Athanasios Manousos
Nuclear Physics and Elementary Particle Physics Department
Aristotle University of Thessaloniki, Greece

Energetic ALPs Production in Galaxies

Outline

- Axions
  - Strong CP Problem, Properties, Dark Matter Candidates
  - Axions from the sun, Axion Helioscopes, Bounds on solar axion properties
- Axion Like Particles (ALPs)
  - Photon-ALPs oscillation
  - cosmic magnetic fields
  - Photon – ALPs conversion
- Energetic Axions from astrophysical sources
  - Stars, Galactic center, SNs, AGNs, Pulsars, GRBs, Extragalactic Photons, Quasars
- LHC experiments as “Axionscopes”?
- Conclusions & future work

Properties, Strong CP Problem Axions as Dark Matter Candidates

- Strong CP Problem
  - Strong interaction does not violate CP - symmetry
  - Possible CP-violating in QCD Langragian:

$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G\tilde{G} \qquad \left(\tilde{G}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} G^{\rho\sigma} \right)$$

  - Experimental consequence:

    Prediction of electric dipole moment for the neutron:

$$|d_n| = A|\theta| \times 10^{-15} e \times cm$$

  - BUT experimental result: $|d_n| < 0.63 \times 10^{-25} e \times cm$
  - So, $|\theta| < 10^{-9}$

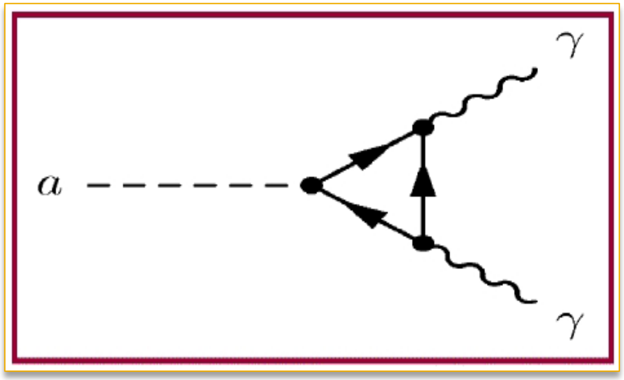
Properties, Strong CP Problem
Axions as Dark Matter Candidates

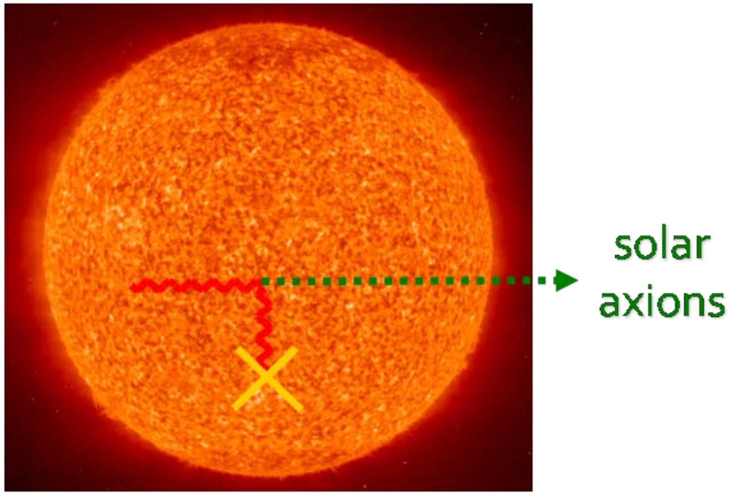
- Axion is a very light pseudo-scalar particle (spin-parity 0^-) originally postulated in connection with the absence of CP violation in strong interactions (QCD).
  - Proposed by Peccei & Quinn (1977)
  - Very low mass: $m_a \approx \left(10^7 GeV / f_a GeV\right) \times 0.62 eV$
    - The axion mass depends on the $U_{PQ}(1)$ symmetry-breaking scale f_a
  - Very low interaction cross-sections
    - The axion coupling strength is: $g_a \propto m_a$
  - Practically stable
  - Were created abundantly during the Big Bang
  - Nearly invisible to ordinary matter
  - Essential component of string theory
  - Good candidate for Dark Matter and quintessential Dark Energy (m_a very light)

Axions from the Sun

Primakoff Effect

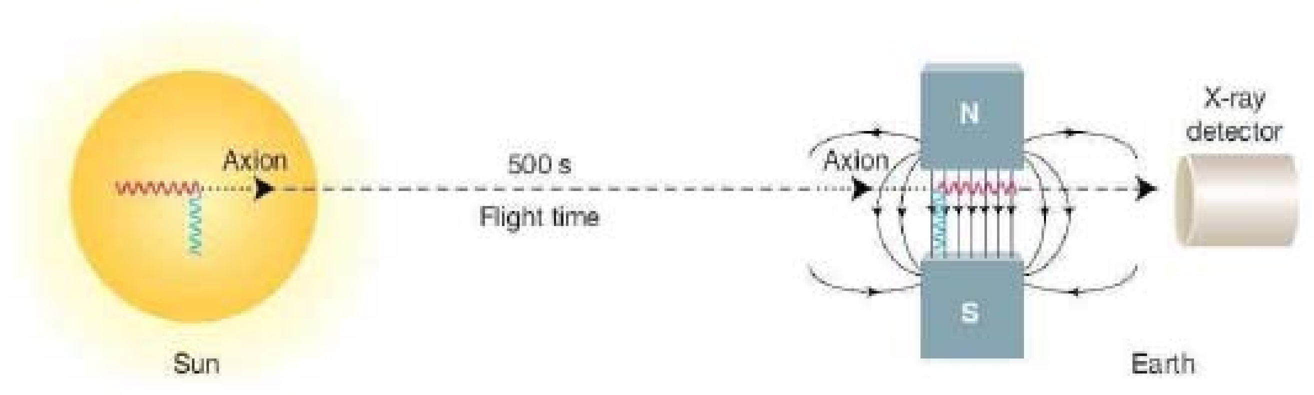
- Two photon coupling.
- Stellar plasmas may be a powerful source of axions..
- Important notice:
  - The closest stellar plasma available is the **Sun**
- Blackbody photons are converted into axions in stellar cores via the Primakoff effect.





Axions from the Sun

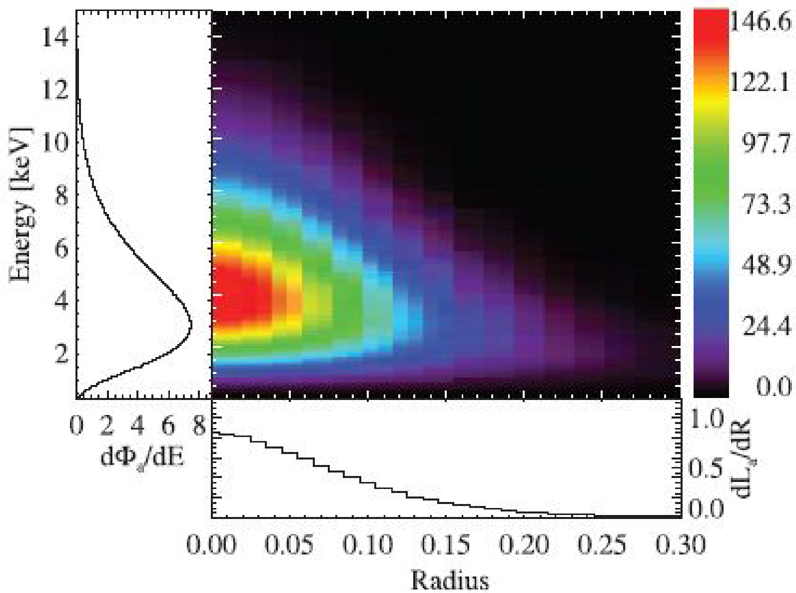
- Inverse Primakoff effect can be utilized for axion detection on Earth.

