Search for solar antineutrinos

PhySun III
Gran Sasso, 9 Oct 12

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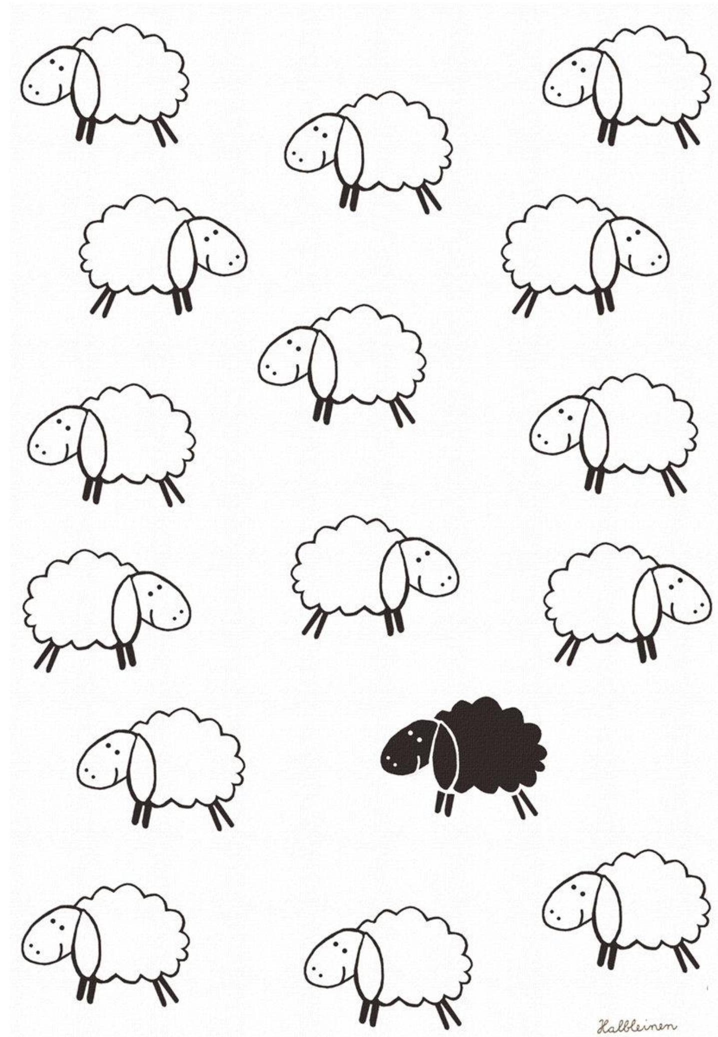
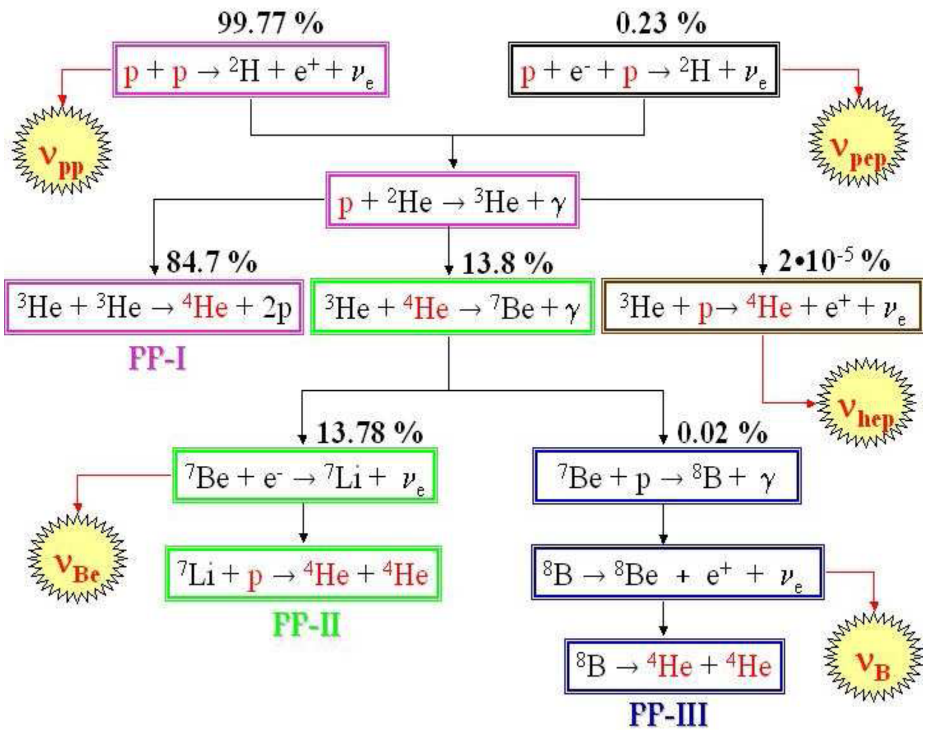
Searching antineutrinos from the Sun

- Motivation
- Signals and Backgrounds
- Experimental limits
  – Super-Kamiokande I
  – SNO
  – Borexino
  – KamLAND
- Implications
- Outlook: Future experiments

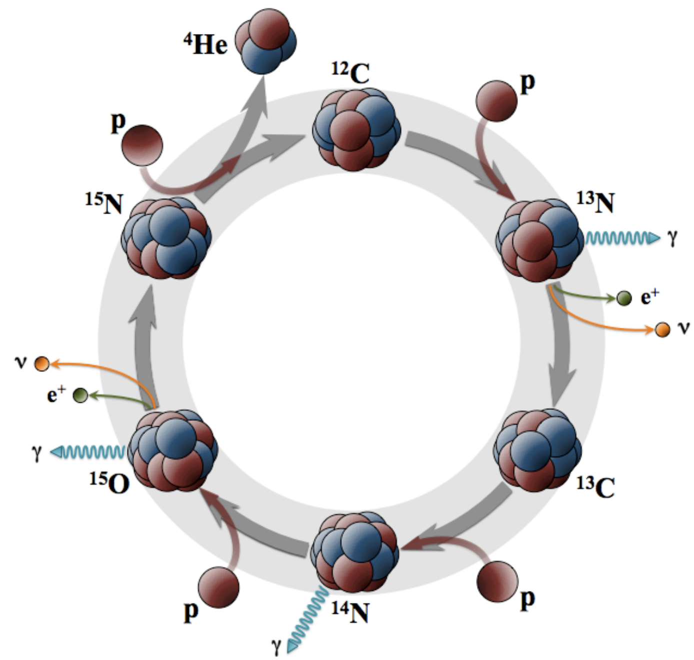


Motivation

pp chain



CNO cycle



Fusion produces isotopes featuring proton excesses.

→ Why should there be antineutrinos from the Sun?

Sources of solar antineutrinos

1) Solar neutrino-antineutrino conversion

- originally proposed by Pontecorvo as $\nu\bar{\nu}$ oscillations
  → suppressed by solar matter effects

- more recently: **Spin-Flavor Precession** (SFP)

e.g. Schechter, Valle (1981)
Akhmedov, Pulido (2002)

$\nu_e \rightarrow \bar{\nu}_\mu$ followed by $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Requirements :
  – Majorana neutrino, with magnetic transition moment
  – strong mangetic field (in solar interior) inducing the SFP
  – vacuum mixing

- SFP did not prove to be the solution of the solar neutrino problem
  → but maybe subdominant process?

Sources of solar antineutrinos

2) Non-radiative decay of solar neutrinos

e.g. Beacom, Bell (2002)

- Inside the sun: $\nu_e \approx \nu_2 \rightarrow \bar{\nu}_1 + \chi$
- Requirement:
  – neutrino couples to a light/massless particle,
  e.g. the Majoron

