Solar & geo neutrinos

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Outline…

1. Neutrino very basics;

2. Solar neutrinos;

3. Geoneutrinos;

General overview
and
more details from the recent
Borexino results

Neutrino basics….

- No electric charge
  = no elmag interactions;
- No color
  = no strong interactions;
- Only weak interactions
  = very small cross sections;

Elementary particles of the SM

particles lepton number +1		3 flavors	antiparticles lepton number -1	
e^-	ν_e		e^+	$\bar{\nu}_e$
μ^-	ν_μ		μ^+	$\bar{\nu}_\mu$
τ^-	ν_τ		τ^+	$\bar{\nu}_\tau$

- Originally, in the SM neutrinos have exactly zero mass, all neutrinos are left-handed and all antineutrinos are right handed;
- Experimental evidences for **neutrino oscillations**: **non-zero mass** required!
- Non-zero mass requires at least a minimal extension of the SM;
- Dirac or Majorana particles?
- If Majorana, then lepton-flavor violation by 2 and 0ν-ββ –decay possible: a big experimental effort is ongoing!

Neutrino oscillations I

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

α = e, μ, τ
Flavour eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

i = 1, 2, 3
Mass eigenstates

Atmospheric -ν

Solar -ν

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

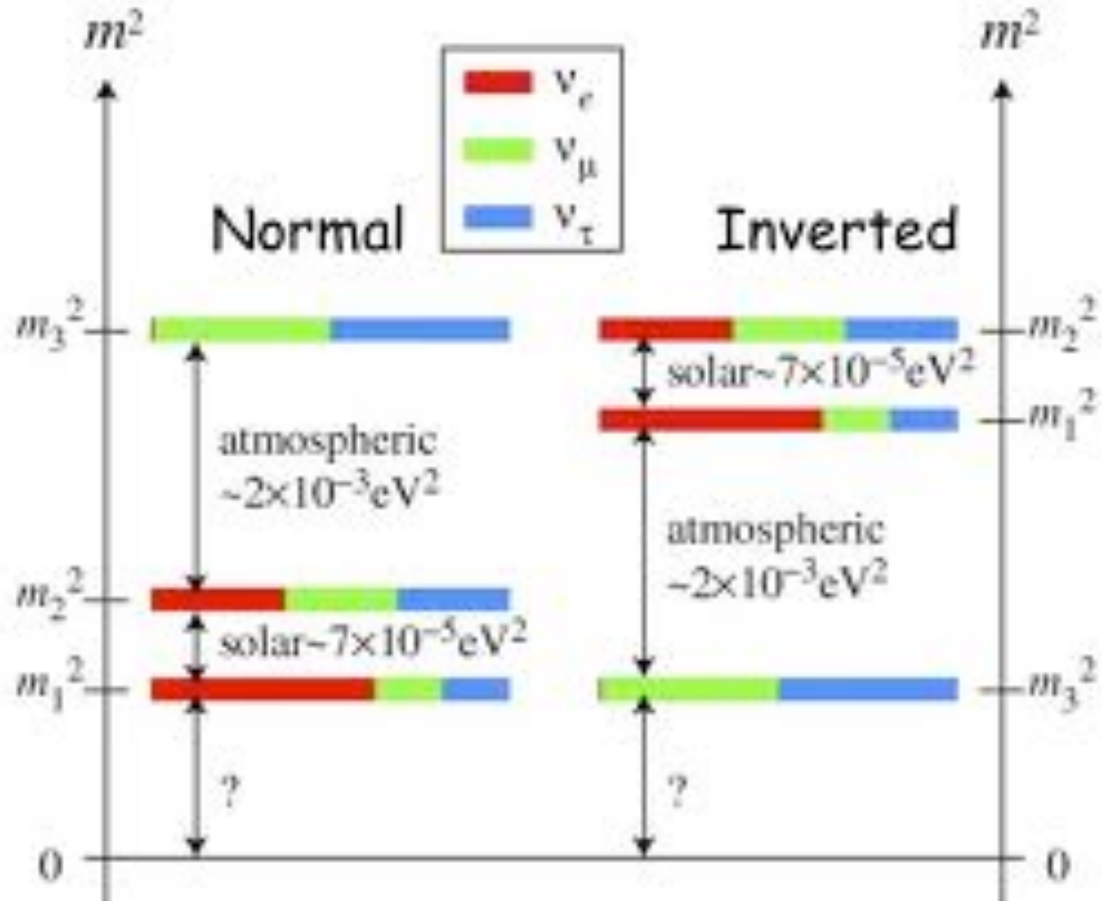
- **Mixing angles θ_{ij}:** mostly measured (bad precision for θ_{23});
- Non-zero θ_{13} confirmed only in 2012 by Daya Bay in China!
- **Majorana phases α1 , α2** (only if Majorana particles) unknown;
- **CP-violating phase δ** unknown;

Neutrino oscillations II

Probability to measure neutrino of original flavour α as a β-flavour:

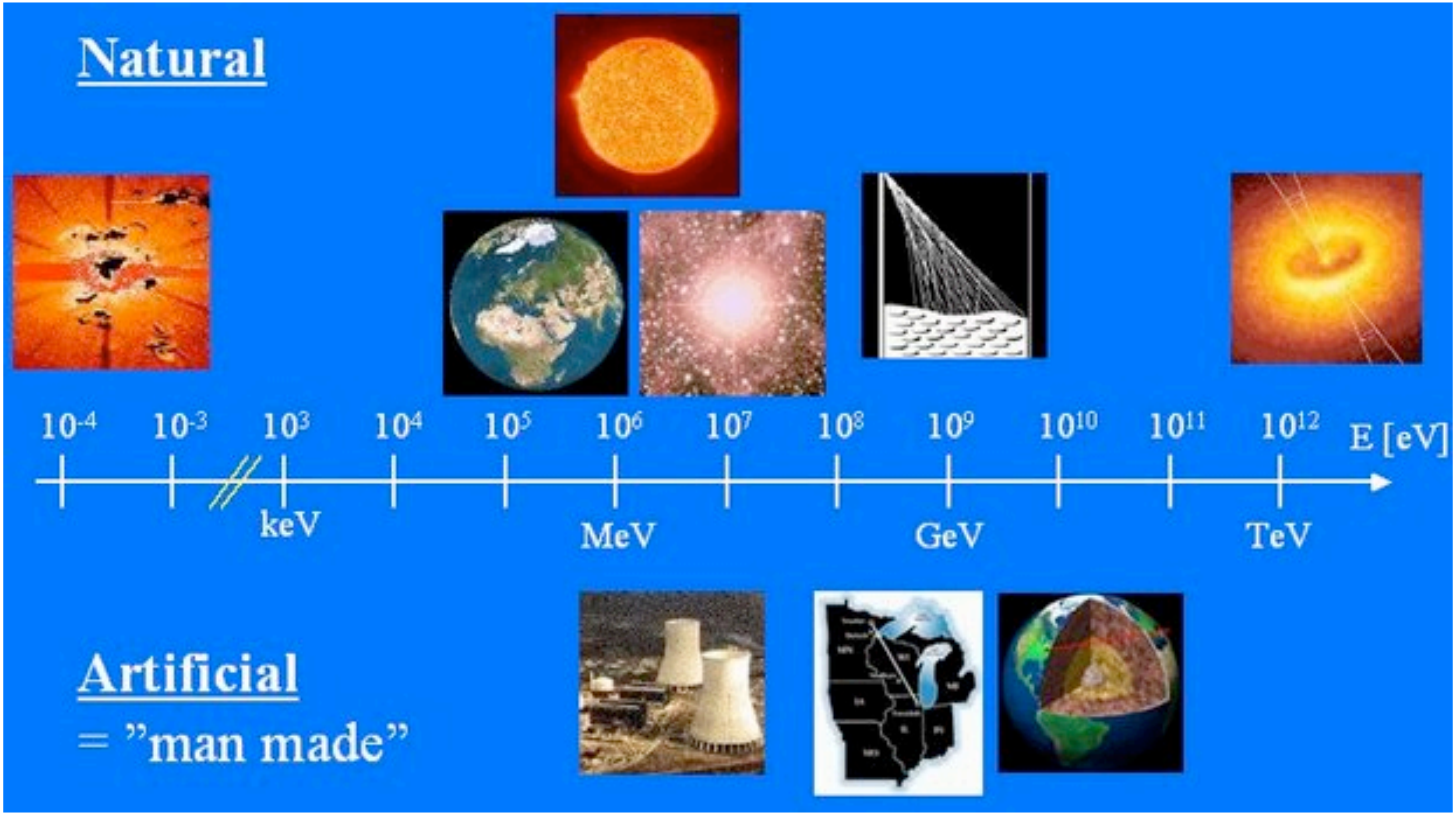
$$P_{\alpha\to\beta} = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/2E}\right|^2 .$$

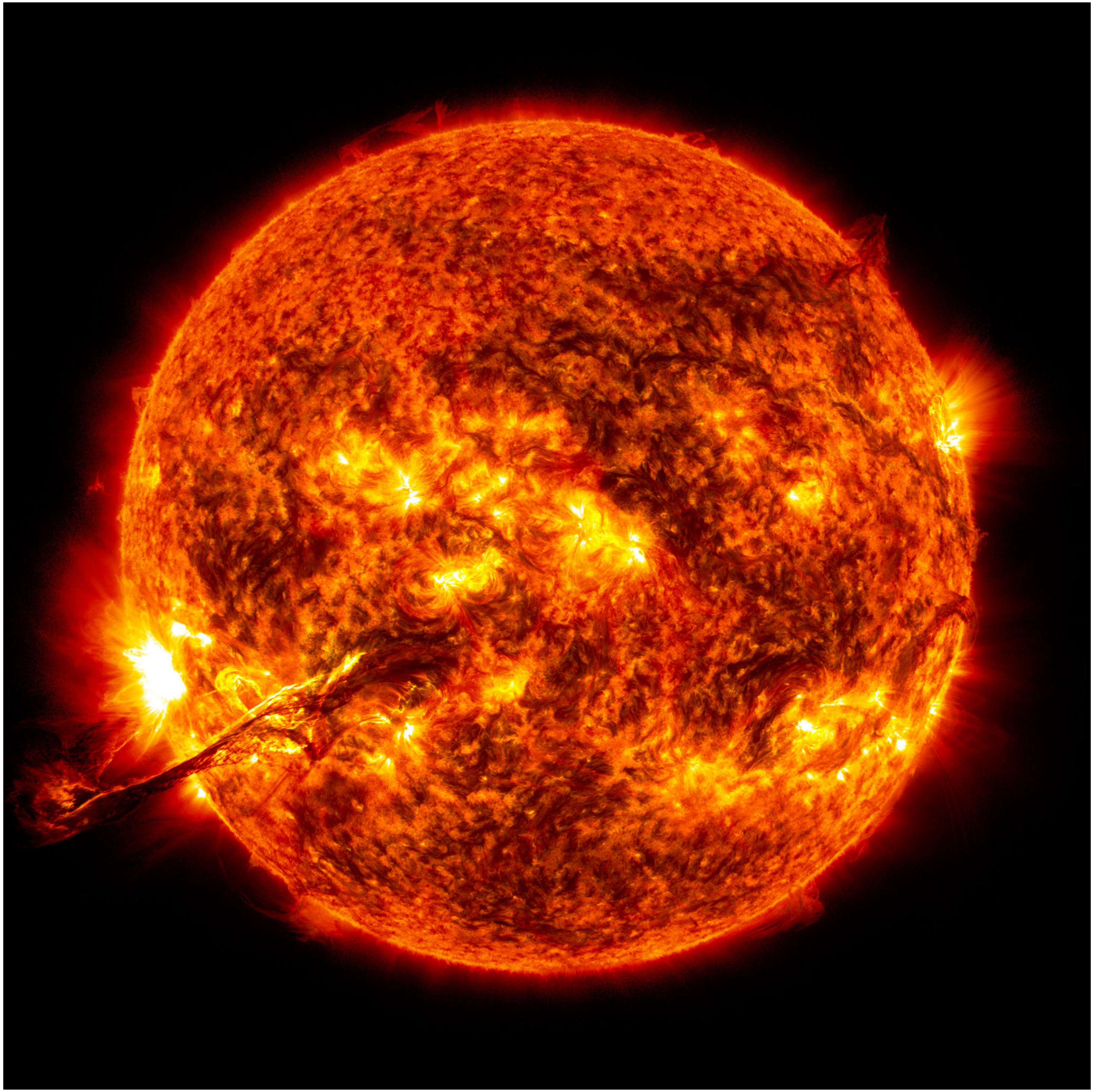
$$P_{\alpha\to\beta} = \delta_{\alpha\beta} \;-\; 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\!\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$
$$+\; 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\!\left(\frac{\Delta m^2_{ij} L}{2E}\right),$$



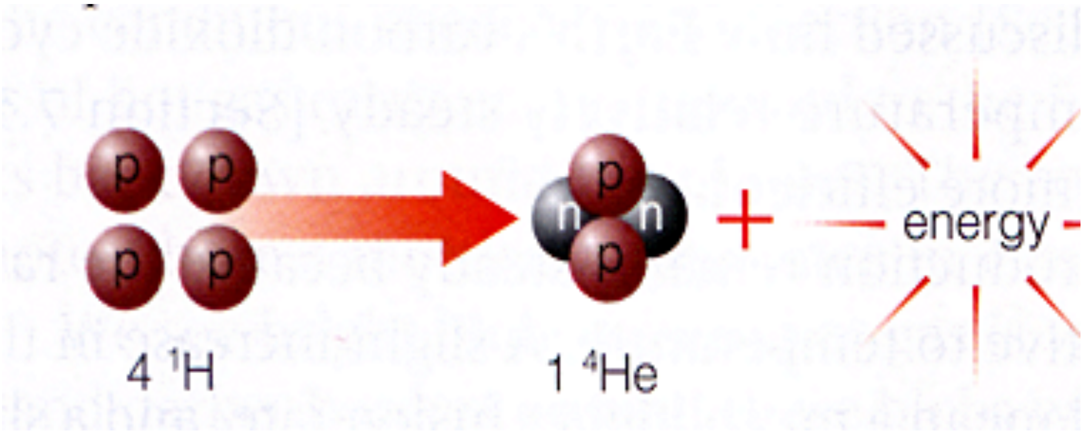
$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

Neutrino sources





How the Sun shines



Core temperature ~ 10^7 K (~1 keV).

(26.7MeV) (+2v)

Binding energy: ^{4}He is 0.7% lighter comparing to 4 protons

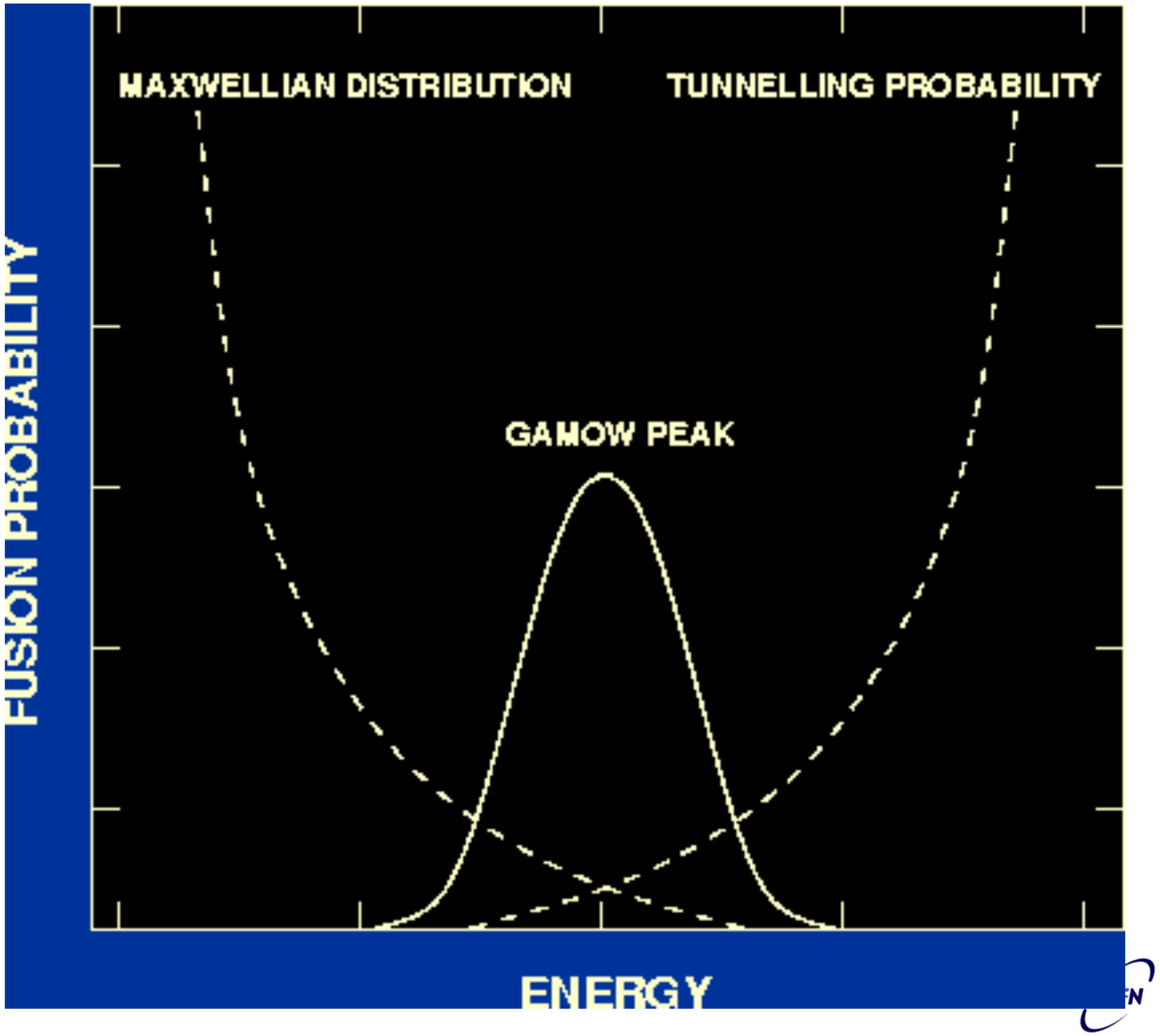
Sun power is **$4\cdot10^{26}$** W ➔ @Earth ~7 x 10^{10} neutrinos/s/cm^2

600 million tones of H are burned every second to produce 596 million tones of He. Every second Sun produces 10^5 times more energy than mankind produced over all its history, but the relative energy production of the Sun is very low 2×10^{-4} W/kg.

Reaction cross sections are low: pico and femto barns

The Gamow peak is the product of the Maxwellian distribution and the tunnelling probability.

Stellar Nuclear reactions occur in the narrow energy range below 100 keV (Gamow peak): the area under the Gamow peak determines the reaction rate.



Standard Solar Model (SSM)

- derived from the conservation laws and energy-transport equations, applied to a spherically symmetric gas sphere, constrained by the luminosity, radius, age, and composition of the Sun.

