Detection of distant AGN by MAGIC: the transparency of the Universe to high-energy photons

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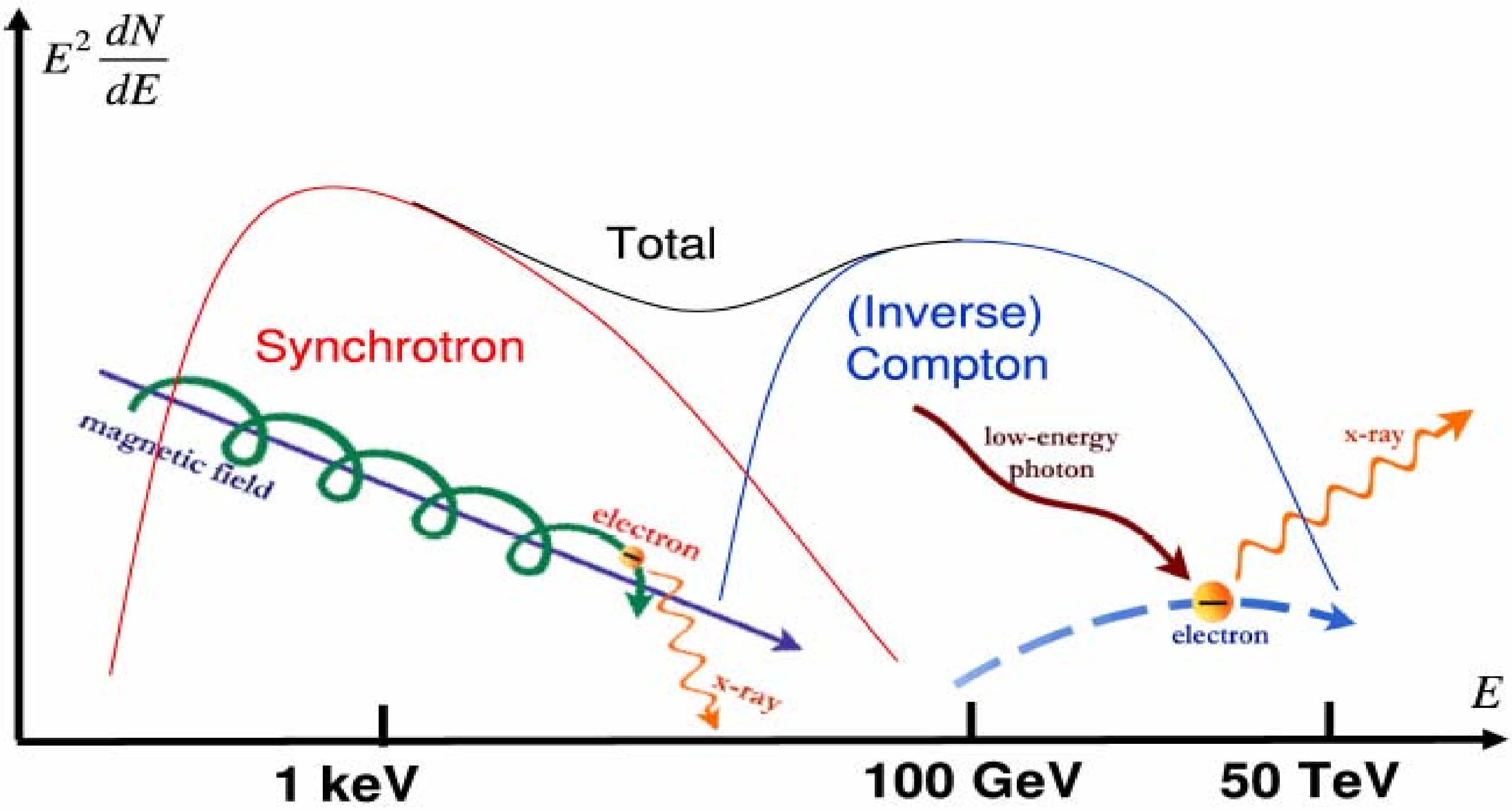
VHE GAMMA-RAY ASTROPHYSICS

A flow of cosmic rays hits the Earth, a small fraction of which is gamma-ray PHOTONS.

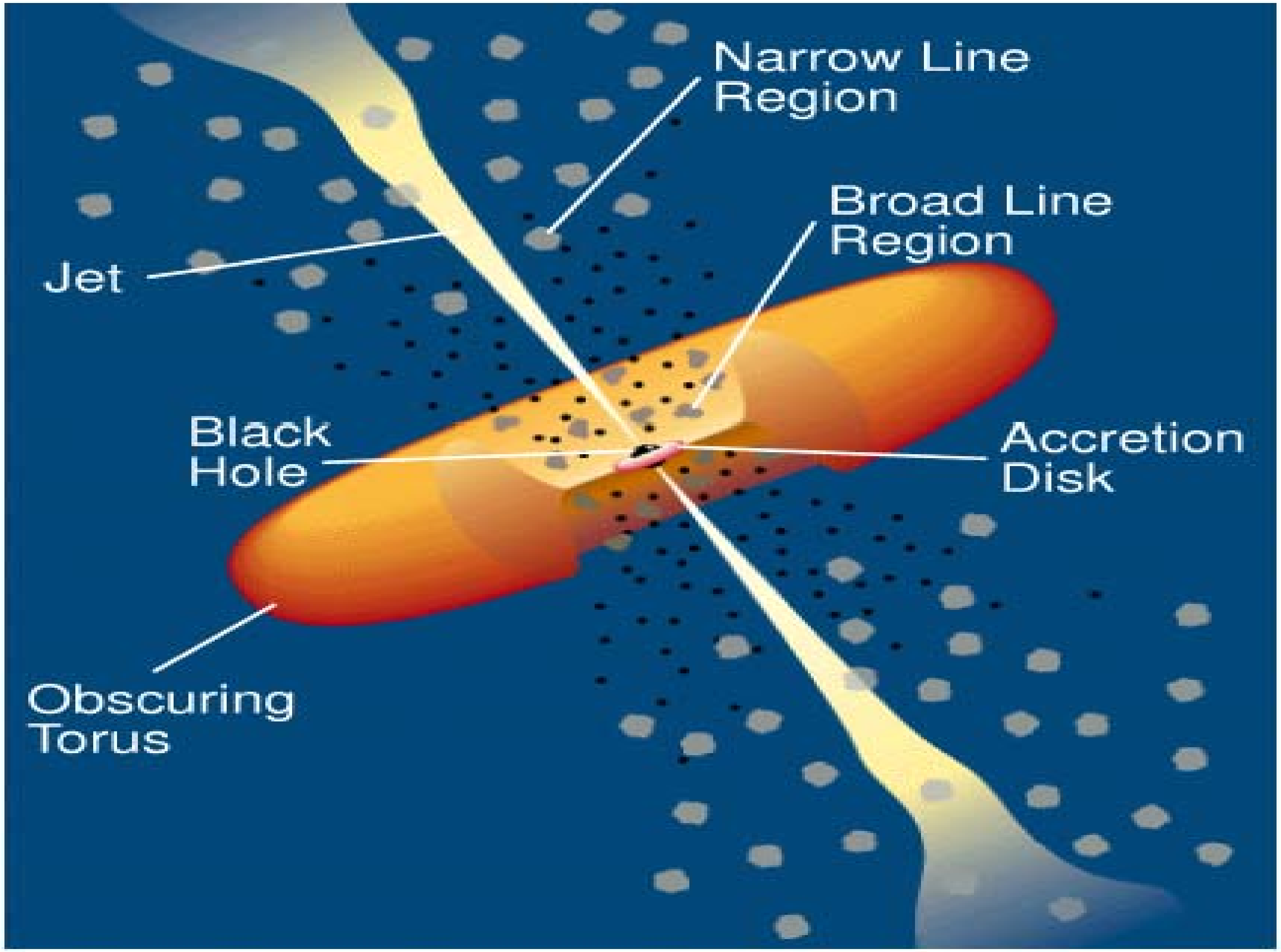
They are believed to be produced inside Active Galactic Nuclei (AGN) i.e. galaxies with a supermassive black hole accreating matter.

