Solar Neutrinos
(an experimental approach)

SUT-IHEP

School of Neutrino Physics

Davide D’Angelo
Università degli Studi di Milano
Instituto Nazionale di Fisica Nucleare (INFN), sez. di Milano

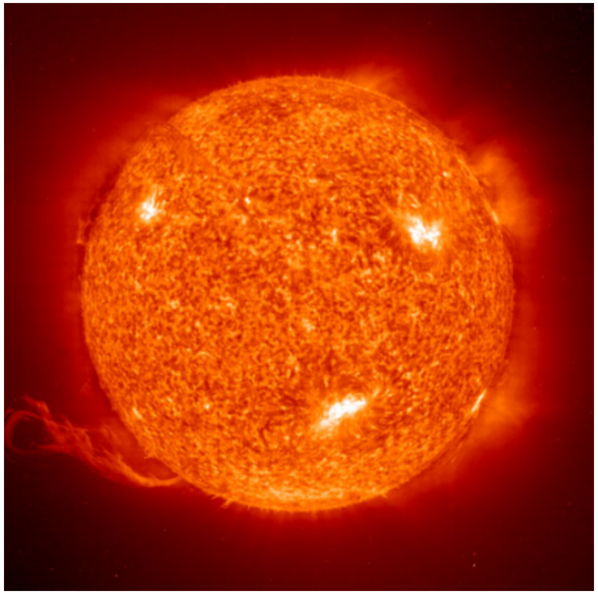
23rd February 2016
Suranaree University of Technology
Nakon Ratchasima, Thailand

Overview

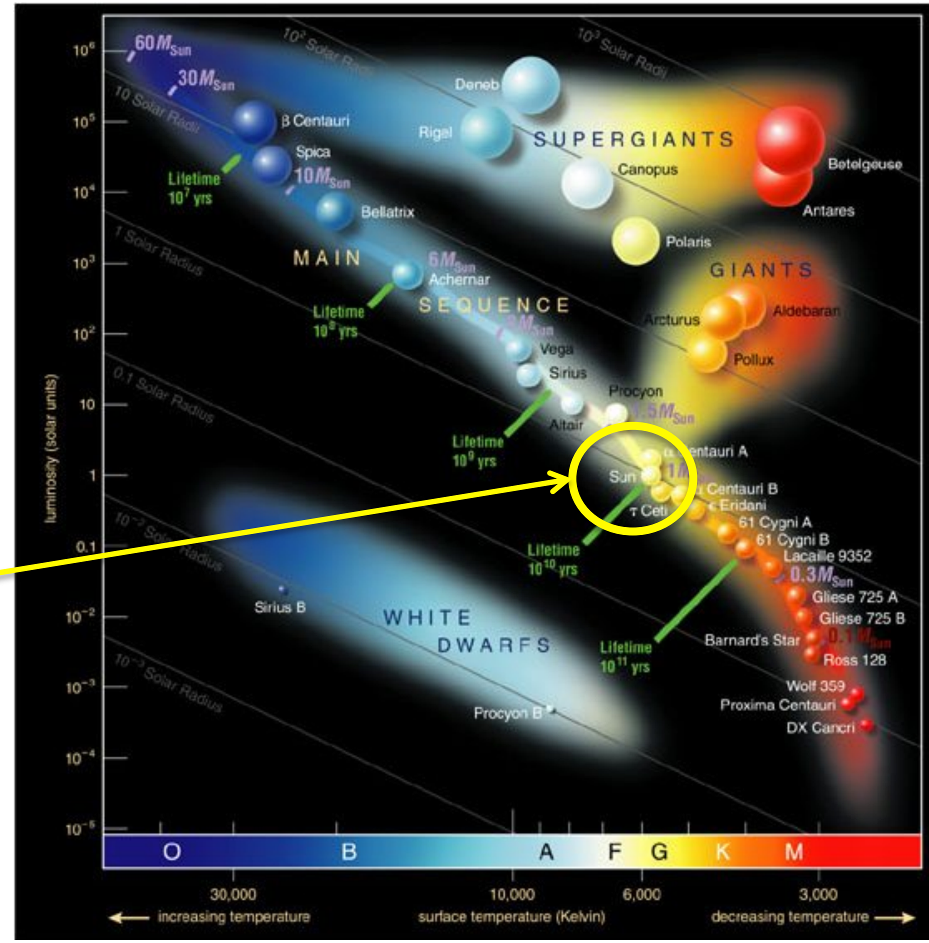
1. The Sun and solar neutrinos
2. Solar Neutrino detection
3. Low Energy solar neutrino spectroscopy
4. Future Projects

1

The Sun
and
the solar neutrinos



I.D. of the Sun

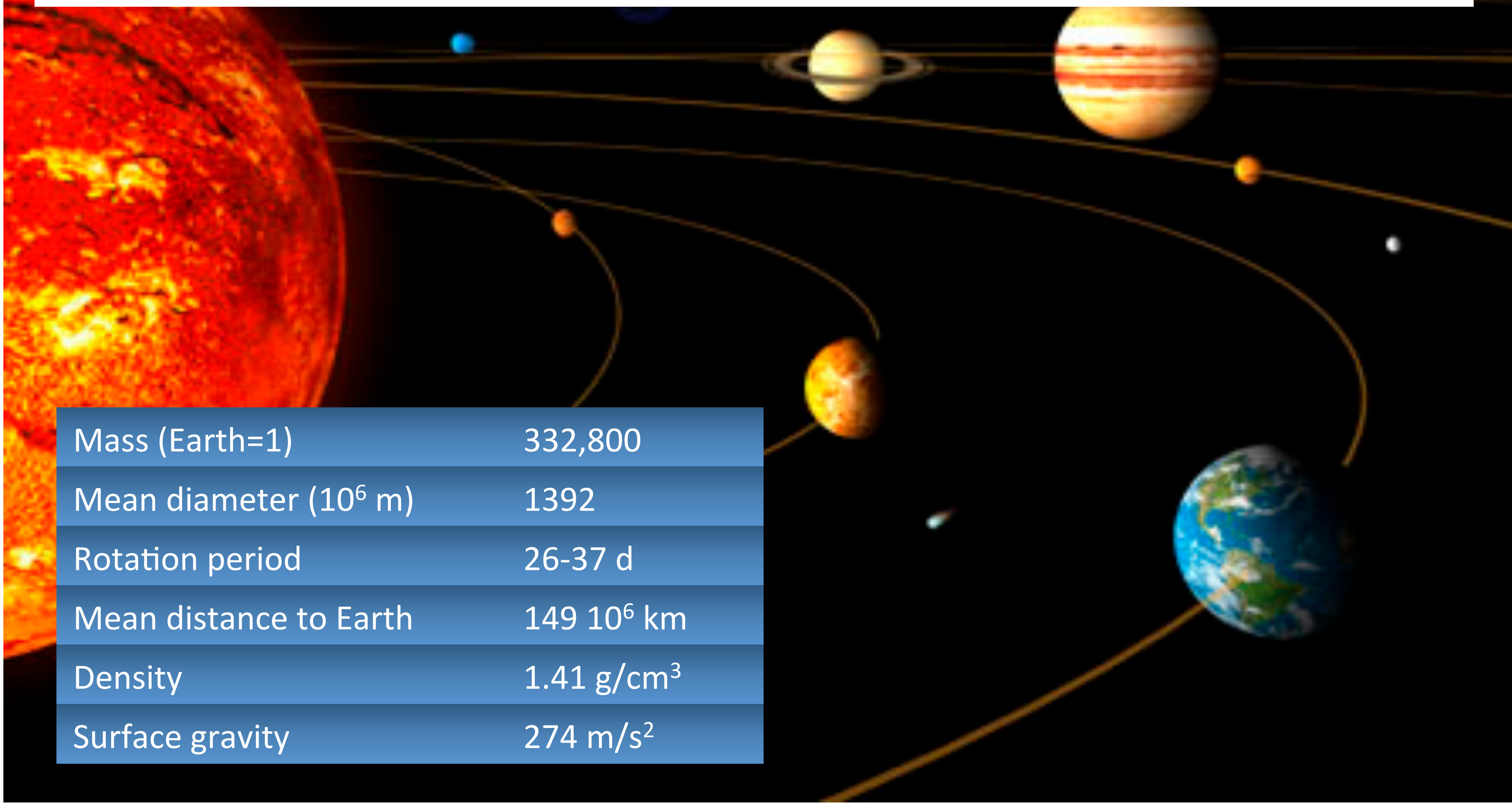


The Sun is a **star of medium size** and lies on the main sequence of the Hertzsprung-Russell diagram

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	149 10^6 km
Density	1.41 g/cm^3
Surface gravity	274 m/s^2

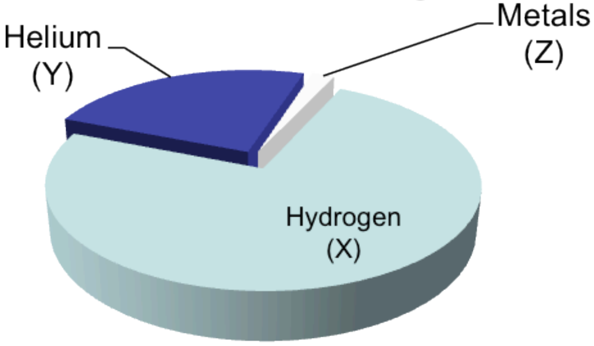
Composition of the Sun

About ¾ of the mass of the Sun consists of hydrogen;

About ¼ 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 ~ 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

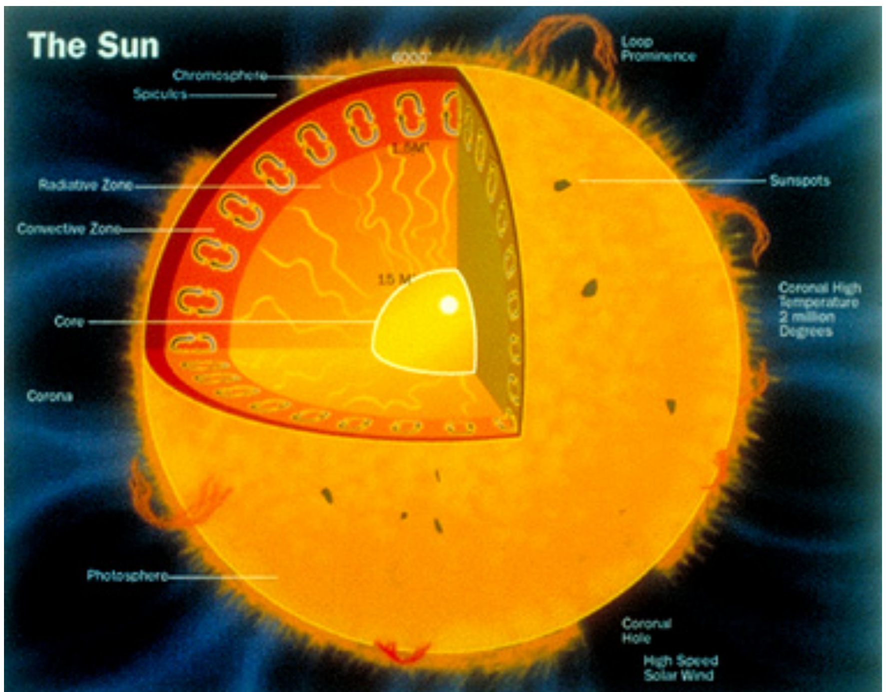
Element	Abundance (% of total number of atoms)	Abundance (% of total mass)
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

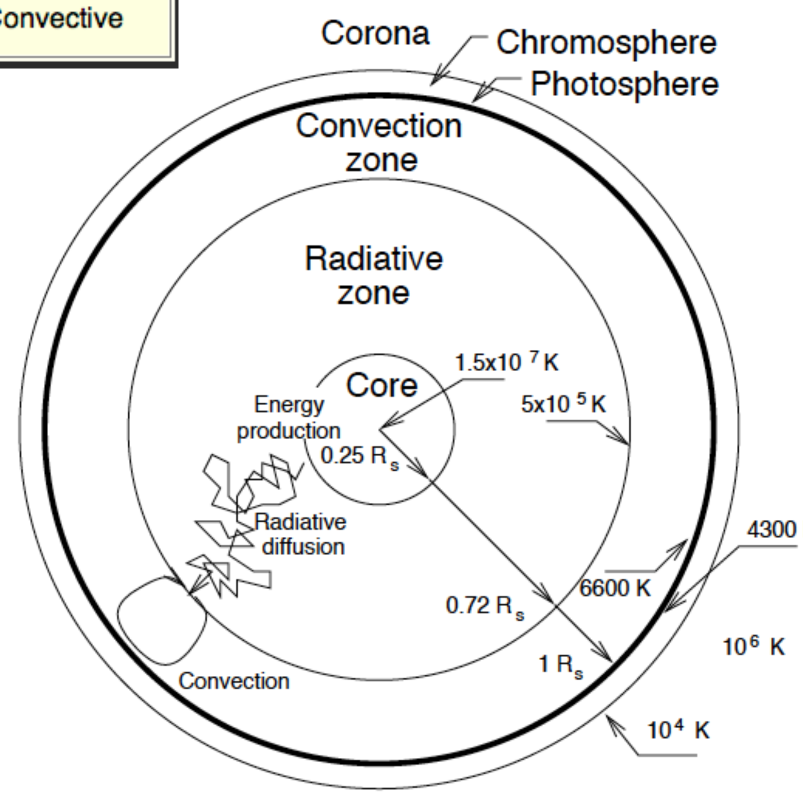
The interior of the Sun

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

Interior Zones of the Sun				
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/cm^3





The Standard Solar Model (SSM)

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

The model is based on the following Assumptions:
(Simulations use basic stellar evolution equation)

1. Hydrostatic equilibrium: (local balance between pressure and gravity) $\frac{dP(r)}{dr} = -\frac{G\,M(r)\rho(r)}{r^2}$
2. Energy conservation: $\frac{dL(r)}{dr} = 4\,\pi\,r^2\,\rho(r)\varepsilon(r)$
3. Energy transport mostly by radiation and convection,
   energy flux is measured by the Temperature gradient

$$I(x) = I_0 e^{-\kappa_\nu \rho x}$$

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

where:
k is opacity,
σ is Stefan-Boltzmann constant
γ is the ratio of specifici heat capacities: c_P/c_V,

together with three state equations for Pressure, Opacity and Energy production rate:

$$P = P(\rho.T, X) \qquad k = k(\rho.T, X) \qquad \varepsilon = \varepsilon(\rho.T, X)$$

The Standard Solar Model (SSM)

- Initial physics parameters:
  - ✓ Helium and metals' abundancies;
  - ✓ Opacity vs. radius
  - ✓ Cross sections of nuclear fusion reactions
- Evolution to t = 4.4 x 10^9 anni (today);
- Compare input/output parameters;
- If needed, modify initial parameters and iterate.

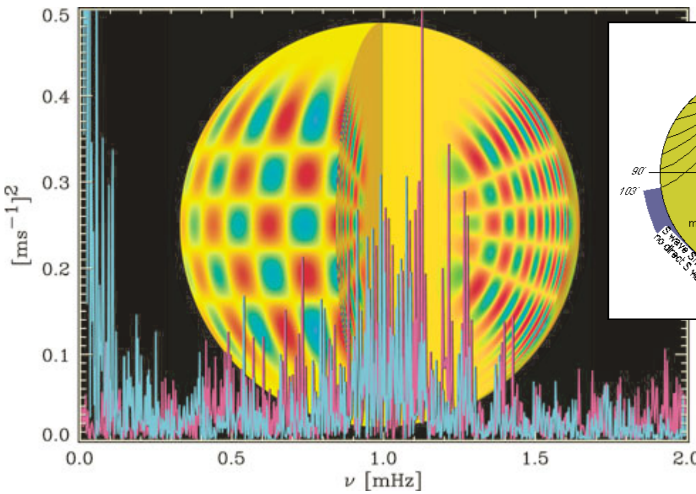
> *By "the standard solar model," we mean the solar model that is constructed with the best available physics and input data.*
> (John N. Bahcall, 1934–2005)

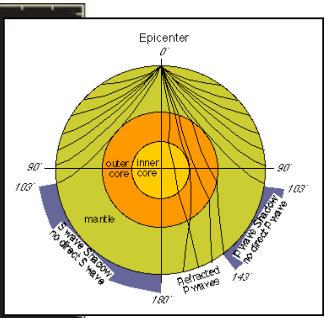
Present Sun properties:

Luminosity $L_\odot$ = 3.846x10^{26} W
Radius $R_\odot$ = 6.96x10^8 m
Mass $M_\odot$ = 1.989x10^{30} kg
Core temperature T_c = 15.6x10^6 K
Surface temperature T_s = 5773 K
Hydrogen fraction in core = 34.1% (initially 71%)
Helium fraction in core = 63.9% (initially 27.1%)
as measured on surface today

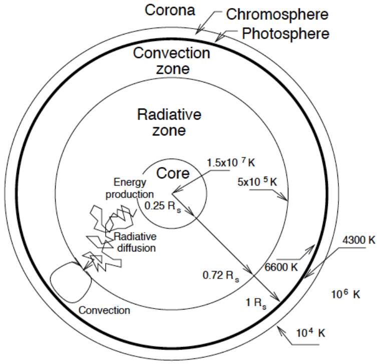
Helioseismology

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.





In the radiative and convective zones sound waves propagate (compression e rarefaction)



Between core and surface **standing waves are establisehd**, observable by **Doppler effect of the surface layers.**

Discovered in 1960 by *R. Leighton*

Typical period: about 5 minutes.

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

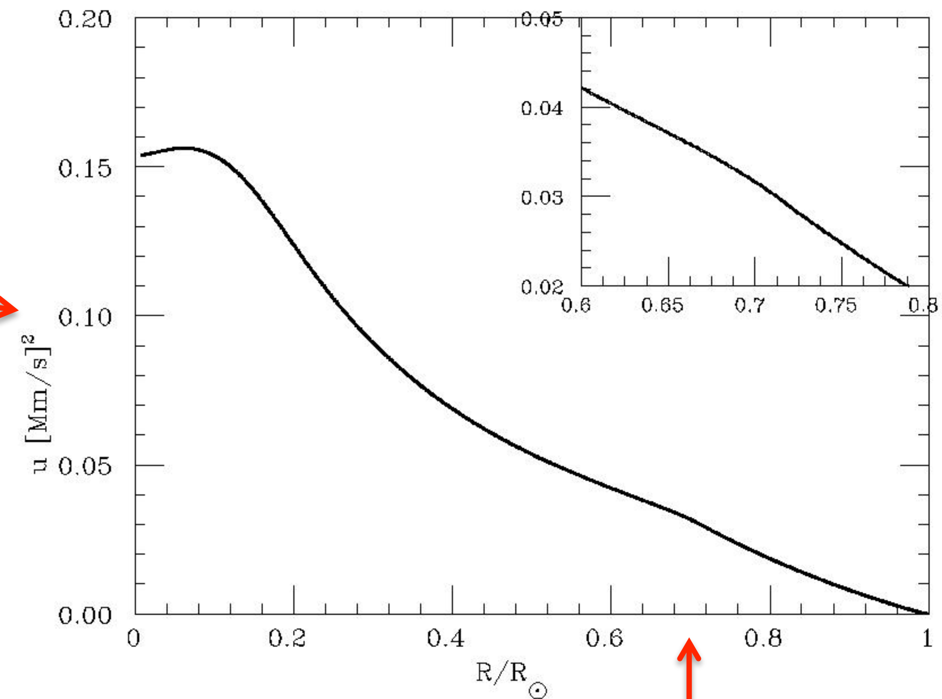
Helioseismology is placing strong constraints on theories of the solar interior.

What do we learn from Helioseismology?

Analyzing the spectrum of oscillation frequencies we can study the Sun's interiors.

We determine:

- Sound speed profile
- beginning of the convective zone (0.711 R)
- ^{3}He abundance at surface: 24.5%
- Solar internal rotation

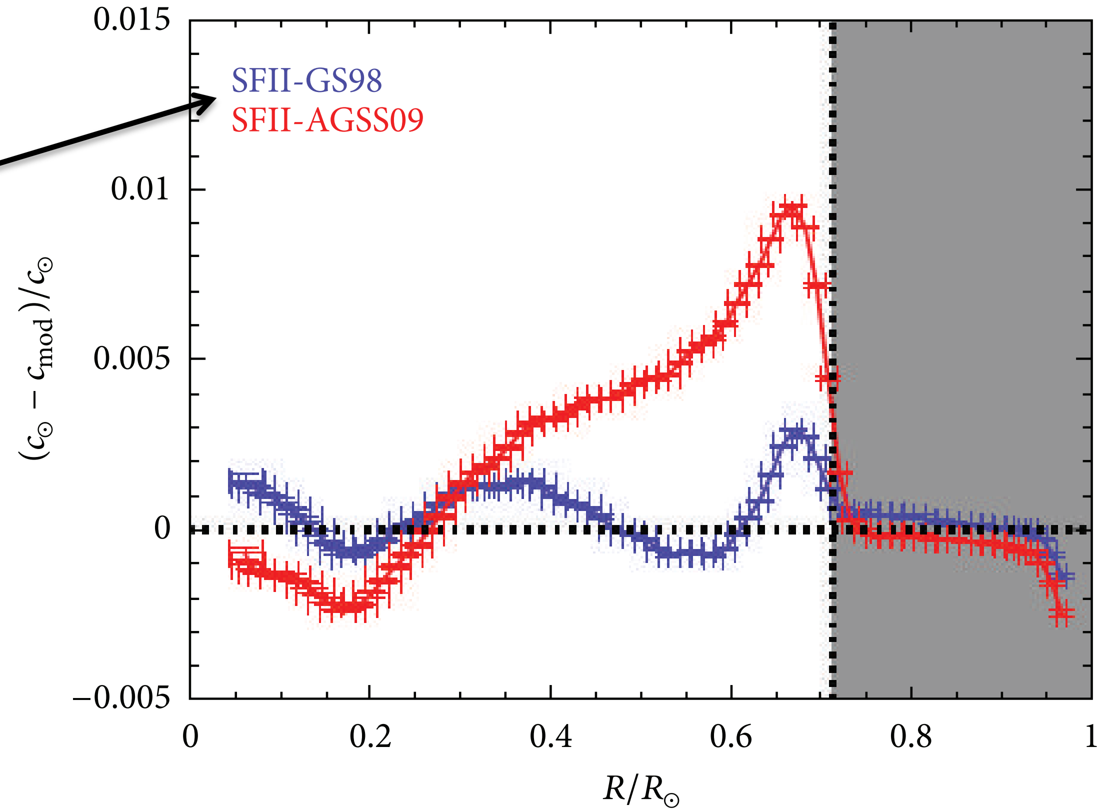


transition

Comparison Helioseismology with SSM

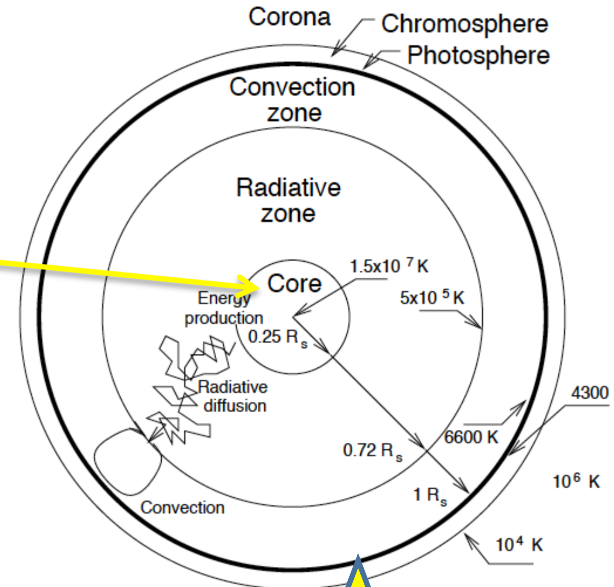
Agreement between sound speed computed by SSM (Model) and that measered by Helioseismology (Sun)

Two different metallicities



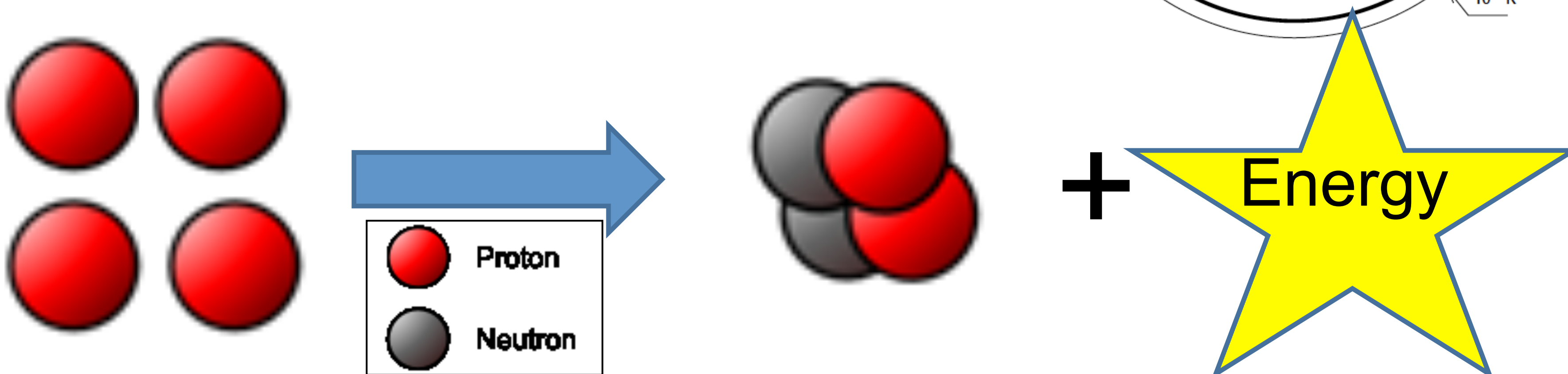
From this comparison much information can be deduced on core's nuclear reaction and on neutrino fluxes and energy spectra

How does the Sun shine?



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 ^{1}H

1 ^{4}He

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:

$4\ {}^{1}H \rightarrow 1\ {}^{4}He + \text{energy}$

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

Using $E=mc^2$ each fusion releases

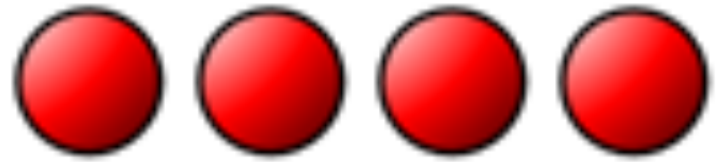
$$0.0477 \cdot 10^{-27}\,kg \cdot \left(3 \cdot 10^{8}\,\frac{m}{s}\right)^{2} = 4.3 \cdot 10^{-12}\,J \xrightarrow{1eV = 1.6 \cdot 10^{-19}\,J} 26.7\,MeV$$

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****.*

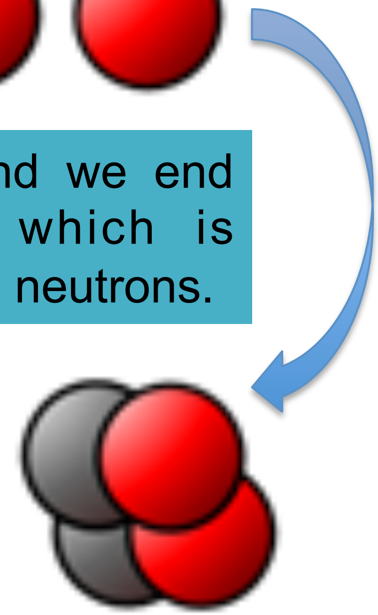
$$Lum = 4.26 \cdot 10^{9}\,kg \cdot \left(3 \cdot 10^{8}\,\frac{m}{s}\right)^{2} = 3.846 \cdot 10^{26}\,W$$

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

What about neutrinos?



We start from 4 protons and we end with 1 Helium nucleus which is composed of 2 protons and 2 neutrons.



This means that we have to transform <u>2 protons into 2 neutrons</u>:

(inverse β-decay)

$$p \rightarrow n + e^{+} + \nu_{e}$$

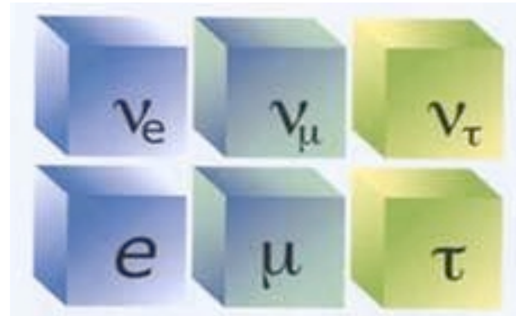
In the inverse beta decay a proton becomes a neutron emitting a **positron** and an **electron neutrino ν_e**

To each charged lepton it is associated a well defined neutrino

$$\nu_e \underset{associated}{\longleftrightarrow} e$$

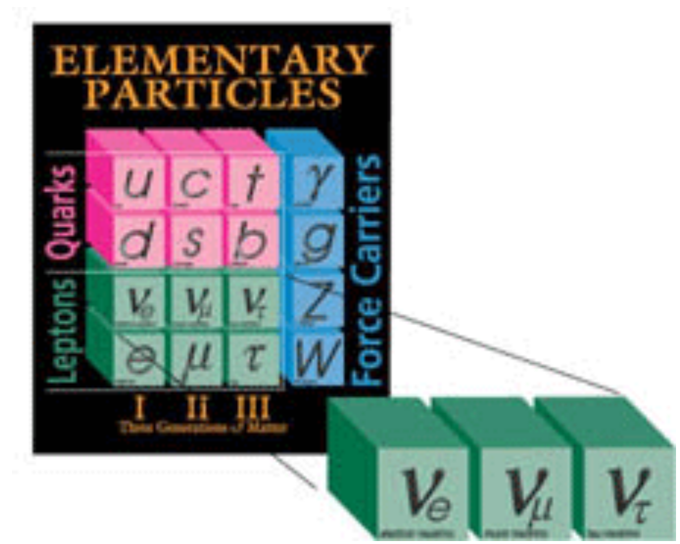
$$\nu_\mu \underset{associated}{\longleftrightarrow} \mu$$

$$\nu_\tau \underset{associated}{\longleftrightarrow} \tau$$

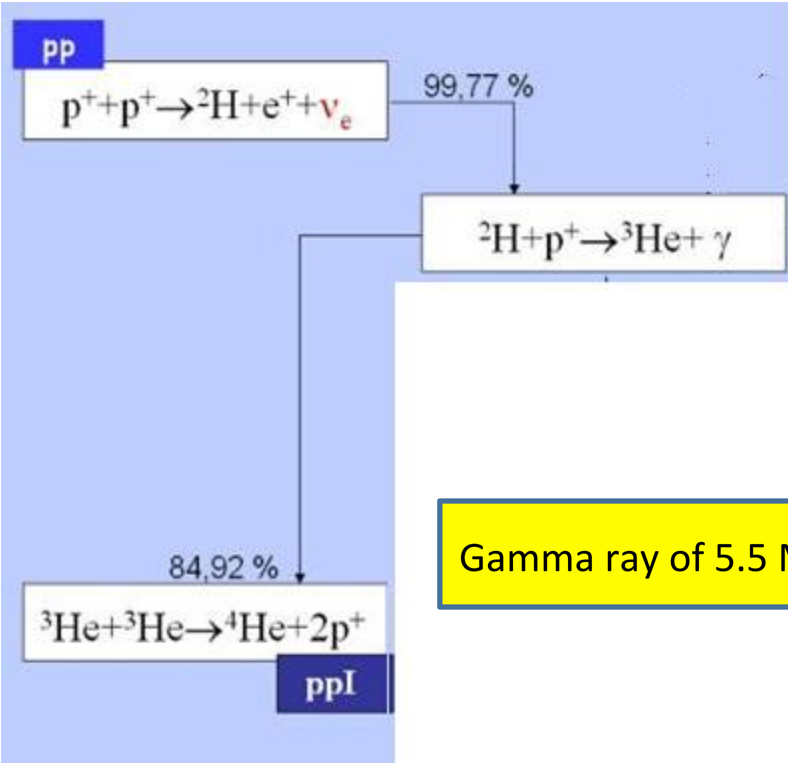


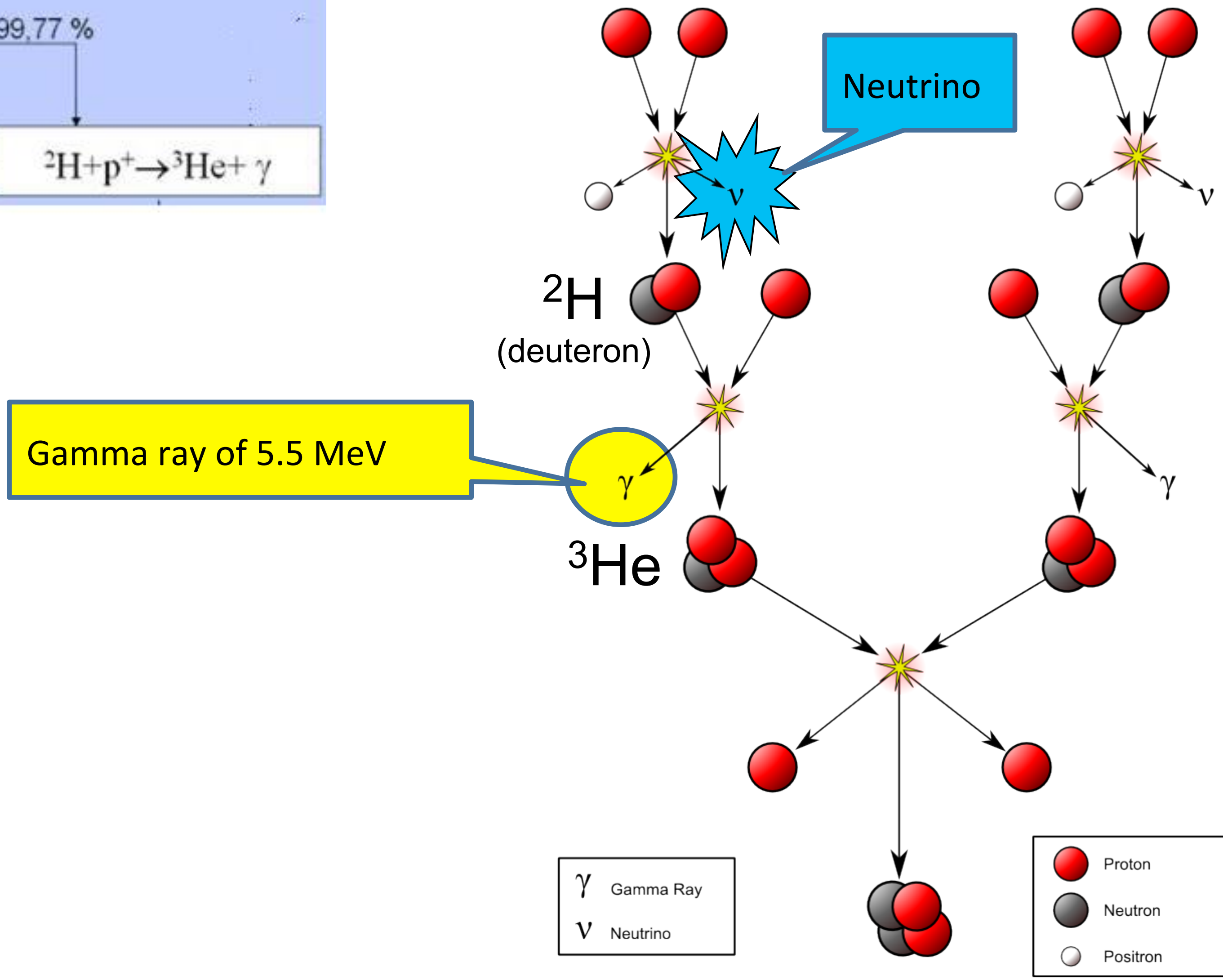
A neutrino of one “flavour”, interacting with matter, will produce a charged lepton of the same flavour

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



From protons to helium nucleus : The ppI chain

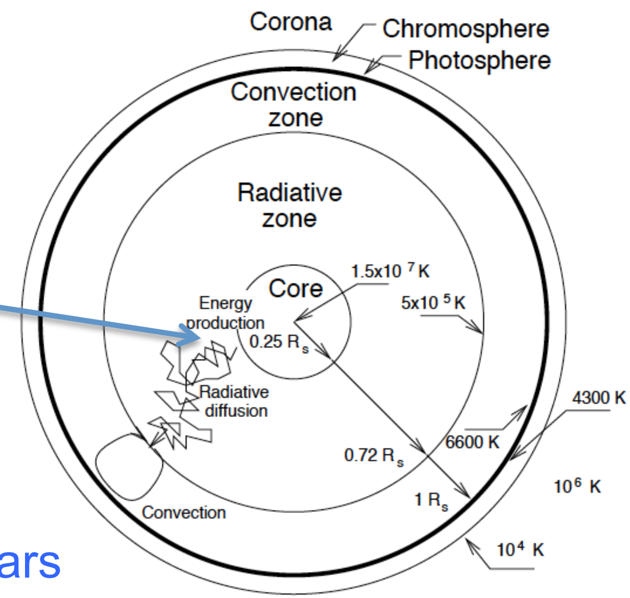




Gamma ray of 5.5 MeV

γ

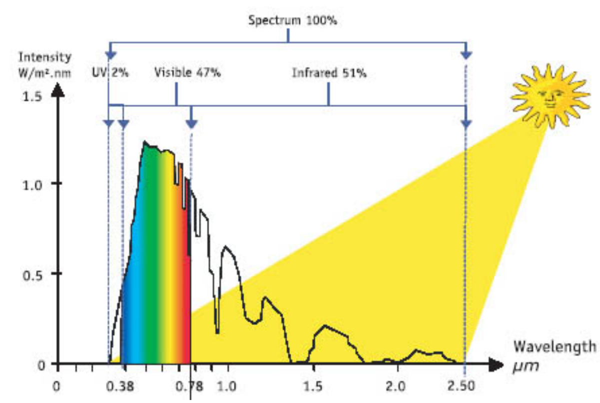
The 5.5 MeV [gamma rays] are **absorbed** in only a **few millimeters** of solar plasma and then **re-emitted** again in random direction (and at slightly lower energy)



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

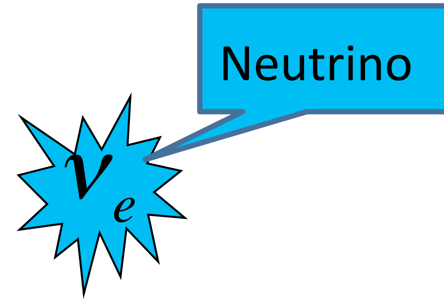
Each gamma ray created in the core of the Sun is converted into several million of visible light photons (energy some eV) before escaping into space. The photons escape as [visible light].

