Universidad Zaragoza

11th Patras Workshop on Axions, WIMPs and WISPs

Axino dark matter and X-ray lines

based on work with H.K. Dreiner, F. Staub and L. Ubaldi

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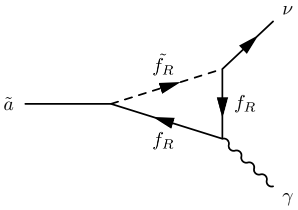
Outline

The 3.5 KeV line

Facts:

- There has been interest recently in an unidentified 3.5 keV line in X-ray observations of galaxy clusters. [Boyarsky et al.,1402.4119; Bulbul et al.,1402.2301]
- Some authors have already pointed out that a generic decaying axino could explain the line. [Liew, 1403.6621; Park et al.,1403.1536]



- To explain the 3.5 keV line via dark matter (DM) decay one needs a decay rate of $\Gamma_{X\to\gamma+\ldots} \sim (10^{28}s)^{-1} \sim 10^{-53}$ GeV, assuming that the decaying DM contributes 100% to the relic abundance.
- The evidence that the 3.5 keV line is due to DM decay has weakened, but one can still wonder wheter it is possible or not to get a X-ray signal from the axino decay.

How to make the axino light: KSVZ vs DFSZ models

All axion models contain a scalar field $A(x)$, charged under $U(1)_{\rm PQ}$: the <u>axion</u> $a(x)$ corresponds to the phase of that field.

In **KSVZ** models:

- the axion is coupled to heavy quarks Q, while the rest of SM do not carry any charge.
- The coupling $f_a A\bar{Q}Q$ generates the coupling $aG_{\mu\nu}\tilde{G}^{\mu\nu} \rightarrow$ solve the **strong CP problem**.
- In their SUSY extensions loop corrections induce high masses:

$$m_{\tilde{a}} \sim 10\ \mathrm{GeV}\left(\frac{m_{3/2} f_Q^2}{100\ \mathrm{GeV}}\right)$$

Embedded in supergravity.

$\rightarrow$ The KVSZ axino prefers to be heavy.

$$m_{\tilde{a}} \sim 0.3\ \mathrm{GeV}\left(\frac{m_{\tilde{g}} f_Q^2}{1\ \mathrm{TeV}}\right)$$

Also always 2-loop contributions from gluino masses.

How to make the axino light: KSVZ vs DFSZ models

In **DSFZ** models:

How to make the axino light: KSVZ vs DFSZ models

In **DSFZ** models:

- All particles are charged under $U(1)_{\rm PQ} \to$ in SUSY : $W_{\rm PQ} \supset c_1 \hat{A}\, \hat{H}_u \hat{H}_d$

[Rajagopal, Turner and Wilczek, Nucl.Phys. B358, 447 (1991)]

- The VEV $\langle A \rangle \sim f_a \gtrsim 10^9$GeV to evade supernova constraints $\to c_1$ small.

[Raffelt, 0611350[

- radiative corrections $\propto c_1^n \to$ they are small once $m_{\tilde{a}} \sim \mathrm{keV}$

$\to$ easier to get a light DFSZ axino

Only the operator $c_1 \hat{A}\hat{H}_u \hat{H}_d$ only leads to tachyonic saxion.

[Dreiner, Staub and Ubaldi, 1402.5977]

Extended the superpotential by terms

[J. E. Kim, Phys. Lett. B136, 378 (1984)]

$$W_{\rm PQ} = \lambda \hat{\chi} \left(\hat{A}\hat{\bar{A}} - \frac{1}{4} f_a^2 \right) ,$$

Charges:
$$\begin{cases} Q_{\rm PQ}(\hat{A}) = -Q_{\rm PQ}(\hat{\bar{A}}) \\ Q_{\rm PQ}(\hat{\chi}) = 0 \end{cases}$$

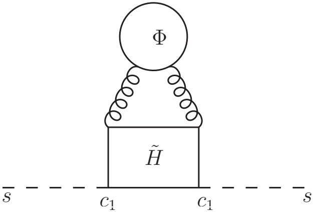
with 3 superfields $\hat{A}$, $\hat{\bar{A}}$, $\hat{\chi}$.

How to make the axino light: high vs low SUSY-breaking

Two possibilities for the scale of symmetry breaking (sparticles masses $\gtrsim$ TeV):

1) Low-scale SUSY breaking:
$M_{SB} < f_a \Rightarrow m_{\tilde{a}} \sim \frac{M^2_{\rm SUSY}}{f_a} \sim \frac{\rm TeV^2}{f_a}$, natural in gauge mediation. Cosmological problems from the 3-loop saxion mass:

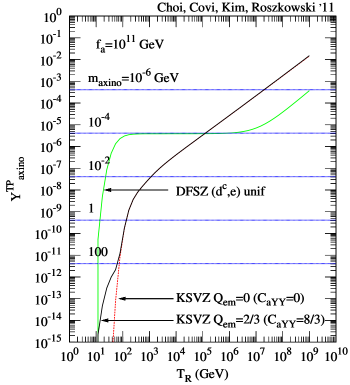
$$m_s \sim 0.1 \text{ keV} \left(\frac{c_1}{10^{-9}}\right)\left(\frac{m_{\tilde{f}}}{1 \text{ TeV}}\right)$$



2) High-scale SUSY breaking: $M_{SB} > f_a \Rightarrow m_{\tilde{a}} \sim M_{\rm SUSY} \sim \rm TeV$, natural in gravity mediation.
- No significant loop corrections, $m_{\tilde{a}}$ can be lowered by tuning down a single parameter λ.