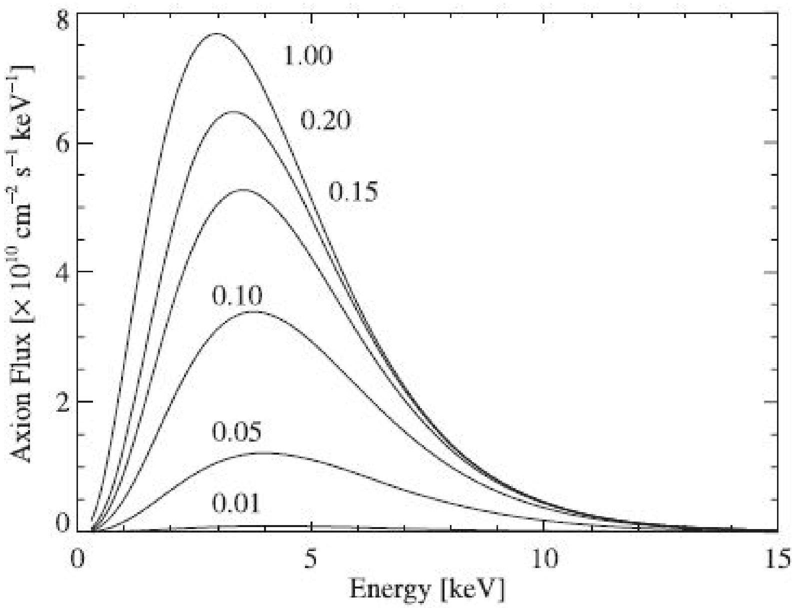


- A thermal photon converts into an axion in the Coulomb fields of nuclei and electrons in the solar plasma.
- The axion converts into a photon under a strong magnetic field in the laboratory (inverse process, Sikivie 1983)

Solar Axion Spectrum & Flux

[CAST Collaboration, JCAP04(2007)010]





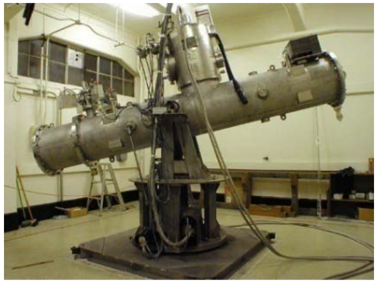
- Solar axion surface luminosity depending on energy and the radius r on the solar disc. The flux is given in units of axions $cm^{-2}\ s^{-1}\ keV^{-1}$ per unit surface area on the solar disc. Also shown is the radial distribution of the axion energy loss rate of the Sun *(dL_a/dR)* as well as the energy distribution of the solar axion flux *($d\Phi_a/dE$)*.
- Differential solar axion spectrum, derived by integrating the model shown on the left up to different values of r in units of the solar radius R. The peak of the spectrum moves towards lower energies if integration radius moves towards the outer rim of the solar disc.

Estimated total Flux at the Earth: $\Phi_a = 3.75 \cdot 10^{11} \cdot (10^{10} GeV \cdot g_{a\gamma})^2\ cm^{-2}\ s^{-1}$

Axion Helioscope Experiments

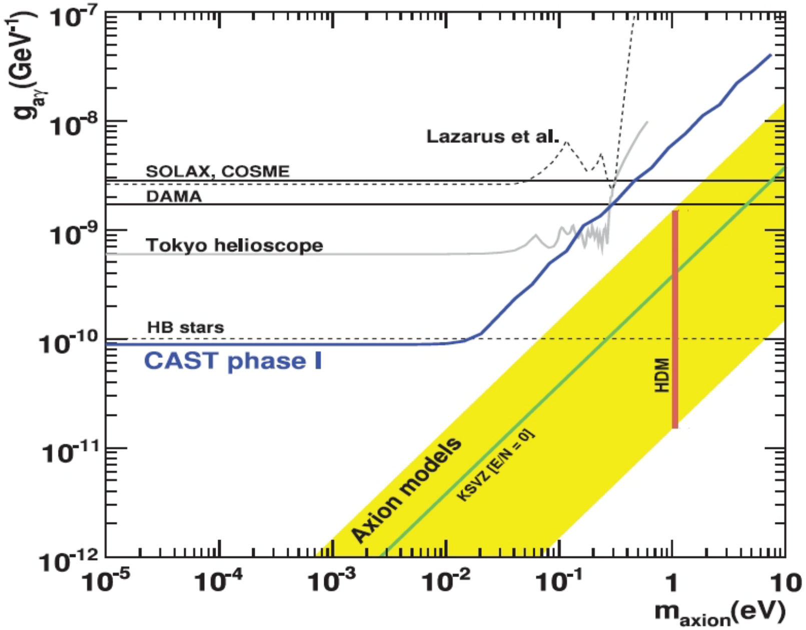
A superconducting magnet points towards the Sun to convert incoming solar axions to X-rays. The axion telescope is equipped with X-ray detectors to record the X-ray signal.

- BNL Helioscope 1992 *[Lazarus et al., Phys.Rev.Lett.69(1992)2333]*
  - S/C Magnet: $B = 2.2$ *Tesla*, $L = 1.8$ *m*
  - S/T: No tracking system
  - X-ray detectors: Proportional counter
- Tokyo Helioscope 1997- *[Inoue et al. 2002 astro-ph/0204388v1]*
  - S/C Magnet: $B = 4$ *Tesla*, $L = 2.3$ *m*
  - S/T: ~12 h/day
  - X-ray detectors: Proportional counter
  - Buffer gas: ^{4}He
- CERN Axion Solar Telescope (CAST)
  - S/C Magnet: B = 9 Tesla, L = 9.26 m
  - S/T: ~3 h/day
  - X-ray detectors: μM, TPC & CCC+X-ray telescope
  - Buffer gas: ^{4}He, ^{3}He



Bounds on Solar Axion's properties

- CAST Experiment:
  - $g_{a\gamma} < 8.8 \times 10^{-11} \text{GeV}^{-1}$ at 95% CL for $m_a < 0.02$ eV



Exclusion plots in the axion–photon coupling versus the axion mass plane.
[CAST Collaboration, JCAP04(2007)010]

ALPs: Axion-like particles

- Axion-Like-Particles (ALPs) are scalar or pseudo-scalar particles with coupling to 2 photons.
  - ALPs coupling strength not related to m_a
- In the presence of magnetic fields, photons and ALPs can mix via the term:

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

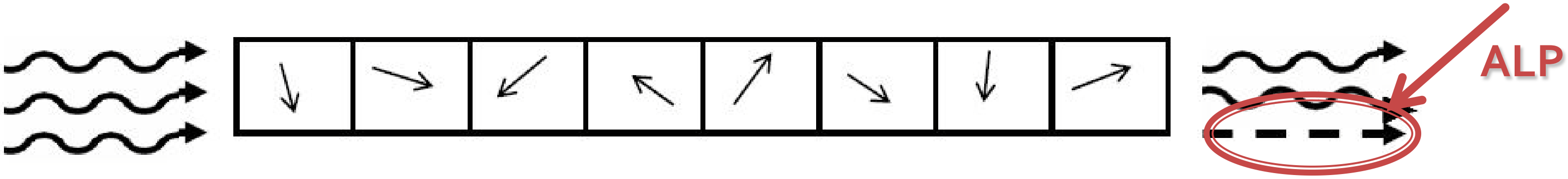
where α is the axion field, F is the electromagnetic field strength tensor, E the electric field, B the magnetic field and $g_{\alpha\gamma}$ is the ALP – photon coupling strength.

