UNIVERSITÀ DEGLI STUDI DI PADOVA

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Corso di Laurea in Fisica

Tesi di Laurea

Measurement of intergalactic magnetic fields using the echo of fast transient signals

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Sommario

I raggi γ provenienti da Nuclei Galattici Attivi (AGN) e Gamma-Ray Bursts (GRBs) sono un importante strumento per l'astrofisica delle alte energie e dalla loro analisi si possono ricavare interessanti informazioni sulla loro propagazione nello spazio.
I meccanismi e lo spettro delle sorgenti che li producono sono tuttora oggetti di studio.
In particolare, alcuni AGN e GRBs sono in grado di emettere raggi γ ad altissima energia, compresa tra circa 100 GigaelectronVolt (GeV) e 100 TeraelectronVolt (TeV), che successivamente si propagano nel Mezzo Intergalattico (IGM) e possono iniziare un processo a cascata di produzione di particelle cariche. L'annichilazione tra i raggi γ e i fotoni del fondo cosmico creano delle coppie elettrone-positrone (e^+e^-), che a loro volta possono accelerare altri fotoni, tramite effetto Compton Inverso (IC), dando vita a un'emissione secondaria di raggi γ.
L'eventuale presenza di Campi Magnetici Intergalattici (IGMFs) causerebbe una deviazione delle particelle cariche e^+e^- dalla traiettoria lungo cui sono state emesse, il che si rifletterebbe in una serie di effetti sullo spettro osservato, tra cui un ritardo tra l'osservazione dell'emissione primaria (i raggi γ direttamente prodotti dalla sorgente) e quella secondaria (generata dalla cascata elettromagnetica).
Pertanto, attraverso l'analisi del tempo di ritardo, si possono ricavare informazioni e limiti sulle proprietà di tali campi magnetici, quali la loro intensità e lunghezza di coerenza.
Lo studio della presenza dei campi magnetici nello spazio intergalattico permette di indagare l'origine e le proprietà dei campi magnetici attualmente osservati nelle galassie e negli ammassi di galassie.
Ci sono diverse teorie che tentano di dare risposta a questi quesiti. In primo luogo, i campi potrebbero essere il risultato di processi locali, di tipo astrofisico. In questo caso, sarebbero presenti solo all'interno di galassie e clusters. In caso contrario, la presenza di campi a grande distanza dalle galassie indicherebbe un'origine cosmologica: i campi che osserviamo oggi sarebbero i discendenti di campi primordiali, creati durante le primissime fasi di vita dell'Universo.
Dai risultati ottenuti finora non è ancora stato possibile ottenere delle risposte certe, a causa di una serie di forti incertezze sulle proprietà delle sorgenti, dei fondi cosmici, ecc., ma ci aspettiamo che i telescopi di nuova generazione, come il Cherenkov Telescope Array (CTA) siano in grado di farci compiere significativi passi in avanti.

Contents

1 Introduction

Magnetic Fields are expected to be present throughout the Universe, not only in galaxies and galaxy clusters but also in intergalactic voids, where they should be much weaker, as shown in Table 1.

Magnetic fields strength	
Earth	$\sim 1\,\mathrm{G}$
Galaxies	$\sim 10^{-6}\,\mathrm{G}$
Galaxy clusters	$\sim 10^{-7} - 10^{-6}\,\mathrm{G}$
Cosmic filaments	$\sim 10^{-9} - 10^{-7}\,\mathrm{G}$
Intergalactic voids	$\sim 10^{-16} - 10^{-9}\,\mathrm{G}$

Table 1: Order of magnitude of the strength of some magnetic fields present in the Universe.

A review of the estimated lower bounds for the magnetic field in intergalactic voids can be found in Section 5.
Considering the volume filling factor of voids, clusters of galaxies, and filaments, it is clear that voids are the dominant factor that dictates how particles propagate over large distances in the Universe, therefore making it possible to neglect the contribution of the other astrophysical objects.
The origin of Intergalactic Magnetic Fields (IGMFs) is still unknown, although there are a few theories. According to cosmological theories, IGMFs are of primordial origin and later decayed to the present state. The existing theoretical models assume that they emerged during different cosmological phases and thus the expected fields strengths depend on how they were created. Another possibility is that weak fields were created by local effects, as predicted by astrophysical models, and were later amplified by some "dynamo mechanism" taking place before or during the gravitational collapse of large-scale structures, creating the magnetic fields in galaxies and galaxy clusters that we observe. Contamination of the seed fields by galactic outflows of magnetic fields is also possible, hence the need to look for signs of magnetization in cosmic voids, where the fields keep their pristine properties.
For this reason, studying IGMFs can lead to relevant information on the early Universe that nowadays is missing.
What we need to discern which theory might offer a correct representation of the fields origin and evolution is a measurement of the fields strengths and their coherence lengths, i.e. the distance scales after which the degree of coherence of the magnetic fields degrades substantially. Indeed, while in galaxies the fields maintain a specific orientation, this is not the case for intergalactic voids, where the orientation of the fields has a globally random distribution. At the present state, since no direct measurements of the IGMF strength and coherence length are possible, and given our scant knowledge of the coherence length, it is only possible to constrain these two parameters simultaneously.
We expect different constraints depending on the mechanisms and processes that generated the IGMFs since they lead to different models for the magnetic power spectrum. In the case of IGMFs of cosmological origin, we expect $\lambda_B \lesssim$ kpc. On the contrary, if the origin was astrophysical, we estimate $\lambda_B \gtrsim$ kpc, of the order of typical galaxy sizes [1].
Because of this, developing observational techniques that allow a separate measurement of the IGMFs strength and coherence lengths will be crucial to reach a conclusion on which is the right theory.
Data from Very High Energy (VHE, $E > 100\,\mathrm{GeV}$) sources, like Active Galactic Nuclei (AGN) - particularly blazars, a subclass of AGN - or Gamma-Ray Bursts (GRBs) make it possible to assess the properties in which we are interested in different ways by observing the effects that the IGMFs have on the particles moving through the Intergalactic Medium (IGM).
One of these is the time delay between two signals: the TeV radiation directly originating from VHE sources (primary emission) and the GeV signal (secondary emission), resulting from the interaction between the first emission and the cosmic background radiation in the IGM. Primary γ-ray photons emitted by a TeV source can be partially absorbed by the Extragalactic Background Light (EBL), as confirmed by the presence of a clear steepening in the EBL spectrum. This interaction process generates electron-positron pairs, charged particles that deviate from the original trajectory when subjected to a magnetic field. In this sense, the particles deflected by the IGMF carry information

about the field itself.
The field strength can be thus extrapolated from the observed data, but one has to bear in mind that several other factors might affect the measurements and therefore they must be taken into account in the data analysis.
As of today, this type of indirect measurement can only constrain the field properties, e.g. finding a lower limit of the strength and probing that it is non-zero.
Observations from different sources leave us with controversial data, first of all, because there are a lot of side effects to consider in the data analysis, but mainly because the fields are extremely weak.
We expect to obtain much better limits from the next generation of telescopes, like the Cherenkov Telescope Array (CTA).

