

I neutrini solari

Corso di Fisica Astroparticellare

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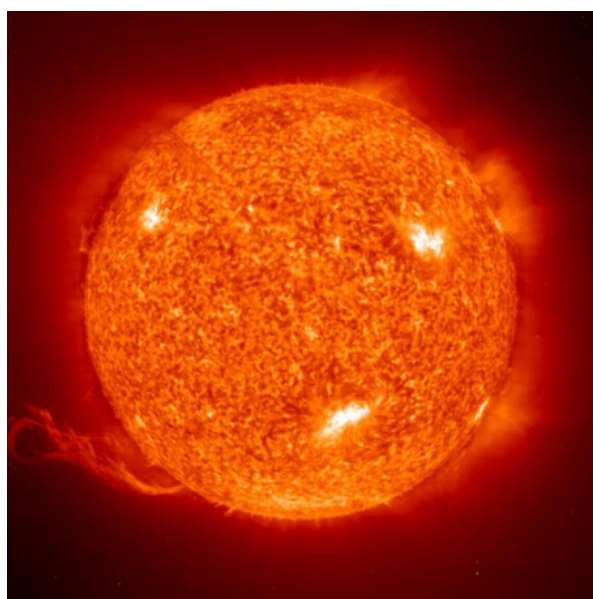


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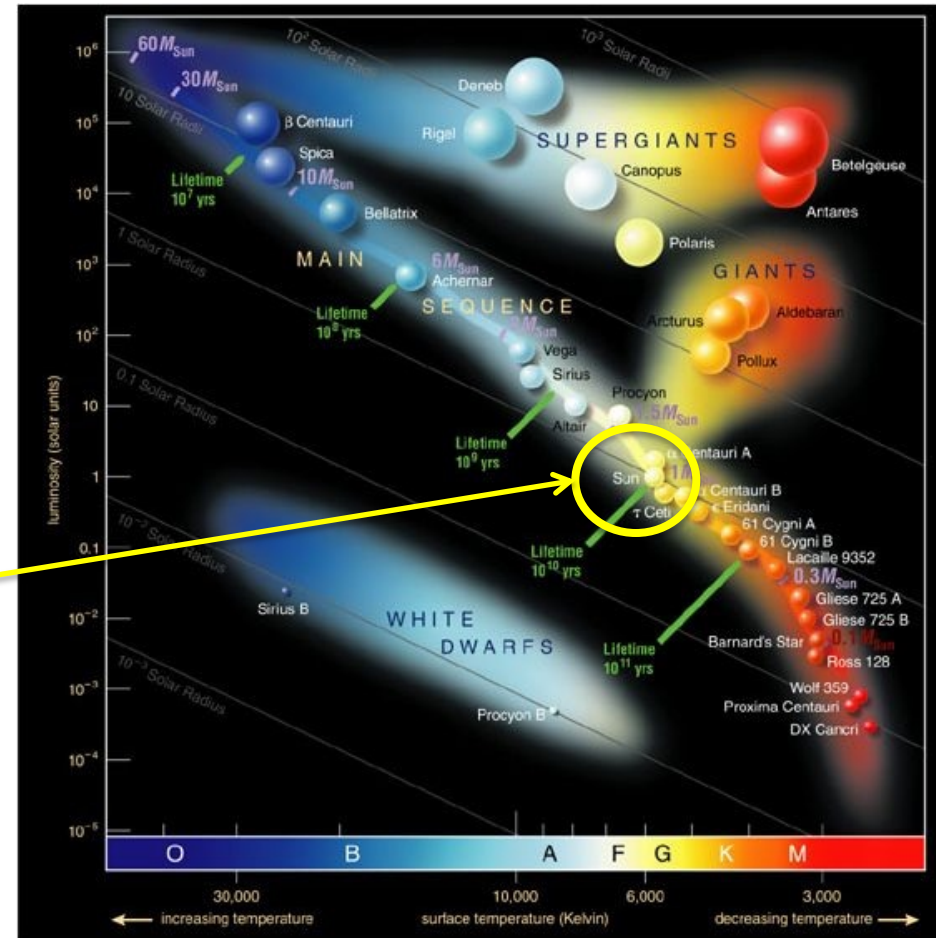
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The Sun and the solar neutrinos

I.D. of the Sun



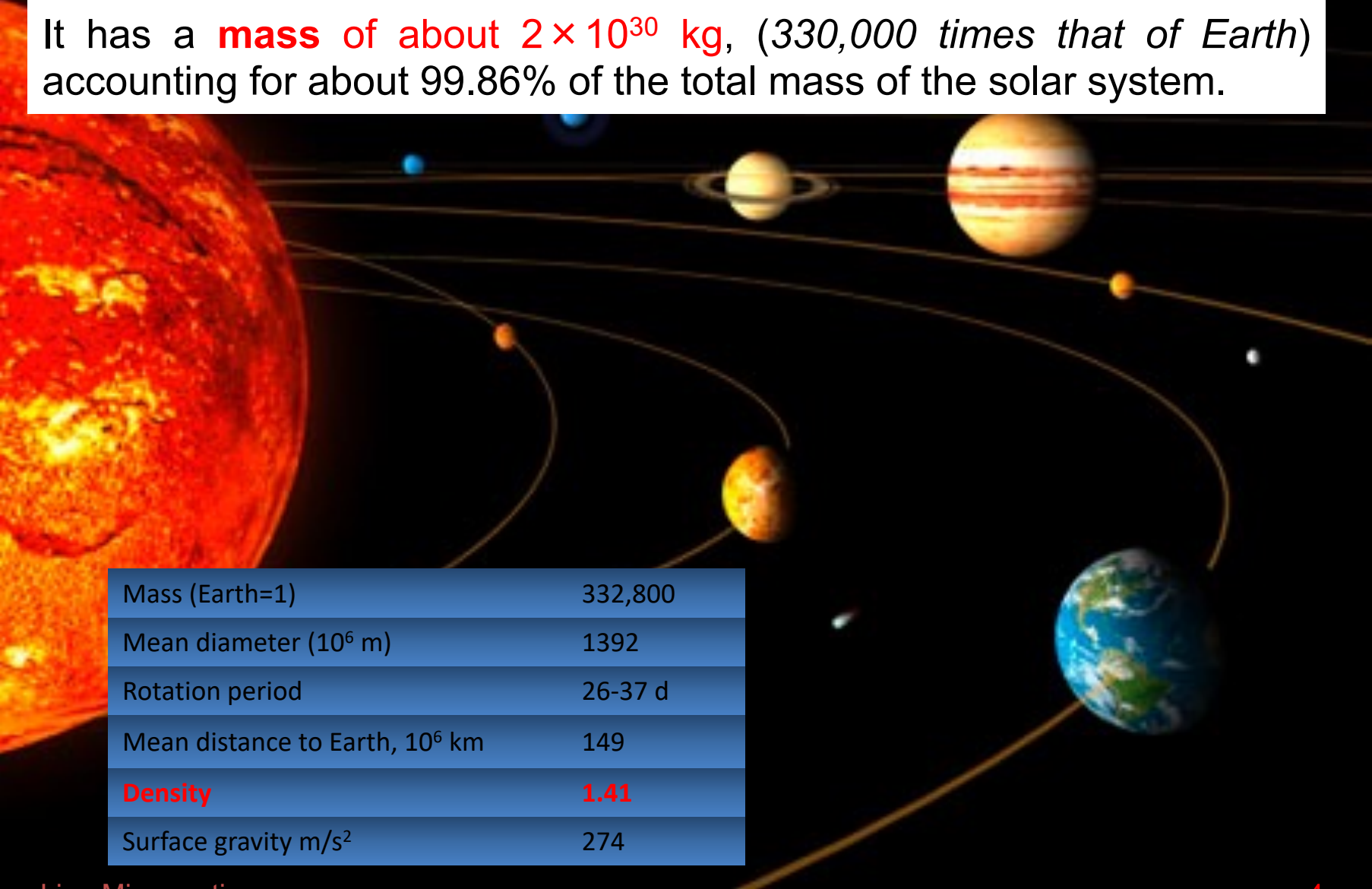
The Sun is a **star of medium size** and lies on the main sequence of the Hertzsprung-Russell diagram



The effective **surface temperature** is 5780 K (spectral class G2).

It has a **radius** of about 700,000 km (109 times that of Earth).

It has a **mass** of about 2×10^{30} kg, (330,000 times that of Earth) accounting for about 99.86% of the total mass of the solar system.



Mass (Earth=1)	332,800
Mean diameter (10^6 m)	1392
Rotation period	26-37 d
Mean distance to Earth, 10^6 km	149
Density	1.41
Surface gravity m/s ²	274

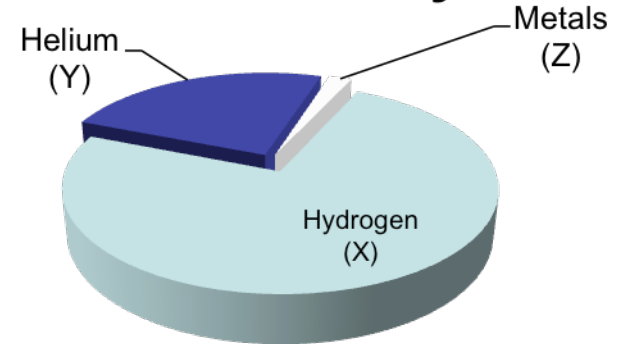
Composition of the Sun

About $\frac{3}{4}$ of the mass of the Sun consists of **hydrogen**;

About $\frac{1}{4}$ of the mass of the Sun consists of **helium**.

Less than 2% consists of **heavier elements**.

Sun Inventory



(In astronomy, any atom heavier than helium is called a "**metal**" atom).

New solar metallicity

Element	Abundance	Contribution to Z (%)
O	8.66	43.7
C	8.39	17.6
Fe	7.45	9.4
Ne	7.84	8.3
Si	7.51	5.4
N	7.80	5.3
Mg	7.55	5.2
S	7.14	2.6

$C+N+O \sim \frac{2}{3} Z$

...for CNO (Bethe) cycle

$X=0.7393$ $Y=0.2485$ $Z=0.0122$ $Z/X=0.0165$

Anders, Grevesse 1989 $Z=0.019$ $Z/X=0.027$
 Grevesse, Noels 1993 $Z=0.017$ $Z/X=0.024$
 Grevesse, Sauval 1998

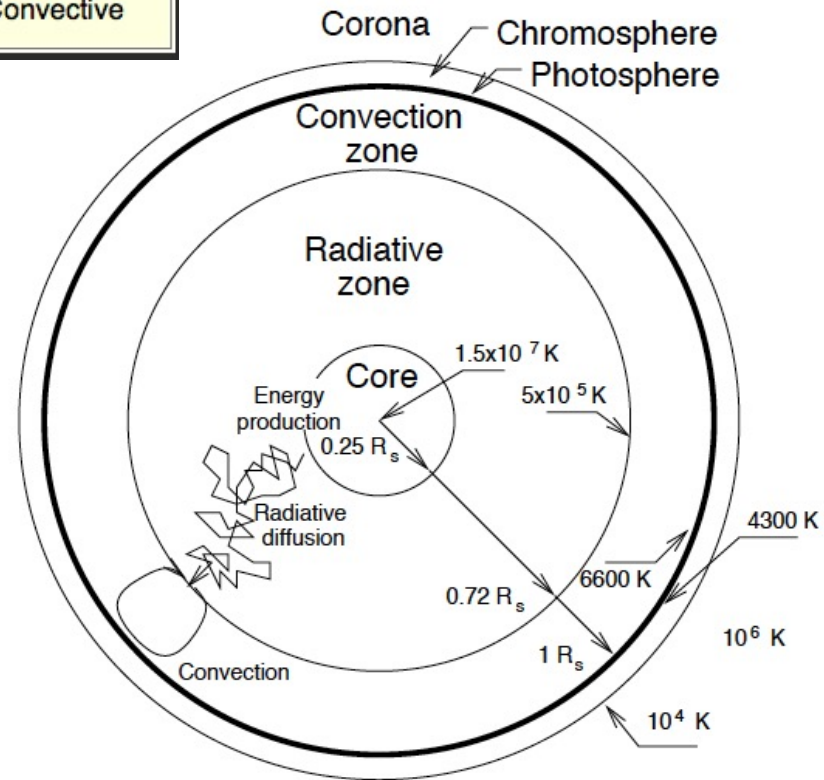
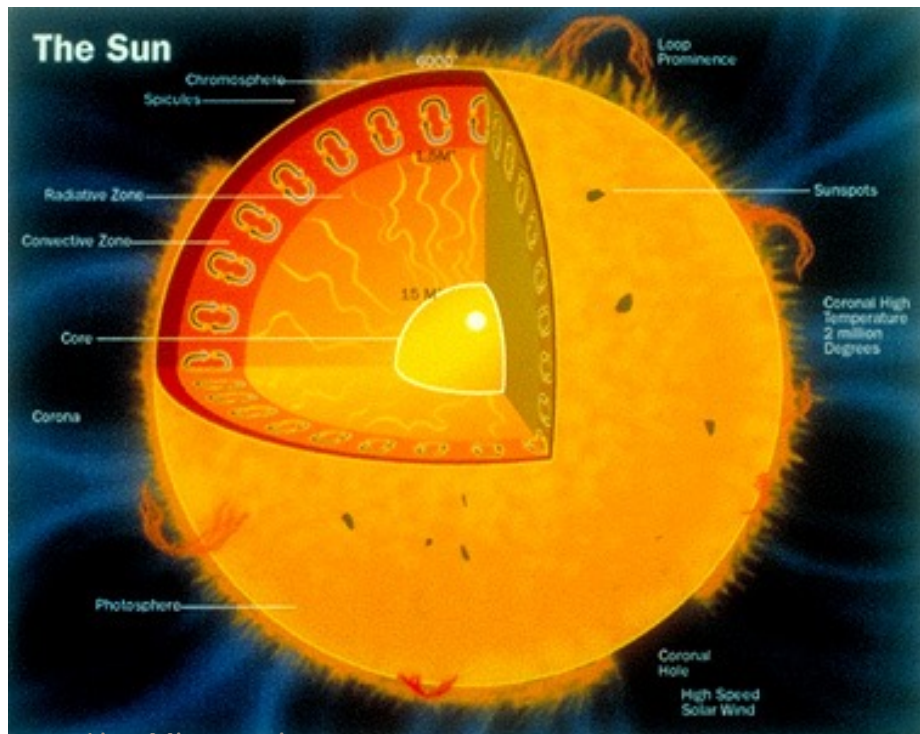
Element	Abundance (% of total number of atoms)	Abundance (% of total mass)
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

The interior of the Sun

It is useful to divide the interior of the Sun into **3 regions**.

Zone	R/R(0)	Temperature (K)	Density (g/cm ³)	Energy Transport
Core	0.0 - 0.25	~ 15,000,000 - 8,000,000	~ 160 - 10	Radiative
Radiative	~ 0.25 - 0.85	~ 8,000,000 - 500,000	~ 10 - 0.01	Radiative
Convective	~ 0.85 - 1.00	~ 500,000 - 10,000	< 0.01	Convective

Core density ~ 150 g/cm³



The Standard Solar Model (SSM)

(developed and continuously updated by J.N. Bahcall since 1960)

Il modello si basa sulle seguenti **ASSUNZIONI**: (Le simulazioni utilizzano le equazioni di base dell'evoluzione stellare)

1. **Equilibrio idrostatico**: (bilancio locale tra pressione e gravità)
$$\frac{dP(r)}{dr} = -\frac{G M(r)\rho(r)}{r^2}$$
2. **Conservazione dell'energia**:
$$\frac{dL(r)}{dr} = 4\pi r^2 \rho(r)\varepsilon(r)$$
3. **Trasporto di energia** prevalentemente per radiazione e convezione, il flusso di energia si misura mediante il gradiente di temperatura prodotto,

$$\begin{cases} \frac{dT(r)}{dr} = -\frac{3}{64\pi\sigma} \frac{k(r)\rho(r)L(r)}{r^2 T(r)^3} \\ \frac{dT(r)}{dr} = \left(1 - \frac{1}{\gamma}\right) \frac{T(r)}{P(r)} \frac{dP(r)}{dr} \end{cases}$$

dove

k è l'opacità, κ

σ è la costante di Stefan-Boltzmann

γ il rapporto tra i calori specifici c_p/c_v ,

insieme a **tre equazioni di stato** per la pressione, l'opacità e la rate di produzione di energia:

$$P = P(\rho, T, X)$$

$$k = k(\rho, T, X)$$

$$\varepsilon = \varepsilon(\rho, T, X)$$

IL METODO:

By "the standard solar model," we mean the solar model that is constructed with the best available physics and input data.
(John N. Bahcall, 1934–2005)

- Parametri iniziali:
 - ✓ ? Abbondanze di elio e metalli;
 - ✓ ? Opacità vs. raggio
 - ✓ ? Sezioni d'urto delle reazioni di fusione
- Evoluzione a $t = 4.4 \times 10^9$ anni (oggi);
- Confronto parametri input/output;
- Se necessario, i parametri iniziali vengono modificati e il processo reiterato.

κ is the **opacity** (or absorption coefficient).
In terms of the photon mean free path μ :

$$\mu = \frac{1}{k \cdot \rho} = \frac{1}{\sigma \cdot n}$$

where

- σ is the cross-section for interaction;
- n is the number density of particles.

With these definitions:

- κ has units $\text{cm}^2 \text{g}^{-1}$,
- ρ has units g cm^{-3} ,
- σ is in cm^2 ,
- n is in cm^{-3} .

Present Sun properties:

Luminosity $\mathcal{L}_{\odot} = 3.846 \times 10^{26} \text{ W}$

Radius $R_{\odot} = 6.96 \times 10^8 \text{ m}$

Mass $M_{\odot} = 1.989 \times 10^{30} \text{ kg}$

Core temperature $T_c = 15.6 \times 10^6 \text{ K}$

Surface temperature $T_s = 5773 \text{ K}$

Hydrogen fraction in core = 34.1% (initially 71%)

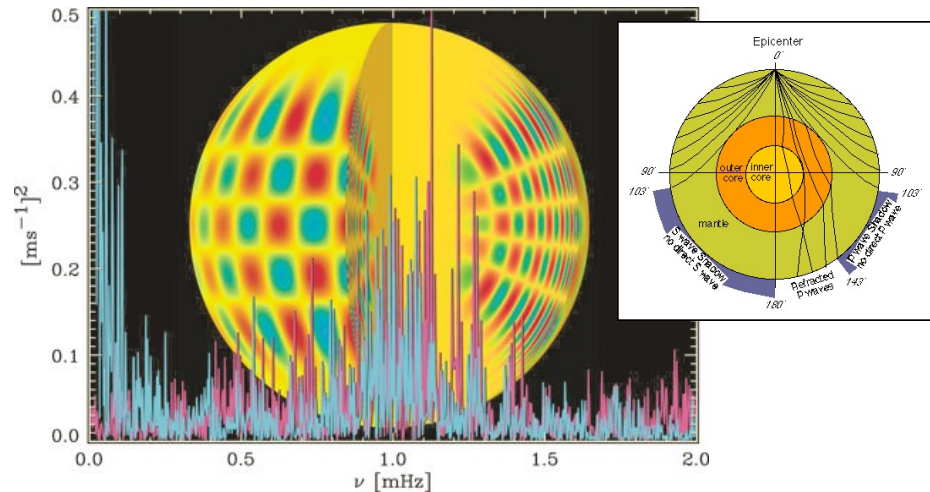
Helium fraction in core = 63.9% (initially 27.1%)

} as measured on
surface today

Helioseismology

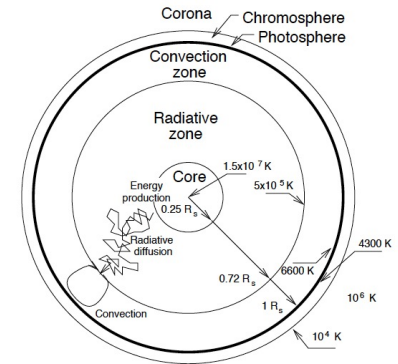
It is possible to study the interior of the Sun through helioseismology.

With helioseismology, it is possible to learn about the properties of the Sun by studying the **propagation of waves** in its body. (These waves cause small oscillations of the surface that are observable) in a manner similar to geologists learning about the interior of the Earth by studying seismic waves.



Nelle zone di propagazione radiativa e convettiva si propagano **onde sonore** (compressione e rarefazione)

Tra il core e la superficie si stabiliscono **onde stazionarie**, che si misurano attraverso **l'effetto Doppler degli strati superficiali**. Queste onde, scoperte nel 1960 da *R. Leighton*, sono di tipo *acustico* e hanno **periodi** caratteristici dell'ordine di **5 minuti**.



Temperature, **composition**, and **motions** deep in the Sun influence the oscillation periods and yield insights into conditions in the solar interior.

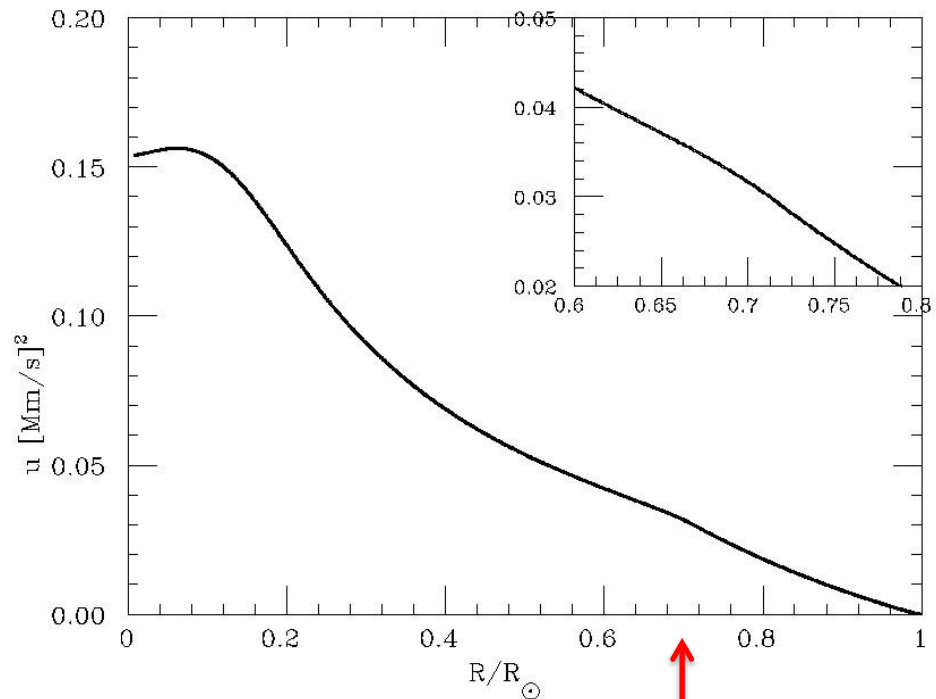
Helioseismology is placing strong constraints on theories of the solar interior.

Cosa si impara dall'eliosismologia?

Analizzando lo “spettro” delle frequenze di oscillazione si può studiare l'interno del sole

In particolare si determinano:

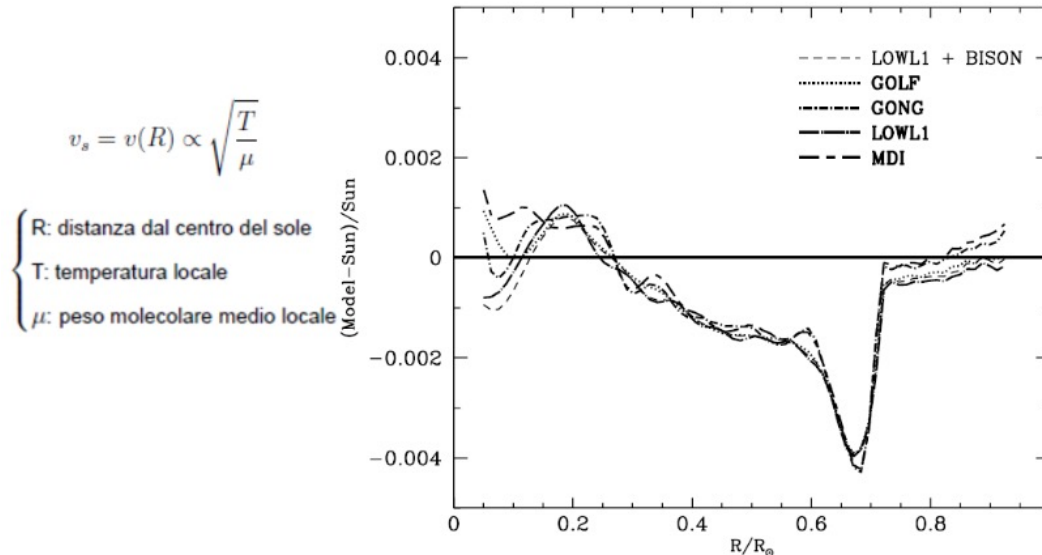
- inizio della zona convettiva (0.711 R)
- L'andamento della **velocità del suono**
- Abbondanza in massa di He (24.5%) alla superficie
- La rotazione dell'interno solare



transizione

Confronto Eliosismologia e SSM

Accordo tra le velocità del suono calcolate dal modello solare standard (Model) e quelle misurate da diverse misure eliosismiche (Sun)



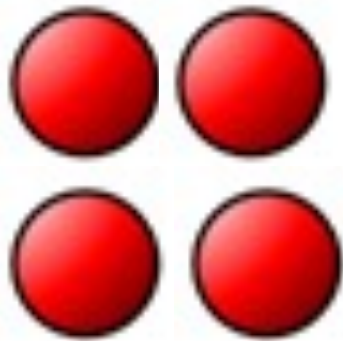
Eccellente accordo tra le velocità del suono calcolate dal modello solare standard (Model) e quelle misurate da diverse misure eliosismiche (Sun). La linea orizzontale a 0 rappresenta il caso ipotetico in cui le velocità del suono calcolate e misurate concordano esattamente, ovunque nel Sole. L'rms tra quelle calcolate e quelle misurate è minore dello 0.50 % per tutti i raggi solari tra $0.05 R_S$ e $0.95 R_S$; vale 0.3 % - 0.4 % dove inizia la zona convettiva ed è 0.08 % per la regione interna profonda, $R \leq 0.25 R_S$, in cui vengono prodotti i neutrini.

Dal **confronto Eliosismologia vs. SSM**, come vedremo, si ricavano informazioni sull'andamento delle **reazioni nucleari** all'interno del sole e sulla produzione dei **neutrini** sia in termini di flussi che di spettri energetici.

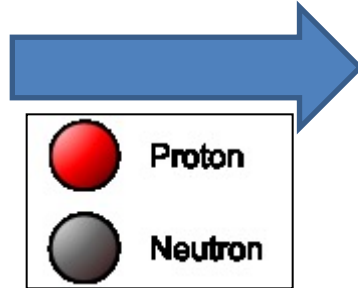
How the Sun shines

The core of the Sun reaches temperatures of
~ 15 million K.

At these temperatures, **nuclear fusion** can occur transforming **4 Hydrogen nuclei** into **1 Helium nucleus**

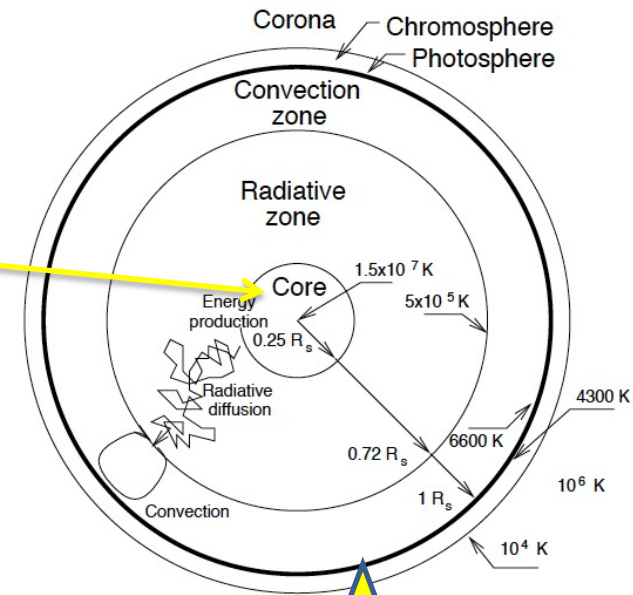


4 ^1H



1 ^4He

+ Energy



1 **Helium nucleus** has a mass that is smaller than the combined mass of the **4 Hydrogen nuclei**.

That “missing mass” is converted to energy to power the Sun.

Net reaction:



Mass of 4 ^1H	6.6943	10^{-27}	kg
Mass of 1 ^4He	6.6466	10^{-27}	kg
	0.0477	10^{-27}	kg (0.7%)

Using $E=mc^2$ each fusion releases

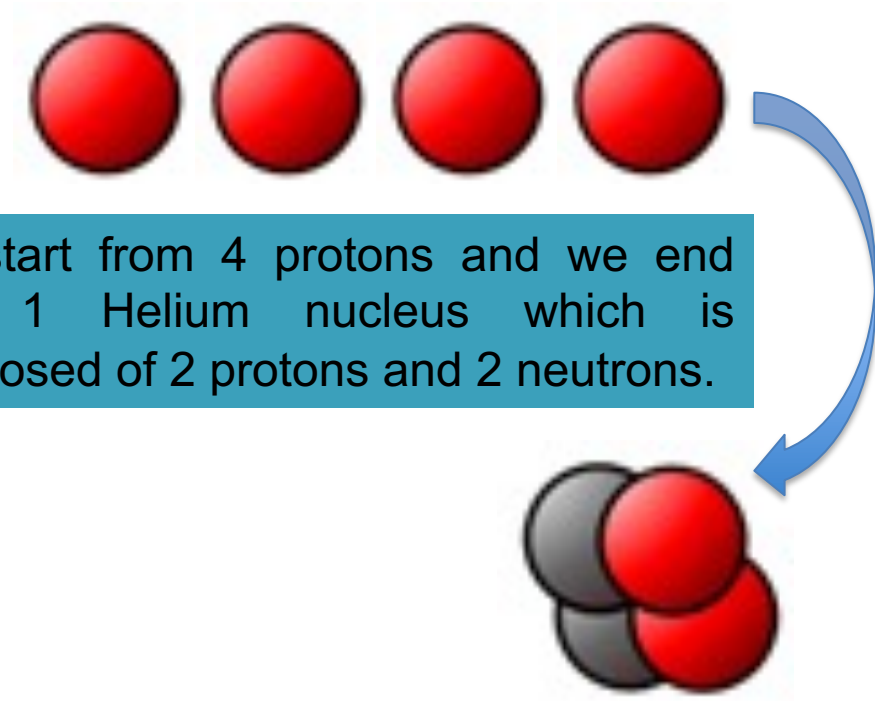
$$0.0477 \cdot 10^{-27} \text{ kg} \cdot \left(3 \cdot 10^8 \frac{\text{m}}{\text{s}} \right)^2 = 4.3 \cdot 10^{-12} \text{ J} \xrightarrow{1\text{eV}=1.6 \cdot 10^{-19} \text{ J}} 26.7 \text{ MeV}$$

Each second about 600 million tons of Hydrogen is converted into about 596 million tons of Helium-4. The remaining 4 million tons (actually **4.26 million tons**) are **converted into energy**.

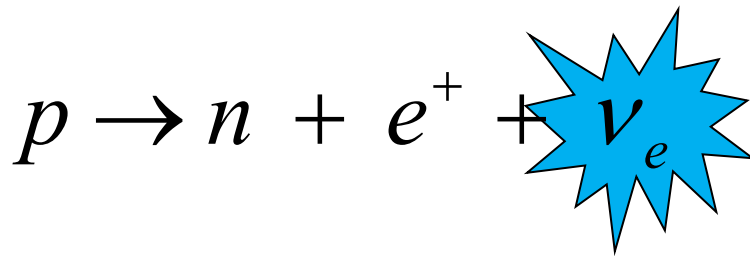
$$L_{\text{um}} = 4.26 \cdot 10^9 \text{ kg} \cdot \left(3 \cdot 10^8 \frac{\text{m}}{\text{s}} \right)^2 = 3.846 \cdot 10^{26} \text{ W}$$

The current luminosity of the Sun is **$3.846 \cdot 10^{26}$ Watts**

What about neutrinos?



This means that we have to transform
2 protons into 2 neutrons:



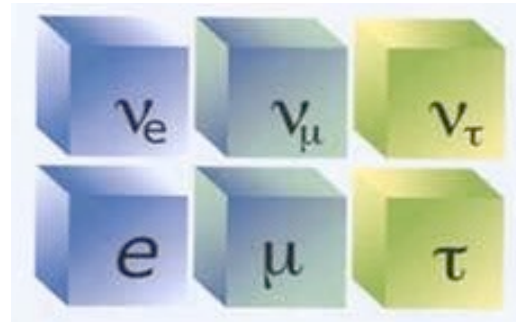
In the inverse beta decay a proton becomes a neutron emitting a **positron** and an **electron neutrino** ν_e

To each charged lepton it is associated a well defined neutrino

$$\nu_e \longleftrightarrow_{\text{associated}} e$$

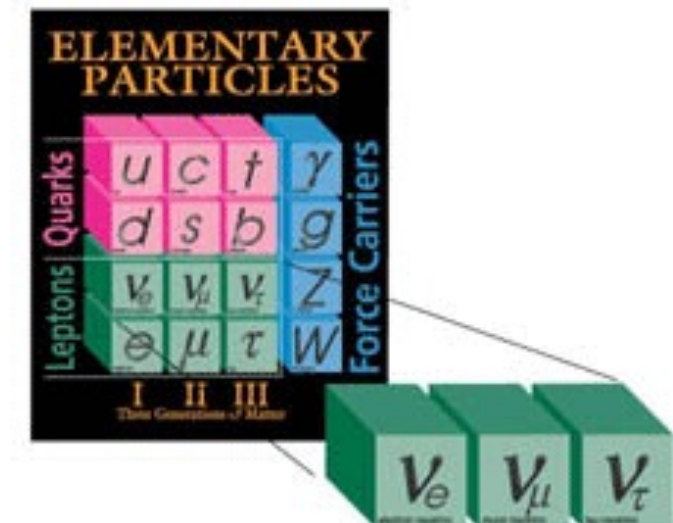
$$\nu_\mu \longleftrightarrow_{\text{associated}} \mu$$

$$\nu_\tau \longleftrightarrow_{\text{associated}} \tau$$

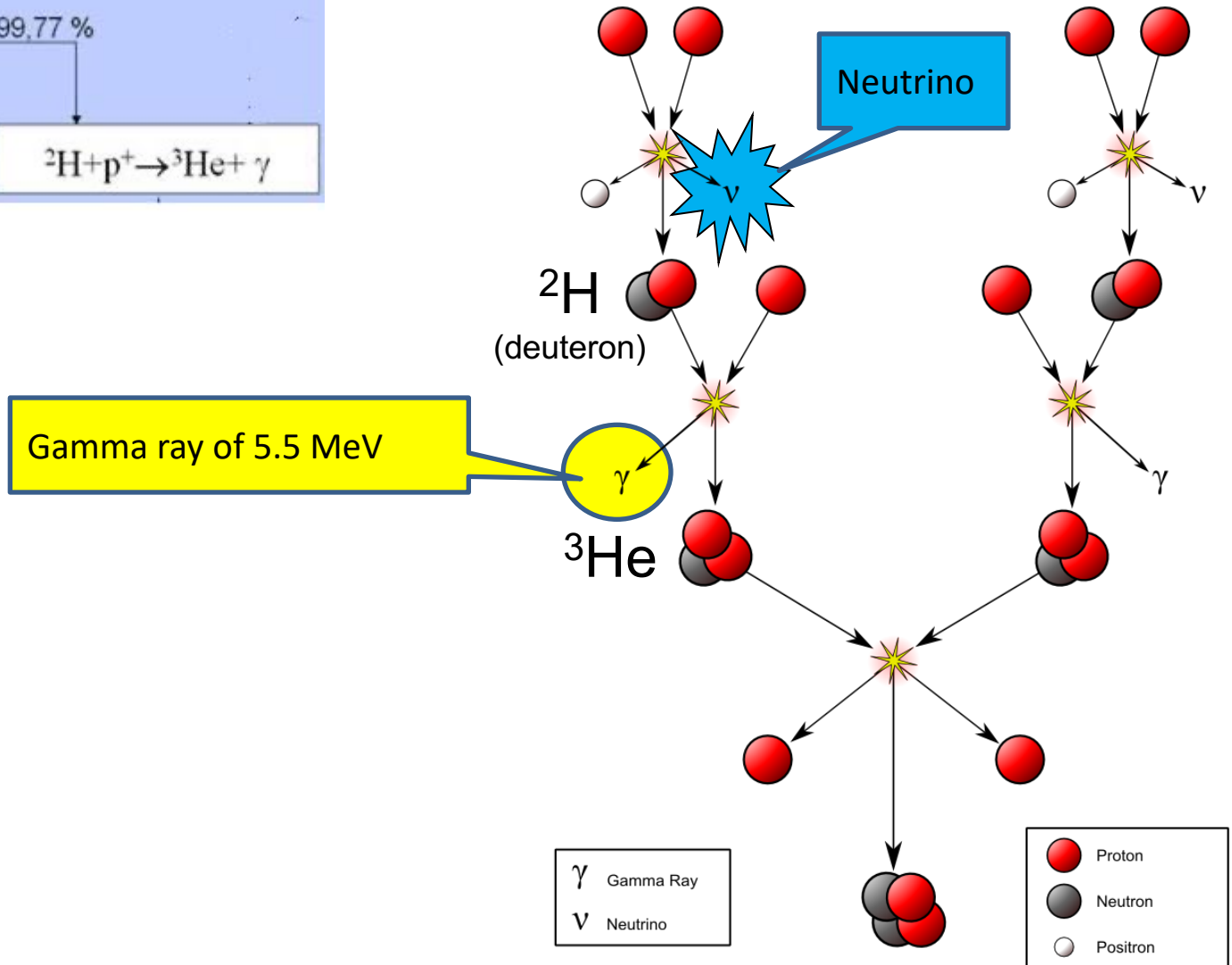
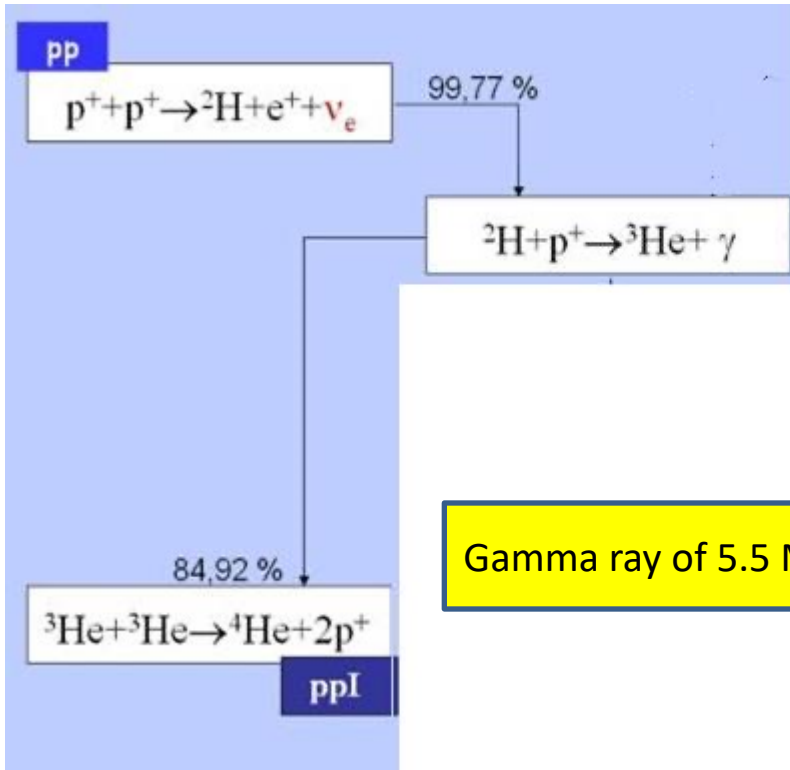


A neutrino of one “flavour”, interacting with matter, will produce a charged lepton of the same flavour

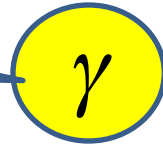
There are **3 types of neutrinos** but the **inverse β -decay** is possible only with electron neutrinos



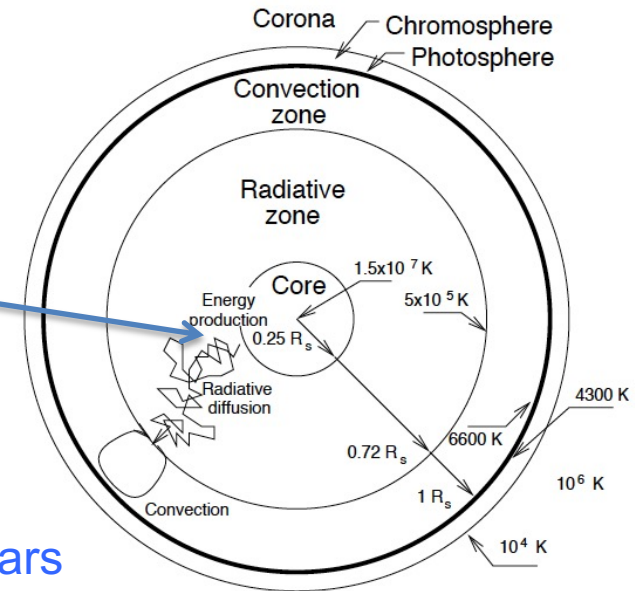
From protons to helium nucleus : The ppl chain



Gamma ray of 5.5 MeV



The 5.5 MeV gamma rays are absorbed in only a **few millimeters** of solar plasma and then re-emitted again in random direction (and at slightly lower energy)



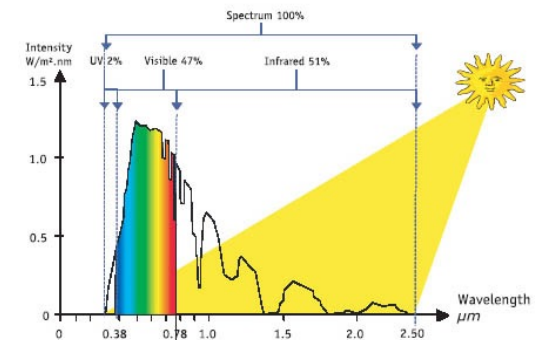
Gamma rays take **10,000 to 170,000 years** to reach the surface of the Sun.

