SOLAR NEUTRINOS

- pp CHAINS convert 4H to He and release several ν_e s
- From 1960s, SEARCHES MADE FOR THESE ν_e s.
- FIRST SEARCH LED TO DETECTION BUT FLUX(ν_e) $\sim \frac{1}{3}$ PREDICTED FLUX for ^8B ν_e's

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THE SOLAR NEUTRINO PROBLEM

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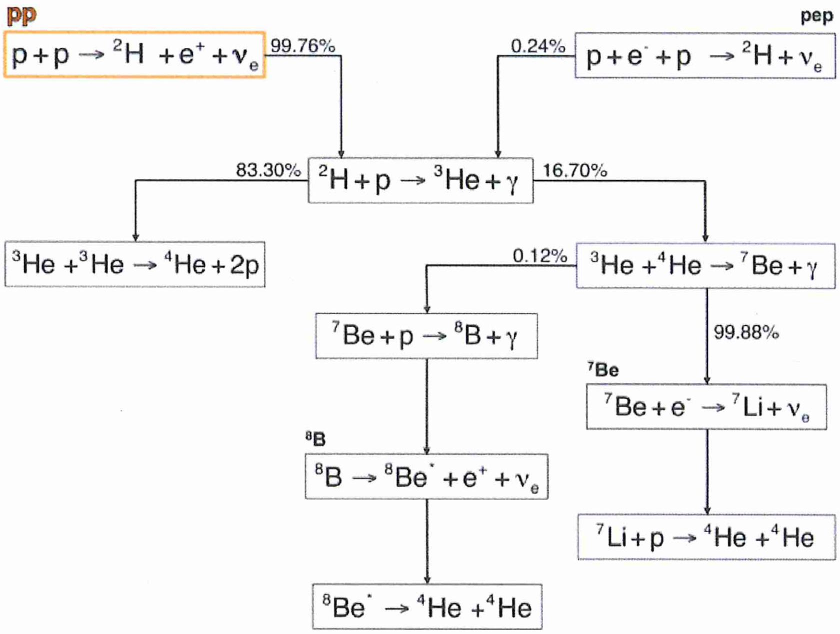
now RESOLVED!



Extended Data Figure 3 | The sequence of nuclear fusion reactions defining the *pp* chain in the Sun. The pp neutrinos start the sequence 99.76% of the time.

A FEW BASIC POINTS

- ν = ELUSIVE ∴ NEED LARGE DETECTOR & LOTS OF OBSERVING TIME IN 'QUIET' LOCATION
- ν = MEASURE CORE TEMPERATURE <u>NOW</u> BUT L(SUN) MEASURES TEMPERATURE ~ 100,000 YRS AGO.
- ν SPECTRUM SHOULD BE SAMPLED
- ALL pp ν NOW MEASURED

