Detecting new very light bosons by Cherenkov telescopes

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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

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

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

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

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).

The most famous example of ALP is the Axion, i.e. the pseudo-Goldstone boson arising from the global U(1) Peccei-Quinn symmetry proposed as a natural solution of the strong CP problem. While for the Axion m and M are correlated, for ALPs they are UNRELATED.

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.

PHOTON-ALP OSCILLATIONS

We work in the short-wavelength approximation, so a beam of energy E travelling along the y-direction is formally described as 3-level non relativistic quantum system by the wave equation

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

with

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

with mixing matrix

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

For an homogeneous B the x-component can be chosen to vanish. Faraday rotation can be neglected but absorption should be taken into account. Then we get

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

with

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

Hence the conversion probability is

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

in terms of the propagation matrix $\mathcal{U}(y, y_0)$ which solves the wave equation.

In the present case the conversion probability can be computed exactly.

We stress that within the STRONG-MIXING regime the conversion probability is MAXIMAL and E-INDEPENDENT. It occurs for E >

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ASTROPHYSICAL IMPLICATIONS

We contemplate the situation in which a distant blazar emits gamma-ray photons with E > 100 MeV. Two situations will be considered.

DIMMING SCENARIO: Owing to the presence of extragalactic B fields, some photons can oscillate into ALPs.

DARMA SCENARIO: ALPs can further back converted to photons, which are ultimately detected.

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.

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

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

DIMMING SCENARIO

The source emission spectrum dN/dE gets modified in such a way that at the observer position it becomes dN/dE times the survival photon probability. Hence It departs from the standard expectation by dN/dE times the conversion probability.

In the strong-mixing regime, the conversion probability is E-independent, so the effect is there but it is unobservable. In order for it to be DETECTABLE a SPECTRAL DISTORTION should be seen.

This requires m to be sufficiently large so that in the range 100 MeV -- 100 Gev the conversion probability behaves as

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which is a prediction for Fermi/LAT.

DARMA SCENARIO

Consider a distant blazar emitting photons with E > 100 GeV by a standard mechanism. Owing to the presence of extragalactic B fields, some photons can oscillate into ALPs. After having travelled some distance, some ALPs can further convert back into photons that are eventually detected. In order to have a sizeable effect, the strong-mixing regime should occur, which requires m to be very light.

EBL (extragalactic background light)

Is such an effect OBSERVABLE?

Before answering that question, an interlude is compelling.

A hard photon from a blazar can scatter off a soft background photon thereby producing an electron-positron pair and so disappearing from the beam. This process becomes efficient for E > 100 GeV and makes the horizon of the gamma-ray Universe shrink as E further increases. The cross section is

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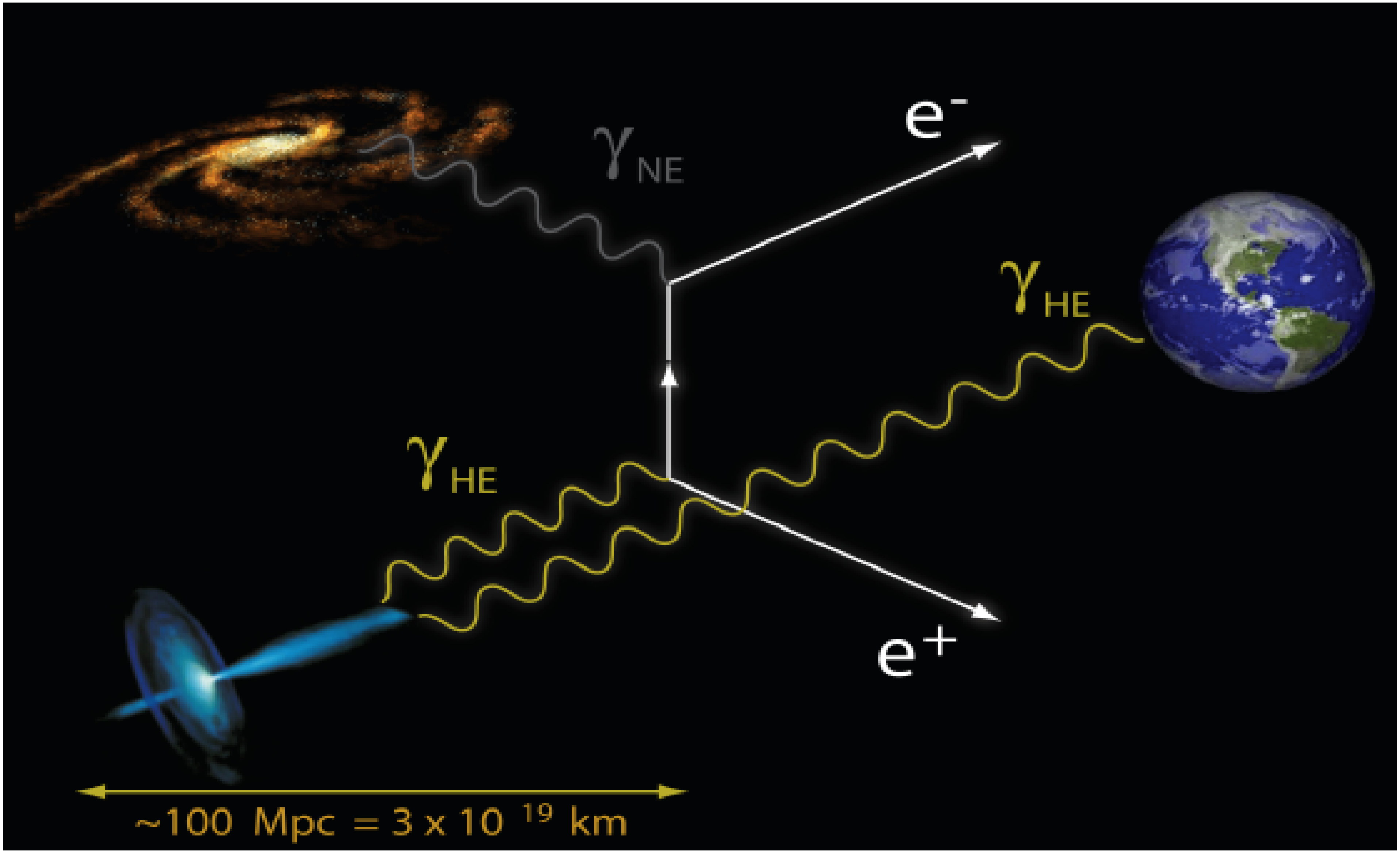


