# Search for axion-like particles in astrophysical observations

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# Outline

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# Motivations for axions

- Strong CP problem and dark matter

**QCD Lagrangian:**

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

**contains CP violating term:**

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

**Neutron electric dipole moment**

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

**Problem: why so small?**

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

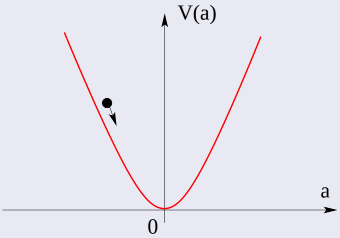
# Strong CP problem: dynamical solution

*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

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

## CP-symmetry dynamically restored




## Axion mass

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

# Outline

1. Axions
   - Motivations
   - Axion-photon interaction
2. Astrophysical searches
   - Shining light through the Sun
   - Gamma-ray astronomy and axions
3. Summary

# Axion-photon conversion/oscillations

*Raffelt and Stodolsky, 1988*

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

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

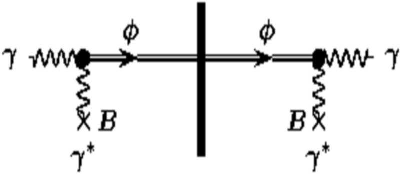
## Photon-axion conversion probability

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

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

# "Shining light through the wall"

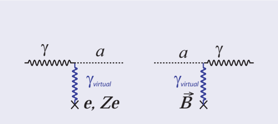
- Solar axions *CAST arXiv:0810.4482, Tokyo helioscope arXiv:0809.0596, . . .*
- X-rays from the Sun with axion signatures
  *Zioutas et al, arXiv:0903.1807, Hannah et al, astro-ph/0702217; Davoudsial, Huber 2006, . . .*
- Detection of laser photons "through the wall"
  *ALPS, arXiv:0905.4159; GammeV, 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

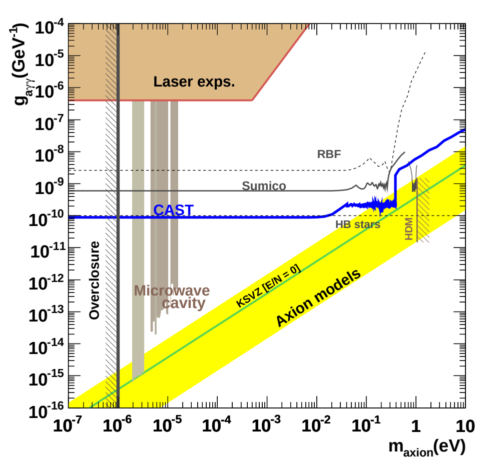
- "Axion helioscope" technique *Sikivie, 1983*
- Strong magnet $B = 9$ Tesla, $L = 9.26$ m (LHC test magnet)
- x-ray detector at the end of pipe
- Observes the Sun 1.5 hour at both sunrise and sunset
- Expected axion flux: $(g_{a\gamma}/(10^{-10}\text{GeV}^{-1}))^2\, 3.75 \times 10^{11}$ cm$^{-2}$ s$^{-1}$
- 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 $\gamma + A \rightarrow A + a$:
$g_{a\gamma} < 10^{-10}$ GeV$^{-1}$ *Raffelt, hep-ph/0611118*

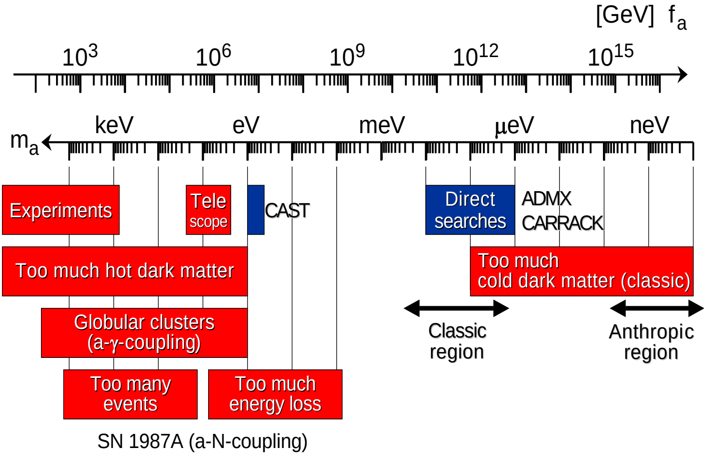
## Axions as a hot dark matter

Thermal axions can form hot dark matter, but the axion decay into photons leads to limit:
$m_a < 1$ eV *Hannestad, Mirrizi, Raffelt'05*