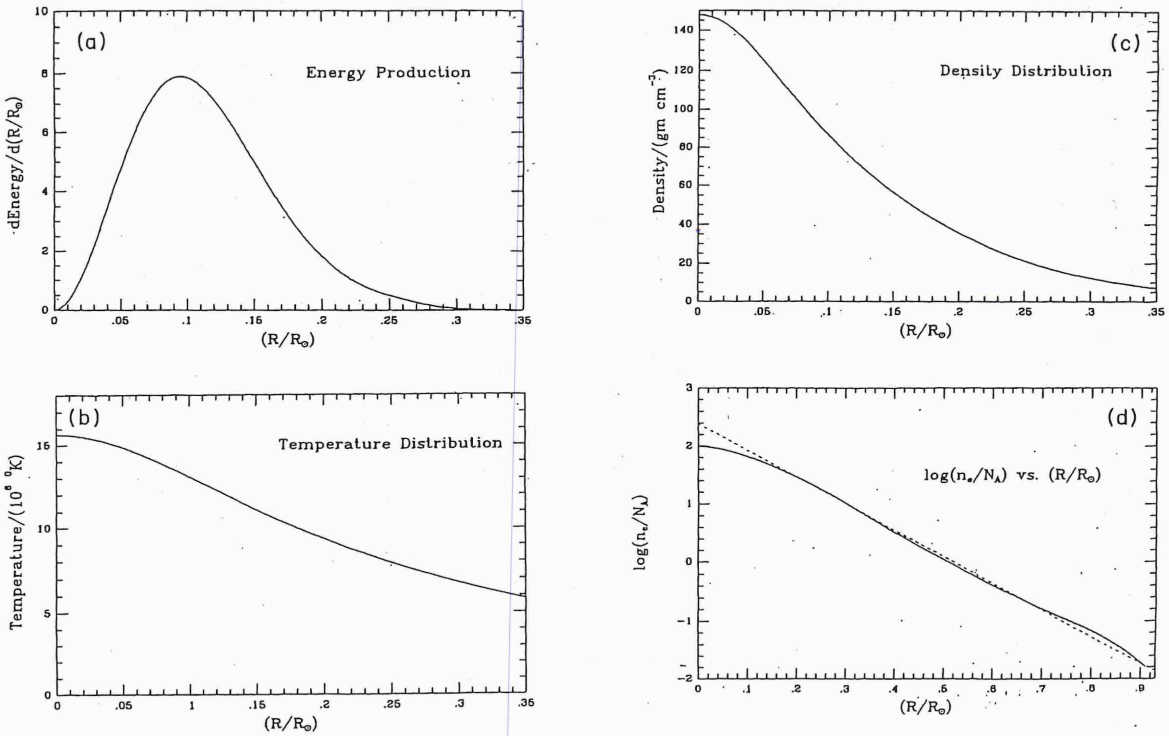


Fig. 5.15. Basic results of the standard solar model. Note that virtually all of the energy production occurs within 20 % of the solar radius, that is, within the inner 1 % of the solar volume. Reprinted with permission from Bahcall and Ulrich (1988). Copyright 1988 by the American Physical Society.

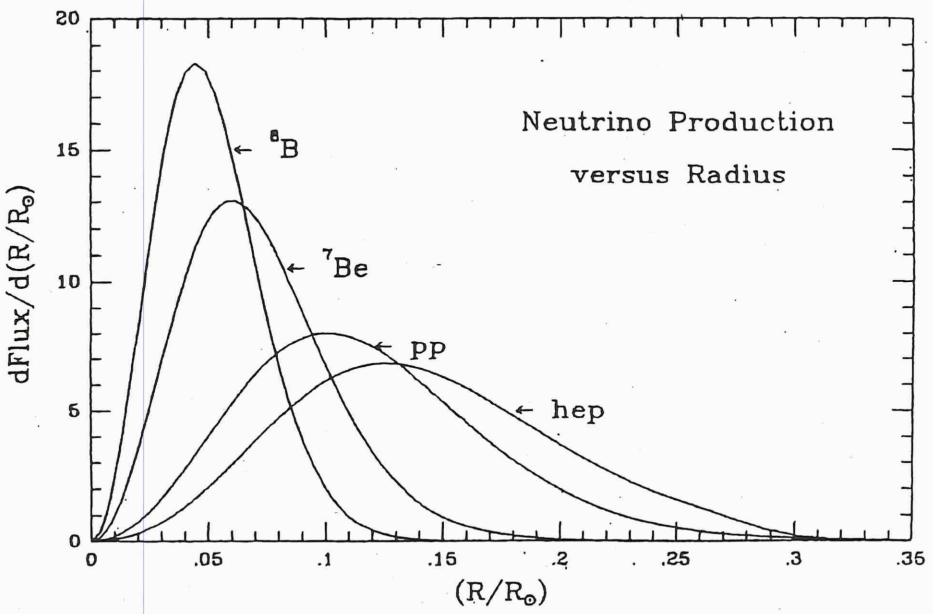


Fig. 5.16. Neutrino production as a function of radius for the different neutrino sources. The fraction of neutrinos that originates in each fraction of the solar radius is given as [dFlux/d(r/R$_\odot$)][d(R/R$_\odot$)]. Reprinted with permission fromBahcall and Ulrich (1988). Copyright 1988 by the American Physical Society.

DAVIS' CHLORINE EXPT.