γ_{NE}
e^-
γ_{HE}
γ_{HE}
e^+
~100 Mpc = 3 x 10 19 km

so that for E > 100 GeV the EBL energy is in the visible/infrared.

Electron-positron pair production produces an energy-dependent OPACITY and so photon propagation is controlled by the OPTICAL DEPTH. Hence

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

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 photons observed by IACTs. NEGLECTING evolutionary effects for simplicity

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

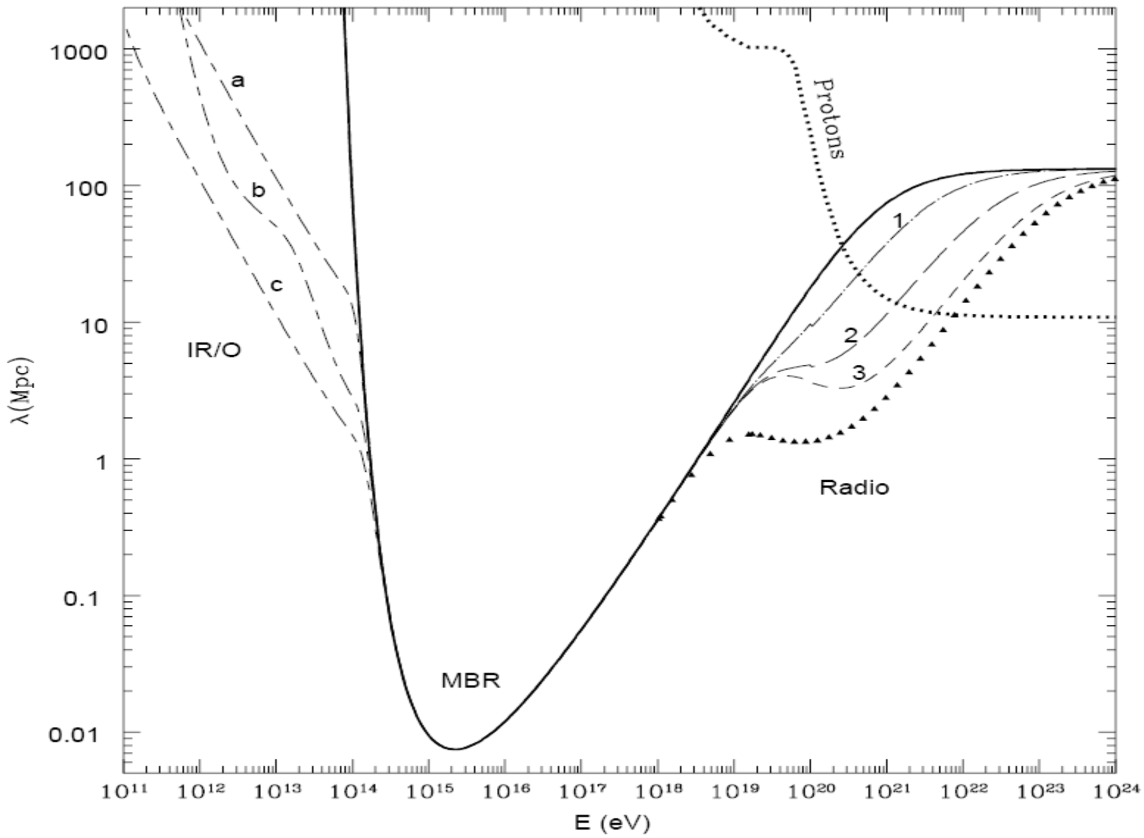
and hence

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

with the photon mean free path given by

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

whose energy behaviour is



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

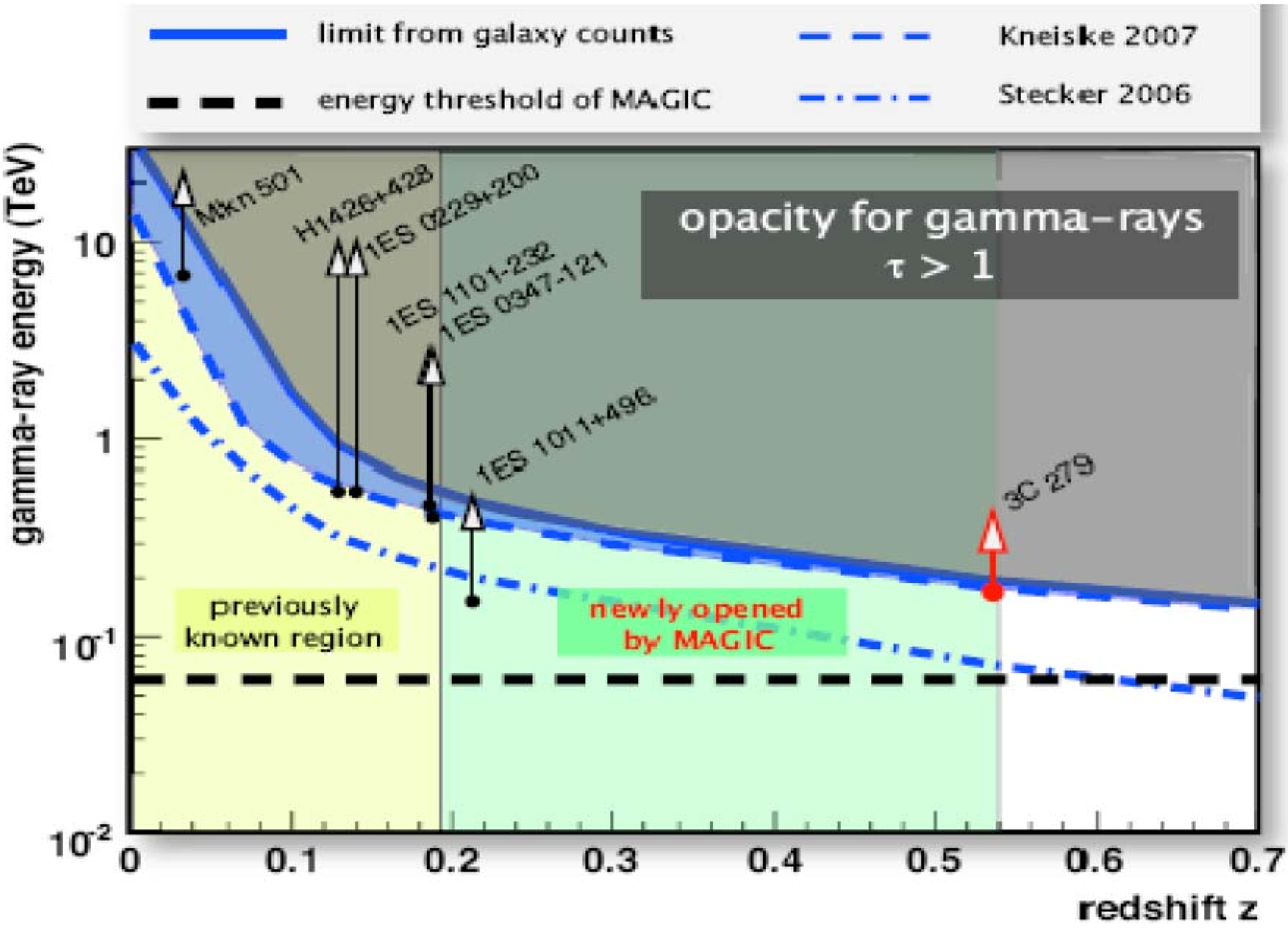