Input parameters:

- Nuclear parameters;
- Luminosity ($3.8418\cdot10^{33}$ erg/s (± 0.35%);
- Age ($4.52\cdot10^{9}$ years (±0.04%) - old meteorites);
- $M = 1.989\cdot10^{30}$ kg (± 0.02%); $R = 6.9598\cdot10^{8}$ m (± 0.01%);
- surface metals – to - hydrogen ratio **(Z/X = metallicity)** = 0.0245 – 0.0178; fractional abundances of individual metals also fixed;
- Equations of state;
- Chemical elements abundance; initial ratio of elements heavier than He to hydrogen;
- Radiation opacity;

Output:

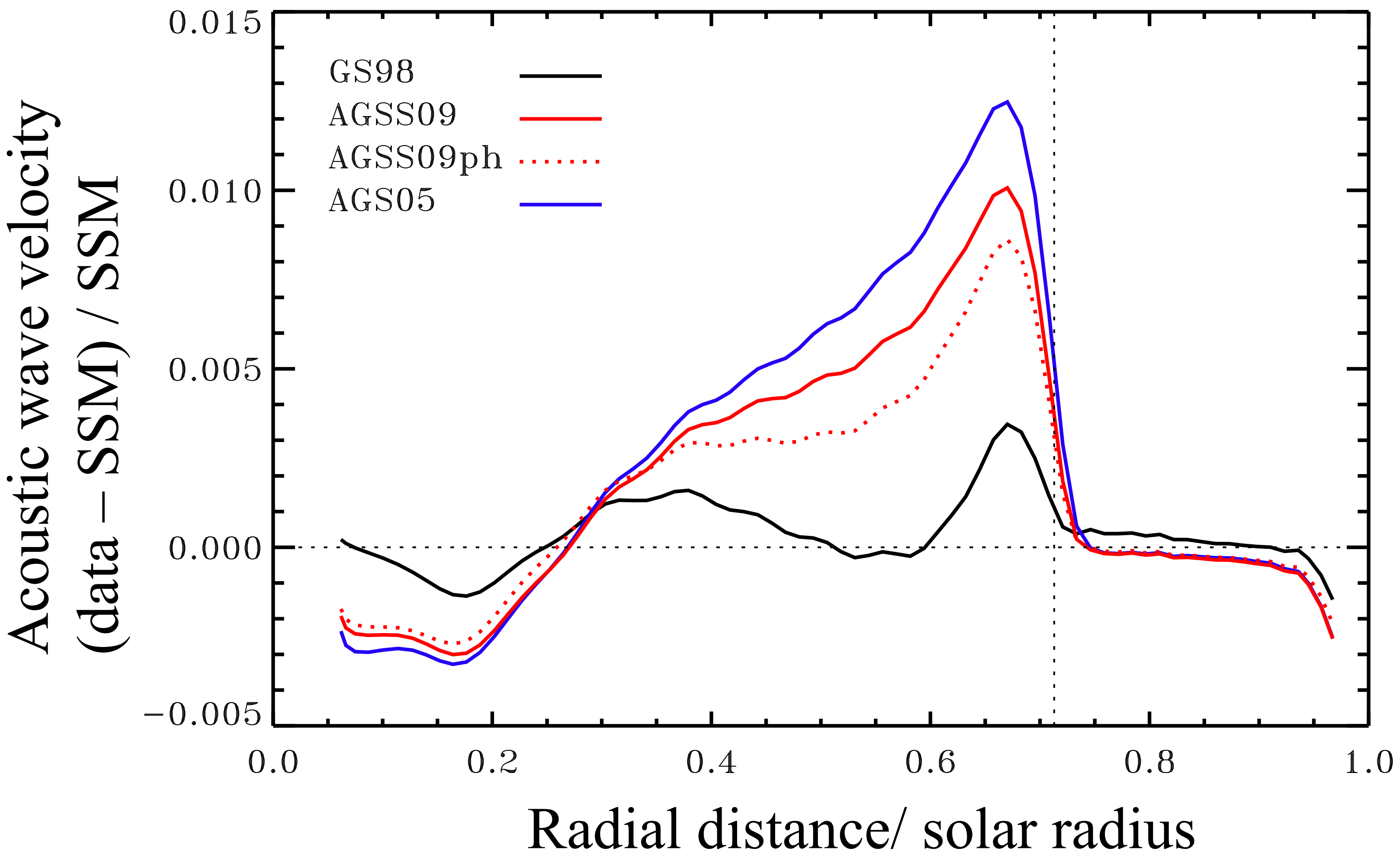
(among others) **neutrino fluxes** (their study is the only way to check the understanding of nuclear processes at the center of the Sun) and **helioseismology** (profiles of the acoustic wave velocity).

Solar metallicity problem

Z = abundance of heavy elements: C, N, O, Ne, Mg, Si, Ar, Fe
X = abundance of H and He

Older High-Metallicity: Z/X (= 0.0229) SSM GS98
Newer Low-Metallicity: Z/X (= 0.0178) SSM AGS05, AGSS09/ph

Newer 3D LOW-Z/X SSM, more internally consistent spectroscopic data, but a strong disagreement with helioseismological data, while older, higher Z/X SSM is in agreement!!!



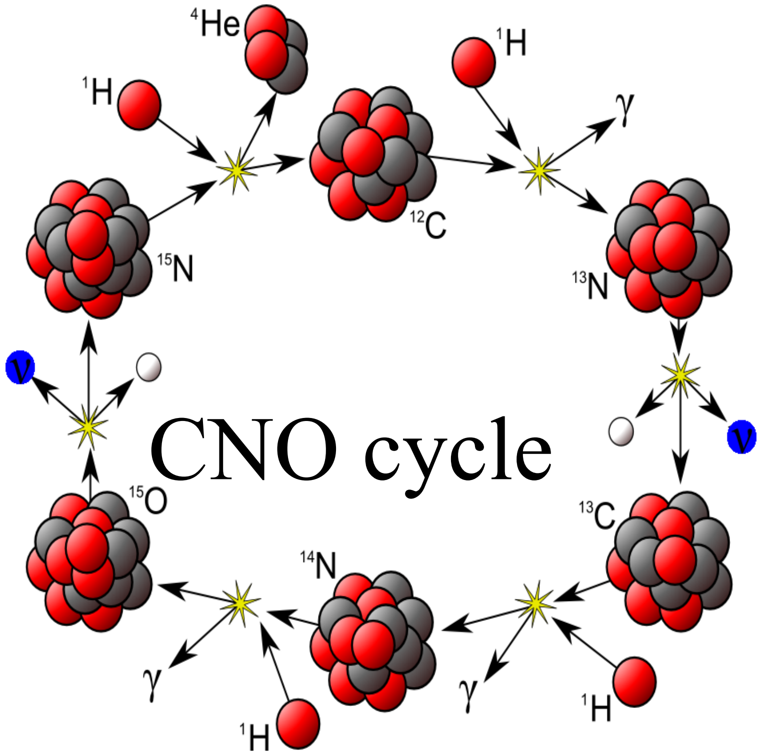
Nuclear reactions in the Sun

- The Sun burns via fusion reactions
  - **pp** cycle (Fowler):
    - 99% of the energy
  - **CNO** cycle (Bethe, 1938): small (<1%) in stars like the Sun, dominant in heavy stars

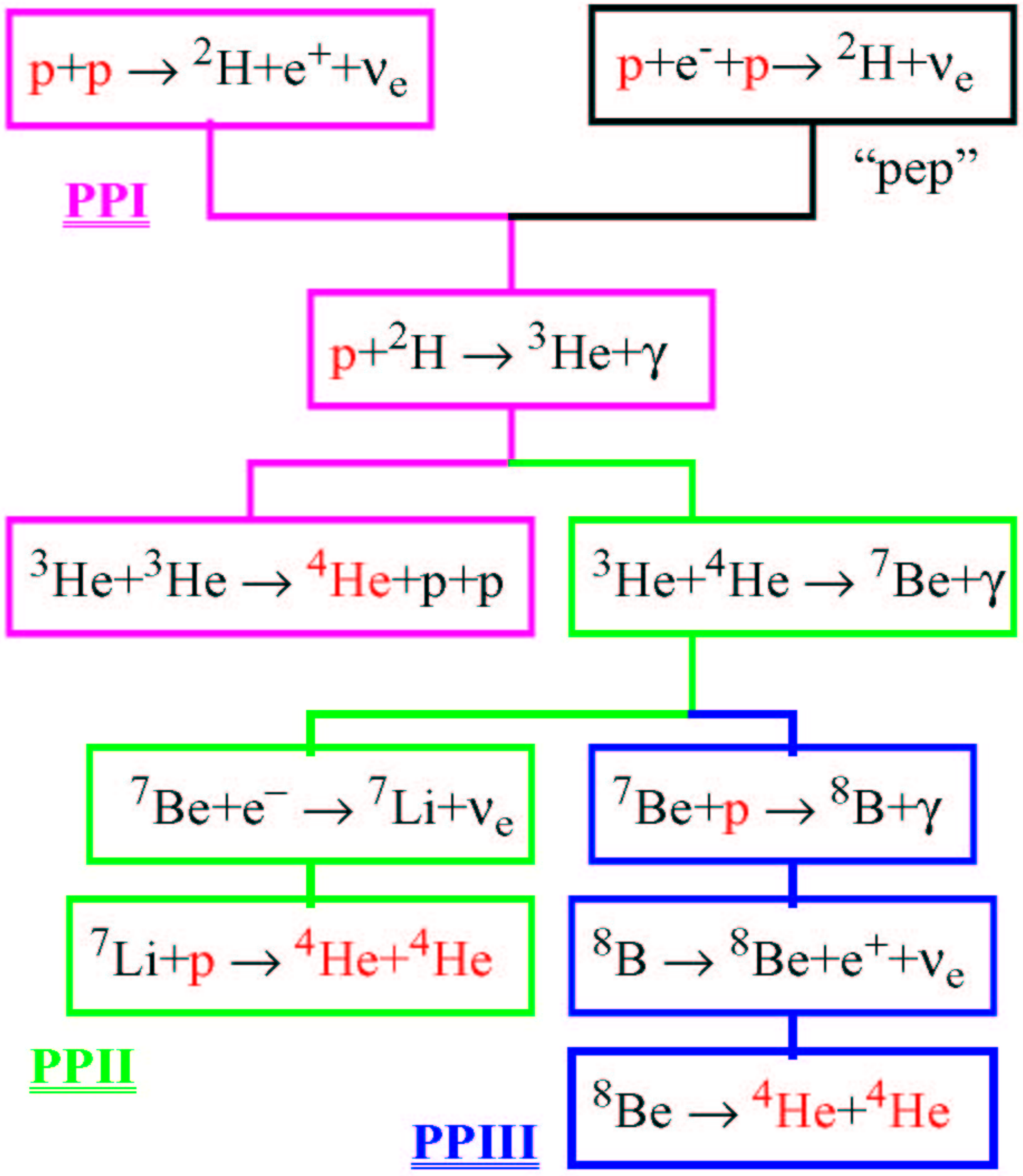
    poorly known and never measured

W. Fowler

H. Bethe



pp cycle



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

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

"pep"

PPI

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

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

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

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

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

PPII

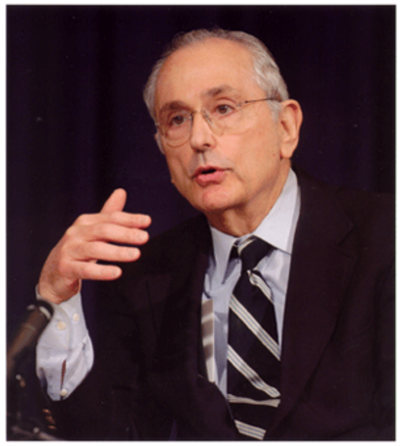
${}^7Be+p \rightarrow {}^8B+\gamma$

${}^8B \rightarrow {}^8Be+e^++\nu_e$

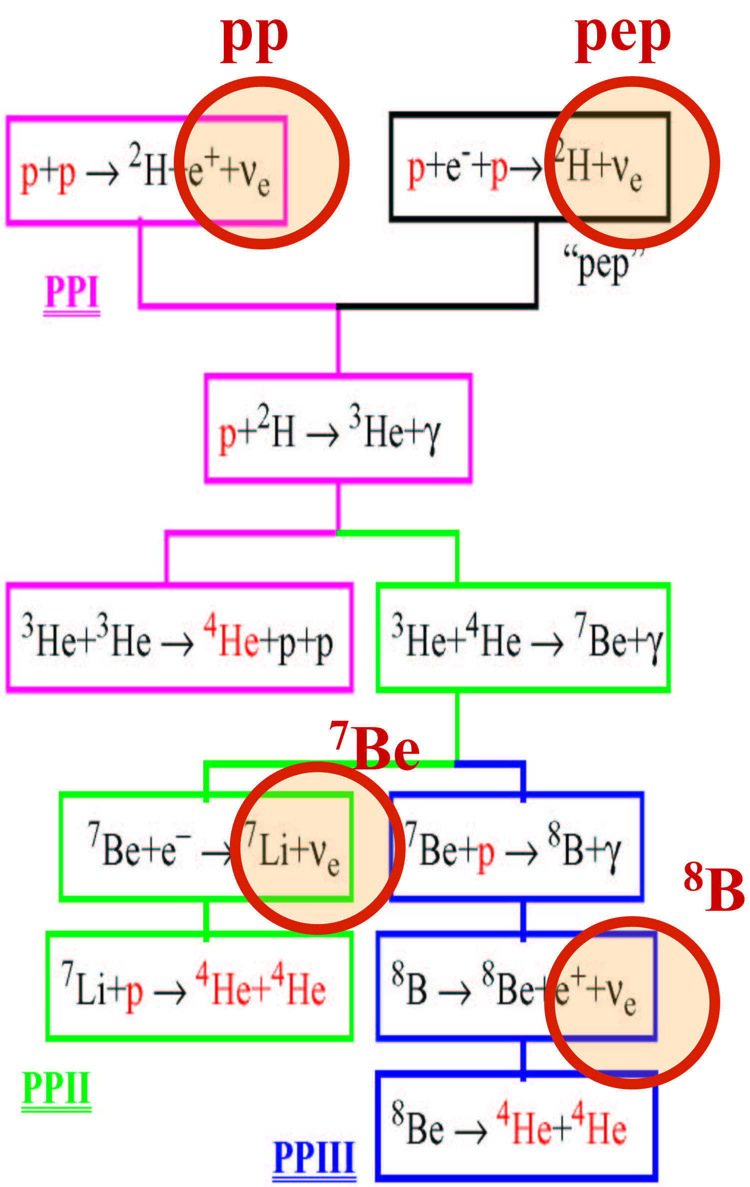
${}^8Be \rightarrow {}^4He+{}^4He$

PPIII

Energy spectrum of solar neutrinos



John N. Bahcall
1934 - 2005



pp

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

pep

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

"pep"

PPI

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

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

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

${}^7Be$

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

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

${}^8B$

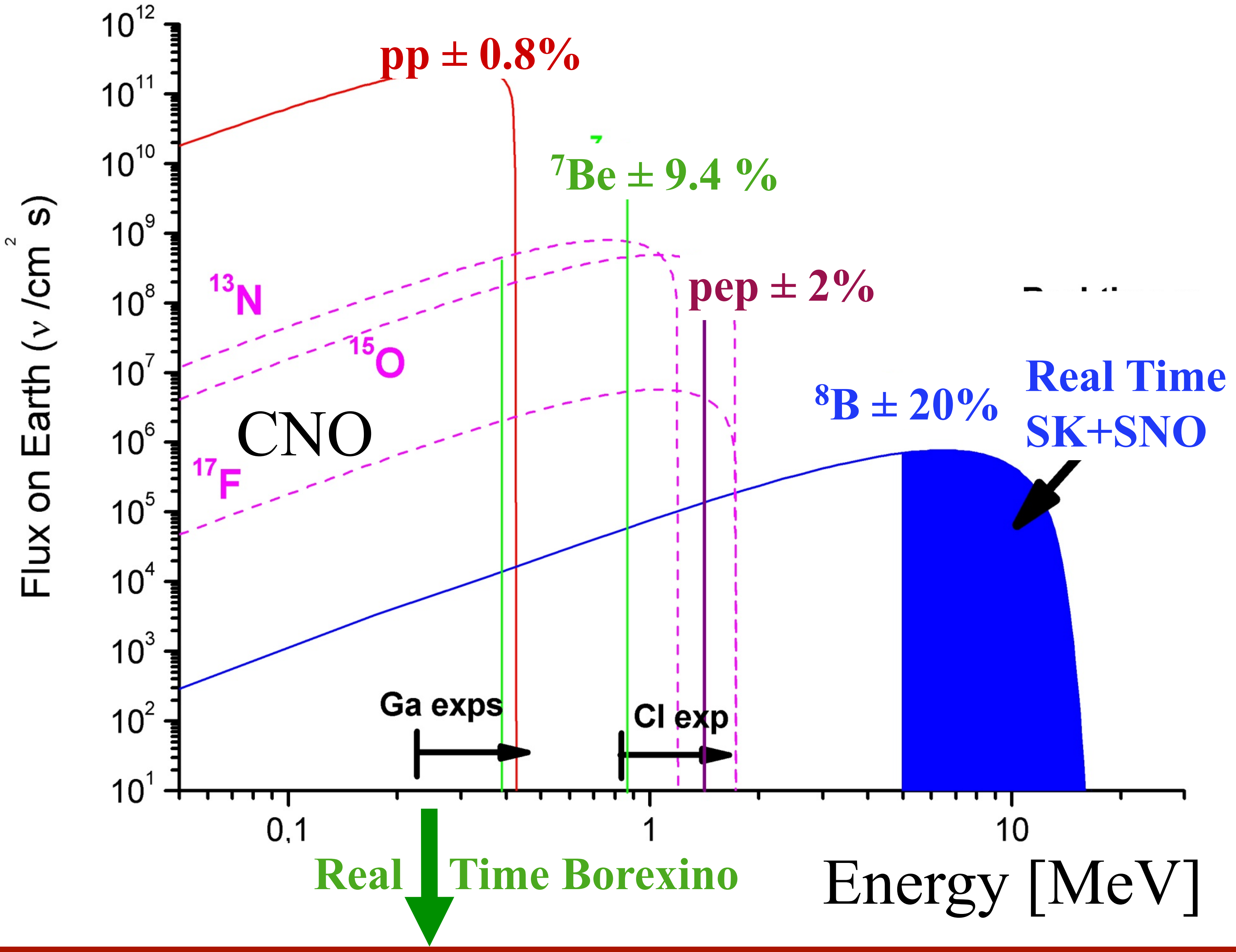
${}^7Li+p \rightarrow {}^4He+{}^4He$

${}^8B \rightarrow {}^8Be+e^++\nu_e$

PPII

PPIII

${}^8Be \rightarrow {}^4He+{}^4He$

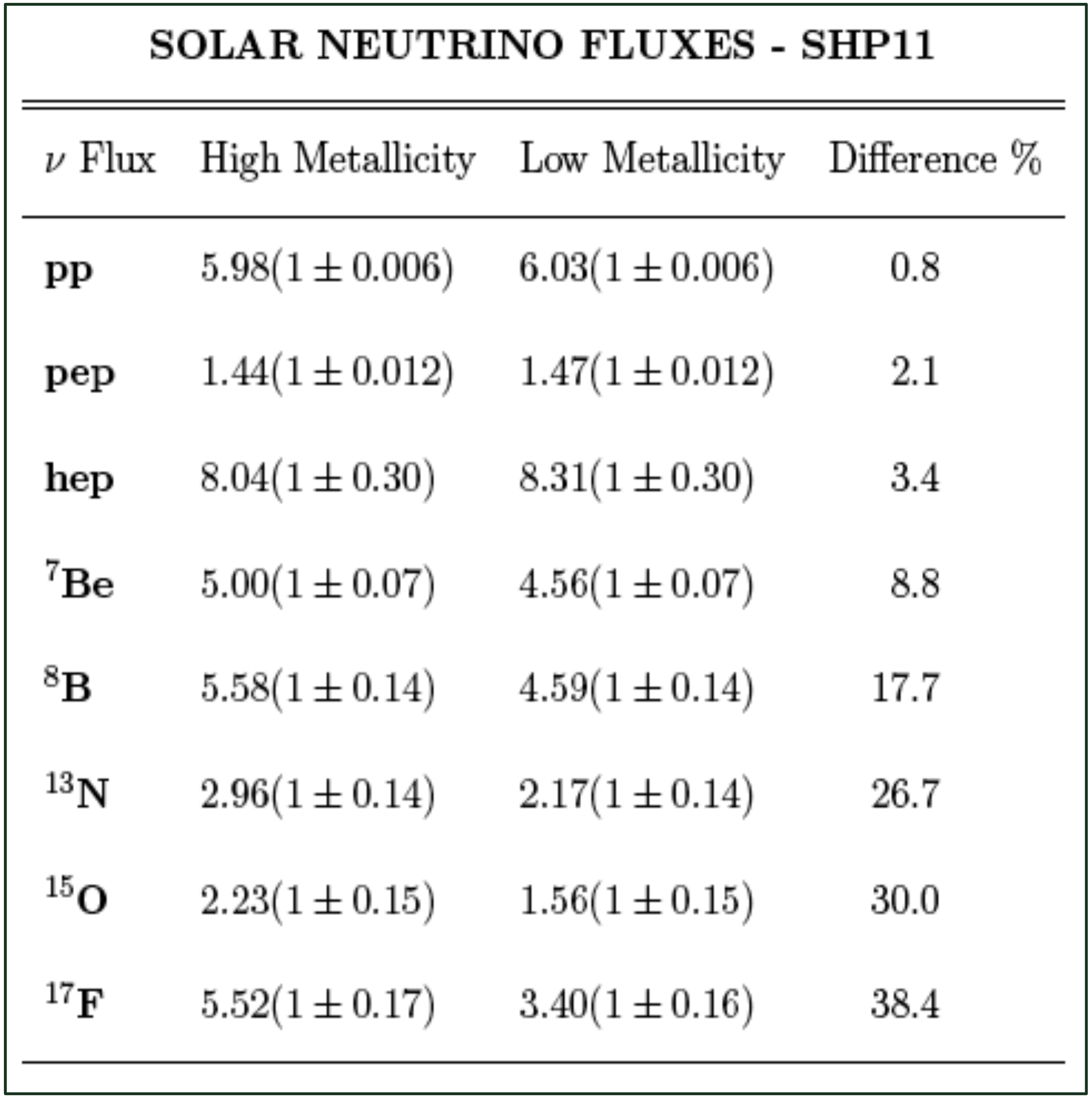


note: hep neutrinos not included
In spectrum (very small)

Expected solar neutrino fluxes

given in units of ν cm^{-2} s^{-1}
x
10^{10} (pp),
10^{9} (^{7}Be),
10^{8} (pep, ^{13}N, ^{15}O),
10^{6} (^{8}B, ^{17}F)
10^{3} (hep)

This last solar model from 2011 uses "newly" analyzed nuclear fusion cross.



