Axions and Cosmic Rays

Domènec Espriu

Departament d'Estructura i Constituents de la Matèria and

Institut de Ciències del Cosmos, Universitat de Barcelona

and

CERN, PH Division

UNIVERSITAT DE BARCELONA

Institut de Ciències del Cosmos

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In collaboration with: A. Andrianov, P. Giacconi, F. Mescia, A. Renau and R. Soldati

Introduction

Cold relic axions resulting from vacuum misalignment in the early universe is a popular and so far viable candidate to dark matter.

Provided that the reheating temperature after inflation is below the Peccei-Quinn transition scale, in later times the axion evolves as

$$a(t) = a_0 \cos m_a t, \qquad \mathbf{k} = 0$$

$$\rho \simeq a_0^2 m_a^2$$

$$\rho \simeq 10^{-30} \mathrm{gcm}^{-3} \simeq 10^{-10} \mathrm{eV}^4, \qquad \rho^* \simeq 10^{-24} \mathrm{gcm}^{-3} \simeq 10^{-4} \mathrm{eV}^4 \qquad (30 \text{ to } 100 \text{ kpc})$$

The axion background provides a very diffuse concentration of a pseudoscalar condensate. The photon density is also low and yet it has an impact on ultra-high energy cosmic rays imposing the GZK cutoff.

What are the consequences of this difuse axion background on high-energy cosmic ray propagation?

Manifest breaking of Lorentz symmetry

Let us consider (for the moment just as a theoretical possibility) the possibility of explicit breaking of Lorentz breaking by means of a time-like constant axial vector. Consider electromagnetism in such a background

$$\mathcal{L} = \mathcal{L}_{\rm INV} + \mathcal{L}_{\rm LIV}$$

$$\mathcal{L}_{\rm INV} = -\,\tfrac{1}{4}\,F^{\alpha\beta}F_{\alpha\beta} + \bar{\psi}[\not{\partial} - e\,\not{A} - m_e]\psi \qquad \mathcal{L}_{\rm LIV} = \tfrac{1}{2}\,m_\gamma^2\,A_\mu\,A^\mu + \,\tfrac{1}{2}\,\eta_\alpha A_\beta \widetilde{F}^{\,\alpha\beta}$$

It will be useful for us to keep $m_\gamma > 0$. Otherwise gauge invariance is manifest.

E.o.M.:

$$\left\{g^{\,\lambda\nu}\left(k^2 - m_\gamma^2\right) + i\,\varepsilon^{\,\lambda\nu\alpha\beta}\,\eta_\alpha\,k_\beta\right\}\tilde{A}_\lambda(k) = 0$$

We can build two complex and space-like chiral polarization vectors $\varepsilon_\pm^\mu(k)$ which satisfy the orthonormality relations

$$-\,g_{\,\mu\nu}\,\varepsilon_\pm^{\mu\,*}(k)\,\varepsilon_\pm^\nu(k) = 1 \qquad\qquad g_{\,\mu\nu}\,\varepsilon_\pm^{\mu\,*}(k)\,\varepsilon_\mp^\nu(k) = 0$$

In addition we have

$$\varepsilon_T^\mu(k) \sim k^\mu \qquad \varepsilon_L^\mu(k) \sim k^2\eta^\mu - k^\mu\eta\cdot k$$

They fulfill

$$g_{\,\mu\nu}\,\varepsilon_A^{\mu\,*}(k)\,\varepsilon_B^\nu(k) \;=\; g_{\,AB} \qquad\qquad g^{\,AB}\,\varepsilon_A^{\mu\,*}(k)\,\varepsilon_B^\nu(k) \;=\; g^{\,\mu\nu}$$

Different physics in different frames

The polarization vectors of positive and negative chirality are solutions of the vector field equations if and only if

$$k^\mu_\pm = (\omega_{\mathbf{k}\,\pm}, \mathbf{k}) \qquad \omega_{\mathbf{k}\,\pm} = \sqrt{\mathbf{k}^2 + m_\gamma^2 \pm \eta|\mathbf{k}|} \qquad \varepsilon^\mu_\pm(\mathbf{k},\eta) = \varepsilon^\mu_\pm(k_\pm) \quad \left(k^0_\pm = \omega_{\mathbf{k}\pm} \right)$$

In order to avoid problems with causality we want $k^2_\pm > 0$. For photons of negative chirality this happens iff

$$|\mathbf{k}| < \frac{m_\gamma^2}{\eta} \equiv \Lambda_\gamma$$

for $m_\gamma = 0$ they cannot exist ($\gamma \to \gamma\gamma\gamma$).

