Possible indirect evidence for axion-like particles from far away AGN?

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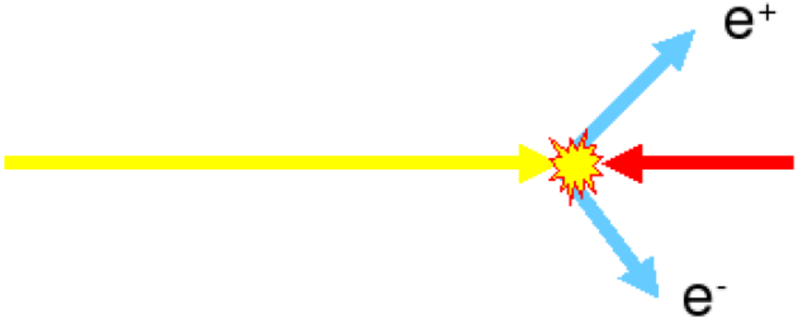
- Photon propagation
- Observation of distant AGN
- Axion-Like Particles & the DARMa scenario
- Conclusions

The work on axions has been done in collaboration with M. Roncadelli, O. Mansutti and M. Persic

Intergalactic absorption of VHE photons

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

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



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

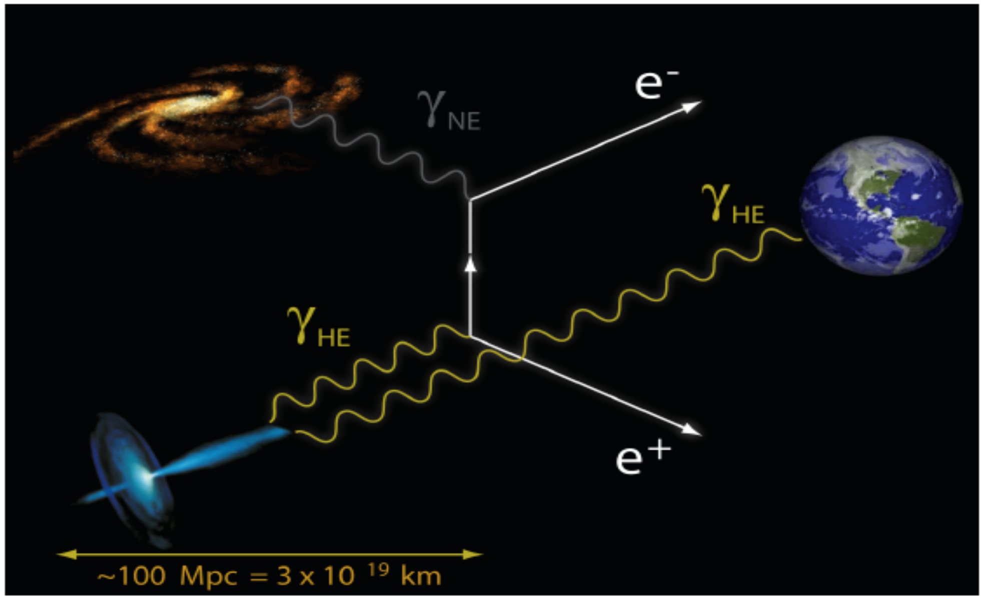
(Heitler 1960)

Around the TeV region:

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

$$\Downarrow$$

Cross section maximized
for infrared/optical photons
(Extragalactic Background Light)



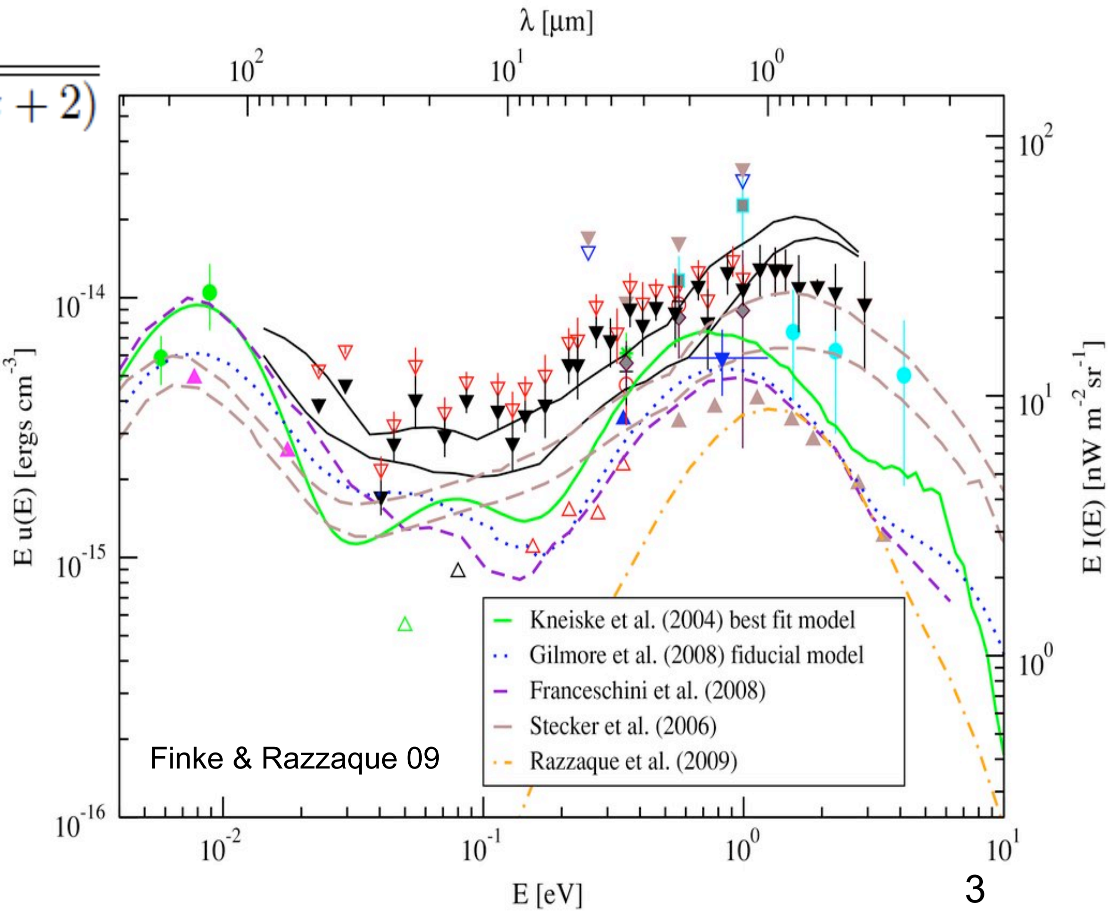
What is the attenuation?

$$\Phi_{\rm obs}(E,z) \equiv \Phi_{\rm em}(E) \times e^{-\tau(E,z)}$$

$$\tau(E,z) = \int_0^z dl(z) \int_{-1}^{1} d\cos\theta \frac{1-\cos\theta}{2} \int_{E_{thr(E,\theta)}}^{\infty} d\epsilon(z)\, n_\epsilon(\epsilon(z),z)\, \sigma(E(z),\epsilon(z),\theta)$$

$$\frac{dl}{dz} = \frac{c}{H_0} \frac{1}{(1+z)\sqrt{(1+z)^2(\Omega_M z+1) - \Omega_\Lambda z(z+2)}}$$

- n_ε (ε,z) is the spectral energy density of background photons ←EBL

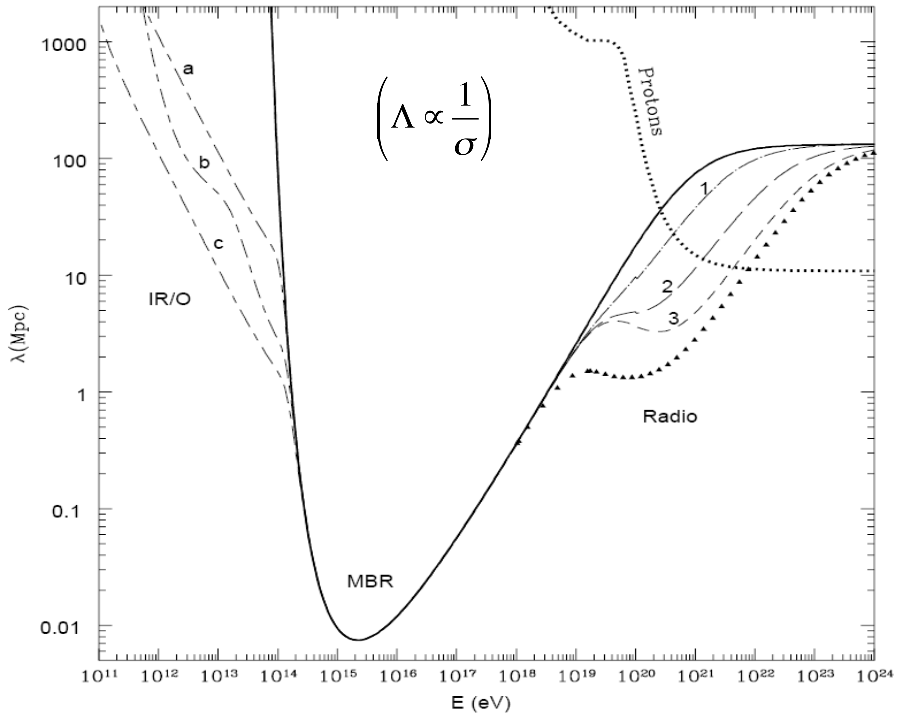


(An approximation)

