Solar Seismic Model as a New Constraint on Supersymmetric Dark Matter

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Draft version 25 February 2022

ABSTRACT

If the Milky Way is populated by Weakly Interacting Massive Particles (WIMPs) as predicted by cosmological models of the large-scale structure of the universe and as motivated by supersymmetric models of particle physics (SUSY), the capture of high-mass WIMPs by the Sun would affect the temperature, density and chemical composition of the solar core. This is because WIMPs provide an alternative mechanism for transporting the energy of the core, other than radiative transfer. Helioseismology provides a means for an independent test of the validity of the WIMP-accreting solar models. We use the sound speed and the density profiles inferred from the helioseismic instruments on the Solar and Heliospheric Observatory (SOHO) to discuss the effect of WIMP accretion and annihilation on the evolution of the Sun. The WIMP transport of energy inside the Sun is not negligible for WIMPs with a mass smaller than 60 GeV and annihilating WIMPs with $\langle \sigma v \rangle \sim 10^{-27} \text{cm}^3/\text{sec}$. WIMP-accreting models with WIMP masses smaller than 30 GeV are in conflict with the most recent seismic data. We combine our new constraints with the analysis of predicted neutrino fluxes from annihilating WIMPs in the solar core. Working in the framework of the Minimal Supersymmetric Standard Model and considering the neutralino as the best dark matter particle candidate, we find that supersymmetric models, consistent with solar seismic data and with recent measurements of dark matter relic density, lead to a measured muon flux on Earth in the range of 1 to 10$^4 \text{km}^{-2} \text{yr}^{-1}$, for neutralino masses between 30 and 400 GeV. The local change of the solar core structure combined with the increasing accuracy of solar models and the increased sensitivity of future neutrino telescopes presents a clear and distinctive seismic signature that will enable us to set strong independent constraints on the physical properties of dark matter particles.

Key words: stars: oscillations - stars: interiors - Sun: oscillations - Sun: interior: cosmology - dark matter

1 INTRODUCTION

The dark matter problem has been an important unresolved problem in astrophysics for several decades. It has motivated much activity in cosmology, in both theoretical and observational areas, leading to significant progress in our understanding of the evolution of the universe. To agree with the measured abundances of helium, deuterium and lithium, the baryonic content of the Universe $\Omega_b$ must satisfy $\Omega_b = 0.04 \pm 0.01$. The dark matter is dominated by non-baryonic relic particles created in the early stages of the Big Bang, amounting to $\Omega_m = 0.3 \pm 0.1$. The best-motivated non-baryonic dark matter candidates are Weakly Interacting Massive Particles (WIMPs), which are stable particles, neutral and weakly interacting with ordinary matter. WIMPs were copiously produced in the early universe through their weak interactions with other forms of matter and radiation. As the universe expanded and cooled, their number density became too low for the annihilation processes to keep up with the Hubble expansion rate. A relic population of WIMPs should exist. Lee & Weinberg (1977) showed that if such a stable particle exists, its relic abundance is $\Omega_x h^2 \simeq 3 \times 10^{-27} \text{cm}^3/\text{sec}^2$, where $\langle \sigma v \rangle$ is the thermally-averaged product of annihilation cross-section and relative velocity. A particle which interacts with baryonic matter within the range of the weak interactions will lead to $\Omega_x$ of the order of unity, in agreement with cosmological determinations. Specifically, a recent analysis (Melchiorri and Silk 2002) points to $\Omega_x h^2 = 0.12 \pm 0.04$, thereby allowing us to restrict ourselves to study the case of an-
nihilating WIMPs with annihilation cross-section, \( \langle \sigma_a v \rangle \sim 10^{-27} \text{cm}^3 \text{s}^{-1} \).

In this paper we choose as our favorite dark matter candidate the so-called neutralino, arising in supersymmetric (SUSY) extensions of the Standard Model of electroweak interactions. More precisely, we work in the framework of the Minimal Supersymmetric Standard Model (MSSM) as implemented by Gondolo et al. (2001). The neutralino is expected to be the Lightest Supersymmetric Particle (LSP) in the MSSM (Ellis 2001), almost independently of the further simplifying assumptions one has to make to reduce the huge number of free parameters (63) contained in the MSSM.

