The 3.5 keV X-ray line and Supersymmetry

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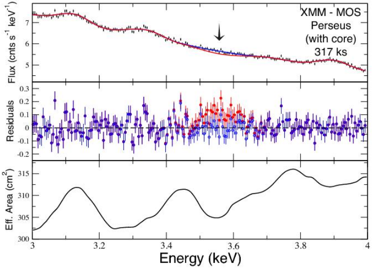
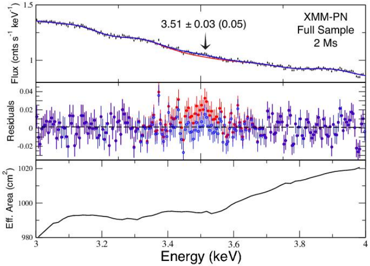
Unidentified X-ray line around 3.5 keV from Perseus galaxy cluster and the Andromeda galaxy

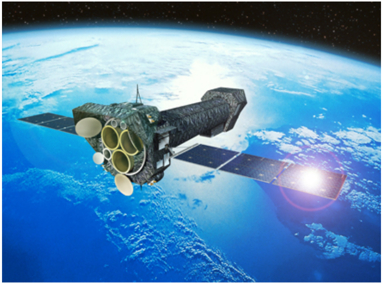
E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein and S. W. Randall, arXiv:1402.2301

A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, arXiv:1402.4119





X-ray Multi Mirror Mission - Newton (XMM-Newton)
Launched by ESA in December 1999



X-ray line at 3.5 keV? If its real, what it implies.

$$\mathbf{m_{DM} \simeq 7\ keV?}$$
$$\boldsymbol{\tau_{DM} \simeq 2 \times 10^{27} - 10^{28}\ sec.}$$

Supersymmetry

Possible keV mass dark matter candidates:

- Neutralino (mostly bino)
- Gravitino
- Axino
- Singlino
- . . .

Massless neutralino

$$\mathbf{L}_{\tilde{\chi}^0} = -\frac{1}{2}M_1\widetilde{B}\widetilde{B} - \frac{1}{2}M_2\widetilde{W}^0\widetilde{W}^0 + \mu\widetilde{h}_d^0\widetilde{h}_u^0 - \frac{g_2}{2}\widetilde{W}^0(v_1\widetilde{h}_d^0 - v_2\widetilde{h}_u^0) + \frac{g_1}{2}\widetilde{B}(v_1\widetilde{h}_d^0 - v_2\widetilde{h}_u^0) \equiv -\frac{1}{2}\psi_0^T\mathcal{M}_{\tilde{\chi}^0}\psi_0$$

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_{\rm w} c_\beta & M_Z c_{\rm w} s_\beta \\ 0 & M_2 & M_Z c_{\rm w} c_\beta & -M_Z c_{\rm w} s_\beta \\ -M_Z s_{\rm w} c_\beta & M_Z c_{\rm w} c_\beta & 0 & -\mu \\ M_Z s_{\rm w} s_\beta & -M_Z c_{\rm w} s_\beta & -\mu & 0 \end{pmatrix}$$

$$\psi_0^T \equiv \left(\widetilde{B}, \;\; \widetilde{W}^0, \;\; \widetilde{h}_d^0, \;\; \widetilde{h}_u^0\right)$$

Massless neutralino

$$\mathbf{M_1} = \frac{\mathbf{M_2 M_Z^2}\sin(\mathbf{2}\beta)\mathbf{s_w^2}}{\mu\mathbf{M_2} - \mathbf{M_Z^2}\sin(\mathbf{2}\beta)\mathbf{c_w^2}} \approx \frac{\mathbf{2M_Z^2 s_w^2}}{\mu\tan\beta}.$$

A massless neutralino is allowed by all existing experimental data and astrophysical and cosmological observations