- Neglecting evolutionary effects for simplicity

$$\tau(E,D) \approx \frac{D}{\Lambda(E)} \qquad \left(\Lambda \propto \frac{1}{\sigma}\right)$$

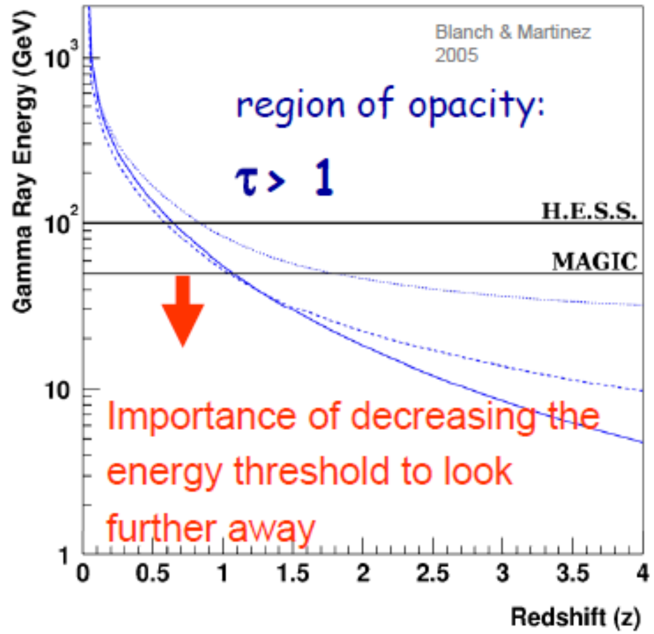
$$\Phi_{\mathrm{obs}}(E,D) \approx \Phi_{\mathrm{em}}(E) \times e^{-\frac{D}{\Lambda(E)}}$$



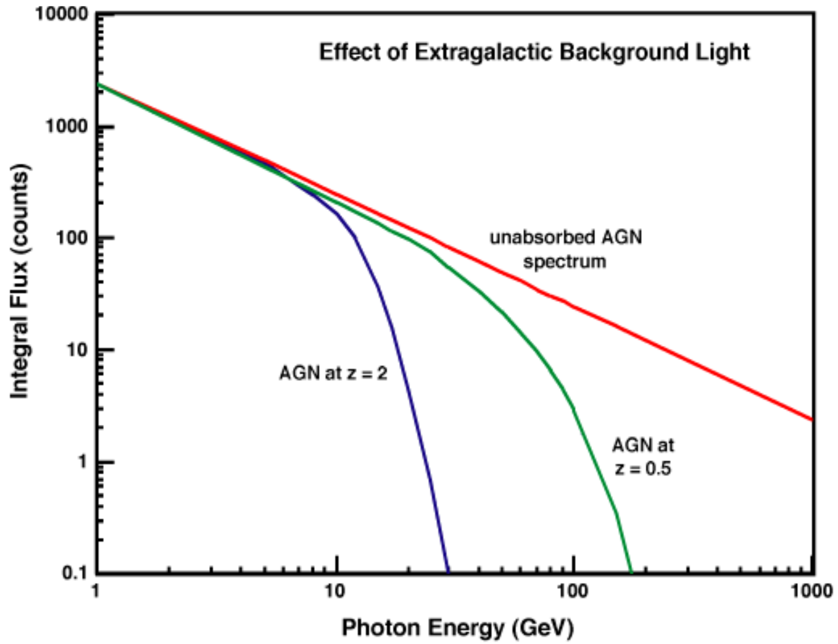
Coppi & Aharonian, ApJ 1997

Consequences

- Since λ becomes < R_{Hubble} for E > 100 GeV:
  - The observed flux should be exponentially suppressed at large distances, so that very far-away sources should become invisible as energy increases



  - The observed flux should be exponentially suppressed at VHE, so that the SED should be steeper than the emitted one.



The VHE Universe far away…

35 Sources

…

PKS 0447-439	z=0.20	HESS 2009
1ES 1011+496	**z=0.21**	**MAGIC 2007**
1ES 0414+009	z=0.29	HESS & Fermi 2009
S5 0716+71	**z=0.31±0.08**	**MAGIC 2009**
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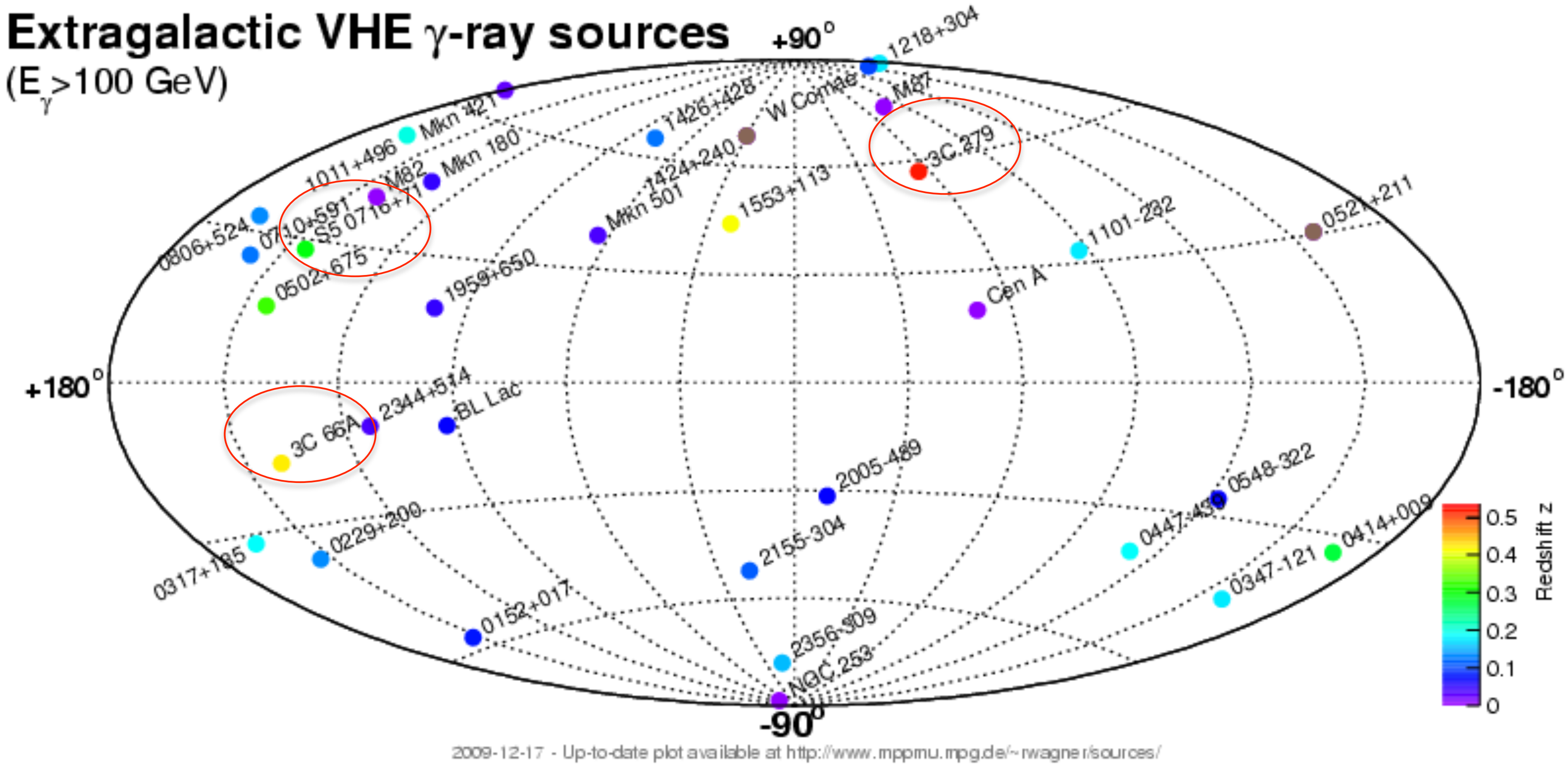
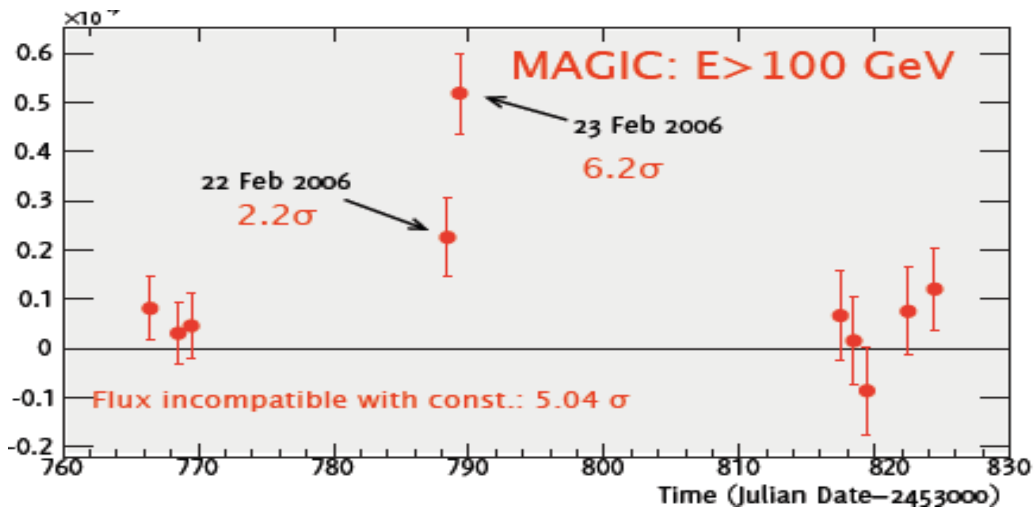
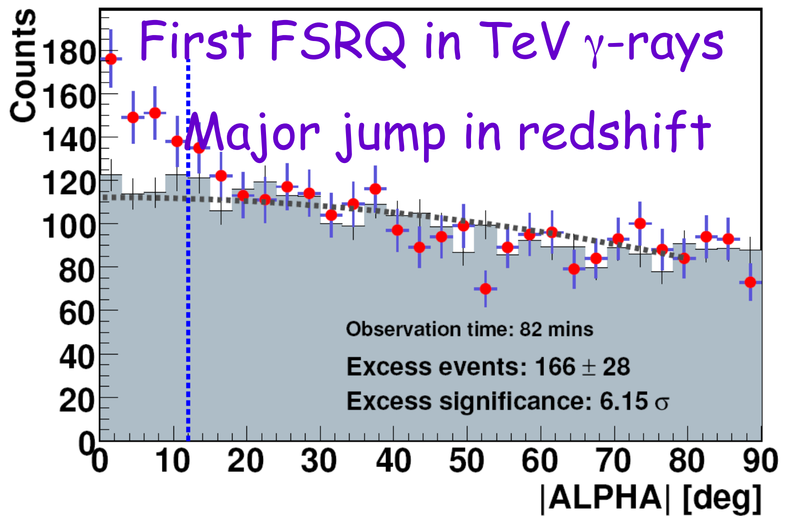
3C 66A	**z=0.44**	**VERITAS 2009**
3C 279	**z=0.54**	**MAGIC 2008**



