On the Inverse Seesaw Mechanism and Axion Like Particles

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UFABC – Brazil

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Outline

Based in a work done in collaboration with:

C. D. R. Carvajal, C. C. Nishi, B. L. Sánchez-Vega, JHEP 15

Prospective experiments, astrophysical limits and hinted phenomena on ALP.

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- ALPS-II experiment [Bähre et al. 13]
- CAST and the helioscope IAXO [Armengaud et al 14]
- Haloscope [Asztalos et at 11]
- Observatories PIXIE and PRISM [Kogut et al. 11; André et al. 14; Mirizzi et al 09; Tashiro et al 13; Ejlli, Dolgov 13]
- ALP from massive stars, Supernova SN 1987A [A. Friedland et al. 13; Grifols et al 96; Brockway et al. 96; Payez et al. 14]
- Universe transparency for very energetic γ-ray, [Mirizzi at al 07, De angelis et al 07; Horns, Meyer 12; Rubtsov, Troitsky 14; Biteau, Williams 15;; Simet et al 07, Sanchez-Conde et al 09; Mirizzi, Montanino 09; Horns at al 14; Tavecchio at al 14]
- Soft X-ray excess through cosmic ALP background [Conlon, Marsh 13; Angus et al. 13; Kraljic 14]

ALP physics described by

$$\mathscr{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 \, a^2 - \frac{g_{a\gamma}}{4} \, a \, F_{\mu\nu} \tilde{F}^{\mu\nu} + \mathscr{L}_{a\psi}(\partial_\mu a \, , \psi)$$

– This effective Lagrangian might result from a $U(1)$ global symmetry broken spontaneously by a VEV of a scalar field hosting the ALP $\sim a(x)$

$$\sigma(x) = \frac{1}{\sqrt{2}}\left[v_\sigma + \rho(x)\right] e^{i\,\frac{a(x)}{v_\sigma}} \,, \qquad v_\sigma \gg 246\mathrm{GeV}.$$

– ALP-photon coupling suppressed by $\langle \sigma \rangle = v_\sigma$

$$g_{a\gamma} = \frac{\alpha \, C_{a\gamma}}{2\pi \, v_\sigma}, \qquad \frac{C_{a\gamma}}{v_\sigma} = \frac{1}{f_a}$$

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But this breaking must be controlled in some way!

Axion Like Particle

– ALP has to be an *ultra-light particle* to be relevant in certain astrophysical phenomena, and also to be discovered in the prospective experiments.

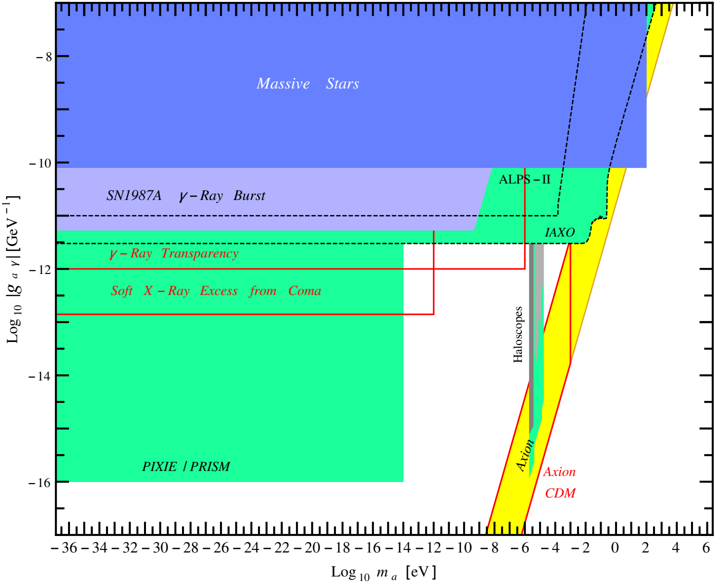
- Universe transparency hint for very high energy γ-rays [Meyer et at 13]

$$|g_{a\gamma}| \gtrsim 10^{-12}\ \mathrm{GeV}^{-1}; \qquad m_a \lesssim 10^{-7}\ \mathrm{eV}.$$