Since mfp becomes SMALLER than the Hubble radius for E > 100 GeV, two crucial facts emerge.

- 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.

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
$\tau > 1$
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)
10
1
10^{-1}
10^{-2}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
redshift z

Taking observations at face value, two options are possible.

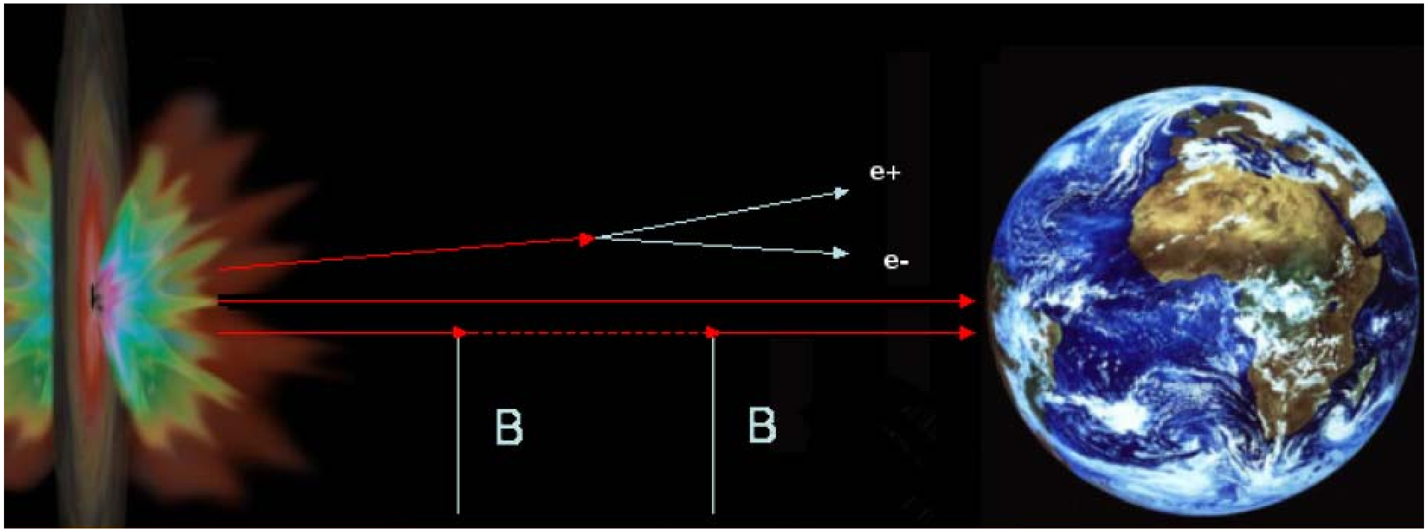
- Assuming STANDARD photon propagation, observed spectra are reproduced only by emission spectra MUCH HARDER than for any other AGN. It is difficult to get these spectra within standard AGN emission models.
  They can be explained by models with either strong relativistic shocks (Stecker et al.) or internal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