## Axions as a cold dark matter

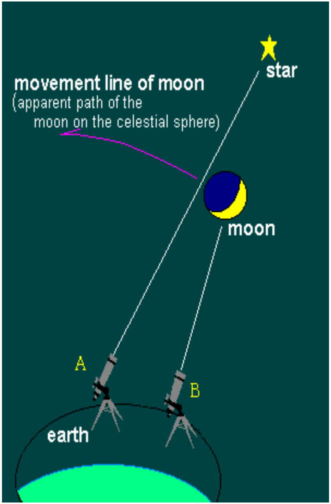
- Axions can be a dominant cold dark matter component with mass $m_a > 10\ \mu$eV *Hannestad, Mirrizi, Raffelt'05*
- Can be probed by ADMX (microwave resonator in magnetic field) $1\mu$eV$< m_a < 100\mu$eV

# Axion Bounds



# Outline

# Astronomy

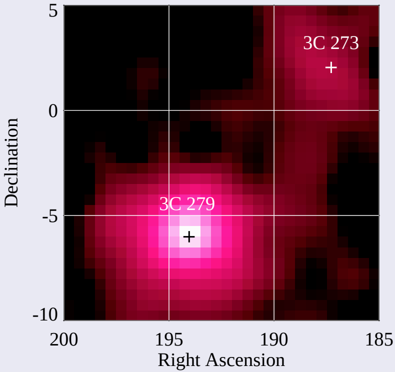



*Astronomers Studying an Eclipse by Antoine Caron (1571)*

# Solar occultation of 3C 279 $\gamma$-ray source?

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

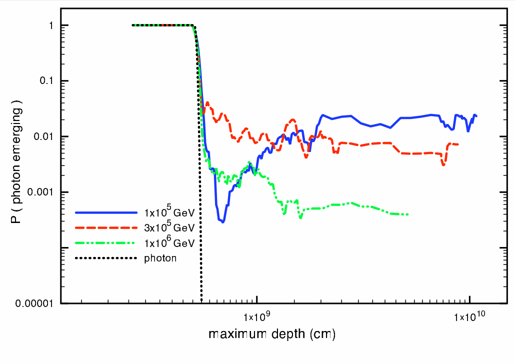
## 3C 279



# Shining light through the Sun by axions

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

## Probaility 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

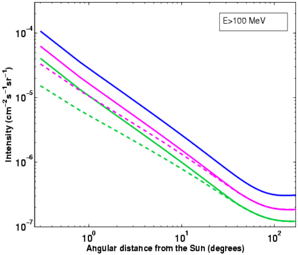
*Orlando, Strong, A&A, 480, 847 (2008)*

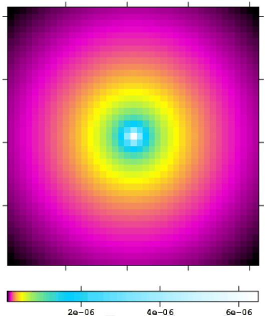
- Upper figure: Model angular profile of the solar emission above 100 MeV.
- Lower figure: Inverse-Compton emission modelled for a region of 10° from the Sun for 300-500 MeV. Intensity is given in $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$.
- Sum of disk and extended components of solar emission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

| Energy (MeV) | solar disk | Total flux |
|---|---|---|
| $>100$ | $0.54\pm0.32$ | $4.44 \pm 2.03$ |

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

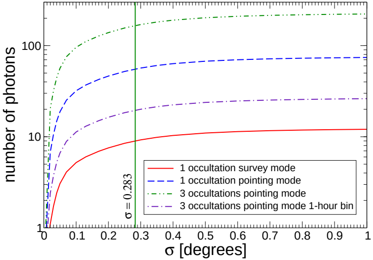
$F^{occult}_{3C279} \approx (6.2^{+3.7}_{-2.7}) \cdot 10^{-7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
$F_{3C279} \approx (8.6 \pm 0.5) \cdot 10^{-7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



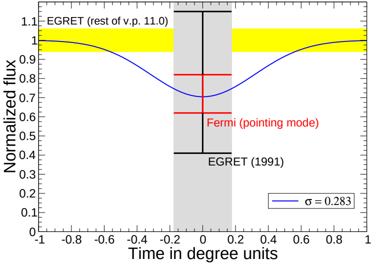



# Fermi Gamma Ray Space Telescope (GLAST)

- Launched in June 2008
- $E = 30$ 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 $\gamma$-ray sky
  - $\gamma$-ray bursts
  - probe dark matter and early Universe