2 Gamma-Ray Bursts

Gamma-Ray Bursts (GRBs) are very energetic transient events that occur at cosmological distances. They are the most electromagnetically luminous events known, with luminosities between $10^{49} - 10^{53}$ erg/s. GRBs are classified as fast transient sources because of the duration of the "prompt" phase, which is the first and most luminous one.
Defining the GRBs duration as the time scale (T_{90}) during which 90% of the photons are detected in the keV-MeV range, GRBs are conventionally classified as "long" if $T_{90} > 2$ s or "short" if $T_{90} < 2$ s. Long GRBs last at best a thousand seconds, although their typical lifetime is about 30 s. Short ones, on the other hand, typically last 1 s. Figure 1 shows the bimodal distribution of the GRBs observed duration from the Fermi GBM catalog. Typically short GRBs display a "hard" spectrum, with more photons observed above 100 keV. On the other hand, long GRBs have a "softer" spectrum [2].
Prompt emission is usually followed by a second emission phase called "afterglow". It consists in a long-lived emission observed in a broad energy range from radio up to gamma-rays. Afterglow flux decays in time and can be detected for several days or even weeks/months after the initial prompt phase.

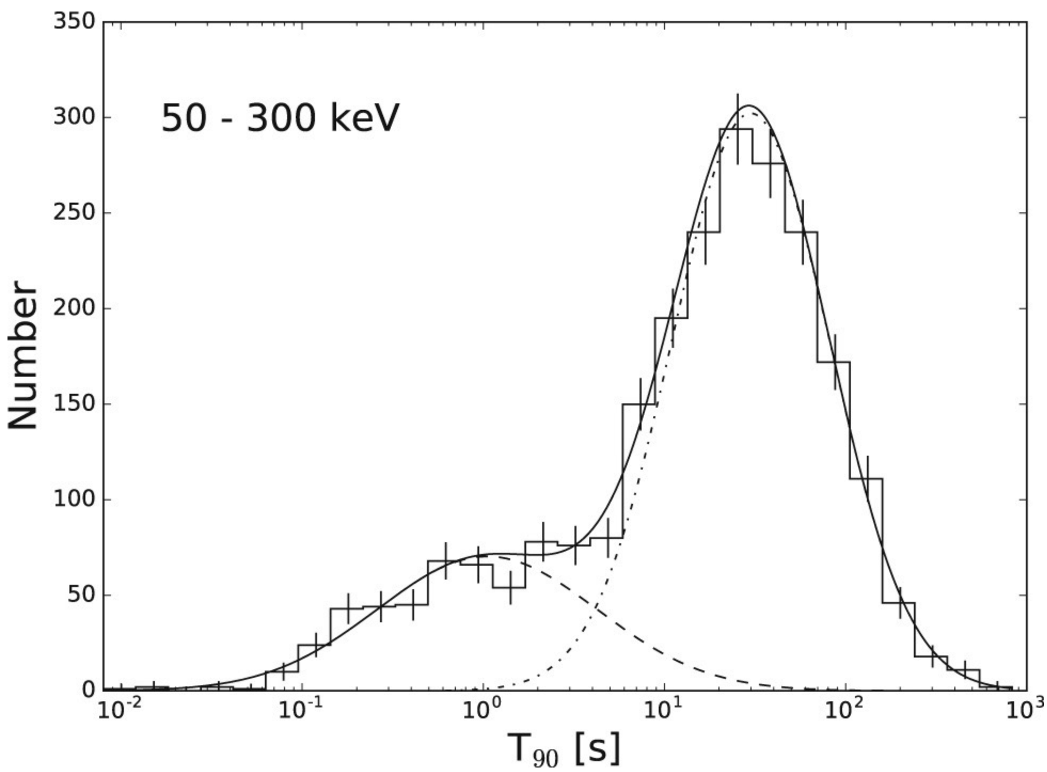

Figure 1: Bimodal duration distribution of GRBs. Credit: [2]

The classification of GRBs into short and long also reflects the different origin of such events. Short GRBs are believed to be generated from very energetic events at high redshifts, such as the coalescence of binary systems of neutron stars (NS-NS) or neutron stars and black holes (NS-BH). Theoretical considerations based on the coalescence time duration lead us to think that GRBs cannot originate from a BH-BH merging: the process would require a much longer time. Indeed, no such events were ever observed.
On the contrary, long GRBs are associated with the collapse of a massive star in a supernova explosion, originating from a "hypernova" of very high mass.
The most credible scenario developed to explain the GRB emission consists in the "fireball" model, schematized in Figure 2. According to it, a central engine, typically a black hole surrounded by an accretion disk, launches an ultra-relativistic jet of material. The prompt emission is then generated as result of internal shocks or magnetic reconnection events, while the afterglow emission is produced from external shocks due to the interaction between the fireball blast wave and the surrounding IGM.

Recently, GRB radiation has also been detected in the TeV range [3,4]. Such detections have confirmed that GRBs can be bright sources of VHE radiation, as expected from several theoretical models [5,6]. The presence of γ-ray photons and the cosmological nature of GRBs open the possibility to explore the properties of the IGMF, as will be shown in the next sections.

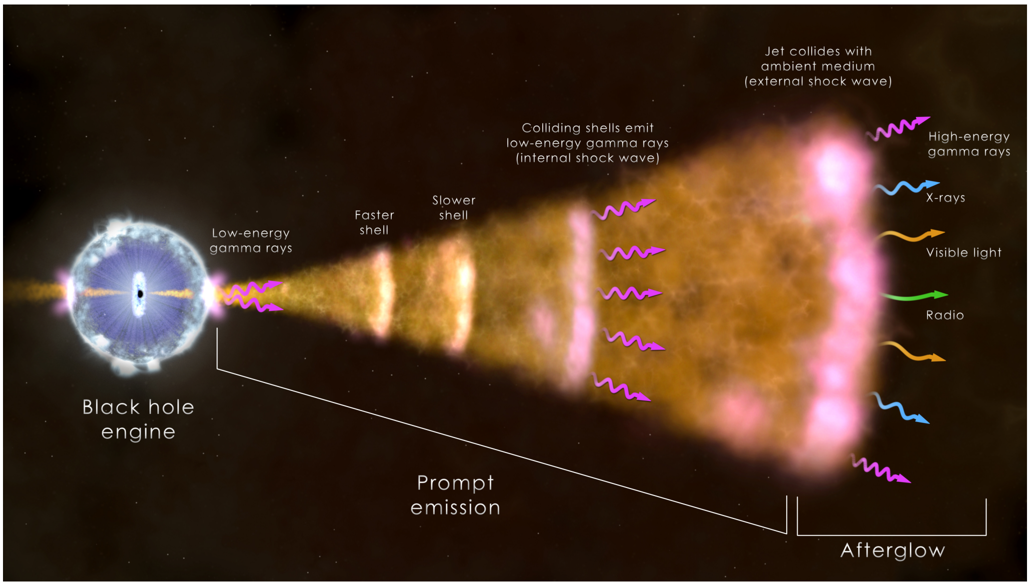

Figure 2: Visual description of the fireball model. Credit: `https://fermi.gsfc.nasa.gov/science/eteu/grbs/`

3 Electromagnetic cascades

VHE γ-rays from extragalactic sources can interact with the background radiation present in the IGM. γ-ray photons of the primary source are absorbed by the EBL and produce electron-positron pairs through $\gamma - \gamma$ annihilation.
Being electrons and positrons charged particles, they are deflected by the IGMF. This creates a time delay between the primary emission, i.e. the photons not absorbed by the EBL that reach the Earth, and the secondary emission, referred to as the "pair echo". The latter is the result of the following Inverse Compton (IC) scattering happening in the interaction between the e^+e^- pairs and the Cosmic Microwave Background (CMB).
A schematic representation of the cascade process can be found in Figure 3.

