Detection of a new light boson by Cherenkov telescopes?

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INTRODUCTION

So far, Imaging Atmospheric Cherenkov Telescopes (IACTs) have detected 24 very-high-energy (VHE) blazars over distances ranging from the pc scale for Galactic objects up to the Gpc scale for extragalactic ones.

By now, the fartest blazar observed by IACTs is 3C279 at z = 0.536 detected by MAGIC.

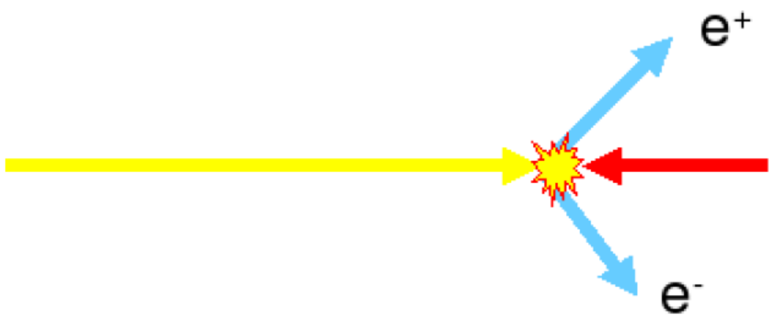
Given that these sources extend over a wide range of distances, not only can their INTRINSIC properties be inferred, but also photon PROPAGATION over cosmological distances can be probed.

This is particularly intriguing because VHE photons from distant sources (hard) scatter off background photons (soft) thereby disappearing into electron-positron pairs.

PHOTON PROPAGATION

Dominant process for the cosmological absorption of gamma-rays:
QED pair-creation processes

$$\gamma + \gamma_{\texttt{background}} \rightarrow e^+ + e^-$$



$$\sigma(E,\epsilon) \simeq 1.25 \cdot 10^{-25}(1-\beta^2)\left[2\beta(\beta^2-2)+(3-\beta^4)\ln\left(\frac{1+\beta}{1-\beta}\right)\right]\mathrm{cm}^2$$

Around the TeV region:

$$\underset{\epsilon}{\mathrm{argmax}}\,\sigma(E,\epsilon) \simeq 0.5\left(\frac{1\,\mathrm{TeV}}{E}\right)\mathrm{eV}$$

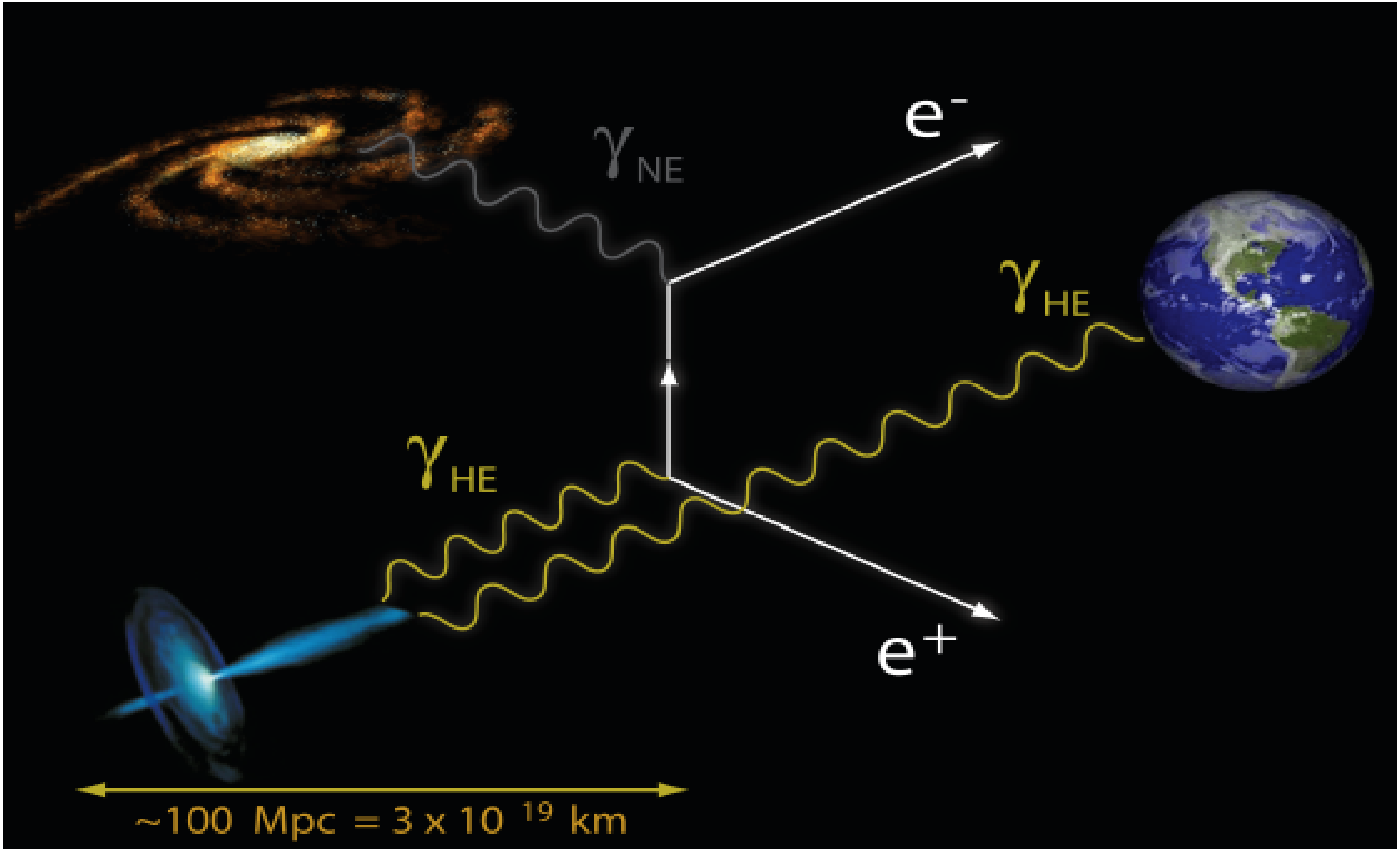
$$\beta = \sqrt{1-\frac{(m_e c^2)^2}{E\,\epsilon}}$$

E = energy of γ

ϵ = energy of γ_{EBL}

$$\Downarrow$$

cross section maximized for infrared and optical background photons
(Extragalactic Background Light - EBL)



e⁻
γ NE
γ HE
γ HE
e+
~100 Mpc = 3 x 10 19 km

It produces an energy-dependent OPACITY and so photon propagation is controlled by the OPTICAL DEPTH. Hence

$$\Phi_{\rm obs}(E,D) = e^{-\tau(E,D)}\,\Phi_{\rm em}(E)$$

As we have seen, for IACT observation the dominant contribution to opacity comes from the EBL.

