The Results and Prospects from Solar Neutrinos

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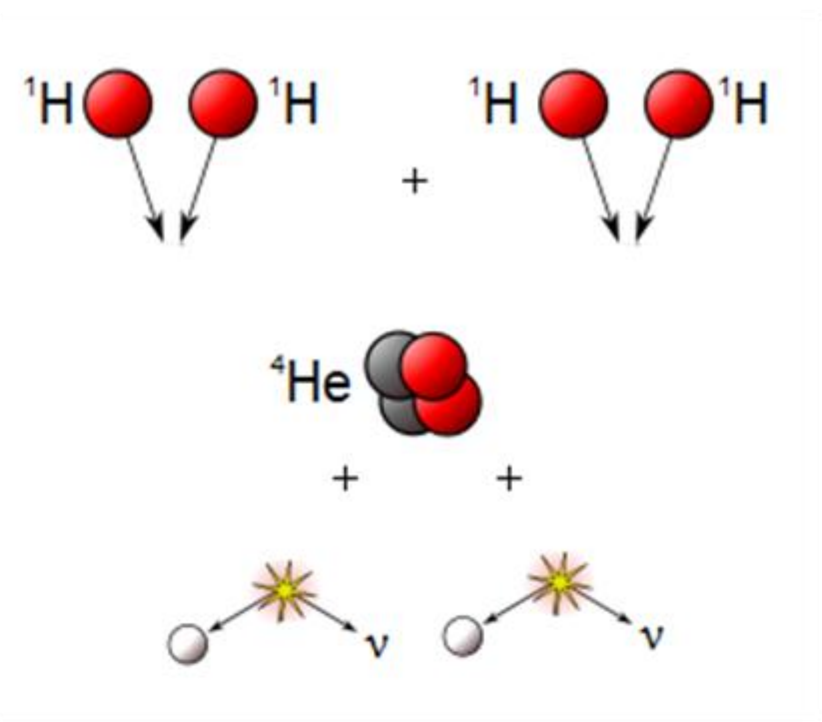
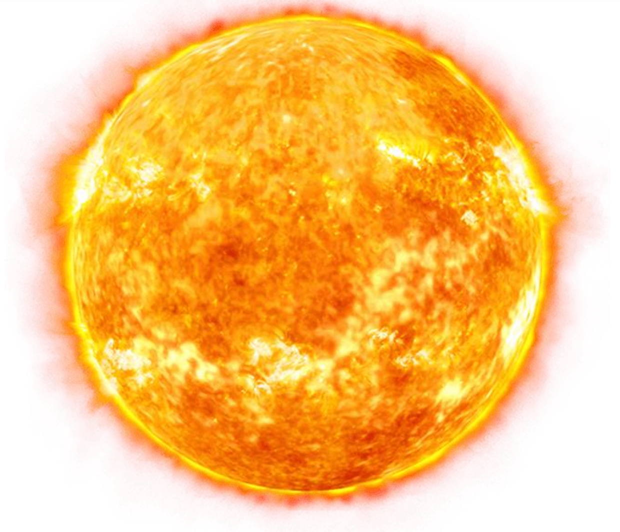
Why Solar Neutrinos

- Probes of stellar fusion (pp chain, CNO cycle)
- Precision test of neutrino oscillations
- Constraints on solar metallicity
- Complementarity
  - astrophysics & particle physics