SOLAR NEUTRINO FLUXES - SHP11

ν Flux	High Metallicity	Low Metallicity	Difference %
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	0.8
pep	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	2.1
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	3.4
^{7}**Be**	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	8.8
^{8}**B**	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	17.7
^{13}**N**	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	26.7
^{15}**O**	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	30.0
^{17}**F**	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	38.4

A. Serenelli, W. Haxton and C. Peña Garay ApJ 743 pp. 24, 2011

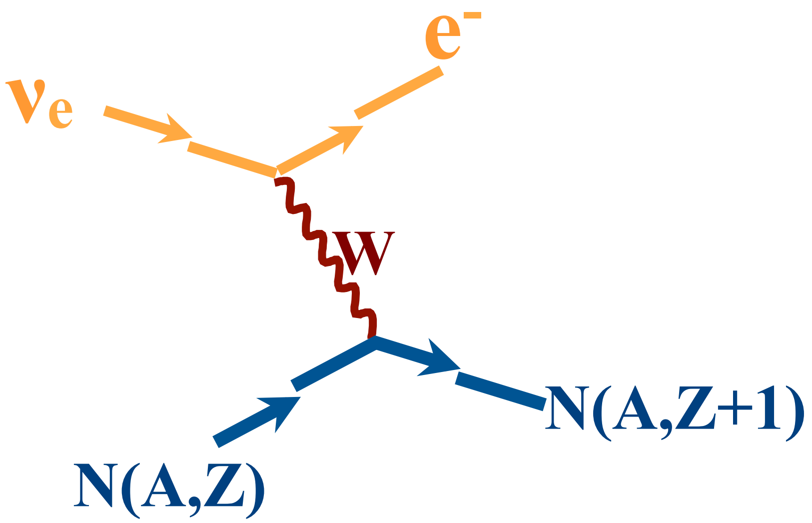
Detection of solar neutrinos: 3 basic reactions

1) Charged current (CC) interaction

Inverse β decay on a proton or a nucleus

ν_e **ONLY** at MeV energies

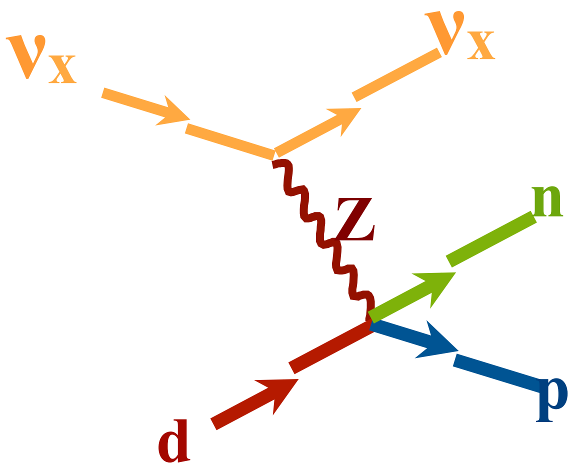
- Muon and Tau lepton too heavy



2) Neutral current (NC)

Elastic scattering on a nucleus

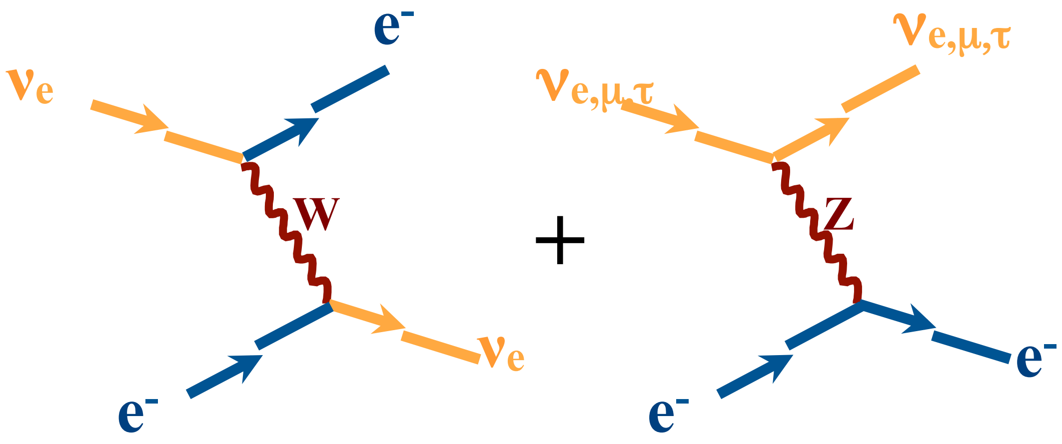
- either with the emission of a recoil neutron
- All neutrino flavors have the SAME cross section



3) Elastic scattering off an electron

(charged current (CC) + neutral current (NC))

- Cross section for ν_e and $\nu_{\mu,\tau}$ is different
- for $\nu_{\mu,\tau}$ NC only;



Experimental techniques

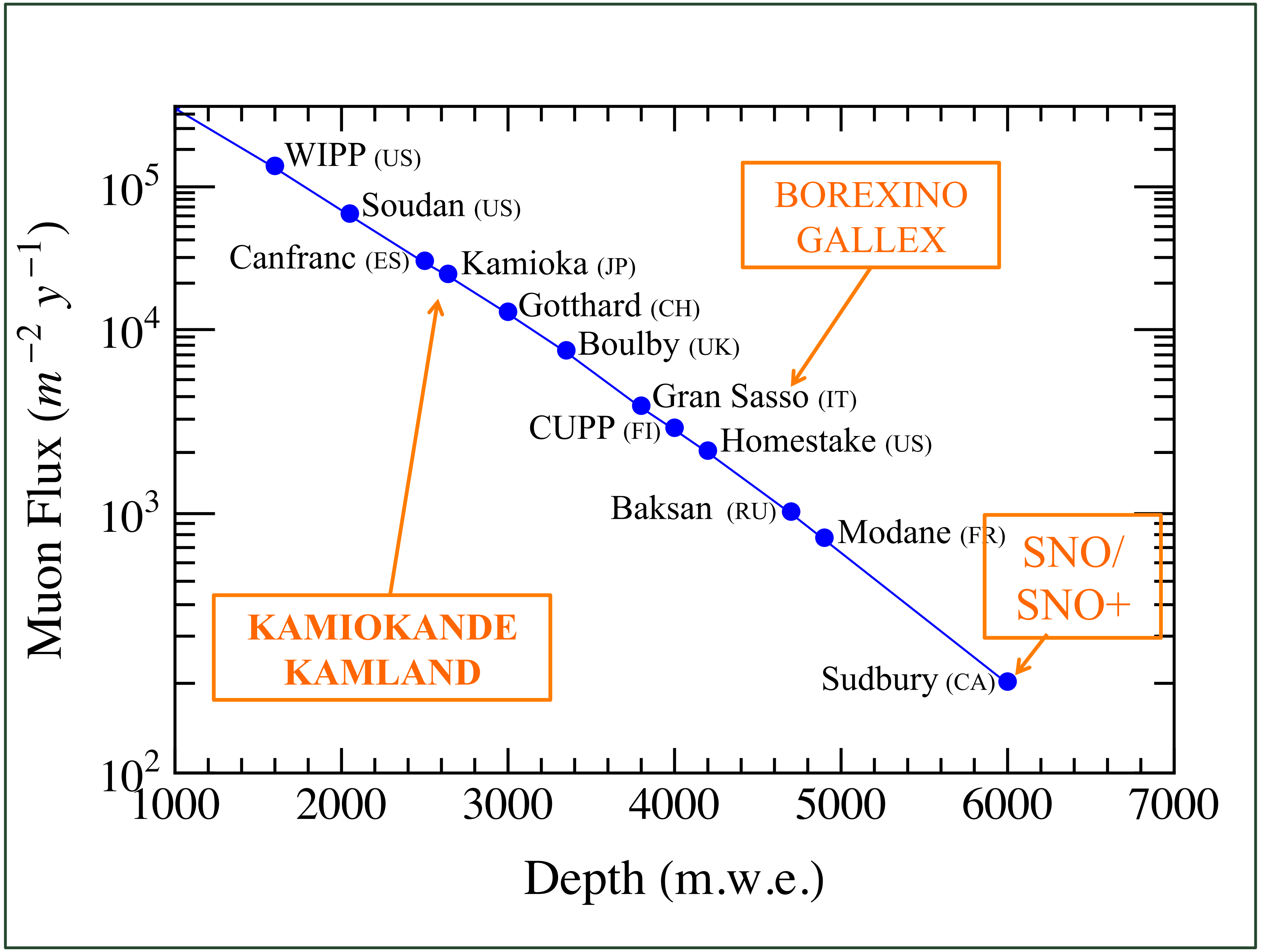
- **Radiochemical**
  - ✓ $^{A}X+\nu_e \rightarrow {}^{A}Y+e^-$ (CC)
  - ✓ can have low energy threshold (~200 keV);
  - ✓ counting the number of Y atoms: no energy spectrum!
  - ✓ only integral neutrino flux above certain threshold.
  - ✓ Homestake, Gallex/GNO, Sage

- **Water cherenkov: real-time technique: Eν spectrum!**
  - ✓ NC, CC, elastic scattering possible (!heavy water!);
  - ✓ ~3-5 MeV energy threshold;
  - ✓ directionality;
  - ✓ (Super)-Kamiokande, SNO

- **Liquid scintillator: real-time technique: Eν spectrum!**
  - ✓ Elastic scattering;
  - ✓ low energy threshold (~200 keV);
  - ✓ High light yield;
  - ✓ No directionality;
  - ✓ Extreme radiopurity required;
  - ✓ Borexino, KamLAND, SNO+;

Small neutrino interaction rates → shielding against cosmic rays

Muon flux in undeground laboratories



Short history of solar ν experiments in 1 slide

- **70's-80's: Homestake (R. Davies)**
  - $^{37}Cl + \nu \rightarrow ^{37}Ar + e^-$, radiochemistry; **$E_\nu$ >814 keV**
  - deficit in neutrino flux observed, skepticism
  - final triumph, Nobel prize 2002
  - J. Bahcall continues the development and refinement of the Standard Solar Model

- **80's-90's: (super)Kamiokande (Water Cherenkov)**
  - confirm deficit on ^8B ν and with real time techniques **E_ν > ~ 5 MeV**
  - first neutrino picture of the Sun (directionality)
  - neutrinos from star sother than the Sun observed (supernova SN1987-A)
- **90's: Gallex (GNO) and Sage:** radiochemistry $\nu_e + ^{71}Ga \rightarrow ^{71}Ge + e^-$
  - deficit observed even at low energy **E_ν >233 keV**
- **2001: SNO (Water Cherenkov)**
  - oscillation of solar neutrinos proved

    by measuring CC (electron flavor) interactions and NC (all flavors) interactions separately in **D_2O**
  - total flux agrees with Standard Solar Model !

- **2002: KamLAND (reactors neutrinos, liquid scintillator detector)**
  - observe and measure oscillations of electron anti-neutrinos from reactors;
- **2007: Borexino (liquid scintillator)**
  - First real time observation of ^7Be neutrinos, low energy ^8B neutrinos, pep neutrinos, best limit on CNO neutrinos and very recently also pp neutrinos;

First detection: Homestake - Nobel 2002

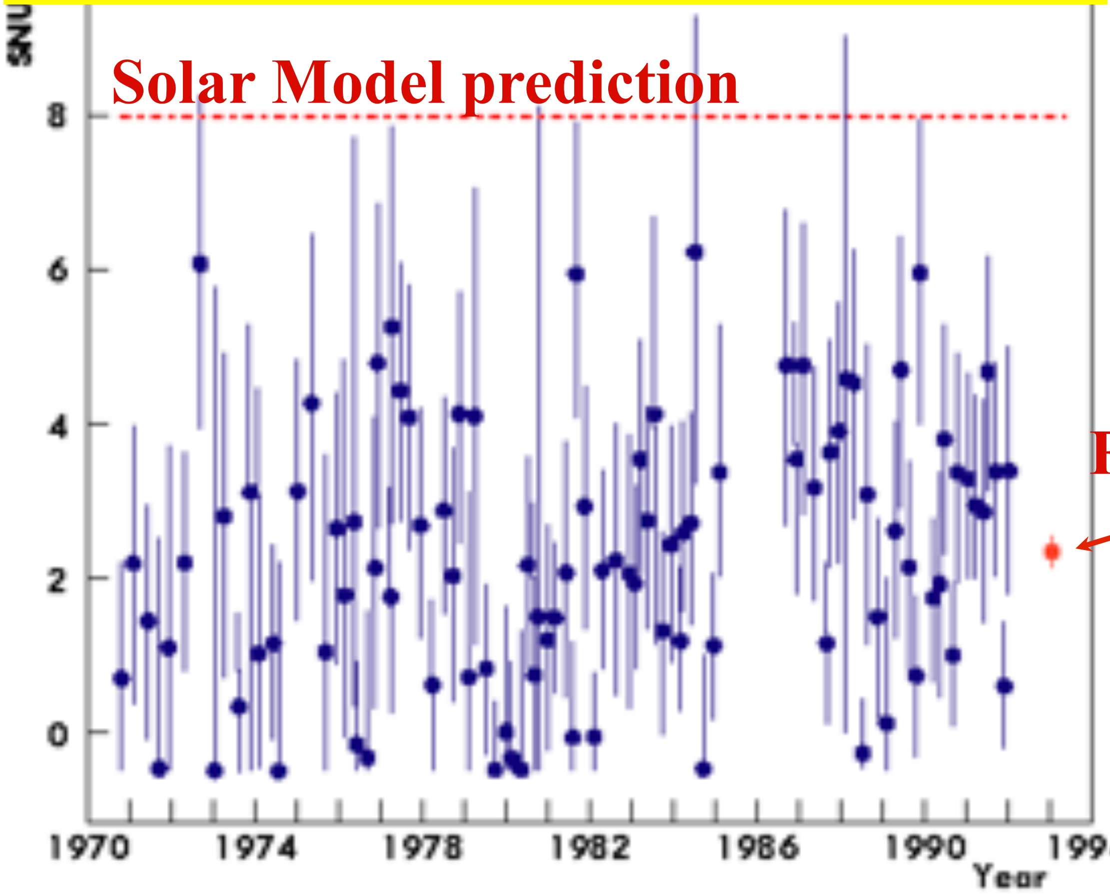
- Raymond Davis experiment: collect ~1 atom/day out of 10^{31}
    - Charged interaction, but no detection of the electron

$$\nu_e + {}^{37}\mathrm{Cl} \text{ --> } e^- + {}^{37}\mathrm{Ar}$$

- Target: a tank with 614 t of liquid soap (C_2Cl_4) placed 1.5 km deep underground; taking data 1970 – 1994.
- Extraction with filters and counting of ^{37}Ar decays (32 d)

$$e^- + {}^{37}\mathrm{Ar} \text{ --> } \nu_e + {}^{37}\mathrm{Cl}$$

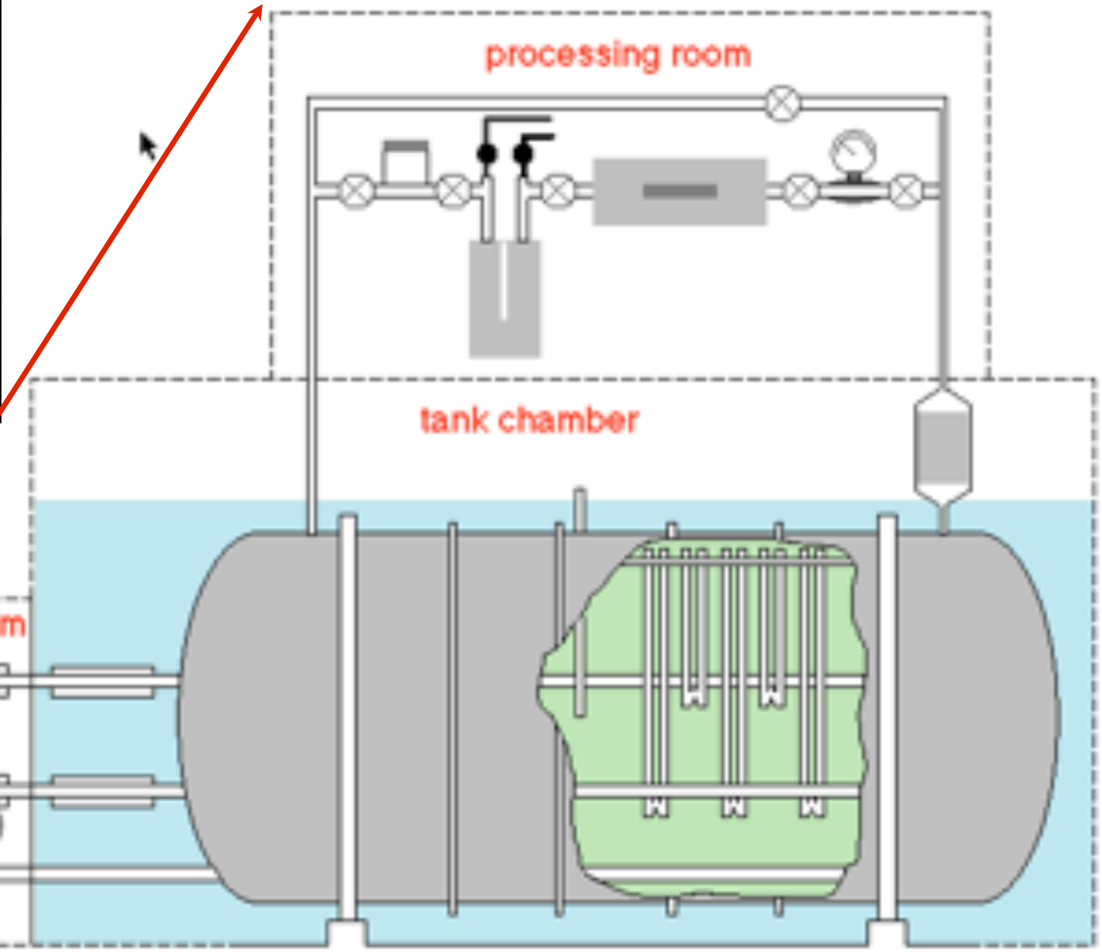
Only 2200 atoms of ^{37}Ar counted in 25 y



Solar Model prediction

Final Result

2.56 ± 0.16 ± 0.16 SNU



1 SNU (Solar Neutrino Unit) = 10^{-36} interactions on target nuclei per second

Super-Kamiokande: 1986- Nobel 2002

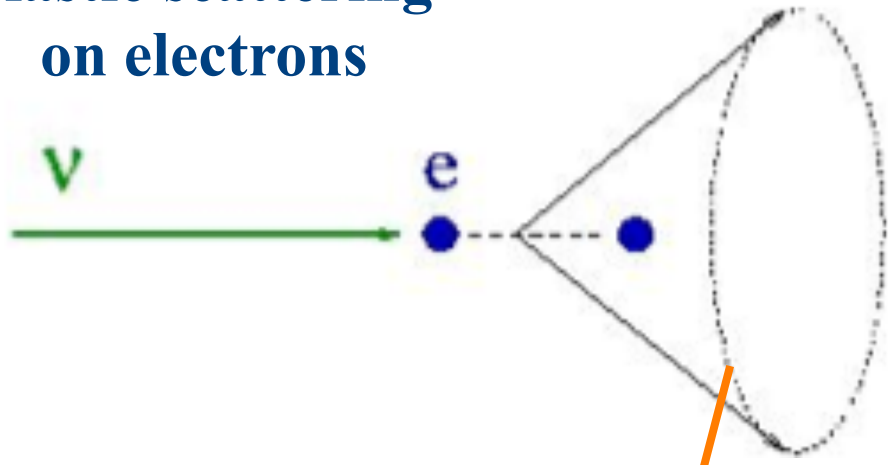
the first real-time solar neutrino detection