H. K. Dreiner et.al., Eur. Phys. J. C 62, 547 (2009).

The cosmological data are suggesting the presence for an extra relativistic component with an effective neutrino number $N_{eff} = 4.08^{+0.71}_{-0.68}$ **at** 95% **c.l.** (Without Planck data)

A. Melchiorri et. al,. J. Phys. Conf. Ser. 485, 012014 (2014).

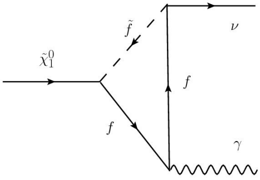
$N_{eff} = 3.52^{+0.48}_{-0.45}$ **at** 95% **c.l.** (Including Planck data)

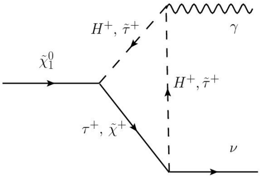
Decaying 7 keV bino LSP

C. Kolda and J. Unwin, arXiv:1403.5580

R-parity violation couplings: $\lambda LLE^c + \lambda' QLd^c + \epsilon H_u L$

$$\tilde{\chi}_1^0 \to \nu + \gamma$$



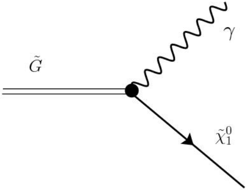


$$\tau_{\tilde{B}} \simeq 5 \times 10^{27}\ \mathrm{sec.} \left(\frac{10^{-8}}{\lambda}\right)^2 \left(\frac{m_{\tilde{f}}}{2\ \mathrm{TeV}}\right)^4 \left(\frac{7\ \mathrm{keV}}{m_{\tilde{B}}}\right)^3$$

The problem is that 7 keV bino as thermal or non-thermal dark matter does not works.

Gravitino dark matter and massless bino

General GMSB scenarios gravitino can have mass between 1 eV to 100 TeV. We assume $m_{\tilde{G}} \approx 7$ keV and massless Bino. $\tilde{\mathbf{G}} \to \chi_{\mathbf{1}}^{\mathbf{0}} + \gamma$



$$\mathbf{\Gamma}(\widetilde{\mathbf{G}} \to \chi_{\mathbf{1}}^{\mathbf{0}}\gamma) = \frac{\cos\theta_{\mathbf{W}}^{\mathbf{2}} \mathbf{m}_{\widetilde{\mathbf{G}}}^{\mathbf{3}}}{\mathbf{8}\pi\mathbf{m}_{\mathrm{Pl}}^{\mathbf{2}}}$$

For $\tau(\widetilde{G} \to \chi_1^0\gamma) \approx 10^{27}$ sec. we need $m_{\mathrm{Pl}} \approx 5 \times 10^{17}$ GeV. It has been arguing that the effective strong gravity scale is given by $\Lambda = m_{\mathrm{Pl}}/\sqrt{N}$

G. Dvali, Fortsch. Phys. 58, 528 (2010)

Gravitino dark matter and massless bino

The gravitino relic density :

$$\Omega_{\tilde{G}} h^2 = 0.27 \left(\frac{100 \text{ GeV}}{m_{\tilde{G}}}\right) \left(\frac{T_R}{10^{10} \text{ GeV}}\right) \left(\frac{m_{\tilde{g}}}{1 \text{ TeV}}\right)^2$$

$\Omega_{\tilde{G}} h^2 \approx 0.1$ **and** $m_{\tilde{g}} \gtrsim 1.4$ **TeV requires** $T_R \lesssim 170$ **GeV.**

Axino dark matter and massless bino

Combination of PQ mechanism with low scale SUSY predicts the SUSY partner of the axion (a), the axino ($\tilde{a}$) and saxion (s).

$$A = \frac{1}{\sqrt{2}}(s + ia) + \sqrt{2}\,\tilde{a}\,\theta + F_A\,\theta\,\theta$$

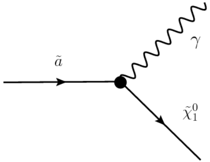
Axino couples to the gauginos and gauge bosons via anomaly induced term.

