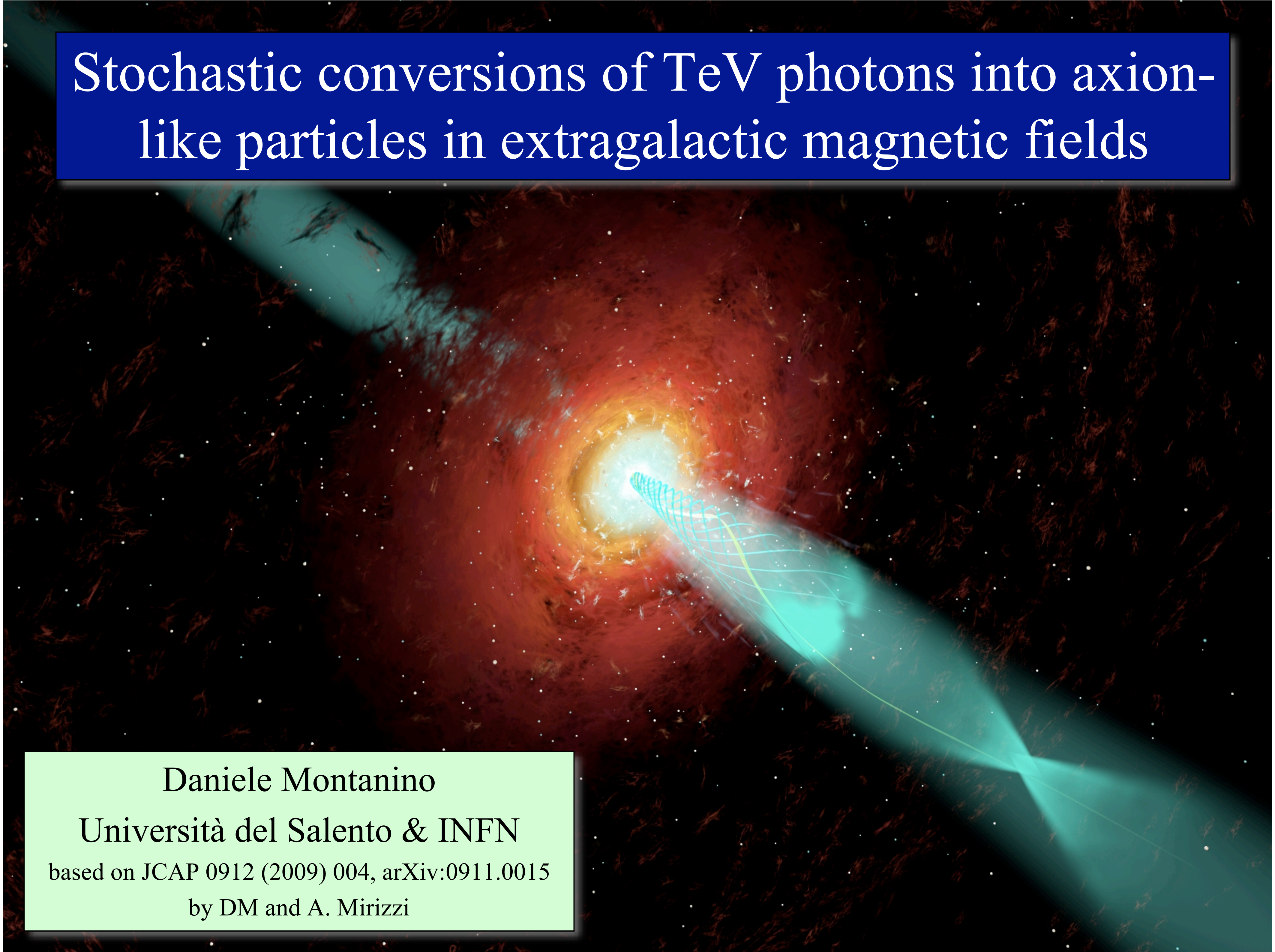
Stochastic conversions of TeV photons into axion-like particles in extragalactic magnetic fields



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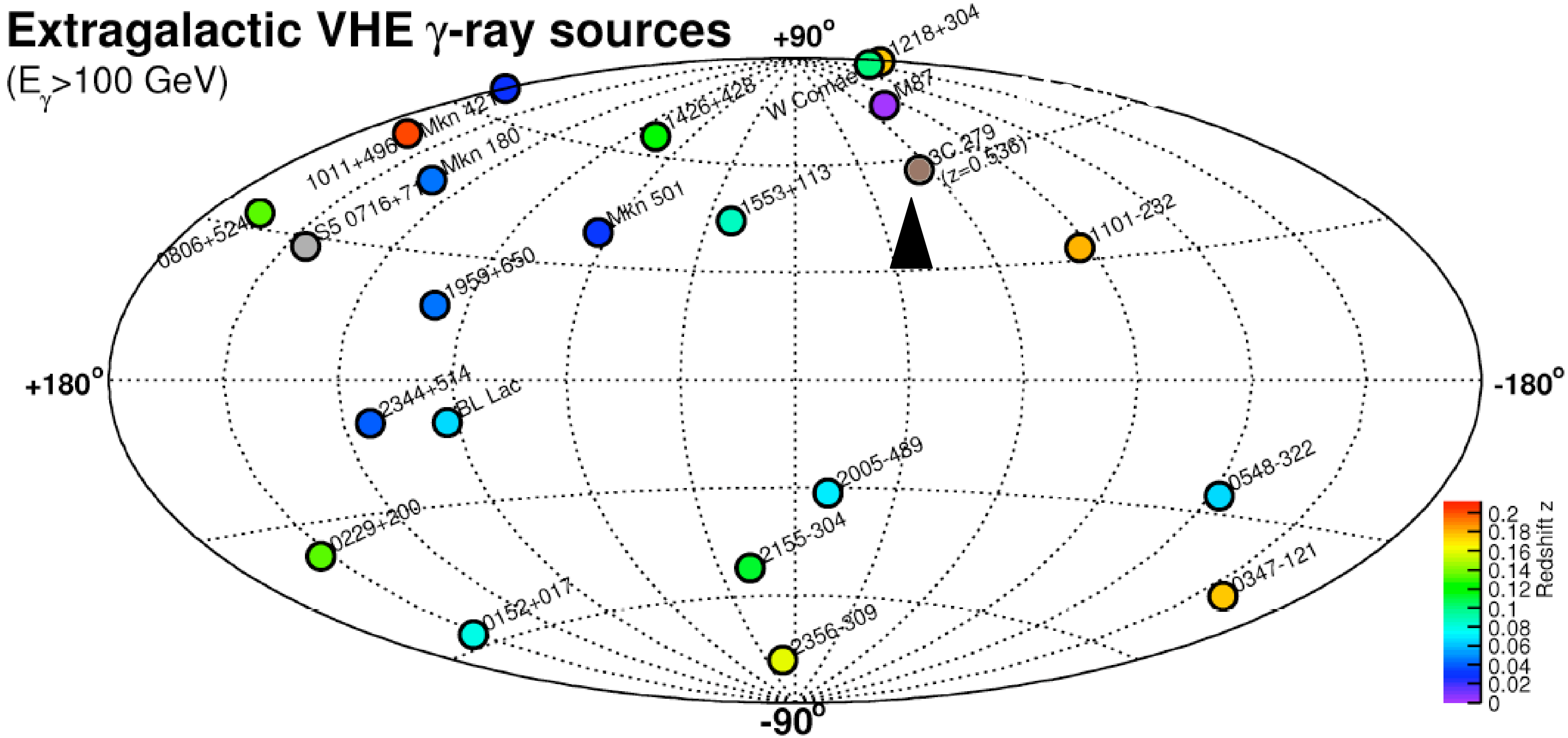
by DM and A. Mirizzi