SOLAR SPECTRUM



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

$$1\,\gamma\left[\approx 10^6 eV\right] \Rightarrow 10^6\,\gamma's\left[\approx eV\right]$$



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

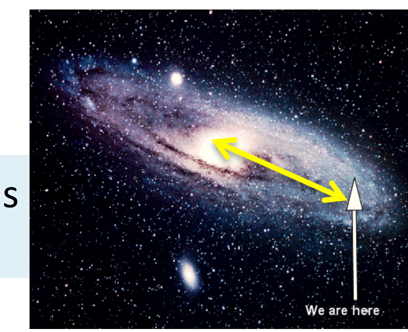
Typical cross section are σ≈10^{-45} cm^2 (It's depends on energy!)

$$absorbtion\ lenght \quad \lambda = \frac{1}{n \cdot \sigma}$$
$$\text{(n number of atoms per cm}^3\text{)}$$

$$\lambda = \frac{1}{n\sigma} \overset{H_2O}{=} \frac{1}{\frac{6.023 \cdot 10^{23}}{18} \frac{n\ atoms}{cm^3} \cdot 10^{-45}\ cm^{-2}} \approx 3 \cdot 10^{21} cm$$

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

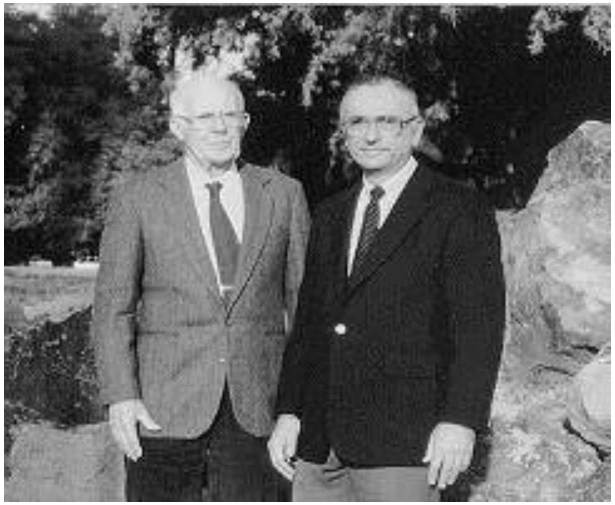
About the distance from us to the Galactic Center



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*

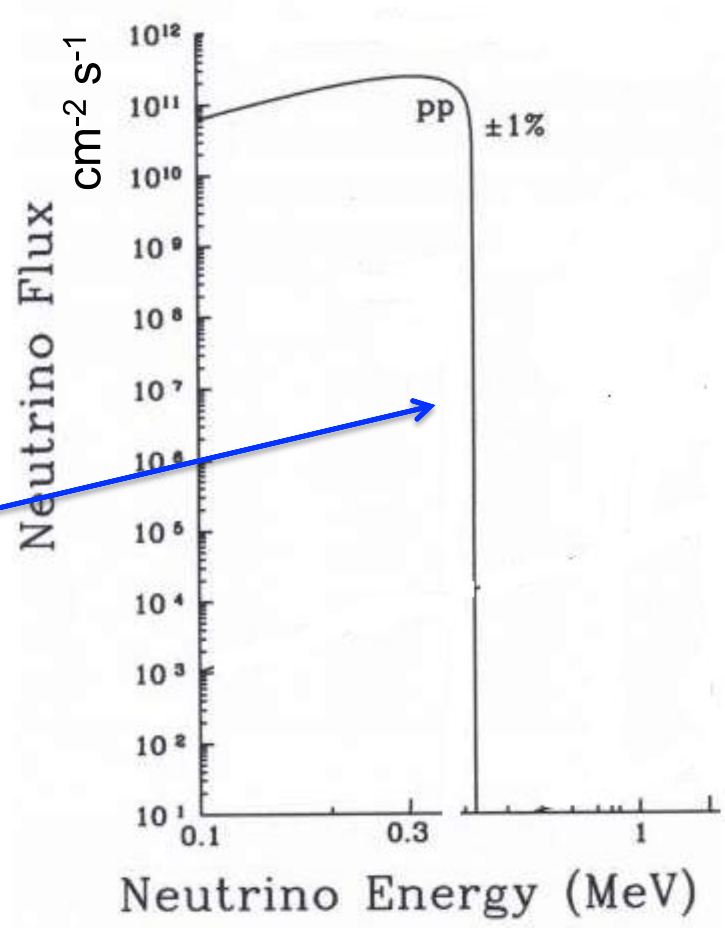
Phys. Rev. Lett. 12, 303–305 (1964)
Solar Neutrinos. II. Experimental
Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York

The neutrino spectrum

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

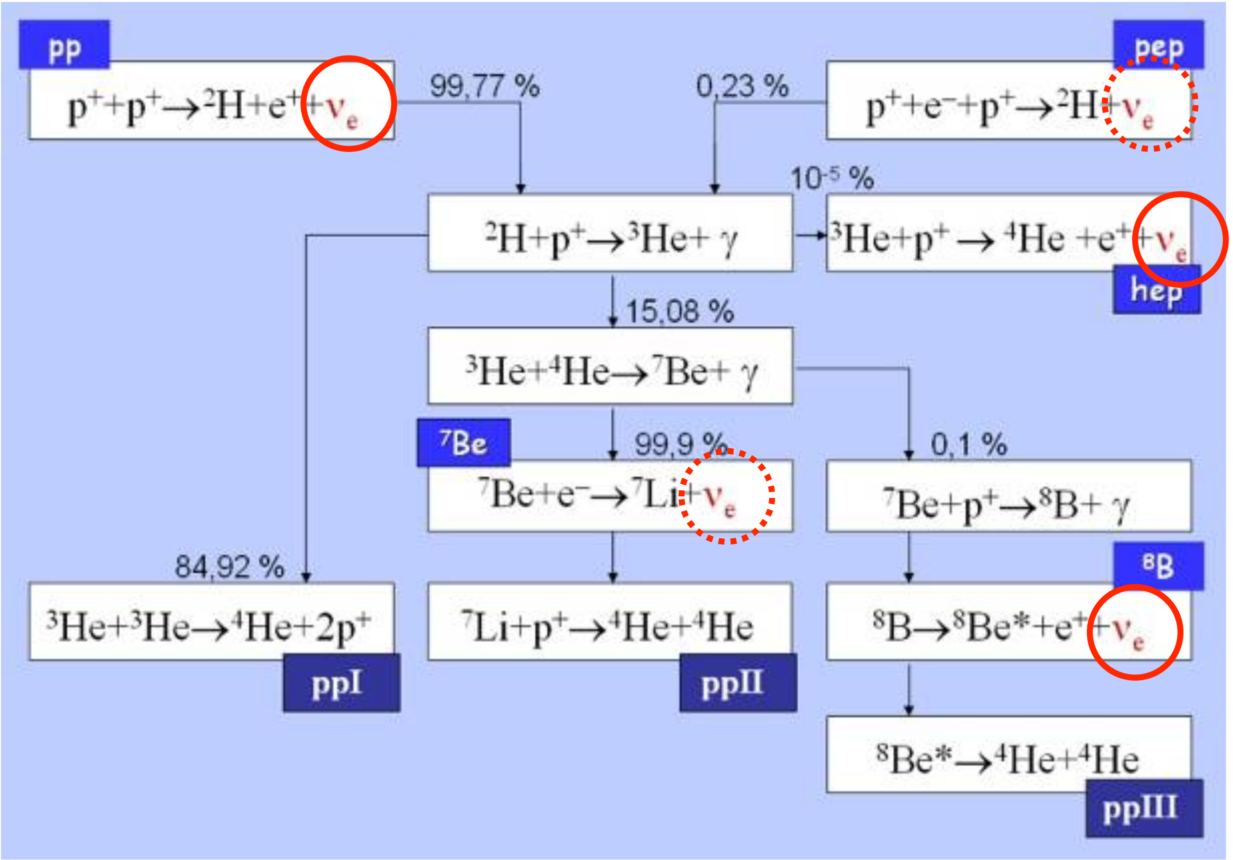
$$Q_{value} = 0.42\ MeV$$

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}Be
- ^{8}B
- hep

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

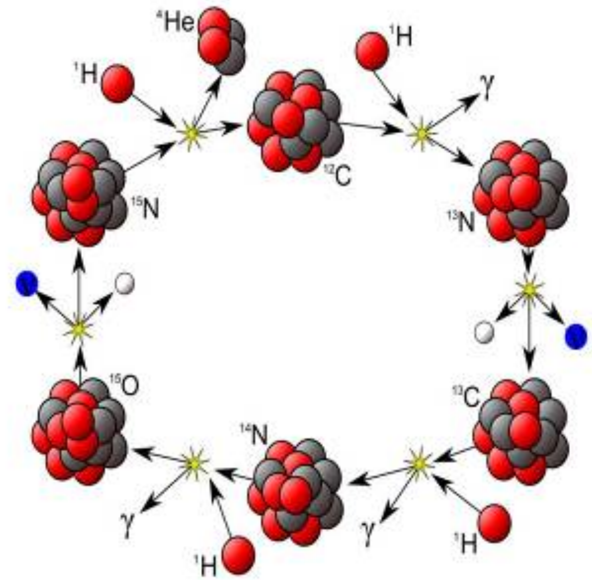
Each neutrino is labeled according to the reaction in which it is emitted:

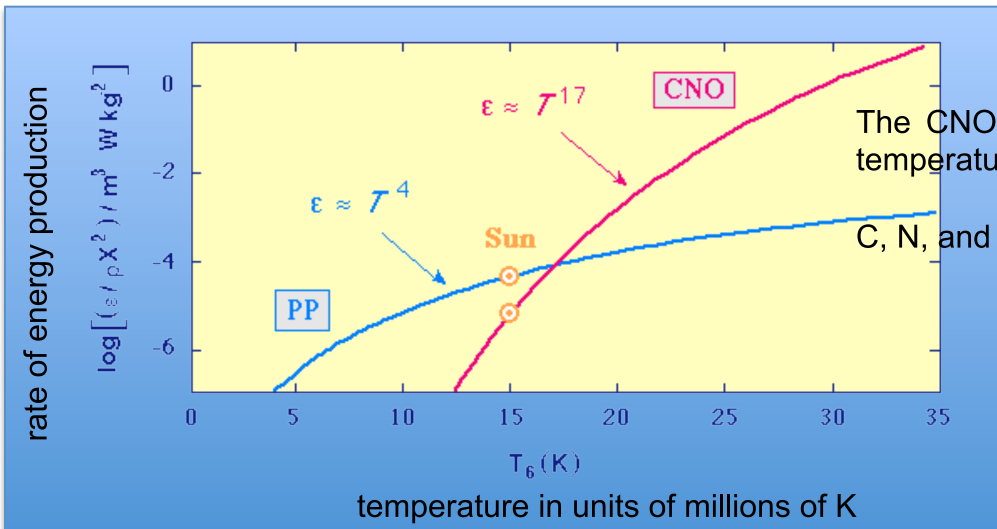
- pp-neutrinos
- pep-neutrinos
- ^{7}Be-neutrinos
- ^{8}B-neutrinos
- hep-neutrinos

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





The CNO cycle has a strong temperature dependence

C, N, and O act as catalyzers

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

CNO Neutrinos

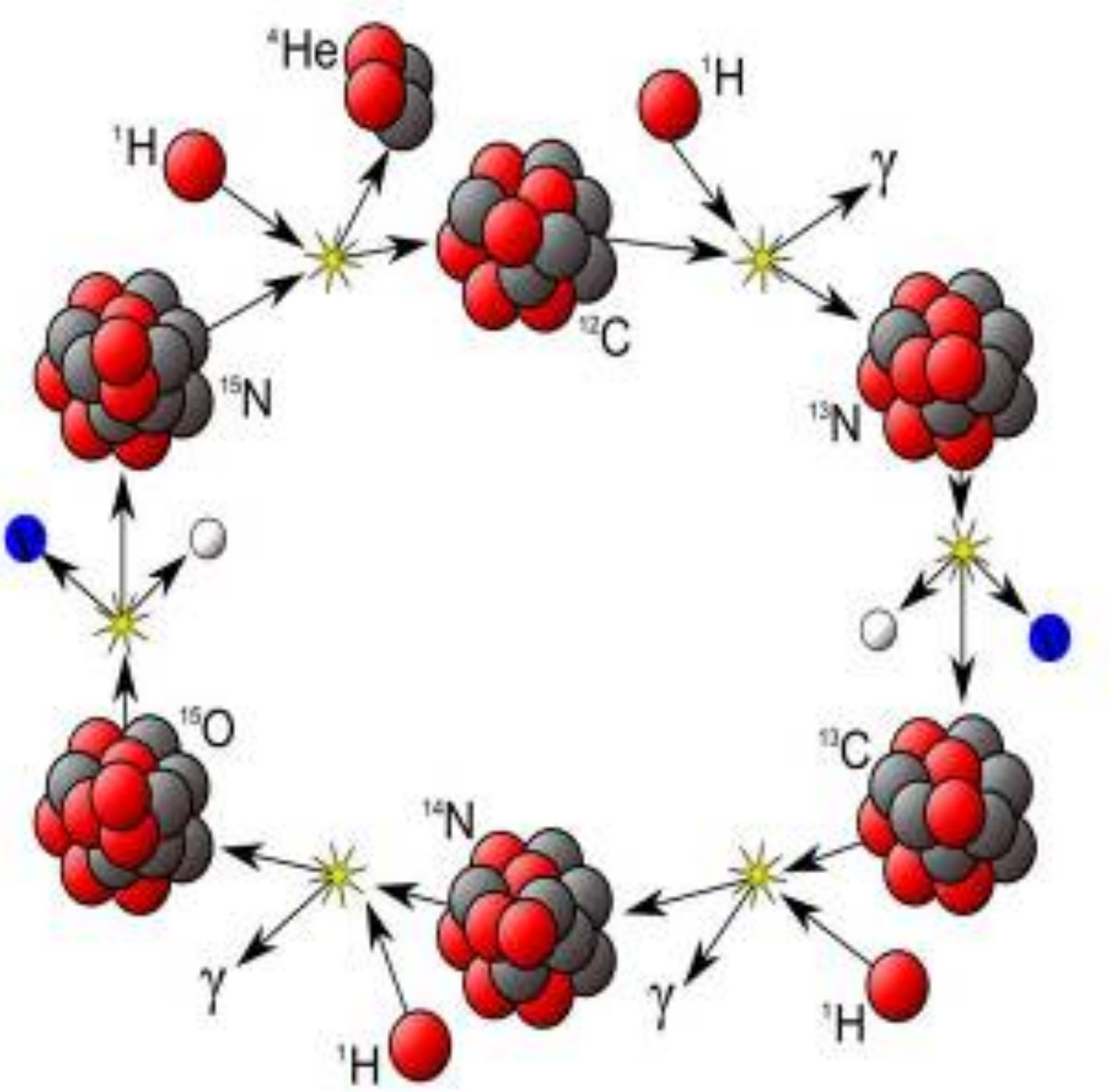
Neutrinos are also produced in the CNO cycle

ν from:

^{13}N

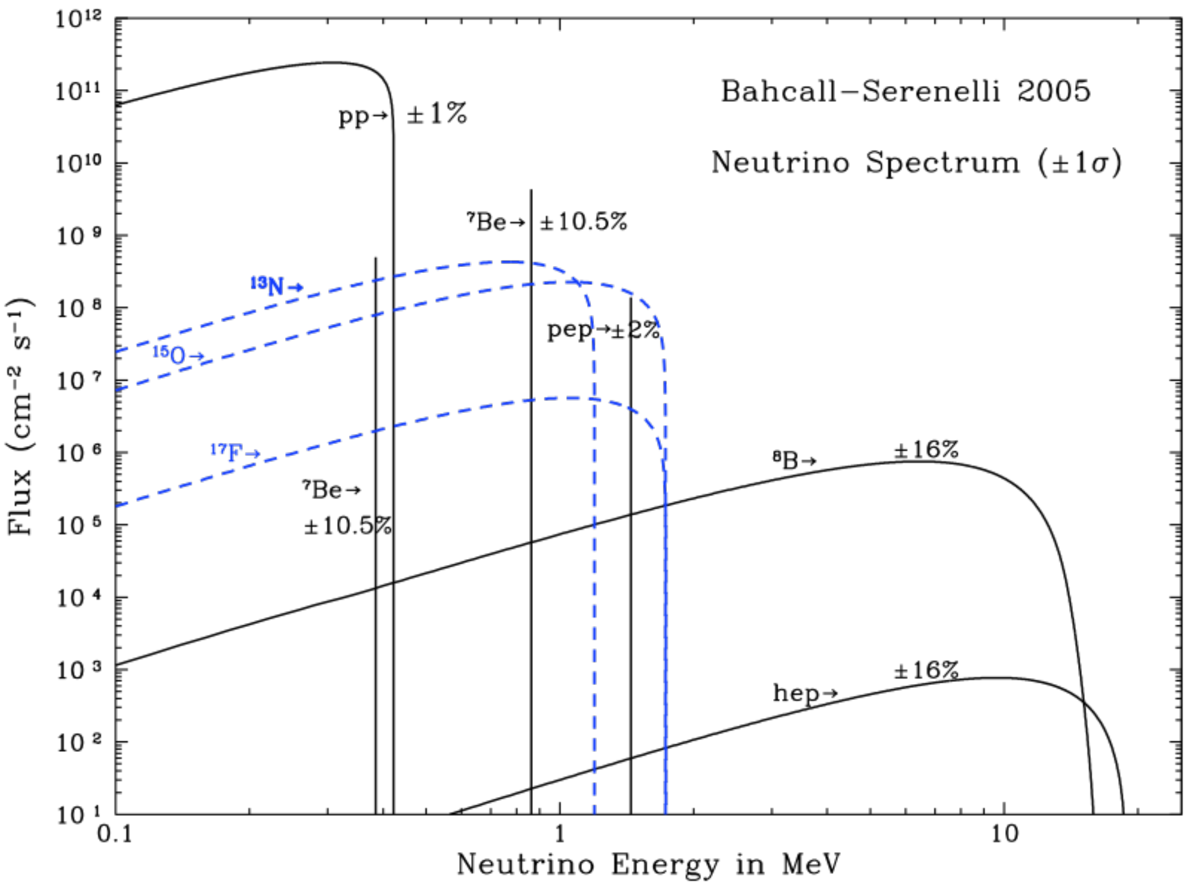
^{15}O

^{17}F



⁴He
¹H
¹H
γ
¹²C
¹⁵N
¹³N
¹⁵O
¹³C
¹⁴N
γ
γ
¹H
¹H

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



ν **from:**
pp
pep
⁷Be
⁸B
hep

ν **from:**
¹³N
¹⁵O
¹⁷F

Monocrhomatic ν's

^{7}Be:

384 keV (10%)

862 keV (90%)

pep:

1.44 MeV

How many neutrinos reach the Earth?

Luminosity of the Sun:
3.846 · 10^{26} Watt

2 neutrinos
produced per reaction

$$\Phi_{\nu_e} \simeq \frac{1}{4\pi D_{\odot}^2} \frac{2L_{\odot}}{(Q - \langle E_\nu \rangle)} = 6 \times 10^{10} \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

Distance Earth-Sun:
~1.5 · 10^{11} m

Energy released
in the reaction:
~26.7 MeV

Energy carried away by ν:
~0.3MeV

Neutrino rate emitted
by the Sun:
N_ν= 1.8 ·10^{38} ν/s

The solar metallicity puzzle

SHP11:
A.M. Serenelli, W. C.Haxton
and C. Pena-Garay,
arXiv:1104.16.39v1 [astro-ph]

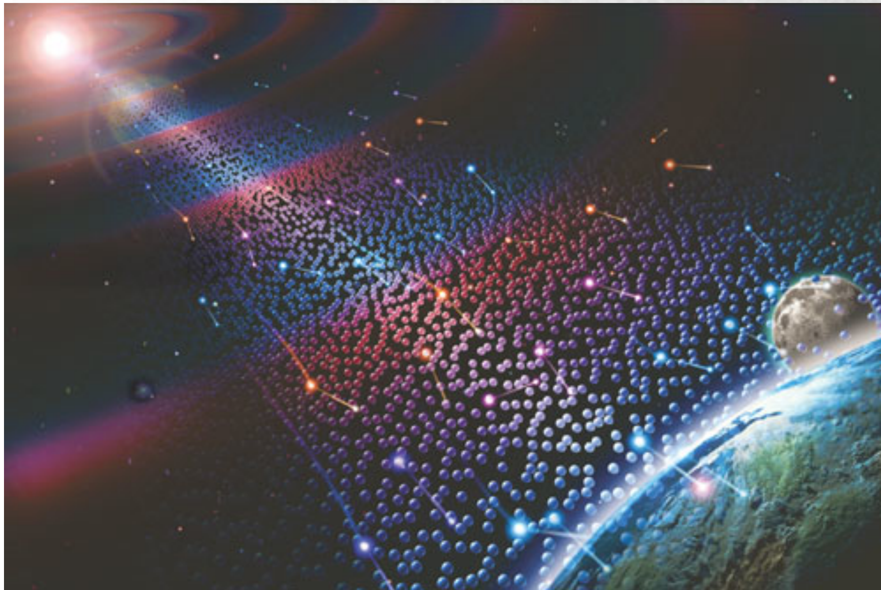
ν flux	GS98	AGS09	$cm^{-2}\ s^{-1}$	Δ
pp	5.98 (1±0.006)	6.03 (1±0.006)	x 10^{10}	+0.8%
pep	1.44 (1±0.012)	1.47(1±0.012)	x 10^{8}	+2.0%
hep	8.04 (1±0.30)	8.31 (1±0.30)	x 10^{3}	+3.3%
^{7}Be	5.00 (1±0.07)	4.56 (1±0.07)	x 10^{9}	-8.8%
^{8}B	5.58 (1±0.14)	4.59 (1±0.14)	x 10^{6}	-18%
^{13}N	2.96 (1±0.14)	2.17 (1±0.14)	x 10^{8}	-27%
^{15}O	2.23 (1±0.15)	1.56 (1±0.15)	x 10^{8}	-30%
^{17}F	5.52 (1±0.17)	3.40 (1±0.16)	x 10^{6}	-38%

1. GS98 (High-metallicity): “old” 1D model
   excellent agreement with helioseismology
2. AGS09 (Low-metallicity): new 3D model; less C, N, O, Ne, Ar
   disagreement with helioseismology

[Both model share the same spectroscopy data set of solar surface abundances]

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 two possible ways to detect solar neutrinos:

- **radiochemical experiments** $\nu_e + {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^-$

- **real time experiments** $\nu_x + e^- \rightarrow \nu_x + e^-$

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

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

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

$\mathit{Only}\ \nu_e$

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

$\mathit{All}\ \nu_x\ \mathit{type}$

How many Solar Neutrinos we can catch?

The **interaction rate R** is given by

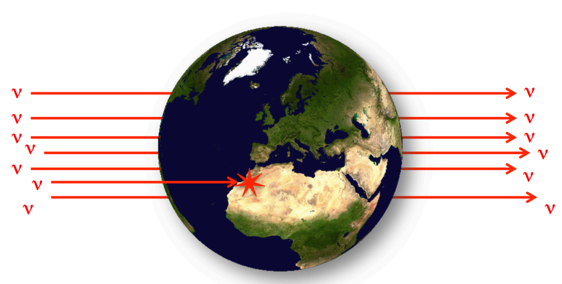
$$R = N \int \Phi(E)\sigma(E)dE$$

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} ν cm^{-2} 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 yield one event per day.

Why is it so hard to detect them?



- With E_ν = 11 MeV the mean free path in lead is 350 billion kilometer
- In earth ~3 out of 1 billion neutrinos would interact

with typical $\Phi \approx 10^{10} \dfrac{\nu}{cm^2 s}$

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

10^{30} target atoms (ktons of matter!) $\Rightarrow$ 1 event per day

Homestake: *The first solar neutrino detector*

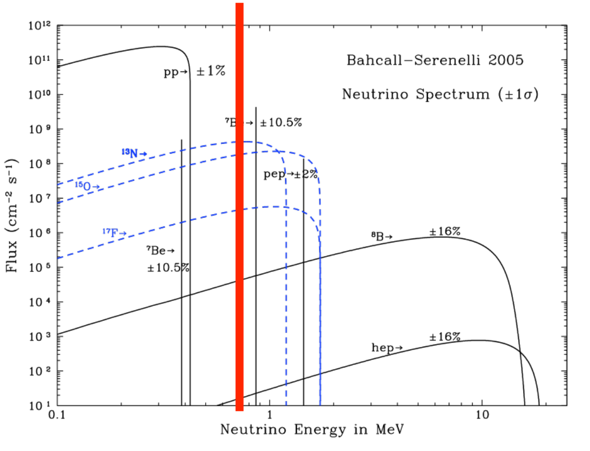
Large tank of 615 tons of liquid containing ^{37}Cl.

Neutrinos are detected via the reaction:

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

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

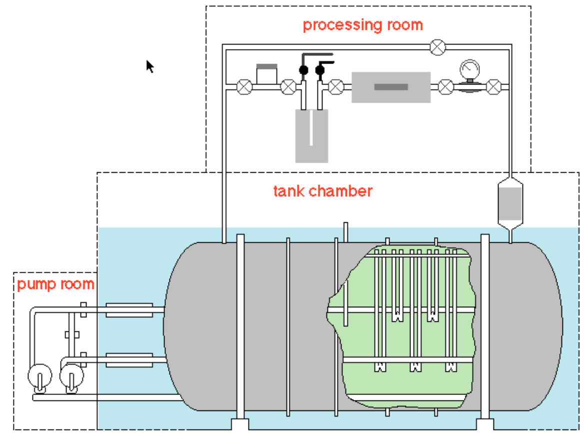
$$^{37}Ar + e^- \rightarrow {}^{37}Cl^* + \nu_e$$



***E*$_{th}$ = 814 keV**

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)*.

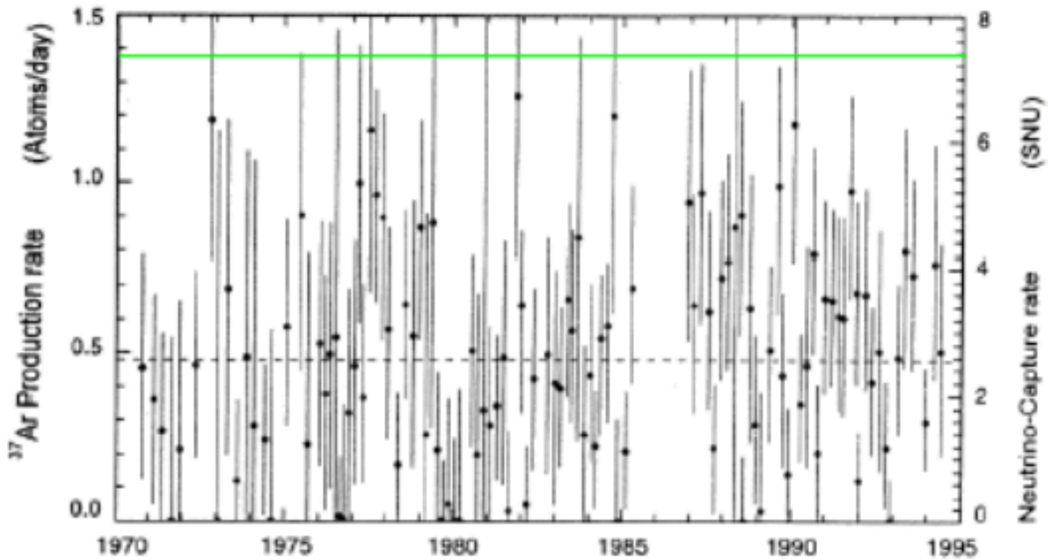
^{37}Ar decays by electron capture emitting a 2.82 keV Auger electron, whose rate was measered by miniaturized proportional counters



$$R_{th} = (7.7^{+1.2}_{-1.0})SNU$$

?

$$R_{exp} = (2.56 \pm 0.22)\, SNU$$



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

different opacity and core's temperature?

…. 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.

❑ Nuclear physicis is not correct

- branching ratios in the pp chain are different?
- but later checked by nuclear astrophysics experiments (LUNA)

❑ 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

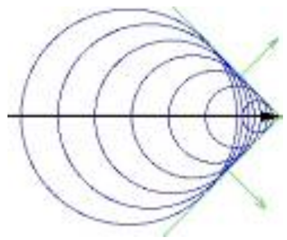
Kamiokande: First real time detection

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

detection channel:
elastic scattering

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

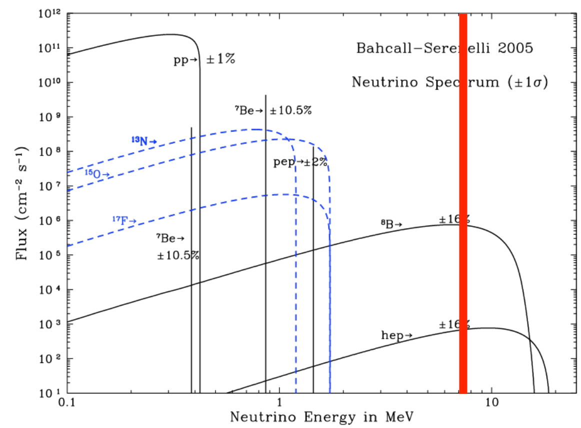
If electrons are scattered with speed *v > c/n* "faster than light", they loose energy by Cherenkov emission



e⁻ Energy threshold for Cherenkov = 0.77 MeV

Originally built to look for proton decay in the Kamioka mine at a depth of 2700 m w.e. di profondità.
Kamiokande worked from 1983 to 1996 with a wider physics program (i.e. including atmospheric neutrinos).
Later replaced by SuperKamiokande, now the site hosts KamLAND.

E_{th} = 7.5 MeV

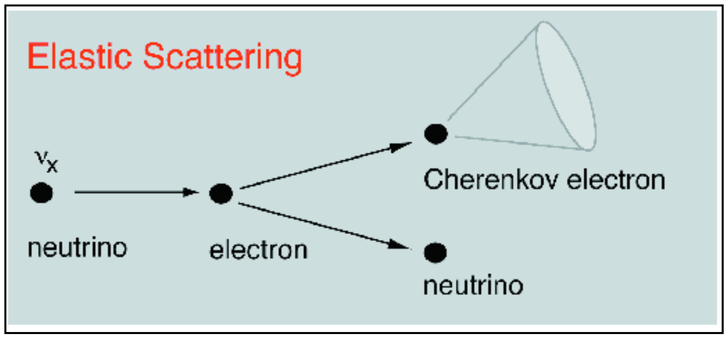


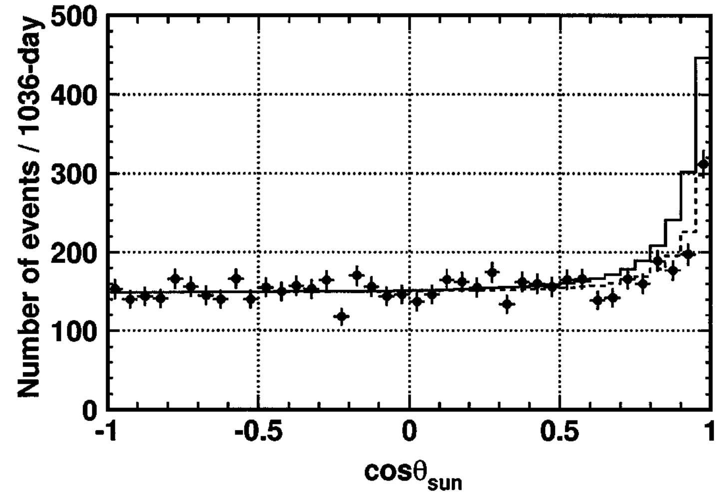
Kamiokande

- 3000 tons of pure water
- 1000 PMTs
- E_{th} = 7.5 MeV
- only ^{8}B (and hep) neutrinos

Kamiokande: we are really watching the Sun

If $E_\nu >> m_e$ electron direction is close to the direction of the incident neutrino: this information allows to distinguish solar neutrinos from atmospheric neutrinos or background events.





Angle between the direction the reconstructed recoil electron direction and the direction of the Sun.

Thanks to direction information -> confirmation of neutrino production by the Sun

Kamiokande [BP00]

$$\Phi_\nu^{spe} = (2.80 \pm 0.38)\times 10^6 cm^{-2}s^{-1} \Longleftrightarrow \Phi_\nu^{th} = (5.05 \pm 0.20)\times 10^6 cm^{-2}s^{-1}$$

Risultati finali

Experiments / Theory ~ 1/2: SNP not solved, but also different ratio then Homestake

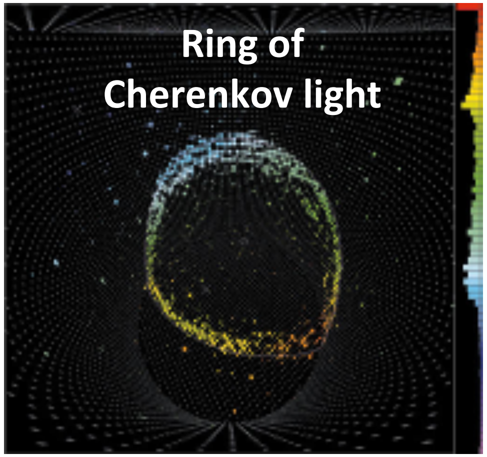
Pros and cons

of (water Cherenkov) real time experiments

Pros:

1) it is possible to obtain a **spectrum energy** and hence to distinguish the different neutrino contribution, unlike radiochemical experiments which integrate in time and in energy.

2) it is possible to infer the **direction** of the origin of the incoming neutrino and hence to point at the source. Check if **neutrinos actually come from the Sun**

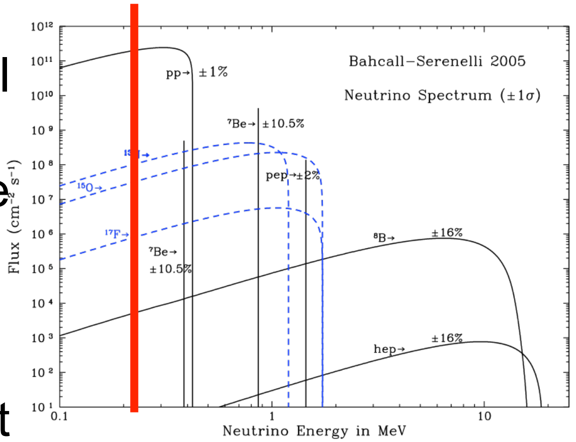


Cons:

Cherenkov light is flebile, the threshold is very high (> ~4-7 MeV), only ~10^{-4} of neutrino flux observed

…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.



E_{th} = 233 keV

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

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

Gallex

Gallex/GNO & SAGE

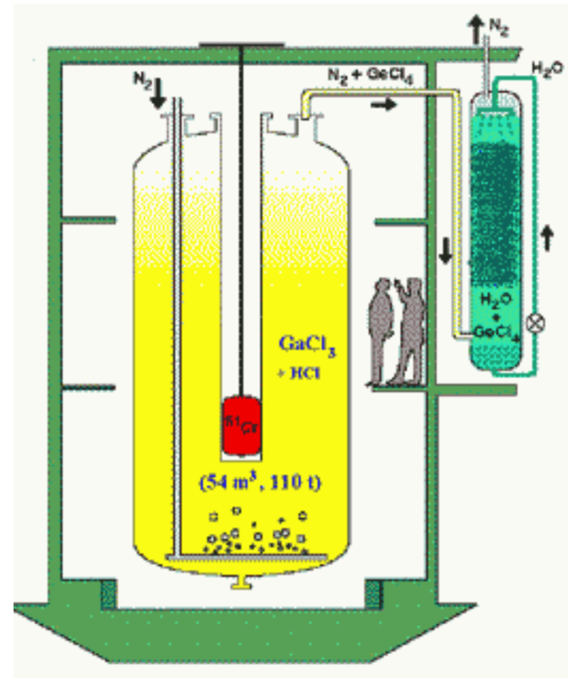
30 tonnes of natural gallium
(at LNGS Italy)

50 tons of metallic gallium
(at Baksan Russia)

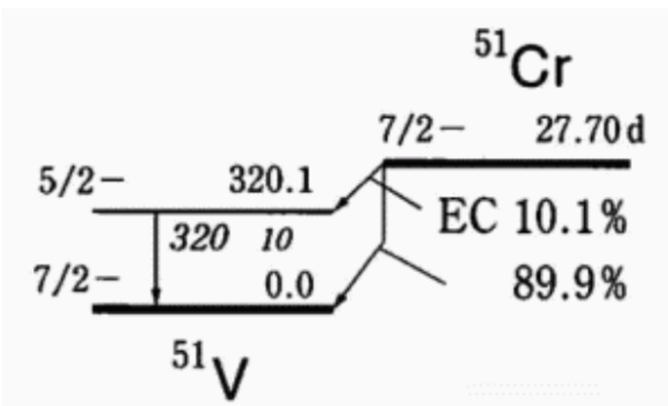
SAGE

…looking for pp neutrinos …

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

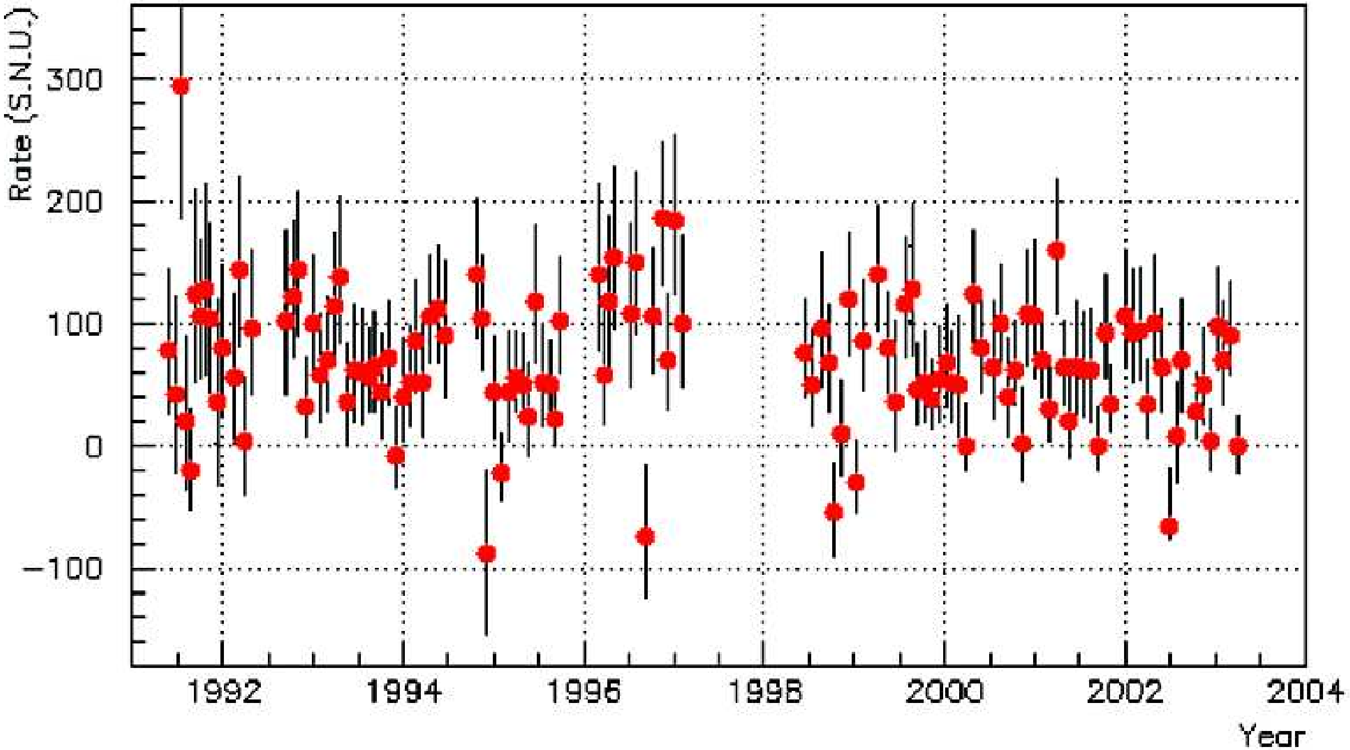


EC source, monoenergetic ν_e: 753 KeV (90%) & 433 keV (10%)
$T_{1/2}$ = 27.7 days
Produced by neutron irradiation of (stable) ^{50}Cr



Gallium experiment results

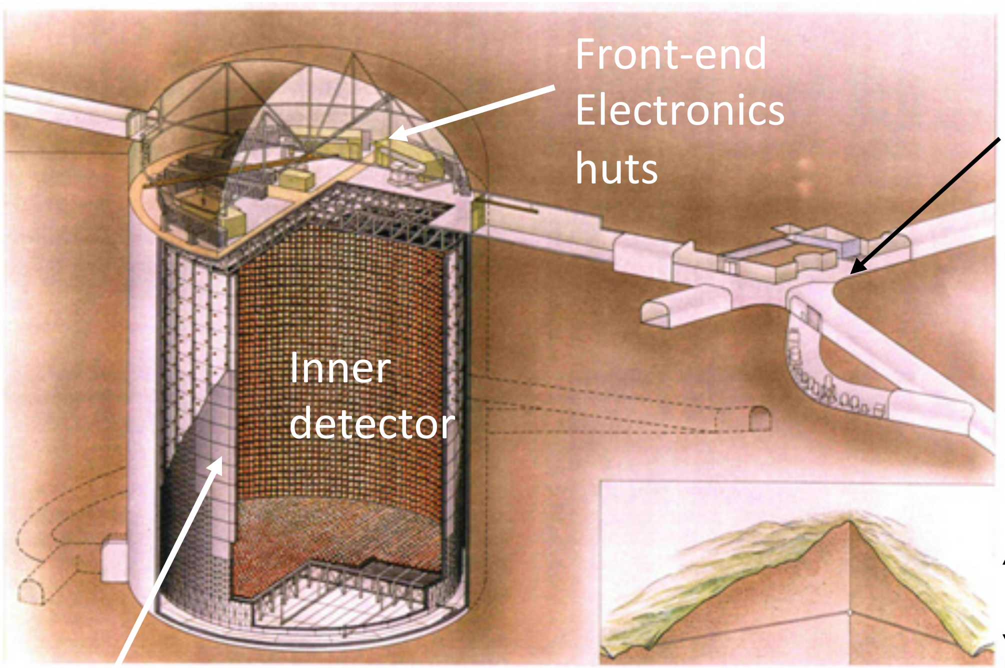
$$R_{th} = (131^{+12}_{-10}) SNU$$



$$R_{Gallex+GNO} = (69.3 \pm 4.1[stat] \pm 3.6[syst])\ SNU$$

Once again the measured neutrino signal was smaller than the one predicted by the standard solar model (**~ 70%**).