Does DARMA provide an explanation?

As we will see, the answer is YES!



In the present situation, strong-mixing demands

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

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

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 $\mathcal{U}(y, y_0)$.

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

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

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

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

Which EBL ?

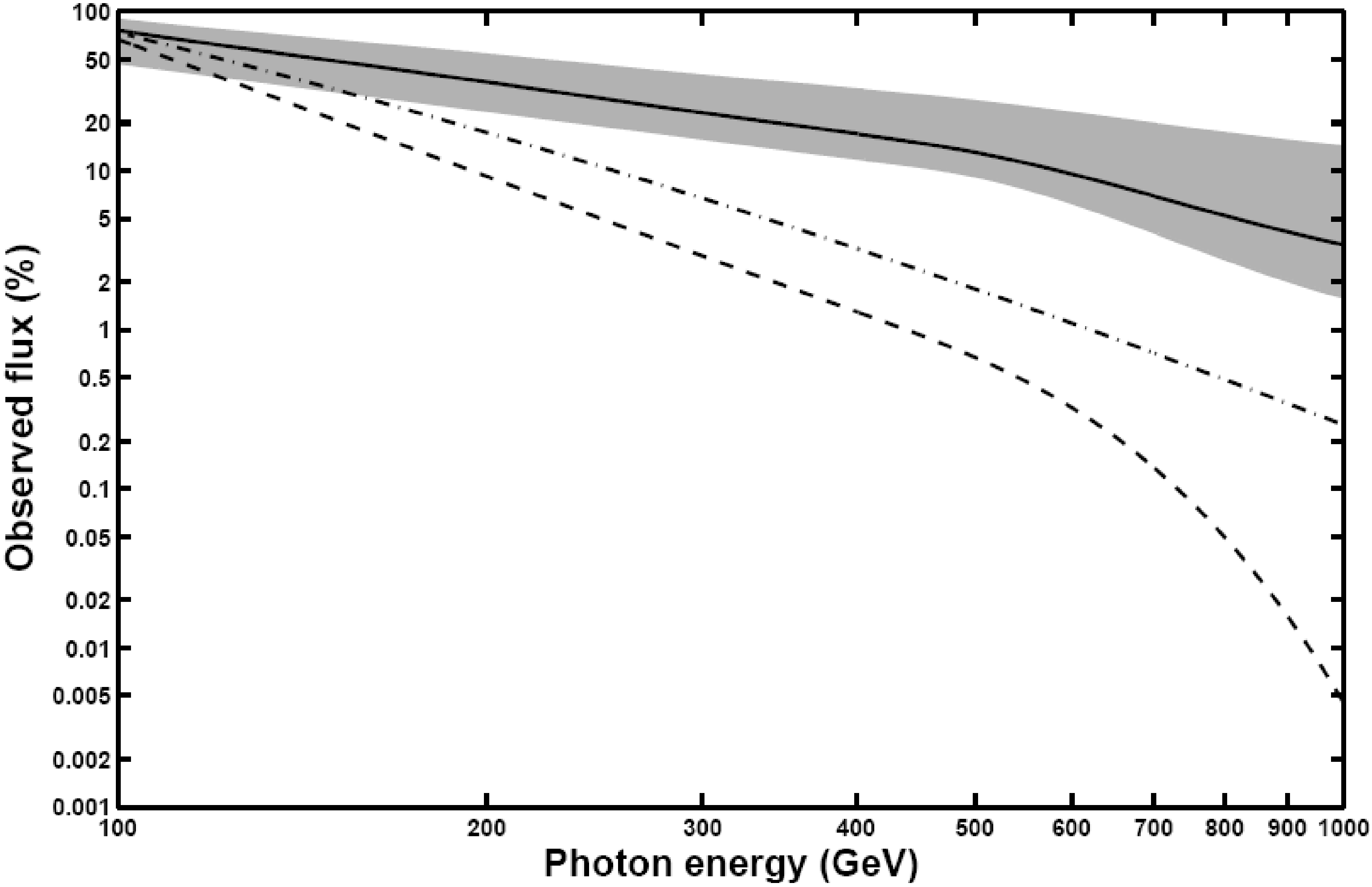
In our first analysis of 3C279 we used the EBL model of Keiske et al. 2004. We exhibit our results for M = 4 $\cdot 10^{11}$ GeV for definiteness in the next figure.