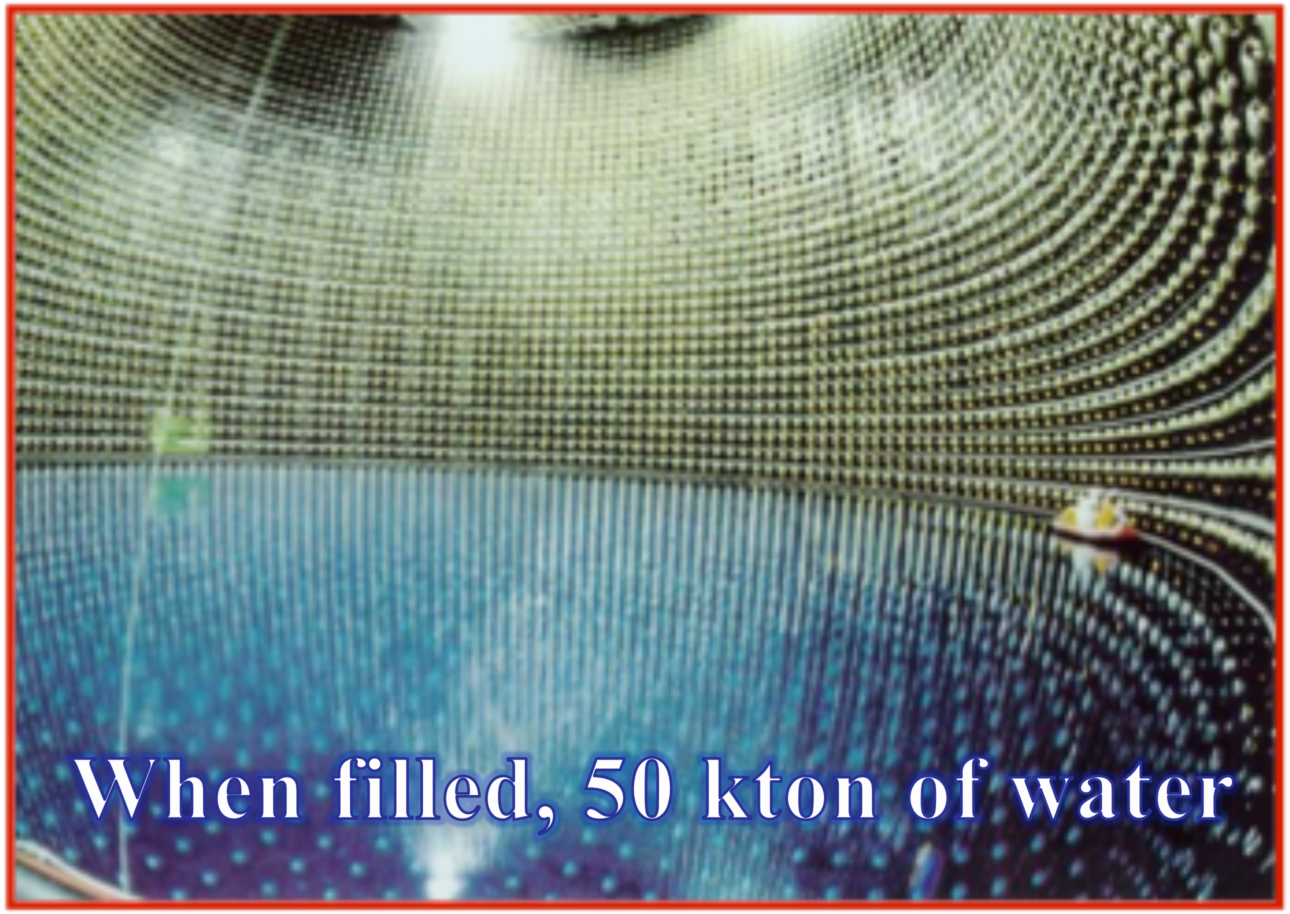
- Detection in Water (NC):

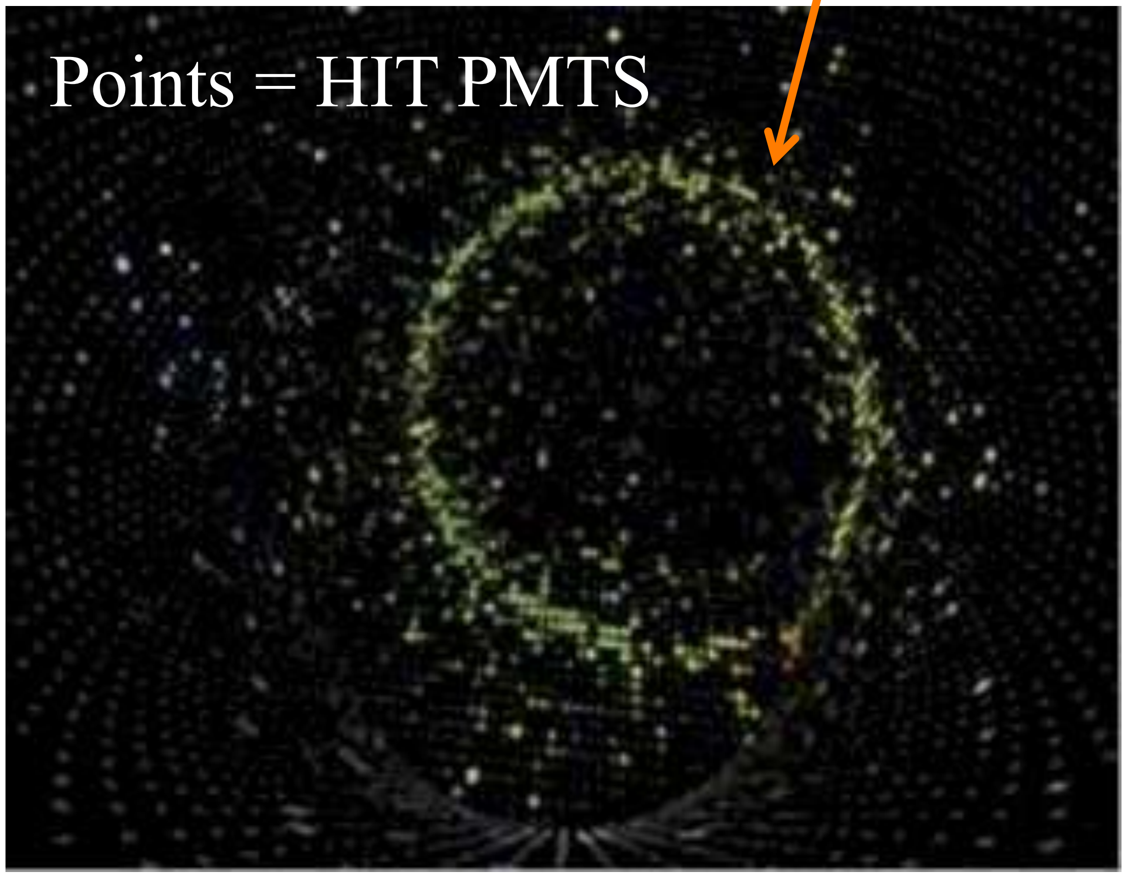
$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$$

  - Diffused electron emits Cherenkov light along a cone
  - This light is detected by a large set of PMTs
  - The amount of light is proportional to energy
  - The space-time distribution yields the direction

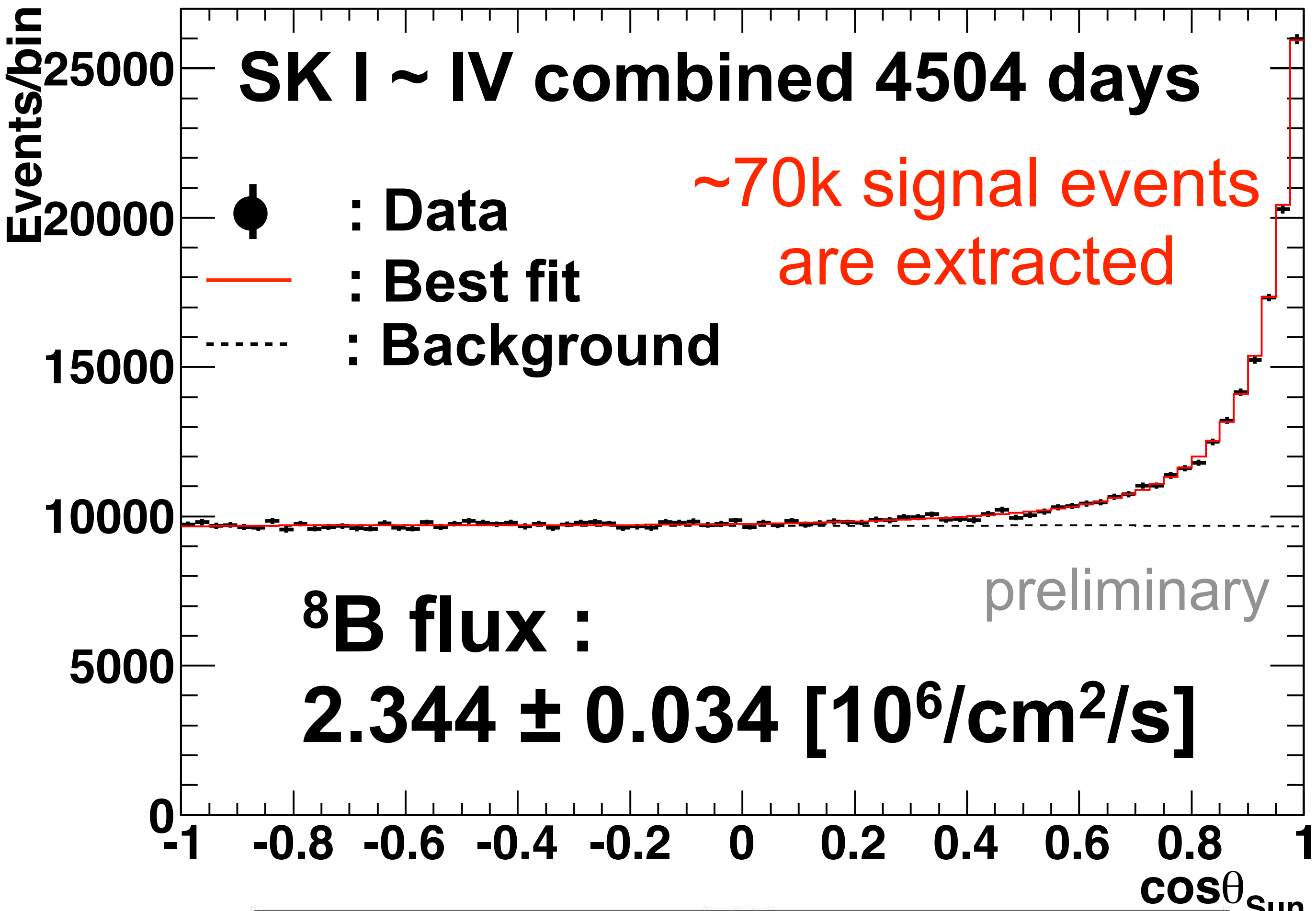
elastic scattering on electrons







Super-Kamiokande latest results

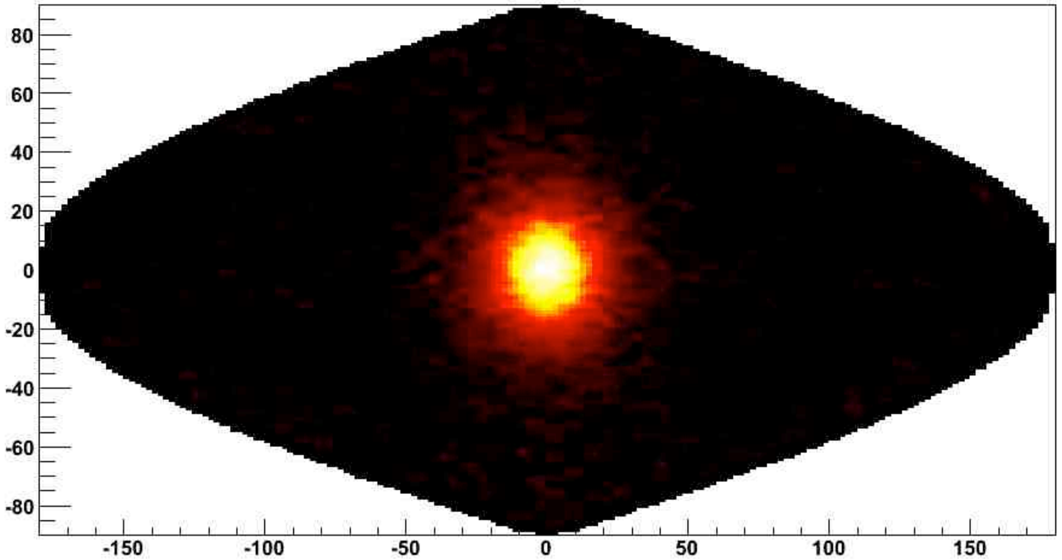


SK I ~ IV combined 4504 days

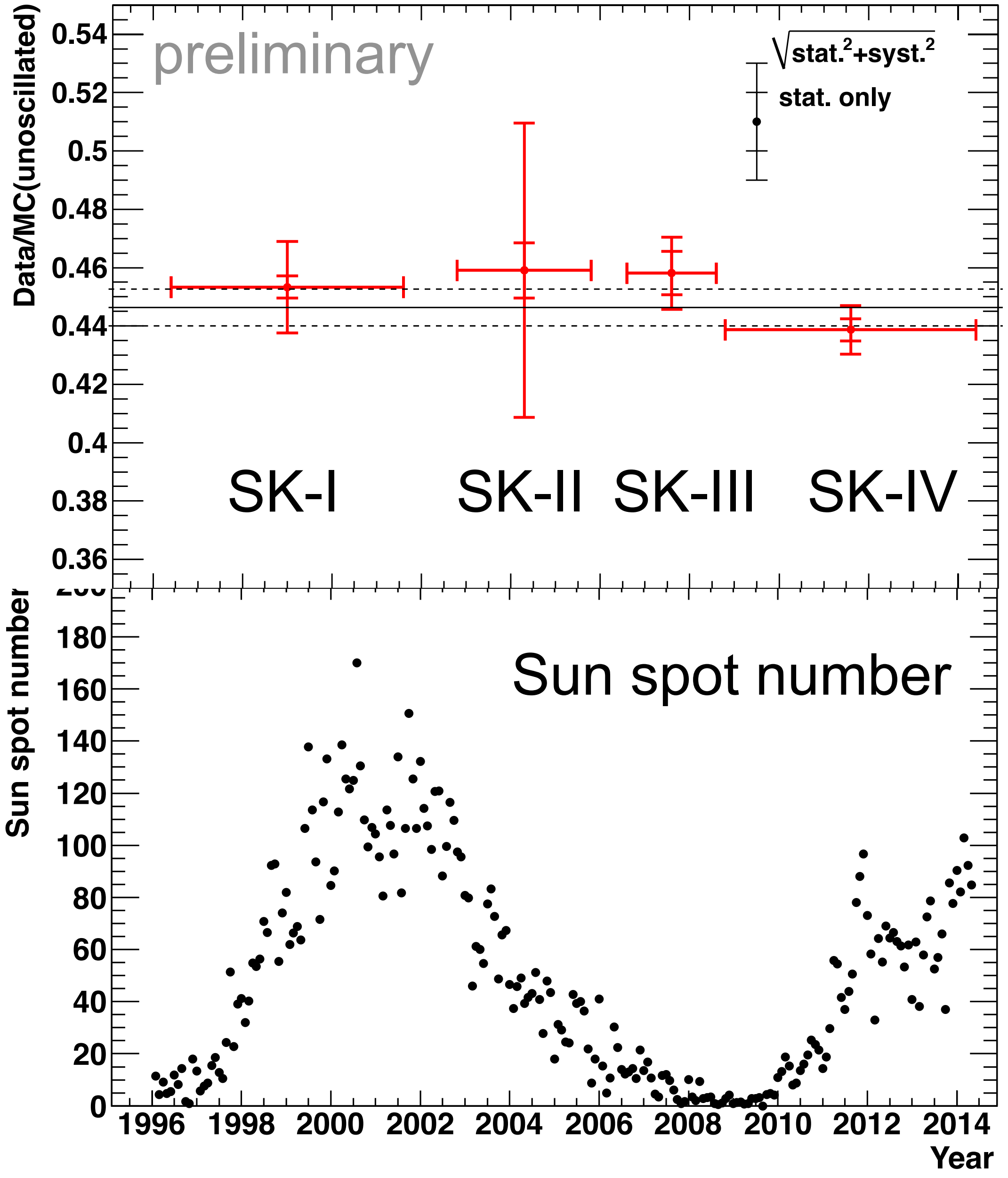
~70k signal events are extracted

^{8}B flux :

2.344 ± 0.034 [10^6/cm^2/s]



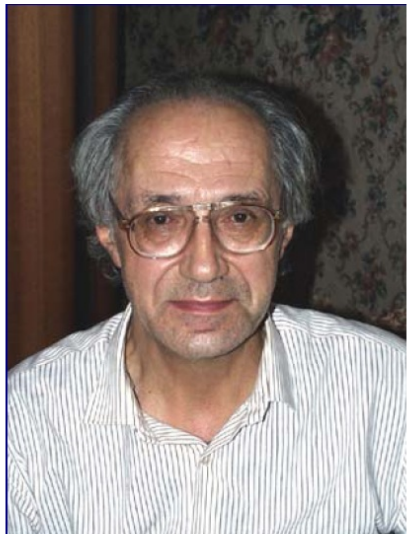
The Sun's picture in neutrinos!



No correlation with solar activity is seen.
More sophisticated analyses such as
yearly flux plot are being prepared.

Radiochemistry again: Gallium experiments

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



idea of Kuzmin
1965

- Detection of **low energy pp neutrinos (threshold 233.2 keV)**
  - Theoretical error (at that time) much lower: **pp is constrained by Sun's luminosity**
    - The **efficiency** of the detector carefully studied with a ^{51}Cr **artificial neutrino source**

GALLEX/GNO@LNGS, Italy

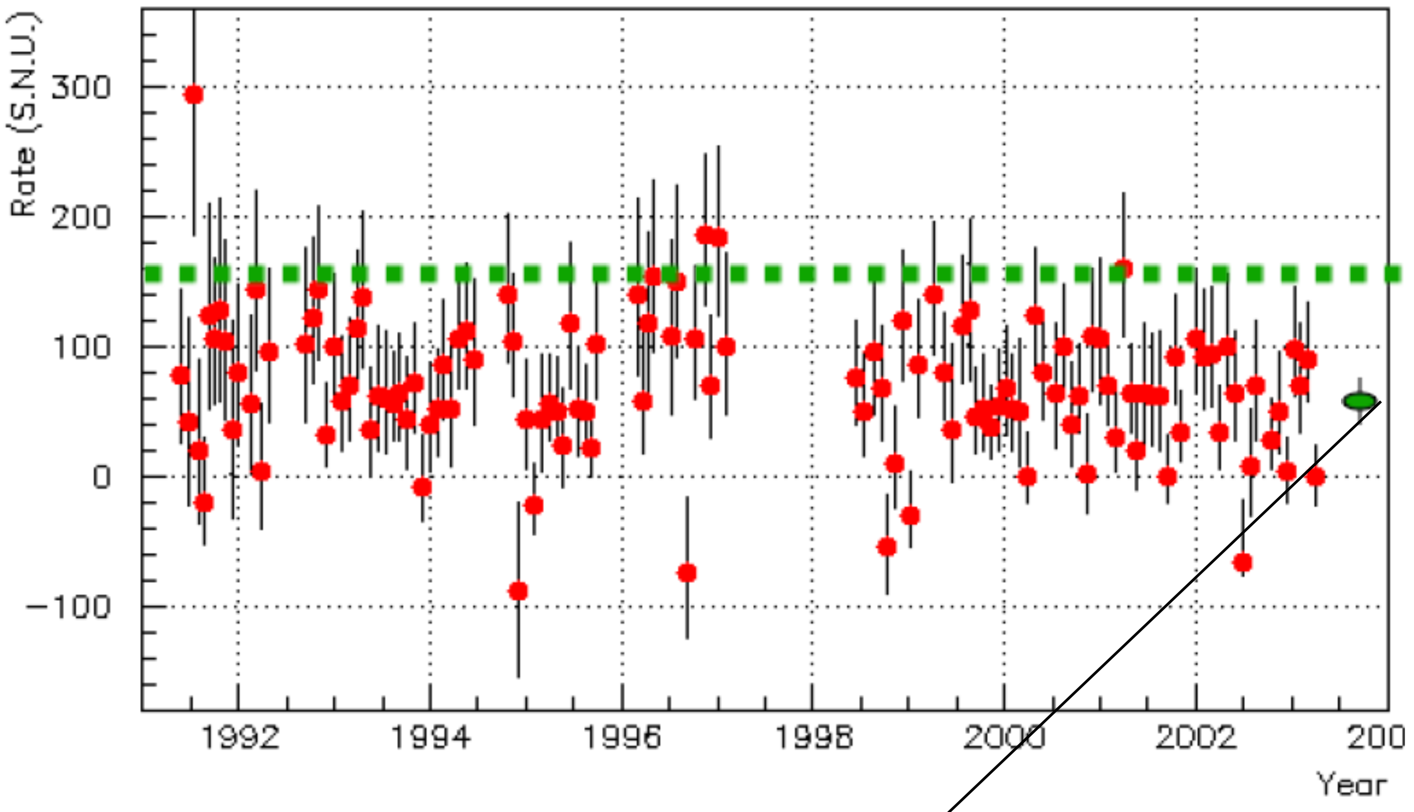
Till Kirsten (MPI Germany)

