Measuring solar neutrinos over Gigayear timescales with Paleo Detectors

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Abstract

Measuring the solar neutrino flux over gigayear timescales could provide a new window to inform the Solar Standard Model as well as studies of the Earth's long-term climate. We demonstrate the feasibility of measuring the time-evolution of the ^{8}B solar neutrino flux over gigayear timescales using paleo detectors, naturally occurring minerals which record neutrino-induced recoil tracks over geological times. We explore suitable minerals and identify track lengths of 15–30 nm to be a practical window to detect the ^{8}B solar neutrino flux. A collection of ultra-radiopure minerals of different ages, each some 0.1 kg by mass, can be used to probe the rise of the ^{8}B solar neutrino flux over the recent gigayear of the Sun's evolution. We also show that the time-integrated tracks are sensitive to models of the Sun [1].

Introduction

Fundamental to the study of the evolution of the Sun is the Solar Standard Model (SSM), a theoretical tool to investigate the solar interior. The Solar standard model accepted today is Bahcall's model [2]. Studying and understanding solar activity and evolution not only benefits science itself, but affects directly our environment as living beings. Initial measurements of solar neutrinos resulted in less neutrinos than predicted by the SSM, known as the "solar neutrino problem". The depletion of the solar neutrino flux is found to be due to the oscillations of ν_e to ν_μ and ν_τ inside the Sun by the Mikhev-Smirnov-Wolfenstein resonance conversion. Recent measurements of the solar elemental abundances (metallicity) by Asplund et al. 2009 [3] have caused a new conflict within the SSM. The new photospheric measurements indicate that the solar metallicity is lower than previously estimated by Grevesse & Sauval 1998 [4]. The SSM is sensitive to transitions in metals (used to refer to anything above helium), which are an important contributor to opacity. Lower metallicity is associated with a cooler solar core, and in this way, affects the solar interior. Solar models using the new metallicity are no longer able to reproduce helioseismic results, causing the so-called "solar abundance problem" [5].

Recently, it has been proposed that rock crystals deep in the Earth could act as a new method to detect dark matter [6]. Paleo detectors have competitive exposures compared to terrestrial experiments.

We consider the detectability of solar neutrinos using paleo detectors. The energies of solar neutrinos are about $\sim 1\,\mathrm{MeV}$, which translate to $\sim$ keV of recoil energy. This is comparable to the recoil energies $E_R = 0.1 - 100\,\mathrm{keV}$ caused by dark matter, meaning solar neutrinos should also give rise to damage tracks. Importantly, paleo detectors not only open a new way to search for solar neutrinos, they allow us to probe the Sun in the past on Gyr time scales, something that is not possible with terrestrial detectors.

To investigate the study of the SSM with paleo detectors, we compute two SSMs that differ in their metallicity. We focus on the ^{8}B neutrino flux, which shows strong dependence on the solar interior temperature and metallicity models.

Rates per track length spectrum

The neutrino induced differential recoil spectrum per unit mass of target nuclei T is given by

$$\left(\frac{dR}{dE_R}\right)_T = \frac{1}{m_T}\int_{E_\nu^{min}} dE_\nu \int_{\Delta t} dt \frac{d\sigma}{dE_R}\frac{d^2\Phi_\nu}{dE_\nu dt}, \tag{1}$$

The differential cross section for coherent neutrino-nucleus scattering is

$$\frac{d\sigma}{dE_R}(E_R, E_\nu) = \frac{G_F^2}{4\pi} Q_W^2 m_T \left(1 - \frac{m_T E_R}{2E_\nu^2}\right) F^2(E_R) \tag{2}$$

