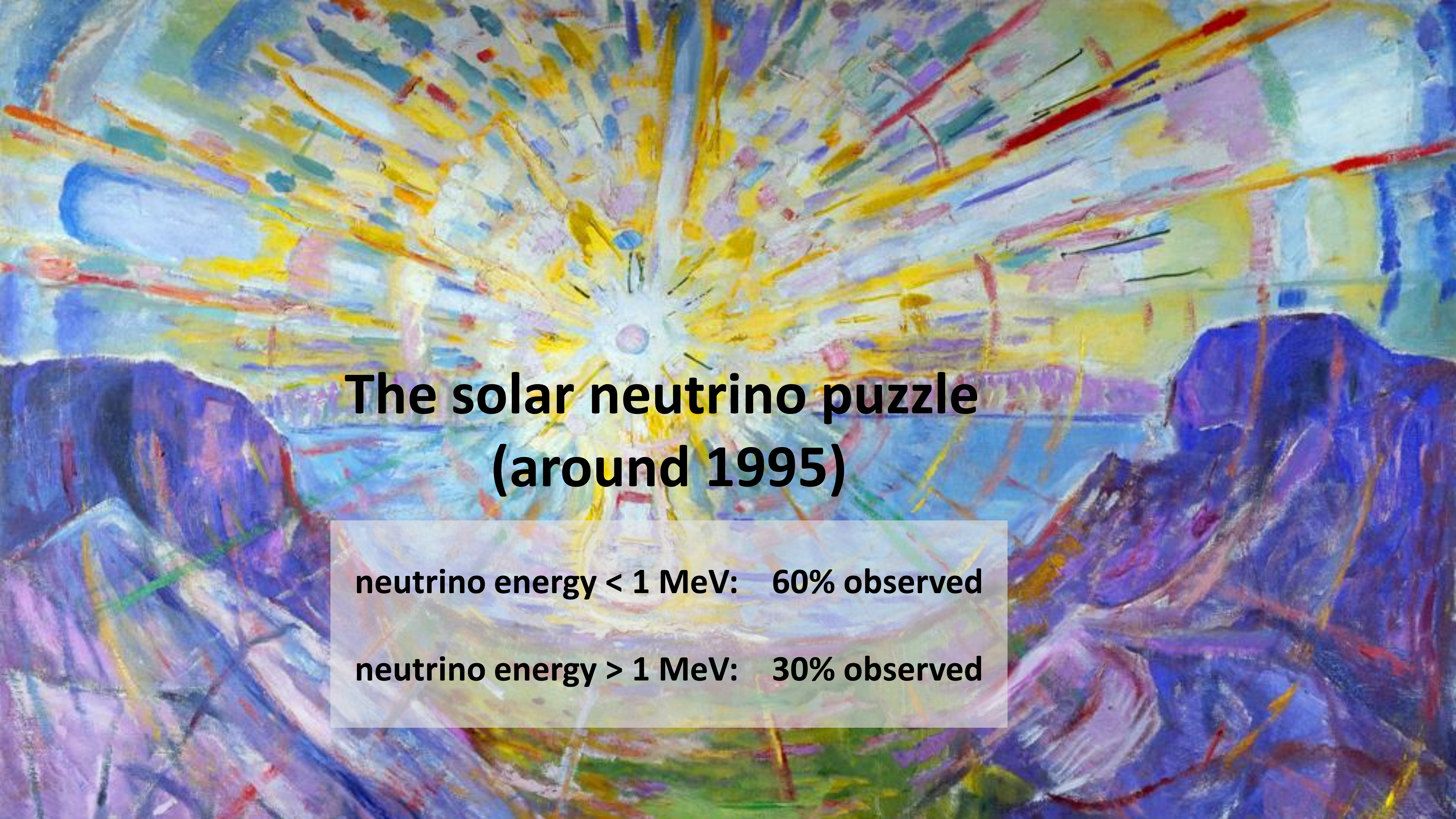


The solar neutrino puzzle (around 1995)

neutrino energy < 1 MeV: 60% observed

neutrino energy > 1 MeV: 30% observed

Two problems:

- **Overall number of neutrinos does not agree with SSM, only 30-60% of expected**
- **Strange energy dependence, like a step function**

Possible solutions:

- Experiments are wrong: (mainstream narrative: Homestake is probably wrong)
  but more and more data and cross checks made this more and more unlikely

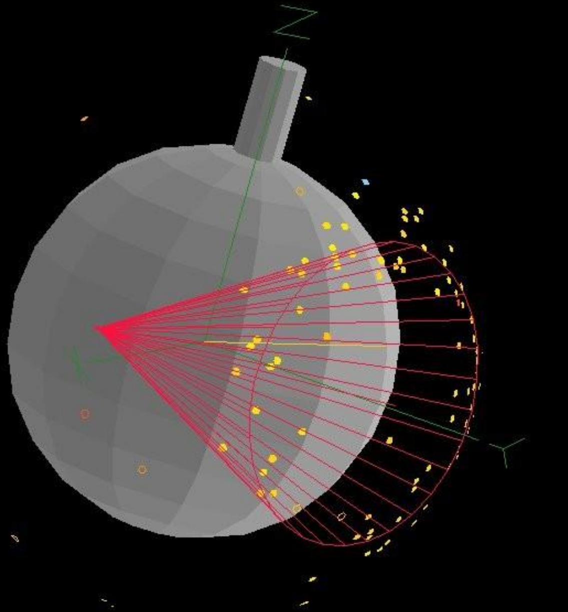
- Solar model is wrong.
  However, it was supported by new data from helioseismology.
  The SSM correctly predicted the sound speed inside the Sun as measured by helioseismology.

- Nuclear cross sections are wrong.
  They were measured at MeV energies and had to be extrapolated to keV energies.
  But first dedicated experiments showed, that the estimates are correct.

- **Particle physics: neutrino masses & neutrino mixing, neutrino oscillations, flavor change of neutrinos**

Sudbury Neutrino Observatory

CC	$\nu_e + d \rightarrow p + p + e^-$
ES	$\nu_e + e^- \rightarrow \nu_e + e^-$
NC	$\nu_x + d \rightarrow p + n + \nu_x$



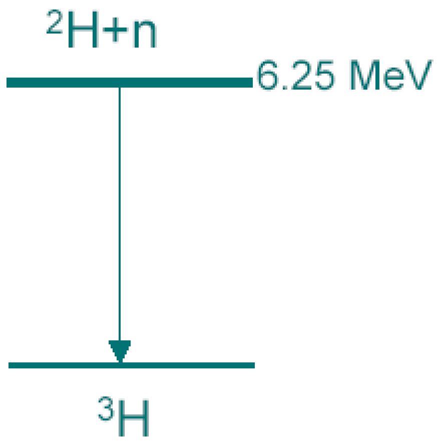
Only ^{8}B neutrinos contribute

Neutron detction in SNO

Phase I (D_2O)

Nov. 99 - May 01

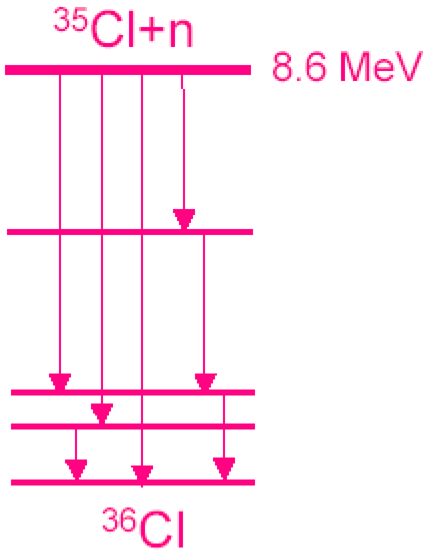
n captures on
$^2H(n, \gamma)^3H$
$\sigma = 0.0005$ b
Observe 6.25 MeV γ
PMT array readout
Good CC



Phase II (salt)

July 01 - Sep. 03

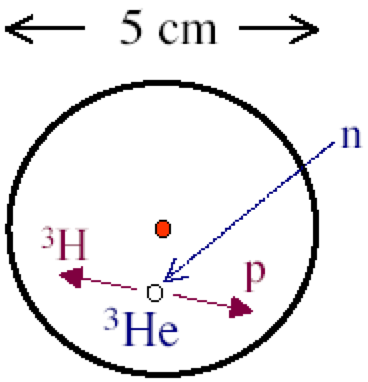
2 t NaCl. n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
$\sigma = 44$ b
Observe multiple γ's
PMT array readout
Enhanced NC



Phase III (^3He)

Summer 04 - Dec. 06

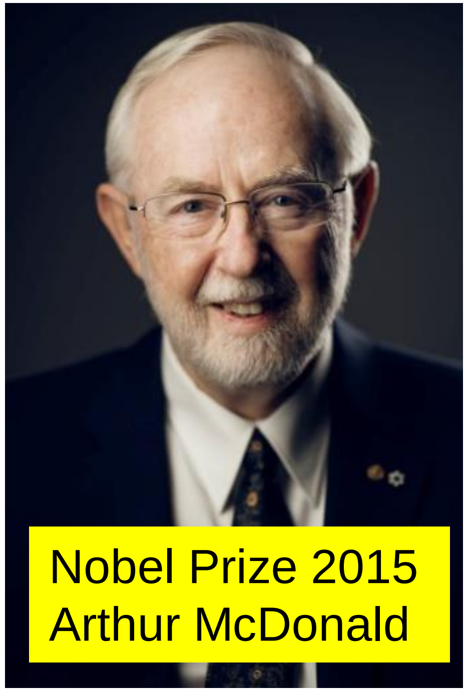
40 proportional counters
$^3He(n, p)^3H$
$\sigma = 5330$ b
Observe p and ^3H
PC independent readout
Event by Event Det.