Introduction

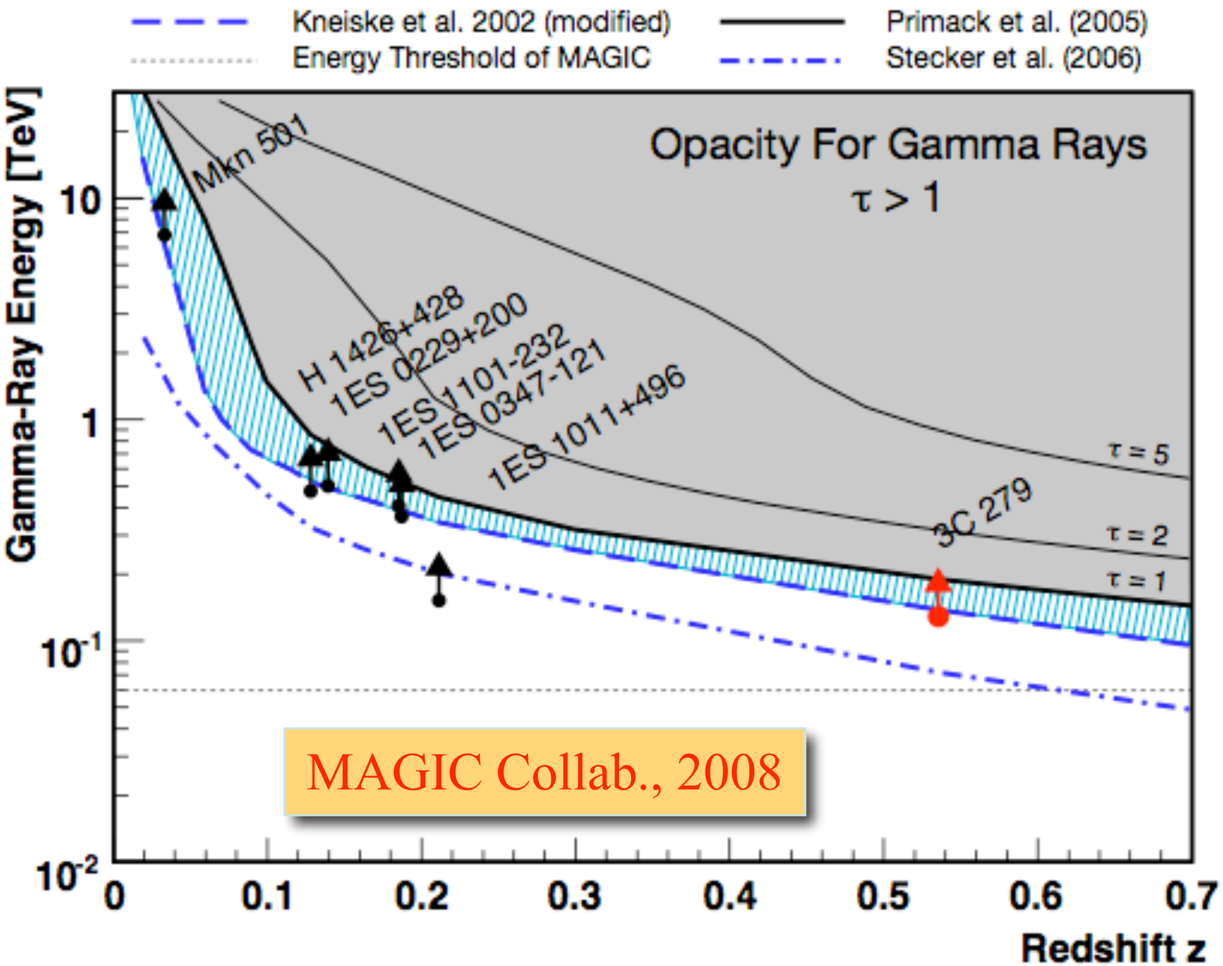
Very High Energy (VHE) photons (E > 100GeV) have been observed from relatively distant sources (up to z~0.6). However, this is a puzzle…



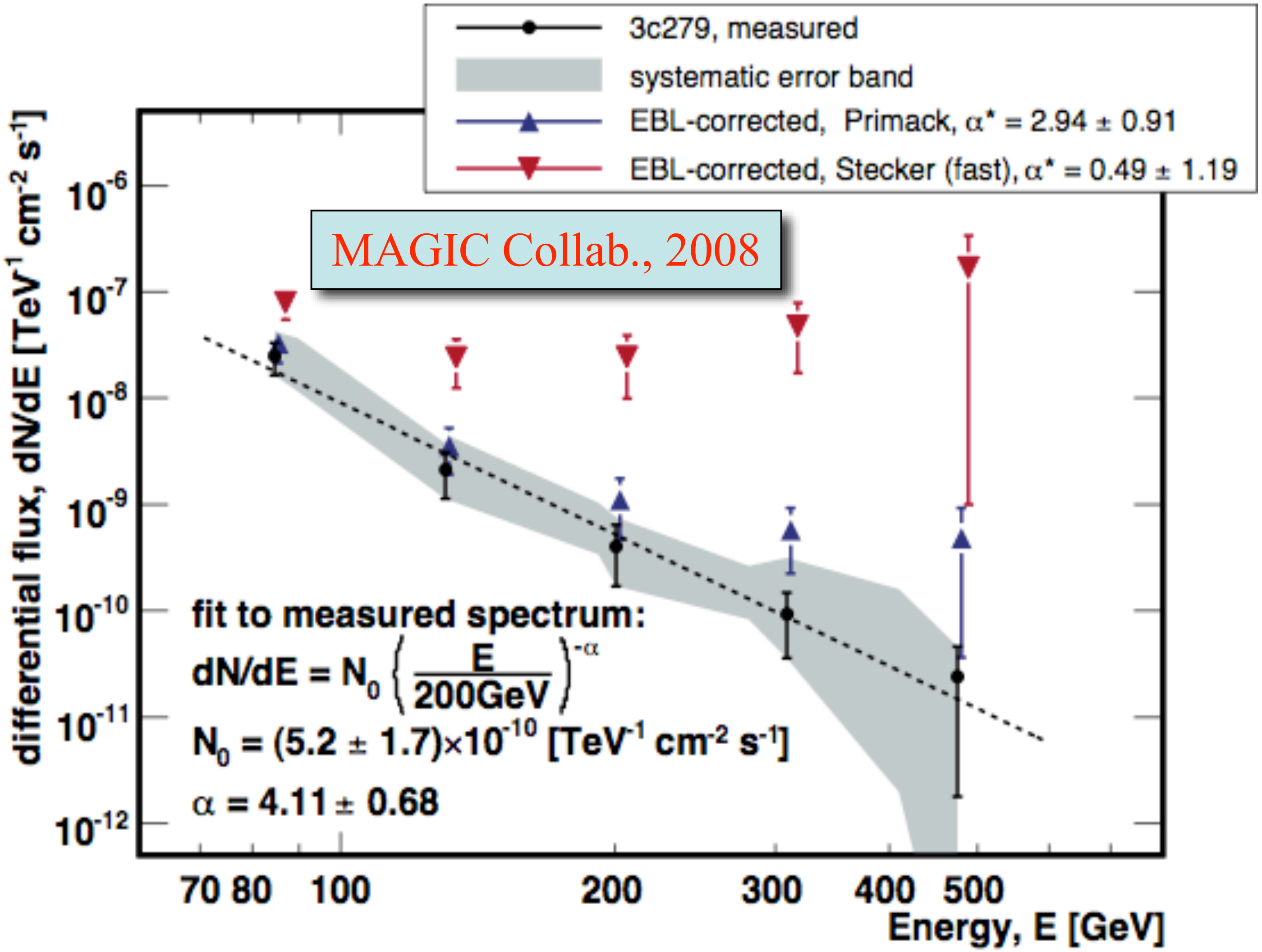
In fact, universe should be opaque to VHE photons due to the scattering on the background photons:

$$\gamma^{\mathrm{VHE}} + \gamma^{\mathrm{bgk}} \rightarrow e^{+} + e^{-}$$

In the energy range 100 GeV < E <10 TeV the main background is the Infrared / Optical Extragalactic Background Light (EBL). Many of the observed sources are beyond the "γ-ray horizon"



The reconstructed (EBL-corrected) spectra of the source is too much hard to be explained by standard explanations



It appears that the universe is exceptionally transparent for γ-rays: a smoking gun for new physics?