As is known to everyone the processes $e^- \to e^-\gamma$ or $\gamma \to e^+e^-$ cannot occur. However here physics is different in different frames and for the latter process

$$\omega_{\mathbf{k}\,\pm} = \sqrt{\mathbf{k}^2 + m_\gamma^2 \pm \eta\,|\mathbf{k}|} = \sqrt{\mathbf{p}^2 + m_e^2} + \sqrt{(\mathbf{p}-\mathbf{k})^2 + m_e^2}$$

Possible iff

$$|\mathbf{k}| \geq \frac{4m_e^2}{\eta} \equiv k_{\,\mathrm{th}} \qquad (m_\gamma = 0)$$

The electron-positron pairs will be created with a large momentum.

Lorentz violation from axions

Axion-photon coupling:

$$\Delta\mathcal{L} = g_{a\gamma\gamma}\frac{\alpha}{2\pi}\frac{a}{f_a}\tilde{F}F$$

Popular models such as DFSZ and KSVZ all give $g_{a\gamma\gamma} \simeq 1$.

$$f_a > \mathcal{O}(10^{11})\ \mathrm{GeV}, \qquad 10^{-3}\mathrm{eV} > m_a > 10^{-6}\ \mathrm{eV}$$

$$\Delta\mathcal{L} = -g_{a\gamma\gamma}\frac{\alpha}{\pi}\frac{a_0}{f_a}\sin(m_a t)\,\epsilon^{ijk}A_i F_{jk}$$

If the momentum of a particle propagating in this background is large $\mathbf{p} >> m_a$ it makes sense to treat the axion background adiabatically

$$\Delta\mathcal{L} = \frac{1}{4}\eta\epsilon^{ijk}A_i F_{jk} = \frac{1}{2}\eta_\alpha A_\beta \tilde{F}^{\alpha\beta}$$

with $\eta_\alpha = (\eta, 0, 0, 0)$ where the “constant” η will change sign with a period $1/m_a$.

$$|\eta| \simeq \alpha\frac{\sqrt{\rho_a}}{f_a} \simeq 10^{-23} - 10^{-24}\mathrm{eV}$$

A (im)possible consequence...

