A NEW POPULATION OF WIMPS IN THE SOLAR SYSTEM AND INDIRECT DETECTION RATES

LARS BERGSTRÖM

Department of Physics, Stockholm University, Box 6730, SE-113 85 Stockholm, Sweden, lbe@physto.se

THIBAULT DAMOUR

Institut des Hautes Etudes Scientifiques, 35 route de Chartres, 91440 Bures sur Yvette, France, damour@ihes.fr

JOAKIM EDSJÖ*

Department of Physics, Stockholm University, Box 6730, SE-113 85 Stockholm, Sweden, edsjo@physto.se

LAWRENCE M. KRAUSS

Departments of Physics and Astronomy, Case Western Reserve University, 10900 Euclid Ave, Cleveland OH 44106-7079, krauss@theory1.phys.cwru.edu

PIERO ULLIO

Mail Code 130-33, California Institute of Technology, Pasadena, CA 91125, USA, piero@tapir.caltech.edu

A new Solar System population of Weakly Interacting Massive Particle (WIMP) dark matter has been proposed to exist. We investigate the implications of this population on indirect signals in neutrino telescopes (due to WIMP annihilations in the Earth) for the case when the WIMP is the lightest neutralino of the MSSM, the minimal supersymmetric extension of the standard model. The velocity distribution and capture rate of this new population is evaluated and the flux of neutrino-induced muons from the center of the Earth in neutrino telescopes is calculated. We show that the effects of the new population can be crucial for masses around 60–120 GeV, where enhancements of the predicted muon flux from the center of the Earth by up to a factor of 100 compared to previously published estimates occur. As a result of the new WIMP population, neutrino telescopes should be able to probe a much larger region of parameter space in this mass range.

1 Introduction

Weakly Interacting Massive Particles (WIMPs) can elastically scatter inside the Sun and Earth, leading to their subsequent capture and annihilation in the cores of these bodies, producing an indirect neutrino signature that might be

newpop: submitted to World Scientific on November 4, 2018

^{*}RAPPORTEUR

accessible to neutrino telescopes.¹ Recently it has been demonstrated that the scattering process in the Sun can populate orbits which subsequently result in a bound Solar System population of WIMPs ^{2,3} and which can be comparable in spectral density, in the region of the Earth, to the Galactic halo WIMP population. This new population consists of WIMPs that have scattered in the outer layers of the Sun and due to perturbations by the other planets (mainly Jupiter and Venus) evolve into bound orbits which do not cross the Sun but do cross the Earth's orbit. This population of WIMPs should have a completely different velocity distribution than halo WIMPs and will thus have quite different capture probabilities in the Earth. The predicted WIMP abundance, and spectrum, relevant for direct detection have been calculated ^{2,3} and here we focus on capture in the Earth, and the predicted indirect neutrino signature.

Following ^{2,3}, we consider here a special WIMP candidate, the neutralino, which arises naturally in supersymmetric extensions of the standard model. Although our numerical results apply only to supersymmetric WIMPs, we expect our qualitative conclusions to be generally valid for any WIMP model of dark matter.

For more details on this work, see ⁴.

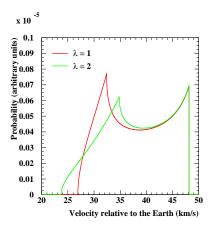
2 The MSSM

We evaluate the capture of neutralinos and the resulting neutrino-induced muon flux within the Minimal Supersymmetric extension of the Standard Model (MSSM) (for a review of neutralino dark matter, see ⁵). For the numerical MSSM calculations we use DarkSUSY ⁶ with which we have generated about 140 000 different MSSM models and for each one we require that they do not violate current accelerator constraints and that they make up a major part of the dark matter, i.e. $0.025 < \Omega_{\chi} h^2 < 1$, with Ω_{χ} being the neutralino relic density and h being the Hubble constant in units of 100 km s⁻¹ Mpc⁻¹.

3 Density and velocity of the new WIMP population

WIMPs that scatter in the outskirts of the Sun can end up in highly elliptical orbits gravitationally bound to the Sun. Jupiter and/or Venus can perturb these orbits so that they no longer cross the Sun, but if the semi-major axis is in the range $0.5a_{\rm earth} < a < 2.6a_{\rm earth}$ they do cross the Earth's orbit and can be captured by the Earth while they still don't reach out to Jupiter in which case they would be gravitationally scattered away.^{2,3}

The orbits will be nearly radial and the velocity with respect to the Earth



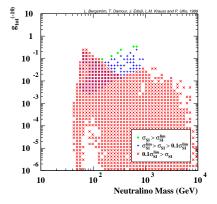


Figure 1. The velocity distribution with respect to the Earth for the new population of neutralinos.