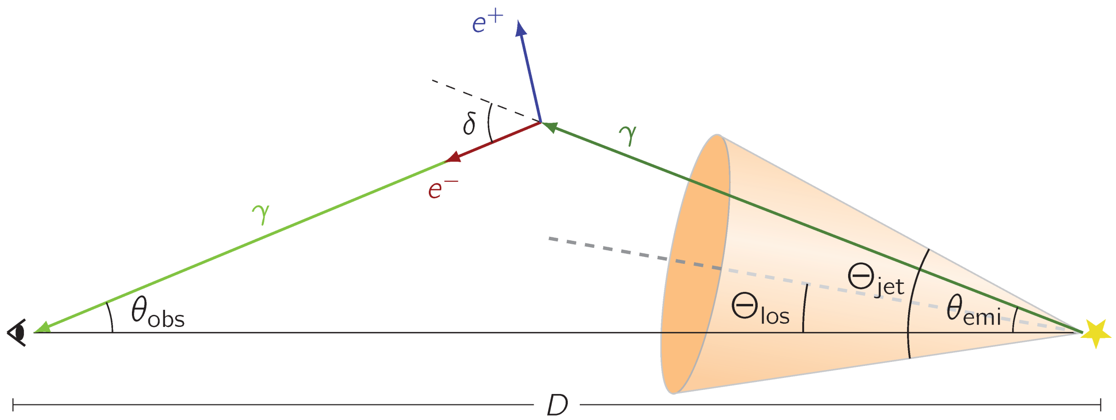

Figure 3: Schematic drawing of the development of an electromagnetic cascade. Credit: [7]

The star symbol represents a source of γ-rays (dark green line), at a distance D from the observer. The source covers a 3D angle of Θ_{jet} and is tilted by an angle Θ_{los} relatively to the line of sight. θ_{emi} is the angle that the γ-rays form with this line. The blue and red lines correspond to the e^+e^- pairs created by the $\gamma - \gamma$ annihilation process. The IGMF deflects the pairs from the original trajectory by an angle δ. The typical distance traveled by the produced pairs is similar to the mean free path for IC scattering. Background photons are thus up-scattered by the deflected electrons or positrons to high energies (light green line), producing the pair echo that is detected at an angle θ_{obs} with respect to the line of sight. The photons forming this secondary radiation are delayed in comparison to the primary photons from γ-rays emitted at the same time. The pairs, being massive particles, propagate with velocity $v < c$ and then lose energy mainly via IC scattering. The IGMF is expected to be very weak, hence the contribution of other processes, like synchrotron emission, is of secondary importance, so some models neglect to take it into consideration in the data analysis.
All these effects and the fact that the secondary emission has to travel a greater distance than the primary, because of the trajectory deflection caused by the IGMF, contribute to accumulating a time delay.
Therefore, through measurements of this delay, it is possible to infer some of the IGMFs properties, although in the literature one can find a number of other methods that aim to do the same thing, e.g. Faraday Rotation measurements. These evaluate the rotation of the polarisation plane to which the emitted electromagnetic radiation is subjected when it passes through a magnetic field and the upper limits on the IGMF in Table 1 were obtained from them.
A combination of different methods is also used.
It is important to observe that, because the sources are located at cosmological distances, some of the secondary emission rays might not able to reach the observer within one Hubble time, depending on the IGMF properties and the duration of the emission. This leads to a flux decrease that depends on the energy of the source.

3.1 Interaction with the EBL: Pair Production

The EBL is the radiation emitted by all stars and AGN, redshifted to lower frequencies during the expansion of the Universe. It integrates light from the radio to the gamma band, as shown in Table 2.

	Frequency	Wavelength	Energy
Cosmic Radio Background (CRB)	$< 10^{10}$ Hz	> 30 mm	$< 40\,\mu$eV
Cosmic Microwave Background (CMB)	$10^{10} - 10^{12}$ Hz	$0.3 - 30$ mm	$0.04 - 4$ meV
Cosmic Infrared Background (CIB)	$10^{12} - 10^{14}$ Hz	$3 - 300\,\mu$m	$4 - 400$ meV
Cosmic Optical Background (COB)	$10^{14} - 10^{15}$ Hz	$0.3 - 3\,\mu$m	$0.4 - 4$ eV
Cosmic Ultraviolet Background (CUB)	$10^{15} - 10^{16}$ Hz	$30 - 300$ nm	$4 - 40$ eV
Cosmic X-ray Background (CXB)	$10^{16} - 10^{19}$ Hz	$0.03 - 30$ nm	$0.04 - 40$ keV
Cosmic γ-ray Background (CGB)	$> 10^{19}$ Hz	< 0.03 nm	> 40 keV

Table 2: Approximate divisons of the Cosmic Background (CB). Credit: [8]

Because of the strong contamination by galactic light, the EBL spectrum is not entirely resolved. This is why the line in Figure 4 is blurred in certain bands of the spectrum.
What we know is that the EBL energy density is about $\rho_{EBL} \approx 0.003\,\text{eV/cm}^3$, but this value is not precise, because measurements in the optical and IR bands are influenced by radiation from the Solar system and our galaxy. This creates big uncertainties in the modeling of the EBL distribution.

