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Hints for an axion-like particle from PKS 1222+216?

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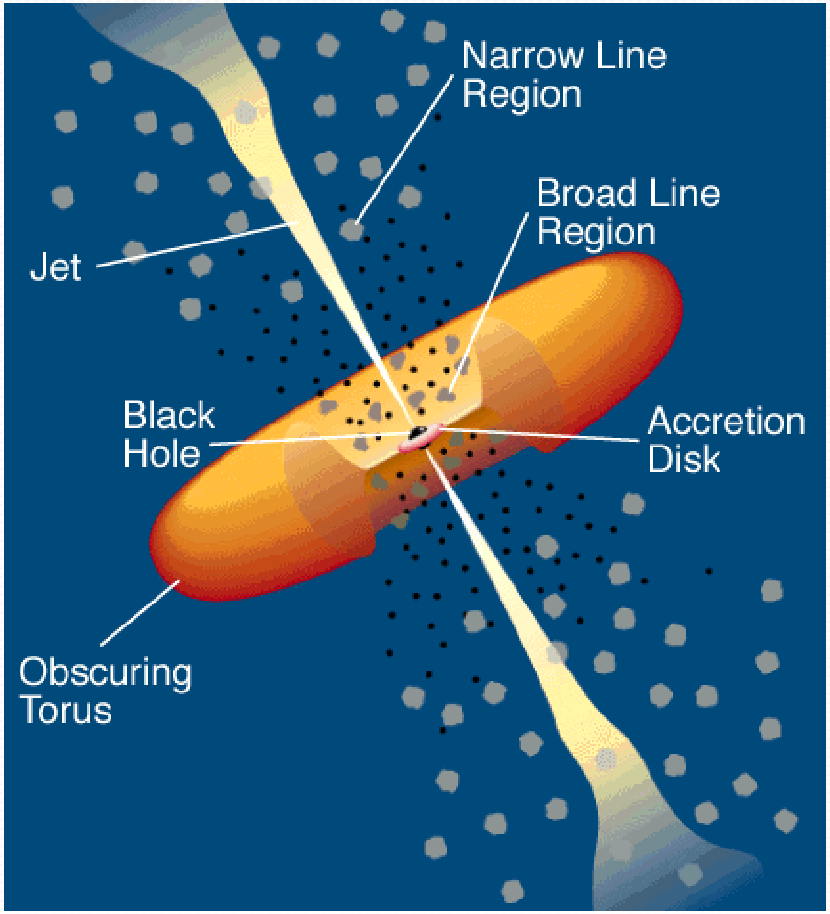
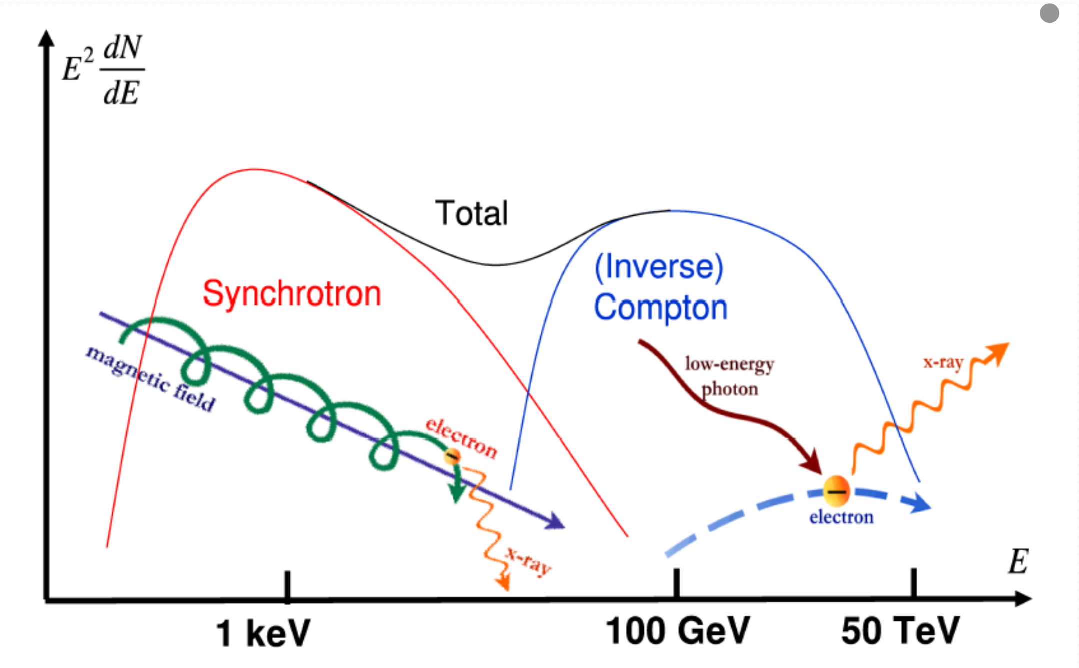
Active Galactic Nuclei

Active Galactic Nuclei (AGNs)