The distant quasar 3C 279

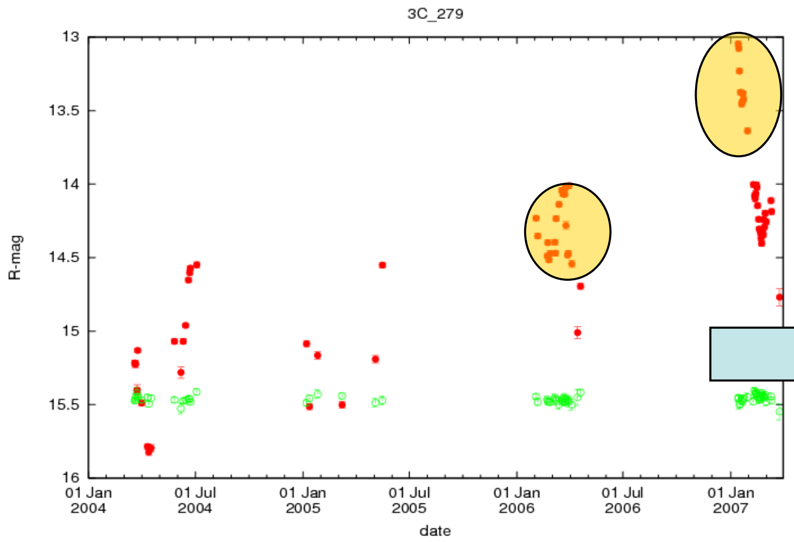
- Flat spectrum radio quasar at z=0.54
- Very bright and strongly variable
  - Brightest EGRET AGN
  - Gamma-ray flares in 1991 and 1996. Fast time variation (~ 6hr in 1996 flare)
- MAGIC observations
  - 10 h between Jan.-April 2006
  - clear detection on 23rd Feb. at 6.2σ

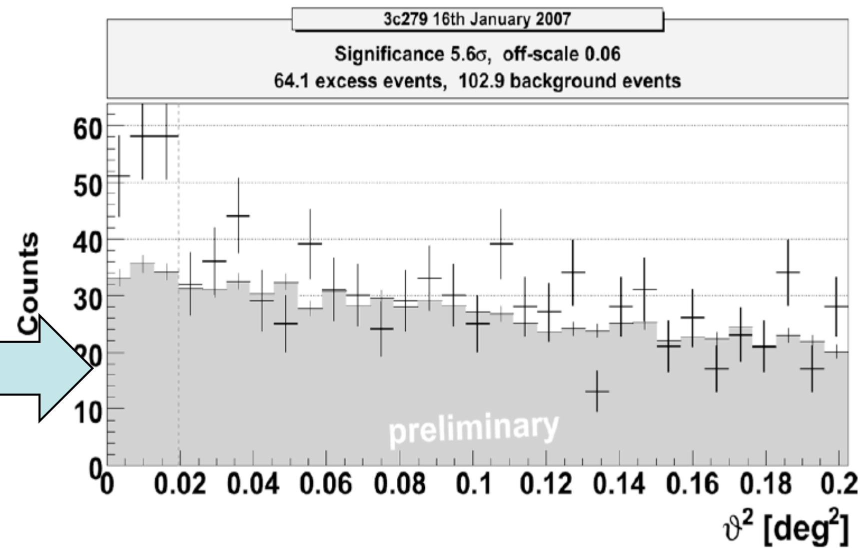




The distant quasar 3C 279 is back!