Axino dark matter

[1108.2282]



Different dependences on reheating temperature T_R:

$$\Omega_{\tilde{a}}^{\rm DFSZ} h^2 = 0.78 \left(\frac{m_{\tilde{a}}}{7\ {\rm keV}}\right) \left(\frac{10^{10}\ {\rm GeV}}{f_a}\right)^2$$

for $T_R > \mu$

$$\Omega_{\tilde{a}}^{\rm KSVZ} h^2 = \frac{6.9}{10^3} \left(\frac{m_{\tilde{a}}}{7\ {\rm keV}}\right) \left(\frac{10^{10}\ {\rm GeV}}{f_a}\right)^2 \left(\frac{T_R}{10^3\ {\rm GeV}}\right)$$

for $10^3\ {\rm GeV} < T_R < f_a$

$\mu \sim {\rm TeV}$ is the SUSY parameter that determines the higgsino mass

In both cases the abundances drop very quickly when T_R is below 100 - 1000 GeV.

Axino decay into photon: RpC vs RpV

The couplings of the axino to the gauge fields is best understood by performing a field rotation that leads to the **GKR** basis in which all the matter fields are invariant under a PQ transformation [Georgi, Kaplan and Randall, Phys. Lett. B169, 73 (1986)]

$$\mathcal{L}_{a\lambda V} = \frac{\tilde{a}}{16\pi^2 f_a}\sigma_{\mu\nu}\left(g_1^2 C_{aBB}\tilde{B}B^{\mu\nu} + g_2^2 C_{aWW}\tilde{W}^a W^{a\mu\nu} + g_3^2 \tilde{G}^a G^{a,\mu\nu}\right)$$

Decay channel can be still different according to the R-symmetry of the superpotential. The minimal one

$$W_{\rm MSSM} = Y_u^{ij}\widetilde{Q}_i\widetilde{H}_u\widetilde{\bar{U}}_j + Y_d^{ij}\widetilde{Q}_i\widetilde{H}_d\widetilde{\bar{D}}_j + Y_e^{ij}\widetilde{L}_i\widetilde{H}_d\widetilde{\bar{E}}_j + \mu\widetilde{H}_u\widetilde{H}_d\,,$$

can be expanded by L/B number operators:

$$W_{\rm RPV} = \mu'^{\,i}\widetilde{L}_i\widetilde{H}_u + \frac{1}{2}\lambda^{ijk}\widetilde{L}_i\widetilde{L}_j\widetilde{\bar{E}}_k + \lambda'^{\,ijk}\widetilde{L}_i\widetilde{Q}_j\widetilde{\bar{D}}_k + \frac{1}{2}\lambda''^{\,ijk}\widetilde{\bar{U}}_i\widetilde{\bar{D}}_j\widetilde{\bar{D}}_k\,.$$

Axino decay into photon: RpC

R-parity conserving models: the bino is lighter than the axino, the X-ray line could be produced by the decay $\tilde{a} \to \tilde{B} + \gamma$. [Dutta, Gogoladze, Khalid, and Shafi, 1407.0863]

$$\Gamma_{\tilde{a}\to\tilde{B}+\gamma} = \frac{1}{128\pi^3}\frac{m_{\tilde{a}}^3}{f_a^2} C_{aBB}^2 \left(\frac{g_1^2}{4\pi}\right)^2 \cos^2\theta_W \sim 7\times 10^{-52}\ \mathrm{GeV}\left(\frac{m_{\tilde{a}}}{7\ \mathrm{keV}}\right)^3 \left(\frac{10^{14}\ \mathrm{GeV}}{f_a}\right)^2$$

$f_a > 10^{14}$ GeV required $\Rightarrow$ DFSZ axino excluded, KVSZ could work for $T_R \sim 10^{12}$ GeV. One has to consider though the axion produce through misalignment mechanism:

[Bae, Choi and Im, 1106.2452; Kawasaki and Nakayama, 1301.1123]

$$\Omega_{a,\mathrm{mis}} h^2 = 0.18\ \theta_1^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19} \left(\frac{\Lambda_{\mathrm{QCD}}}{400\ \mathrm{MeV}}\right).$$

$\Rightarrow$ overabundant DM, unless you don't tune down θ to really small values.