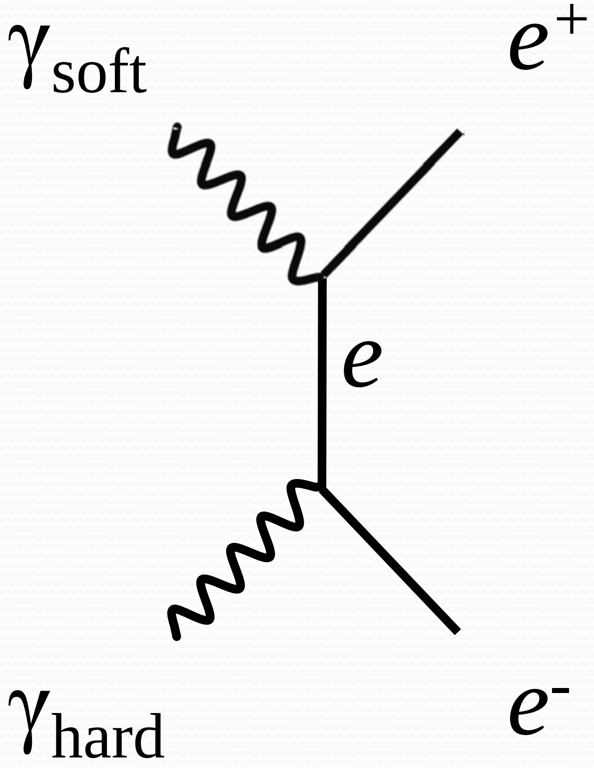
- Accreting ***supermassive black holes*** (10^6-10^9 M_{sun}) inside most galaxies
- Collimated ***jets*** develop, if towards us: AGNs called ***blazars***
- Blazars divided into ***BL Lacs*** and ***FSRQs***
- ***FSRQs*** show broad optical lines → existence of the ***BLR*** → high absorption region
- Presence of high ***magnetic fields*** (0.1 – 1 *G*)

AGNs (2)



- ***Leptonic mechanism***
  - Photons generated through ***synchrotron*** emission (E_{ph} ~ infrared-X-ray)
  - e^- interact with photons through an ***inverse Compton scattering*** (***internal*** photons, **SSC model**, AND/OR ***external*** photons (BLR, disc)) (E_{ph} ~ *GeV*-*TeV*)
- Above 0.1 *TeV* blazar spectra can be approximated by using a ***power-law approximation***
- Competitive mechanism → ***hadronic mechanism*** (decay of π^0-mesons into $\gamma\gamma$)

AGN Photon Propagation

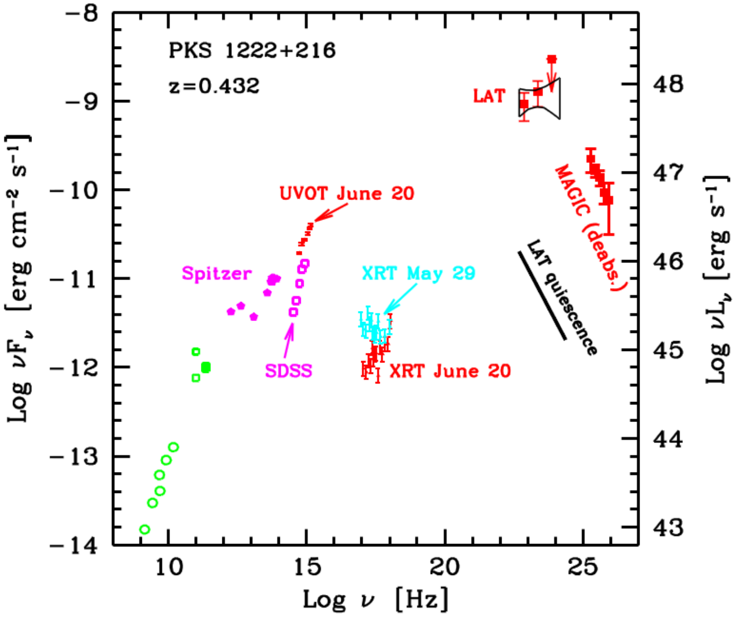


- ***Very-High-Energy*** (VHE) photons from AGNs ***scatter*** on ***background*** (BLR) photons
- ***Pair Production*** ($\gamma\gamma \rightarrow e^+e^-$) with the ***Breit-Wheeler*** cross section

Considered Problem

Possible hints of photon-ALP oscillation mechanism from MAGIC observational data of PKS 1222+216

PKS 1222+216



Tavecchio et al. 2011

- Surrounding of the inner jet in FSRQs ***rich*** of ***optical-UV photons*** emitted by the ***BLR*** therefore:
  - A ***huge optical depth*** for photons above 20-30 *GeV* due to ($\gamma\gamma \rightarrow e^{+}e^{-}$)
  - So above 20-30 *GeV* FSRQs should be ***unobservable***

- **HOWEVER:** an ***intense VHE emission*** from PKS 1222+216 (**Aleksic et al. 2011a**) observed by MAGIC (70 – 400 GeV)
- SIMULTANEOUSLY detected by *Fermi*/LAT (0.3 – 3 GeV)
- MAGIC: ***flux doubling*** in ***only*** about ***10 minutes*** → ***extreme compactness*** of the emitting region → ***difficult fit*** within the AGN ***standard model***