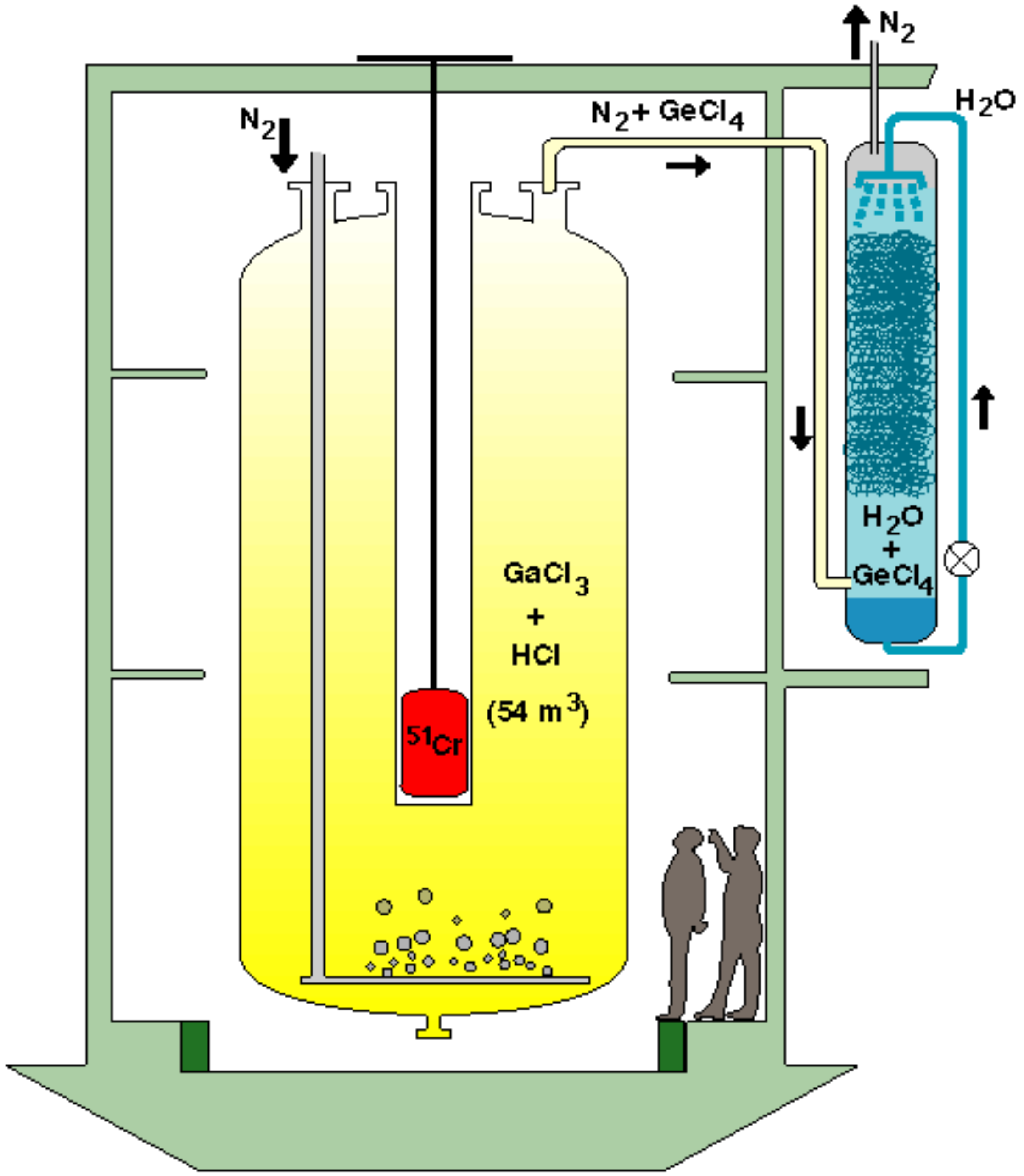
SAGE @ Baksan, Russia

Vladimir Gavrin (Russia)

- Both experiments measured deficit also for low energies: the community started seriously to believe the Solar Neutrino Problem

1991-2003 Gallex-GNO experimental results





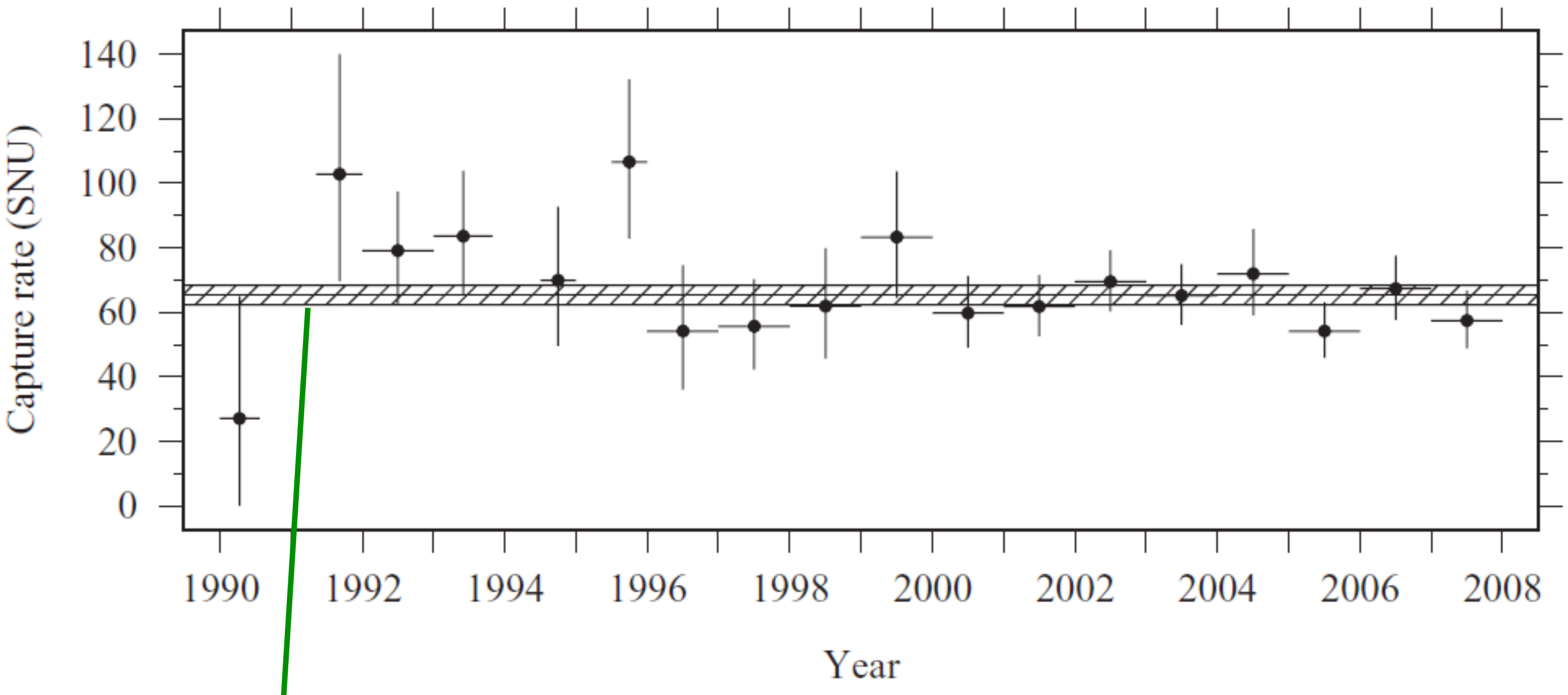
Final result:

67.6 ± 5.1 SNU

0.541 ± 0.081

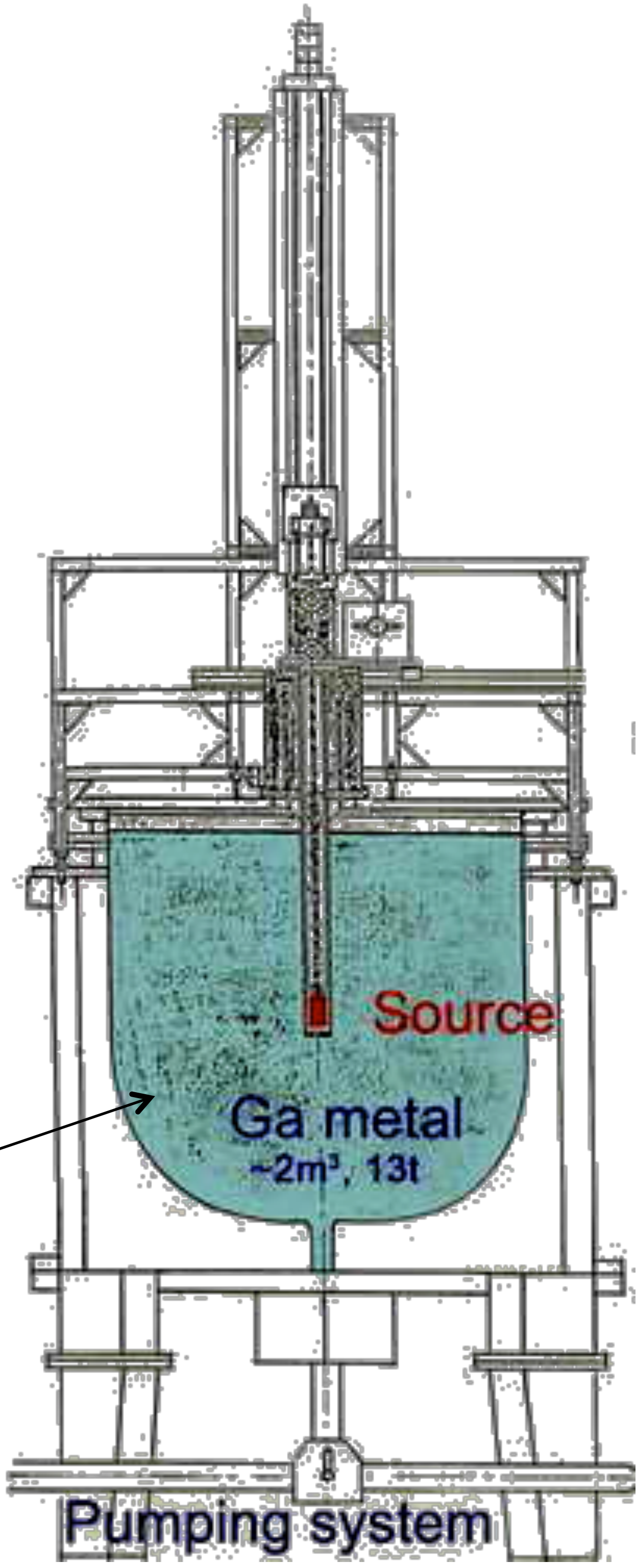
as a fraction of SSM prediction

1990-2011 SAGE experimental results

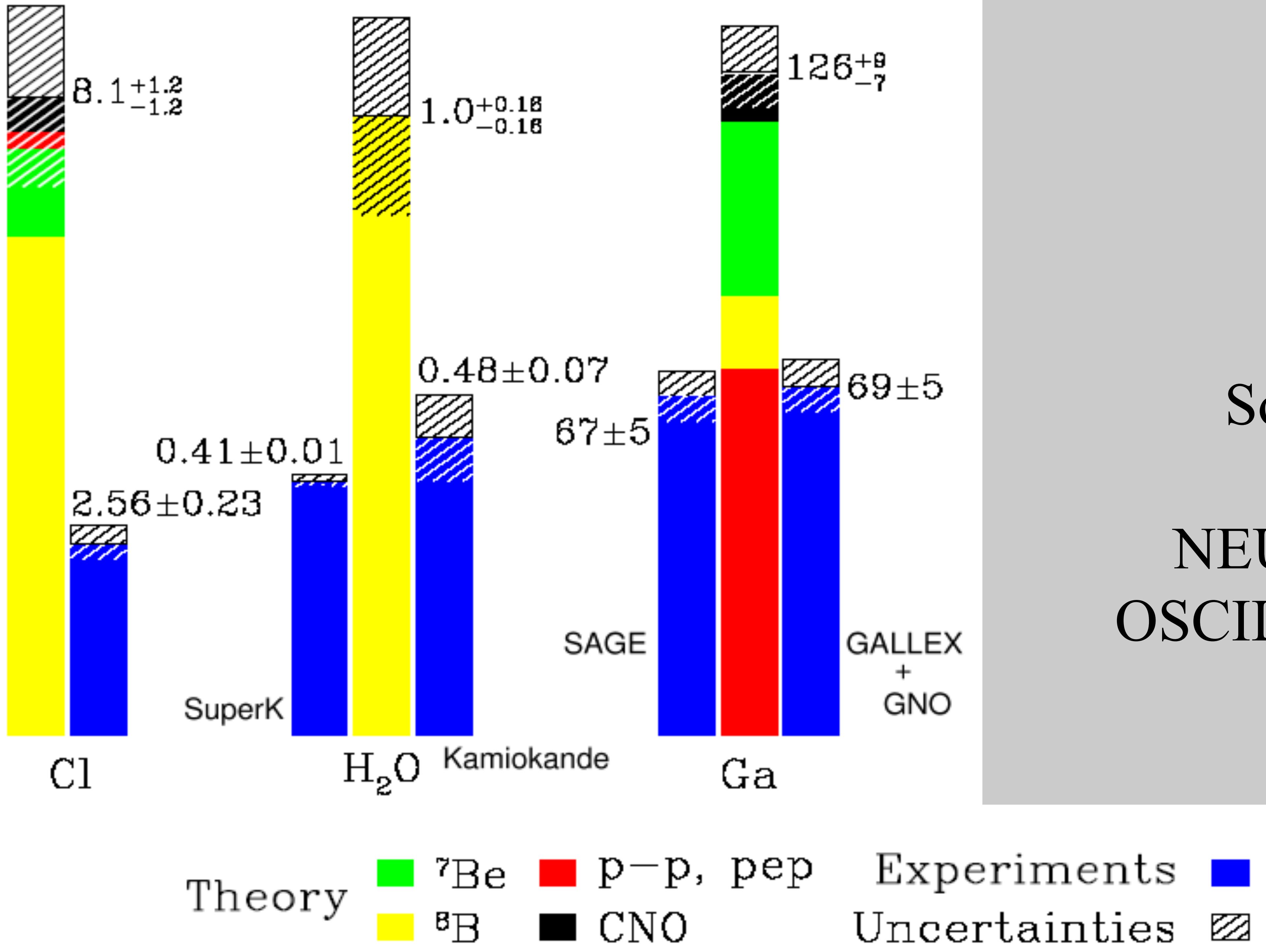


Final result: $65.4^{+3.1}_{-3.0}{}^{+2.6}_{-2.8}$ SNU

Liquid metallic Ga in the window of chemical reactor



Solar Neutrino Problem: energy dependent deficit of observed solar neutrinos with respect to the SSM;



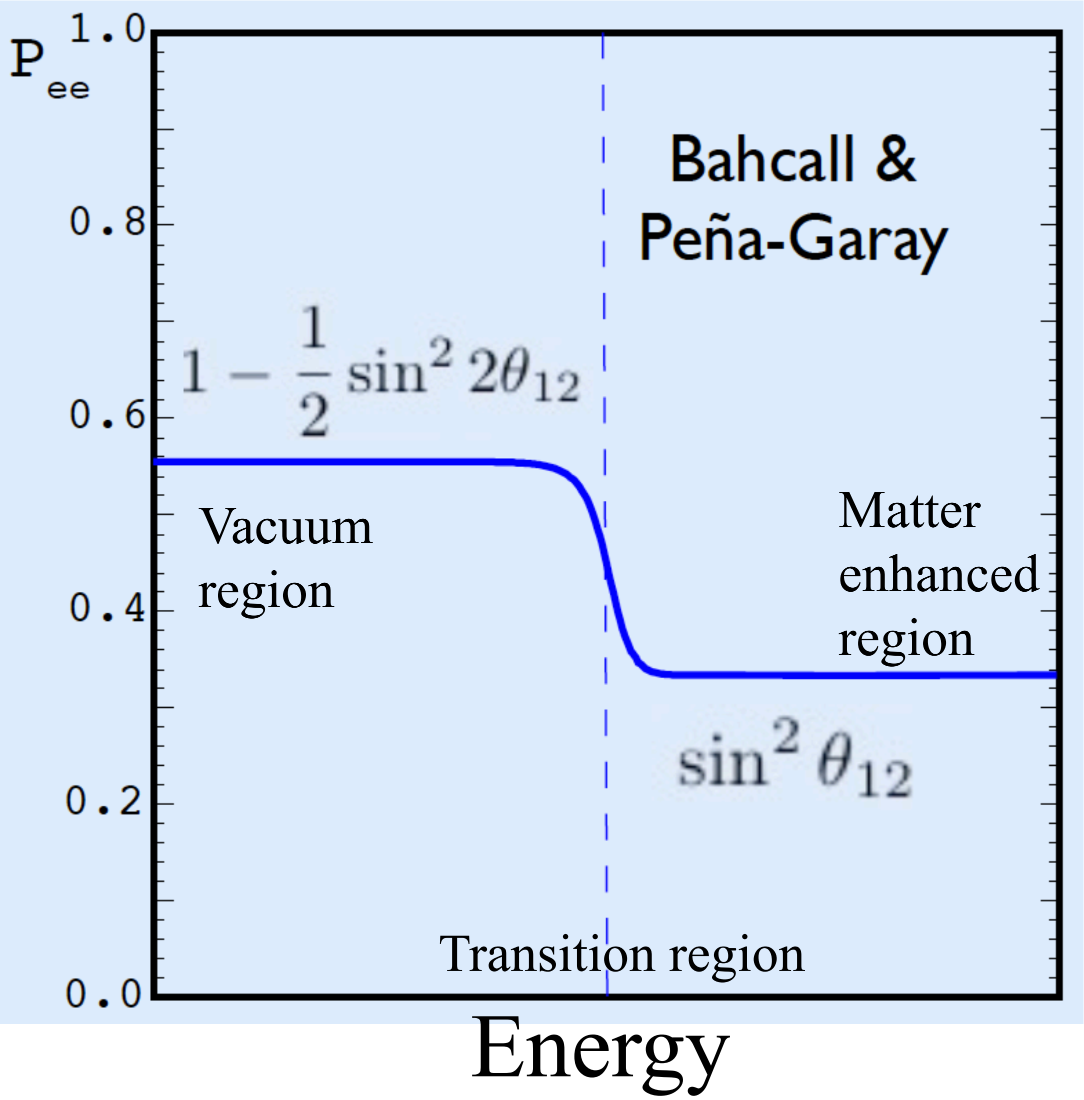
SNO

Solution

NEUTRINO
OSCILLATIONS

Neutrino oscillations in matter

- Being matter made of e^- (and not μ / τ), it affects oscillations (Wolfenstein, '78)
  - Both charged and neutral current interactions between ν_e and e (for ν_μ and ν_τ NC only)
    - **"Refractive index"** for ν_e is different from the other flavors
  - The effect can be enhanced by a **resonance** Mikheyev & Smirnov, 1985
  - **This yields the necessary energy dependence of the "survival probability": P_{ee}(E)**
    - Low energy pp neutrinos are affected much less than high energy one (^{8}B), where matter MSW is maximal
    - The region in between (1-3 MeV) is called the **"transition region"**



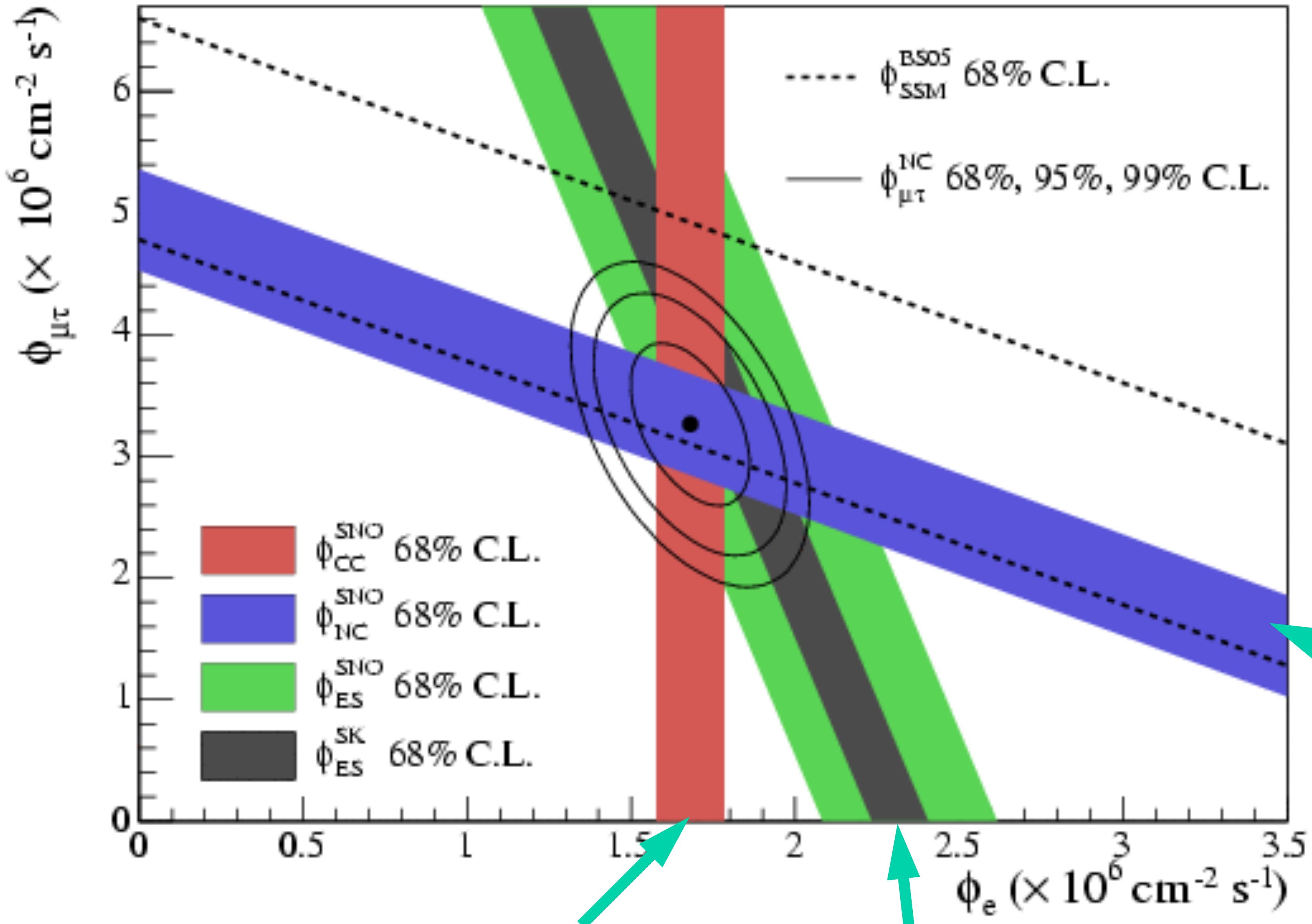
- No data in the transition region were available before Borexino