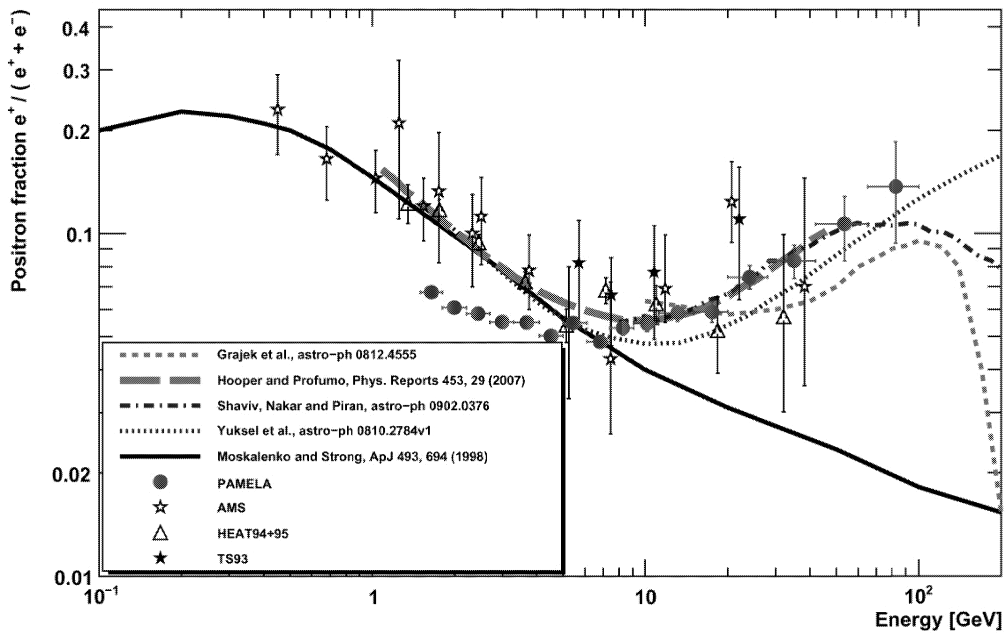


Figure 1: Positrons detected by the PAMELA mission

The key relation is

$$|\mathbf{k}| > \frac{4m_f^2}{\eta}$$

However this would require $\eta \sim 1$ keV - totally unrealistic for an axion background!

Other possible consequences?

The polarizations

$$\varepsilon^{\mu}_{+}(k),\, \varepsilon^{\mu}_{-}(k)$$

correspond only approximately to the usual ones of QED. As a consequence light propagation in an axion background may be subject to modifications (dichroism). For visible light or radiowaves there is no marked separation of scales w.r.t m_a and the time variation of the background cannot be treated adiabatically and the net effect should average to zero.

We need processes where $\mathbf{k} >> m_a$.

Cosmic rays-induced processes such as $p \to p\gamma$ or $e \to e\gamma$ are possible in LIV QED. This is a prompt process that is not affected by a slight time variation of the background. The net effect shall not average to zero.

Effective photon mass:

$$m_\gamma^2 = 4\pi\alpha \frac{n_e}{m_e}, \quad n_e = 10^{-7}\text{c}m^{-3}$$

This number is of the order of 10^{-15} eV, but we shall assume the more conservative limit 10^{-18} eV, compatible with some astrophysical bounds in the 10^{-16} to 10^{-17} eV region.

a-Bremsstrahlung in cosmic rays

$$p(\mathbf{p}) \to p(\mathbf{p}-\mathbf{k})\gamma(\mathbf{k})$$

Energy conservation:

$$\sqrt{E^2+k^2-2pk\cos\theta}+\sqrt{k^2\pm\eta k+m_\gamma^2}-E=0, \qquad \eta>0$$

Kinematical constraints:

Let us first consider the case $m_\gamma = 0$ (but note that η is very small). The kinematic limits are

$$p_{th}=0$$

$$k_{min}=\eta, \quad \text{for} \cos\theta=-\eta/2p$$

$$k_{max}=\frac{E^2}{p+\frac{m_p^2}{\eta}}, \quad \text{for} \cos\theta=1$$

$k_{max} \simeq E$ for $E \gg m_p^2/|\eta|$ $\qquad k_{max} \simeq |\eta| E^2/m_p^2$ for $E \ll m_p^2/|\eta|$.

Kinematical constraints for $m_\gamma > 0$

Let us now consider $m_\gamma > 0$

$$p_{th} \simeq \frac{2m_\gamma m_p}{\eta}$$

$$k(\theta_{max}) \simeq \frac{2m_\gamma^2}{\eta}(1 - 3\frac{pm_\gamma^2}{E^2\eta}) \xrightarrow{p>>p_{th}} \frac{2m_\gamma^2}{\eta}, \qquad \sin^2\theta_{max} \to \frac{\eta^2}{4m_\gamma^2}$$

θ_{max} is small, photons are emitted in a narrow cone

In the opposite extreme, for zero angle there are two solutions

$$k_+(0) \simeq \frac{E^2\eta + pm_\gamma^2 + E\sqrt{E^2\eta^2 - 4m_p^2m_\gamma^2 + 2p\eta m_\gamma^2}}{2p\eta + 2m_p^2} \xrightarrow{p>>p_{th}} \frac{E^2}{p + \frac{m_p^2}{\eta}}$$

which is the same result obtained before, and

$$k_-(0) \simeq \frac{E^2\eta + pm_\gamma^2 - E\sqrt{E^2\eta^2 - 4m_p^2m_\gamma^2 + 2p\eta m_\gamma^2}}{2p\eta + 2m_p^2} \xrightarrow{p>>p_{th}} \frac{m_\gamma^2}{\eta}$$

