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Title: First Evidence of pep Solar Neutrinos by Direct Detection in Borexino
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In the modern era of astrophysics, astronomers now rely on more on just light to offer information about the universe. In this age of "multi-messenger" astrophysics, the next most useful tracer of cosmic phenomena are neutrinos: small, neutral, non-baryonic, and weakly interacting particles which are made in ludicrous numbers in weak nuclear reactions like those in stellar interiors.

Neutrinos offer a unique insight into the inner workings of stellar cores as tracers of the weak nuclear reactions which happen within. The reaction chains which dominate stars of approximately solar mass are the p-p chain, where hydrogen is fused into helium, and the CNO cycle, where hydrogen produces some heavier nuclei like carbon, nitrogen, and oxygen. Since we cannot directly detect the light from photons generated in stellar cores, our best option to determine reaction rates for each of these chains (and the sub-chains within them) are through the detection of neutrinos. Since neutrino energies are defined by the weak nuclear reactions in which they are produced, detection of neutrinos of certain energies are direct tracers of the three sub-processes of the three p-p chain and the two paths of the CNO cycle.

Neutrinos interact with other particles very weakly, meaning that the scattering rates are very low compared to the neutrino fluxes, often by tens of orders of magnitude. When they do interact, the scattering releases a shower of particles which can interact with detectors to produce a signal. So how could we ever reliably detect neutrinos if they are so weakly interacting? The name of the neutrino detection game is "bigger is definitely better", so those in the hunt for these stealthy particles build enormous (hundreds or thousands of tons) tanks filled with some fluid, often very pure water or a noble gas. This raw size gives neutrinos as much of a chance to react with nuclei (or sometimes the electrons) of the fluid as possible.

In 2012, observers at the Borexino neutrino observatory (a ∼278 ton organic liquid scintillator target) in Italy achieved the first direct detection of a nuclear process adjacent to the p-p chain, called the pep reaction, where two protons and an electron react to produce a deuterium nucleus and a neutrino. The detection of these 1.44 MeV pep neutrinos offer a constraint on the reaction rates of the CNO cycle since the neutrino energies of the two processes are similar, so elimination of the pep background offers a bound on the CNO neutrino detections. This is visible in the top panel of Bellini et al. Figure 1.

This CNO reaction constraint has important astrophysical implications, since the CNO cycle is the driving nuclear process fueling massive ($> 1.5\ M_\odot$) stars. This constraint offered by Bellini et al. in 2012 is the strongest to date, but cannot yet distinguish between high and low metallicity solar models. Future work at Borexino will offer even tighter constraints on the CNO neutrino interaction rates by further eliminating backgrounds.

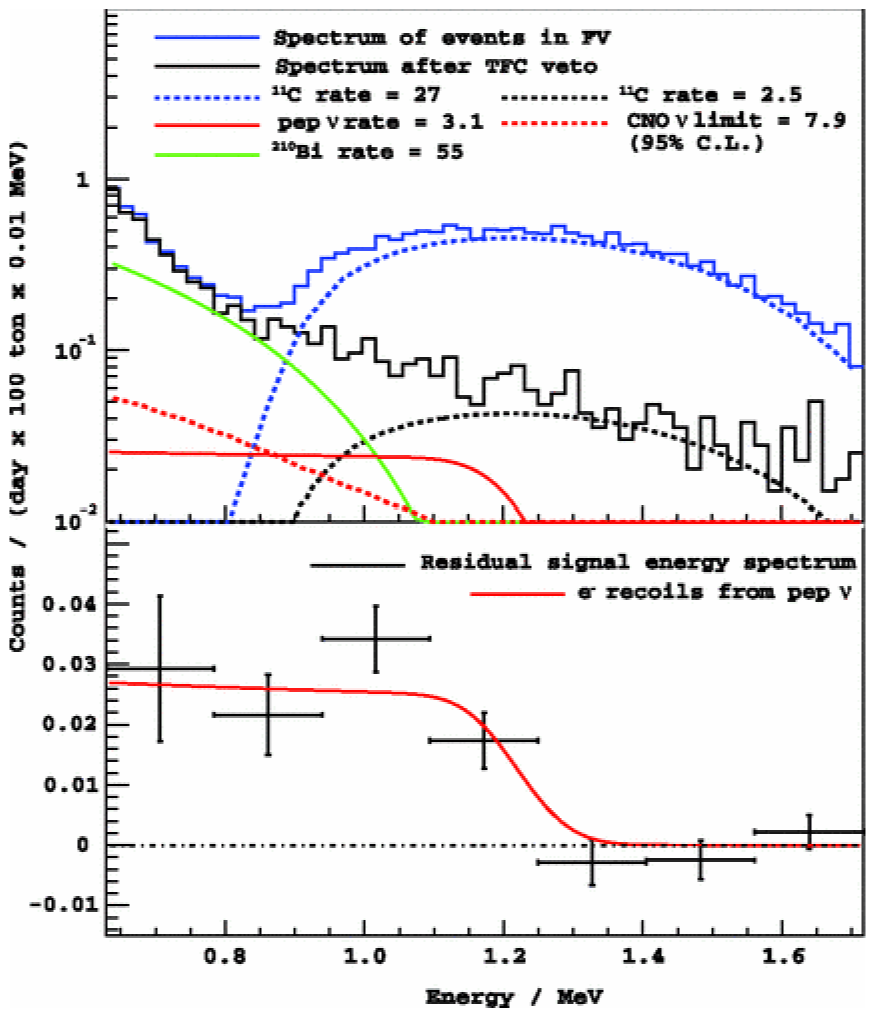

Figure 1: Fig. 1 from Bellini et al. 2012. The largest background in the energy domain of CNO produced neutrinos (black) is from the pep reaction (red). The detection of the pep neutrinos offers a constraint on the CNO production, and further constraints can be made by eliminating the next largest background, ^{210}Bi (green).