Solar Neutrinos

pp-chain



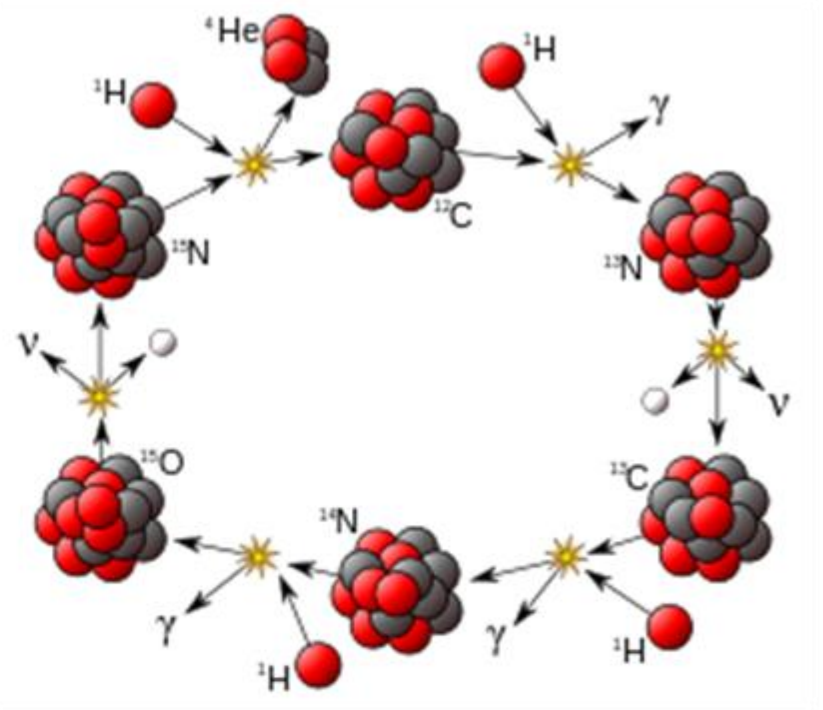


Density ~146 g/cm³
Temp. ~15.5 mln K

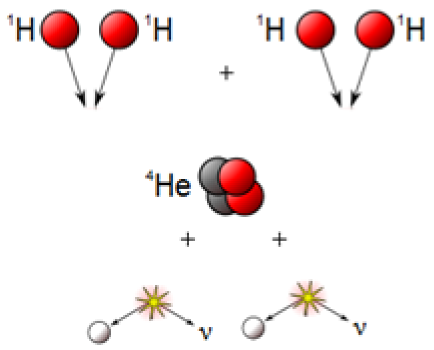
After only 8mins.
Solar-ν reach Earth

Energy production in the Sun:
pp chain→ 99% of energy in Sun
CNO cycle→ minor contribution (<1%)

CNO-cycle



Solar Neutrinos



Continuous

Monochromatic

pp

$p + p \rightarrow {}^2H + e^+ + \nu_e$

$p + e^- + p \rightarrow {}^2H + \nu_e$

pep

99.8% 0.02%

$^2H + p \rightarrow {}^3He + \gamma$

83.3% 16.7% 10^{-5}%

$^3He + {}^3He \rightarrow {}^4He + 2p$

$^3He + p \rightarrow {}^4He + e^+ + \nu_e$

hep

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.9% 0.10%

7Be

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

$^7Li + p \rightarrow {}^4He + {}^4He$

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow 2\,{}^4He + e^+ + \nu_e$

8B

Solar Neutrinos

Continuous
Monochromatic

Dominant

^{13}N

^{15}O

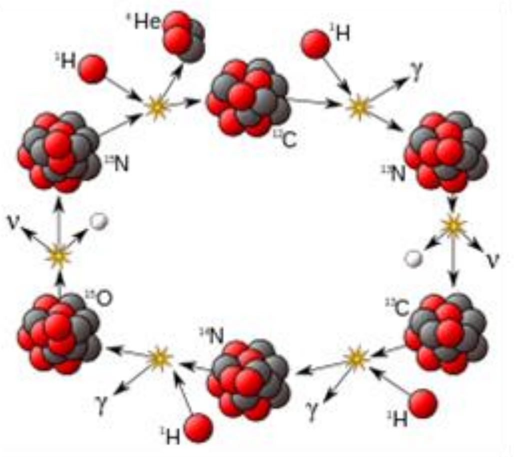
$$^{12}C + p \rightarrow {}^{13}N + \gamma \qquad \longrightarrow \qquad {}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$$

$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He \qquad\qquad {}^{13}C + p \rightarrow {}^{14}N + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e \qquad \longleftarrow \qquad {}^{14}N + p \rightarrow {}^{15}O + \gamma$$

$$^{15}N + p \rightarrow {}^{16}O + \gamma \qquad\qquad {}^{17}O + p \rightarrow {}^{14}N + {}^{4}He$$