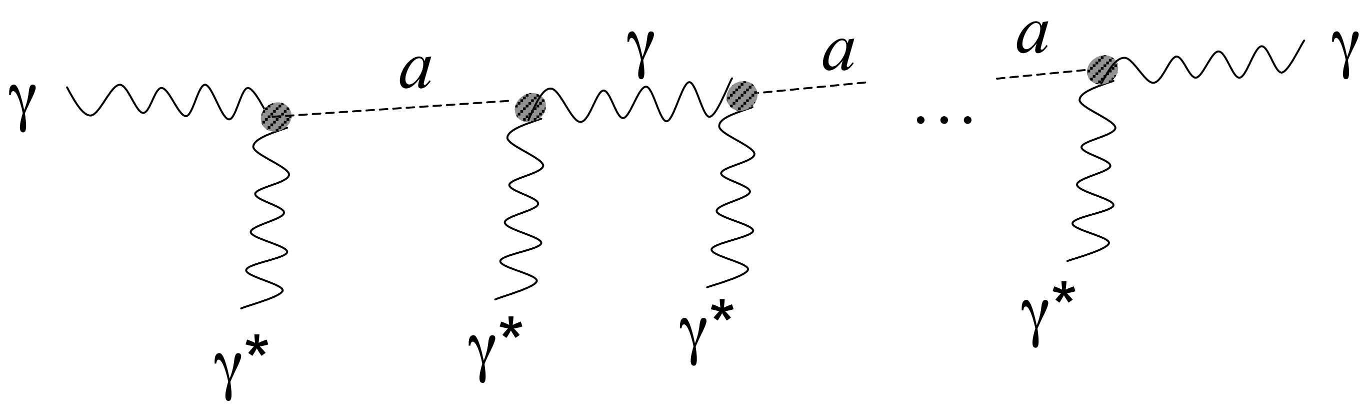
Axion Like Particle (ALP)

One intriguing possibility that have been recently proposed (DeAngelis-Mansutti-Roncadelli, 2007; DeAngelis-Mansutti-Persic-Roncadelli, 2008) is that conversion of γ's into axions into the random extragalactic magnetic fields give rise to a sort of cosmic *light-shining through wall* effect.

Axions have been introduced by Peccei & Quinn to solve the strong CP problem. Axion like particles with aγγ coupling are predicted in many extensions of the Standard Model. Pseudoscalar axions couple with the EM field through the effective Lagrangian

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$

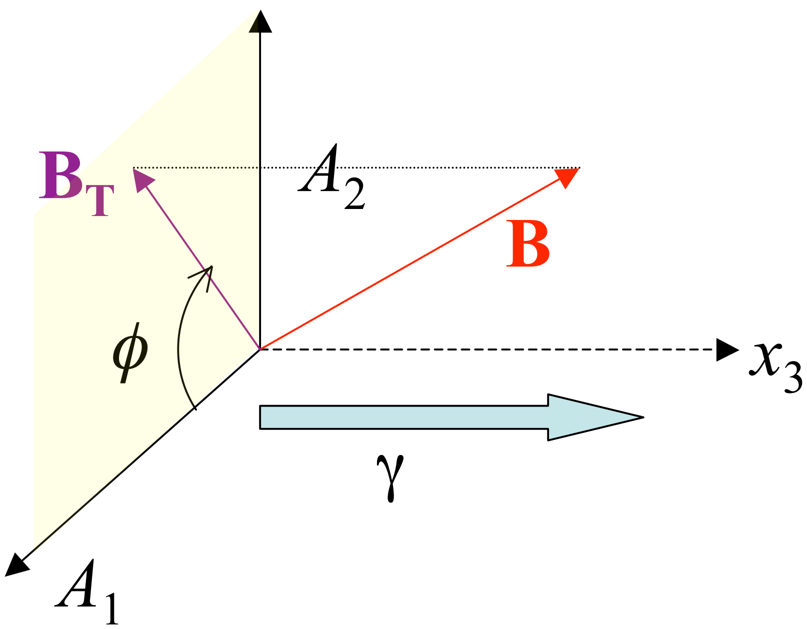
Photons propagating in an external magnetic field can undergo to photon-axion oscillations



Photon-axion oscillations

For a photon of energy E propagating in the x_3 direction the evolution equation for the γ-a system is (Raffelt-Stodolsky, 1987)

$$i\frac{\partial}{\partial x_3}\begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} = \begin{bmatrix} \Delta_{\|}c_\phi^2 + \Delta_\perp s_\phi^2 & (\Delta_{\|} - \Delta_\perp)s_\phi c_\phi & \Delta_{a\gamma}c_\phi \\ (\Delta_{\|} - \Delta_\perp)s_\phi c_\phi & \Delta_{\|}s_\phi^2 + \Delta_\perp c_\phi^2 & \Delta_{a\gamma}s_\phi \\ \Delta_{a\gamma}c_\phi & \Delta_{a\gamma}s_\phi & \Delta_a \end{bmatrix}\begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix}$$



Where:

$$\begin{aligned}
\Delta_{\|} &= \Delta_{\rm plasma} + \tfrac{7}{2}\Delta_{\rm QED} \\
\Delta_\perp &= \Delta_{\rm plasma} + 2\Delta_{\rm QED} \\
\Delta_{\rm plasma} &= -\frac{2\pi\alpha n_e}{m_e E} \\
\Delta_{\rm QED} &= \frac{\alpha E}{45\pi}\left(\frac{B_T}{m_e^2/e}\right)^2 \\
\Delta_{a\gamma} &= \tfrac{1}{2}g_{a\gamma}B_T \\
\Delta_a &= -\frac{m_a^2}{2E}
\end{aligned}$$

