Theoretical astroparticle activity

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1. Axion like particles and dark radiation

Axion-like particles (ALPs) with a two-photon vertex are hypothetical particles predicted in many extensions of the Standard Model. Pseudoscalar ALPs couple with photons through the following effective Lagrangian [1]

$$\mathcal{L}_{a\gamma} = -\frac{1}{8} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a \,, \tag{1}$$

where a is the ALP field with mass m_a, $F^{\mu\nu}$ the electromagnetic field-strength tensor, and $g_{a\gamma}$ the ALP-photon coupling. As a consequence of this coupling, ALPs and photons do oscillate into each other in an external magnetic field.

ALPs have been invoked recently to explain the excess of relativistic degree of freedom (Dark Radiation) measured by Planck. In the (string-inspired) scenario in Ref. [2], a non-thermal background of very light ($m_a < 10^{-9}$ eV) ALPs (Cosmic Axion.-like Background, CAB) with energy is generated by the decay of primordial scalar particles called Moduli. The ALPs background can be detected by conversion in astrophysical magnetic fields, for example in galaxy clusters [3] or in Milky Way [4]. We intend to enlarge the study performed in by [4] by studying the degree of polarization of the X-ray background generated by the conversion of cosmic ALPs into the Milky Way magnetic field ($\sim 1\mu$g). A preliminary map of the sky with the the degree of linear polarization ($\equiv \sqrt{Q^2+U^2}/I$, where Q, U, I are Stokes parameters) for 1 keV photons coming from the conversion of ALPs is shown in fig. 1. As we can see, the X-ray background is always almost linearly polarized. Therefore, the observation of a linearly polarized background almost uniformly distributed in the sky would be a strong indication of the existence of a CAB [5].

Another intriguing possibility is that ALPs can be converted into photons by the primordial Intergalactic Magnetic Field. Although this field has not been measured yet, there are many indication of its existence, with strength $B <$ 1ng. In this case the conversion of ALPs into photons after the recombination phase induced by (turbulent) primordial magnetic field can reionize the neutral hydrogen thus increasing the opacity of the Universe to CMB. Since the optical depth is well measured by Planck, this set a strong

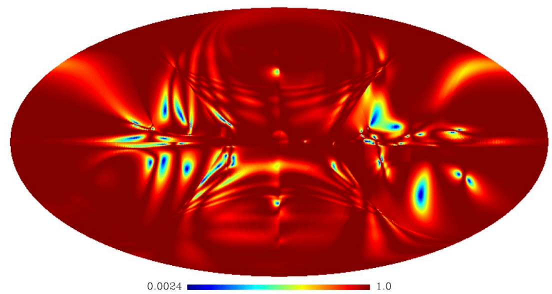

Figure 1. Sky map of the polarization degree for E =1keV photons from ALPs conversion in the Milky-Way.

limit on the product $g_{a\gamma}B$: $g_{a\gamma}B < 10^{-14} \div 10^{-15}$ GeV^{-1}ng (depending on the mass of the Moduli) [6].

2. Precision measurement of three neutrino oscillation parameters

We have upgraded the previous analysis performed in 2012 [7] including the new data coming from reactor and accelerator experiments. Neutrino oscillations are a well-estabilished quantum phenomenon in which neutrinos can change their flavor during propagation. The origin of this phenomenon comes from the fact that flavor (i.e., interaction) eigenstates are not the same of mass (i.e., propagation) eigenstates. Instead, the two basis are related by a unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} . \tag{2}$$

Here ν_i are the mass eigenstates with mass m_i. By convention $m_1 < m_2 \ll m_3$ (Normal Hierarchy, NH) or $m_3 \ll m_1 < m_2$ (Inverted Hierarchy, IH). Since oscillations depend only to $\delta m^2_{ij} = m^2_j - m^2_i$ oscillation experiments can probe only two mass square differences and not absolute neutrino masses. Although mass square differences are well known, the true hierarchy is still unknown. The unitary matrix $\mathbf{U}$ can be parameterized as the product of three unitary matrices $\mathbf{U}_{ij}$

$$\mathbf{U} = \mathbf{U}_{23}(\theta_{23})\, \mathbf{U}_{13}(\theta_{13}, \delta)\, \mathbf{U}_{12}(\theta_{12}) \tag{3}$$

