

Search for axion-like particles in astrophysical observations

Timur Rashba

MPI (Katlenburg-Lindau, Germany) and IZMIRAN (Troitsk, Russia)

14th Lomonosov Conference, Moscow, August 19-25, 2009

Outline

1 Axions

- Motivations
- Axion-photon interaction

2 Astrophysical searches

- Shining light through the Sun
- Gamma-ray astronomy and axions

3 Summary

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Motivations for axions

- Strong CP problem and dark matter

QCD Lagrangian:

$$\mathcal{L} = -\frac{1}{4} \text{Tr} G_{\mu\nu} G^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2} \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu} + \bar{\psi} \left(i\gamma^\mu D_\mu - M_q e^{i\theta' \gamma_5} \right) \psi$$

contains CP violating term:

$$\mathcal{L}_{CP} = -\frac{g^2}{32\pi^2} \Theta \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Neutron electric dipole moment

$$d_n \approx \Theta 10^{-16} \text{e} \cdot \text{cm} < 10^{-25} \text{e} \cdot \text{cm}$$

Problem: why so small?

$$\Theta < 10^{-9}$$

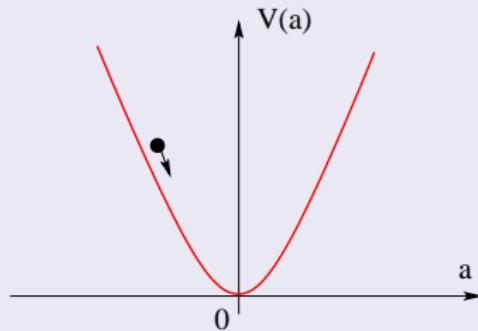
Strong CP problem: dynamical solution

Peccei&Quinn'77, Wiczeck'78, Weinberg'79

Postulate new global U(1) symmetry - Peccei-Quinn symmetry
Re-interpret Θ as a scalar field a - axion - Nambu-Goldstone boson

$$\mathcal{L}_{CP} = -\frac{g^2}{32\pi^2} \Theta \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu} \implies \mathcal{L}_{CP} = -\frac{g^2}{32\pi^2} \frac{a(x)}{f_a} \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

CP-symmetry dynamically restored



Axion mass

$$m_a \approx \frac{f_\pi m_\pi}{f_a} \approx \frac{6.0 \text{ eV}}{f_a / 10^6 \text{ GeV}}$$

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Axion-photon conversion/oscillations

Raffelt and Stodolsky, 1988

$$i\partial_z \Psi = -(\omega + \Delta) \Psi, \quad \Psi = \begin{pmatrix} A_{||} \\ A_{\perp} \\ a \end{pmatrix}, \quad \Delta \equiv \begin{pmatrix} \Delta_p & 0 & \Delta_{a\gamma} \\ 0 & \Delta_p & \Delta_{a\gamma} \\ \Delta_{a\gamma} & \Delta_{a\gamma} & \Delta_m \end{pmatrix}$$

$$\Delta_p = \frac{\omega_p^2}{2\omega}, \quad \Delta_m = \frac{m_a^2}{2\omega}, \quad \Delta_{a\gamma} = \frac{B}{2M}, \quad M = g_{a\gamma}^{-1}$$

Photon-axion conversion probability

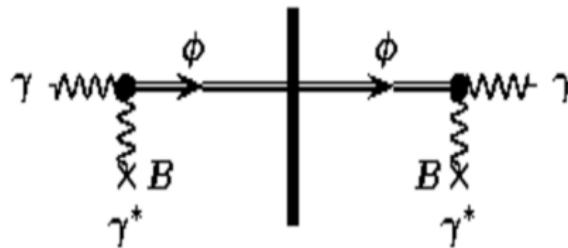
$$P_{\gamma \rightarrow a} = \frac{4B^2\omega^2}{M^2 (\omega_p^2 - m_a^2)^2 + 4B^2\omega^2} \sin^2 \left(\pi \frac{z}{l_{\text{osc}}} \right),$$

$$l_{\text{osc}} = \sqrt{\frac{4\pi\omega M}{M^2 (\omega_p^2 - m_a^2)^2 + 4B^2\omega^2}}, \quad B = \text{const}, \quad \omega_p = \text{const}$$