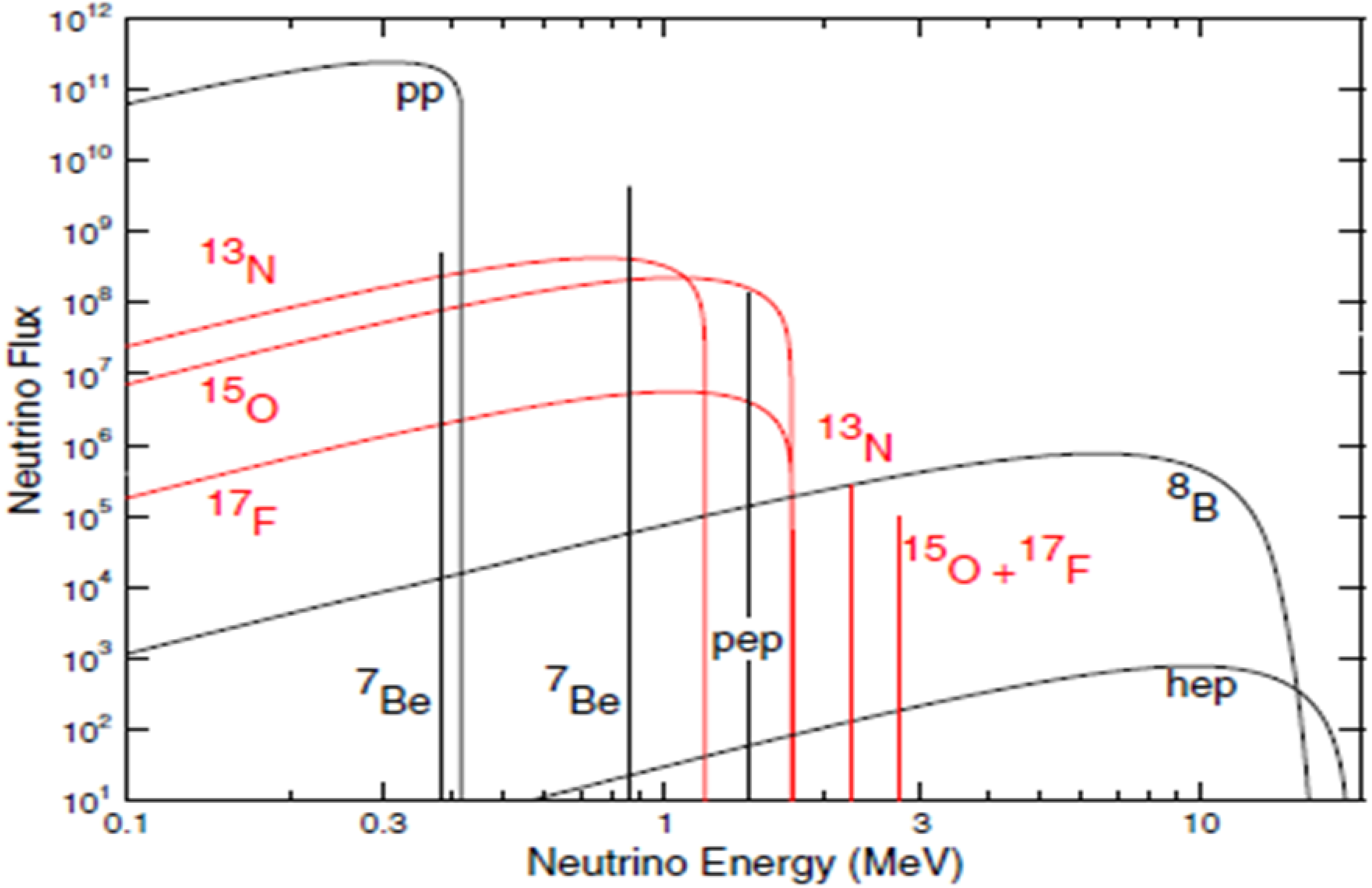
$$^{16}O + p \rightarrow {}^{17}F + \gamma \qquad \dashrightarrow \qquad {}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$$



Solar Neutrinos Now

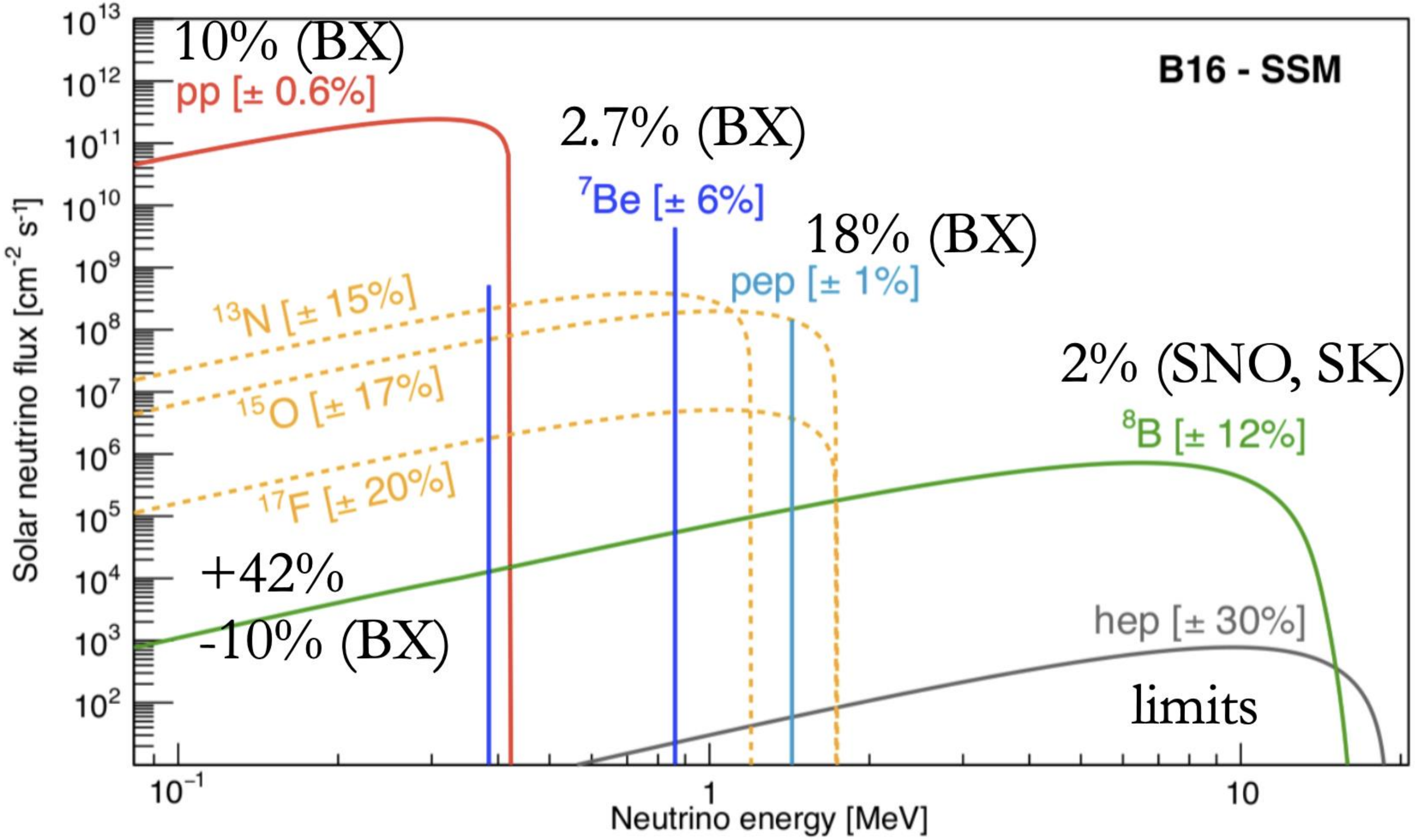
- Measured fluxes
  - pp (~10%), ^{7}Be (~2.7%), pep (~20%), ^{8}B (~3–5%), CNO (~30–35%).
  - hep (upper limits only, not yet directly observed.
- Oscillation parameters
  - $\Delta m^2_{21} \approx 7.4 \times 10^{-5}\ eV^2$,$\theta_{12} \approx 33°$(LMA-MSW solution).
  - Solar neutrino data alone prefer slightly lower Δm^2_{21} than reactor data, giving a ~2σ tension.
  - Day–night asymmetry measured with low significance; more precise measurements needed.
- Survival probability $P_{ee}(E)$
  - Measured in low-energy (pp, ^{7}Be) and high-energy (^{8}B) regimes.
  - Consistent with LMA-MSW predictions, but intermediate upturn region (2–5 MeV) remains poorly constrained.

