions

In summary, the radio technique brings noticeable advantages to astroparticle detection and characterization. Firstly, its role as a cost-effective component in hybrid observatories is becoming increasingly widespread, substantially improving the accuracy of shower measurements. Secondly, with 100% duty cycle, and cheap detectors, the exposure of radio observatories can be stretched even to match the limits of ultra-high-energy neutrinos (in the EeV energy range, are expected $\mathcal{O}(10)$ cosmic neutrinos/(year $\cdot$ km^2)).
However, the radio spectrum is heavily populated by anthropogenic radio-frequency interference (RFI) from sources like radio stations, satellites, and industrial equipment, which complicate the self-triggering feature. Furthermore, radio signals, due to their long wavelengths (from $\mathcal{O}(100)$ cm to few meters), are highly susceptible to natural effects such as atmospheric refraction, ionospheric influence and surfaces reflection, which could cause non negligeble uncertainties.

The next chapter illustrates the multiple ways the atmosphere, in all its layers, can affect radio waves propagation. This is especially important for all radio obervatories that aim to trigger on, and reconstruct, radio signals that went through a large portion of the atmosphere, both coming from the horizon and from below the ionosphere. Because of atmospheric irregularities, it should not be excluded a priori that RFI signals can easily mimic astroparticle pulses when operating at such large apertures.