$n + {}^3He \rightarrow p + {}^3H$

SNO Result (salt-phase)

(PRL 92, 181301, 2004)



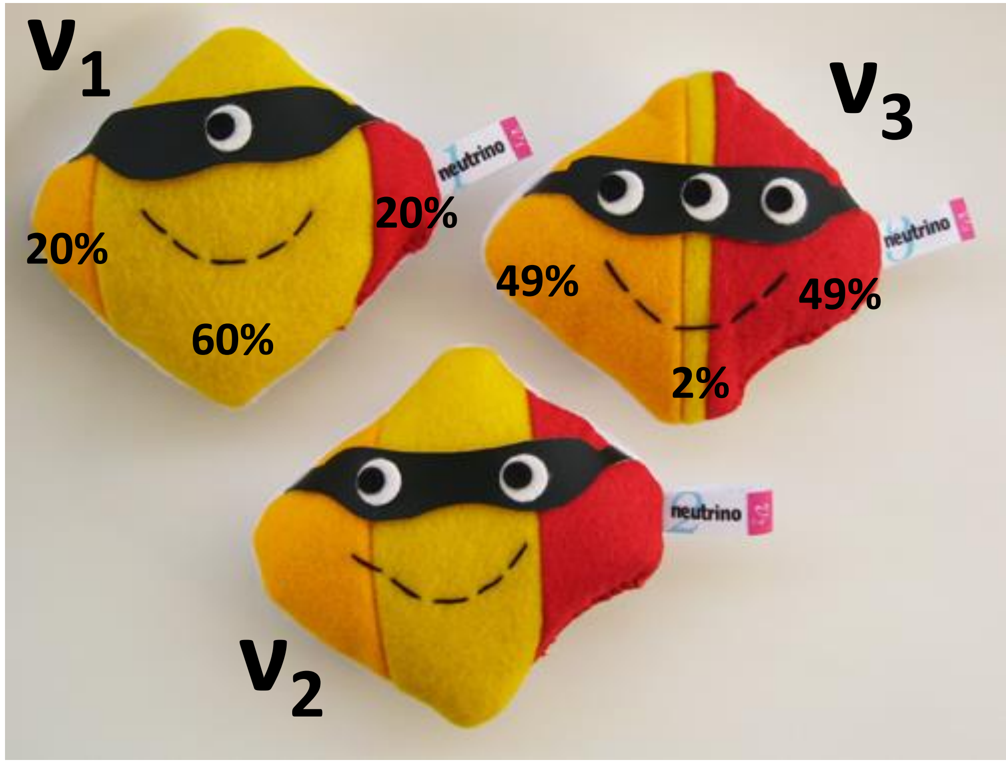
$$\phi(^{8}B)_{meas} = (0.88 \pm 0.04\ (exp) \pm 0.23\ (th)\ )\ \phi(^{8}B)_{SSM}$$

- 1/3 of ν_e arrive on Earth.
- 2/3 of ν_e have transformed into ν_μ or ν_τ .
- measured total neutrino flux = prediction by SSM

Result of first phase (without salt):
"Direct Evidence for Neutrino Flavor Tranformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory“,
The SNO Collaboration Phys. Rev. Lett. volume 89, No. 1, 011301 (2002).

Flavor-Eigenstates

Mass-Eigenstates



Theoretical Prediction of Neutrino Oscillations:

Bruno Pontecorvo
(1913 – 1993)

- 1957-58: **Pontecorvo:**
  states for first time possibility of **Neutrino Oscillations**
  (But: at that time only ν_e were known, so he was thinking of Neutrino ↔ Anti-Neutrino oscillations)
  B. Pontecorvo, J.Exptl. Theoret. Phys.34(1958) 247 [Sov. Phys. JETP7(1958) 172]

- 1962 **Maki, Nakagawa, Sakata:**
  describe **mixing of 2 flavors** and discuss transitions between neutrino flavors.

- 1967 **Pontecorvo :**
  thorough discussion of 2 flavor mixing,
  oscillations of solar-neutrinos
  and possible existence of sterile neutrinos.
  Also possibility of Cl-Ar experiments

Very nice overview on history:
Samoil M. Bilenky „Neutrino oscillations: brief history and present status“
arXiv:1408.2864v1 [hep-ph] 12 Aug 2014

Die Affäre Pontecorvo

Die ungewöhnliche Karriere des italienischen Kernphysiker

Simone Turchetti

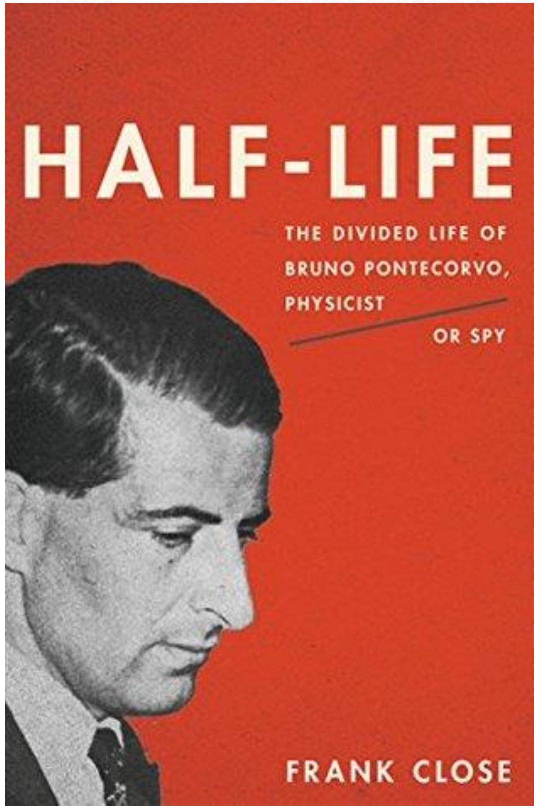
One of last great unsolved cold-war science mysteries

Dipartimento di Fisica, Sapienza – Università

Bruno Pontecorvo (links) im Jahr 1949, ein Jahr vor seinem rätselhaften Verschwinden zusammen mit Enrico Fermi (2. von rechts) bei der Besichtigung einer Fabrik von Olivetti, dem italienischen Hersteller für Büro- und Rechenmaschinen.

in german: Physik Journal 12 (2013) Nr.10

■ *S. Turchetti*, The Pontecorvo Affair. A Cold War Defection and Nuclear Physics, Univ. of Chicago Press, Chicago (2012)



…and here a talk by F. Close

https://youtu.be/d4rCjoWiOrw

And a discussion of this book in Nature
https://www.nature.com/articles/518032a

Neutrino Mass and Mixing

Precondition: neutrino masses $m_1, m_2, m_3 \gtrsim 0$

flavor eigenstates $\neq$ mass eigenstates

ν_e, ν_μ, ν_τ — ν_1, ν_2, ν_3

$\nu_\alpha \quad \alpha = e, \mu, \tau$ — $\nu_i \quad i = 1,2,3$

Neutrino Mixing:

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

→ $|U_{e1}|^2$ probability that ν_e contains ν_1

$|\langle\nu_1|\nu_e\rangle|^2$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{Neutrino Mixing Matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS Matrix

Pontecorvo
Maki
Nakagawa
Sakata

Neutrino Oscillations (simplified)

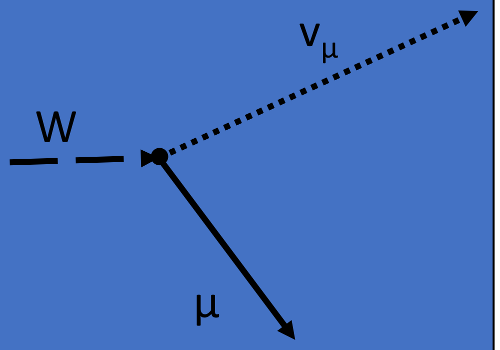
For $\Theta \approx 45^o$

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} +1 & +1 \\ -1 & +1 \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