Neutralinos or other WIMP candidates have not as yet been detected in accelerators, although LEP measurements set a lower bound of about 50 GeV on the WIMP mass (Baltz and Gondolo 2001). If WIMPs populate the halo of the Milky Way, then they can be detected either directly in low-background laboratory detectors or indirectly via observation of anomalous cosmic-ray antiprotons, positrons, and gamma rays from WIMPs that have annihilated in the Galactic halo (Silk & Srednicki 1984). Furthermore, WIMPs may be captured in the Sun (Press and Spergel 1985; Silk, Olive and Srednicki 1985) or in the Earth (Freese 1986; Gaisser, Steigman and S. Tilav 1986; Krauss, M. Srednicki and F. Wilczek 1986; Gould, Frieman and Freese 1989) and annihilate, thereby producing high-energy neutrinos. Annihilations balance capture, leading to an equilibrium concentration in the solar core (Gilliland, Faulkner, Press and Spergel 1986; Krauss, Freese, Spergel, Press 1985; Jungman, Kamionkowski and Griest 1996; Lopes, Silk and Hansen 2002). We henceforth only consider solar captures since the resultant neutrinos dominate the terrestrial muon detector signal.

The accretion by the Sun of WIMPs from the galactic background population leads to efficient mechanisms of transport of energy in the solar interior: such WIMPs provide an additional process for transferring energy of the deeper layers to the external layers, depending upon the scattering cross-section of the WIMPs on the solar nuclei. By virtue of their long mean free paths, WIMPs transport energy radially, and tend to produce an isothermal core. WIMP-accreting solar models that have a current relatively low concentration number of WIMPs reduce the temperature at the star’s core and produce a reduction in the solar neutrinos generated by some nuclear reactions of the pp chain and CNO cycle.

This leads to a reduction of solar neutrino counting rates measured on Earth. If such WIMPs exist, a decrease of the solar neutrino fluxes arising from the existence of a WIMP isothermal core could be successfully measured in the coming years by future solar neutrino experiments (Lopes & Silk 2002). Furthermore, if heat transport by WIMPs is significantly changing the structure of the solar core, a particular signature of this peculiar Sun’s core should be expected in solar seismic data (Lopes, Silk and Hansen 2002).

The seismic diagnostics of the Sun’s interior have been for many years the most important constraint on the internal thermodynamic structure of the Sun. Indeed, such research has led to significant improvements in the microphysics such as an update of the equation of state and the opacity calculations, and to a better determination of specific cross-sections of the pp chain (Turck-Chièze & Lopes 1993; Christensen-Dalsgaard et al. 1996; Turck-Chièze, NGHIEM, Couvidat & Turcotte 2001; Bahcall, Pinsonneault, Basu 2001; Provost, Berthomieu & Morel 2000). This research, motivated by helioseismology, has led to a significant improvement of the so-called Standard Solar Model. In addition, through helioseismic inversion diagnostics, it is possible to build solar models that evolve in an halo of WIMPs, which are consistent with oscillation data and hence predict the annihilating neutrino flux. Furthermore, there exist WIMP-accreting solar evolution models with different masses, scattering cross-sections, and annihilation cross-sections, for which the present solar structure is inconsistent with solar seismic data. The present article discusses the validity of such models and the independent method of diagnostic that seismology can provide for probing the SUSY parameter space.

2 THE EVOLUTION MODEL OF THE SUN

Application of Newton’s laws to our Galaxy tell us that the luminous disk and bulge must be immersed in a dark halo with a local density of 0.3 GeV cm\(^{-3}\) and that dark matter particles move with velocities comparable to the local circular speed. Additional theoretical arguments suggest that the velocity distribution of these particles is locally nearly isotropic and nearly a Maxwell-Boltzmann distribution. When a WIMP enters a star, it may interact with nuclei and lose enough kinetic energy to be trapped by the gravitational potential well. The evolution of the Sun is performed within a sea of WIMPs. The WIMP gas tends towards thermalization with baryonic matter with a time-scale much shorter than the time scale of stellar evolution. The WIMP spatial distribution is then simply the barometric equilibrium density, i.e., near a Gaussian with a typical length scale of \( r_s \sim 0.13 \sqrt{\left(1 \text{GeV}/m_{\chi}\right) R_\odot} \). The more massive are the WIMPs, the more they are concentrated in a very small region within the core of the star. The trapped WIMPs supply another means of transferring energy from the energy producing core to the outside, and thus supplement the usual transfer by photon diffusion (Lopes, Silk and Hansen 2002). WIMPs might have spin-independent (scalar) interactions in which case they would interact with all chemical elements in the Sun, or they might have only spin-dependent (axial) interactions in which case they would interact essentially only with hydrogen.