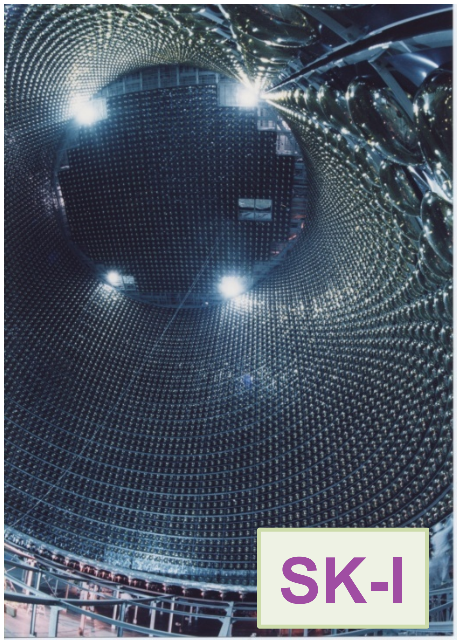
Super Kamiokande

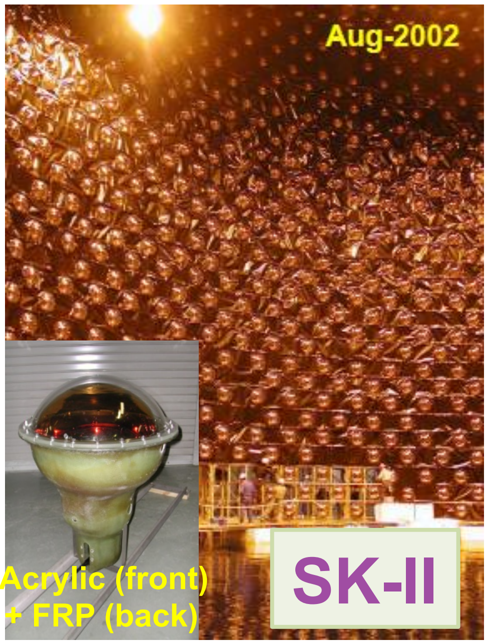


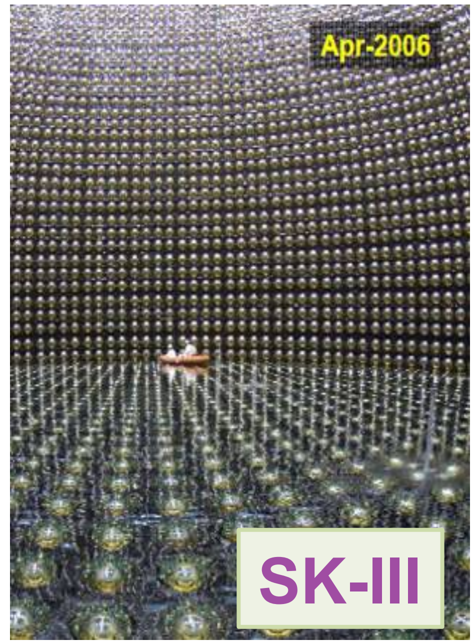
- 50 kton water Cherenkov detector
at 1000m underground (2700 w.e.)
with ~13000 PMTs to detect Cherenkov light
- Inner detector: 11129 PMTs (20inch)
- Outer detector : 1885 PMTs (8inch)
- Fiducial volume : 22.5kton

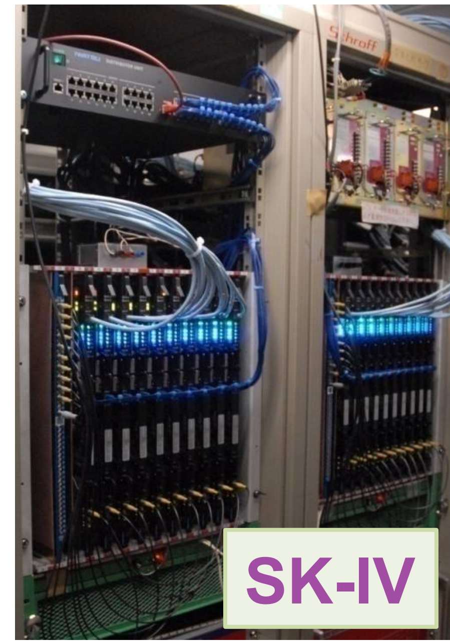
Phases of Super-Kamiokande

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016





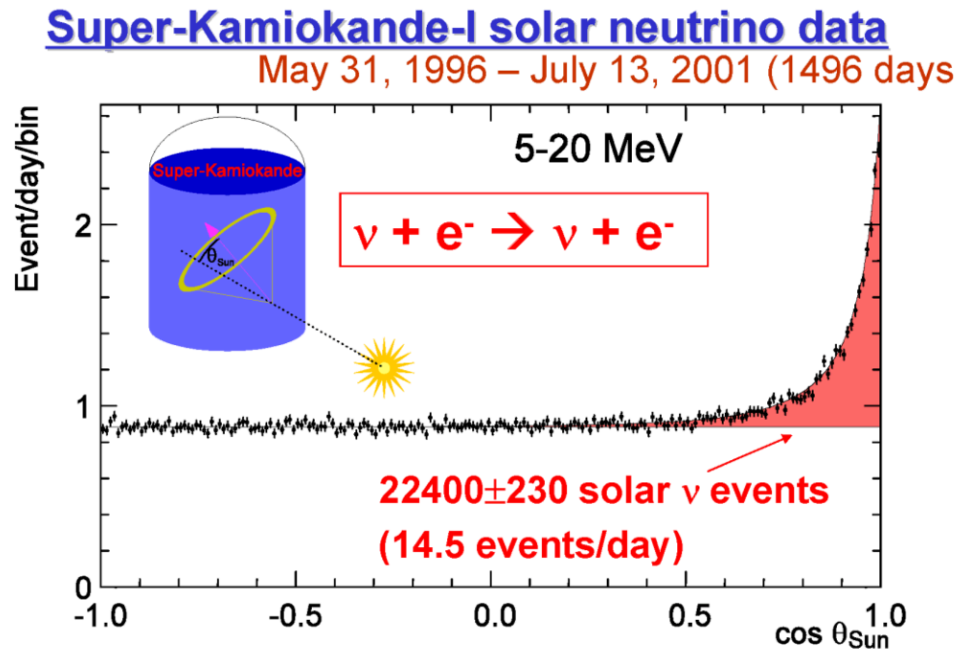


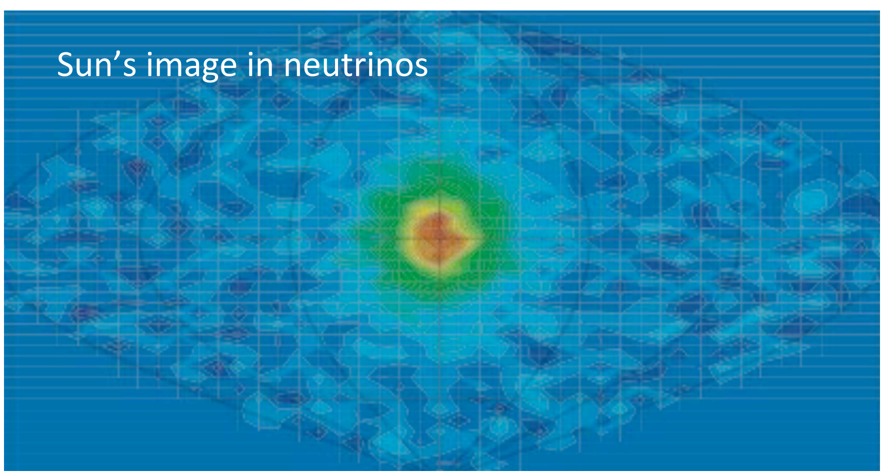


	SK-I	SK-II	SK-III	SK-IV	
	11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	
(Total E)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic E)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV
				Initial	Current

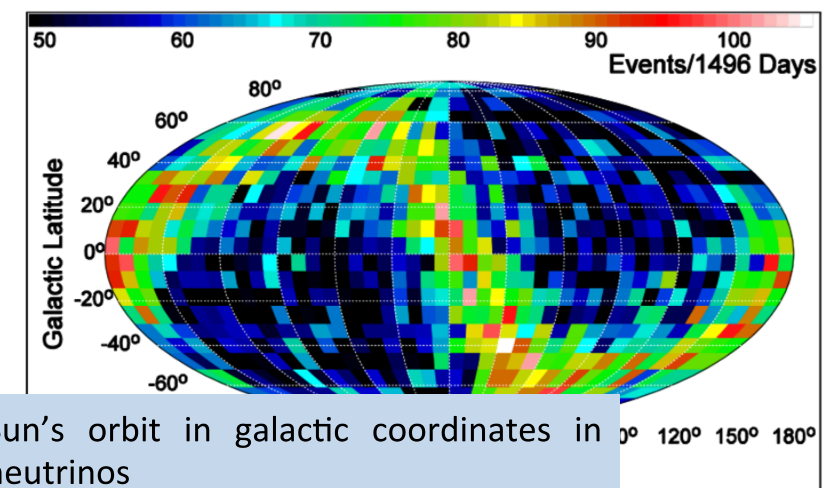
SuperKamiokande: Angular distribution

Higher statistics
confirmation of solar origin





Sun's image in neutrinos

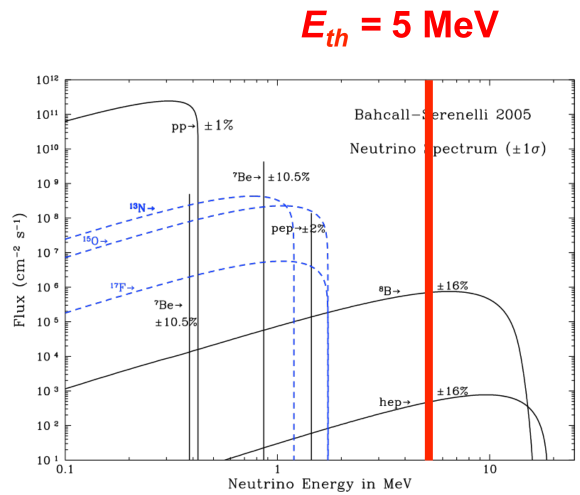


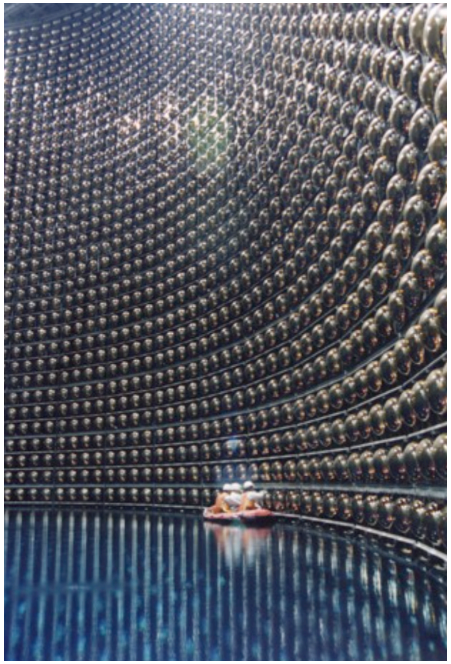
Sun's orbit in galactic coordinates in neutrinos

SuperKamiokande:Flux

SuperKamiokande

- 50000 tons of pure water
- 11200 PMTs
- E_{th} = ~5 MeV (SuperK I and III)
- only ^{8}B and hep neutrinos

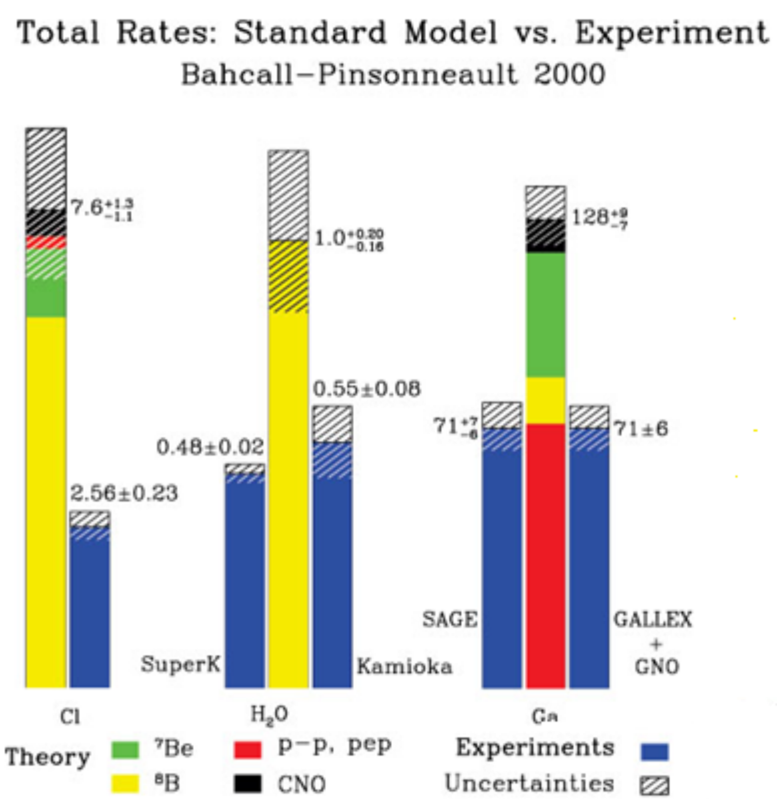




Kamiokande	[BP00]	SK
$\Phi_\nu^{spe} = (2.80 \pm 0.38)\times 10^6 cm^{-2}s^{-1}$ ⟺	$\Phi_\nu^{th} = (5.05 \pm 0.20)\times 10^6 cm^{-2}s^{-1}$	⟺ $\Phi_\nu^{spe} = (2.35 \pm 0.10)\times 10^6 cm^{-2}s^{-1}$

Experiments / Theory ~ **1/2**: consistent with Kamiokande but with smaller error

All experiments detect less neutrino than expected from the SSM !



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

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

at the turn of the century almost no room left for astrophyisical solutions

something big was around the corner

Neutrino oscillations!

Neutrino oscillations

$$|\nu_l\rangle = \sum_{i=1}^{3} U_{li} |\nu_i\rangle$$

PMNS neutrino mixing matrix, analogous to CKM matrix for quarks

atmospheric $\quad s_{ij} = \sin\theta_{ij} \quad c_{ij} = \cos\theta_{ij}$ $\quad$ solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{atm} $\quad$ $\sin 2(\theta 12$ θ_{13}, δ $\quad$ θ_{sol}

PDG (2014)

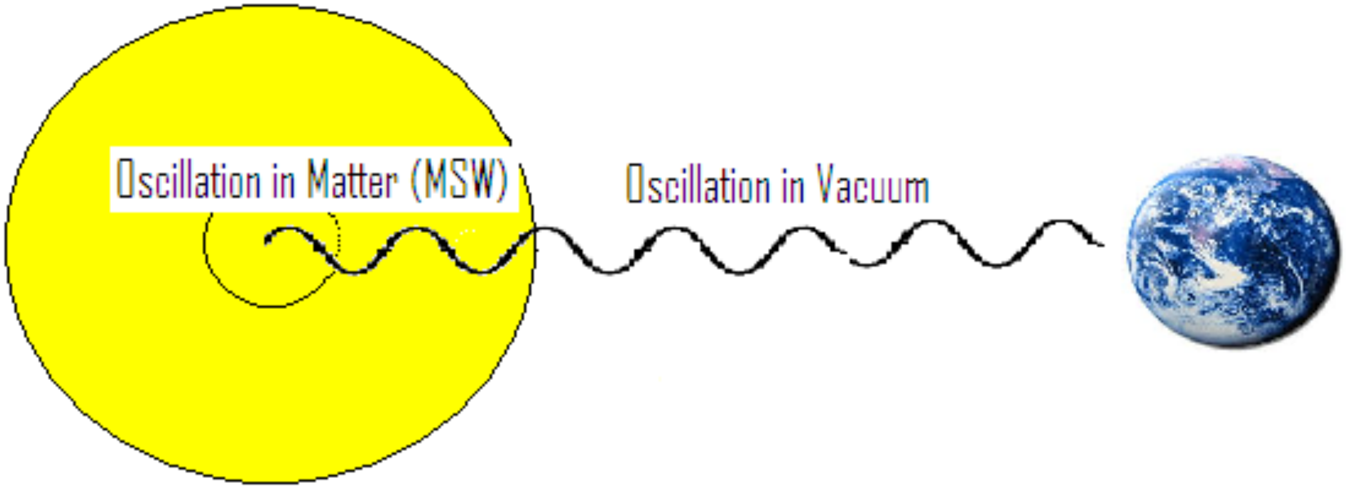
$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$	Solar
$\Delta m^2_{21} = (7.53 \pm 0.18) \cdot 10^{-5} eV^2$	reactor LBL (KamLAND)
$\sin^2(2\theta_{23}) > 0.92 @ 90\% C.L.$	Atmospheric
$\Delta m^2_{32} = (2.44 \pm 0.06) \cdot 10^{-3} eV^2$	accelerator LBL (MINOS, T2K)
$\sin^2(2\theta_{13}) = 0.093 \pm 0.008$	reactor SBL (Daya bay, RENO)

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

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

Neutrino oscillations can be enhanced by traveling through (solar) matter

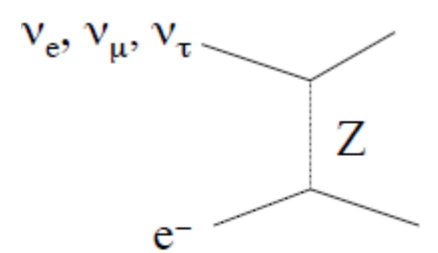
(*The core of the Sun has a density of about 150 g/cm^3*)



MSW Effect

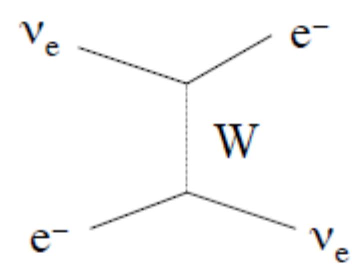
This happens because the Sun is made of up/down quarks and electrons

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 .

MSW Effect

ν (matter) mass eigenstates mix with an *effective* mixing angle

$$\sin^2 2\theta \rightarrow \sin^2 2\theta_m$$

ρ_e is the electron density

$$sin2\theta_m = \frac{\frac{\Delta m^2}{4p}\sin 2\theta}{\sqrt{(\frac{\Delta m^2}{4p}cos2\theta - \frac{G_F\rho_{e^-}}{\sqrt{2}})^2 + (\frac{\Delta m^2}{4p}\sin 2\theta)^2}}$$

$$\rho_{e^-} \ll \rho_{e^-}^{res}$$

matter effect is negligible

$$\rho_{e^-} = \rho_{e^-}^{res} \equiv \frac{\Delta m^2 cos2\theta}{2\sqrt{2}pG_F}$$

resonance condition:
$\sin 2\theta_m = 1$

$$\rho_{e^-} \gg \rho_{e^-}^{res}$$

oscillation suppressed

$$\frac{P_{matter}}{P_{vac}} \simeq \frac{\sin 2\theta_m}{\sin 2\theta}$$

Neutrinos travelling trough solar matter experience a gradient of densities, eventually crossing the resonance density, however Neutrino energy must be:

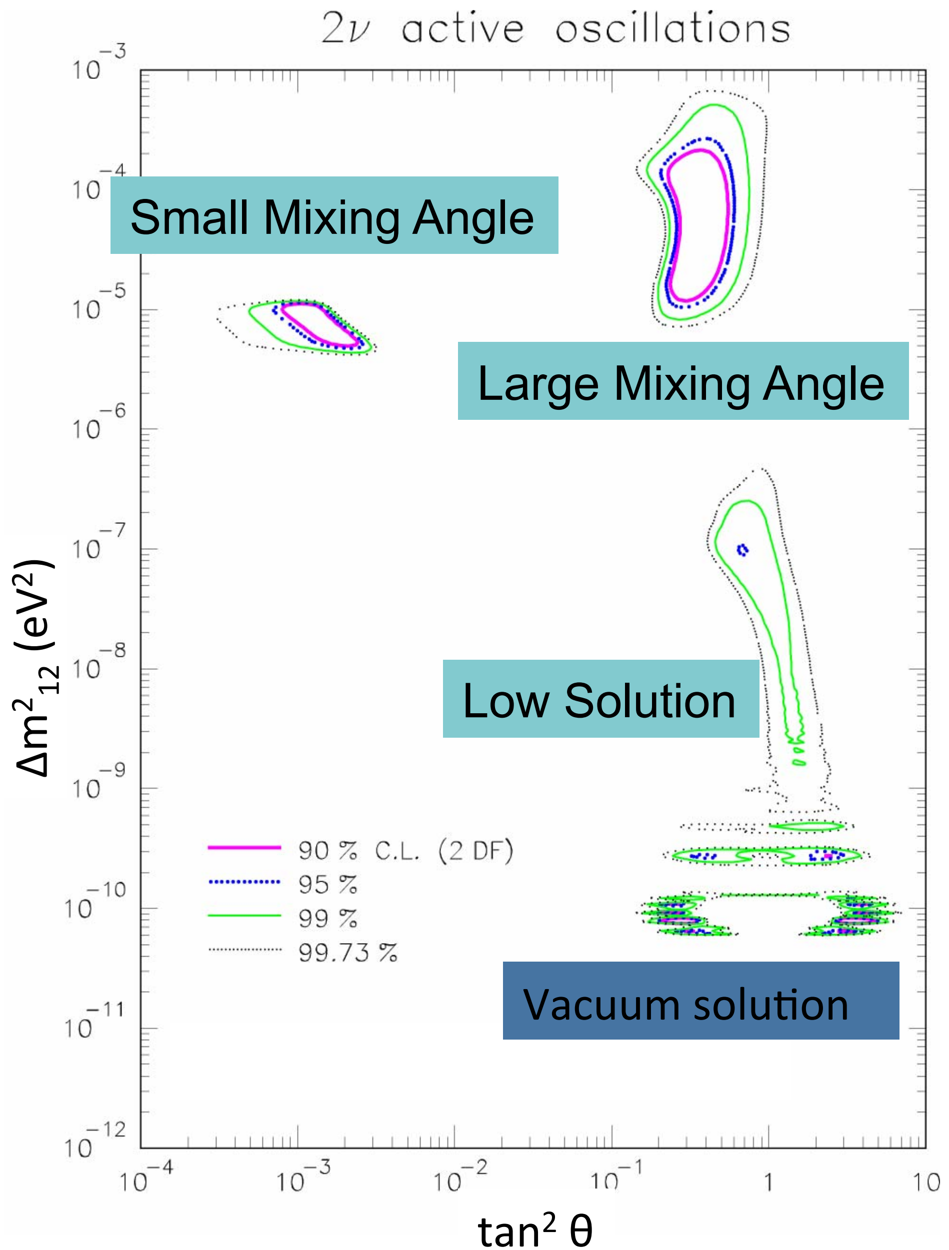
1) above a the minimum for ρ_e^{res} to be present in the Sun
2) enough to preserve adiabaticity: density changes << oscillation length (~$4\pi E/\Delta m^2$)

Global Analysis

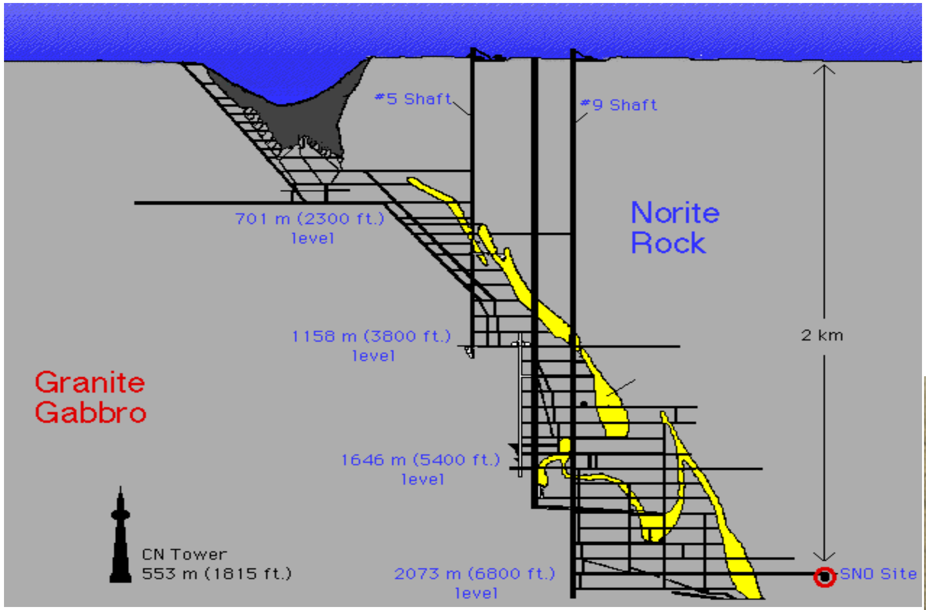
Fit to existing experimental data with free oscillation parameters.

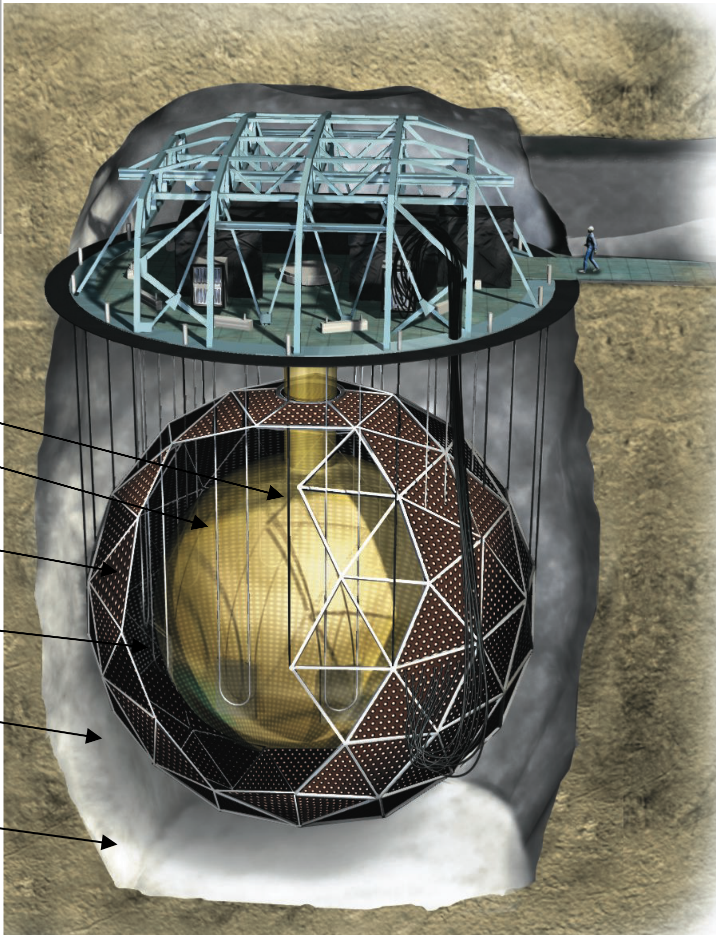
Results in the Δm^2_{12} , θ_{12} plane.

At the turn of the century there were several possibilities.



Sudbury Neutrino Observatory





1000 tonnes D_2O

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~60% photocathode coverage)

1700 tonnes inner shielding H_2O

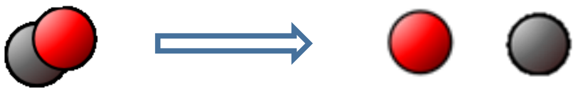
5300 tonnes outer shielding H_2O

Urylon liner radon seal

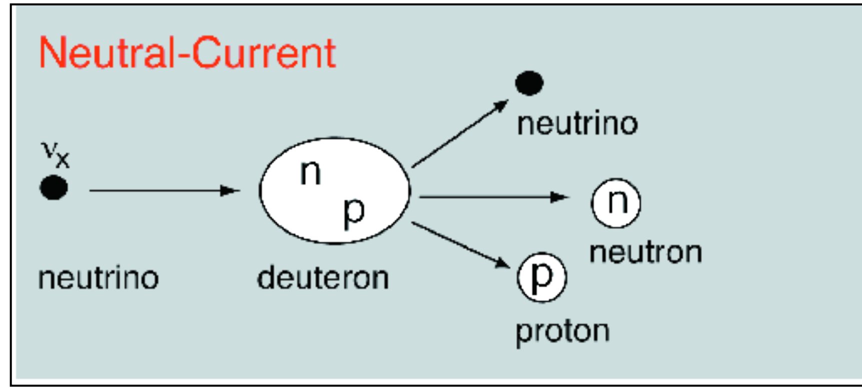
depth: 2092 m (~6010 m.w.e.) ~70 muons/day

The Three Neutrino Reactions in SNO

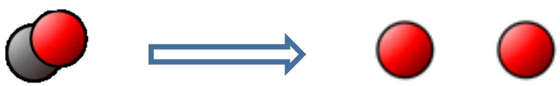
NC $\nu_x + d \rightarrow p + n + \nu_x$

E>2.2MeV 

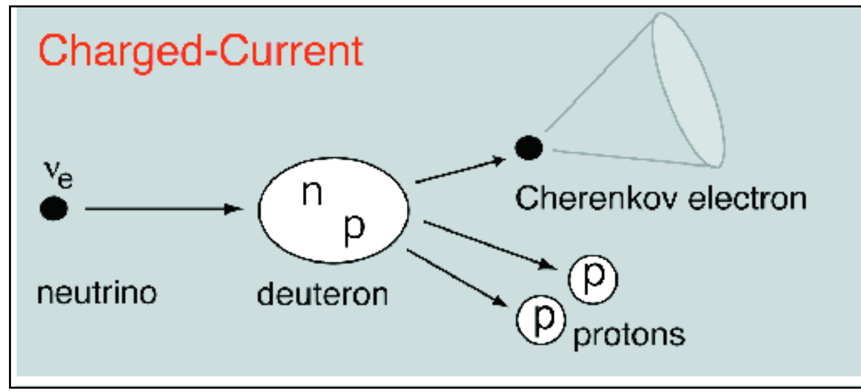
Equal cross section for all ν flavors



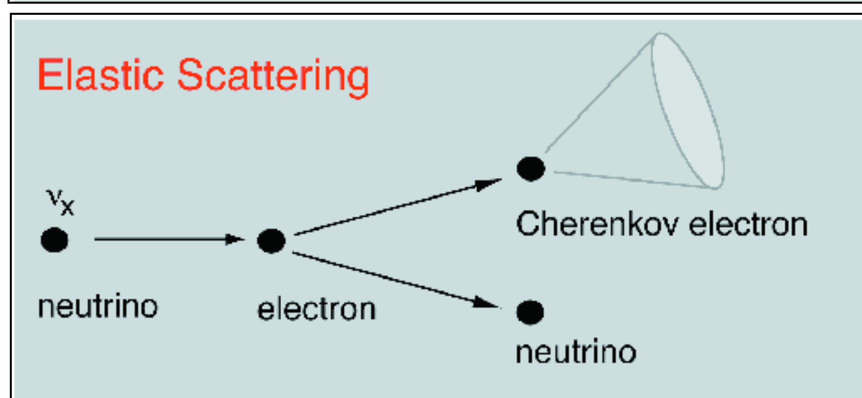
CC $\nu_e + d \rightarrow p + p + e^-$

E>1.44MeV 

Possible only for electron ν_e

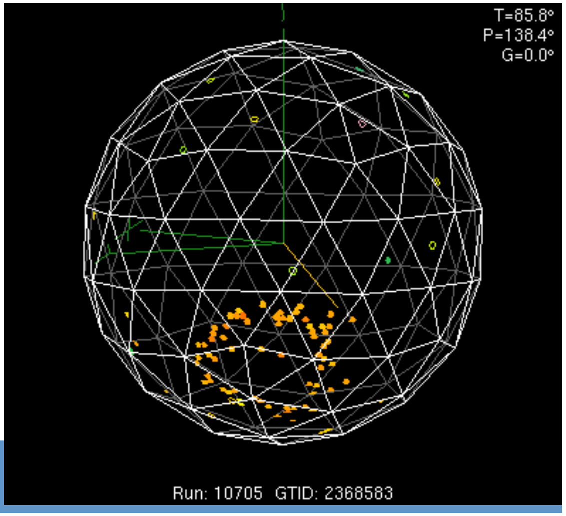


ES $\nu_x + e^- \rightarrow \nu_x + e^-$



Evidence of flavor conversion

Neutral and charged current interactions have different signatures and the fluxes are measured independently



Experiment	Theory
$\phi_{CC} = 1.68 \; {}^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.}) \cdot 10^6 \; cm^{-2} s^{-1}$ $\phi_{NC} = 4.94 \; {}^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.}) \cdot 10^6 \; cm^{-2} s^{-1}$	Solar Standard Model (*BPS07*) $(4.7 \pm 0.5) \cdot 10^6 \; cm^{-2} s^{-1}$

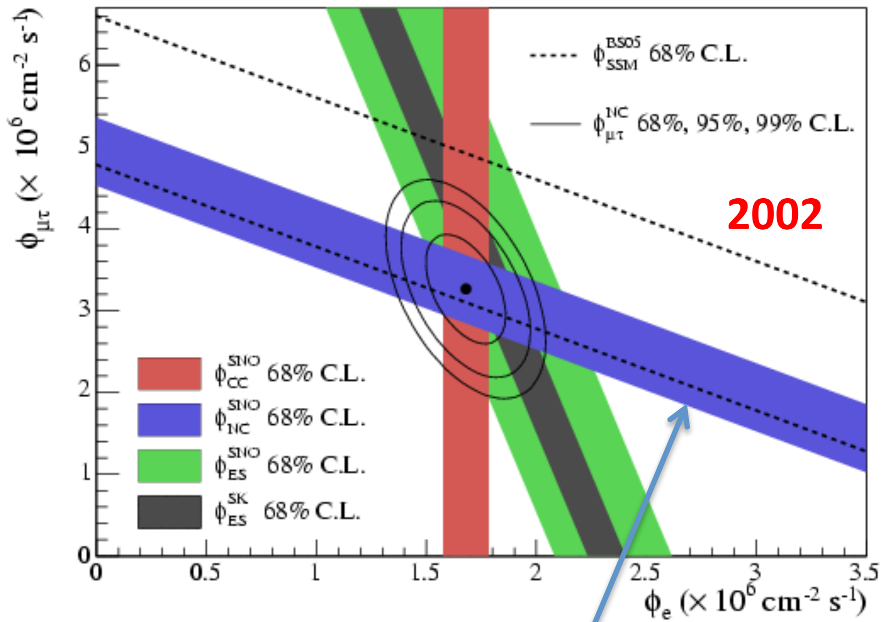
Two brilliant conclusions could be taken:

1. NC = SSM, first neutrino confirmation of SSM
2. CC != NC, evidence of flavor conversion.

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

The plot that changed the "world"

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



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

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

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

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

example (blue):

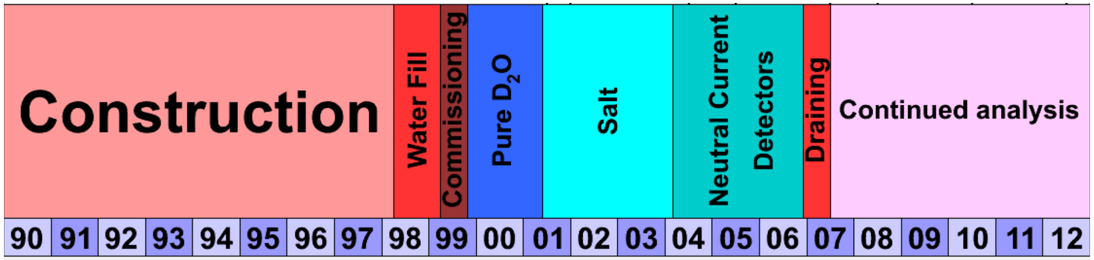
$$\varphi_{NC} = \varphi_{\nu_e} + \varphi_{\nu_\mu} + \varphi_{\nu_\tau}$$

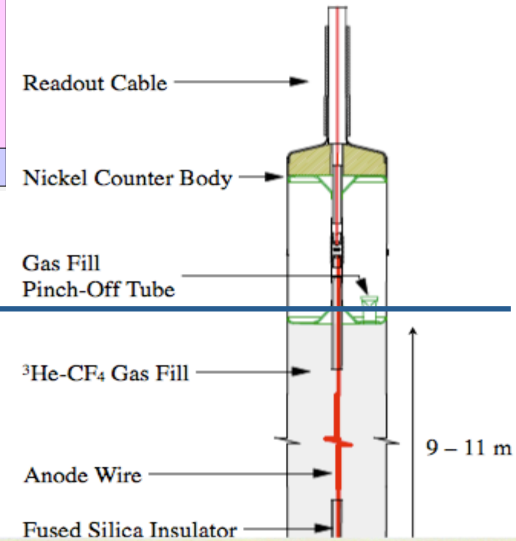
$$4.94 = \varphi_{\nu_e} + (\varphi_{\nu_\mu} + \varphi_{\nu_\tau})$$

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

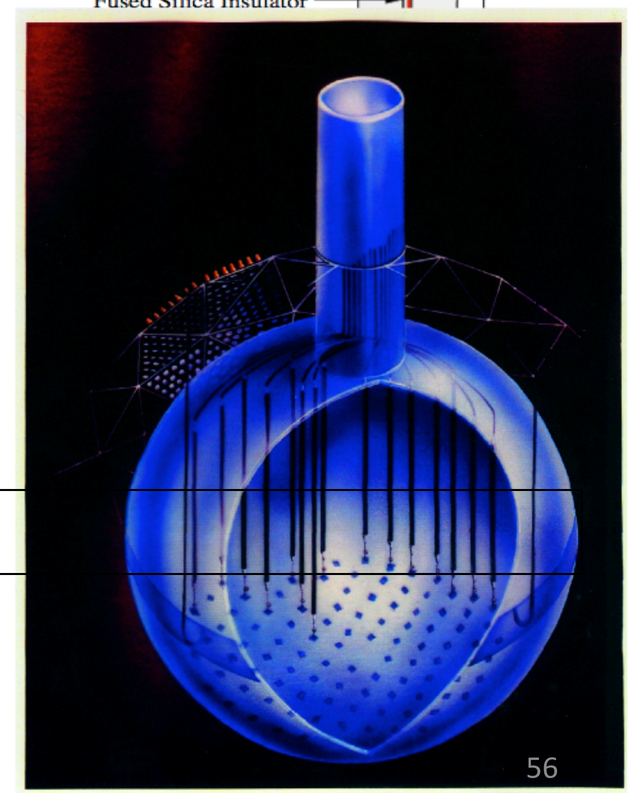
$$y = 4.94 - x$$

$$P_{ee}(^8B) = \frac{\varphi_{CC}}{\varphi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$



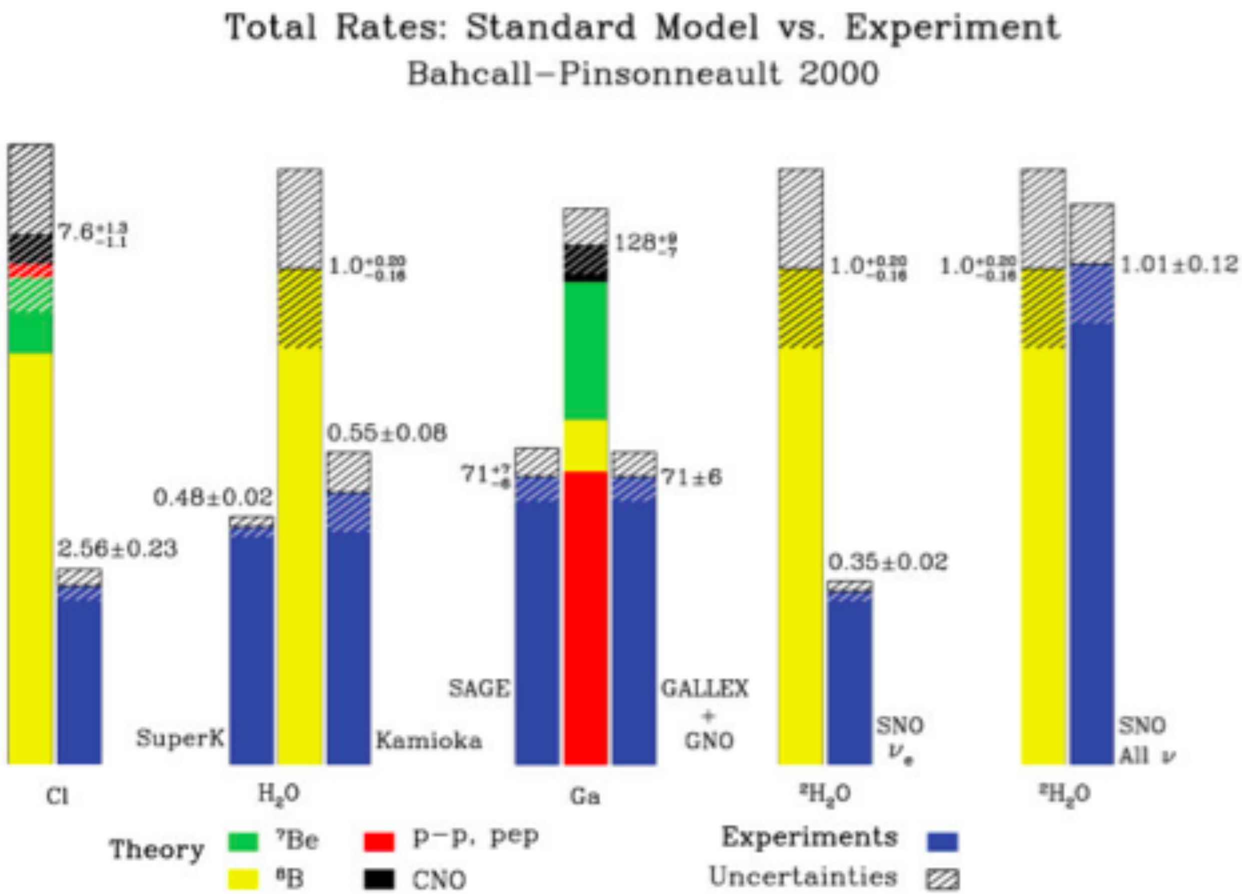


Pure D_2O	Salt
Nov 99 – May 01	Jul 01 – Sep 03
$n + d \rightarrow t + \gamma$	$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$
(E_γ = 6.25 MeV)	($E_{\Sigma\gamma}$ = 8.6 MeV)
	enhanced NC rate and separation
PRL **87**, 071301 (2001)	
PRL **89**, 011301 (2002)	
PRL **89**, 011302 (2002)	PRL **92**, 181301 (2004)
PRC **75**, 045502 (2007)	PRC **72**, 055502 (2005)



LETA: PRC **81**, 055504 (2010)