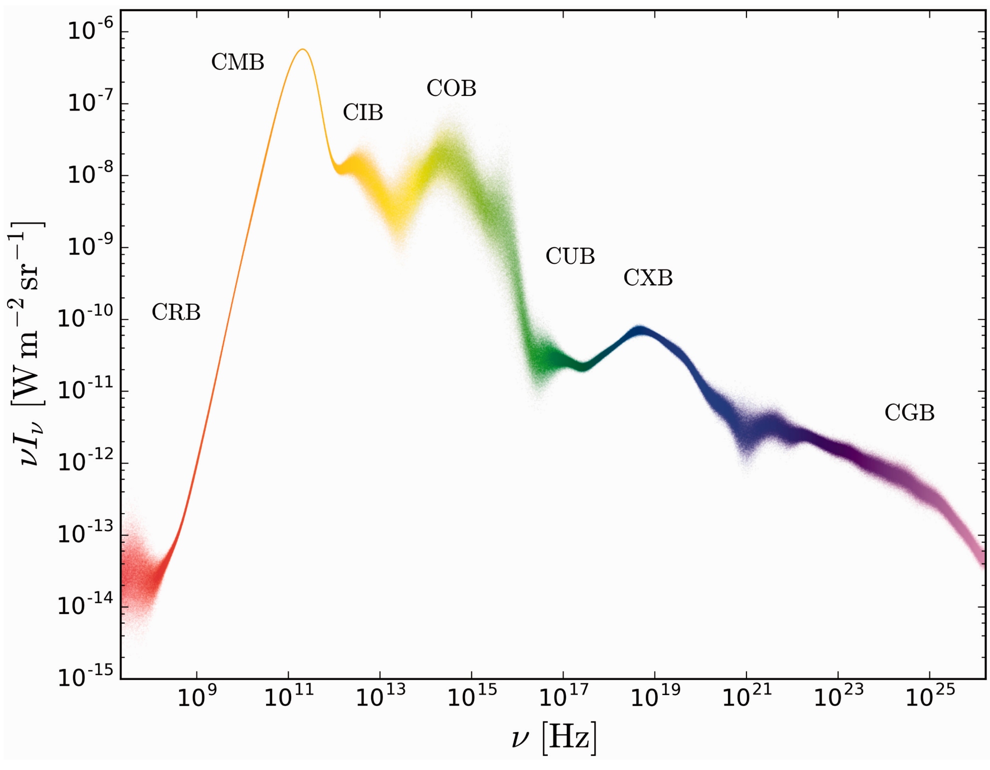

Figure 4: Spectrum of the continuous CB. Credit: [8]

γ-rays absorbed by the EBL cause attenuation of distant sources spectra, depending on the energies of the rays. This effect can be used to study the EBL properties.
Indeed, the interaction process leads to a steepening in the γ-ray spectrum in the VHE range, an effect that depends on the energy of the rays and the distance of the source or rather the EBL density along the line of sight.
An open problem in using this method of investigation is that it would require a thorough understanding and modeling of the γ-ray spectra of the sources, which we have not reached yet. For this reason, discerning between the EBL intrinsic characteristics and the effects caused by the interaction

with γ-rays is complicated.
The VHE photons emitted from GRBs during the prompt emission interact with the EBL in the IGM, predominantly in the Infrared (IR) band, via electron-positron Pair Production (PP):

$$\gamma + \gamma_{bg} \rightarrow e^{+} + e^{-}. \tag{1}$$

γ-rays with energy E_γ propagating through a background of soft photons with energy ϵ can produce pairs if their energy is higher than the sum of the electron and positron rest energies, in the center-of-mass frame of reference: $E_\gamma \geq 2m_e c^2$. The cross-section is a maximum near threshold

$$E_\gamma \gtrsim \frac{m_e^2 c^4}{\epsilon}, \tag{2}$$

in the laboratory frame, with m_e the mass of the electron/positron. The calculus is derived in the approximation of a γ-ray and a background photon at the same redshift, forming an angle of 180° (head-on collision).
The typical mean free path of γ-rays, i.e. the average distance they cover before starting the process, is:

$$\lambda_{\gamma\gamma}\left(E_\gamma\right) = \frac{1}{\int_{\frac{m_e^2}{E_\gamma}}^{\infty} \sigma_{\gamma\gamma}\left(E_\gamma, \epsilon\right) n_{EBL}\left(\epsilon\right) d\epsilon} \approx \frac{1}{\sigma_{\gamma\gamma} n_{EBL}}. \tag{3}$$

Here, $\sigma_{\gamma\gamma}$ is the PP cross-section and $n_{EBL} \approx \frac{\rho_{EBL}}{\epsilon}$ is the photon density of EBL.
$\lambda_{\gamma\gamma}$ becomes shorter or comparable to the typical distances D of extragalactic sources in the TeV band. This causes an exponential flux attenuation in the γ-ray spectrum of

$$e^{-\frac{D}{\lambda_{\gamma\gamma}}}. \tag{4}$$

If the intrinsic source spectrum is known, from the comparison between that and the observed one, it is potentially possible to derive a measurement of the suppression factor and consequently the EBL density.

3.2 Interaction with the CMB: Inverse Compton

The electron-positron pairs can interact with some background photons, mostly of the CMB, isotropic and constant radiation, notoriously discovered by accident in 1965. The CMB's spectrum, shown in Figure 5, is one of a single temperature blackbody radiation, with a mean temperature around 2.73 K. The resulting total photon energy density is about $\rho_{CMB} \approx 0.26\,\mathrm{eV/cm^3}$ - greater than the EBL one of a factor 10^2 - which corresponds to $411\,\mathrm{photons/cm^3}$.

The initial energy of the VHE γ-rays is transferred to the e^+e^- pairs (each particle acquires $E_e \approx \frac{E_\gamma}{2}$), but it is quickly lost in the interaction with CMB photons, via IC scattering.
The mean free path along which the pairs lose energy is:

$$\lambda_{IC} = \frac{3m_e^2}{4\sigma_T \rho_{CMB} E_e}, \tag{5}$$

with σ_T the Thomson cross section.
Compton scattering involves a photon and a free electron, which normally is at rest and acquires momentum from the collision. The photon practically loses kinetic energy and cedes it to the electron. Consequently, it is scattered at an angle θ, to which corresponds energy given by the Compton formula:

$$E' = \frac{E}{1 + \frac{E}{m_e c^2}\left(1 - \cos\theta\right)}, \tag{6}$$

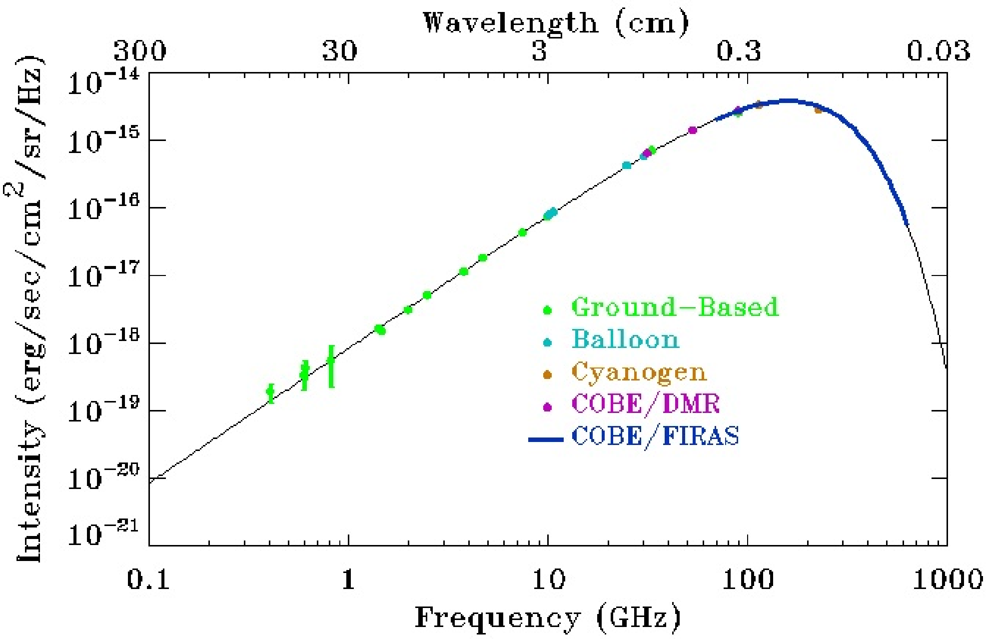

Figure 5: Measurements of the CMB intensity as a function of its frequency/wavelength. Credit: `https://asd.gsfc.nasa.gov/archive/arcade/cmb_intensity.html`