Each gamma ray created in the core of the Sun is converted into **several million of visible light photons** (energy some eV) before escaping into space. The photons escape as visible light.

From 1 photon of some 10^6 eV to some 10^6 of photons of some eV

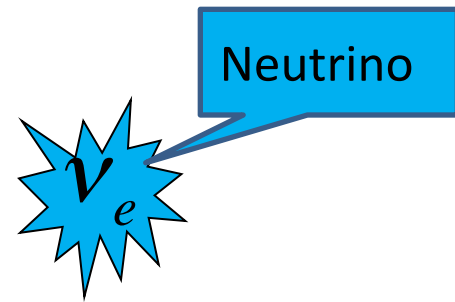
$$1 \gamma [\approx 10^6 \text{ eV}] \Rightarrow 10^6 \gamma' s [\approx \text{eV}]$$

SOLAR SPECTRUM



Neutrinos, unlike charged leptons and quarks, interact only via weak force.

Typical cross section are $\sigma \approx 10^{-45} \text{ cm}^2$ (It's depends on energy!)



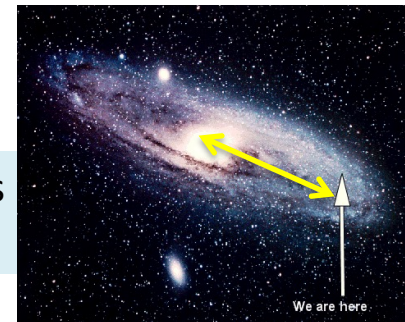
$$\text{absorbtion lenght} \quad \lambda = \frac{1}{n \cdot \sigma}$$

(n number of atoms per cm^3)

$$\lambda = \frac{1}{n\sigma} = \frac{1}{\frac{6.023 \cdot 10^{23}}{18} \frac{n \text{ atoms}}{\text{cm}^3} \cdot 10^{-45} \text{ cm}^{-2}} \approx 3 \cdot 10^{21} \text{ cm}$$

$$\lambda \approx 3 \cdot 10^{21} \text{ cm} = 3 \cdot 10^4 \text{ ligh year}$$

About the distance from us
to the Galactic Center



Since neutrinos interact with matter only via the weak force, neutrinos generated by solar fusion pass immediately out of the core and into space.

The study of solar neutrinos was conceived as a way *to test* the nuclear fusion reactions at the core of the Sun.

“.....to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.”



Davis and Bahcall

Phys. Rev. Lett. 12, 300–302 (1964)

Solar Neutrinos. I. Theoretical

John N. Bahcall California Institute of Technology, Pasadena, California

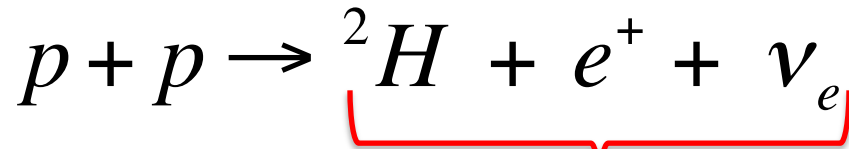
Phys. Rev. Lett. 12, 303–305 (1964)

Solar Neutrinos. II. Experimental

Raymond Davis, Jr.

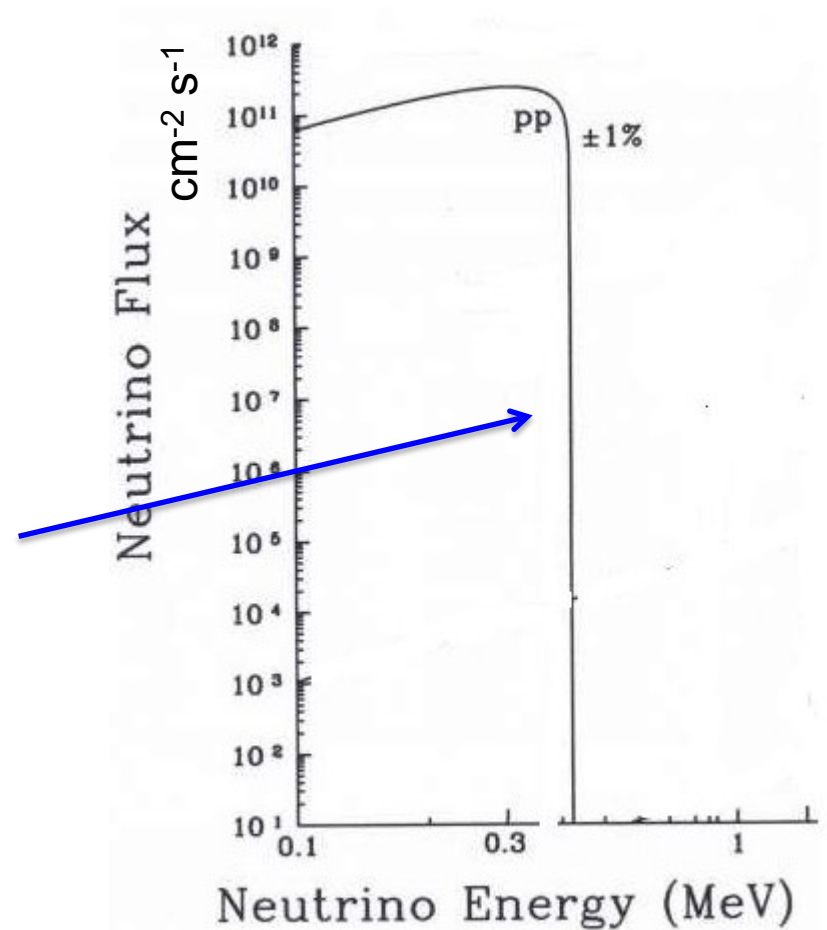
Chemistry Department, Brookhaven National Laboratory, Upton, New York

The neutrino spectrum



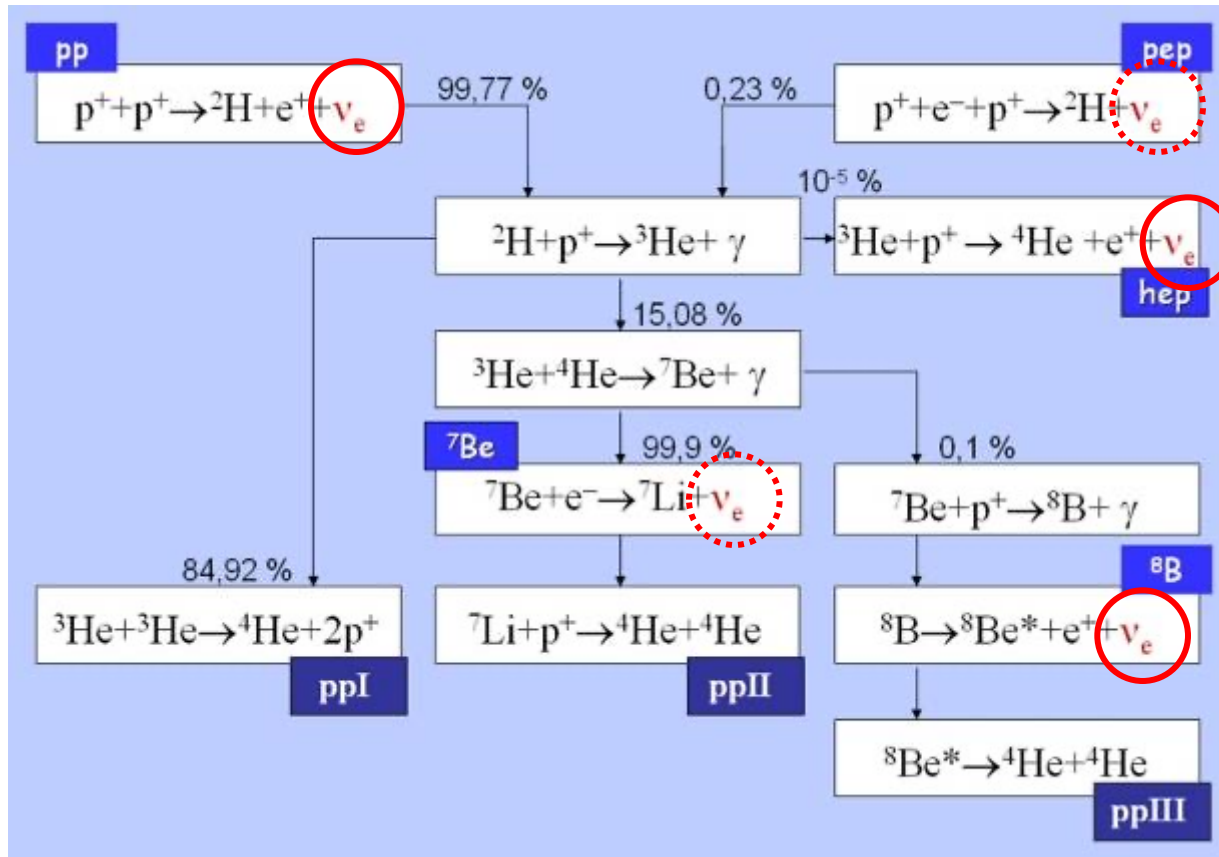
$$Q_{value} = 0.42 \text{ MeV}$$

We have **3 bodies in the final state**; this means that the emitted neutrino (like the electron) has a **continuous spectrum** extending from 0 to 0.42 MeV.



The pp chain

There are different steps in which energy (and neutrinos) are produced



ν from:

pp

pep

${}^7\text{Be}$

${}^8\text{B}$

hep

Monochromatic ν 's
(2 bodies in the final state)

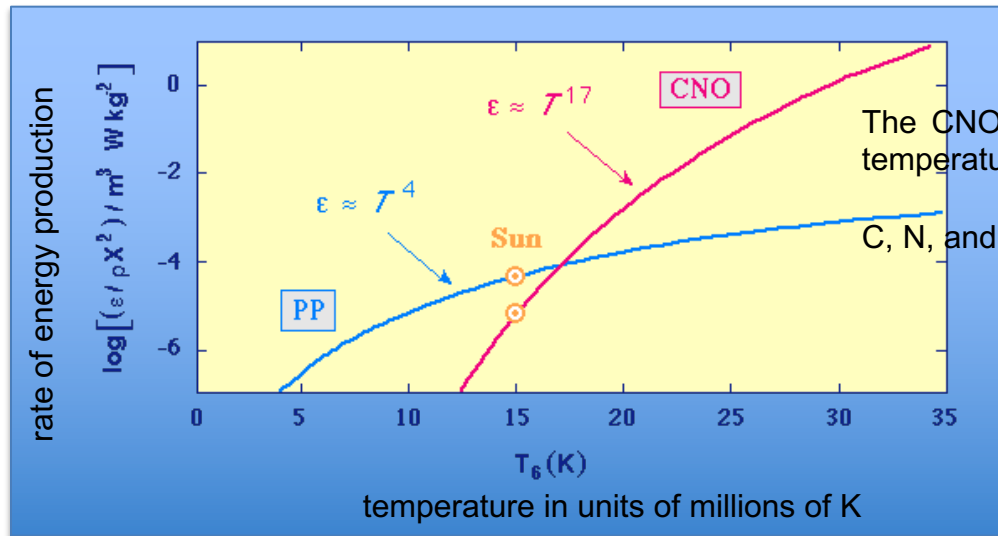
Each neutrino is labeled according to the reaction in which it is emitted:

- pp-neutrinos
- pep-neutrinos
- beryllium_seven-neutrinos
- boron_high-neutrinos
- hep-neutrinos

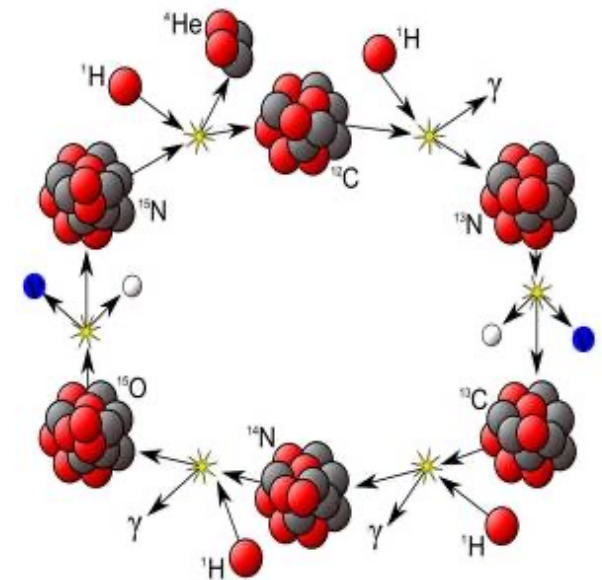
The CNO cycle

.... but pp chain is not the only reaction that transform protons into helium

There is also the **CNO cycle** that become the dominant source of energy in stars heavier than the Sun



In the Sun the CNO cycle represents only 1-2 %



The CNO cycle has a strong temperature dependence

C, N, and O act as catalyzers

CNO Neutrinos

Neutrinos are also produced in the CNO cycle

ν from:

^{13}N

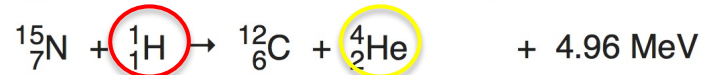
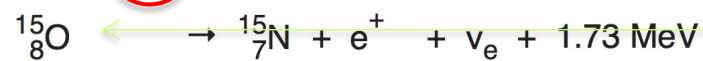
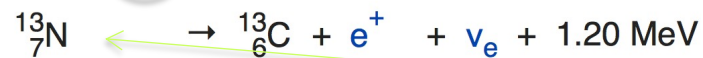
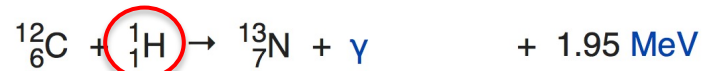
^{15}O

^{17}F

The CNO cycle

https://en.wikipedia.org/wiki/CNO_cycle

CNO-I carbon–nitrogen cycle (CN cycle),



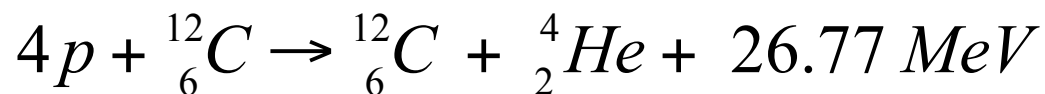
+ 2.044 MeV (1.022 MeV x 2
dell'annichilazione dei positroni)

26.77 MeV

ν from:

${}^{13}\text{N}$

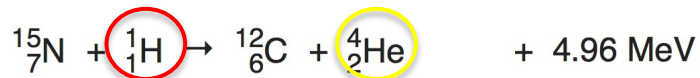
${}^{15}\text{O}$



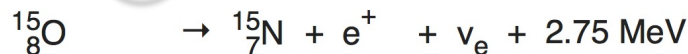
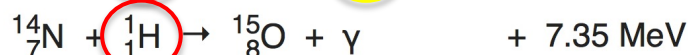
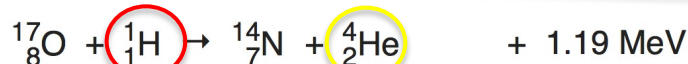
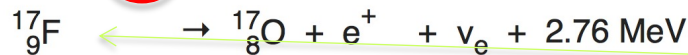
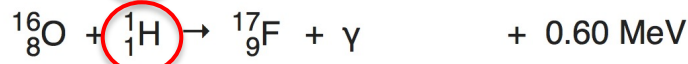
The CNO cycle

CNO-II

Nello **0.04%** dei casi l'ultima reazione



forma **Ossigeno-16** più un gamma



ν from:

${}^{17}\text{F}$

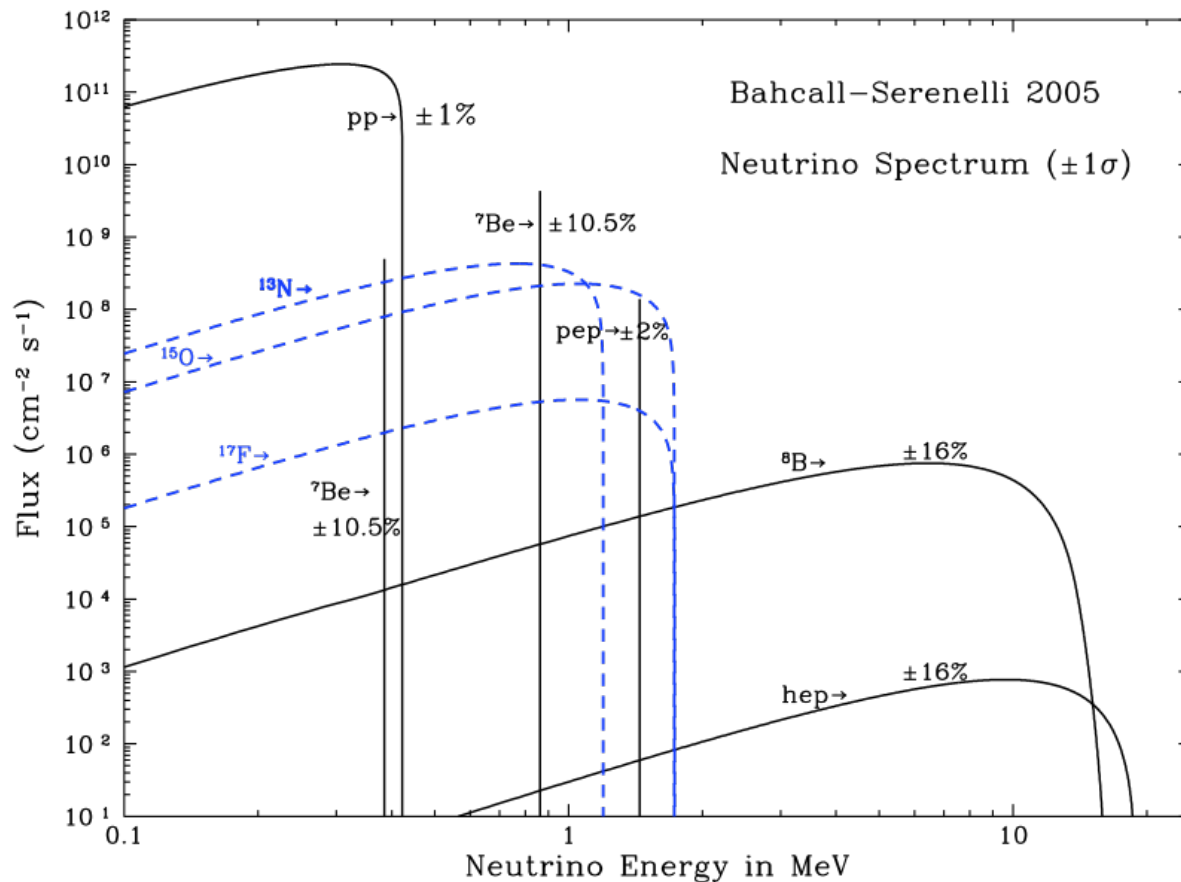
esistono altri due cicli subdominanti detti:

CNO-III in cui al posto del Azoto-14 + alfa si forma Fluoro-18 + gamma

e

CNO-IV in cui al posto del azoto-15 –alfa del ciclo del CNO-III si forma Fluoro-19 - gamma

Neutrino energy spectrum as predicted by the Solar Standard Model (SSM)



ν from:

pp

pep

^7Be

^8B

hep

ν from:

^{13}N

^{15}O

^{17}F

Monochromatic ν 's

^7Be :

384 keV (10%)

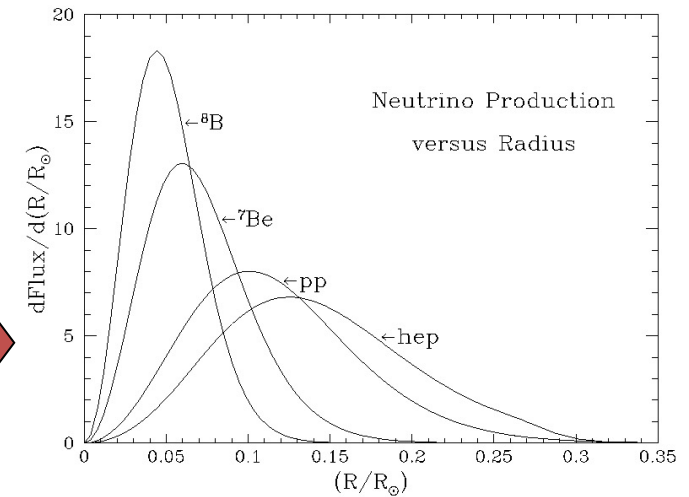
862 keV (90%)

pep:

1.44 MeV

Distributions of neutrino production

Radial distributions of neutrino production inside the Sun, as predicted by the SSM

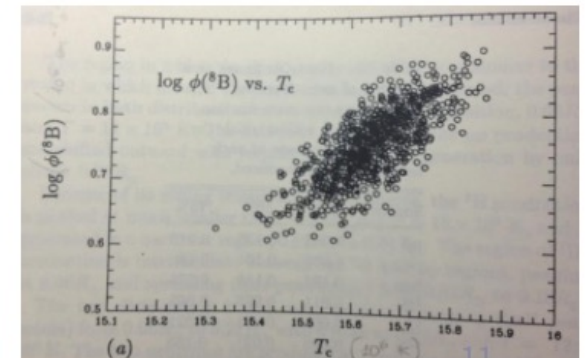
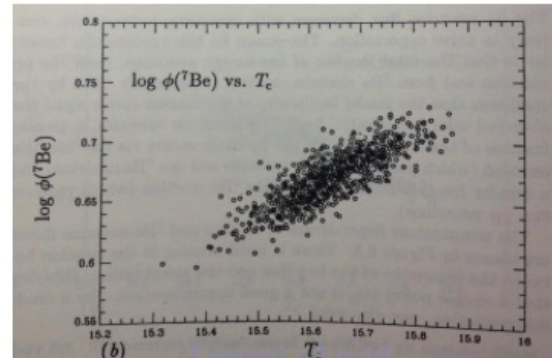
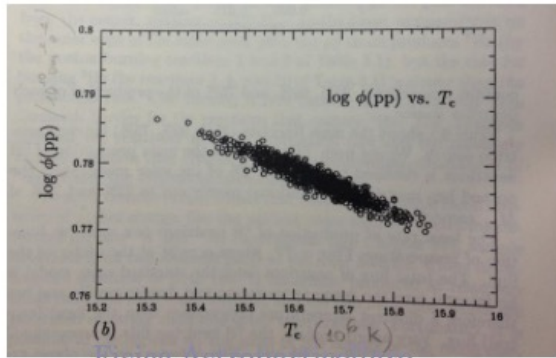


e hanno dipendenze molto diverse dalla temperatura T_c del nucleo del sole (questo perché ci sono potenziali coulombiani da superare):

$$\phi(pp) \sim T_c^{-1.2}$$

$$\phi(^7\text{Be}) \sim T_c^8$$

$$\phi(^8\text{B}) \sim T_c^{18}$$



La forte dipendenza da T_c rende molto più “robusta” la previsione teorica dei flussi di neutrini per il **pp** (**$\approx 1\%$**) che non per i flussi di neutrini da ^7Be (**$\approx 10\%$**) e ^8B (**$\approx 15\%$**).

How many neutrinos reach the Earth?

The current luminosity of the Sun is $3.846 \cdot 10^{26}$ Watt

The distance Earth-Sun is about $1.5 \cdot 10^{11}$ m

$$Lum_{at\ Earth} = \frac{3.846 \cdot 10^{26} \text{ W}}{4\pi (1.49 \cdot 10^{11} \text{ m})^2} = 1.370 \cdot 10^3 \frac{J}{s \cdot m^2}$$

$$\frac{1.370 \cdot 10^3 \frac{J}{s \cdot m^2}}{1.6 \cdot 10^{-19} \frac{J}{eV}} = \frac{0.856 \cdot 10^{18} \frac{eV}{s \cdot cm^2}}{\left(\frac{26.7 \cdot 10^6 eV}{2\nu_e} \right)} = 6.4 \cdot 10^{10} \frac{\nu_e}{s \cdot cm^2}$$

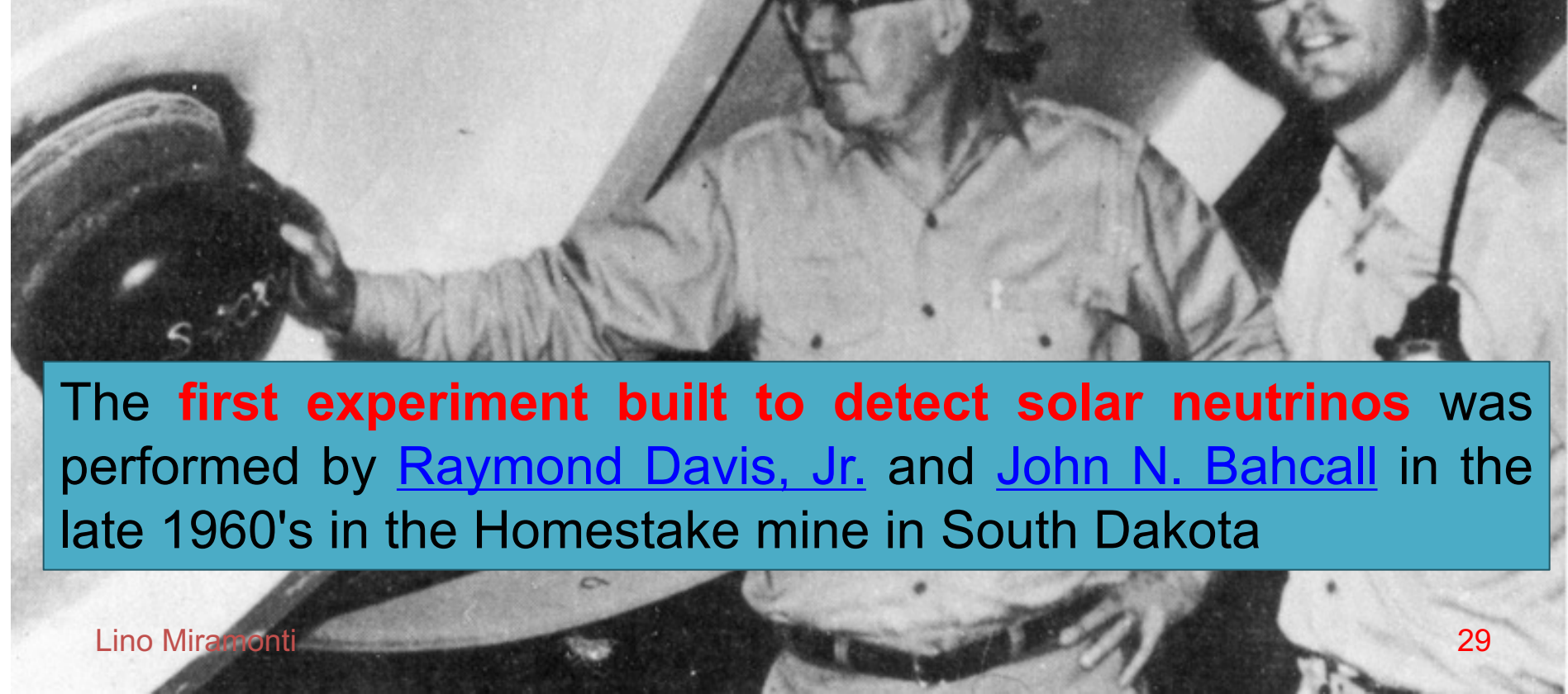
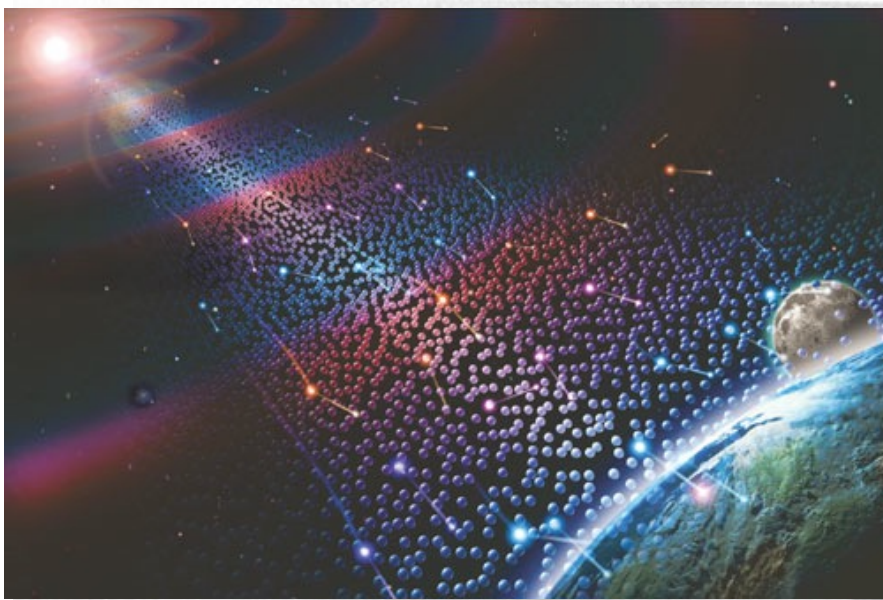
For each reaction we have 26.7 MeV plus 2 ν_e

Numero di neutrini emessi dal Sole:

$$N_\nu = 1.8 \cdot 10^{38} \text{ v/s}$$

2

Solar neutrinos detection



The **first experiment built to detect solar neutrinos** was performed by [Raymond Davis, Jr.](#) and [John N. Bahcall](#) in the late 1960's in the Homestake mine in South Dakota

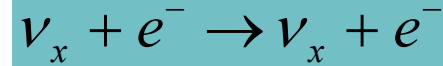
How to detect Solar Neutrinos?

There are 2 possible ways to detect solar neutrinos:

- **radiochemical experiments**



- **real time experiments**



$$\begin{aligned}\sigma(\nu_e e) &\approx 1.0 \cdot 10^{-44} E_{MeV} cm^2 \\ \sigma(\nu_{\mu,\tau} e) &\approx 0.15 \cdot 10^{-44} E_{MeV} cm^2\end{aligned}$$

$$\frac{\sigma(\nu_{\mu,\tau} e)}{\sigma(\nu_e e)} \approx \frac{1}{6}$$

In **radiochemical experiments** people use isotopes which, once interacted with an electron neutrino, produce radioactive isotopes.

Only ν_e

In **real time experiments** people detect the light created from the electron scattered by the impinging neutrinos

All ν_x type

How many Solar Neutrinos we can catch?

The **production rate R** is given by

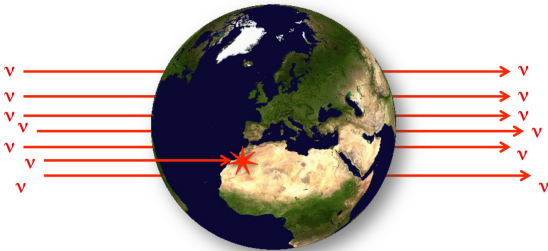
$$R = N \int \Phi(E) \sigma(E) dE$$

where

- Φ is the solar neutrino **flux**
- σ is the **cross section**
- N is the number of **target atoms**.

With a typical **neutrino flux of $10^{10} \text{ v cm}^{-2} \text{ s}^{-1}$** and a **cross section of about 10^{-45} cm^2** we need about 10^{30} target atoms (that correspond to ktons of matter) **to produce one event per day.**

Why is it so hard to detect them?



- With $E_\nu = 11 \text{ MeV}$ the mean free path in lead is 350 billion kilometer
- In earth ~3 out of 1 billion neutrinos would interact

with typical

$$\Phi \approx 10^{10} \frac{\text{v}}{\text{cm}^2 \text{s}}$$

with typical

$$\sigma \approx 10^{-45} \text{ cm}^2$$

10^{30} target atoms
(ktons of matter!)

$\Rightarrow$

1 event per day

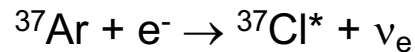
Homestake: *The first solar neutrino detector*

Large tank of 615 tons of liquid containing ^{37}Cl .

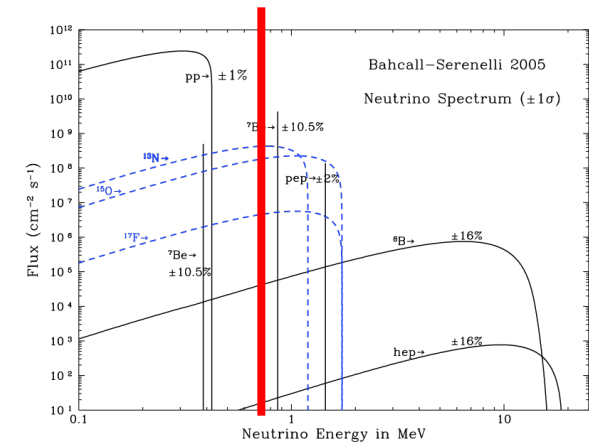
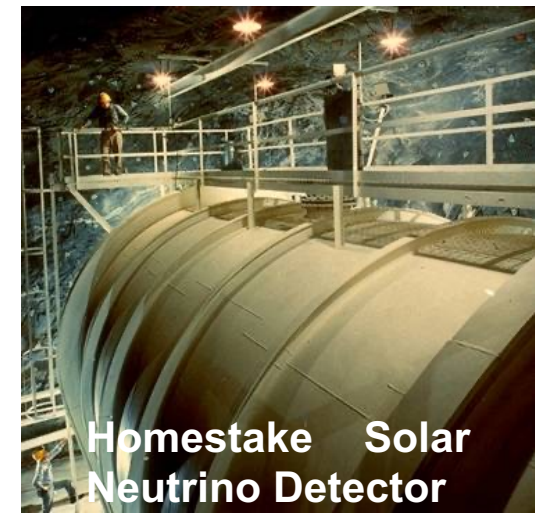
Neutrinos are detected via the reaction:



^{37}Ar is radioactive and decays by EC with a $\tau_{1/2}$ of 35 days into $^{37}\text{Cl}^*$

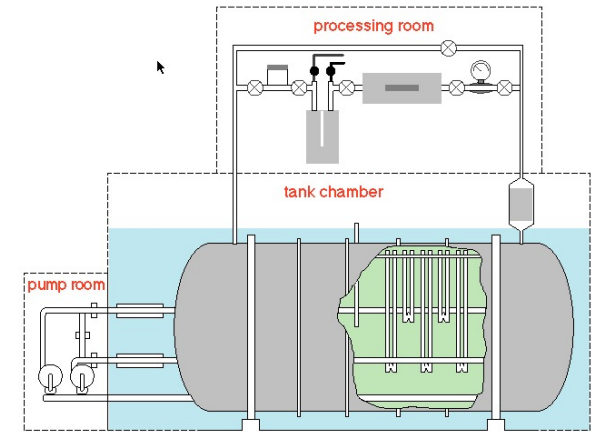


Once a month, bubbling helium through the tank, the ^{37}Ar atoms were extracted and counted (*only ≈ 5 atoms of ^{37}Ar per month in 615 tons C_2Cl_4*).



$$E_{th} = 814 \text{ keV}$$

Dopo un tempo di presa dati da uno a circa tre mesi, l'argon veniva estratto dalla soluzione **flussando azoto**, purificato e inserito in contatori proporzionali miniaturizzati, in grado di rivelare gli elettroni di 2.82 keV emessi per effetto Auger.