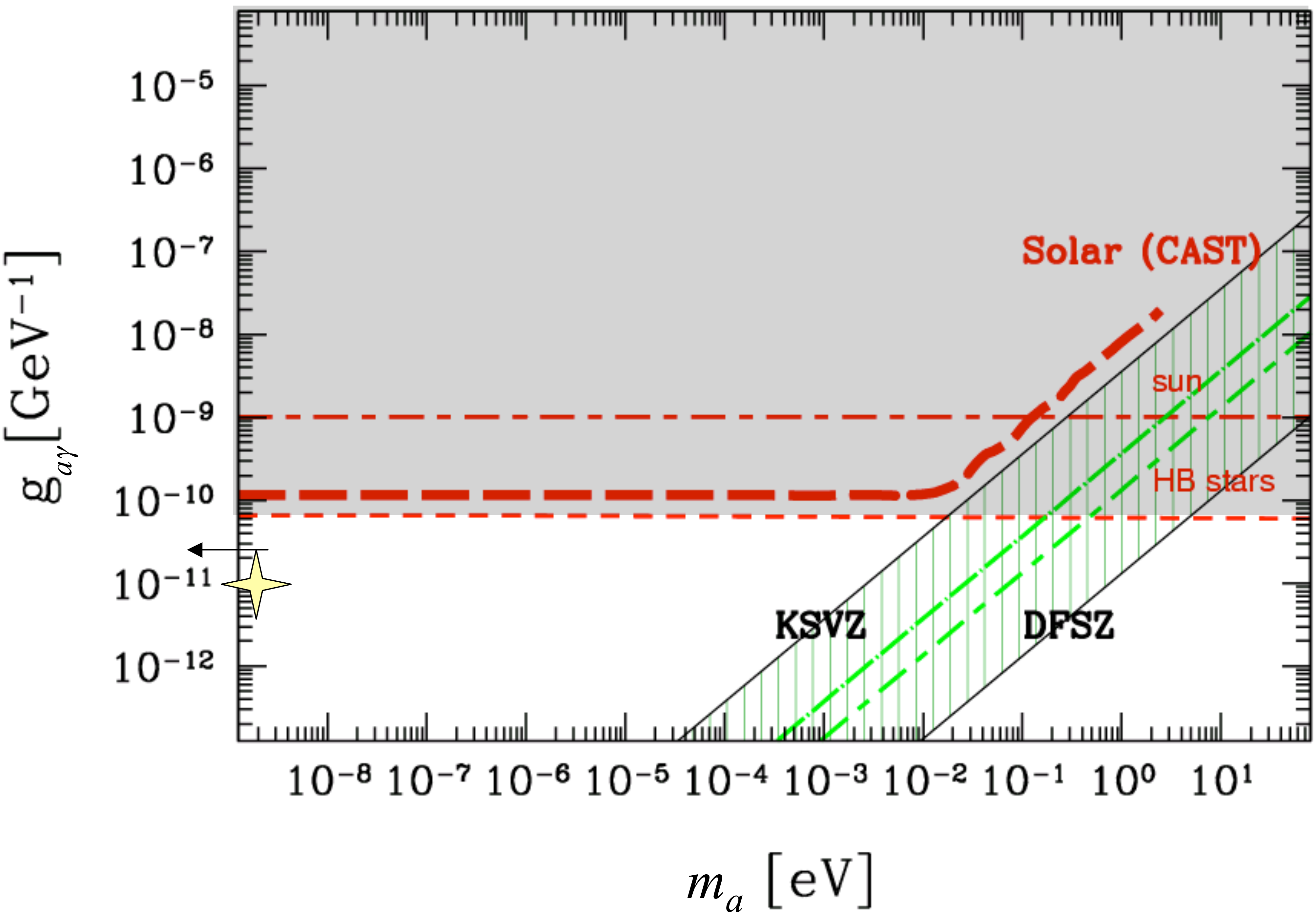
n_e= electron density of the medium

Numerically we have

$$\Delta_{\text{plasma}} \simeq -1.1 \times 10^{-11} \left(\frac{E}{\text{TeV}}\right)^{-1} \left(\frac{n_e}{10^{-7}\,\text{cm}^{-3}}\right) \text{Mpc}^{-1}$$
$$\Delta_{\text{QED}} \simeq 4.1 \times 10^{-9} \left(\frac{E}{\text{TeV}}\right) \left(\frac{B_T}{10^{-9}\,\text{G}}\right)^2 \text{Mpc}^{-1}$$
$$\Delta_{a\gamma} \simeq 1.52 \times 10^{-2} \left(\frac{g_{a\gamma}}{10^{-11}\text{GeV}^{-1}}\right) \left(\frac{B_T}{10^{-9}\,\text{G}}\right) \text{Mpc}^{-1}$$
$$\Delta_a \simeq -7.8 \times 10^{-4} \left(\frac{m_a}{10^{-10}\text{eV}}\right)^2 \left(\frac{E}{\text{TeV}}\right)^{-1} \text{Mpc}^{-1}$$

- ✓ The intergalactic (IG) magnetic field is $B < 2.8\times10^{-7}$ G on a typical scale of $l\sim$1Mpc (Blasi-Burles-Olinto, 1999). However, a value B $\lesssim$ 1 nG is more reasonable
- ✓ The IG electron density is $n_e \lesssim 2.7\times10^{-7}$ cm^{-3} (WMAP, 2009)
- ✓ $g_{a\gamma}<10^{-11}$ GeV^{-1} from the non observation of γ-rays from the SN1987A (Brockway-Carlson-Raffelt, 1996)
- ✓ We assume a very light ALP: $m_a < 0.1$ neV

We will assume the values in the previous numerical estimation as benchmark values. In this case Δ_a, Δ_{plasma} and Δ_{QED} are negligible.


Solar (CAST)
sun
HB stars
KSVZ
DFSZ
10^{-5}
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10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$g_{a\gamma}\,[\mathrm{GeV}^{-1}]$
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
m_a [eV]

Photon absorption

The photon absorption rate is given by

$$\Gamma_\gamma(E) = \int_{m_e^2/E}^{\infty} d\epsilon \, \frac{dn_\gamma^{\mathrm{bkg}}}{d\epsilon} \int_{-1}^{1-\frac{2m_e^2}{E\epsilon}} d\xi \, \frac{1-\xi}{2} \sigma_{\gamma\gamma}(E, \epsilon, \xi)$$

where ξ is the cosine of the angle between the incident and the background photon and the cross section $\sigma_{\gamma\gamma}$ is given by the Bethe-Heitler formula. Due to the optical theorem the Raffelt-Stodolsky equation with absorption becomes (in our case)

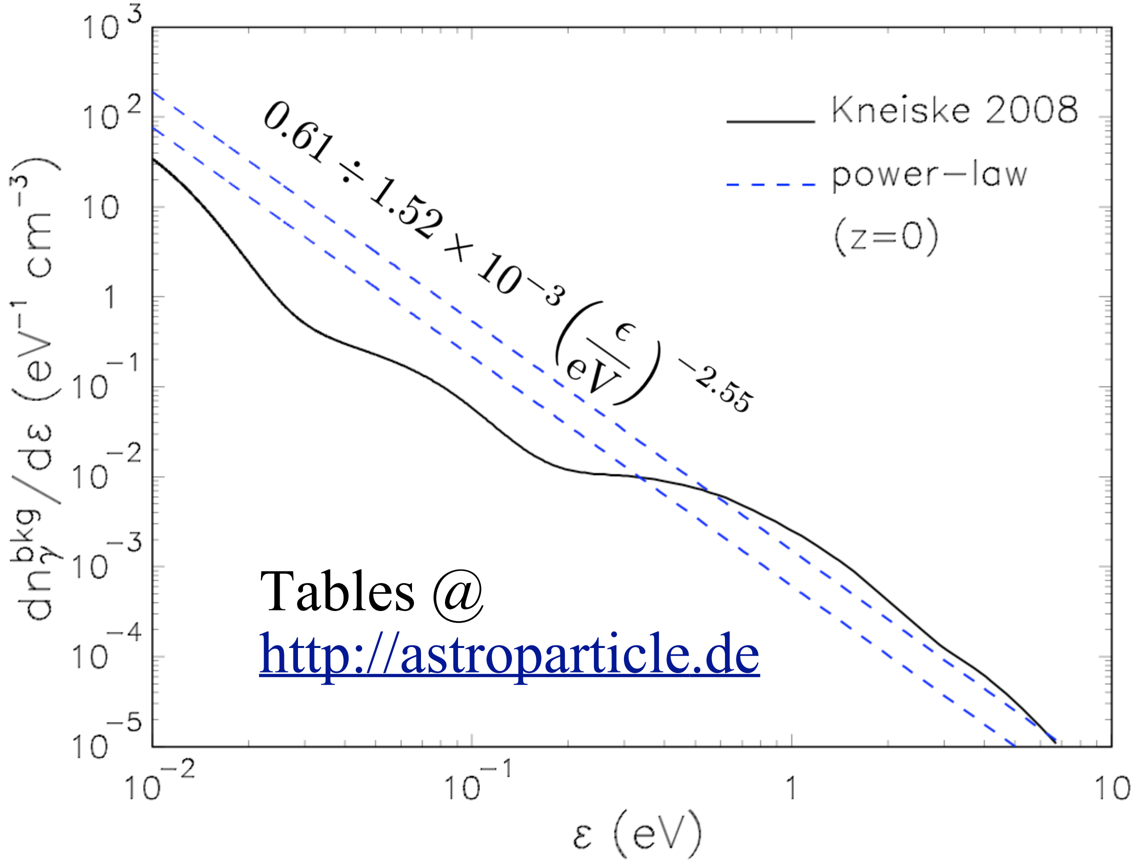
$$i\frac{\partial}{\partial x_3}\begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} = \begin{bmatrix} -i\frac{\Gamma_\gamma}{2} & 0 & \Delta_{a\gamma}c_\phi \\ 0 & -i\frac{\Gamma_\gamma}{2} & \Delta_{a\gamma}s_\phi \\ \Delta_{a\gamma}c_\phi & \Delta_{a\gamma}s_\phi & 0 \end{bmatrix}\begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} \equiv \mathcal{H}\begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix}$$