Photon – ALPs oscillation

- Gamma-rays can oscillate in intergalactic B-fields into very light ALPs and vice-versa:

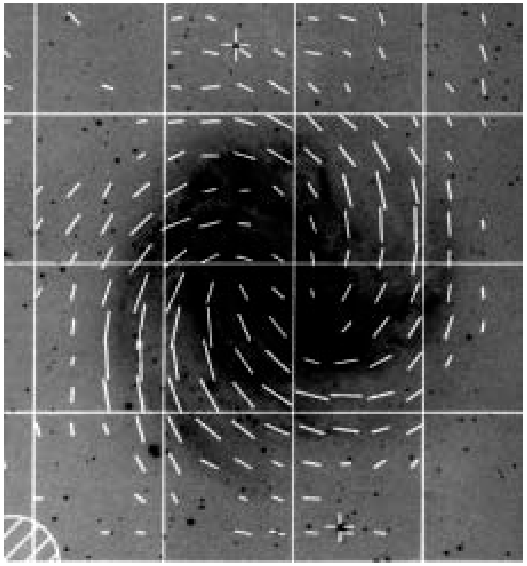
$$\gamma \rightarrow X \rightarrow \gamma$$

- The morphology of Intergalactic Magnetic Fields is supposed that has a domain-like structure with random orientation.
- Axion-photon oscillation dim photon flux, creating also energetic ALPs, an effect which is enhanced with distance and saturates after a very long path.



Cosmic Magnetic Fields

- Intergalactic field:
  - B ≈1nG, Coherence length L≈1Mpc
  - Mean electron density: $n_e \approx 10^{-7} cm^{-3}$
    - e.g. plasma energy: $w_{pl} \approx 10^{-14} eV$
- Galactic Magnetic field:
  - B ≈1nG, Coherence length L≈1Mpc
  - Mean electron density: $n_e \approx 1.1 x 10^{-2} cm^{-3}$
    - e.g. plasma energy: $w_{pl} \approx 4.1 x 10^{-12} eV$



Note: Strong photon – ALP mixing for $m_\alpha < \omega_{pl}$

Photon – Axion Conversion

- As it was mentioned before, ALPs by definition have a two – photon coupling. More specified, for pseudoscalars ALPs, it is of the form:

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

- Calculations show that after traversing large intergalactic distances about 1/3 of the light would have been converted to axions. The effect actually saturates at this value, so beyond a certain distance there is no additional dimming.

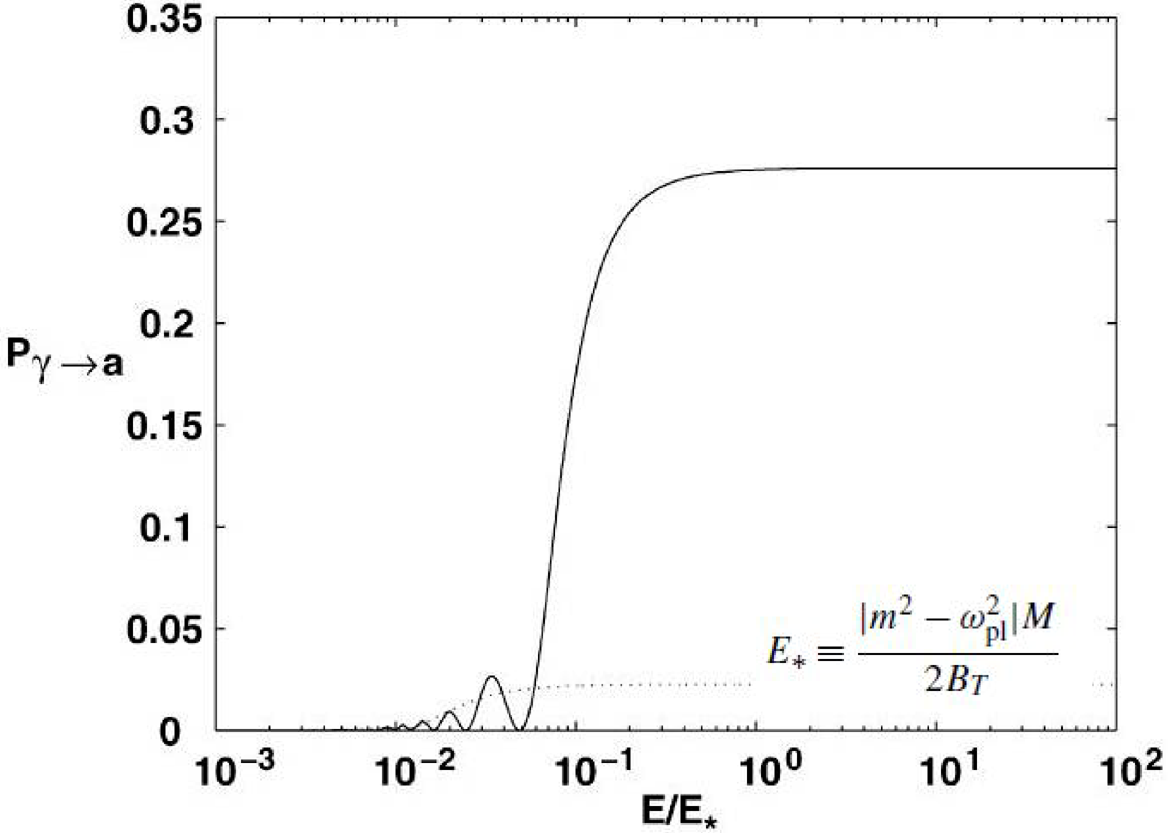
- The correct continuum limit after traveling over z >> s is:

$$P_{\gamma \to a}(z) = \frac{1}{3}\left[1 - \exp\left(-\frac{3P_0 z}{2s}\right)\right]$$

A. Mirizzi et al. / arXiv:0704.3044v2

- So, for z/s→∞, the conversion probability saturates so that ≈ 1/3 of all photons converts to axions.