RISULTATO FINALE

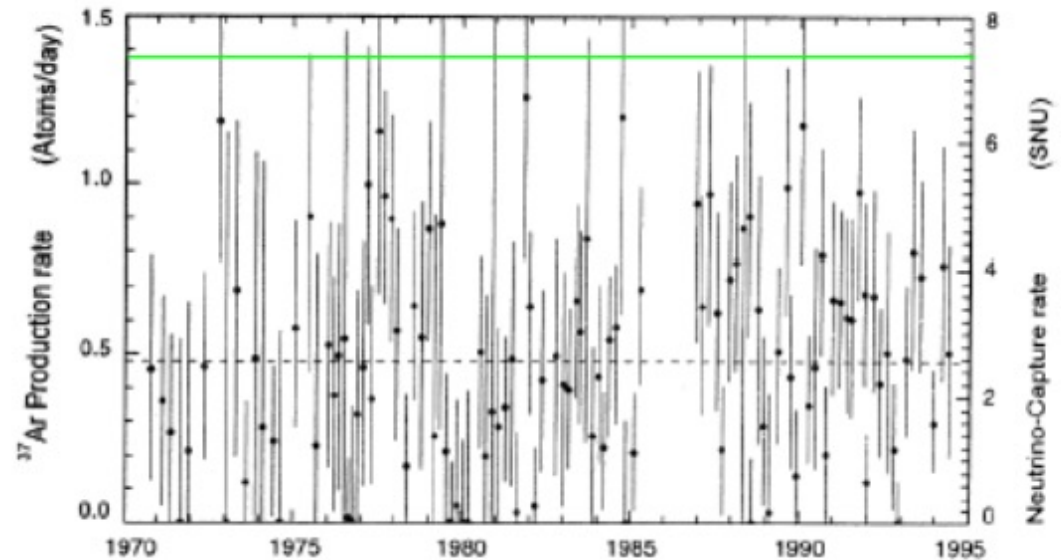
$$R_{\nu}^{\text{spe}} = (2.56 \pm 0.23) \text{ SNU}$$

↕

$$R_{\nu}^{\text{th}} = (8.1 \pm 1.2) \text{ SNU} \text{ [BS05]}$$

⇓

Deficit di 2/3 nella rate:
nascita del **Solar Neutrino Problem**



1 SNU (Solar Neutrino Unit) = 1 capture/sec/ 10^{36} atoms

The number of detected neutrino was about **1/3** lower than the number of expected neutrino → **Solar Neutrino Problem (SNP)**

Possible Explanations to the SNP

❑ Standard Solar Model is not correct

.... **but** Solar models have been tested independently by **helioseismology**, and the standard solar model has so far passed all the tests.

beside Non-standard solar models seem very unlikely.

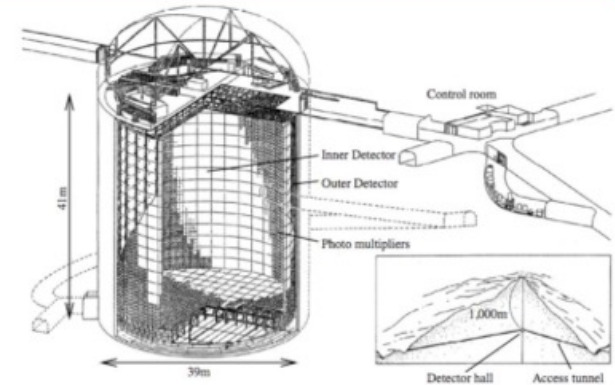
❑ Homestake is wrong

for instance some inefficiencies in the counting rate.

❑ Something happens to ν 's travelling from the core of the Sun to the Earth

Kamiokande & SuperKamiokande: *Real time detection*

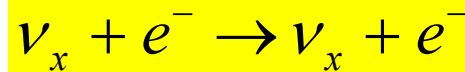
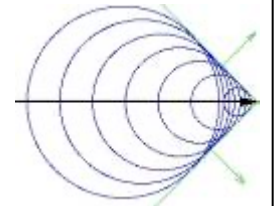
In 1982-83 was built in Japan the **first real time detector**.
It consisted in a Large water Cherenkov Detector



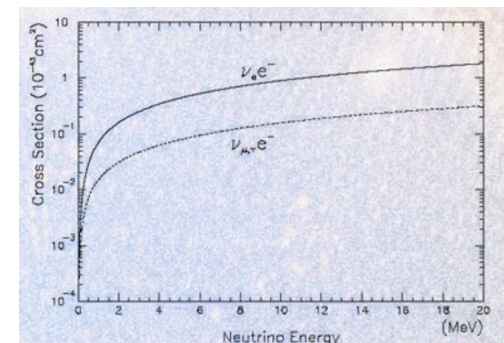
Entrambi situati nella miniera di Kamioka in Giappone a 2700 mwe di profondità. Kamiokande ha funzionato dal 1983 al 1996 con lo scopo originario di cercare il decadimento del protone, mentre SuperKamiokande è versione successiva e ampliata del precedente, ed ha operato dal 1996 al 2004.

In real time experiments people looks for the **Cherenkov light** produced by the electrons scattered by an impinging neutrino
(*soglia per gli e^- = 0.77 MeV*)

Electrons are accelerated to speeds $v > c/n$ "faster than light".

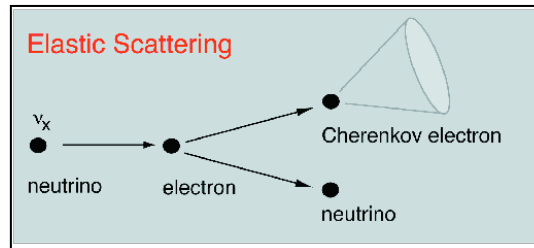


$$\sigma_{\nu_e} : \sigma_{\bar{\nu}_e} : \sigma_{\nu_{\mu,\tau}} : \sigma_{\bar{\nu}_{\mu,\tau}} \cong 1 : 0.42 : 0.16 : 0.14 \quad \sqrt{s} \gg m_e$$



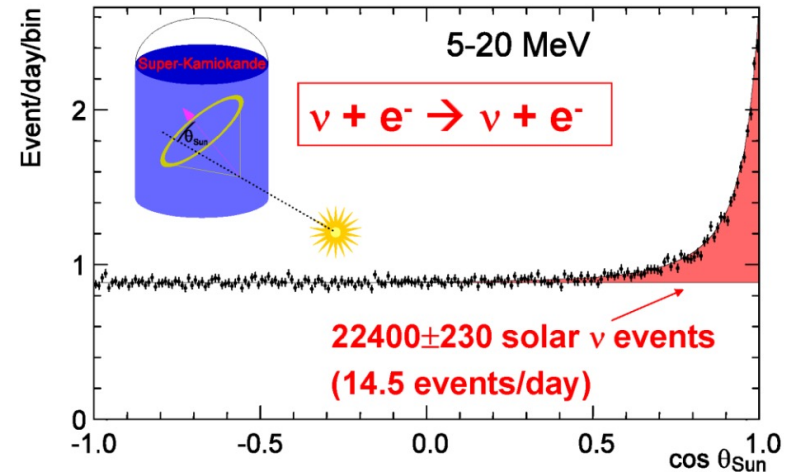
Kamiokande & SuperKamiokande: *Real time detection*

per $E_\nu \gg m_e$ l'elettrone mantiene la direzione del neutrino incidente, questa informazione viene sfruttata per individuare gli eventi da neutrino solare e distinguerli, ad esempio, da quelli atmosferici.



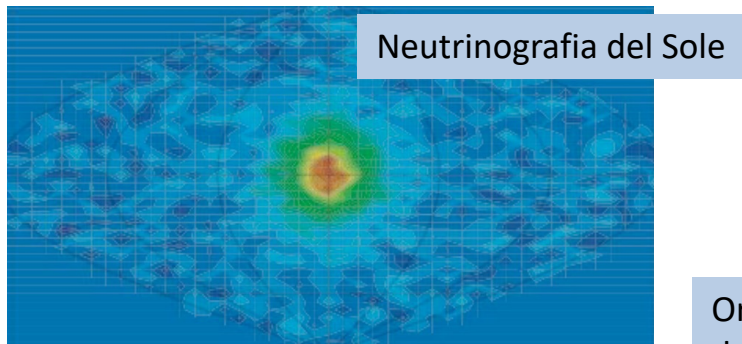
Super-Kamiokande-I solar neutrino data

May 31, 1996 – July 13, 2001 (1496 days)



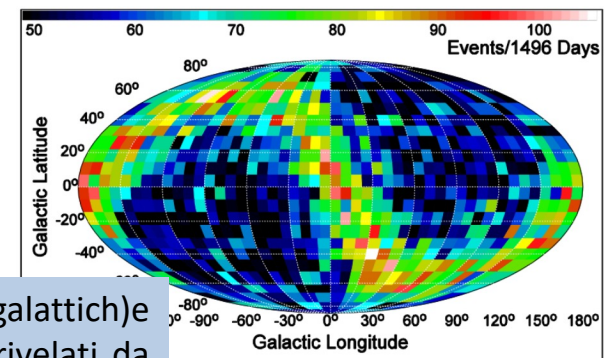
θ Angolo tra la direzione di rinculo dell'elettrone ricostruita e direzione del Sole

Grazie all'informazione della direzione della particella incidente furono i primi esperimenti in assoluto a confermare l'emissione di ν neutrini da parte del Sole.



Lino Miramonti

Orbita del Sole (in coordinate galattiche) e determinata con i ν neutrini rivelati da SK



Kamiokande & SuperKamiokande: *Real time detection*

Kamiokande

- 3000 tons of pure water
- 1000 PMTs

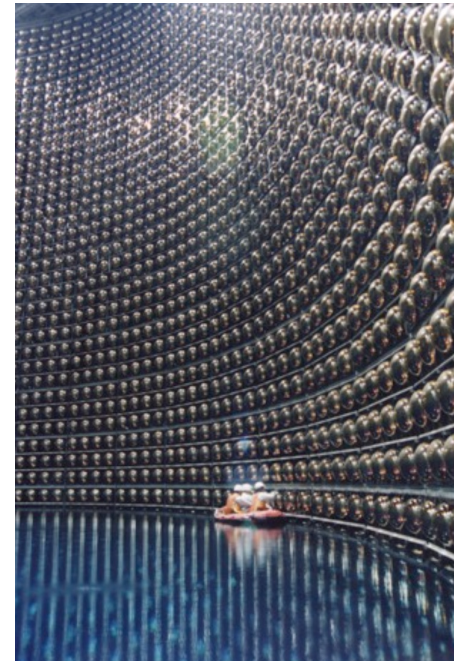
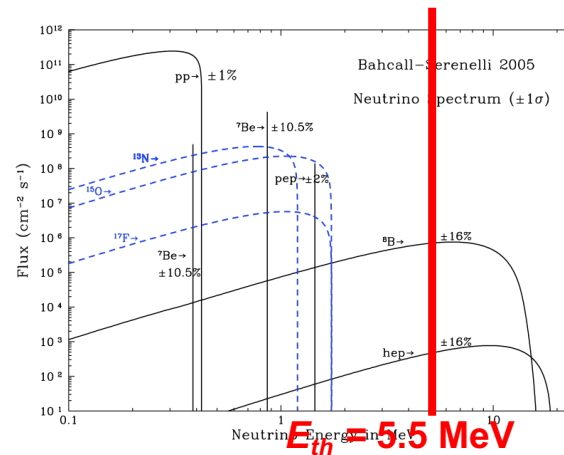
SuperKamiokande

- 50000 tons of pure water
- 11200 PMTs

$E_{th} = 7.5 \text{ MeV}$ (for Kamiokande)

$E_{th} = 5.5 \text{ MeV}$ (for SKamiokande)

only ${}^8\text{B}$ -neutrinos and hep-neutrinos



Kamiokande		[BP00]		SK
$\Phi_v^{spe} = (2.80 \pm 0.38) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$	$\longleftrightarrow$	$\Phi_v^{th} = (5.05 \pm 0.20) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$	$\longleftrightarrow$	$\Phi_v^{spe} = (2.35 \pm 0.10) \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$
		Risultati finali per flusso di ν da ${}^8\text{B}$ SNP non risolto		

Pros and cons of water Cherenkov real time experiments

Cons: In real time experiments the threshold is very high (> 5.5 MeV)

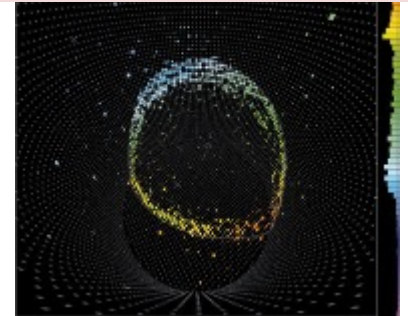
Pros:

Radiochemical experiments integrate in time and in energy.

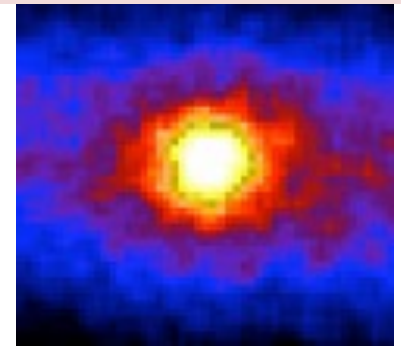
Unlike in radiochemical experiments, in real time experiments it is possible to obtain a **spectrum energy** and hence to distinguish the different neutrino contribution.

Furthermore, in water Cherenkov experiments thank to the fact that the scattered electron conserves the **direction** of the impinging neutrino, it is possible to infer the direction of the origin of the incoming neutrino and hence to point at the source. **Neutrinos come from the Sun!**

Ring of Cherenkov light



Picture of the center of the Sun made with neutrinos

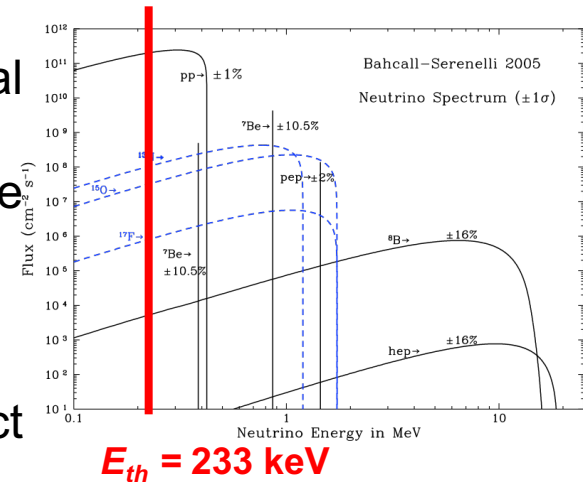


The number of detected neutrino was about **1/2** lower than the number of expected neutrino confirming the Solar Neutrino Problem.

...looking for pp neutrinos ...

Until the year 1990 there was no observation of the initial reaction in the nuclear fusion chain (i.e. pp-neutrinos). pp-neutrinos are **less model-dependent** and hence more robust to prove the validity of the SSM.

Two radiochemical experiments were built in order to detect solar **pp-neutrinos**; both employing the reaction:



Gallex

30 tonnes of natural gallium
(at LNGS Italy)

50 tons of metallic gallium
(at Baksan Russia)



SAGE

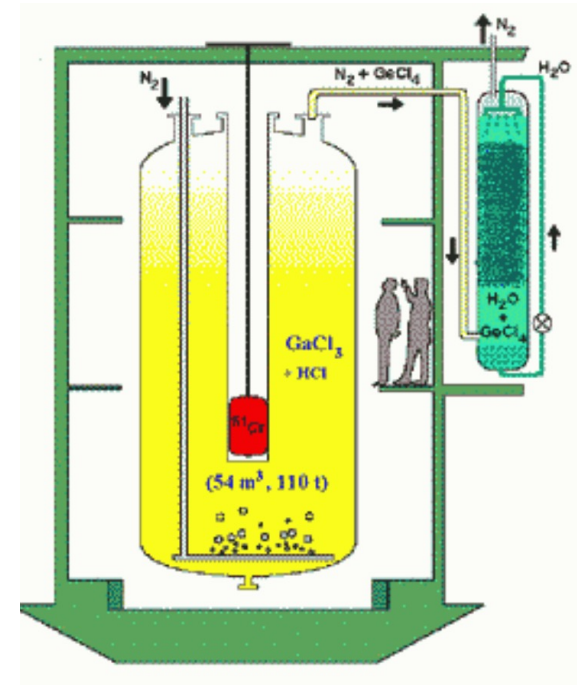
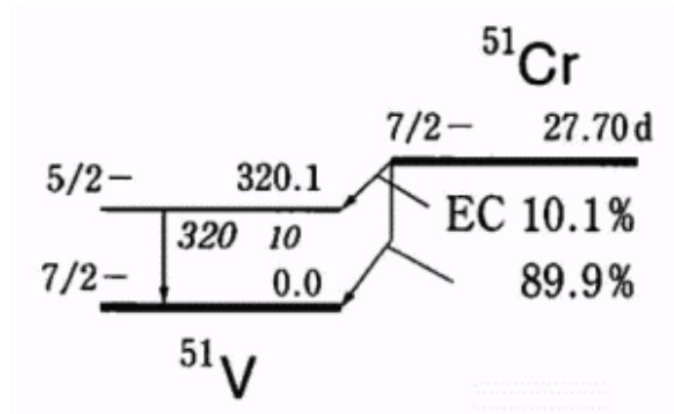
...looking for pp neutrinos ...

Calibration tests with an large intensity: **~1M** **artificial neutrino source** (**^{51}Cr**) confirmed the **efficiencies** of the detectors.

EC source, monoenergetic ν_e : 753 KeV (90%) & 433 keV (10%)

$T_{1/2} = 27.7$ days

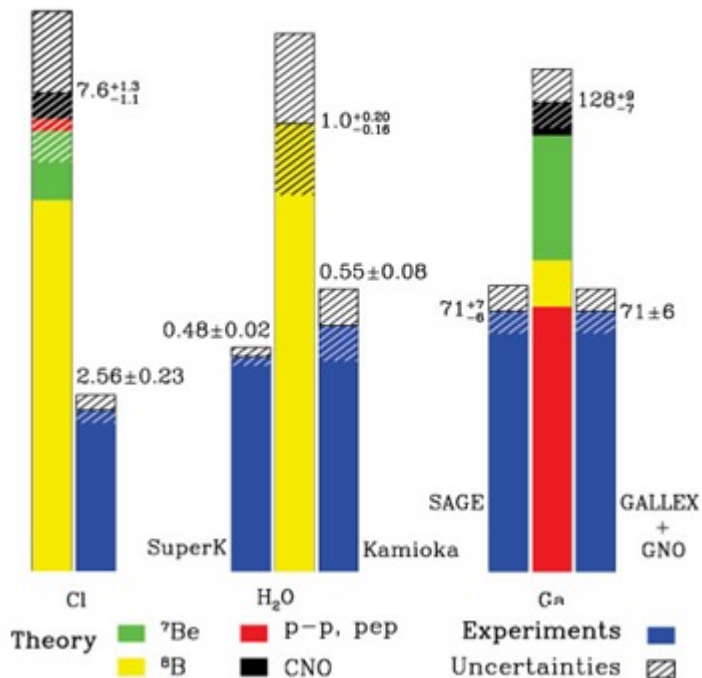
Produced by neutron irradiation of (stable) ^{50}Cr



Once again the measured neutrino signal was smaller than the one predicted by the standard solar model (**~ 60%**).

All experiments detect less neutrino than expected from the SSM !

Total Rates: Standard Model vs. Experiment
Bahcall-Pinsonneault 2000



Rate measurement	Reaction	Obs / Theory
Homestake	$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$	0.34 ± 0.03
Super-K	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.46 ± 0.02
SAGE	$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$	0.59 ± 0.06
Galex+GNO	$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$	0.58 ± 0.05

1 SNU (Solar Neutrino Unit) = 1 capture/sec/ 10^{36} atoms

..... something happens to neutrinos!

Neutrinos have the peculiar property that their **flavour eigenstates** do not coincide with their **mass eigenstates**.

Flavour eigenstates ν_e, ν_μ, ν_τ

$\neq$

Mass eigenstates ν_1, ν_2, ν_3

I neutrini nel Modello Standard

Nel **Modello Standard** i neutrini (antineutrini) sono descritti come **leptoni left-handed** (right-handed) a **spin 1/2** e **massa nulla**.

La parte di simmetria che afferisce a **$SU(2)_L$** , ossia alle **interazioni deboli**, è **chirale** e, pertanto, tratta in modo differente particelle aventi elicità left da quelle aventi elicità right: mentre le prime sono descritte attraverso la rappresentazione di dimensione due del gruppo, le seconde sono in rappresentazione banale.

Nel Modello Standard:

- i **leptoni left-handed** sono suddivisi in tre famiglie, ciascuna contenente un leptone carico ed un neutrino associato alla famiglia;
- i **leptoni right-handed** sono in stato di singoletto:

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L, \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L, \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L \quad (e)_R, (\mu)_R, (\tau)_R$$

In definitiva

il Modello Standard descrive i neutrini come particelle left-handed ed a massa nulla.

I neutrini possono mutare il loro sapore durante il volo:

I neutrini sono prodotti in interazioni deboli con un **sapore definito** e, poiché l'**autostato di massa** e l' **autostato di interazione** non coincidono, possono mutare il loro sapore durante il volo.

Sapore definito significa che ad esempio:

- Nel decadimento beta all'elettrone emesso è associato un ν_e
- Nel decadimento del pione al muone emesso è associato un ν_μ .
- Ecc.....

Un neutrino prodotto a $t = 0$ nell'autostato α può essere descritto come:

$$|\nu_\alpha\rangle = \sum_{i=1}^n U_{\alpha i}^* |\nu_i\rangle$$

Nella trattazione vengono usati

- indici greci per gli **autostati di sapore**,
- Indici latini per gli **autostati di massa**.

$$\nu_\alpha \equiv \nu_e, \nu_\mu, \nu_\tau$$

$$\nu_i \equiv \nu_1, \nu_2, \nu_3$$

con U matrice unitaria.

E' la trasformazione unitaria che lega gli autostati di massa con quelli di sapore.

Equivalentemente:

$$|\nu_i\rangle = \sum_{\alpha=1}^n U_{\alpha i} |\nu_\alpha\rangle$$

Ogni autostato di massa evolve nel sistema del laboratorio come:

$$|\nu_i(t)\rangle = e^{-i(E_i t - p_i L)} |\nu_i(0)\rangle$$

*Evoluzione
dell'autostato di massa*

dove L è la distanza percorsa nell'intervallo di tempo t .

Se si tiene conto che i neutrini sono approssimativamente senza massa si può scrivere

$$L = t; \quad E_i = \sqrt{p_i^2 + m_i^2} \approx p_i + \frac{m_i^2}{2E}$$

dove $E \sim p_i \sim p_j$. Si può scrivere

$$|\nu_\alpha(L)\rangle = \sum_{i=1}^n U_{\alpha i}^* e^{-i \frac{m_i^2}{2E} L} |\nu_i(0)\rangle$$

e, pertanto, la **probabilità di osservare un sapore β a distanza L** è pari a:

$$\langle \nu_\beta | \nu_\alpha(L) \rangle = \sum_{i=1}^n U_{\alpha i}^* e^{-i \frac{m_i^2}{2E} L} \sum_{j=1}^n U_{\beta j} \langle \nu_j | \nu_i \rangle = \sum_{i=1}^n U_{\alpha i}^* U_{\beta i} e^{-i \frac{m_i^2}{2E} L}$$

La probabilità di oscillazione è pertanto data da: $P_{\alpha\beta} = \left| \langle \nu_\beta | \nu_\alpha(L) \rangle \right|^2$

Trattazione a 2 sapori

La trattazione si semplifica molto nel caso si assuma **invarianza di CP** nel settore leptónico e si considerino **solo due sapori**.

In questo caso la matrice U diventa ortogonale con un solo angolo di mixing θ_{12} .

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} \\ -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix}$$

La **formulazione a due sapori** è appropriata per la discussione della transizione da

- ν_μ - ν_τ nel caso delle oscillazione dei **neutrini atmosferici** in quanto ν_e non gioca alcun ruolo e
- nei **neutrini solari** in cui la transizione avviene tra ν_e - ν_x (con ν_x superposizione tra ν_μ e ν_τ).

Queste approssimazioni sono possibili perché

- l'angolo θ_{13} è piccolo;
- due stati di massa sono molto ravvicinati rispetto al terzo.

e pertanto la **probabilità di oscillazione**, in questo caso, diventa:

$$P_{12}(L) = P_{21}(L) = \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{12}^2 L}{4E}$$

$$P(\nu_e \rightarrow \nu_{\mu,\tau}) = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$

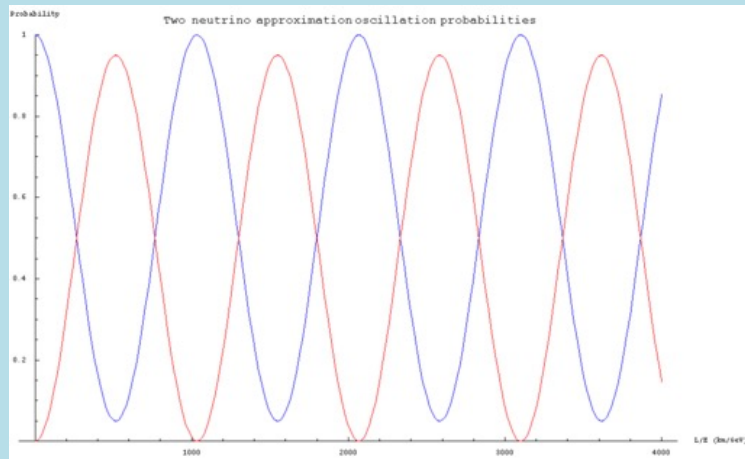
Probability of an electron neutrino produced at $t=0$ to be detected as a muon or tau neutrino

...Depends Upon Two Experimental Parameters:

- L – The distance from the ν source to detector (km)
- E – The energy of the neutrinos (GeV)

...And Two Fundamental Parameters:

- $\Delta m^2 = m_1^2 - m_2^2 \quad (eV^2)$
- $\sin^2 2\theta$



L/E (km/GeV)

This means that, for a given energy E and a detector at distance L it is possible to determine θ and Δm^2 .

The **blue curve** shows the probability of the original neutrino retaining its identity. The **red curve** shows the probability of conversion to the other neutrinos.

Mescolamento a **tre neutrini**

U is the Pontecorvo-Maki-Nakagawa-Sakata matrix .

Nel caso di mescolamento di **tre neutrini**, la matrice U , detta PMNS, viene descritta, in analogia con la matrice CKM, come una sequenza di rotazioni di Eulero per una matrice contenente le fasi di Majorana

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot \begin{pmatrix} e^{i\frac{\varphi_1}{2}} & 0 & 0 \\ 0 & e^{i\frac{\varphi_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1.40)$$

dove si è abbreviato $c_{ij} = \cos \theta_{ij}$ e $s_{ij} = \sin \theta_{ij}$.

Il mescolamento fra i tre neutrini viene parametrizzato in funzione di

- **tre angoli di mixing** (θ_{12} , θ_{23} , θ_{13}),
- **un fattore di fase δ di Dirac**, (il cui valore è legato alla **violazione di CP**),
- **due fasi di Majorana φ_1 e φ_2** che non influenzano la probabilità di oscillazione (hanno senso fisico solo se il neutrino è una particella di Majorana)

In caso di neutrino di Dirac $\varphi_1 = \varphi_2 = 0$ e $\delta \neq 0$.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad \begin{array}{l} \nu_e, \nu_\mu, \nu_\tau - \text{flavor eigenstates} \\ \nu_1, \nu_2, \nu_3 - \text{mass eigenstates with masses} \\ m_1, m_2, m_3 \end{array}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \exp(i\alpha_1) & 0 & 0 \\ 0 & \exp(i\alpha_2) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

3 angles: $\theta_{12}, \theta_{13}, \theta_{23}$

1 CP-violating Dirac phase: δ

2 CP-violating Majorana phases: α_1, α_2
(physical only if ν 's are Majorana fermions)

La probabilità di sopravvivenza risulta essere:

$$\begin{aligned}
 P(\nu_\alpha \rightarrow \nu_\beta) &= -4 \sum_{i>j} (U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j}) \sin^2(1.27 \Delta m_{ij}^2 \frac{L}{E}) \\
 &= -4[(U_{\alpha 1} U_{\beta 1} U_{\alpha 2} U_{\alpha 2}) \sin^2(1.27 \Delta m_{12}^2 \frac{L}{E}) \\
 &\quad + (U_{\alpha 1} U_{\beta 1} U_{\alpha 3} U_{\alpha 3}) \sin^2(1.27 \Delta m_{13}^2 \frac{L}{E}) \\
 &\quad + (U_{\alpha 2} U_{\beta 2} U_{\alpha 3} U_{\alpha 3}) \sin^2(1.27 \Delta m_{23}^2 \frac{L}{E})]
 \end{aligned}$$

Possiamo distinguere **due casi**:

For **small L/E** $\sin^2(1.27 \Delta m_{12}^2 \frac{L}{E}) \rightarrow 0$ $\Delta m_{13}^2 \approx \Delta m_{23}^2$:

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4[U_{\alpha 1} U_{\beta 1} U_{\alpha 3} U_{\beta 3} + U_{\alpha 2} U_{\beta 2} U_{\alpha 3} U_{\beta 3}] \sin^2(1.27 \Delta m_{23}^2 \frac{L}{E})$$

For **large L/E** the terms involving Δm_{23}^2 and Δm_{13}^2 are rapidly oscillating and average to 0.5

$$\begin{aligned}
 \sin^2(1.27 \Delta m_{23}^2 \frac{L}{E}) &\rightarrow \langle \sin^2(1.27 \Delta m_{23}^2 \frac{L}{E}) \rangle = \frac{1}{2} \\
 \sin^2(1.27 \Delta m_{13}^2 \frac{L}{E}) &\rightarrow \langle \sin^2(1.27 \Delta m_{13}^2 \frac{L}{E}) \rangle = \frac{1}{2}
 \end{aligned}$$

$$\begin{aligned}
 P(\nu_\alpha \rightarrow \nu_\beta) &= -4[(U_{\alpha 1} U_{\beta 1} U_{\alpha 2} U_{\beta 2}) \sin^2(1.27 \Delta m_{12}^2 \frac{L}{E}) \\
 &\quad + \frac{1}{2}(U_{\alpha 1} U_{\beta 1} U_{\alpha 3} U_{\beta 3} + U_{\alpha 2} U_{\beta 2} U_{\alpha 3} U_{\beta 3})]
 \end{aligned}$$

Replacing the elements U_{ij} with the mixing angle terms from the PMNS matrix

For **small** L/E

$$\begin{aligned}P(\nu_\mu \rightarrow \nu_\tau) &= \cos^2(\theta_{13})\sin^2(2\theta_{23})\sin^2(1.27\Delta m_{23}^2 \frac{L}{E}) \\P(\nu_e \rightarrow \nu_\mu) &= \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(1.27\Delta m_{23}^2 \frac{L}{E}) \\P(\nu_e \rightarrow \nu_\tau) &= \sin^2(2\theta_{13})\cos^2(\theta_{23})\sin^2(1.27\Delta m_{23}^2 \frac{L}{E})\end{aligned}$$

For **large** L/E

$$P(\nu_e \rightarrow \nu_{\mu,\tau}) = \cos^2(\theta_{13})\sin^2(2\theta_{12}) \sin^2(1.27\Delta m_{12}^2 \frac{L}{E}) + \frac{1}{2}\sin^2(2\theta_{13})$$

If **$\vartheta_{13}=0$** they reduce to:

For **small** L/E

$$\begin{aligned}P(\nu_\mu \rightarrow \nu_\tau) &= \sin^2(2\theta_{23})\sin^2(1.27\Delta m_{23}^2 \frac{L}{E}) \\P(\nu_e \rightarrow \nu_\mu) &= 0 \\P(\nu_e \rightarrow \nu_\tau) &= 0\end{aligned}$$

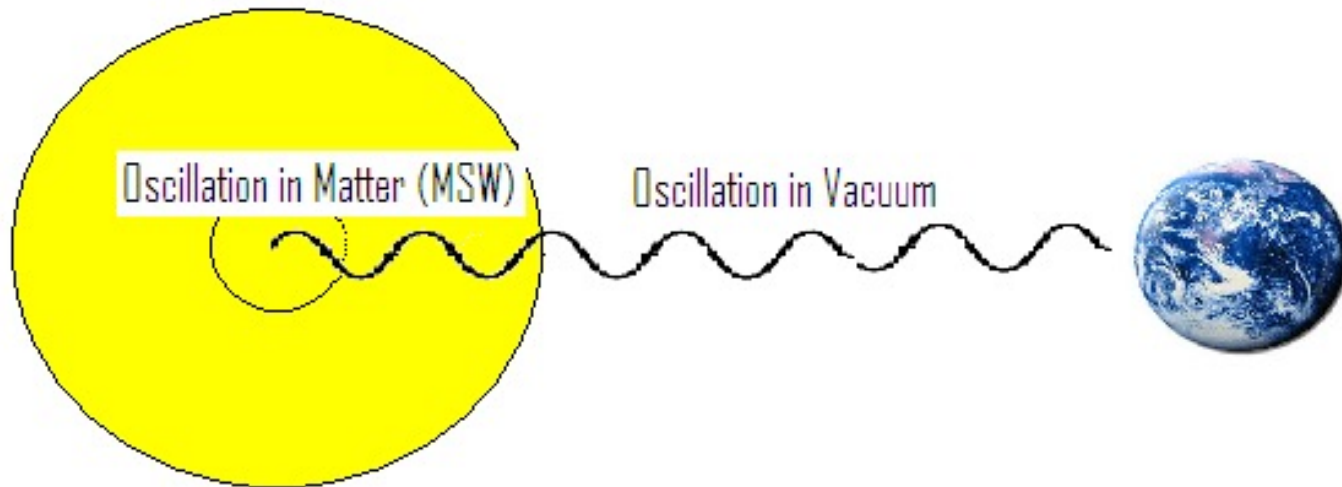
For **large** L/E

$$P(\nu_e \rightarrow \nu_{\mu,\tau}) = \sin^2(2\theta_{12}) \sin^2(1.27\Delta m_{12}^2 \frac{L}{E})$$

The Mikheyev Smirnov Wolfenstein Effect (**MSW**) ... or Matter Effect

Neutrino oscillations can be enhanced by traveling through matter

(The core of the Sun has a density of about 150 g/cm^3)



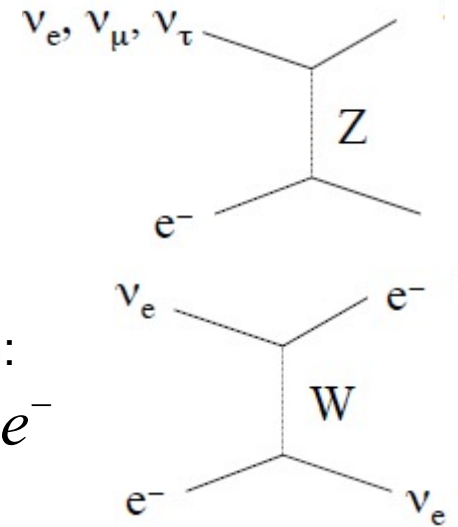
This happens because the Sun is made of **up/down quarks** and **electrons**

ν_e, ν_μ, ν_τ . All neutrinos can interact through **NC** equally.

ν_e , Only electron neutrino can interact through **CC** scattering:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

The interaction of ν_e is different from ν_μ and ν_τ .



The MSW effect gives for the **probability** of an electron neutrino produced at $t=0$ to be detected as a muon neutrino:

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_m \sin^2\left(\frac{\pi x W}{\lambda_{osc}}\right)$$

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{W^2}$$

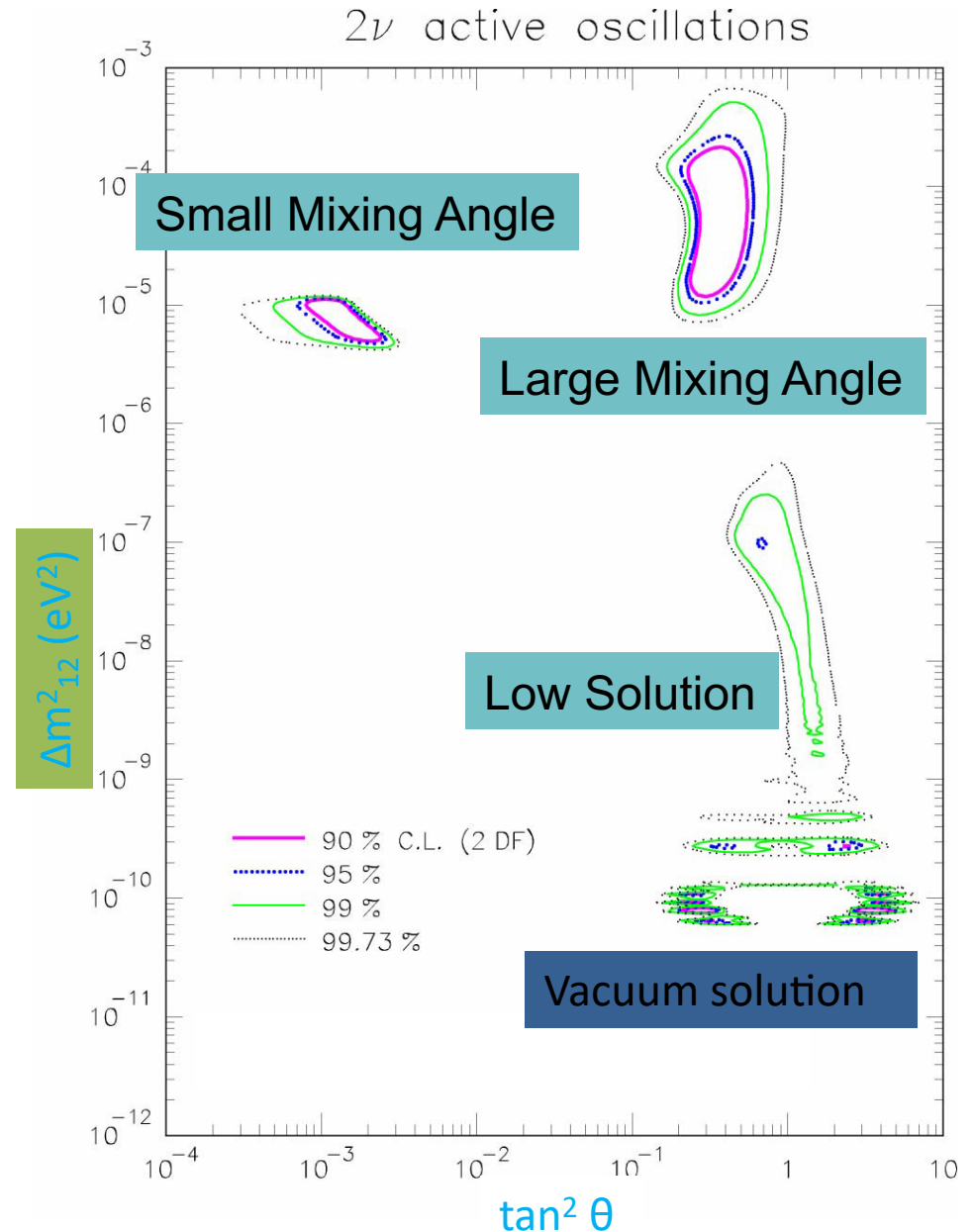
$$W^2 = \sin^2 2\theta + (D - \cos^2 2\theta)^2$$

$$D = \sqrt{2} G_F N_e \frac{2E_\nu}{\Delta m^2}$$

N_e being the **electron density**.