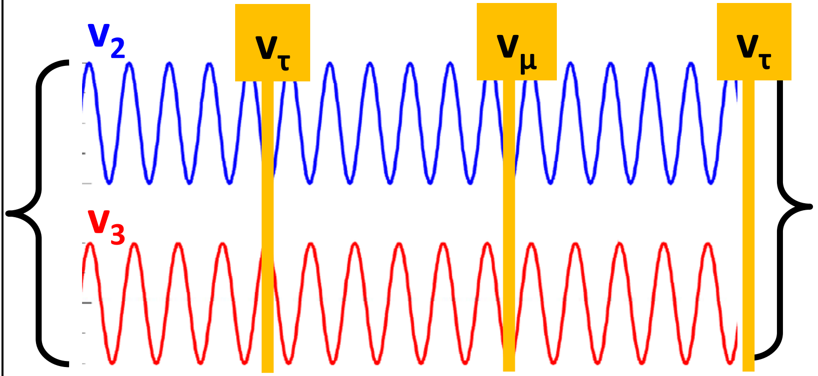
Flavor Eigenstates
ν_μ, ν_τ

Mass Eigenstates
ν_2, ν_3 with m_2, m_3

Source produces
Flavor-Eigenstates



Propagation in vacuum:
Mass-Eigenstates

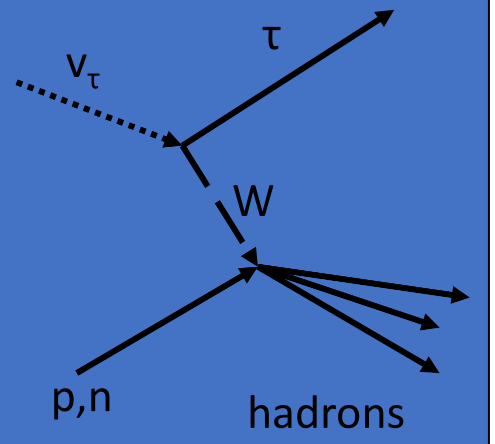


$$\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}$$

$$|\nu_\mu\rangle = 1/\sqrt{2}\left(|\nu_2\rangle + |\nu_3\rangle\right)$$

$$|\nu_\tau\rangle = 1/\sqrt{2}\left(-|\nu_2\rangle + |\nu_3\rangle\right)$$

Detection process:
Flavor-Eigenstates

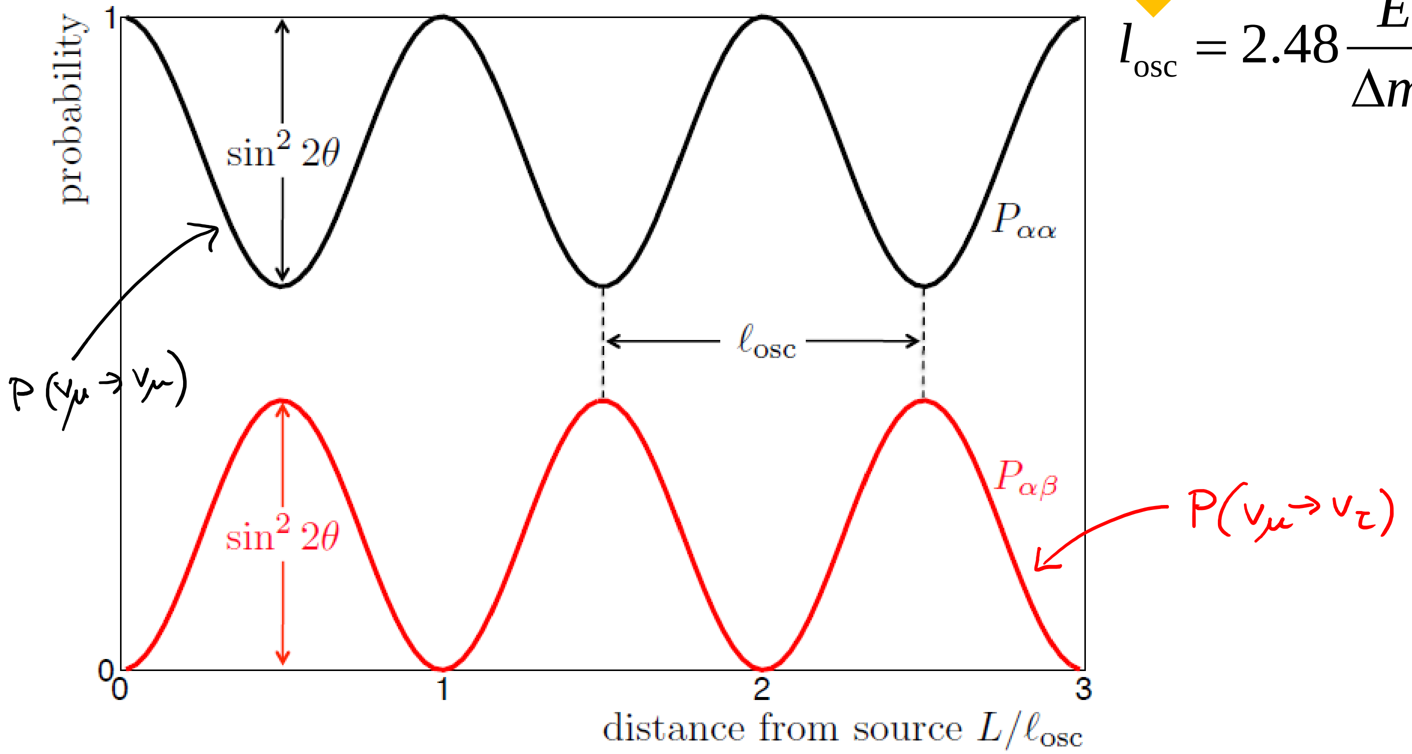


Neutrino Oscillations (2 Flavors)

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23}) \cdot \sin^2\left(1.267 \frac{\Delta m_{23}^2(\text{in eV}^2) \cdot L(\text{in km})}{E(\text{in GeV})}\right)$$

$$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_\tau)$$

$$l_{\text{osc}} = 2.48 \frac{E(\text{in GeV})}{\Delta m_{23}^2(\text{in eV}^2)} \text{km}$$



Example:
for $\Delta m^2 = 2.5 \cdot 10^{-3} eV^2$
and $E_\nu = 1GeV$ we get
$l_{osc} = 1000km$

We assume $\Delta m^2 \approx 8 \cdot 10^{-5}\,eV^2$, $\theta \approx 33°$

Survival probability for a ν_e (produced in the Sun)

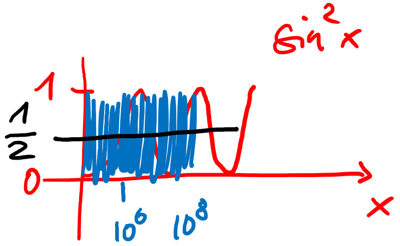
$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \cdot \sin^2\left(\underbrace{1.27\, \frac{\Delta m^2[eV^2] \cdot L[m]}{E[MeV]}}_{\delta}\right)$$

In Vacuum

$L \approx 1\,AU = 1.5 \cdot 10^{11}\,m$ (150 Mio km)

$E \approx 0.1 - 10\,MeV$

$$\delta = 1.27 \cdot \frac{8 \cdot 10^{-5} \cdot 1.5 \cdot 10^{11}}{10^{-1} \ldots 10^{1}} \approx \underbrace{10^{7 \pm 1}}_{\text{phase is not precise}} \quad 10^6 - 10^8$$



$\Longrightarrow$ incoherent in phase

you don't see $\sin^2(\delta) \longrightarrow \frac{1}{2}$

$$\longrightarrow \quad P(\nu_e - \nu_e)_{\text{average over phase}} = 1 - \frac{1}{2}\sin^2 2\theta = 0.6$$

independent of energy

This explains why 60% of pp, ^7Be neutrinos survive

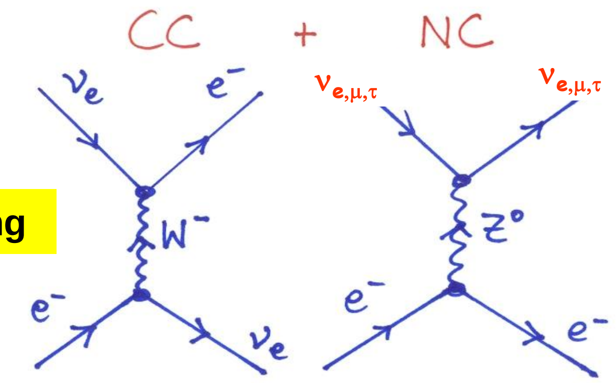
For 30% of ^8B ν need other mechanism!

$\hookrightarrow$ matter effects MSW

Neutrino Propagation in Matter (Overview)

Important: ν_e and $\nu_{\mu,\tau}$ have different interaction with matter

(ν_e can do both CC and NC, $\nu_{\mu,\tau}$ only NC!)