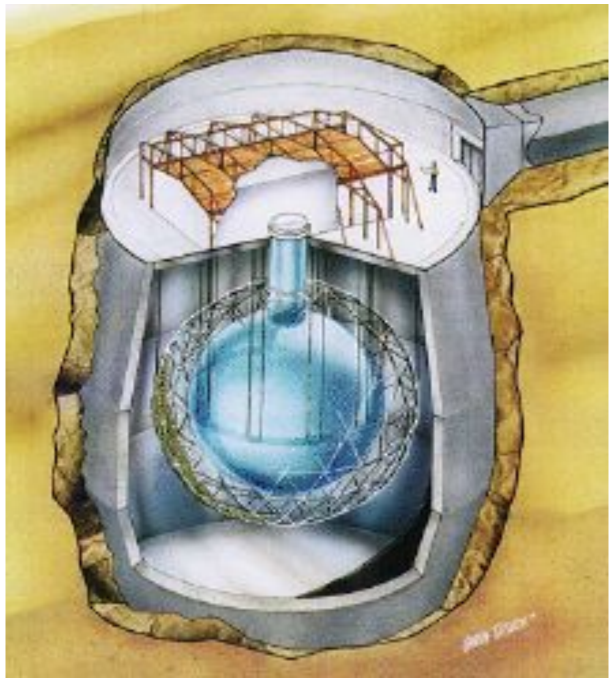
SNO: Heavy Water Cherenkov detector in Canada
2001: Discovery of solar neutrino oscillations

Prove that $\Phi(\nu_e)$ is DIFFERENT from $\Phi(\nu_\mu, \nu_\tau)$

Prove that the TOTAL neutrino flux is consistent with the Standard Solar Model;

Big success for SNO, neutrino oscillations, and solar model theoreticians;



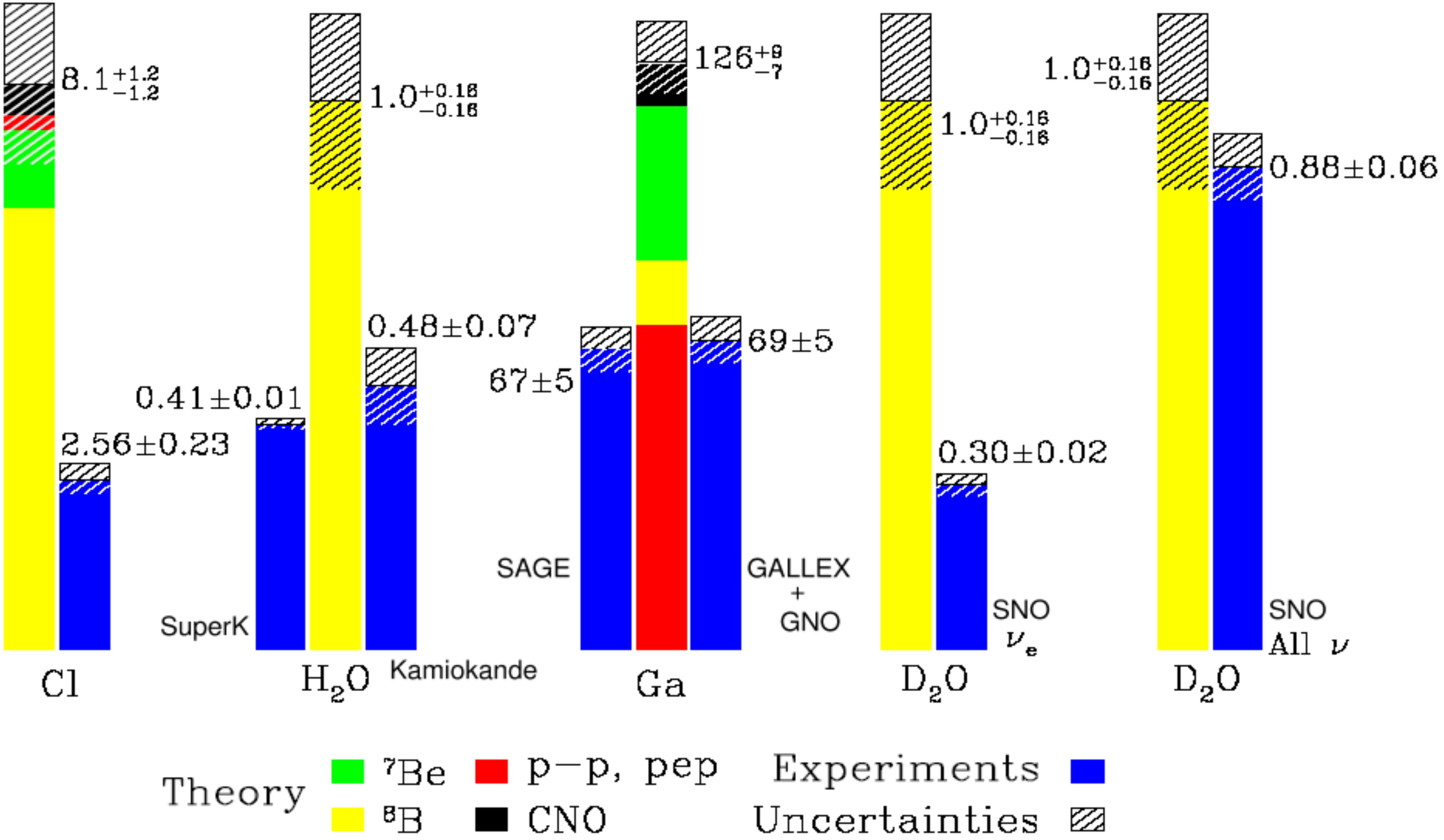


NC

CC (only e-flavour)

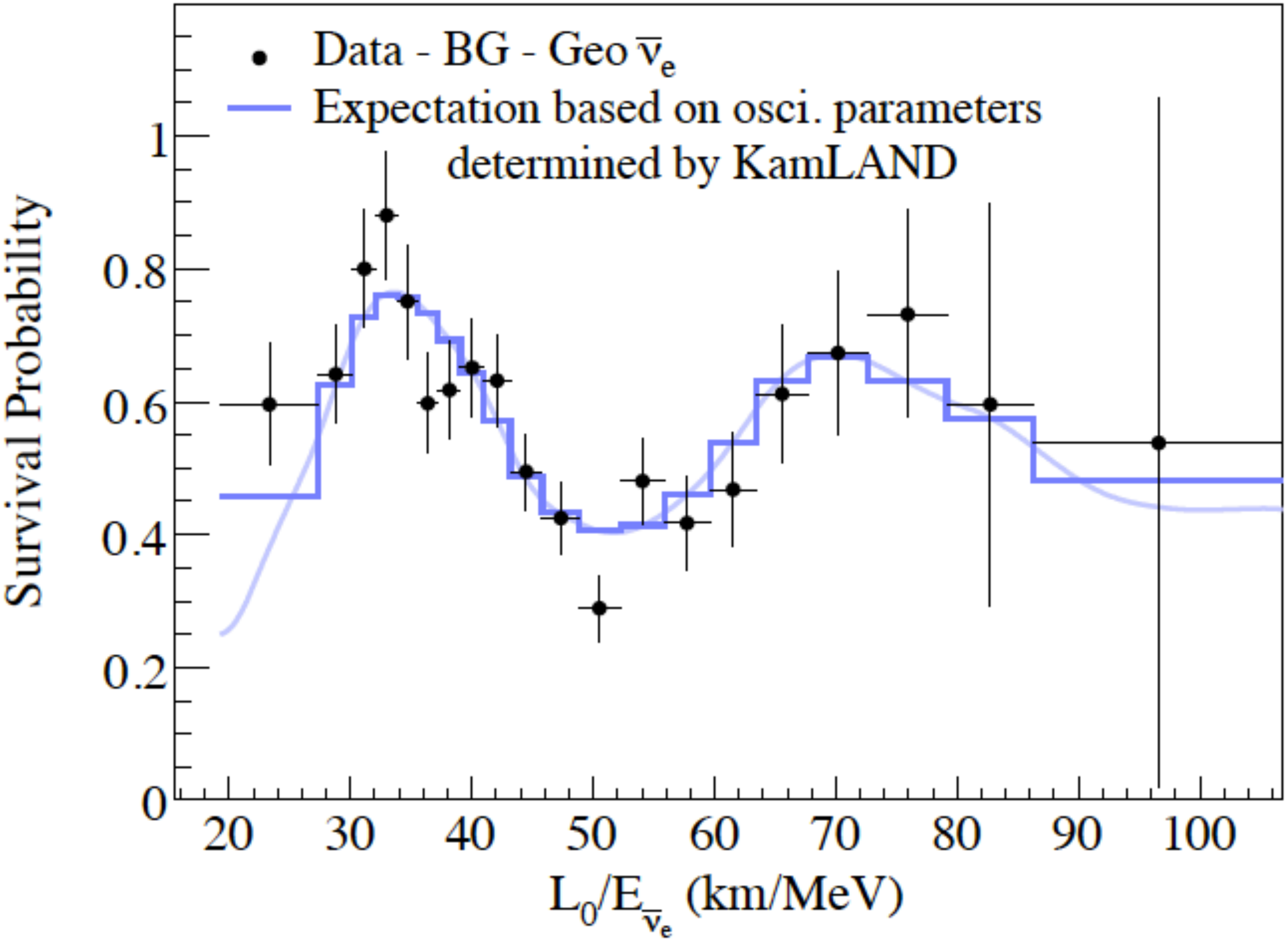
ES

Solar Neutrino Problem Solved

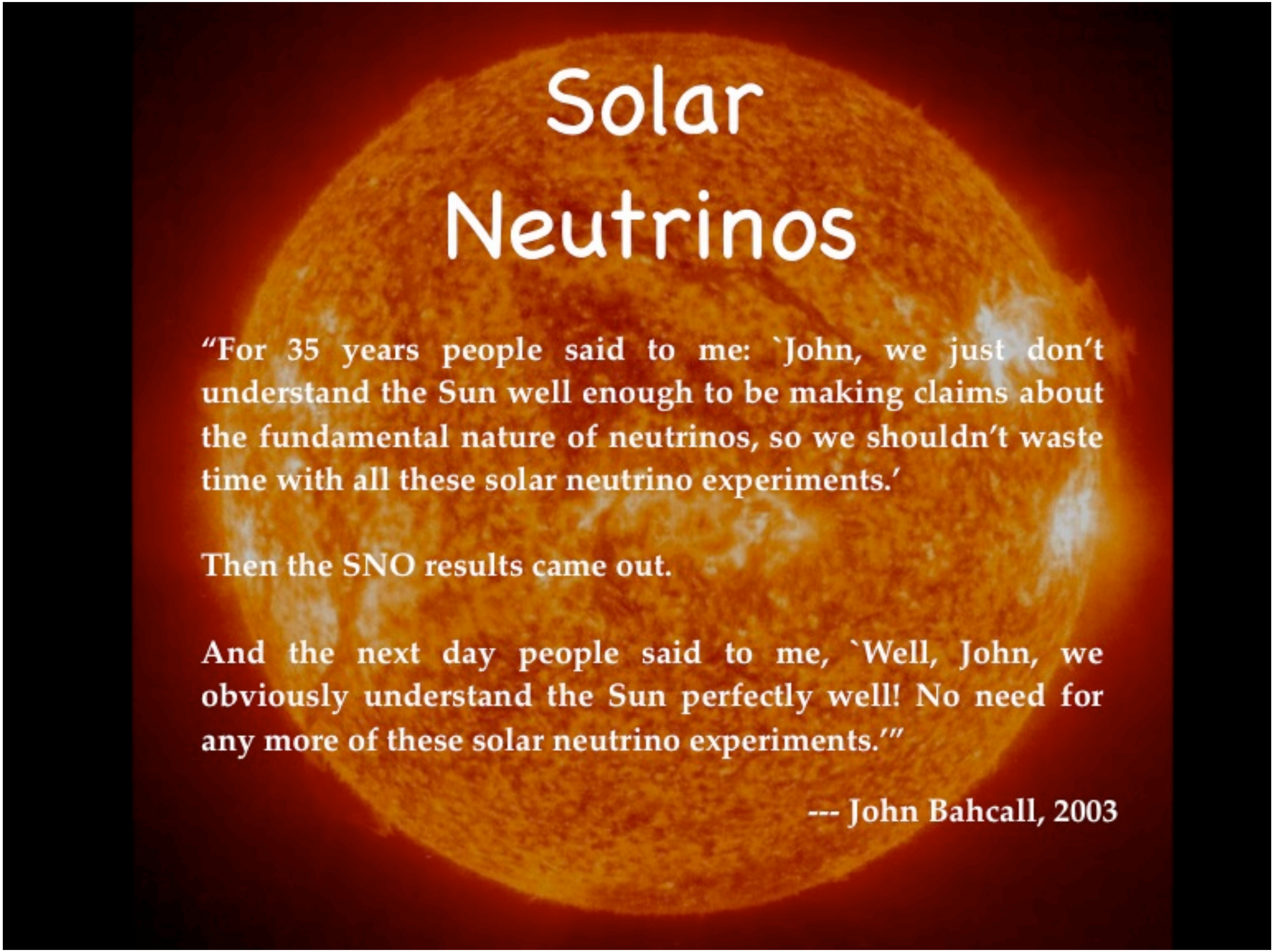


Precise measurement of Δm^2 and final proof of oscillations (on anti-neutrinos from reactor!)

KamLAND, 2002



THE FIRST OSCILLATION PATTERN WAS SEEN!



Solar Neutrinos

"For 35 years people said to me: `John, we just don't understand the Sun well enough to be making claims about the fundamental nature of neutrinos, so we shouldn't waste time with all these solar neutrino experiments.'

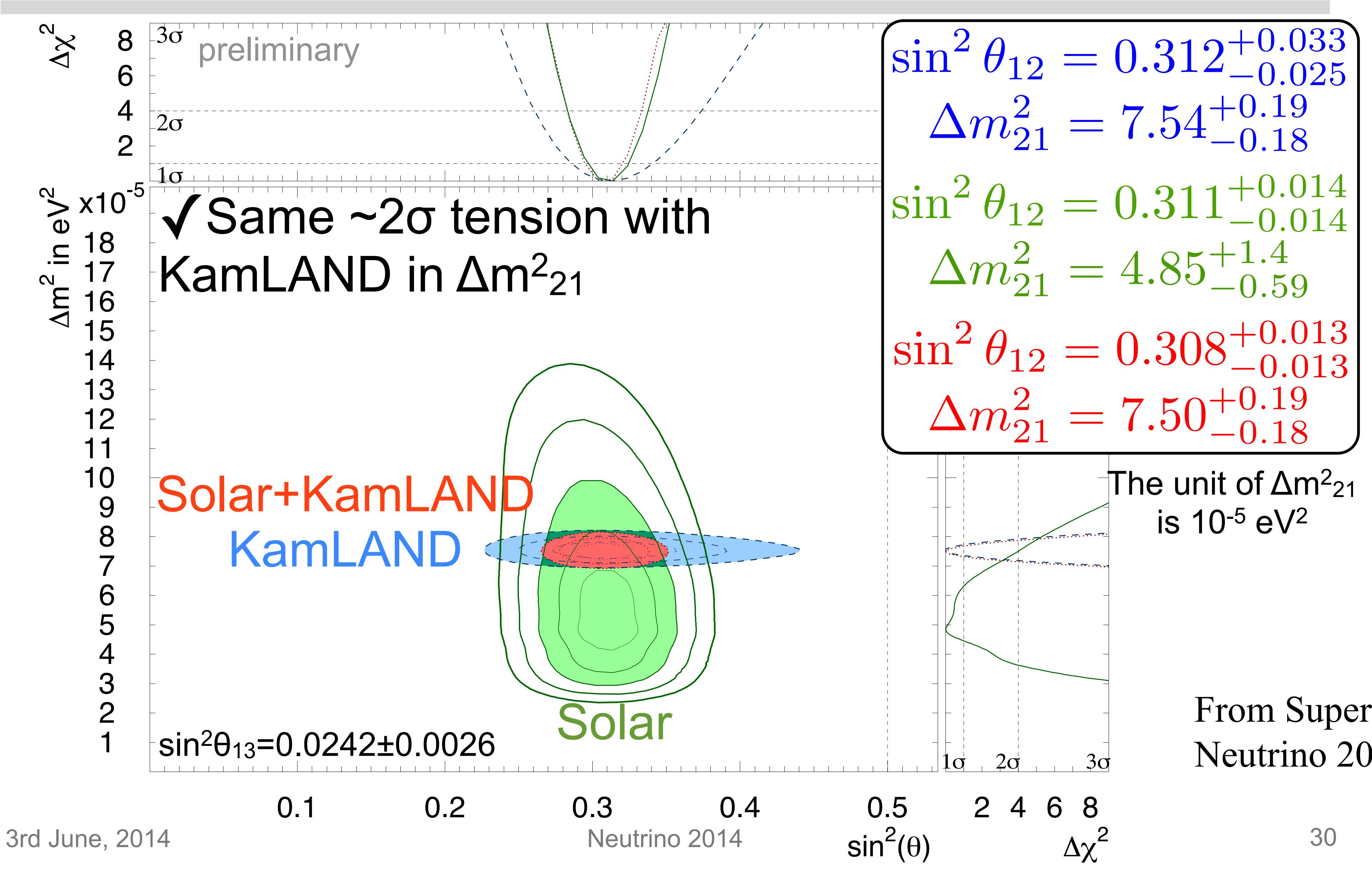
Then the SNO results came out.

And the next day people said to me, `Well, John, we obviously understand the Sun perfectly well! No need for any more of these solar neutrino experiments.'"

--- John Bahcall, 2003

Where we are today?