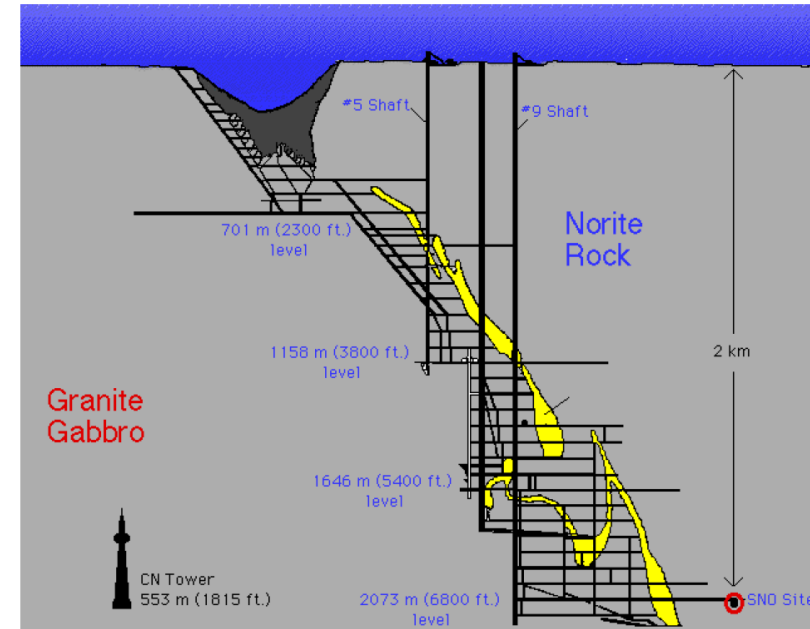
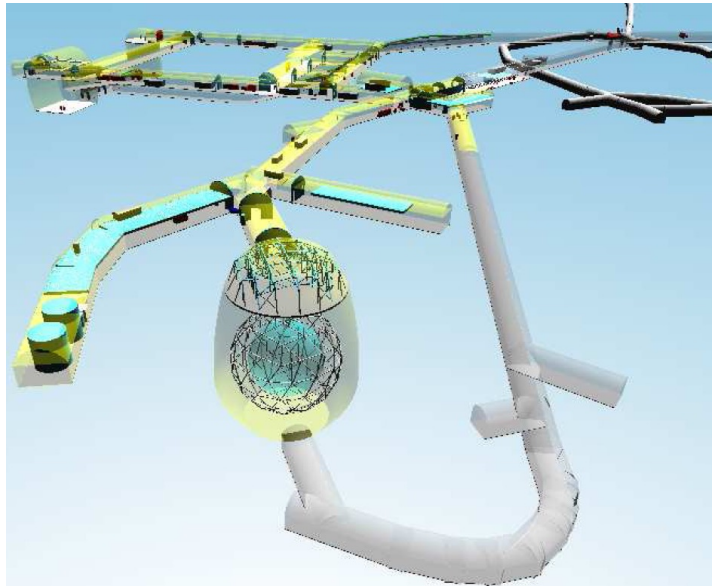
At the turn of the century there were **several possibilities** in the Δm^2_{12} vs θ_{12} plane.

$$P(\nu_e \rightarrow \nu_{\mu,\tau}) = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$



..... detecting all ν types

Sudbury Neutrino Observatory (SNO)



1000 tonnes D₂O (**Heavy Water**)

12 m diameter Acrylic Vessel

9500 PMTs

1700 tonnes inner shielding H₂O

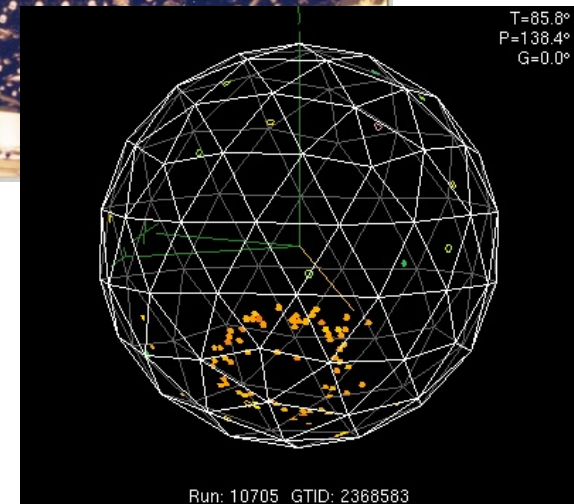
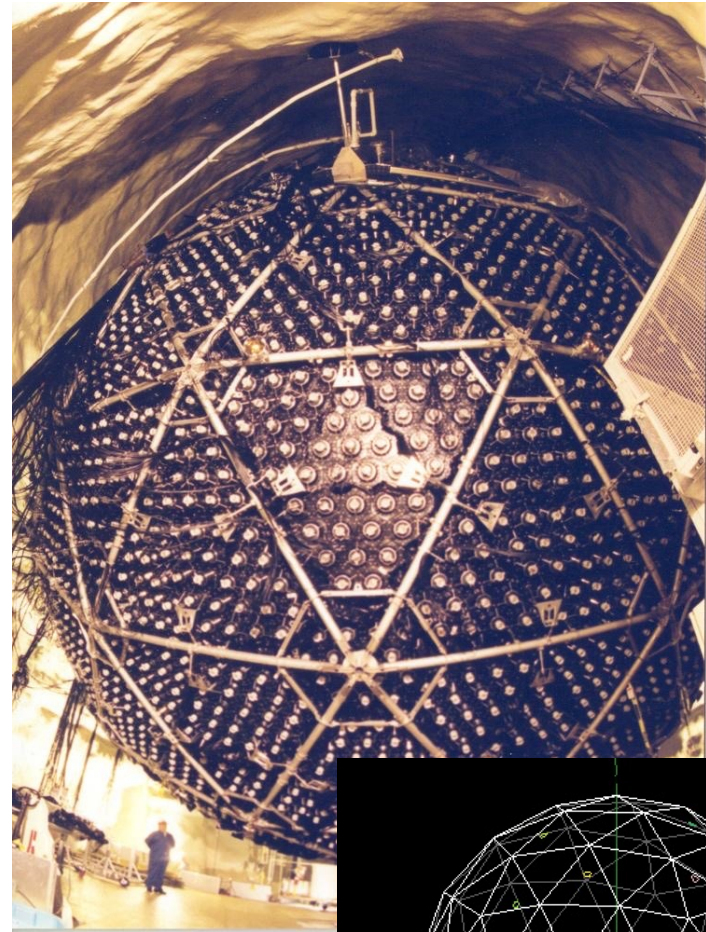
5300 tonnes outer shielding H₂O

At Sudbury Ontario Canada (since 1999)

$$E_{th} = 5.5 \text{ MeV}$$

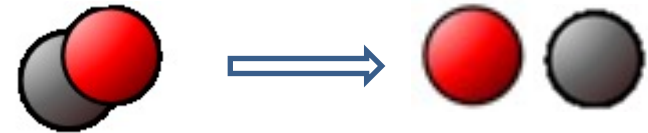
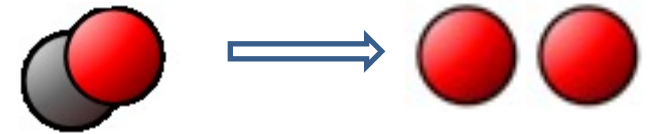
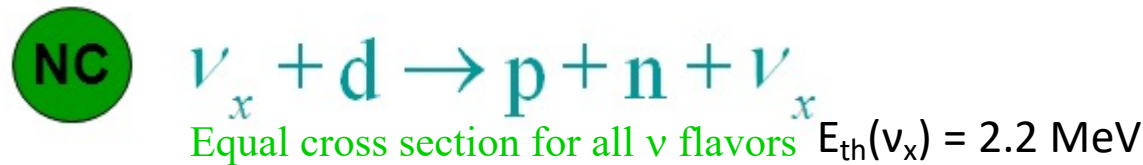
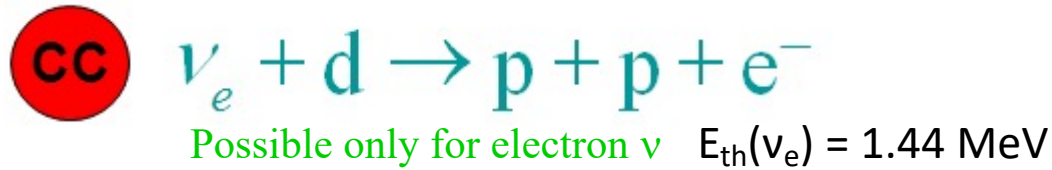
only ⁸B-neutrinos and hep-neutrinos

In **deuterium** one can separate **CC** events (induced by ν_e only) from **NC** events (induced by ν_e , ν_μ , ν_τ), and double check via **ES** (Elastic Scattering events, due to both NC and CC)



Neutrino reactions in SNO

**CC, NC FLUXES
MEASURED INDEPENDENTLY**



$$\begin{cases} \phi_{CC} = \phi_{\nu_e} \\ \phi_{NC} = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} \end{cases}$$

Experiment	Theory
$\phi_{CC} = 1.68^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.}) \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ $\phi_{NC} = 4.94^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.}) \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$	The total flux calculated with the solar standard model is (BPS07) $(4.7 \pm 0.5) \cdot 10^6 \text{ cm}^{-2} \text{ s}^{-1}$

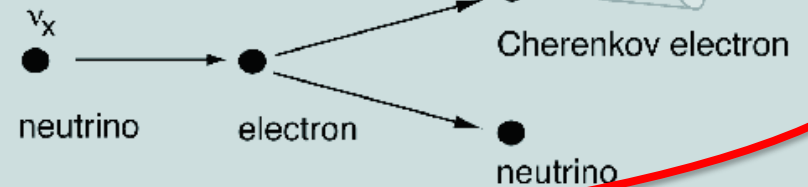
$$\frac{\phi_{CC}}{\phi_{NC}} = \frac{1.68}{4.94} \sim \frac{1}{3}$$

Also ES Neutrino Reactions in SNO

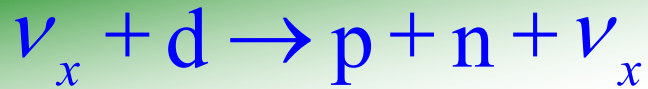
ES



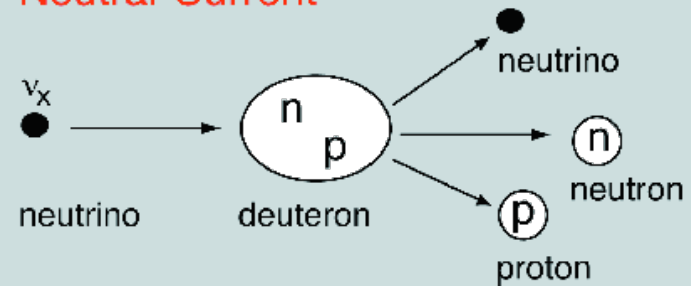
Elastic Scattering



NC



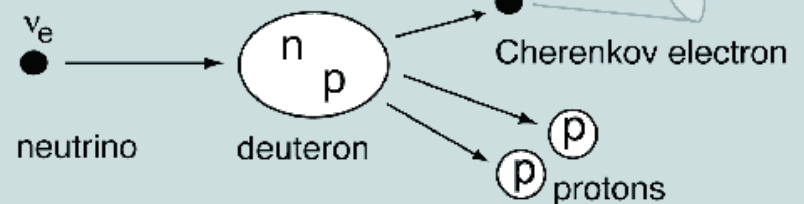
Neutral-Current



CC



Charged-Current



$$\begin{cases} \varphi_{CC} = \varphi_{\nu_e} \\ \varphi_{NC} = \varphi_{\nu_e} + \varphi_{\nu_\mu} + \varphi_{\nu_\tau} \\ \varphi_{ES} = \varphi_{\nu_e} + 0.154(\varphi_{\nu_\mu} + \varphi_{\nu_\tau}) \end{cases}$$

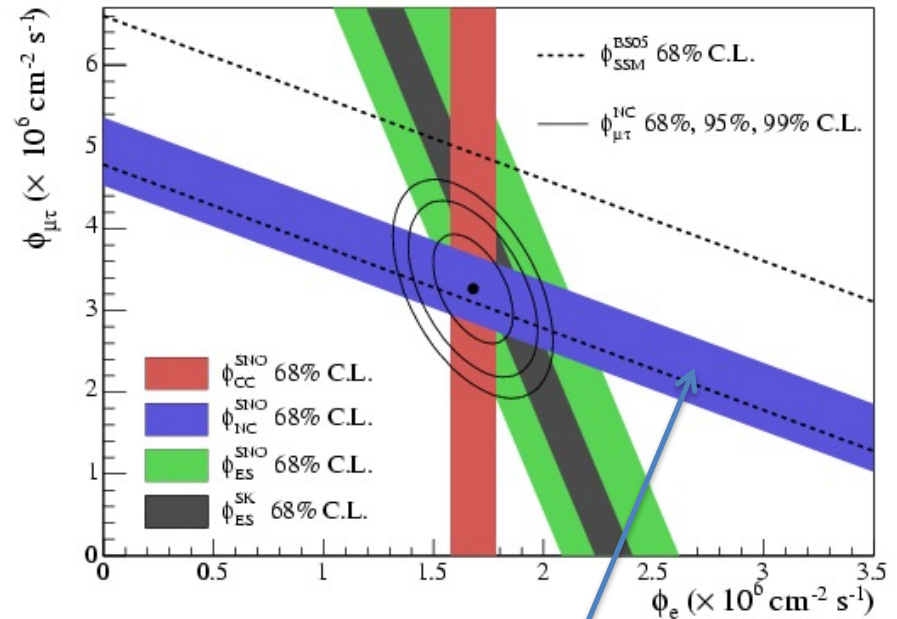
$$\varphi_{CC} = 1.68^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\varphi_{NC} = 4.94^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\varphi_{ES} = 2.35^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

(In units of $10^6 \text{ cm}^{-2} \text{ s}^{-1}$)

$$P_{ee} = \frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}_{12}$$



esempio (blue):

$$\varphi_{NC} = \varphi_{\nu_e} + \varphi_{\nu_\mu} + \varphi_{\nu_\tau}$$

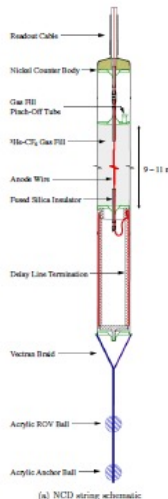
$$4.94 = \varphi_{\nu_e} + (\varphi_{\nu_\mu} + \varphi_{\nu_\tau})$$

$$\varphi_{\mu,\tau} = -\varphi_e + 4.94$$

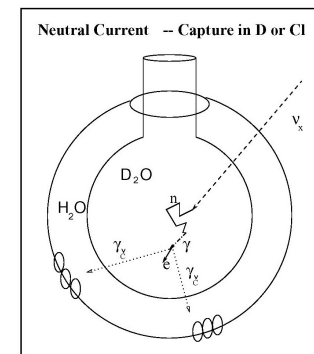
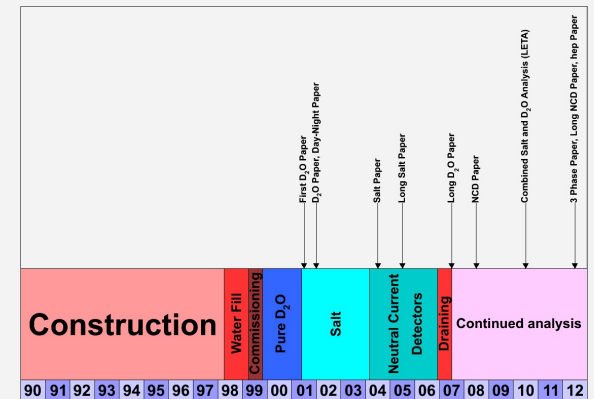
$$y = -x + 4.94$$

The Three Phases of SNO

- **Phase I: Pure D₂O**
 - Measurement of all three reactions, but NC signal can only be extracted with “Energy Constrained” fit
- **Phase II: Salt (NaCl)**
 - Neutron capture cross-section increased as well as energy released from capture (2.5 gammas on average)
 - The increase in isotropy of Cherenkov light from NC significantly increases the statistical separation between CC and NC (energy unconstrained)
- **Phase III: The Neutral Current Detectors**
 - Designed to independently measure the NC flux
 - Addition of 40 ³He proportional counters to count neutrons
 - Ended November 28th 2006 !



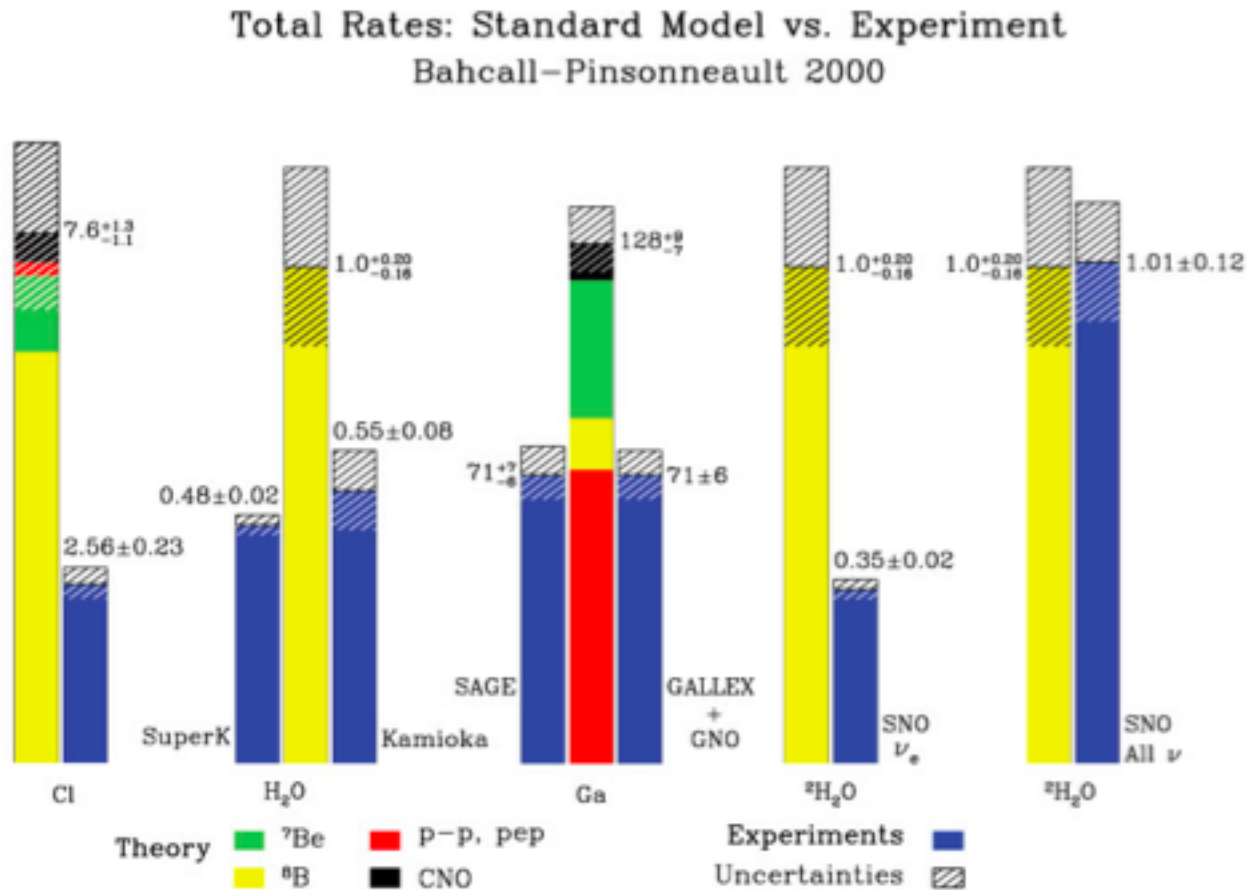
SNO Activities and Solar Neutrino Publications 1990-2012



Why three phases?

1. Additional information to separate NC and CC
2. Completely different systematics, which allowed us to check for consistency.
3. Allowed us to “repeat” the measurement

Summary of all Solar neutrino experiments before Borexino



All experiments “see” less neutrinos than expected by SSM

..... (but SNO in case of Neutral Currents!)

electron neutrinos (ν_e)
oscillate into non-electron
neutrino (ν_μ , ν_τ) with these
parameters:

from KamLAND Collab.
arXiv:0803.4312v1 (2008)

$$\Delta m_{12}^2 = 7.6 \cdot 10^{-5} \text{ eV}^2$$

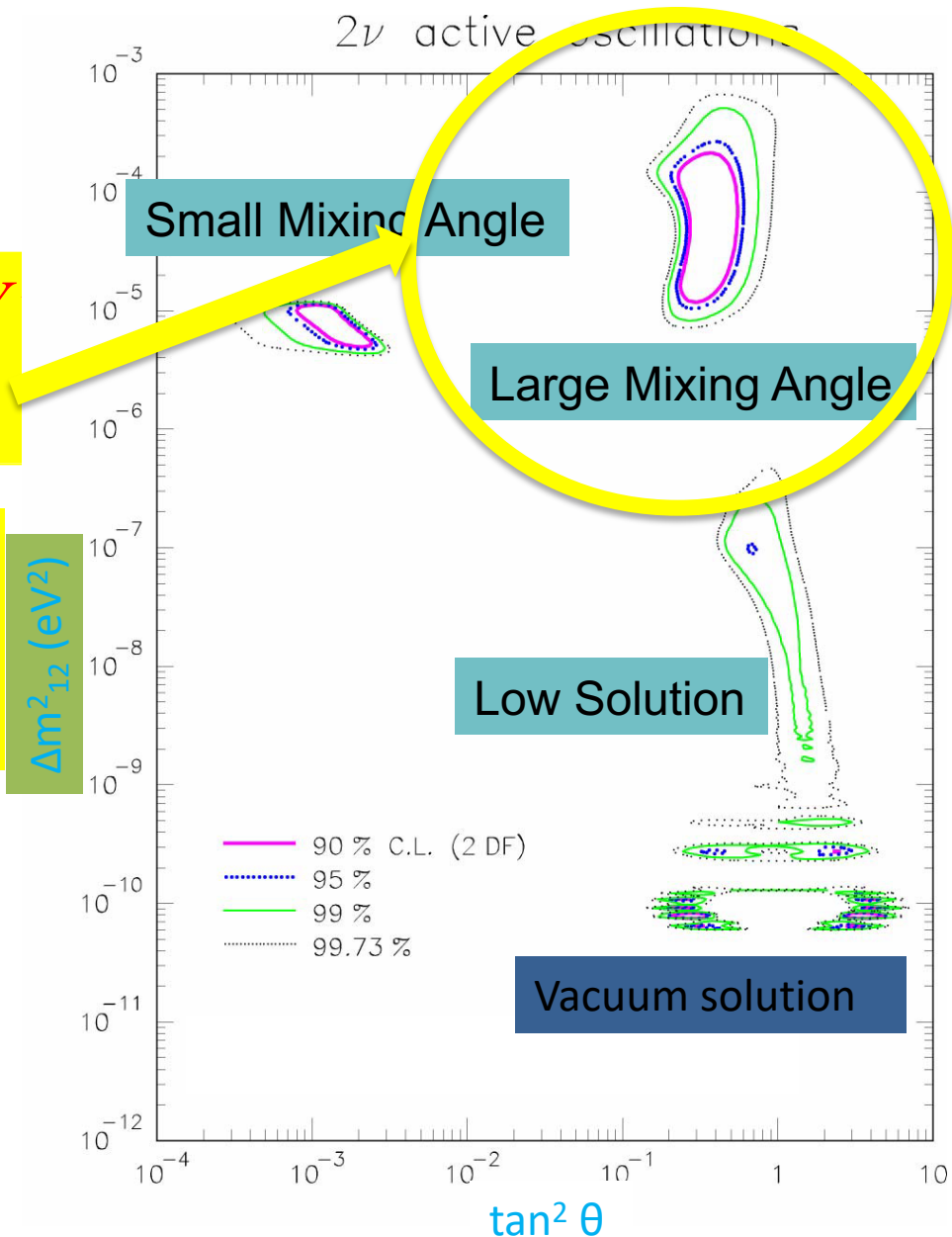
$$\sin^2 2\theta_{12} = 0.87$$

Corresponding to the
Large mixing Angle (**LMA**) Region:
MSW - Effect

After Borexino (2011)

$$\Delta m^2 = 5.37 \left\langle_{-1.08}^{+1.47} \cdot 10^{-5} \text{ eV}^2 \right.$$

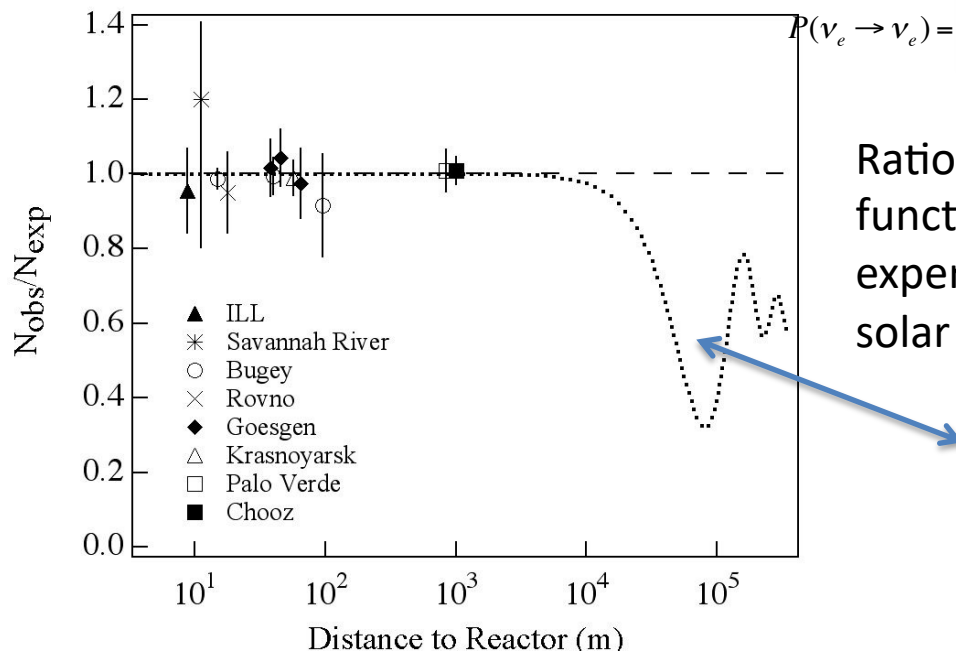
$$\tan^2 \theta = 0.47 \left\langle_{-0.04}^{+0.03} \quad (\Rightarrow \theta \approx 34^\circ)$$



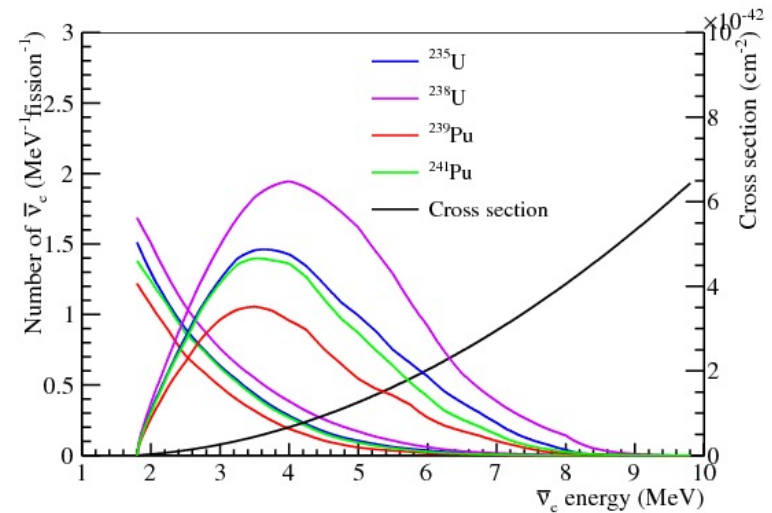
Reactor experiments

(source of electron anti-neutrinos with energy from 0-8 MeV)

Under CPT invariance: $\nu_e = \text{anti-}\nu_e$



Neutrino yield per fission, the interaction cross section of the inverse beta decay, and the observable spectra of the listed isotopes.



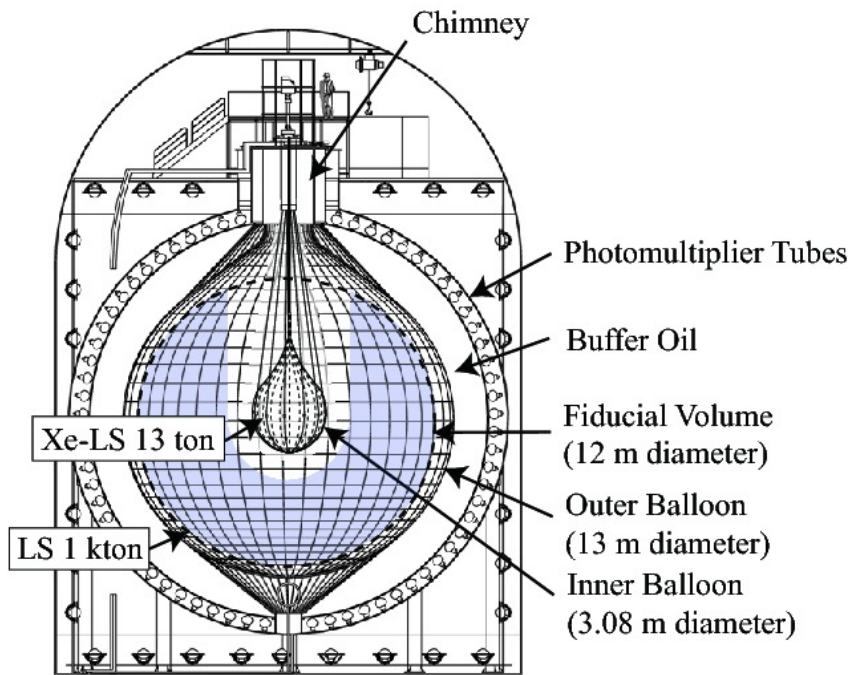
Ratio of observed to expected flux as a function of detector distance for reactor experiments before KamLAND plus the solar LMA prediction.

Oscillations are expected at a distance of the order of 100 km

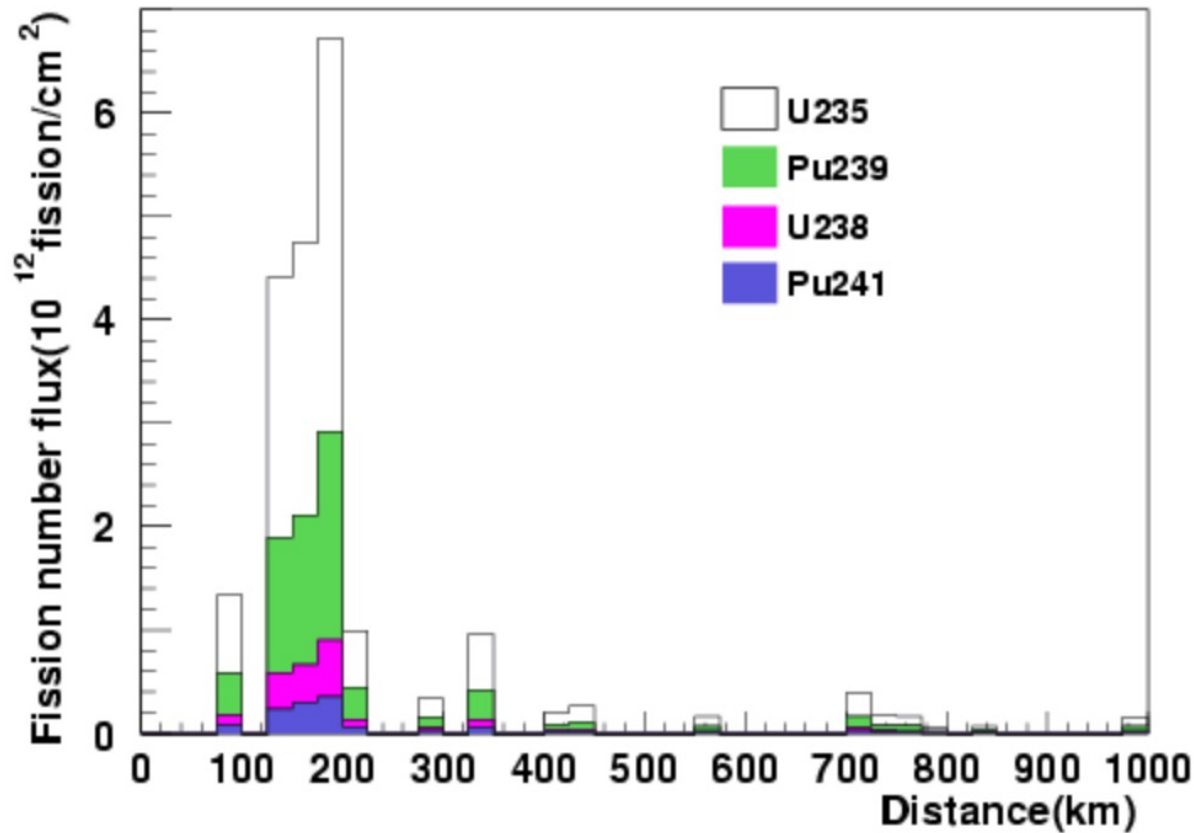


The Kamioka Liquid Scintillator Antineutrino Detector (**KamLAND**) aim reproducing “solar ν oscillations” in laboratory

(Long Baseline Neutrino experiments: aim of reproducing “atmospheric ν oscillations” in Laboratory)



- Site is surrounded by 53 Japanese commercial power reactors at an average distance $L = 180$ km
- 9 m radius stainless steel vessel
- 1879 photomultipliers on the inner surface to measure scintillator light
- 6.5 m radius nylon balloon inside filled with 1000 t liquid scintillator (mineral oil, benzene and fluorescent chemicals)
- Balloon surrounded by non-scintillating oil shielding external radiation and supporting (nylon film is too thin to support 1000t)
- Steel vessel is surrounded by ultrapure water + Cerenkov counters – further shielding and veto against muons



integrated fission flux at the Kamioka site for the four main nuclei that have fission products contributing to the anti-neutrino flux from reactors up to a distance of 1000km from the experimental site.