In fact, at present, direct laboratory searches are restricted to SUSY particles with scalar interactions. For this reason, the research reported in this work will focus only on this type of interactions. Current detectors (DAMA, CDMS, UKDMC) are sensitive to scattering cross-sections \( \sigma_s \gtrsim 10^{-32} \text{cm}^2 \), with one to two orders of magnitude improvement possible in the near future. Future detectors (e.g. GENIUS, Cryoarray) plan to be sensitive down to \( \sigma_s \gtrsim 10^{-35} \text{cm}^2 \). The WIMP-accreting solar models are computed in a way similar to the standard solar model, the only difference being the existence of an alternative mechanism of transport of energy supplemented by the presence of WIMPs.

As usual, in stellar evolution through the main sequence, we assume that the star is in hydrostatic equilibrium and is spherically symmetric, and that effects of rotation and magnetic fields are negligible. The evolution of the star
starts on the pre-main sequence, 0.05 Gyr from the ZAMS. The solar structure and evolution are calculated starting from an initially homogenous star with a given composition. A Henyey method is used to solve the system of nonlinear differential equations describing the stellar structure (Morel 1997). Starting with a standard primordial chemical composition the present solar luminosity and radius is reached at its present age 4.6 Gyr, by readjusting the initial helium abundance and the mixing length parameter (Lopes, Silk and Hansen 2002). It follows that the final WIMP-accreting solar model is very similar to the solar standard model, the difference between the two models possibly being identifiable via seismic diagnostics. The transport of energy by WIMPs is strongly dependent on the mass and scattering cross-sections.

In summary, the heat transport is optimized for \( \sigma \sim \sigma_c \) when the WIMP scale height is roughly equal to its mean free path. \( \sigma_c \) is a natural geometrical scattering cross-section, depending on the proton mass \( m_p \) and the radius and mass of the star, \( \sigma_c = m_p/M \times 8 \times 10^{-36} \text{ cm}^2 \). In order to be effective in heat transport, the WIMPs must have mean scattering cross-section per baryon in the range of \( 10^{-43} \text{ cm}^2 \leq \sigma \lesssim 10^{-33} \text{ cm}^2 \), depending upon the annihilation cross-section and mass of the WIMP. The transport of energy by WIMPs falls rapidly outside this range, and it becomes very difficult to test this effect on the solar structure against the solar seismic data. At higher cross-sections the energy is transported locally and the conductivity falls as \( \sigma/\sigma_c \). At lower cross-sections the conductivity falls as \( \sigma/\sigma_c \) and in addition only a fraction are captured by the Sun (Lopes, Silk and Hansen 2002).

### 3 SEISMIC DIAGNOSTIC OF THE SOLAR INTERIOR

The WIMPs are thermalized within the solar core and are on Keplerian orbits around the solar center, interacting through elastic scattering with solar nuclei, such as hydrogen and helium, thereby providing an alternative mechanism of energy transport other than radiation. The result is a nearly flat temperature distribution, leading to an isothermal core. Consequently, the central temperature is reduced. This reduction of temperature has two main consequences: since central pressure support must be maintained, the central density is increased in the WIMP-accreting models, and since less hydrogen is burnt at the center of the Sun, the central helium abundance and the central molecular weight are smaller than in standard solar models. The increase of the central density and hydrogen partially offset the effect of lowering the central temperature in the central production of energy. In fact, this is the reason why minor changes are required to the initial helium abundance and the mixing-length parameter in order to produce a solar model of the Sun with the observed luminosity and solar radius (Lopes, Silk and Hansen 2002). This readily leads to a balance between the temperature, \( T \), and the molecular weight, \( \mu \), in the core, leading to the peculiar profile of the square of the sound speed, \( c_s^2 \propto T/\mu \), and the density, \( \rho \propto \mu/T \), within the solar interior. This seems to be the case for most of the WIMP-accreting solar models.