Contrary to what happens in main-sequence stars, emission is based on conversion of gravitational energy to electromagnetic energy via the Synchro-Self-Compton (SSC) mechanism



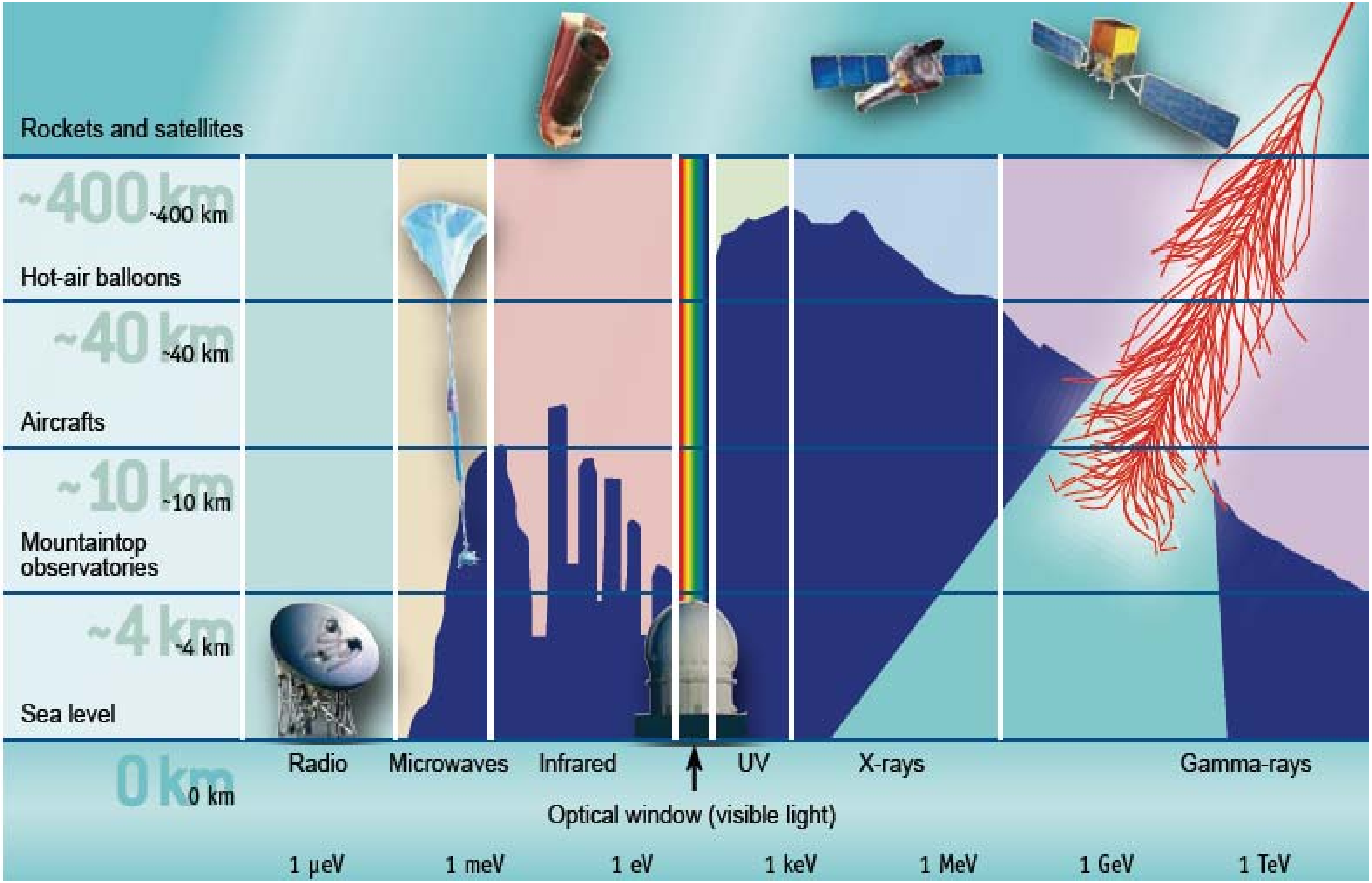
$E^2 \frac{dN}{dE}$
Total
Synchrotron
(Inverse)
Compton
magnetic field
electron
x-ray
low-energy
photon
x-ray
electron
E
1 keV
100 GeV
50 TeV

An AGN consists in an accretion disk and two emission jets



and in about 1 % of the cases one jet points toward us, giving rise to a BLAZAR.

Atmosphere is opaque to X and gamma-rays, so only SATELLITE-BORNE detectors can discover PRIMARY X and gamma-rays.


Rockets and satellites
~400 km
~400 km
Hot-air balloons
~40 km
~40 km
Aircrafts
~10 km
~10 km
Mountaintop observatories
~4 km
~4 km
Sea level
0 km
0 km
Radio
Microwaves
Infrared
UV
X-rays
Gamma-rays
Optical window (visible light)
1 μeV
1 meV
1 eV
1 keV
1 MeV
1 GeV
1 TeV

But PRIMARY gamma-ray fluxes are low and further decrease with energy: e.g. a 1 square-meter detector can collect only 1 photon in 2 hours from the brightest source above 10 GeV.

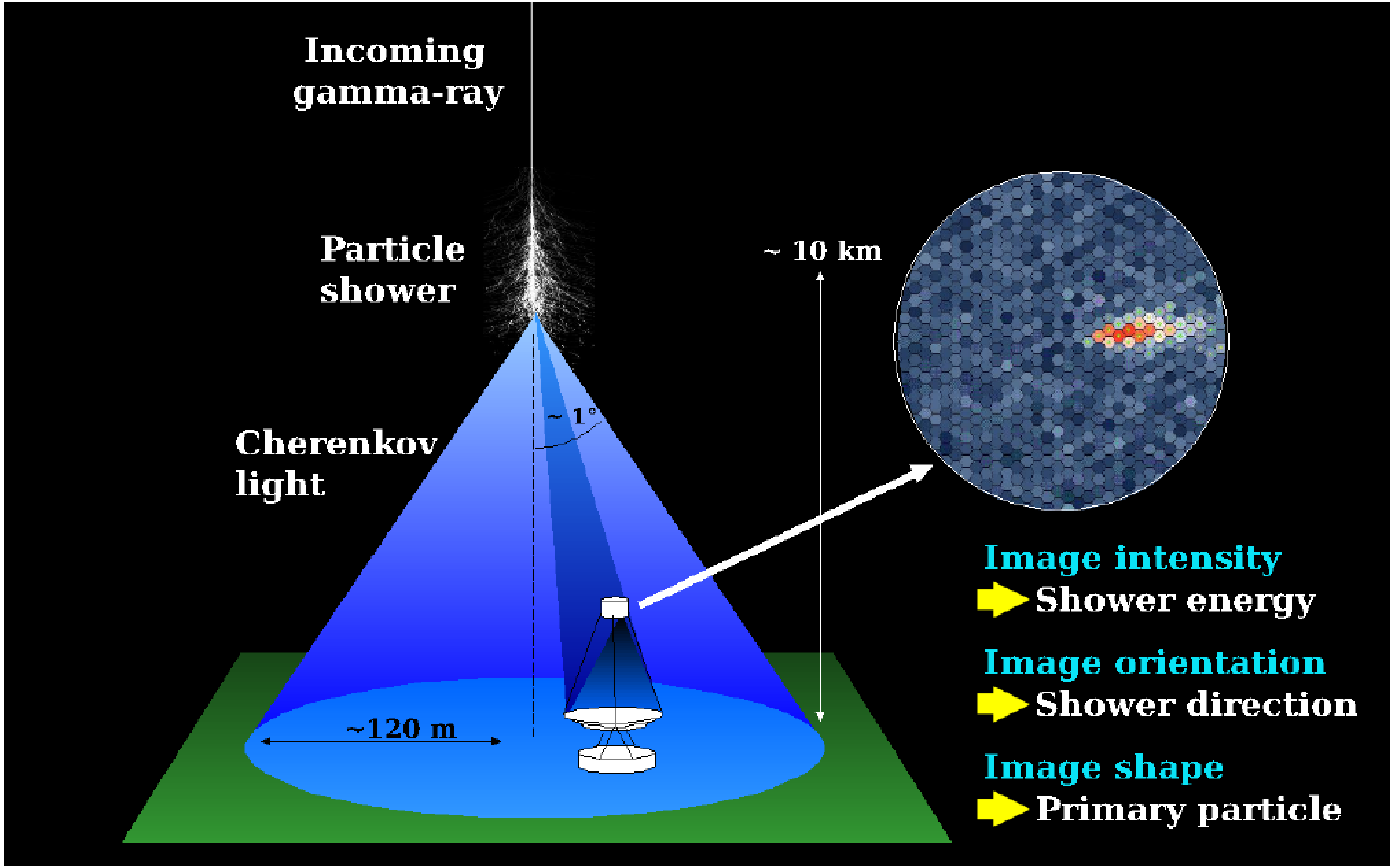
Still, atmospheric SHOWERS initiated by primary gamma-rays can be detected by EARTH-BASED instruments.