In absence of photon-axion conversion the final attenuation is given (apart the trivial L^{-2} factor) by

$$\begin{aligned} I_{\mathrm{obs}}(E) &= T_\gamma(E, L) \cdot I_{\mathrm{source}}(E_0) \\ &\equiv \exp\left[-\int_0^L dx \, \Gamma_\gamma(E, x)\right] \cdot I_{\mathrm{source}}(E_0) \end{aligned}$$

with $E_0 = E\cdot(1+z)$ is the initial (non-redshifted) photon energy

The minimal EBL model

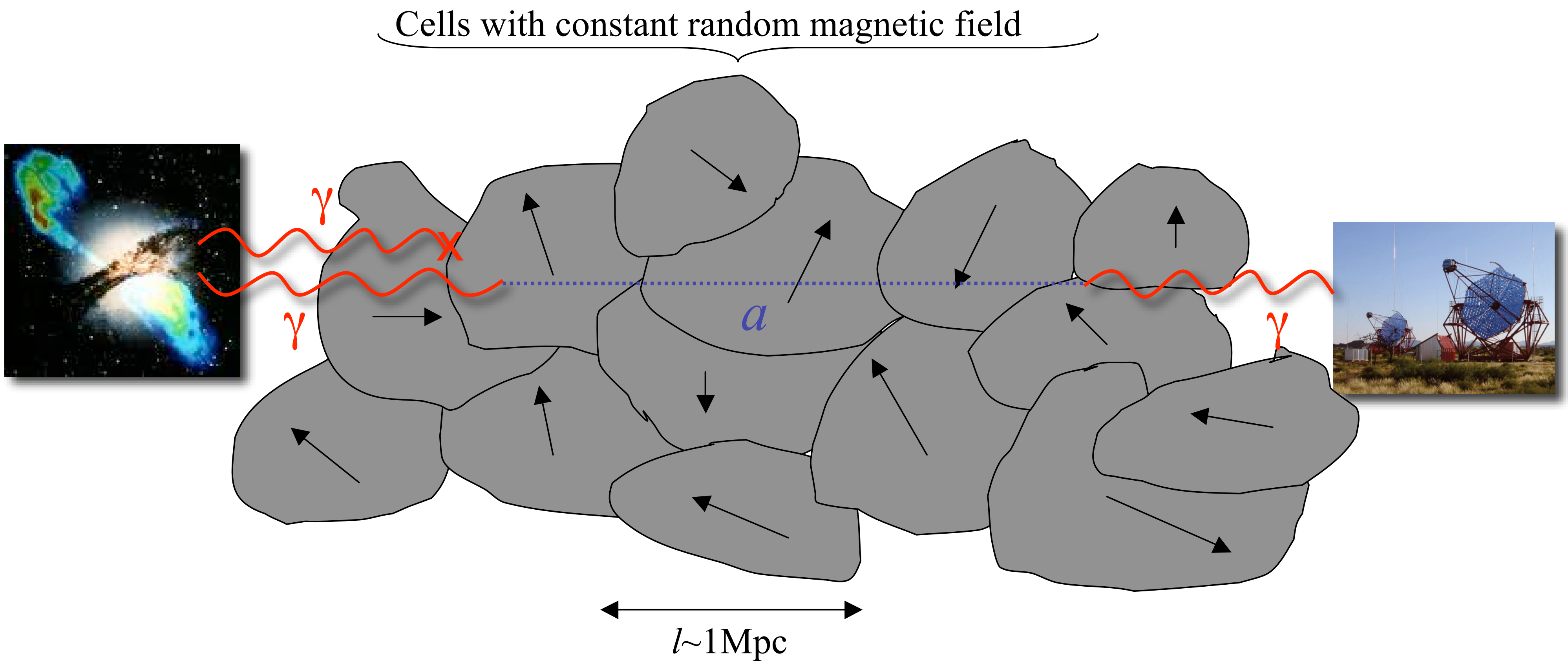


The model has the advantage that gives us the maximal possible transparency compatible with the standard expectations. An evidence of a greater transparency would have to be attributed to nonstandard effects in the photon propagation. For the power law fit we have

$$\frac{\Gamma_\gamma(E)}{\mathrm{Mpc}^{-1}} \simeq 1.1 \times 10^{-3} \times \left(\frac{E}{\mathrm{TeV}}\right)^{1.55}$$

Cell model

For the intergalactic magnetic field we will assume the "cell model", in which the magnetic field is constant in cells with a typical dimension of about l~1Mpc. For simplicity we assume that the magnetic field strengths and directions are uncorrelated and randomly distributed on the various cells.



Average on the cell configurations

Since we do tot know the actual magnetic field configuration crossed by the magnetic field, is reasonable to average on all possible cell configurations. For this reason is convenient to work in the formalism of density matrix

$$\rho = \begin{pmatrix} A_1 \\ A_2 \\ a \end{pmatrix} \otimes \begin{pmatrix} A_1 & A_2 & a \end{pmatrix}^*$$

For the *k*-th domain the density matrix is given by

$$\rho_k = e^{-i\mathcal{H}_k l} \cdot \rho_{k-1} \cdot e^{i\mathcal{H}_k^\dagger l}$$

During their path with a total length L, photons cross $k = 1 \ldots n$ domains ($n = L/l$) representing a given random realization of B_k and ϕ_k. We perform an ensemble average over all the possible realizations on the domains. Defining this ensemble average as $\overline{\rho}_n = \langle \rho \rangle_{1\ldots n}$ we have

$$\overline{\rho}_n^{ij} = \left\langle \left(e^{-i\mathcal{H}_n l} \cdot \rho_{n-1} \cdot e^{i\mathcal{H}_n^\dagger l} \right)_{ij} \right\rangle_{1\ldots n} = \left\langle \left(e^{-i\mathcal{H}_n l} \right)_{ir} \left(e^{i\mathcal{H}_n^\dagger l} \right)_{sj} \right\rangle_n \cdot \overline{\rho}_n^{rs}$$