$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$$

$\nu_e > 0.814$ MeV

∴ primarily sensitive to ^8B ν's but also ^7Be and pep's

- HOMESTAKE GOLD MINE (5000 ft)
- 100,000 gallons of perchlorethylene
- expose for ~1 month & flush out ^{37}Ar
- count ^{37}Ar decays in the lab
- ran 1970 – 1994

RESULT ν FLUX ~ $\frac{1}{3}$ PREDICTED FLUX

EXPT CHECKED & RECHECKED

e.g. inject known amount of ^{37}Ar and test for recovery

SOLUTIONS

1. SOLAR MODEL
   - composition of core not same as surface : core composition sets T(core) and ∴ F(ν)
   - oscillation? F(ν) ∝ T(now)
     L ∝ T(-100,000 yrs)
2. NUCLEAR PHYSICS
   - fewer ^8B is a minor perturbation on energy generation
3. ν OSCILLATION

$$\nu_e \rightleftharpoons \nu_\mu \rightleftharpoons \nu_\tau$$

ν_e's converted to ν_μ & ν_τ in flight

MORE but DIFFERENT EXPTS

- ENERGY
- DETECT NOT ONLY ν_e

GALEX/GNO (1998-2003) and SAGE (1990-2007)

$$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$$

ν_e > 232 keV & pick up some pp ν's

- TONS OF ^{71}Ga
  ^{71}Ge extracted chemically as germane ($^{71}GeH_4$) ($\tau_{1/2}$ = 11.4 days)
- COMBINATION OF ALL DATA
  → 66.1 ± 3.1 SNU against ~128±8 (Pagel) predicted

PROBLEM CONFIRMED

KAMIOKANDE (baryon decay) (SN1987A)

- Vast H_2O tank with photomultipliers in the walls
- Threshold ~9 MeV ∴ high energy ^8B ν's + atmospheric ν + ...
- ν_e collide with nuclei and create high energy $e^\pm$ which emit Cherenkov radiation in the FORWARD direction. (A CRUDE TELESCOPE!)

PROBLEM CONFIRMED

SUDBURY NEUTRINO OBSERVATORY

- 12 METER CONTAINER OF HEAVY WATER
- CAN DETECT ν_μ AND ν_τ AS WELL AS ν_e
- TOTAL ν FROM SUN = PREDICTED FLUX

$\therefore$ ν's OSCILLATE

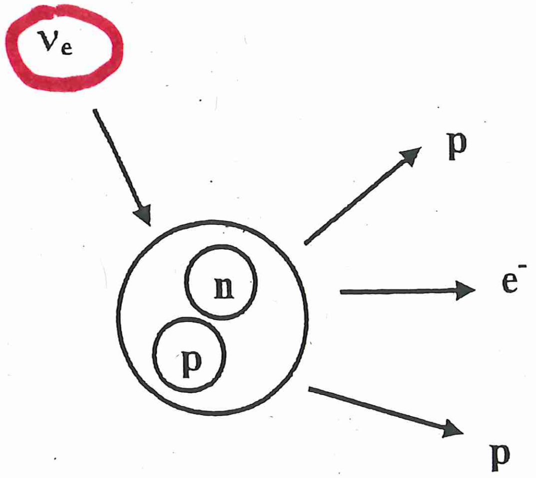


Fig. 5.5. A charged-current event, as would be observed in *SNO*.

← DETECTED BY CHERENKOV RADIATION

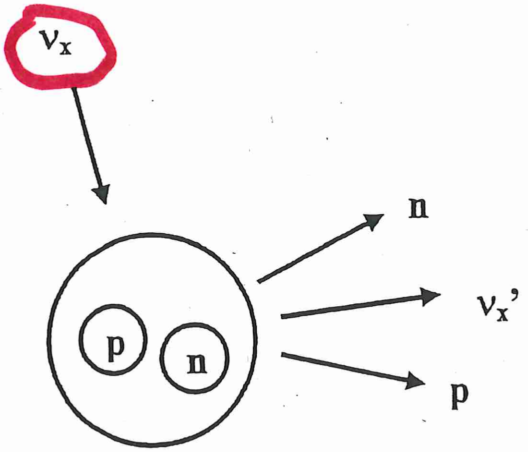


Fig. 5.6. A neutral-current event, as would be seen in *SNO*.