Figure 1 illustrates the differences between the radial profile of the square of the sound speed and the radial profile of density for WIMP-accreting solar models and the Sun, as predicted by the solar standard model theory. In the same figure, we illustrate the square of the sound speed and the density as inferred for the present Sun by using the data of Global Oscillations at Low Frequency (GOLF) and Michelson Doppler Imager (MDI) experiments. The average mean hydrostatic structure of the Sun has been obtained by an optimally localized averaging inversion method by Kosovichev (1999). The method for independently determining the radial dependencies of the sound speed and density also yields the radial dependence of the first adiabatic index or the chemical composition. All the different methods of inversion are extremely sensitive to the quality of the frequency measurements, and very accurate seismic data for the low-degree acoustic modes is necessary for a precise inversion. The nuclear region is probed by as many as 120 acoustic modes that are significantly influenced by the turbulence, non-adiabatic effects and magnetic field perturbations at the surface layers (Lopes & Gough 2001). Nevertheless, the long duration of continuous measurements has reduced the uncertainty related with dynamics of the outer layers.

In particular the global modes, dipole modes and quadruple modes measured by the GOLF experiment (Bertello et al. 2000), coupled with high-degree modes obtained by MDI experiment data (Rhodes et al. 1997), enable us to significantly constrain the central region of the Sun, where the presence of WIMPs could be detected. However, the inversion of the sound speed seems to be in better agreement with the SSM than the inversion of density. This is due to the fact that this inversion uses only acoustic modes. Naturally, in such a case it is adequate to infer the sound speed profile rather than the density profile in the nuclear region. To successfully obtain the same level of accuracy for the density profile as in the case of the square of the sound speed profile, it is necessary to use gravity modes, which have not yet been unequivocally detected (Turk-Chi`eze et al. 2002).

Obviously, another reason for the density difference could come from the physics of the solar standard model, and not only from the density profile inversion. However, this is more unlikely because the sound speed difference is very small, reinforcing the view that the physics in the solar nuclear region is already described with the necessary accuracy.

Even if the answers to some questions about the inversion are still unclear, it seems very likely that there exists a class of annihilating WIMPs with annihilation cross-section \( \langle \sigma v \rangle \) of the order of \( 10^{-27} \text{ cm}^3/\text{sec} \) and relatively small masses that are excluded by the present seismic results. WIMPs with masses smaller than 60 GeV and scattering cross-sections between \( 10^{-38} \text{ cm}^2 \) and \( 10^{-40} \text{ cm}^2 \) seem to significantly modify the profile of the sound speed near the core.

This result is also reinforced by the density profile inversion. If we accept these results, both inverted quantities reject the existence of WIMPs with masses smaller than 30 GeV in the proposed scattering cross-section range. It follows that the acoustic spectrum of the previous WIMP-accreting solar models is incompatible with the observed solar spectrum measured by the SOHO seismic experiments. Usually, the solar model of the present Sun which best reproduces the observed acoustic spectrum is referred as the
4 THE NEUTRINO FLUX OF ANNihilATING WIMPS

Model-independent predictions can be made for neutrinos from the centre of the Sun, where neutralinos may have been gravitationally trapped and therefore their density enhanced. Today, the rate of change of the number of neutralinos between capture and annihilation in the Sun is in equilibrium. As they annihilate, many of the possible final states produce, after decays and hadronization, energetic neutrinos which propagate out from the interior of the Sun. In particular, the muon neutrinos are useful for indirect detection of neutralino annihilation processes, since muons have quite a long range in a suitable detector medium like ice or water. They can be detected through their Cherenkov radiation after having been produced at or near the detector. Detection of neutralino annihilation into neutrons is one of the most promising indirect detection methods, and it will be subject to extensive experimental investigations in view of the new neutrino telescopes such as AMANDA, ICeCube, Baikal, BAKSAN, MACRO, NESTOR and ANTARES planned or under construction (Halzen 1997). The neutrino-induced muon flux may be detected in a neutrino telescope by measuring the muons that come from the direction of the centre of the Sun or Earth. The energy of these muons will typically be between 1/2 and 1/3 of the neutralino mass, so they will be much more energetic than ordinary solar neutrinos. These neutrinos have energies of the order of a GeV, well above the energy of solar neutrinos which is of the order of MeV.