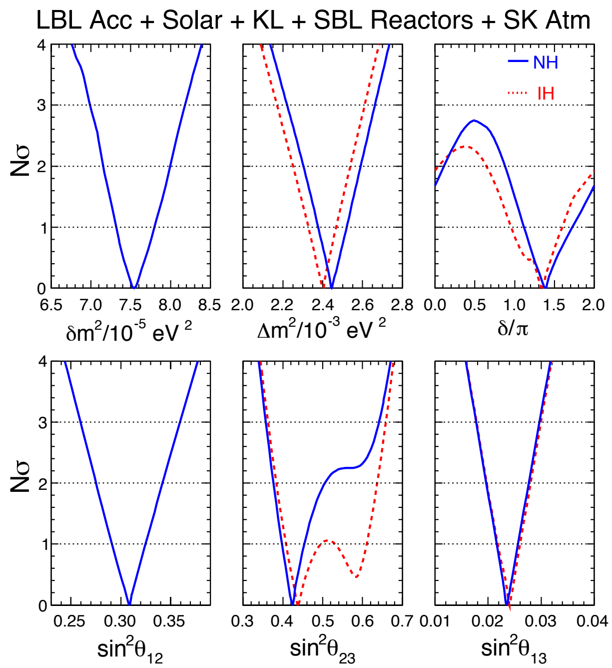

Figure 2. Combined 3ν analysis in terms of $N\sigma$. Blue (red) line refers to Normal (Inverted) Hierarchy.

with

$$\mathbf{U}_{23}(\theta_{23}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix}$$
$$\mathbf{U}_{13}(\theta_{13},\delta) = \begin{pmatrix} C_{13} & 0 & S_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{-i\delta} & 0 & C_{13} \end{pmatrix}$$
$$\mathbf{U}_{12}(\theta_{12}) = \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad (4)$$

where we have used the shorthand $C_{ij} \equiv \cos\theta_{ij}$ and $S_{ij} \equiv \sin\theta_{ij}$ with $\theta_{ij} \in [0, \pi/2]$ are three mixing angles and $\delta \in [0, 2\pi]$ is a phase related to CP violation in the leptonic sector. In particular, the effect of the phase δ on neutrino oscillations is that $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ (CP violation effect) or $P(\nu_\alpha \to \nu_\beta) \neq P(\nu_\beta \to \bar{\nu}_\alpha)$ (T violation effect), where P is the conversion probability, unless $\delta = 0, \pi$. For simplicity, in the following we refer simply to CP violations.

The results are summarized in table 1 (see [8] for further details) while the marginalized χ^2's for each variable are shown in fig. 2. The main differences respect to previous analysis are a reduction in the θ_{13} uncertainties and some changes in $(\Delta m^2, \theta_{23})$ ranges. In particular, an overall preference for the first θ_{23} octant and a non-zero CP violation ($\sin\delta < 0$) emerge from the data. Unfortunately there is not a significant difference between the two hierarchies. Further studies and refined experimental data will be necessary to establish the true mass hierarchy and the θ_{13} octant as well the CP violation phase.

Table 1
Best fit and 3σ range of all oscillation parameters.

Parameter	Best fit	3σ range
$\delta m^2/10^{-5}\mathrm{eV}^2$ (NH, IH)	7.54	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH, IH)	3.08	2.59 – 3.59
$\Delta m^2/10^{-3}\mathrm{eV}^2$ (NH)	2.44	2.22 – 2.66
$\Delta m^2/10^{-3}\mathrm{eV}^2$ (IH)	2.40	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	1.77 – 2.97
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.39	1.78 – 3.00
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.25	3.57 – 6.41
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.37	3.63 – 6.59
δ/π (NH)	1.39	—
δ/π (IH)	1.35	—

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