$$k_-(0) < k(\theta_{max}) < k_+(0)$$

Decay rate and energy loss

The differential decay width will be

$$d\Gamma(Q) = (2\pi)^4 \delta^{(4)}(q + k - p) \frac{1}{2E} \overline{|M|^2} dQ$$

$$d\Gamma(Q) = \frac{\alpha}{2} \frac{|\mathbf{k}|}{|\mathbf{p}|} \frac{1}{E\omega_{\mathbf{k}}} (-p \cdot k + |\mathbf{p}|^2 \sin^2\theta) d|\mathbf{k}|$$

The rate of energy loss:

$$\frac{dE}{dx} = -\frac{1}{v} \int d\Gamma(Q) w(Q)$$

$$\frac{dE}{dx} = -\frac{\alpha}{2} \frac{1}{p^2} \int kdk[-\frac{1}{2}(m_\gamma^2 + \eta k) + p^2(1 - \cos^2\theta)]$$

There are two relevant limits

$$E \ll \frac{m_p^2}{|\eta|} \longrightarrow \frac{dE}{dx} = -\frac{\alpha \eta^2 E^2}{4m_p^2}.$$

$$E \gg \frac{m_p^2}{|\eta|} \longrightarrow \frac{dE}{dx} = -\frac{\alpha|\eta|}{3} E$$

The axion (very weak) shield

There are two key scales in this problem

$$E_{th} \simeq 2m_\gamma m_p/\eta \qquad \text{and} \qquad m_p^2/\eta$$

If $E \gg m_p^2/|\eta|$

$$E(x) = \exp - \frac{\alpha|\eta|}{3} x$$

For the expected values of η this would give a mean free path in the range $\mathcal{O}(1)$ to $\mathcal{O}(10)$ kpc.

This would imply that cold axions act as a powerful shield againts very energetic cosmic rays. Since $E_{th} \simeq 10^{15}$ eV the detection of cosmic rays above that energy would in fact impose a rather stringent bound on the combination $\sqrt{\rho_a}/f_a$.

However, this is not so because even for the most energetic cosmics, just below the GZK cut-off of 10^{20} eV, we are well below the cross-over scale $m_p^2/|\eta|$. In this regime the expression for $E(x)$ is

$$E(x) = \frac{E(0)}{1 + \frac{\alpha\eta^2}{4m_p^2} E(0)x}$$

It is peculiar to see that for extremely large distances $E(x) \sim \frac{1}{x}$,

The axion whistle

From the obvious fact that we detect (likely) extragalactic rays of large energy we can set at present the largely irrelevant bound

$$\eta < 10^{-14}\ \mathrm{eV}$$

However this does not mean that the whole effect is irrelevant. Let us consider the radioemission from the a-Bremsstrahlung.

For primary protons there is activity in the region

$$10^{-12}\ \mathrm{eV}(300\ \mathrm{Hz}, \lambda = 1000\ \mathrm{km}) < k < 10^{-2}\ \mathrm{eV}(3\ \mathrm{THz}, \lambda = 0.1\ \mathrm{mm})$$

For primary electrons

$$10^{-12}\ \mathrm{eV} < k < 10\ \mathrm{keV}$$

Spectrum of emission (per unit time)

$$\int_{E_{th}}^{\infty} dE\, n(E) \frac{d\Gamma}{dk} \qquad E_{th} = 2\frac{m_{p,e} m_{\gamma}}{|\eta|}$$

Listening to axions

Broadcasters:

Proton primaries

$$n(E) = N \times \begin{cases} E^{-2.68} & 10^9 \leq E \leq 4 \cdot 10^{15} \\ 1.12 \cdot 10^{19} E^{-3.26} & 4 \cdot 10^{15} \leq E \leq 4 \cdot 10^{18} \\ 3.85 \cdot 10^{-4} E^{-2.59} & 4 \cdot 10^{18} \leq E \leq 2.9 \cdot 10^{19} \\ 7.34 \cdot 10^{29} E^{-4.3} & E \geq 2.9 \cdot 10^{19} \end{cases}$$

Electron (+positrons) primaries

$$n(E) = N \times \begin{cases} 0.01 E^{-2.68} & E \leq 5 \cdot 10^{10} \\ 71.1 E^{-3.04} & E \geq 5 \cdot 10^{10} \end{cases}$$

Need to assume a given function $L(E)$ and combine with isotropy hypothesis to find the photon yield.