- New observations after optical outburst in Jan. 2007
  ➔New flare detected

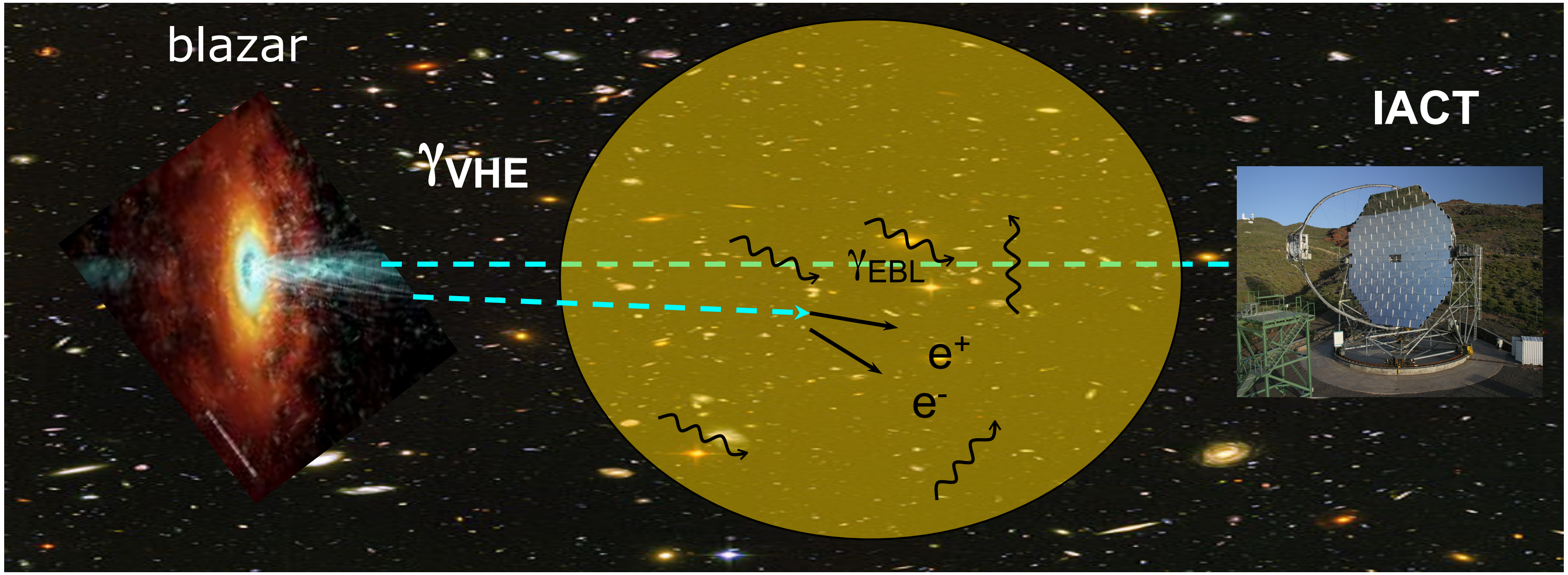


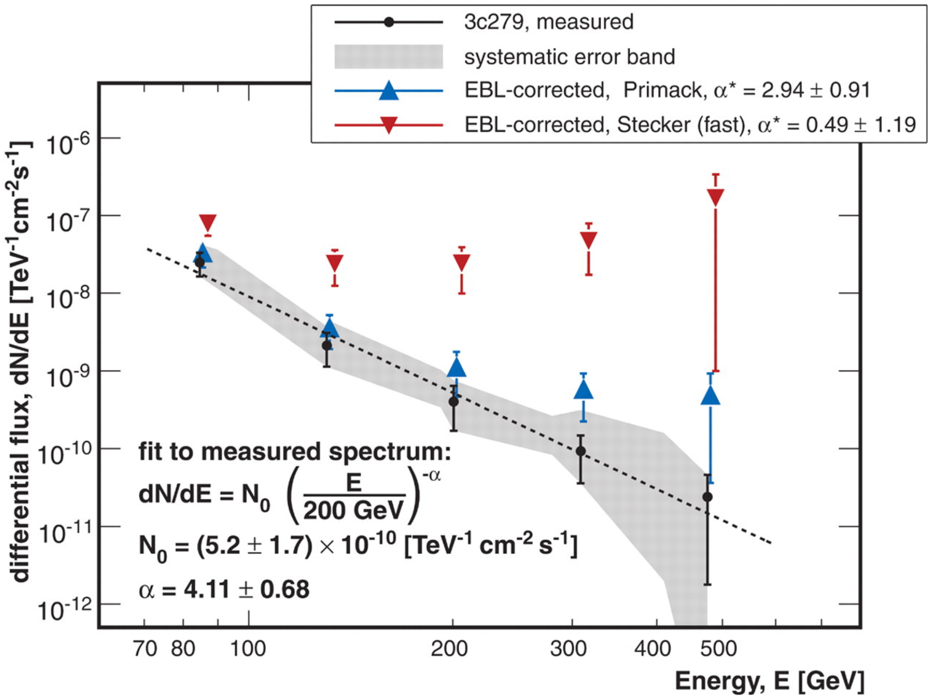


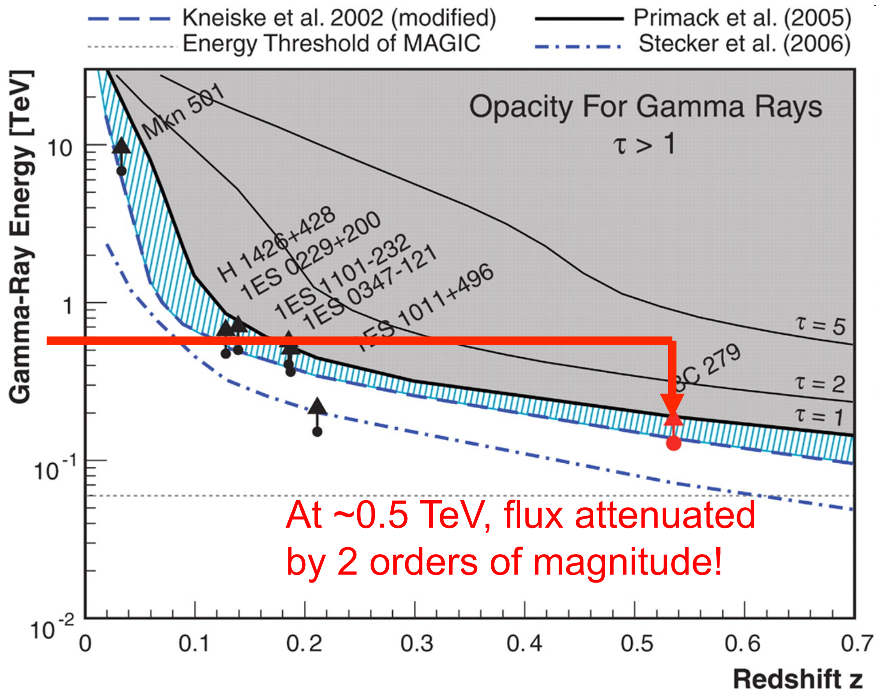
Most distant object ever detected at VHE - two flares
(Feb. 2006 and Jan. 2007)

Emission harder than expected -> constrains the EBL, universe more transparent to γ-rays than expected

Implications on Extragalactic Background Light





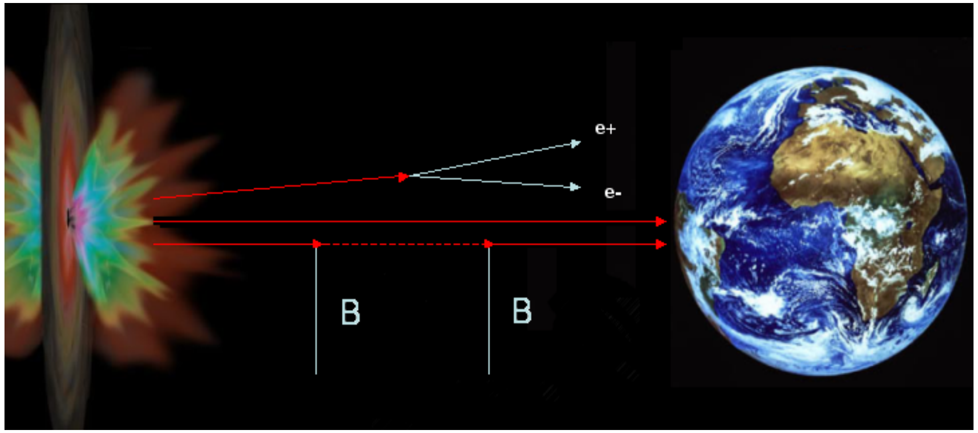


Could it be seen?

- At ~0.5 TeV, flux attenuated by 2 orders of magnitude!
- The measurement of spectral features permits to constrain EBL models:
  - Power law $\Gamma = 4.1 \pm 0.7$, measured up to 0.5 TeV
    - ➔ Spectrum sensitive to 0.2 to 2 μm
  - Assume minimum reasonable index $\Gamma_{em} = 1.5$:
    - Upper limit close to lower limit from galaxy count
- Explanations go
  - from standard ones
    - very hard emission mechanisms with intrinsic slope < 1.5 (Stecker 2008)
    - Very low EBL
  - to possible evidence for new physics
    - Oscillation to a particle traveling unimpeded?

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

Oscillation to an Axion-Like Particle



$$L = \frac{1}{M} \left(\vec{E} \cdot \vec{B} \right) a$$

$$P_0 = (\Delta_B s)^2 \frac{\sin^2(\Delta_{\mathrm{osc}} s/2)}{(\Delta_{\mathrm{osc}} s/2)^2}.$$

- Oscillation during the propagation: DA, Roncadelli & Mansutti [DARMa], PLB2008, PRD2008
- Conversion at the emitter (Hooper et al., PRD2008)
- Mixed mechanisms (Sanchez-Conde et al., PRD 2009)
- …