Solar ν Spectrum



S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

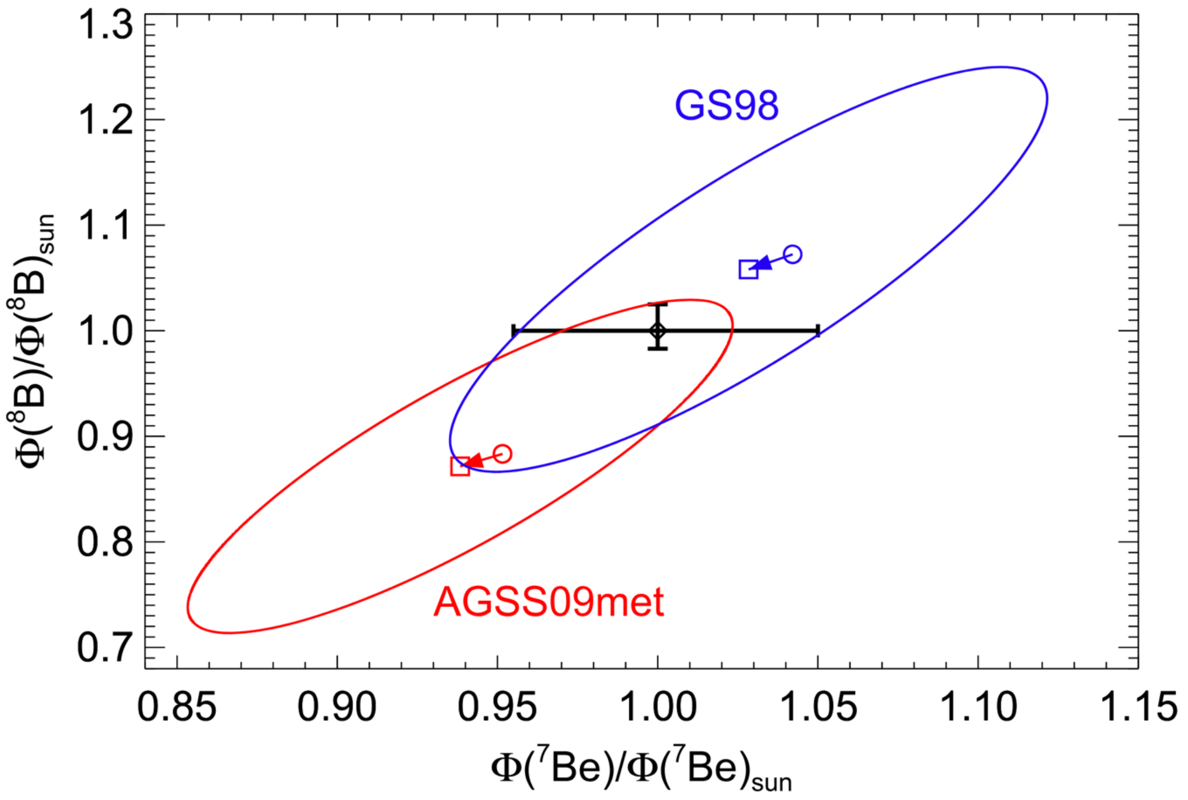
Solar ν Spectrum



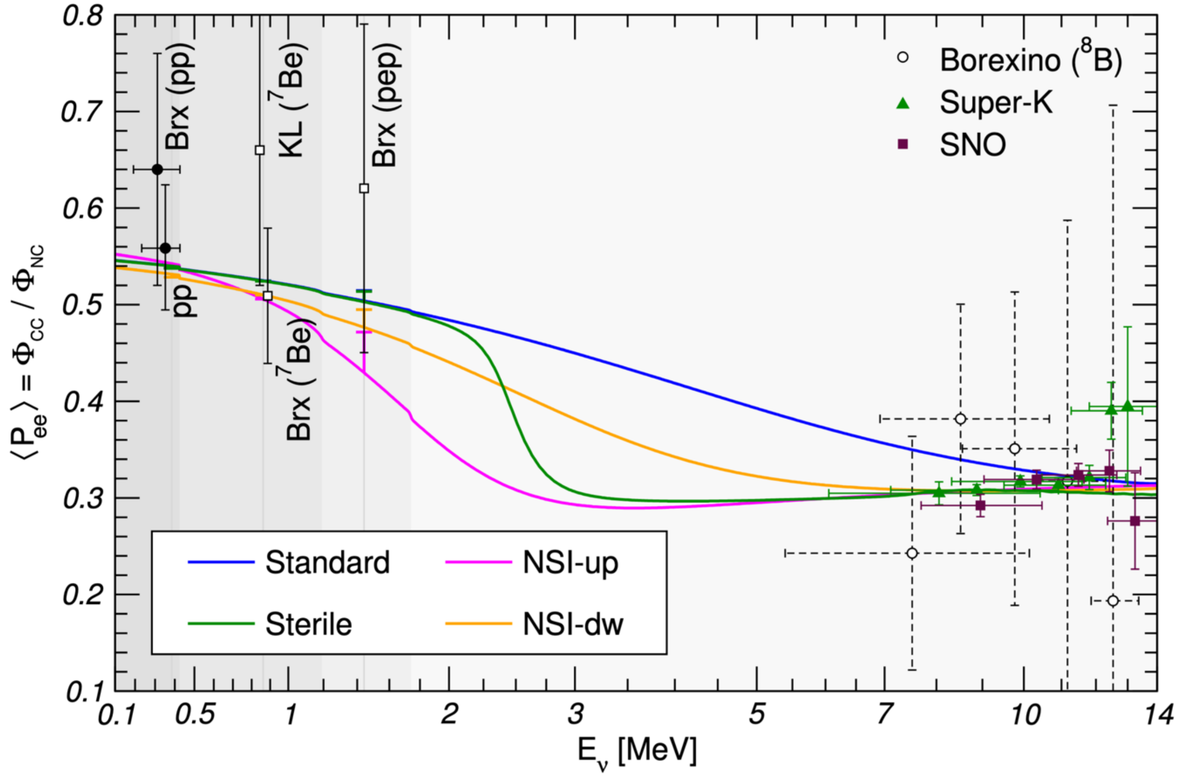