Possible solutions

- Conventional physics solutions:
  - strong ***recollimation*** and ***focusing*** of the ***flow*** (e.g. ***Stawarz et al., 2006***; ***Bromberg & Levinson, 2009***; ***Nalewajko & Sikora, 2009***)
  - ***existence*** of ***very small*** ($r \sim 10^{14}\ cm$) ***emitting region beyond*** the ***BLR*** ($R \sim 10^{18}\ cm$) (e.g. ***Aleksic et al., 2011b***; ***Tavecchio, et al., 2011***)
  - Problematic

- New physics solutions:
  - ***photon-ALP oscillations*** take place ***inside the source*** (***Tavecchio, F., Roncadelli, M., Galanti, G., & Bonnoli, G., Phys. Rev. D, 86, 085036 (2012)***)

Axion-like particles (ALPs)

Axion-like particles (ALPs)

- ***Standard Model*** (SM) → ***low-energy*** manifestation of a ***more fundamental theory*** (FT) of high energy scale

- We infer ***effective theory*** at low energy

- New particles in the effective theory

- Among them, the ***axion***

- Axion → linked to the symmetry proposed as a natural solution of the ***strong CP problem***

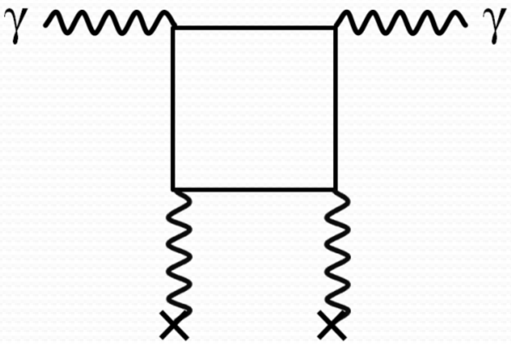
Axion-like particles (ALPs) (2)

- ***ALPs*** have just the same properties of the axion apart from the fact that m and M are unrelated and ***only*** interactions with photons are considered
- With **B** an ***external magnetic field***, ALPs are described by

$$\mathcal{L}_{ALP} = \frac{1}{2}\partial^{\mu} a \partial_{\mu} a - \frac{1}{2} m^2 a^2 + \frac{1}{M}\mathbf{E}\cdot\mathbf{B}a$$

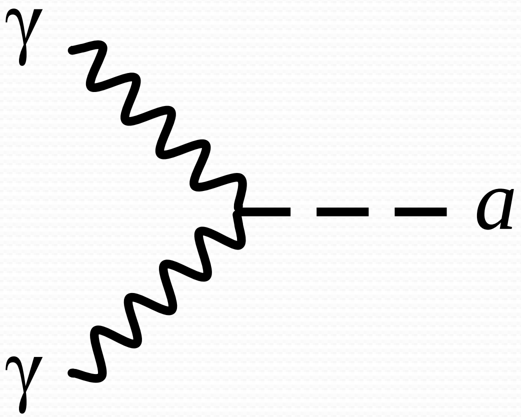
- In addition, Lagrangian accounting for the photon one-loop vacuum polarization

$$\mathcal{L}_{HEW} = \frac{2\alpha^2}{45 m_e^4}\left[(\mathbf{E}^2 - \mathbf{B}^2)^2 + 7(\mathbf{E}\cdot\mathbf{B})^2\right]$$



Axion-like particles (ALPs) (3)

- ALPs are very light pseudo-scalar spin-0 bosons with



$$\mathcal{L}_{int} = \frac{1}{M}\mathbf{E}\cdot\mathbf{B}a$$

- Depending on the values of coupling and mass m, ALPs can be good candidates for either ***nonbaryonic dark matter*** or ***quintessential dark energy***

Photon-ALP Mixing

- Due to the ***γγa vertex***

- Analogous to what happens in the case of massive neutrinos with different flavours

- But here an external magnetic field necessary to compensate the ***spin mismatch*** between photon (spin-1) and ALP (spin-0)

A Model for PKS 1222+216

ALPs from PKS 1222+216?

- VHE photons emitted by PKS 1222+216 suffer:
    - ***absorption*** due to the BLR
    - ***photon-ALP oscillation***
- **Photons can be absorbed (finite mean free path) while ALPs propagate unimpeded**
- BLR absorption ***decreases*** the VHE photon ***mean free path*** → flux dimming
- Photon-ALP oscillation mechanism ***increases*** the photon ***effective mean free path*** → flux enhancement

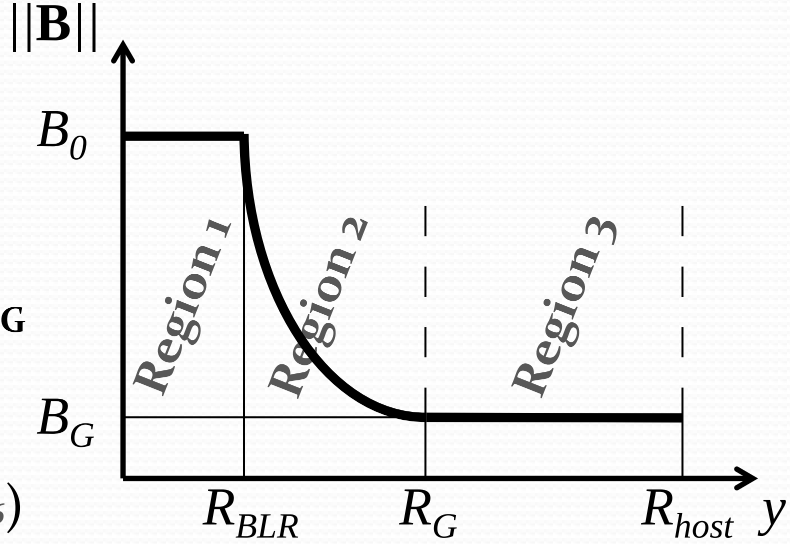
$$P_{\gamma\to\gamma}(E,D) = e^{-D/\lambda_\gamma(E)}$$