"Shining light through the wall"

- Solar axions *CAST arXiv:0810.4482, Tokyo helioscope arXiv:0809.0596, ...*
- X-rays from the Sun with axion signatures
Zioutas et al, arXiv:0903.1807, Hannah et al, astro-ph/0702217; Davoudsiai, Huber 2006, ...
- Detection of laser photons "through the wall"
ALPS, arXiv:0905.4159; GammeV, arXiv:0908.1529 [hep-ex], ...
- Detection of high energy photons from very distant astrophysical objects
(gamma-ray telescopes, groundbased and satellite)
Simet, Hooper, Serpico, arXiv: 0712.2825; Angelis et al, arXiv:0807.4246; Fairbairn, TR, Troitsky arXiv:0901.4085; Bassan, Roncadelli arXiv:0905.3752; Burrage et al arXiv:0902.2320; Sanchez-Conde et al, arXiv:0905.3270; Hochmuth, Sigl arXiv:0708.1144
...
- Appearance of photons from nowhere (dark matter or cosmic axions search)
ADMX, astro-ph/0603108; Fairbairn et al arXiv:0706.0108; ...



CAST - CERN axion solar telescope

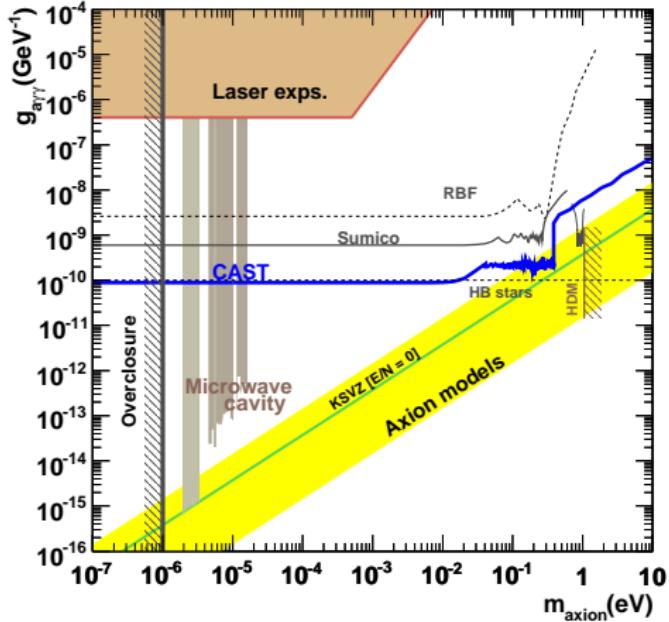
- "Axion helioscope" technique Sikivie, 1983
- Strong magnet $B = 9$ Tesla, $L = 9.26$ m (LHC test magnet)
- x-ray detector at the end of pipe
- Observes the Sun 1.5 hour at both sunrise and sunset
- Expected axion flux: $(g_{a\gamma}/(10^{-10}\text{GeV}^{-1}))^2 3.75 \times 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$
- Average solar axion energy 4.2 keV
- Variable-pressure gas filling

Primakoff effect



CAST and other limits

Zioutas, Tsagri, Papaevangelou, Dafni, arXiv:0903.1807



Cooling limits and dark matter

Globular cluster stars

Cooling of red giants by $\gamma + A \rightarrow A + a$:

$$g_{a\gamma} < 10^{-10} \text{ GeV}^{-1}$$

Raffelt, [hep-ph/0611118](#)