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

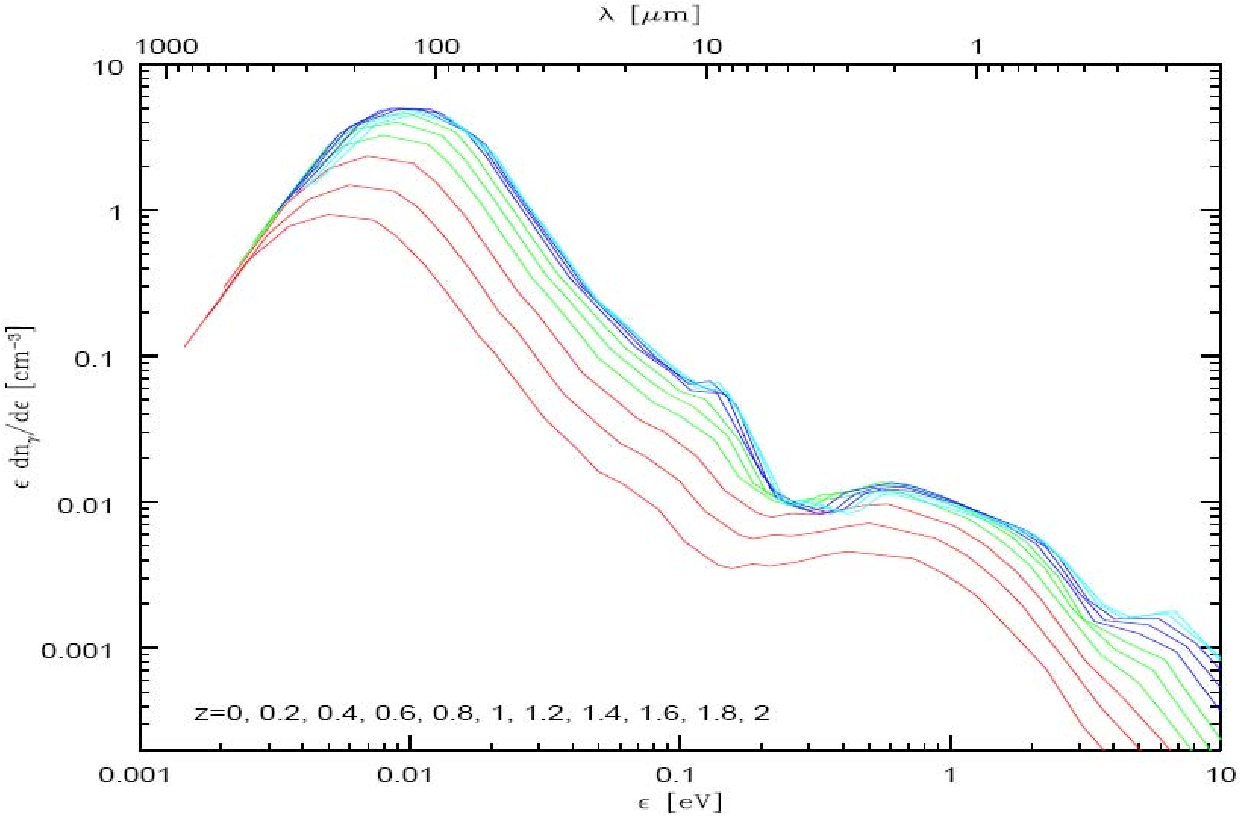
We have checked that practically the same result remains true for .

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

3C279 – EBL of Kneiske et al.