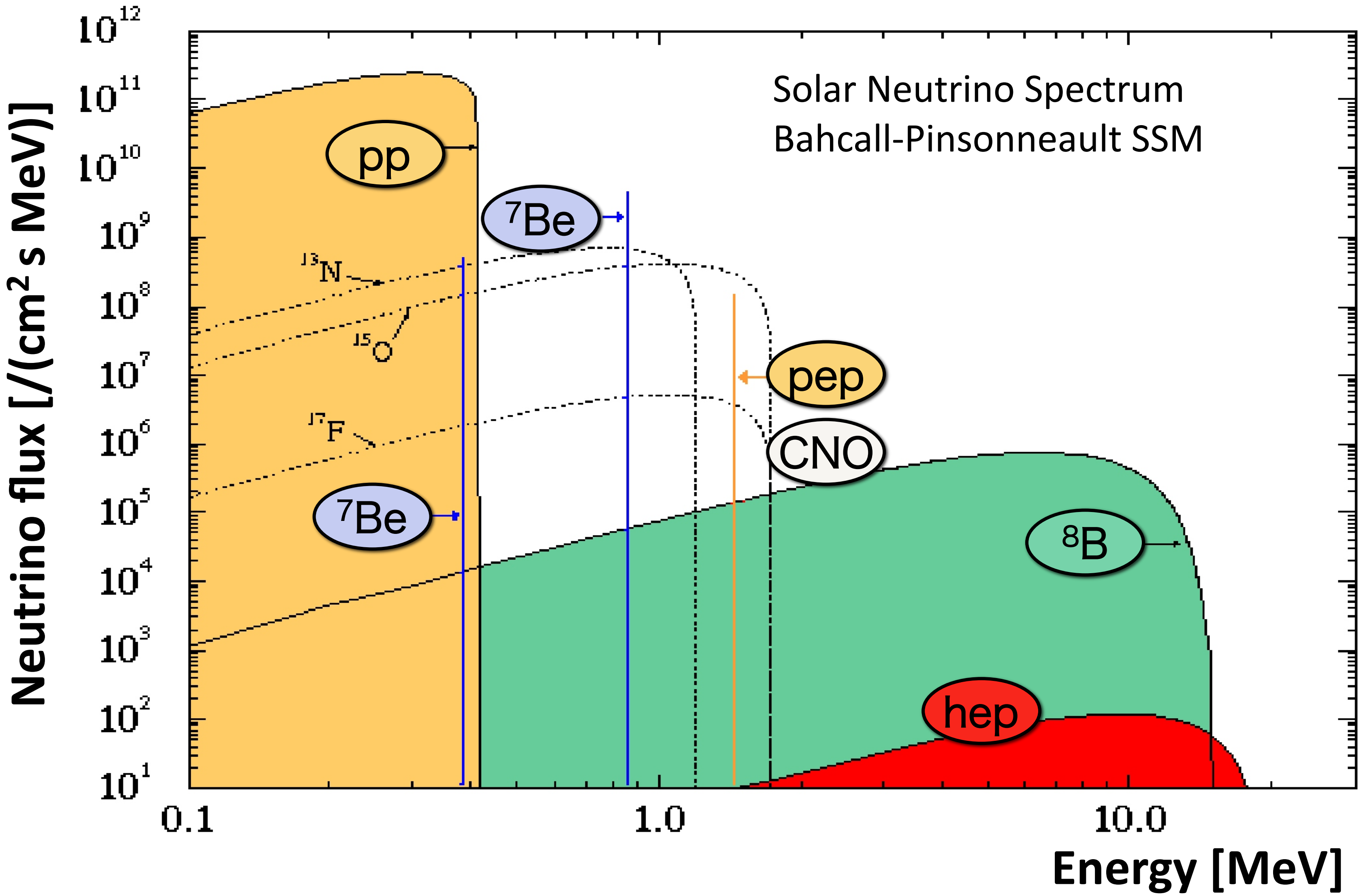
3) Annihilation/decay of non-standard particles

e.g. light dark matter

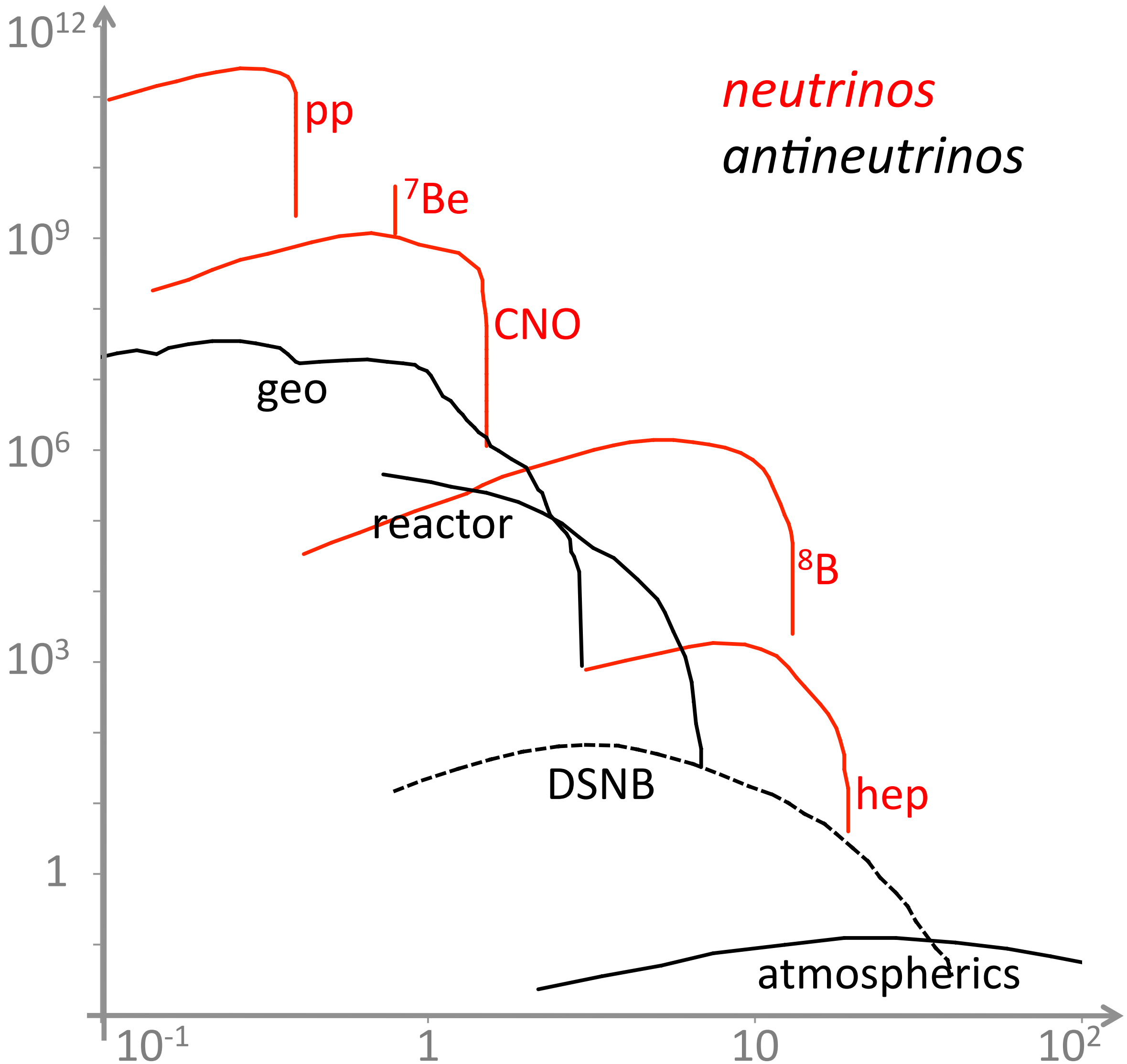
Note:

- $\bar{\nu}$'s from SFP and n.r. decay limited to energies of solar spectrum
- Wide range of possible energies for annihilation $\bar{\nu}$'s

Solar neutrino spectrum



Signal and Background



1) Irreducible backgrounds

→ other $\bar{\nu}_e$ sources

- geoneutrinos
- reactor neutrinos
- diffuse SN neutrinos
- atmospheric neutrinos

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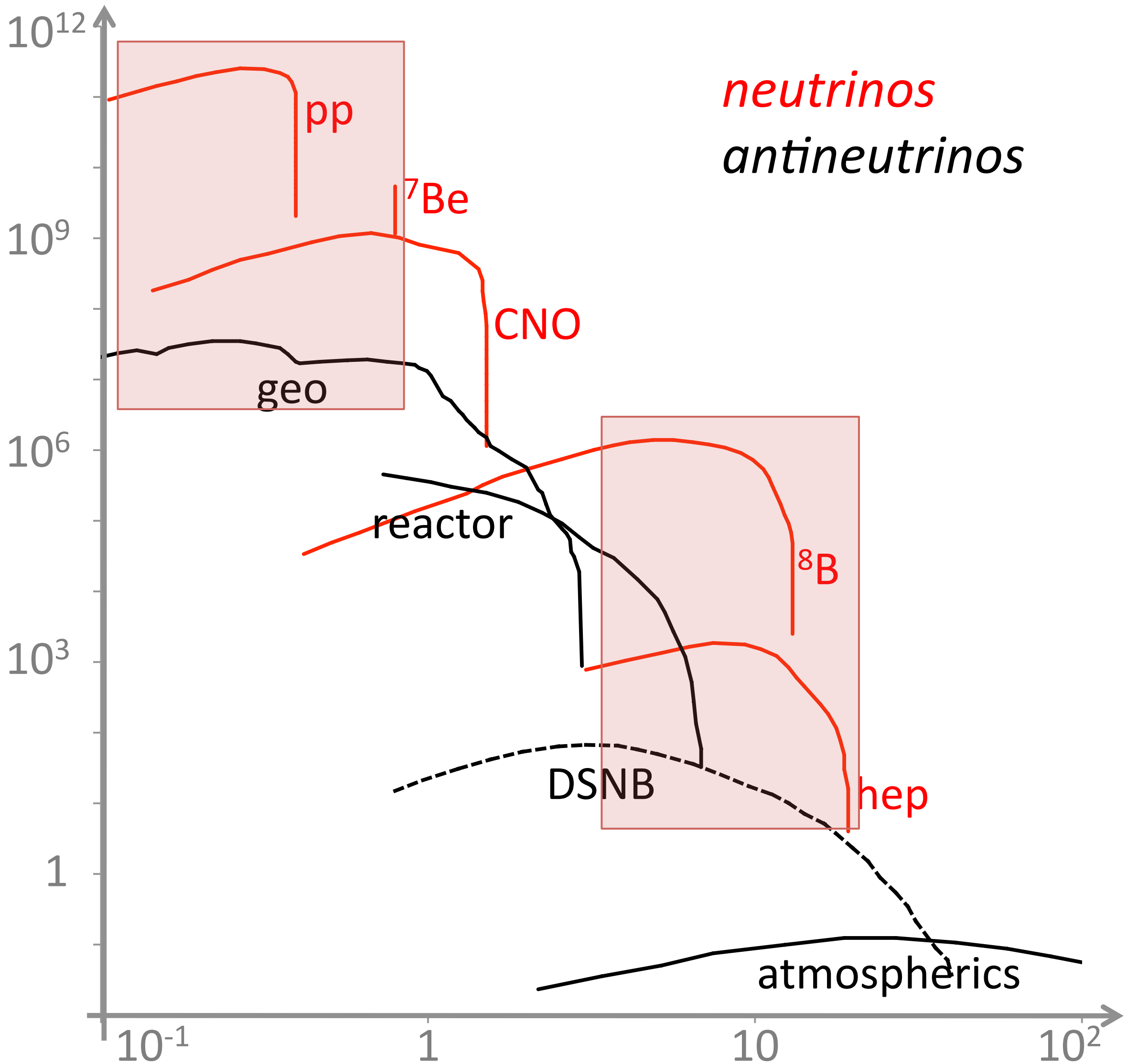