Figure 2. $g_{\text{tot}}^{(-10)}$, which is related to the overdensity is shown for the new population of neutralinos.

is between 27 km/s and 48 km/s. Based on a detailed calculation⁴, we show the velocity distribution of these neutralinos in Fig. 1. λ is a parameterization of the non-conservation of the z-component of the angular momentum (if the orbit is in the xy-plane. $\lambda=1$ corresponds to full conservation of J_z and $\lambda=2$ corresponds a non-conservation by a factor of two. We have checked that our results not depend much on λ and we will in the following focus on $\lambda=1$.

In 7 , the phase space distribution of WIMPs at the Earth was investigated including the effects of the Earth being deep in the Sun's potential well. There it was found that even though the velocity distribution of WIMPs at the Earth is different than it would be in free space, both Jupiter, the Earth and Venus will disturb the orbits of these unbound WIMPs into bound orbits that have the same phase space distribution as would be the case in free space. This transfer in phase space is only fast enough (compared to the age of the solar system) for low velocities, $\lesssim 27$ km/s. For our new population of WIMPs, which has higher velocities, this means that they are not diffused out of the solar system by gravitational interactions with the other planets. The scatterings in the outskirts of the Sun will thus have built up this new population since the solar system was formed.

We can write the enhancement of the local neutralino density from this

new population as

$$\delta_E \equiv \frac{\text{WIMP density from new population}}{\text{WIMP density from old population}} = \frac{0.212}{(v_o/220 \,\text{km s}^{-1})} g_{\text{tot}}^{(-10)}. \quad (1)$$

Here, $g_{\rm tot}^{(-10)}$ is a quantity that depends on the details of the scattering of WIMPs in the outskirts of the Sun and on the perturbation of the orbits from mainly Jupiter and Venus. v_o is the local rotation velocity around the galactic center. In Fig. 2 we show the values for $g_{\rm tot}^{(-10)}$ evaluated for our MSSM models. Using Eq. (1) we see that the overdensity is up to $\delta_E \simeq 0.08$. For the local halo density of neutralinos we have used 0.3 GeV/cm³.

4 Capture rate of the new population

Even though the density of the new population is at maximum 10% of the halo density, the velocity distribution is quite different. Since the capture efficiency in the Earth is highly velocity dependent we would expect the capture rate to be quite different from the normal scenario. For capture in the Earth, scattering off iron nuclei is the most efficient process and given the lower limit of the velocity distribution in Fig. 1, we can calculate that capture of the new population is only possible when the neutralino mass, $m_{\chi} \leq 2.90 m_{Fe} \simeq 150$ GeV.

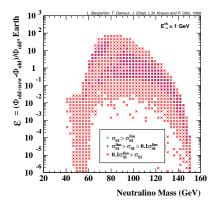
For our set of MSSM models, we have calculated the capture rate from this new population and derived the neutralino annihilation rate by solving the evolution equation for neutralinos in the Earth including both the old and the new population of neutralinos.⁴ We then define the enhancement of the annihilation rate (and hence on the resulting neutrino-induced muon fluxes) from this new population as

$$\mathcal{E} \equiv \frac{\Gamma_a^{\text{tot}} - \Gamma_a^{\text{old}}}{\Gamma_a^{\text{old}}} = \frac{\Phi_\mu^{\text{old+new}} - \Phi_\mu^{\text{old}}}{\Phi_\mu^{\text{old}}}.$$
 (2)

In Fig. 3 we show the enhancement factor for our MSSM models, and as we see, the enhancement can be up to two orders of magnitude when the mass of the neutralino is in the region 60–120 GeV where scattering off iron is efficient.

5 Neutrino-induced muon fluxes

We are now ready to compare the absolute fluxes of neutrino-induced muons from neutralino annihilation in the center of the Earth when we include or not include the new population of neutralinos. We calculate the neutrino-induced muon flux as described in ⁸ and in Fig. 4 we show the fluxes above



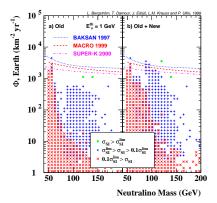


Figure 3. The enhancement factor from the new population of neutralinos.

