Abstract

With the discovery of evidence for neutrino mass, a vivid gamma ray sky at multi-TeV energies, and cosmic ray particles with unexpectedly high energies, astroparticle physics currently runs through an era of rapid progress and moving frontiers. The non-vanishing neutrino mass establishes one smooth component of dark matter which does not, however, supply a critical mass to the Universe. Other dark matter particles are likely to be very massive and should produce high-energy gamma rays, neutrinos, and protons in annihilations or decays. The search for exotic relics with new gamma ray telescopes, extensive air shower arrays, and underwater/-ice neutrino telescopes is a fascinating challenge, but requires to understand the astrophysical background radiations at high energies. Among the high-energy sources in the Universe, radio-loud active galactic nuclei seem to be the most powerful accounting for at least a sizable fraction of the extragalactic gamma ray flux. They could also supply the bulk of the observed cosmic rays at ultrahigh energies and produce interesting event rates in neutrino telescopes aiming at the cubic kilometer scale such as AMANDA and ANTARES. It is proposed that the extragalactic neutrino beam can be used to search for tau lepton appearance thus allowing for a proof of the neutrino oscillation hypothesis. Furthermore, a new method for probing the era of star formation at high redshifts using gamma rays is presented which requires new-generation gamma ray telescopes operating in the 10-100 GeV regime such as MAGIC and GLAST.

1 Introduction and practical definition of high-energy astroparticle physics

Central to modern astronomy is the dark matter problem and it is commonly believed that its solution will trigger major advances in particle physics and cosmology [1]. So far dark matter is only known through its gravitational effects, but the understanding of the nature and origin of dark matter requires to obtain more direct information about its mass and interactions. Cosmology and particle physics qualify weakly interacting massive particles (WIMPs) with masses between 100 GeV and a few TeV as likely candidates. The WIMPs violently annihilate with their anti-particles in rare collisions or they could be unstable. These modes lead to secondary gamma rays and neutrinos which can be detected on Earth [2]. The
suspected large WIMP mass then corresponds to gamma ray and neutrino energies in excess of 100 GeV. In addition to the dark matter particles, there may be other relics from the early Universe, such as quintessence, vacuum energy, or topological defects. Quintessence is a slowly rolling scalar field connected with massive bosons, and this could also lead high-energy phenomena, although no worked-out model exists to my knowledge. The recent discovery of accelerating expansion using SNIa as a tracer of cosmic geometry seems to make a strong case for quintessence \cite{3, 4}. Similarly, if the scalar field has settled to some false (meta-stable) vacuum, the energy density of this vacuum could drive the deceleration parameter away from $\Omega/2$. Topological defects preserve false vacuum in pointlike (monopoles), one-dimensional (strings), two-dimensional (domain walls), or higher dimensional space-time structures. They are topologically stable, but have a variety of ways to communicate to our world in addition to their gravitation. E.g., they can dissipate into GUT-scale bosons ($\sim 10^{16}$ GeV) which are unstable themselves and fragment into jets consisting of gamma rays, neutrinos, and protons at ultra-high energies \cite{5}. After their propagation through intergalactic space, electromagnetic cascading and secondary particle production shift most energy injected by these exotic processes to much lower energies where the energy release competes with that due to ordinary astrophysical sources.

In order to identify new physics phenomena, it is therefore of crucial importance to obtain a complete inventory of the astrophysical high-energy sources which act as a background for these searches. This defines the high-energy astroparticle physics program from a practical point of view and follows the logic inherent to the general astronomical exploration of the sky to cover the entire range of wavelengths with comparable sensitivity.

Among the non-thermal sources in the Universe, radio-loud active galactic nuclei (AGN) seem to be the most important energetically. There are other interesting sources, such as gamma ray bursts (GRB) and clusters of galaxies, but their non-thermal energy release does not come close that of AGN. There are some intriguing complications arising through calorimetric effects, since the intracluster medium in clusters of galaxies surrounding AGN confines escaping relativistic particles for some time and thereby gives rise to a secondary luminosity tied to the energy release of the AGN and the cooling time scale of the intracluster medium. The radio-loud AGN come in various disguises, depending on the orientation of their radio jet axes and the properties of the circum-nuclear matter in their host galaxies. The most extreme versions are radio galaxies with the radio jet axes almost in the plane of the sky and the blazars with the radio jets pointing close to the line of sight to the observer which leads to a dramatic flux increase owing to special relativistic effects (the so-called Doppler boosting). In Sect.2 it is argued that radio-loud AGN can be expected to produce the entire extragalactic gamma ray background from an energetical point of view. Owing to beaming statistics, the number of unresolved sources responsible for most of this background should not be too large. Indeed the flux from the $\sim 50$ resolved sources in the flux-limited EGRET sample already equals a sizable fraction (of the order of 15%) of the extragalactic background flux. With the next-generation gamma ray telescopes MAGIC
(giant 17m air-Cerenkov telescope) and GLAST \[7\] (space-borne silicon strip detector) it will be possible to probe deeper into the astrophysical source population producing the extragalactic background below 100 GeV thereby narrowing the range of opportunity for particle physics models of exotic processes producing gamma rays. In fact, the gamma ray background below 100 GeV provides a good measure of the entire electromagnetic energy release during the history of the Universe, since gamma rays from remote sources cascade down to the energy range below 100 GeV which is shown in Sect.3. It is pointed out in Sect.4 that a MAGIC observing campaign for high-redshift gamma ray sources can be used to probe the era of star formation and the evolution of the optical-ultraviolet metagalactic radiation field back to redshifts of $\sim 5$.