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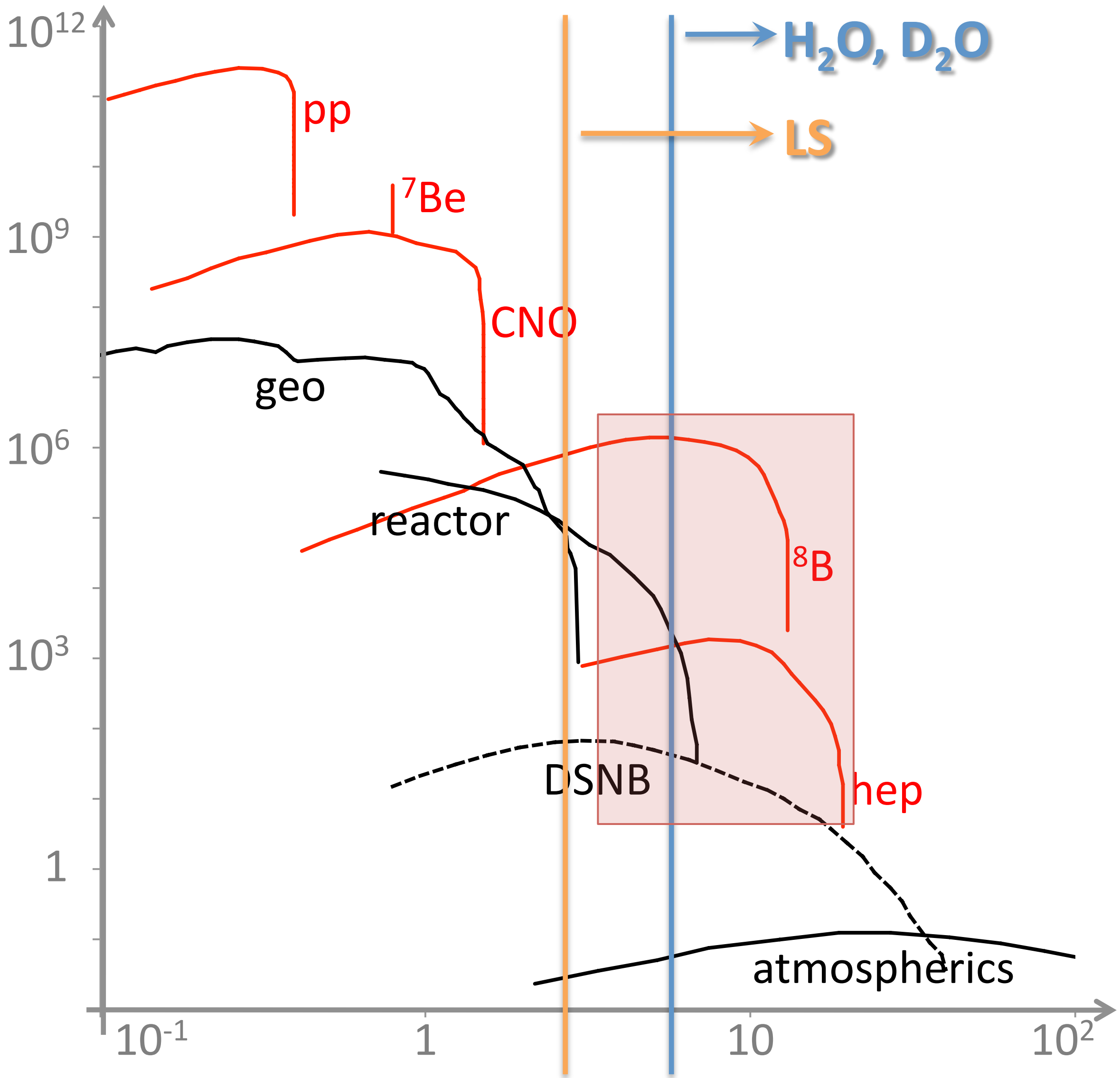
- atmospheric neutrinos

→ only two regions where solar/BG ratio > $10^{3\text{-}4}$

Signal and Background



1) Irreducible backgrounds
→ other $\overline{\nu}_e$ sources

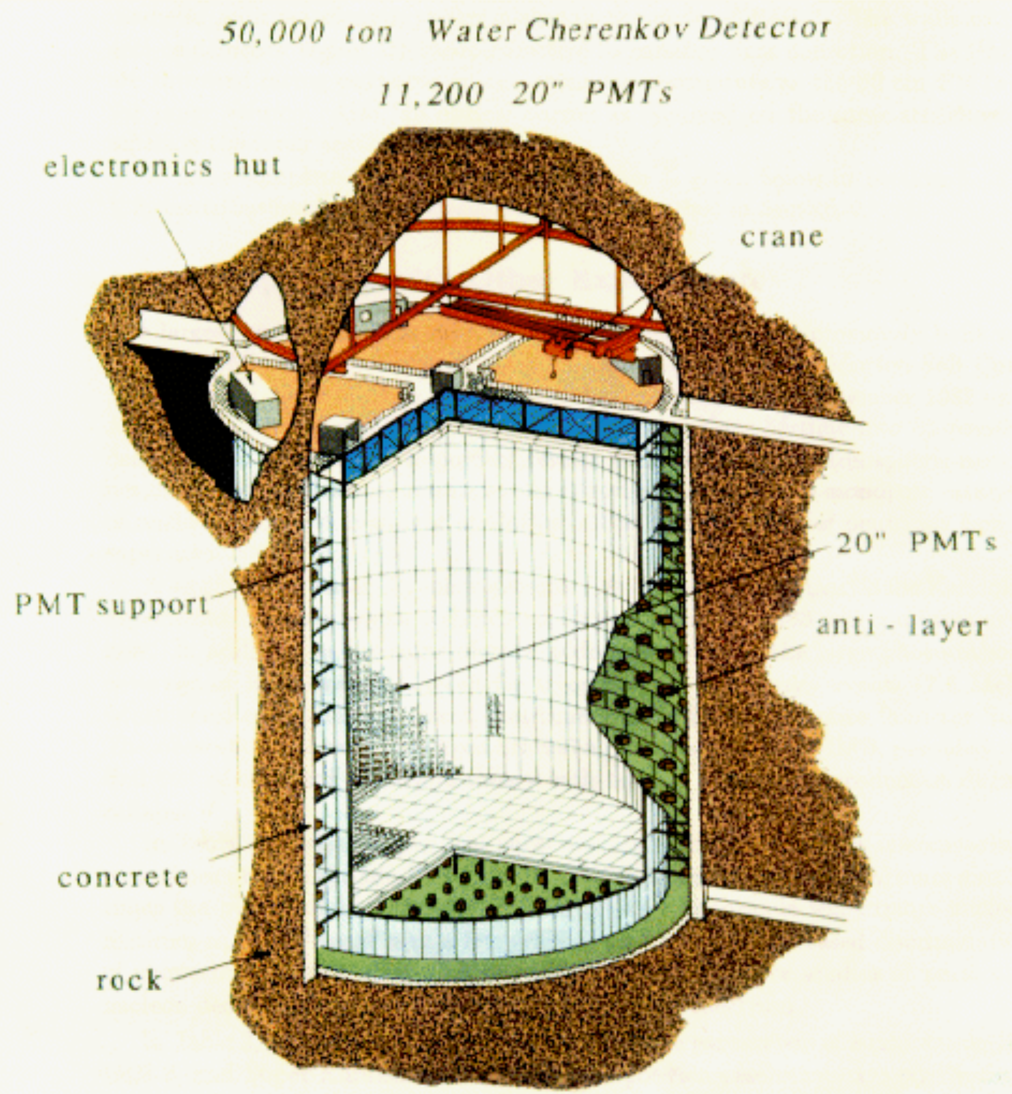
- geoneutrinos
- reactor neutrinos
- DSNB
- atmospheric neutrinos

→ only two regions where solar/BG ratio > 10^{3-4}

2) Detection threshold for $\overline{\nu}_e$

- Water detectors: ~5 MeV
- Liquid scintillator: 2 MeV

Super-Kamiokande I – $\bar{\nu}_e$ detection



Target mass: 22.5 kt of H_2O
Exposure: 1496 days

Detection channel

- Inverse beta decay (IBD):

  $\bar{\nu}_e + p \rightarrow e^+ + n - 1.8$ MeV

- only e^+ are detected

  → no coincidence signature!