A Model for PKS 1222+216

- Magnetic field $\mathbf{B}(y)$:
  - Constant in the BLR
  - Decreasing like $1/y$ until galactic field $\mathbf{B_G}$
  - Constant but turbulent until galaxy border (elliptical galaxy) (*Moss & Shukurov, 1996*)
- Luminosity: $L_D \approx 1.5 \cdot 10^{46}\ erg \cdot s^{-1}$
- BLR radius: $R_{BLR} \approx 0.23\ pc$
- BLR cloud number density: $n_c \approx 10^{10}\ cm^{-3}$
- BLR cloud temperature: $T_c \approx 10^4\ K$

BUT

- Lower effective number density: $n_e \approx 10^4\ cm^{-3}$



$||\mathbf{B_0}|| = 0.1 - 1\ G$

$||\mathbf{B_G}|| = 5\ \mu G$

$R_{BLR} \approx 0.23\ pc$

$R_G \approx 6.7\ kpc$

$R_{host} \approx 10\ kpc$

A Model for PKS 1222+216 (2)

- Energy range of interest: $1\ GeV < E < 600\ GeV$
- ALP mass: $m < 10^{-9} - 10^{-10}\ eV$

IDEA:

- Photons produced by a ***standard*** AGN emission mechanism
- Photons become mostly ***ALPs in the BLR*** thanks to the ***jet magnetic field***
- ***ALPs*** go ***UNIMPEDED*** through the BLR
- Outside the BLR ***ALPs reconvert*** into ***photons*** in the ***outer magnetic field***

AS A RESULT:

- ***LOWER*** effective ***optical depth***
- ***STANDARD SED*** (*Fermi*/LAT + MAGIC data)

Calculation Scheme

- We start with an unpolarized beam
- We calculate the transfer matrixes U_1, U_2, U_{3n} in all 3 regions
- We calculate the total transfer matrix U_n

$$U_n\left(R_{host}, 0; \phi_{1_n} \cdots \phi_{N_n}\right) = U_{3_n}\left(R_{host}, R_G; \phi_{1_n} \cdots \phi_{N_n}\right) U_2(R_G, R_{BLR}) U_1(R_{BLR}, 0)$$

- We calculate the photon survival probability

$$P_{\gamma\to\gamma}(y) = \sum_{i=x,z} \langle \mathrm{Tr}\left(\rho_i U_n(y,0) \rho_{unp} U_n^{\dagger}(y,0)\right)\rangle_n$$