where E is the initial photon energy and $m_e c^2$ is the electron rest energy. The electron resulting energy is $E - E'$.
The process also causes a variation in the incoming photon wavelength. After the collision:

$$\lambda' = \lambda + \lambda_C \left(1 - \cos\theta\right), \tag{7}$$

where λ is the wavelength of the incoming photon and $\lambda_C = \frac{h}{m_e c} \approx 2.4\,\mathrm{pm}$ (with h the Planck's constant) is the so-called Compton wavelength of the electron and corresponds to the wavelength of a virtual photon with energy equal to the rest energy of the electron.
IC scattering happens when the electron involved is not at rest but already has momentum before the collision, as in our case of interest. As a result, the photon has larger energy after the scattering than initially, so it is essentially "accelerated" by the interaction and can reach GeV energies.
Considering a non-relativistic regime, where the photon energy is at first much smaller than the rest energy of the electron ($E \ll m_e c^2$), the differential cross section for the scattering is given by the Thomson limit:

$$\sigma_T \approx \frac{8\pi\alpha^2}{3m_e^2} = \frac{8\pi r_e^2}{3}, \tag{8}$$

where $\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c}$ is the fine structure constant and $r_e = \frac{e^2}{4\pi\epsilon_0 m_e c^2}$ is the classical radius of the electron.
In the opposite case, if the photon energy is much larger than the electron rest energy ($E \gg m_e c^2$), the total cross section is:

$$\sigma_{KN} = \frac{3\sigma_T}{8}\frac{\ln 2E}{E} \tag{9}$$

(Klein-Nishina limit).
As a result of this process, the absorption of VHE γ-rays originating from extragalactic sources leads to the generation of a secondary γ-ray emission, with lower energies than the primary one, in the range of $1 - 100\,\mathrm{GeV}$.
The IC scattered photons can then restart the whole process, creating an electromagnetic cascade in the IGM, until the energy of the photons is below the threshold for pair production (see equation 2).

3.3 Pair deflection

Any charged particle is susceptible to the presence of an external magnetic field through the action of the Lorentz force.
Suppose that a particle is moving at velocity $\vec{v}$ under the only influence of a magnetic field $\vec{B}$. The corresponding equation of motion is:

$$\frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B}, \tag{10}$$

where $\vec{p}$ is the momentum of the particle under consideration and q its charge.
Because of the dependence on q, the electrons and positrons produced previously drift away from each other and the original direction, following a circular trajectory around the field lines.
The deflection radius - the so-called Larmor radius - is:

$$r_L = \frac{p}{eB}, \tag{11}$$

with p and B the absolute values of the corresponding vectors and $q = e$ for the e^+e^- pairs.
The coherence length of IGMFs impacts the deflection angle as it interplays with the characteristic scale of IC. Therefore, we can distinguish two regimes of propagation: if the coherence length is greater than the distance traveled by the pairs without experiencing an energy loss, $\lambda_B > \lambda_{IC}$, we can treat the magnetic field as homogeneous and the deflection angle results:

$$\theta_B = \frac{\lambda_{IC}}{r_L}. \tag{12}$$

On the contrary, if $\lambda_B < \lambda_{IC}$, the pairs move through regions where the magnetic field has different orientations and they experience random walks in angle, i.e. they diffuse before producing the secondary emission via IC scattering. Because of this, θ_B requires another factor of

$$\sqrt{\frac{\lambda_B}{\lambda_{IC}}}. \tag{13}$$

It is during this phase that the secondary emission accumulates a time delay: the stronger the magnetic field, the smaller the Larmor radius. As a result, the e^+e^- pairs require more time to propagate if they have to travel a great distance, i.e. if the field is weak, and this creates an "echo" of the primary emission. Also, the velocity of massive particles must be $v < c$ and this contributes to the delay.
The time delay Δt_B can thus be defined as the difference between two observable quantities: the cumulative propagation time of the electromagnetic cascade and the light-travel time of the primary emission, t_{prim}. The first one has two contributions: the time t_{PP} that passes between the primary emission and the PP process and the duration t_{sec} of the secondary emission.
Hence, the definition of the time delay as:

$$\Delta t_B = (t_{PP} + t_{sec}) - t_{prim}. \tag{14}$$

Other minor effects that contribute to accumulating a time delay are the synchrotron radiation emitted by the pairs and the adiabatic expansion of the Universe. A precise analysis of the electromagnetic cascade development has to take into account these effects too, but not everyone shares this way of approach and some do not consider these effects at all.
One last note is of duty: to exert a sufficient effect on the electromagnetic cascade, the IGMF presence in voids (along the line of sight) has to be significant and this poses a lower limit on its possible volume filling factor at the level of $\gtrsim 60\%$.

4 Coherence length

When the γ-ray jet emitted from the source is aligned to the line of sight, from the observer's point of view, the cascade looks like an extended "halo"- referred to as a "pair halo", as it is the effect of the e^+e^- pairs deflected by the IGMF.
The extended emission surface brightness profile depends on the coherence length λ_B. Indeed, in the case $\lambda_B < \lambda_{IC}$, the signal has a flat surface brightness curve while, if $\lambda_B > \lambda_{IC}$, the brightness profile is steep and presents a peak in correspondence with the source.
As a result, studying the light curve of the cascade emission can potentially be useful to derive constraints on λ_B: measuring a non-zero slope would mean that the coherence length lies within the range $\lambda_B > \lambda_{IC}$ and vice versa.
Nonetheless, if $\lambda_B > \lambda_{IC}$, for the highest energy electrons/positrons, but $\lambda_B < \lambda_{IC}$, for the lowest energy ones, we expect a change in the slope of the brightness profile, at $\lambda_B \approx \lambda_{IC}$. This would happen at a corresponding break energy $E_{\gamma,br}$ and based on this we can derive a measurement of the coherence length:

$$\lambda_B = 0.2 \left(\frac{E_{\gamma,br}}{GeV} \right)^{-\frac{1}{2}}. \tag{15}$$

Another method that can be used to test the coherence length possible values is the study of the cascade emission brightness profile, as a function of the time delay, i.e. the cascade duration.
The difference from the previous method lies in the fact that the two are based on different models: the first supposes an extended emission model, while this one assumes a narrow jet, misaligned by a certain angle with respect to the line of sight.
This time, the interesting quantity is the initial slope of the light curve, which once again depends on λ_B.
In particular, if $\lambda_B \gg \lambda_{IC}$, the flux is proportional to $\frac{1}{\sqrt{\Delta t_B}}$. Otherwise, if $\lambda_B \ll \lambda_{IC}$, the flux is approximately constant.
This method can provide bounds on the coherence length scales in an interval restrained by the energy range of the telescope.
The first limits to simultaneously constrain the coherence length and the strength of the IGMF were obtained in 2020 from observations of high-energy neutrinos and the delayed electromagnetic radiation emitted from the flaring blazar TXS 0506+506 [9].
The coherence length is constrained between $30\,\text{kpc} \lesssim \lambda_B \lesssim 300\,\text{Mpc}$, at a 90% Confidence Level.
These limits are strongly dependent on the neutrino-γ-ray correlation and the EBL model.