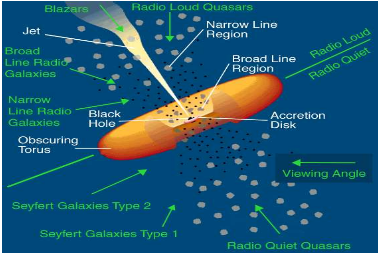


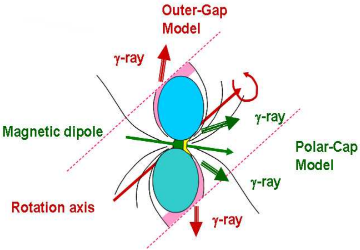


# Outline

# $\gamma$-ray astronomy

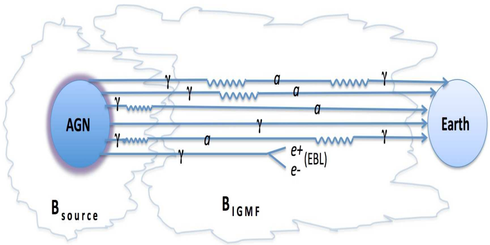
- Predicted in 40s
- Detected in 60s
- $\gamma$-rays absorbed by atmosphere
- Ballons
- Satellites (recent INTEGRAL, EGRET, Fermi, ...)
- Atmospheric imaging Cherenkov telescopes (H.E.S.S., MAGIC, VERITAS, ...)
- Sources: AGN, pulsars, SNR, secondary cosmic rays



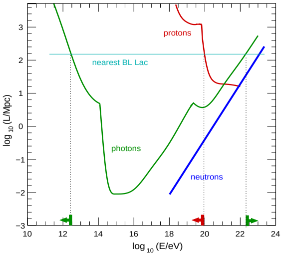



# Photon attenuation length

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

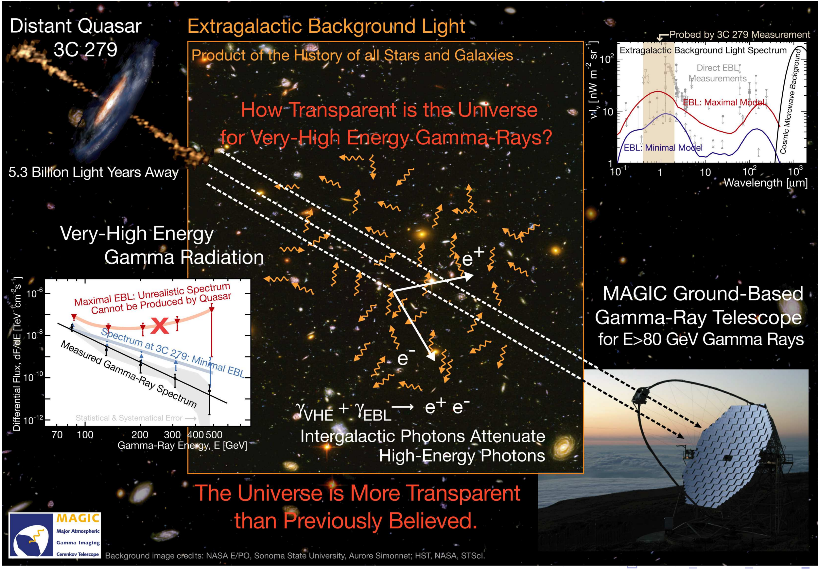



*Sanchez-Conde et al arXiv:0905.3270*



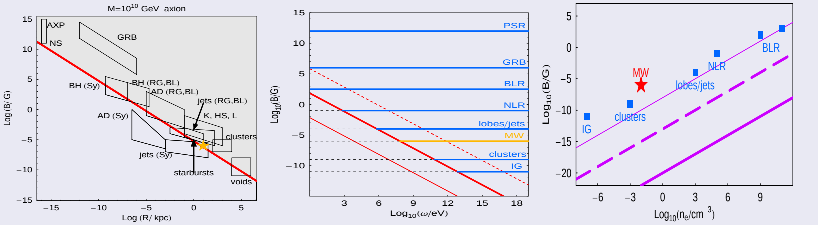

*Fairbairn, TR, Troitsky, arXiv:0901.4085*

# 3C 279 observation by MAGIC



# Axion-photon mixing in astrophysical objects

*Fairbairn, TR, Troitsky, arXiv:0901.4085*




## Photon-axion conversion probability

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

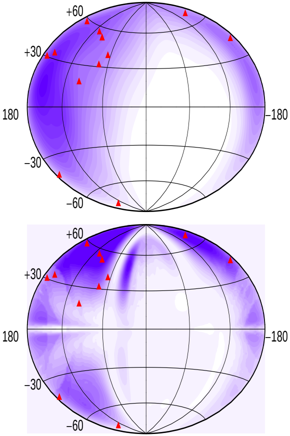
$$l_{\rm osc} = \frac{4\pi\omega M}{\sqrt{M^2\left(\omega_p^2 - m_a^2\right)^2 + 4B^2\omega^2}}, \quad B = const, \quad \omega_p = const$$

# Correlation of UHECR events with BL Lacs

- Charged particles are deflected in IGMF and in GMF
- Neutral particles are absorbed at $> 10^{18}$eV, $> 100$Mpc
- Correlation of AGASA, Yakutsk, HiRes UHE events with BL Lacs, *Tinyakov, Tkachev, astro-ph/0102476; Gorbunov et al, astro-ph/0406654*
- Cannot be $\nu$ (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 $10^{-10}$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 quazars

  *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 telesopes (Fermi).