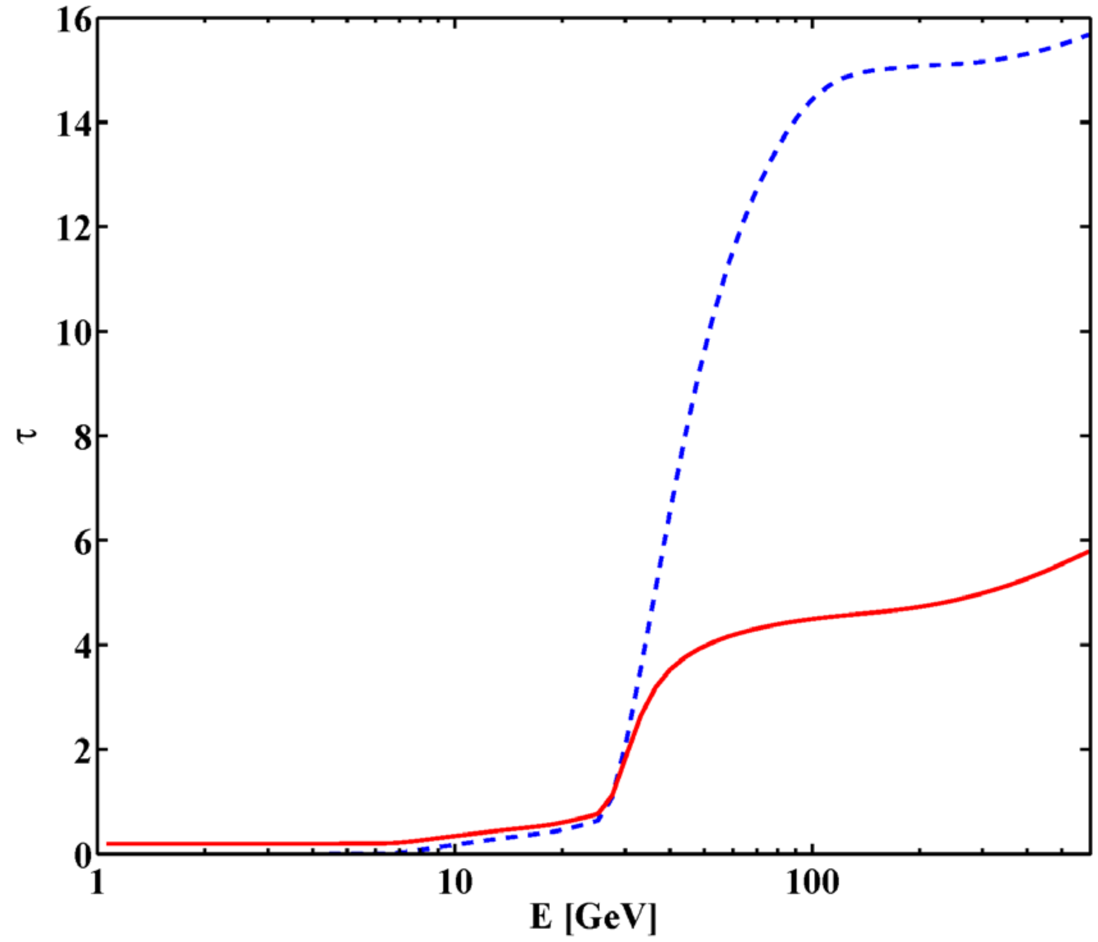
ρ beam polarization density matrix

- We calculate the intrinsic flux F_{int} in relation with the EBL-deabsorbed one F_{obs}