n's DETECTED BY (n,γ) ON NUCLEUS - ^3He or ^{35}Cl - γ-RAY SCATTERS OF AN e WHICH → CHERENKOV RADIATION

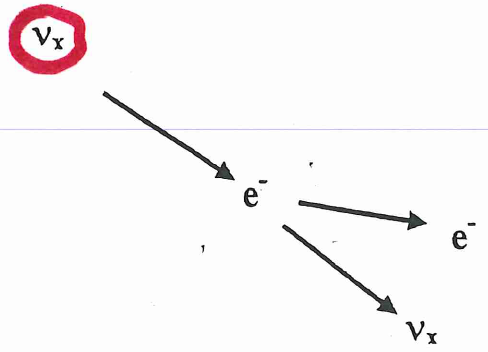
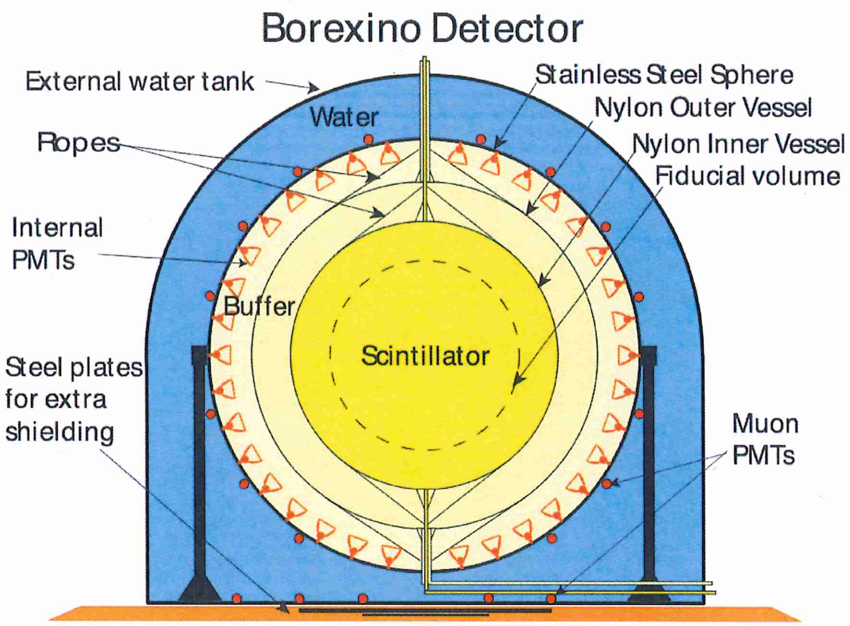


Fig. 5.7. An electron scattering event, as would be seen in *SNO*.

NOT UNIQUE TO D_2O - see KAMIOKANDE's H_2O

e^- → CHERENKOV RADIATION

tubes; the amount of light produced is proportional to the energy of the incident ν_e.



Extended Data Figure 1 | The Borexino detector. The characteristic onion-like structure of the detector[22] is displayed, with fluid volumes of increasing radiological purity towards the centre of the detector. Although solar neutrino measurements are made using events whose positions fall inside the innermost volume of scintillator (the fiducial volume, shown as spherical for illustrative purposes only), the large mass surrounding it is necessary to shield against environmental radioactivity. The water tank (17 m high) contains about 2,100 t of ultraclean water. The diameter of the stainless steel sphere is 13.7 m, and that of the thin nylon inner vessel containing the scintillator is 8.5 m. The buffer and target scintillator masses are 889 and 278 t, respectively.