S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)

Solar Neutrinos

- Metallicity and survival probability



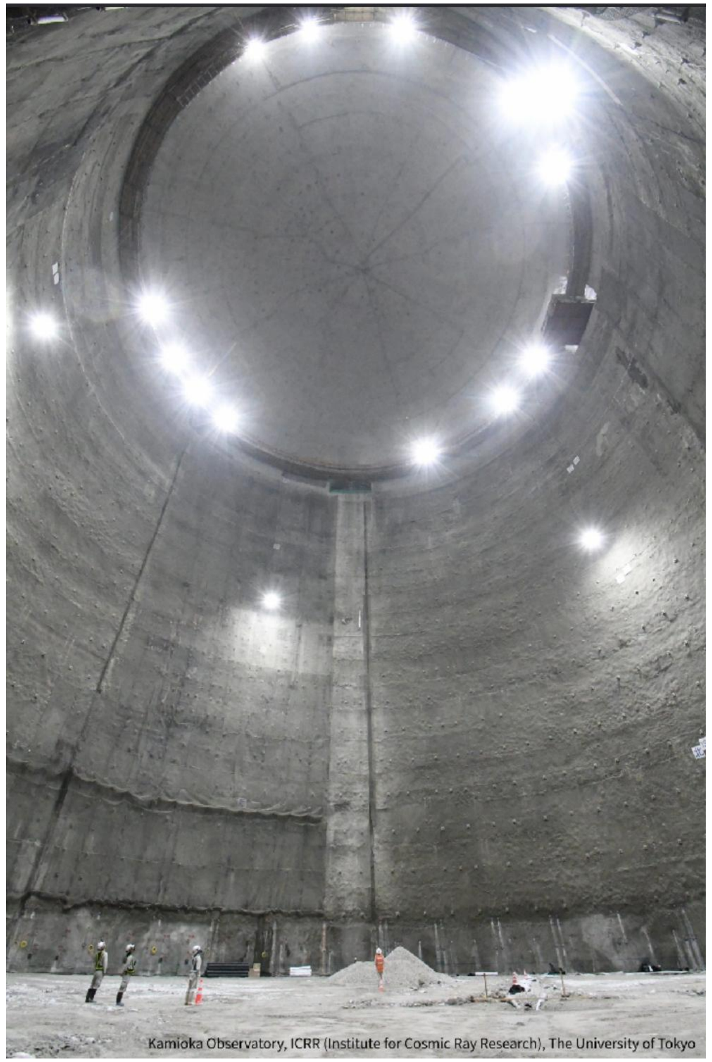
N. Vynioles et al., ApJ 835 202 (2017)