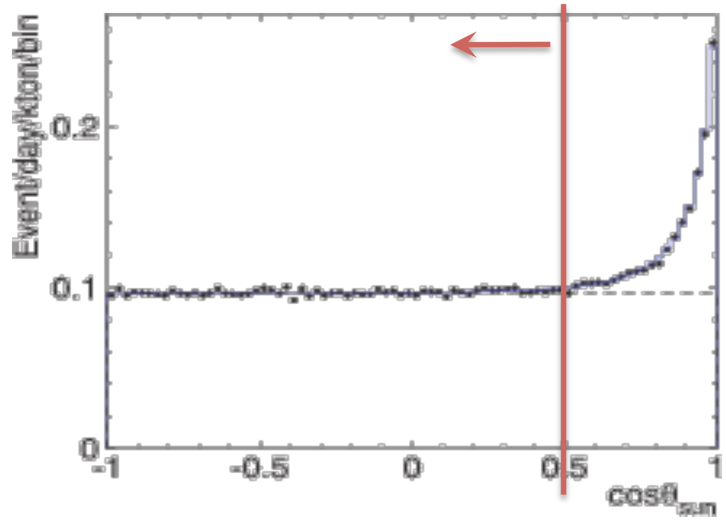
→ No intrinsic discrimination of single-event backgrounds!

Super-Kamiokande I – backgrounds

Dominant backgrounds

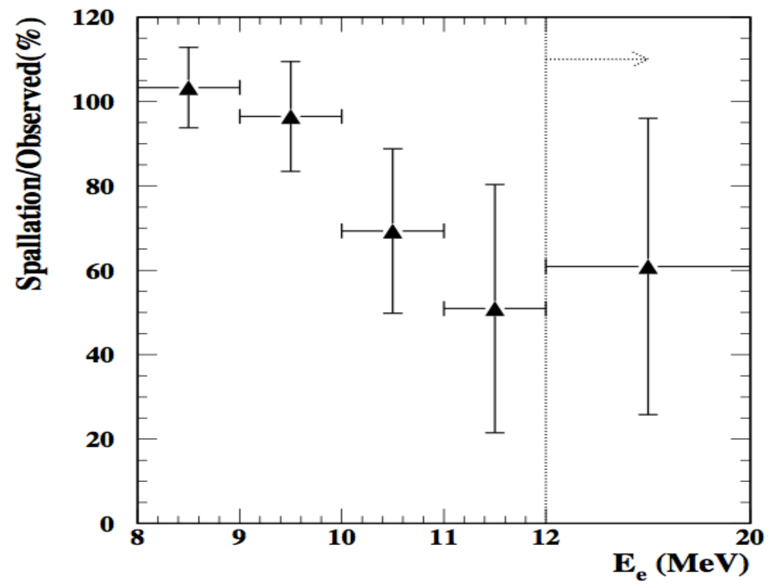
- electron-scattering of solar ν_e's
  - – angular correlation to sun
  - – quasi-flat distribution for IBD e^+

→ angular cut: $\cos\theta < 0.5$



- spallation products ($\mu \rightarrow {}^{16}O$)
  - – correlation to parent muons
  - – time and spatial cuts to remove short-lived and 90% of long-lived isotopes

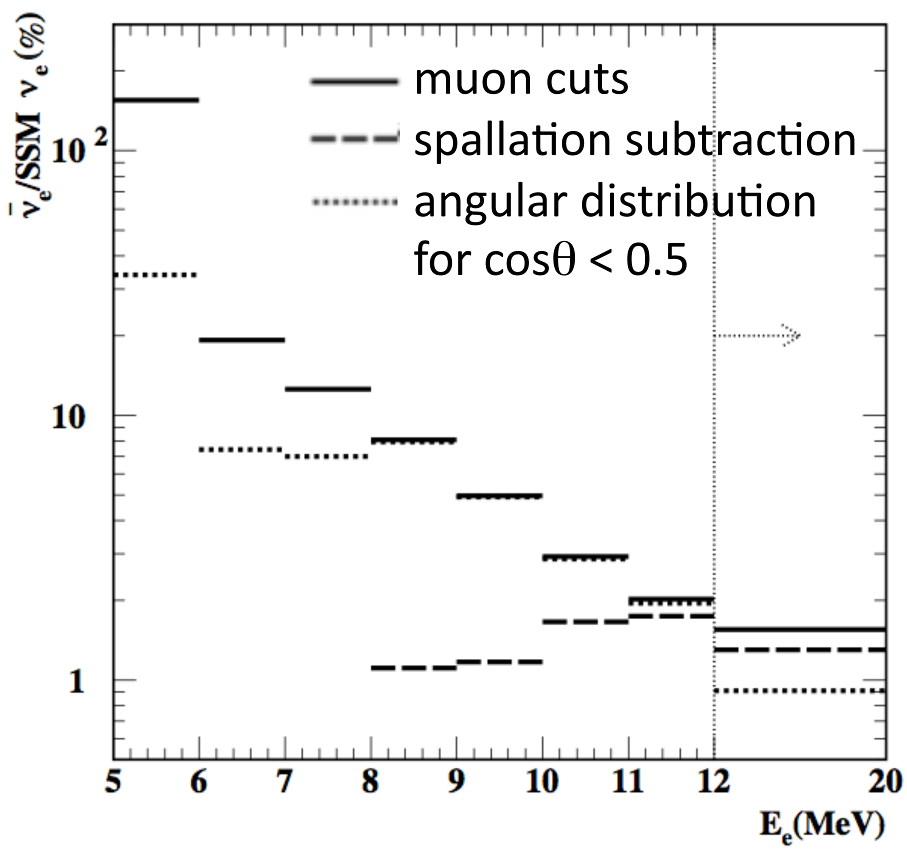
→ residual events compatible with remaining isotopes: (93±7)%