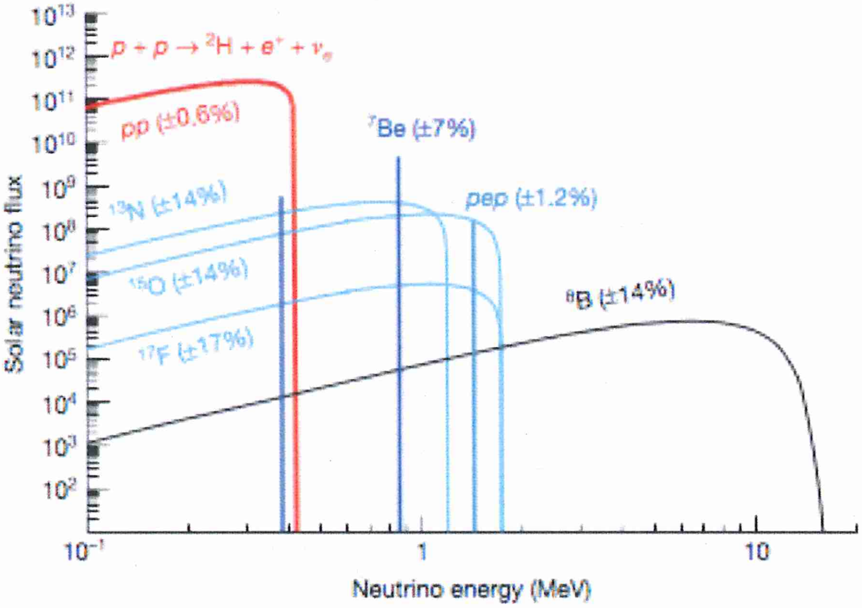


Figure 1 | **Solar neutrino energy spectrum.** The flux (vertical scale) is given in $cm^{-2} s^{-1} MeV^{-1}$ for continuum sources and in $cm^{-2} s^{-1}$ for mono-energetic ones. The quoted uncertainties are from the SSM[9].

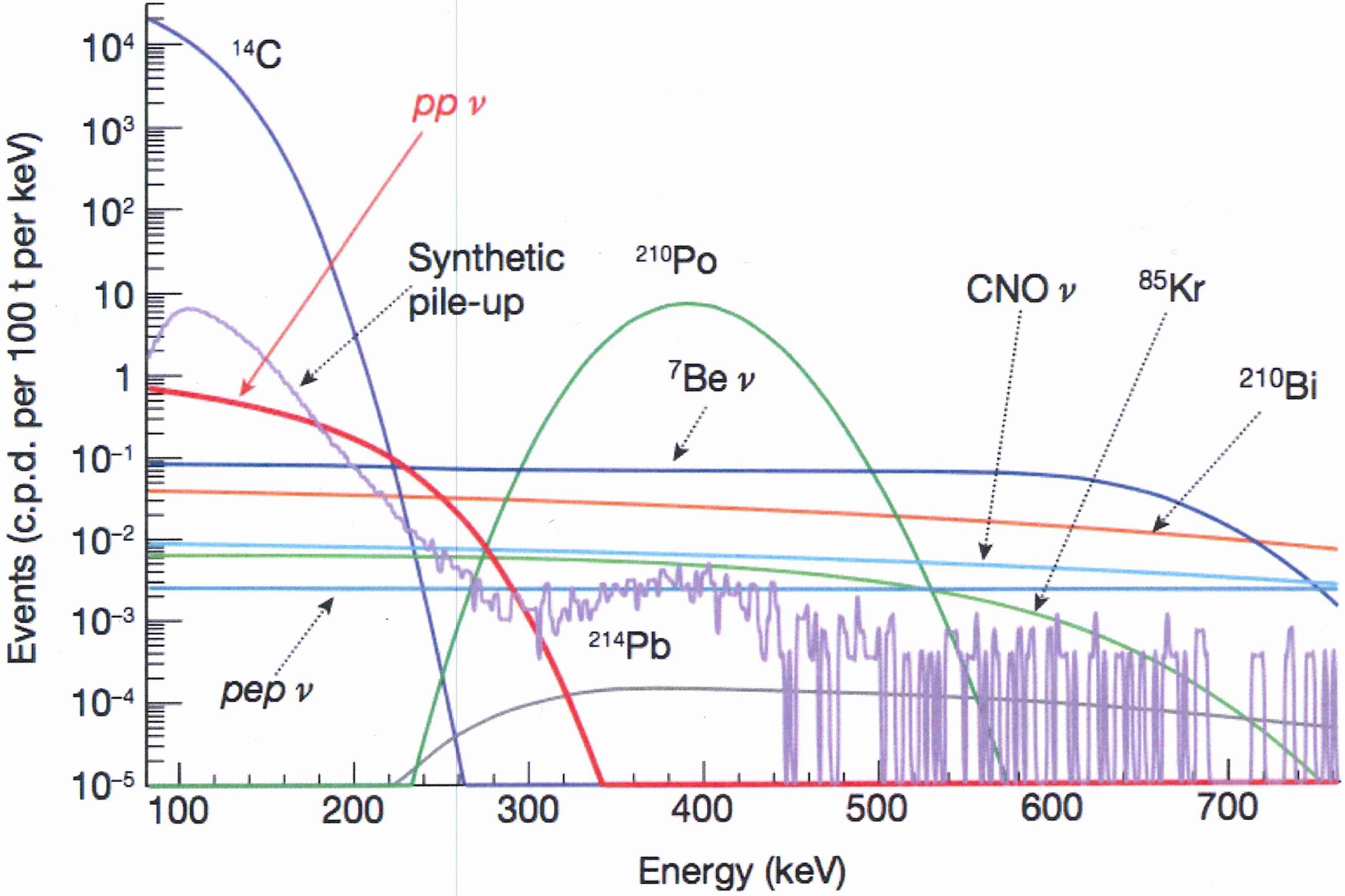
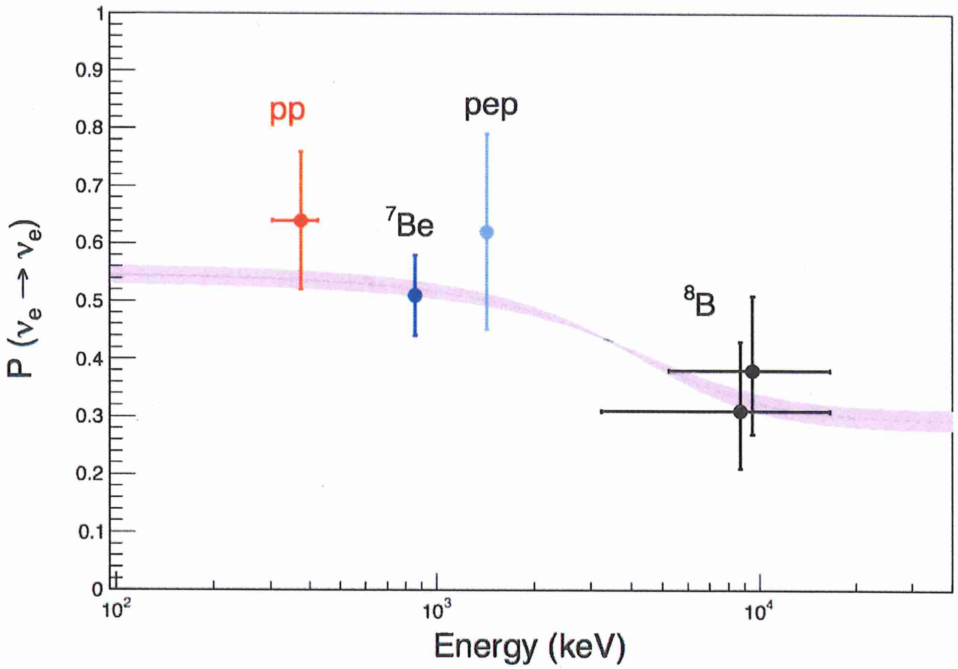