Unlike CMB, EBL is produced by galaxies. Stellar evolution models + deep galaxy counts yield the spectral energy density of the EBL and ultimately

the optical depth of the photons observed by IACTs.
NEGLECTING evolutionary effects for simplicity

$$\tau_\gamma(D, E) = \frac{D}{\lambda_\gamma(E)}$$

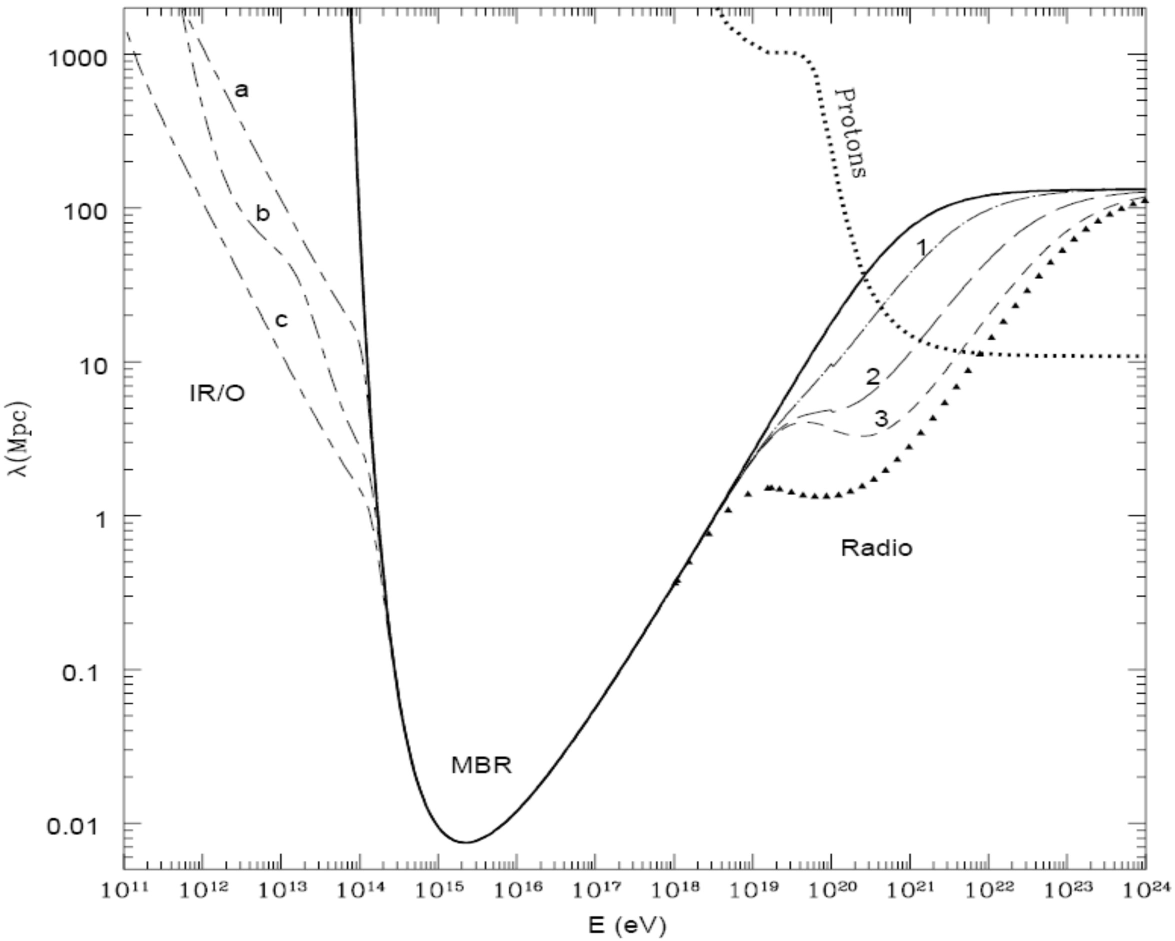
and h

$$\Phi_{\rm obs}(E, D) \simeq e^{-D/\lambda_\gamma(E)}\ \Phi_{\rm em}(E)$$

with t

$$\lambda_\gamma(E) = \frac{1}{n(E)\,\sigma(E, \gamma\gamma \to e^+e^-)}$$

whose energy behaviour is



From Coppi & Aharonian, APJ 487, L9 (1997)

EXPECTATIONS

Since mfp becomes SMALLER than the Hubble radius for E > 100 GeV, two crucial facts emerge.