To investigate this question, we concentrate our attention on supersymmetric dark matter and evaluate the expected flux of neutrinos (and consequent muon fluxes in detectors) from annihilating neutralinos in the solar core. The numerical results discussed in this work are obtained in the framework of the Minimal Supersymmetric Standard Model as implemented in the DarkSUSY code (DMSSM; Gondolo et al. 2000), which takes into account the most recent particle physics constraints, such as the LEP lower bounds on the lightest Higgs and chargino masses. We extended our analysis to some benchmark points of a different supersymmetric scenario, the Constrained Minimal Supersymmetric Standard Model (CSSM; Ellis et al. 2000). In this work we are mainly concerned with WIMP candidates, such as the neutralinos capable of producing changes in the structure of the solar core which can be tested against the solar seismic model. Indeed, even after all the particle accelerator and relic abundance constraints are taken into account, there are large numbers of SUSY models which can produce neutralino dark matter. It is in this large parameter space of candidates proposed by the different extensions of the standard model of particle physics that the Sun can provide another independent diagnostic of the SUSY parameter space.

One should be aware that the choice of nuclear form factors needed to compute neutralino-nucleus elastic scattering, as well as other specific quantities related to hadronic physics which relate quarks/gluons with nucleons and also the quantities related with the step from nucleons to nuclei, are at best approximate. This is the reason why detailed processes such as scattering cross-sections are difficult to obtain with any generality. A more sophisticated treatment would, however, change the values by much less than the spread due to the unknown super-symmetric parameters. Indeed, our understanding of SUSY models is still developing, so predictions of annihilation rates in the early Universe, and thus relic neutralino densities may require modification. More significantly, another source of incertitude in modeling the incoming flux of annihilating neutrinos is related with the poor description of the solar core usually assumed in the computations. However, the present and future capability of solar seismology will provide the means to reduce this source of error.

Future solar seismic experiments will be able to detect deviations of order $10^{-5}$ from the luminosity predicted in the solar standard model. If the microphysics of the solar standard model is understood with the necessary precision, then at this level of accuracy a large portion of the supersymmetric parameter space would be ruled out by means of the seismic diagnostics. We show in Fig. 2 how this analysis would affect the expected muon flux, induced by high energy neutrinos from neutralino annihilation in the solar core, in the two different supersymmetric scenarios discussed above: DMSSM and CMSSM. A wide portion of the models obtained in DMSSM, namely the models leading to the highest fluxes, would be probed at $10^{-5}$ accuracy using solar seismic data. The benchmark points for CMSSM lie outside most of the parameter space where solar seismic data are sensitive enough to the neutralino annihilation luminosity. The SUSY parameter space that is constrained by helioseismology will be discussed in more detail in a future paper (Bertone, Lopes, Sigl & Silk 2002, in preparation).

5 DISCUSSION AND CONCLUSIONS

Although important questions still remain that need to be addressed regarding the structure of the Sun, such as the asymmetric macroscopic motions in the core, the dynamical effects in the nuclear reaction rates and the chemical abundances in the nuclear region (Turck-Chèze et al. 2001), seismic analysis has been a powerful diagnostic tool for the Sun’s interior. This has led us to constrain the WIMP parameters based on the proposition that the present standard solar model is an accurate approximation of the observed Sun.

The WIMP-accreting solar models of this article are not certainly an unequivocal constraint on the SUSY parameters. If we had modified some of the solar parameters within the error bars, such as for example the age of the Sun, we would probably have found other solutions. However, the general results, as far as the WIMPs are concerned, would be qualitatively the same. The results discussed in the article highlight the powerful tool that solar seismology represents in order to constrain the WIMP parameters within the expected experimental values. Such results strongly favor the non-existence of annihilating WIMPs with $(\sigma v) \sim 10^{-27} \text{cm}^3/\text{sec}$, masses lower than 60 GeV, and with scalar cross-sections from $10^{-40} \text{cm}^2$ to $10^{-38} \text{cm}^2$.