The recent discovery of multi-TeV emission from Mrk 421 and Mrk 501 \[8\], the measurement of their spectra using the HEGRA air-Cerenkov imaging telescopes \[9\], and the improved measurements of the extragalactic infrared background \[10\], make a strong point in favor of accelerated protons in extragalactic radio sources which is shown in Sect.5. The following Sect.6 discusses the immediate implications that the radio-loud AGN could well produce the observed cosmic rays at highest energies and high-energy muon neutrinos. Finally, in Sect.7 it is pointed out that the extragalactic muon neutrino beam is likely mixed with tau neutrinos \[11\] which leads to very interesting experimental signatures, such as the disappearance of the Earth shadowing effect at ultra-high energies and the appearance of tau leptons in underwater/-ice detectors.

2 Origins of extragalactic background radiation

Inspection of Fig. 1 shows an interesting pattern in the present-day energy density of the diffuse isotropic background radiation consisting of a sequence of bumps each with a strength that is decreasing with photon energy. The microwave bump is recognized as the signature of the big bang at the time of decoupling with its energy density given by the Stefan-Boltzmann law $u_{3K} = aT^4$. The bump in the far-infrared is due to star formation in early galaxies, since part of the stellar light, which is visible as the bump at visible wavelengths, is reprocessed by dust obscuring the star-forming regions. The energy density of the two bumps can be inferred from the present-day heavy element abundances. Heavy elements have a mass fraction $Z = 0.03$ of the total mass density $\rho_*$ and were produced in early bursts of star formation at redshift $z_f$ by nucleosynthesis with radiative efficiency $\epsilon = 0.007$ yielding

$$ u_{ns} \sim \frac{\rho_* Z \epsilon c^2}{1 + z_f} . \tag{1} $$

Inserting plausible parameter values one obtains

$$ u_{ns} \sim 6 \times 10^{-3} \left( \frac{\Omega_* h^2}{0.01} \right) \left( \frac{1 + z_f}{3} \right)^{-1} \text{eV cm}^{-3} \tag{2} $$

for the sum of the far-infrared and optical bumps. Probably all galaxies (except dwarfs) contain supermassive black holes in their centers which are actively accret-
Extragalactic radiation background

![Graph showing the energy density of the extragalactic radiation background from radio waves to gamma rays.]

**Fig.1:** Sketch of the present-day energy density of the extragalactic radiation background from radio waves to gamma rays. The dashed line shows the expected AGN contribution to the low-energy diffuse background from the average quasar spectral energy distribution.

Integrating over a fraction of $t_{\text{agn}}/t_\ast \sim 10^{-2}$ of their lifetime implying that the electromagnetic radiation released by the accreting black holes amounts to

$$u_{\text{accr}} \sim \frac{\epsilon_{\text{accr}} M_{\text{bh}} t_{\text{agn}}}{Z_\epsilon M_\ast} u_{\text{ns}} \sim 1.4 \times 10^{-4} \text{ eV cm}^{-3}$$

(3)

 adopting the accretion efficiency $\epsilon_{\text{accr}} = 0.1$ and the black hole mass fraction $M_{\text{bh}}/M_\ast = 0.005$ [14]. Most of the accretion power emerges in the ultraviolet where the diffuse background is unobservable owing to photoelectric absorption by the neutral component of the interstellar medium. However, a fraction of $u_x/u_{\text{bh}} \sim 20\%$ taken from the average quasar spectral energy distribution [13] shows up in hard X-rays due to coronal emission from the accretion disk to produce the diffuse isotropic X-ray background bump with

$$u_x \sim 2.8 \times 10^{-5} \text{ eV cm}^{-3}$$

(4)

[14].

Jets with non-thermal $\gamma$-ray emission show up only in the radio-loud fraction $\xi_{\text{rl}} \sim 20\%$ of all AGN and their kinetic power roughly equals the accretion power [15]. Hence one obtains for the background energy density due to extragalactic jets

$$u_j = \left( \frac{\xi_{\text{rl}}}{0.2} \right) u_{\text{accr}} \sim \left( \frac{\xi_{\text{rl}}}{0.2} \right) 2.8 \times 10^{-5} \text{ eV cm}^{-3}$$

(5)

If unresolved extragalactic jets are responsible for the diffuse gamma ray background, this requires a particle acceleration efficiency given by

$$\xi_{\text{acc}} = \frac{u_{\text{accr}}}{u_j} = \frac{u_x}{\xi_{\text{rad}} u_j}$$

(6)
where $u_j$ denotes the total (kinetic + magnetic + randomized relativistic particle) energy density in extragalactic jets. Inserting the energy density of the observed extragalactic gamma ray background\(^1\) one obtains a limit for the acceleration efficiency

$$\xi_{\text{acc}} \geq 0.18 \xi_{\text{rad}}^{-1} \left( \frac{\xi_{\text{rl}}}{0.2} \right)^{-1}$$

which is of the same order of magnitude as the 13% efficiency required for supernova remnants to produce the Galactic cosmic rays. Accelerated protons achieve this high radiative efficiency, if they reach energies of up to $10^8$ TeV. In the next section it is shown that protons at such high energies cannot go unnoticed, they produce interesting gamma ray spectra owing to the photo-production of secondaries. Some of the protons turn into neutrons due to $\pi^+$ production and can leave the jets without adiabatic losses. These particles would have just the right flux to produce the observed extragalactic cosmic rays dominating the local spectrum above $10^{18.5}$ eV, as will be shown in Sect.6.