$$i\frac{\alpha_Y C_Y}{16\pi}\frac{\tilde{a}}{f_a}\gamma_5[\gamma^\mu, \gamma^\nu]\tilde{B}\,B_{\mu\nu}$$

Assuming 7 keV axino and massless bino then we can have

$$\tilde{a} \to \chi_1^0 + \gamma.$$

Axino dark matter and massless bino



$$\Gamma(\tilde{a} \to \chi_1^0 \gamma) = \frac{\alpha_{em}^2 C_{a\chi\gamma}^2}{128\pi^3} \frac{m_{\tilde{a}}^3}{f_a^2}$$

Axino lifetime can be written as:

$$\tau(\tilde{a} \to \chi_1^0 \gamma) = 1.3 \times 10^{23}\text{sec} \left(\frac{f_a}{10^{12}\,\text{GeV}}\right)^2 \left(\frac{7.1\,\text{keV}}{m_{\tilde{a}}}\right)^3$$

We need to have $f_a \approx 10^{14}$ **GeV for** $\tau(\tilde{a} \to \chi_1^0 \gamma) \approx 10^{27}$ **sec.**

Axino dark matter and massless bino

- **Small initial axion mis-alignment angle $\theta \approx 0.1 - 0.01$.**
- **Massive fields with late decays properties**
- **assuming to have axion like particle.**

The axino relic density :

$$\Omega_{\tilde{a}} h^2 \approx \left(\frac{m_{\tilde{a}}}{0.1\mathrm{GeV}}\right) \left(\frac{10^{11}\mathrm{GeV}}{f_a}\right)^2 \left(\frac{T_R}{10^4\mathrm{GeV}}\right)$$

$\Omega_{\tilde{a}} h^2 \approx 0.1$ **and** $f_a \approx 10^{14}$ **GeV requires** $T_R \approx 10^{13}$ **GeV.**

NMSSM, Decaying singlino dark matter

$$\mathcal{L}^{m}_{\tilde{\chi}^0} = -\frac{1}{2}\Psi^{0^T}\mathcal{M}_{\tilde{\chi}^0}\Psi^0 + \text{h.c.}, \quad \Psi^{0^T} \equiv (\tilde{B}^0, \tilde{W}^0_3, \tilde{h}^0_d, \tilde{h}^0_u, \tilde{s}, \nu_i)$$

$$M_N = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W & 0 \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W & 0 \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu_{eff} & -\lambda v s_\beta \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu_{eff} & 0 & -\lambda v c_\beta \\ 0 & 0 & -\lambda v s_\beta & -\lambda v c_\beta & 2\kappa x \end{pmatrix}$$

$$\kappa = \lambda\frac{1}{2}\left(\frac{\lambda v}{\mu}\right)^2 \frac{0.6 m_z^2 M_2 - 0.5\mu M_2^2 \sin 2\beta}{-\mu M_1 M_2}$$

NMSSM, Decaying singlino dark matter

R-parity (lepton number) breaking terms:

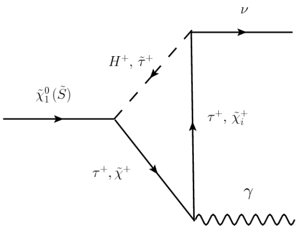
$$\mathcal{L}_{\not R} = \lambda_1 L H_u S + \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} Q_i L_j d^c_k + \epsilon_i H_u L_i$$

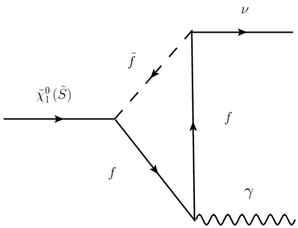
$$\mathcal{L}^m_{\tilde{\chi}^0} = -\frac{1}{2} \Psi^{0^T} \mathcal{M}_{\tilde{\chi}^0} \Psi^0 + \text{h.c.}, \quad \Psi^{0^T} \equiv (\tilde{B}^0, \tilde{W}^0_3, \tilde{h}^0_d, \tilde{h}^0_u, \tilde{s}, \nu_i)$$