Summary of all Solar neutrino experiments before Borexino

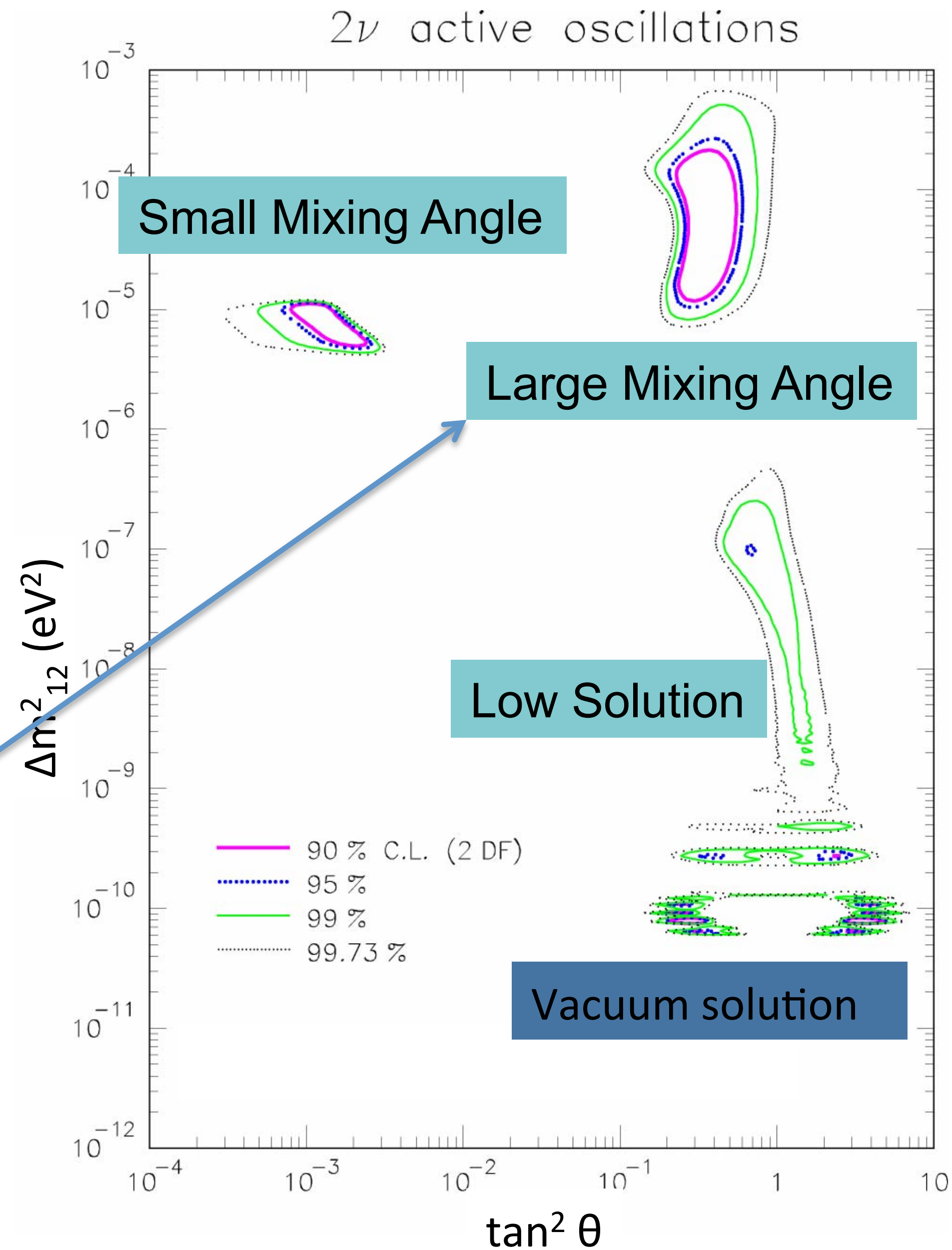


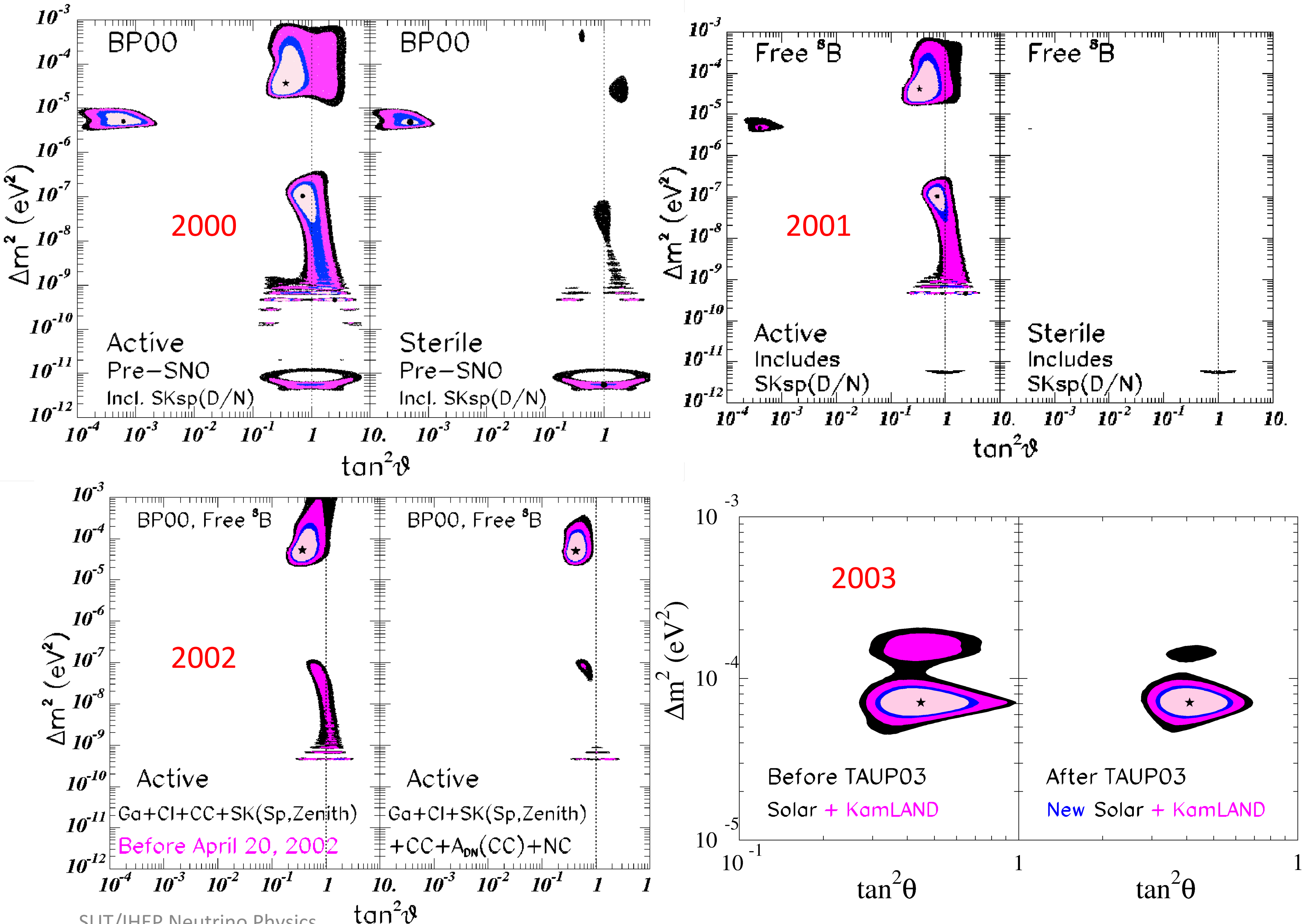
All experiments "see" less neutrinos than expected by SSM ……..

……. (except SNO in case of Neutral Currents!)

We had proof of flavor conversion, not yet of neutrino oscillations.

But if electron neutrinos (ν_e) oscillate into non-electron neutrino (ν_μ , ν_τ) with these parameters with MSW this parameters area was favored

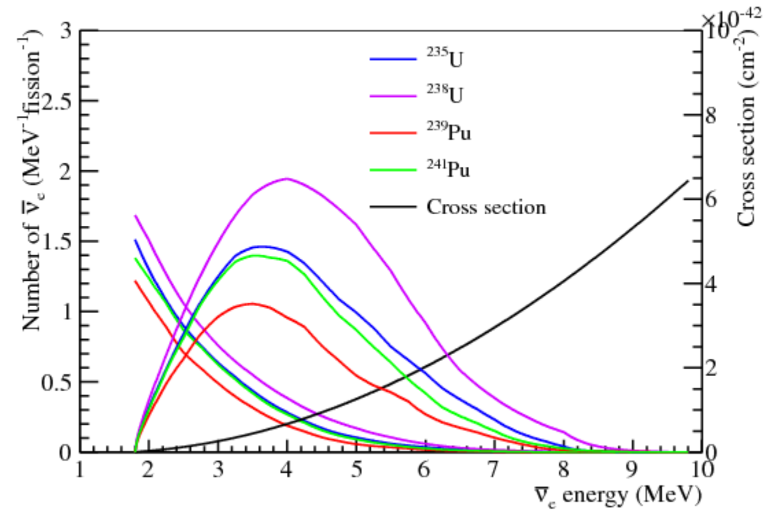



2000
BP00
Active
Pre−SNO
Incl. SKsp(D/N)
BP00
Sterile
Pre−SNO
Incl. SKsp(D/N)
Δm^2 (eV^2)
$\tan^2\vartheta$
2001
Free ^{8}B
Active
Includes
SKsp(D/N)
Free ^{8}B
Sterile
Includes
SKsp(D/N)
Δm^2 (eV^2)
$\tan^2\vartheta$
2002
BP00, Free ^{8}B
Active
Ga+Cl+CC+SK(Sp,Zenith)
Before April 20, 2002
BP00, Free ^{8}B
Active
Ga+Cl+SK(Sp,Zenith)
+CC+A$_{DN}$(CC)+NC
Δm^2 (eV^2)
$\tan^2\vartheta$
2003
Before TAUP03
Solar + KamLAND
After TAUP03
New Solar + KamLAND
Δm^2 (eV^2)
$\tan^2\theta$

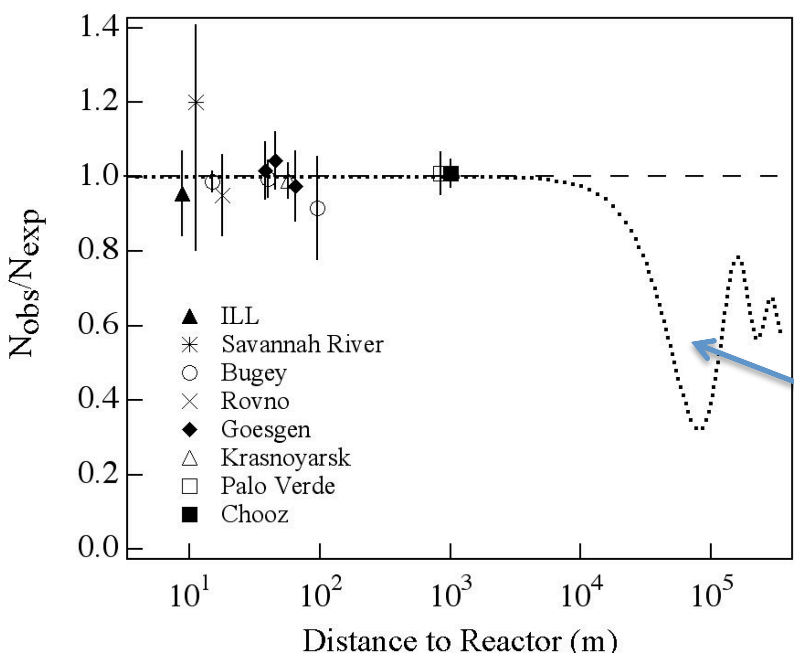
Reactor experiments

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

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



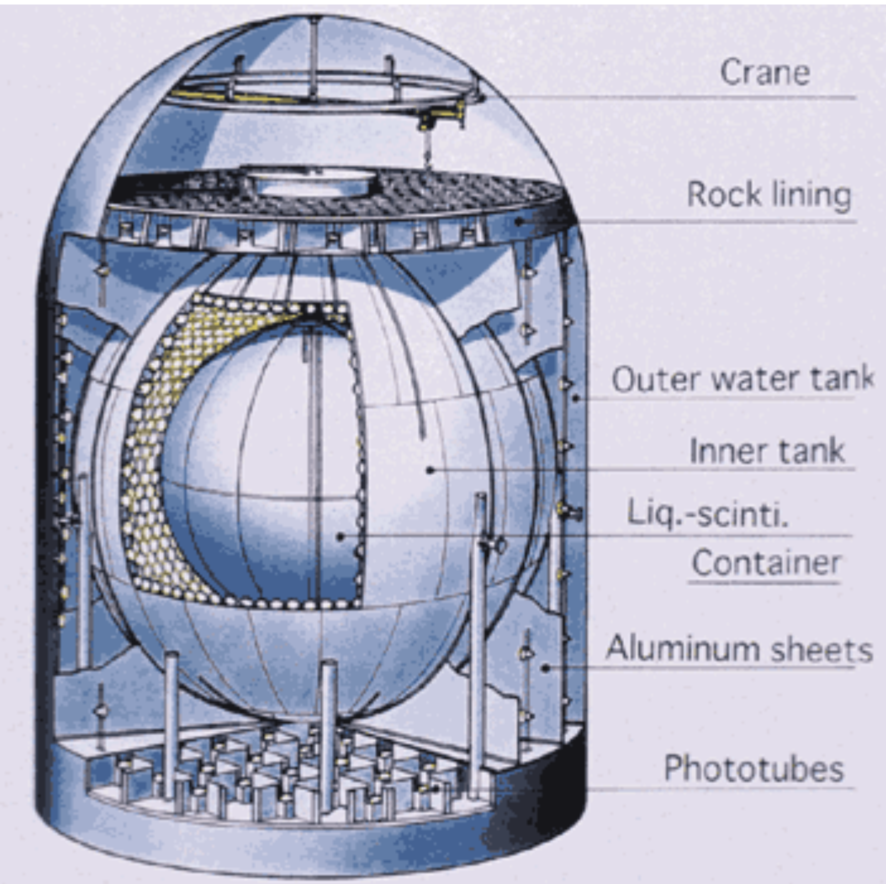
Under CPT invariance: ν_e = anti-ν_e



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**)



- 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

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

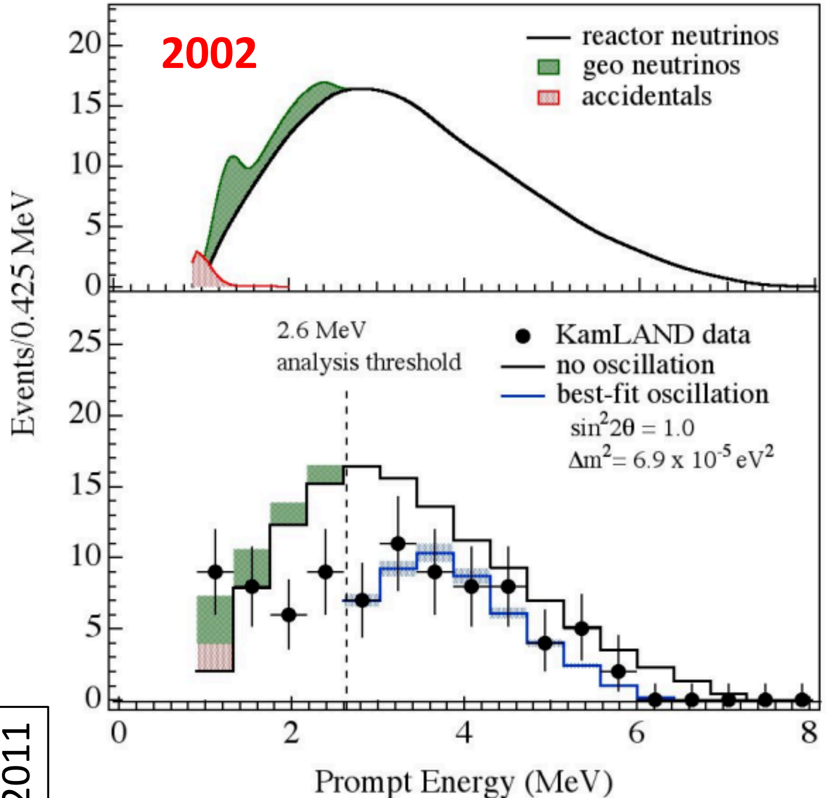
$$E_\nu = E_{\text{prompt}} + \langle E_{n\,\text{recoil}} \rangle + 0.8\,\text{MeV}$$

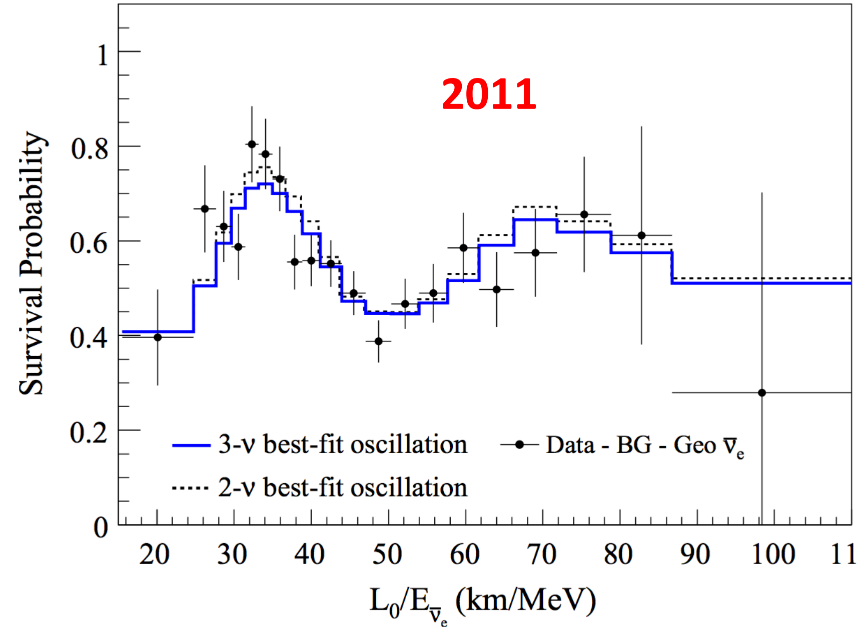
n capture by proton produces another 2.2 MeV γ-ray delayed by 200 μs
- allows good background control

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

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

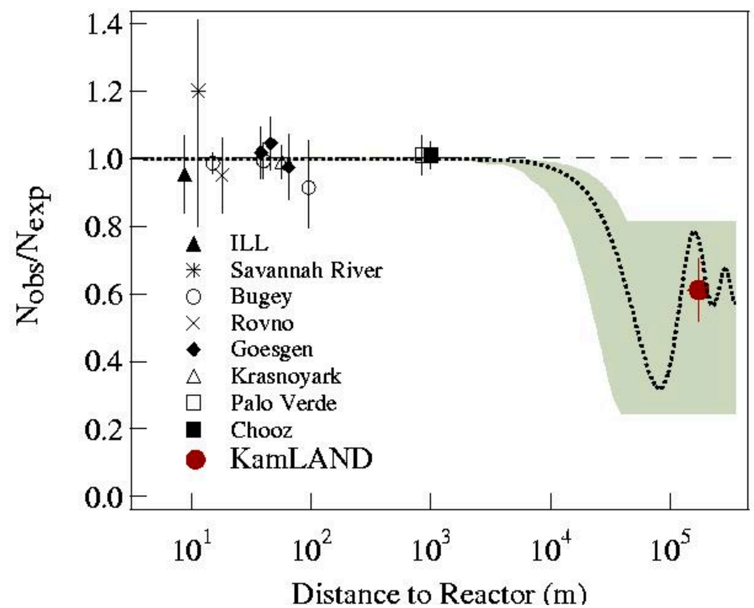
Note: solar neutrino are ν_e, reactor neutrinos are $\bar{\nu}_e$. Different signature:
for ν_e there is no combination of prompt and delayed light.





Phys.Rev.D83:052002,2011

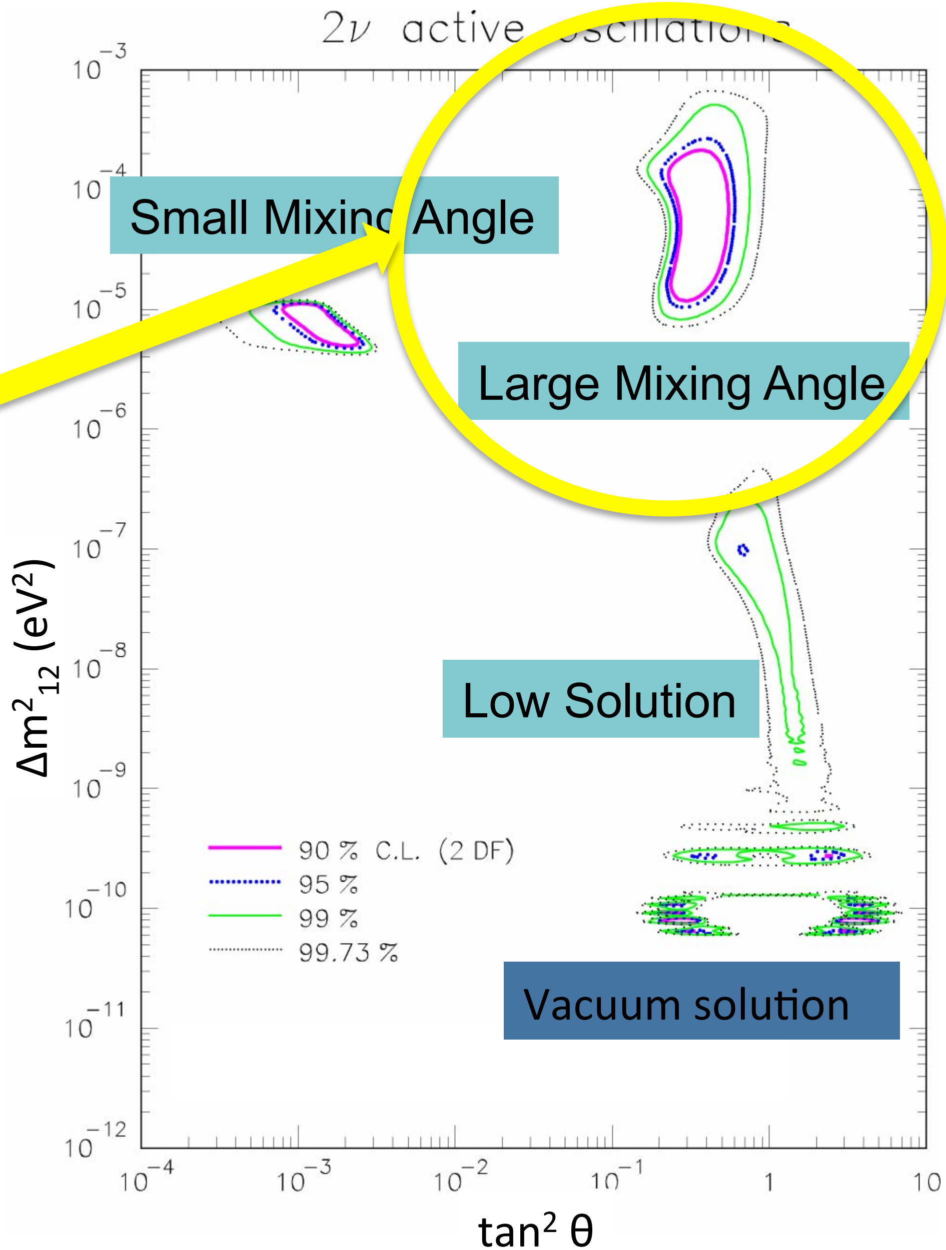
Ratio of observed to expected anti-neutrino flux as a function of distance from nuclear reactors, including KamLAND. From 2002 PRL



In 2003, spectral distortion proves MSW effect and identifies the LMA region as “the solution”.

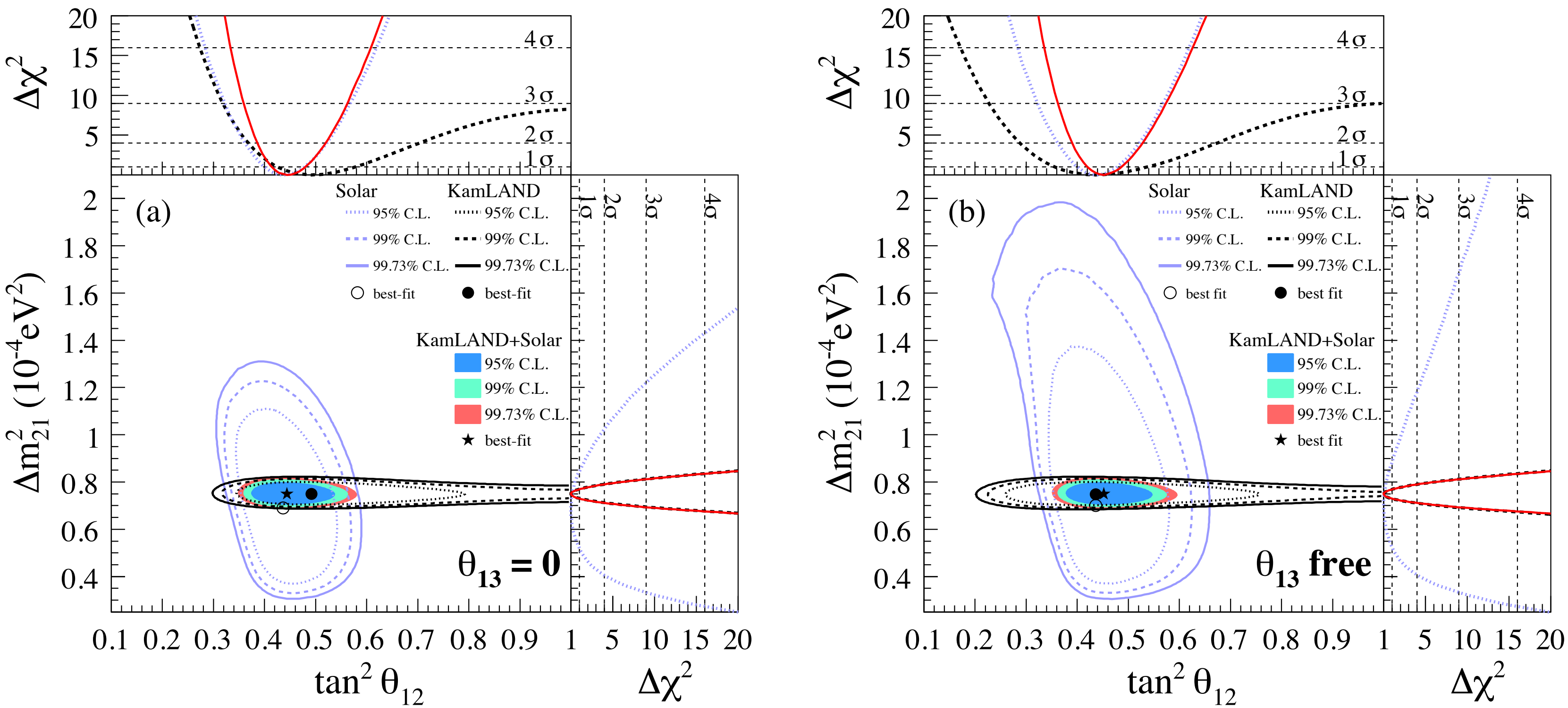
$$\Delta m^2_{12} = 7.5 \pm 0.2 \cdot 10^{-5}\, eV^2$$

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



KamLAND: global analysis

Phys.Rev.D83:052002,2011



Data set	Analysis method	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
KamLAND	two-flavor	$0.492^{+0.086}_{-0.067}$	$\equiv 0$
KamLAND + solar	two-flavor	$0.444^{+0.036}_{-0.030}$	$\equiv 0$
KamLAND	three-flavor	$0.436^{+0.102}_{-0.081}$	$0.032^{+0.037}_{-0.037}$
KamLAND + solar	three-flavor	$0.452^{+0.035}_{-0.033}$	$0.020^{+0.016}_{-0.016}$
Global	three-flavor	$0.444^{+0.039}_{-0.027}$	$0.009^{+0.013}_{-0.007}$

Δm^2_{12}=
$7.50 \pm 0.20\ 10^{-4}$ eV^2
(in all cases)

SNP solution: MSW-LMA

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Below 1 MeV neutrinos never find a density high enough to produce resonant conversion, so they are basically in vacuum oscillation regime.

As the oscillation length λ_{osc}=4Eν/Δm^2~10^4m << Sun-Earth distance, the oscillation effect is averaged. Survival probability becomes:

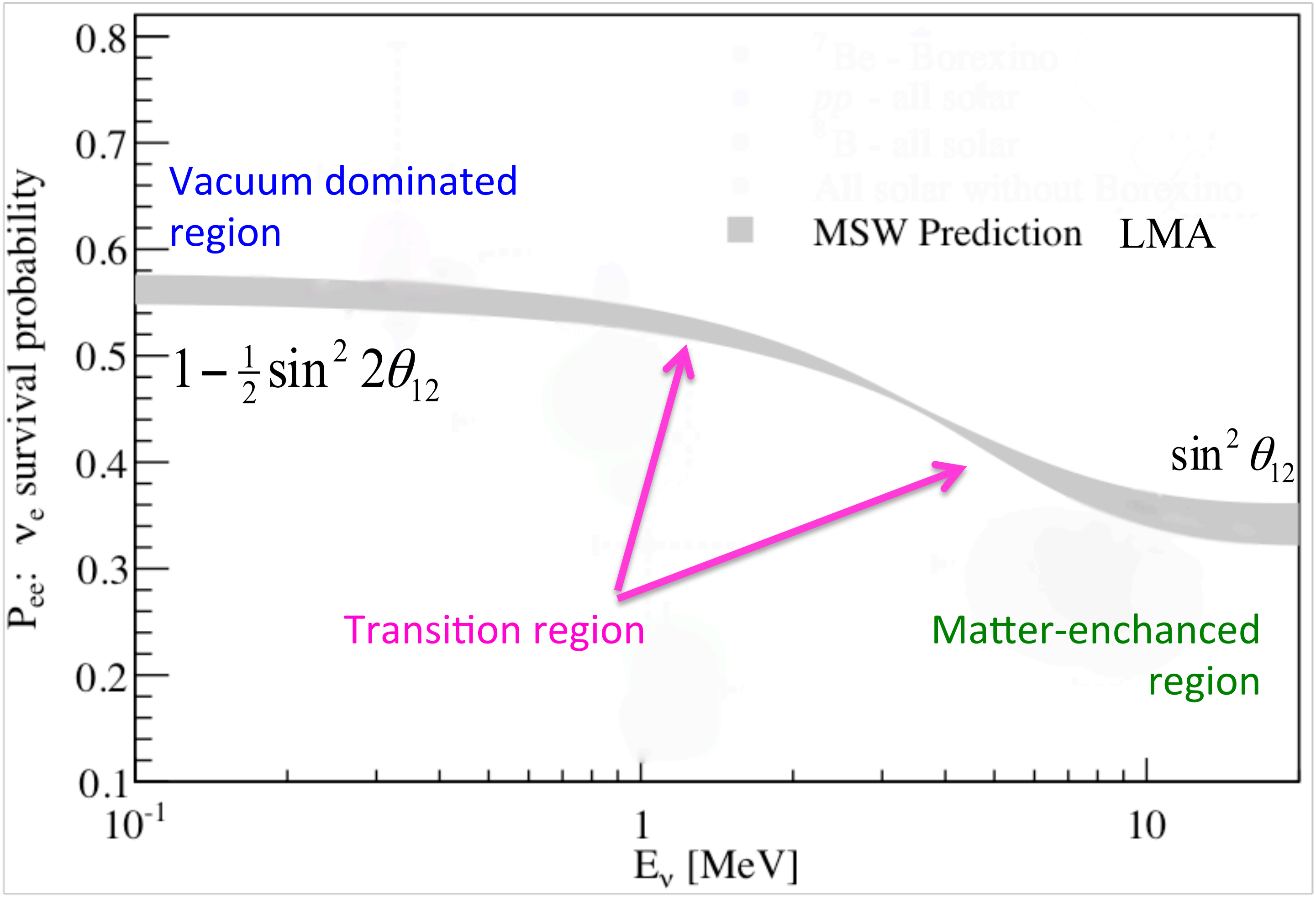
$$P(\nu_e \to \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta \approx 0.6$$

$$\theta \approx 32.5^O$$

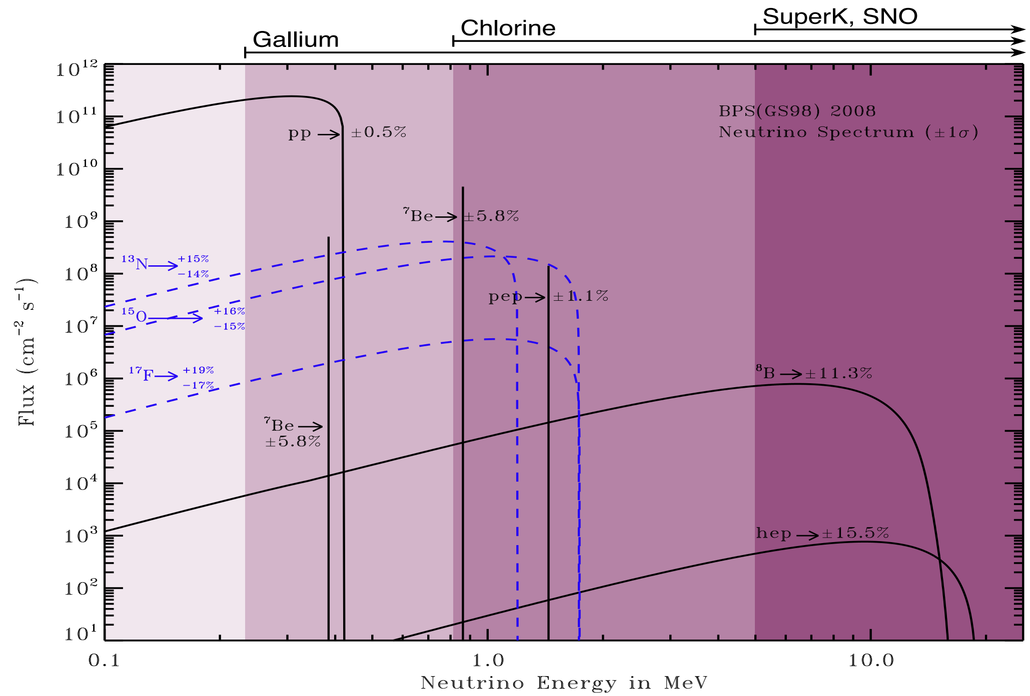
For neutrinos with energy above 10 MeV oscillation in matter dominates. Survival probability becomes:

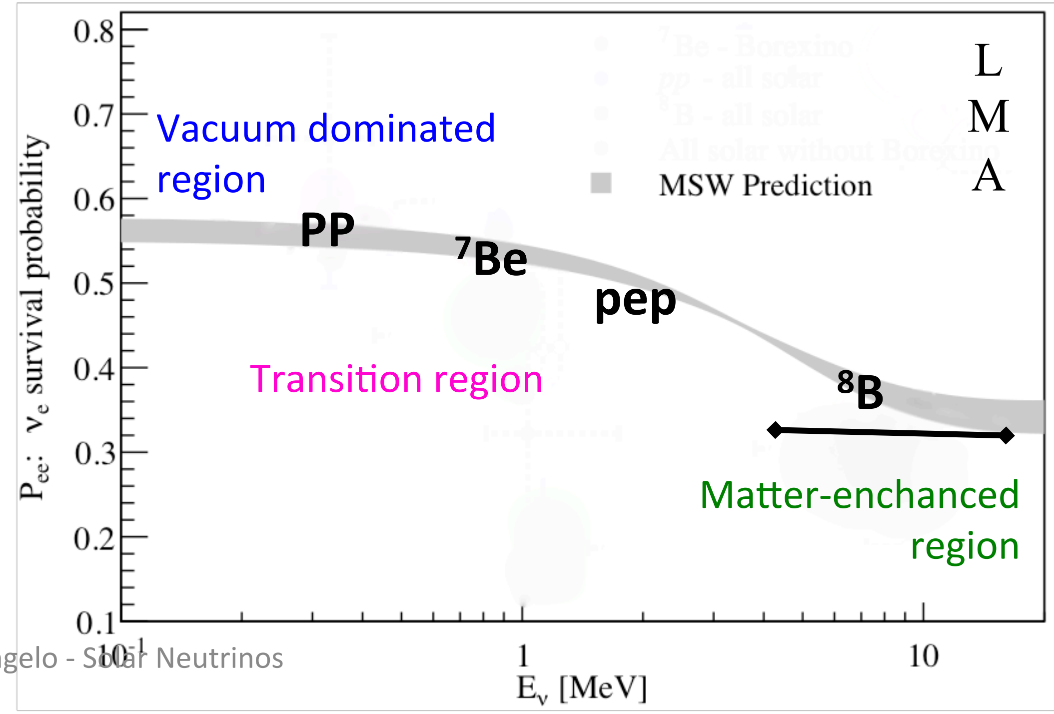
$$P(\nu_e \to \nu_e) = \sin^2\theta \approx 0.3$$

SNP solution: MSW-LMA



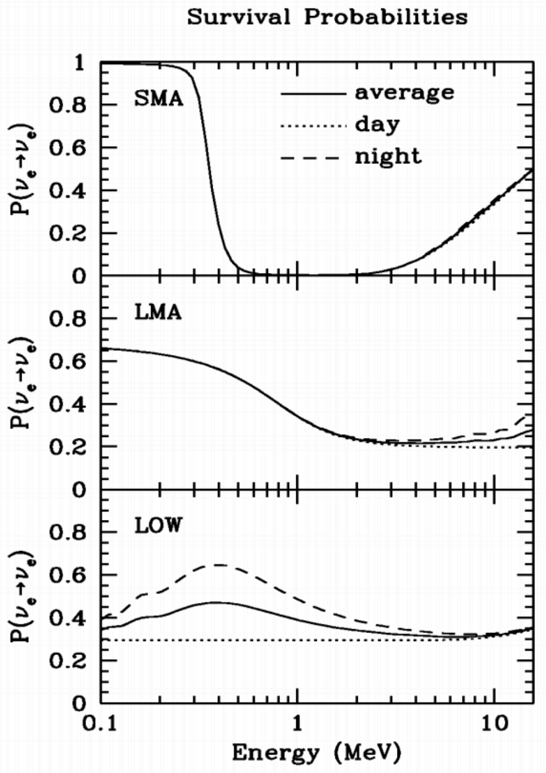
Combining sun and particles

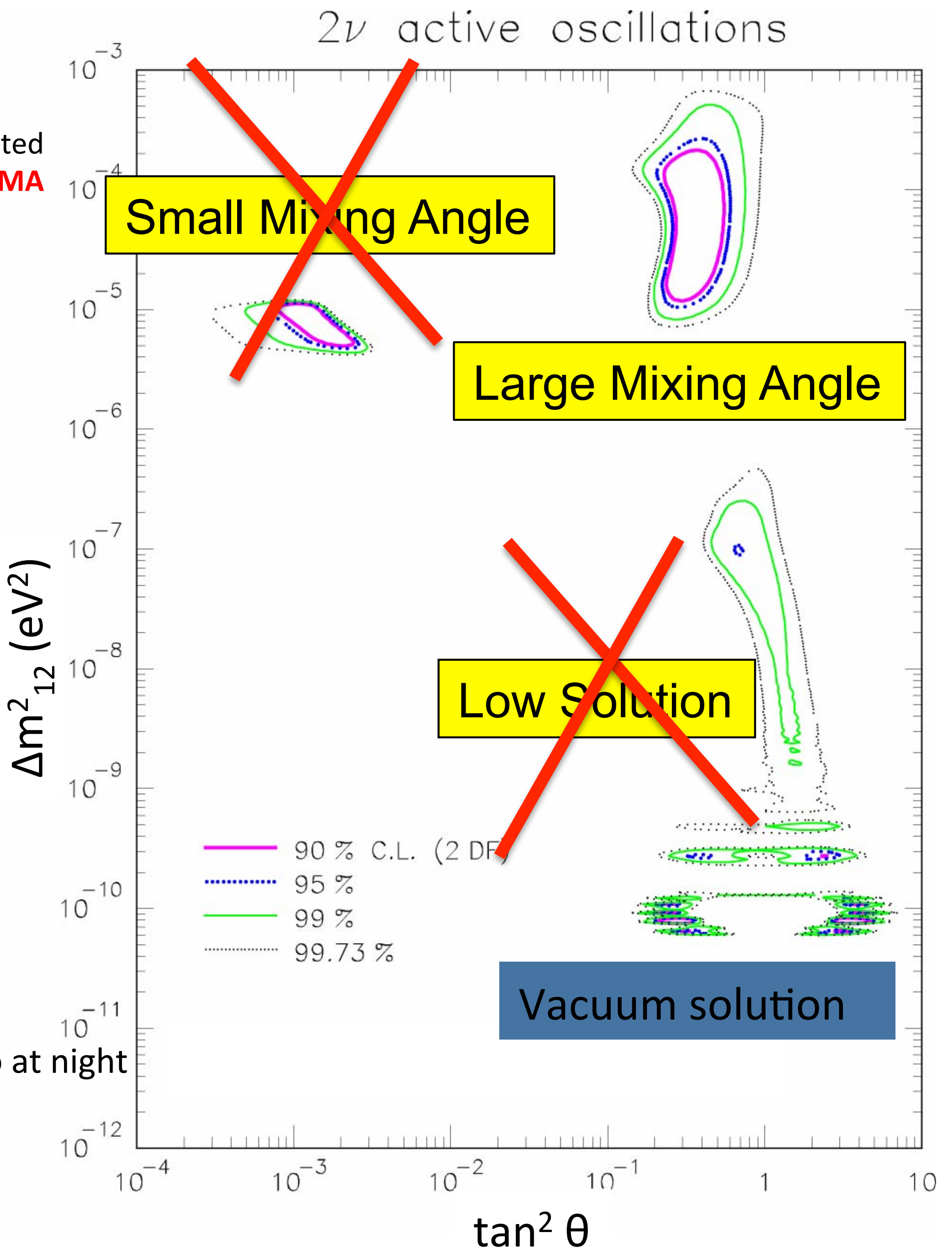




What about the others solutions?