- Soft X-ray excess hint from Coma cluster [Conlon et at 13]

$$|g_{a\gamma}| \gtrsim 10^{-13}\ \mathrm{GeV}^{-1}\sqrt{0.5/\Delta N_{\mathrm{eff}}}\,; \qquad m_a \lesssim 10^{-12}\ \mathrm{eV},$$

Axion Like Particle: parameter space



AD, Machado, Nishi, Ringwald, Vaudrevange, arXiv:1403.5760

Axion Like Particle: m_a through explicitly breaking of $U(1)$

– Certain gravity induced nonrenormalizable operators need to be suppressed in order to have such ultra-light particles (no expectations that gravity respect continuous global symmetries).

$$V_{grav} = g\frac{\sigma^D}{M_{Pl}^{D-4}} + \mathrm{H.c.} \quad \rightarrow \quad m_a \approx |g|D\,\frac{v_\sigma}{\sqrt{2}} \times \left[\frac{v_\sigma}{\sqrt{2}M_{\mathrm{Pl}}}\right]^{\frac{D}{2}-2}$$

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– In particular, the effects of gravity induced nonrenormalizable operators over the strong CP problem solution with the axion were observed many years ago [Ghigna et al.; Holman et al.; Kamionkowski et al. 92; Kallosh et al. 95] .

Let us imagine that the mass scales *beyond the Standard Model* are given by ratios

$$\text{masses} \sim \langle \sigma \rangle \times \left(\frac{\langle \sigma \rangle}{M_{Pl}} \right)^m , \qquad M_{Pl} = 2.4 \times 10^{18}\,\text{GeV}$$

$\sqrt{2}\langle \sigma \rangle = v_\sigma$ is within the ALP decay constant: $10^9\ \text{GeV} \lesssim v_\sigma \lesssim 10^{14}\ \text{GeV}$

– Mass scales beyond the Standard Model appear in the neutrinos physics.

Neutrinos mass generation mechanism involving two energy scales beyond the Standard Model.
[Mohapatra, Valle 86]

The Inverse Seesaw Mechanism

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– Texture

$$\begin{pmatrix} 0 & \mathbf{M_D}^T & 0 \\ \mathbf{M_D} & 0 & \mathbf{M}^T \\ 0 & \mathbf{M} & \mu \end{pmatrix}$$

– $\mathbf{M_D} \sim$ electrowek scale, $\mathbf{M} \sim$ 0.1-1 TeV scale, $\mu \sim$ keV scale (breaks lepton number).

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$$\mathcal{L} \supset \overline{N_R}\mathbf{M_D}\nu_L + \overline{S_R}\mathbf{M}N_R^c + \frac{1}{2}\overline{S_R}\mu S_R^c + \mathrm{h.c.}$$

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– There is a symmetry leading to the required texture and scales from $\langle\sigma\rangle \times \left(\frac{\langle\sigma\rangle}{M_{Pl}}\right)^m$

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$$\begin{aligned}\mathscr{L} \supset\ & y_{ij}\overline{N_{iR}}\widetilde{H}^{\dagger}L_j + \eta_{ij}\frac{\sigma^2}{M_{\rm Pl}}\overline{S_{iR}}N^c_{jR} + \zeta_{ij}\frac{\sigma^{*3}}{2M^2_{\rm Pl}}\overline{S}_{iR}S^c_{jR} \\ & +\kappa_i\frac{\sigma}{M_{\rm Pl}}\overline{L}_i H E_R + \kappa\frac{\sigma^2}{M_{\rm Pl}}\overline{E}_L E_R + {\rm H.c.}\end{aligned}$$

y_{ij}, η_{ij}, ζ_{ii} of order $\mathcal{O} \sim 0.1 - 1$, H, L the Higgs lepton SM doublets.