### 3 Cascading and gamma ray calorimetry

Gamma rays of energy $E$ can interact with low-energy photons of energy $\epsilon$ from the diffuse isotropic background over cosmological distance scales $l$ producing electron-positron pairs $\gamma + \gamma \rightarrow e^+ + e^-$, if their energy exceeds the threshold energy

$$\epsilon_{\text{th}} = \frac{2(m_e c^2)^2}{(1 - \mu)(1 + z)^2 E} \sim 1 \left( \frac{1 + z}{4} \right)^{-2} \left( \frac{E}{30 \text{ GeV}} \right)^{-1} \text{eV \hspace{0.5cm} (} \mu = 0 \right)$$

where $\mu$ denotes the cosine of the scattering angle.\(^1\) The $\gamma$-ray attenuation $e^{-\tau}$ due to pair production becomes important if the mean free path $\lambda$ becomes smaller than $l$, i.e. if the optical depth across the line of sight through a sizable fraction of the Hubble radius obeys $\tau = l/\lambda \geq 1$. For the computation of $\tau$ one first needs to know the pair production cross section

$$\sigma_{\gamma\gamma} = \frac{3\sigma_T}{16} (1 - \beta^2) \left[ 2\beta(\beta^2 - 2) + (3 - \beta^4) \ln \left( \frac{1 + \beta}{1 - \beta} \right) \right]$$

where $\beta = \sqrt{1 - 1/\gamma^2}$ with $\gamma^2 = \epsilon/\epsilon_{\text{th}}$, and where $\sigma_T$ denotes the Thomson cross section.\(^1\) Then one needs the geodesic radial displacement function $dl/dz = \pi^{-1} (1 + z) E(z)^{-1}$ to compute the line integral from $z = 0$ to some $z = z_0$. For a cosmological model with $\Omega = 1$ and $\Lambda = 0$ the function $E(z)$ simplifies to $(1 + z)^{3/2}$. Hence one obtains the optical depth

$$\tau_{\gamma\gamma}(E, z_0) = \int_0^{z_0} dz \int_{-1}^{+1} d\mu \int_{\epsilon_{\text{th}}}^{\infty} d\epsilon_{\text{th}} \epsilon_{\text{th}}^2 \frac{1}{2} \int_0^{\infty} d\epsilon_{\text{th}} \epsilon_{\text{th}}^2 \sigma_{\gamma\gamma}(E, \epsilon, \mu, z)$$

\hspace{1cm} = \frac{c}{H_0} \int_0^{z_0} dz (1 + z)^{1/2} \int_0^{2} dx \frac{x}{2} \int_{\epsilon_{\text{th}}}^{\infty} d\epsilon_{\text{th}} \epsilon_{\text{th}}^2 \sigma_{\gamma\gamma}(E, \epsilon, x - 1, z) \hspace{1cm} (10)$$

\(^1\) Note that the flux in the gamma ray background observed by CGRO is close to the bolometric gamma ray flux of the Universe, since pair attenuation and cascading must lead to a steepening of the background spectrum above $20 - 40$ GeV.\(^1\),\(^2\).
Fig. 2: The diffuse isotropic microwave-to-ultraviolet background. Solid curve: 10th order polynomial interpolation of observational data ([20, 22, 21], and references in [16]).

adopting a non-evolving present-day background density \( n_b \), i.e. \( n'_b(z, \epsilon')d\epsilon' = (1+z)^3n_b(\epsilon)d\epsilon \) where the dash indicates comoving-frame quantities. The simplifying assumption that the photon density transforms geometrically corresponds to the situation in which an initial short burst of star formation at \( z_f > z_0 \) produced most of the diffuse infrared-to-ultraviolet background radiation. This simple assumption is replaced by a more realistic one in Sect.4. Fig.2 shows the spectrum of the low-energy diffuse background used to solve Eq.(10) numerically.

Figure 3 shows the resulting \( \tau(E, z) = 1 \) (omitting the subscript hereafter) curve for the microwave-to-ultraviolet diffuse background spectrum shown in Fig.2. It is obvious that \( \gamma \)-rays above \( \sim 10-50 \) GeV cannot reach us from beyond redshifts of \( z = z_f = 2-4 \). Higher energy \( \gamma \)-rays can reach us only from sources at lower redshifts (e.g. \( \gamma \)-rays with energies up to 10 TeV have been observed from Mrk 501 at \( z = 0.033 \) in accord with Fig.3 [22]).

**Corollary I:** If the extragalactic gamma ray background originates from unresolved sources distributed in redshift similar to galaxies, its spectrum must steepen above \( \sim 30 \) GeV due to \( \gamma \)-ray pair attenuation.

Here is has been tacitly assumed that the \( \gamma \)-rays which have turned into electron-positron pairs do not show up again. This is, in fact, not quite true, since the pairs are subject to inverse-Compton scattering off the microwave background thereby replenishing \( \gamma \)-rays. The 2.7 K background is more important as a target than the shorter wavelength background, since there is no threshold condition for Thomson scattering contrary to pair production and since 2.7 K photons greatly outnumber
Fig.3: The $\gamma$-ray horizon $\tau(E,z) = 1$ for the low-energy background spectrum shown in Fig.2. Cosmological parameters are $h = 0.6$, $\Omega = 1$, and $\Omega_\Lambda = 0$. For a general discussion of pair attenuation, see reference [23].

the latter. The inverse-Compton scattered microwave photons turn into $\gamma$-rays of energy

$$E_{ic} \sim 10 \left( \frac{1+z}{4} \right) \left( \frac{E}{30 \text{ GeV}} \right)^2 \text{ MeV}$$

(11)

conserving the energy of the absorbed $\gamma$-ray which corresponds to a constant $E^2 dN/dE$, i.e. the expected slope of the differential spectrum is about -2 (-2.1 observed). A small amount of energy is lost to lower frequency synchrotron emission, if magnetic fields are present in the intergalactic medium.