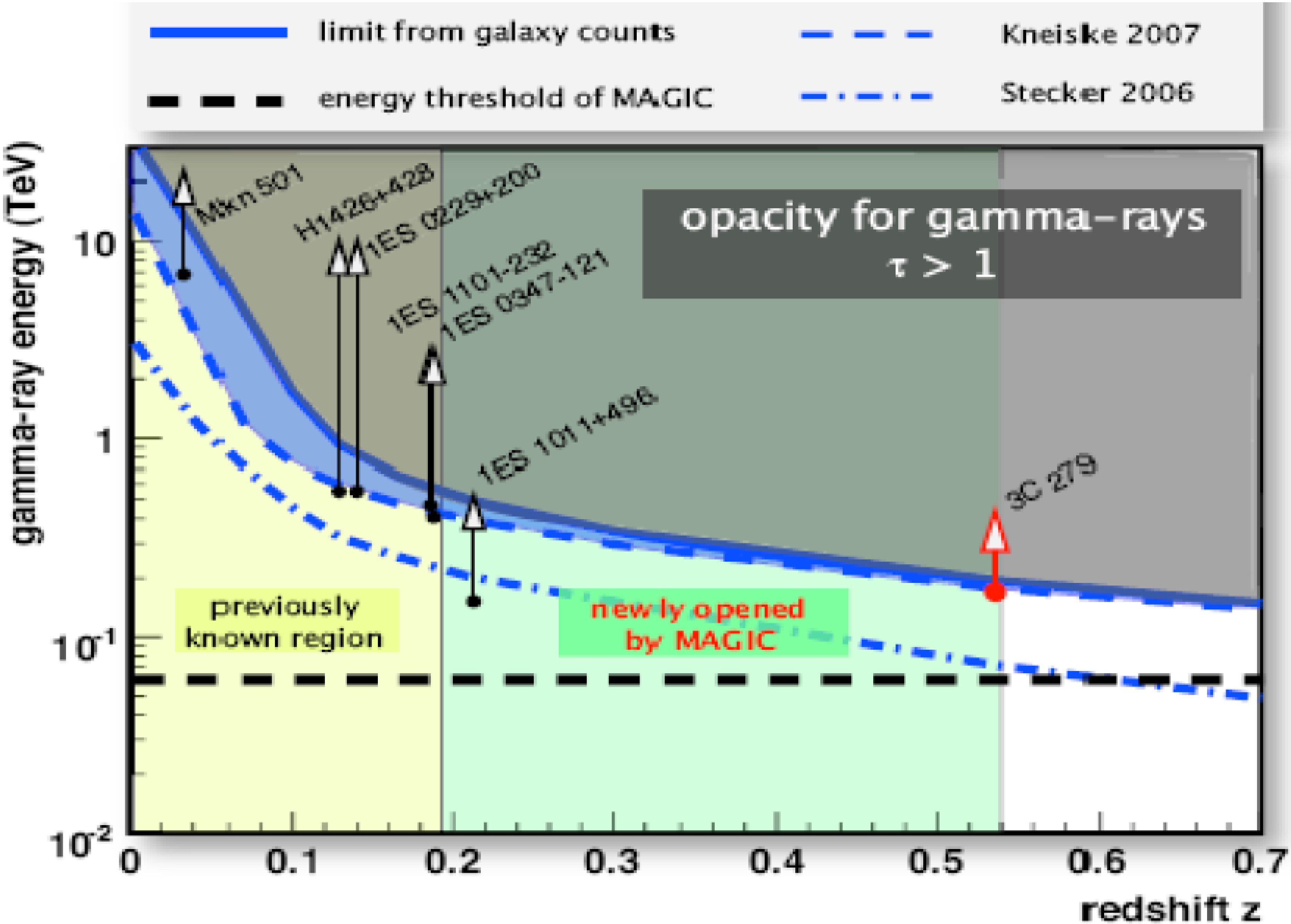
- Observed flux should be EXPONENTIALLY suppresed at LARGE distances, so that very far-away sources should become INVISIBLE.
- Observed flux should be EXPONENTIALLY suppressed at VHE, so that it should be MUCH STEEPER than the emitted one.

OBSERVATIONS

Yet, observations have NOT detected such a behaviour

- First indication in 2006 from H.E.S.S. at
  E = 1 – 2 TeV for 2 sources
  AGN H2356-309 at z = 0.165,
  AGN 1ES1101-232 at z = 0.186.

- Stronger evidence in 2007 from MAGIC at E = 400 – 600 for 1 source: AGN 3C279 at z = 0.536. In this case, the minimal expected attenuation is 0.50 at 100 GeV and 0.018 at 500 GeV. So, this source is VERY HARDLY VISIBLE at VHE. Yet, signal HAS been detected by MAGIC, with a spectrum QUITE SIMILAR to that of nearby AGN.



limit from galaxy counts
Kneiske 2007
energy threshold of MAGIC
Stecker 2006
opacity for gamma-rays
τ > 1
Mkn 501
H1426+428
1ES 0229+200
1ES 1101-232
1ES 0347-121
1ES 1011+496
3C 279
previously
known region
newly opened
by MAGIC
gamma-ray energy (TeV)
redshift z

WHAT IS GOING ON?

Taking observations at face value, two options are possible.

- Assuming STANDARD photon propagation, observed spectra are reproduced only by emission spectra MUCH HARDER than for any other AGN. It is difficult to get these spectra within standard AGN emission models. They can be explained by models with either strong relativistic shocks (Stecker et al.) or internal photon absorption (Aharonian et al.).

Still, these attempts fail to explain why ONLY for the most distant blazars do such new effects play a crucial role.

- Photon propagation over cosmic distances is NON STANDARD. Specifically, photons should have a LARGER mfp than usually thought. We stress that even a SMALL increase in the mfp yields a BIG enhancement of the observed flux owing to its exponential dependence on the mfp.

Thus, it looks sensible to investigate which kind of NEW PHYSICS yields a substantially larger effective mfp for VHE photons.

DARMA SCENARIO

Our proposal rests upon the second option.

We suppose that the basic principles are still valid, so that e.g. Lorentz invariance is not violated.

Yey, we imagine that a remnant particle X of some MORE FUNDAMENTAL theory shows up at LOW ENERGY and couples to photons.
Specifically, a photon can OSCILLATE into a very

light remnant X and become a photon again before detection i.e. in INTERGALACTIC SPACE we have

$$\gamma \to X \to \gamma$$

Then the X particles travel UNIMPEDED over cosmic distances. So the observed photons from an AGN seem to have a LARGER mfp simply because they do NOT behave as photons for most of the time!

Quite remarkably, there is a REALISTIC theoretical framework in which this mechanism is implemented NATURALLY!

AXION-LIKE PARTICLES

Nowadays the Standard Model (SM) is viewed as an EFFECTIVE LOW-ENERGY THEORY of some more FUNDAMENTAL THEORY – like superstring theory – characterized by a very large energy scale M >> 100 GeV and containing both light and heavy particles. Its partition function is

$$Z[J,K] = N \int \mathcal{D}\phi \int \mathcal{D}\Phi \, \exp\left(i \int d^4x \, \left[\mathcal{L}(\phi, \Phi) + J\phi + K\Phi \right] \right)$$

The associated low-energy theory then emerges by integrating out the heavy particles, that is

$$\exp\left(i\int d^4x\,\mathcal{L}_{\rm eff}(\phi)\right) = \int \mathcal{D}\Phi\,\exp\left(i\int d^4x\,\mathcal{L}(\phi,\Phi)\right)$$