Electrons do matter

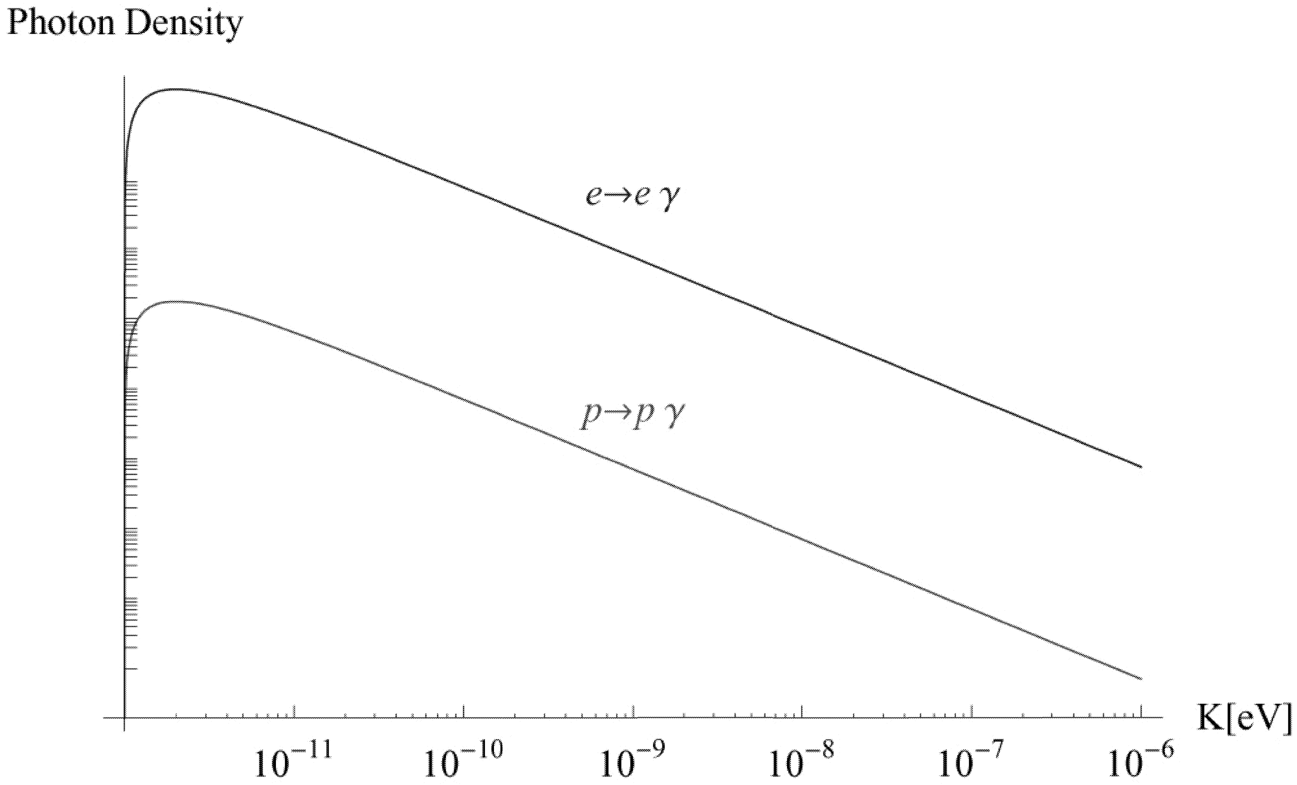


Figure 2: Radioemision from electrons vs. protons. $L(E)$ constant assumed