Relevant for propagation is elastic forward scattering

Vacuum:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta & \Delta m^2\sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Matter:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta+2\sqrt{2}G_F N_e E & \Delta m^2\sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta-2\sqrt{2}G_F N_e E\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

$$2\sqrt{2}G_F \underbrace{N_e}_{\frac{Y_e\rho}{m}} E = 1.53\cdot 10^{-7}\,\mathrm{eV}^2\left(\frac{Y_e\rho}{\mathrm{g/cm}^3}\cdot\frac{E}{\mathrm{MeV}}\right)$$

Center of the Sun: $\frac{Y_e\rho}{\mathrm{g/cm}^3}\cong 100$

The flavour propagation equation in matter

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta+2\sqrt{2}G_F N_e E & \Delta m^2\sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta-2\sqrt{2}G_F N_e E\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Can also be written as:

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m_m^2\cos 2\theta_m & \Delta m_m^2\sin 2\theta_m\\ \Delta m_m^2\sin 2\theta_m & \Delta m_m^2\cos 2\theta_m\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Compare with vacuum equation::

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}=\frac{1}{4E}\begin{pmatrix}-\Delta m^2\cos 2\theta & \Delta m^2\sin 2\theta\\ \Delta m^2\sin 2\theta & \Delta m^2\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

with $\Delta m_m^2 = m_2^2 - m_1^2$ and θ_m, being "effective" masses and mixing angles in matter, for which we get:

$$\Delta m_m^2\cos 2\theta_m = \Delta m^2\cos 2\theta - 2\sqrt{2}G_F N_e E$$
$$\Delta m_m^2\sin 2\theta_m = \Delta m^2\sin 2\theta$$

When Neutrinos propagate in matter, they acquire effective masses and mixing angles:

Solving the above equations, we obtain:

$$\Delta m_m^2 = \sqrt{\left(\Delta m^2\cos 2\theta - 2\sqrt{2}G_F N_e E\right)^2 + \left(\Delta m^2\sin 2\theta\right)^2}$$

$$\sin 2\theta_m = \frac{\sin 2\theta}{\sqrt{\left(\frac{2\sqrt{2}G_F N_e E}{\Delta m^2} - \cos 2\theta\right)^2 + (\sin 2\theta)^2}}$$

$$\Delta m_m^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - 2\sqrt{2}G_F N_e E\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$\sin 2\theta_m = \frac{\sin 2\theta}{\sqrt{\left(\frac{2\sqrt{2}G_F N_e E}{\Delta m^2} - \cos 2\theta\right)^2 + (\sin 2\theta)^2}}$$

$$2\sqrt{2}G_F N_e E \approx 1.53 \cdot 10^{-7}\,\mathrm{eV}^2 \left(\frac{Y_e \varrho}{\mathrm{g/cm^3}} \cdot \frac{E}{\mathrm{MeV}}\right)$$

$\frac{Y_e \varrho}{\mathrm{g/cm^3}} \approx 100$ in the Sun

Quasi Vacuum

$$2\sqrt{2}G_F N_e E \ll \Delta m^2 \cos 2\theta$$

$\hookrightarrow$ $\Delta m_m^2 \simeq \Delta m^2$

$\theta_m \simeq \theta$

pp-neutrinos, ^{7}Be-neutrinos

Resonance

$$2\sqrt{2}G_F N_e E = \Delta m^2 \cos 2\theta$$

for $\Delta m^2 = 8 \cdot 10^{-5}\,\mathrm{eV}^2$; $\theta = 33°$

$\Downarrow$

$E \approx$ 1-2 MeV

$$\Delta m_m^2 = \Delta m^2 \sin 2\theta$$

$$\theta_m = \frac{\pi}{4}$$

Matter dominated

$$2\sqrt{2}G_F N_e E \gg \Delta m^2 \cos 2\theta$$

$$\Delta m_m^2 \rightarrow 2\sqrt{2}G_F N_e E$$

$$\theta_m \rightarrow \frac{\pi}{2} \; (90°)$$

In the Sun, for $E_\nu = 5\,\mathrm{MeV}$

with $\Delta m^2 = 8 \cdot 10^{-5}\,\mathrm{eV}^2$, $\theta = 33°$

$Y_e \varrho = 90\,\mathrm{g/cm^3}$

$\hookrightarrow$ $\theta_m \approx 73°$

^{8}B-neutrinos

For ^{8}B Neutrinos at center of the Sun:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos 73^\circ & \sin 73^\circ \\ -\sin 73^\circ & \cos 73^\circ \end{pmatrix} \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix}$$

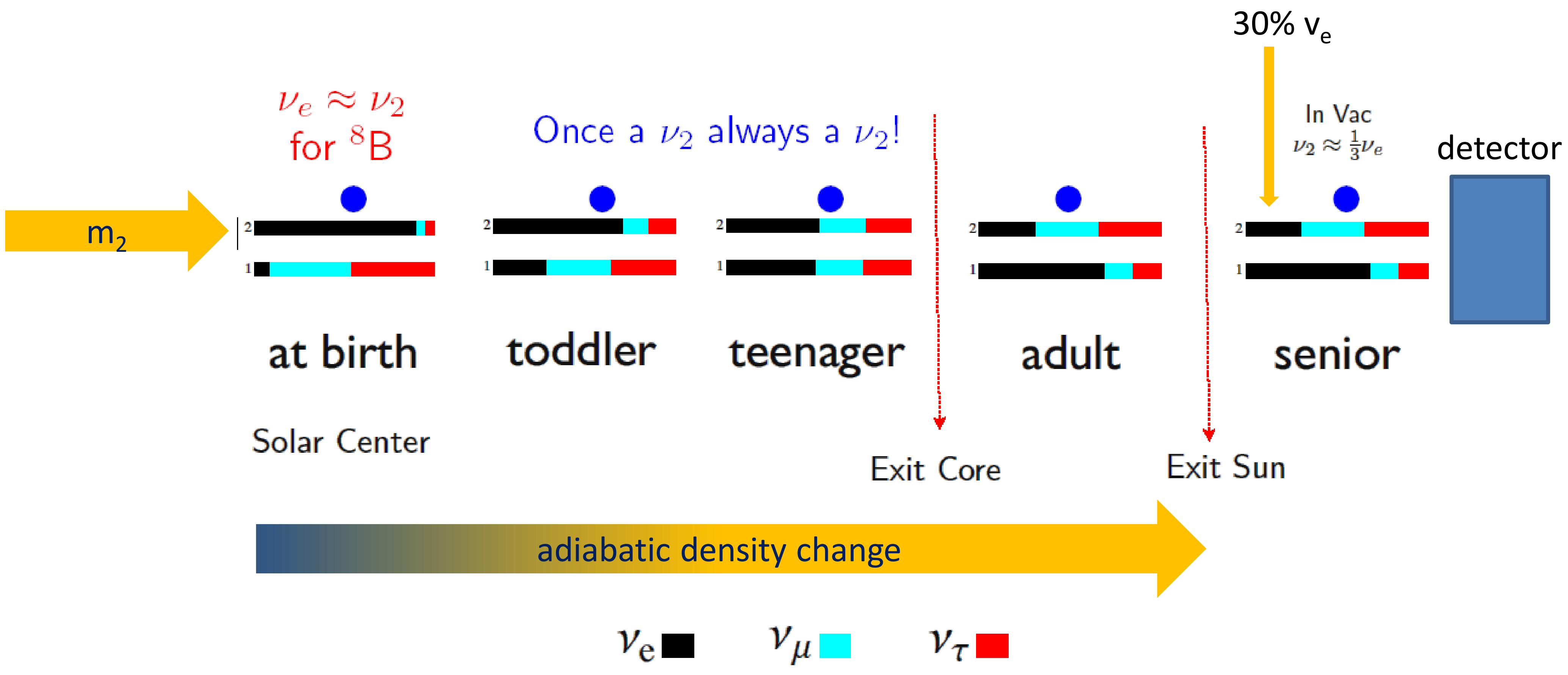
This means, the probability that ν_e has mass m_2 is $\sin^2(73°) = 91\%$

For ^{8}B Neutrinos in vacuum (at earth):

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{12} & -\sin\theta_{12} \\ \sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

The probability that ν_2 is a ν_e is $\sin^2\theta_{12}$

Life of a Boron-8 Solar Neutrino:



Neutrino Propagation in Matter: MSW mechanism

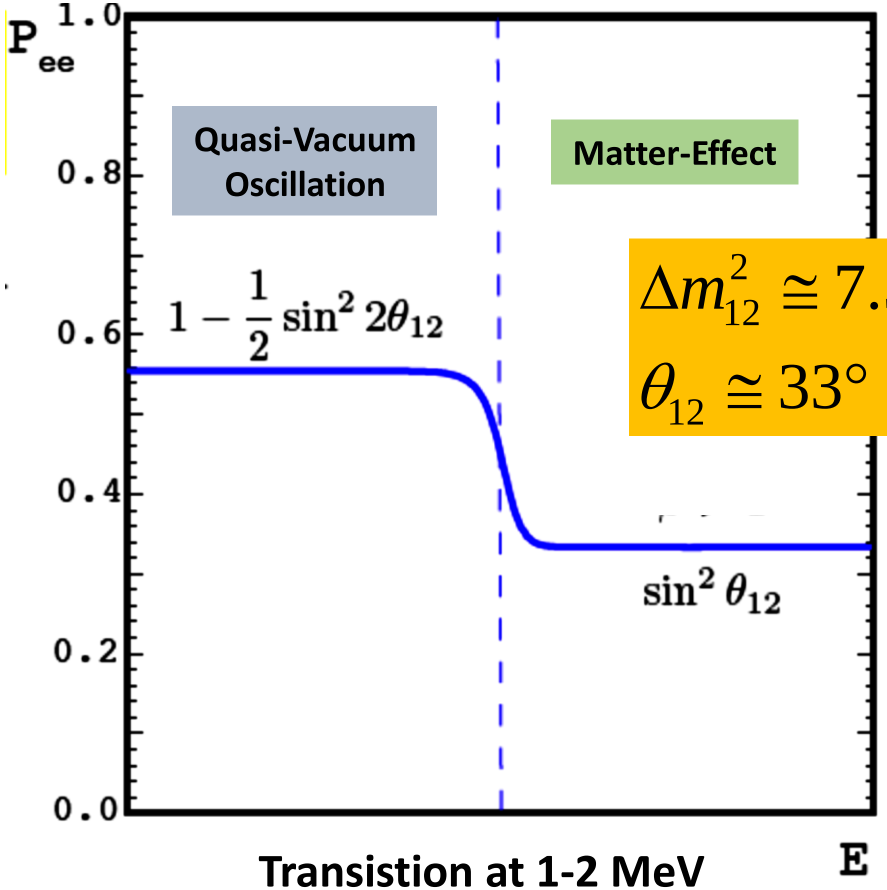


Stanislav **Mikheev** (1940-2011) Alexei **Smirnov** Lincoln **Wolfenstein** (1923-2015)