This procedure produces non-renormalizable terms in the effective lagrangian that are suppressed by inverse powers of M. So the SM is embedded in the low-energy theory defined by

$$Z_{\rm eff}[J] = N\int \mathcal{D}\phi\,\exp\left(i\int d^4x\,\mathcal{L}_{\rm eff}(\phi) + J\phi\right)$$

Slightly broken global symmetries in the fundamental theory give rise to very light pseudoscalar particles X which are present in low-energy theory. Explicitly

$$\mathcal{L}_{\rm eff}(\phi) = \mathcal{L}_{\rm SM}(\phi_0) + \mathcal{L}_{\rm ren}(\phi') + \mathcal{L}_{\rm nonren}(\phi_0, \phi')$$

Axion-like particles (ALPs) are just a concrete realization of such a scenario and are described by the effective lagrangian

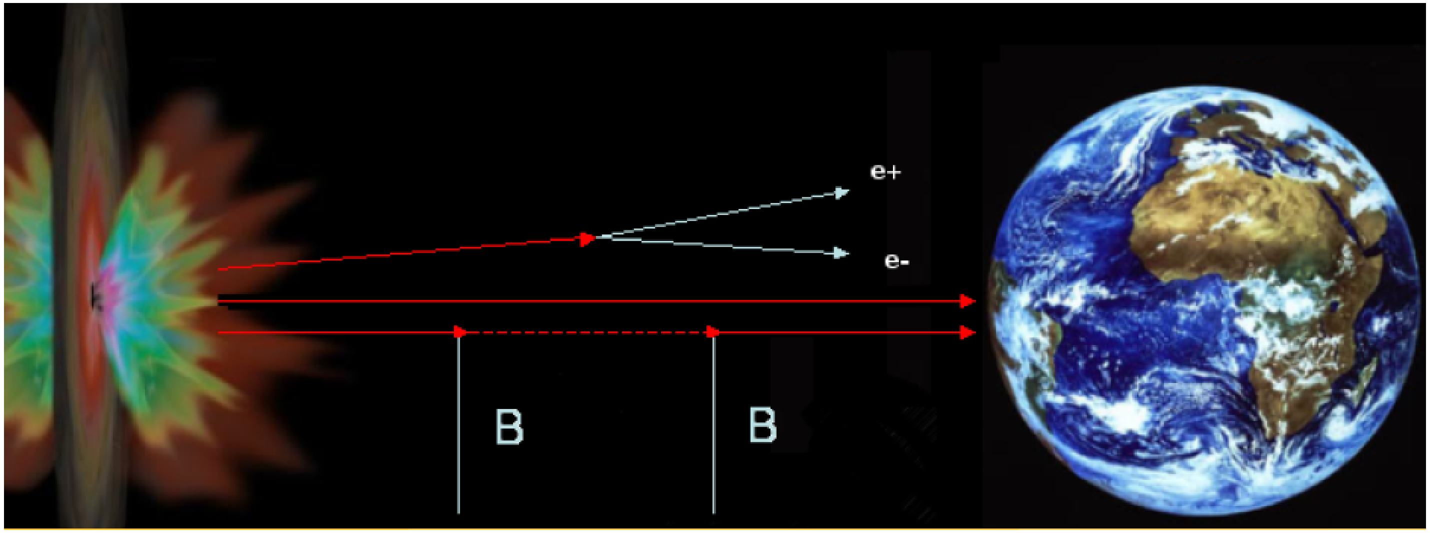
$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\,\partial^\mu a\,\partial_\mu a - \frac{1}{2}\,m^2\,a^2 - \frac{1}{4M}\,F^{\mu\nu}\,\tilde{F}_{\mu\nu}\,a$$

ALP are common to many extensions of the SM and are also a good candidate for DARK MATTER and quintessential DARK ENERGY (if they are very light).

Photon-ALP OSCILLATIONS are quite similar to neutrino oscillations but external B is NECESSARY.
Bounds on the INDEPENDENT parameters M and m:

- CAST experiment at CERN entails $M > 1.14 \cdot 10^{10}$ GeV for $m < 0.02$ eV,
- arguments on star cooling yield SAME RESULT,
- energetics of 1987a supernova yields $M > 10^{11}$ GeV for $m < 10^{-10}$ GeV even if with uncertainties.

Our proposal amounts to suppose that photon-ALP oscillations $\gamma \to X \to \gamma$ take place in intergalactic magnetic fields, i. e. schematically



e+
e-
B
B

INTERGALACTIC MAGNETIC FIELDS

They DO exist but their morphology is poorly known.

We suppose they have a domain-like structure with

- strength 0.5 nG,
- coherence length 7 Mpc,
- RANDOM orientation in each domain.

N.B. Picture consistent with recent AUGER data: strength 0.3 – 0.9 nG for coherence length 1 – 10 Mpc (DPR, Mod. Phys. Lett A23, 315, 2008).

Plasma frequency $\omega_{\rm pl,0} \simeq 1.17 \cdot 10^{-14}\,{\rm eV}.$

PROPAGATION OVER ONE DOMAIN

We work in the short-wavelength approximation, so the beam with energy E is formally a 3-level non relativistic quantum system described by the wave equation

$$\left(i\frac{\partial}{\partial y} + \mathcal{M} \right) \psi(y) = 0$$

with

$$\psi(y) \equiv \left(\begin{array}{c} A_x(y) \\ A_z(y) \\ a(y) \end{array} \right)$$

and mixing matrix

$$\mathcal{M} = \begin{pmatrix} \Delta_{xx} & \Delta_{xz} & B_x/2M \\ \Delta_{zx} & \Delta_{zz} & B_z/2M \\ B_x/2M & B_z/2M & -m^2/2E \end{pmatrix}$$

which in the presence of absorption becomes

$$\mathcal{M} = \begin{pmatrix} \Delta_{xx}^{\mathrm{QED}} + \Delta_{\mathrm{PL}} + \Delta_{\mathrm{abs}} & 0 & 0 \\ 0 & \Delta_{zz}^{\mathrm{QED}} + \Delta_{\mathrm{PL}} + \Delta_{\mathrm{abs}} & B_T/2M \\ 0 & B_T/2M & -m^2/2E \end{pmatrix}$$