$$F_{int} = F_{obs}/P_{\gamma\to\gamma}$$

Results

Results – γγ Optical Depth



Conventional physics

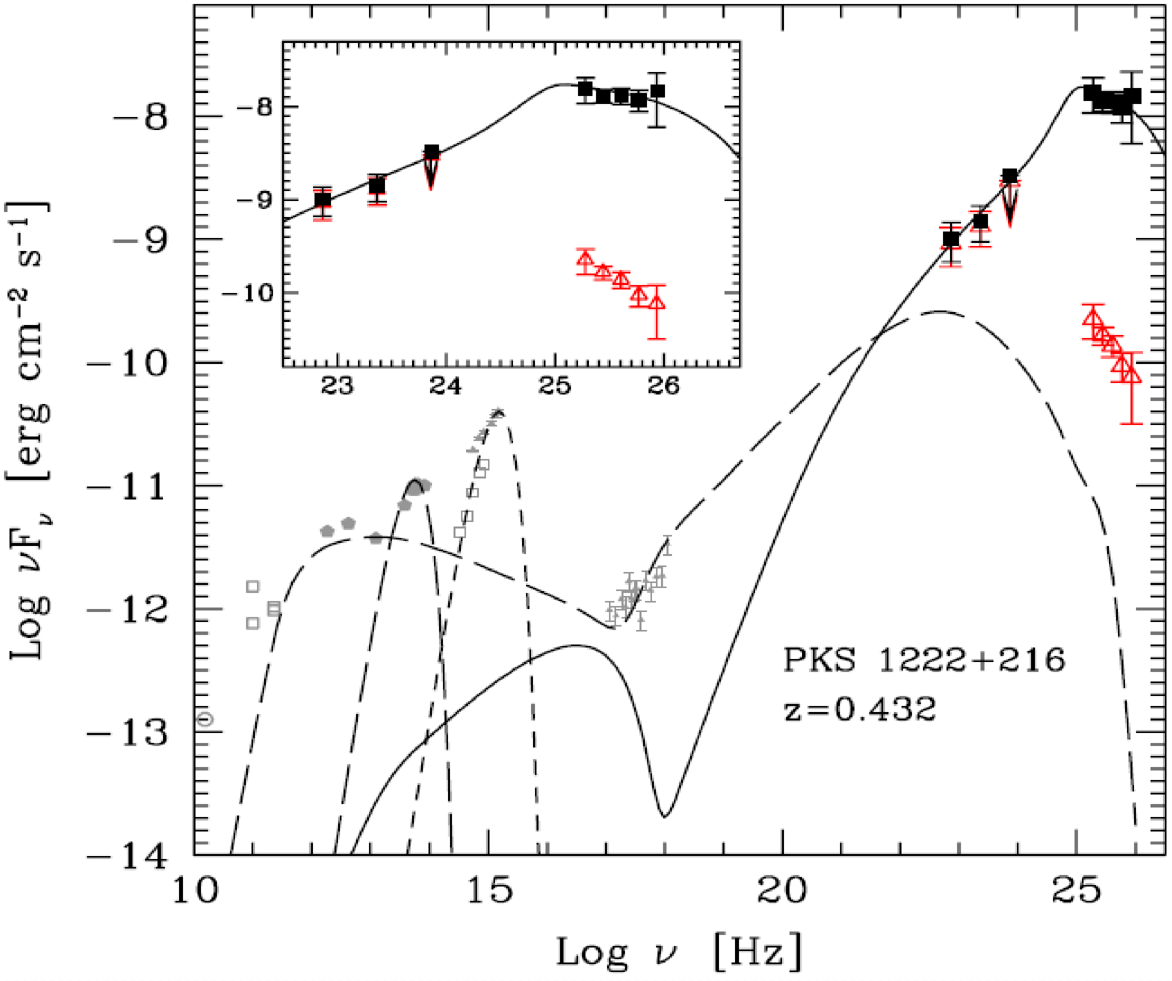
γ-ALP conversion

$||\mathbf{B}_0|| = 0.2\ G$

$||\mathbf{B}_{0_T}|| = 0.14\ G$

$M = 7 \cdot 10^{10}\ GeV$

Results (2) – SED



△ ***EBL-deabsorbed spectrum (Conv. physics)***

■ ***EBL-deabsorbed spectrum + γ-ALP conversion***

$||\mathbf{B}_0|| = 0.2\ G$

$||\mathbf{B}_{0_T}|| = 0.14\ G$

$M = 7 \cdot 10^{10}\ GeV$

Conclusions

Conclusions

- ***No photon-ALP*** conversion → ***two emission regions***
  - One ***inside*** the BLR (IR to X-ray emission)
  - The other ***outside*** the BLR (γ-ray emission)
- ***Photon-ALP conversion*** → ***both*** the emission regions ***inside*** the BLR
- Explanation of PKS 1222+216 ***within*** AGN ***conventional models***
- ***Standard SED*** (*Fermi*/LAT + MAGIC data)
- Same "photon-ALP" parameters as those of photon-ALP conversion in the extragalactic space (***De Angeli A., Galanti G., Roncadelli M., 2011, Phys. Rev. D84***)
- Scenario applicable also to other VHE FSRQs ***3C279***, ***PKS 1510-089***
- TEST → feature in the optical thin/thick transition in the spectrum
- ***ALPs*** with these properties ***detectable*** by experiment ***ALPS at DESY***

Thank you for attention

BACKUP SLIDES

Photon-ALP Mixing

Photon-ALP Mixing

- We consider a photon/ALP beam with energy E which propagates along y in a medium with the following properties:
  - presence of a magnetic field **B**
  - ionized matter
  - photons can be absorbed (finite mean free path) while ALPs propagate unimpeded
- The beam ***propagation equation*** by using the short-wavelength approximation (justified in the case of $E >> m$), becomes

$$\left(i\frac{\partial}{\partial y}+E+\mathcal{M}\right)\psi(y)=0 \qquad \psi(y)=\begin{pmatrix}A_x(y)\\A_z(y)\\a(y)\end{pmatrix}$$

$$\psi(y)=U(y,y_0)\psi(y_0)$$

$$U(y_0,y_0)=1$$

where $\mathcal{M}$ is the photon-ALP ***mixing matrix***

The beam is described as a nonrelativistic 3-level unstable quantum system

Photon-ALP Mixing (2)

- The mixing matrix reads

$$\mathcal{M} = \begin{pmatrix} \Delta_{xx} & \Delta_{xz} & \Delta_{a\gamma}^{x} \\ \Delta_{zx} & \Delta_{zz} & \Delta_{a\gamma}^{z} \\ \Delta_{a\gamma}^{x} & \Delta_{a\gamma}^{z} & \Delta_{aa} \end{pmatrix}$$

$$\Delta_{xx,zz} = \Delta_{abs} + \Delta_{pl} + \Delta_{xx,zz}^{QED}$$

$$\Delta_{xz} = \Delta_{zx} = 0$$

$$\Delta_{a\gamma}^{x,z} = B_{x,z}/2M$$

$$\Delta_{aa} = -m^2/2E$$

where

$$\Delta_{abs} = -i/2\lambda_\gamma$$

$$\Delta_{pl} = -\omega_{pl}^2/2E$$

$$\Delta_{xx}^{QED} = \frac{4}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2 E$$

$$\Delta_{zz}^{QED} = \frac{7}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2 E$$

Photon-ALP Mixing (3)

- Considering $B_T = B_z$ and no absorption

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

and defining

$$\Delta_{osc} \equiv \left[\left(\Delta_{zz} + \frac{m^2}{2E} \right)^2 + \left(\frac{B_T}{M} \right)^2 \right]^{\frac{1}{2}} \qquad L_{osc} = 2\pi/\Delta_{osc}$$

we can get

$$P_{\gamma_z \to a}(y) = \left(\frac{B_T}{M\Delta_{osc}} \right)^2 sin^2 \left(\frac{\Delta_{osc}}{2} y \right)$$

Photon-ALP Mixing (4)

- ***Small-probability regime*** if $y \ll L_{osc}/\pi$

$$P_{\gamma_z \to a}(y) \cong \left(\frac{B_T}{2M} y\right)^2$$

- ***Strong-mixing regime*** if $\left|\Delta_{zz} + \frac{m^2}{2E}\right| \ll \frac{B_T}{M}$
  - Plasma and “QED” terms ***not*** relevant
  - Probability ***energy-independent*** between two cut-off energies

$$P_{\gamma_z \to a}(y) \cong sin^2\left(\frac{B_T}{2M} y\right)$$

- ***Weak-mixing regime*** if outside the two cut-off energies
  - Plasma term is relevant at ***low*** energies
  - “QED” term is relevant at ***high*** energies

Photon-ALP Mixing (5)

- In the case of a unpolarized beam the generalized ***polarization density matrix*** must be introduced

$$\rho(y) = \begin{pmatrix} A_x(y) \\ A_z(y) \\ a(y) \end{pmatrix} \otimes \begin{pmatrix} A_x(y) & A_z(y) & a(y) \end{pmatrix}^*$$

it obeys the Liouville-Von Neuman equation

$$i\frac{\partial \rho}{\partial y} = \rho \mathcal{M}^\dagger - \mathcal{M}\rho$$