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Spontaneous Symmetry Breaking: $\langle H \rangle = v/\sqrt{2}$, $\langle \sigma \rangle = v_\sigma/\sqrt{2}$

The value $v_\sigma = 3 \times 10^{10}$ GeV gives the natural scales for the inverse seesaw mechanism!

$$\mathbf{M} = \frac{\eta v_\sigma^2}{2M_{Pl}} = \eta \times 187\,\mathrm{GeV}, \quad \mu = \frac{\zeta v_\sigma^3}{2^{\frac{3}{2}} M_{Pl}^2} = \zeta \times 1.6\mathrm{keV}$$

Inverse Seesaw Mechanism and ALP: required symmetry

– Construction based on a specific discrete gauge symmetry [Krauss, Wilckzec 89; Coleman et al 92]

– Discrete symmetry derived from conditions to cancel the anomalies: [Ibáñez, Ross 91; Banks, Dine 92]

$$\mathbb{Z}_{13} \equiv e^{i2\pi \frac{k}{13}}, \qquad k = 0,\, 1,\, ...12.$$

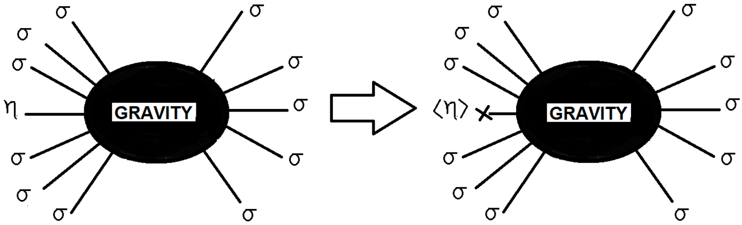
It allows for having an ultra-light ALP, and the required operators for the inverse seesaw mechanism.

$$\mathrm{SM} \otimes \mathcal{U}(1) \otimes ...$$
$$\Downarrow$$
$$\mathrm{SM} \otimes \mathbb{Z}_{13} \otimes ...$$

$\mathcal{U}(1)$ respected by gravity $\rightarrow$ $\mathbb{Z}_N$ respected by gravity as well.

Inverse Seesaw Mechanism and ALP: required symmetry

Such *"discrete gauge symmetries"* might be respected by gravitational interactions. Local symmetries can masquerade as Z_N to an observer having only low energy probes [Krauss, Wilczek 89; Coleman et al. 92].



$$\mathcal{O}_{N+1} \equiv \frac{\eta(x)\,\sigma(x)^N}{M_{Pl}^{N-3}} \qquad \Longrightarrow \qquad \mathcal{O}_N \equiv \frac{\langle\eta\rangle}{M_{Pl}^{N-3}}\sigma(x)^N$$

Being $\mathcal{O}_{N+1}$ invariant under $\mathcal{U}(1)$, $\mathcal{O}_N$, and all other interactions below the scale $\langle\eta\rangle$, will be invariant by Z_N.

– Fields charges under $\mathbb{Z}_{13}$ symmetry: $\psi_k \to e^{i2\pi\frac{Z_k}{13}}\psi_k$

$\mathbb{Z}_{13}$	q_{iL}	d_{iR}	u_{iR}	H	L_i	l_{iR}	N_{iR}	S_{iR}	E_L	E_R	σ
Z_k	2	2	2	0	7	7	7	-3	9	5	2

– $\mathbb{Z}_{13}$ charges in terms barion and an extension of lepton number:

$$Z_k = (6\mathcal{B} + 7\mathcal{L})_k$$

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– $E_{L,R}$ chiral under $U(1)_X$, allowing for the ALP-photon coupling.