with

$$\Delta_{\mathrm{abs}} = \frac{i}{2\lambda_\gamma(E)}$$

Hence the conversion probability reads

$$P^{(0)}_{\rho_1\to\rho_2}(y) = \frac{\mathrm{Tr}\left(\rho_2\,\mathcal{U}(y,0)\,\rho_1\,\mathcal{U}^\dagger(y,0)\right)}{\mathrm{Tr}\left(\rho_1\,\mathcal{U}^\dagger(y,0)\,\mathcal{U}(y,0)\right)}$$

in terms of the propagation matrix $\mathcal{U}(y,y_0)$. We find that a nonvanishing conversion probability over the WHOLE range $10^2\,\mathrm{GeV} < E < 10^5\,\mathrm{GeV}$ requires

$$m_* < 0.2\cdot 10^{-9}\left(\frac{B_T}{0.5\,\mathrm{nG}}\right)^{1/2}\ \mathrm{eV}$$

with

$$m_* \equiv 10^{-6}\left|\left(\frac{m}{10^{-6}\,\mathrm{eV}}\right)^2 - 1.37\cdot 10^{-16}\left(\frac{\omega_{\rm pl}}{1.17\cdot 10^{-14}\,\mathrm{eV}}\right)^2\right|^{1/2}\ \mathrm{eV}$$

In the present situation, we have

$$\left| \Delta_{zz} + \frac{m^2}{2E} \right| \ll \frac{B_T}{M}$$

$$\left| \Delta_{xx} + \frac{m^2}{2E} \right| \ll \frac{B_T}{M}$$

and so the mixing matrix reduces to

$$\mathcal{M} = \begin{pmatrix} \frac{i}{2\lambda_\gamma(E)} & 0 & 0 \\ 0 & \frac{i}{2\lambda_\gamma(E)} & \frac{B_T}{2M} \\ 0 & \frac{B_T}{2M} & 0 \end{pmatrix}$$

Following Csaki et al. ICAP 05 (2003) 005, we get the explicit form of the propagation matrix $\mathcal{U}(y, y_0)$.

PROPAGATION OVER MANY DOMAINS

When all domains are considered at once, one has to allow for the randomness of the direction of **B** in the n-th domain. Let be θ_n the direction of **B** in the n-th domain with respect to a FIXED fiducial direction for all domains and denote by $\mathcal{U}_n\left(E, \theta_n\right)$ the evolution matrix in the n-th domain.

Then the overall beam propagation is described by

$$\mathcal{U}\left(E, D; \theta_0, ...\theta_{N_d - 1}\right) = \prod_{n=0}^{N_d - 1} \mathcal{U}_n\left(E, \theta_n\right)$$

We evaluate $\mathcal{U}\left(E, D; \theta_0, ...\theta_{N_d-1}\right)$ by numerically computing $\mathcal{U}_n\left(E, \theta_n\right)$ and iterating the result N_d times by randomly choosing θ_n each time.

We repeat this procedure 5.000 times and next average all these realizations of the propagation process over all random angles. So, the PHYSICAL propagation matrix of the beam is

$$\mathcal{U}(E, D) = \left\langle \mathcal{U}\left(E, D; \theta_0, ...\theta_{N_d-1}\right) \right\rangle_{\theta_0, \ldots \theta_{N_d-1}}$$

Assuming that the initial state of the beam is unpolarized and fully made of photons, the initial beam state is

$$\rho_1 = \frac{1}{2}\left(\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{array}\right)$$

So, we finally get

$$P_{\gamma\to\gamma}(E,,D) = \frac{\langle\gamma_x|\mathcal{U}(E,D)\,\rho_1\,\mathcal{U}^\dagger(E,D)|\gamma_x\rangle}{\mathrm{Tr}\left(\rho_1\mathcal{U}^\dagger(E,D)\mathcal{U}(E,D)\right)} + \frac{\langle\gamma_z|\mathcal{U}(E,D)\,\rho_1\,\mathcal{U}^\dagger(E,D)|\gamma_z\rangle}{\mathrm{Tr}\left(\rho_1\mathcal{U}^\dagger(E,D)\mathcal{U}(E,D)\right)}$$

WHICH EBL ?

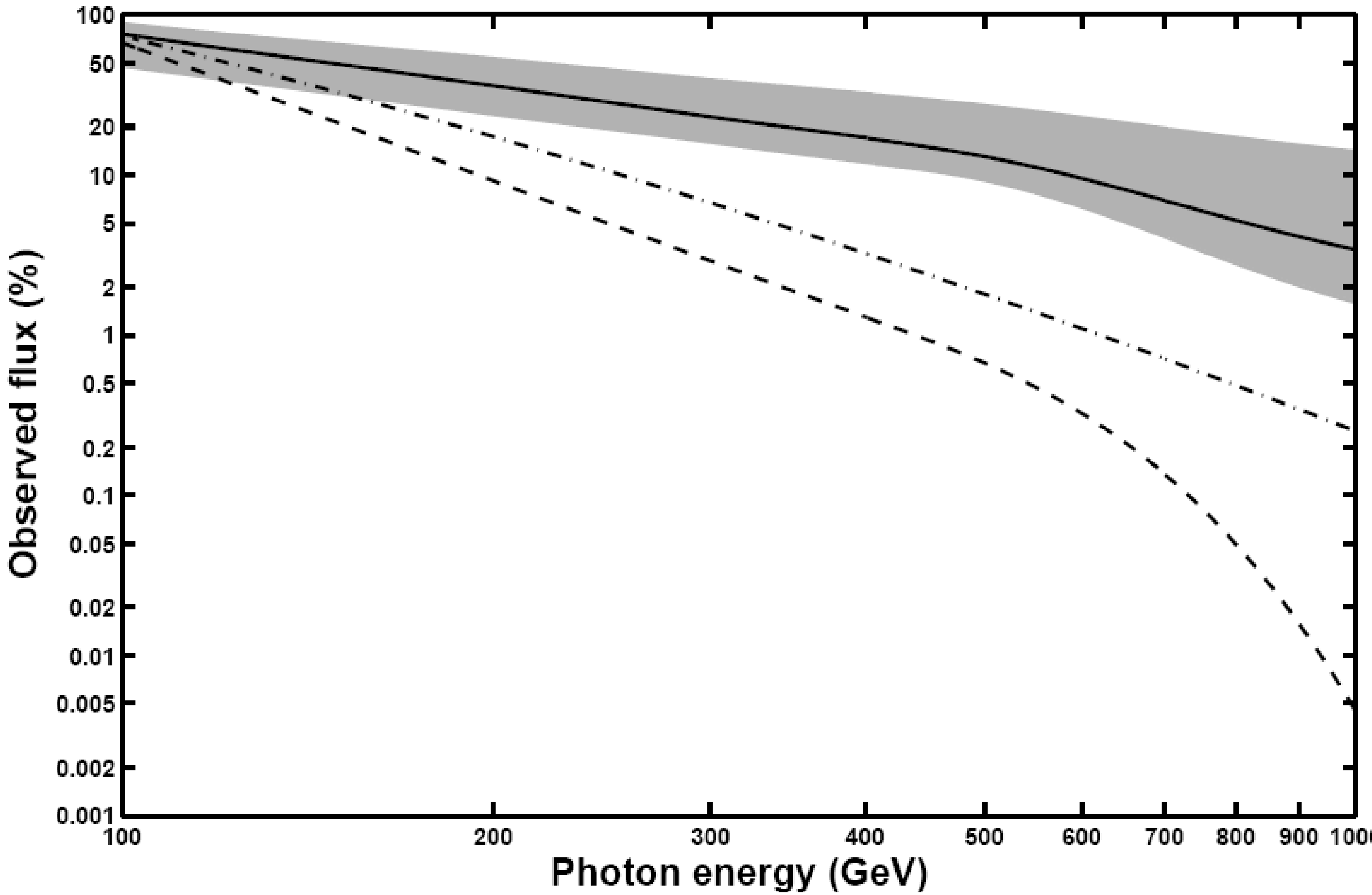
In our first analysis of 3C279 we used the EBL model of Keiske et al. 2004. We exhibit our results for M = $4 \cdot 10^{11}$ GeV for definiteness in the next figure.