Detecting the axion whistle

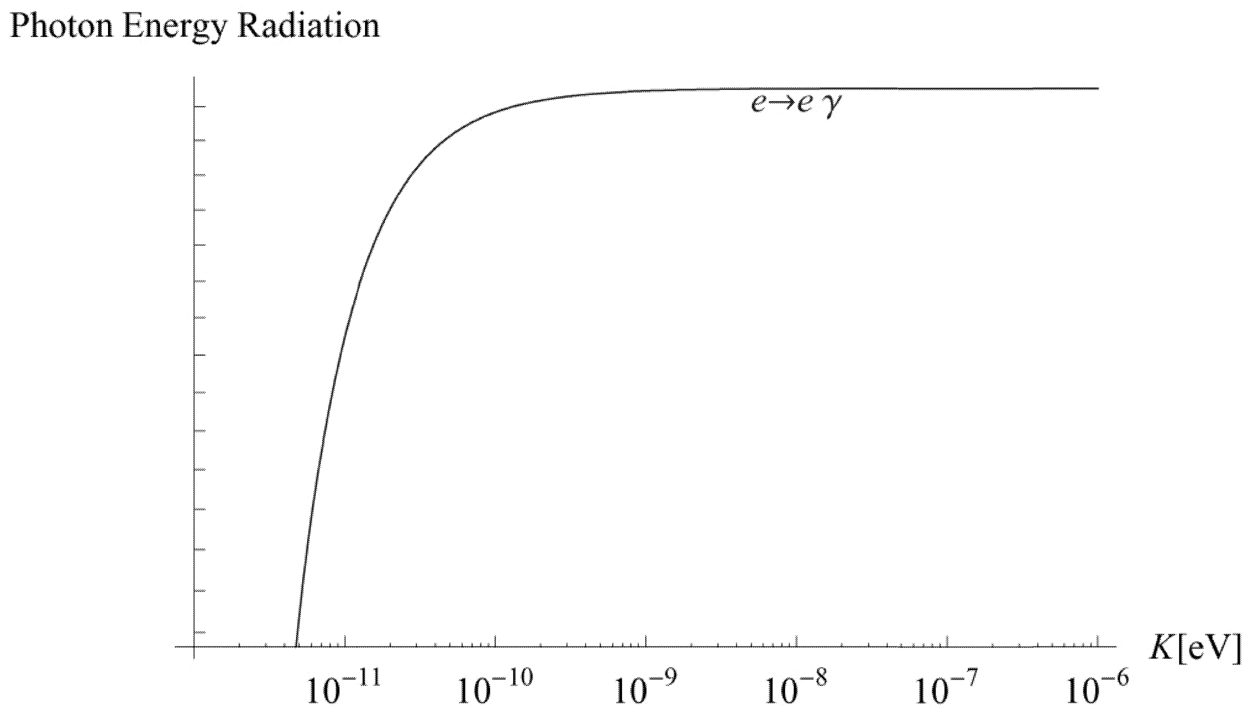


Figure 3: Energy radiated as a function of the wave vector. $L(E)$ constant assumed

