Axion bound from globular clusters

Adrian Ayala
University of Granada/University of Rome Tor Vergata
in collaboration with Inma Domínguez (PhD advisor), Maurizio Giannotti, Alessandro Mirizzi, Oscar Straniero (PhD advisor)

December 2, 2014

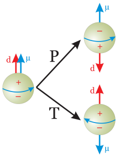
Overview

Axions and strong CP violation problem in QCD

- Axion: scalar particle proposed to solve strong CP problem in QCD
- QCD lagrangian has a CP violating term, related to a phase angle θ

$$\mathcal{L}_\theta = \theta \frac{g^2}{32\pi^2} G_{\mu\nu a} \tilde{G}^{\mu\nu a}$$

- CP violating term should produce a non-vanishing electric dipole moment of neutron



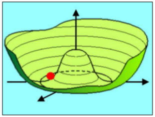
$$d_n = \frac{e\theta m_q}{m_N^2}$$

But electric dipole moment of the neutron is

$$d_n \leq 0.29 \times 10^{-25} e \cdot cm \implies \theta \leq 10^{-11} \, (?!)$$

Pecci-Quinn mechanism

- Why is θ so small?
- Pecci and Quinn proposed a new global symmetry $U(1)_{PC}$, broken dynamically



- Symmetry breaking keeps CP violation below a small value

$$\mathcal{L}_{\theta'} = \left(\theta - \frac{m_a}{f_a}\right) G_{\mu\nu a}\tilde{G}^{\mu\nu a}$$

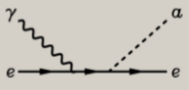
- Particle associated, a Nambu-Goldstone boson was named axion by Frank Wilczek

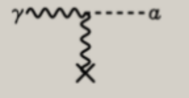
Cosmological relevance

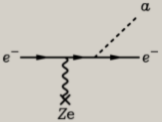
- Axions can acquire mass by pion coupling
- Depending on mass values axions can be a suitable dark matter candidate or not
- mass $\sim \mu eV \implies$ cold dark matter: Bose Einstein Condensate
- mass $\sim meV \implies$ hot dark matter produced during QCD transition. Disfavoured by cosmic large scale structures
- For QCD axions, it holds $\frac{m_a}{f_a} \sim \frac{m_\pi}{f_\pi}$. f_a related to $\sim 10^{12}$ GeV scale.

Axion interactions with quarks and leptons

- We can consider models where axions interact only with hadrons or with both hadrons and charged leptons
- In KSVZ model axions interact neither with charged leptons nor lighter quarks, only with heavy quarks
- In DFSZ model axions interact with both, charged leptons and hadrons, by means of Compton, Primakoff and Bremsstrahlung







Primakoff effect

- Coupling to photon by Primakoff effect is a general property of axions and axionlike particles

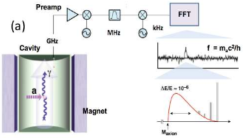
$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma} E \cdot B$$

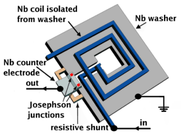
- "Light shinning through the walls" experiments
- Direct production of axions in stellar plasma
- Astrophysical evidence: universe transparency to high energy gamma rays, cooling rate of white dwarves

Axion direct detection experiments

- Conversion in photons of sun produced axions, in presence of a magnetic field (CAST: Cern Axion Solar Telescope)

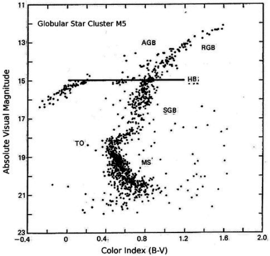
- Axion conversion in microwave photons in resonant cavities. ADMX (Axion Dark Matter eXperiment).



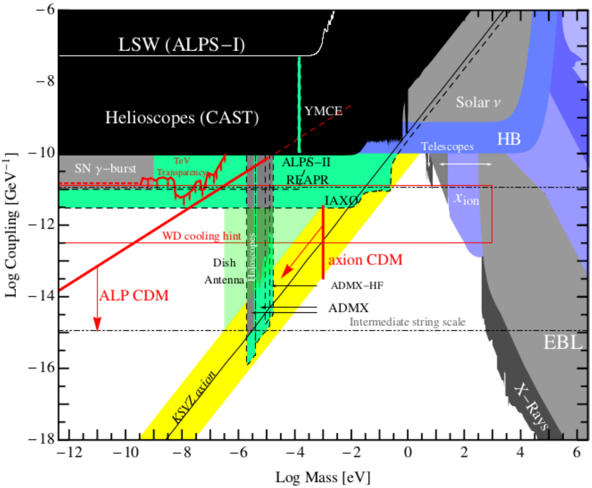


Indirect search. Stellar evolution

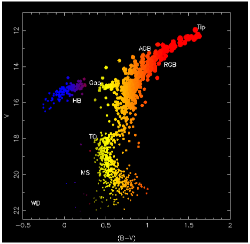
- Axion production in stellar interior $\Longrightarrow$ Primakoff effect
- Axions interact weakly with matter and escape freely from stars, carrying energy
- Energy loss influence stellar evolution $\Longrightarrow$ constraints from stellar evolution
- Globular Cluster Isochrones.

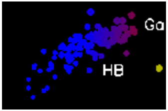


Axion space parameter. Excluded regions.