**Corollary II:** Energy conservation in the reprocessing of $\gamma$-rays from higher to lower energies by pair production and subsequent inverse-Compton scattering produces an approximate $dN/dE \propto E^{-2}$ power law extragalactic gamma ray background between $\sim 10$ MeV and $\sim 30$ GeV.

4 Evolution of the metagalactic optical-ultraviolet radiation field
4.1 A simple model based on the observed "effective" star formation rate

Consider an effective cosmic star formation history \( \dot{\rho}_{\star}(z) \) denoting the production rate per unit volume of mass which has formed to stars at a redshift of \( z \). Such star formation histories have been inferred from galaxy counts in the Hubble Deep Field \(^2\). Since the present-day infrared background is strong enough to absorb gamma rays in the TeV range in the local Universe far from the peak of the star formation history, its evolution in the past is rather irrelevant in this context. However, the present-day optical radiation background scaled back to the peak of the star formation history at a redshift of \( z_b \sim 1.5 \) implies gamma ray attenuation in the 20 GeV regime from sources at this redshift. Over this distance scale the evolution of the background becomes important, since it is gradually produced by the forming stars.

The evolving background must be normalized to yield the observed present-day radiation background

\[
n(\epsilon, 0) d\epsilon = \int_0^{z_f} d\epsilon' n(\epsilon', z') \frac{d\epsilon'}{d\epsilon} (1 + \epsilon')^{-3} d\epsilon'
\]

(13)

As a simple example consider a burst of star formation at a high redshift \( \dot{n} \propto \delta(z - z_f) \). Inserting this in Eq.(12) and combining with Eq.(13) we obtain

\[
n(\epsilon, z) d\epsilon = (1 + z)^{-3} n(\epsilon', z) d\epsilon' \quad (z \leq z_f)
\]

(14)

which represents a constant co-moving density background density where the \((1 + z)^3\) term reflects the geometric scaling of the cosmic volume. To obtain a realistic parametrization of \( \dot{n}(z, \epsilon') d\epsilon' \) we approximate the Madau curve \(^2\) as a broken power law

\[
\dot{n}(z, \epsilon')(1 + \epsilon')^{-3} \propto \left( \frac{\dot{\rho}_{\star}(z)}{\epsilon} \right) \propto (1 + z)^{\alpha - 1}
\]

(15)

with \( \alpha = \alpha_M = 3.8 \) for \( 0 \leq z \leq 1.5 = z_b \) and \( \alpha = \beta_M = -4.0 \) for \( z_b = 1.5 \leq z \leq 10 = z_f \). We also investigate a star formation rate which exhibits a plateau beyond \( z_b \).

Equation (1) enters the formula for the gamma ray optical depth:

\[
\tau(E_\gamma, z) = \int_0^z \frac{d\mu}{dz} \int_{-1}^{+1} d\mu (1 - \mu) \int_{\epsilon_{\text{th}}}^{\infty} d\epsilon \rho_n(\epsilon, z) \sigma(E, \epsilon, \mu)
\]

(16)

\(^2\)The term “effective” means that only the star formation rate inferred from photons which have made it through possible obscuring dust clouds are of relevance for the build-up of a metagalactic radiation field.
Note that cosmology enters through \( dl/dz \) (which depends on \( \Omega, \Omega_\Lambda \), and \( H_o \)), not through \( n(\epsilon, z) \) for a given parametrization of \( \tilde{\rho}_i(z) \). However, the parametrizations \( \tilde{\rho}_i(z) \) must also satisfy observational constraints such as number counts and the present-day diffuse background which themselves depend on cosmology. Turning this around it means that one must find the cosmology parameters for which a measured gamma ray horizon (i.e., the curve \( \tau(E_o, z) = 1 \)) and the star formation history data come into mutual consistency.

The gamma ray horizon from Eq.(16) is shown in Fig.4 using the low-energy background spectrum template shown in Fig.2. The template was used to normalize the evolving background such that is identical to the template at \( z = 0 \) and scales to higher redshifts according to Eq.(12). The fact that there is a redshift with a maximum star formation is very important. If power law evolution of the background emissivity were to continue all the way in the past, one could easily infer power law solutions for the scaling of \( n(\epsilon, z) \) which are more shallow than \((1 + z)^3\) as in ref. [16], but such solutions become unrealistic beyond \( z_b \).

### 4.2 Extragalactic gamma ray background

The origin of the observed diffuse isotropic gamma ray background is unknown. The spectral shape and flux density suggest that unresolved faint radio loud AGN are responsible for this background, similar to the situation in the X-ray band where deep observations have revealed that faint AGN are responsible for more than 90% of the background emission. The EGRET-type radio-loud AGN seem contribute not more than \( \sim 25\% \) to the extragalactic gamma ray background. The uncertainties about the faint end of the gamma ray luminosity function in the EGRET band allow for a larger contribution from the general class of radio-loud AGN. According to beaming statistics, the flux-limited EGRET sample of AGN is dominated by highly beamed sources with a rather flat luminosity function. A much fainter, less beamed population with a steeper luminosity function is likely to fill in the remaining 75%, at least this seems very plausible considering the energetics of radio jets as was shown in Sect.2. I strongly expect that the flat-spectrum/steep-spectrum classes are mirrored in different populations of gamma ray sources. The nearest steep-spectrum radio sources would have been detected by EGRET even if they were faint (with their gamma ray luminosity roughly a factor of \( \sim 50 \) larger than the 5 GHz luminosity). However, with a lower compactness for instrinsic gamma ray absorption \( \propto L/R \) the steep-spectrum radio sources could emit most of their gamma ray power above the EGRET range. It is up to new air-Cerenkov telescopes with threshold energies above 10 GeV and GLAST to probe this proposal.