We vary B in the range 0.1 – 1 nG and its coherence length in the range 5 – 10 Mpc continuously and independently.

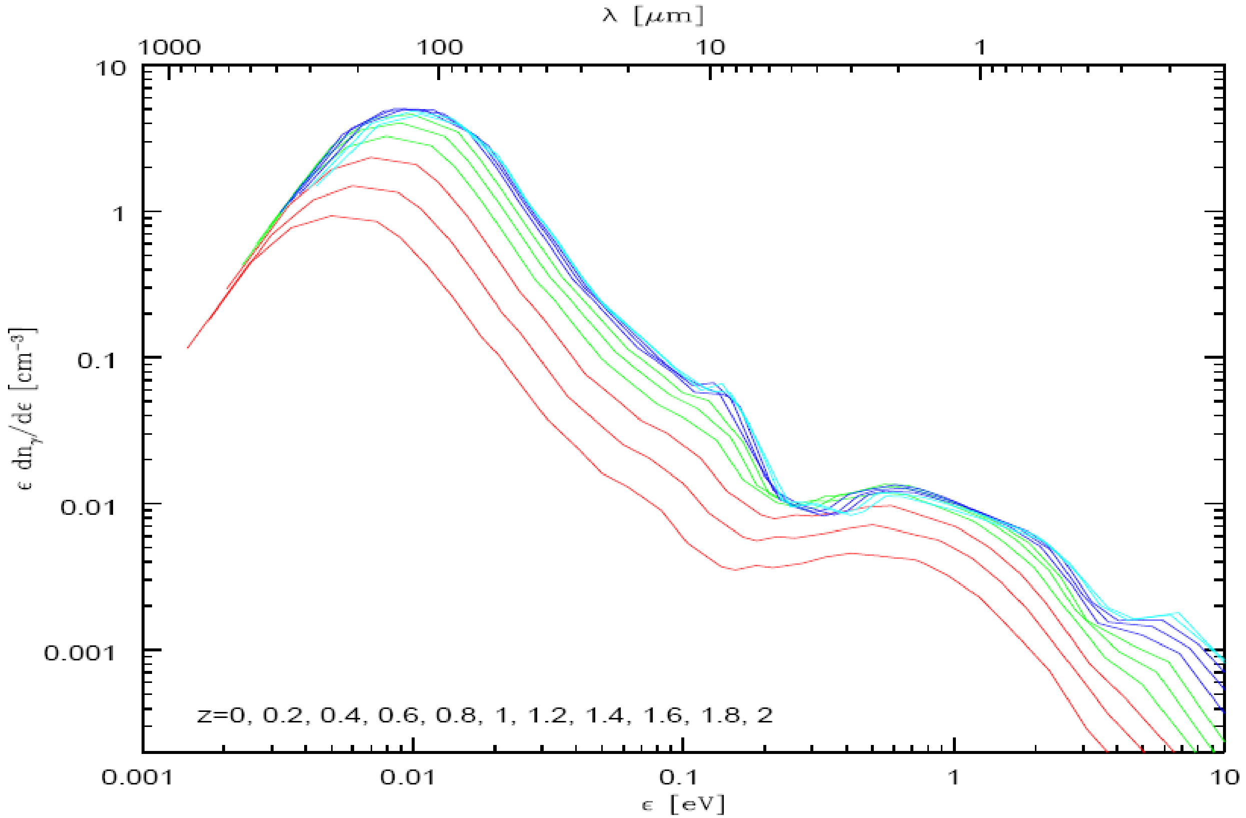
We have checked that practically the same result remains true for .

$$10^{11}\,\mathrm{GeV} < M < 10^{13}\,\mathrm{GeV}$$

3C279 – EBL of Kneiske et al.



The most updated EBL model of Franceschini et al. 2008 yields for the EBL spectral number density