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).





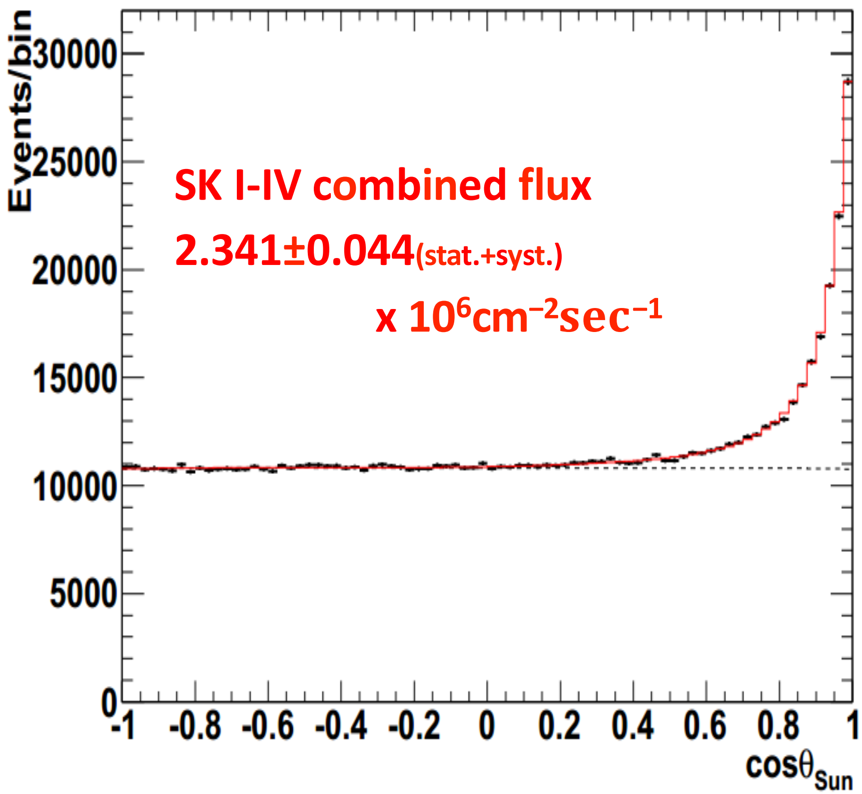
- For LOW solution, at night the Sun is brighter in neutrino at night
- For SMA solution, no room for ^{7}Be neutrinos.

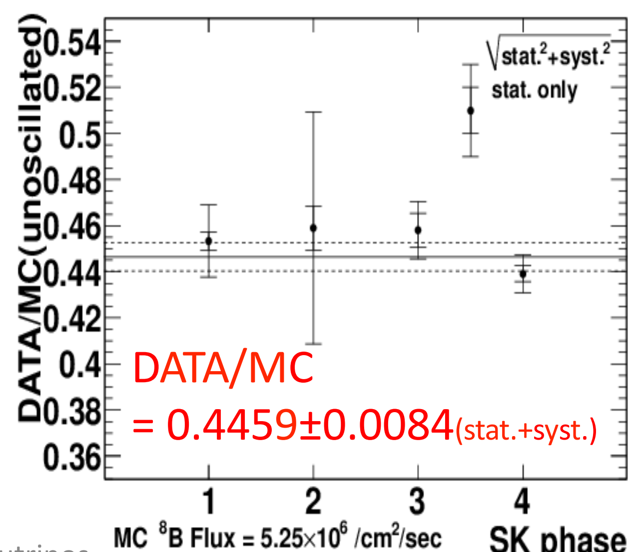
→ Now we know that both solutions are wrong!

SK ^{8}B Solar neutrino observation

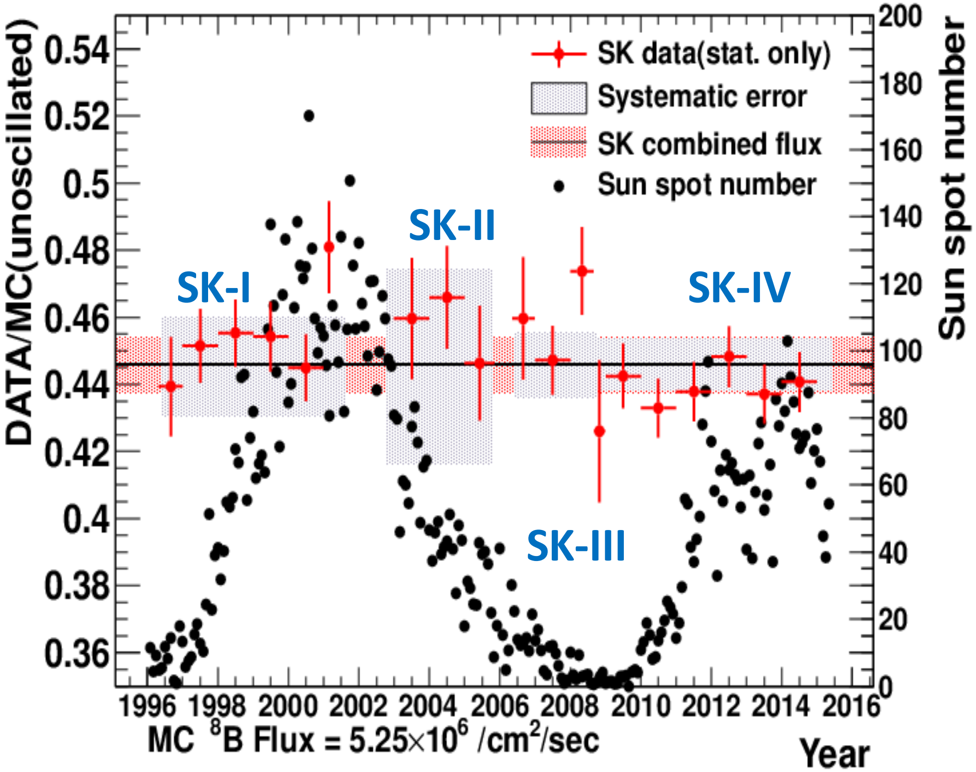
- SK has observed solar neutrino for 18 years(~ 1.5 solar cycle)
  - ~77000 solar ν interactions

Phase	Energy threshold MeV(kin.)	Live time (say)	^{8}B Flux $\times 10^6/cm^2/sec$
SK-I	4.5	1496	2.38±0.02±0.08
SK-II	6.5	791	$2.41\pm0.05^{+0.16}_{-0.15}$
SK-III	4.0	548	2.40±0.04±0.05
SK-IV	3.5	2034	2.31±0.02±0.04





Time variation of ^{8}B solar neutrino flux



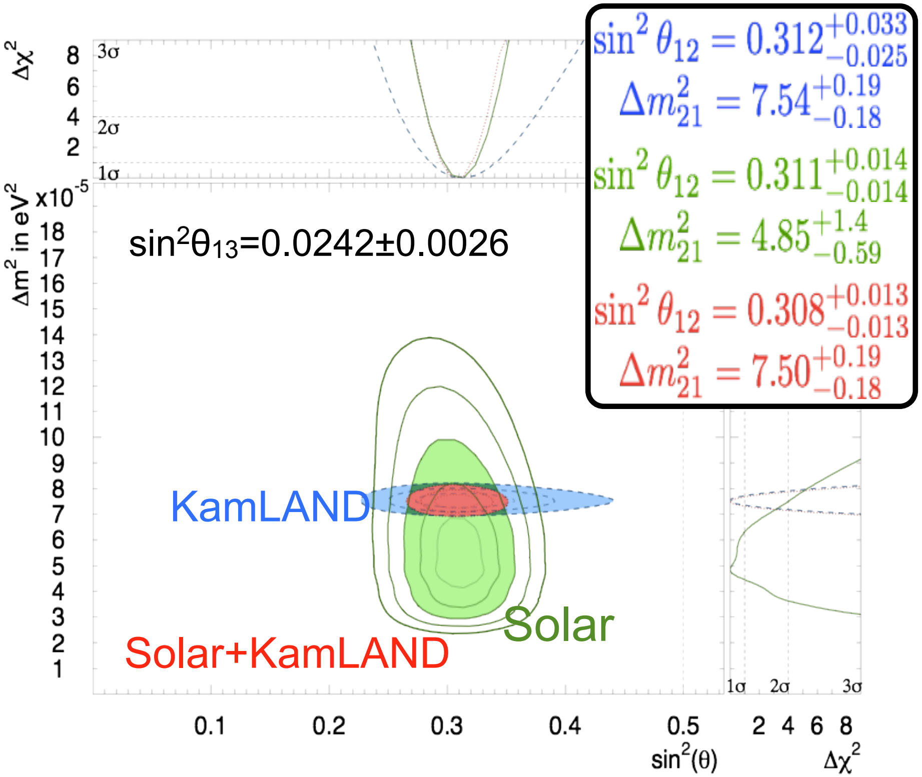
- No correlation with the 11 years solar activity is observed.
- Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.
  - χ^2 = 13.10/18(dof)

Sun spot number was obtained by the web page of NASA
http://solarscience.msfc.nasa.gov/greenwch/spot_num.txt

Oscillation analysis: Solar global fit

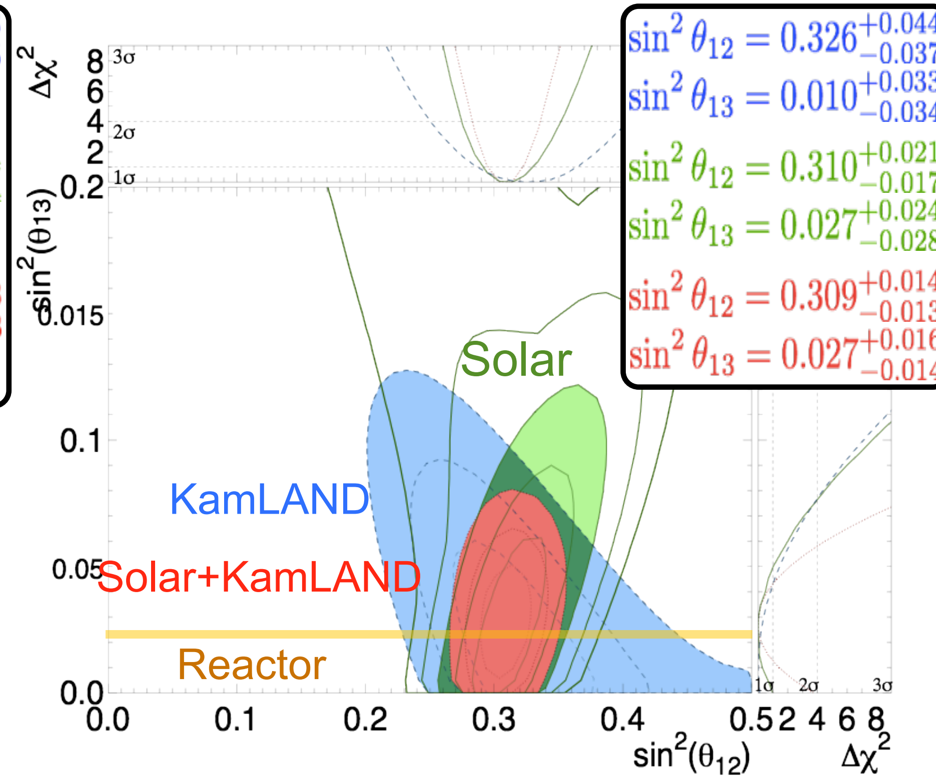
Including SK-IV 2015 results

Combined solar fit with KamLAND



~2σ tension in Δm^2_{21} between solar and KamLAND

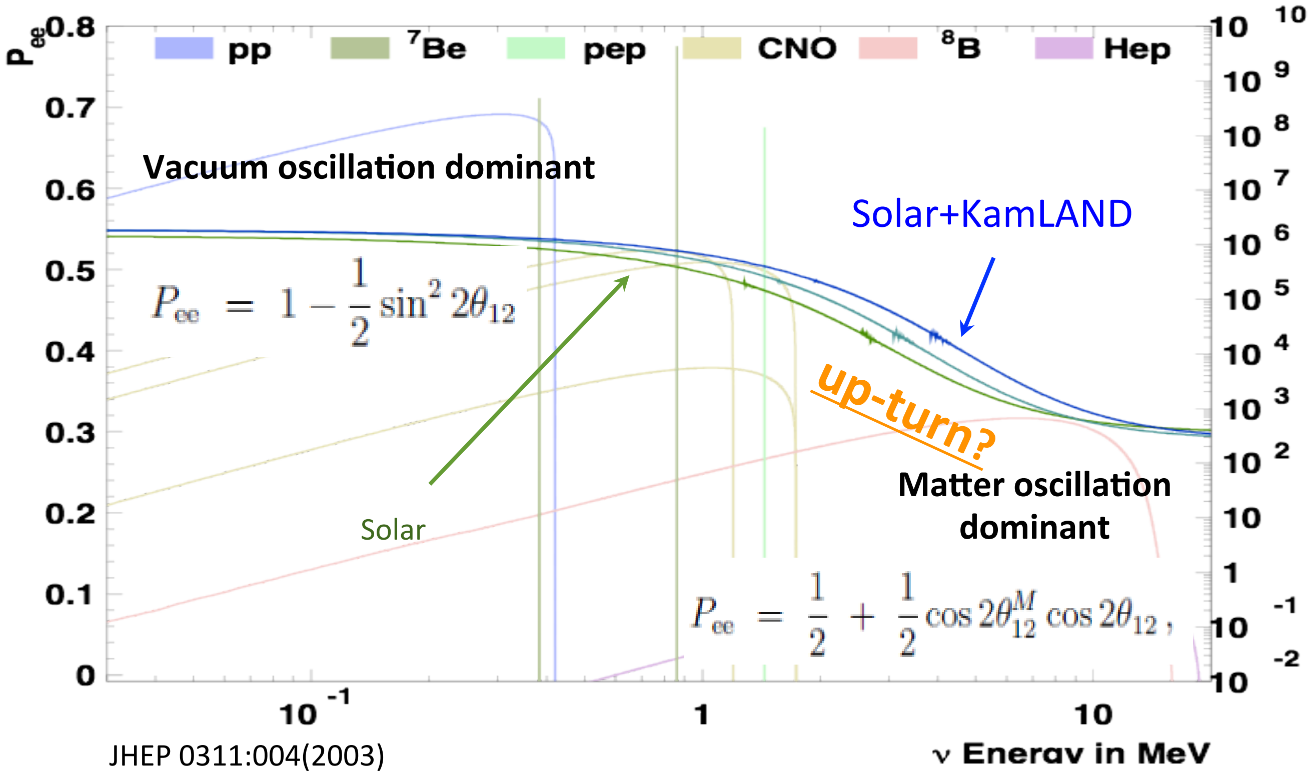
Without reactor θ_{13} constraint



Non-zero θ_{13} at 2σ from solar+KamLAND
Good agreement with Daya Bay, RENO, DC

Search for the direct MSW signal #1

Current main motivation of SK ^{8}B ν observation



JHEP 0311:004(2003)

Energy spectrum distortion

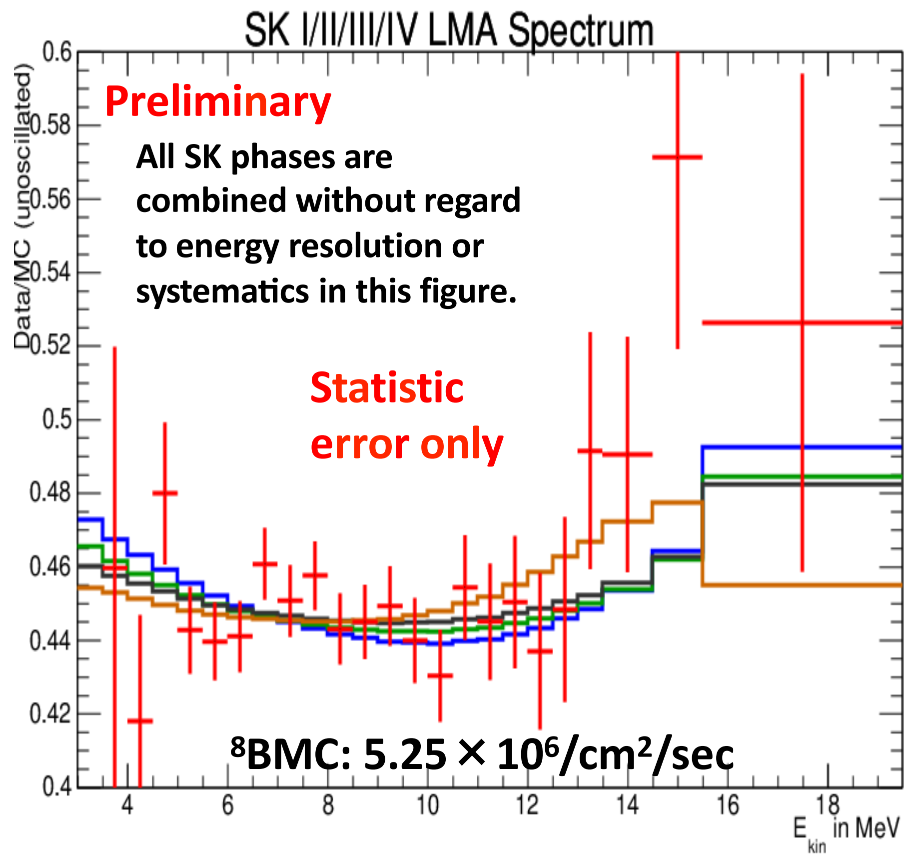
SK I-IV combined recoil spectrum

Test of "spectrum upturn"

– MSW is slightly disfavored by

- ~1.7 σ using the Solar + KamLAND best fit parameters
- ~1.0 σ using the Solar Global best fit parameters.

Total # of bins of SK I-IV is 83	χ^2
Solar + KamLAND	**70.13**
Solar global	**68.14**
Quadratic fit	**67.67**
Exponential	**67.54**

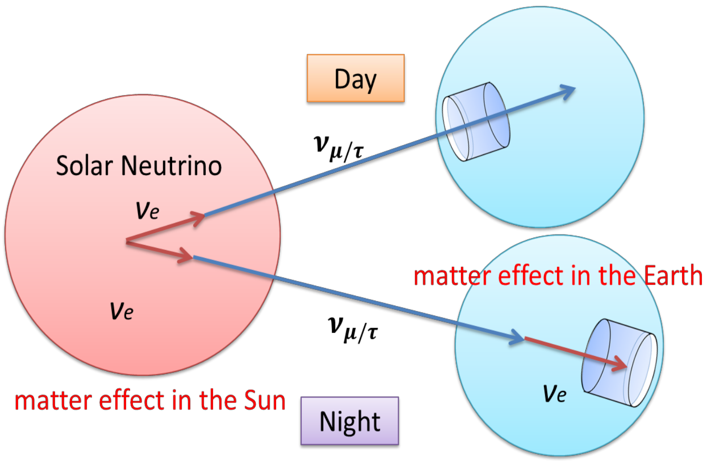


$$P_{ee}(E_\nu) = c_0 + c_1\left(\frac{E_\nu}{MeV} - 10\right) + c_2\left(\frac{E_\nu}{MeV} - 10\right)^2 \text{ (quadratic)}$$

$$P_{ee}(E_\nu) = e_0 + \frac{e_1}{e_2}\left(\exp\left(e_2\left(\frac{E_\nu}{MeV} - 10\right)\right) - 1\right) \text{ (exponential)}$$

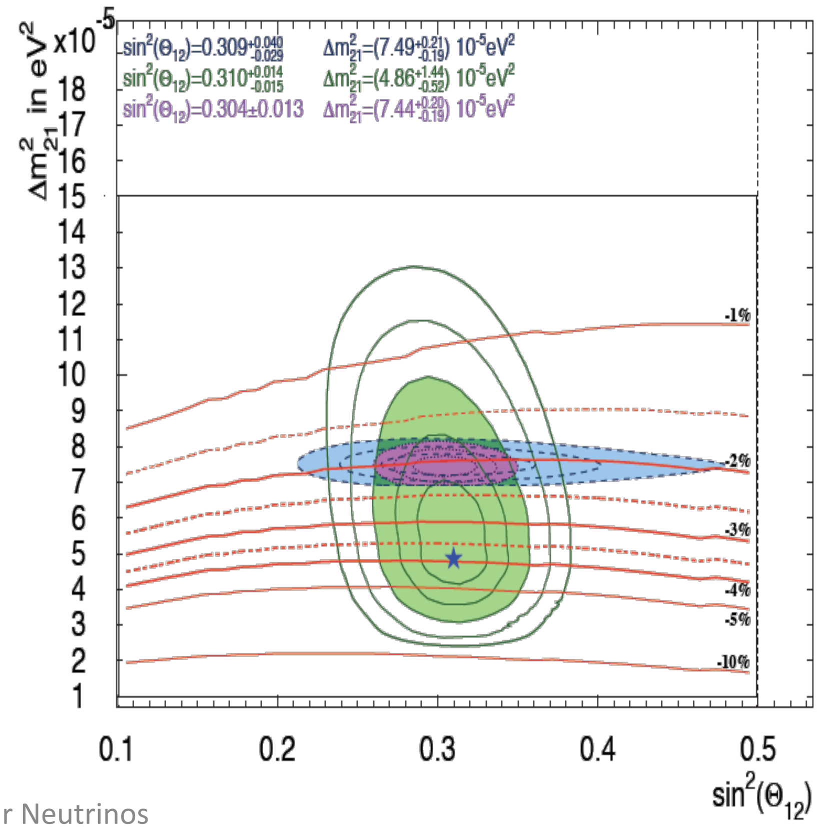
Search for the direct MSW signal #2

Current main motivation of SK ^{8}B ν observation

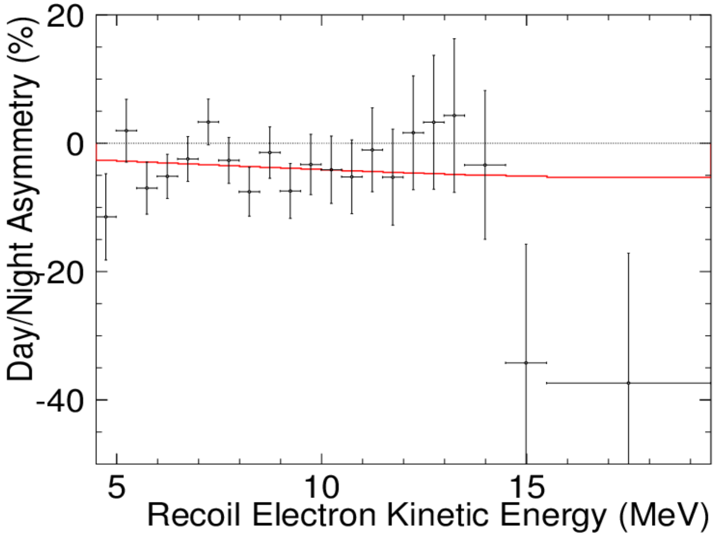


Flux day-night asymmetry

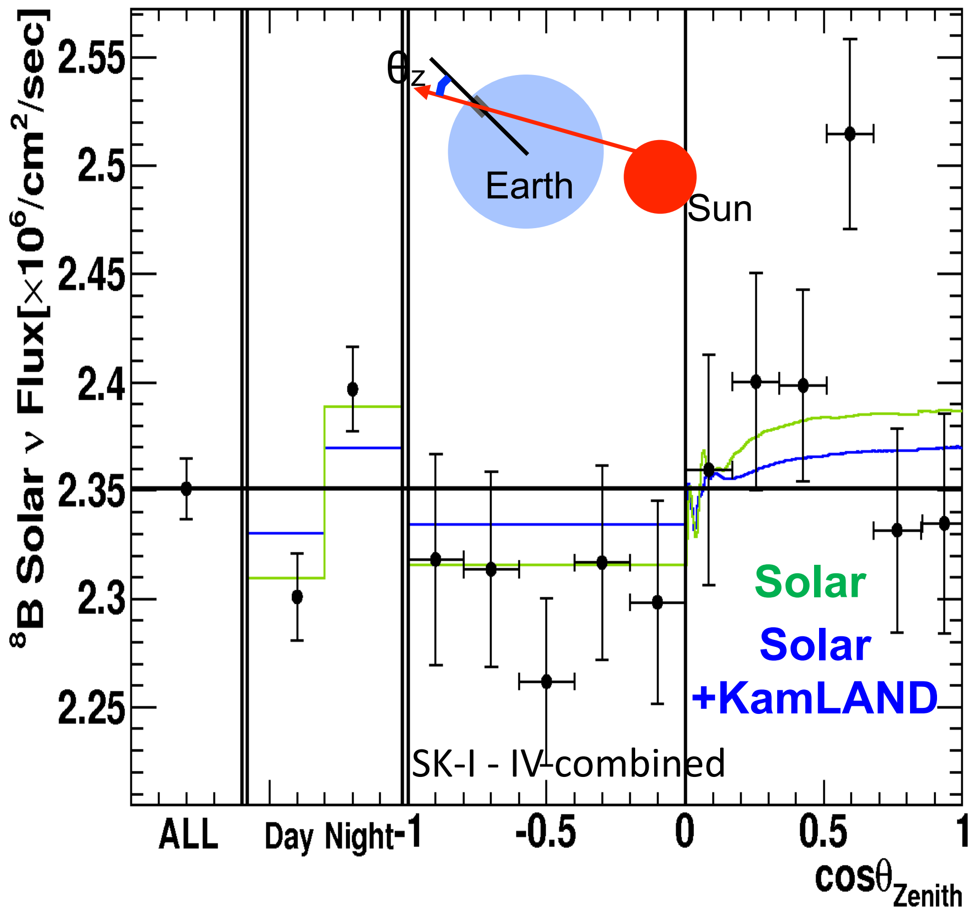
"Nighttime regeneration" of ν_e by earth matter effect



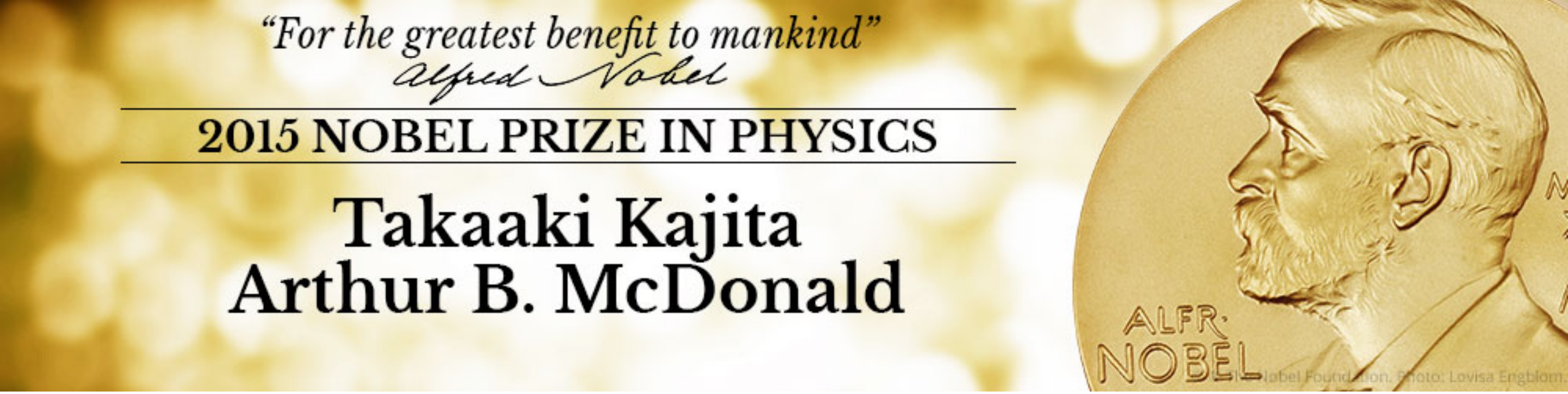
Day-Night flux asymmetry



SK-I	-2.0±1.8±1.0%
SK-II	-4.4±3.8±1.0%
SK-III	-4.2±2.7±0.7%
SK-IV	-3.6±1.6±0.6%
combined	**-3.3±1.0±0.5%**
non-zero significance	3.0σ



This is the "direct" indication for matter enhanced neutrino oscillation



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

3

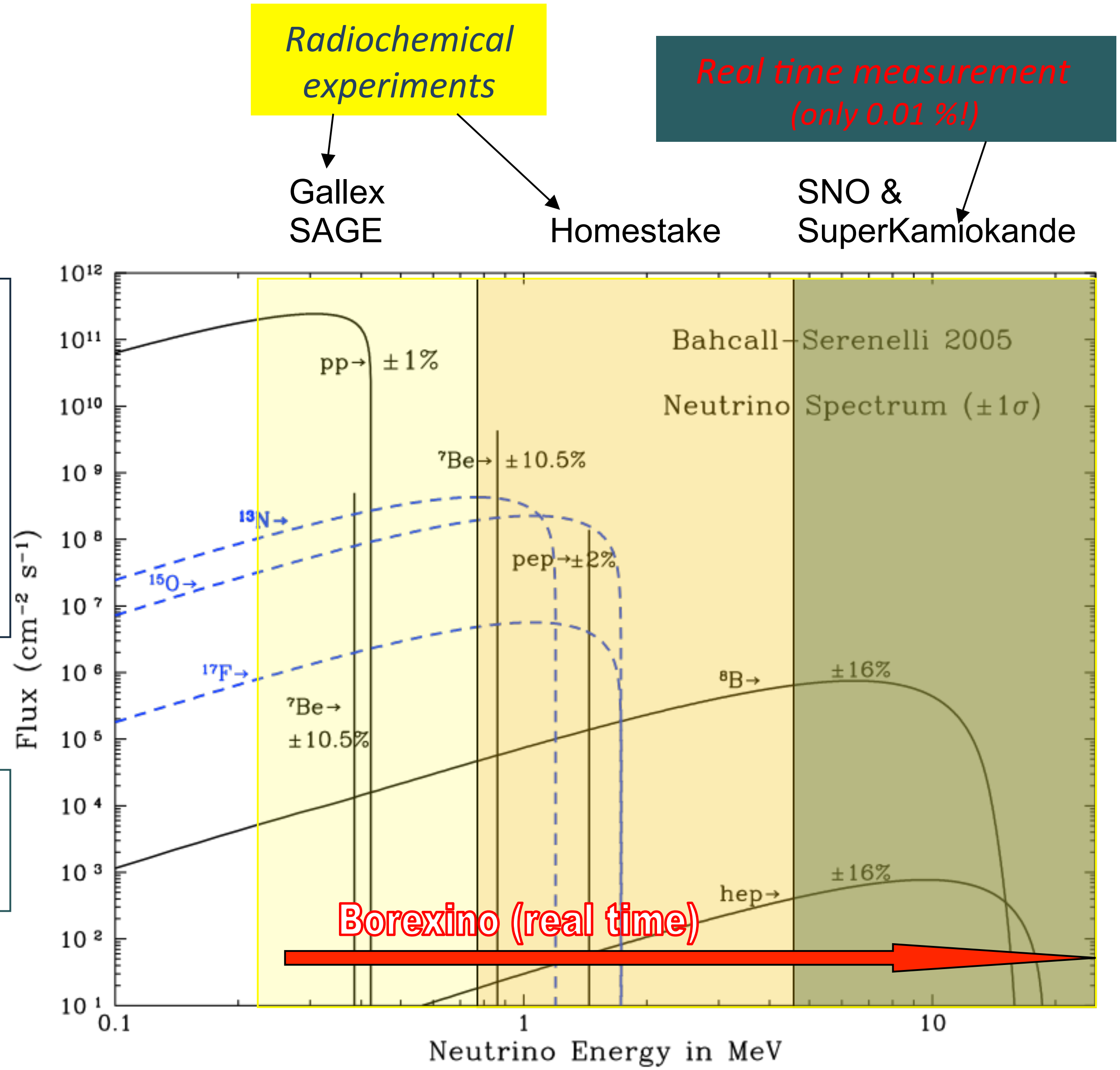
Low Energy Solar neutrinos spectroscopy (The Borexino detector)

To measure in real time below 1 MeV

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 $E_{th} \sim 200$ keV

Borexino is a detector able to measure neutrinos coming from the Sun in real_time with low_energy threshold (~ *200 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

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

High light yield ~10^4 photons per MeV

Detection principle:
elastic scattering (ES) on electrons

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

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)**

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)**

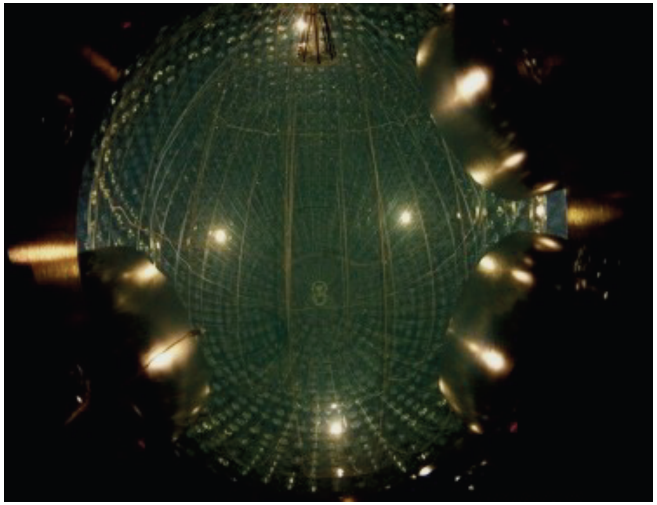
$$\frac{Signal(\nu)}{Noise(BKG)} = 1$$

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 10 orders of magnitude below natural radioactivity)*

≈100 tons
Liq. Scint.
PC+PPO

The **100 tons target mass** (**liquid scintillator**) is composed of pseuducumene **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

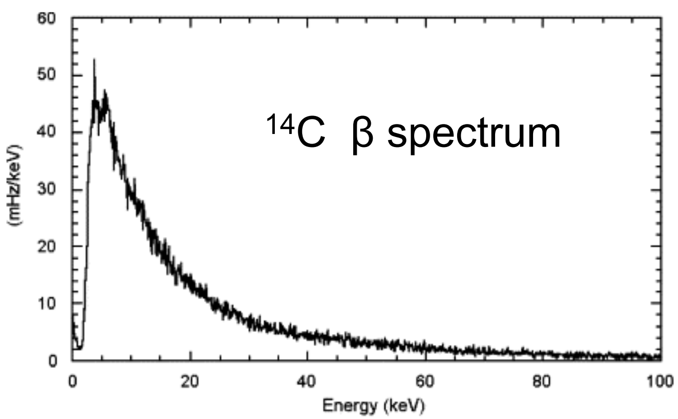
Background	Source	Typical Concentration	Borexino Levels (per scintillator mass)	Reduction Method
^{14}C	Scintillator	10^{-12} g/g	10^{-18} g/g	Underground Source
^{238}U	Dust	10^{-4} g/g (Dust)	10^{-17} g/g	Purification
^{232}Th	Dust	10^{-4} g/g (Dust)	10^{-18} g/g	Purification
^{85}Kr	Air	10^{7} cpd/ton (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

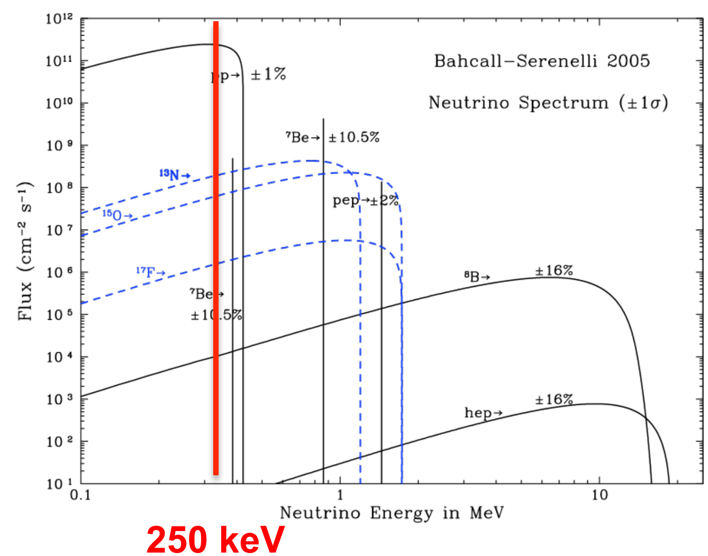
Solar neutrino Spectroscopy from 250 keV

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 300 tons of scintillator.

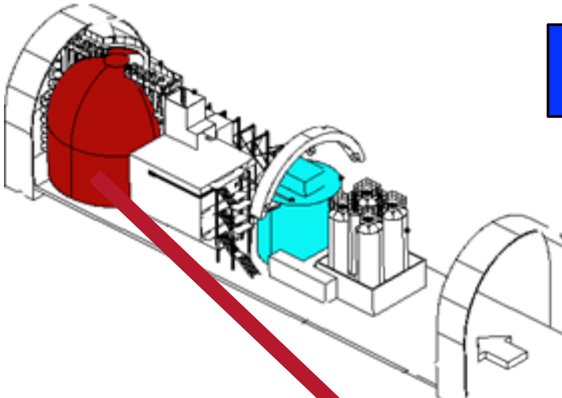
^{14}C is a pure beta emitter with an end-point of 156 keV.

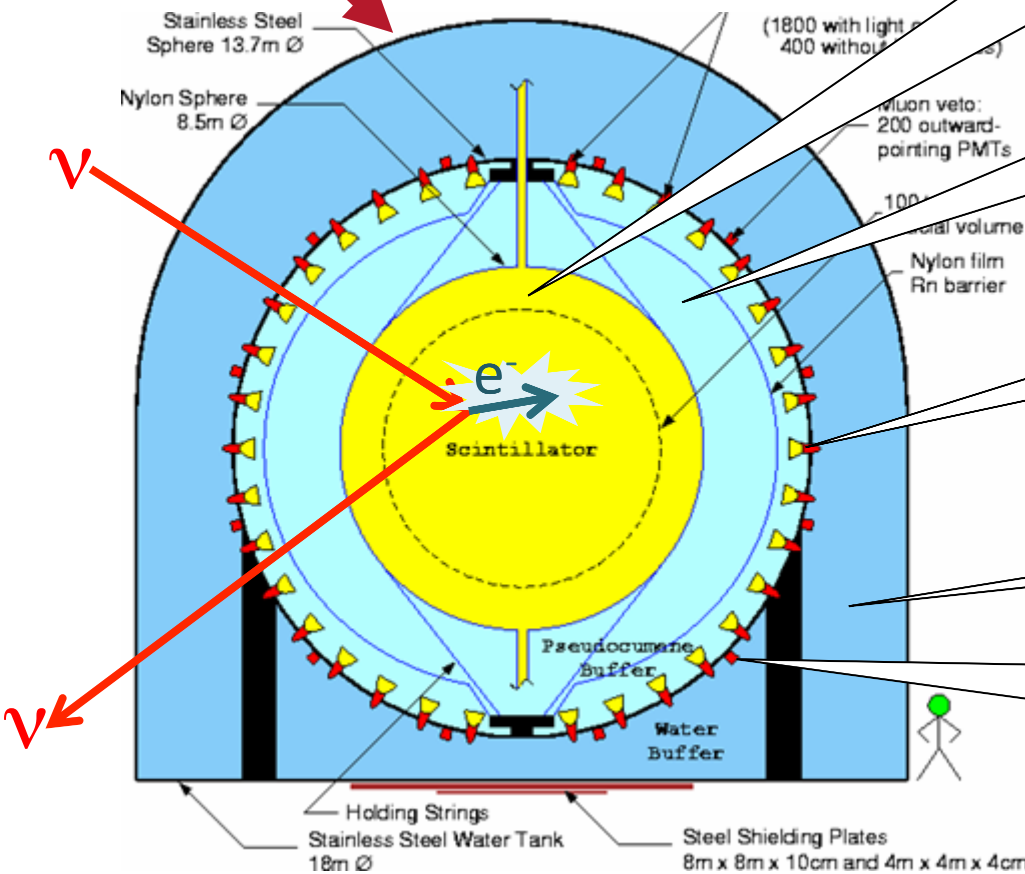
Due to the pile-up events and the finite energy resolution the energy threshold of the detector is (was?) set at **250 keV**.





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.