Axions as a hot dark matter

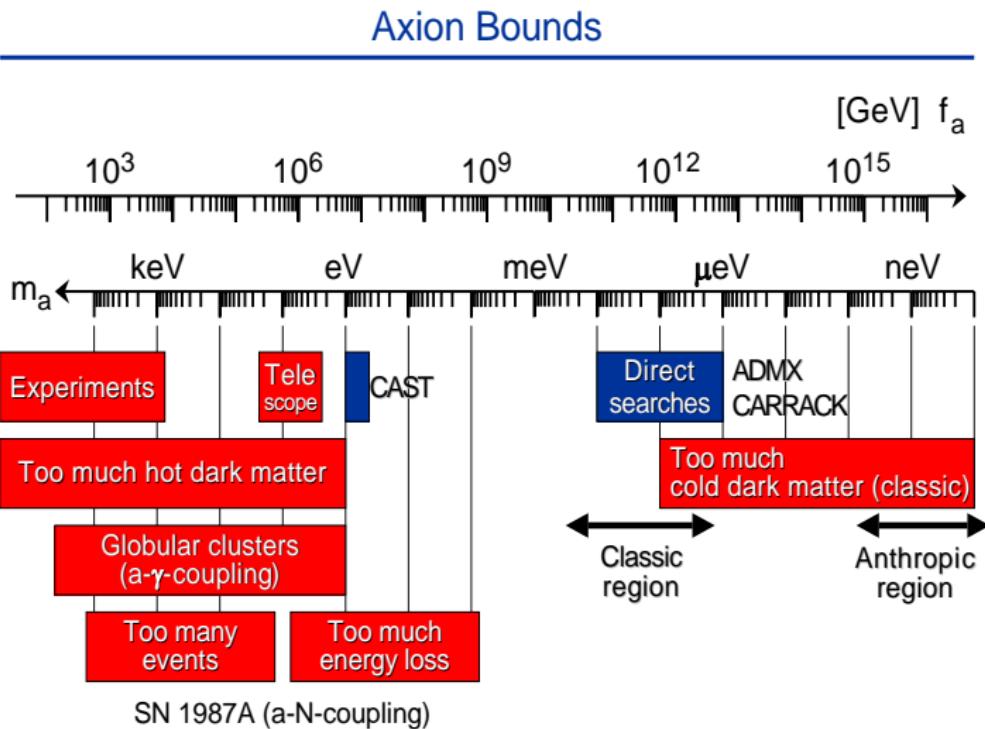
Thermal axions can form hot dark matter, but the axion decay into photons leads to limit:

$$m_a < 1 \text{ eV}$$

Hannestad, Mirzizi, Raffelt'05

Axions as a cold dark matter

- Axions can be a dominant cold dark matter component with mass $m_a > 10 \mu\text{eV}$ Hannestad, Mirzizi, Raffelt'05
- Can be probed by ADMX (microwave resonator in magnetic field)
 $1 \mu\text{eV} < m_a < 100 \mu\text{eV}$



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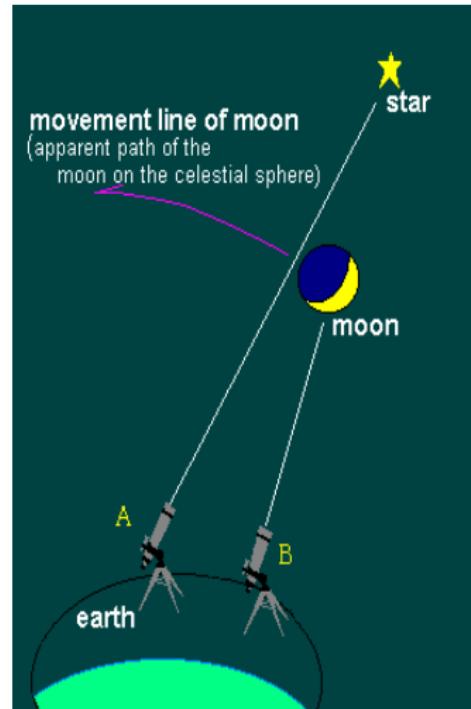
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Astronomy