- solar neutrinos do oscillate in their trip from the Sun's core to the Earth;
- LMA (Large Mixing Angle) solution: range of allowed Δm^2 and $\theta_{12;}$
- oscillation is enhanced by the **MSW effect**, yielding an **energy-dependent ν_e survival probability (P_{ee});**
- the active neutrino flux ($\nu_e + \nu_\mu + \nu_\tau$) is in fair agreement with the SSM



✓Same ~2σ tension with KamLAND in Δm^2_{21}

$\sin^2\theta_{13}=0.0242\pm0.0026$

$$\sin^2\theta_{12} = 0.312^{+0.033}_{-0.025}$$
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$$
$$\sin^2\theta_{12} = 0.311^{+0.014}_{-0.014}$$
$$\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$$
$$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.013}$$
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$$

The unit of Δm^2_{21} is 10^{-5} eV^2

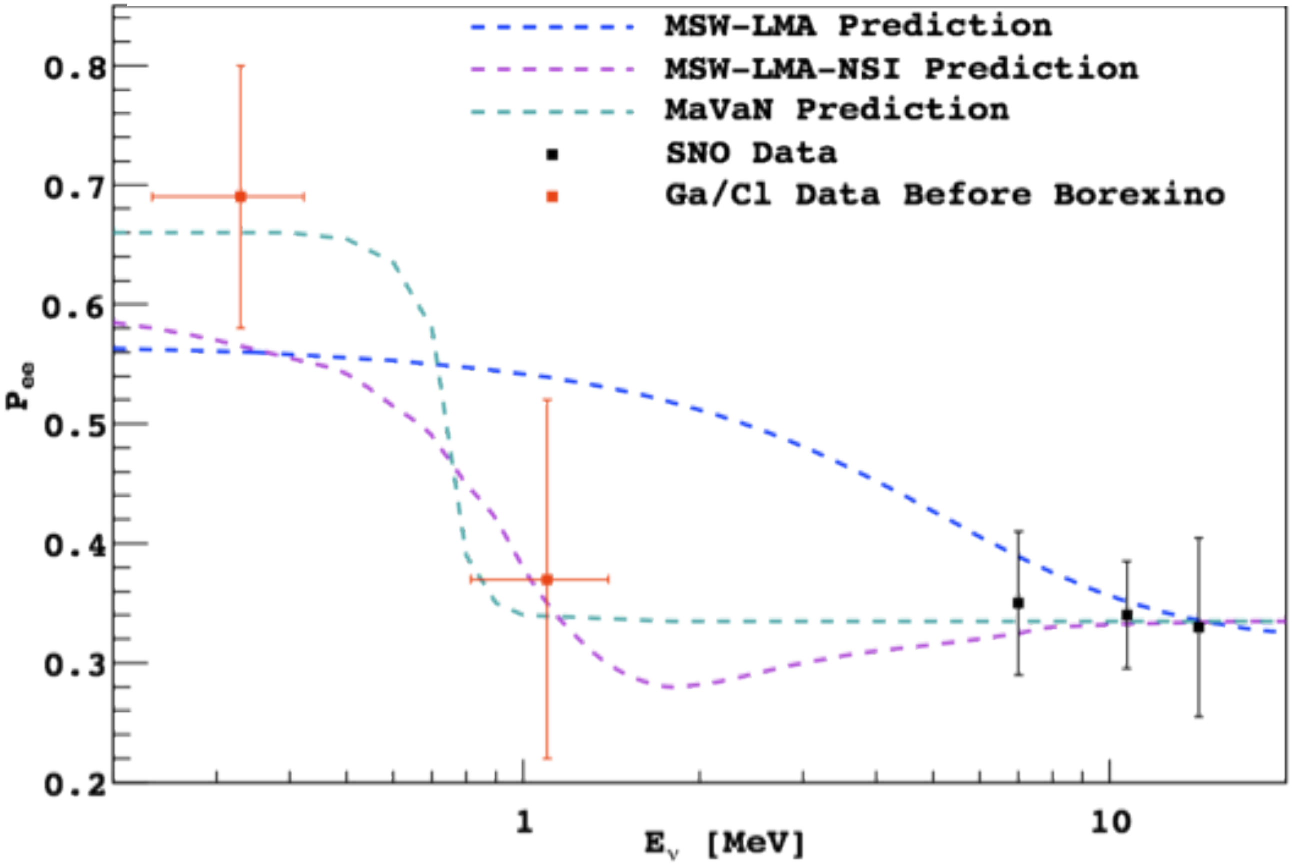
3rd June, 2014 Neutrino 2014 30

From SuperK
Neutrino 2014

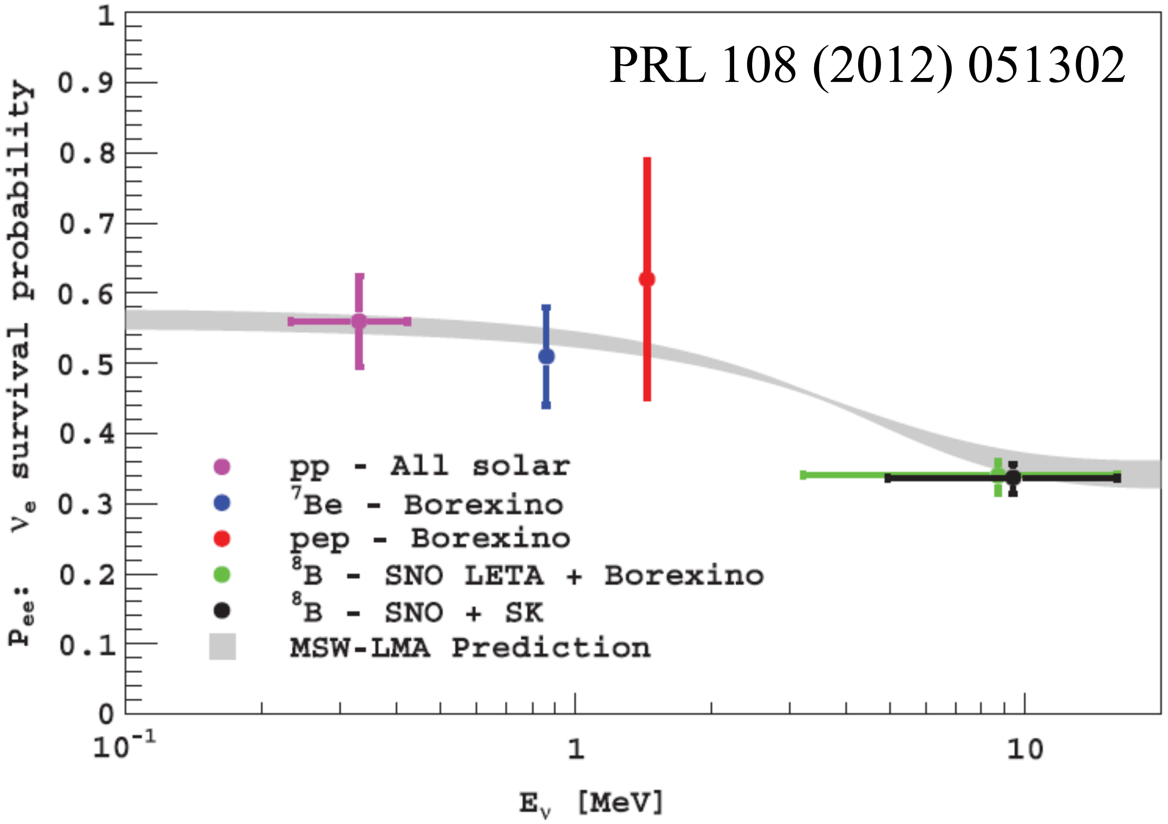
Why to measure solar ν's today ?

- **Neutrino Physics:** MSW-LMA scenario is our current understanding of solar ν oscillations, but there is still room for exotic models (e.g. mass varying neutrinos or non-standard interactions models)

Before Borexino

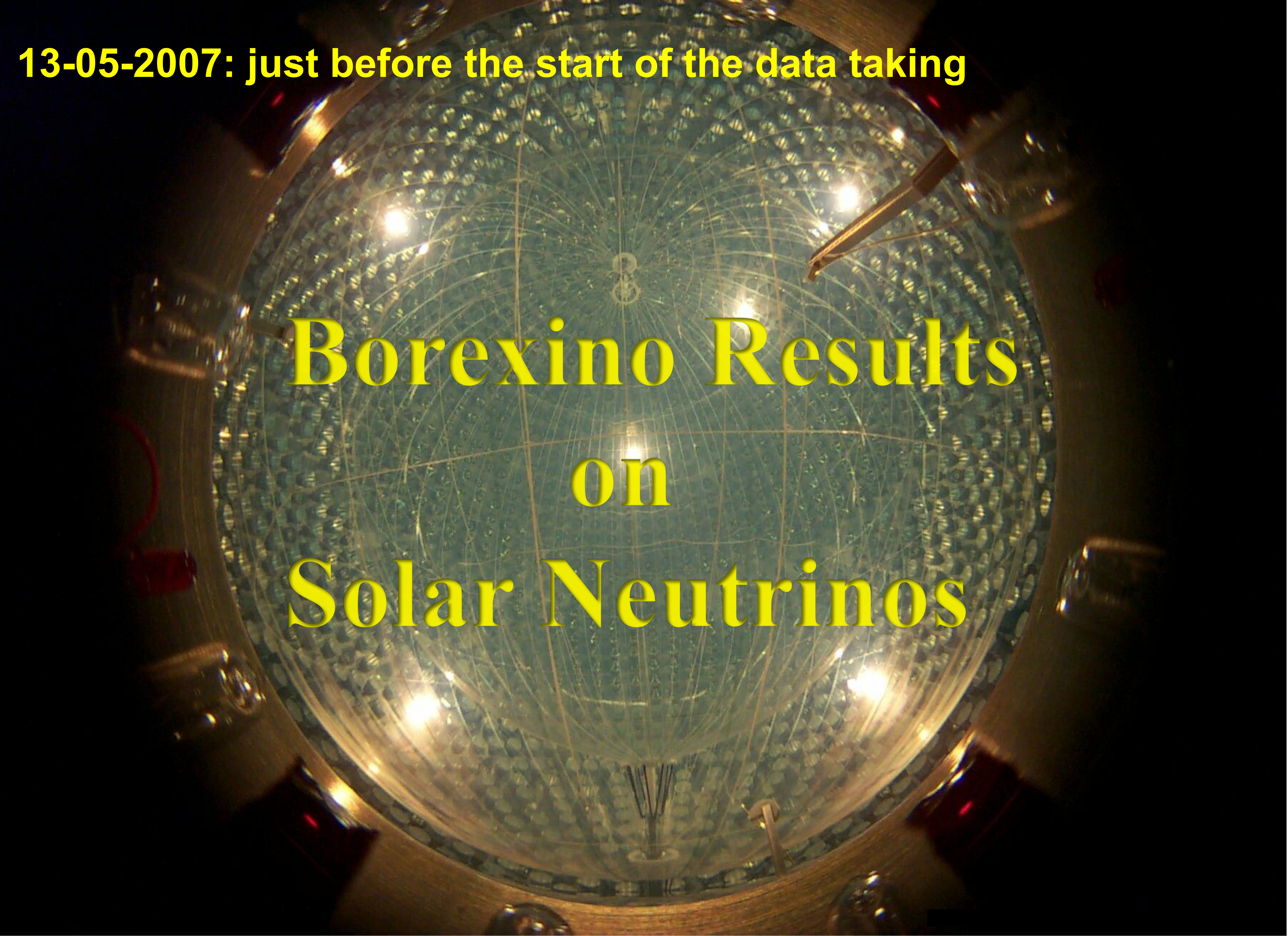


2012



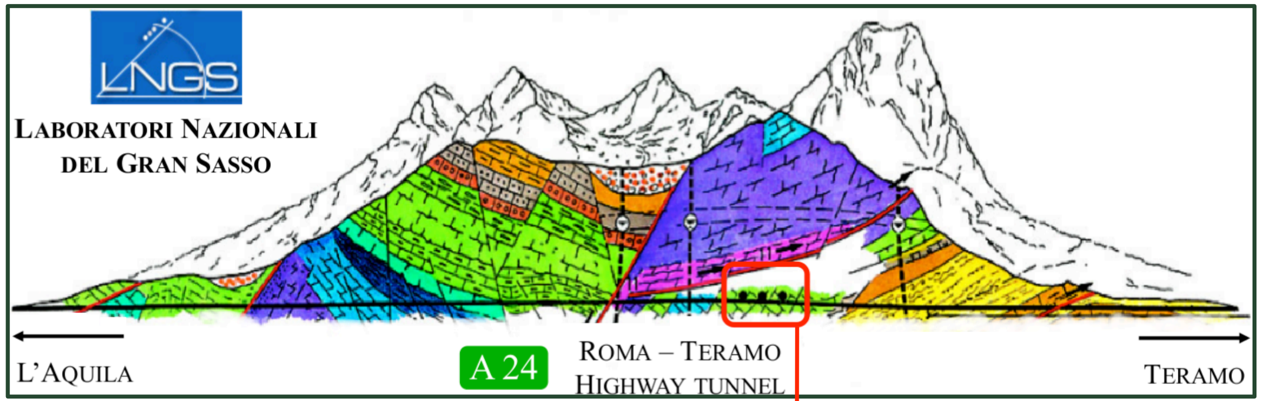
- **Solar Physics:** metallicity problem: Low and High Metallicity models predict different neutrino fluxes!

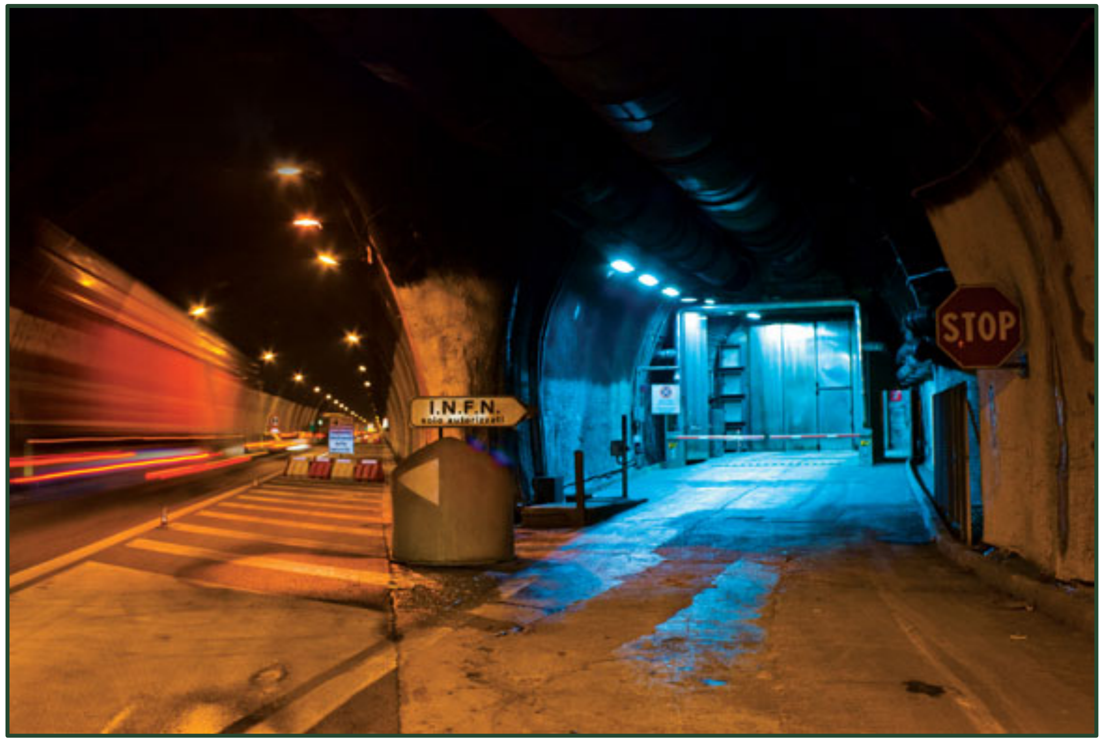
Borexino Results on Solar Neutrinos

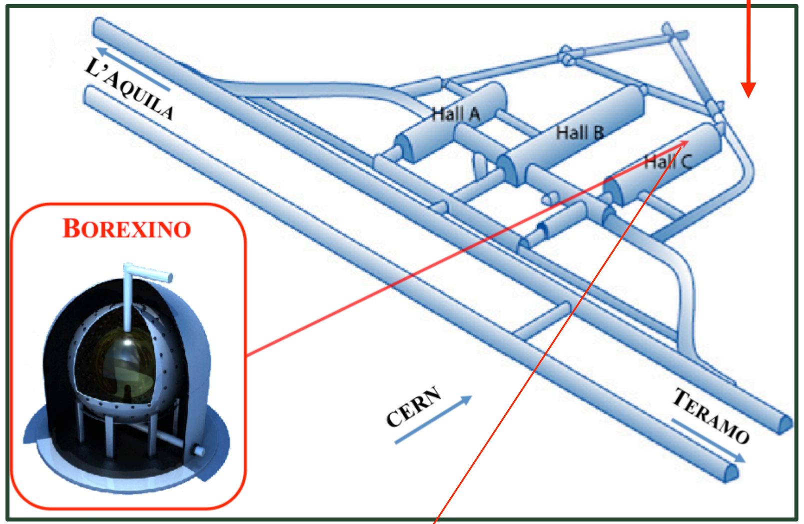


13-05-2007: just before the start of the data taking

LABORATORI NAZIONALI GRAN SASSO / LNGS (ITALY)





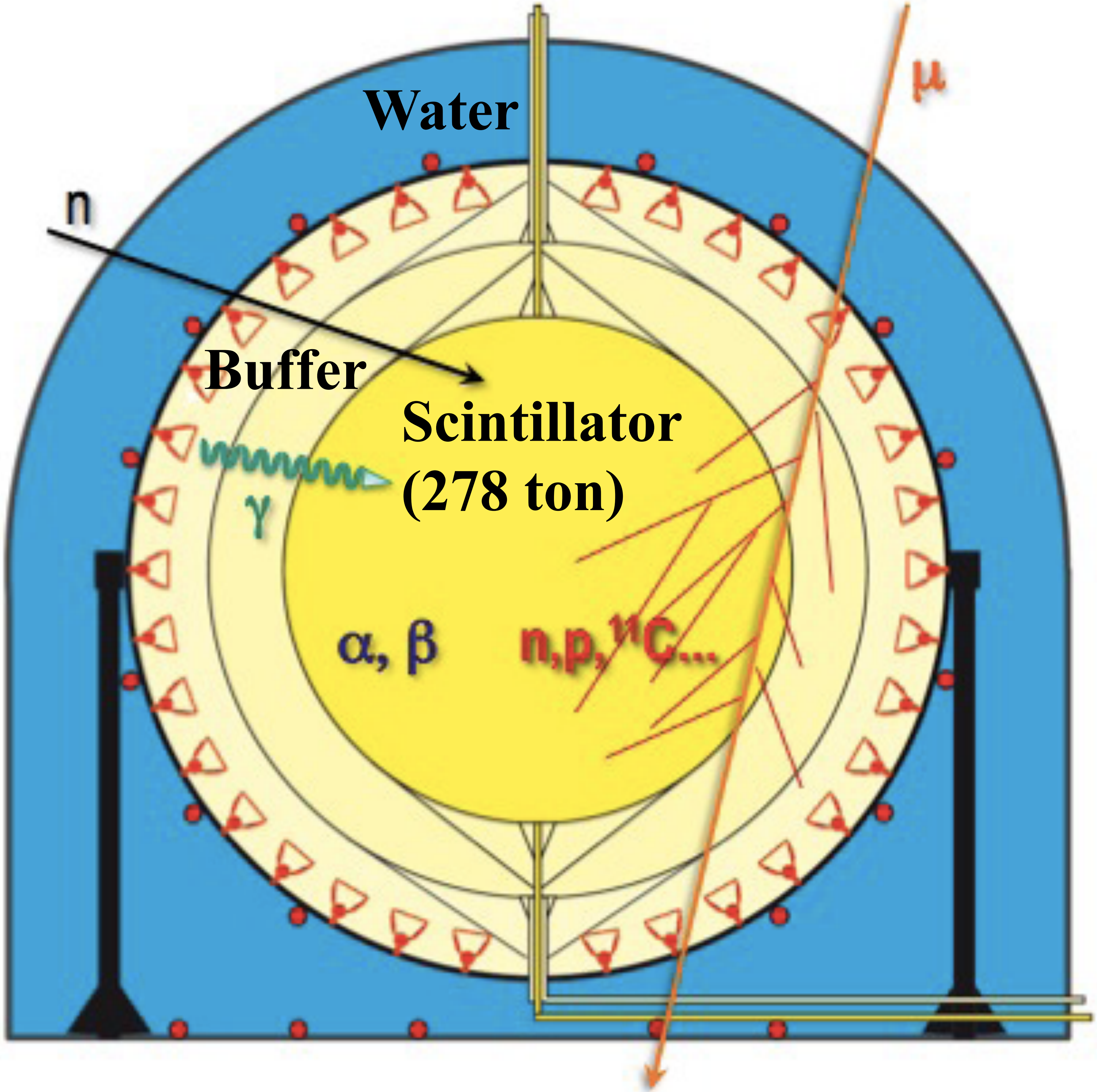


The **LNGS** altitude is 963 m and the average rock cover is about 1,400 m.

The shielding capacity against cosmic rays is about 3,800 meter water equivalent (m.w.e.): the muon flux is reduced of a factor 10^6 respect to the surface.

$$\Phi(\mu) \sim 1\,\mu/\mathrm{m}^2/\mathrm{h}$$

Borexino detector



- **Materials more and more pure** as they get closer to the "core", the Fiducial Volume

- Ultimate background depending on material purity and, mainly, **radioactive traces** in the scintillator at extremely low levels

15 years of work to reach required radio-purity

Why so long to reach the goal ?