It should be noticed that the resolution in the in-
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The inner core is relatively poor; about 0.05\(R_\odot\), which is insufficient to detect small discontinuities, probably due to the WIMP isothermal core. This certainly justifies further searching for gravity modes. The modelling of WIMP-accreting solar models is central to the prediction of the muon flux that is to be measured by the neutrino telescopes such as AMANDA, ICeCube, Baikal, BAKSAN, MACRO, NESTOR and ANTARES (Halzen 1997 and references therein). Assuming that the WIMP is a neutralino and the density of neutralinos is in agreement with CMB and large-scale structure observations, the prediction of the muon flux is within the range of 1 to 10\(^4\) km\(^{-2}\) yr\(^{-1}\), for neutralinos with masses between 60 GeV and 400 GeV. Theoretically, it is the low-degree gravity modes that are the most sensitive to the conditions of the nuclear region, at present the only region where substantial deviations from the standard models occur. Indeed, accreting-WIMP solar models have gravity modes period spacing that are markedly different from that of other solar models, at least for the case of smaller WIMP masses. The asymptotic period spacing of high-order gravity modes of low degree is proportional to an integral of the ratio of the buoyancy frequency by the radius, and its present value for the solar standard model is of the order of 36 min (Lopes & Turk-Chièze 2002, in preparation). Following the period separation between modes of the same degree and consecutive radial-order, the period separation is expected to be relatively smaller than in the case of solar standard models, by as much as a few percent for the WIMP-accreting solar models discussed in this work. It is the sensitivity to the buoyancy that can be used to invert the density in the very deep layers of the solar core. Therefore, gravity mode observations hold the promise of a sensitivity test, although their current interpretation is difficult between the possible candidates detected (Turck-Chièze et al. 2002). Furthermore, the gravity mode data reduction is done assuming that the Sun is well represented by the solar standard model, which could be a major difficulty in terms of detection, if dark matter changes the structure of the solar core.

In any case, the physical processes presented here are meant to be indicative of what one might expect for realistic WIMP-accreting models. Furthermore, since the physics of solar models, the seismic data reduction, as well as the SUSY model predictions are themselves evolving, the detailed model results quoted here should be taken as indicative of the general order of magnitude of expectations for muon fluxes.

ACKNOWLEDGMENTS

The authors wish to thank P. Morel for using the CESAM code, and P. Gondolo, J. Edsjo, L. Bergstrom, P. Ullio, E. A. Baltz, for using the darkSUSY code. Thanks also to S. Hansen, G. Sigl and S. Turck-Chièze for stimulating discussions on the physics of super-symmetric models of particle physics and solar models. IPL is grateful for support by a grant from Fundação para a Ciência e Tecnologia.

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Figure 1: The relative differences between the square of the sound speed (a) and the density (b) of the standard solar model and solar models, evolved within an halo of WIMPs. The continuous curves correspond to models with WIMP masses of 15 GeV, 30 GeV and 60 GeV and with annihilation rate of $10^{-27}$ cm$^3$/s, and scalar scattering cross-section of $10^{-38}$ cm$^2$ or $10^{-40}$ cm$^2$. The curves are as follows: $m_x \sim 60$ GeV $\sigma_s \sim 10^{-38}$ cm$^2$ (black curve), $m_x \sim 60$ GeV $\sigma_s \sim 10^{-40}$ cm$^2$ (dark grey curve), $m_x \sim 30$ GeV $\sigma_s \sim 10^{-38}$ cm$^2$ (light grey curve), $m_x \sim 30$ GeV $\sigma_s \sim 10^{-40}$ cm$^2$ (dashed light grey curve), $m_x \sim 15$ GeV $\sigma_s \sim 10^{-38}$ cm$^2$ (dashed dark grey curve) and $m_x \sim 15$ GeV $\sigma_s \sim 10^{-40}$ cm$^2$ (dashed black curve). The curve with error bars represents the relative differences between the square of the sound speed in the Sun (as inverted from solar seismic data) and in a standard solar model (Kosovichev et al. 1997; 1999). The horizontal bars show the spatial resolution, and the vertical bars are error estimates.
Figure 2: Predicted neutrino-induced muon flux produced by neutralino annihilation in the Sun. Small squares correspond to models obtained with the DarKSUSY code (DMSSM; Gondolo et al. 2000), triangles correspond to selected benchmark points of the Constrained Minimal Supersymmetric Standard Model (CMSSM; Ellis et al. 2000). Big squares are used to highlight models leading to a local variation of luminosity of the solar core larger than $10^{-5}$ (which could thus be potentially probed by upcoming solar seismic observations). The dotted and dashed curves represent the current limit sensitivity of MACRO and Icecube experiments.