Phenomenology of the oscillations

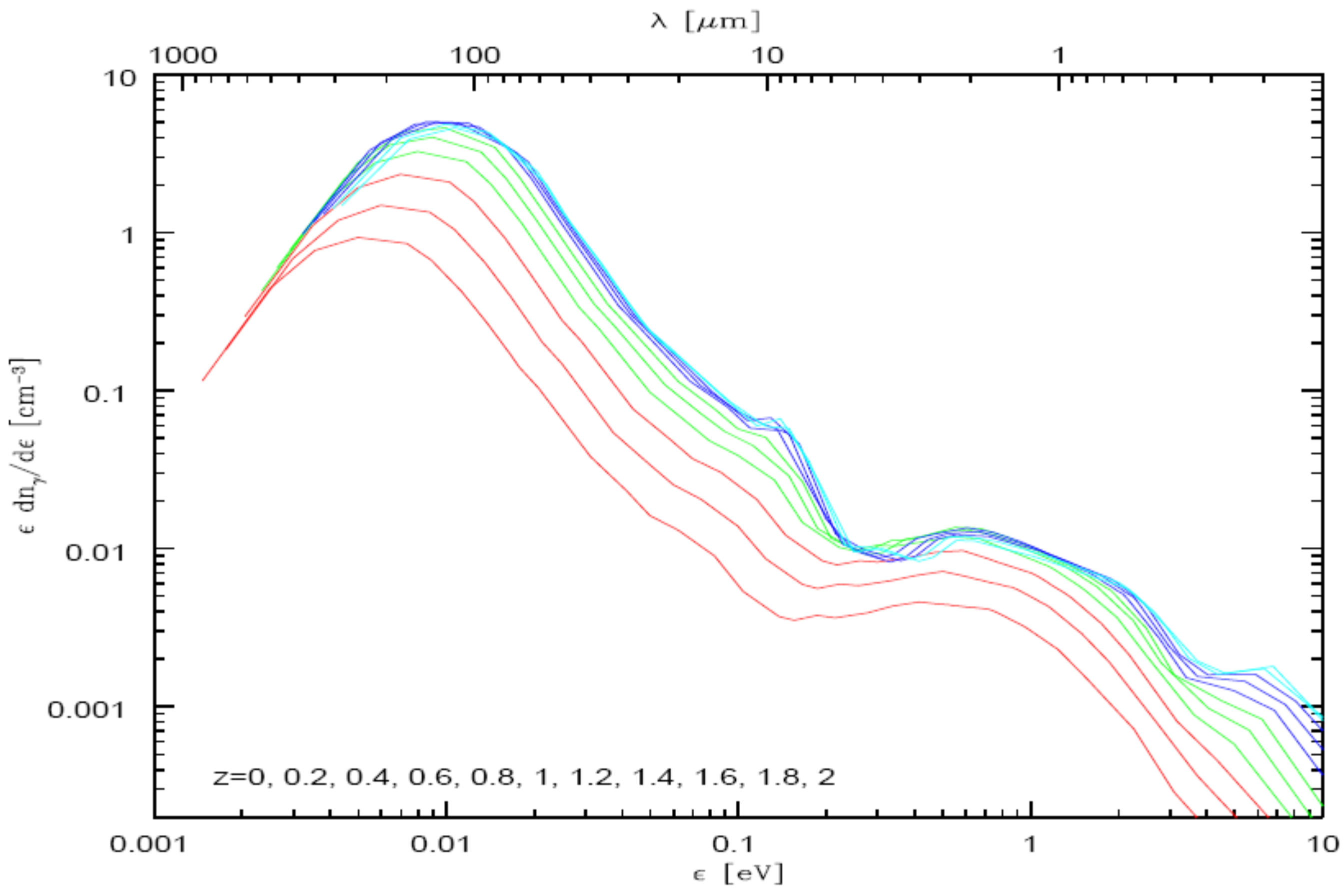
- Photon-ALP oscillations are similar to neutrino oscillations but **external B** is needed
- Bounds on the parameters **M and m**:
  - CAST & astrophysical arguments:

$M > 10^{10}$ GeV ; $m < 0.01$ eV (PDG 08)

For the standard axion, $m \sim (10^{10}$ GeV / $M)$ eV

Which EBL ?

- First analysis of 3C279: EBL model by Kneiske+ 2004.
- Analyses to be improved using Franceschini+ 2008



DARMa: Intergalactic magnetic fields

Their morphology is poorly known. It is supposed that they have a domain-like structure with

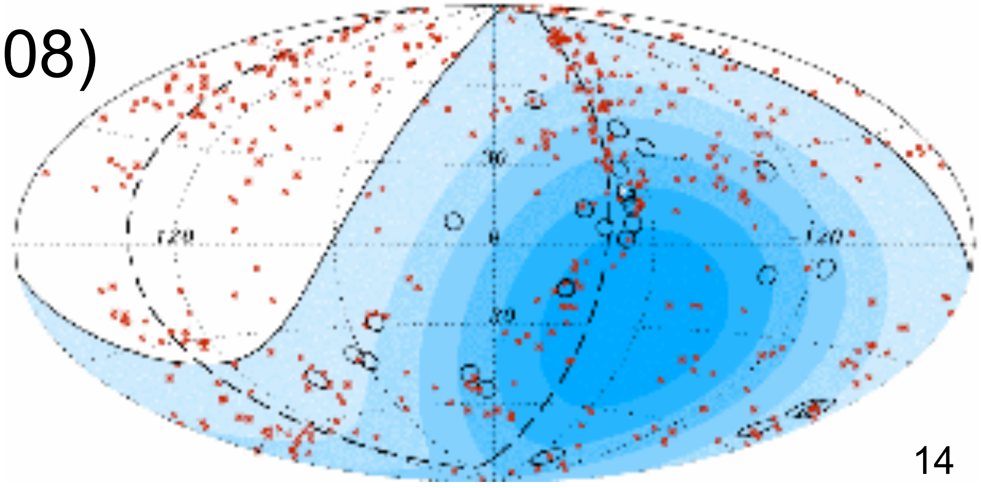
- strength ~ 0.5 nG,
- coherence length λ ~ 10 Mpc,
- random orientation in each domain.

N.B. - Picture consistent with first AUGER data:

strength 0.3 – 0.9 nG for λ ~ 1 – 10 Mpc

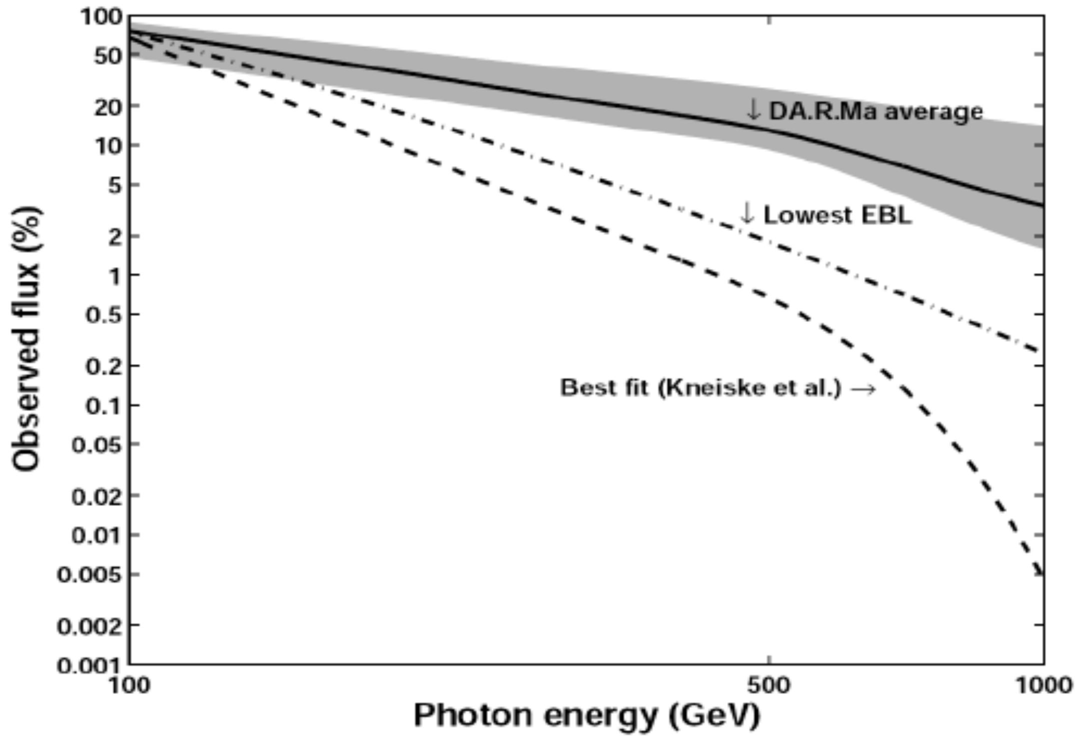
(DA, Persic, Roncadelli, MPLA 2008)

$$\theta \simeq 0.25^\circ \left(\frac{d}{\lambda}\right)^{1/2} \left(\frac{\lambda}{1\,\mathrm{Mpc}}\right) \left(\frac{\mathrm{B}}{1\,\mathrm{nG}}\right) \left(\frac{10^{20}\,\mathrm{eV}}{E}\right)$$



DARMa results

- Small mass, small coupling (within limits) naturally explain the enhancement at large E