Axino decay into photon: RpV

RpV models: the term $W = \epsilon_i L_i H_u$ introduces mixing among neutrinos, bino and wino, and opens up the decay channel $\tilde{a} \to \nu_i + \gamma$:

$$\begin{aligned}\Gamma_{\tilde{a}\to\nu_i+\gamma} &= \frac{1}{128\pi^3}\frac{m_{\tilde{a}}^3}{f_a^2}\left[r_{\nu_i\tilde{B}}^2 C_{aBB}^2\left(\frac{g_1^2}{4\pi}\right)^2\cos^2\theta_W + r_{\nu_i\tilde{W}}^2 C_{aWW}^2\left(\frac{g_2^2}{4\pi}\right)^2\sin^2\theta_W\right]\\ &\sim 7\times10^{-42}\ \mathrm{GeV}\,(r_{\nu_i\tilde{B}}^2 + 3r_{\nu_i\tilde{W}}^2)\left(\frac{m_{\tilde{a}}}{7\ \mathrm{keV}}\right)^3\left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)^2\end{aligned}$$

[**SC**, Dreiner, Staub and Ubaldi, *in preparation*]

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$$\sim\ 7\times10^{-42}\ \mathrm{GeV}\ (r^2_{\nu_i\tilde{B}} + 3r^2_{\nu_i\tilde{W}})\left(\frac{m_{\tilde{a}}}{7\ \mathrm{keV}}\right)^3\left(\frac{10^9\ \mathrm{GeV}}{f_a}\right)^2$$

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What do we know about r's ?

$\Rightarrow$ Diagonalize the neutralino mass matrix: $R\mathcal{M}_0R^T = \mathrm{diag}(\mathcal{M}_0)$ to get

[Hirsch and Valle, hep-ph/9812463, 0405015]

$$r_{\nu_i,\tilde{B}}\,,\, r_{\nu_i,\tilde{W}} \propto (\Lambda_i, M_1, M_2)\,, \qquad \Lambda_i = \mu\omega_i - v_d\epsilon_i$$

The parameters Λ_i are related to the neutrino mixing angles:

$$\tan\theta_{13} = -\frac{\Lambda_e}{(\Lambda_\mu^2+\Lambda_\tau^2)^{1/2}}\,, \qquad \tan\theta_{23} = \frac{\Lambda_\mu}{\Lambda_\tau}\,.$$

Measured values: $\theta_{13} \sim \pi/20\,,\ \theta_{23} \sim \pi/4\ \Rightarrow\ \Lambda_\mu = \Lambda_\tau \equiv \Lambda\,,\ \Lambda_e = 0.23\Lambda.$

From CMB $m_{\nu_3} < 0.23\mathrm{eV}$ and with $\mu, M_1, M_2 \sim \mathrm{TeV}$ (and no *magic cancellation*):

$$r^2_{\nu_1 \tilde{B}} < 2.3 \times 10^{-15}\,,$$

and similarly for the others. Plugging these values back into $\Gamma_{\tilde{a}\to\nu_i+\gamma}$ we find that the rate is too small to explain the 3.5 keV line.

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$\Rightarrow$ Massless neutralino might still be a possibility, but force some tuning between f_a and T_R.

The role of the gravitino

The axino is expected to be heavier than the gravitino. A light gravitino would overclose the universe unless T_R is sufficiently small: [Cheung, Elor and Hall, 1104.0692]

$$\Omega_{3/2}h^2 = 0.27 \left(\frac{T_R}{100\ \mathrm{GeV}}\right)\left(\frac{\mathrm{keV}}{m_{3/2}}\right),$$

for $m_{3/2} \gtrsim \mathrm{keV}$

$$\Omega_{3/2}^{\mathrm{HDM}}h^2 \sim 0.1\,\frac{m_{3/2}}{100\ \mathrm{eV}},$$

for $m_{3/2} < 100\ \mathrm{eV}$

The axino decays into a gravitino and an axion with a lifetime

$$\tau_{\tilde{a}\to G+a} \simeq 10^9\ \mathrm{s}\left(\frac{m_{3/2}}{\mathrm{MeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_{\tilde{a}}}\right)^5 \overset{!}{\gtrsim} \underbrace{10^{18}\,s}_{\text{age of universe}} \quad \Rightarrow \quad m_{3/2} > 10^{-5}\,\mathrm{keV}$$

$\Rightarrow$ RpC case is viable with a gravitino up to keV (with the tuning of θ).
For heavier gravitino too much DM if T_R is such that you get a line.

$\Rightarrow$ RpV case $m_{3/2} \ll \mathrm{keV}$ prefered, no T_R dependence (still limits from ν's)

Summary and conclusions

1. A light axino has been often presented as a good DM candidate to explain the 3.5 keV line
2. In principle many possible scenarios:
   - KSVZ vs DFSZ models
   - high vs low SUSY breaking-scale
   - R-parity conserved or violated
3. Cosmological constraints (neutrinos, gravitinos, ...) reduce drastically the available parameter space.
4. It seems very unlikely to explain the line with the axino !

Thanks for your attention!