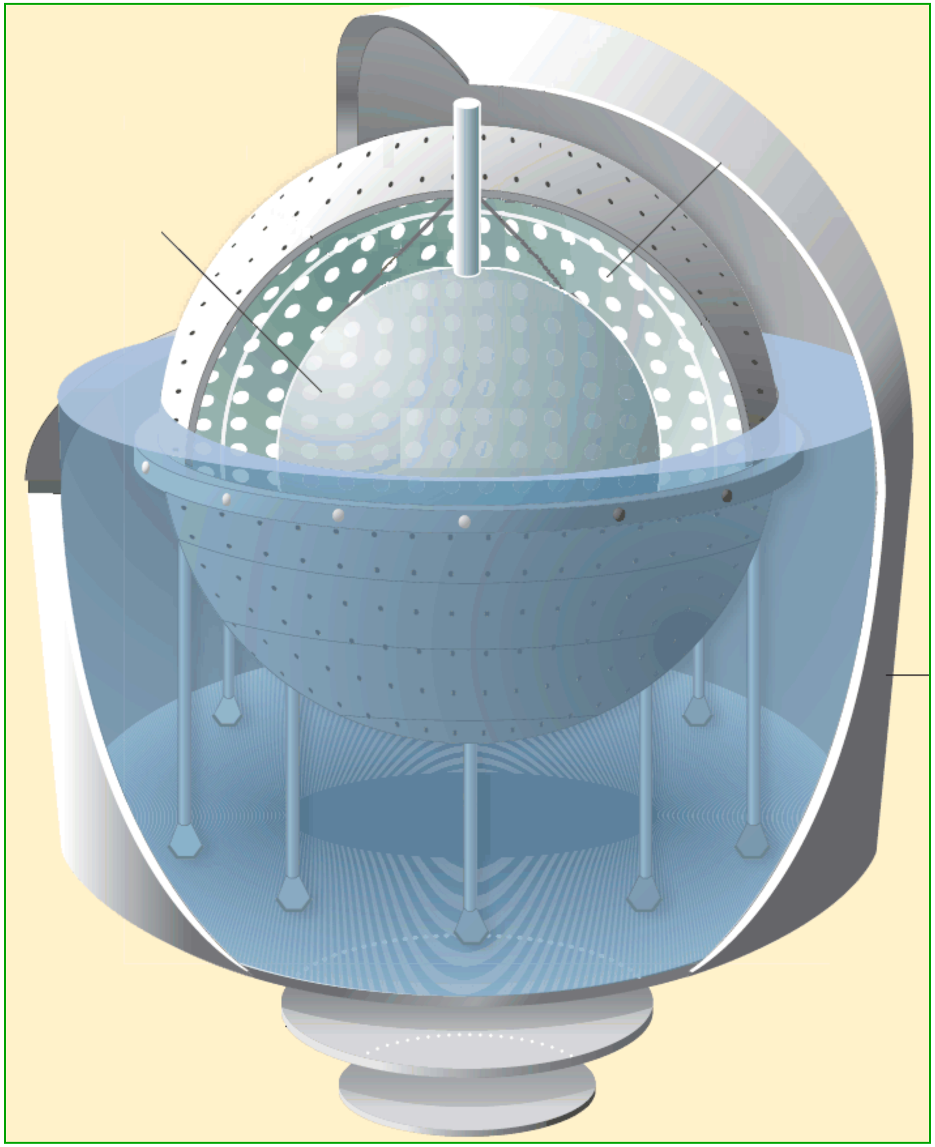
1st shield: 1000 tons of ultra-pure buffer liquid (PC+DMP) contained in a stainless steel sphere of 13.7 m diameter (SSS).

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.

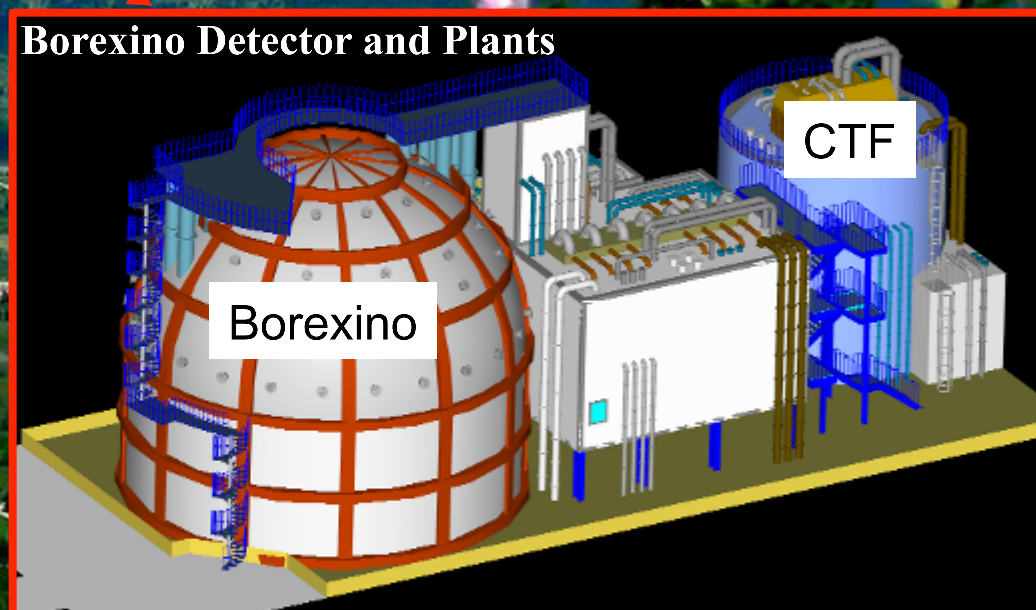
200 photomultiplier tubes mounted on the SSS pointing outwards to detect Cerenkov light emitted in the water by muons.

3D view of Borexino Detector

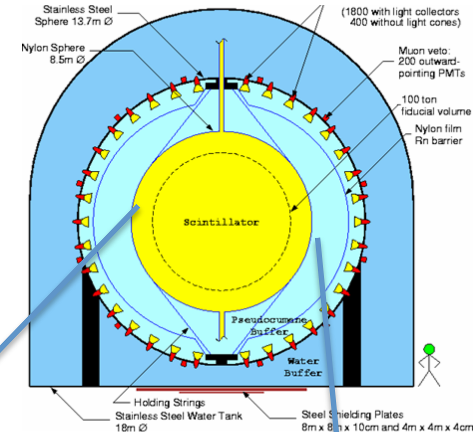


"Onion-like" structure

Laboratori Nazionali del Gran Sasso (LNGS)



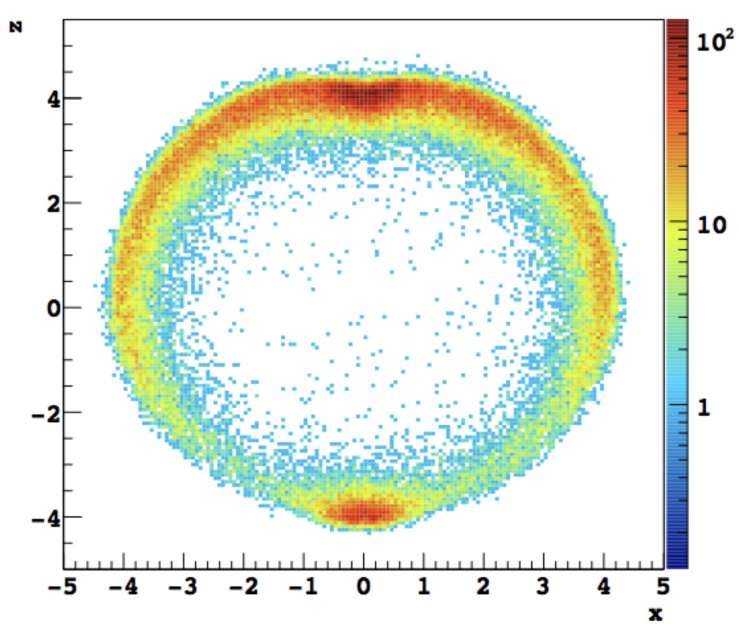
Fiducial Volume

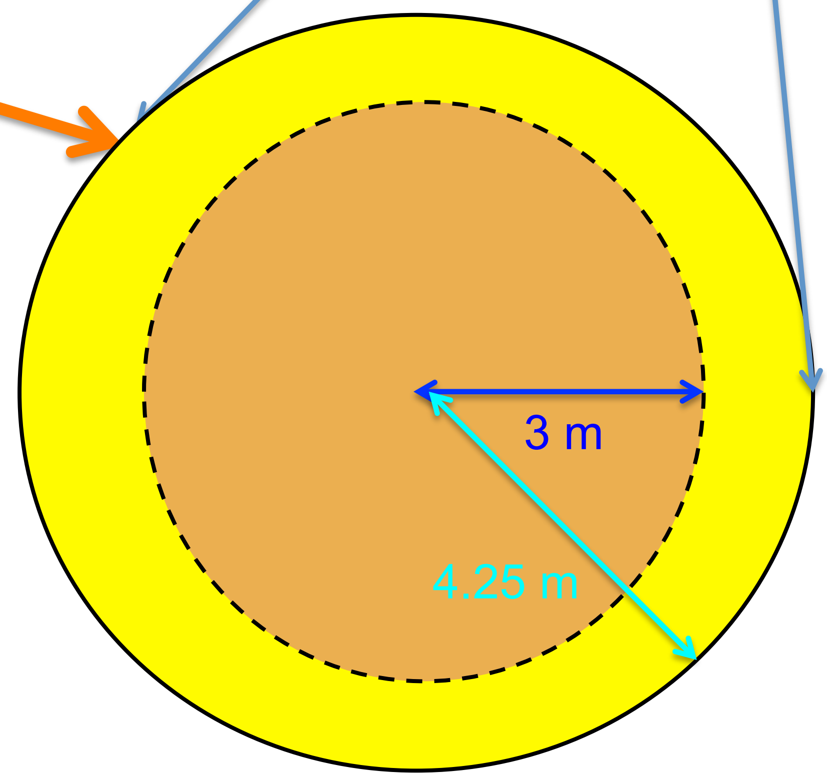


Thanks to the <u>4π PMT's distribution</u> it is possible to reconstruct the position were the event took place.

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

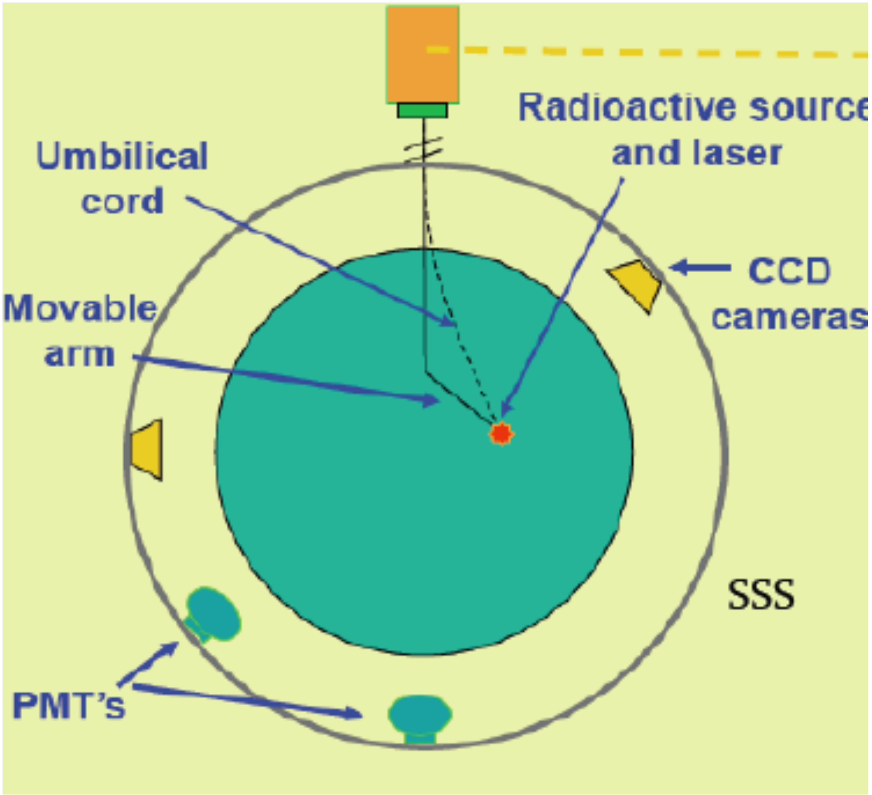
Definition of a **Fiducial Volume** of about 100 Tons





Space calibration

JINST 7(2012)P10018



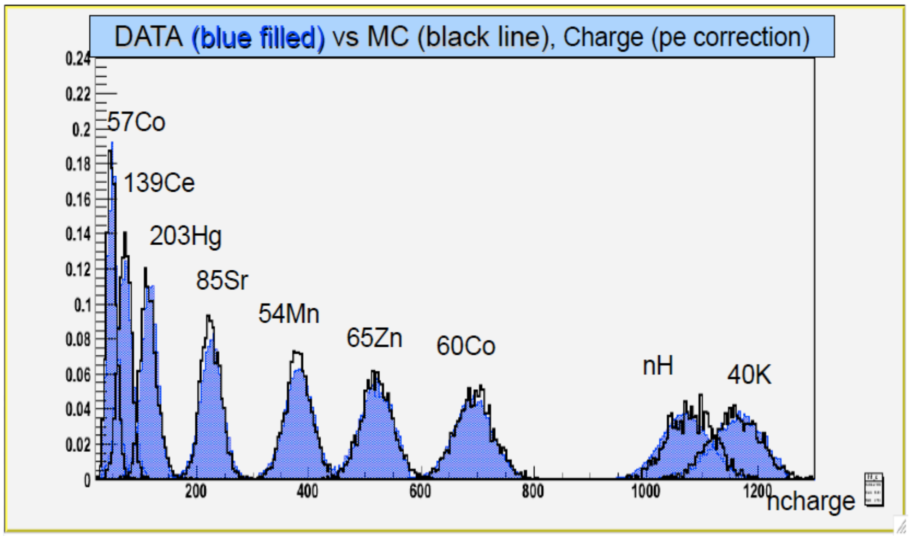
Spatial resolution 14 cm @ 1 MeV.

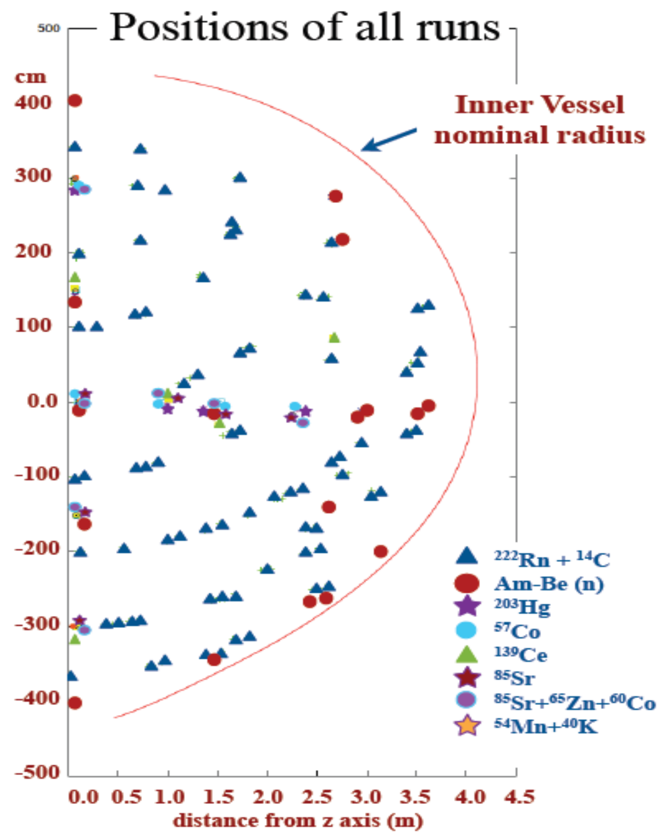
- Movable arm to place a source off-axis
- 7 CCD cameras indpendently determin the position of the source
- Using 184 points of Rn calibration data, the fiducial volume uncertainty was determined to be **-1.3% +0.5%**

Energy Calibration

JINST 7(2012)P10018

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

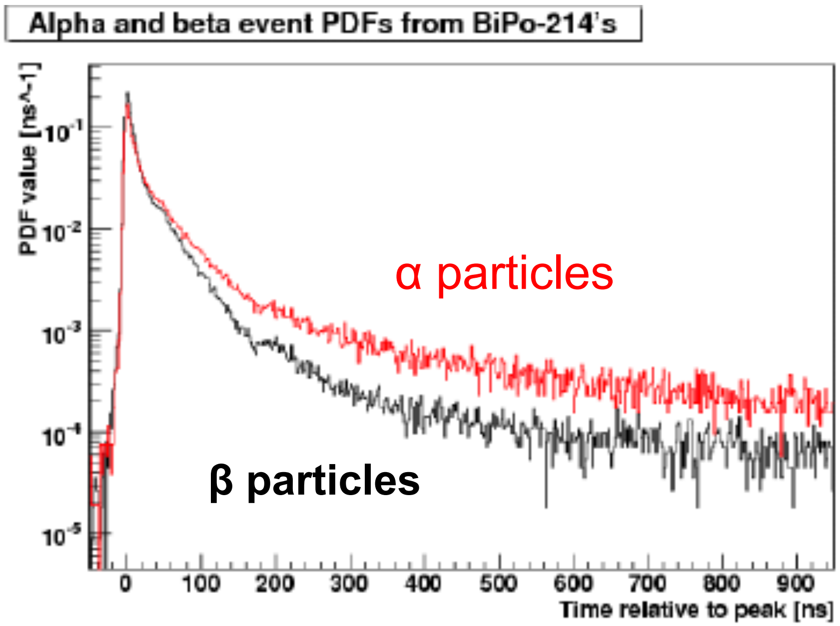




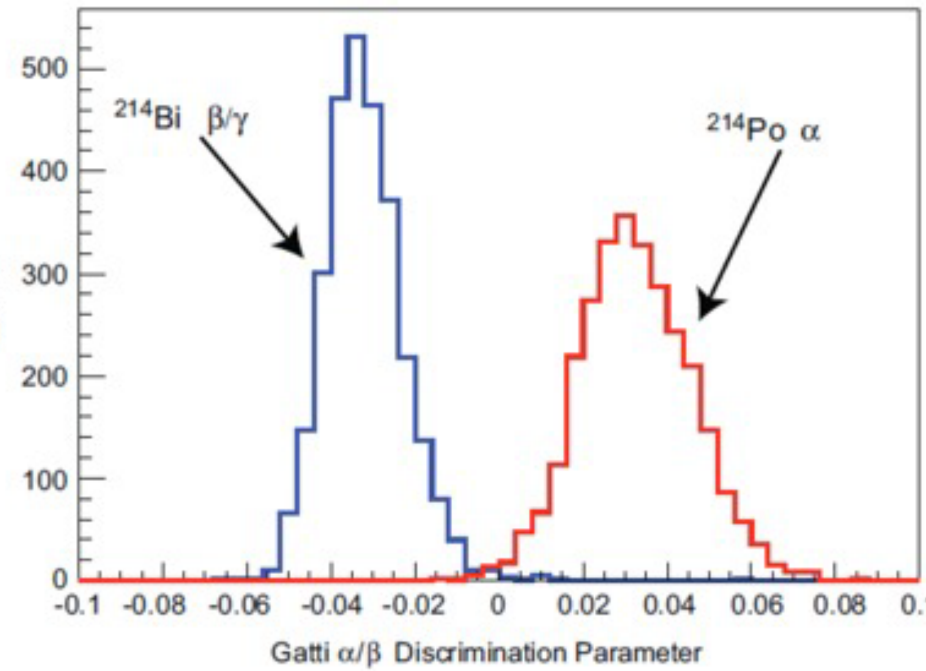
Energy resolution 6% @ 1 MeV (14% FWHM)

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.

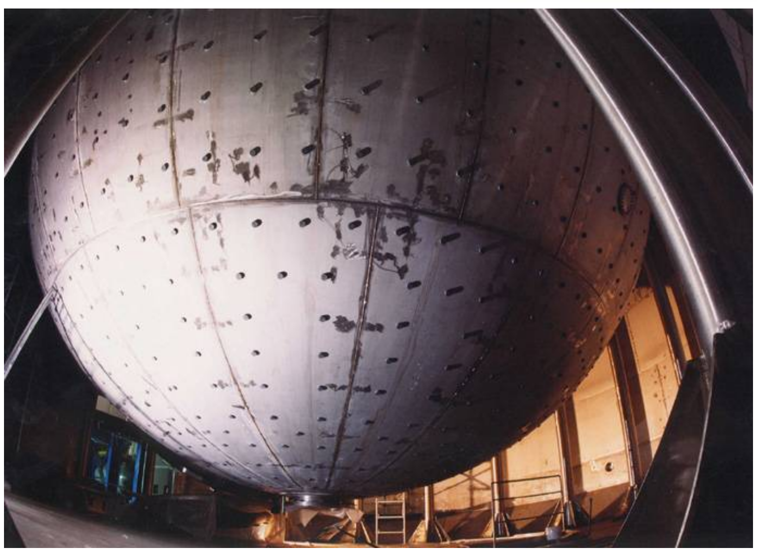


Time decay distribution of the scintillation light excited by α or β-γ radiation

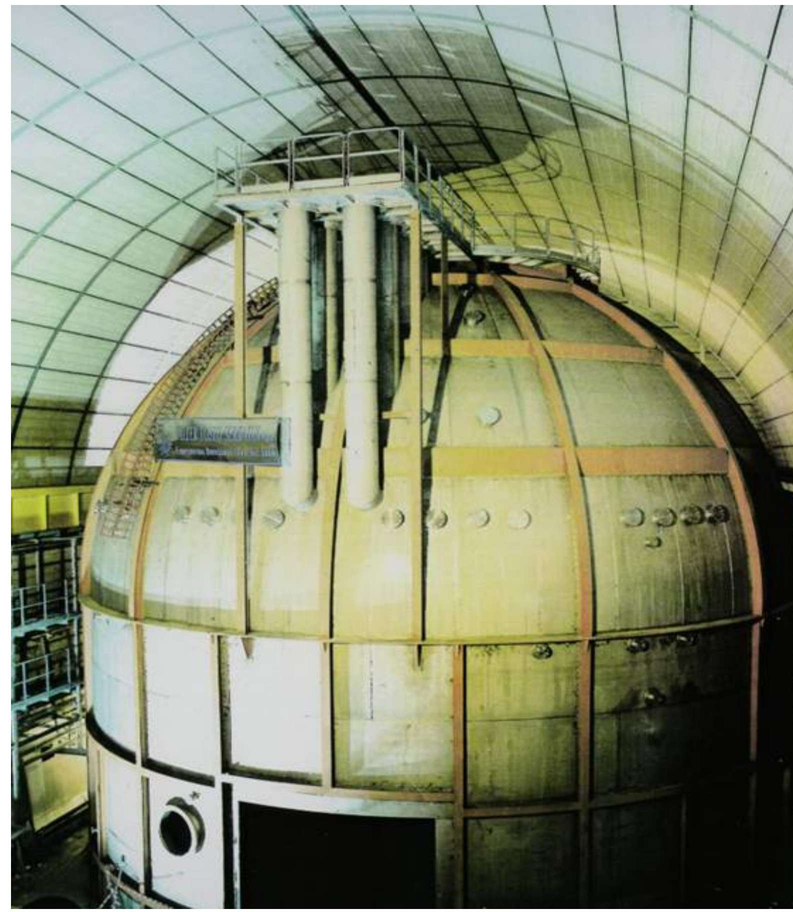


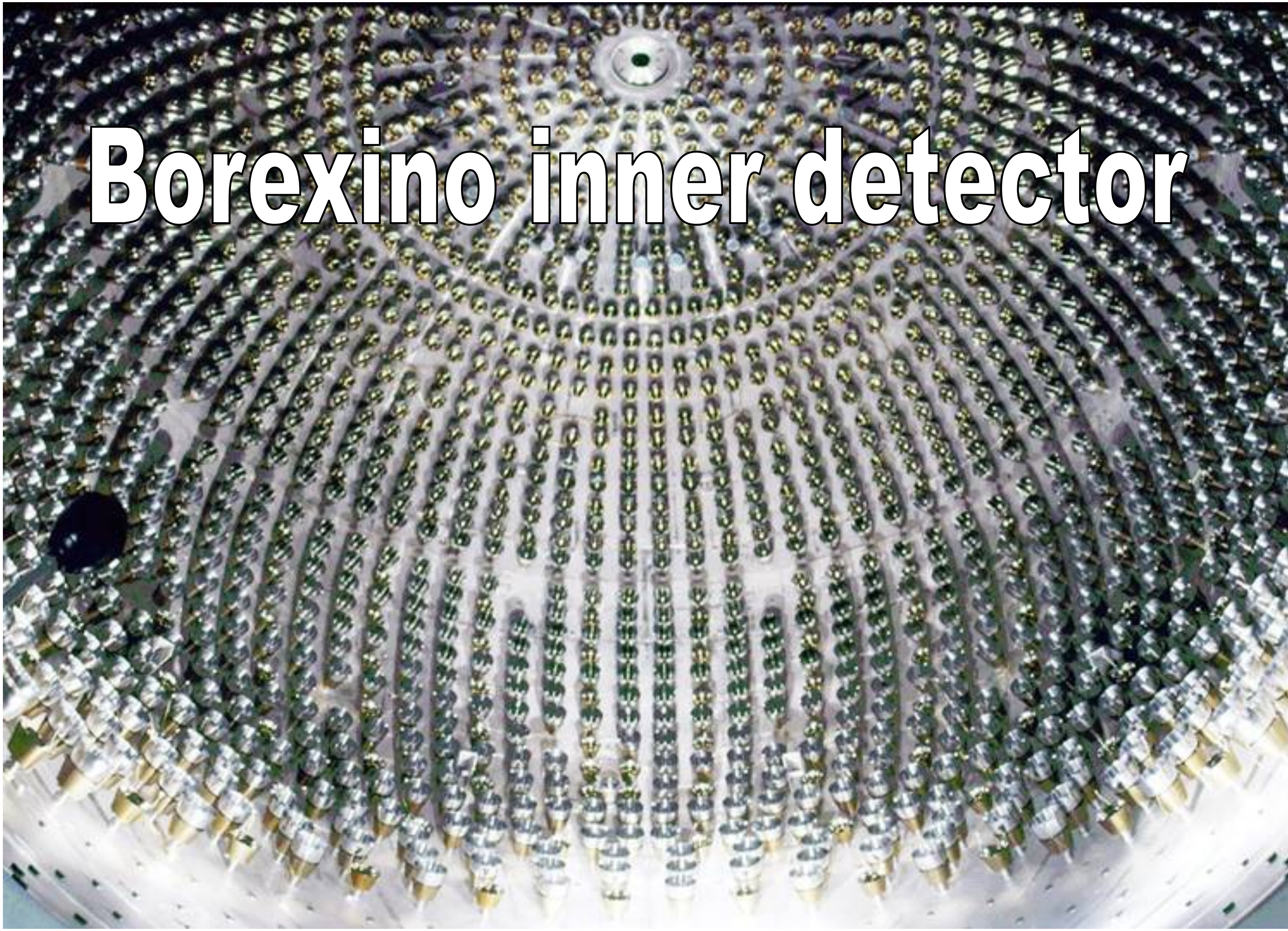
α / β separation (^{214}Bi - ^{214}Po)

Just some pictures…

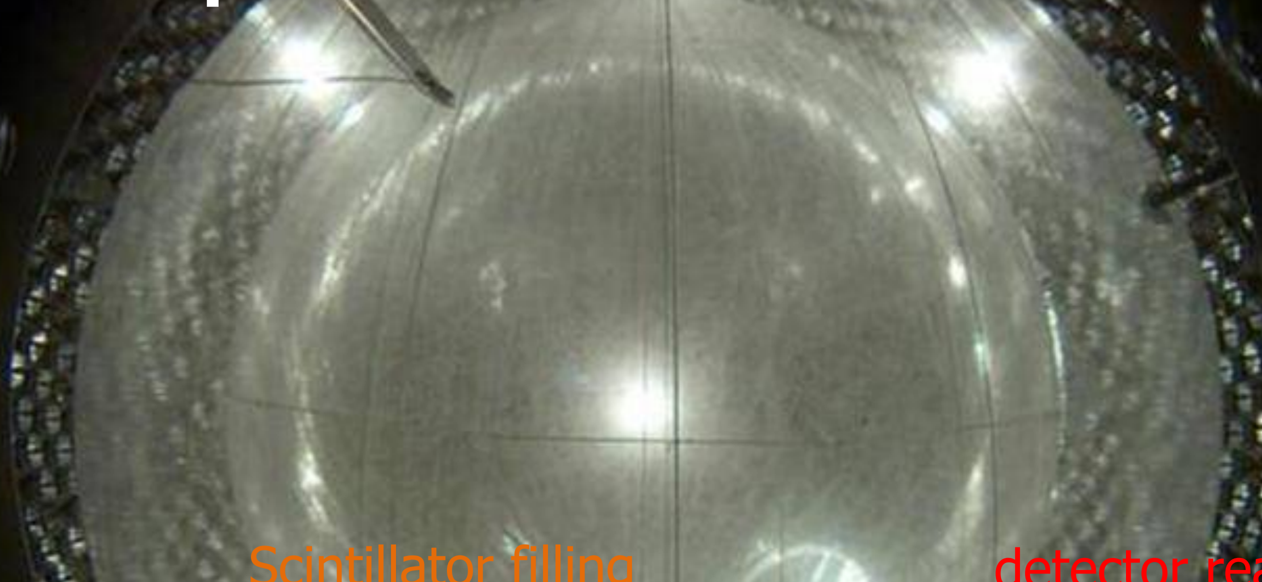


18 m

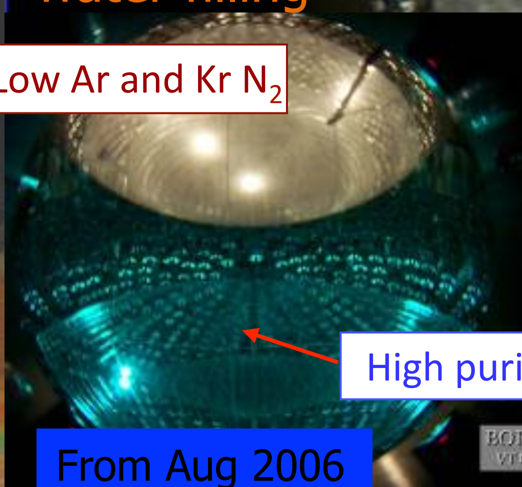



Borexino inner detector

Nylon vessels inflated, filled with water and replaced with scintillator



water filling

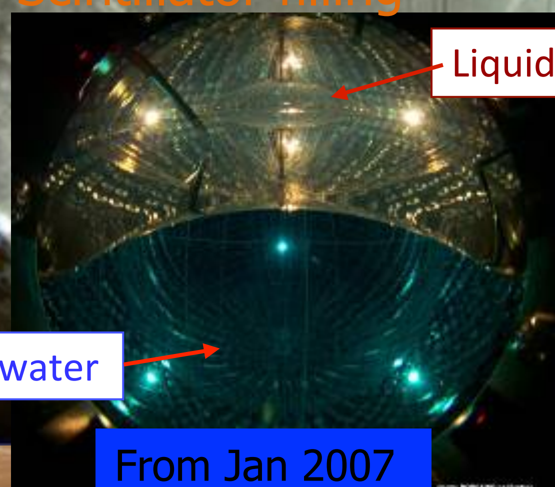


Low Ar and Kr N_2

High purity water

From Aug 2006

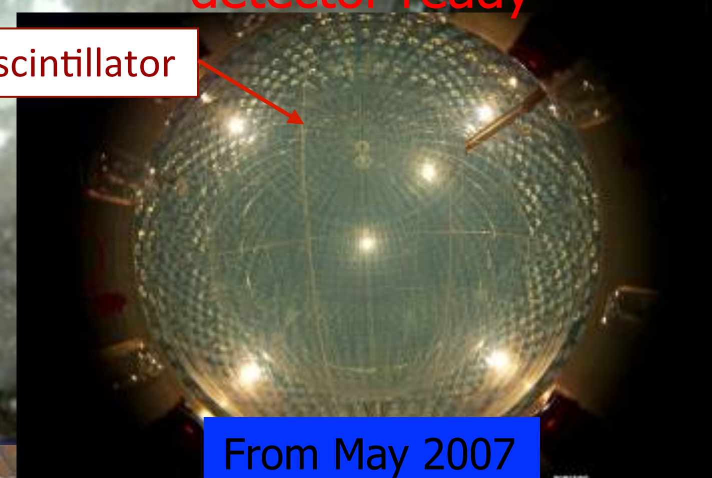
Scintillator filling



Liquid scintillator

From Jan 2007

detector ready

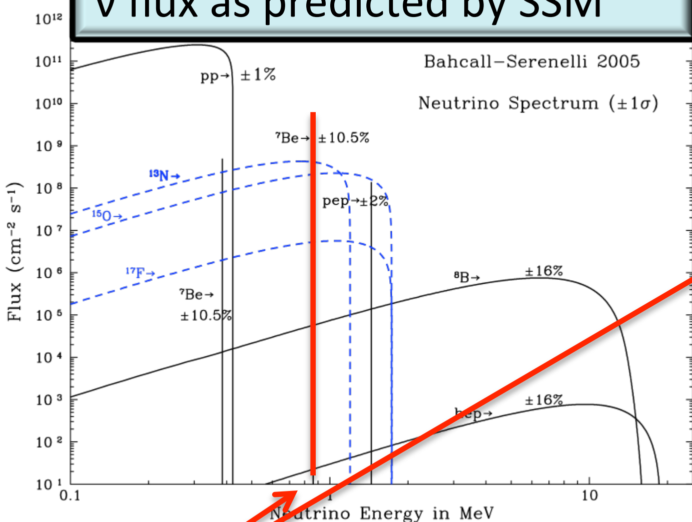


From May 2007

From raw data to neutrino signal

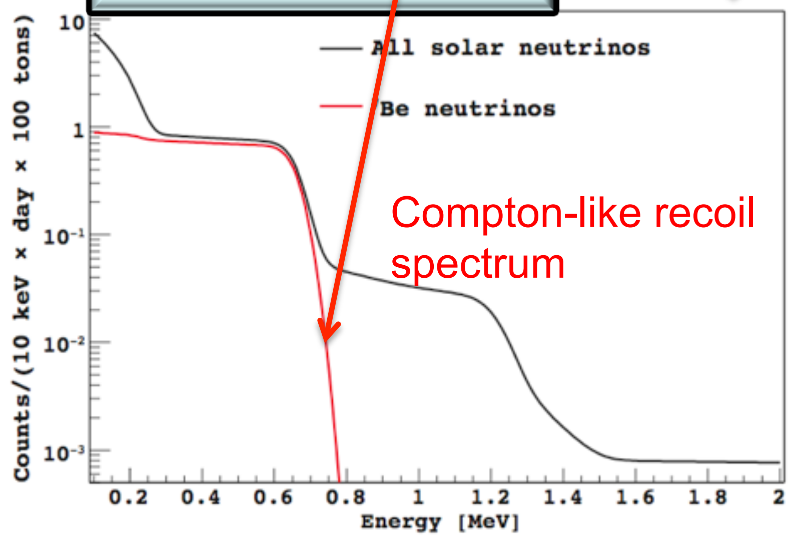
Example of ^{7}Be neutrino line

ν flux as predicted by SSM



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

ν signal in Borexino

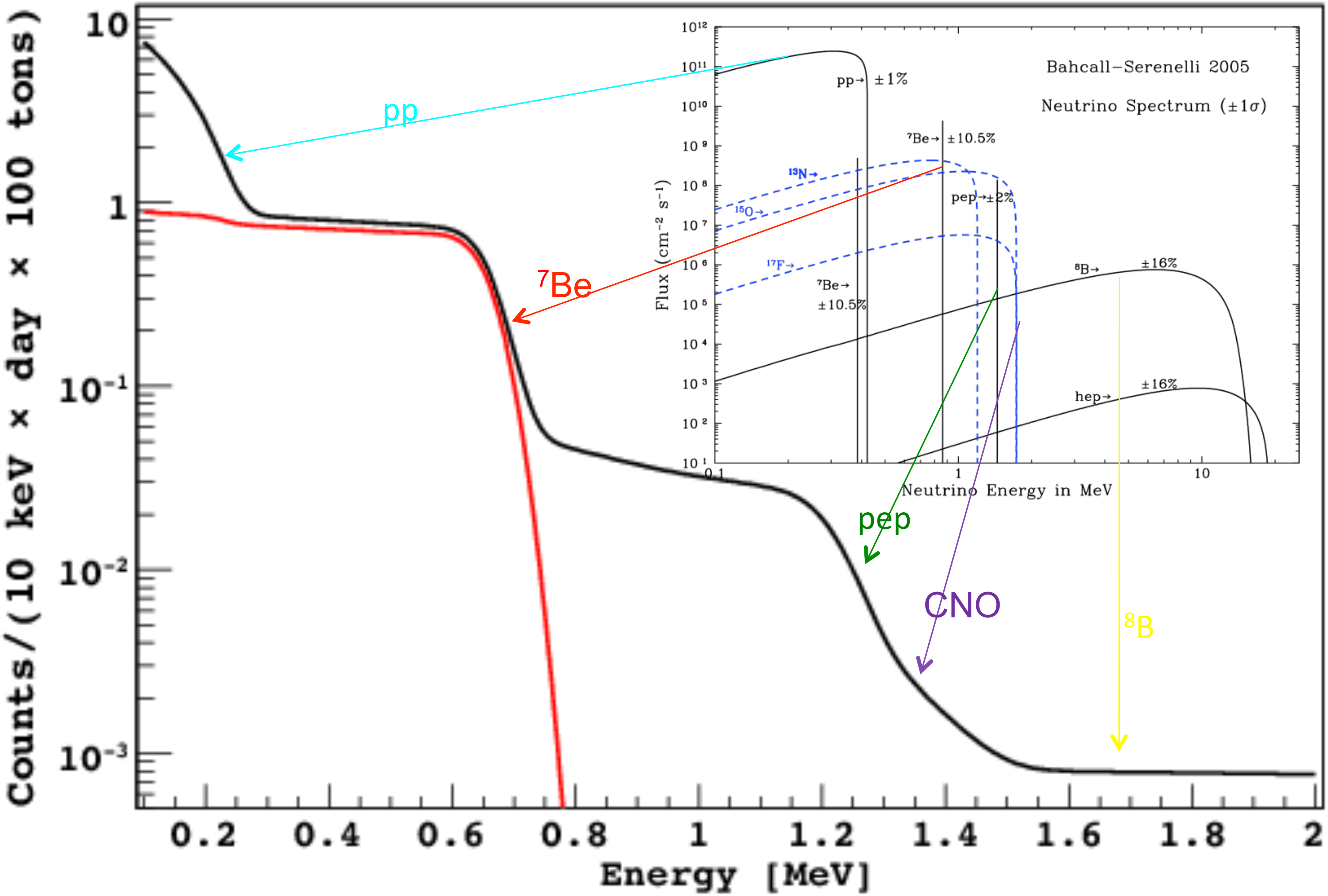


^{7}Be monochromatic line at 0.862 MeV

Compton-like recoil spectrum

Maximum ES of e^- 0.662 MeV

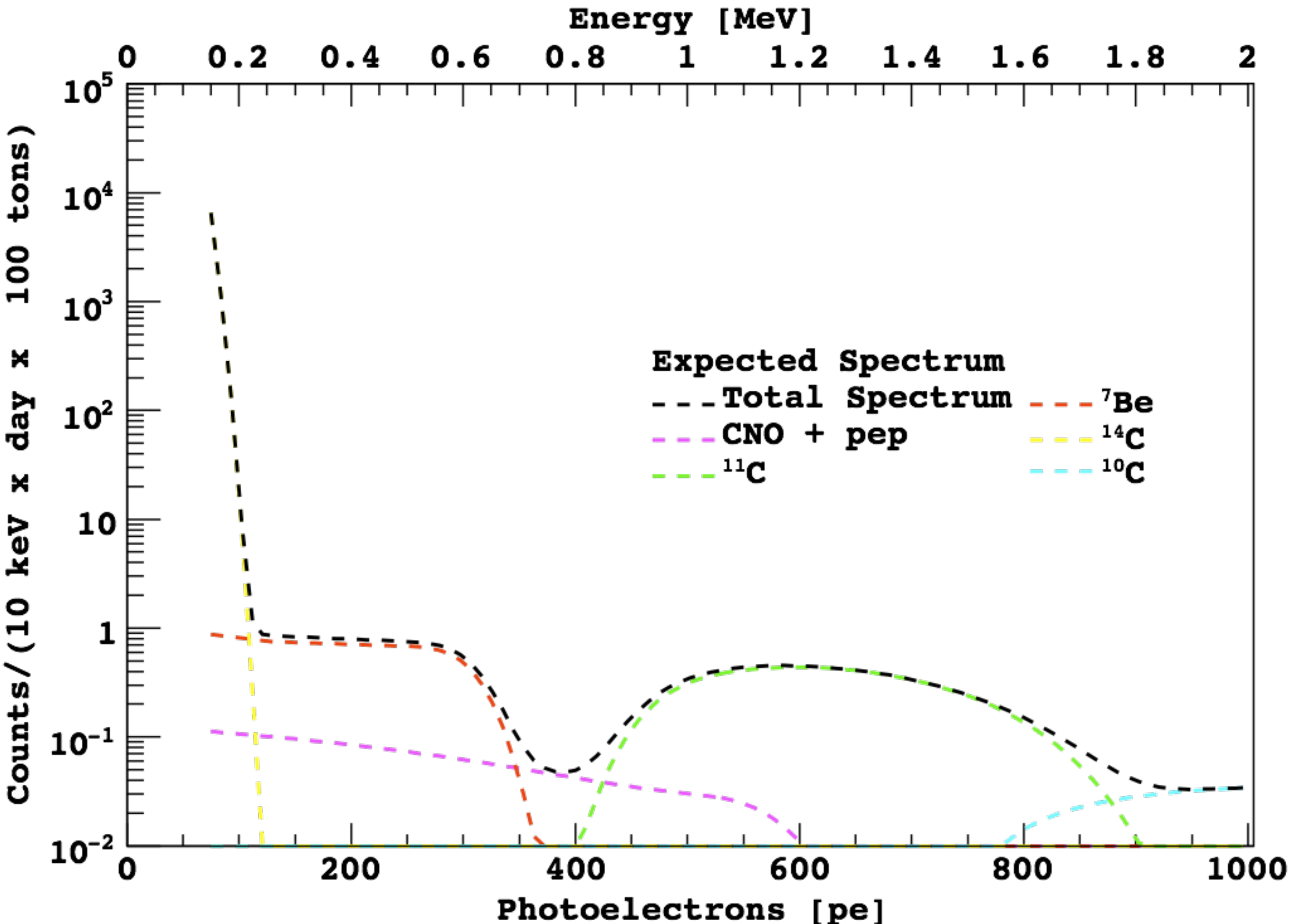
Warning: we have to take into account the energy resolution of the detector