Detecting the axion whistle

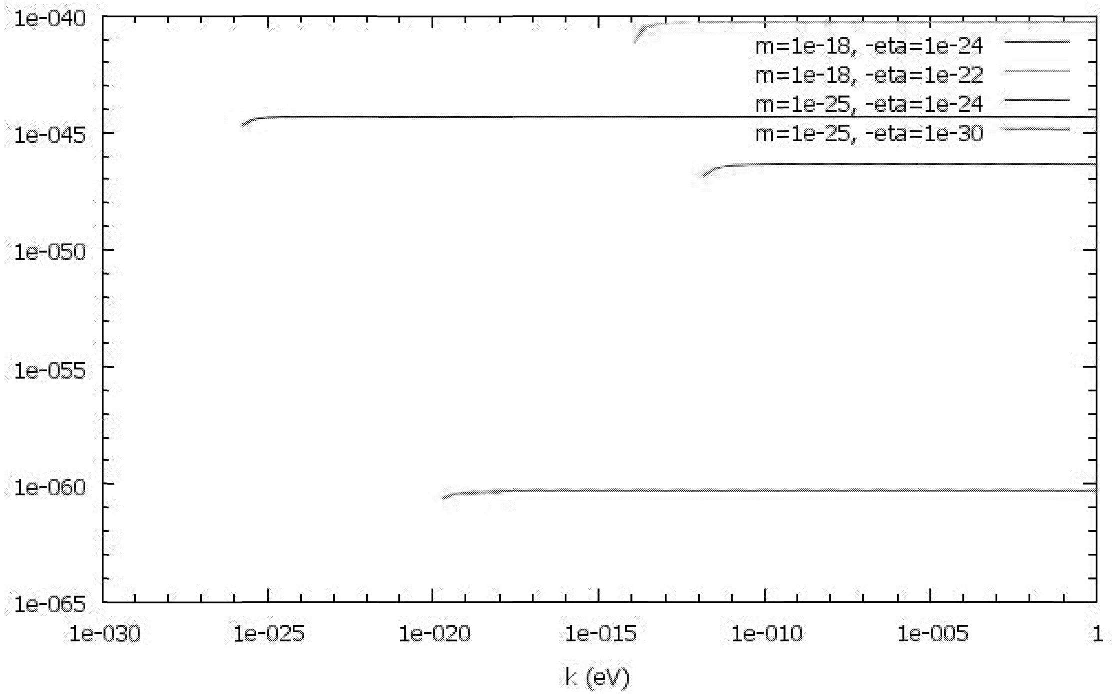
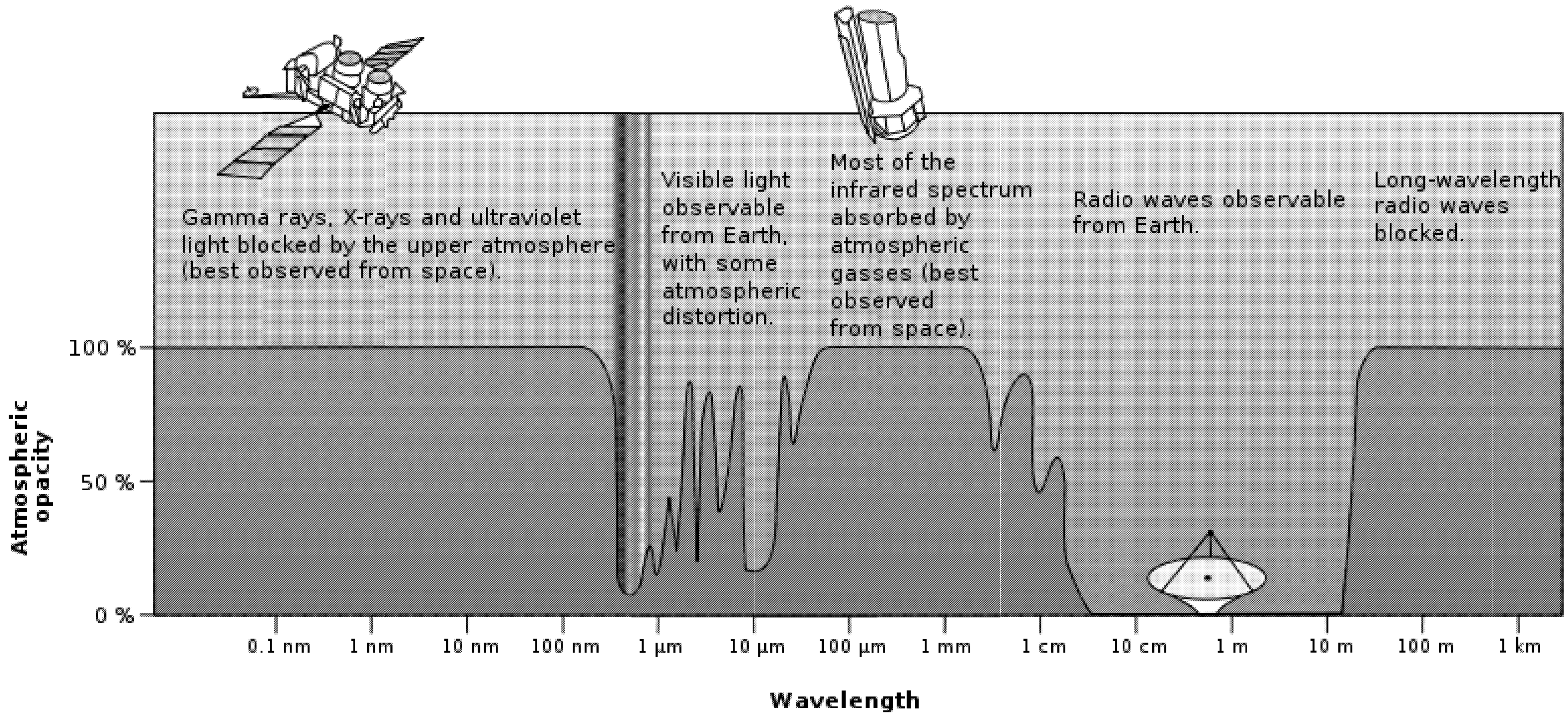