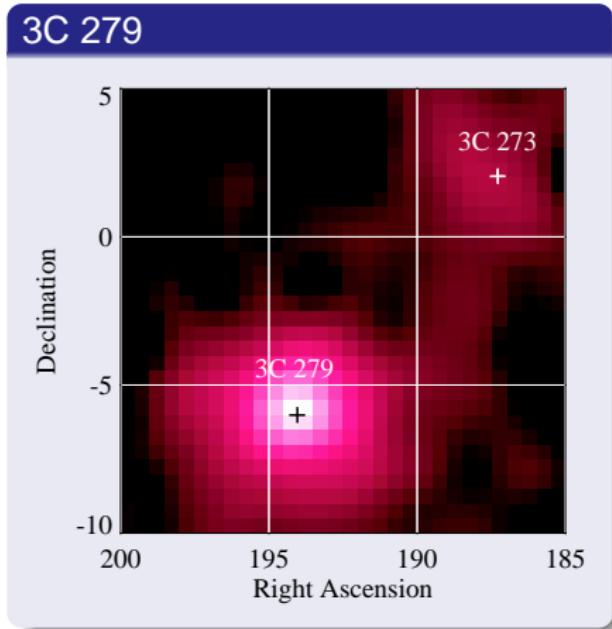


Astronomers Studying an Eclipse by Antoine Caron (1571)



Solar occultation of 3C 279 γ -ray source?

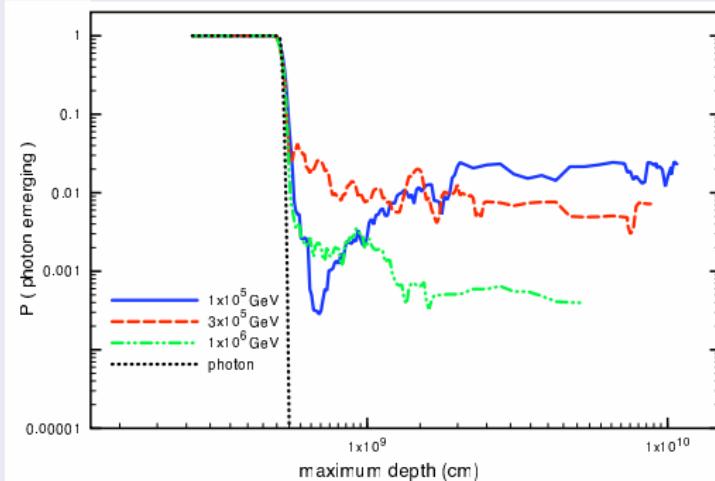
- 271 sources in 3EG catalogue
- 101 identified
- 1 occulted by the Sun
- 3C 279 (brightest QSO)
- ecliptic latitude 0.2°
- once per year, October 8
- occultation period ≈ 8.5 hours



Shining light through the Sun by axions

Fairbairn, T.R., Troitsky, astro-ph/0610844

Probability of photon emerging



Conditions

- axion mass:
 $m_a \sim 10^{-3}$ eV
- inverse coupling:
 $M = 10^5 - 10^6$ GeV
- photon energy:
around GeV

Solar halo and disk emission

Orlando, Strong, A&A, 480, 847 (2008)

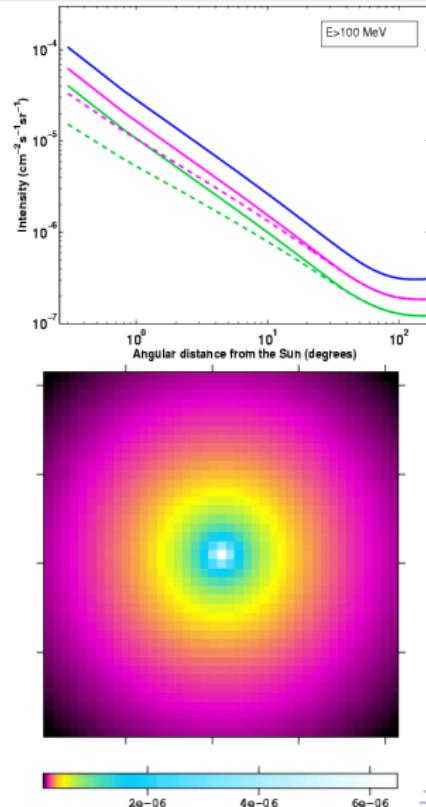
- Upper figure: Model angular profile of the solar emission above 100 MeV.
- Lower figure: Inverse-Compton emission modelled for a region of 10° from the Sun for 300-500 MeV.
Intensity is given in $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$.
- Sum of disk and extended components of solar emission ($10^{-7} \text{ cm}^{-2} \text{s}^{-1}$).