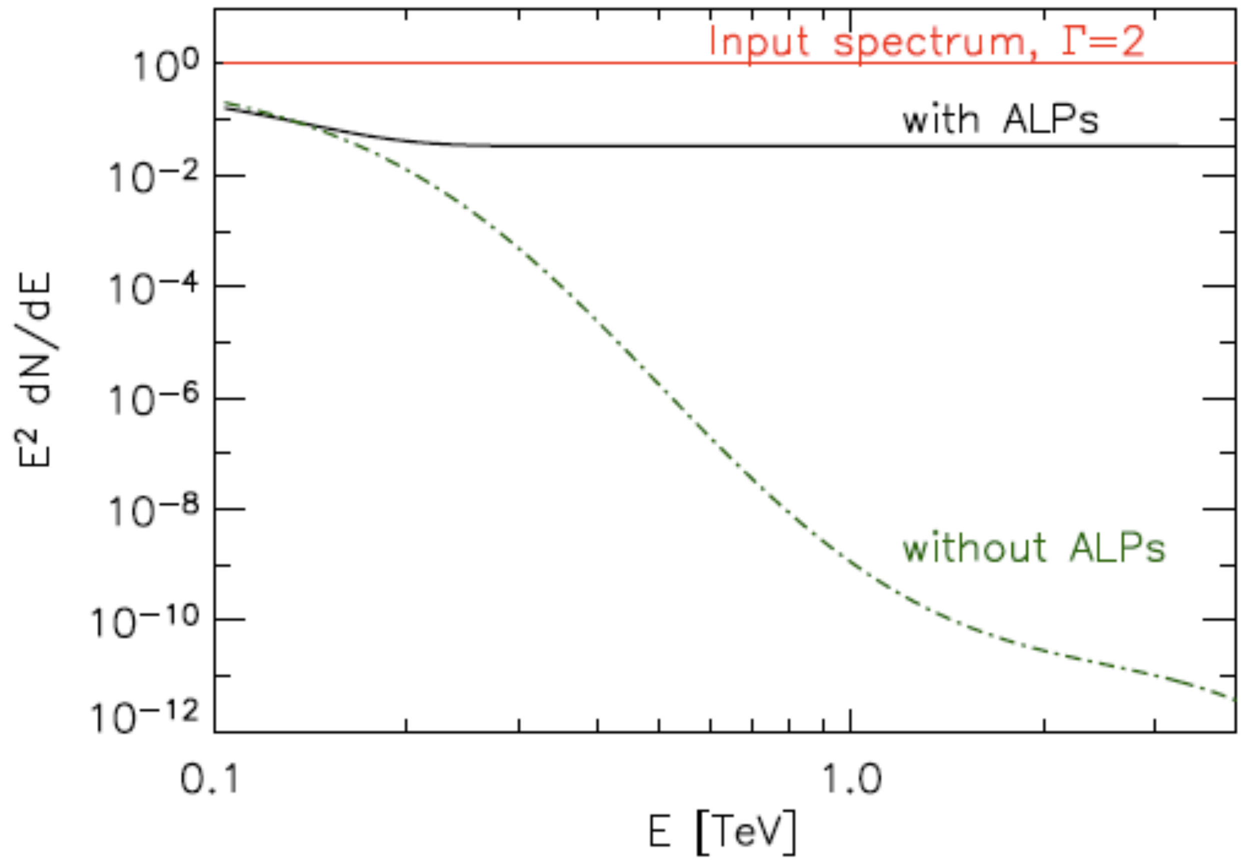


$m << 10^{-10}$ eV (maximal mixing)

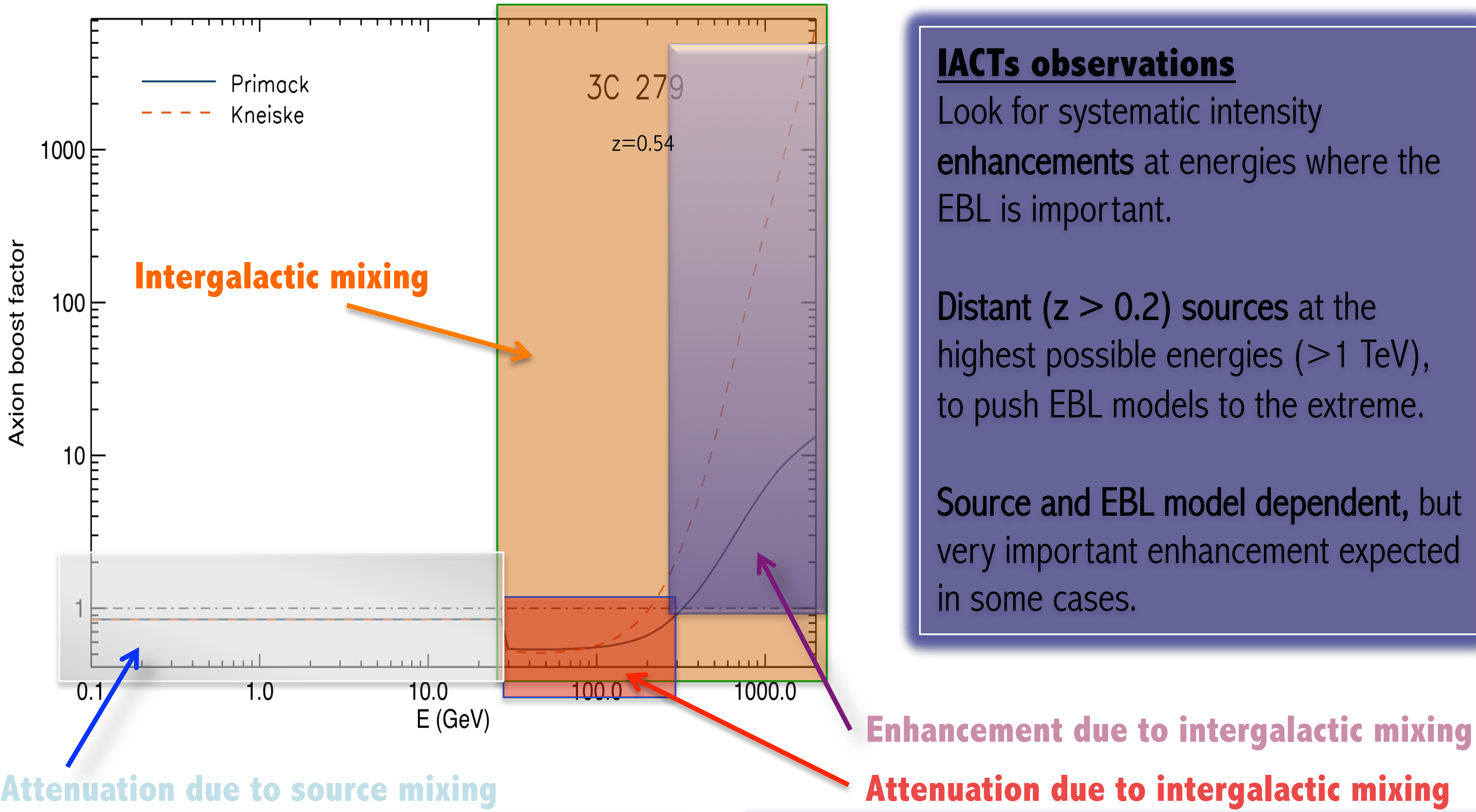
10^{11} GeV $<$ M $<$ 10^{13} GeV

Simet, Hooper & Serpico, PRD 08

- Conversion at the emission
- Milky Way acts as a converter to photons



Sanchez-Conde+, PRD 09



IACTs observations
Look for systematic intensity **enhancements** at energies where the EBL is important.

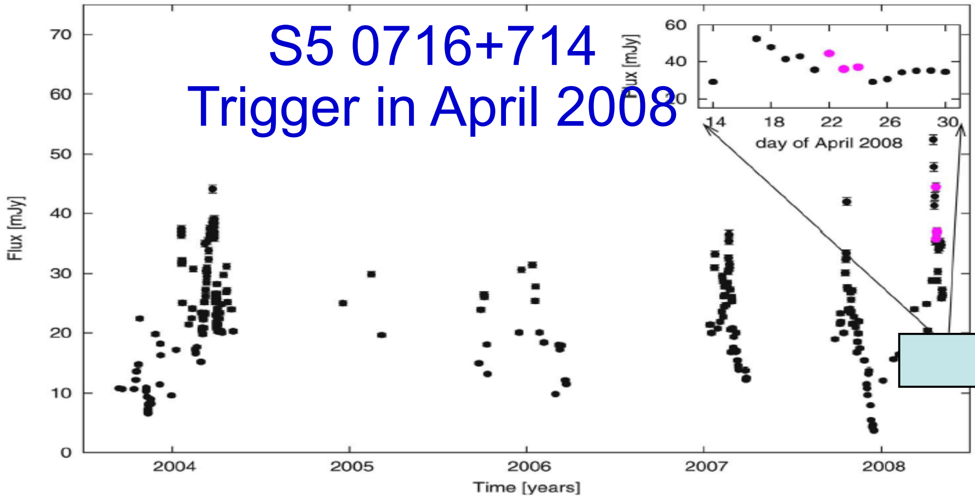
Distant (z > 0.2) sources at the highest possible energies (>1 TeV), to push EBL models to the extreme.