Primakoff effect and axion emission along horizontal branch stars

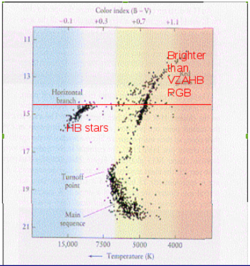




- Primakoff effect is $\propto T^7$. HB cores temperature about $(10^8 K) \implies$ axion rate significant
- Energy loss $\implies$ nuclear reactions rate increases $\implies$ time spent in HB phase reduces
- This can be tested $\implies$ R parameter

R parameter

- $R = \frac{Number\ \ of\ \ HB\ \ stars}{Number\ \ of\ \ RGB\ \ stars\ \ brighter\ \ than\ \ V_{ZAHB}}$
- V_{ZAHB}= "Zero age horizonta branch V magnitude" interpolated to $\log \mathrm{T_{eff}} = 3.85$
- R also equals $\frac{t_{HB}}{t_{RGB}}$
- R parameter affected through axion emission in HB phase, which decreases t_{HB}. t_{RGB} remains unchanged if helium is more or less the same

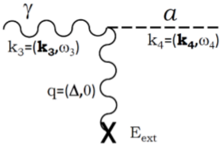


Observations. R parameter and Y

- We obtained average R parameter from a 39 GGC sample (Salaris et al, 2004). $[M/H] < -1.1$ to avoid "RGB" bump. Unique Helium abundance.
- Y determination from Izotov et al, 2013, low metallicity H_{II} regions
- We use central average values and σ error values to find upper and lower bounds
- $R = 1.39 \pm 0.04$, 1σ
- $Y = 0.255 \pm 0.003$ 1σ

Simulations. FUNS code

- Axion or ALP up to few keV can be produced in stellar plasmas, by means of Primakoff effect (photons in presence of external electric fields)



- We include axion emission in FUNS, taking into account ion and electron screening effect and electron degeneracy, following Raffelt & Dearborn (1987)

$$\epsilon \propto g_{a\gamma\gamma}^2 \frac{T^7}{\rho}$$

Simulations. FUNS code

- Accurate stellar evolution considering full nuclear network and neutrino effects. Axions considered as an effective energy sink
- Full evolutionary tracks and HB and RGB times for a single $0.85 M_{\odot}$, $Z = 0.001$ star.
- Helium mass fraction homogeneity, RGB and HB branches populated enough
- Evolutionary times t_{HB} and t_{RGB} $\Longrightarrow$ R_{th}

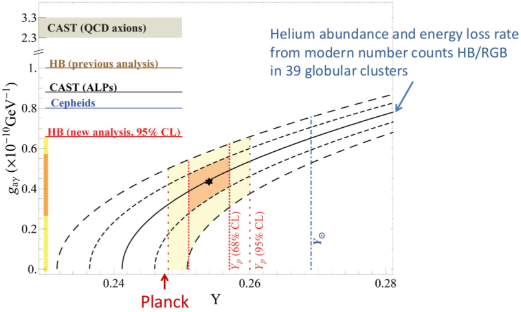
R parameter as a $g_{a\gamma\gamma}$ and Y function

$$R_{th}(g_{a\gamma\gamma}, Y) = 6.26Y - 0.41g_{10}^2 - 0.12$$

- g_{10} is coupling constant in 10^{-10} GeV^{-1}
- Parabolic dependency on g, linear on helium
- Degeneracy between g and $R \implies Y$ knowledge important to constrain axion-photon coupling

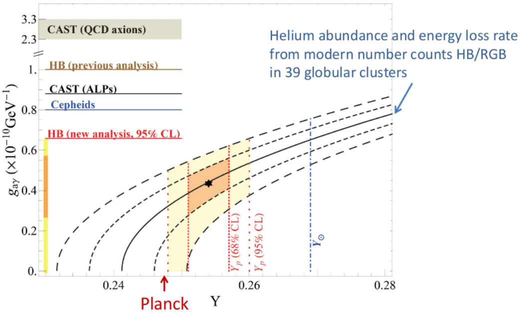
$g_{a\gamma\gamma}$ constraints

- Previous upper bound by Raffelt & Dearborn (1987), based on HB supression, $g_{a\gamma\gamma} < 10^{-10}$ GeV^{-1}
- Giannotti et al (2013) $g_{a\gamma\gamma} < 0.8 \times 10^{-10}$ GeV^{-1}
- Our upper bound $g_{a\gamma\gamma} < 0.66 \times 10^{-10}$ GeV^{-1} , 95% c. l.



$g_{a\gamma\gamma}$ upper and lower bound

- $g_{a\gamma\gamma} < 0.66 \times 10^{-10}$ GeV^{-1} , 2σ R and Y variations
- Compatible with bound Y < solar helium mass fraction
- We can not exclude $g_{a\gamma\gamma} = 0$
- Better Y determination needed



Model Uncertainties

- Nuclear reaction rates
- Convection
- Interpolation to ZAHB temperature

Conclusions

- We obtain the strongest $g_{a\gamma\gamma}$ upper bound till now
- We can't discard $g_{a\gamma\gamma} = 0$ ($\implies$ no axions) as lower bound at 2σ
- Y uncertainty remains important, specially for the lower bound

Work in progress

- Synthetic isochrones to avoid ZAHB temperature interpolation error
- Monte Carlo study of uncertainties due to nuclear reaction rates and convection
- Extension to other stellar evolutionary phases: RGB, massive stars, . . . and study of other particle constraints: "milicharged particles", hidden photons, WIMPs