If the extragalactic jets are indeed responsible for most of the gamma ray background, it is straightforward to investigate the effect of pair attenuation on the spectrum of the background. The precise shape of the spectra of the individual sources at high redshifts is rather unimportant owing to the effects of cascading discussed in Sect.3. Adopting a power law gamma ray spectrum per source with
Fig. 4: Gamma ray horizon due to interactions with an evolving metagalactic radiation field as computed from the effective star formation rate. Sources below the horizon curve suffer no significant pair-attenuation along the line of sight. The grey band indicates the uncertainty of the horizon as estimated from the range of interpolations allowed between observational upper and lower bounds of the flux of the present-day optical-UV diffuse background. Note that the metagalactic radiation field before the maximum of the cosmic star formation rate (indicated by the dashed line) is too weak to significantly attenuate gamma rays below 20-40 GeV resulting in a near-constant optical depth. The light solid line shows the effect of a star formation rate with an extended plateau which causes the optical depth to continue to grow with redshift beyond $z = 1.5$. The horizontal lines indicate the effective threshold energies for various air-Cerenkov telescopes. It is emphasized that triggering below 20-40 GeV, which can be achieved by the MAGIC telescope, is crucial for probing the star formation era. Such an investigation is complementary to studies of galaxies at high redshifts, since it is additionally sensitive to diffuse sources of optical-UV photons such as would be arising from exotic particle decays (one possible scenario for the reionization epoch).
the average slope of the resolved EGRET sources

\[ \frac{dN}{dE} = A \left( \frac{E}{E_1} \right)^{-2.1} \]  

(17)

extending from \( E_1 = 10 \) MeV to \( E_2 = 1 \) TeV and taking into account the luminosity density evolution \( \Psi(z) \) of AGN, we obtain a good approximation of the present-day background energy density

\[ u(E) = \frac{4\pi}{c} EI_E \]  

(18)

from the equation

\[ u(E) \propto \int_0^{z_l} dz \frac{dt}{dz} \Psi(z)(1 + z)^{-4} B \left( \frac{E(1 + z)}{E_1} \right)^{-0.1} e^{-\frac{E(1 + z)}{E_2}} C[E, z] \]  

(19)

where \( \frac{dt}{dz} \) is given by

\[ \frac{dt}{dz} = \frac{1}{(1 + z)\sqrt{\Omega(1 + z)^4 + (1 - \Omega - \Omega_A)(1 + z)^2 + \Omega_A}} \]  

(20)

and the function \( C[E, z] \) for the effect of pair attenuation can be approximated as

\[ C[E, z] = e^{-\frac{E}{E_t(z)}} \]  

(21)

with \( E_t(z) \) denoting the solution of the equation \( \tau(E, z) = 1 \) (the gamma ray horizon). The result is shown in Fig. 5. It will be possible with GLAST to find whether the diffuse gamma ray background indeed turns over in this shallow fashion or continues as a power law into the 100 GeV domain. In the latter case, the gamma ray background would have to be due to some local source population [26].

5 Comparison of proton blazar predictions with observed multi-TeV spectra

In the previous sections arguments based on energetics have been used to favor extragalactic jets as the sources of the gamma ray background. This requires that the jets radiate a sizable fraction of their kinetic energy in gamma rays when integrated over their lifetimes. Since the cooling of relativistic particles increases with their energy, a high radiative efficiency is equivalent with high energies. For electrons, Lorentz factors required for a high radiative efficiency are at least \( \gamma_e \sim 10^3 \), and for protons \( \gamma_p \sim 10^9 \left( \frac{u_e}{u_B} \right) \gamma_e \sim 10^{10} \). The Lorentz factor for protons may seem outrageously high, but in a statistical acceleration process such as Fermi acceleration with the balance between energy gains and losses determining the maximum energy, such high energies are an inevitable consequence of the acceleration theory. Moreover, particles with energies in excess of \( 10^{19} \) eV are observed in the local spectrum of cosmic rays. Their energy is too high for the gyrating particles to be isotropized in the Galactic disk, so that an extragalactic origin is very likely. The energy requirements can be converted to an energy supply rate for extragalactic sources, and this requires sources as strong as radio galaxies. Thus,
Fig. 5: The gamma ray horizon enforces a shallow turnover beyond $\sim 30 \text{ GeV}$ in the spectrum of the extragalactic gamma ray background which is only weakly dependent on cosmology (results from further investigations by T. Kneiske will soon be reported elsewhere.).