M. Maltoni et al., Eur. Phys. J. A 52 (2016) 87

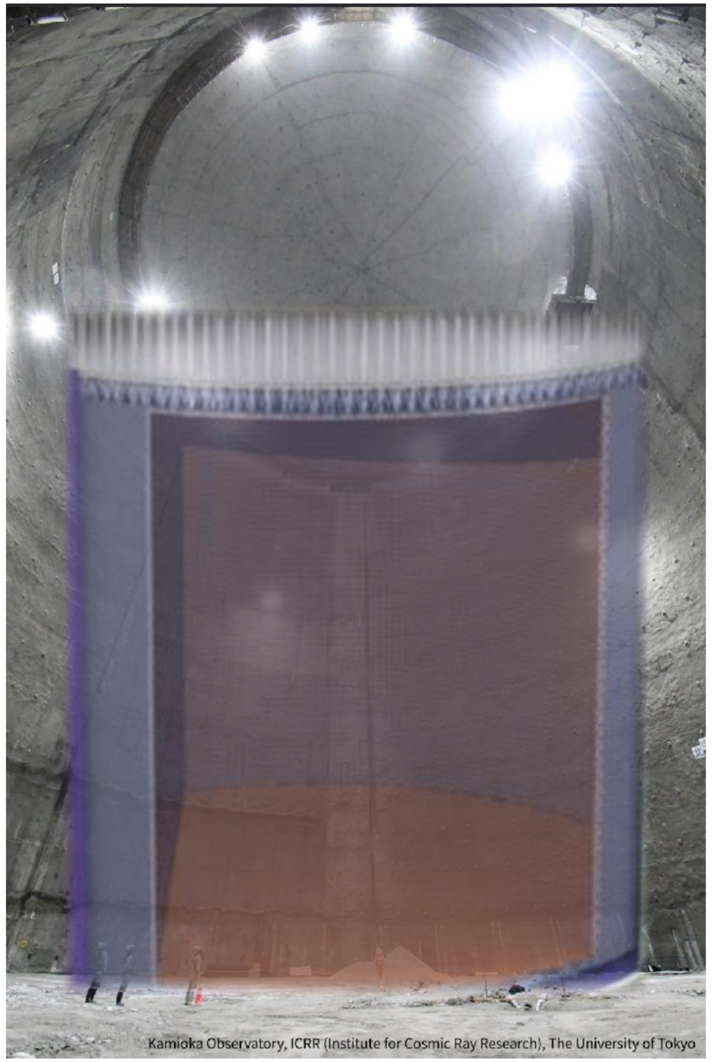
Feasible Future

- Hyper-K
  - ~258 kton of UPW 12× Super-Kamiokande's mass.
  - Elastic scattering of solar ν_e (ν_μ/ν_τ with reduced cross section) on electrons in water.
  - Sensitive to solar neutrinos with E$\nu \gtrsim 5$ MeV (so primarily the ^{8}B and potentially hep components).



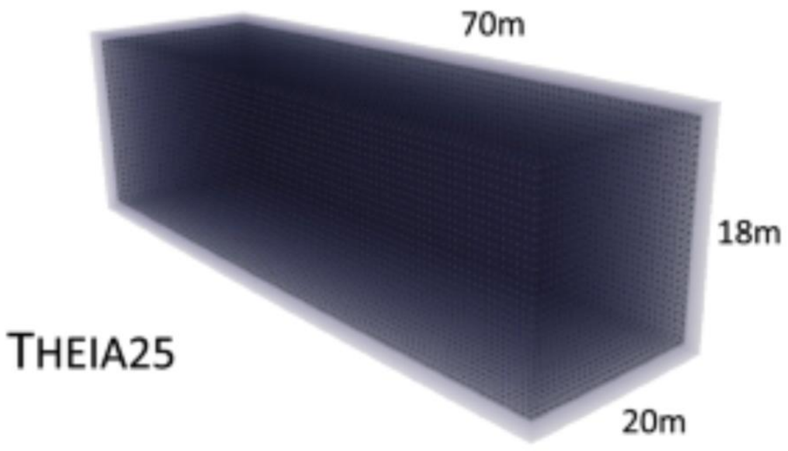
Feasible Future

- Hyper-K
  - Expected event rate: ~60–70 per day per 22.5 kt in Super-K → scaled to HK, ~500 events/day.
    - That's ~2×10^5 solar neutrino events per year!
    - This gives a percent-level precision on the ^{8}B flux (currently ~3–4%).
  - Day–night asymmetry (MSW matter effect in the Earth):
    - HK can measure day–night differences with ~0.5% statistical precision.
    - Improves sensitivity to Δm^2_{21} and tests the LMA-MSW solution.
    - hep neutrinos (rare, ~10^{-3} of ^{8}B flux) but perhaps credible for evidence – 2000 hep ES events per year (bf cuts & eff).
  - HK's high-stat ^{8}B and day-night data could decisively test the Δm^2_{21} tension.