Transfer function

Defining $T_\gamma = \overline{\rho}^{11} + \overline{\rho}^{22}$ as the mean transfer function for the (unpolarized) photon and $T_a = \overline{\rho}^{aa}$ for the axion, and using the fact that $\overline{\rho}_{n+1} - \overline{\rho}_n \approx l \cdot \partial_3 \overline{\rho}(x_3)$ we obtain the evolution equation (at second order in $\mathcal{H}l$) for the mean transfer functions

$$\frac{\partial}{\partial x_3}\begin{pmatrix} T_\gamma \\ T_a \end{pmatrix} = \frac{P_{a\gamma}}{l}\begin{bmatrix} -\left(\alpha + \frac{1}{2}\right) & 1 \\ \frac{1}{2} & -1 \end{bmatrix}\begin{pmatrix} T_\gamma \\ T_a \end{pmatrix}$$

where $P_{a\gamma} = g_{a\gamma}\langle|\mathbf{B}|^2\rangle l^2/6$ is the average photon-axion conversion probability in each cell and $\alpha(x_3) = \Gamma_\gamma l/P_{a\gamma}$ is the ratio between the absorption and the conversion probability in each cell. Using the variable $dy = P_{a\gamma} dx_3/l$, for a constant α and for an initial photon state we obtain the solution

$$T_\gamma(y) = e^{-\nu y}\left[\cosh \kappa y + \frac{1 - 2\alpha}{4\kappa}\sinh \kappa y\right]$$

$$\nu = \frac{\alpha}{2} + \frac{3}{4}, \quad \kappa = \sqrt{\nu^2 - \alpha}, \quad y = \frac{P_{a\gamma} x_3}{l}.$$

For $\alpha = 0$ (no absorption) we recover the well known formula (Csaki-Kaloper-Terning, 2002)

$$T_\gamma = \frac{2}{3} + \frac{1}{3} e^{-3y/2} = \frac{2}{3} + \frac{1}{3} e^{-3P_{a\gamma} x_3 / 2l}$$

For $\alpha >> 1$ (strong absorption) we obtain

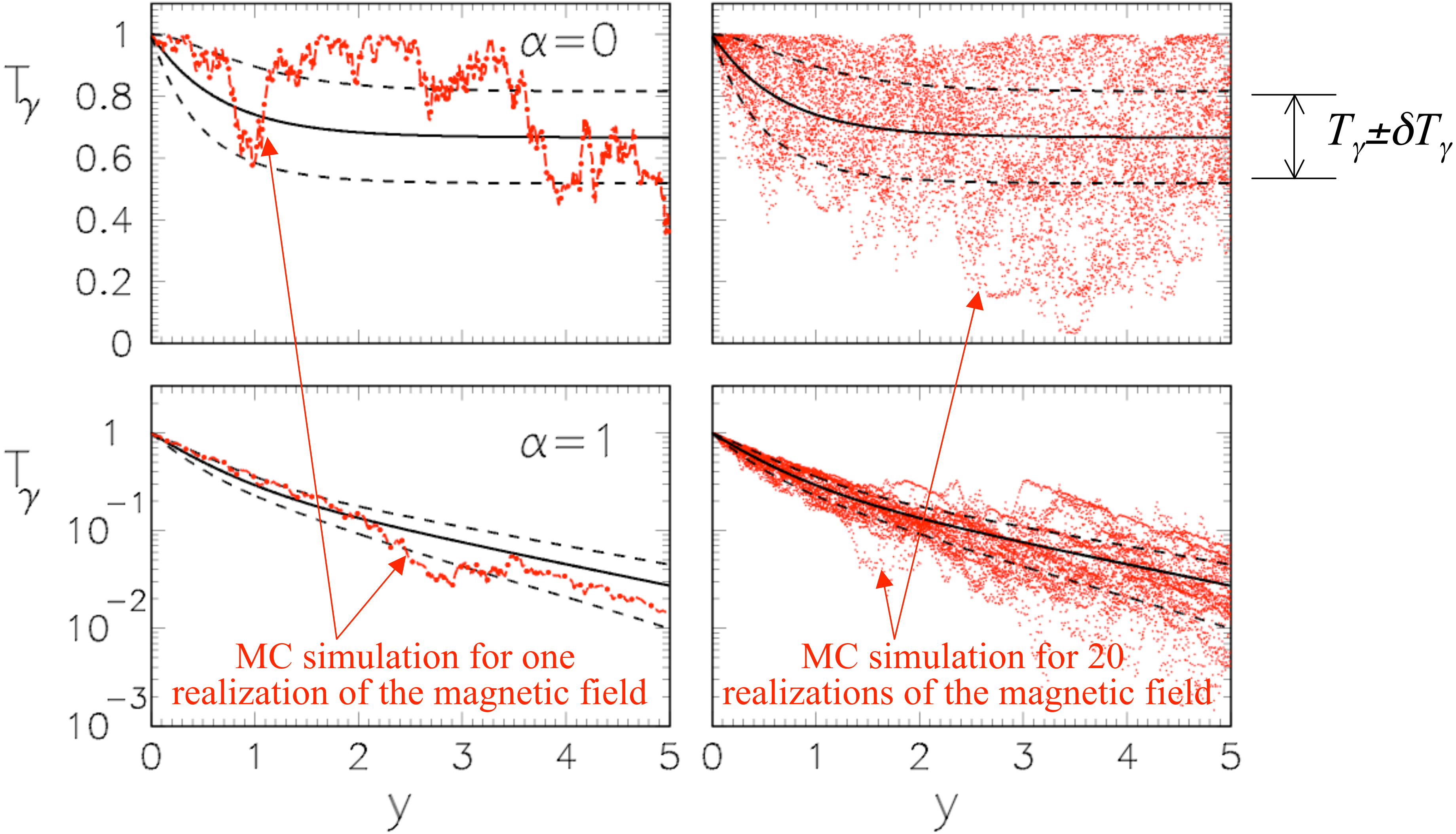
$$T_\gamma \simeq \frac{1}{2\alpha^2} e^{-y} = \frac{P_{a\gamma}^2}{2\Gamma_\gamma^2 l^2} e^{-\Gamma_\gamma x_3/\alpha}$$

Using the approximate expression $\Gamma_\gamma(E) \propto E^{1.55}$ we notice that the transfer function drops only as a power law of the energy rather then exponentially (notice that the argument of the exponential is energy-independent).

Moreover, also the attenuation of the transfer function with the distance is less than in the case of absence of conversions since the argument of the exponential (the optical depth) is suppressed by a factor $1/\alpha$ respect to the no-conversion case.