An important, although not necessary, assumption of the original model is that the magnetic field pressure energy density is in equipartition with that in relativistic particles implying that synchrotron cooling dominates over Compton cooling (since the photon energy density remains below that in particles). This affects accelerated electrons as well as secondary electrons at ultrahigh-energies. Evaluating a simple conical jet geometry shows that typical blazars are optically thin to gamma rays up to the TeV range. Unsaturated synchrotron cascades initiated by accelerated protons interacting with the synchrotron photons from the accelerated electrons are computed as the stationary solution of a coupled set of kinetic equations which is then Doppler boosted to an appropriate observer’s frame. A series solution is
found employing Banach’s fixed point theorem which can be physically interpreted as a series of superimposed cascade generations. The cascade generation of gamma rays emerging in the TeV range on the optically thin side has a spectral index $s \sim 1.7$ (differential spectrum $I_\gamma$) steepening by $\alpha = 0.5 - 0.7$ above TeV. The index $\alpha$ is the energy index of the optical synchrotron photons which act as a target for both gamma rays and protons. The reason for the break is the onset of intrinsic pair attenuation characterized by the escape probability $I_\gamma = P_{\text{esc}} I_\circ$ for a homogeneously mixed absorber and emitter

$$P_{\text{esc}} = \frac{1 - \exp[-\tau(E)]}{\tau(E)} \to \frac{1}{\tau(E)} \propto E^{-\alpha} \quad \text{for} \quad \tau \gg 1$$ (22)

The shape of the multi-TeV spectrum is therefore not sensitive to changes in the maximum energy and can remain constant under large-amplitude changes of the flux associated with changes in the maximum energy.

The observed multi-TeV spectrum is modified by the quasi-exponential pair attenuation due to collisions of the gamma rays with photons from the infrared background. A recent evaluation of this background based on direct measurements obtained from COBE data in the far-infrared, and inferred as a lower limit from number counts based on ISO observations of the HDF shows that this effect compensates the shallow downward curvature discovered by the HEGRA collaboration in the spectrum of Mrk 501 [3]. If the gamma rays were due to inverse-Compton scattering, the shallow curvature is difficult to understand for a number of reasons given in ref. [22]. The most important of them is that one must expect the accelerated electrons not to be able to reach energies much higher than 10 TeV. An inverse-Compton spectrum produced by these electrons would therefore have to show significant curvature approaching this maximum energy adding to the inevitable curvature due to gamma ray interactions with the infrared background photons. There are some rumours that quantum gravity effects could possibly suppress pair production over intergalactic distances, but that remains highly speculative. I consider the agreement between the proton blazar prediction and observation very promising for the model, albeit minor discrepancies must be expected, since the proton blazar model is highly simplified in order to avoid too many free parameters and to be predictive. Therefore I take the freedom to speculate about the emissions associated with the gamma rays, viz. cosmic rays and high-energy neutrinos in the following sections.

6 Neutrino and cosmic ray predictions

The photo-production of pions leads to the emission of neutrons and neutrinos. The neutrons decay to protons, and such extragalactic cosmic rays suffer energy losses traversing the microwave background [29]. At an observed energy of $10^{19}$ eV, the energy-loss distance is $\lambda_p \sim 1$ Gpc owing to pair production. This distance corresponds to a redshift $z_p$ determined by $\lambda_p = (c/H_\circ) \int_0^z \frac{dz}{[1 + z \bar{E}(z)]}$ where $\bar{E}(z) = [\Omega(1 + z)^3 + \Omega_R(1 + z)^2 + \Omega_\Lambda]^{1/2}$ with $\Omega + \Omega_R + \Omega_\Lambda = 1$. Almost independent on cosmology, the resulting value for $z_p$ is given by $z_p = h_{50}/(6 - h_{50}) \simeq 0.2h_{50}$
Fig. 6: Comparison of predicted and observed flux density spectrum in the multi-TeV range for Mrk 501. The thin solid line shows the spectrum published in [28]. The upper thick solid lines show this spectrum scaled to the 300 GeV flux levels during the two observation epochs where the air-Cerenkov data indicated by the solid and open symbols were obtained with the HEGRA telescopes. The dashed line shows the spectrum without the effect of the assumed marginal intergalactic gamma ray attenuation due to interactions of the gamma rays with metagalactic infrared radiation. More recent HEGRA observations with higher statistical significance show some downward curvature in the 10 TeV range which may be attributed to a stronger attenuation which is in line with new analyses of COBE data and ISO galaxy counts in the Hubble Deep Field [10].
where \( h_{50} = H_\circ/50 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Therefore, when computing the contribution of extragalactic sources to the observed cosmic ray flux above \( 10^{19} \text{ eV} \), only sources with \( z \leq z_p \) must be considered. Assuming further that extragalactic sources of cosmic rays and neutrinos are homogeneously distributed with a monochromatic luminosity density \( \Psi(z) \propto (1 + z)^{3+k} \) where \( k \sim 3 \) for AGN \( ^{31} \), their contribution to the energy density of a present-day diffuse isotropic background is given by

\[
u(0) = \int_0^{z_{m}} \Psi(z)(1 + z)^{-4} \frac{dl}{dz} dz = \frac{\Psi(0)}{H_\circ} \int_0^{z_{m}} \frac{(1 + z)^k dz}{(1 + z)^2 \bar{E}(z)} \]  

(23)

where \( z_m = 2 \) denotes the redshift of maximum luminosity density. The factor \( (1 + z)^{-4} \) accounts for the expansion of space and the redshift of energy. For a simple analytical estimate of the effect of energy losses on the proton energy density at \( 10^{19} \text{ eV} \), we collect only protons from sources out to the horizon redshift \( z_p \sim 0.2 \) for \( 10^{19} \text{ eV} \) protons, whereas neutrinos are collected from sources out to the redshift of their maximum luminosity density \( z_m \). This yields the energy density ratio for neutrinos at an observed energy of \( \sim 5 \times 10^{17} \text{ eV} \) and protons at \( 10^{19} \text{ eV} \)

\[
\frac{\nu(0)}{\nu_p(0)} = \xi \frac{\int_0^{z_{m}} (1 + z)^{k-2}/\bar{E}(z) dz}{\int_0^{z_p} (1 + z)^{k-2}/\bar{E}(z) dz} \sim 2 - 3
\]  

(24)

using \( \xi \sim 0.3 \) from decay and interaction kinematics, and considering an open Universe with \( \bar{E}(z) = (1 + z) \) and a closed one with \( \bar{E}(z) = (1 + z)^{3/2} \).