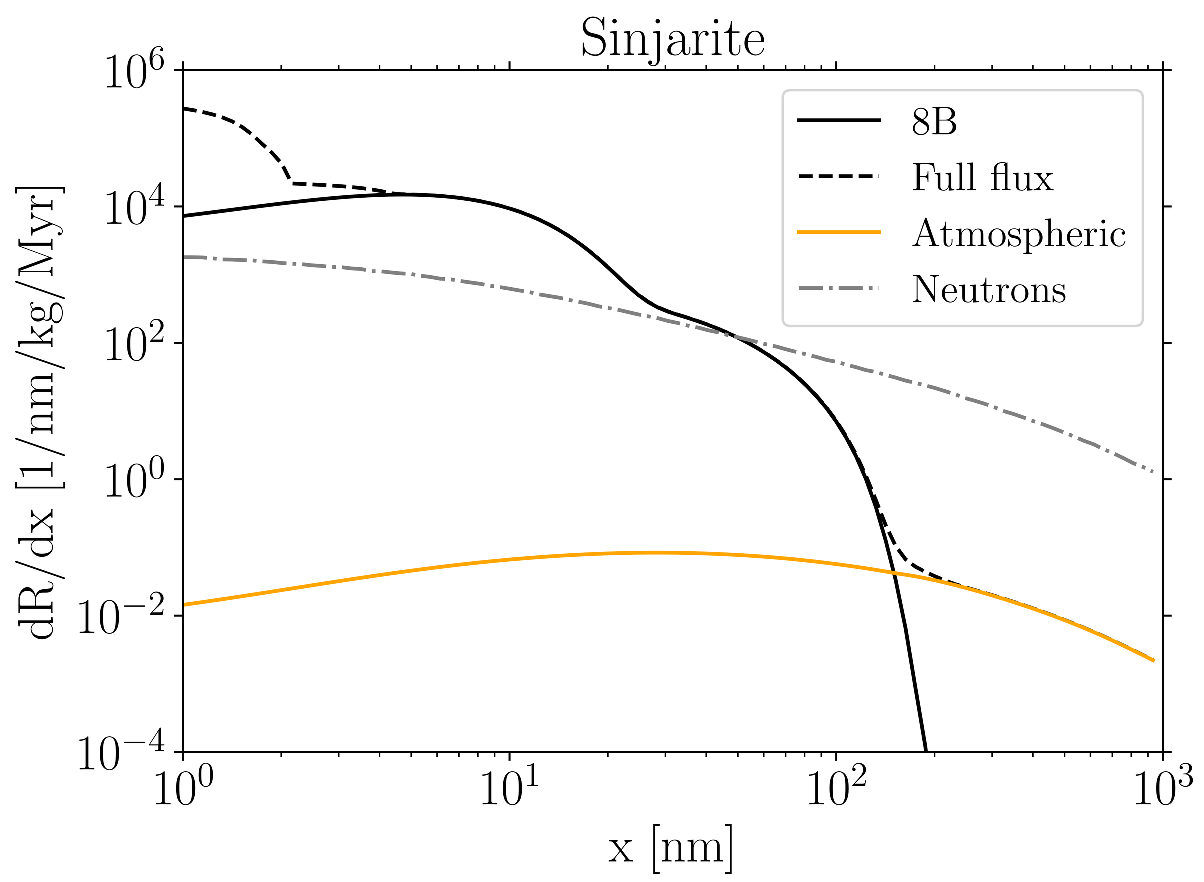

Figure 1: Track length spectra for sinjarite (left panel) and halite (right panel). Shown are the tracks induced by neutrinos and neutrons, as labeled. The tracks caused by the ^{8}B flux and atmospheric neutrinos are shown separately for clarify. The central peak above tens of nm is induced by the ^{8}B flux, while above around 200 nm the tracks are induced by the atmospheric neutrino flux, while below 2–3 nm the tracks arise from the contributions of multiple solar neutrino components with lower energies than ^{8}B.

Finally, the track length spectra is obtained by summing over the target nuclei in the mineral,

$$\frac{dR}{dx} = \sum_T \xi_T \frac{dE_R}{dx_T}\left(\frac{dR}{dE_R}\right)_T, \tag{3}$$

where ξ_T is the mass fraction of each constituent nuclei T.

Solar Neutrino & Metallicity Models

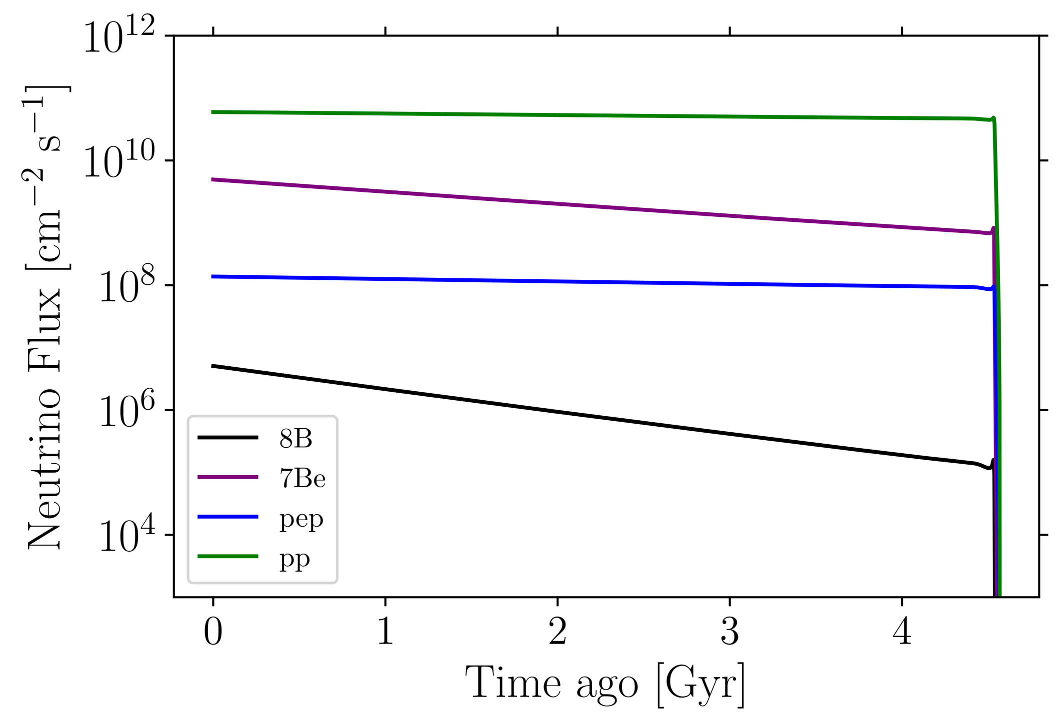

Figure 2: Neutrino flux variation over time, for different components of the solar neutrino flux, for the GS metallicity model.