Figure 4. The neutrino-induced muon fluxes are shown for a) the old population and b) the old and the new population of neutralinos.

1 GeV without and with the new population included. We see that for the models with the highest fluxes, we get an enhancement of about an order of magnitude when the neutralino mass is 60–120 GeV. We also show the current limits from Baksan⁹, Macro¹⁰ and Super-Kamiokande¹¹ and we see that these experiments are much more sensitive to MSSM models in this mass range when this new population of neutralinos is included.

6 Conclusions

We have investigated a new population of WIMPs in the solar system which arise when WIMPs that have scattered in the outskirts of the Sun are trapped in orbits gravitationally bound to the Sun, but due to perturbations by mainly Jupiter and Venus no longer intersect the Sun. This new population of WIMPs have nearly radial orbits and can cross the Earth's orbit and be captured by the Earth. There they can annihilate pair-wise producing muon neutrinos that can be searched for with neutrino telescopes. We have focused on when the WIMP is a neutralino in the MSSM and have shown that the fluxes can be enhanced by up to a factor of 10 when the neutralino mass is in the range 60–120 GeV. Hence, this significantly enhances the sensitivity for these experiments to neutralino dark matter.

Acknowledgments

L.B. was supported by the Swedish Natural Science Research Council (NFR). T.D. was partially supported by the NASA grant NAS8-39225 to Gravity Probe B (Stanford University). The research of L.M.K. was supported in part by the U.S. Department of Energy.

References

- 1. L. Krauss, Harvard preprint HUTP-85/A008A (1985); W.H. Press and D.N Spergel, Astrophys. J. 296 (1985) 679; J. Silk, K. Olive and M. Srednicki, Phys. Rev. Lett. 55 (1985) 257; L. Krauss, M. Srednicki and F. Wilczek, Phys. Rev. D33 (1986) 2079; T. Gaisser, G. Steigman and S. Tilav, Phys. Rev. D34 (1986) 2206; K. Griest and S. Seckel, Nucl. Phys. **B283** (1987) 681; L.M. Krauss, K. Freese, D.N. Spergel and W.H. Press, Astrophys. J. 299 (1985) 1001; J. Hagelin, K. Ng and K. Olive, Phys. Lett. **B180** (1987) 375; K. Freese, Phys. Lett. **B167** (1986) 295; M. Kamionkowski, Phys. Rev. **D44** (1991) 3021; F. Halzen, T. Saltzer and M. Kamionkowski, Phys. Rev. D45 (1992) 139; A. Bottino, V. de Alfaro, N. Fornengo, G. Mignola and M. Pignone, Phys. Lett. **B265** (1991) 57; R. Gandhi, J.L. Lopez, D.V. Nanopoulos, K. Yuan and A. Zichichi, Phys. Rev. **D49** (1994) 3691; A. Bottino, N. Fornengo, G. Mignola, L. Moscoso, Astropart. Phys. 3 (1995) 65; R. Gandhi, J.L. Lopez, D.V. Nanopoulos, K. Yuan and A. Zichichi, Phys. Rev. **D49** (1994) 3691; L. Bergström, J. Edsjö and P. Gondolo, Phys. Rev. D55 (1997) 1765.
- 2. T. Damour and L.M. Krauss, Phys. Rev. Lett. 81 (1998) 5726.
- 3. T. Damour and L.M. Krauss, Phys. Rev. **D59** (1999) 063509.
- L. Bergström, T. Damour, J. Edsjö, L.M. Krauss and P. Ullio, JHEP 08(1999)010.
- G. Jungman, M. Kamionkowski and K. Griest, Phys. Rep. 267 (1996)
- 6. P. Gondolo, J. Edsjö, L. Bergström, P. Ullio and E.A. Baltz, in preparation, http://www.physto.se/~edsjo/darksusy.
- 7. A. Gould, Astrophys. J. 368 (1991) 610.
- 8. L. Bergström, J. Edsjö and P. Gondolo, Phys. Rev. **DD58** (1998) 103519.
- 9. M. M. Boliev et al., Nucl. Phys. Proc. Suppl. **70**(1999)371-373.
- 10. M. Ambrosio et al., Phys. Rev. **D60** (1999) 082002.
- 11. A. Okada *et al.*, Proc. of the 30th Intl. Conf. on High-Energy Physics, Osaka, Japan, 27 Jul 2 Aug (2000).