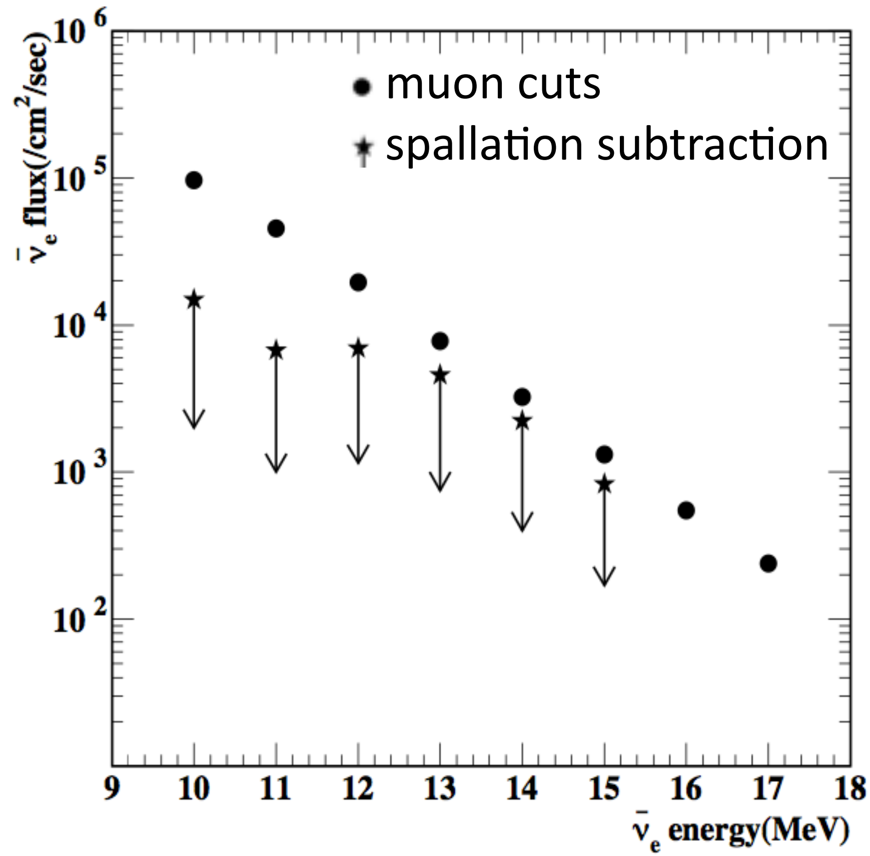
Super-Kamiokande I – results

Limit on ^8B conversion

assuming no spectral distortion



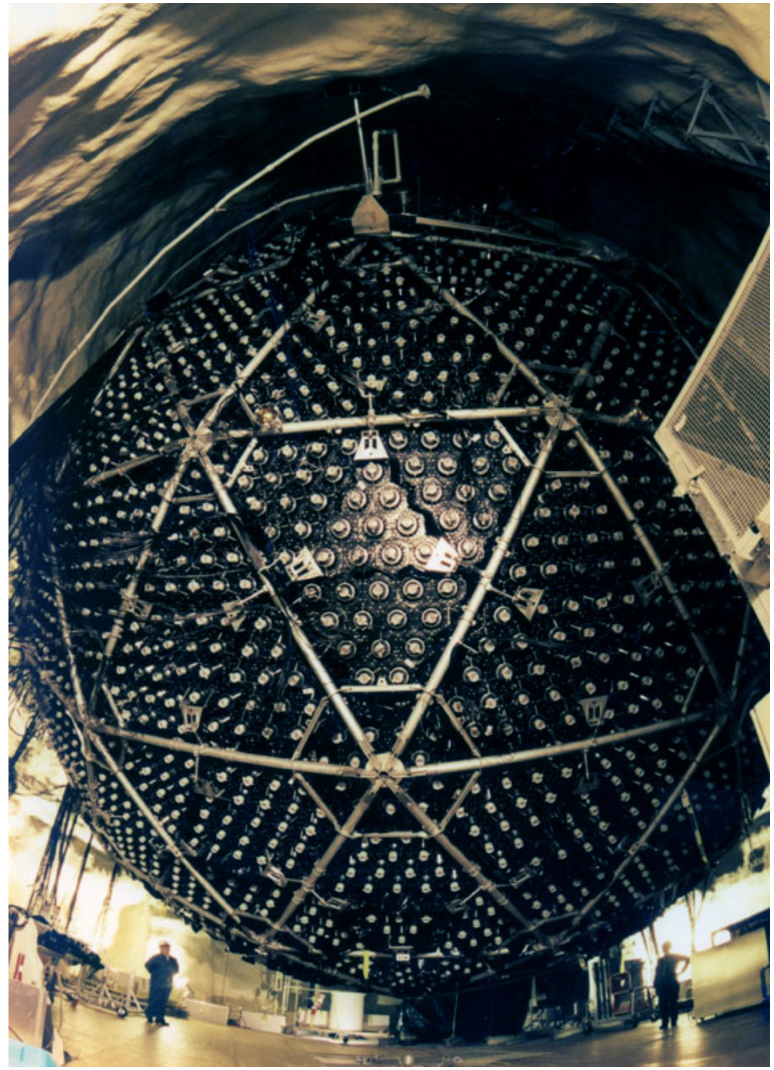
Monochromatic $\bar{\nu}_e$ fluxes



→ **from 8-20 MeV:** upper limit is 8×10^{-3} of the solar ν_e flux

SNO – $\bar{\nu}_e$ detection

Target mass: 1 kt of D_2O
Exposure: 306 days *after 0.5s μ-veto*



Detection channel

- $\overline{\text{CC}}$ reaction on deuterons:

  $\bar{\nu}_e + d \rightarrow e^+ + n + n - 4.03$ MeV

→ search for 3-fold coincidence!

But: Low detection efficiencies

- e^+ only detected for T > 4 MeV
- nD capture: $\gamma_{[6.25\ \text{MeV}]} \rightarrow \varepsilon = 14\%$

→ $\varepsilon(e^+,n,n) \approx \varepsilon(n,n) \approx 1\%$
$\varepsilon(e^+,n) \approx 10\%$

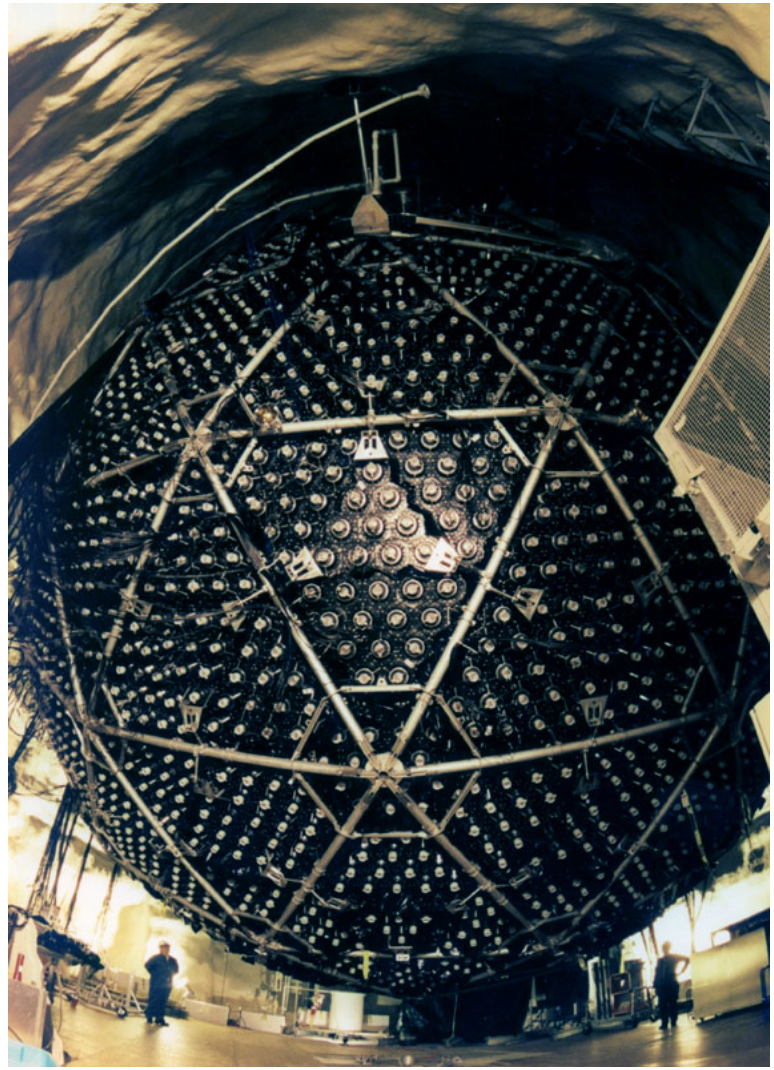
SNO – $\bar{\nu}_e$ backgrounds

Antineutrino backgrounds

▪ Atmospheric	0.07±0.01
▪ Reactor	0.019±0.002
▪ Diffuse supernovae	<0.005
▪ Geoneutrinos	0.0
→ Total	0.09±0.01

Other backgrounds

▪ Atmospheric neutrinos	1.5±0.5
▪ ^{238}U spontaneous fission	<0.79
▪ Accidental coincidences	0.13±0.06
▪ ...	
→ Total	$1.6^{+0.9}_{-0.5}$



SNO – results

Event rates (4-14.8 MeV)

Expected background: $1.7^{+0.9}_{-0.5}$

Observation: 1 double coincidence
1 triple coincidence

Limit on ^{8}B conversion

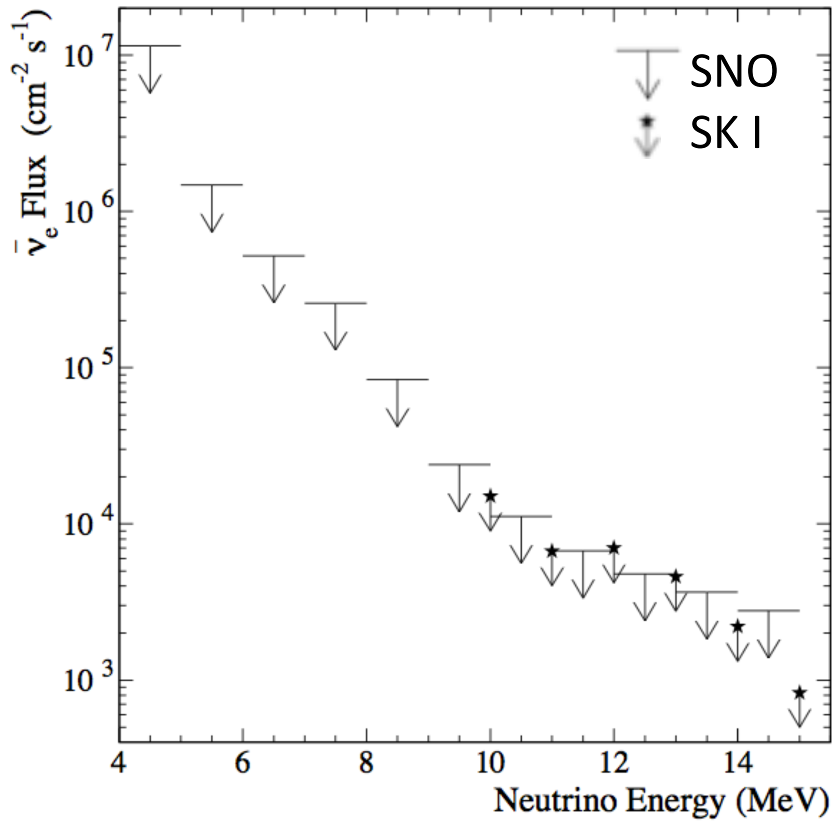
- Feldman-Cousins limit based on BG estimate and detected events