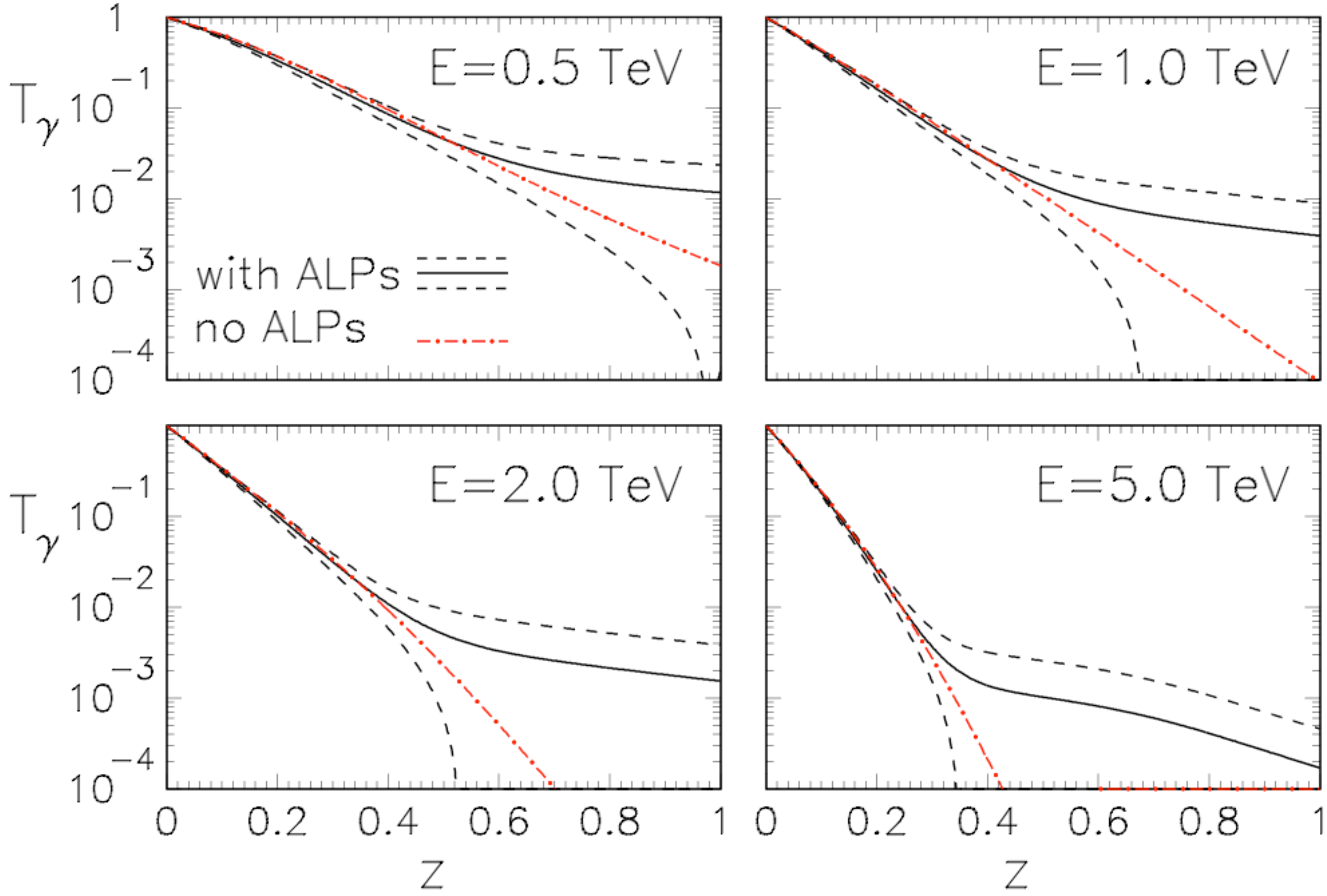
Standard deviation

With the same procedure we can also find the evolution equation for the higher momenta (by calculating the average $\langle\rho\otimes\rho\otimes\ldots\otimes\rho\rangle$). In particular we can calculate the "1σ" uncertainty on the transfer function by calculating $\delta T_\gamma = [\langle T_\gamma^2\rangle - T_\gamma^2]^{1/2}$.



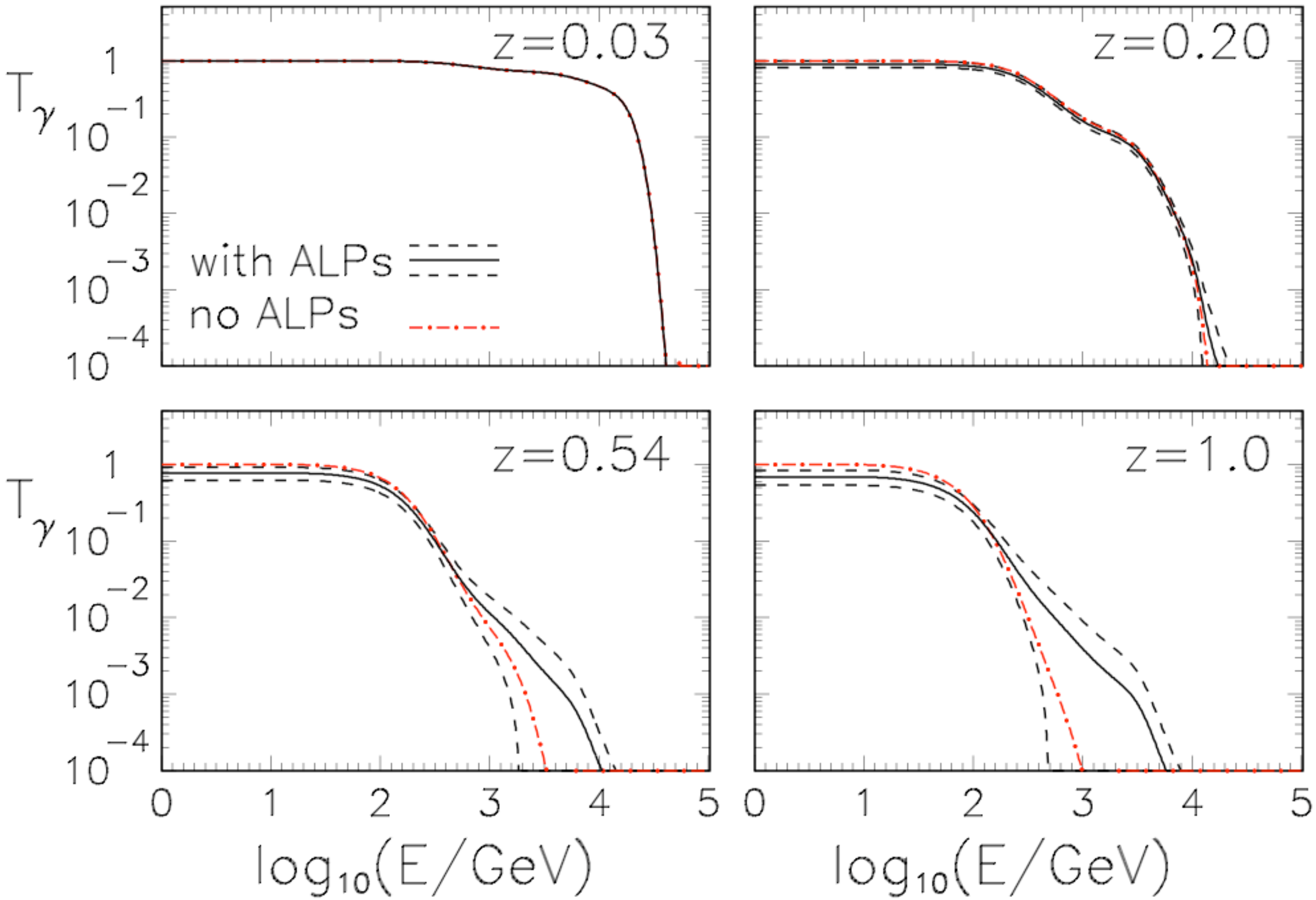
Realistic transfer function

For realistic applications we must take into account the evolution of the EBL and of the magnetic fields as well as of the redshift of the photon energy. We assume that magnetic field are “frozen”, i.e., they evolve simply as $B(z) = B_0(1+z)^2$ (due to the flux conservation) and the coherence length is simply “stretched”: $l(z) = l_0/(1+z)$.