Actually, two strategies have been developed.

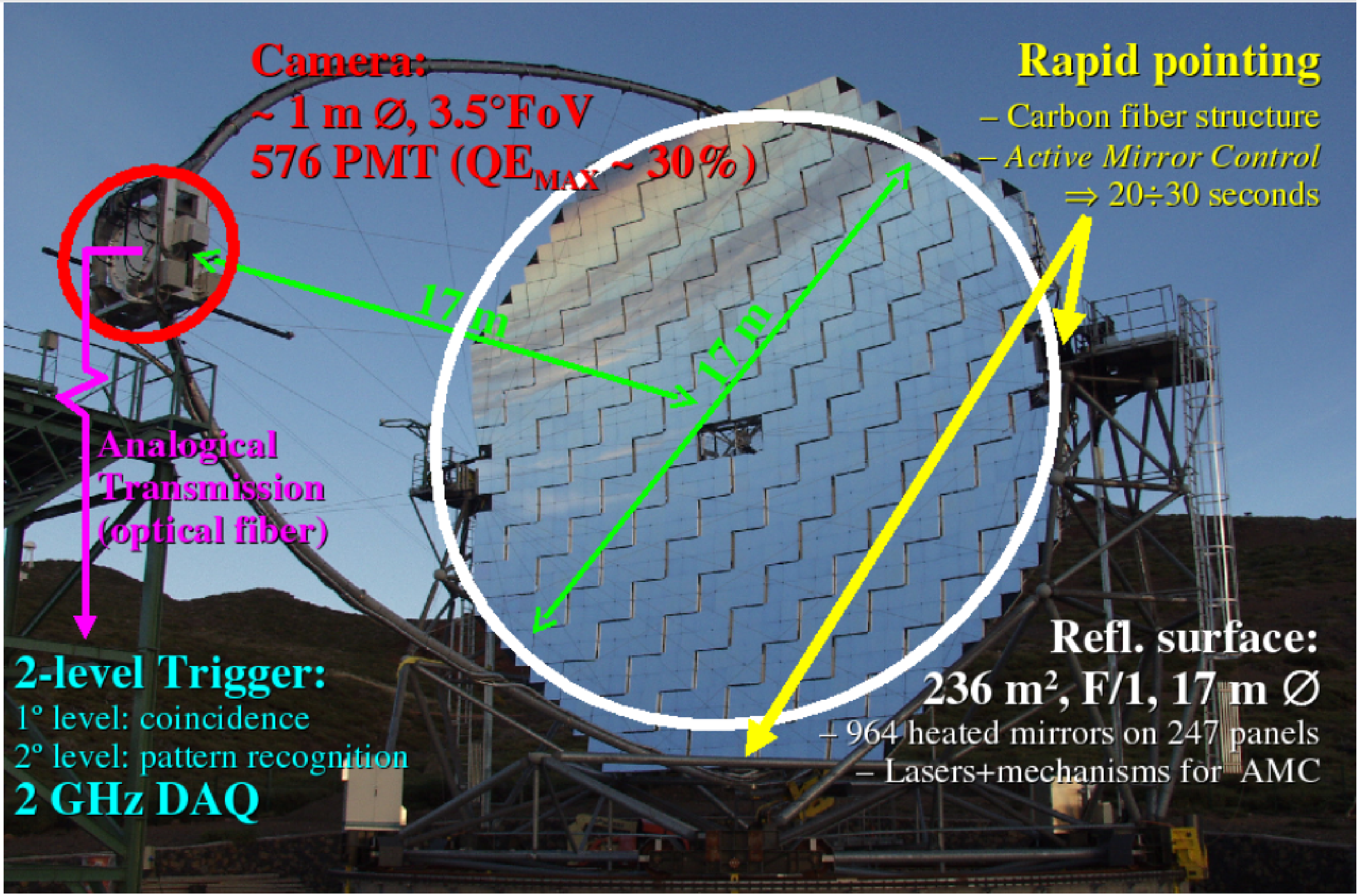
- AIR SHOWER DETECTORS like e.g. ARGO-YBJ observe secondary CHARGED particles.

- CHERENKOV TELESCOPES observe secondary PHOTONS with $100\ \mathrm{GeV} < E < 100\ \mathrm{TeV}$.

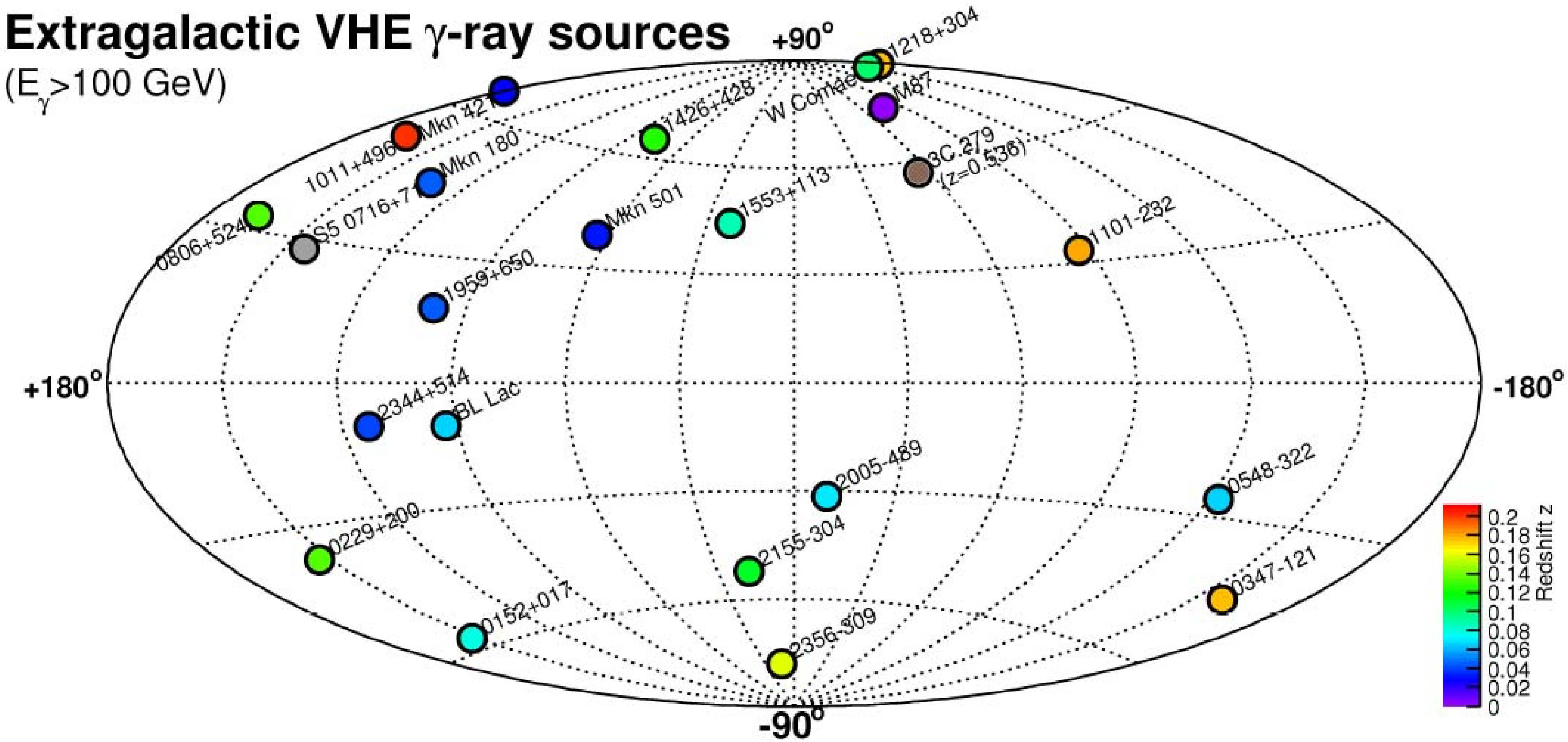
Cherenkov Telescopes



Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) Telesco



So far 23 AGN have been detected by Imaging Atmospheric Cherenkov Telescopes (IACTs) H.E.S.S., MAGIC, CANGOROO III, VERITAS.