Probability g → a vs. Photon Energy



Conversion probability versus photon energy in units of E_* in the intergalactic magnetic field.
The plot arises for $M = 10^{11}$GeV.
Dotted and solid lines correspond to $B = 10^{-9}$G and $B = 5*10^{-9}$G

[A. De Angelis et al. / Physics Letters B 659 (2008) 847–855]

Possible consequences of Photon – ALPs Oscillation

- Dimming of distant SN $I_{a.}$ It makes the accelerated cosmic expansion not necessary *[Csaki et al. Phys. Rev. Lett. 88 161302 (2002)], [Grossman et al. Physics Letters B 543 (2002) 23–28].*
- TeV photons from distant galaxies travel cosmological distances and reach Earth, bypassing the microwave background without absorption in microwave background photons *[De Angelis A., Roncadelli M.,Mansutti O., 2007, Phys. Rev. D, 76, 121301].*
- Substantial distortions in the spectra of AGN sources *[Burrage et all, PRL 102, 201101(2009)]*.
- Possible effects observable by gamma ray telescopes, e.g. observations with Fermi-LAT instrument and Imaging Atmospheric Cherenkov Telescopes *[M. A. SANCHEZ-CONDE et al. Phys. Rev. D 79,123511 (2009)]*.

Potential sources for Energetic Axions

- Energetic axions could be produced via the conversion of photons to ALPs due to magnetic fields in the source and/or in their path.
- Sources:

→ Solar: Sun, solar flairs

E_a < 10keV (low energy axions)

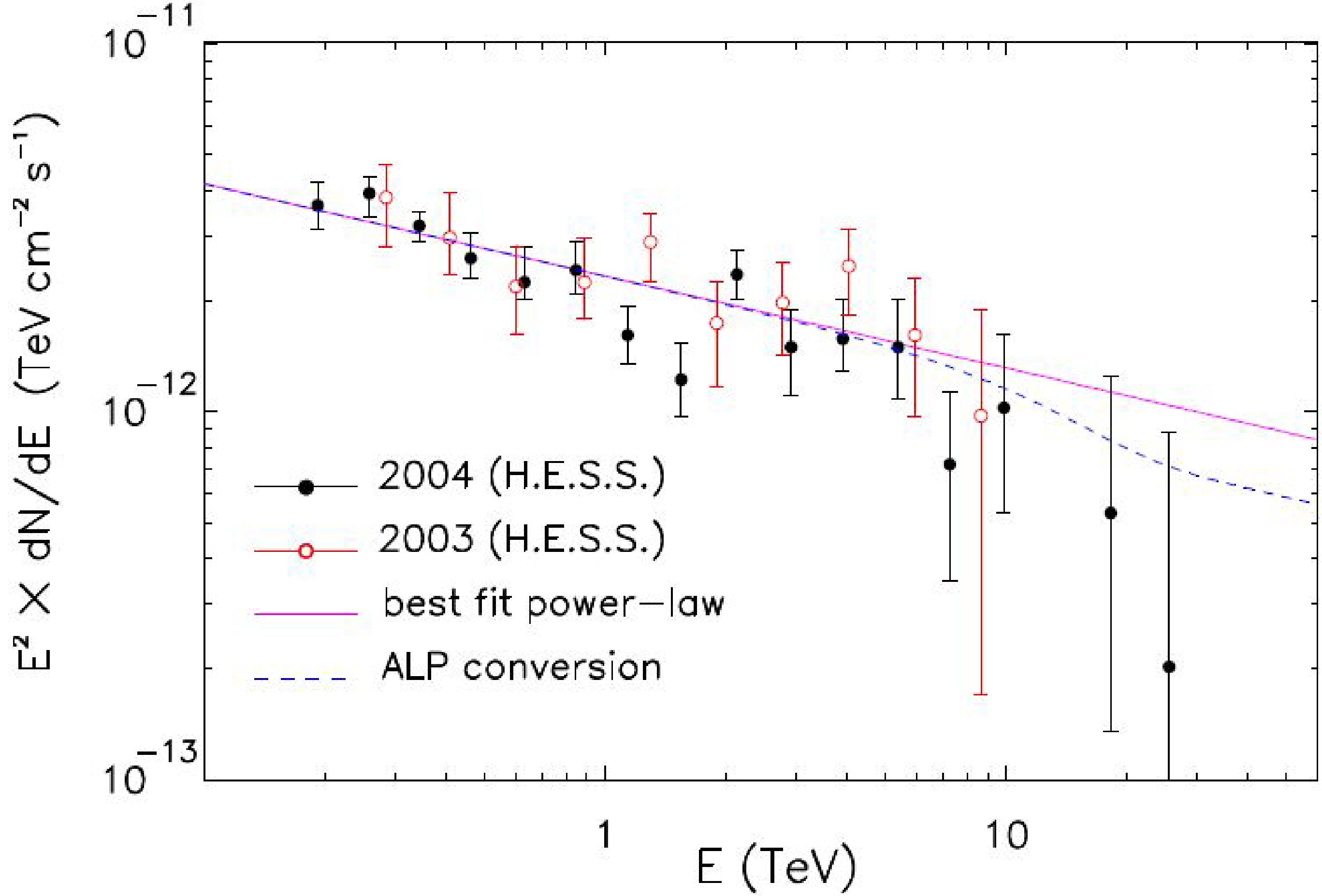
→ Galactic: Stars, white dwarfs, SNs, galactic center

$m_a < 10^{-3}$eV, E_a < 50MeV

→ Extragalactic: SN in galaxies, AGNs, Quasars, GRBs

$m_a < 10^{-10}$eV, E_a < 1TeV, Max flux: 1/3 of extragalactic photons

Galactic Center

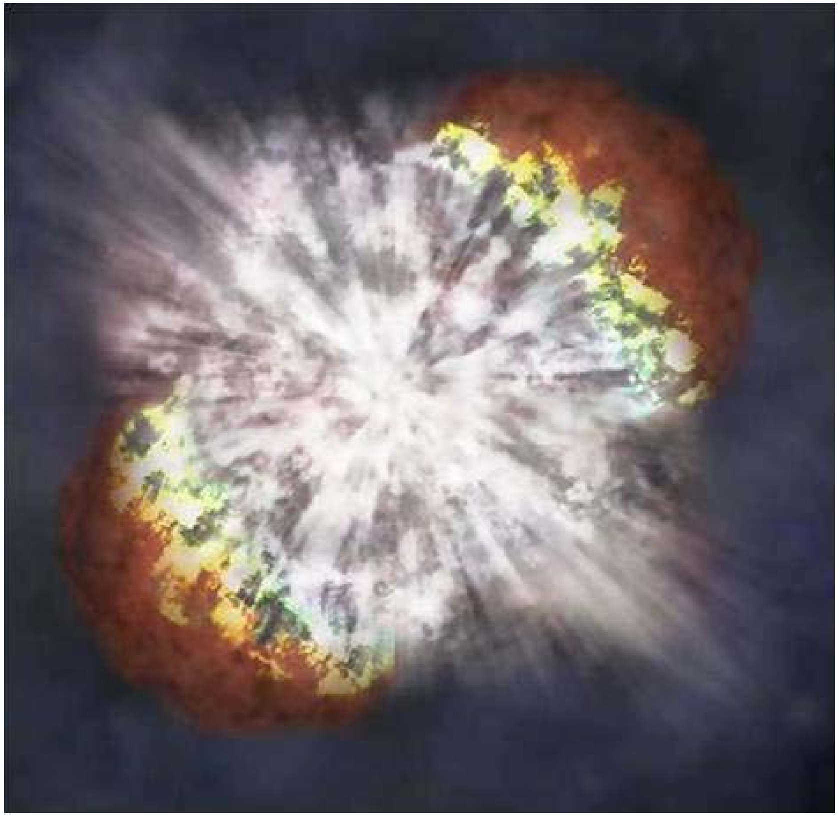


Spectral energy density E_2 dN/dE of photons from the galactic center source
[A.Mirizzi et al. arXiv:0704.3044v2]