- The ***probability*** that a photon/ALP beam initially in the state ρ_1 will be found in the state ρ_2 after a distance y is

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

REMARK:

- The photon-ALP mixing is maximal and energy independent in the ***strong-mixing*** regime

Astrophysical Implications

- ***Astronomical observations*** can provide bounds on the values of the ALP mass m and of M
- ***CAST*** (no ALP from Sun) → $M > 0.86 \cdot 10^{10}\ GeV$ for $m < 0.02\ eV$
- Theoretical considerations about ***ALP emission from stars*** provides $M > 10^{10}\ GeV$
- $M > 10^{11}\ GeV$ for $m < 10^{-10}\ eV$ ***with large uncertainty*** (SN1987A)
- ***Pair-production anomaly*** and analyses about ***extragalactic magnetic field*** confirm the importance of photon-ALP oscillations (***Horns & Meyer, 2012***; ***Finke et al., 2013***)

A Model for PKS 1222+216

A Model for PKS 1222+216

- Energy range of interest: $1\ GeV < E < 600\ GeV$

- ALP mass: $m < 10^{-9} - 10^{-10}\ eV$

- Recalling the mixing matrix

$$\mathcal{M} = \begin{pmatrix} \Delta_{xx} & \Delta_{xz} & \Delta_{a\gamma}^{x} \\ \Delta_{zx} & \Delta_{zz} & \Delta_{a\gamma}^{z} \\ \Delta_{a\gamma}^{x} & \Delta_{a\gamma}^{z} & \Delta_{aa} \end{pmatrix}$$

- In all the regions we can write

$$\Delta_{xz} = \Delta_{zx} = 0$$

Region 1

- In the strong mixing regime for $E < 20\ GeV$
- Plasma and ALP mass terms are negligible
- "QED" term not negligible for $E > 20\ GeV$ (high $||\mathbf{B_0}||$)
- $||\mathbf{B}(y)|| = ||\mathbf{B_0}||$

$$\Delta_{xx,zz} = \Delta_{abs} + \Delta_{xx,zz}^{QED} \qquad \Delta_{aa} = 0$$

$$\Delta_{xx}^{QED} = \frac{4}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2 E \qquad \Delta_{zz}^{QED} = \frac{7}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2 E$$

$$\Delta_{abs} = -i/2\lambda_\gamma^{BLR} \qquad \Delta_{a\gamma}^{x,z} = B_{0_{x,z}}/2M$$

- We can analytically calculate the transfer matrix

$$U_1(R_{BLR}, 0)$$

Region 2

- In the strong mixing regime for all energies
- No absorption
- $||\mathbf{B}(y)|| = ||\mathbf{b}_y||/y$

$\Delta_{xx} = \Delta_{zz} = 0 \qquad \Delta_{aa} = 0$

$\Delta_{a\gamma}^{x,z} = b_{y_{x,z}}/2My$

- We can analytically calculate the transfer matrix

$U_2(R_G, R_{BLR})$

Region 3

- In the strong mixing regime for all energies
- No absorption
- $||\mathbf{B}(y)|| = ||\mathbf{B_G}||$ with domain-like structure ($L_{dom} = 150\ pc$)
- Same strategy of the DARMA model