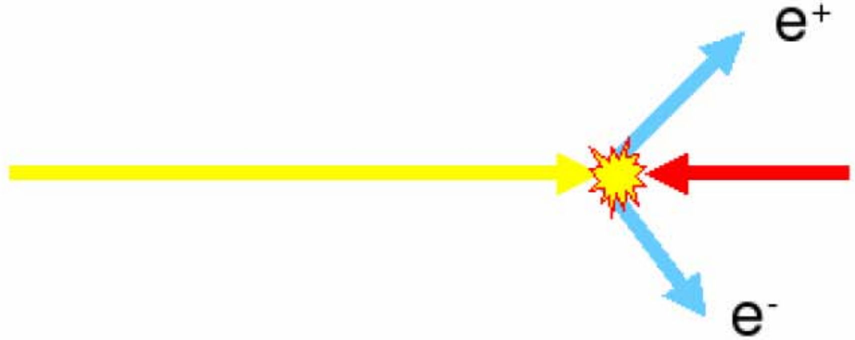
Given that these sources extend over a wide range of distances, not only can their INTRINSIC properties be inferred, but also photon PROPAGATION over cosmic distances can be probed.

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

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



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

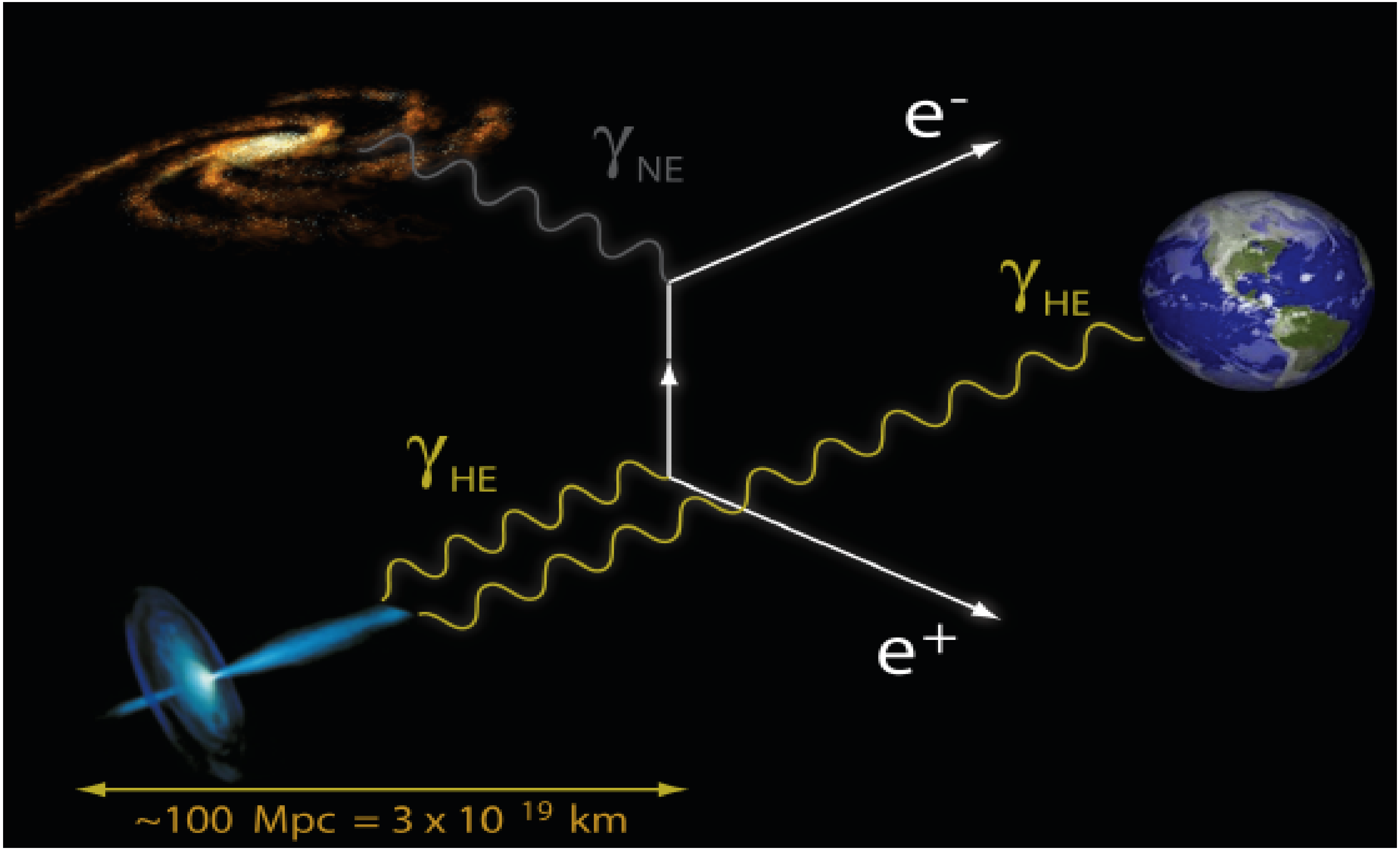
Around the TeV region:

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

$$\Downarrow$$

$\beta = \sqrt{1-\frac{(m_e c^2)^2}{E\,\epsilon}}$
E = energy of γ
ϵ = energy of $\gamma_{\mathtt{EBL}}$