Figure 4: Dependence of the energy radiated on η

Atmosphere opacity

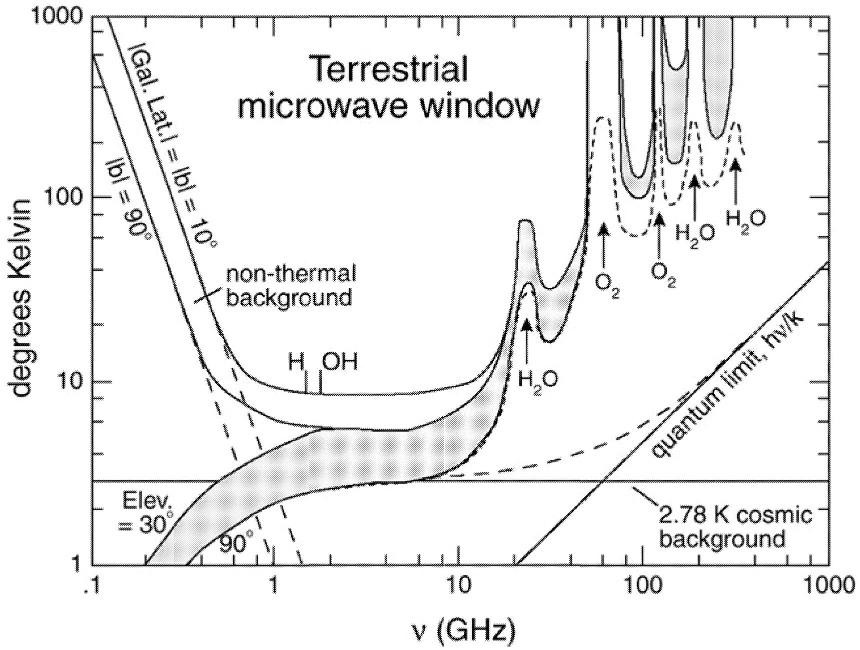


Galactic noise

The window $\lambda = 10$ cm (3 GHz) to $\lambda = 100$ m (30 MHz) corresponds to 10^{-5} eV to 10^{-8} eV.

This region is affected by galactic noise from synchrotron radiation.

A better control of $L(E)$ and the strong directionality of the emission should help in disentangling (or not) the signal from the background.



Summary

Propagation of photons, electrons, protons,... in a pseudoscalar background is well described by a LIV version of QED sometimes termed Chern-Simons QED.

Properties are rather unfamiliar (cf. talk by A. Andrianov on the PHENIX anomaly)

The dispersion relation is modified and this makes possible processes such as $\gamma \to e^+e^-$ or $p \to p\gamma$, not unlikely the Cerenkov effect.

A background of cold axions can be described in this way and it has striking consequences on cosmic ray propagation.

The lack of relativistic invariance makes some order-of-magnitude estimates non-trivial.

The background has no significant consequences on the reach of cosmic rays, but induces a continuous process of bremsstrahlung that might be detectable and could potentially lead to relevant bounds on the ratio $\sqrt{\rho_a}/f_a$.