5 Results

To investigate the IGMF properties, two classes of instruments are used: the satellite observatory Fermi Large Area Telescope (Fermi-LAT) and the ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs), such as the High Energy Stereoscopic System (H.E.S.S.), the Major Atmospheric Gamma Imaging Cherenkov telescope (MAGIC) and the Very Energetic Radiation Imaging Telescope Array System (VERITAS). Data sets from different telescopes are often combined, to aim for more stringent constraints.
IACTs work by reconstructing the Cherenkov radiation trace left by the particle shower produced in the interaction between VHE γ-rays and the Earth's atmosphere. On the other hand, Fermi-LAT can directly detect incoming photons and has an energy range between 10 keV and 300 GeV.
This technique provides a major window to the γ-ray Universe.

5.1 Results from blazars

Blazars are a sub-class of Active Galactic Nuclei (AGN), galaxies with extremely bright centers, powered by Supermassive Black Holes (SMBH). AGN can accelerate bipolar jets of ejected material to relativistic speeds, making it possible for the jets to stretch up to hundreds of kpc outside the galaxy. Blazars are AGN with extremely bright jets, from the radio band to γ-rays, that point towards the Earth, close to the line of sight. Along with GRBs, they are the primary sources of extragalactic VHE γ-rays that can be used to constrain the IGMF properties.

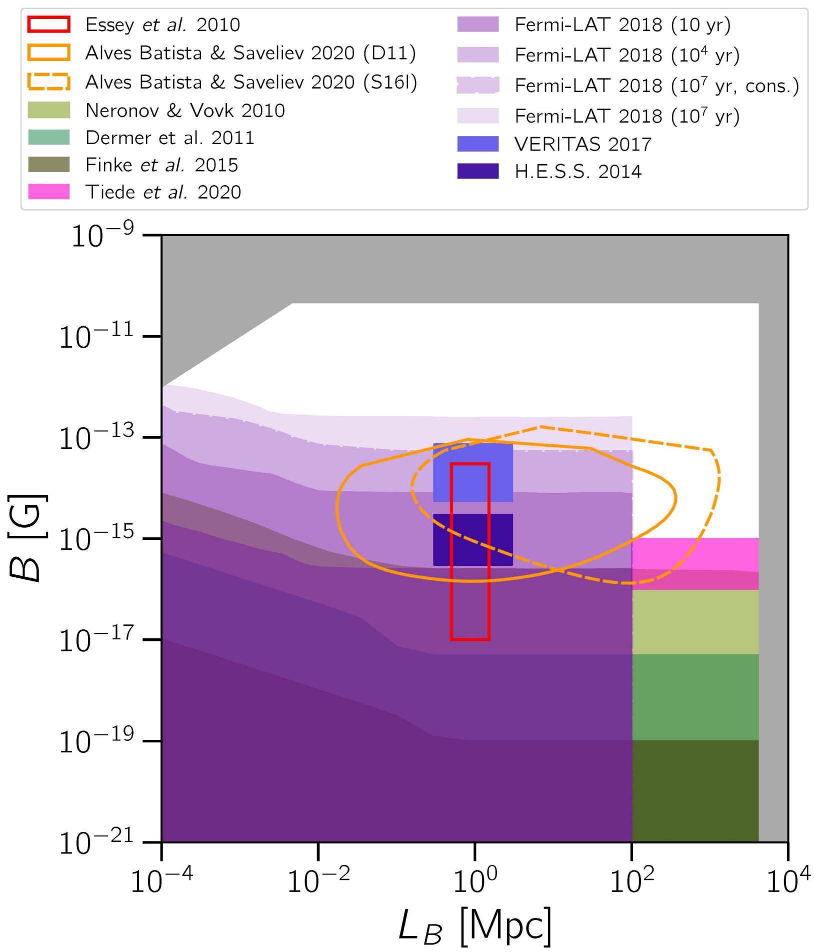

Figure 6: Compilation of some constraints on the IGMF parameters. Credit: [7]

Figure 6 shows the results obtained by some of the more significant works on blazars. The colored regions represent excluded areas of the parameter space, as obtained by the references indicated in

the legenda. On the contrary, non-filled areas, bounded by a line, indicate allowed regions. The grey region represents the area excluded by other methods.
The first results obtained using γ-ray sources were derived by Neronov & Vovk [10], from observations of the blazars 1ES0347+121, 1ES 0229+200 and 1ES 1101-232. They reported a lower bound of $B \geq 3 \times 10^{-16}$ G for the strength of the IGMF, which improves as $\lambda_B^{-\frac{1}{2}}$, if $\lambda_B \ll 1$ Mpc.
After Neronov & Vovk's influential results, there have been many efforts toward deriving constraints on the IGMF using blazars. For instance, Essey et al. [11] considered that the observed γ-rays are a combination of the direct emission of the sources and the secondary emission from Cosmic Rays interactions and derived: 10^{-17} G $\leq B \lesssim 10^{-14.5}$ G, at a 95% C.L..
Finke et al. [12] combined Fermi-LAT and IACTs observations of five blazars and concluded that $B \lesssim 10^{-19.5}$ G, with $\lambda_B \gtrsim 1$ Mpc, at a 5σ level. Furthermore, the authors performed checks on the energy range of Fermi-LAT, to demonstrate that the results do not depend on whether the starting energy of the γ-rays in the dataset is 100 MeV o 1 GeV. The quality of the derived constraints worsens slightly when considering different EBL models.
The H.E.S.S. collaboration in [13] combined its observations with those of Fermi-LAT and used the pair halo method to study PKS 2155-304. They excluded the range 3×10^{-15} G $< B < 3 \times 10^{-14}$ G, for a coherence length of 1 Mpc, at a 99% C.L..
The VERITAS Collaboration [14] obtained limits around the same range, from the observations of 1ES 1218+304, considering various EBL models. For each of these, the C.L. on the results is of 95%.
Later on, the Fermi-LAT Collaboration [15]compiled a catalog of sources used to constraint the IGMF and concluded that there was not any evidence of extended halos, which made it possible to derive the limit of $B \gtrsim 10^{-16.5}$ G G, with $\lambda_B \gtrsim 10$ kpc. This is a conservative result, based on the assumption that the source intrinsic variability, i.e. the time scale over which it emits γ-rays, is of $\tau = 10$ years. Assuming, otherwise, $\tau = 10^4$ years or $\tau = 10^7$ years, the bounds are even more stringent: $B \gtrsim 10^{-14}$ G in the first case and $B \gtrsim 10^{-12.5}$ G in the second. The quality of the results can be improved by removing from the analysis the sources that show a high degree of variability, such as 1ES0229+200 and 1ES1218+304. For example, from observations of the blazar 1ES 0229+200, a highly variable source, Dermer et al. [16] derived $B \gtrsim 10^{-18}$ G, with $\lambda_B \gtrsim 1$ Mpc.
In Ref. [17], Takahashi et al. use the pair echo method to analyze the spectrum of Mrk 421 and concluded that $B \gtrsim 10^{-20.5}$ G, with $\lambda_B \approx 1$ kpc, at a 4σ level. This result is significant because there are not any assumptions made on the source spectrum during periods in which it is not observed.
Due to the strong constraints derived from recent observations with Fermi-LAT, there are not any allowed values of the parameters left: the allowed region in Fig. 7, is non-existent. Indeed, Tiede et. al [18] stated that γ-ray observations cannot be explained with IGMFs and there is some other process involved in the electromagnetic cascades. Finally, they claimed, as a result, to have found evidence of the non-existence of pair halos and excluded $B \approx 10^{-16} - 10^{-15}$ G, for a coherence length of $\lambda_B > 100$ Mpc, at 3.9σ.
It has to be noted that the derived results on the IGMF strength and coherence length can be very different, mainly due to the uncertainties in the EBL distribution. For this reason, results are strongly dependent on the assumed EBL model.