→ Flux limit (4–14.8 MeV)

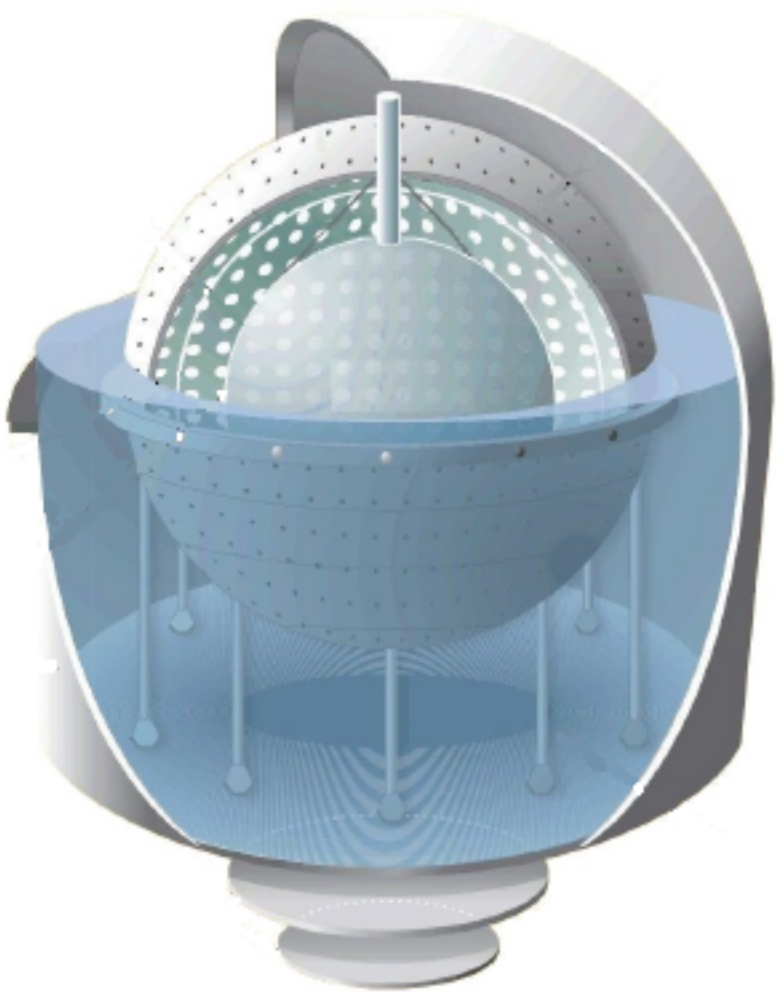
$\Phi < 3.4 \times 10^4$ cm^{-2}s^{-1}

8.1×10^{-3} of solar ^{8}B ν_e flux

Monochromatic $\bar{\nu}_e$ fluxes



BOREXINO – $\bar{\nu}_e$ detection



Target mass: 270t of LS

Exposure: > 2 years

Detection channel

- Inverse beta decay (IBD):

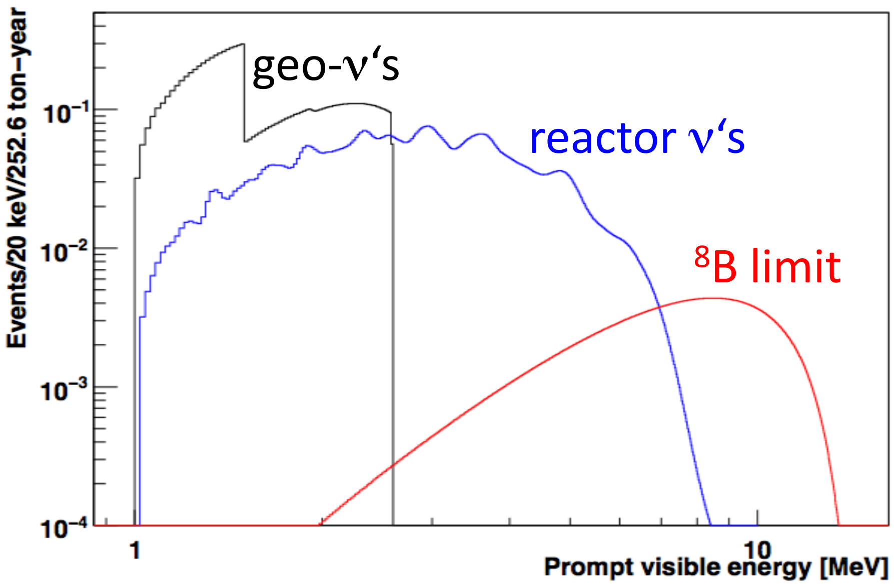
  $\bar{\nu}_e + p \rightarrow e^+ + n - 1.8\ \mathrm{MeV}$

- both e^+ and $\gamma_{[2.2\mathrm{MeV}]}$ from n capture on H are detected

→ fast (250μs) 2-fold coincidence signature for BG discrimination

→ high efficiency: (85±1)%

BOREXINO – backgrounds



Antineutrino backgrounds

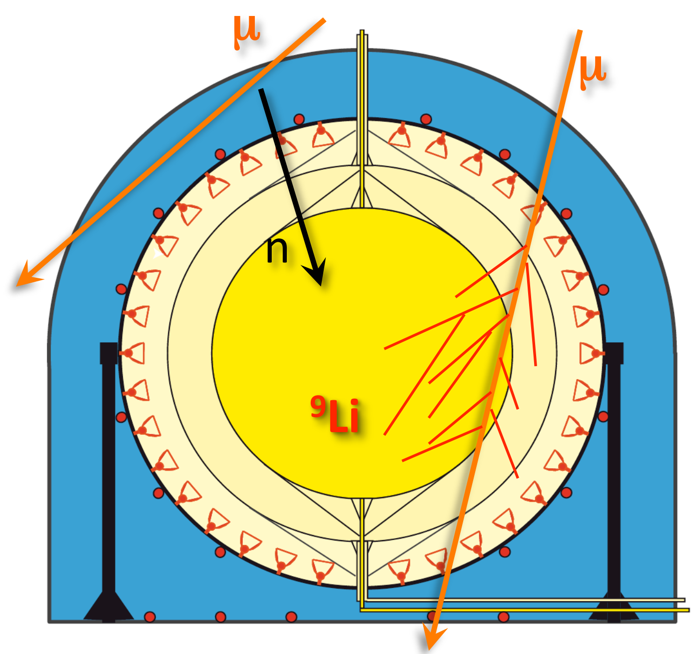
- reactors $4.3^{+1.7}_{-1.4}$ /(100t·yr)
- geo-ν's $3.9^{+1.6}_{-1.3}$

→ 21 IBD events below 7.8 MeV

Cosmic backgrounds

- μ-induced fast neutrons
- cosmogenic βn-emitters: ^{9}Li, ^{8}He

→ removed by long (2 sec) time veto following each muon



BOREXINO – results

No event observed above 7.3 MeV!

Limits on ^{8}B conversion

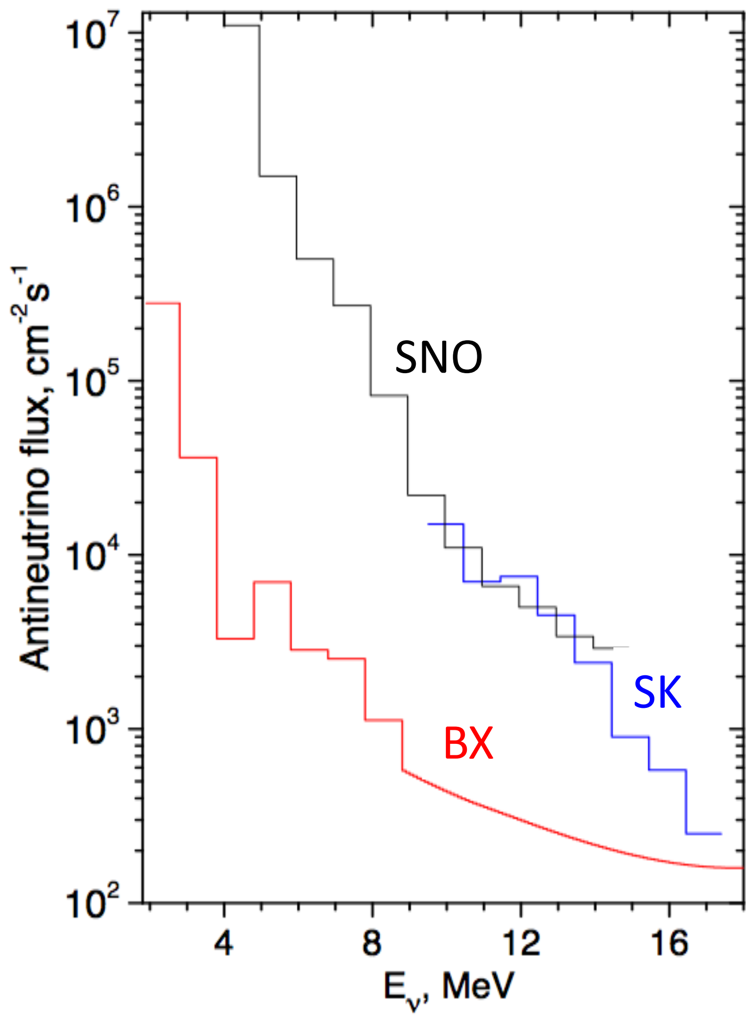
- $\bar{\nu}_e$ flux above 7.3 MeV:
  $\Phi_{E>7.3MeV} < 415\ cm^{-2}s^{-1}$ (90%C.L.)
- $\bar{\nu}_e$ flux for total range:
  $\Phi < 760\ cm^{-2}s^{-1}$ (90%C.L.)