L. Wolfenstein, Phys. Rev. D17 (1978) 2369
S. P. Mikheev and A. Yu. Smirnov, Nuovo Cim.C9 (1986)17

Interaction of $\mathbf{v}_e$ and $\mathbf{v}_{\mu,\tau}$ with electrons different.
→ Effective masses, effective mixing angles depending on electron density N_e and energy of neutrino

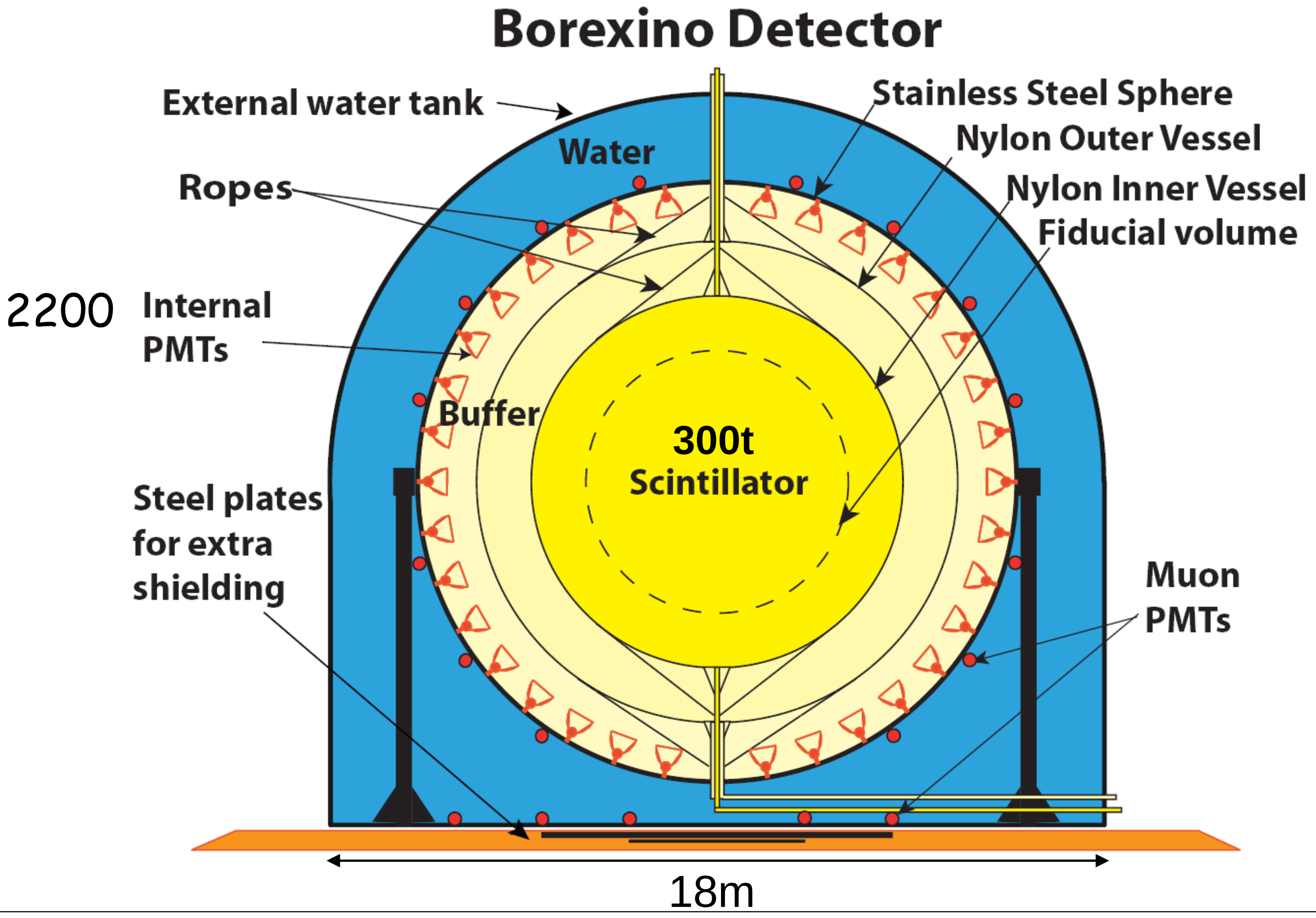
Important for solar neutrinos:
Survival probability



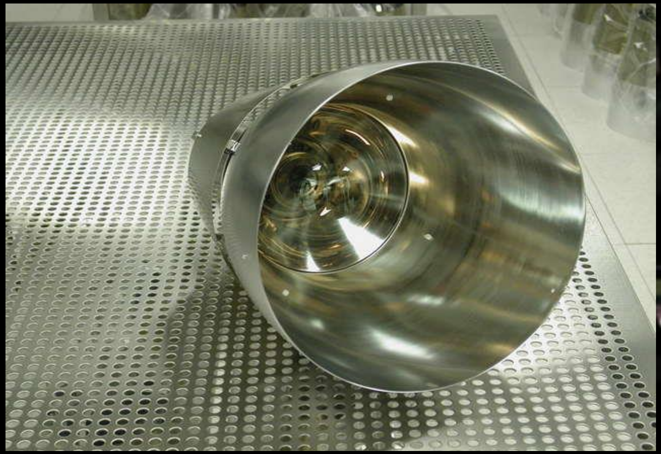
Transistion at 1-2 MeV

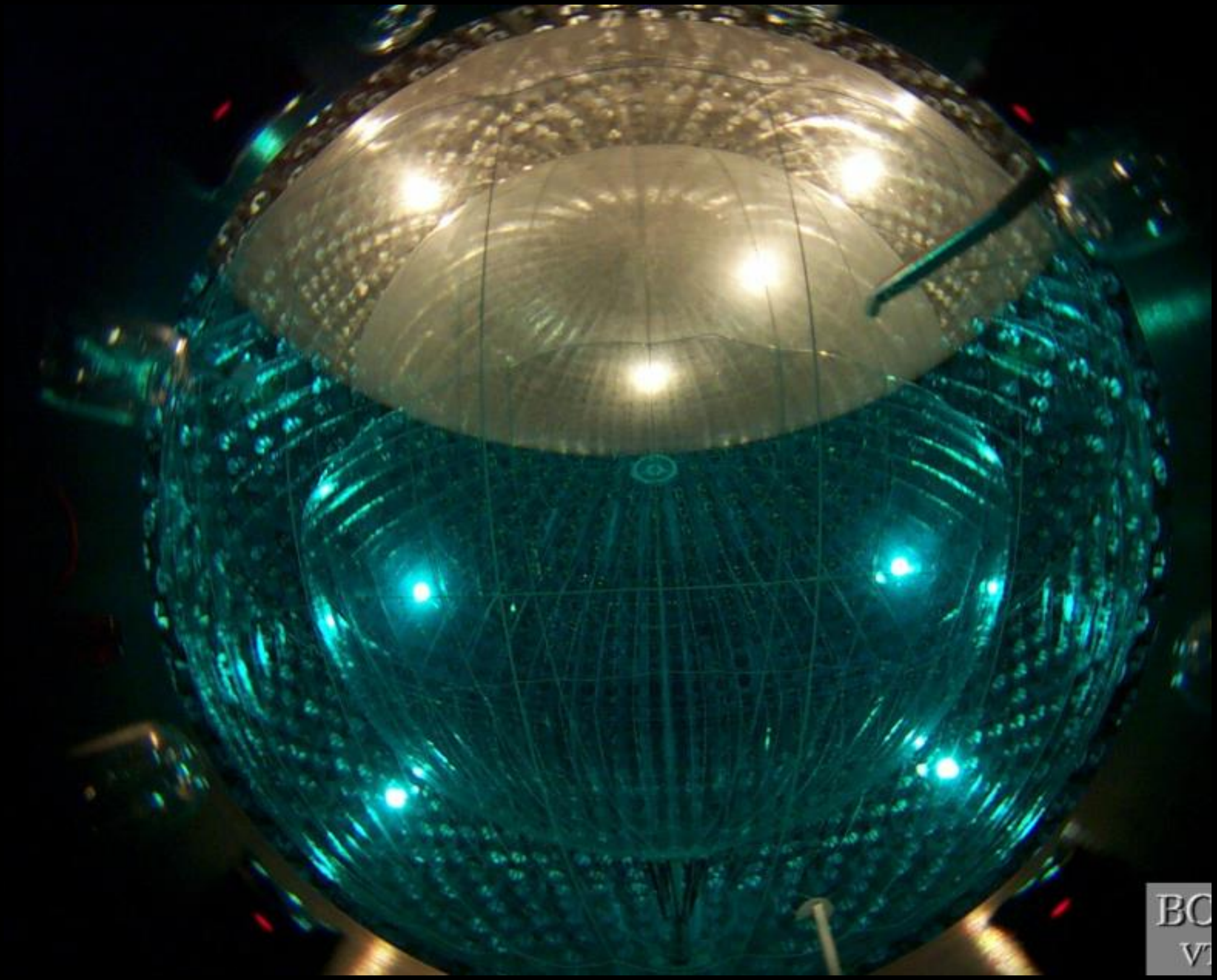
$$\Delta m^2_{12} \cong 7.5\cdot 10^{-5}\,\mathrm{eV}^2$$
$$\theta_{12} \cong 33°$$