Fig. 6 shows exact energy-dependent results for \( \Omega = 1 \) from a full Monte-Carlo simulation employing the matrix doubling method of Protheroe & Johnson \( ^{31} \) and using the model A neutrino spectrum from the original work \( ^{33} \). The associated gamma ray flux corresponds to the observed background flux above 100 MeV \( ^{3} \). The neutrino flux is consistent with the bound given in ref. \( ^{32} \), although it is possible to have extragalactic neutrino sources of higher neutrinos fluxes without violating the observed cosmic ray data as a bound \( ^{34} \). Note that there are a few cosmic ray events at energies above \( 10^{20} \text{ eV} \) which are difficult to reconcile with an origin in extragalactic radio sources, since the radio galaxies are typically at such large distances that pion production quenches their spectrum above \( 10^{19.5} \text{ eV} \). However, cosmic ray particles from the few closest radio galaxies deflected by magnetic fields could possibly explain these events. If not, they might originate from the decay of still higher energy particles, such as the gauge bosons produced at cosmic strings \( ^{5} \) indicating new physics.

7 Neutrino oscillations and event rates

The neutrino flux shown in Fig. 7 corresponds to a very low muon event rate even in a km\(^2\) detector which is of the order of 1 event per year and per steradian. This event rate could be increased if there is additional neutrino production due to pp-interactions of escaping nucleons diffusing through the host galaxies which is

\(^{3} A recent paper by Waxman and Bahcall \( ^{32} \) refers to the neutrino flux from model B in the original work which was given only to demonstrate that hadronic jets cannot produce a diffuse gamma ray background with an MeV bump (as measured by Apollo and which is now known to be absent from a COMPTEL analysis) without over-producing cosmic rays at highest energies.
Fig. 7: Comparison of proton (solid line) and neutrino fluxes (dotted lines, from top to bottom $\nu_\mu$, $\bar{\nu}_\mu$, and $\nu_e$) from the proton blazar model (Monte-Carlo computations and figure by R.J. Protheroe). The open symbols represent the observed cosmic ray flux.

difficult to predict due to their unknown magnetic fields and turbulence level. The reason for the low rate is that the neutrino spectrum is extremely hard, a differential proton spectrum of index $s_p = 2$ photo-producing pions in a synchrotron photon target also with differential index $s_{syn} = 2$ yields a differential neutrino spectrum of index $s_\nu = 1$ ($dN/dE \propto E^{-s}$) up to some very high energy. The spectrum may be more shallow, if the target photons have a spectral index of 0.7 as suggested for Mrk 501, thereby increasing the number of lower energy neutrinos while keeping the bolometric flux the same. Because of the long lever arm from $10^{6.5}$ TeV to 1 TeV, a factor of $\sim 100$ increase in the event rate would result from this effect.

At this point the discovery of neutrino mass announced by the Super-Kamiokande collaboration \textsuperscript{[1]} comes in changing the situation in a major way. A deficit of atmospheric muon neutrinos was observed with Super-Kamiokande at large zenith angles with the most likely explanation being a full-amplitude oscillation of muon flavor eigenstates to tauon flavor eigenstates across the Earth at GeV energies. While this would make long-baseline experiments searching for the appearance of the tauon in a muon neutrino beam with laboratory beams extremely difficult (if not impossible), it qualifies the expected extragalactic sources of muon neutrinos as an ideal neutrino beam. The energies are high enough to produce tauons on the mass-shell and the distance large enough to obtain full mixing. Since tauons decay before interacting in the Earth and since the Earth is opaque to tau neutrinos above $\sim 100$ TeV, a fully mixed extragalactic muon neutrino beam must initiate tauon cascades in the Earth shifting the tauon neutrino flux down to energies of $\sim 100$ TeV \textsuperscript{[35]} and obliterating the Earth-shadowing effect \textsuperscript{[36]} that makes the
muon solid angle very narrow at high energies.

The neutrino oscillations would have another important consequence. Current data suggested a maximal mixing between muon and tauon flavors and a mass difference given by

\[ \Delta m_{\mu\tau}^2 = m_{\nu_{\tau}}^2 - m_{\nu_{\mu}}^2 = 5 \times 10^{-3} \text{ eV}^2 \]  

(25)

The mass difference between electron and muon flavored neutrinos inferred from the solar neutrino deficit is orders of magnitude less, and this implies that the neutrino masses could be highly degenerate if they are at the eV level. Using the limit \( m_{\nu_e} < 5 \text{ eV} \), the maximum allowed combined neutrino mass would be

\[ m_{\nu} \approx 3m_{\nu_e} < 15 \text{ eV}. \]  

(26)

Inserting this into the Cowsik-McClelland bound one obtains the maximum contribution to the (hot) dark matter of the Universe

\[ \Omega_{\nu} < \frac{15}{91.5} h^{-2} \approx 0.4 \left( \frac{h}{0.65} \right)^{-2}. \]  

(27)

Due to free streaming of the neutrinos at the time of recombination, density fluctuations of this dark matter component would be wiped out on scales less than

\[ \lambda_{\nu} = 30 \left( \frac{h}{0.65} \right)^{-2} \text{ Mpc} \]  

(28)

and would therefore have no consequence for the dark matter inferred from studies of galaxy halos or galaxy clusters which yield \( \Omega = 0.3 \pm 0.1 \) [3]. Structure formation simulations exclude \( \Omega_{\nu} \) to be larger than 0.15 [38] which is in agreement with the above upper limit and both evidences together rule out neutrinos as the dark matter which could supply a critical mass to the Universe.