Feasible Future

- THEIA
  - Large-scale water-based liquid scintillator (WbLS) detector (30 kton target), combining water Cherenkov and scintillation detection.
  - Simultaneous low energy threshold and directional sensitivity.
  - Energy threshold: down to ~1–2 MeV, enabling detection of low-energy solar neutrinos (pp, ^{7}Be, pep, CNO).



Feasible Future

- THEIA (WbLS)
  - CNO neutrinos: flux with <12% uncertainty; Transformative for solar metallicity problem → distinguishing high-metallicity vs low-metallicity Standard Solar Models.

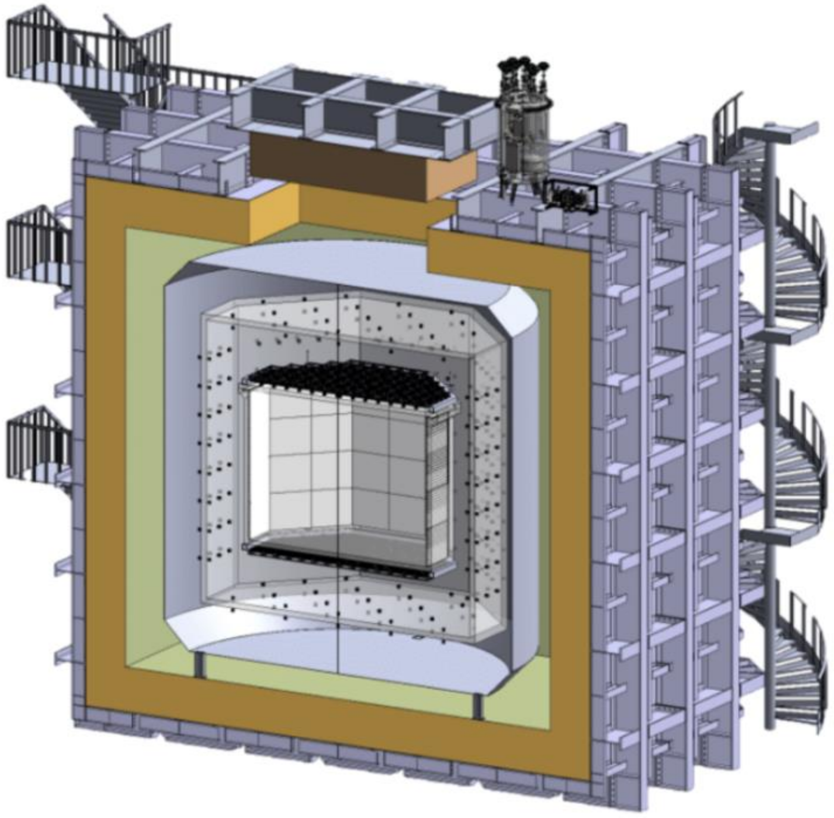
  - ^{8}B neutrinos: excellent statistics for ^{8}B spectrum → precise measurement of $P_{ee}(E)$ in the MSW transition region (~2–10 MeV).

  - Low-energy neutrinos
    - pp neutrinos: Could decisively test solar luminosity constraints and the solar fusion rate.
    - pep neutrinos: pep flux to ~1–2%; Critical to test neutrino oscillations in vacuum–MSW transition region.

THEIA talk by Logan Lebanowski: Friday, 2:00PM.

Feasible Future

- LAr (DarkSide-20k and ARGO)
  - Target: ~20 tonnes of ultra-pure liquid argon (LAr).
  - Primary goal: WIMP dark matter detection via nuclear recoils.
  - Secondary goal: Low-background electron recoil physics → solar neutrino detection.
  - Energy threshold: ~1 keV (for electron recoils), but solar neutrino physics is dominated by events in the MeV range.



The DarkSide-20k cryostat containing the veto system and the argon TPC.