$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} \mathcal{M}_{\rm N} & \xi^T_{\not R} \\ \xi_{\not R} & \mathcal{M}^\nu_{3\times 3} \end{pmatrix}$$

$$\xi_{\not R} = \begin{pmatrix} -\frac{g' v_1}{\sqrt{2}} & \frac{g v_1}{\sqrt{2}} & 0 & \mu_1 + \lambda_1 \langle s \rangle & \lambda_1 v_u \\ -\frac{g' v_2}{\sqrt{2}} & \frac{g v_2}{\sqrt{2}} & 0 & \mu_2 + \lambda_2 \langle s \rangle & \lambda_2 v_u \\ -\frac{g' v_3}{\sqrt{2}} & \frac{g v_3}{\sqrt{2}} & 0 & \mu_3 + \lambda_3 \langle s \rangle & \lambda_3 v_u \end{pmatrix}.$$

NMSSM, Decaying singlino dark matter





$$\Gamma(\tilde{\chi}_1^0 \to \nu\,\gamma) \sim \frac{1}{8\pi}\left(\frac{\lambda Y^2}{4\pi^2}\right)^2 \frac{\tilde{\chi}_1^3}{M_H^2}$$

$$M_H \equiv (m_{\tilde{\chi}_i^+} \approx m_{H^+})$$

$$\tau(\tilde{\chi}_1^0 \to \nu\,\gamma) = 2 \times 10^{27}\text{sec}\left(\frac{M_H}{10^5\text{GeV}}\right)^2 \left(\frac{10^{-9}}{\lambda}\right)^2$$

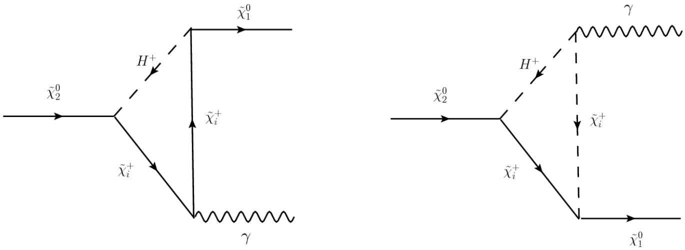
NMSSM, Decaying singlino dark matter

Because of small coupling singlinos are out of equilibrium at high temperature. They are not produced in the freeze-out from the equilibrium. Singlinos can be produced for instance from modulus decay from out of equilibrium. The thermal abundance gets diluted by $(T_R/T_f)^3$.

Quasi-degenerate light neutralinos

$$M_N = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W & 0 \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W & 0 \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu_{eff} & -\lambda v s_\beta \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu_{eff} & 0 & -\lambda v c_\beta \\ 0 & 0 & -\lambda v s_\beta & -\lambda v c_\beta & 2\kappa x \end{pmatrix}$$

$M_{\chi_1^0} \approx 0$ **and** $M_{\chi_2^0} \approx 7$ **keV or** $M_{\chi_2^0} - M_{\chi_1^0} \approx 7$ **keV**



Quasi-degenerate light neutralinos

$$\Gamma \sim \frac{\alpha_{em}^2 \lambda^2}{64\pi^4} \frac{(\Delta m_\chi)^3}{m_H^4} m_\chi^2,$$

$M_H \equiv (m_{\tilde{\chi}_i^+} \approx m_{H^+})$

Assuming $m_\chi^2 \approx 1$ GeV and $\Delta m_\chi \approx 3.5$ keV then we need to have $\lambda \sim 10^{-5}$ GeV for $\tau(\chi_2^0 \rightarrow \chi_1^0 \gamma) \approx 10^{27}$ sec.

Conclusion

We show that in low scale supersymmety it is possible to accommodate 3.5 keV X-ray line, satisfy the WMAP bound on dark matter abundance and captivate all experimental constraints.