Supernovae (SNs)

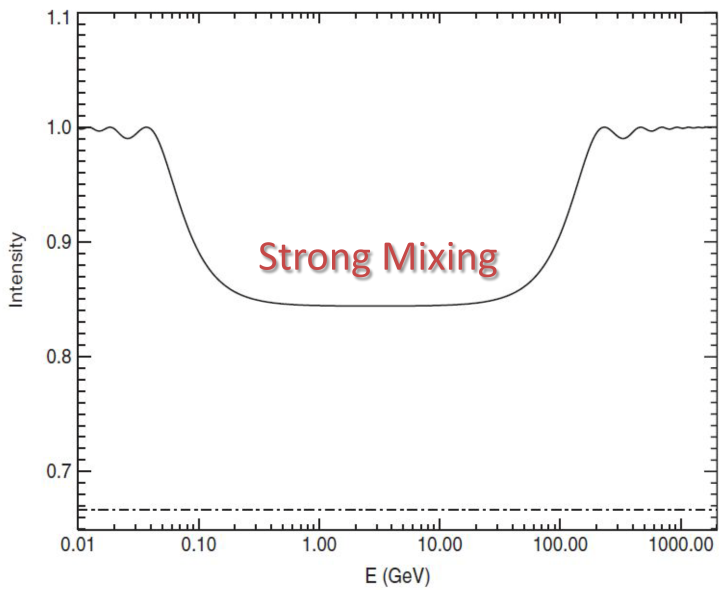
- Expected integrated axion flux on Earth:
  - ~10^9 axions/cm^2 from a SN explosion, with duration ~10 seconds and distance L=6kpc.

[K. Zioutas et al. Physics Letters B 443(1998)201–208]



AGNs

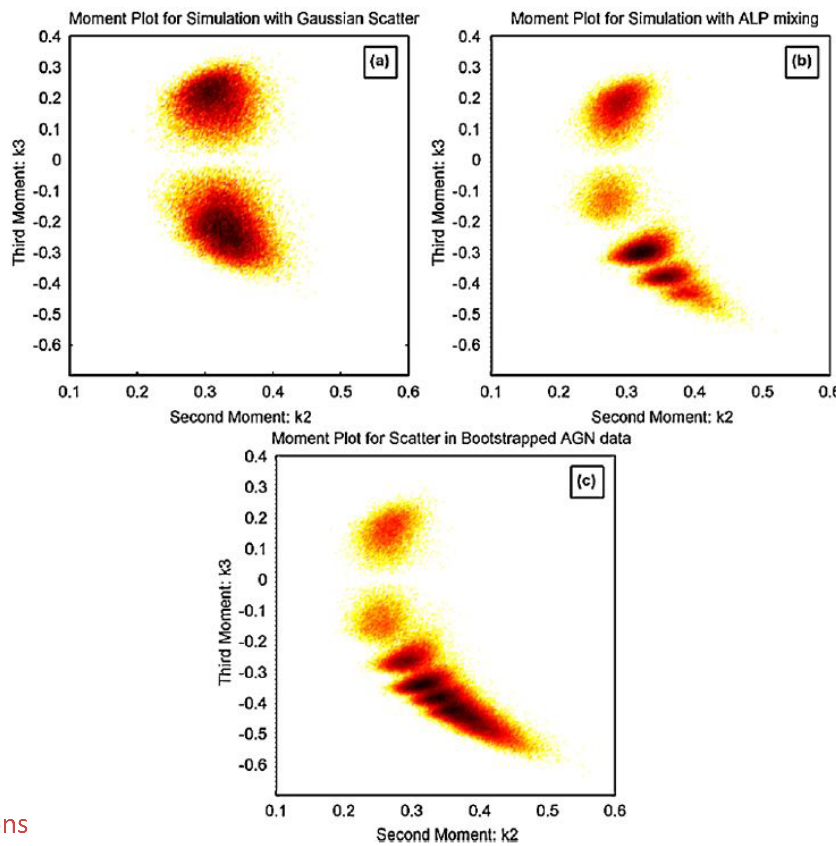
- Existance of ALPs can produce substantial distortions in the spectra of AGN sources



Example of photon/axion oscillations inside the source or vicinity, and its effect on the source intensity (solid line)

For the strong mixing regime, there are almost enegy-indipedent conversions

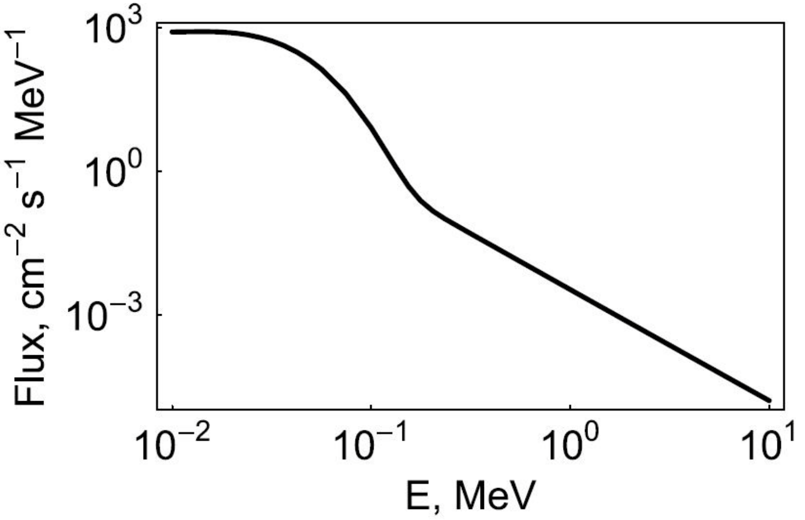
[M. A. SANCHEZ-CONDE et al. PRD 79, 123511 (2009)]



Active galactic nuclei - Fingerprints.
[Burrage et all, PRL 102, 201101(2009)]

Pulsars

- Typical magnetosphere of a neutron star:
  - B ~10^{13} G at lengths L~10km
- Maximal photon-ALP mixing takes place at energies as low as $E \geq 10^{-4}$ eV
- Estimation of fluxes of ALPs for photon energy:
  - 100MeV ≤ E ≤ 10GeV, from EGRET and INTEGRAL data
- The total expected flux of astrophysical axions from pulsars and GRBs is given, as a function of energy, in the following figure:

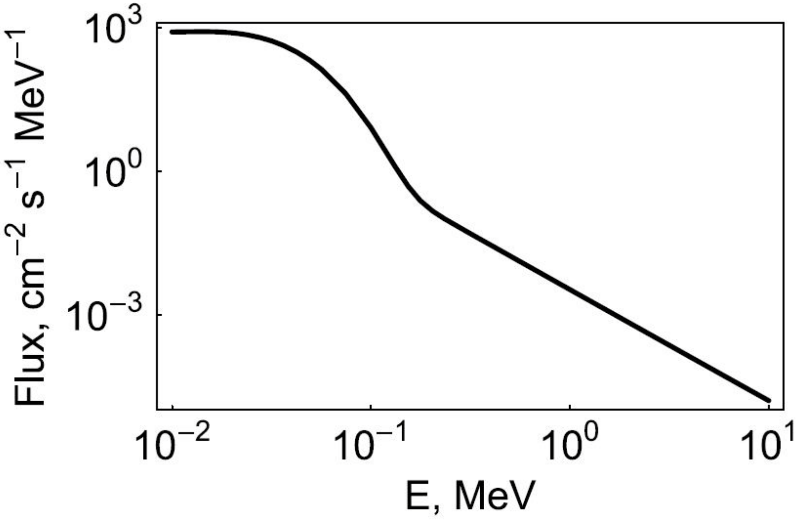


Expected axion flux from all astrophysical sources versus energy [M. Fairbairn et al. Eur. Phys. J. C 52, 899–904 (2007)]