– ALP mass and effective coupling with electromagnetic field

$$V(\sigma) = g\frac{\sigma^{13}}{M_{Pl}^{9}} + \mathrm{H.c.} \;\Rightarrow\; m_a \simeq 1.6 \times 10^{-16}|g|^{\frac{1}{2}}\left(\frac{v_\sigma}{3\times 10^{10}\,\mathrm{GeV}}\right)^{5.5}\mathrm{eV}$$

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$$g_{a\gamma} \approx 1.5 \times 10^{-13}\left(\frac{3 \times 10^{10}\,\mathrm{GeV}}{v_\sigma}\right)\mathrm{GeV}^{-1}\,.$$

A Model with one ALP and $\mathbb{Z}_{13}$ symmetry

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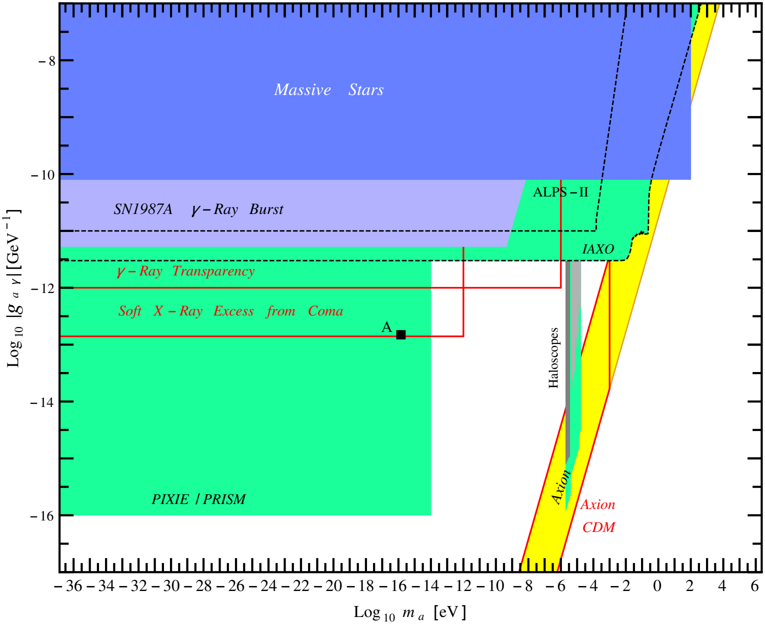
– These values can provide explanation to the Soft X-ray excess from Coma cluster (being inside the region prospected by PIXIE/PRISM).

A Model with one ALP and $\mathbb{Z}_{13}$ symmetry: benchmark point



– Heavy lepton mass controlled by the discrete symmetry

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$$\Downarrow$$

$$M_E = \kappa_E \frac{v_\sigma^2}{2M_{\rm Pl}} \approx \kappa_E \times 187\text{GeV}$$

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$$\Downarrow$$

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– Lifetime

$$\tau_E \simeq \frac{32\pi}{3} \frac{M_{\rm Pl}^2}{\kappa_i^2 v_\sigma^2} \frac{m_E^3}{\left(m_E^2 - m_h^2\right)^2} \times 6.5822 \times 10^{-25}\,{\rm s}$$

$$\leq 10^{-9}\,{\rm s} \qquad \text{[\textit{CMS} 2013]}$$

$m_h = 125$ GeV, $\quad m_E \gtrsim 250$ GeV

– Decay channel: $\quad E \to h + e^-$

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4. Interesting restrictions for ALP parameters may be obtained using a scheme with $\mathbb{Z}_N$, or any other sort of, symmetries producing appropriate textures for neutrinos mass matrix/mixing.

A Model with one ALP and $\mathbb{Z}_{13}$ symmetry: summarizing

1. Appropriated texture and mass scales for the inverse seesaw mechanism triggered by v_σ;
2. Ultra-light ALP which could explain the soft X-ray excess from Coma cluster, and well inside the PIXIE/PRISM prospective region;
3. Heavy lepton E with mass near electroweak scale;
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Thank you!