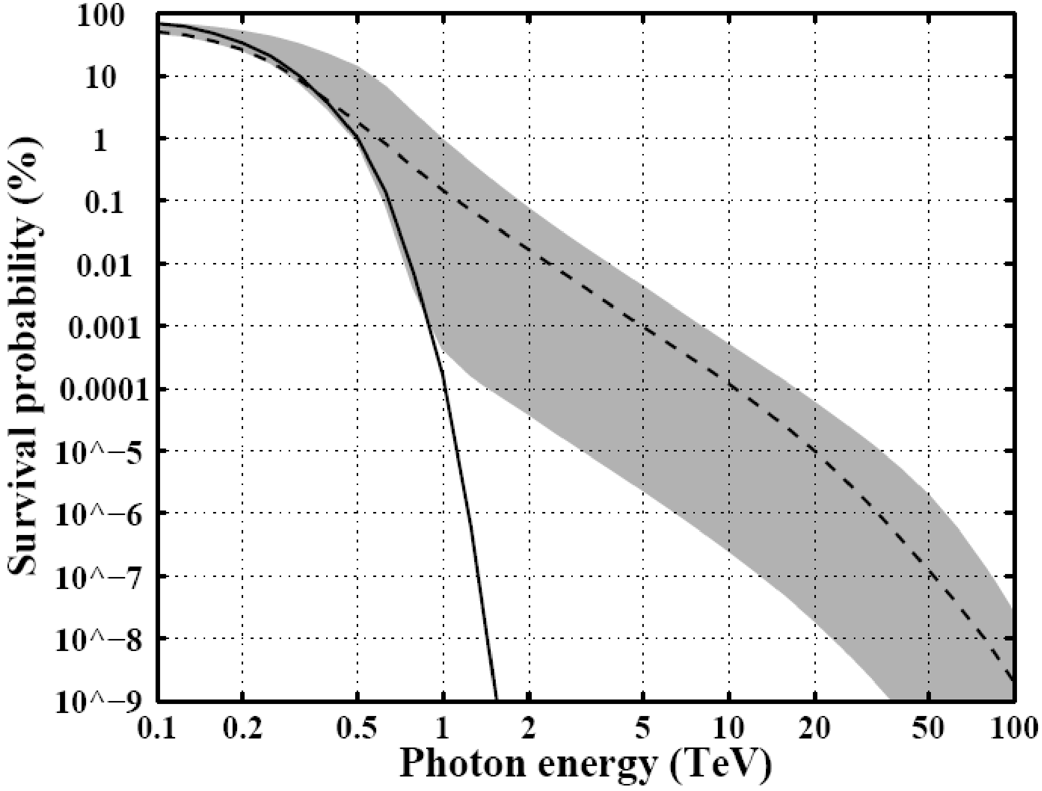


Within the range 200 GeV < E < 2 TeV it can be approximated by the power law of Stecker et al. 1992

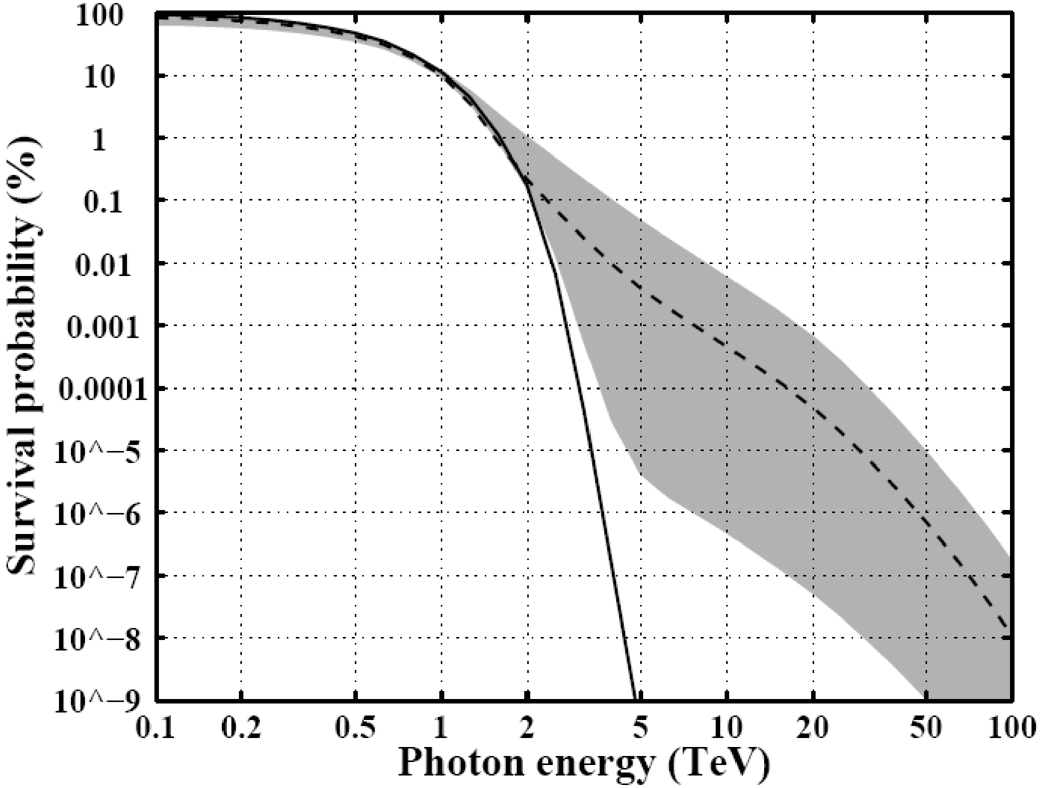
$$n_\gamma(\epsilon_0, 0) \simeq 10^{-3}\,\alpha\left(\frac{\epsilon_0}{\mathrm{eV}}\right)^{-2.55}\ \mathrm{cm}^{-3}\,\mathrm{eV}^{-1}$$

with the values $\alpha = 0.5$ and $\alpha = 3$ that bracket a linear stripe in the above plot. Actually, such an approximation makes sense up to E = 20 TeV. Accordingly, we get for α = 1.5, with the meaning of the shadowed region the same as before