GRBs

- Typical Magnetic field: $B \sim 10^9 G$ at lengths $L \sim 10^4 km$
- Data from BATSE – detected GRBs
  - 10^5 photons/cm^2/s/year for the sum of peak count rates of all
  - Total flux:

    ~10^{-3} photons/cm^2/s/year/keV
  - Energy band between 50keV and 300keV
- The total expected flux of astrophysical axions from pulsars and GRBs is given, as a function of energy, in the following figure:

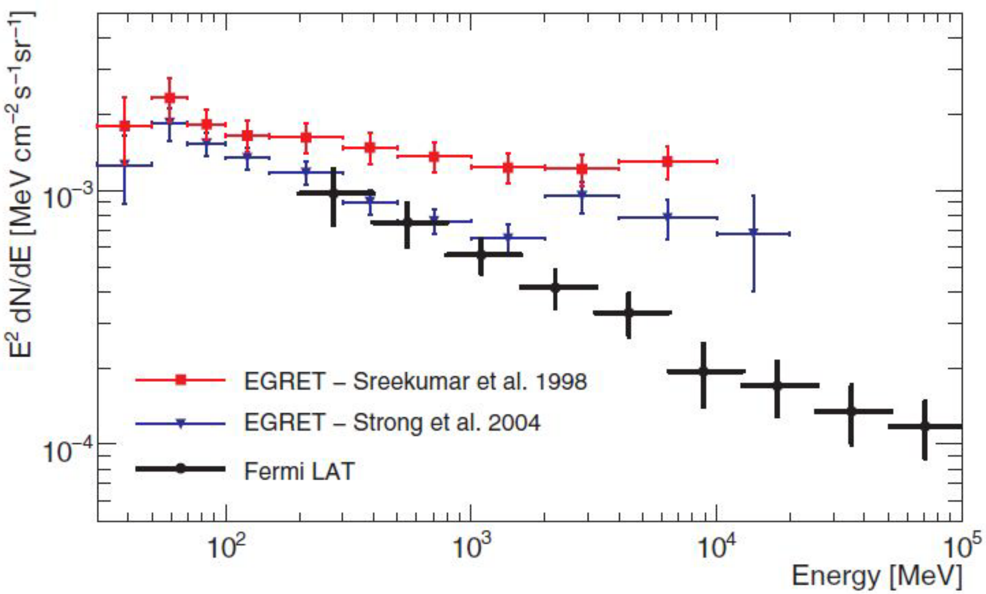


Expected axion flux from all astrophysical sources versus energy [M. Fairbairn et al. Eur. Phys. J. C 52, 899–904 (2007)]

Extragalactic Photons

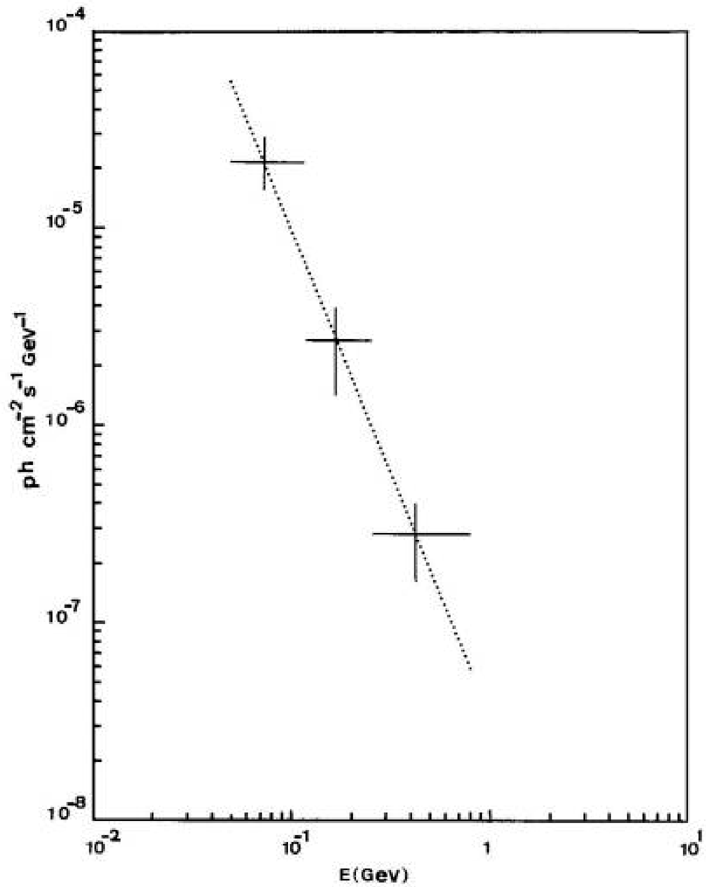
- Extragalactic diffuse of *γ*-ray emission (~isotropic):
  - ~10^{-5} photons cm^{-2} s^{-1} sr^{-1}, above 100 MeV.

    [X. Chi, J. Phys. G: NPPhys. 15 (1989) 1509-1518]
- Power law with a differential spectral index:
  - *γ* = 2.41 0.05

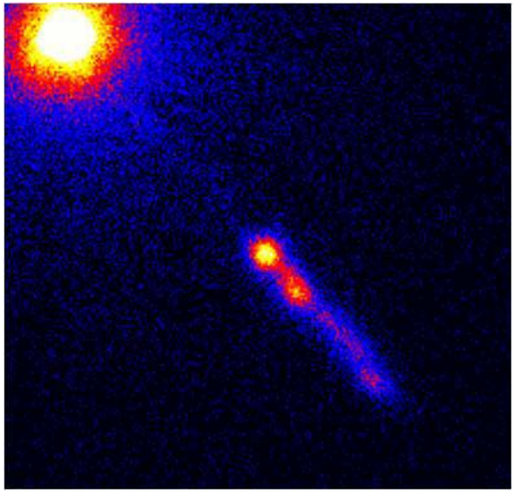


EGB intensity derived compared with EGRET-derived intensities
[Fermi collaboration, PRL 104, 101101 (2010)]