BOREXINO @ LNGS

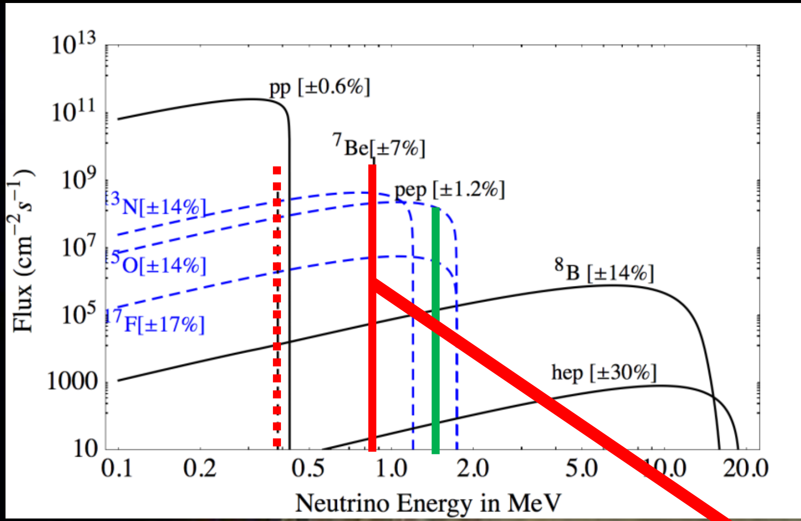


Photomultipliers and light concentrators in Borexino



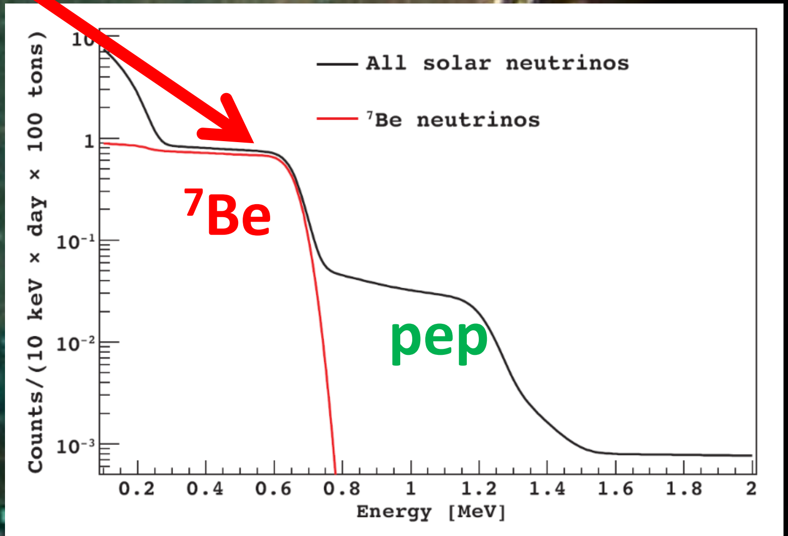


Borexino during filling (on top scintillator, lower part water)

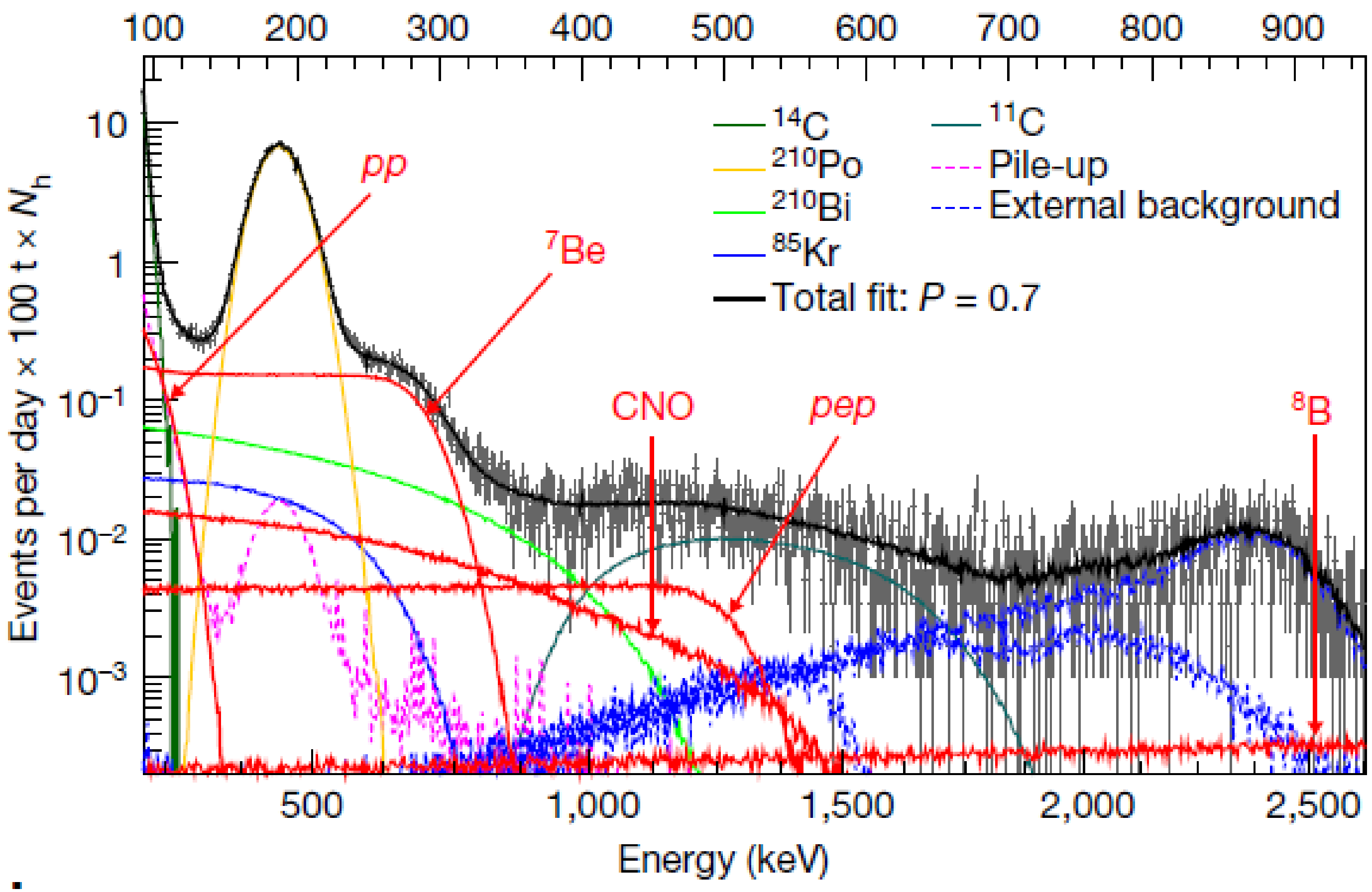


elastic scattering of neutrinos on electrons:

neutrino „lines“ → Compton-like edge in spectrum of recoil electrons



Borexino Result 2018: Flux of pp-chain Neutrinos



Borexino Coll. „Comprehensive measurement of pp-chain solar neutrinos“, Nature Vol562, pages505–510 (2018)

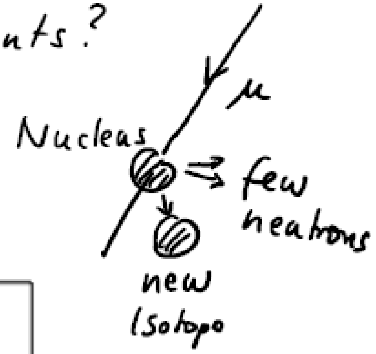
Why are μ a background for solar neutrino experiments?