5.2 Results from GRBs

GRBs with hard power-law spectra are expected to be good candidates to derive limits on the IGMF properties through the pair echo method, due to the fast transient nature of their primary emission. Indeed, in the case of blazars, there could be an overlap between the direct emission and the echo radiation, whereas for GRBs the prompt emission fades away. The only potential difficulty lies within the distinction between the secondary emission and the GeV afterglow.
In Ref. [19], Veres et al. developed a Monte Carlo code that treats pair creation and simulates the spectrum of the echo radiation. Because no GRBs were detected previously, they had to assume a theoretically expected TeV flux, so the code works by calculating the echo radiation from a VHE source with a known spectrum. They assume a power-law distribution, with a high-energy cutoff at 30 TeV. They conclude that data from a powerful GRB, such as GRB 130427A, can be used by Fermi-LAT to constrain the IGMF parameters, in the $10^{-21} - 10^{-17}$ G range, for a coherence length

of 1 Mpc. This range might be broader, depending on the assumed spectrum and cutoff energy. By comparing the echo radiation calculated from the simulation and the VERITAS measurements, they show that the VERITAS non-detection of this GRB can constrain B and the cutoff energy in the TeV band. The results are based on the EBL model described in Ref. [20].
TeV γ-ray emission from a GRB (GRB 190114C, at redshift $z = 0.4245$) has been recently detected by the MAGIC telescope, allowing to estimate the observable cascade intensity.
In Ref. [21], Wang et al. constrain the IGMF with the GeV flux limit obtained from the Fermi-LAT observations and conclude $B > 10^{-19.5}$ G, for a coherence length of 1 Mpc. This is the first limit ever obtained from observations of GRBs and, although it is weaker than the one derived using blazars, it provides an independent constraint on the IGMF. They also conclude that the best limits can be derived when the observation time matches the duration of the echo emission. The main adopted assumptions are the followings:

1. They obtain a low flux of the echo emission with energy > 200 GeV (above which γ-rays are strongly absorbed by the EBL) and therefore neglect the effect of the second generation pairs.
2. The used EBL model is the one described in Ref. [20], the same used by Veres et al.

They argue that the resulting limit is weaker than the one obtained by Veres et al. from GRB 1304227A mainly because Veres et al. overestimate the echo emission flux and because the assumed fluence in the TeV emission of GRB 130427A is higher than that of GRB 190114C. Furthermore, plasma instabilities, due to the interaction of the electron-positron pairs with the IGM, cool down the pairs faster than the IC scattering, and, for this reason, the limit based on the cascade flux may become weaker.
The same GRB has been studied by Dzhatdoev et al. [22], who performed a detailed Monte Carlo simulation, in order to reconstruct the cascade signal. They conclude that the sensitivity of Fermi-LAT is insufficient to derive constraints on the IGMF parameters, due to the uncertainties in the intrinsic VHE γ-ray spectrum and the EBL intensity. Moreover, any additional systematic effect would be the equivalent of adding a nuisance parameter, increasing thus the measurement uncertainty and supporting the conclusion.
They also argue that Wang et al. did not perform a thorough reconstruction of the γ-ray spectrum in the TeV band, for example, because they assumed a power-law decay ($\propto E^{-\alpha}$) with fixed spectral index $\alpha = 2$, starting at 6 s, which is not justified since the maximum is situated at ~ 20 s and not at 6 s. Additionally, even if the total energy of primary γ-rays is fixed, the observable intensity of the cascade significantly depends on the shape of the primary emission.
Furthermore, they assert that Wang et al. significantly overestimated the normalization parameter of the observable pair echo intensity and neglected to consider the EBL uncertainty, which could decrease the observable pair echo flux at $E = 1$ GeV by a factor of 5.
Finally, in the calculation, Dzhatdoev et al. do not include the prompt phase γ-rays in the simulations, because, theoretically, the prompt emission phase of GRB 190114C could produce some additional VHE γ-rays. However, the internal opacity is high, so the absorption of the prompt phase emission is expected to be very strong.
As a result, the sensitivity of the Fermi-LAT γ-ray telescope is insufficient to detect the intergalactic electromagnetic cascade signal from GRB 190114C over the time period of one month.
Wang et al. promptly responded to the critique moved to them by Dzahtdoev et al.. According to them, Dzahtdoev et al. erroneously neglected to take into account that the power-law decay of the afterglow flux starts from 6 s and only consider the primary TeV photons in the interval between 6 s and 2454 s. This is the reason why the energy of the primary TeV photons is about a factor of 5 lower than Wang et al.'s.
Resolving the issue would require a deep understanding and modeling of the inner workings of the GRB and is therefore far from simple.

6 Future prospects

IACTs have been able to provide significant results for γ-ray astrophysics. However, it was not possible to obtain from them unambiguous constraints on the IGMF: the measurements are highly affected by uncertainties on the EBL properties, the distribution of the fields, the intrinsic sources spectra, etc. It follows that telescopes of the new generation are going to need higher sensitivities to be able to unequivocally constrain the IGMF.

The Cherenkov Telescope Array (CTA) has been specifically designed with the aim of improving the sensitivity of the current results in many fields of research. It is an international initiative and it will operate as an open observatory, with a Science Data Centre (SDC) (in Germany) providing access to data and analysis tools. The CTA will be the most advanced ground-based γ-ray detector, so it will significantly expand the current γ-ray emitters catalog, up to 1000 more new objects. The telescopes will be located in two array sites: the one working from the southern hemisphere in Chile (Figure 7) and the one working from the northern hemisphere in La Palma. The future CTA Headquarters will be located in Italy (Bologna) and will be responsible for the overall direction of the Observatory operations.