De Angeli A., Galanti G., Roncadelli M., 2011, Phys. Rev. D84

$$\Delta_{xx} = \Delta_{zz} = 0 \qquad \Delta_{aa} = 0$$

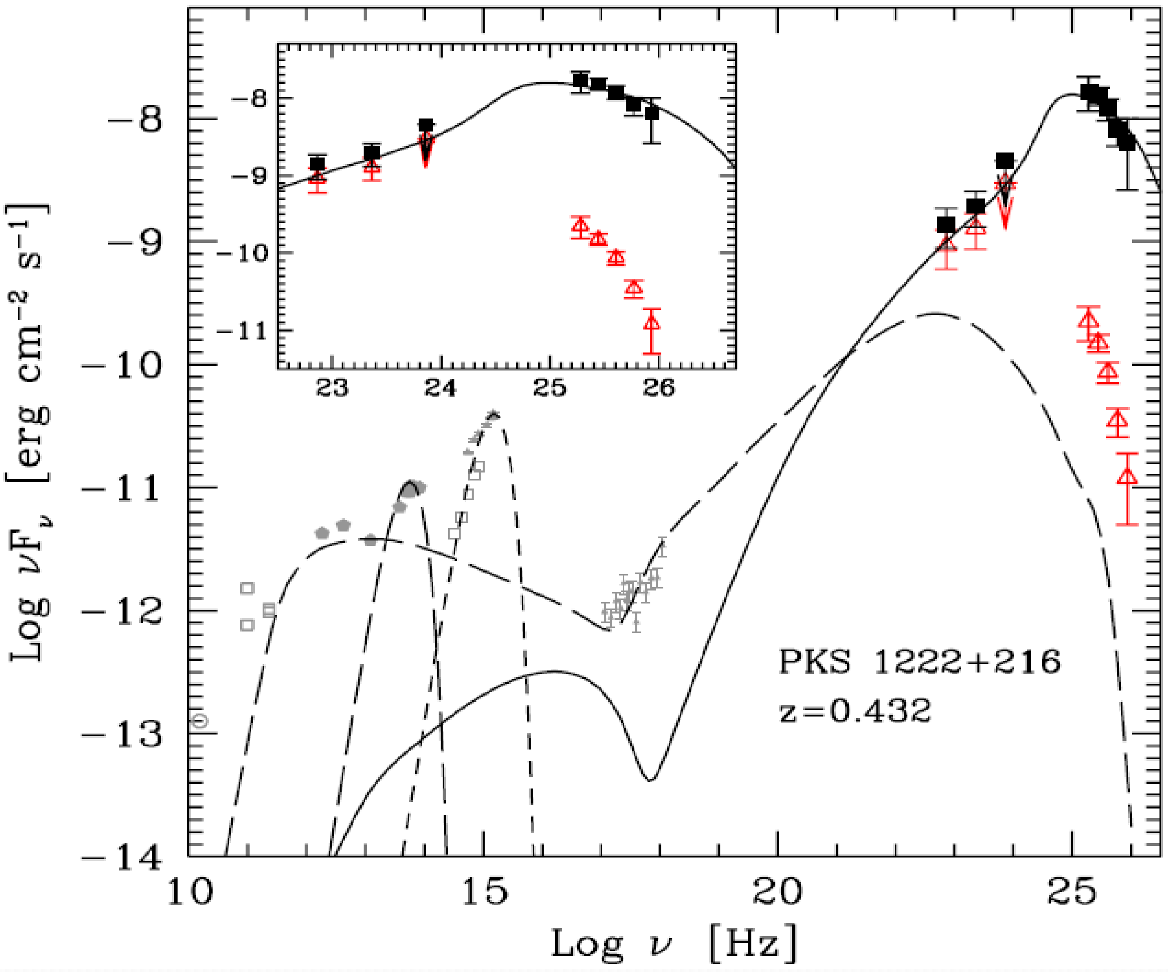
$$\Delta_{a\gamma}^{x,z} = B_{G_{x,z}}/2M$$

- Iterating and averaging we can calculate the transfer matrix

$$U_{3_n}(R_{host}, R_G; \phi_{1_n} \cdots \phi_{N_n})$$

Results

Results – SED



△ ***NON-EBL-deabsorbed spectrum***

■ ***DARMA-deabsorbed spectrum + γ-ALP conversion***

$||\mathbf{B}_0|| = 0.2\ G$

$||\mathbf{B}_{0_T}|| = 0.14\ G$

$||\mathbf{B}_{exG}|| = 0.7\ \mathrm{n}G$

$M = 7 \cdot 10^{10}\ GeV$

EBL and Cosmic B

Extragalactic Background Light (EBL)

- Direct product of the ***stellar radiation*** and ***light absorbed and reradiated*** by the ***dust*** during the whole cosmic evolution
- Several models of EBL based either on ***observations*** or on ***semi-analytic models*** of the galactic formation process
- The observational model of ***Franceschini et al.***, 2008 is used here

EBL (2)

- VHE photons (of energy E) ***scatter*** on the EBL ones (of energy ε) producing ***e^+e^- pairs***

- This effect important above 100 GeV and maximal for

$$\varepsilon(E) \cong \left(\frac{500\ GeV}{E}\right)\ eV$$

- Cosmic opacity dominated by the interaction with the EBL photons with $0.005\ eV < \varepsilon < 5\ eV$ for $100\ GeV < E < 100\ TeV$

Cosmic magnetic fields

- Their ***morphology*** is ***unknown***
- One supposes a ***domain-like structure***
  - $||\mathbf{B}||$ ***constant*** over a domain of size L_{dom} (equals to its coherence length)
  - $\mathbf{B}$ ***randomly*** changes ***direction*** from one domain to another
- Allowed range is $||\mathbf{B}|| \leq 6\ nG$, plausible range $1\ Mpc \leq L_{dom} \leq 10\ Mpc$

DARMA Scenario

DARMA Scenario

- VHE photons emitted by distant sources suffer:
  - ***absorption*** due to the EBL
  - ***photon-ALP oscillation***
- EBL absorption ***decreases*** the VHE photon ***mean free path*** → flux dimming
- Photon-ALP oscillation mechanism ***increases*** the photon ***effective mean free path*** → flux enhancement

$$P_{\gamma\to\gamma}(E,D) = e^{-D/\lambda_\gamma(E)}$$

DARMA Scenario (2)

- VHE photon propagation in the ***strong mixing*** regime ($m < 10^{-10}\ eV$) ($100\ GeV < E < 100\ TeV$)
- Correspondingly the photon-ALP ***mixing matrix*** takes the form

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

DARMA Scenario (3)

- We fix an overall fiducial direction equal for all domains
- We consider a random direction for **B** in each domain
- We evaluate analytically the beam propagation over ***a single domain*** (propagation in an homogeneous magnetic field)
- We ***iterate*** such a propagation as many times as the number of domains crossed by the beam

DARMA Scenario (4)

- This procedure must be repeated many times randomly changing the direction of **B** in each domain
- We ***average*** all the realizations of the propagation process over all the considered directions of **B**
- In this way we get the ***photon survival probability*** $P_{\gamma \to \gamma}(E, z)$