Disappearance experiment:

$\bar{\nu}_e$ produced in reactors are detected via inverse β -decay with threshold $E > 1.8$ MeV

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

Prompt scintillation light from e^+ gives E_ν – study E spectrum

$$E_\nu = E_{\text{prompt}} + \langle E_{n \text{ recoil}} \rangle + 0.8 \text{ MeV}$$

n capture by proton produces another 2.2 MeV γ -ray delayed by 200 μs

- allows good background control

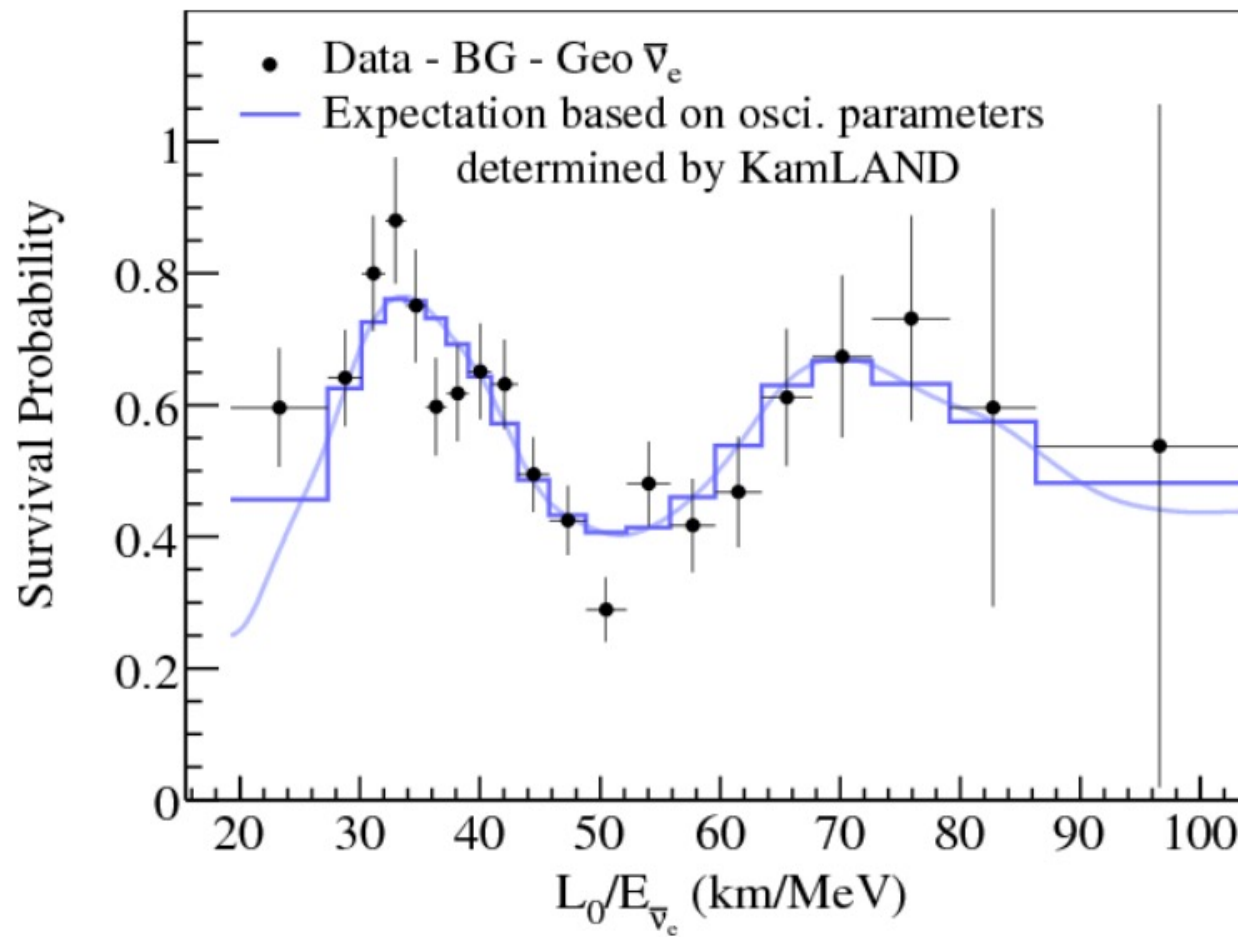
Very good sensitivity to Δm^2 due to rather large $L = 180$ km

$$P(\nu_\alpha \rightarrow \nu_\beta, t) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2}{4E} L \right)$$

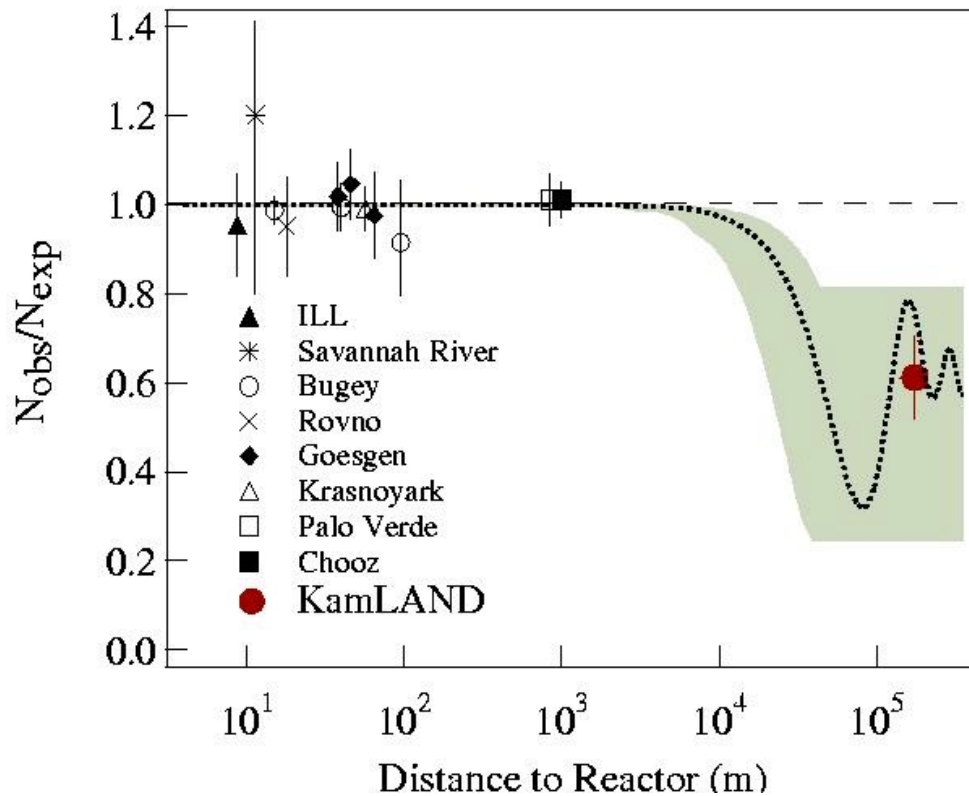
Note: solar neutrino are ν_e , reactor neutrinos are $\bar{\nu}_e$. Different signature:
for ν_e there is no combination of prompt and delayed light.

KamLAND Results

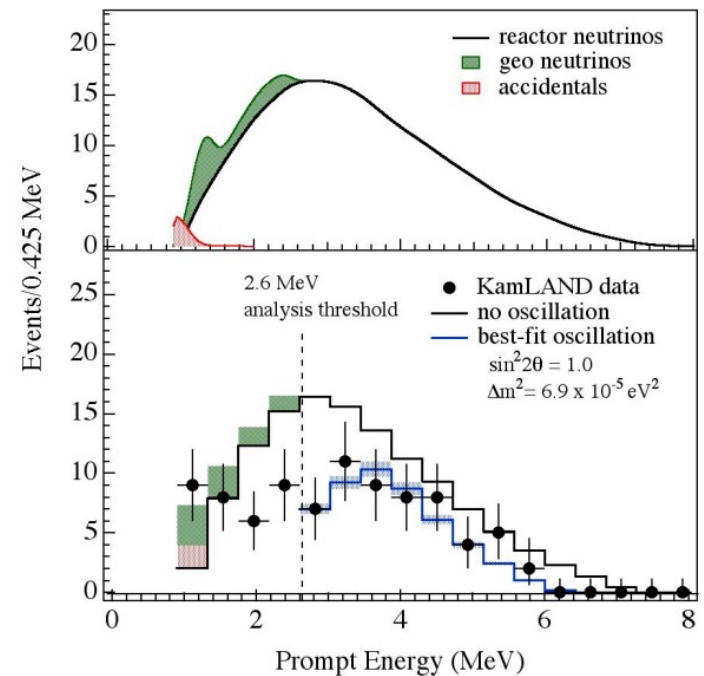
- Big deficit observed – in 1st study (2004) 258 ν_e w. $E > 3.4$ MeV out of 365 expected
- Newest result for ratio (signal – geo bg) / expectation w/o oscillations



Using average $L_0 = 180$ km



Ratio of observed to expected anti-neutrino flux as a function of distance from nuclear reactors, including KamLAND. From 2002 PRL



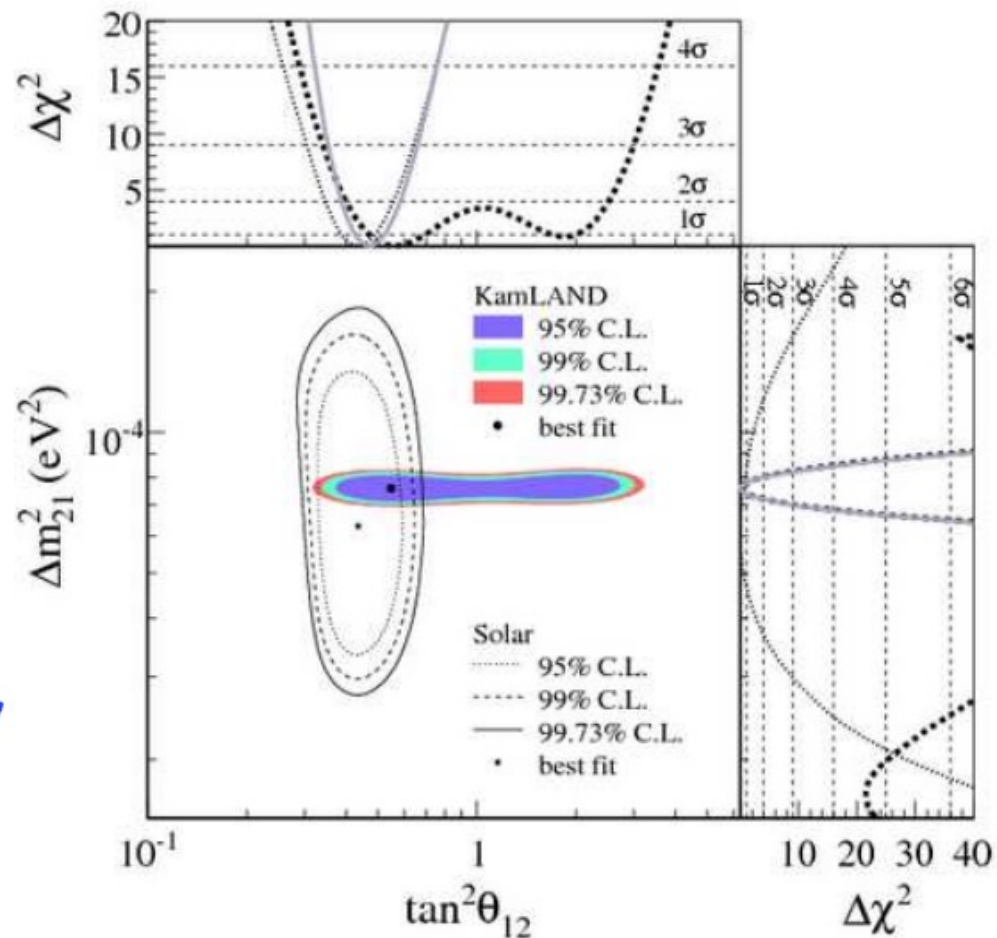
KamLAND Results

Two-flavour analysis $P(\nu_\alpha \rightarrow \nu_\beta, t) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2}{4E} L \right)$

$$\Delta m^2 = (8.2 \pm 0.6) \times 10^{-5} \text{ eV}^2$$

$$\sin^2 2\theta \approx 0.83$$

LMA = large mixing angle:
MSW effect necessary for solar ν



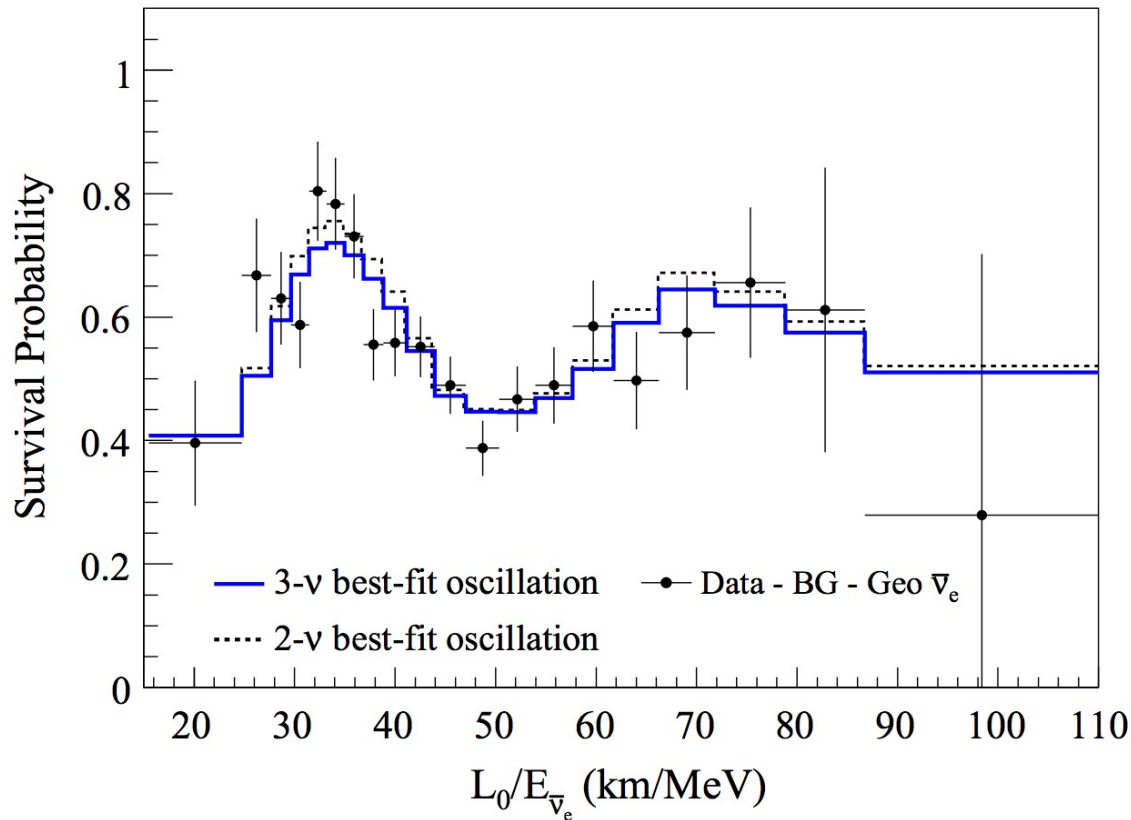


Figure 14.4: The ratio of the background and geoneutrino-subtracted $\bar{\nu}_e$ spectrum, observed in the KamLAND experiment, to the predicted one without oscillations (survival probability) as a function of L_0/E , where $L_0=180$ km. The histograms show the expected distributions based on the best-fit parameter values from the two- and three-flavor neutrino oscillation analyses. The figure is from Ref. 131.

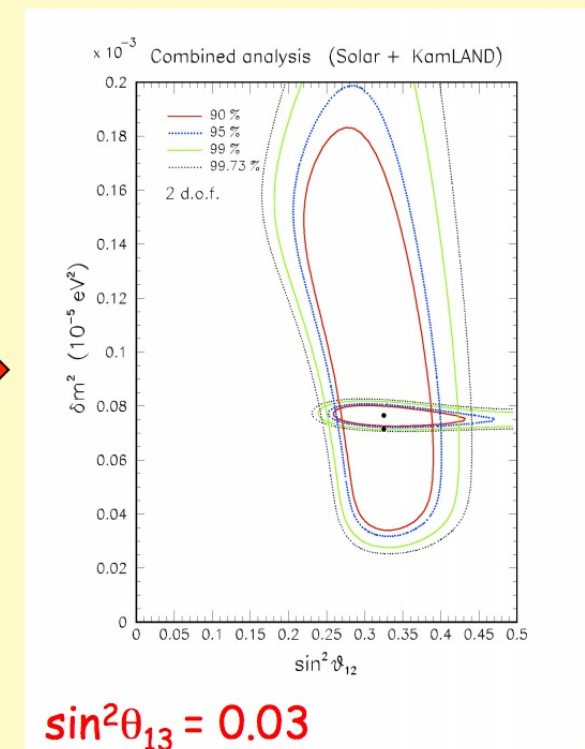
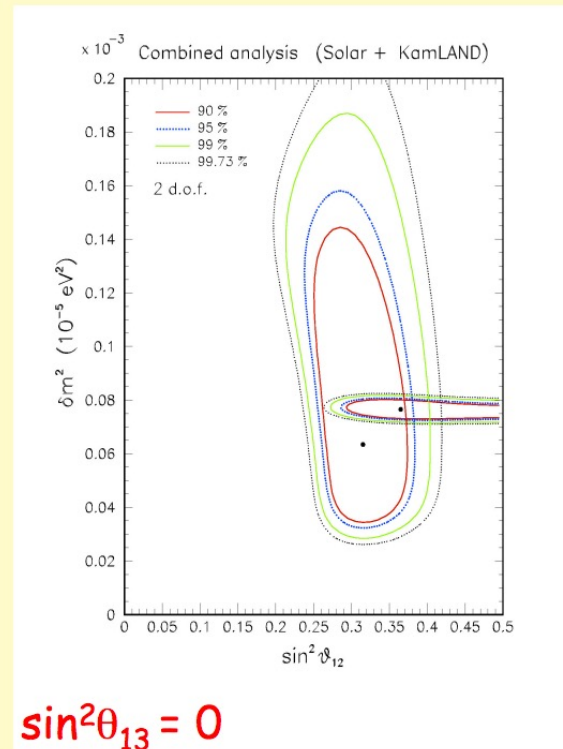
A. Gando et al., [KamLAND Collab.], Phys. Rev. D83, 052002 (2011).

2 Slight disagreement between

- Solar data (SNO dominated)
- KamLAND data (at $\sin^2\theta_{13} = 0$)

Disagreement reduced if $\sin^2\theta_{13} > 0$ is assumed ...

... thanks to the different correlation between θ_{12} and θ_{13} in KamLAND and SNO data.



Including the data on θ_{13} from accelerator and short-baseline reactor experiments, a combined

3-neutrino oscillation analysis of solar and KamLAND data gives:

$$\tan^2 \theta_{12} = 0.436 \pm 0.029 \pm 0.025, \text{ -----} \rightarrow \theta_{12} = 33.44^\circ$$

$$\Delta m_{21}^2 = (7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta_{13} = 0.023 \pm 0.002$$

0.7 Summary of Current Knowledge

We can now summarise our current level of knowledge of neutrino oscillations and neutrino mass from oscillation experiments.

We now know that there are 3 light neutrinos. The neutrino mass states are different from the flavour states. There are two mass splittings

$$\Delta m_{12}^2 = 8 \times 10^{-5} \text{ eV}^2 \quad (128)$$

and

$$|\Delta m_{23}^2| = 2.3 \times 10^{-3} \text{ eV}^2 \quad (129)$$

We know the sign of Δm_{12}^2 but not Δm_{23}^2 . This is shown in Figure 24. The mixing angles have now all been determined, to various levels of precision, and are shown in Table 2

Parameter	Measurement	Angle
$\sin^2(2\theta_{23})$	> 0.92	$(45.0 \pm 2.4)^\circ$
$\sin^2(2\theta_{12})$	0.85 ± 0.1	$(32.5 \pm 2.4)^\circ$
$\sin^2(2\theta_{13})$	0.089 ± 0.01	$(8.9 \pm 0.3)^\circ$

Table 2: Current results of measurements of all mixing angles in the PMNS matrix.

Il tasso di osservazione deve essere mediato considerando la regione di emissione nel Sole, la regione di assorbimento sulla Terra e l' intervallo di energia dello spettro.

$$P(\nu_e \rightarrow \nu_{\mu,\tau}) = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$

Dopo le medie si ottiene:

I **neutrini** di energia **inferiore al MeV** non attraversano mai una risonanza nella loro fuoriuscita dal Sole, pertanto, sono sostanzialmente in regime di oscillazione nel vuoto. Poiché il diametro del nucleo del Sole, regione nella quale sono prodotti i neutrini, è maggiore della lunghezza di oscillazione, l'effetto è mediato, e la probabilità di sopravvivenza diventa:

$$P(\nu_e \rightarrow \nu_e) = 1 - \frac{1}{2} \sin^2 2\theta_{12}$$

$$\theta \approx 32.5^\circ$$

$$P(\nu_e \rightarrow \nu_e) = 1 - \frac{1}{2} \sin^2 2\theta \approx 0.6$$

Per i **neutrini** di energie **superiori a 10 MeV** domina invece l'oscillazione nella materia, e la probabilità di sopravvivenza risulta essere uguale a:

(il neutrino emerge dal Sole come autostato ν_2 che è l'autostato di massa maggiore, e come tale raggiunga la Terra senza oscillare. La probabilità di osservarlo sulla Terra come ν_e risulta quindi

$$P_{MSW}(\nu_e \rightarrow \nu_e) = \left| \langle \nu_e | \nu_2 \rangle \right|^2 = \sin^2 \theta_{sol}$$

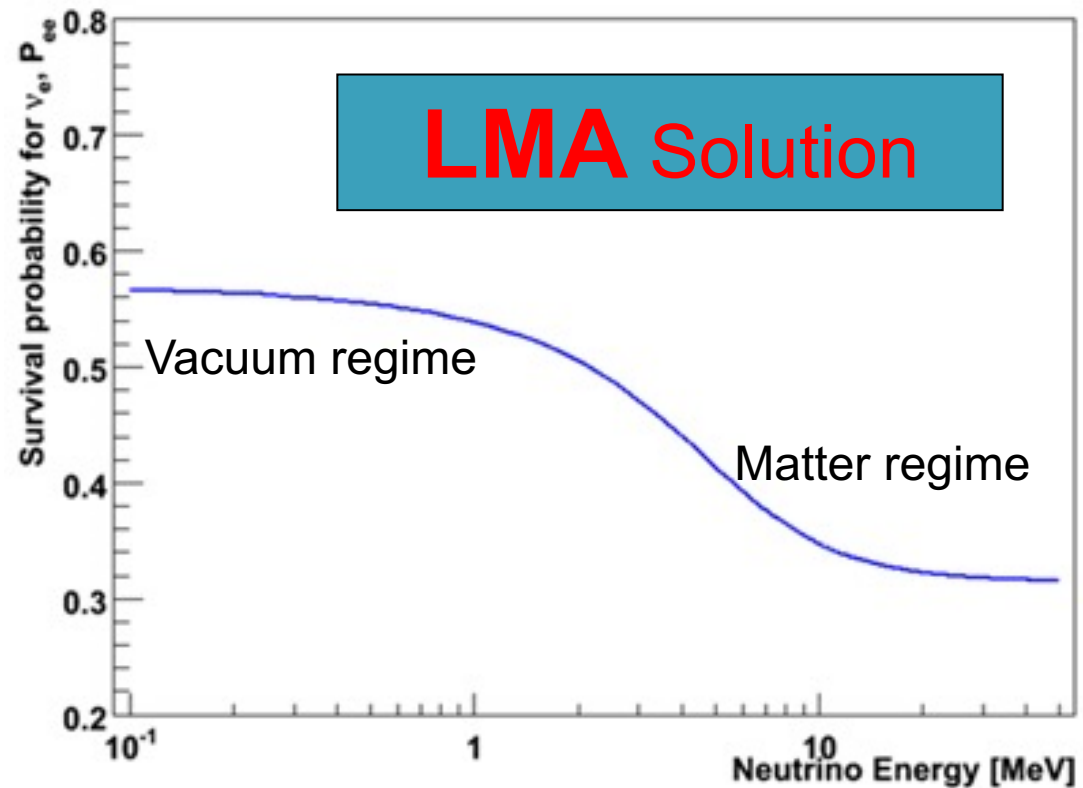
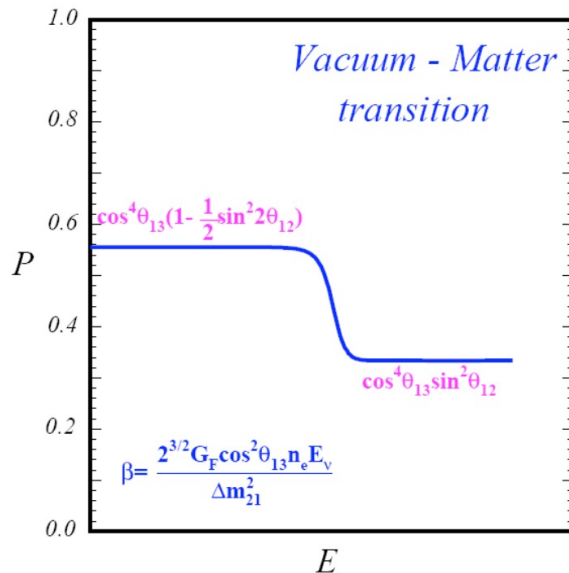
$$\theta \approx 32.5^\circ$$

$$P(\nu_e \rightarrow \nu_e) = \sin^2 \theta \approx 0.3$$

Survival probability vs energy

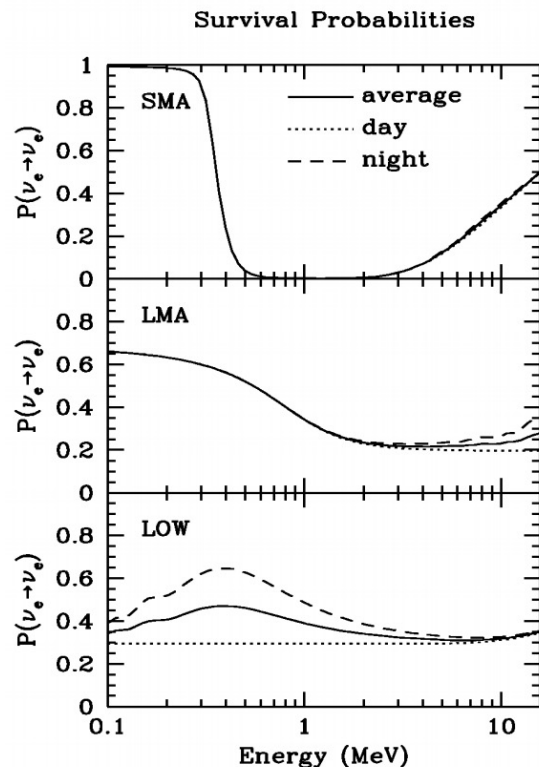
$$P(\nu_e \rightarrow \nu_e) = 1 - P_{\nu_e \rightarrow \nu_{\mu,\tau}}(E)$$

- For **high-energy** solar neutrinos the MSW effect is important
- For the **low-energy** solar neutrinos, on the other hand, the MSW effect is negligible, and the formalism of oscillations in vacuum is valid.



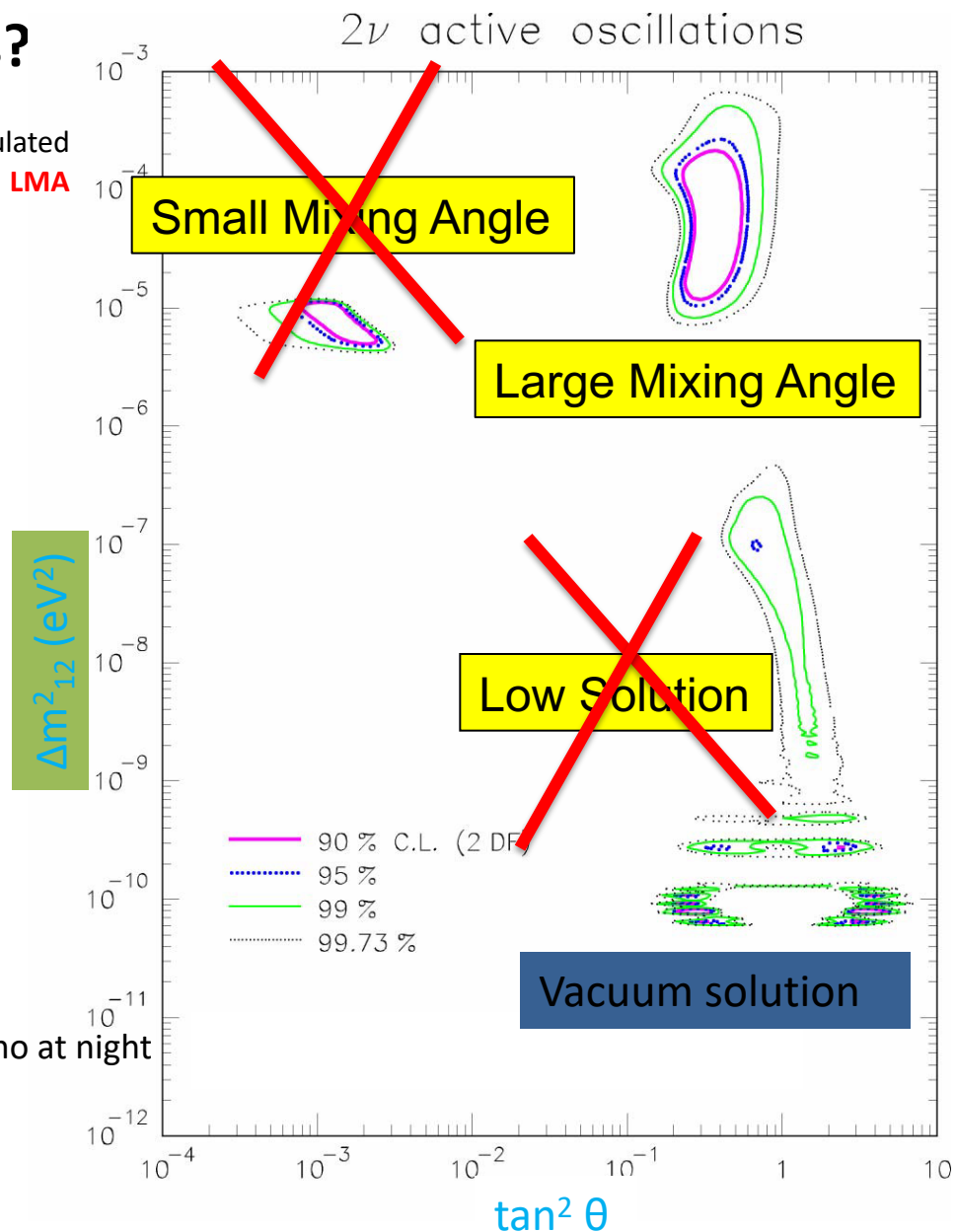
What about the others solutions?

The ν_e survival probability due to neutrino flavor conversion, calculated for the **three different MSW** solutions: **SMA** (Small Mixing Angle), **LMA** (Large Mixing Angle), and **LOW** (Low probability, low mass).



- For LOW solution, at night the Sun is brighter in neutrino at night
- For SMA solution, no room for ${}^7\text{Be}$ neutrinos.

→ Now we know that both solutions are wrong!



3

Solar neutrinos spectroscopy (The Borexino detector)

To measure in real time below 1 MeV

Radiochemical experiments

Gallex
SAGE

Homestake

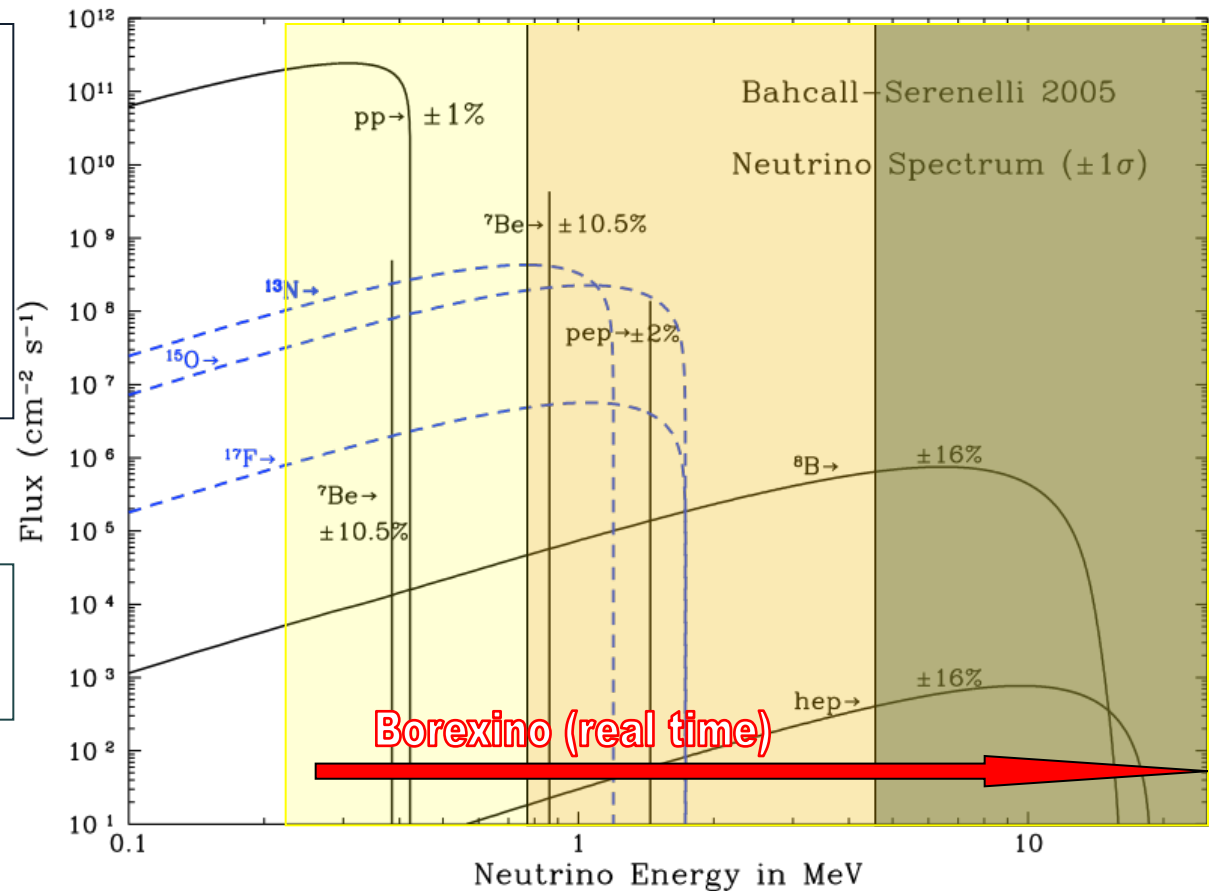
Real time measurement
(only 0.01 %!)

SNO &
SuperKamiokande

Radiochemical experiments
(Homestake, Gallex, SAGE)
integrate in time and energy.

Real time experiments
(Kamiokande, SuperK, SNO) can
detect solar neutrinos starting from
about 5 MeV.

Need to build a detector able to
detect solar neutrinos in **real time**
with a **low energy threshold**.



Borexino: A low energy threshold real time experiment

$$E_{th} \sim 200 \text{ keV}$$

Borexino is a detector able to measure neutrinos coming from the Sun in **real_time** with **low_energy threshold** ($\sim 200 \text{ keV}$) and **high_statistic** (*tens of events per day*).

This is made possible using **Ultra high-purity liquid scintillator** (~ 100 tons).

In liquid scintillators the light yield is about 50 times greater compared to the Cherenkov emission light

scintillation light $\approx 50 \text{ times}$ cherenkov light

High light yield $\sim 10^4$ photons per MeV

Detection principle:
elastic scattering (ES) on electrons



It is possible to distinguish the different neutrino contributions. **Spectroscopy**

A very challenging experiment ... to fight against radioactivity.

Unlike Cherenkov light, the scintillation light is emitted isotropically; this means that the ν induced events can't be distinguished from other γ/β events due to **natural radioactivity**.

Neutrino signal:

The neutrino signal is on the order of ≈ 10 events/day/100 tons above threshold.

This means **10^{-9} events/(kg s)**

$$\frac{Signal(\nu)}{Noise(BKG)} \equiv 1$$

Radioactive background (ex: ^{238}U):

1 g of ^{238}U corresponds to about 12500 Bq.

The typical concentration of ^{238}U in rocks is of the order of ppm (10^{-6} g/g).

This means that in 1 kg of material we have about 10 Bq of radioactivity

This means **10 events/(kg s)**

Signal to noise ratio:

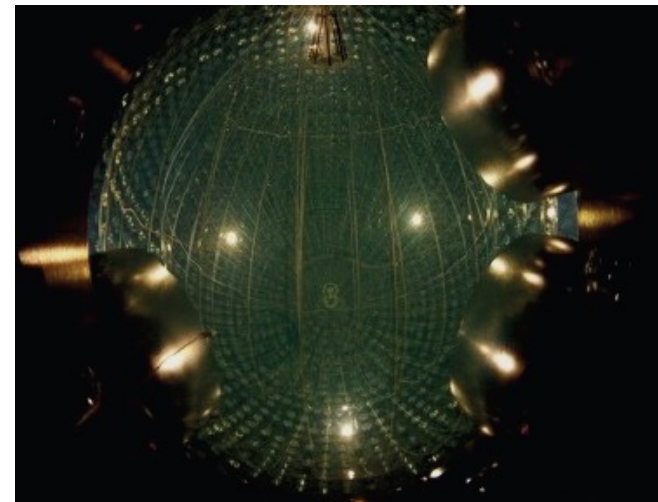
In order to have a signal to noise ratio on the order of 1, the ^{238}U (and ^{232}Th) intrinsic contamination can't exceed **10^{-16} g/g!** (*this means 9-10 orders of magnitude less radioactive than anything on Earth*)

≈100 tons
Liq. Scint.
PC+PPO

The **100 tons target mass** (liquid scintillator) is composed of pseudocumene **PC** as solvent and **PPO**, to enhance the scintillation property, as solute (1.5 g/l) .

In order to reach such a low radioactivity level several techniques have been applied:

- **Distillation**,
- **Water extraction**,
- **Nitrogen stripping**,
- ecc.....



Unprecedented low levels of background

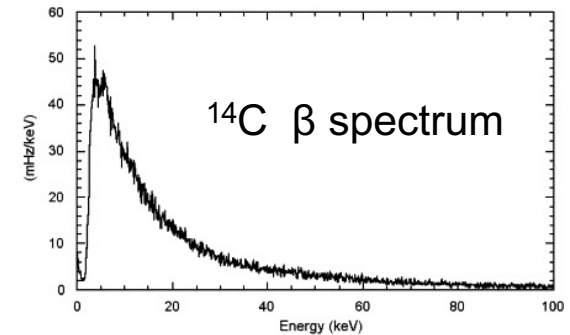
Background	Source	Typical Concentration	Borexino Levels (per scintillator mass)	Reduction Method
^{14}C	Scintillator	10^{-12} g/g	10^{-18} g/g	Underground Source
^{238}U	Dust	10^{-4} g/g (Dust)	10^{-17} g/g	Purification
^{232}Th	Dust	10^{-4} g/g (Dust)	10^{-18} g/g	Purification
^{85}Kr	Air	10^7 cpd/ton (Air)	0.3 cpd/ton	LAKN
^{40}K	PPO	10^{-13} g/g	$<10^{-18}$ g/g	Purification
^{210}Po	^{210}Pb	10^4 cpd/ton	20 cpd/ton	Purification
^{210}Bi	^{210}Pb	10^4 cpd/ton	0.4 cpd/ton	Purification

Threshold at 200 keV:

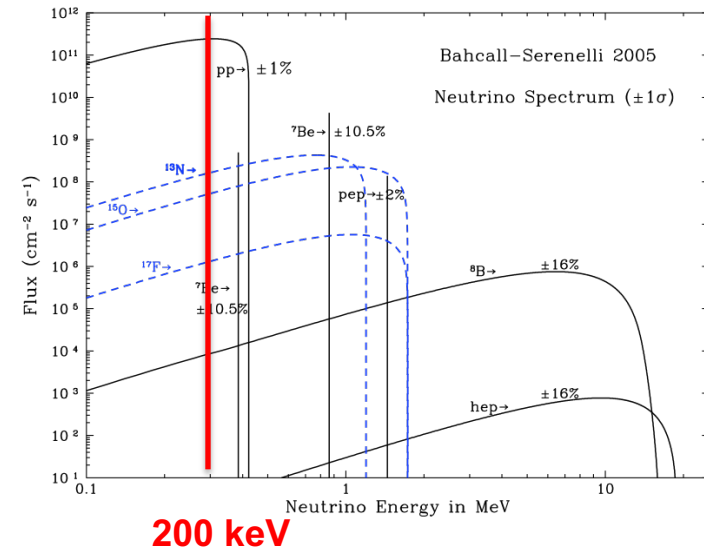
In organic compounds (such as liquid scintillators) there is always ^{14}C . This radioisotope can't be removed with chemical procedures and it is impossible to isotopically separate 100 tons of scintillator.