To cover a whole energy range between 20 GeV and 300 TeV, three classes of telescopes are required: 8 Large-Sized Telescopes (LST), 23 Medium-Sized Telescopes (MST) and 37 Small-Sized Telescopes (SST). A large segmented mirror in each telescope will receive the Cherenkov light originating from the interaction between γ-rays and our atmosphere and it will reflect it to a high-speed camera, making it possible to obtain a digitalization of the image of the shower. The LST mirror will have a diameter of 23 m, a parabolic shape, and a field view of $\sim 4.5°$. Their large size is required to detect low energy γ-rays since they do not have many interactions and therefore will not produce a high amount of Cherenkov light. The telescopes will be able to reposition every 20 s, in order to rapidly point toward targets, a characteristic which is common to the other two classes of telescopes too. The MST mirror will have a 12 m diameter and will cover $7 - 8°$, taking a quick survey of the γ-ray sky. Finally, the SST will detect the highest energy γ-rays from our galaxy, which is best observed from the southern hemisphere. For this reason, the SST mirror will be spread out in the southern hemisphere array only. Its diameter will be just 4 m and it will have a large field of view of $\sim 9°$.

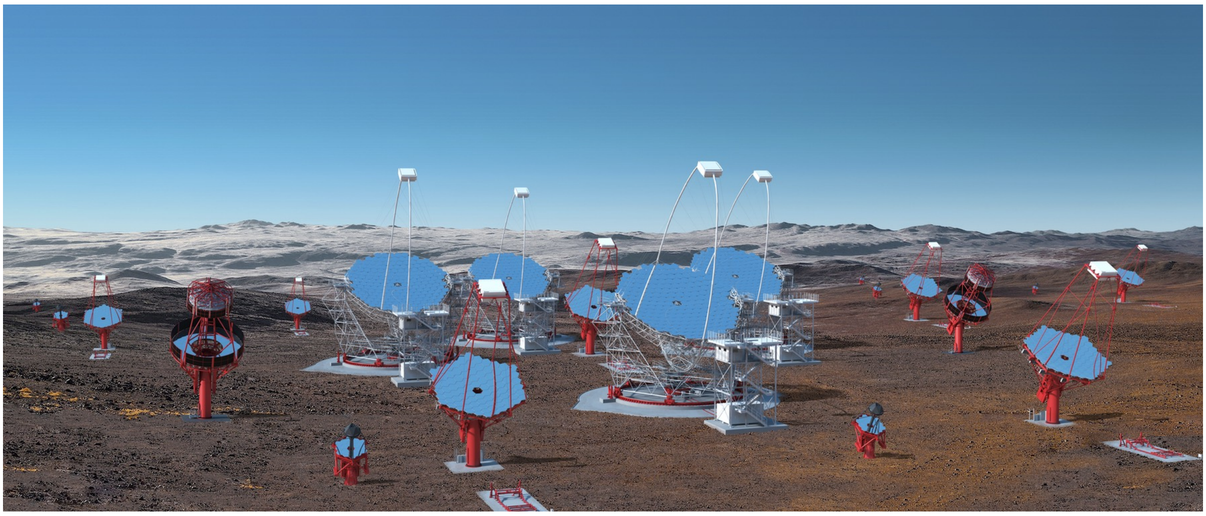

Figure 7: CTA southern hemisphere site rendering. Credit: `https://www.cta-observatory.org/about/how-cta-works/`

The goal of the CTA regarding IGMFs will be to address several open issues, including the study of the time delay of pair echoes and derive more certain information.

The authors of [23] use simulations of AGN observations foreseen in the CTA Key Science Program to establish better limits on the strength of IGMFs. In the paper, they simulate the development of electromagnetic cascades from the blazar 1ES 0229+ 200. This is one of the best sources to look for cascade signatures in, due to its hard and weakly variable intrinsic spectrum extending to ~ 10 TeV.

They assume a randomly oriented IGMF in cells of 1 Mpc and the intrinsic source's spectrum to be a power law with an exponential cutoff at 10 TeV. Vovk et al. simulate a 50-hour-long observation and find that the CTA will be able to detect a cascade emission if $B < 2 \times 10^{-13}$ G, for a coherence length of 1 Mpc, at a $\gtrsim 5\sigma$ level, for blazars with a small variability: $\tau \approx 10^7$ years (Figure 8).
To conclude, they are confident that combining data from the CTA and the Fermi-LAT will provide simultaneous observations, useful to investigate variable γ-ray sources, and broaden the parameter range that can be proved for IGMFs.

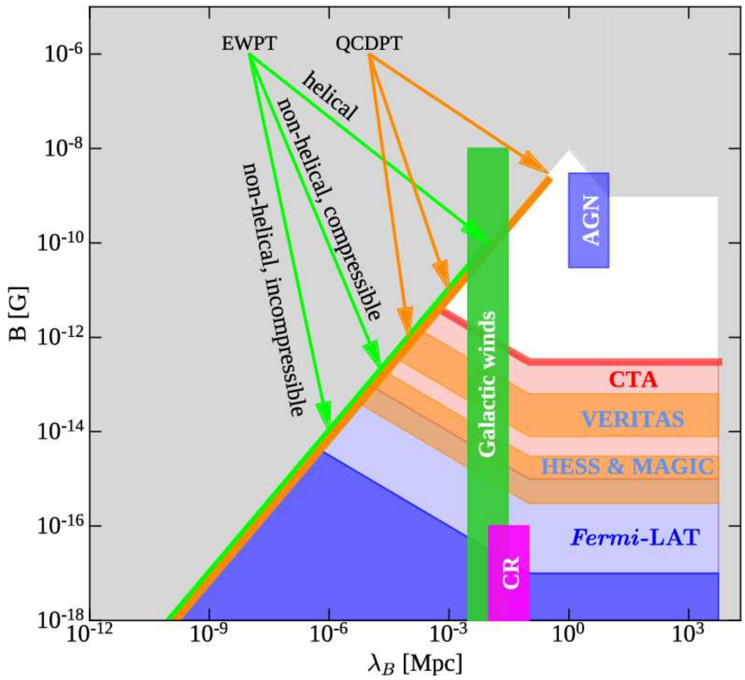

Figure 8: Sensitivity of the CTA to IGMF signatures compared to existing observational constraints and theoretical predictions. Credit: [23]

7 Conclusions

The pair echo method has been used to constrain the Intergalactic Magnetic Fields, using either blazars or Gamma-Ray Bursts, as discussed in Section 5. GRBs are the most promising sources for such a method of analysis, because of the fast transient nature of their emitted radiation, which does not allow overlap between the primary and the secondary emission, as can happen in the case of blazars. Results are unclear, due to significant uncertainties, mostly in the Extragalactic Background Light modeling. Also, many approximations were made in the theory of propagation of γ-rays through the Intergalactic Medium. Therefore, results are highly dependent on the assumptions made in the analysis and can vary widely from one another.
Nonetheless, γ-rays remain a very important instrument to investigate the IGMF properties and we expect much better constraints from the next generation γ-ray ground-based observatory, the Cherenkov Telescope Array. It is expected to have a much higher sensitivity than the Cherenkov telescopes currently working on the topic and it will provide a major window to the γ-ray Universe.

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