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

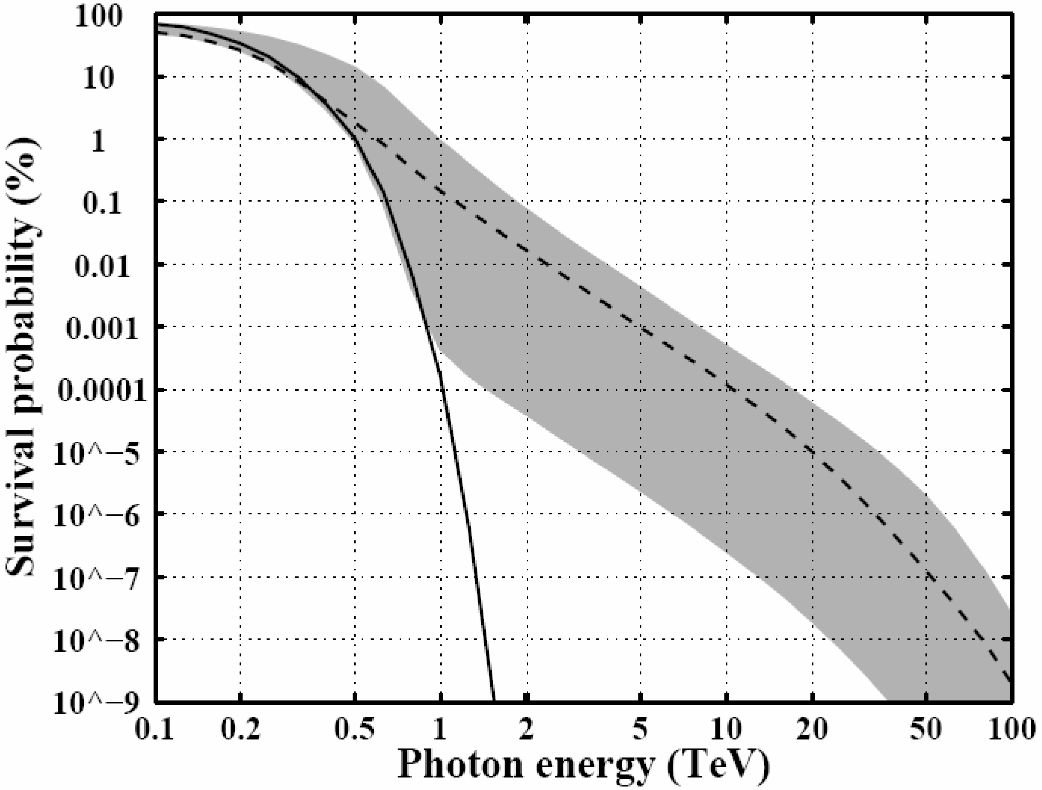


Within the range 200 GeV < E < 2 TeV it can be approximated by the power law of Stecker et al. 1992

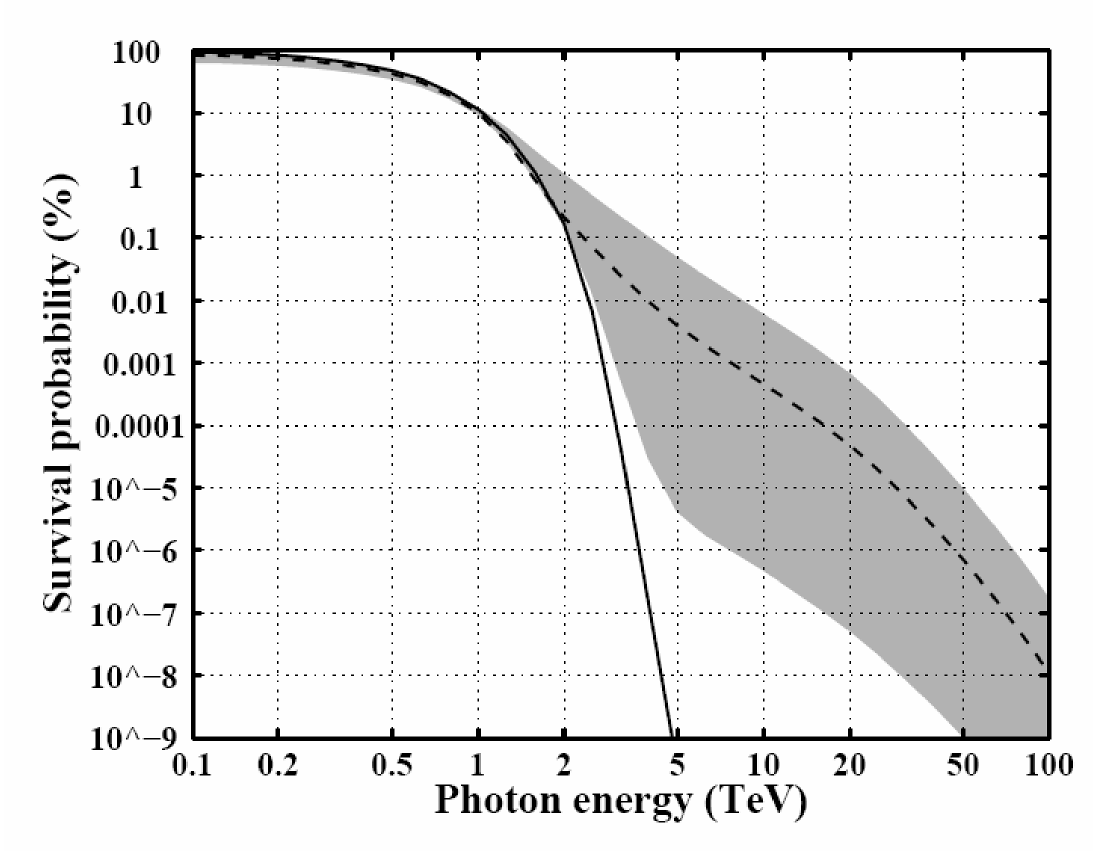
$$n_\gamma(\epsilon_0, 0) \simeq 10^{-3}\,\alpha \left(\frac{\epsilon_0}{\mathrm{eV}}\right)^{-2.55}\ \mathrm{cm}^{-3}\,\mathrm{eV}^{-1}$$

with the values $\alpha = 0.5$ and $\alpha = 3$ that bracket a linear stripe in the above plot. Actually, such an approximation agrees with the Stecker, Malkan, Scully “baseline model”. Accordingly, we get for α = 1.5, with the meaning of the shadowed region the same as before