^{14}C is a pure beta emitter with an end-point of 156 keV.

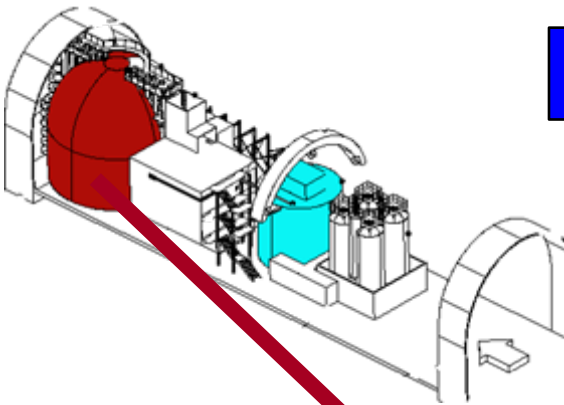
Due to the pile-up events and the finite energy resolution the energy threshold of the detector is set at **200 keV**.



Solar neutrino Spectroscopy from 200 keV



Borexino design



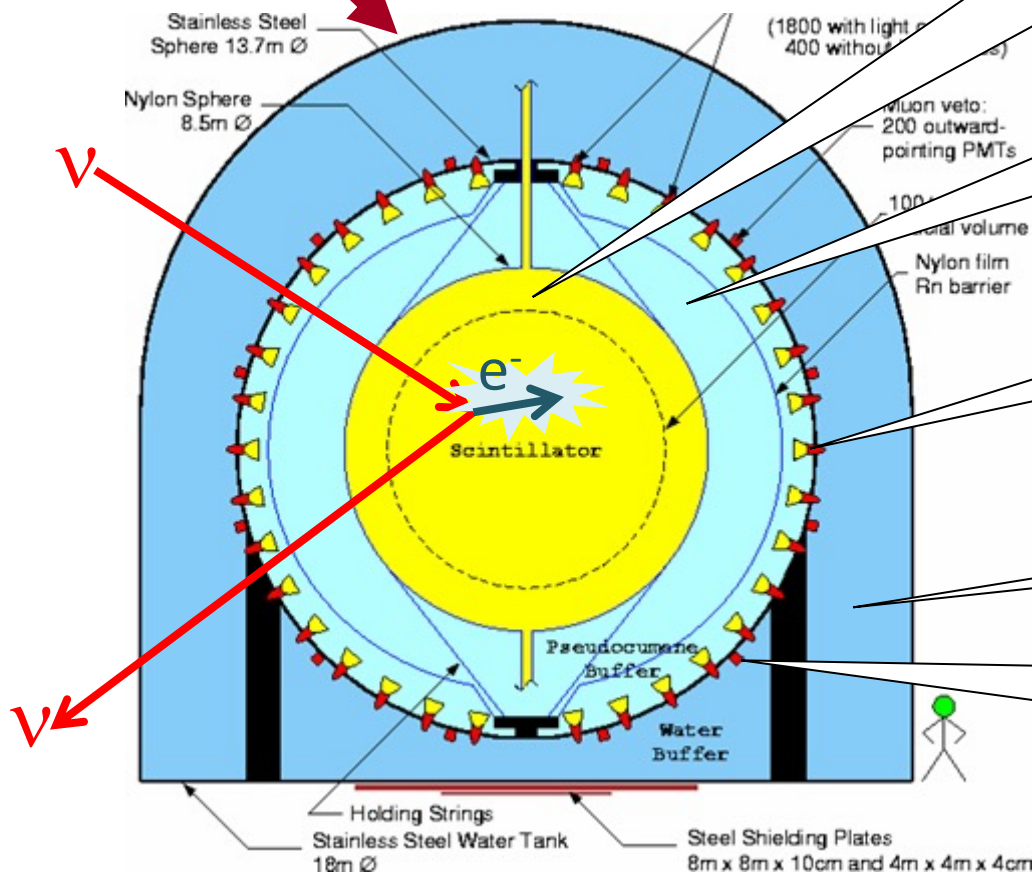
Core of the detector: 300 tons of liquid scintillator (PC+PPO) contained in a nylon vessel of 8.5 m diameter. The thickness of nylon is 125 μm .

1st shield: 1000 tons of ultra-pure buffer liquid (PC+DMP) contained in a stainless steel sphere of 13.7 m diameter (SSS).

2200 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator.

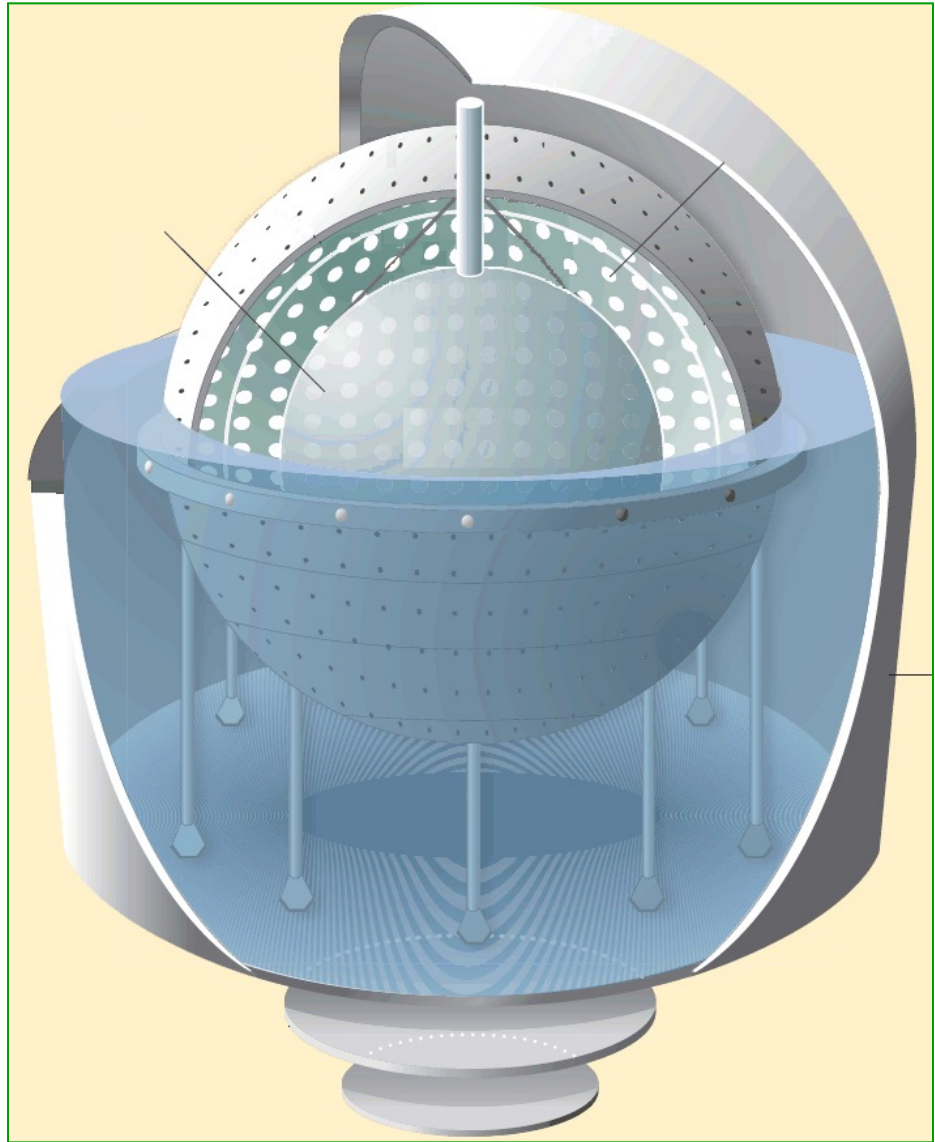
2nd shield: 2400 tons of ultra-pure water contained in a cylindrical dome.

200 photomultiplier tubes mounted on the SSS pointing outwards to detect Cerenkov light emitted in the water by muons.



3D view of Borexino Detector

“Onion-like”
structure

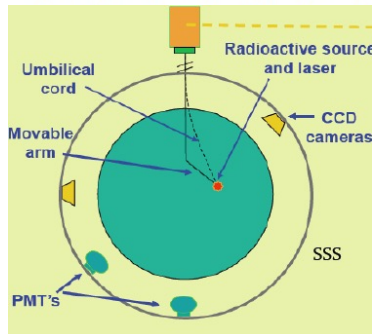
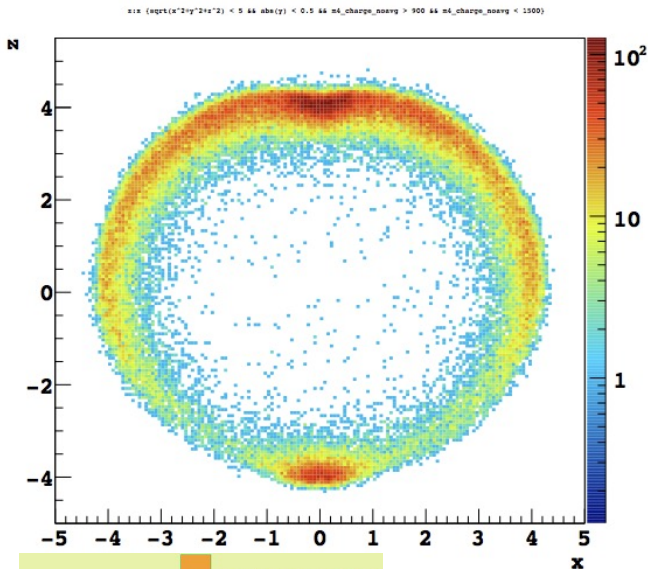
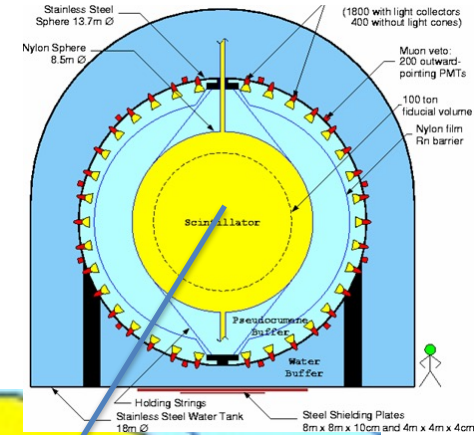


Fiducial Volume

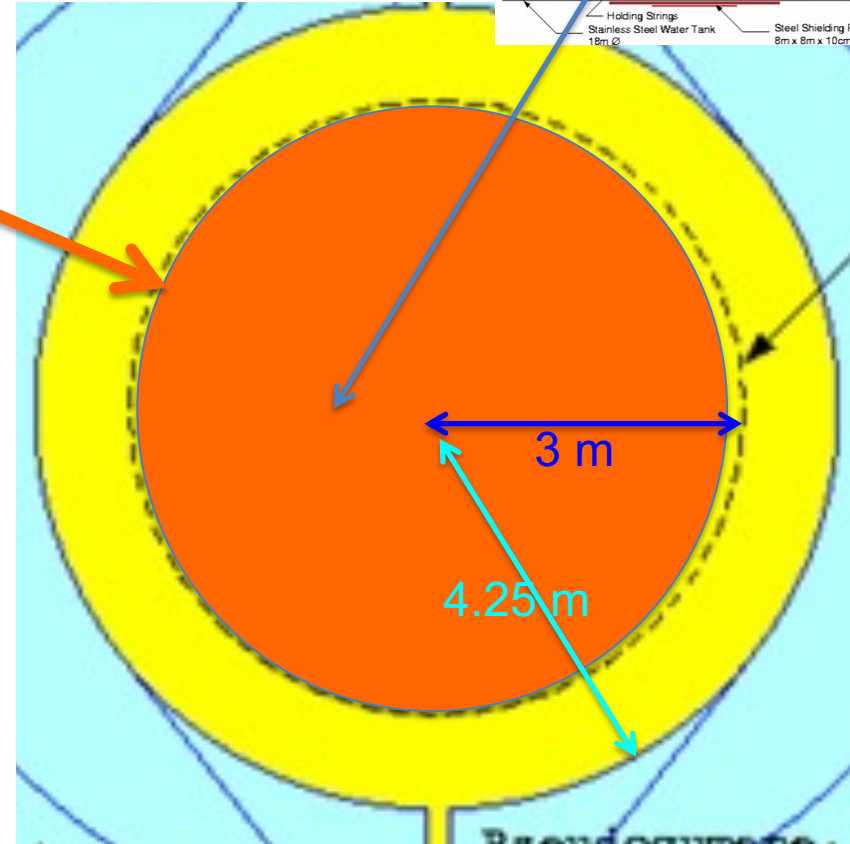
Thanks to the 4π PMT's distribution it is possible to reconstruct the position where the event took place.

Thus it is possible to select only events coming from the internal part of the Inner Vessel rejecting all the events created by high-energy gammas coming from the SSS and the PMT's

Definition of a **Fiducial Volume** of about 100 Tons



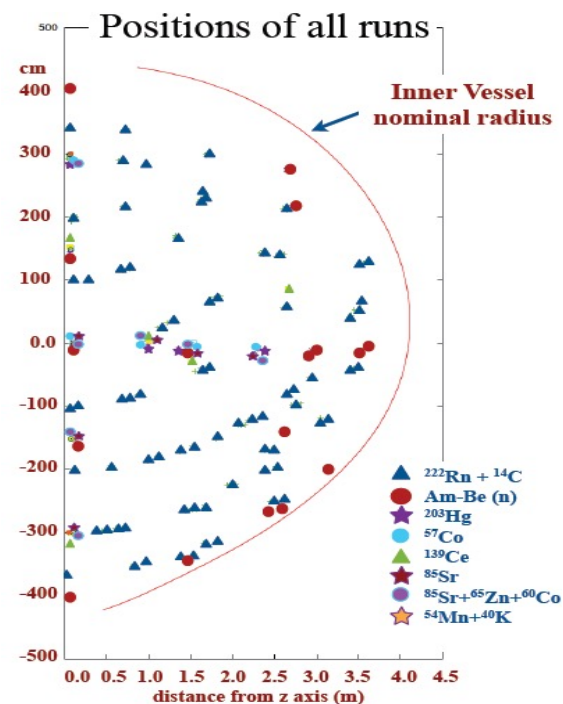
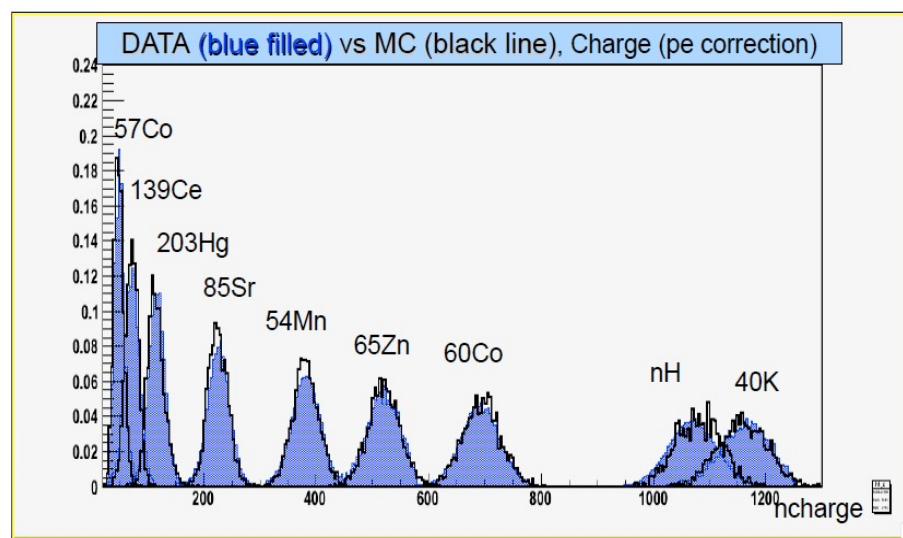
Using 184 points of Rn calibration data, the fiducial volume uncertainty appeared to be -1.3% +0.5%



Spatial resolution 14 cm @ 1 MeV.

Energy Calibration

Thanks to an extensive calibration campaign, with radioactive sources, the energy scale uncertainty (in the range $0.2 \div 2$ MeV) is better than **1.5%**

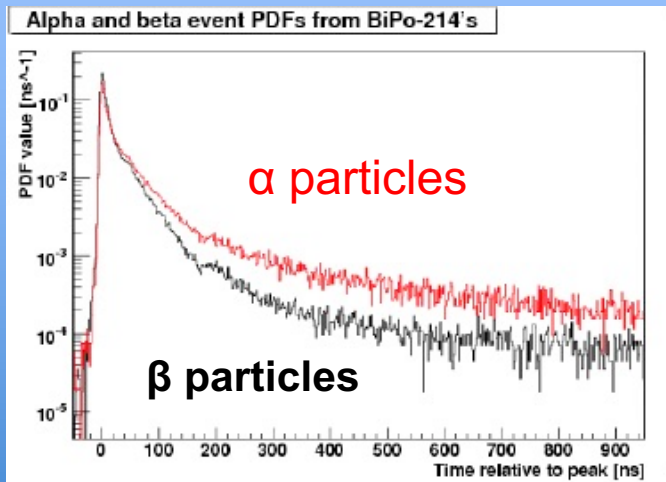


Energy resolution 6% @ 1 MeV (14% FWHM)

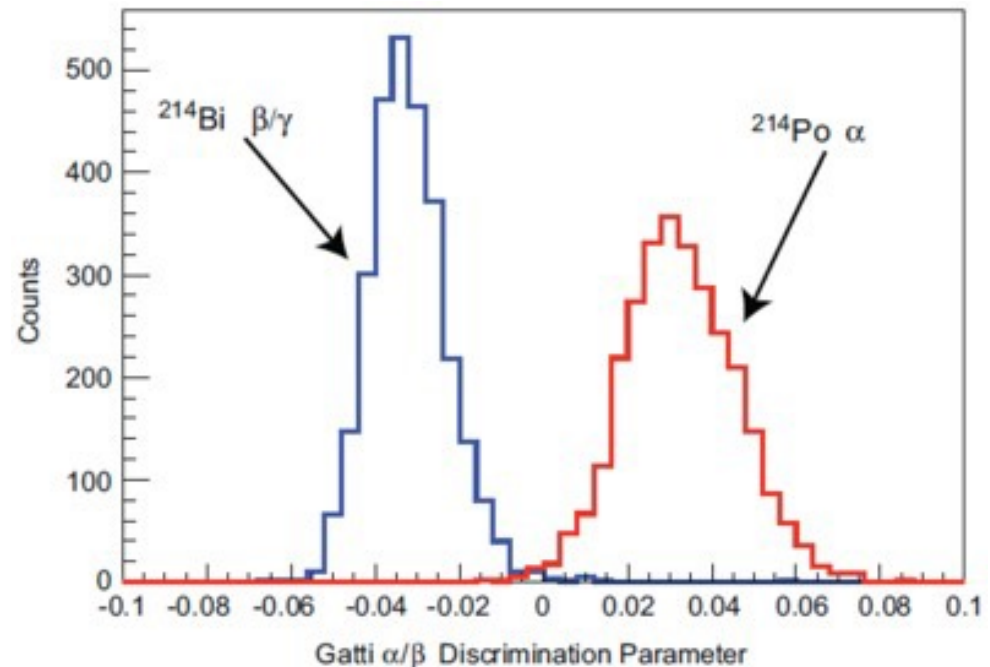
α / β separation

Thanks to the **Pulse Shape Analysis** it is possible to disentangle the light generated by **beta particles and gamma rays**, from the light induced by **alpha particles**.

Time decay distribution of the scintillation light excited by α or β - γ radiation



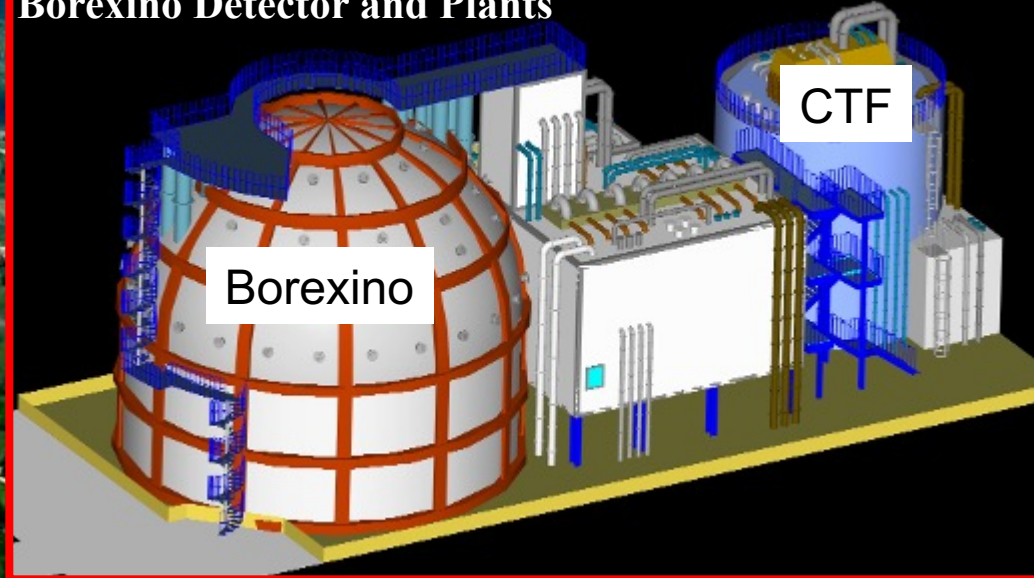
α / β separation (^{214}Bi - ^{214}Po)



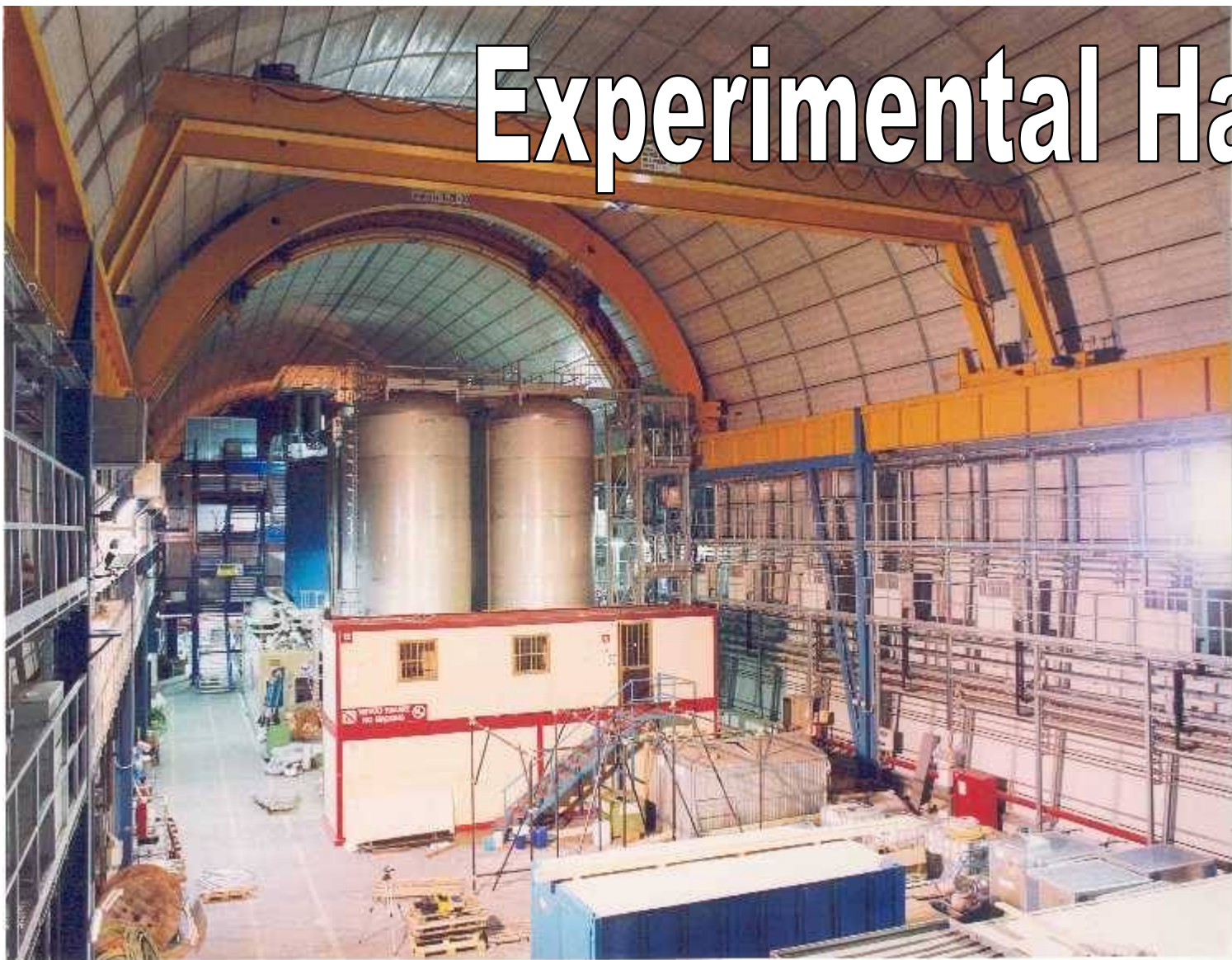
Laboratori Nazionali del Gran Sasso (LNGS)



Borexino Detector and Plants

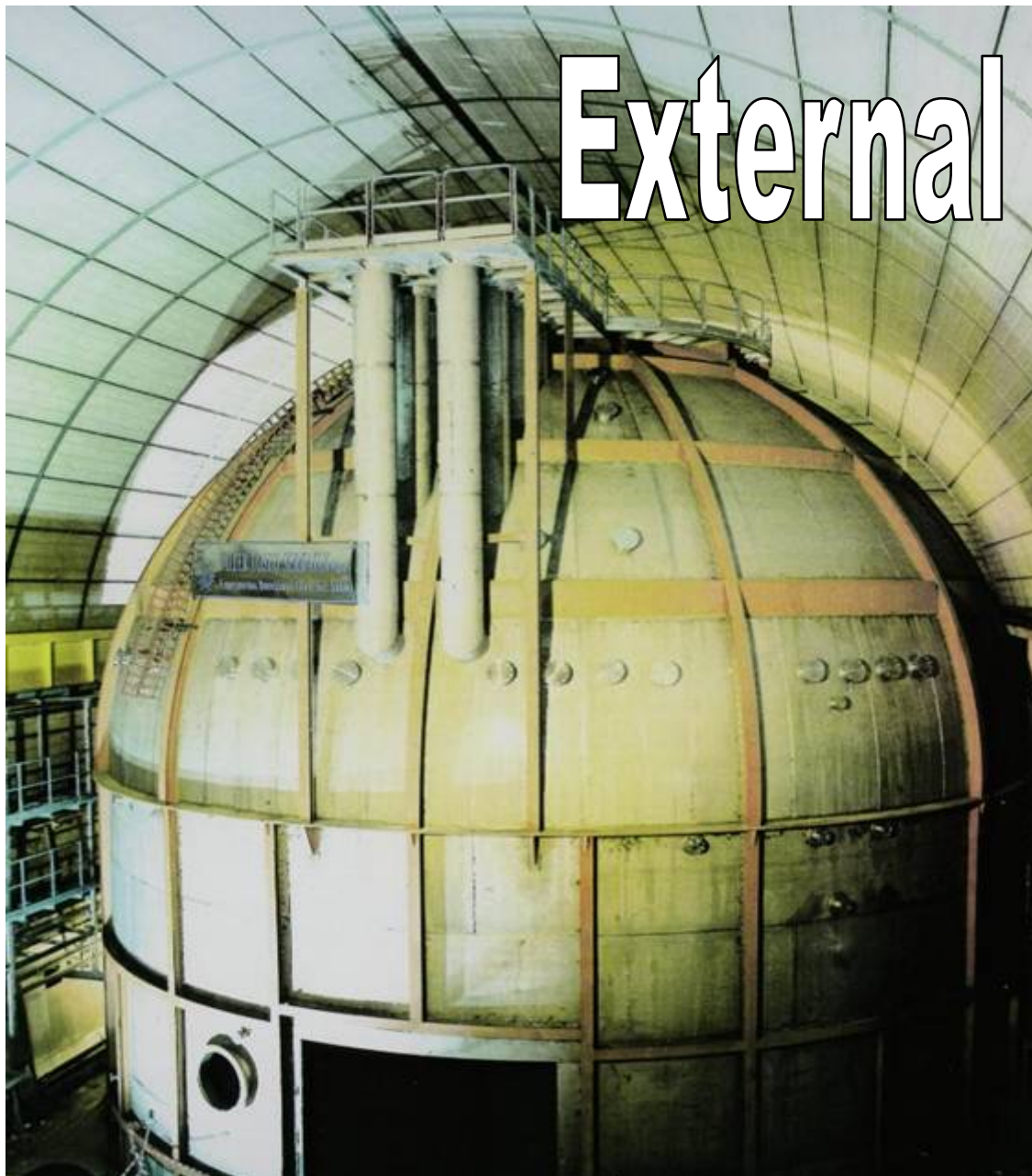


Experimental Hall C

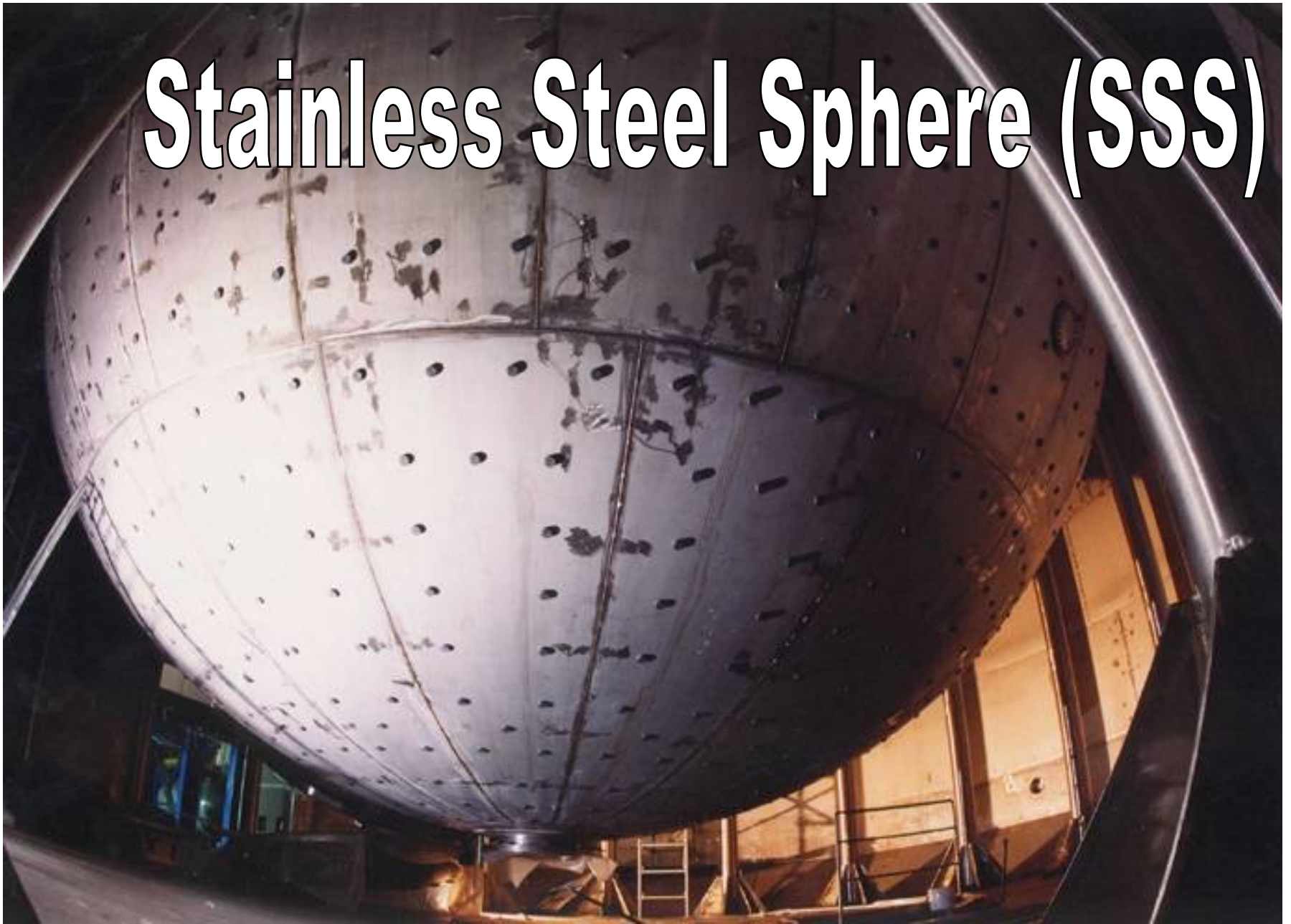


External dome

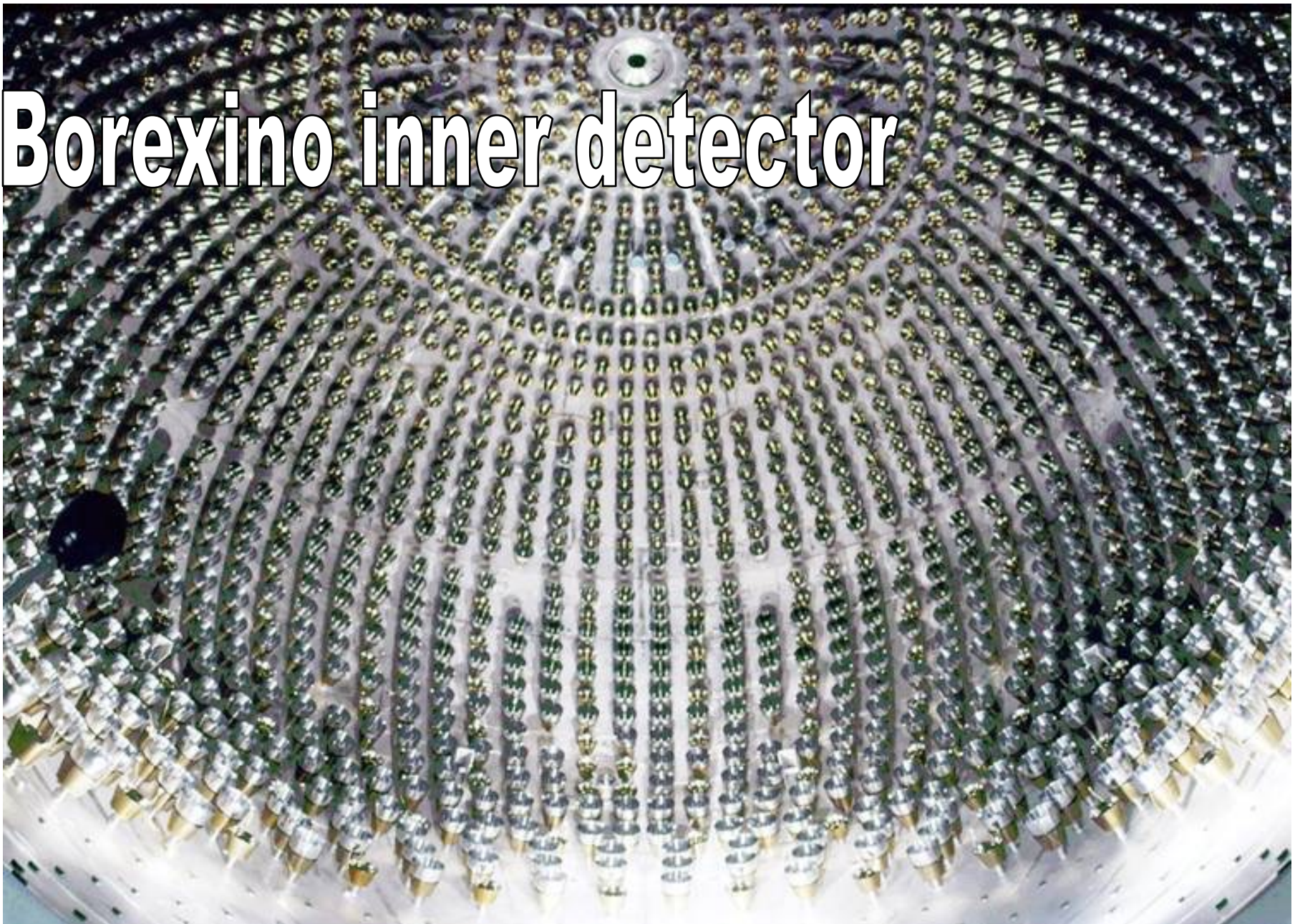
18 m



Stainless Steel Sphere (SSS)