Energy (MeV)	solar disk	Total flux
>100	0.54 ± 0.32	4.44 ± 2.03

- Fairbairn, T.R., Troitsky, arXiv:0809.4886

$$F_{3C279}^{occult} \approx (6.2^{+3.7}_{-2.7}) \cdot 10^{-7} \text{ cm}^{-2} \text{s}^{-1}$$

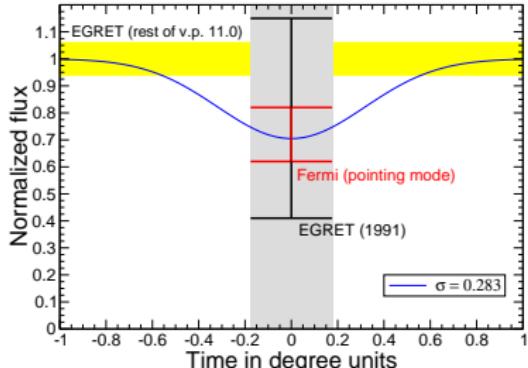
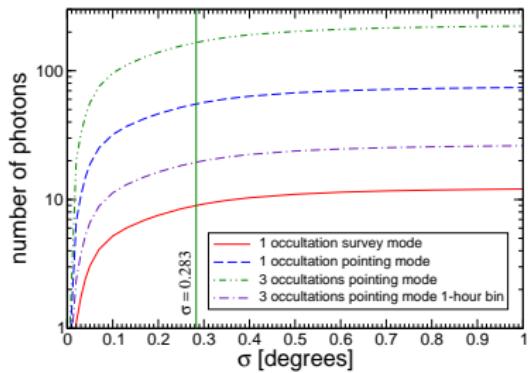
$$F_{3C279} \approx (8.6 \pm 0.5) \cdot 10^{-7} \text{ cm}^{-2} \text{s}^{-1}$$



Fermi Gamma Ray Space Telescope (GLAST)



- Launched in June 2008
- $E = 30 \text{ MeV}$ to 300 GeV
- Sensitivity about 50 times that of EGRET at 100 MeV
- Fermi goals:
 - particle acceleration in AGNs, pulsars, and SNRs
 - resolve the γ -ray sky
 - γ -ray bursts
 - probe dark matter and early Universe



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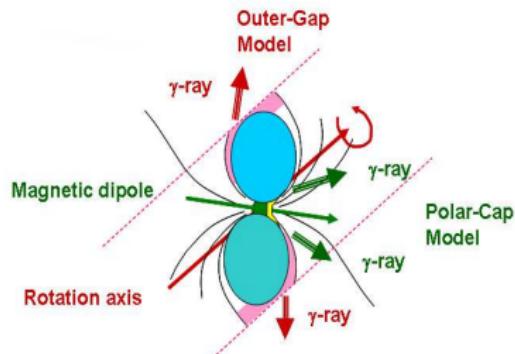
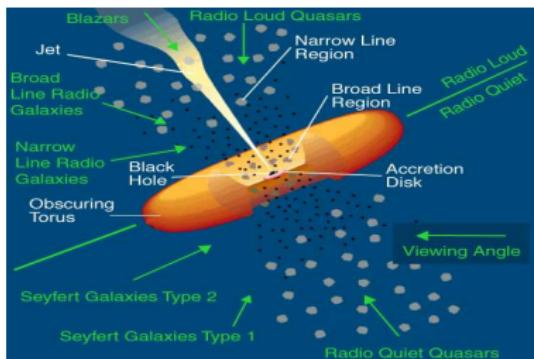
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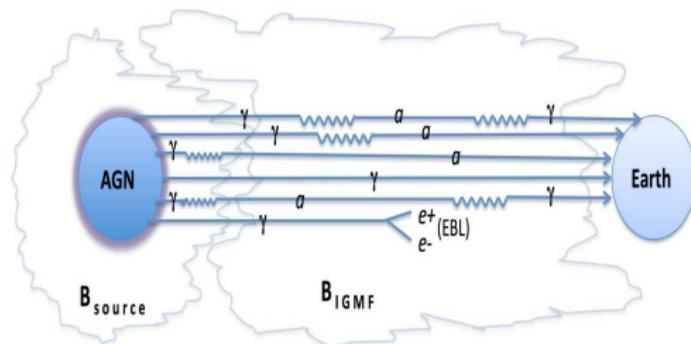
γ -ray astronomy