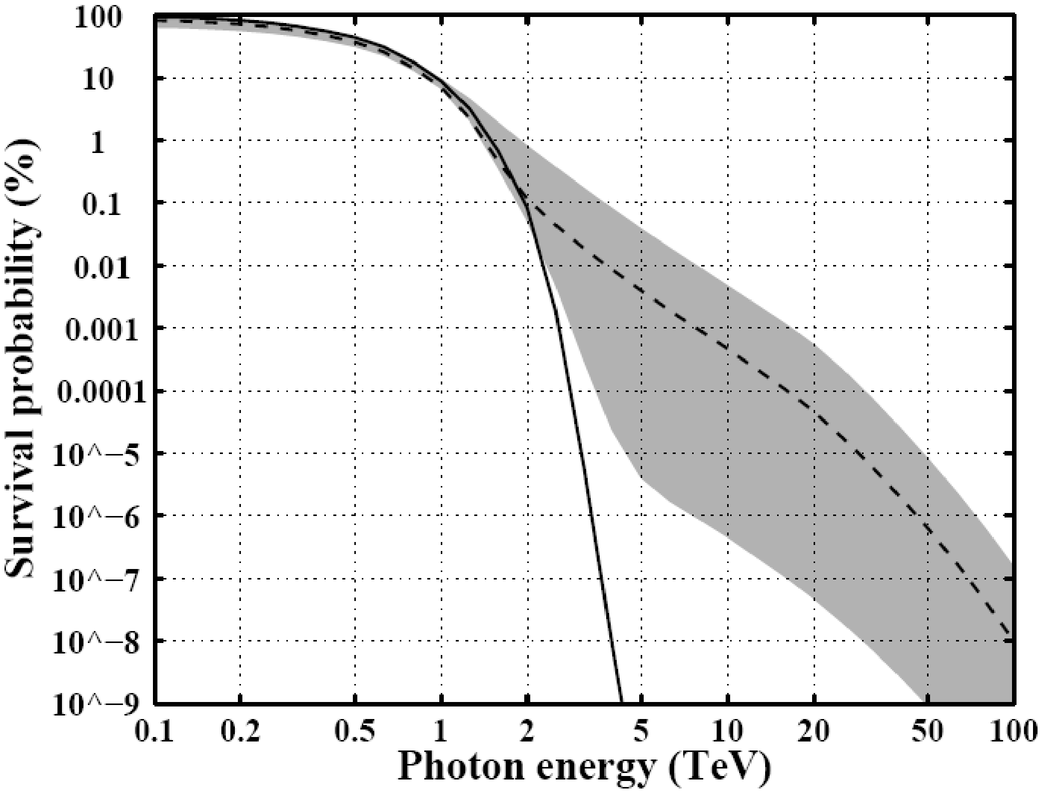
3C279 – EBL of Stecker, Malkan, Scully



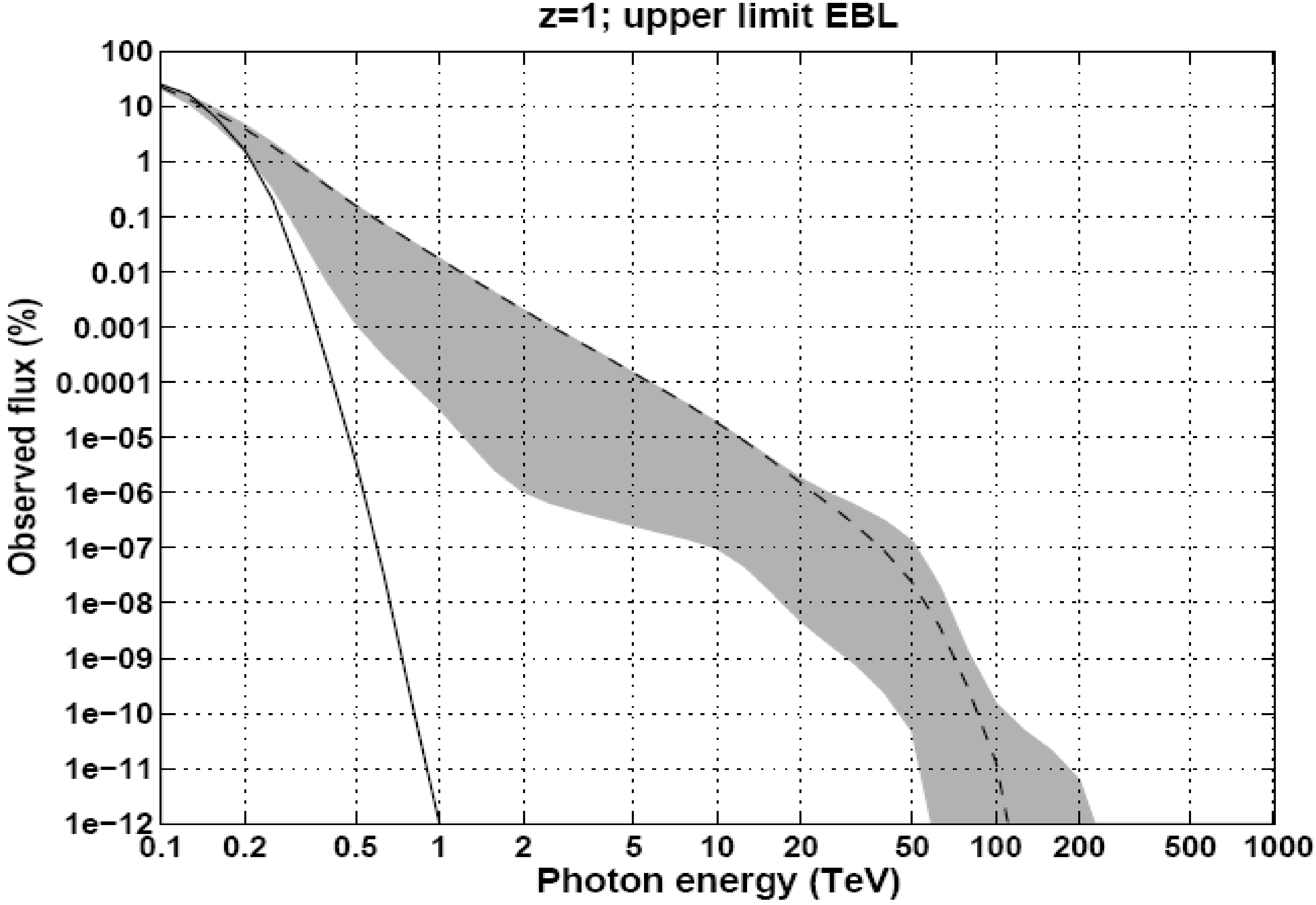
H2356-309 – EBL of Stecker, Malkan, Scully