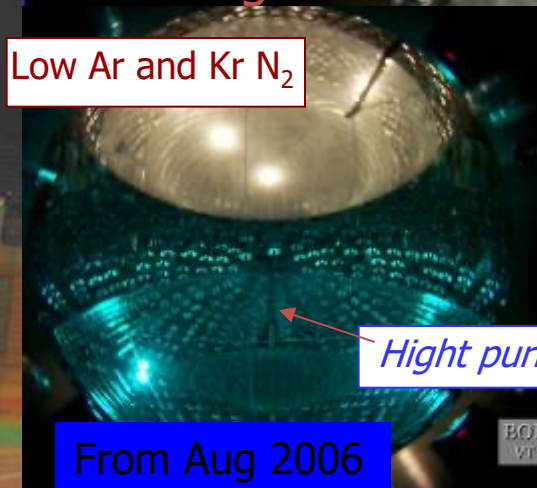


Borexino inner detector



Nylon vessels inflated, filled with water and replaced with scintillator

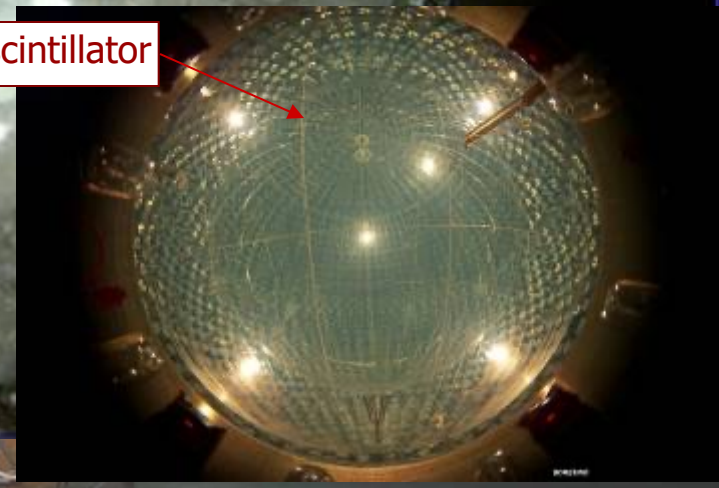
water filling



Scintillator filling

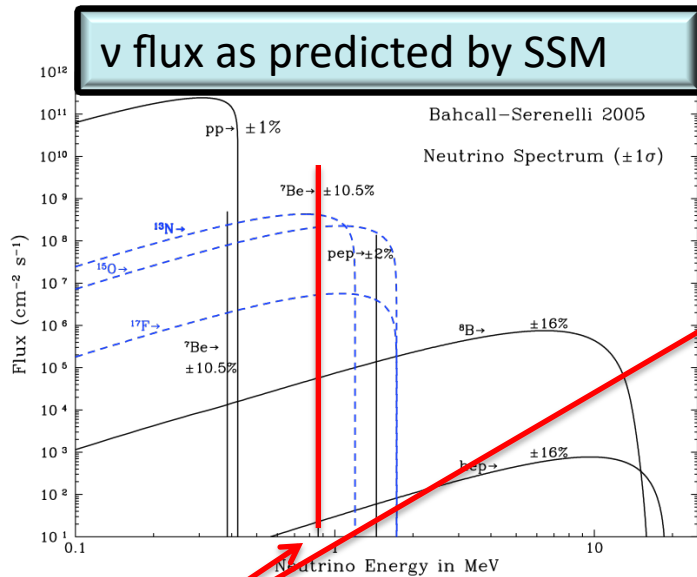


May 15th, 2007

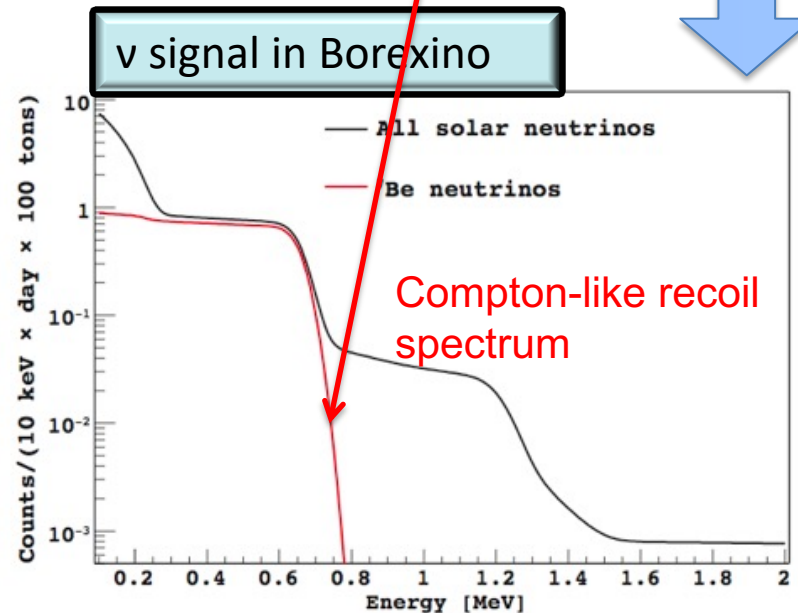
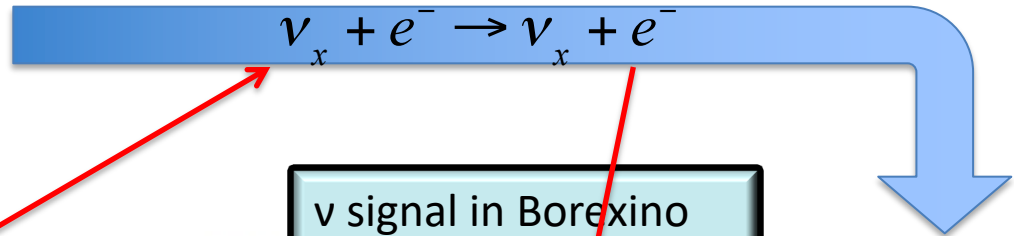


From raw data to neutrino signal

Example of ${}^7\text{Be}$ neutrino line

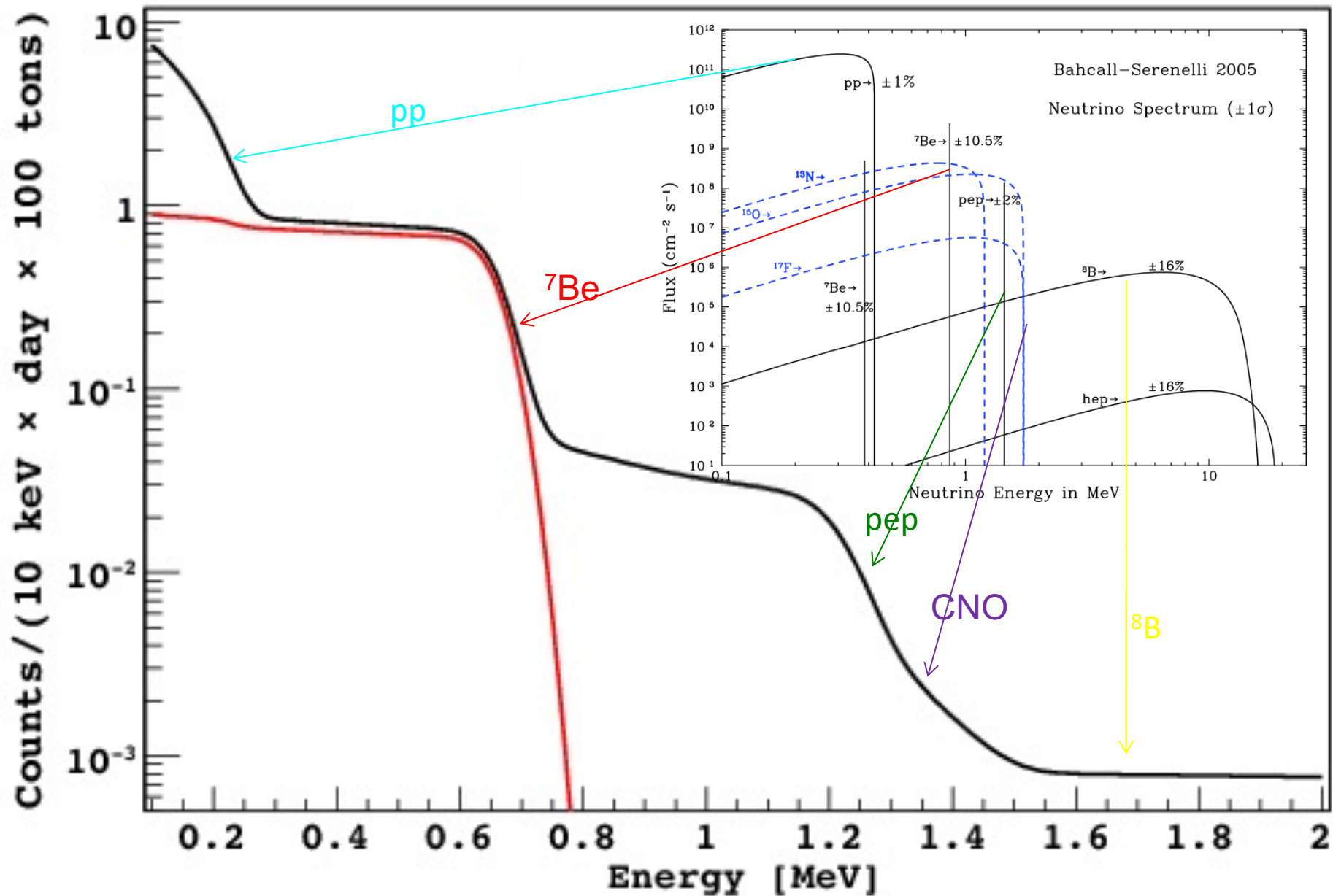


${}^7\text{Be}$ monoenergetic
line at 0.862 MeV



Maximum ES of e^- 0.662 MeV

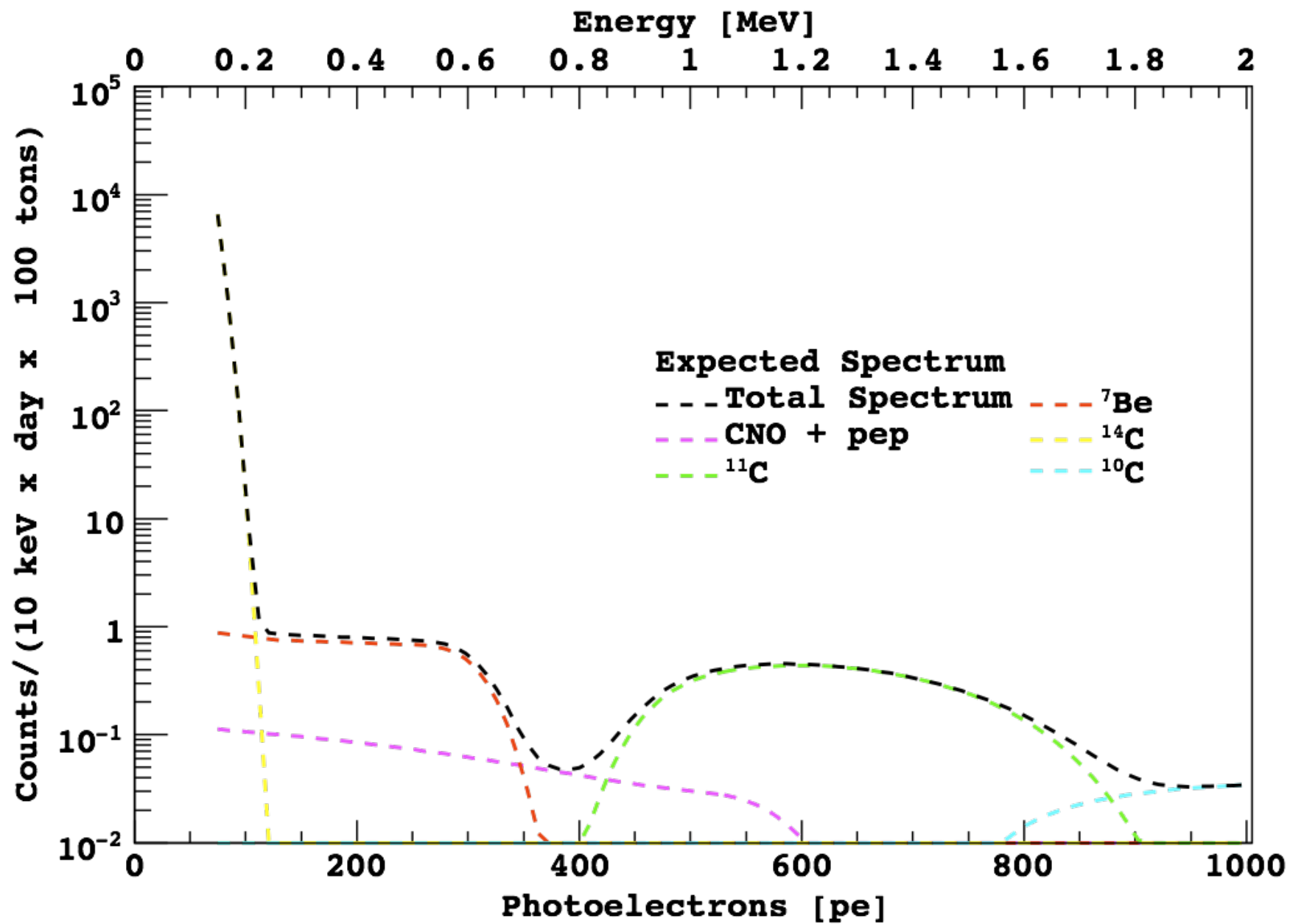
Warning: we have to take into account
the energy resolution of the detector

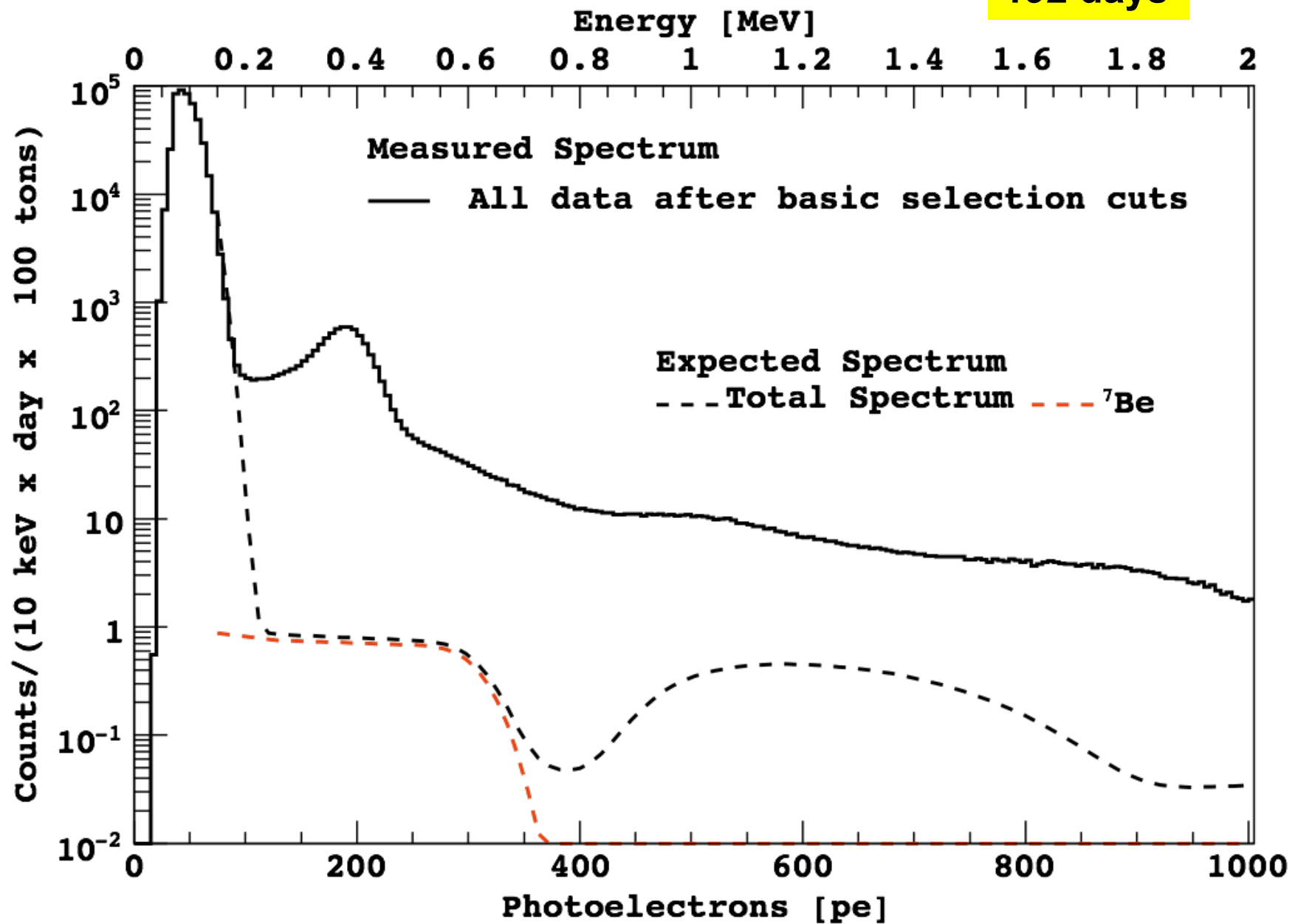


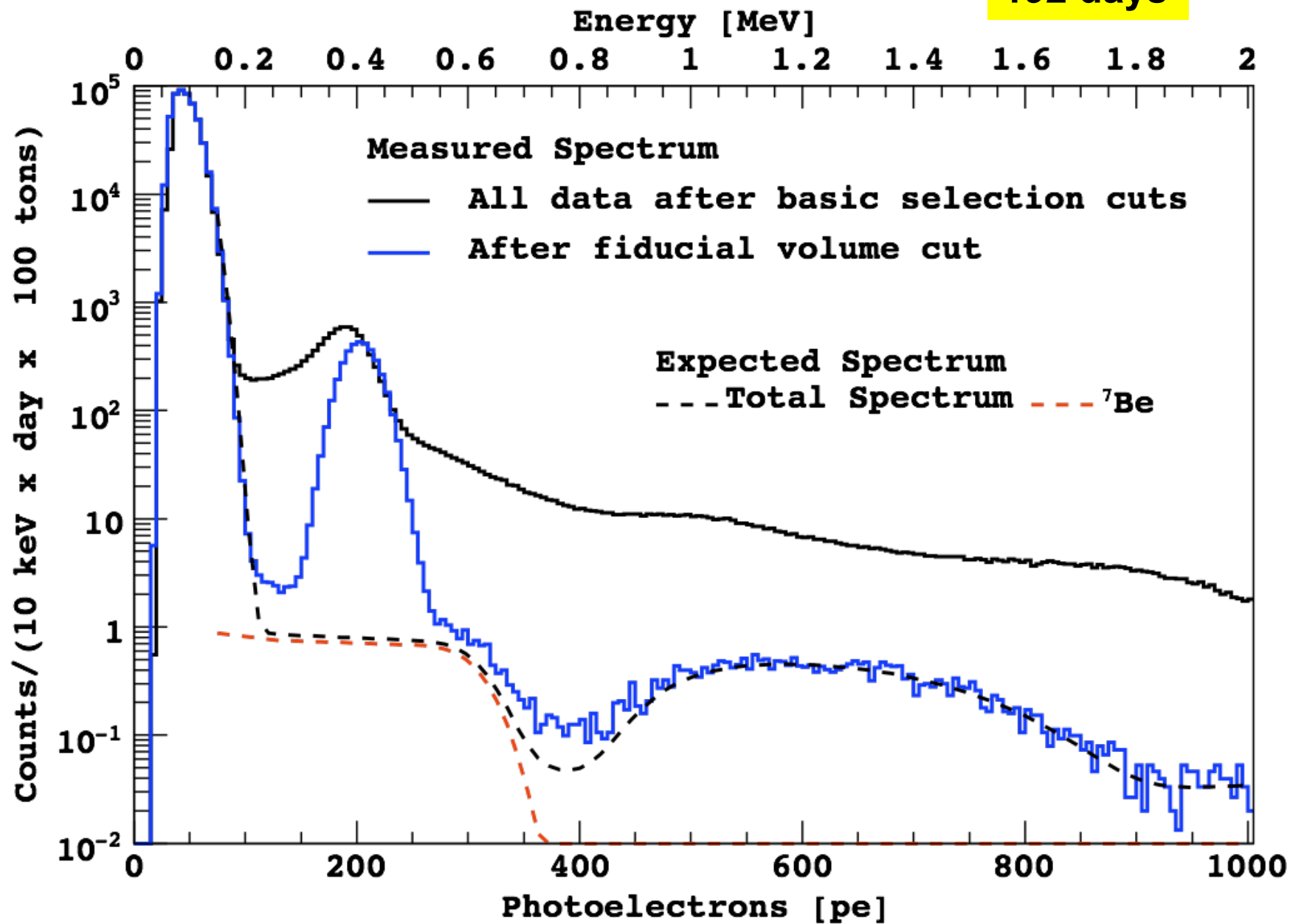
How to extract the neutrino signal from the background

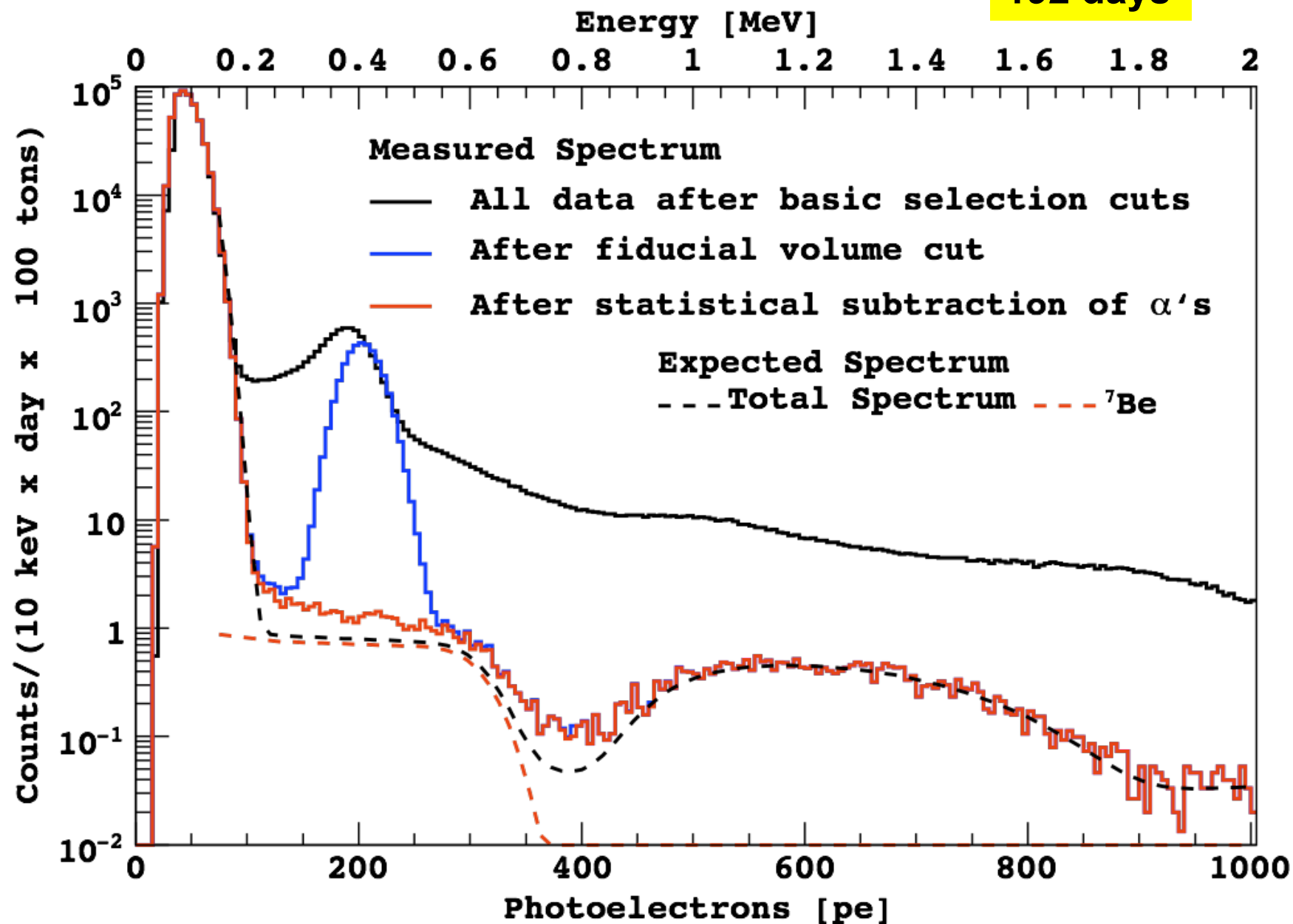
Example with data obtained collected
by Borexino in 192 live days

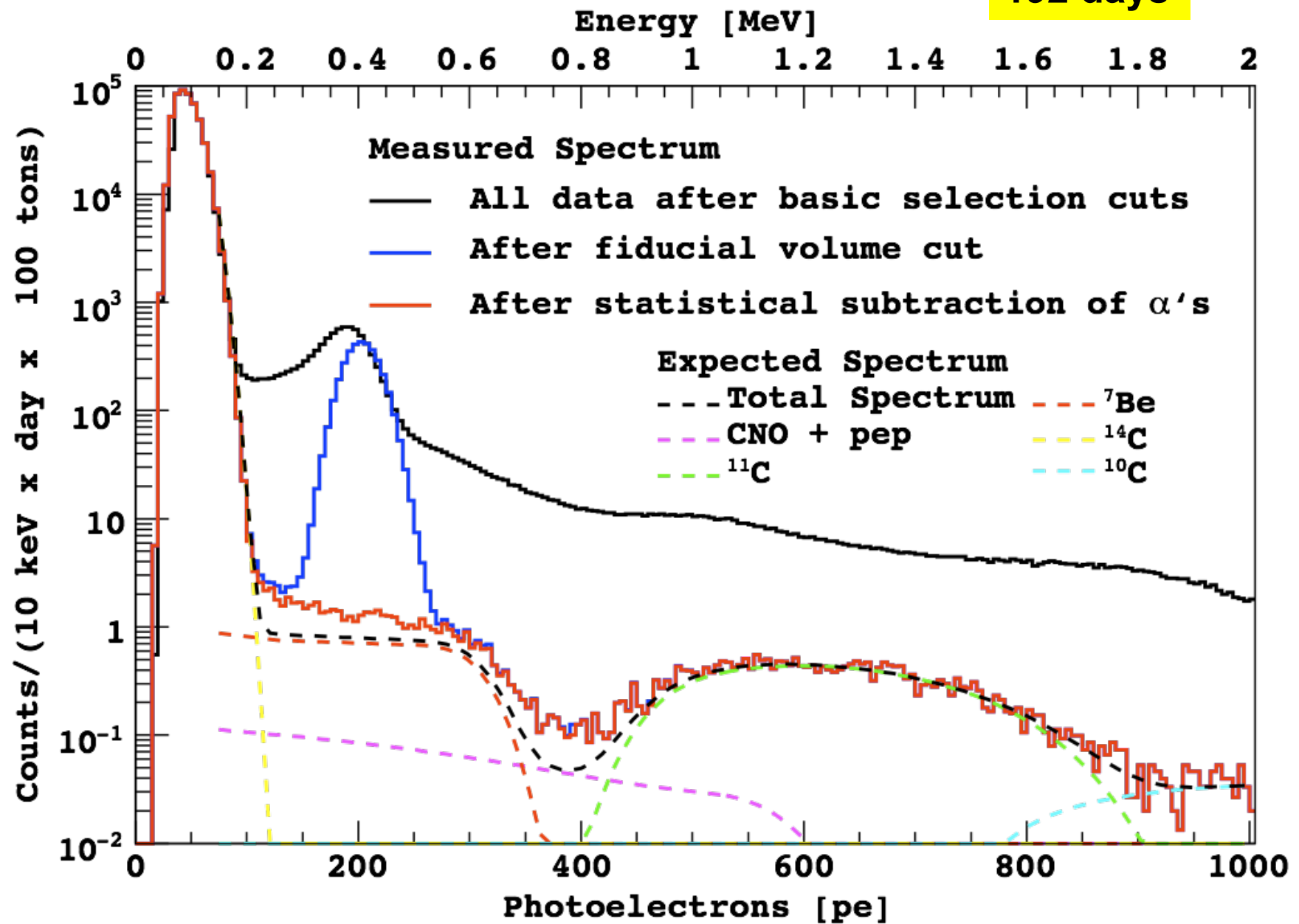
Expected Spectrum



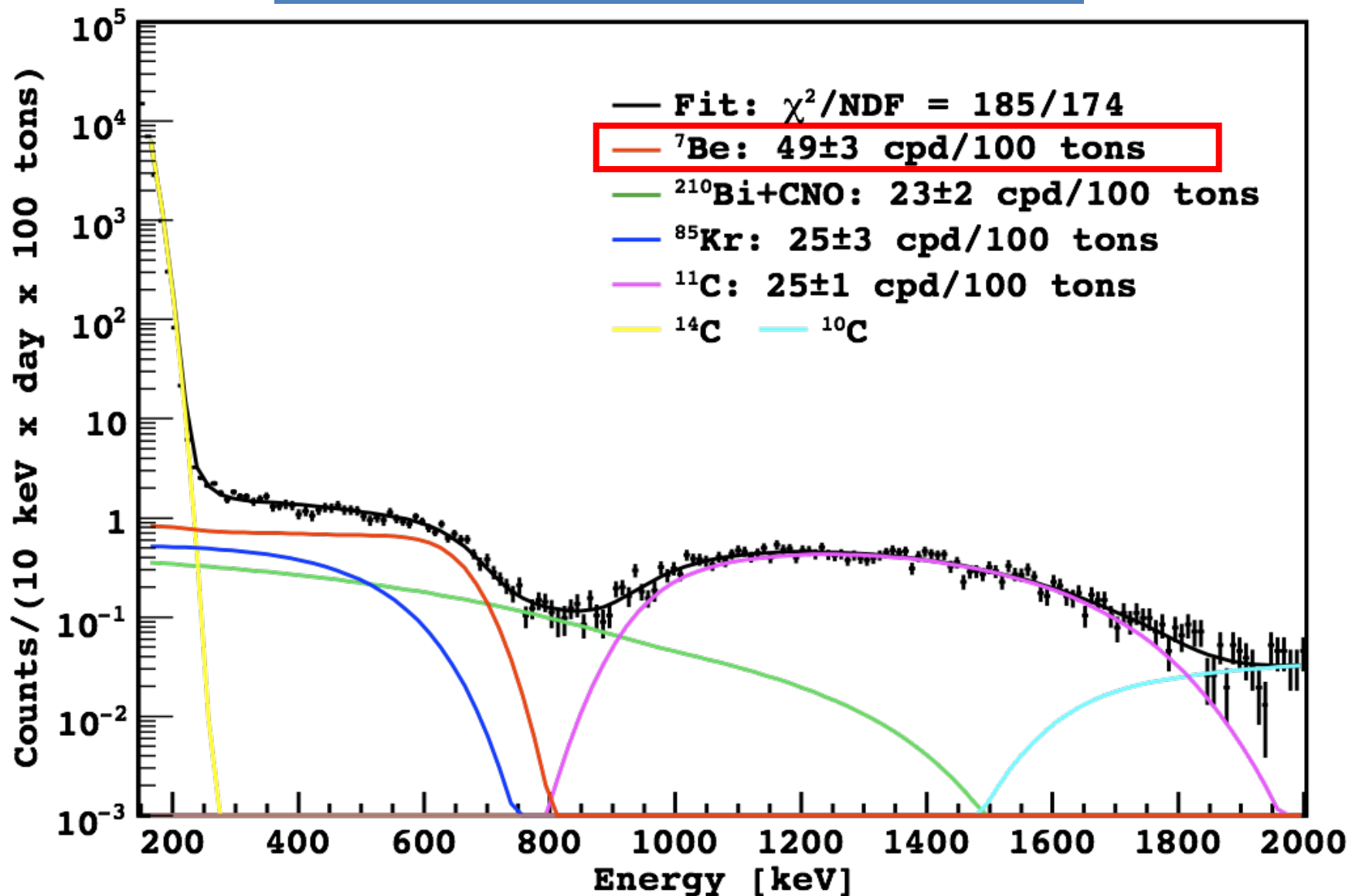








New Results: 192 Days



We have to add the systematic error:

$$49 \pm 3_{stat} \pm 4_{syst} \text{ cpd} / 100 \text{ tons}$$

First real time detection of ^7Be solar
neutrinos by Borexino
[Physics Letters B Volume 658](#), Jan 2008,

Expected ^7Be interaction rate
for MSW-LMA oscillations:

$$48 \pm 4 \text{ cpd} / 100 \text{ tons}$$

High Metallicity

$$44 \pm 4 \text{ cpd} / 100 \text{ tons}$$

Low Metallicity

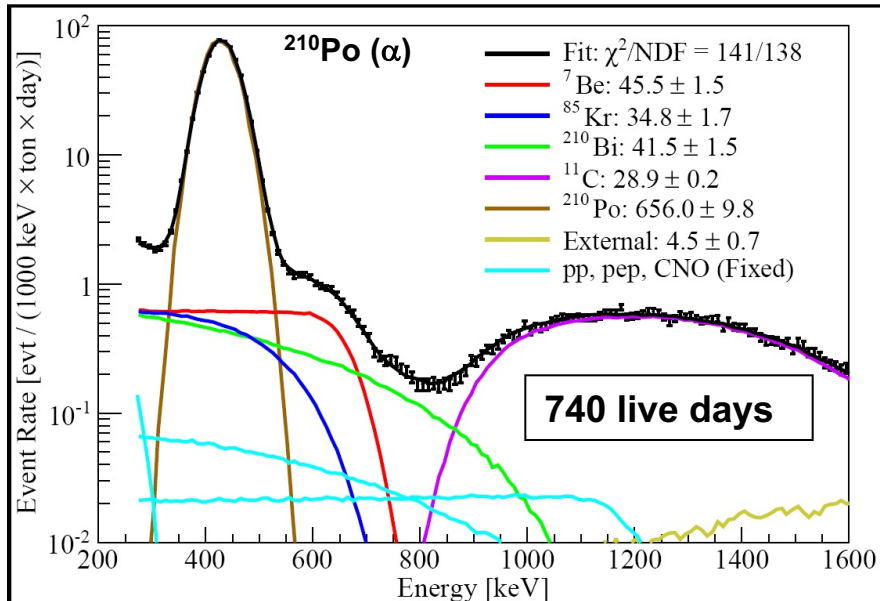
See later about Metallicity

Estimated 1σ Systematic Uncertainties* [%]

Total Scintillator Mass	0.2
Fiducial Mass Ratio	6.0
Live Time	0.1
Detector Resp. Function	6.0
Cuts Efficiency	0.3
Total	8.5

*Prior to Calibration

After 740 live days and a **calibration campaign** Borexino published the new result on **^7Be rate with a total error at 4.6%** (SSM prediction at 7%)

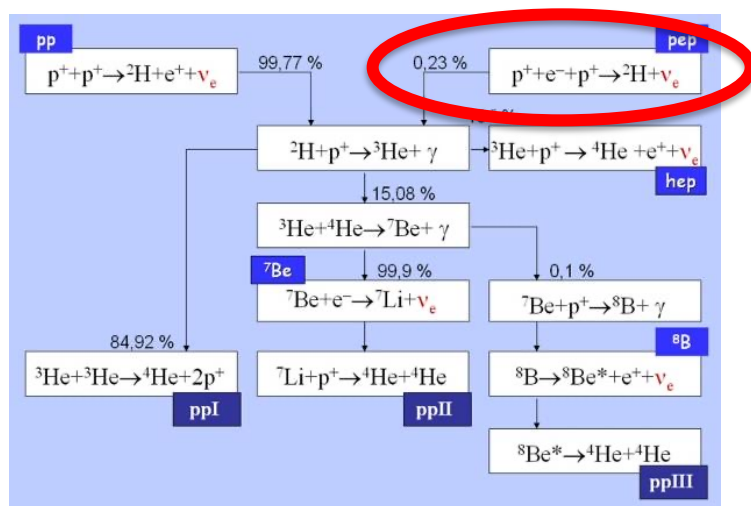


$$46.0 \pm 1.5(\text{stat}) \begin{matrix} +1.5 \\ -1.6 \end{matrix} (\text{syst}) \text{ cpd} / 100 \text{ tons}$$



The first measurement of pep neutrinos

As we said **pp** (and **pep**!) neutrinos are less model-dependent and hence more robust to prove the validity of the SSM.



pp vs pep

Unlike pp-neutrinos, pep-neutrinos are monochromatic and are emitted with a larger energy (1.442 MeV).

But the flux is very poor (about 2 order of magnitude compared to pp-neutrinos)

In the **Borexino Fiducial Volume** the expected number of events from **pep-neutrinos** is on the order of **some events per day**.

Compared to ${}^7\text{Be}$ -neutrinos, pep-neutrinos events are 1 order of magnitude smaller.

$$\frac{\text{events pep}}{\text{events } {}^7\text{Be}} \approx \frac{1}{10}$$

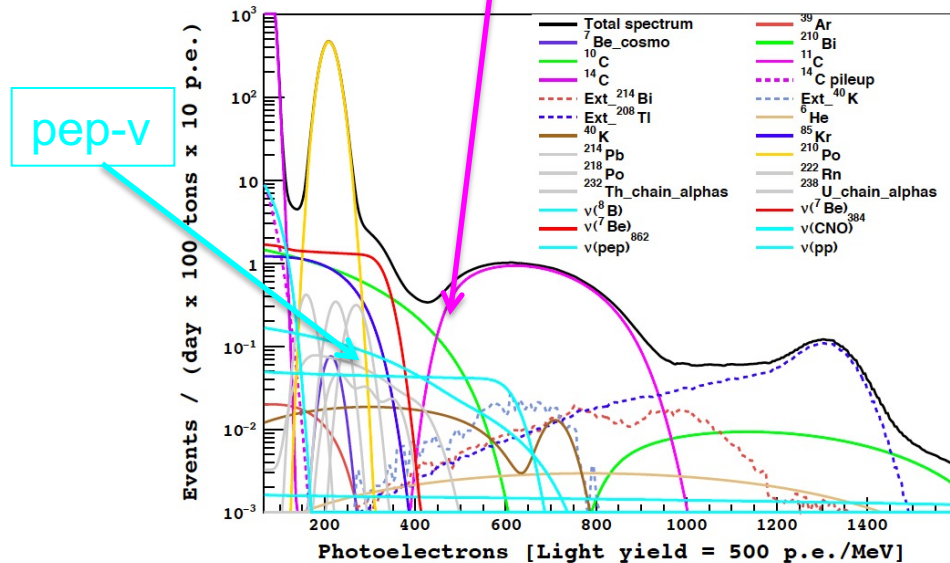
Moreover there is the problem related to the **cosmogenic ^{11}C** that cover the pep-neutrinos signal.

Main background ^{11}C (e^+) (with $\tau = 29.4$ min) created by cosmic muons.