- Predicted in 40s
- Detected in 60s
- γ -rays absorbed by atmosphere
- Balloons
- Satellites (recent INTEGRAL, EGRET, Fermi, ...)
- Atmospheric imaging Cherenkov telescopes (H.E.S.S., MAGIC, VERITAS, ...)
- Sources: AGN, pulsars, SNR, secondary cosmic rays

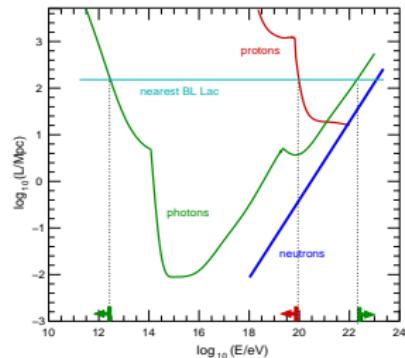


Photon attenuation length

- Universe is not transparent for photons of energies above 1 TeV because of extragalactic background light (EBL)



Sanchez-Conde et al arXiv:0905.3270



Fairbairn, TR, Troitsky, arXiv:0901.4085

3C 279 observation by MAGIC

Distant Quasar 3C 279

Extragalactic Background Light

Product of the History of all Stars and Galaxies

How Transparent is the Universe for Very-High Energy Gamma-Rays?

Very-High Energy Gamma Radiation

5.3 Billion Light Years Away

MAGIC Ground-Based Gamma-Ray Telescope for E>80 GeV Gamma Rays

The Universe is More Transparent than Previously Believed.

Background image credits: NASA E/PO, Sonoma State University, Aurore Simonnet; HST, NASA, STScI.

Figure 1: 3C 279 observation by MAGIC

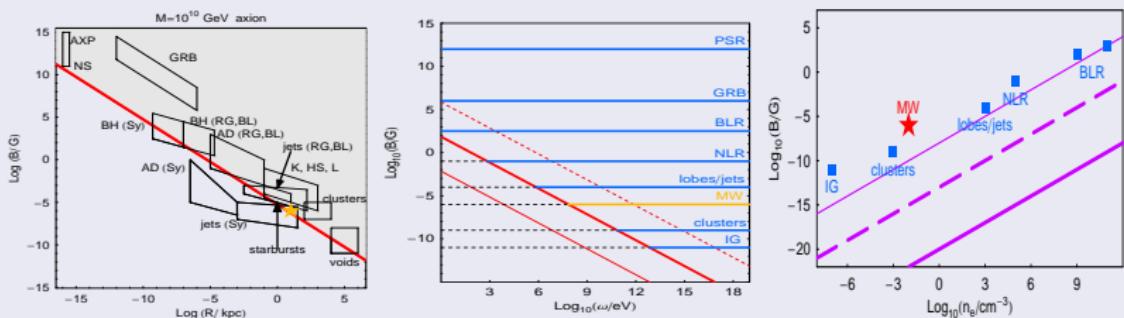
This figure illustrates the MAGIC observation of the quasar 3C 279 and its implications for the extragalactic background light (EBL). It includes:

- Top Left:** An image of the quasar 3C 279, described as being 5.3 billion light years away.
- Top Right:** A plot of the extragalactic background light spectrum, showing "Probed by 3C 279 Measurement" (black points) and theoretical models (red and blue curves) for the EBL: Maximal Model and EBL: Minimal Model. The x-axis is Wavelength [μm] and the y-axis is $W_L [n\text{W m}^{-2} \text{sr}^{-1}]$.
- Middle Left:** A plot of the differential flux $dF/dE [\text{TeV cm}^{-2} \text{s}^{-1}]$ versus gamma-ray energy $E [\text{GeV}]$. It shows the "Measured Gamma-Ray Spectrum" (blue line with points) and the "Maximal EBL: Unrealistic Spectrum" (red line), noting that the spectrum at 3C 279 is "Minimal EBL". Error bars are shown for the measurements.
- Middle Center:** A diagram showing the interaction of very-high-energy gamma radiation (γ_{VHE}) with the extragalactic background light photons (γ_{EBL}). The interaction results in the annihilation of an electron-positron pair ($e^+ e^-$).
- Middle Right:** Text explaining that intergalactic photons attenuate high-energy photons.
- Bottom Left:** MAGIC logo and text: Major Atmospheric Gamma Imaging Camera.
- Bottom Right:** Image of the MAGIC telescope dish at sunset.