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

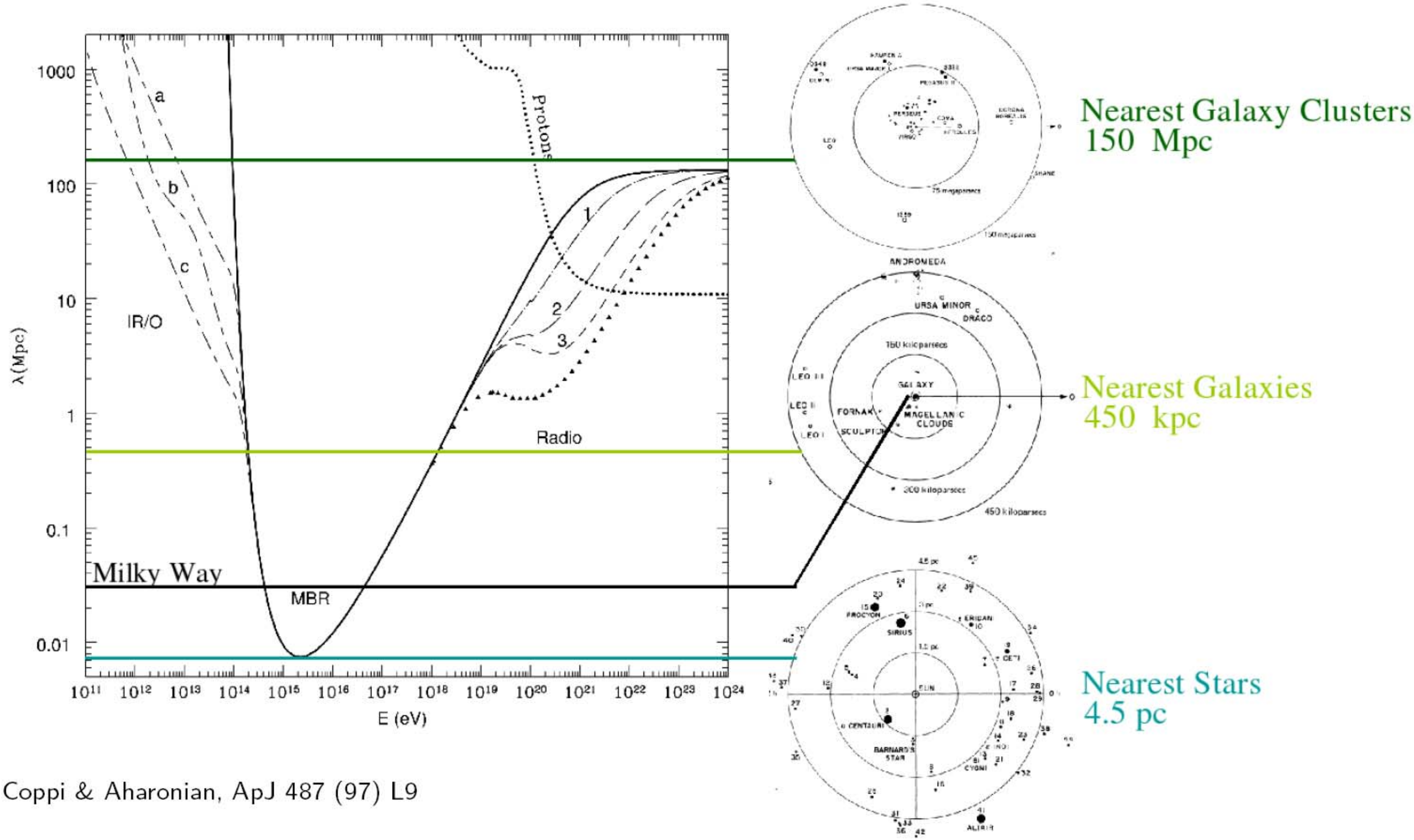
$$\tau_\gamma(D, E) = \frac{D}{\lambda_\gamma(E)}$$

and hence

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

with the mean free path given by

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



Coppi & Aharonian, ApJ 487 (97) L9

EXPECTATIONS

We stress that the mfp becomes SMALLER than the Hubble radius for E > 100 GeV.

Thus, two crucial facts emerge.

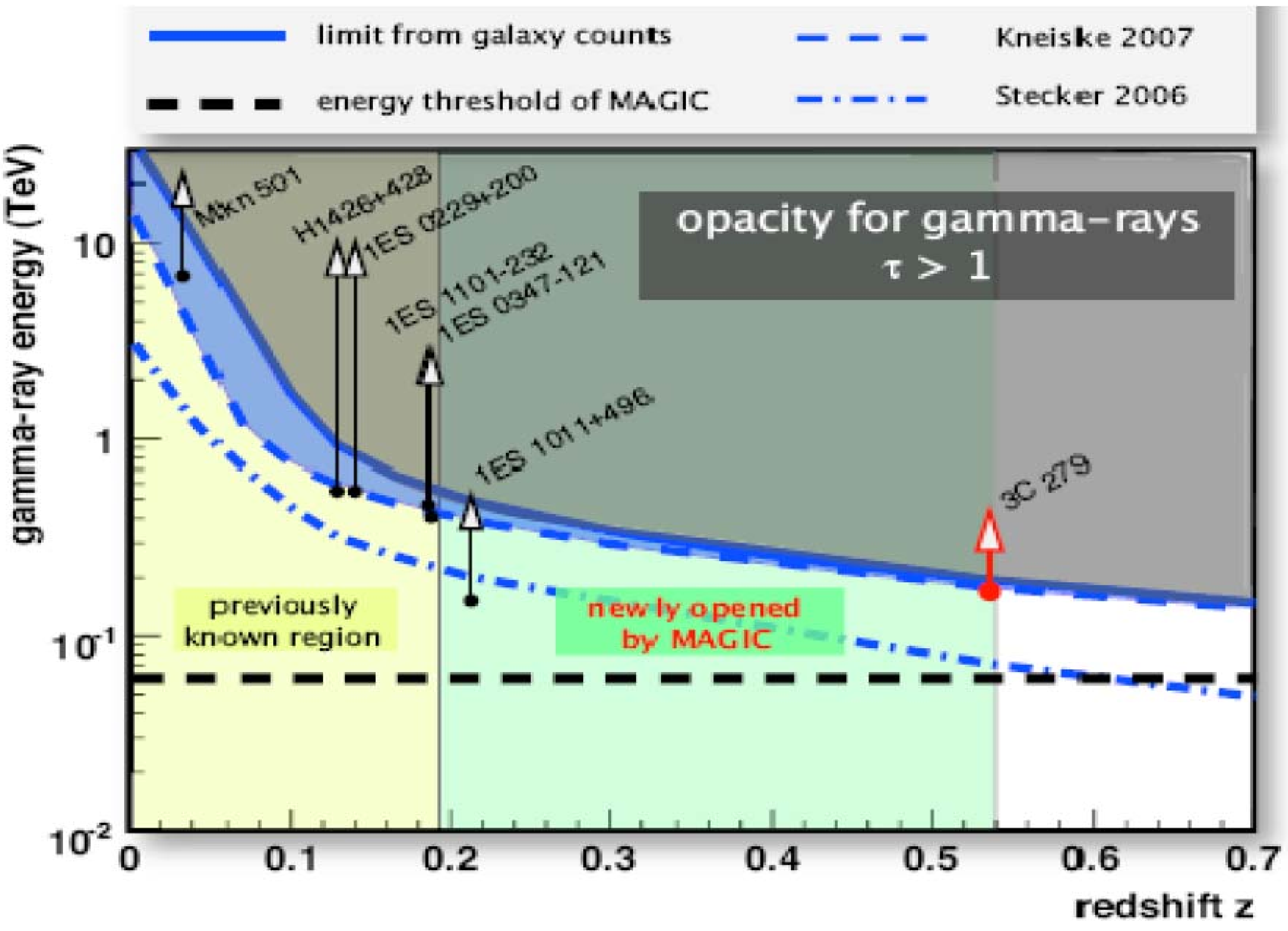
- Observed flux should be EXPONENTIALLY suppresed at LARGE distances, so that very far-away sources should become INVISIBLE.
- Observed flux should be EXPONENTIALLY suppressed at VHE, so that it should be MUCH STEEPER than the emitted one.

OBSERVATIONS

Yet, observations DISPROVE BOTH EXPECTATIONS!

- 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 3C 279 at z = 0.538. 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 ALMOST IDENTICAL statistical relevance for E < 220 GeV and 220 GeV < E < 600 GeV.



limit from galaxy counts
Kneiske 2007
energy threshold of MAGIC
Stecker 2006
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
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

WHAT IS GOING ON?

Taking observations at face value, two options are possible.

- Assuming STANDARD photon propagation, observed spectra are riproduced only by emission spectra MUCH HARDER than for any other AGN and LARGELY INCONSISTENT with STANDARD AGN models.

  Possible in very UNCONVENTIONAL models which however FAIL to explain all other AGN.

- Photon propagation over cosmic distance is NONSTANDARD, in that VHE photons must have a LARGER effective mfp than in the Standard Model.

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

We stress that due to the exponential dependence of the observed flux on the mfp, even a SMALL increase of the mfp yields a BIG flux enhancement.

TWO PROPOSALS

- A radical option invokes the breakdown of Lorentz invariance. But then the whole body of modern physics has to be redone from scratch!