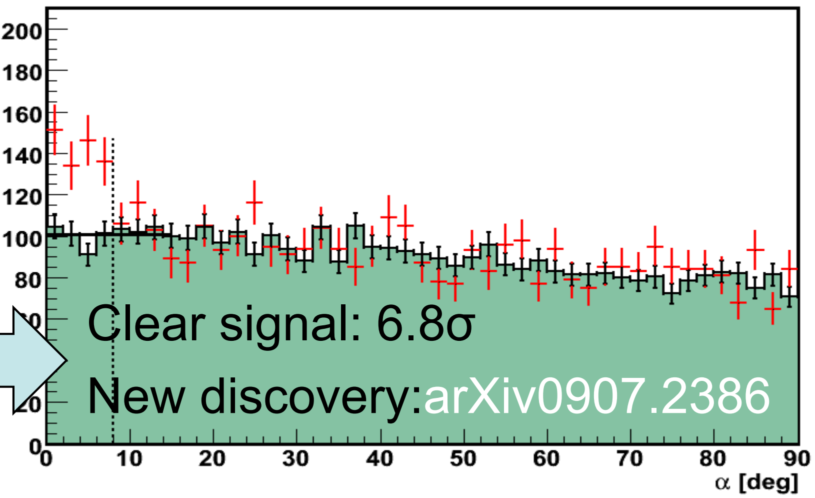
Source and EBL model dependent, but very important enhancement expected in some cases.

Fermi/LAT
Look for intensity **drops** in the residuals ("best-model"-data; model dependent).
Powerful, relatively **near** AGNs.

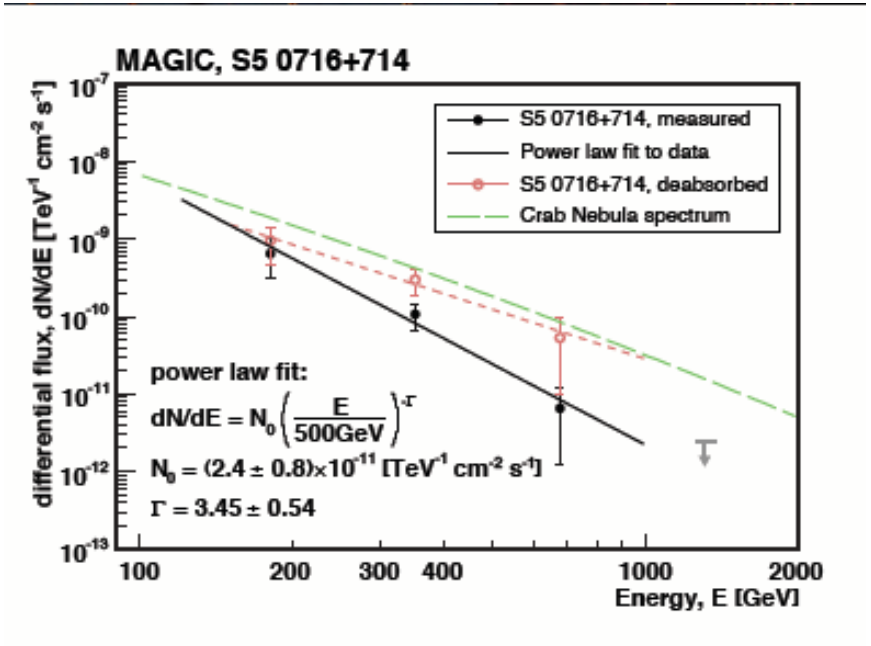
Fermi/LAT and/or IACTs
Look for intensity **drops** in the residuals.
Depends on the IGMF and axion properties (M&m).

Experimental input from more sources at high z: MAGIC S5 0716+714



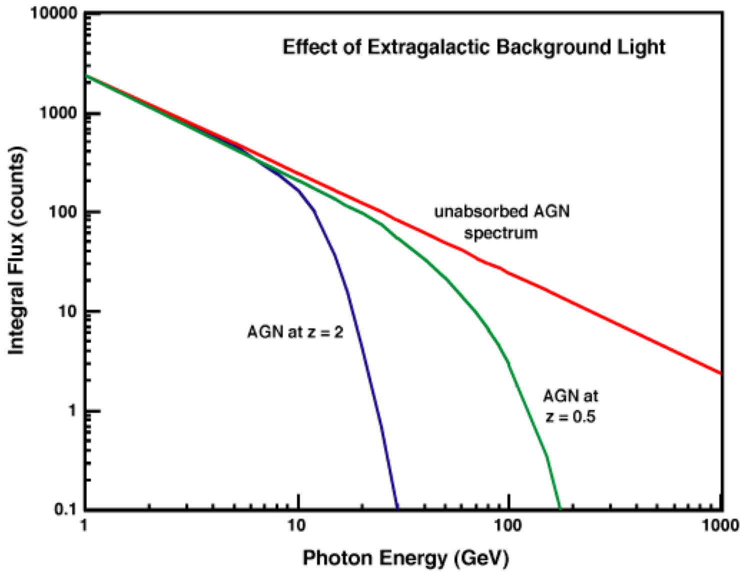


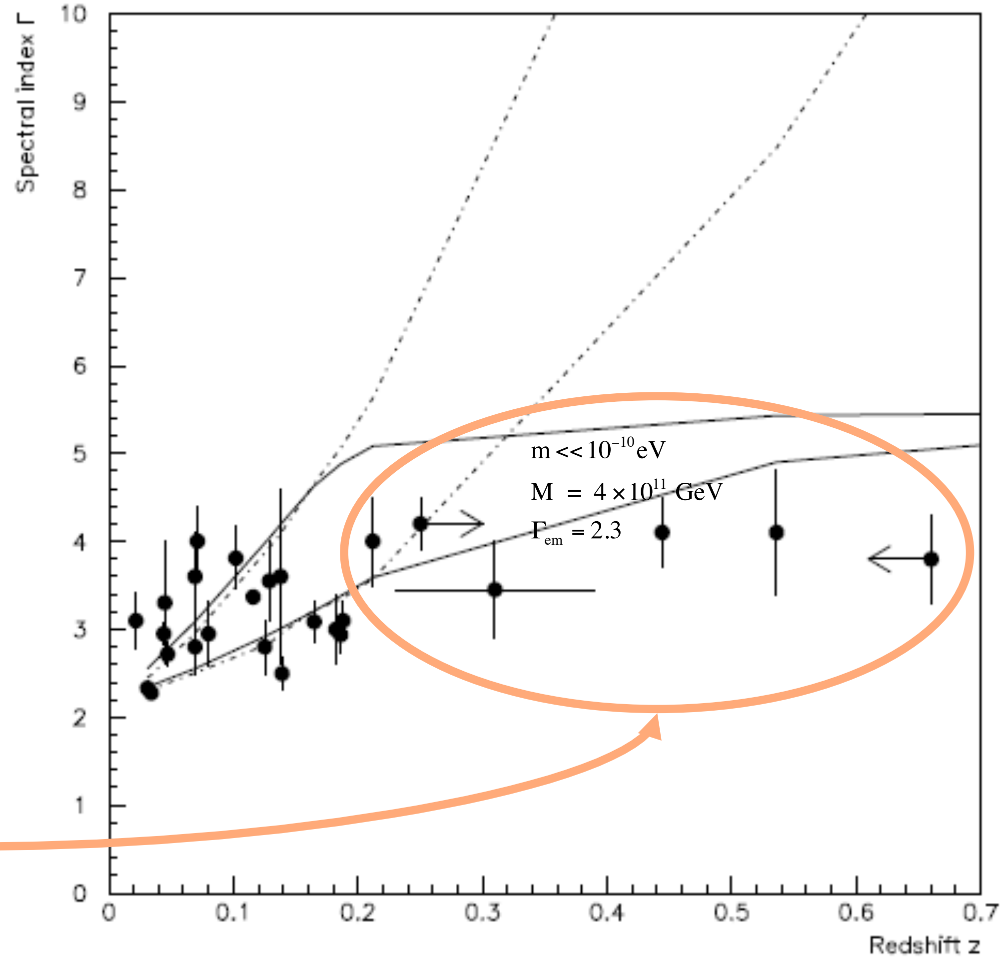
- After trigger, MAGIC observed 2.6h
  - April 28: Swift reports flux about 50% larger than that observed in 2007
  - Apr 29: ATel #1500, MAGIC reports 6.8 σ discovery Apr 23-25. F(>400 GeV) ≈25% Crab
- 3rd low-peaked VHE blazar after BL Lac & W comae
- Host galaxy detected: Z=0.31+/-0.08 => 3rd farthest VHE emitter for which the spectral index has been measured



Deformation of the SED

…and more new sources are coming into the game (VERITAS, HESS, MAGIC)





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Did we already see axions?