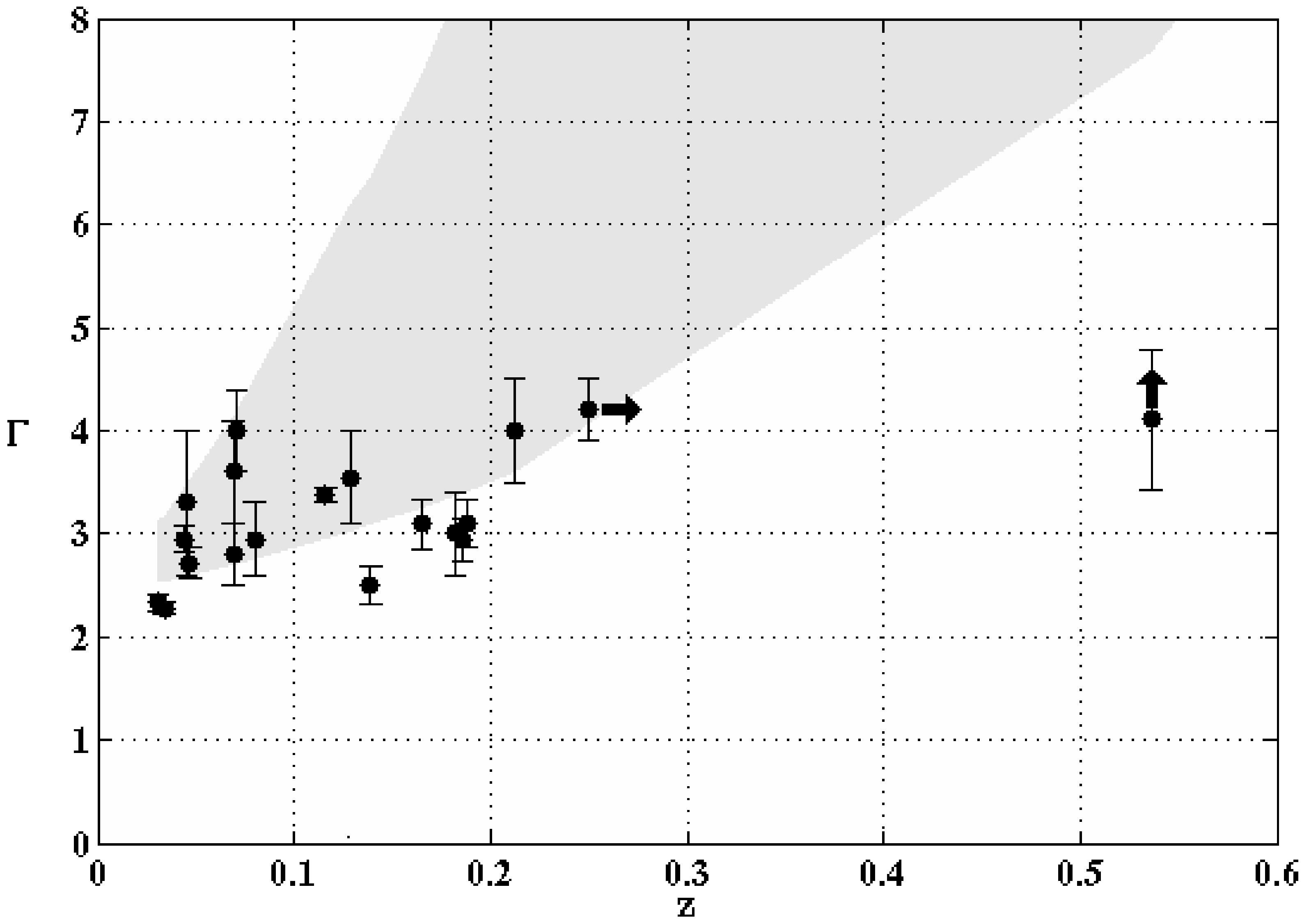
1ES1101-232 – EBL of Stecker, Malkan, Scully



Ideal case z = 1 – EBL of Syecker, Malkan, Scully



Observed spectral index vs. redshift



Idem within DARMA

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Adding 3C66A (z = 0.44) + S5 0716+714 (z = 0.31)

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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.