→ conversion probability: $<1.3\times10^{-4}$

Limit on ^{7}Be conversion

- difference in spectral recoil shape of ν_ee- & $\bar{\nu}_e$e-scattering → $p_{\nu\rightarrow\bar{\nu}} < 0.35$

Monochromatic $\bar{\nu}_e$ fluxes



KamLAND – $\bar{\nu}_e$ detection

Target mass: 1kt of LS

Exposure: 4.53 kt·yrs

Detection channel

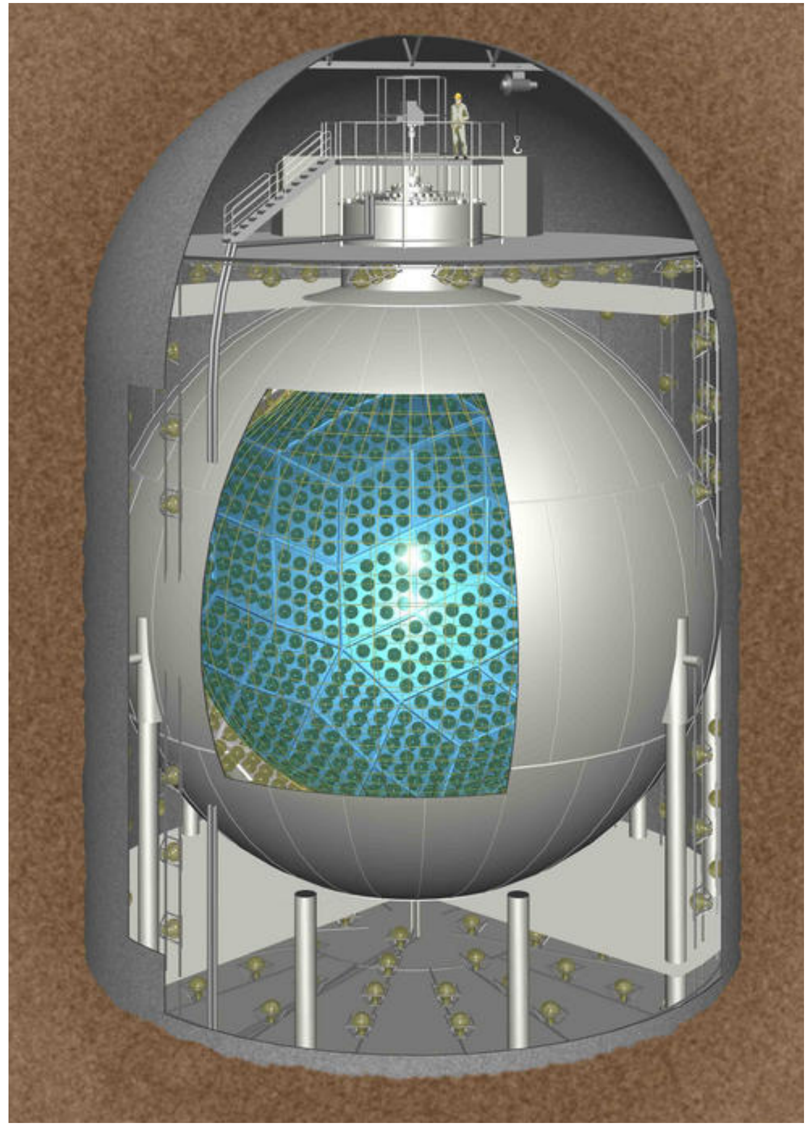
- Inverse beta decay (IBD):

  $\nu_e + p \rightarrow e^+ + n - 1.8$ MeV

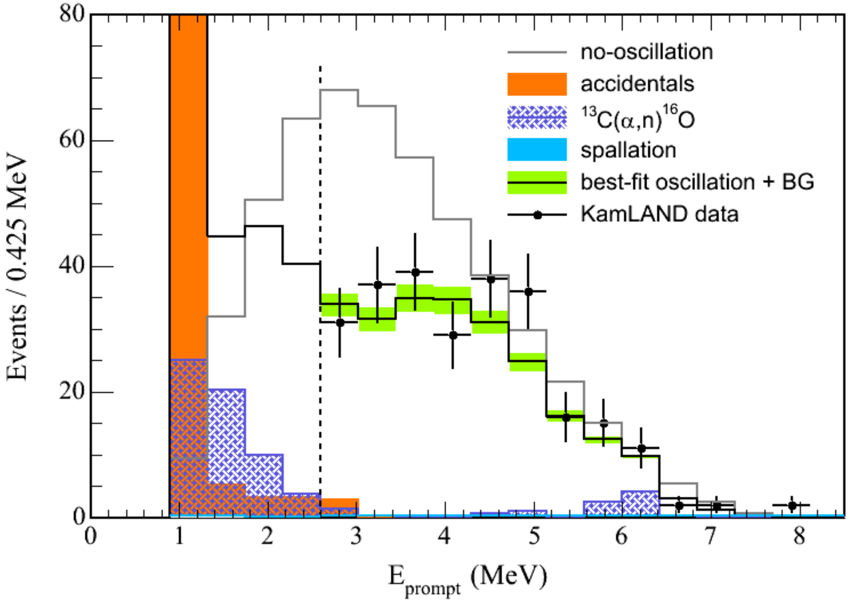
- both e^+ and $\gamma_{[2.2\mathrm{MeV}]}$ from n capture on H are detected

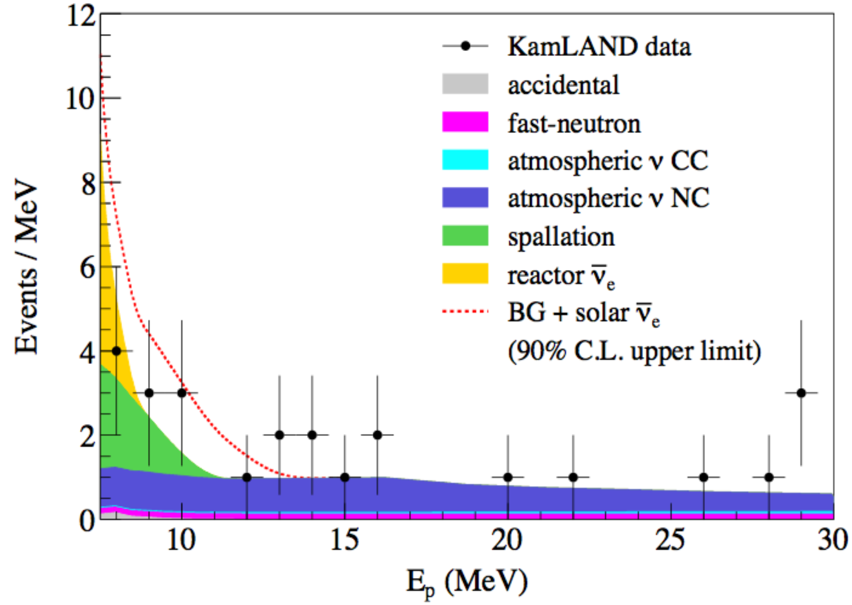
→ fast (209μs) 2-fold coincidence signature for BG discrimination

→ high efficiency: 92%



KamLAND – backgrounds





For E_ν < 8.3 MeV:

Reactor/geoneutrinos etc.

→ large backgrounds to solar $\bar{\nu}_e$ search

→ no $\bar{\nu}_e$ limit given

For E_ν > 8.3 MeV:

- fast neutrons: 3.2±3.2
- ^{9}Li: 4.0±0.3
- reactor ν's: 2.2±0.7

large muon rate compared to Bx no complete veto

→ expected BG: 9.4±3.3

AND: 16±5 atmospheric ν NC events!