Axion-photon mixing in astrophysical objects

Fairbairn, TR, Troitsky, arXiv:0901.4085



Photon-axion conversion probability

$$P_{\gamma \rightarrow a} = \frac{4B^2\omega^2}{M^2 (\omega_p^2 - m_a^2)^2 + 4B^2\omega^2} \sin^2 \left(\pi \frac{z}{l_{\text{osc}}} \right),$$

$$l_{\text{osc}} = \frac{4\pi\omega M}{\sqrt{M^2 (\omega_p^2 - m_a^2)^2 + 4B^2\omega^2}}, \quad B = \text{const}, \quad \omega_p = \text{const}$$

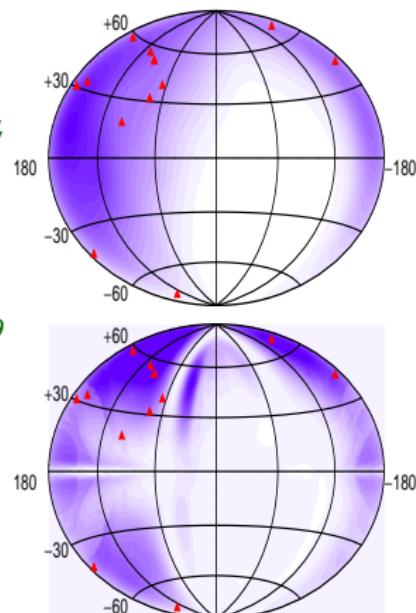


Correlation of UHECR events with BL Lacs

- Charged particles are deflected in IGMF and in GMF
- Neutral particles are absorbed at $> 10^{18} \text{ eV}$, $> 100 \text{ Mpc}$
- Correlation of AGASA, Yakutsk, HiRes UHE events with BL Lacs, *Tinyakov, Tkachev, astro-ph/0102476; Gorbunov et al, astro-ph/0406654*
- Cannot be ν (shower development)
- Milky way galactic magnetic field model HMR *Harari, Mollerach, Roulet, astro-ph/9906309*
- Probability of correlation is higher in the low panel (exposure + magnetic field) than upper (exposure)
- Correlation by chance is about 2.4%
- Axions parameters: mass 10^{-7} eV , coupling $10^{-10} \text{ GeV}^{-1}$

Fairbairn, TR, Troitsky

arXiv:0901.4085



Other effects of axionlike particles in astrophysical observations

- Detection of TeV photons from blazars

Simet, Hooper, Serpico, arXiv:0712.2825

- White dwarf luminosity function

Isern, Garcia-Berro, Torres, Catalan, arXiv:0806.2807

- Large-scale correlation in polarization of quasars

Payez, Cudell, Hutsemekers, arXiv:0805.3946

- Polarization of extragalactic radio sources

Payez, Cudell, Hutsemekers, arXiv:0805.3946

- Solar X-rays

Zioutas et al, arXiv:0903.1807

- ...

Summary

- Axion-like particles (ALP) can be searched in astrophysical observations. In case of discovery they could provide significant contribution to dark matter, depending on their masses;
- Continuous effort in exploring of axion-like particle parameters is taken in laboratory experiments using helioscopes (CAST, Tokyo), cavity experiments (ADMX and others) and laser experiments (ALPS and others);
- Many interesting effects with axion-like particles could be searched using atmospheric imaging Cherenkov telescopes (H.E.S.S., MAGIC and future CTA) and space-based telescopes (Fermi).