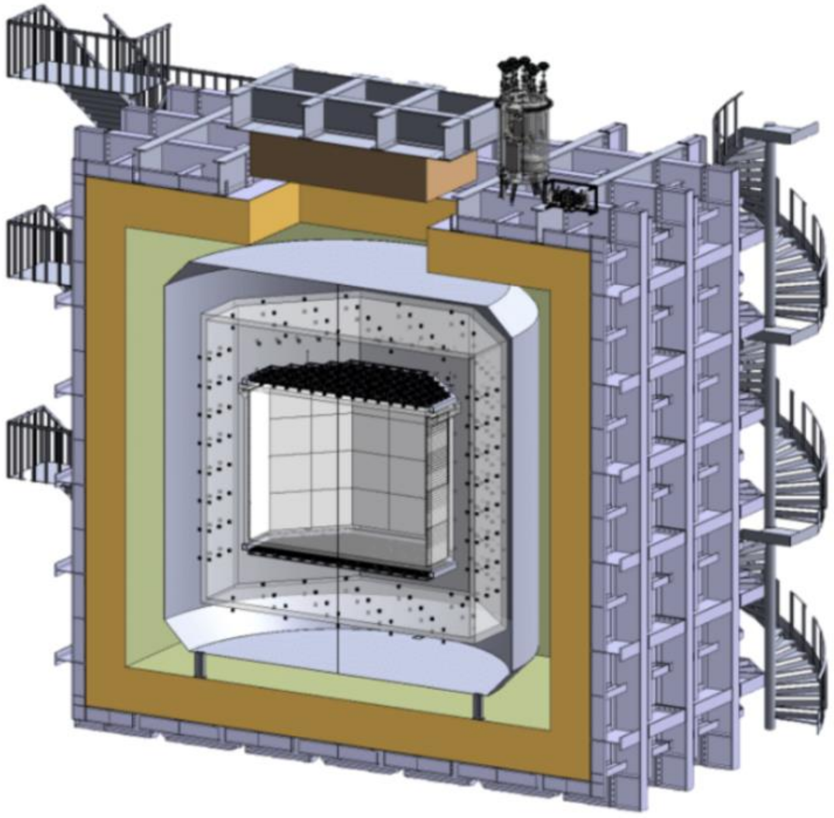
Feasible Future

- LAr (DarkSide-20k and ARGO)
  - Large ES cross-section for high energies solar neutrinos.
  - Low intrinsic background for these energies.
  - Spectral reconstruction of recoils above ~1 MeV.

  - ^{8}B neutrinos:
  - Predicted event rate: ~5–10 events per day in 20 tonnes.
  - Over a few years: thousands of events → percent-level measurement of ^{8}B flux.

  - hep neutrinos (rare, >10 MeV):
  - With large exposure, DarkSide-20k could see hints, complementing Hyper-Kamiokande and other detectors.

  - CNO neutrinos:
  - Rates low and backgrounds challenging.
  - Larger argon detectors (ARGO scale, 300 tonnes) would improve sensitivity.



The DarkSide-20k cryostat containing the veto system and the argon TPC.

ARGO talk by Asish Moharana: Friday, 9:00AM.

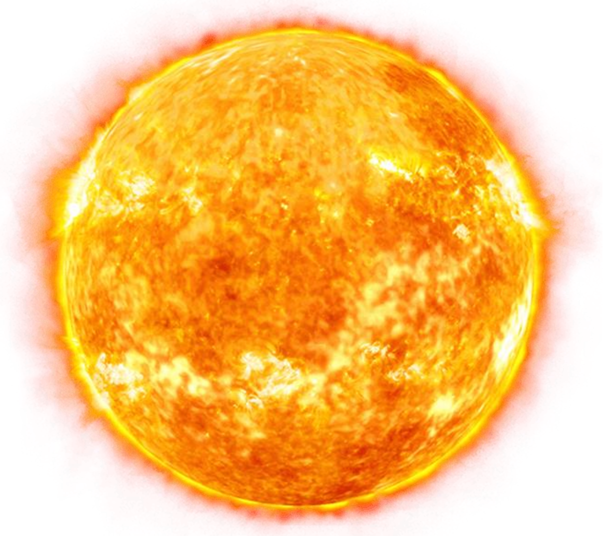
Feasible Future

- LAr vs LXe

	LXe	LAr
Low-energy threshold	lower (~1 keV achievable)	somewhat higher (~few keV)
pp neutrinos	excellent	poor sensitivity
^{7}Be neutrinos	excellent	poor
pep neutrinos	possible	possible
^{8}B neutrinos	measurable, but statistics limited	excellent
CNO neutrinos	possible with isotope (d)enrichment	possible
hep neutrinos	challenging	challenging
Energy resolution	~1–2% at MeV scale	~3–5% at MeV scale

- Xe is expensive → hundreds of $millions for large detectors.
- Ar is cheap and abundant → easier to scale to multi-ktonnes.

Conclusions



- Perhaps in the next 15 years?
- Solar spectroscopy:
  - ~1% measurements of pp, ^{7}Be and pep neutrino flux and high-precision ^{8}B spectrum.
- Solar metallicity problem resolution
  - Direct detection of CNO neutrinos with <10% uncertainty.
- Testing neutrino oscillation theory in detail
  - Map $P_{ee}(E)$ across vacuum–MSW transition region with high precision → test LMA predictions and search for deviations.
  - Potential resolution of Δm^2_{21} tension between solar and reactor data.
  - Day/night asymmetry and matter effect tests at the percent level.
- Astrophysics and solar physics
  - Direct measurement of solar luminosity via neutrinos → test stellar energy generation in real time.
  - Solar composition and fusion cycle diagnostics from combined pp, pep, ^{7}Be, ^{8}B, CNO spectra.

Backup