Figure 2 | Energy spectra for all the solar neutrino and radioactive background components. All components are obtained from analytical expressions, validated by Monte Carlo simulations, with the exception of the synthetic pile-up, which is constructed from data (see text for details).



Extended Data Figure 2 | Survival probability of electron-neutrinos produced by the different nuclear reactions in the Sun. All the numbers are from Borexino (this paper for pp, ref. 17 for ^{7}Be, ref. 18 for pep and ref. 19 for ^{8}B with two different thresholds at 3 and 5 MeV). ^{7}Be and pep neutrinos are mono-energetic. pp and ^{8}B are emitted with a continuum of energy, and the reported P(n_eR n_e) value refers to the energy range contributing to the measurement. The violet band corresponds to the 6 1s prediction of the MSW-LMA solution[25]. It is calculated for the ^{8}B solar neutrinos, considering their production region in the Sun which represents the other components well. The vertical error bars of each data point represent the 6 1s interval; the horizontal uncertainty shows the neutrino energy range used in the measurement.

BOREXINO in GRAN SASSO

- LOW ENERGY ν's DETECTED BY RECOIL ELECTRONS IN LIQUID SCINTILLATOR $(\nu_x + e \rightarrow \nu_x + e)$
  - BOREXINO
    - pep ν's PRL 107 141302 (2011)
    - ^8B νs " 108 051302 (2012)
    - low energy pp spectrum Nature 512, 383 (2014)
- ASSUME SOLAR FLUX AND CALCULATE ν OSCILLATION PROPERTIES
- NEXT GOAL
  DETECT CNO ν's → Z (core)
- ABUNDANCE PROBLEM!