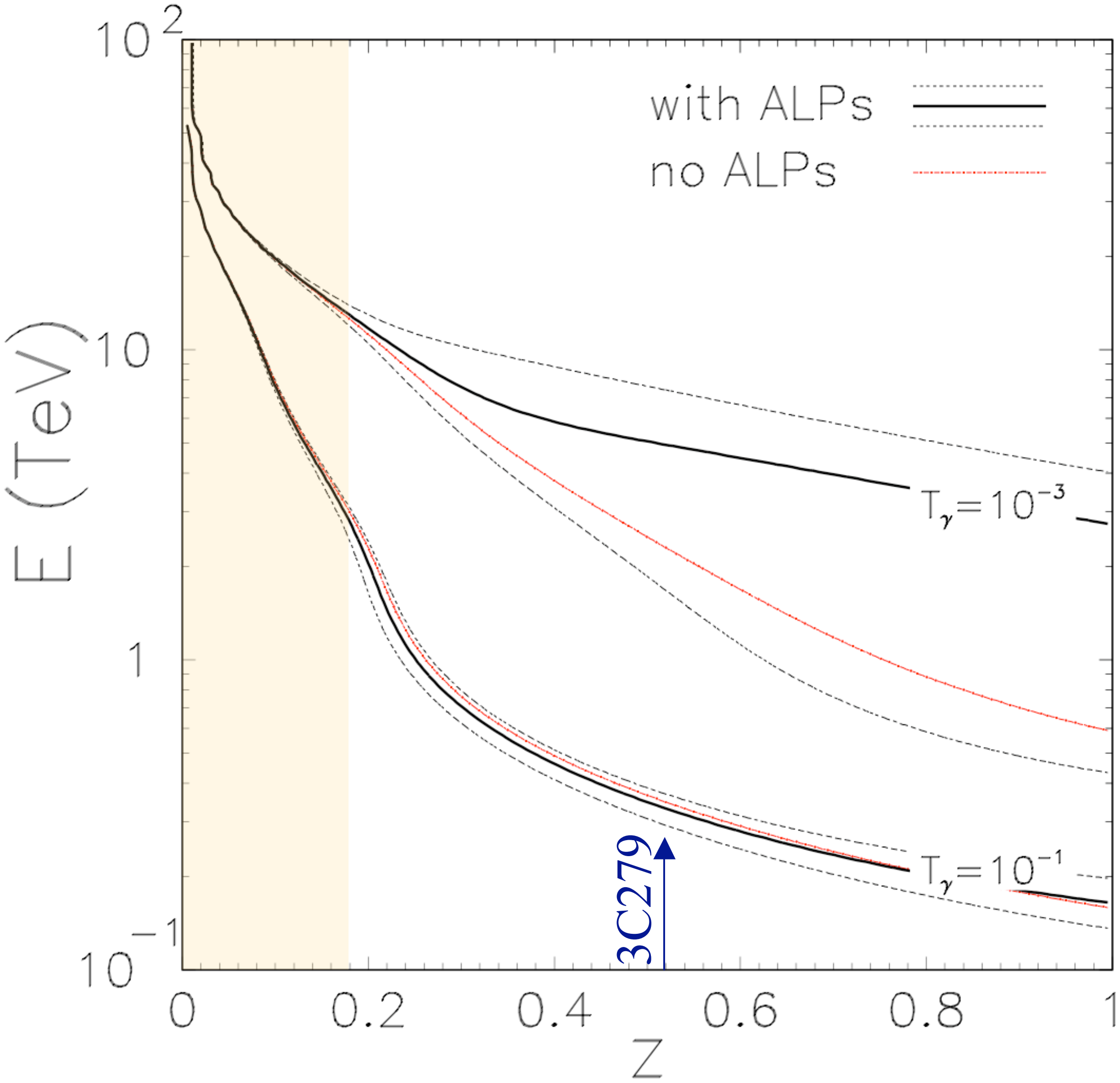


Realistic transfer function

We notice that the effect of mixing with ALPs for VHE photons emitted by distant γ sources would be strongly dependent on the particular realization of the extragalactic magnetic fields crossed by them during their propagation.



Realistic transfer function

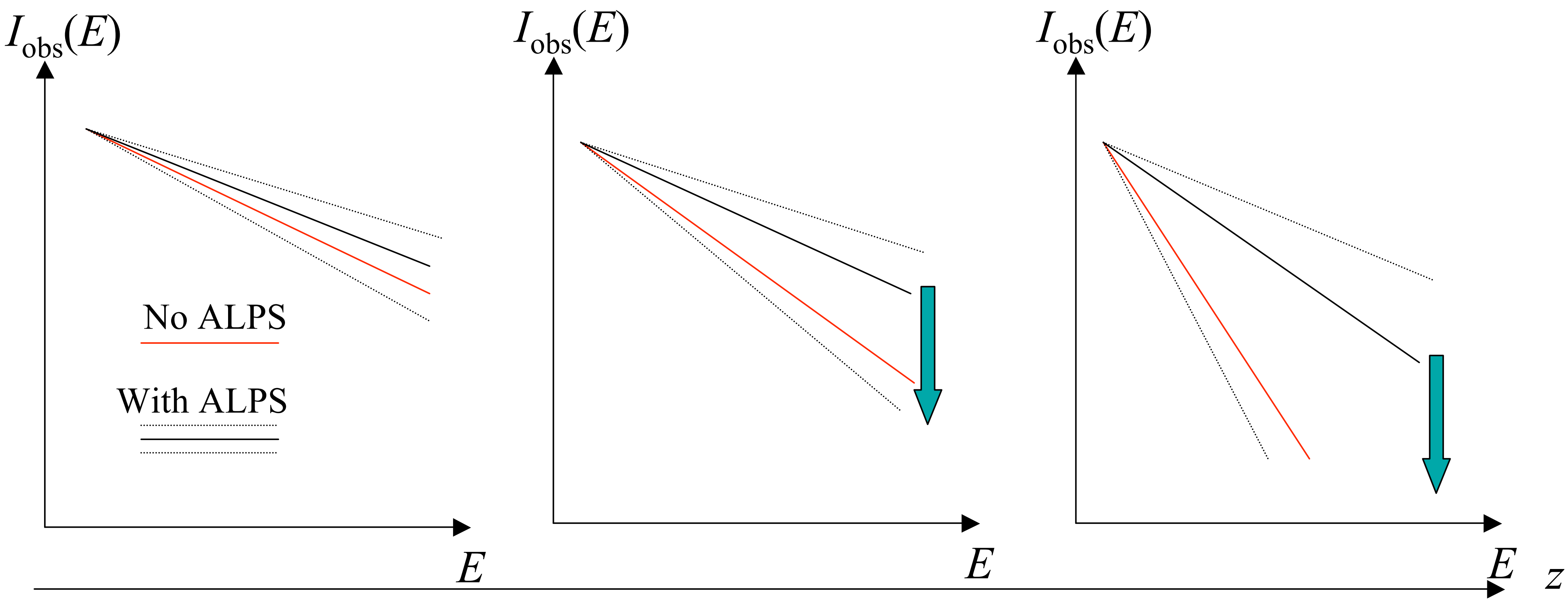


For $z \leq 0.2$ the inclusion of the ALPs does not produce any significant change in the photon transfer function. Thus, it would be difficult to interpret in terms of ALP conversions the presumed transparency to gamma radiations for the sources at $z = 0.165$ and $z = 0.186$.

Conversely, ALP conversions could play a significant role for the source 3C279 at redshift $z = 0.54$

A smoking gun…

- The spectrum of the various sources is harder (on average) than those expected (near sources can be used as "standard candles" for the spectral slope)
- Sources at (almost) same z but in different positions in the sky show a spread in the spectral slope:



…however a big statistics is needed: this is a task for the future of the γ-astronomy!

Conclusions

- ✓ VHE γ-ray observations would open the possibility to probe the existence of axion-like particles
- ✓ Recent observations of cosmologically distant γ-ray sources have revealed a surprising degree of transparency of the universe to VHE photons
- ✓ The oscillations between γ's and ALPs in the random extragalactic magnetic fields have been proposed as an intriguing possibility to explain these observations
- ✓ The turbulent nature of the magnetic field introduces a complication in the treatment of the problem. In the past, brute force numerical simulations have been implemented (Csaki et al., 2003; De Angelis-Mansutti-Roncadelli, 2007). We have developed a simple method based on a differential equation for the mean and the variance of the transfer function T_γ
- ✓ We have also found that T_γ presents a relevant dispersion around the mean value due to the randomness of the extragalactic magnetic fields crossed by the photons
- ✓ The most striking signature of the mixing with ALPs would be a reconstructed EBL density from TeV photon observations which appears to vary over different directions of the sky
- ✓ To test this effect we would need to collect data from sources along different directions in the sky in order to perform a study of the photon energy distributions

THANK YOU!