KamLAND – results

Event rates (8.3 – 30 MeV)

Expected background: 26.9±5.7

Observed events: 25

Limit on ^{8}B conversion

$\bar{\nu}_e$ flux above threshold:

$\Phi_{E>8.3MeV} < 93\ cm^{-2}s^{-1}$

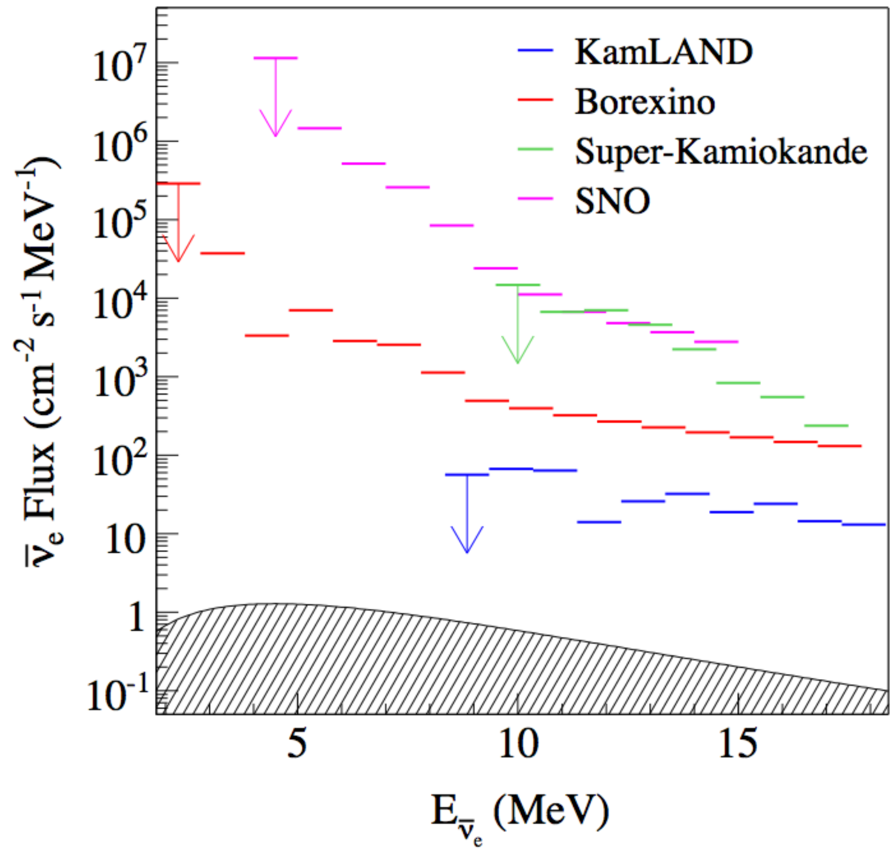
→ $p_{\nu\rightarrow\bar{\nu}} < 5.3\times10^{-5}$ (90%C.L.)

Limit on diffuse SN ν background

based on spectrum by Ando (2004)

→ $\Phi_{E>8.3MeV} < 139\ cm^{-2}s^{-1}$ (90%C.L.)

Monochromatic $\bar{\nu}_e$ fluxes



Limits on magnetic transition moment

- Limit on $\nu \rightarrow \bar{\nu}$ conversion probability can be transformed to a limit on the neutrino magnetic moment from SFP:

$$P(\nu_{eL} \rightarrow \bar{\nu}_{eR}) \simeq 1.8 \times 10^{-10} \sin^2 2\theta \left[\frac{\mu}{10^{-12}\mu_B} \frac{B_\perp(0.05R_\odot)}{10\,\mathrm{kG}} \right]^2$$

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ x $P(\nu_e \rightarrow \bar{\nu}_\mu)$

- $\sin^2 2\theta_{12}$ well defined, but wide range of values for the solar magnetic field: 600 G – 7 MG

→ **For KamLAND limit** $\mu_\nu <$ $8\times10^{-13}\,\mu_B$ for 7 MG
$p_{\nu\rightarrow\bar{\nu}} < 5.3\times10^{-5}$ (90%CL) $\mu_\nu <$ $10^{-10}\,\mu_B$ 600 G

Best limit from reactor ν's $\mu_\nu < 3.2\times10^{-11}\,\mu_B$ from GEMMA
– from solar ν_ee scattering $\mu_\nu < 5.4\times10^{-11}\,\mu_B$ from BOREXINO

Sensitivity of future experiments

- **Liquid scintillator detectors** arguably seem the most promising technique for further improvement of $\nu \rightarrow \bar{\nu}$ limit

  future detectors: SNO+
  LENA

- Possible alternative:
  Gd-doped water Cherenkov detectors

- scintillator is background limited:

→ *Is it possible to suppress the atmospheric ν NC background?*

Atmospheric NC background in LS detectors

Characteristics of NC events

- Initial interaction:
  $\nu + {}^{12}C \rightarrow \nu + {}^{11}C^* + n$
- IBD conincidence mimicked by
  – ${}^{11}C$ de-excitation → prompt
  – neutron H capture → delayed

${}^{11}C$ de-excitation channels

${}^{11}C^*$	$\rightarrow {}^{11}C + \gamma$	80%
	$\rightarrow {}^{10}C + n$	0.6%
	$\rightarrow {}^{10}B + p$	8.5%
	$\rightarrow {}^{6}Li + \alpha + p$	8.5%
	$\rightarrow {}^{9}Be + 2p$	1.8%

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In a BOREXINO-like detector:

$^{11}C \rightarrow {}^{11}B + e^{+}$
$^{10}C \rightarrow {}^{10}B + e^{+}$
} can be tagged by delayed coincidence

} pulse shape discrimination of prompt event: $p,\alpha \leftarrow\rightarrow e^{+}$

Sensitivity expected for LENA

Target mass: 50 kt of LS
Exposure: 500 kt·yrs

Estimated sensitivities for ^{8}B conversion
(using E>8MeV, 90%CL)

- No discrimination of atm. NC bg

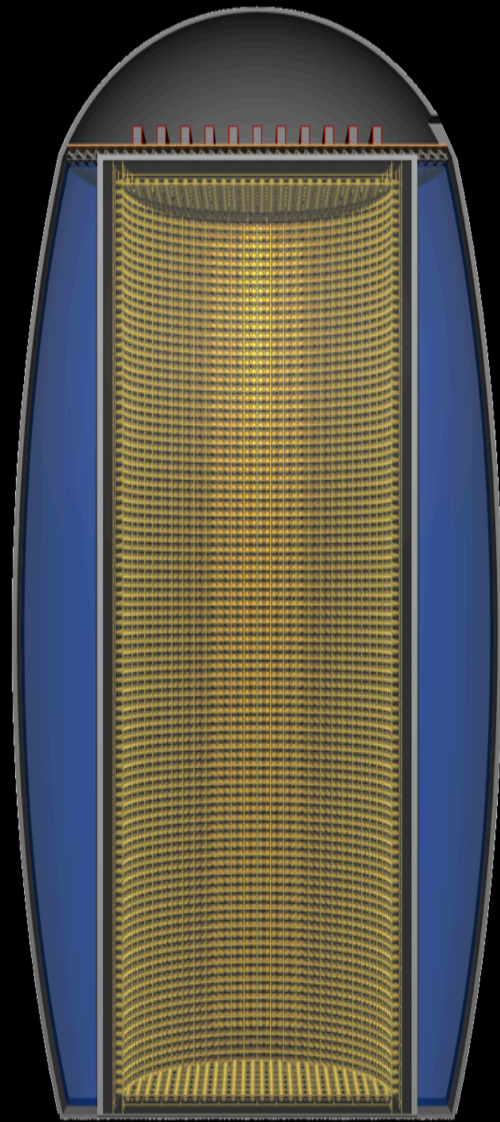
  $\Phi < 13\ \mathrm{cm^{-2}s^{-1}}$ → $p_{\nu\to\bar{\nu}} < 2.2\times10^{-6}$

- Veto of NC events by delayed ^{11}C decay

  $\Phi < 6\ \mathrm{cm^{-2}s^{-1}}$ → $p_{\nu\to\bar{\nu}} < 10^{-6}$

→ compared to KamLAND sensitvity: **x50**

But: Flux of $\bar{\nu}_e$ from the diffuse SN neutrino background is on the same level



Conclusions

- $\nu \rightarrow \bar{\nu}$ conversion has been excluded as source of the solar neutrino deficit, but might be a subdominant process hinting at μ_ν.
- The last decade has seen continuous improvements of the limits on the solar antineutrino flux and $p_{\nu \rightarrow \bar{\nu}}$.

Super-K I	**SNO**	**BOREXINO**	**KamLAND**
$p < 8 \times 10^{-3}$	$p < 8 \times 10^{-3}$	$p < 1.3 \times 10^{-4}$	$p < 5.3 \times 10^{-5}$
$E > 8$ MeV	$E > 4$ MeV	$E > 1.8$ MeV	$E > 8.3$ MeV

$\Phi_{\bar{\nu}}(^8B) < 93\ cm^{-2}s^{-1}$ (90%C.L.)

- Future experiments will further improve the limits until they reach the DSNB flux ... or find a signal.


Thank you!

Backup Slides