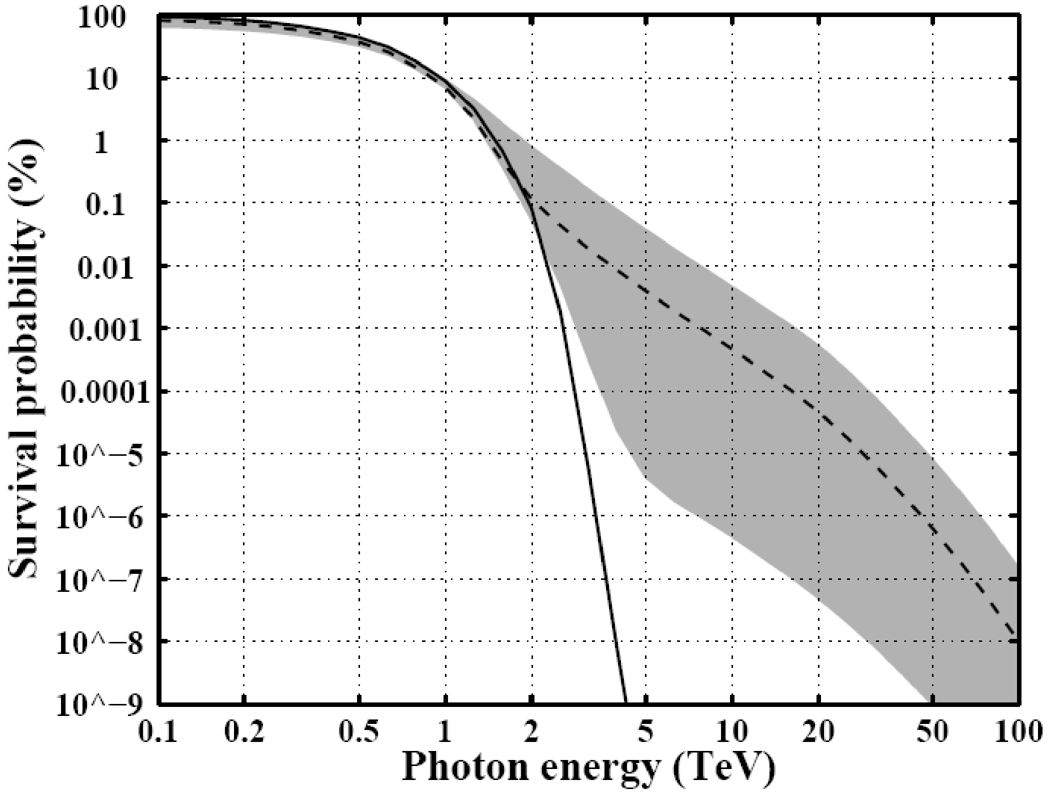
3C279 – EBL of “Franceschini et al”.



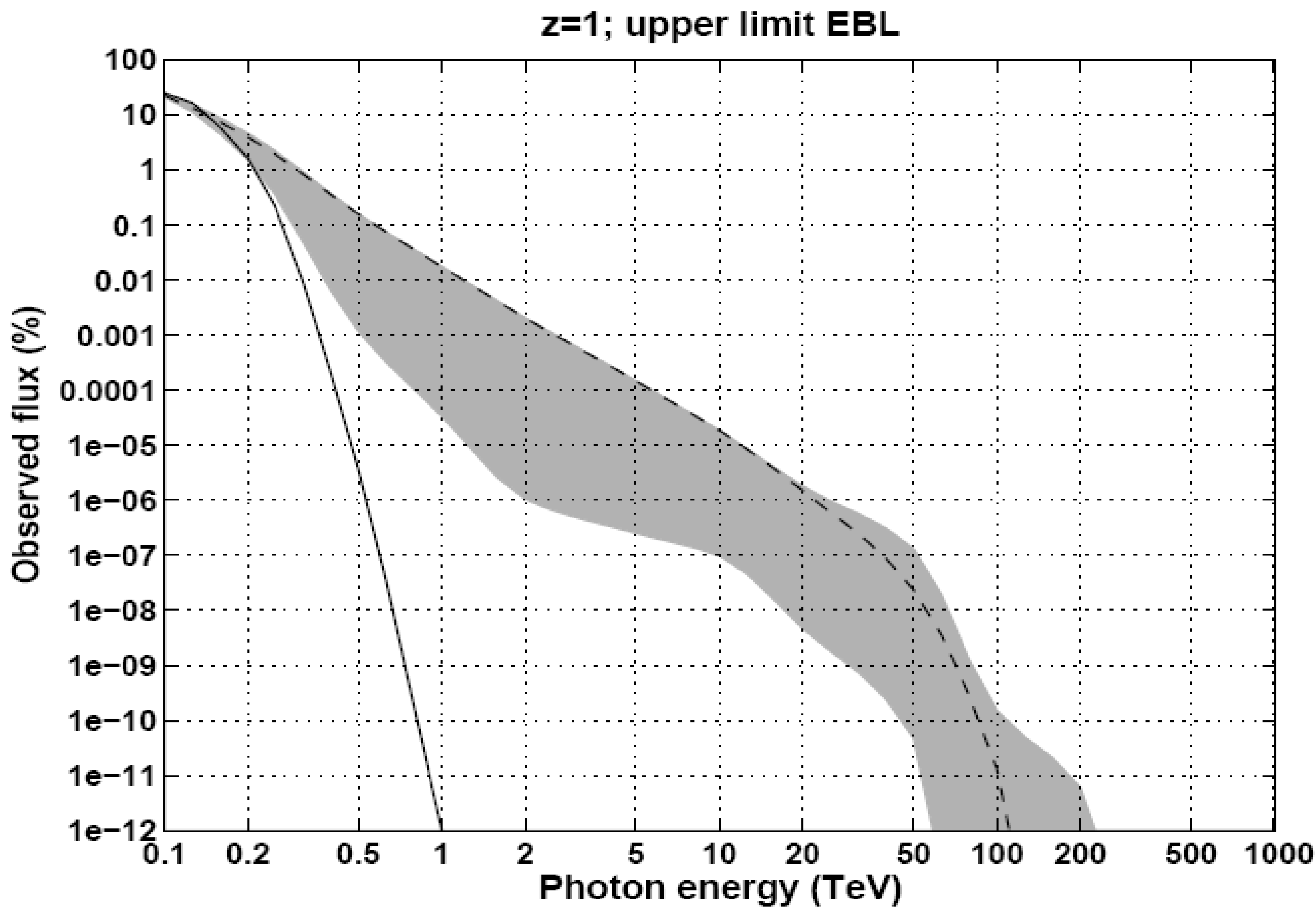
H2356-309 – EBL of “Franceschini et al”.



1ES1101-232 – EBL of “Franceschini et al”.



Ideal case z = 1 – EBL of “Franceschini et al”.



CONCLUSIONS

- The existence of a very light ALP – as predicted by many extensions of the Standard Model – naturally explains the observed transparency of the VHE gamma-ray sky.
- As a bonus, we also explain why ONLY the most distant AGN would demand an unconventional emission spectrum.
- Our prediction concerns the spectral change of observed AGN flux at VHE and becomes observable for ALL KNOWN AGN provided the band 1 – 10 TeV is carefully probed.
- It can be tested with IACTs, with FERMI, and with extensive air-shower detectors like ARGO-YBJ and MILAGRO.