Results

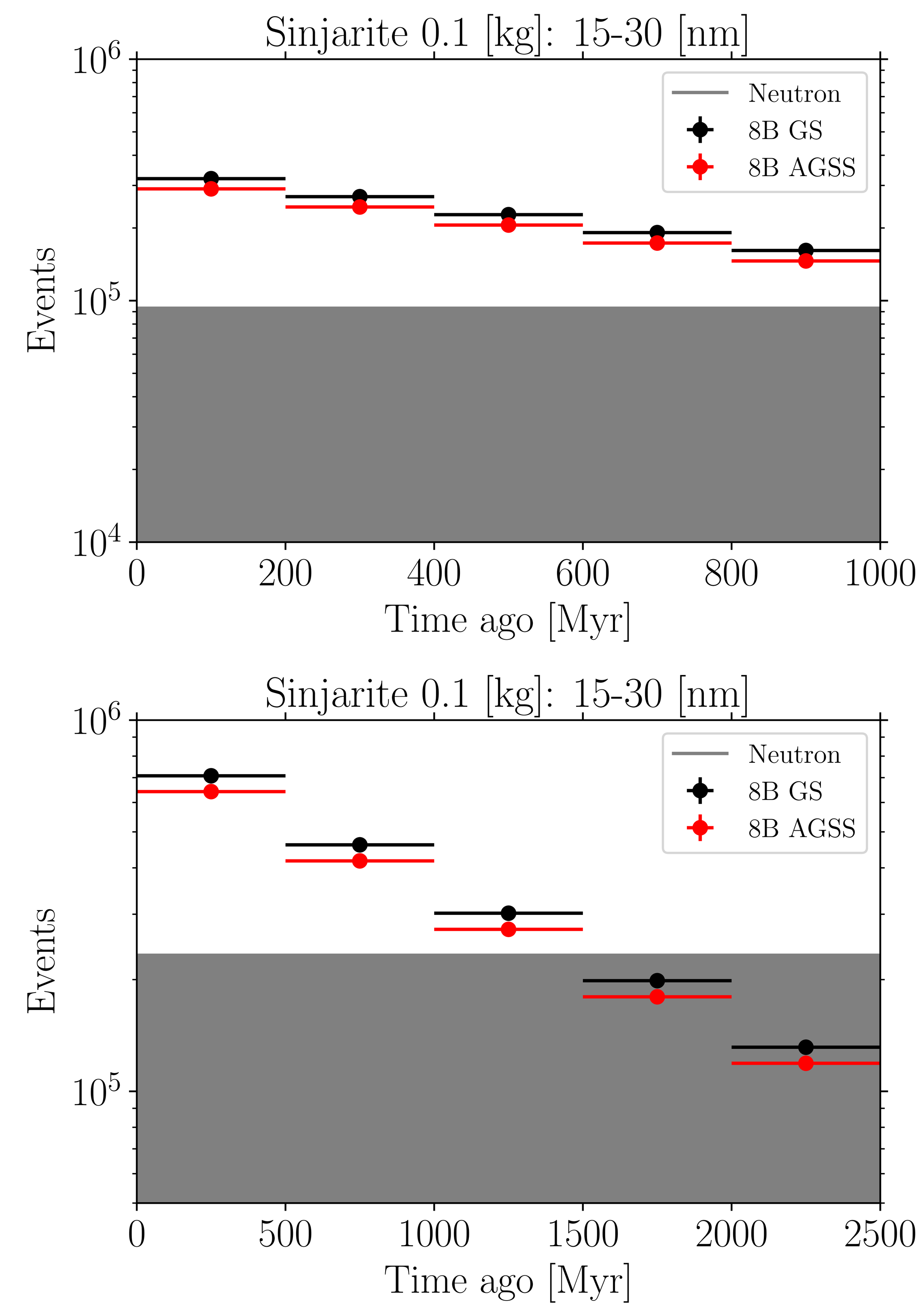

Figure 3: Above:Number of events per 200 Myr time bins, for 0.1 Kg of Sinjarite. Events are summed over track lengths of 15 to 30 nm. The black dots represent the GS (reference) SSM and red represents AGSS SSM. The shaded region is where the neutron backgrounds will dominate the events. Below: The same as above, but extending out to 2.5 Gyr and with wider 500 Myr time bins.

Conclusions

- Paleo Detectors are a complement to Direct Detection Experiments.
- Competitive exposure due to giga year old samples.
- We have studied rocks up to 2.5 Gyr finding that up to 1.5 Gyr the samples show good signal to background ratio.
- We have considered up to 10% uncertainty in neutron background, allows differentiation of metallicity models.

References

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