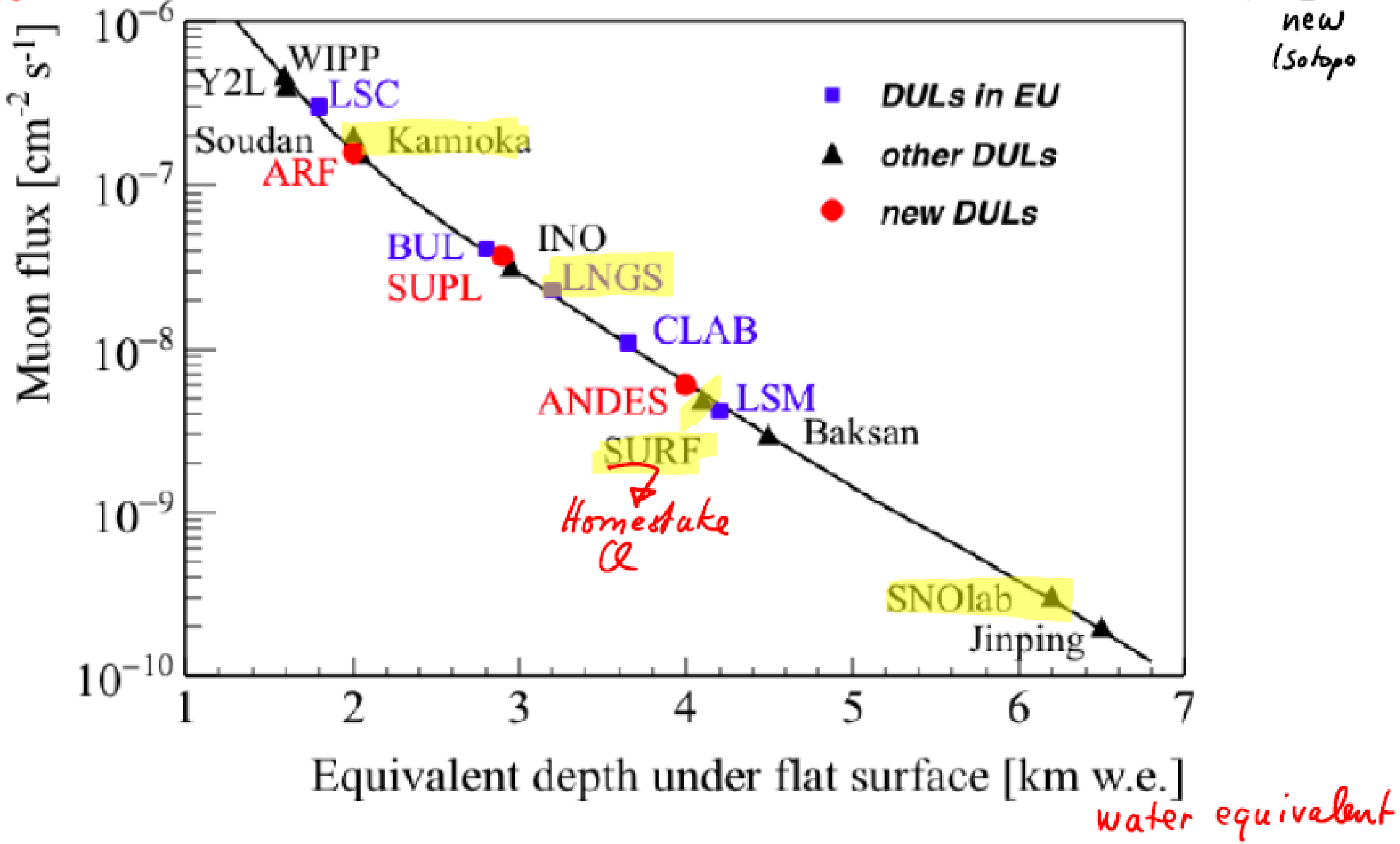
μ can do spallation of nuclei ⇒ produce radioactive isotopes

⇒ produces neutrons

↳ produce radioactive isotope

COSMOGENIC BACKGROUND





BX Analysis 2018: Flavor Transition in Matter

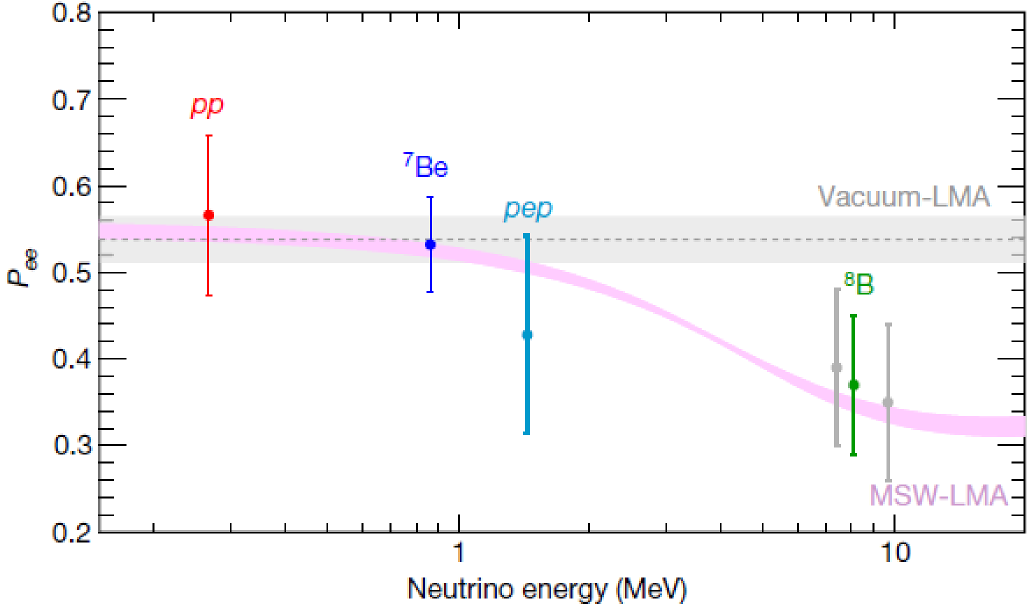


Fig. 3 | Electron neutrino survival probability P_{ee} as a function of neutrino energy. The pink band is the $\pm 1\sigma$ prediction of MSW-LMA with oscillation parameters determined from ref. [19]. The grey band is the vacuum-LMA case with oscillation parameters determined from refs [38,39]. Data points represent the Borexino results for *pp* (red), ^{7}Be (blue), *pep* (cyan) and ^{8}B (green for the HER range, and grey for the separate HER-I and HER-II sub-ranges), assuming HZ-SSM. ^{8}B and *pp* data points are set at the mean energy of neutrinos that produce scattered electrons above the detection threshold. The error bars include experimental and theoretical uncertainties.

Borexino Coll. „Comprehensive measurement of pp-chain solar neutrinos“, Nature Vol562, pages505–510 (2018)

Volume 587 Issue 7835, 26 November 2020

Catching the rays

The Sun generates the vast majority of its energy from the fusion of hydrogen to form helium in a process called the proton–proton chain. But a small amount of its energy was thought to come from a secondary fusion process catalysed by carbon, nitrogen and oxygen, known as the CNO cycle. In this week's issue, the Borexino Collaboration presents results that offer the first direct experimental evidence for the CNO cycle occurring in the Sun. The... show more