Quasars / Quasar Spectrum

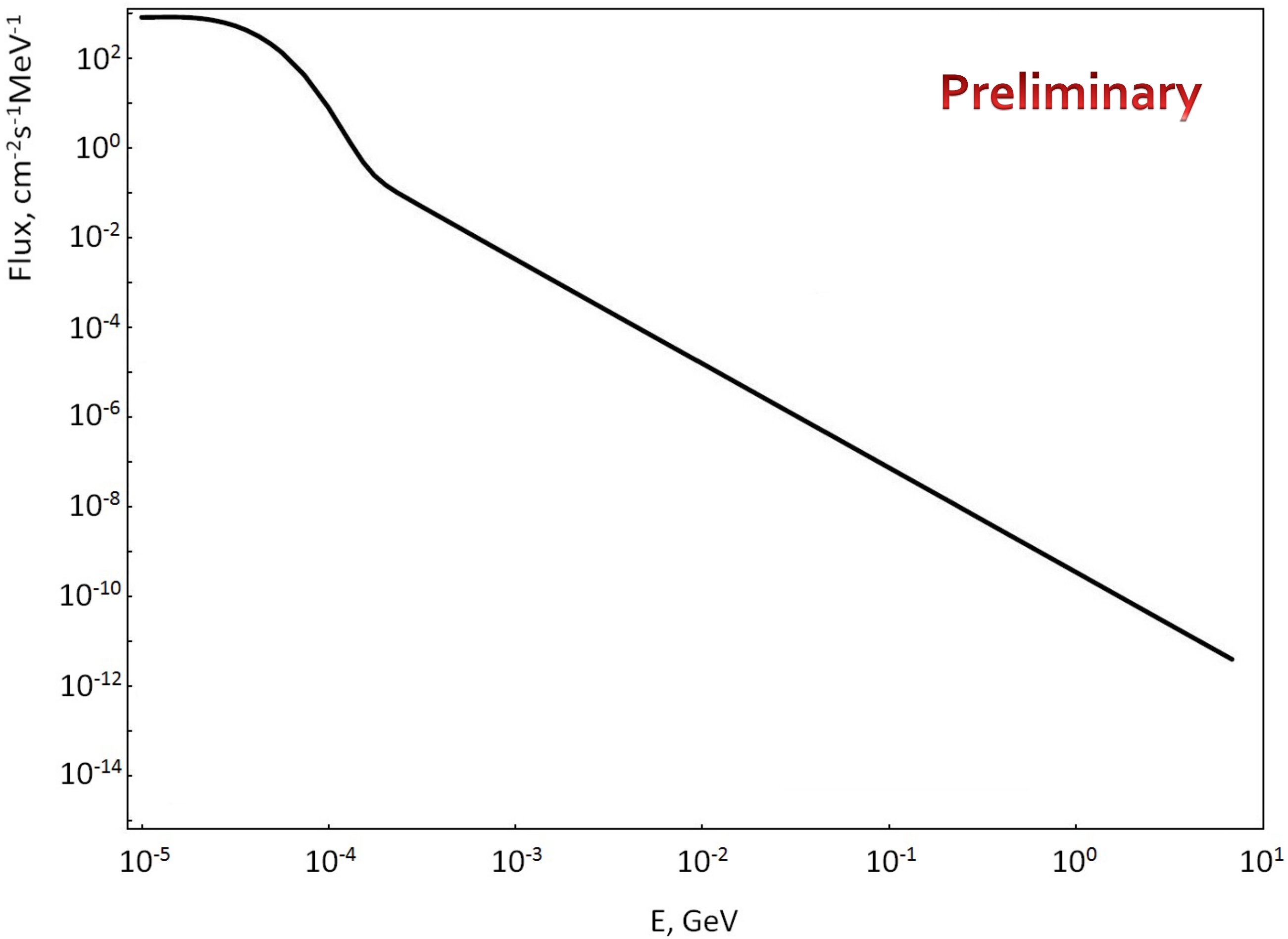


ESA's Satellite Cos-B
http://astronomy2009.esa.int/science-e/www/object/index.cfm?fobjectid=36238



- Differential photon number spectrum obtained by Cos-B for the Quasar 3C273, with the best power law fit also shown as the dotted line.

Energetic ALPs' Flux



Axion Flux estimation from astrophysical sources
(extrapolation from fig. in [M. Fairbairn et al. Eur. Phys. J. C 52, 899–904 (2007)])

LHC experiments as “Axionscopes”?

High Energy Axions

- Are High Energy Axions around?
  - Probably
- How?
  - From photon-axion conversion of high energy gamma rays
- How many are they?
  - It has been suggested and calculated, as it was mentioned before, that photon-axion conversion saturates at 1/3.

LHC experiments as "Axionscopes"?

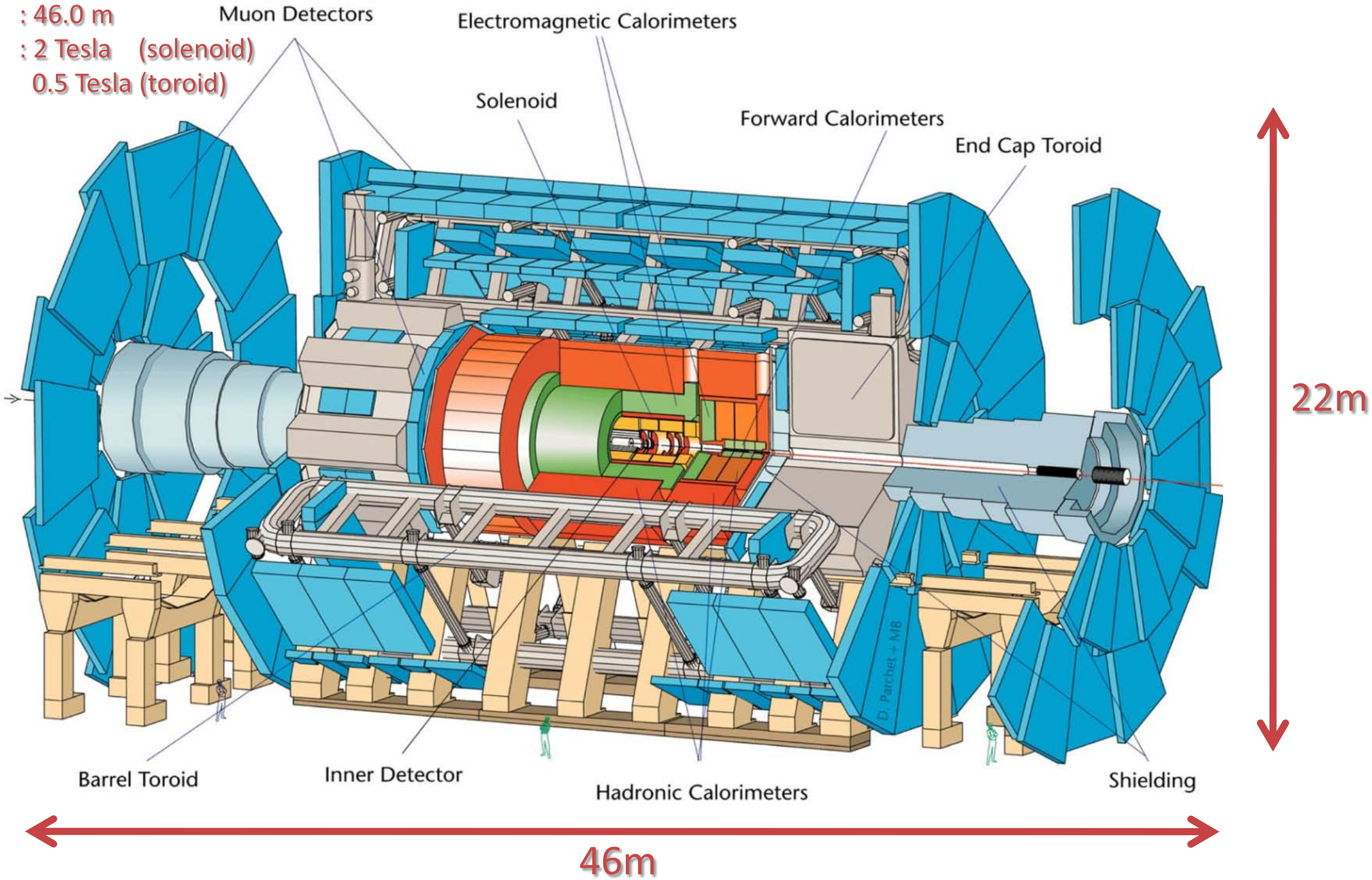
How to measure high energy axions from anywhere?