8 Discussion and summary

The paper highlights in a personally biased way on a few developments in high-energy astroparticle physics, rather than to give a review of all the activities in the field which encompass a much wider scope from the origin of cosmic rays to quantum gravity and which involve a truly impressive number of experimental efforts. From my point of view, the identification of one component of dark matter using the discovery of the atmospheric neutrino anomaly with Super-Kamiokande represents a major achievement, and I have highlighted its consequence that neutrinos cannot close the Universe. Furthermore, this discovery is not sufficient to prove the neutrino oscillation hypothesis conclusively. An experiment is needed which shows the appearance of the tau lepton in a beam of muon neutrinos, and I have shown that neutrinos due to proton acceleration in extragalactic sources would be ideally suited as a beam for a tau-appearance experiment in one of the major neutrino telescopes which are under construction. From an astrophysical point of view, the oscillations are also important for another reason, since they remove the Earth shadowing effect which suppresses the response of a neutrino telescope to
extraterrestrial sources of very high-energy neutrinos. This makes the discovery of neutrinos from radio-loud AGN much more probable in a few years.

Other kinds of dark matter such as right-handed neutrinos, supersymmetric particles, magnetic monopoles, or other topological defects and their associated gauge bosons, are likely to be very massive. It is a formidable task to find other than gravitational evidence for this dark matter due to the electromagnetic (photons), weak (neutrinos), and strong (protons) couplings of its decay and annihilation products. Inevitably this task requires to understand all the astrophysical background radiations at high energies. The astrophysics governing this energy domain itself has proven to be a fascinating realm. A good example is the discovery of multi-TeV emission from nearby blazars using the HEGRA imaging air-Cerenkov telescopes. The observational findings frustrate the worldwide elite in theoretical astrophysics and seem to provide key insights into the extraordinary physics driven by weakly accreting black holes.

If the recent determinations of the infrared background from ISO galaxy counts (lower limits) and COBE/DIRBE and FIRAS are correct, then the steepening in the multi-TeV spectrum of Mrk 501 observed with the HEGRA air-Cerenkov telescopes is due to the predicted gamma ray attenuation in collisions with these infrared background photons. Predictions of the attenuation process for sources at higher redshifts depend strongly on the evolution of the metagalactic optical-UV radiation field. It will therefore soon be possible to independently probe the star formation history using 10-100 GeV gamma rays from extragalactic high-redshift sources when lower threshold gamma ray telescopes such as MAGIC and GLAST are available. The method is sensitive to truly diffuse photons between the galaxies and, when compared with calculations based on the observed star formation rate in early galaxies, allows to test the hypothesis whether the background photons originate from the stars or other sources (possibly connected with the reionization epoch).

The multi-TeV spectra from nearby blazars predicted on the basis of the proton blazar model are in accord with the observations if the effect of pair attenuation due to the extragalactic infrared background is taken into account. This is surprising, since the model gives stationary spectra, whereas the observed flux is highly variable. Nevertheless, the spectra seem to remain rather constant in the multi-TeV domain. There are several properties which are not explained in the framework of a stationary quasi-homogeneous model by construction, such as the apparently different variability pattern of Mrk 421 in the GeV and TeV ranges. This does not argue against the proton acceleration hypothesis, since one could construct inhomogeneous, non-stationary models to explain this phenomenology. The same is true for the problem of short-term variability, which may require to describe the passage of shocks traveling through narrowly-spaced inhomogeneities. It is amazing, however, that a general feature expected from models based on electron acceleration is certainly not seen in the data of Mrk 501, viz. the change of the upper cutoff energy with varying flux. This can only mean that the cutoff is indeed due to intergalactic attenuation and that the electron maximum energy is much higher.
than 20 TeV which is difficult to understand in the presence of synchrotron and inverse-Compton losses. Another peculiar finding is that the multi-TeV emission in Mrk 501 is accompanied by 100 keV synchrotron photons in some epochs, but not in all of them. Moreover, in Mrk 421 100 keV synchrotron flares have not been observed in spite of flaring TeV emission. So the story is not simple and likely to continue, brainstorming is always desired when confronted with a new phenomenon.

An interesting corollary from hadronic models of extragalactic gamma ray sources is that they would also emit cosmic rays and neutrinos at about equal luminosities (within a factor of a few). If the cosmic ray flux emitted by hadronic accelerators equals that of the observed cosmic rays above $10^{19}$ eV, the associated gamma ray power from these sources is enough to produce the observed extragalactic gamma ray background above about 100 MeV. The gamma ray power is larger than that in cosmic rays, since the cosmic rays lose energy traversing the low-energy background radiation fields and most sources have high redshifts. It has been proposed in ref. [39] that GRBs are responsible for the highest energy cosmic rays, but more recent GRB observations indicate that most of them have high redshifts which is expected if they trace star formation. The strong evolution of the GRB luminosity density would then rule out GRBs as possible sources of the highest energy cosmic rays, since their cumulative gamma ray flux is far below the putatively extragalactic gamma ray flux. Although the muon event rate in neutrino telescopes from hadronic extragalactic gamma ray sources supplying the highest energy cosmic rays is low, neutrino oscillations lead to tau cascades canceling the Earth shadowing effect thereby increasing the detection probability. Tau lepton appearance in the neutrino telescopes would constitute the first direct measurement of the tauon (which so far has only been inferred from momentum conservation) and would prove the neutrino oscillation hypothesis.

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