- We take the less radical view that a remnant particle X of some MORE FUNDAMENTAL theory shows up at LOW ENERGY and couples to photon. Specifically, a photon could OSCILLATE into a very light remnant X and become a photon again before detection i.e. in INTERGALACTIC SPACE we have

$$\gamma \rightarrow X \rightarrow \gamma$$

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

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

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

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

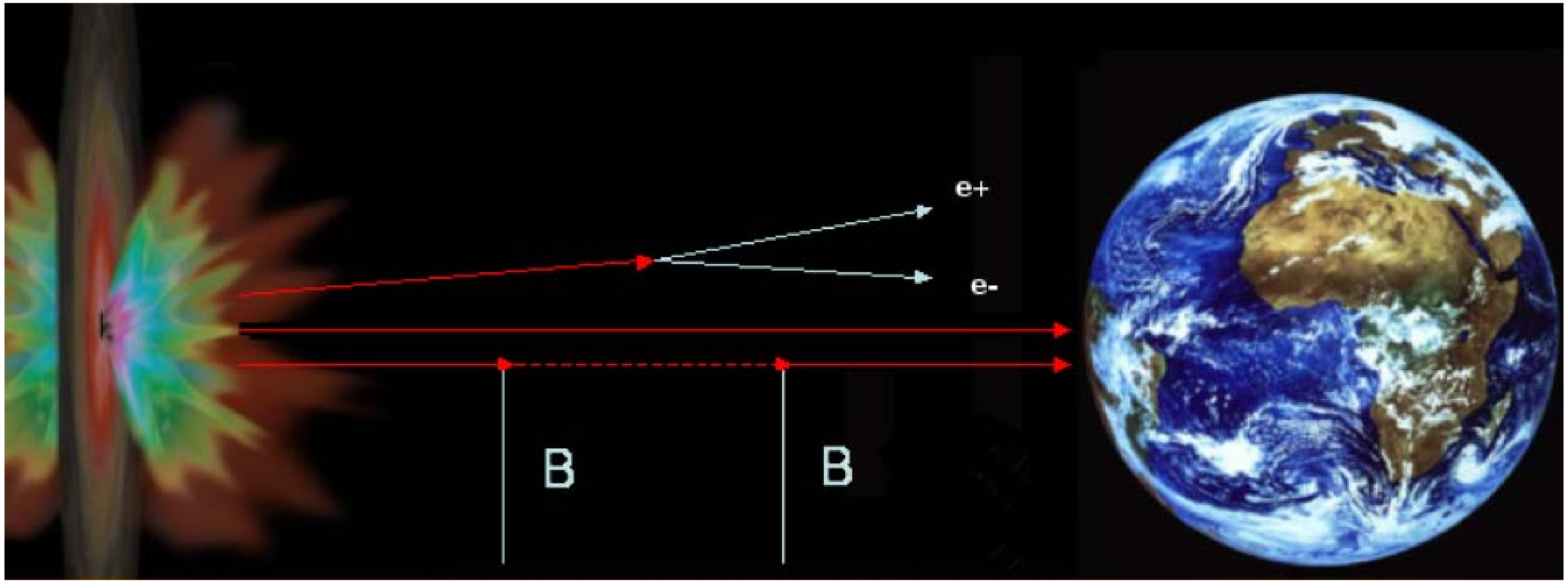
ALP are common to many extensions of the SM and are also a good candidate for quintessential DARK ENERGY (if they are extremely light).

Photon-ALP OSCILLATIONS quite similar to neutrino oscillations but external B is necessary.

Bounds on the INDEPENDENT parameters M and m:

- CAST experiment 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 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 **B** are poorly known and have a complicated morphology. We suppose that 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 $\omega_{\mathrm{pl},0} \simeq 1.17 \cdot 10^{-14}\,\mathrm{eV}.$

Propagation over a SINGLE 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

$$\psi(y) \equiv \begin{pmatrix} A_x(y) \\ A_z(y) \\ a(y) \end{pmatrix}$$

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

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

with

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

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. We find that a nonvanishing conversion probability over the WHOLE $10^2\,\mathrm{GeV} < E < 10^5\,\mathrm{GeV}$ requires

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

with

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

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

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

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 randomply choosing θ_n each time.
We repeat this procedure 5.000 times and next average all these realizations of the propagation process over all randon angles. So, the PHYSICAL propagation matrix of the beam is

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

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

$$\rho_1 = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

So, we finally get

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

We exhibit our results for M = 4 $\cdot 10^{11}$ GeV in the following figures, where we vary B in the range 0.1 – 1 nG and its coherence length in the range 5 – 10 Mpc continuously and independently.

Result for z = 0.536 (3C 279)

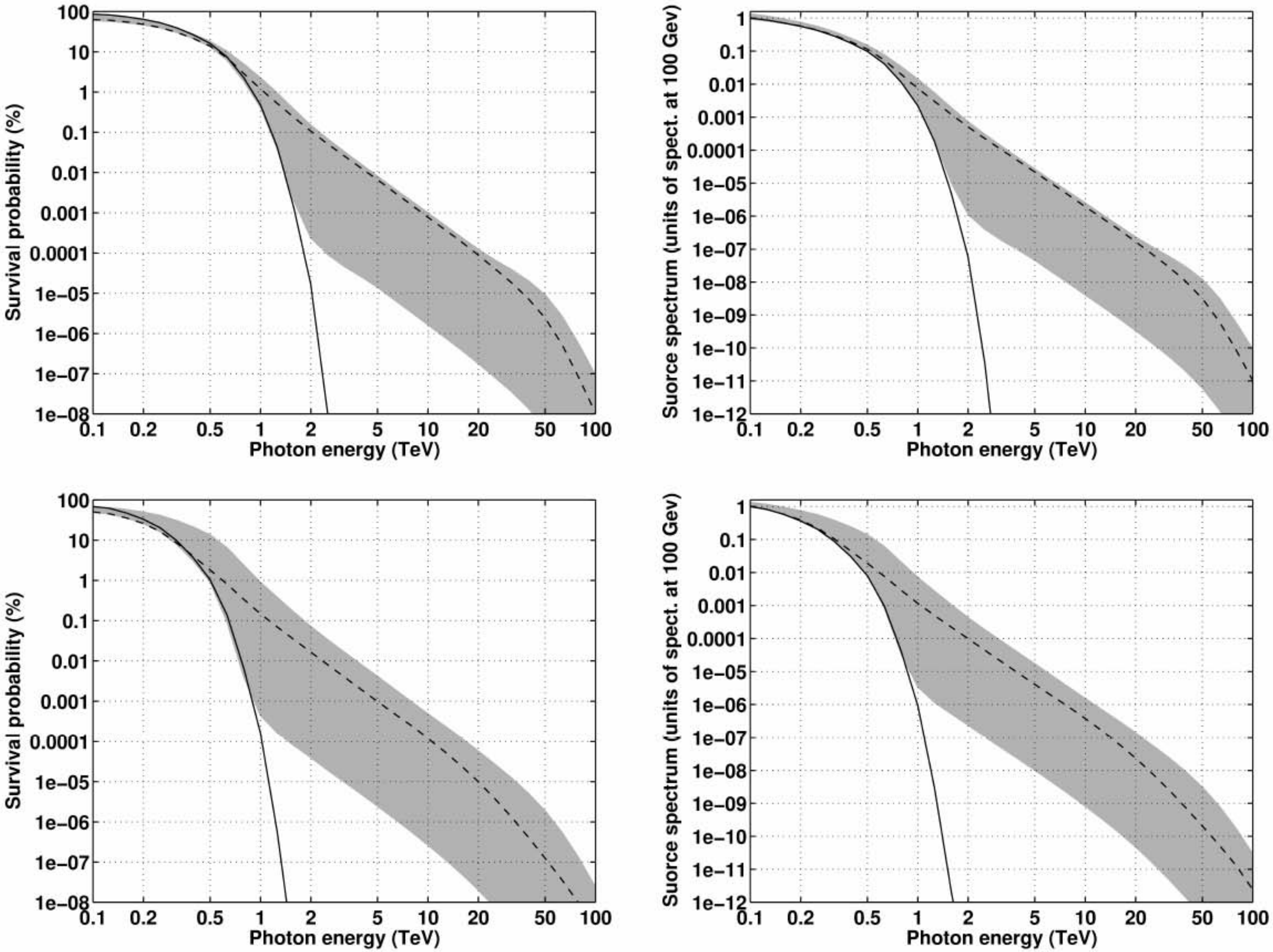
source spectral index: 2.4

solid line: "Lower limit" EBL density

(Stecker et al.)