- With existing detectors with strong magnetic fields, such as ATLAS and CMS
- Axions entering the solenoids may be converted to photons.
- And recorded as Minimum Bias events
- However, it is worth looking at the detailed geometry of the detectors.

LHC experiments as “Axionscopes”?

ATLAS (A Toroidal LHC ApparatuS) detector

Total weight : 7000 T
Overall diameter : 22.0 m
Overall Length : 46.0 m
Magnetic field : 2 Tesla (solenoid)
0.5 Tesla (toroid)



LHC experiments as "Axionscopes"?

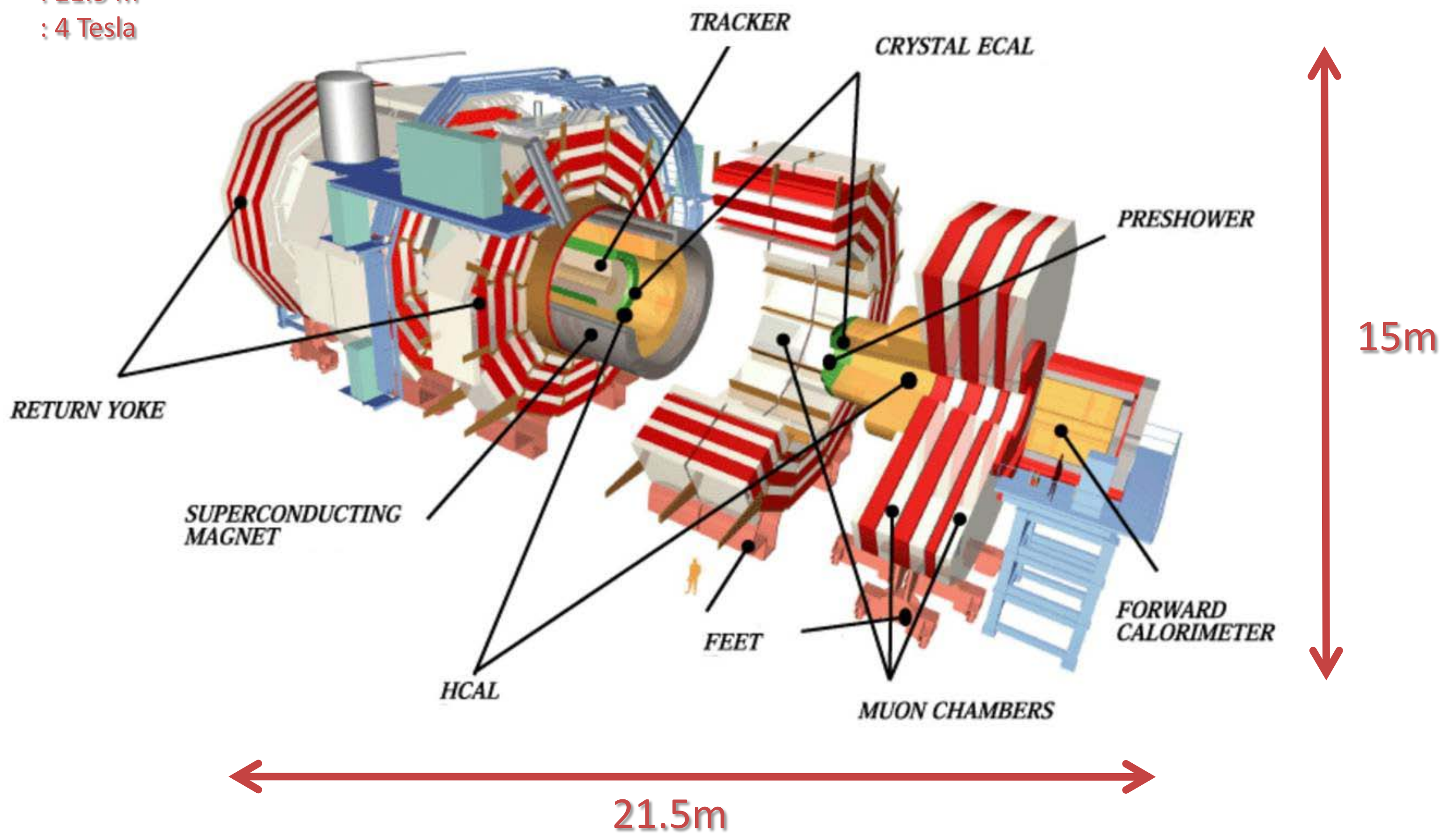
ATLAS detector

- The ATLAS Solenoid is rather small. Only the inner detector is inside
- In case of axion to photon conversion, the photon will probably escape to the Electromagnetic Calorimeter and it will be recorded as a Minimum Bias event
- Somehow, a more complicated event topology is expected for the toroidal magnet
- A Monte Carlo study is under way…

LHC experiments as "Axionscopes"?

CMS (Compact Muon Solenoid) detector

Total weight	: 12500 T
Overall diameter	: 15.0 m
Overall Length	: 21.5 m
Magnetic field	: 4 Tesla



LHC experiments as "Axionscopes"?

Compact Muon Solenoid (CMS) detector

- The CMS Solenoid is big. Tracker, EM and Hadronic Calorimeters are inside.
- In case of axion to photon conversion, the photon will be recorded in the EM Calorimeter, as a Minimum Bias event (single photon).
- A Monte Carlo study is under way…

Cosmic ALP detection in the MeV region

- Considering the estimates for ALP fluxes from astrophysical sources
- Taking into account the dimensions and the magnetic field in ATLAS and CMS detector systems
- Assuming an ALP to photon conversion probability $P_{\alpha\gamma}$ in the above detectors of the same order of that of CAST (10^{-15}).

→ We can reach to the conclusion that it is highly improbable to find some ALP-events in these experiments with GeV or TeV energies

→ If we take into account the energy dependence of the probability $P_{\alpha\gamma}$ we conclude that the most favorable case for cosmic ALP detection is in the MeV region, close to the lower limit of the detectors' performance.

Conclusion & future work

- ALPs are good candidates for Dark Matter particles
- Axion-photon oscillation in cosmic magnetic fields dim photon flux, creating also energetic ALPs, an effect which is enhanced with distance and saturates after a very long path
- Some of TeV photons from distant galaxies can be transformed to Energetic ALPs
- Estimates of flux of energetic ALPs could be in principle be extracted from the measured fluxes of energetic photons from distant astrophysical sources
- It is worth exploiting existing general purpose detectors such as ATLAS and CMS for ALP – events in their background in MeV region
- Monte Carlo studies would be essential..

The END

Thank you for your attention