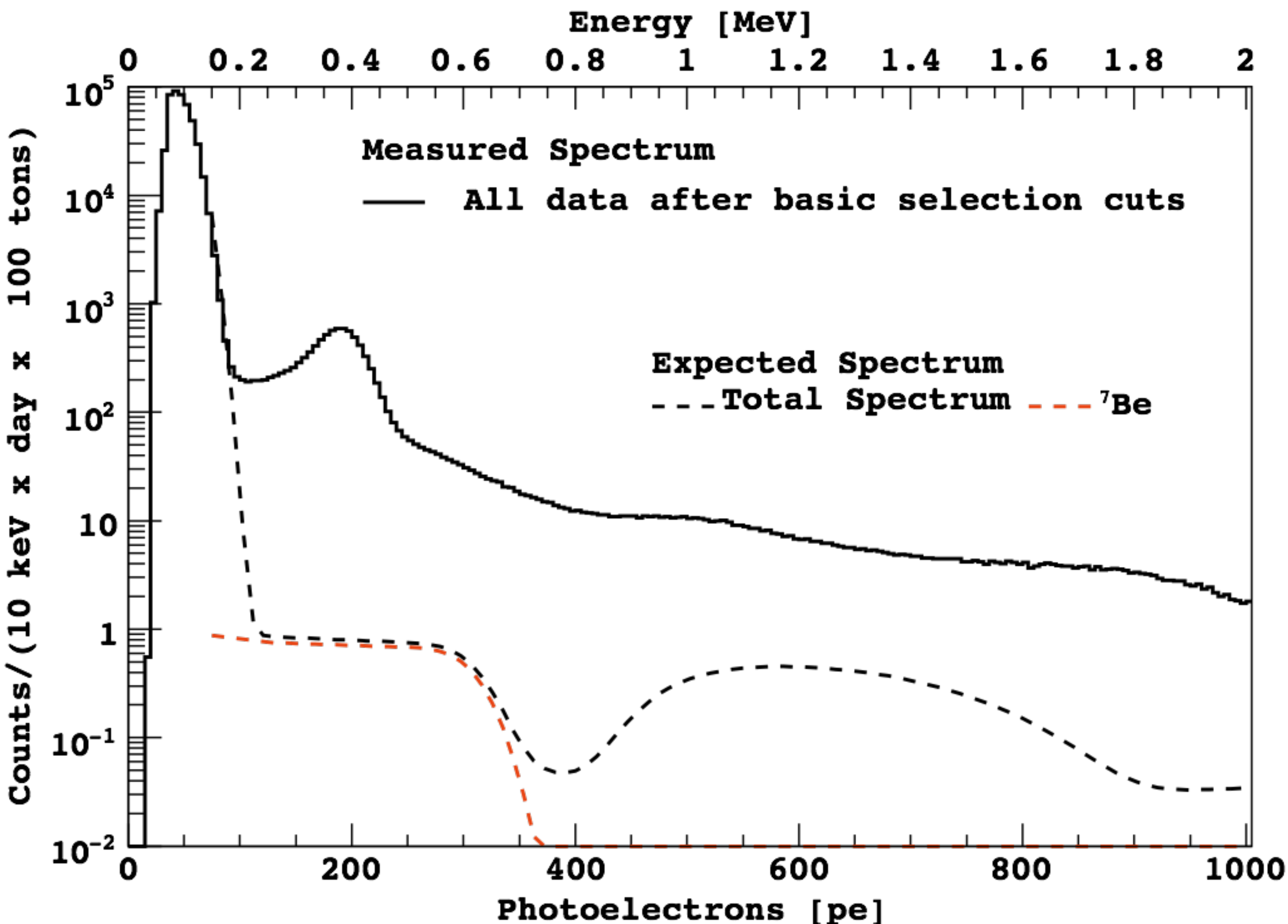
Counts/(10 keV × day × 100 tons)
10
1
10^{-1}
10^{-2}
10^{-3}
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Energy [MeV]
pp
^{7}Be
pep
CNO
^{8}B
Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
Flux (cm^{-2} s^{-1})
Neutrino Energy in MeV
pp→ ±1%
^{7}Be→ ±10.5%
^{13}N→
^{15}O→
^{17}F→
pep→±2%
^{7}Be→ ±10.5%
^{8}B→ ±16%
hep→ ±16%

How to extract the neutrino signal from the background

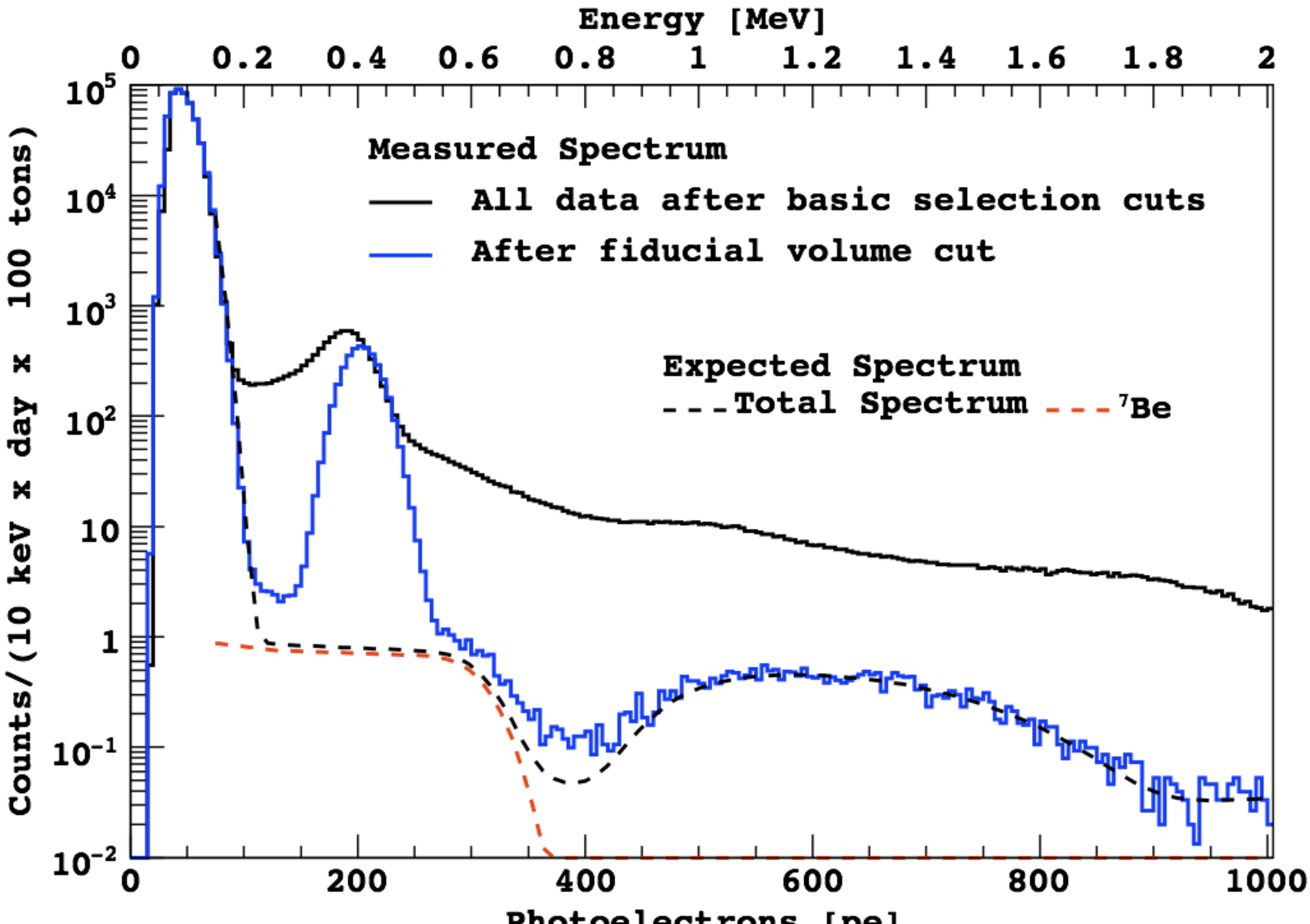
Expected Spectrum



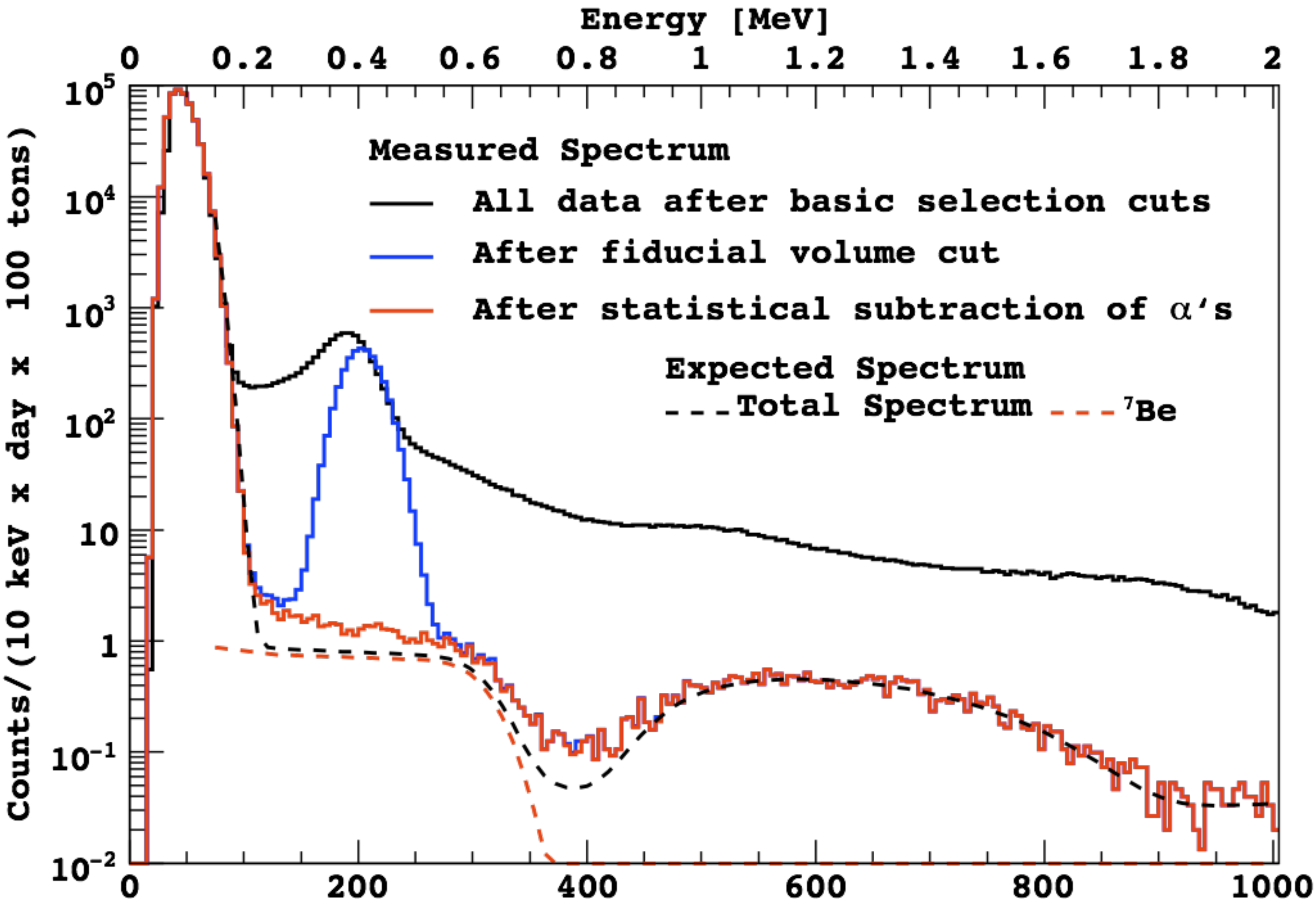
Data: Raw Spectrum (Before any Cuts)



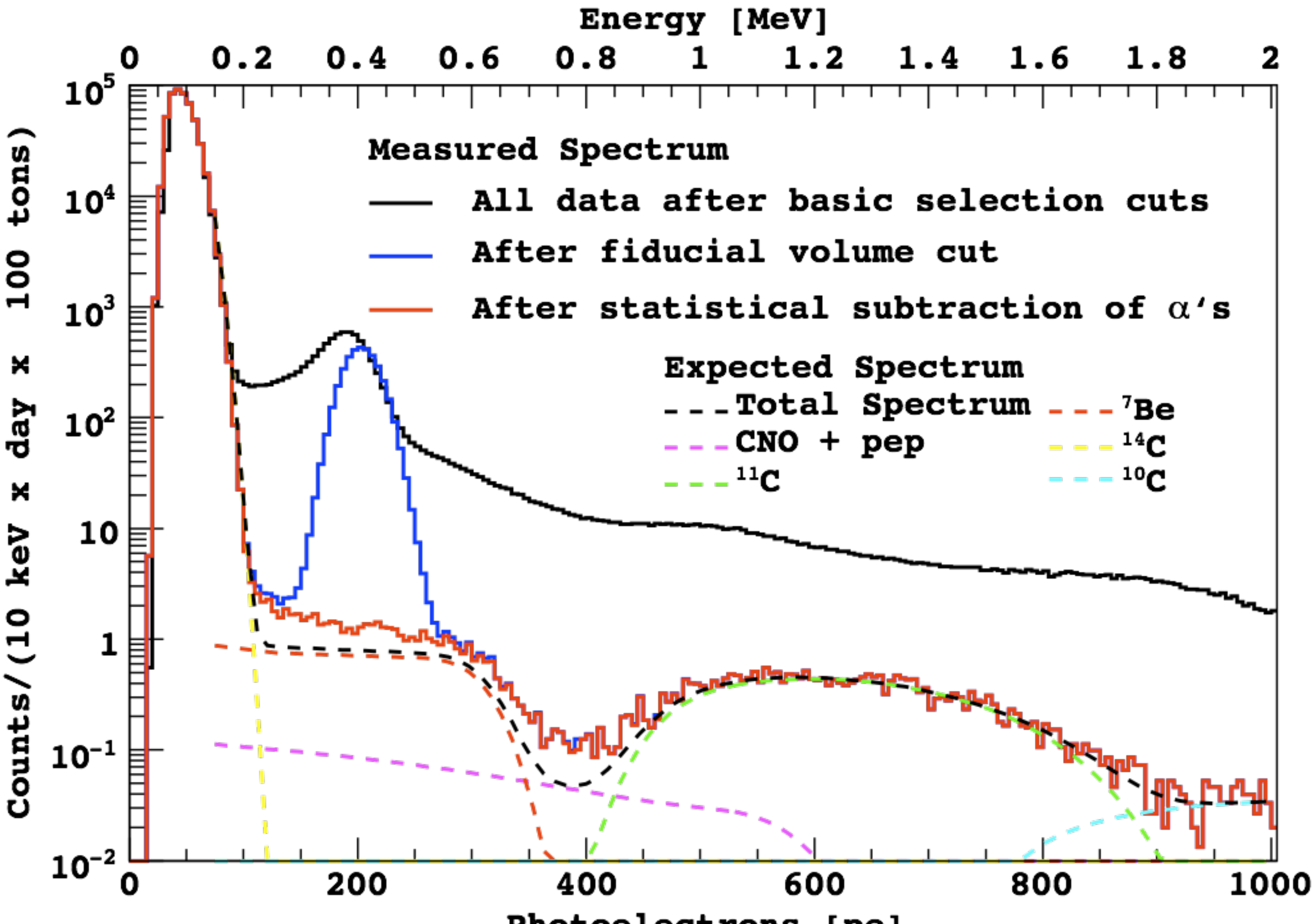
Data: Fiducial Volume Cut (100 tons)



Data: α/β Stat. Subtraction

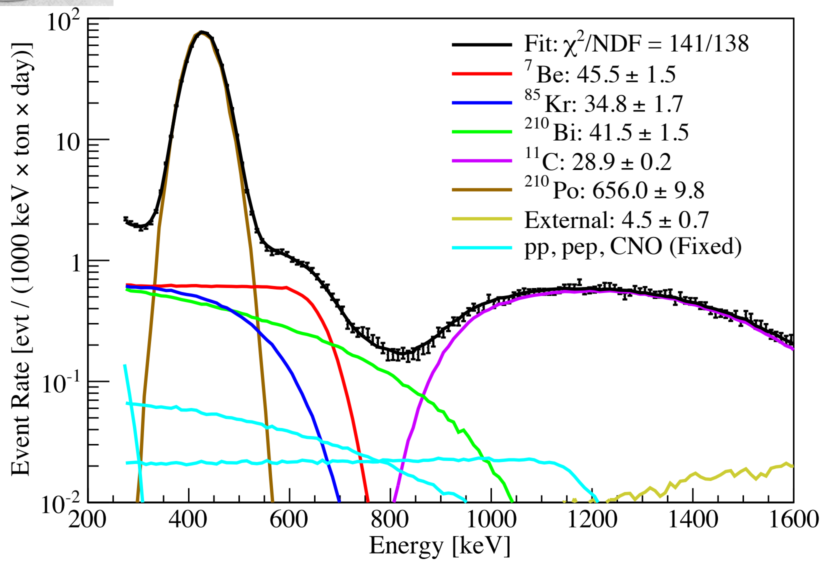


Data: Final Comparison



2 fit approaches

Phys. Rev. Lett. 107, 141302 (2011)



MonteCarlo fit

range: 250-1600 keV

Soft α subtraction

External gammas included

pp, pep, CNO, ^{8}B:

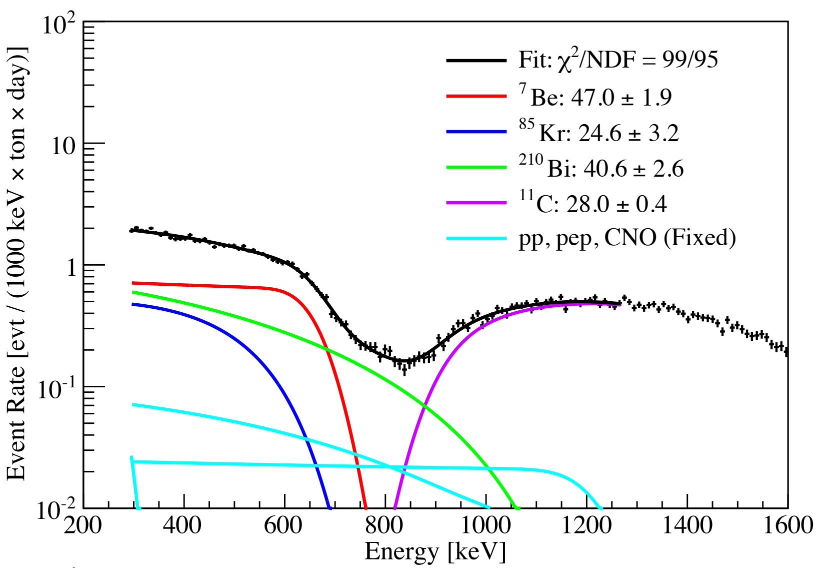
fixed to SP11(high-Z) with LMA

^{7}Be, ^{85}Kr(β^-), ^{210}Bi(β^-), ^{11}C(β^+), ^{210}Po(α)

free

^{214}Pb, ^{222}Rn, ^{218}Po (not shown)

fixed to ^{214}BiPo



Analytical fit

range: 300-1250 keV

statistical α subtraction

energy scale and resolution floated

^{7}Be results

2008 (192d):

Source	Uncertainty, %
Total scintillator mass	0.2
Fiducial volume	6.0
Live Time	0.1
Detector resp. func.	6.0
Cuts efficiency	0.3
Total Syst. error	**8.5**

$$49 \pm 3(stat) \pm 4(syst) / d / 100t$$

10% error

PRL **101**, 091302 (2008)

2011 (741d):

Source	Uncertainty, %
Scintillator density	0.05
Fiducial volume	+0.5 -1.3
Live Time	0.04
Detector resp. func.	2.7
Cuts efficiency	0.1
Fit methods	2.0
Trigger eff. & stability	<0.1
Total Syst. error	**+3.4 −3.6**

$$46.0 \pm 1.5(stat)^{+1.5}_{-1.6}(syst) / d / 100t$$

4.8% error

PRL **107**, 141302 (2011)

SSM comparison

	Flux (^{7}Be) 10^9 cm^{-2} s^{-1}
Borexino	3.10±0.15
BX-*unoscillated*	4.84±0.24
SSM-High Z	5.00±0.35
SSM-Low Z	4.56±0.32

for the first time the experimental error (4.8%) is smaller then theoretical error (7%)

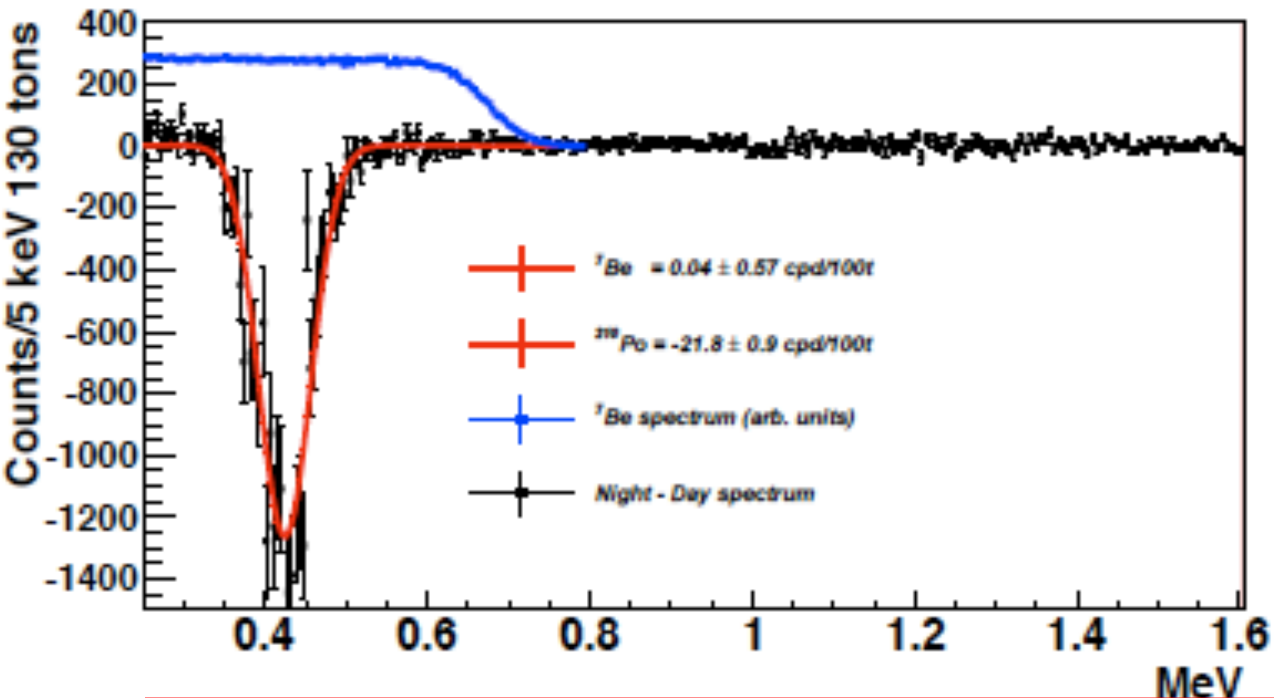
$$\frac{\Phi_{meas}}{\Phi_{\exp}} = 0.62 \pm 0.05 \xrightarrow{MSW-LMA} P_{ee} = 0.51 \pm 0.07$$

$$f(^7Be) = 0.97 \pm 0.09$$

Assumptions:
SSM: Serenelli et al., 2011 [arXiv:1104.1639]
Metallicity: GS98 (High-Z)
LMA: Particle Data Group 2010.

Phys. Lett. B 707, 1 (2012) 22-26

^{7}Be day-night asymmetry?

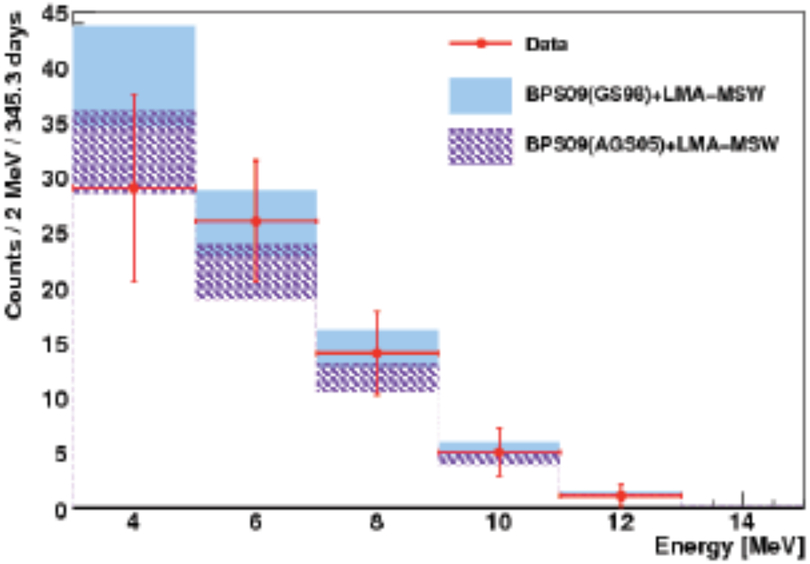


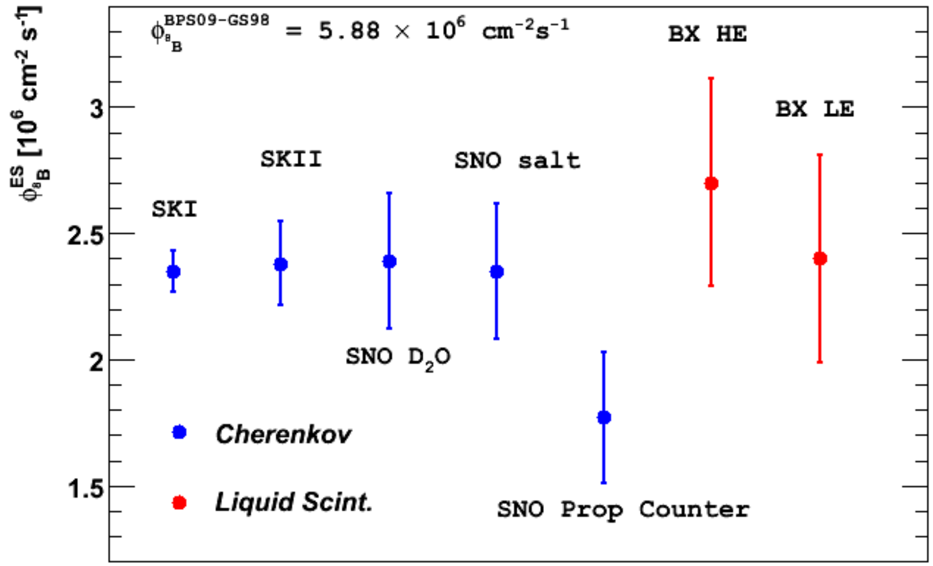
$$\boxed{A_{DN} = \frac{N - D}{(N + D)/2} = 0.001 \pm 0.012\,(stat) \pm 0.007(sys)}$$

Then solar neutrino results with Borexino can isolate the LMA region without the Kamland antineutrino data

PRD 82 (2010) 033006

^{8}B flux at 3MeV



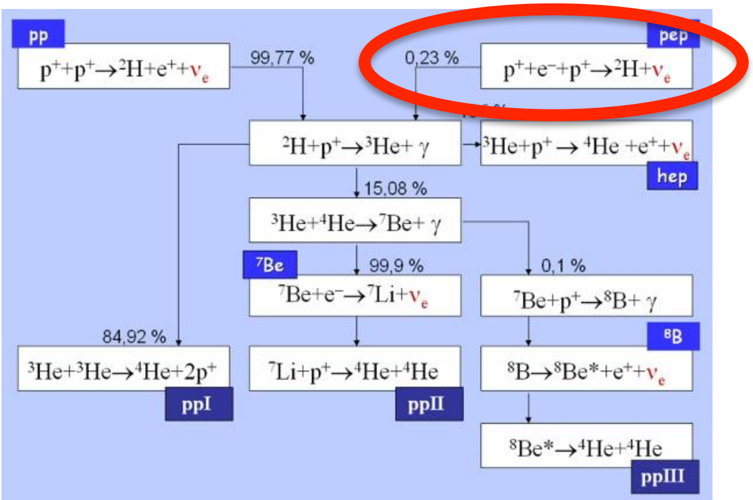


	3.0–16.3 MeV	5.0–16.3 MeV
Rate [c/d/100 t]	0.22±0.04±0.01	0.13±0.02±0.01
Φ^{ES}_{exp} [10^6 cm^{-2}s^{-1}]	2.4±0.4±0.1	2.7±0.4±0.2
$\Phi^{ES}_{exp}/\Phi^{ES}_{th}$	0.88±0.19	1.08±0.23

Phys. Rev. Lett. 108, 051302 (2012)

Measuring pep neutrinos

pp (and **pep**!) neutrinos are **<u>less model-depended</u>** 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}Be-neutrinos, pep-neutrinos events are 1 order of magnitude smaller.

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

Phys. Rev. Lett. 108, 051302 (2012)

The ^{11}C background

Moreover there is the problem related to the **cosmogenic ^{11}C** that cover the pep-neutrinos signal: S/N ~ 0.1

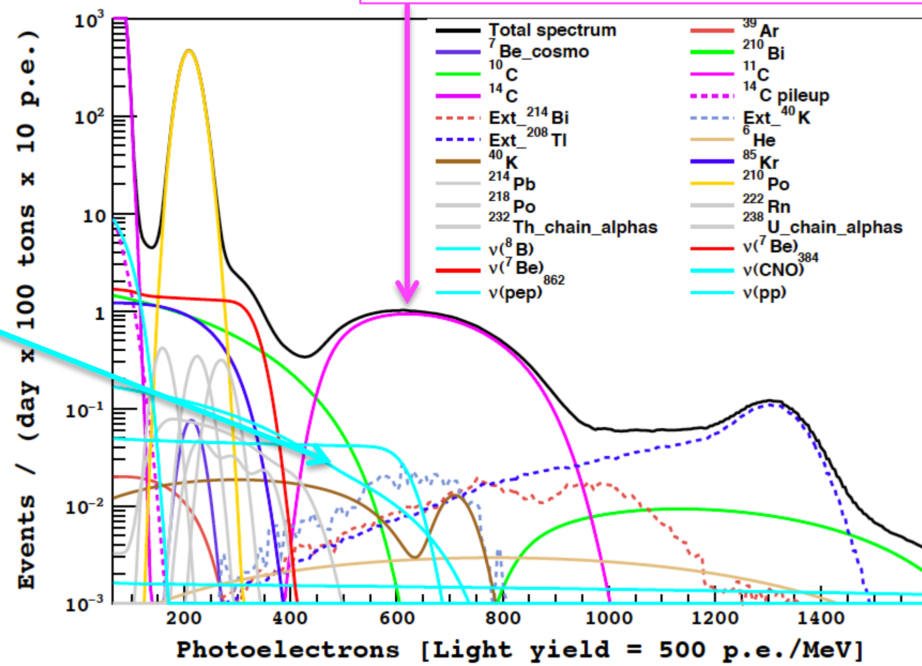
$$\mu + {}^{12}C \longrightarrow \mu + n + {}^{11}C$$

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

^{11}C Cosmogenic
~28 ev/d

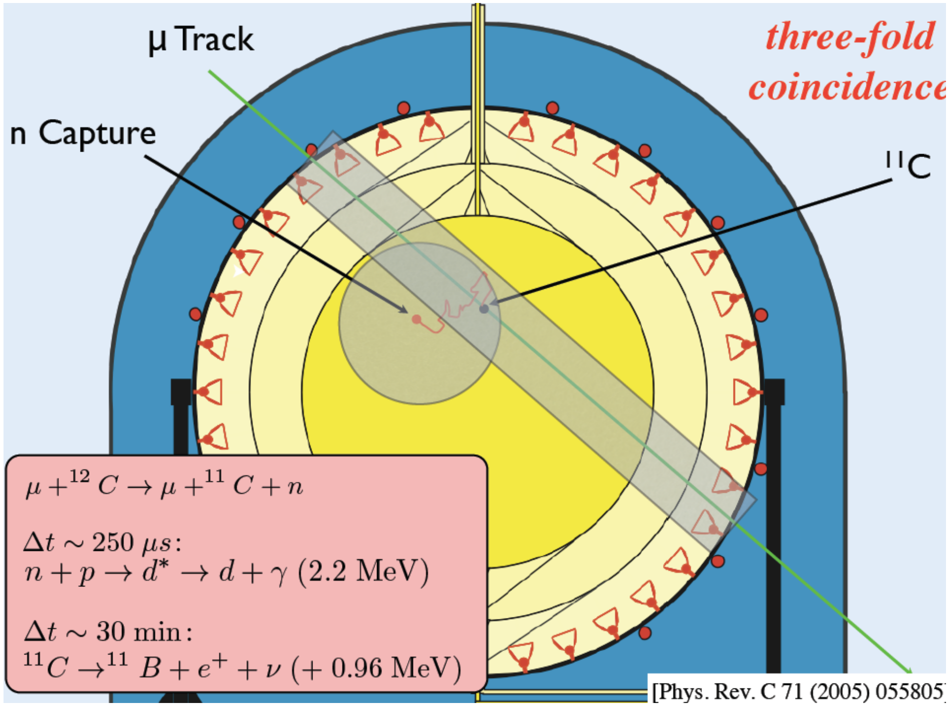
^{11}C decay e^+ with τ = 29.4 min and Q=0.96MeV but we must add 1.022MeV for annihilation.

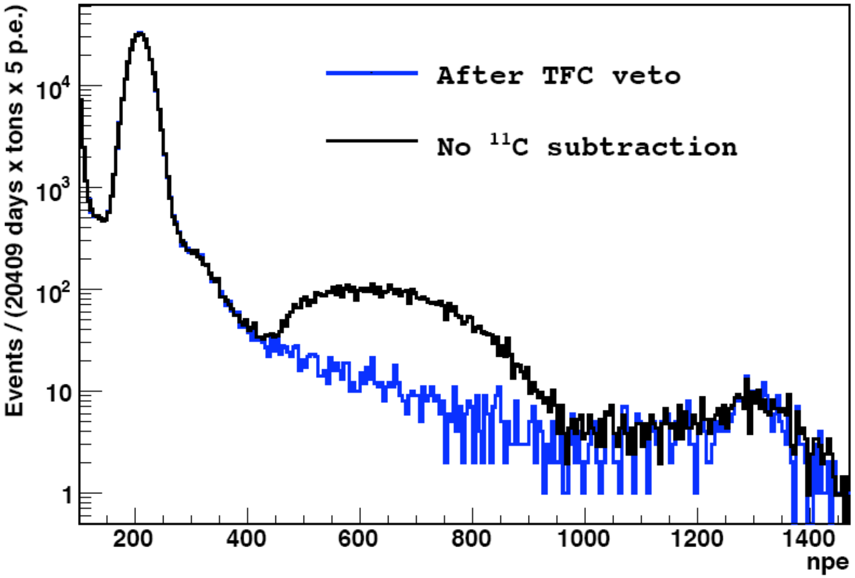
pep-ν
~3 ev/d



Phys. Rev. Lett. 108, 051302 (2012)

Three-Fold Coincidence

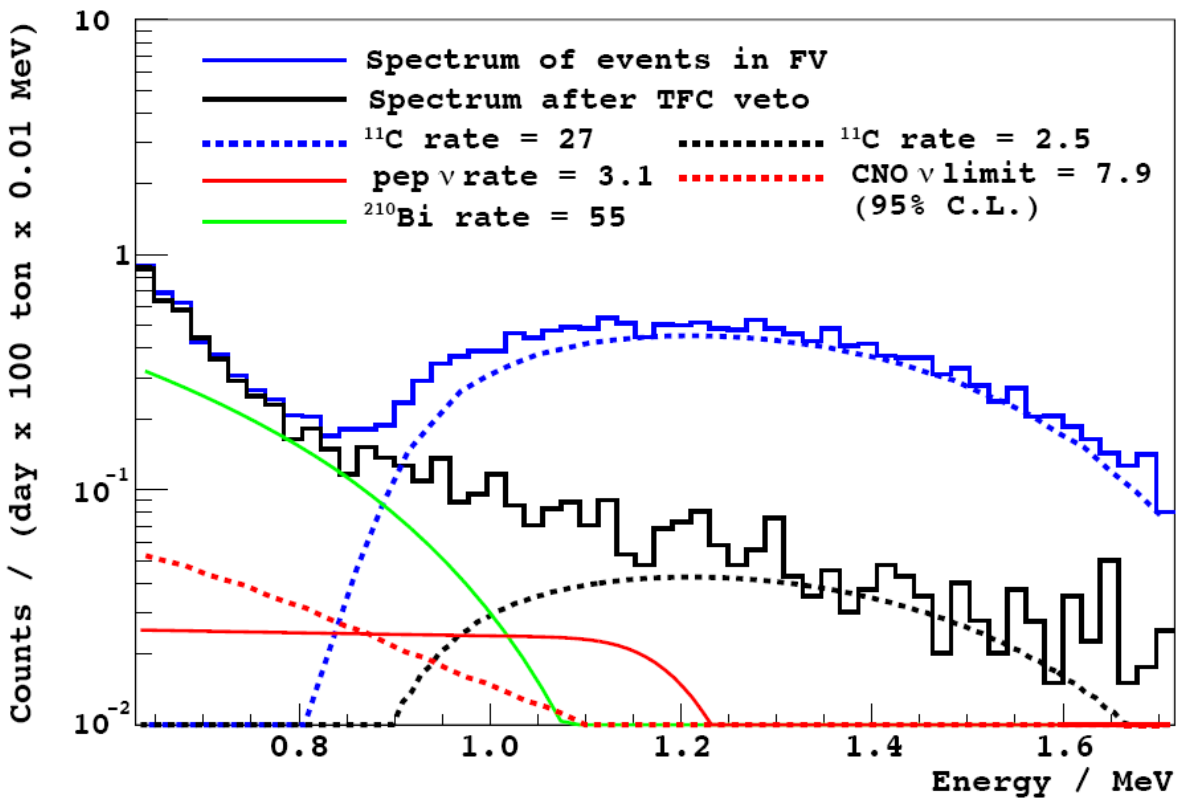




Three Fold Coincidence (TFC) technique:
apply a combination of vetos related in space and time to possible 11C-producing μ-n pair.
It removes 90% of ^{11}C (with 50% loss of exposure)

Phys. Rev. Lett. 108, 051302 (2012)

pep flux



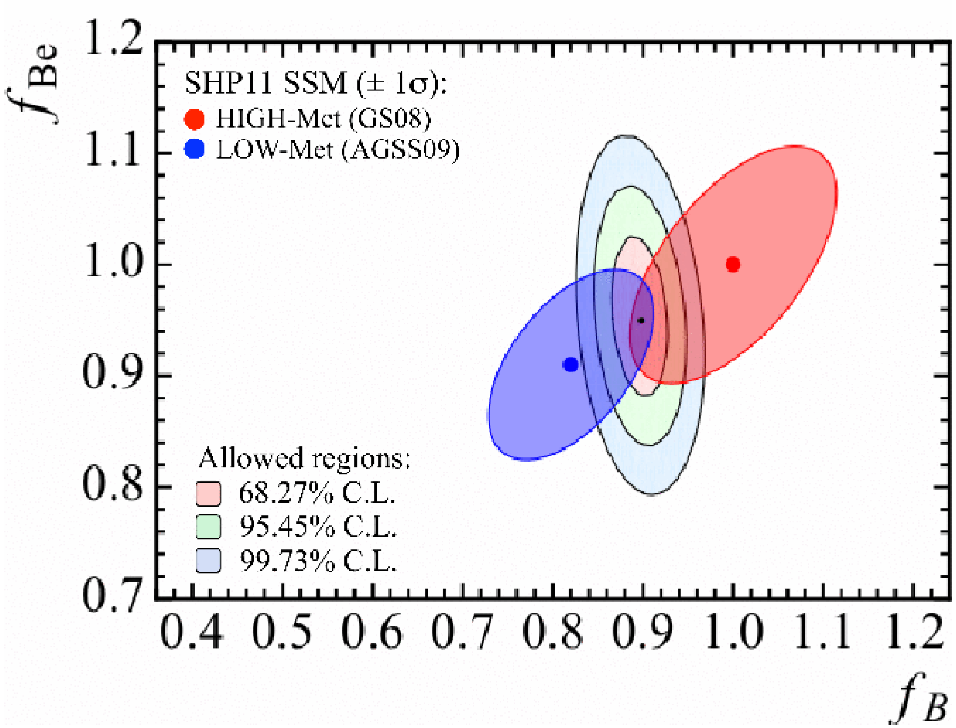
$$R = (3.1 \pm 0.6_{stat} \pm 0.3_{sys})\ \text{cpd/100 t}$$