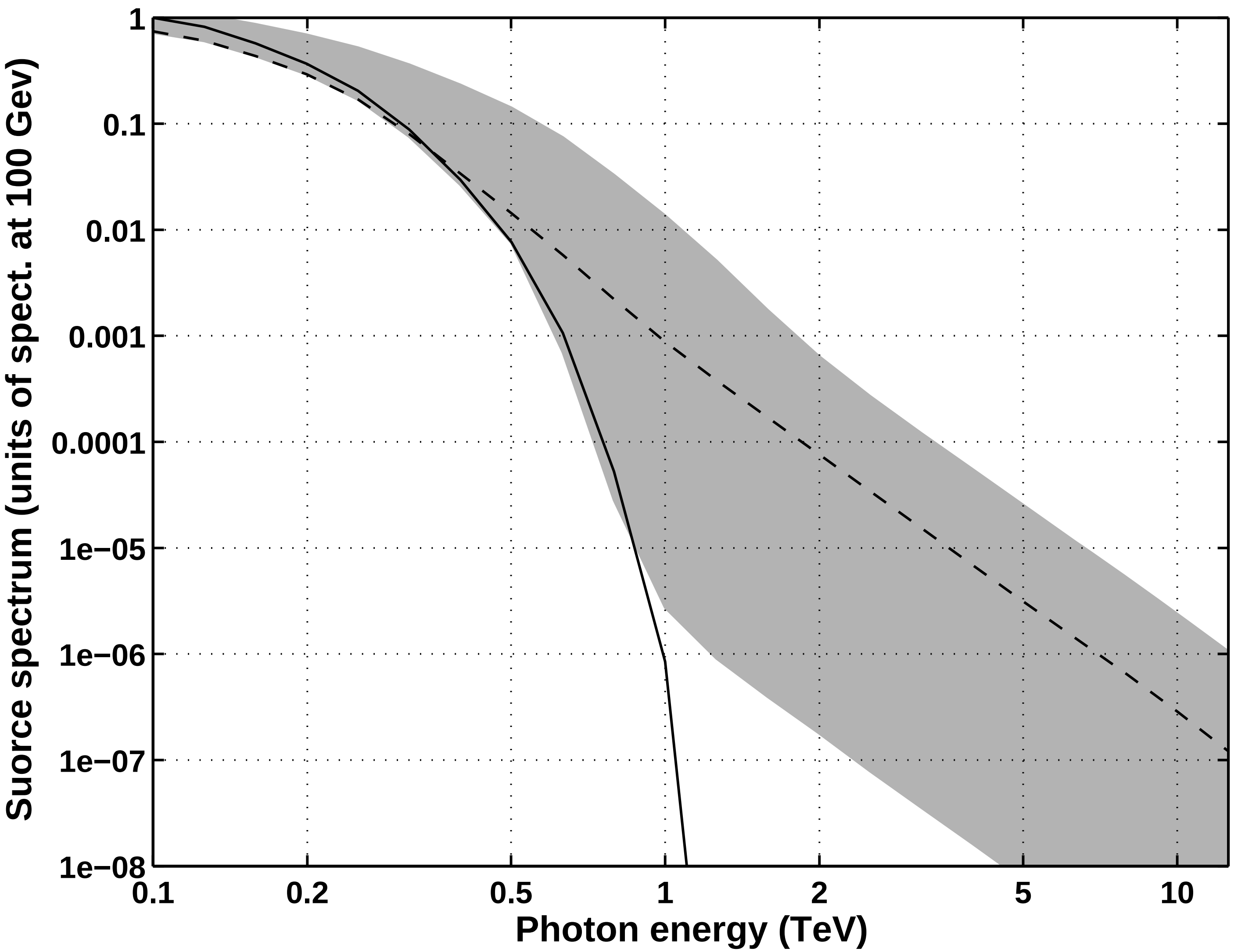
solid line: "Upper limit" EBL density

(Stecker et al.)

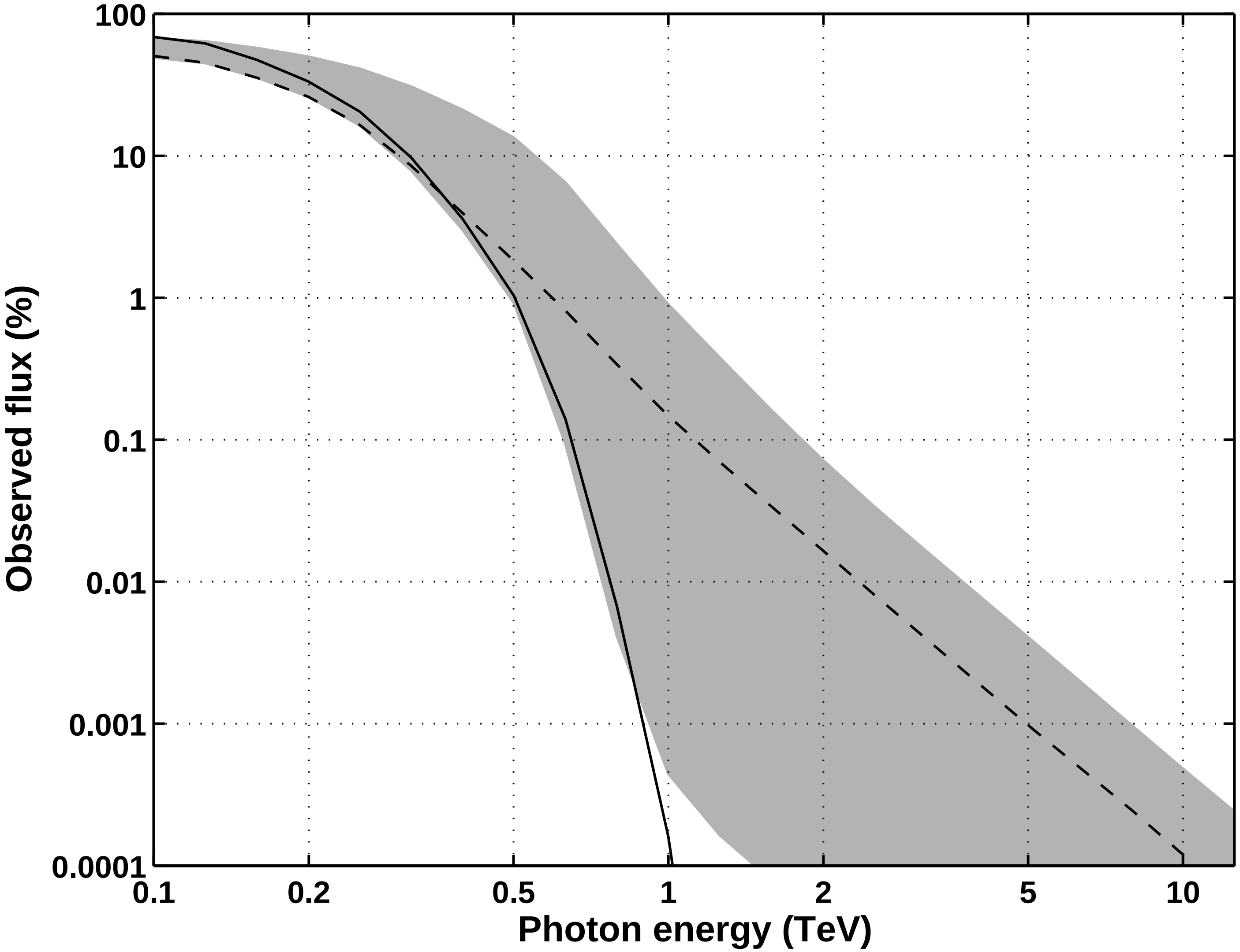


dashed line: DA.R.MA for strength ($\mathbf{B}$) = 0.5 nG and dom. size ($\mathbf{B}$) = 7 Mpc