- Recent gamma observations might already pose substantial challenges to the conventional models to explain the observed source spectra and/or EBL density.
  - MAGIC 3C279 at z=0.54; VERITAS recent detection above 0.1 TeV from 3C66A (z=0.44). EBL-corrected spectrum harder than 1.5 (Acciari+09); …
    - TeV photons coming from 3C 66A? (Neshpor+98; Stepanyan+02). Difficult to explain with conventional EBL and physics.
  - The lower limit on the EBL at 3.6 μm was recently revised upwards by a factor ~2, suggesting a more opaque universe (Levenson+08).
  - Some sources at $z = 0.1 - 0.2$ seem to have harder intrinsic energy spectra than previously anticipated (Krennrich+08).
  - Spectral indices don't grow with increasing distance.

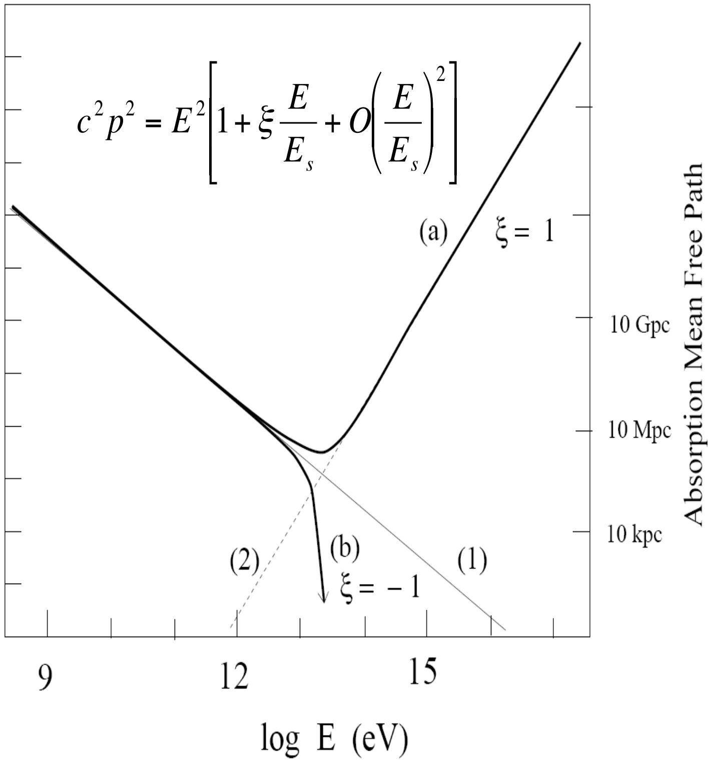
- While it is still possible, although difficult, to explain the above points with conventional physics, the axion/photon oscillation would naturally explain these puzzles:
  - More high energy photons than expected
  - Softer unfolded intrinsic spectrum when including axions

Extraordinary claims require extraordinary evidence

Other possible explanations related to new physics

- Kifune 2001: Violation of the Lorentz invariance “a la Coleman-Glashow”
- We should keep in mind that
  - Extraordinary claims require extraordinary evidence
    - New Scientist, SciAm blog/news, …, and then?
  - Claims must be followed up
    - What else do we expect?
    - Fundamental implications of unexpected findings?
    - Are we seeing a part of the same big picture?

    - **By the way, you can also increase pair production & energy dependence of c…**



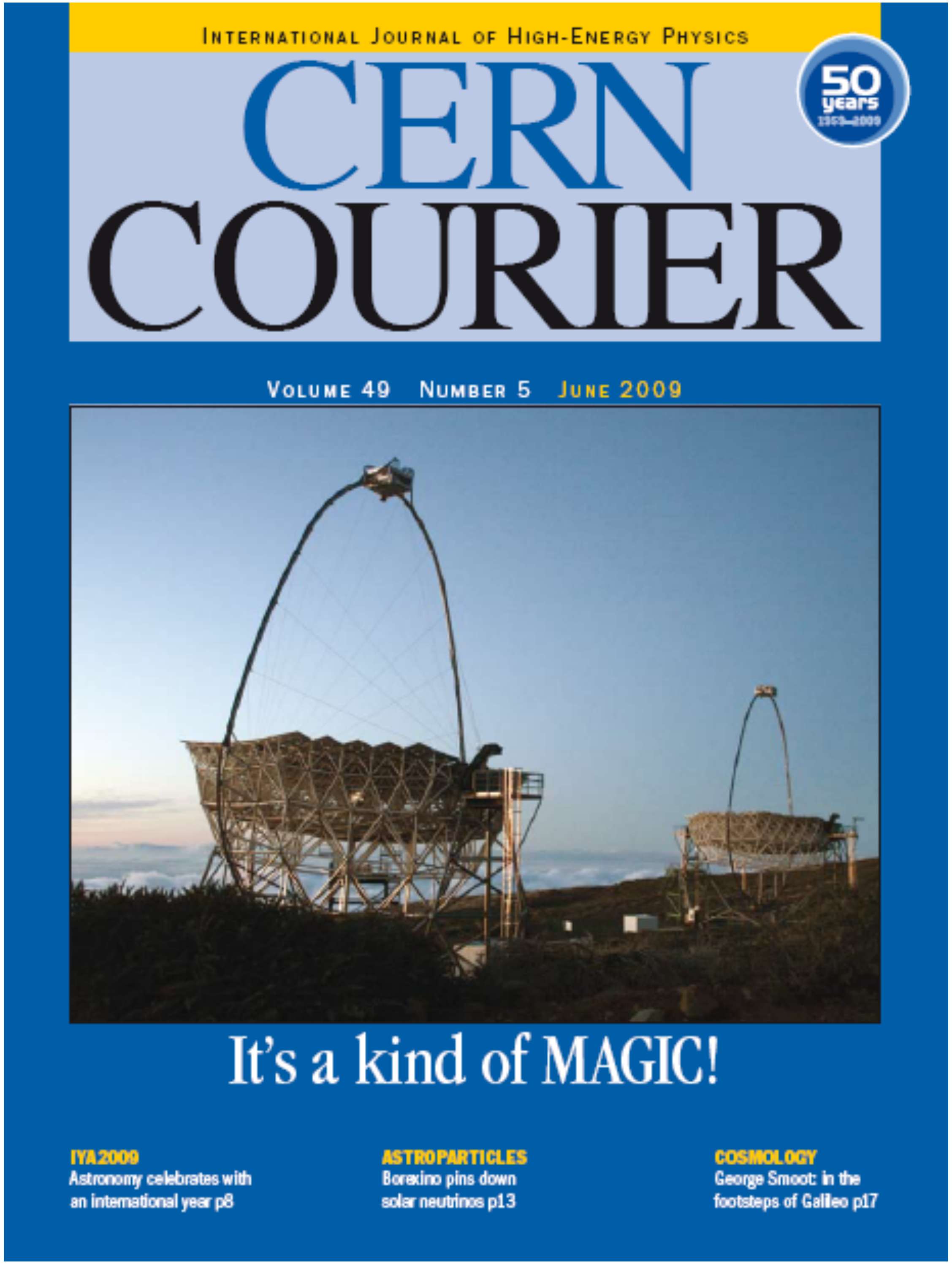
Conclusions

- The existence of a very light ALP, predicted by many extensions of the SM, naturally explains the observed transparency of the VHE gamma-ray sky
  - As a bonus, it explains why only the most distant AGN seem to demand an unconventional emission spectrum
- The DARMa prediction, in particular, concerns the spectral change of observed AGN flux at VHE
- The constraints impose a very light mass ($m \ll 10^{-10}$ eV) and a small coupling ($\sim 10^{11}$ GeV). Incompatible w/ the standard axion.
  - Required magnetic fields for the conversion: OK
- More data on distant AGN will tell

Appendix: some recent MAGIC results on DM annihilations into photons

- dSPHs
  - Draco ApJ 08: 8h of observation, no signal
  - Willman I Apj 09: 16h of observation, no signal

  Boost factors ~ $10^3 – 10^5$ needed
- Segue I globular cluster: 30h observation, results soon
- Clusters
  - Perseus ApJ 10: 24h of observation, no signal, boost ~10^4
- Substantial improvement (sensitivity, E resolution, angular resolution) expected for MAGIC in phase II



"A textbook example of the merging of particle physics and astronomy into the modern field of astroparticle physics"

BACKUP

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

which in the presence of absorption becomes

with

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

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

Ideal case z = 1 – EBL of Franceschini et al