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

$P_{ee} = 0.62 \pm 0.17$ at 1.44 MeV

Comparison with SSM: the metallicity puzzle

ν	**Diff. %**
pp	0.8
pep	2.1
^{7}Be	8.8
^{8}B	17.7
^{13}N	26.7
^{15}O	30.0
^{17}F	38.4



SHP11:
A.M. Serenelli, W. C.Haxton and C. Pena-Garay, Astro-phys. J. 743 (2011) 24

GS98:
N. Grevesse and A. J. Sauval, Space Sciences Reviews 85, 161 (1998)

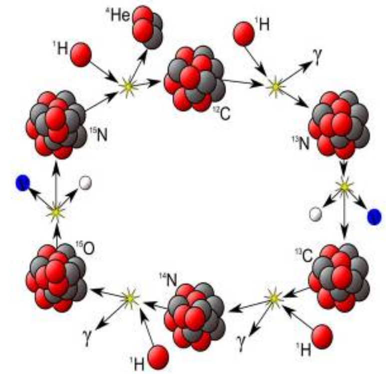
AGSS09:
Aldo M. Serenelli *et al 2009* *ApJ* ***705 L123***

^{7}Be and ^{8}B currently cannot discriminate

↓

need to go for CNO

CNO neutrinos measurement and the Solar Model Chemical Controversy



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

$$\nu_{CNO}$$

Solar Model Chemical Controversy

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

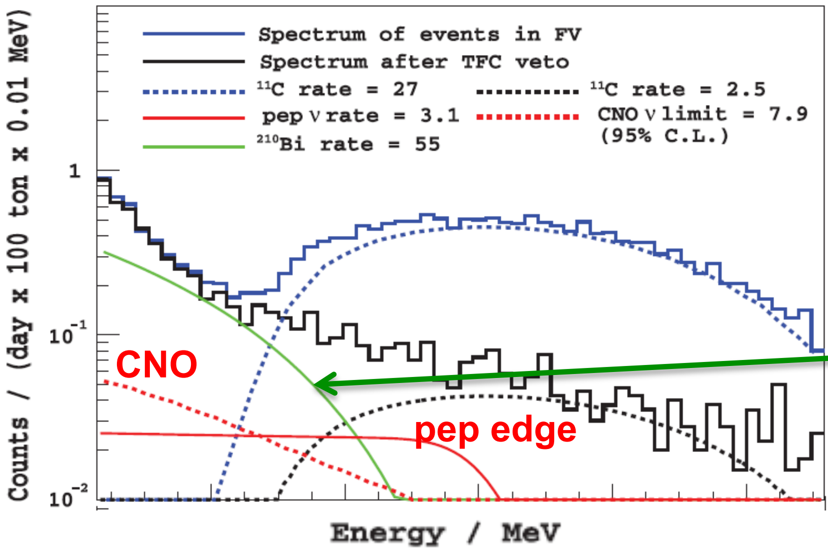
A lower metallicity implies a variation in the neutrino flux (**reduction of ~ 30% for CNO neutrino flux**)

Serenelli, Haxton, Pena-Garay arXiv 1104.1639	**CNO Flux** (10^8 cm^{-2} s^{-1})
HIGH Z SSM	5.24 ± 0.84
LOW Z SSM	3.76 ± 0.60
ΔΦ	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

Phys. Rev. Lett. 108, 051302 (2012)

pep flux and CNO limits



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)

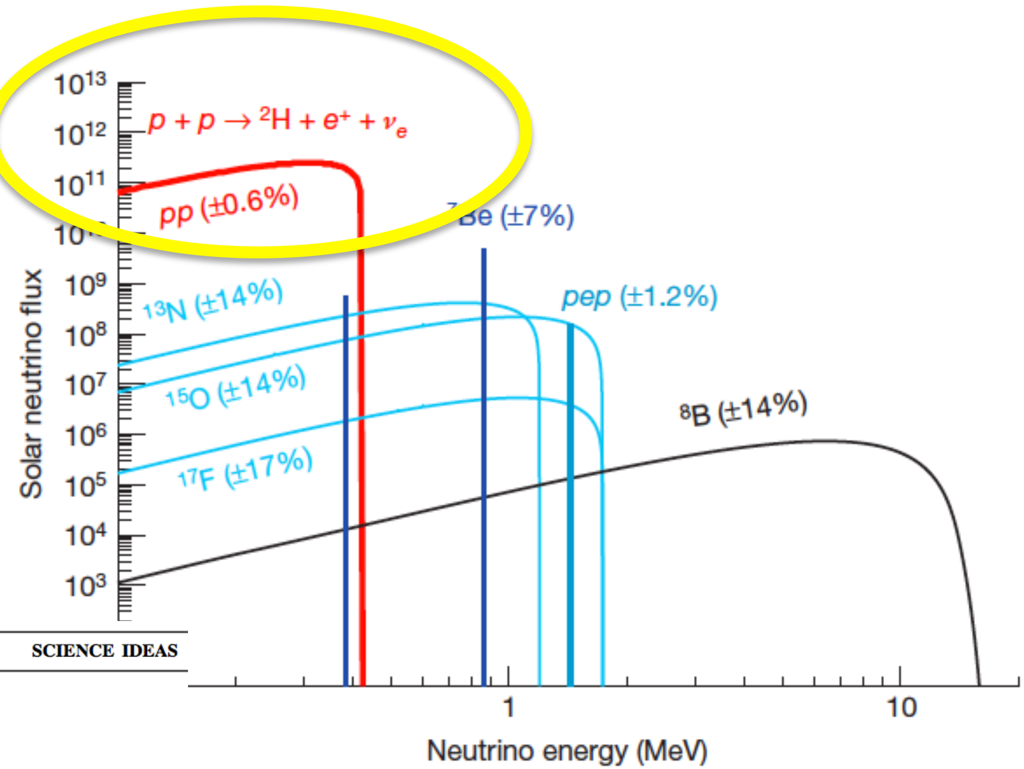
$$< 7.9 \quad cpd / 100\, tons\,(95\%\, CL)$$

Not sufficient to resolve the metallicity problem

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

The importance of PP neutrinos

Neutrino and optical observations in combination provide experimental confirmation that the Sun has been in thermodynamic equilibrium over 10,000-170,000 years timescale.



SCIENCE IDEAS

Solar Variability

Glacial Epochs, and Solar Neutrinos

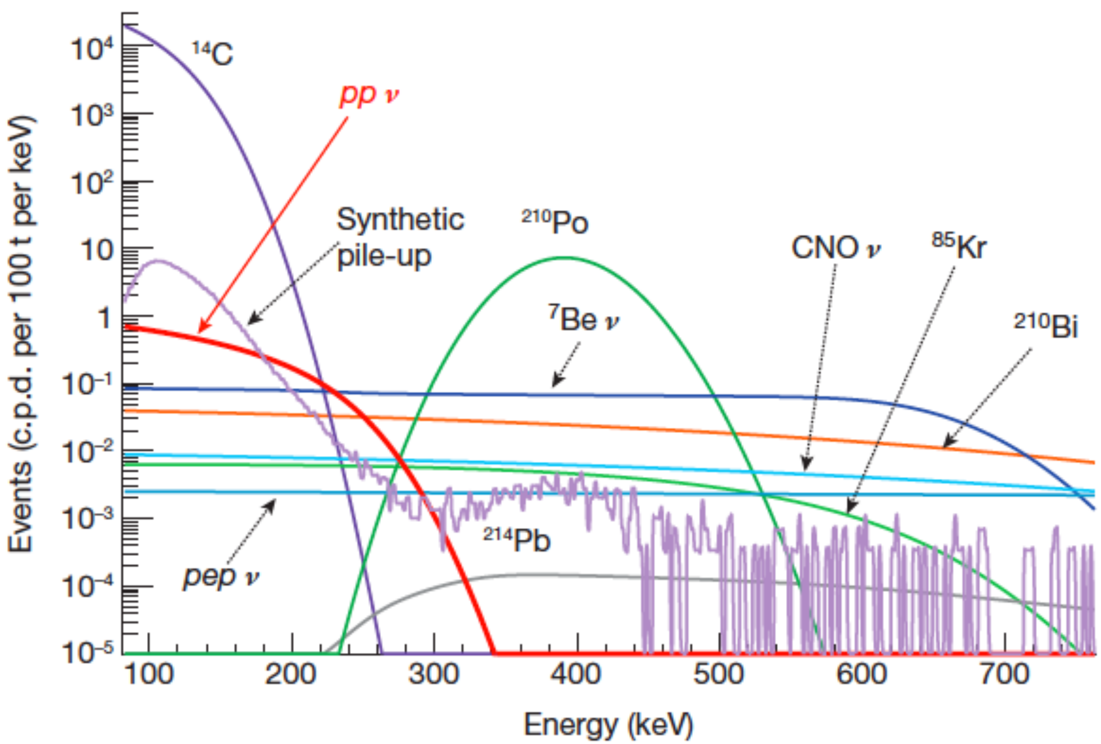
by George A. Cowan and Wick C. Haxton

PP neutrinos with Borexino

Most of the pp neutrino events are buried under the vastly more abundant ^{14}C β-emitter with a Q-value of 156 keV.

$^{14}C/^{12}C \approx 2.7\ 10^{-18}$

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



Neutrino energy: < 420keV

Electron recoil energy: < 264keV

This analysis threshold: 165keV (cmp. design thresh. 250KeV, radiochem. exp. 233keV)

January 2012 to May 2013
Borexino Phase 2
Live Time: 408 days

pp neutrino results

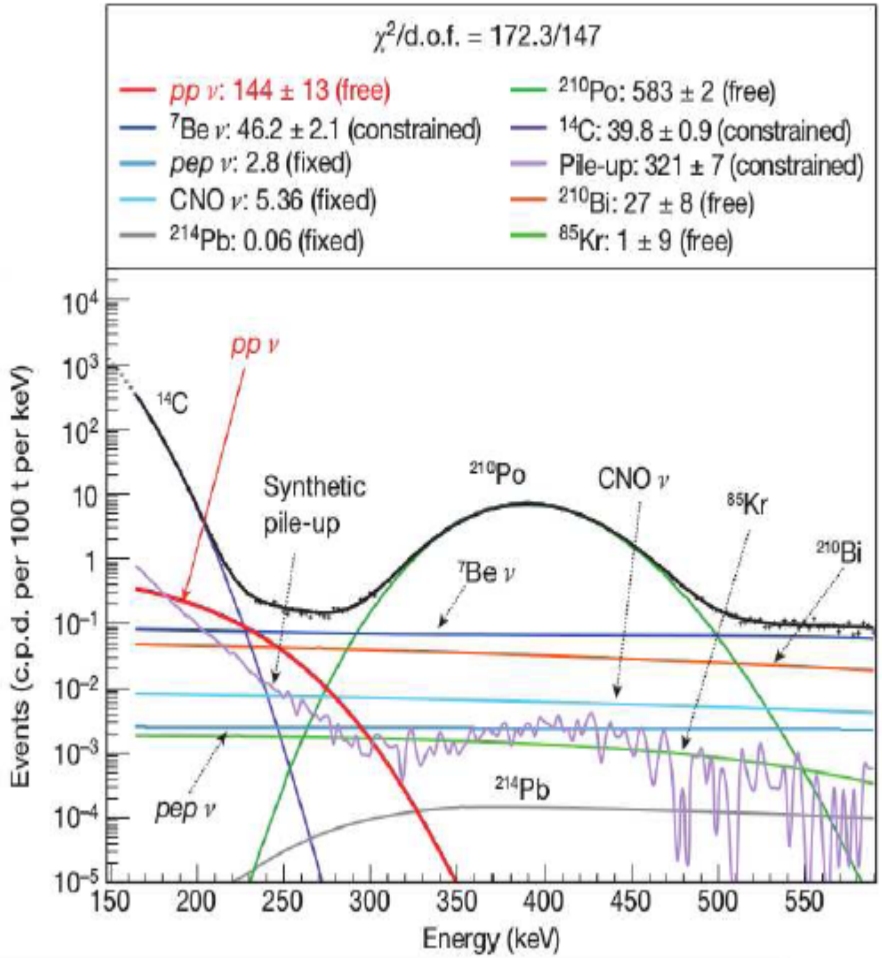
Nature, Vol. 512, Aug 28, 2014

ARTICLE

doi:10.1038/nature13702

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration*



Parameter	Systematics:
energy estimator	±7%
fit energy range	
data selection	
pile-up evaluation	
fiducial mass	±2%

Null hypothesis rejection: **10σ**

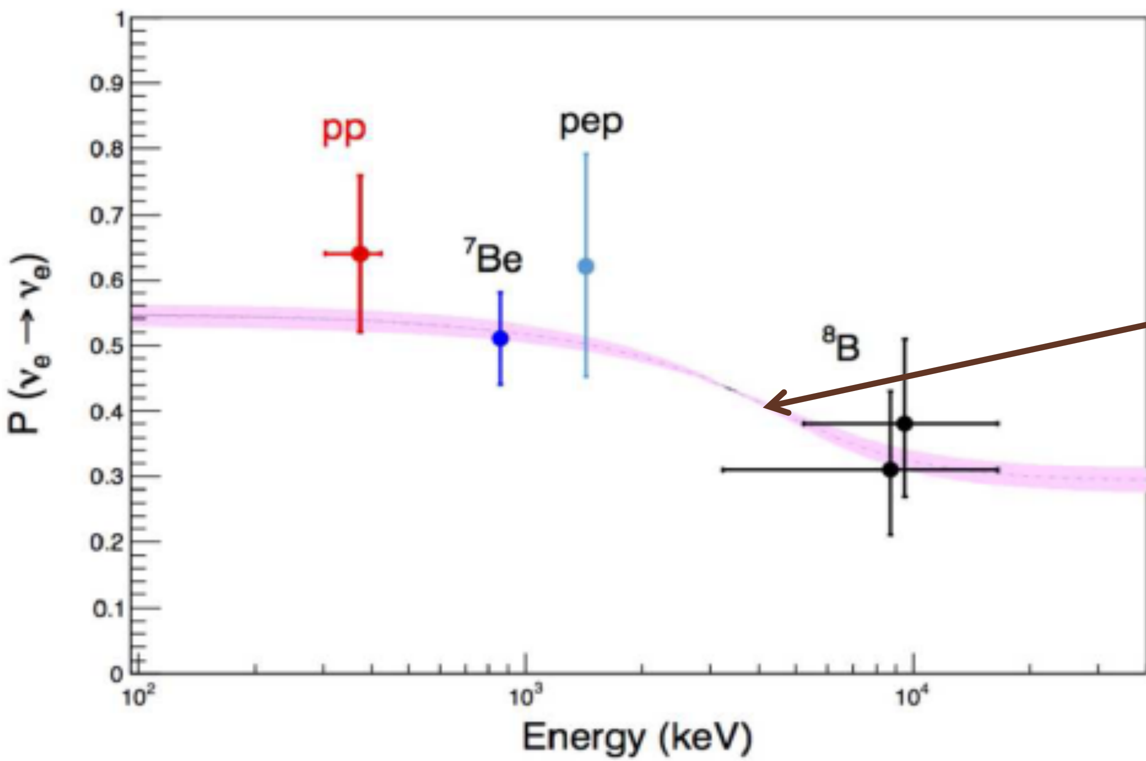
Expected: 131±2 c/d/100ton

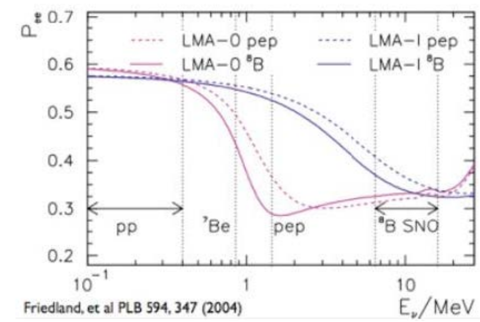
Interpretations:

1. If you believe SSM:
   - confirms MSW-LMA
2. If you believe MSW-LMA:
   - confirms SSM
3. If you believe both:
   - the sun is stable over 10^5 time span

Rate = 144±13(stat)±10(sys) c/d/100ton

P_{ee} after Borexino





In the transition region:
Is there room
for new physics?

still missing
CNO
neutrinos

Two approaches to transition region:
1. Reduce error on pep (and ^{7}Be) flux
2. Lower threshold on ^{8}B
   (upturn not yet observed by SNO-LETA or SK)

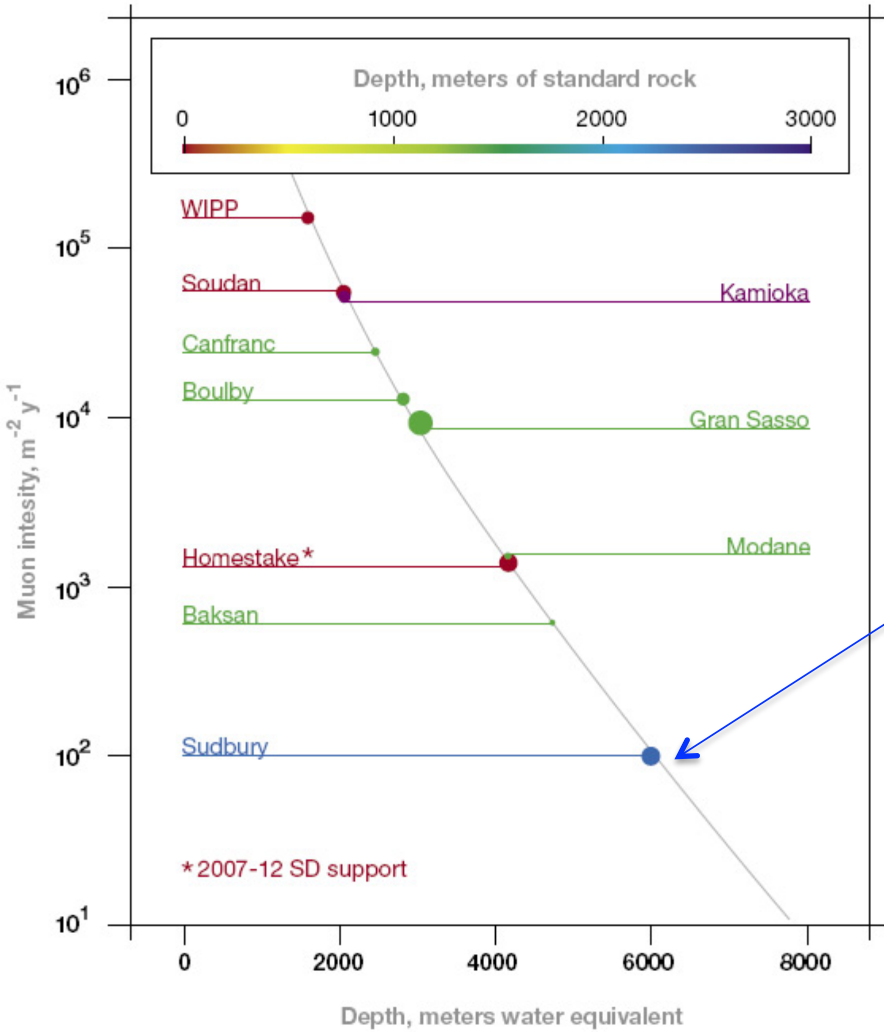
Borexino will work on both sides

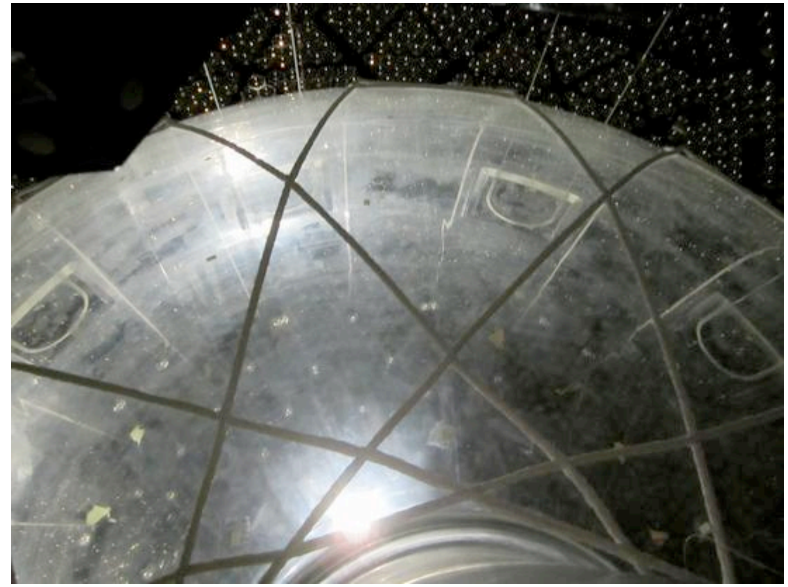
4

Future projects

SNO+

SNO conversion: heavy water is replaced by **liquid scintillator** (linear Alkylbenzene – LAB) compatible with the acrylic vessel.





One of the deepest Underground facilities in the world:
2km rock overburden -> ~ 6km w.e.

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

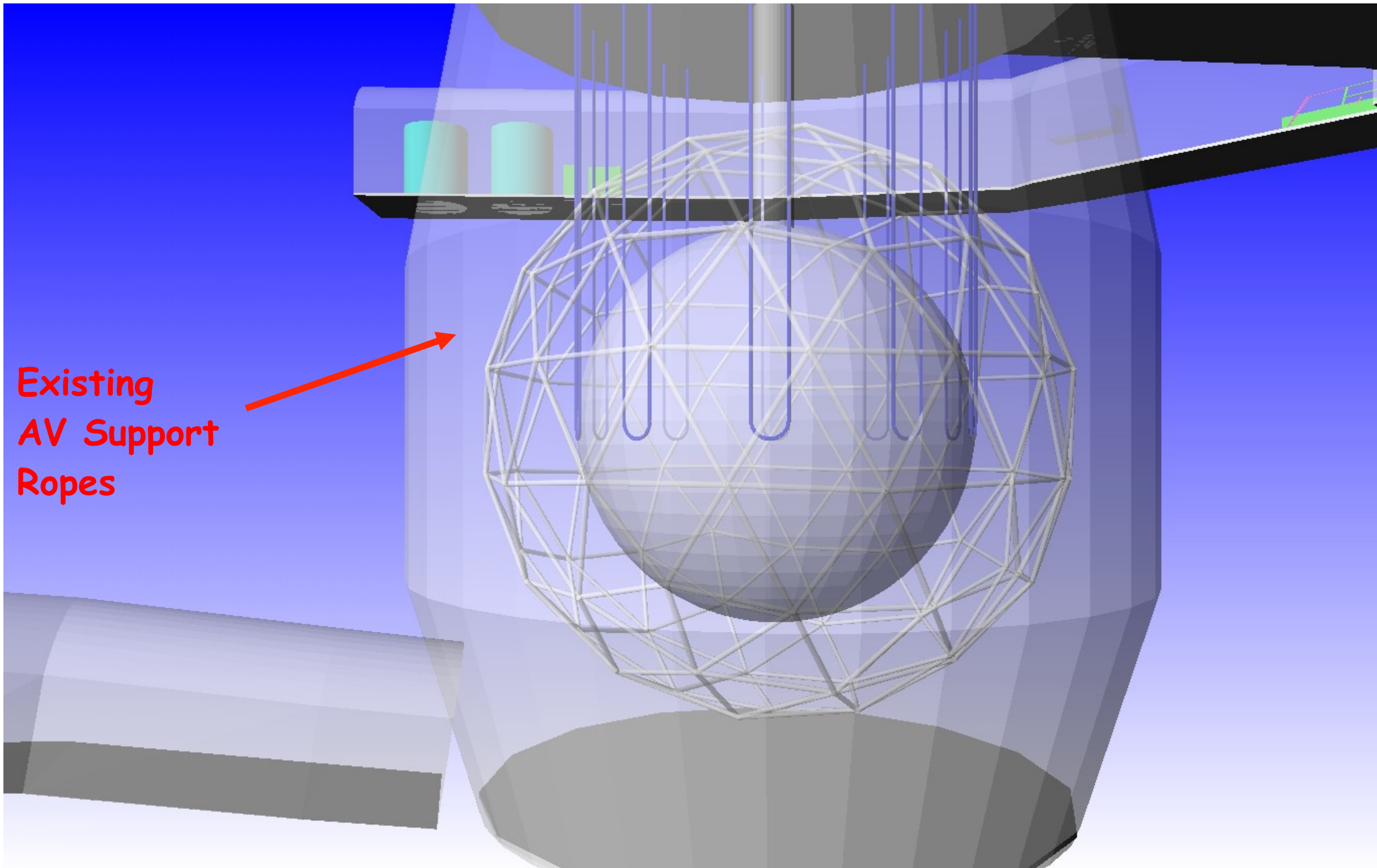
Excellent for pep/CNO neutrinos

SNO+ physics program

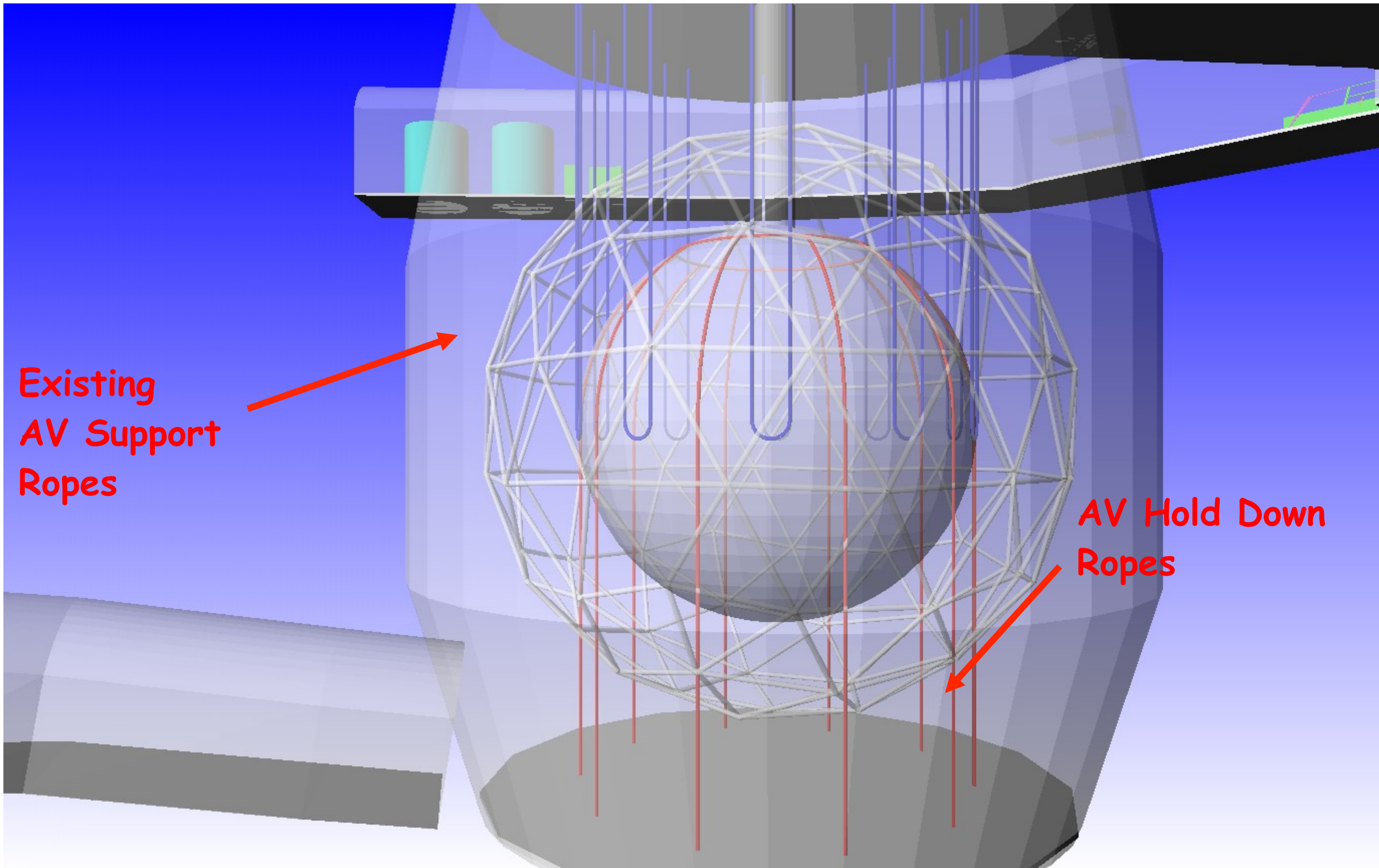
- **Neutrinoless double beta decay**
  Te doping (2016-2017)
- Low energy **solar neutrinos** (starting in 2018)
  pep, CNO, ^{8}B and potentially ^{7}Be & pp
- **Geo-neutrinos:** unmatched sensitivity
- 240 km baseline **reactor neutrino** oscillation
  Δm^2 resolution comparable to KamLAND
- **Supernova neutrinos:** major player
- "Invisible" modes of **nucleon decay:**
  unique sensitivity with initial water data

A Diverse Instrument for Neutrino Research within the SNOLAB Underground facility

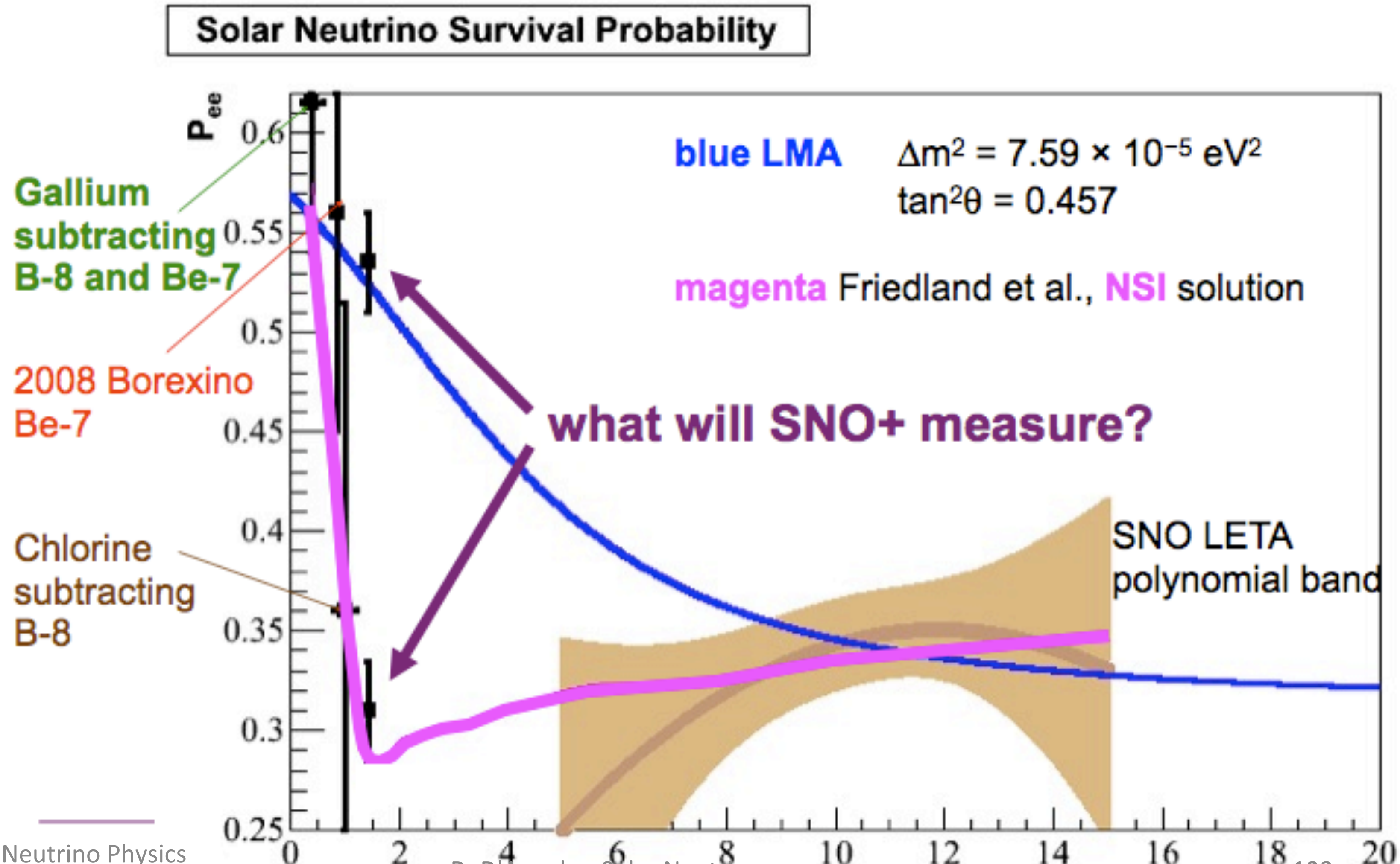
SNO Acrylic Vessel Support



SNO+ Acrylic Vessel Hold Down



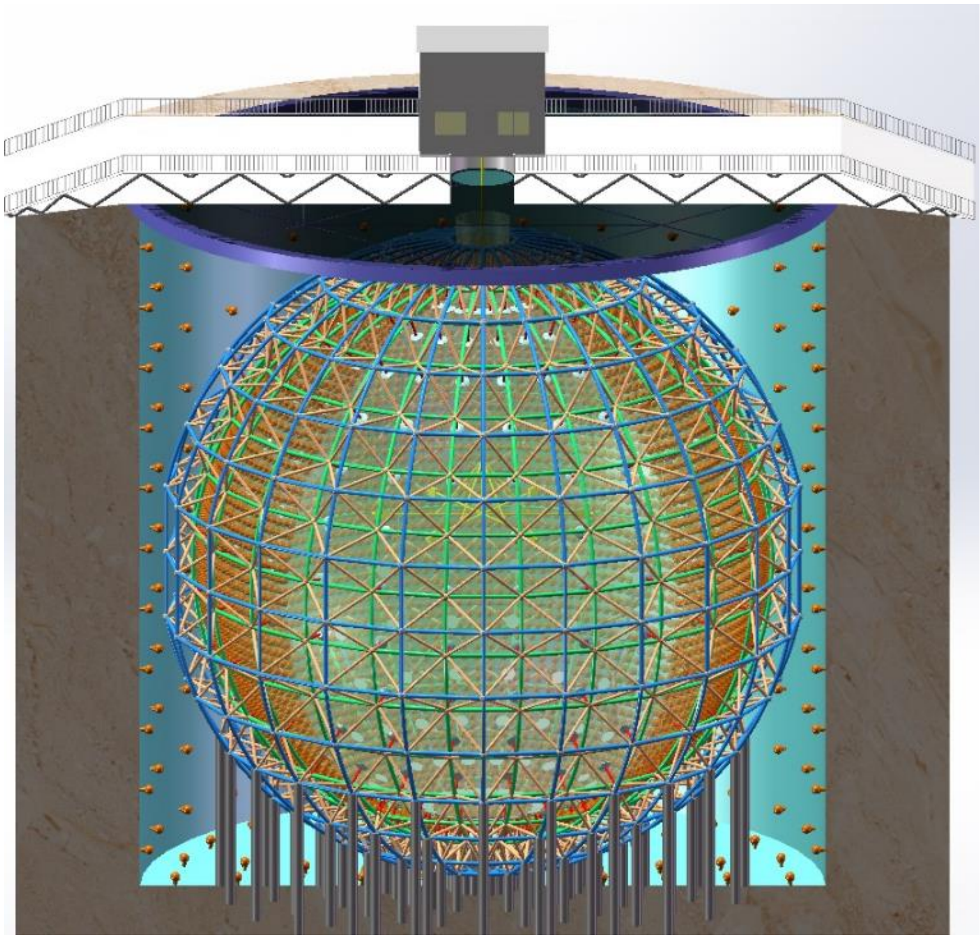
SNO+ Solar: ^{8}B



Solar Neutrino Survival Probability
P_ee
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0
2
4
6
8
10
12
14
16
18
20
Gallium subtracting B-8 and Be-7
2008 Borexino Be-7
Chlorine subtracting B-8
blue LMA
Δm² = 7.59 × 10⁻⁵ eV²
tan²θ = 0.457
magenta Friedland et al., NSI solution
what will SNO+ measure?
SNO LETA polynomial band

The JUNO Experiment

- **Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M$.**



- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich physics program**
  - **including solar ν with incredibly high statistics**

Source	Rate [cpd/1kt]
pp	1337
^{7}Be [line 0.384 MeV]	19
^{7}Be [line 0.862 MeV]	475
pep	28
^{8}B	4.5
^{13}N	25
^{15}O	28
^{17}F	0.7

What next? ……….The far future

50000 tons scale detector: LENA

50 kilotons of liquid scintillator (linear Alkylbenzene – LAB)

Fiducial volume of the order of 30 ktons

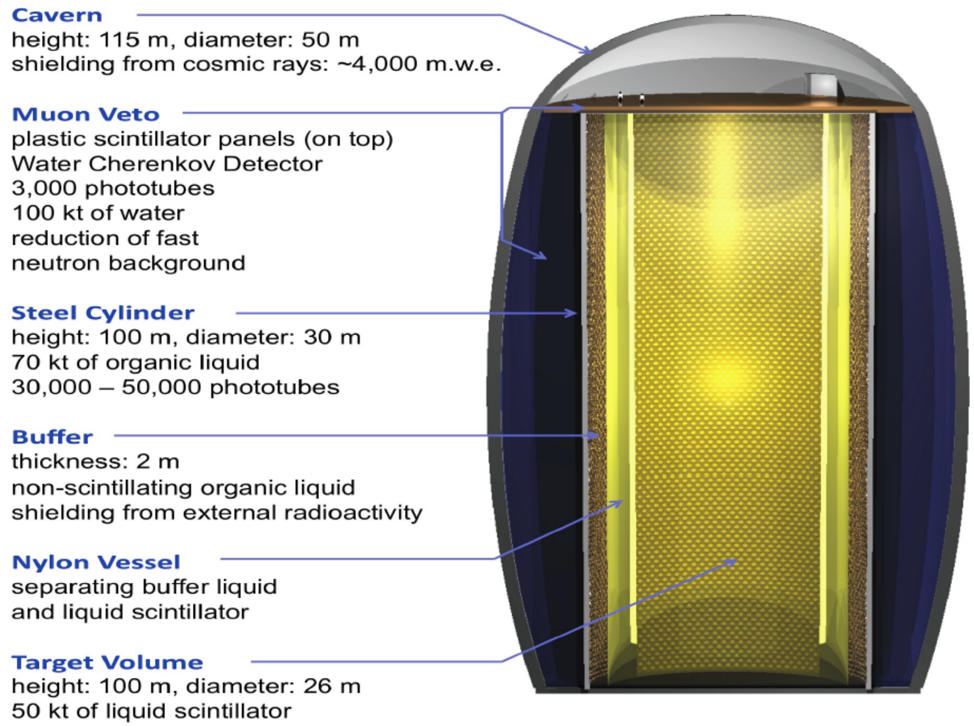
45000 photomultipliers

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
^{7}Be	>0.25	35	1.0×10^4
^{8}B	>2.8	35	79
CNO	$0.8-1.4$	30	1.9×10^2

Low Energy Neutrino Astronomy



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

Detectors with new technique: LENS

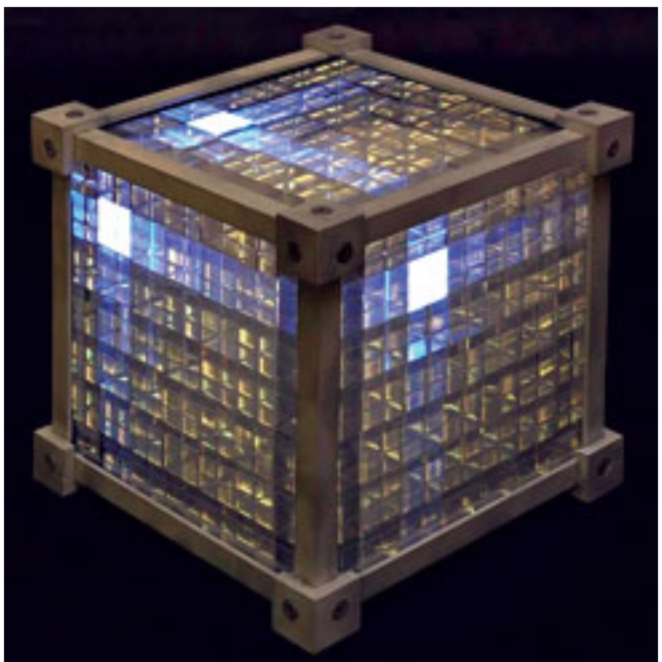
In order to make an energy spectrum measurement on low energy neutrinos, it is necessary to reach a low threshold for the charged current (CC) process

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

$$^{115}\mathrm{In} + \nu_e \rightarrow {}^{115}\mathrm{Sn}^* + e^- \; (E = E_\nu - 114\ \mathrm{keV}) \quad (\tau_{\mathrm{Sn}^*} = 4.76\ \mu s)$$

$$\hookrightarrow {}^{115}\mathrm{Sn} + \gamma\,(498\ \mathrm{keV}) + \gamma\,(116\ \mathrm{keV})$$

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



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

The combination of the 4.76 μs 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,