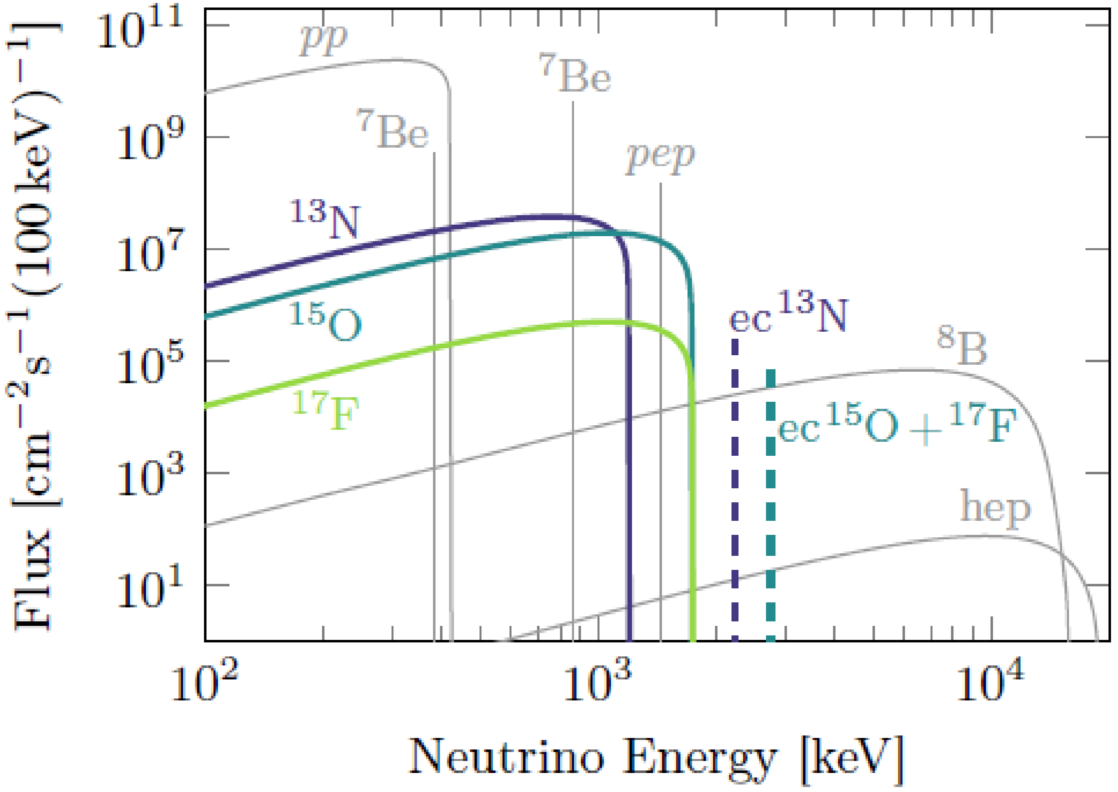
SPIEGEL Wissenschaft

Neutrino-Analyse

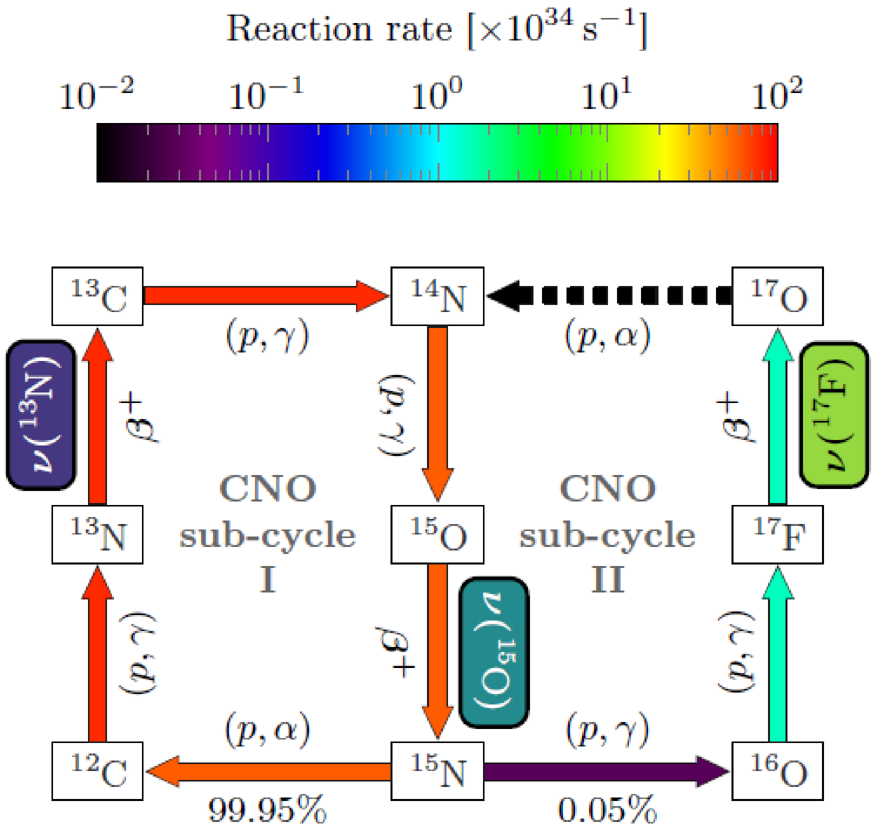
Forscher bestätigen alte Theorie zur Sonnenfusion

Schon Ende der Dreißigerjahre hatten Physiker eine spezielle Funktion der Sonne postuliert. Nun wurde ihre Theorie erstmals experimentell nachgewiesen – durch die Hilfe von geisterhaften Elementarteilchen.

26.11.2020, 19.27 Uhr



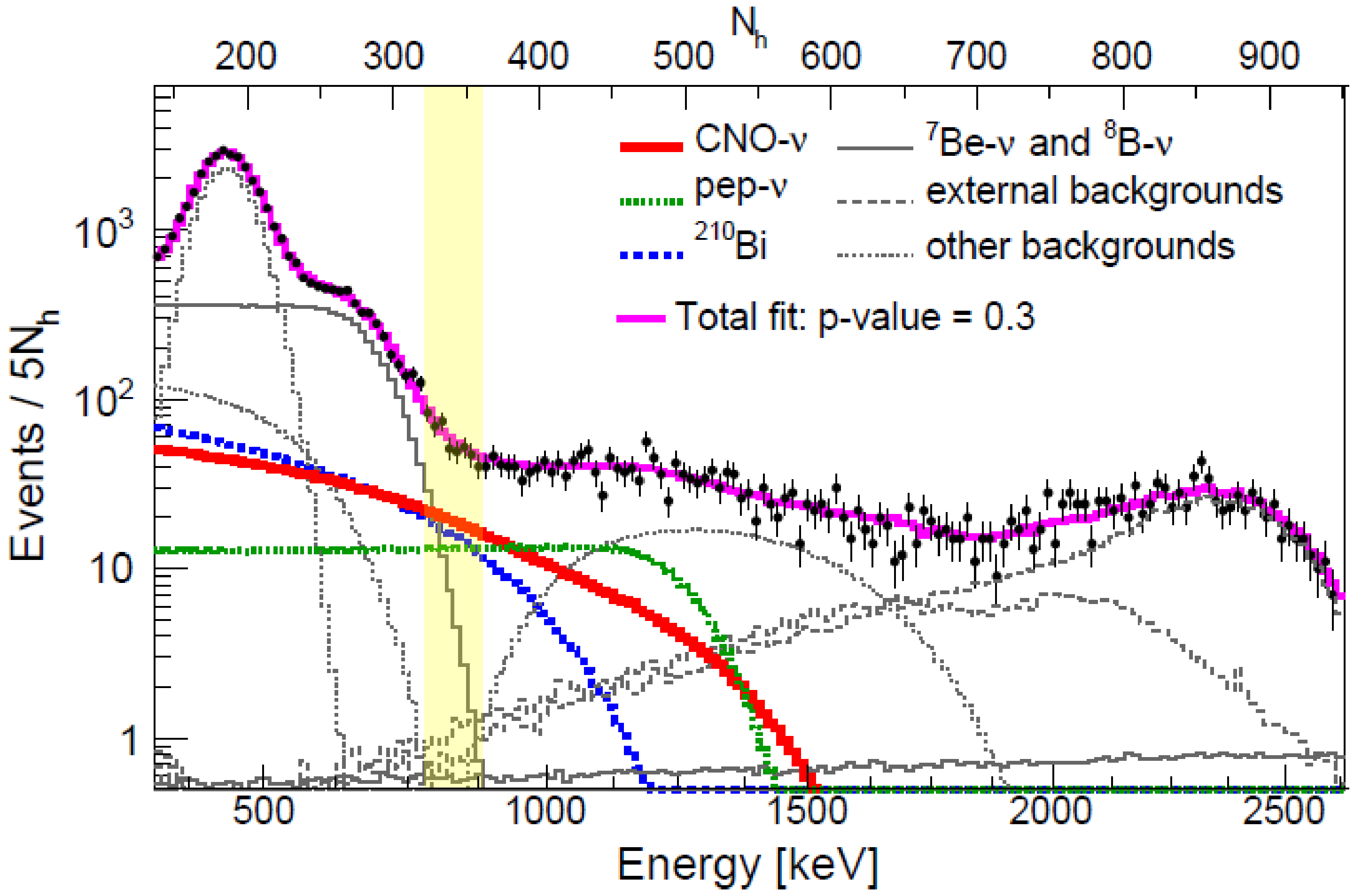
Flux [cm^{-2}s^{-1}(100 keV)$^{-1}$]
Neutrino Energy [keV]
pp
^{7}Be
^{7}Be
pep
^{13}N
^{15}O
^{17}F
ec ^{13}N
ec ^{15}O + ^{17}F
^{8}B
hep



Reaction rate [$\times 10^{34}$ s^{-1}]
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
^{13}C
^{14}N
^{17}O
(p, γ)
(p, α)
$\nu(^{13}$N)
β^+
(p, γ)
β^+
$\nu(^{17}$F)
CNO sub-cycle I
CNO sub-cycle II
^{13}N
^{15}O
^{17}F
(p, γ)
β^+
$\nu(^{15}$O)
(p, γ)
^{12}C
^{15}N
^{16}O
(p, α)
(p, γ)
99.95%
0.05%

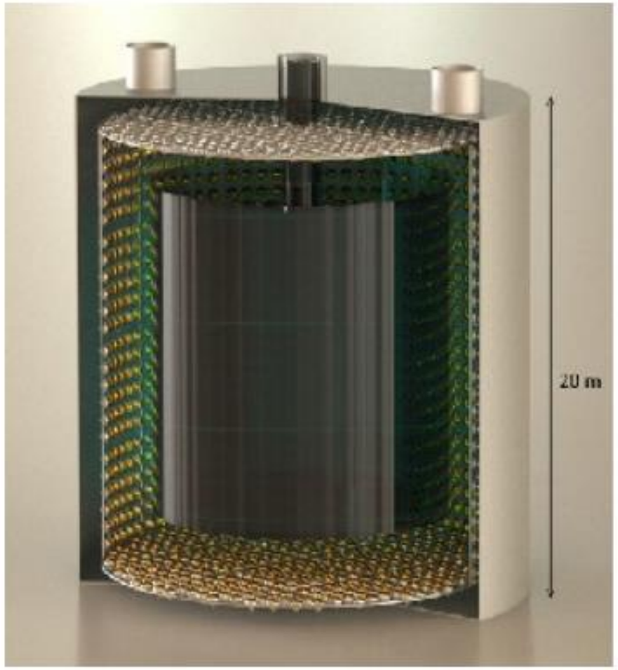
BOREXINO measures CNO neutrino flux

$7.2^{+3.0}_{-1.7}$ counts/day → $\Phi_{CNO} = 7.0^{+3.0}_{-2.0} \times 10^8\,\mathbf{cm}^{-2}\,\mathbf{s}^{-1}$



JinPing underground lab

scintillator uploaded
water detectors?



FV: 100 times bigger than
BOREXINO

Deeper than SNO