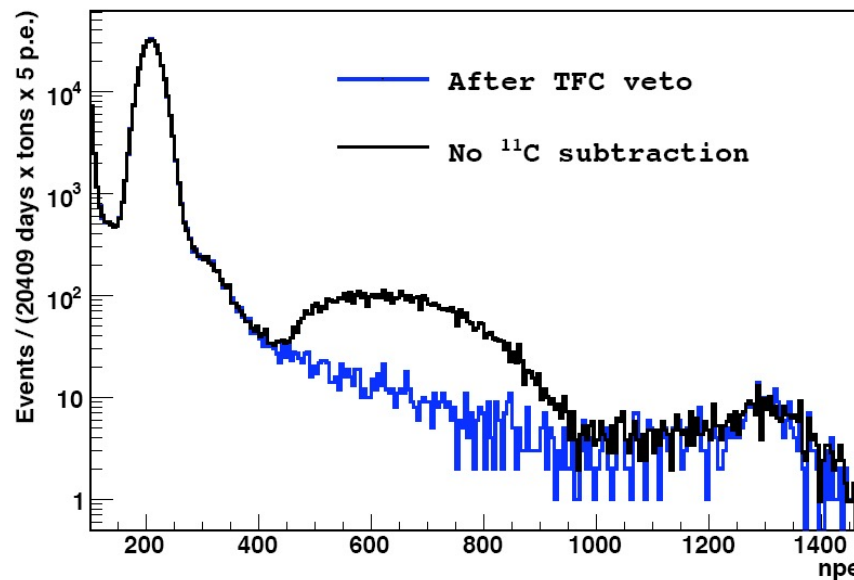
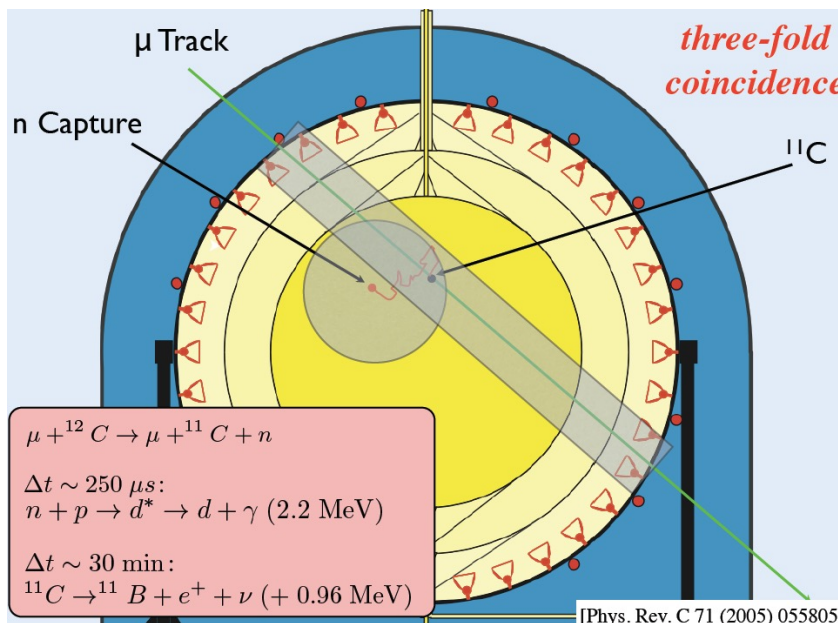


The **muon flux** in the LNGS underground laboratory is on the order of $1 \mu \text{ m}^{-2} \text{ h}^{-1}$.

^{11}C Cosmogenic
Borexino muon rate = 4200/day



Within the Borexino Collaboration has been developed the **Three Fold Coincidence (TFC)** technique: space-time veto **removes 90% of ^{11}C** (with 50% loss of exposure)



$$3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}} \text{ cpd} / 100 \text{ tons}$$

$$\Phi = (1.6 \pm 0.3) \cdot 10^8 \text{ cm}^{-2} \text{ s}^{-1}$$

Assuming MSW-LMA

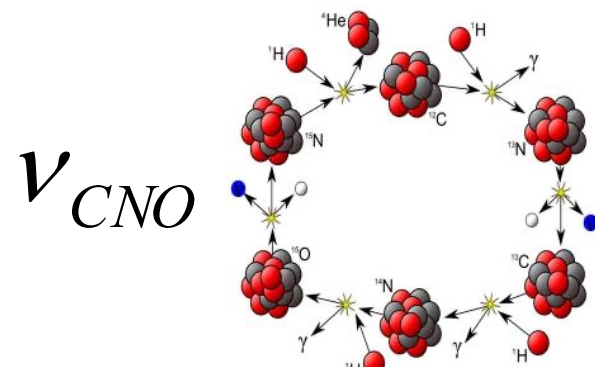


CNO neutrinos measurement and the Solar Model Chemical Controversy

So far, neutrinos produced in CNO cycle, have never been observed.

Remind:

Beside pp chain there is also the **CNO cycle**. In the Sun the CNO cycle represents 1-2 %.



Solar Model Chemical Controversy

One fundamental input of the Standard Solar Model is the **metallicity** (abundance of all elements above Helium) of the Sun

A lower metallicity implies a variation in the neutrino flux (reduction of $\sim 30\%$ for CNO neutrino flux)

Serenelli, Haxton, Pena-Garay
arXiv 1104.1639

HIGH Z SSM

LOW Z SSM

$\Delta\Phi$

CNO Flux ($10^8 \text{ cm}^{-2} \text{ s}^{-1}$)

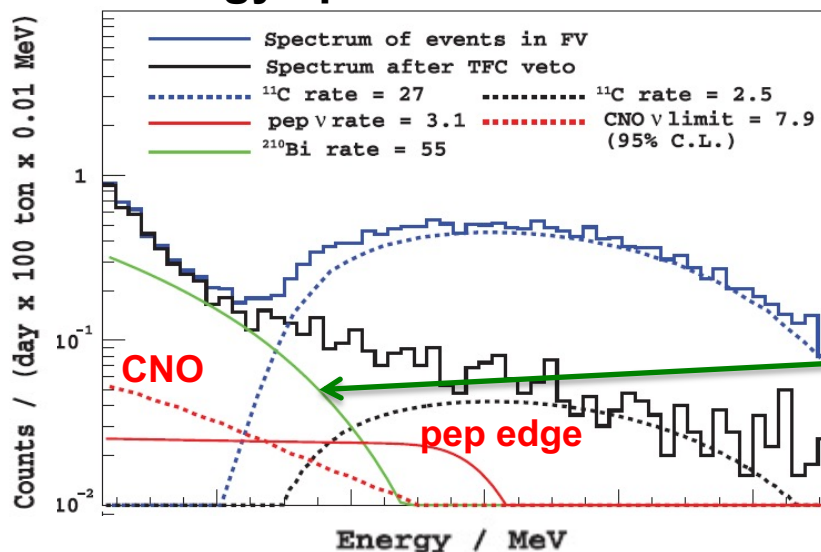
5.24 ± 0.84

3.76 ± 0.60

28%

A direct measurement of the CNO neutrinos rate could help to solve this controversy giving a direct indication of metallicity in the core of the Sun

Energy spectral fit



To measure the CNO neutrino flux, the same analysis as for pep has been adopted

^{210}Bi similar to CNO-neutrinos signal but 10 times bigger.

Only limit (the strongest to date)

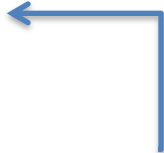
$$< 7.9 \text{ cpd} / 100 \text{ tons} (95\% \text{ CL})$$

Not sufficient to resolve the metallicity problem

$$\Phi < 7.7 \cdot 10^8 \text{ cm}^{-2} \text{ s}^{-1} (95\% \text{ CL})$$

Borexino phase II

Since July 2010 Borexino has undertaken a series of **purification campaigns** to decrease radioactive background



Quite effective on ^{85}Kr , good on ^{210}Bi ,
unprecedented purity in ^{238}U and
 ^{232}Th

Main Goals of Borexino phase II:

- Measure **pep**-neutrinos at more than 3σ ;
- Improve limit on **CNO**-neutrinos;
- Refine ^7Be rate measurement at 3% error;
- Improve ^8B measurement with low energy threshold;
- Attempt **pp**-neutrinos detection.

doi:10.1016/j.jmb.2006.07.009

112

Most of the pp neutrino events are buried under the vastly more abundant ^{14}C , which is a β -emitter with a Q-value of 156 keV. $^{14}\text{C}/^{12}\text{C} \approx 2.7 \cdot 10^{-18}$

The measured ^{14}C rate of 40 ± 1 Bq per 100 t.

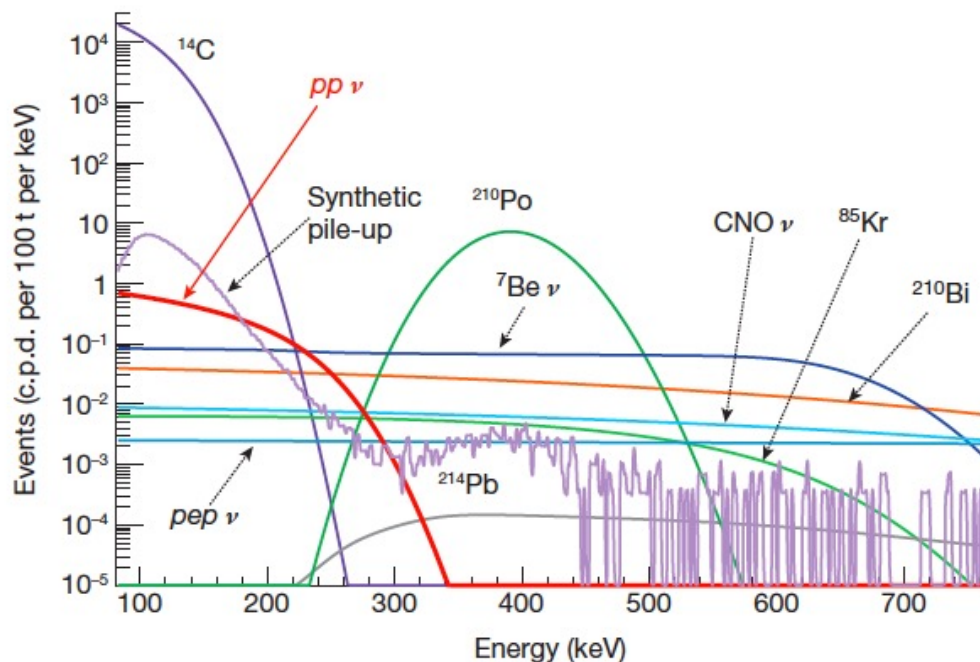


Figure 2 | Energy spectra for all the solar neutrino and radioactive background components. All components are obtained from analytical expressions, validated by Monte Carlo simulations, with the exception of the synthetic pile-up, which is constructed from data (see text for details).

pile-up events:

occurrences of two uncorrelated events so closely in time that they cannot be separated and are measured as a single event.

Fortunately, the pile-up component can be determined independently, using a data-driven method, which we call '**synthetic pile-up**'

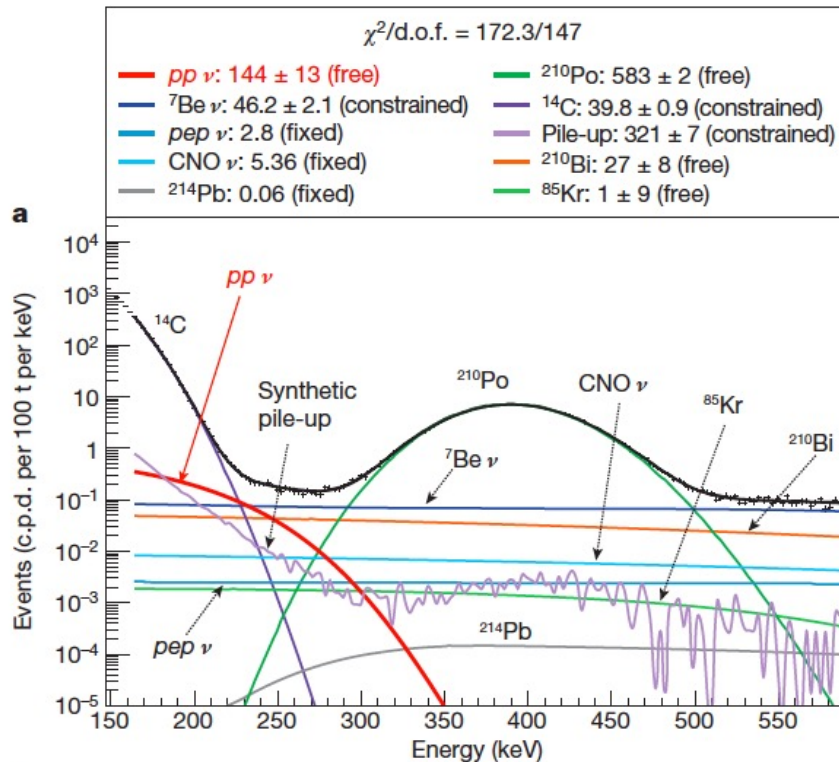
This method provides the spectral shape and the rate of the pile-up component.

The synthetic pile-up is mainly due to the overlap of two ^{14}C events, but includes all possible event combinations, for example ^{14}C with the external background, PMT dark noise or ^{210}Po .

^{14}C – ^{14}C pile-up events 154 ± 10 c.p.d. in 100 t

The data used for this analysis were acquired from January 2012 to May 2013 (408 days of data; [Borexino Phase II](#)).

The pp neutrino rate has been extracted by fitting the measured energy spectrum of the selected events in the 165–590 keV energy window with the expected spectra of the signal and background components.



The solar pp neutrino interaction rate measured by Borexino is:

$$144 \pm 13 \text{ (stat.) } \pm 10 \text{ (syst.) c.p.d. per 100 t}$$

The absence of pp solar neutrinos is excluded with a statistical significance of 10σ

The measured solar pp neutrino flux is:

$$(6.6 \pm 0.7) 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$$

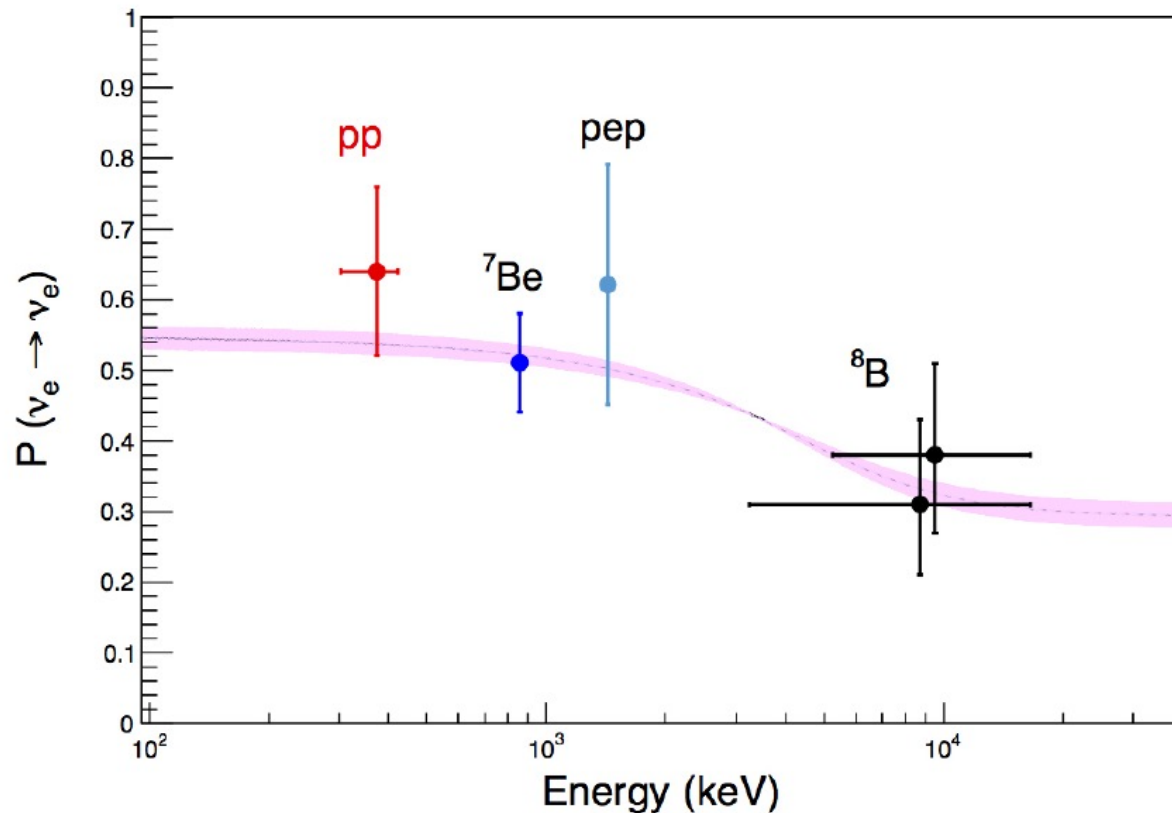
Good agreement with the SSM prediction:

$$5.98 (1 \pm 0.006) 10^{10} \text{ cm}^{-2} \text{ s}^{-1}.$$

The measured value is in very good agreement with the predictions of both the high-metallicity and the low-metallicity SSMs.

Future Borexino-inspired experiments might be able to measure solar pp neutrinos with the level of precision ($\approx 1\%$) needed to cross-compare photon and neutrino solar luminosities, while providing insight into solar dynamics over 10^5 -yr timescales.

Precise measurement of pp neutrinos would yield the ultimate test for the **MSW-LMA neutrino oscillation model** and allow precision tests for exotic neutrino properties

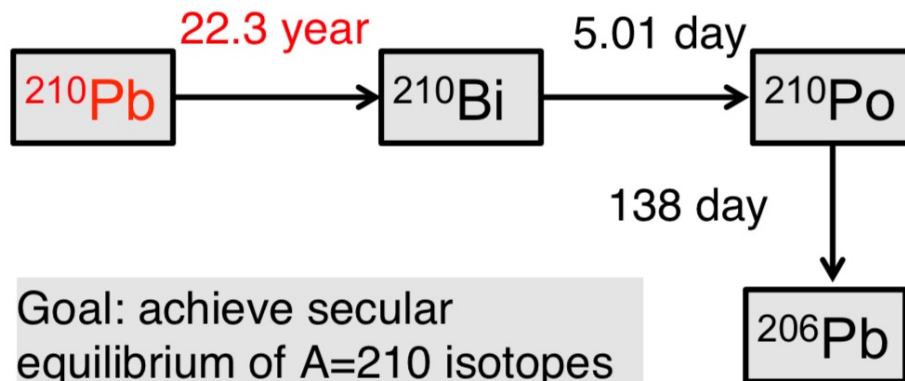


Extended Data Figure 2 | Survival probability of electron-neutrinos produced by the different nuclear reactions in the Sun. All the numbers are from Borexino (this paper for pp , ref. 17 for ${}^7\text{Be}$, ref. 18 for pep and ref. 19 for ${}^8\text{B}$ with two different thresholds at 3 and 5 MeV). ${}^7\text{Be}$ and pep neutrinos are mono-energetic. pp and ${}^8\text{B}$ are emitted with a continuum of energy, and the reported $P(\nu_e \rightarrow \nu_e)$ value refers to the energy range contributing to the

measurement. The violet band corresponds to the $\pm 1\sigma$ prediction of the MSW-LMA solution²⁵. It is calculated for the ${}^8\text{B}$ 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 $\pm 1\sigma$ interval; the horizontal uncertainty shows the neutrino energy range used in the measurement.

Borexino:

- Combined Phase I and Phase II analysis
- Trying hard to measure **CNO**: CNO spectrum degenerate with that of ^{210}Bi : thermal isolation of the detector to stop convection and to constrain ^{210}Bi through ^{210}Po in secular equilibrium

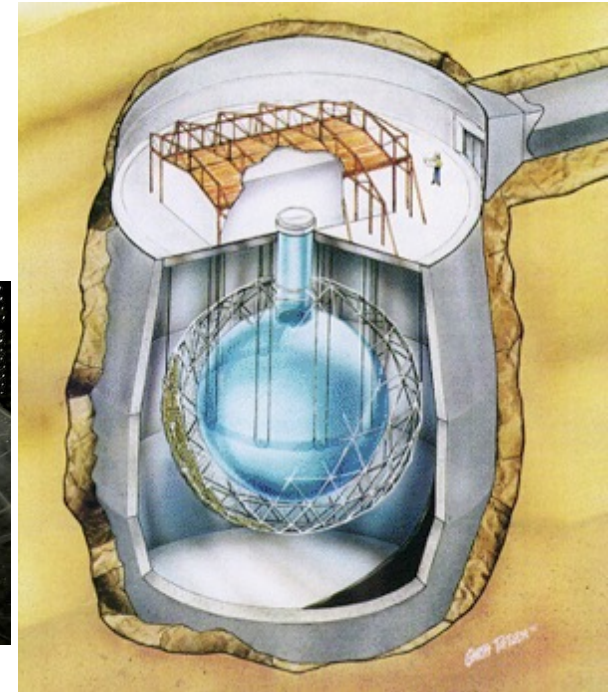


Goal: achieve secular equilibrium of A=210 isotopes in the fiducial volume



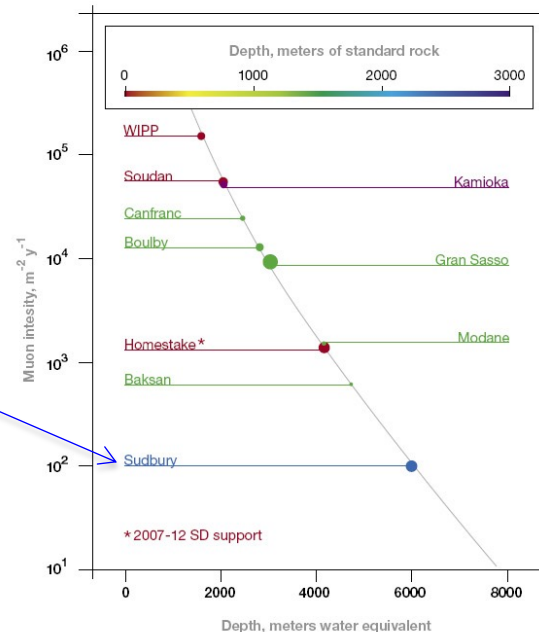


Heavy water is replaced by **liquid scintillator** (linear Alkylbenzene – LAB) compatible with the 12m diameter acrylic sphere.



Located at approximately **2km** underground in Creighton mine near Sudbury, Ontario, Canada

The **muon flux** is **2 order of magnitude** less than in Gran Sasso



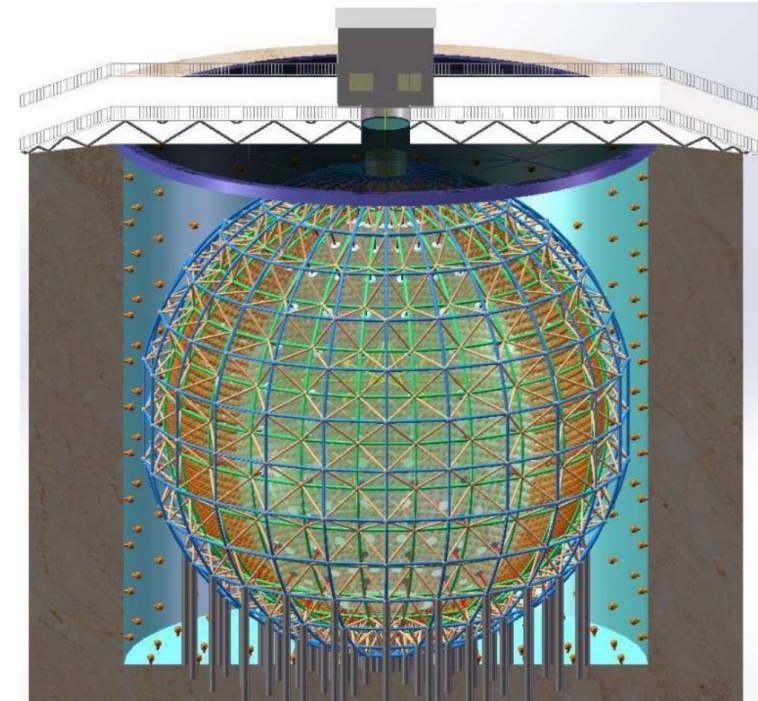
Very good position to study **pep-neutrinos** and **CNO-neutrinos**



JUNO

Jiangmen Underground Neutrino Observatory

20 kton LS detector under construction in south China (neutrino mass hierarchy), possibilities to measure ^8B and ^7Be

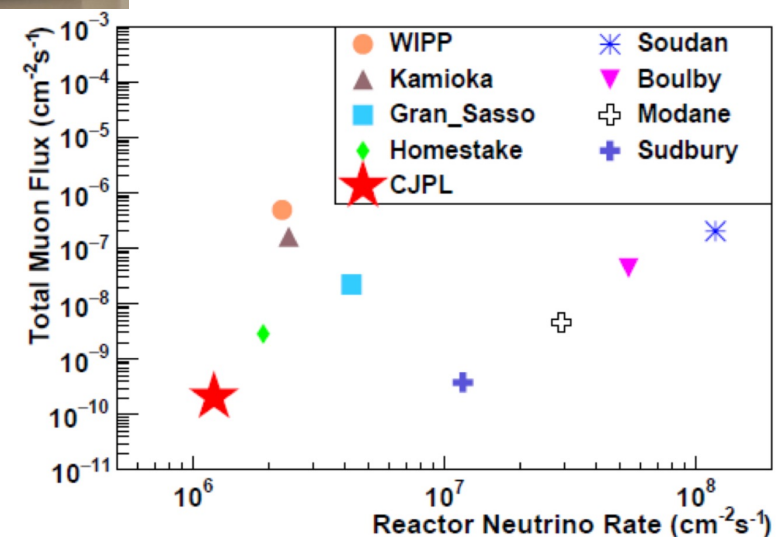
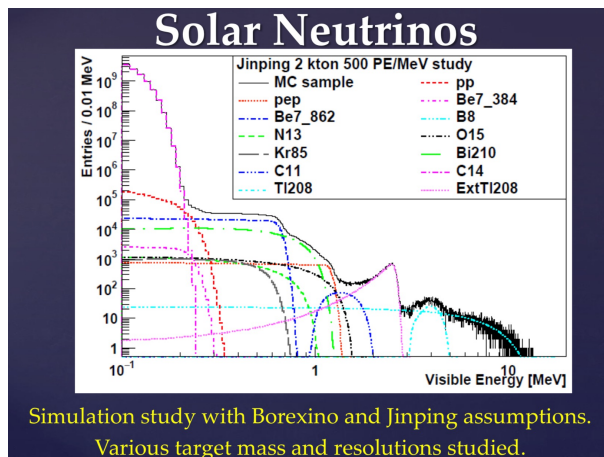
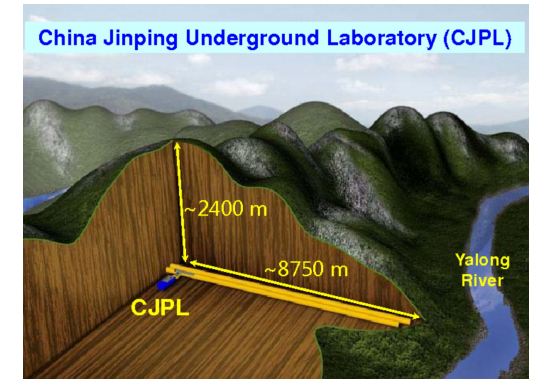
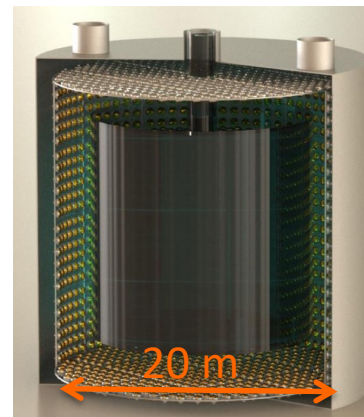


Jinping Neutrino Experiment



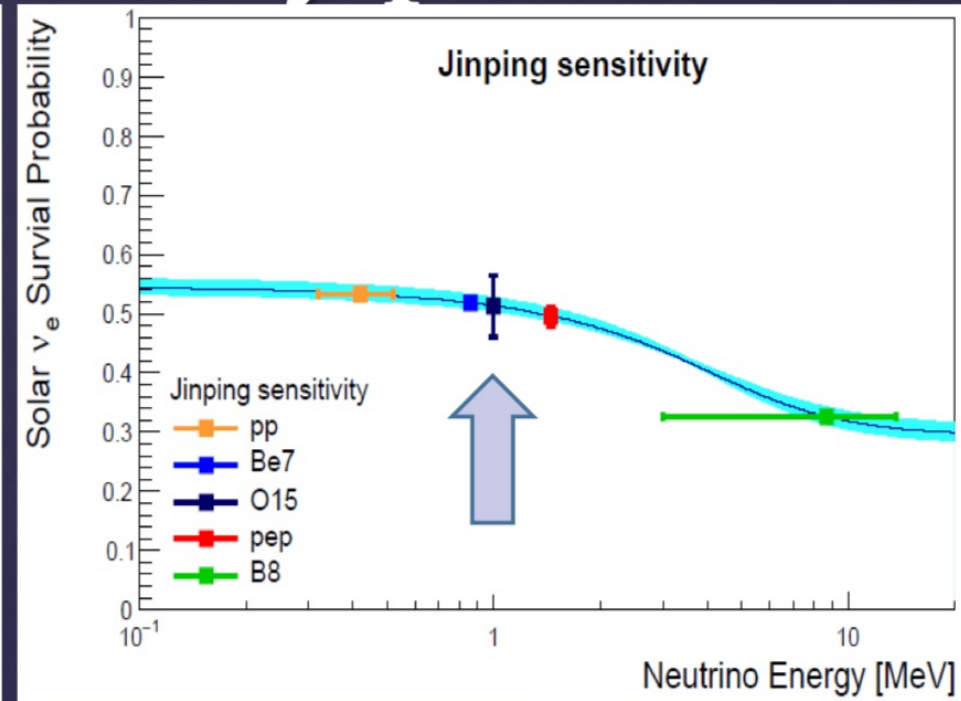
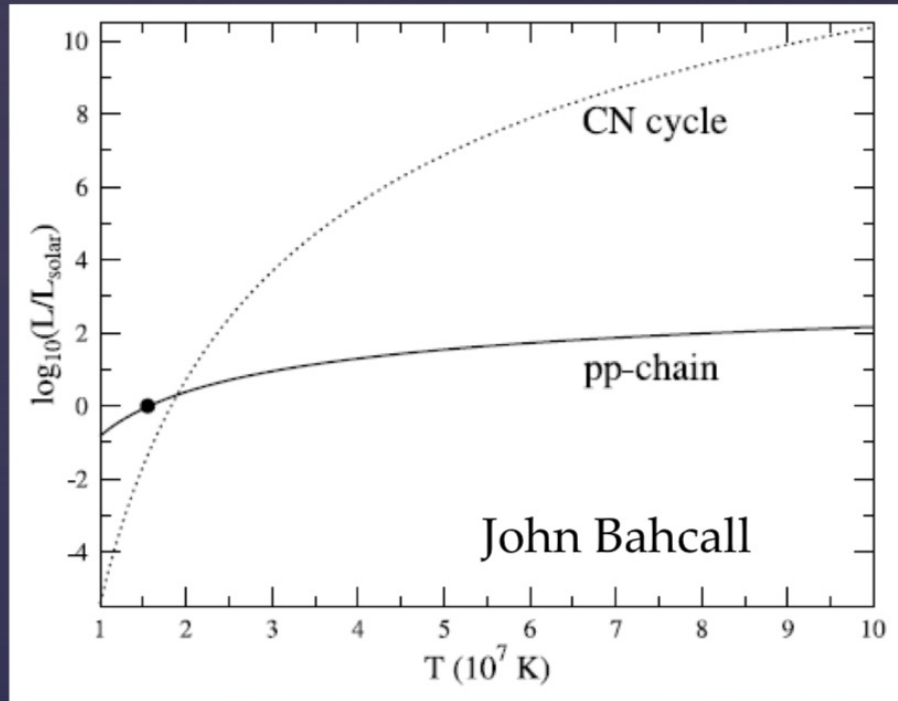
China JinPing underground Laboratory
located in Jinping Mountain of Sichuan.
Overburden of about 2400 m.
(6720 m.w.e.)

~2 kton FV LS detector proposed
in the world deepest underground
lab in the world.
Very low ^{11}C background, thus
great for **pep** and **CNO**



Discover CNO neutrino

Address metallicity problem



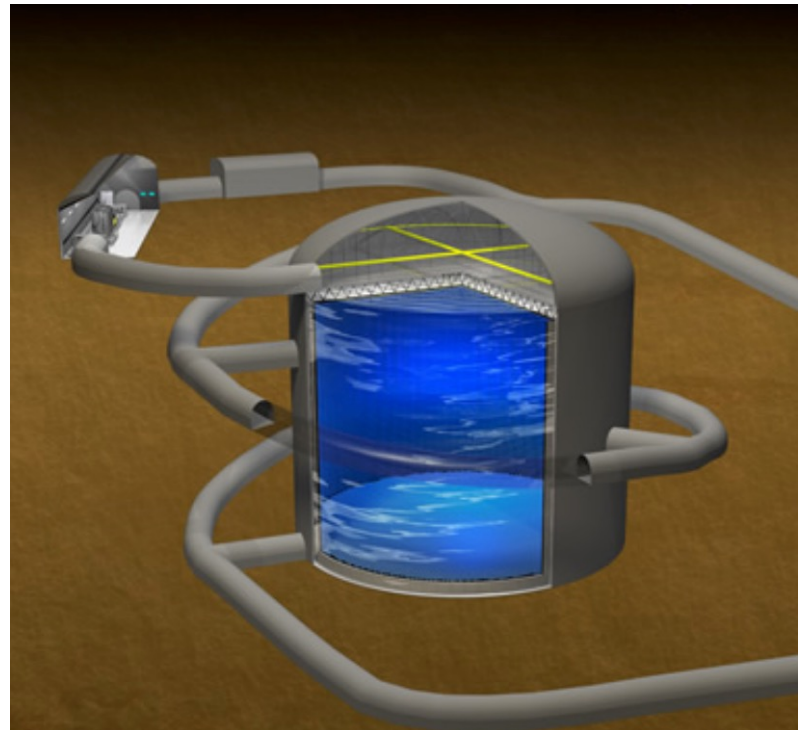
Above 15 MK
CN fuel the
stars

- Precise measure of all components
- Expected to discover CN ν
- O-15 precision 10%
- Direct proof for metallicity problem

Hyper-Kamiokande

- precision ^8B

The Hyper-Kamiokande (Hyper-K) detector is to be located 650m underground in the Kamioka mine, Hida city, Gifu prefecture, Japan. The detector design consists of a cylindrical tank with outer dimensions of **60m height × 74m diameter**; this is filled with 260,000 metric tons of ultrapure water to form a 'water Cherenkov detector'. The detector fiducial volume of Hyper-K is planned to be 10 times larger than that of Super-Kamiokande, which will make it the world's largest underground water tank.



50 kilotons of liquid scintillator (linear Alkylbenzene – LAB)

Fiducial volume of the order of 30 ktons

45000 photomultipliers

A **high statistics** can be obtained in short times and in both Pyhsalmi and Frejus underground laboratories

Expected solar neutrino rates in LENA

Source	EW [MeV]	m_{fid} [kt]	Rate [cpd]
pp	>0.25	30	40
pep	0.8–1.4	30	2.8×10^2
^7Be	>0.25	35	1.0×10^4
^8B	>2.8	35	79
CNO	0.8–1.4	30	1.9×10^2

Low Energy Neutrino Astronomy

Cavern

height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w.e.

Muon Veto

plastic scintillator panels (on top)
Water Cherenkov Detector
3,000 phototubes
100 kt of water
reduction of fast neutron background

Steel Cylinder

height: 100 m, diameter: 30 m
70 kt of organic liquid
30,000 – 50,000 phototubes

Buffer

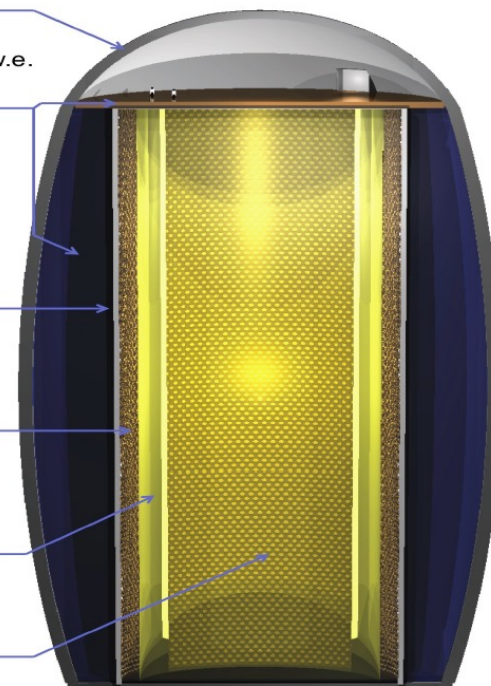
thickness: 2 m
non-scintillating organic liquid
shielding from external radioactivity

Nylon Vessel

separating buffer liquid and liquid scintillator

Target Volume

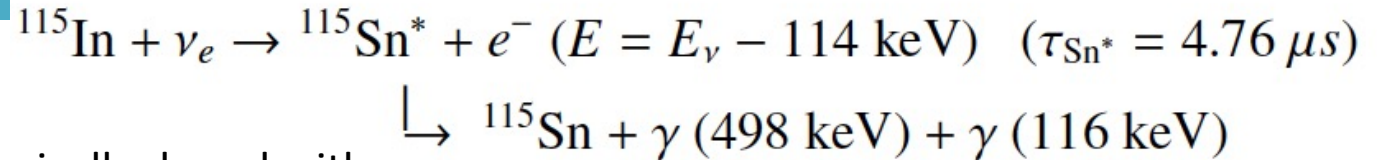
height: 100 m, diameter: 26 m
50 kt of liquid scintillator



Because the smaller ratio of surface to volume compared to the Borexino detector, in LENA it is very likely to reach the excellent background conditions of Borexino.

Detectors with new technique: LENS

The CC process employed in LENS is the neutrino induced transition of ^{115}In to an excited state of ^{115}Sn :



Liquid scintillator chemically doped with natural indium ($^{115}\text{In} = 95.7\%$)



In order to make an **energy spectrum** measurement on **low energy** neutrinos, it is necessary to reach a low threshold for the charged current (CC) process

The primary interaction and secondary gamma cascade make a **triple coincidence**, correlated in both time and space

The combination of the $4.76 \mu\text{s}$ mean delay and the spatial correlation of the primary electron and the two de-excitation γ 's of known energies provides a sharp tag for neutrino interactions

Thanks to that it is possible to detect low energy neutrinos with a **threshold of 114 keV** and measure their energy,

For a recent review of solar neutrinos see:

Solar Neutrinos

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Advances in High Energy Physics Volume 2013 (2012) Article ID 351926.