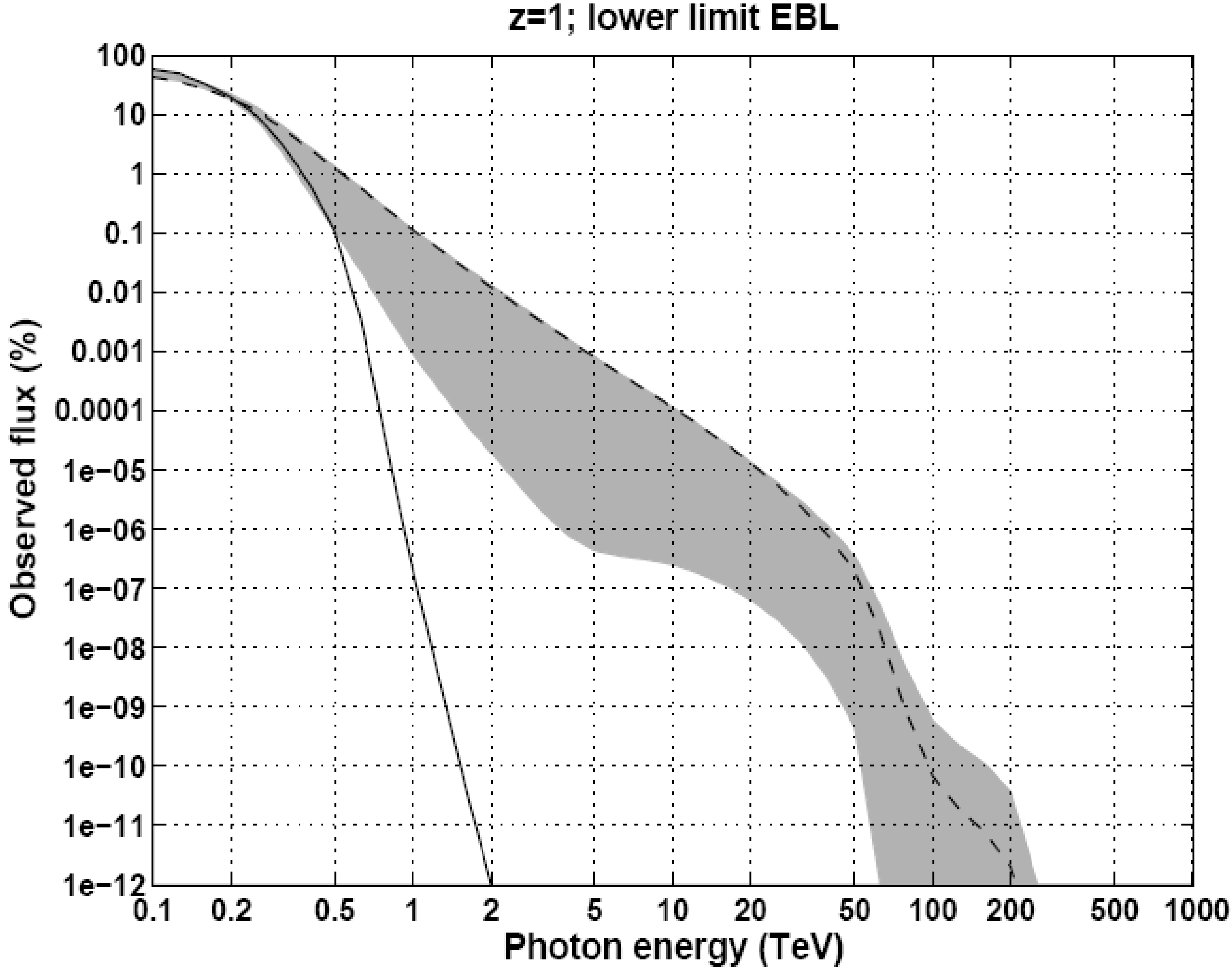
Case of 3C279 without Milky Way contribution

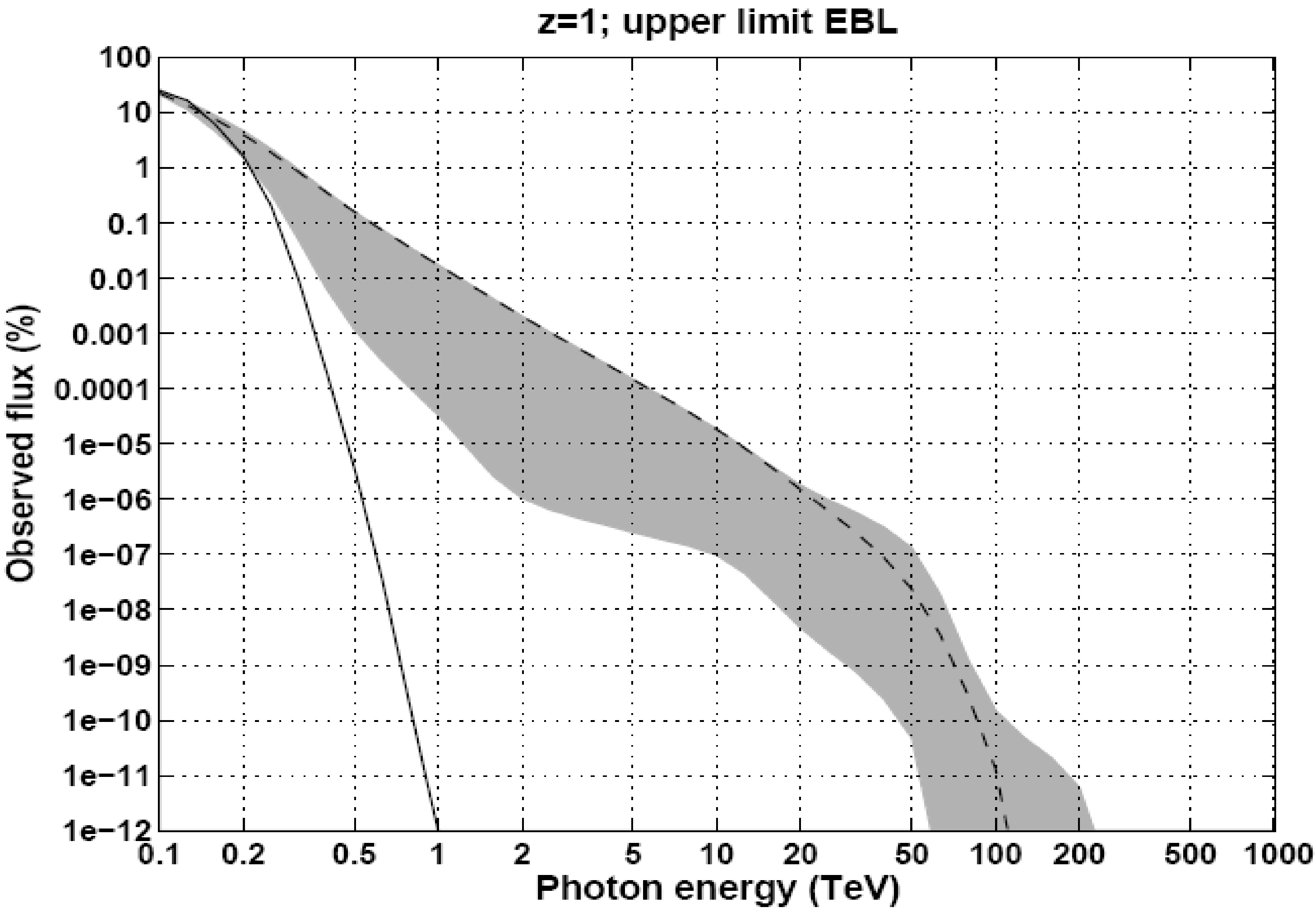


Case of 3C279 with Milky Way contribution



PREDICTIONS





z=1; upper limit EBL
Observed flux (%)
100
10
1
0.1
0.01
0.001
0.0001
1e−05
1e−06
1e−07
1e−08
1e−09
1e−10
1e−11
1e−12
0.1
0.2
0.5
1
2
5
10
20
50
100
200
500
1000
Photon energy (TeV)

CONCLUSIONS

- We have shown that the existence of a very light spin-zero boson coupled to photons – as predicted by many extensions of the Standard Model – naturally explains the observed transparency of the VHE gamma-ray sky.
- Our predictions concern the spectral distortion of VHE gamma-ray sources at cosmological distances and at very high energies.
- They can be tested with IACTs as well with air-shower detectors like ARGO-YBJ.