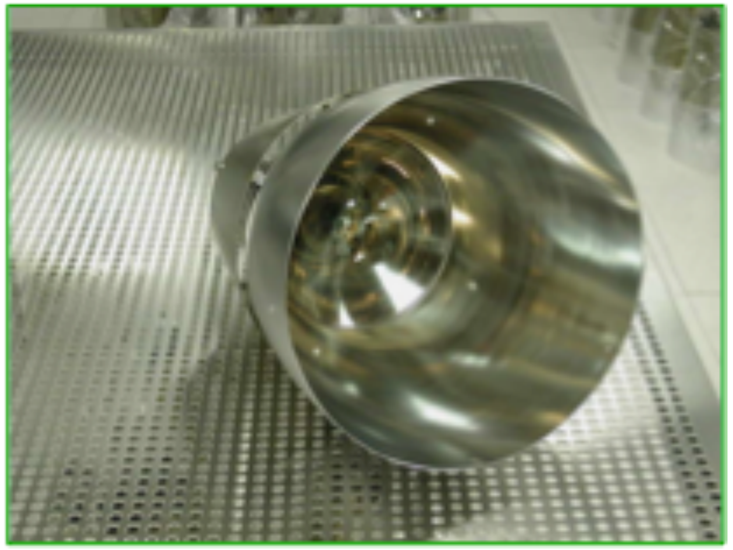
- A few numbers:
  - Assuming **100 ton** of target mass, you expect about **50 events/day** from ^{7}Be solar ν
    - 50 / 86400 / 100 t = ~ **6 10^{-9} Bq/kg**
  - The scattering of a neutrino on an electron is **intrinsically not distinguishable** from a **β radioactivity** event or from Compton scattering from **γ radioactivity**

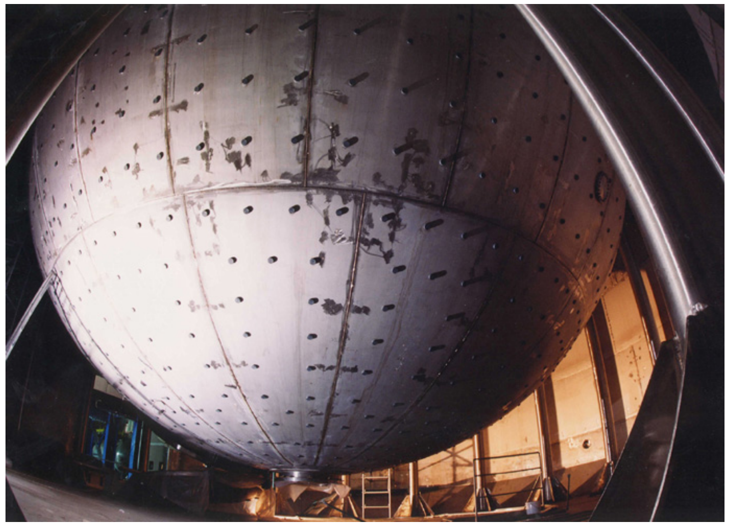
- **BUT:**

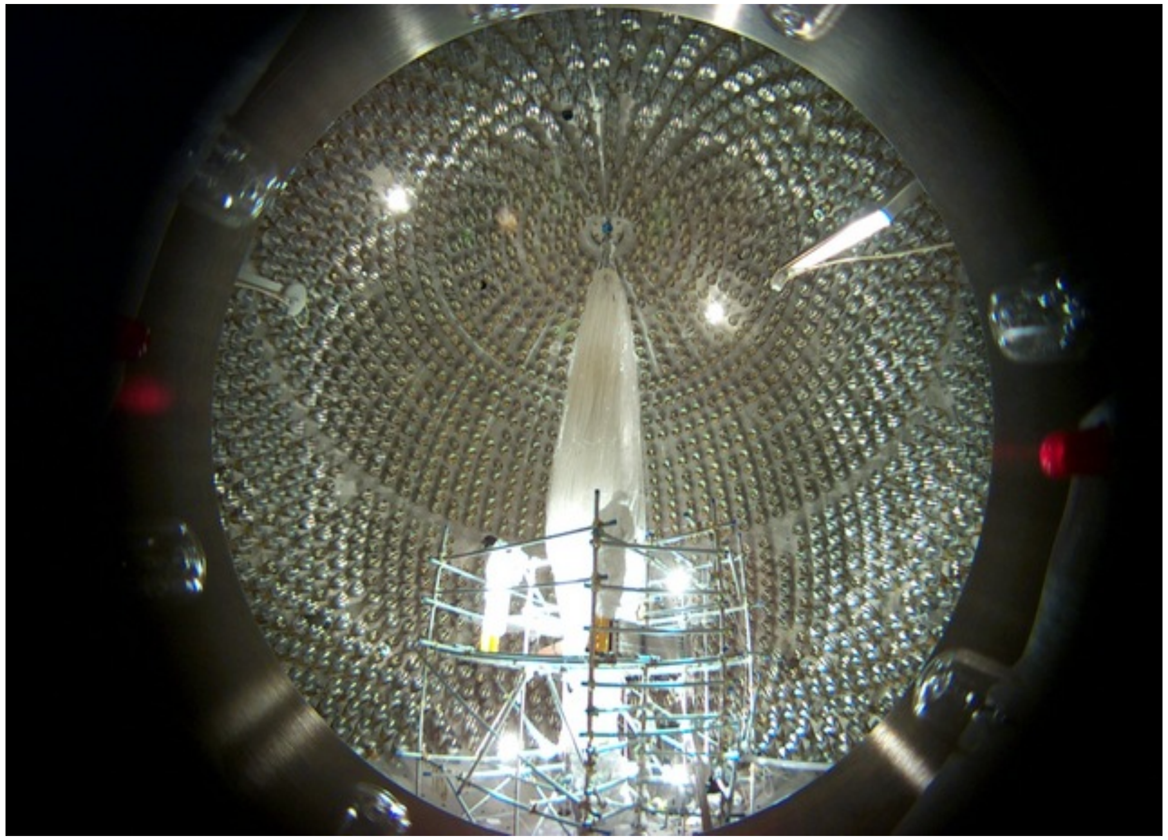
Good mineral water:	**~10 Bq/kg**	**^{40}K, ^{238}U, ^{232}Th**
Air:	**~10 Bq/m^{3}**	**^{222}Rn, ^{39}Ar, ^{85}Kr**
Typical rock	**~100-1000 Bq/kg**	**^{40}K, ^{238}U, ^{232}Th, + many others**

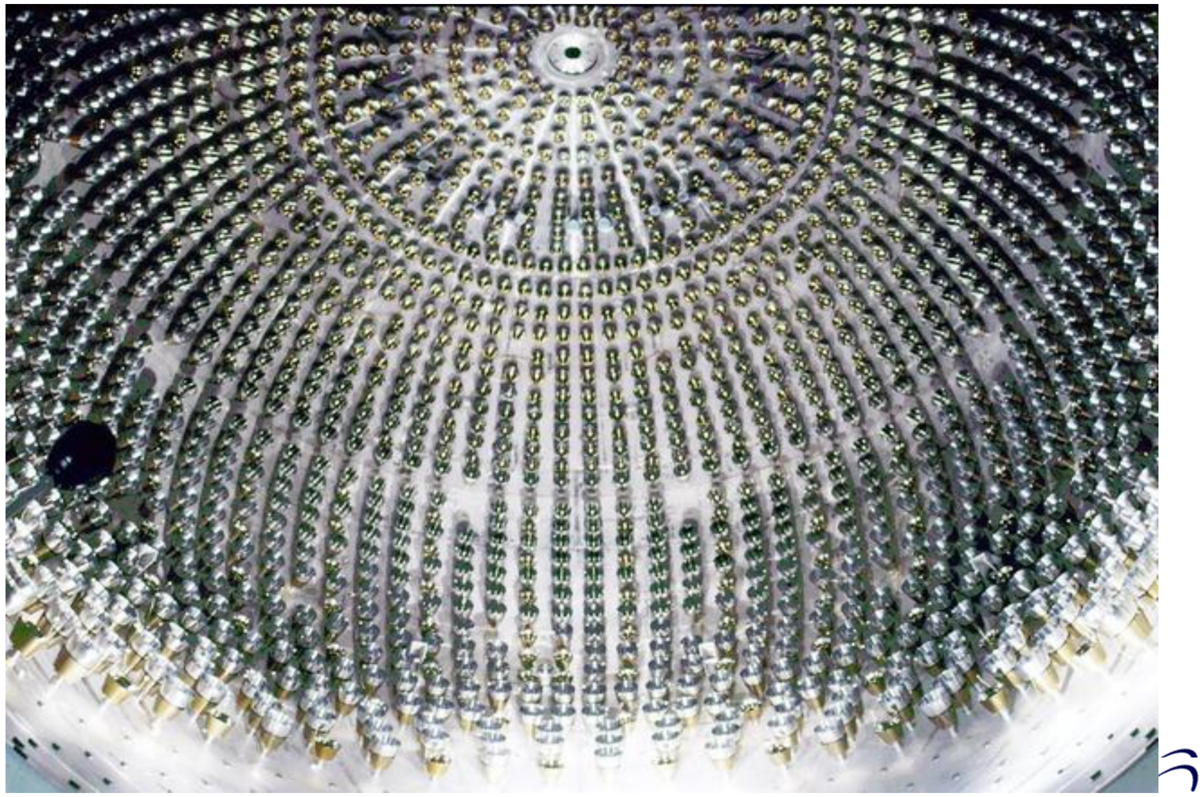
- If you want to detect solar neutrinos with liquid scintillator, you must be **9-10 orders of magnitude more pure than anything on earth**
  - **Not easy, but possible !**

Detector picture gallery







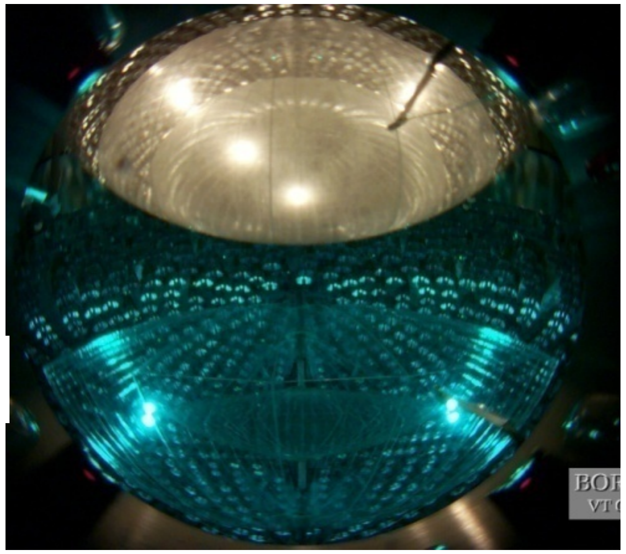


Detector fully filled on May 15th, 2007: DAQ starts

End October 2006

LAKN –
Low Argon and
Krypton Nitrogen

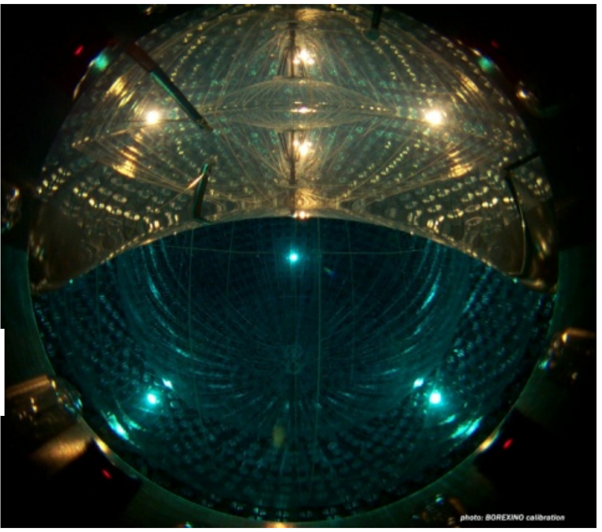
Ultra-pure water



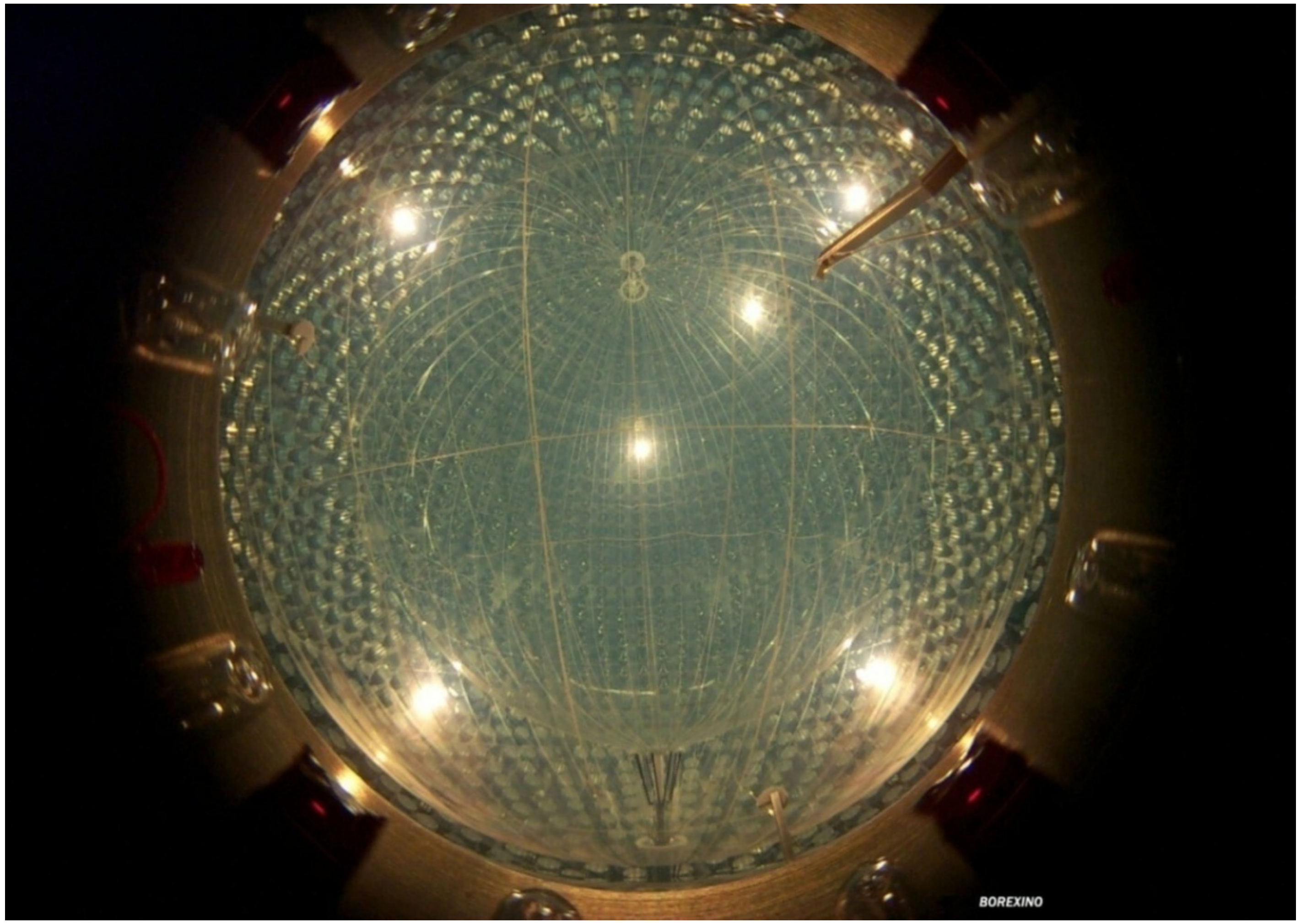
March 2007

Liquid scintillator

Ultra-pure water



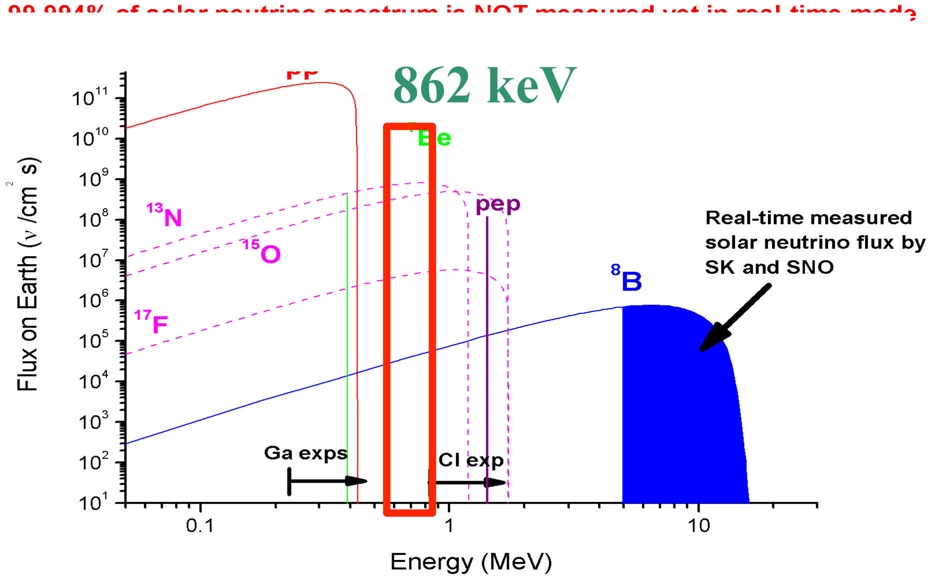
May 2007

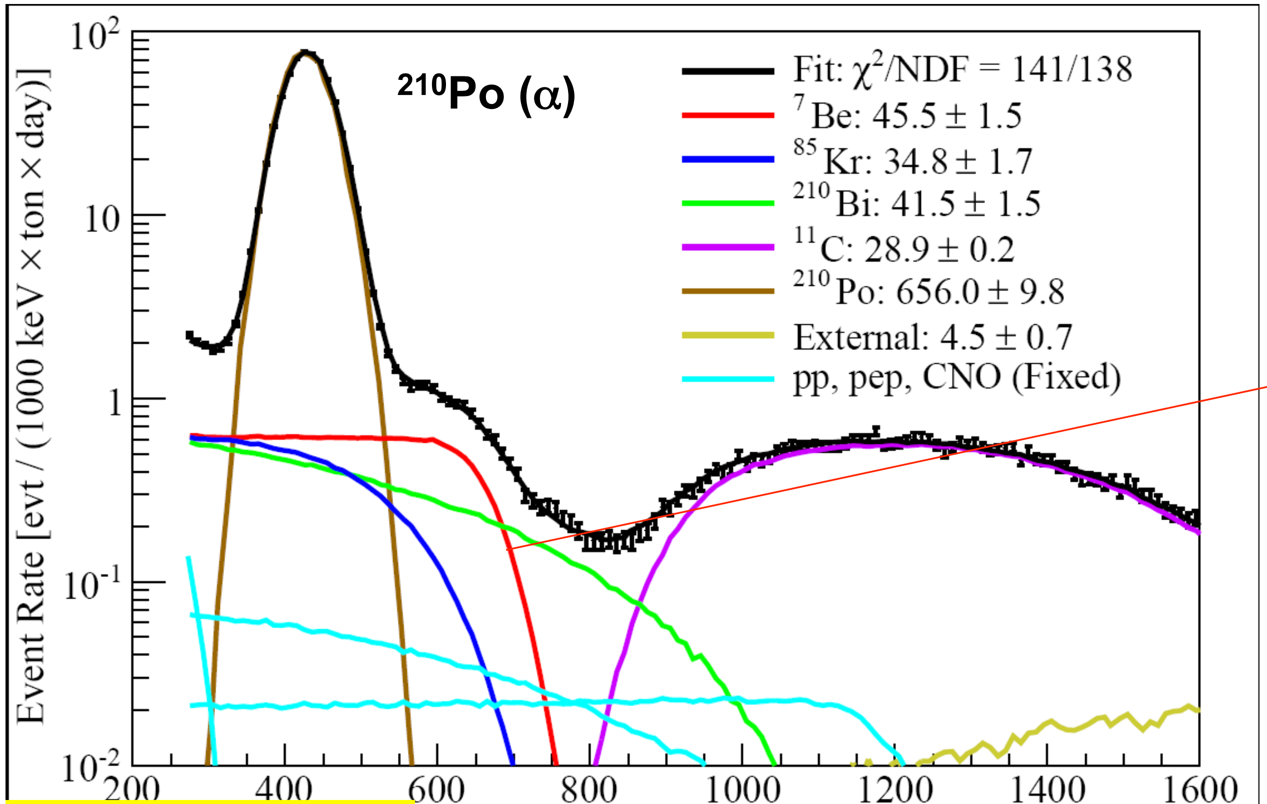


Fotos taken with one of 7 CCD cameras
placed inside the detector

^{7}Be neutrino (862 keV) rate @ 4.6%

(SSM prediction @ 7%)





740 live days

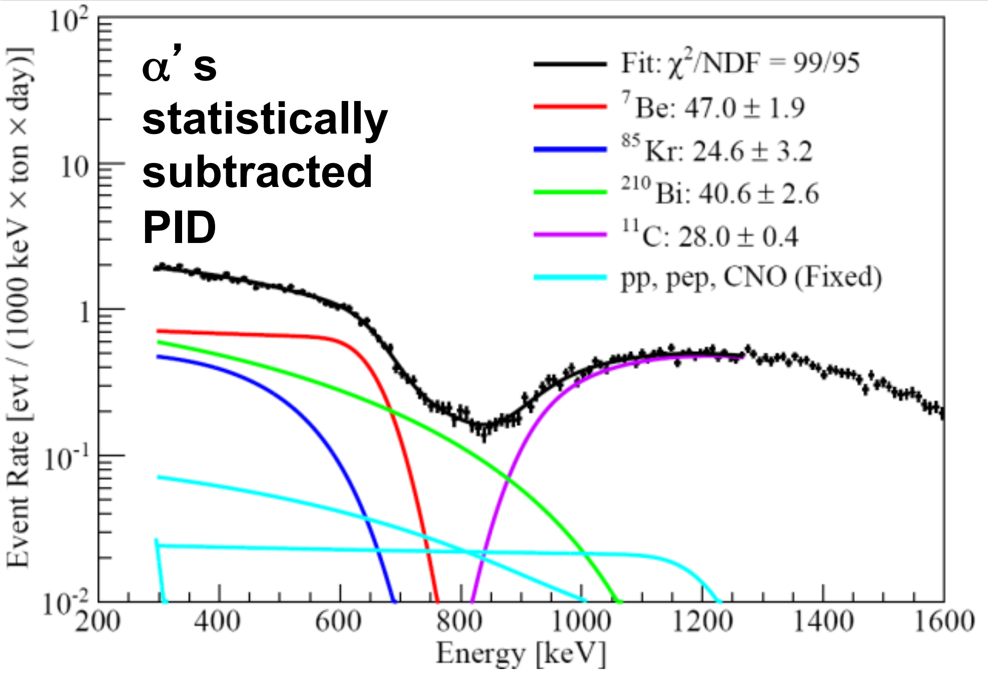
Spectral feature: compton-like edge from scattered electrons

$$46.0 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{syst})$$

PRL 107, 141302 (2011)

cpd/100 tons

1ton of LS = (3.307 ± 0.003) x 10^{29} electrons



- Spectral fit including neutrino signal + background components;
- Two independent methods:
  MC based and the analytical one;
- fit with and without α's statistical subtraction;

Implications of the ^{7}Be measurement

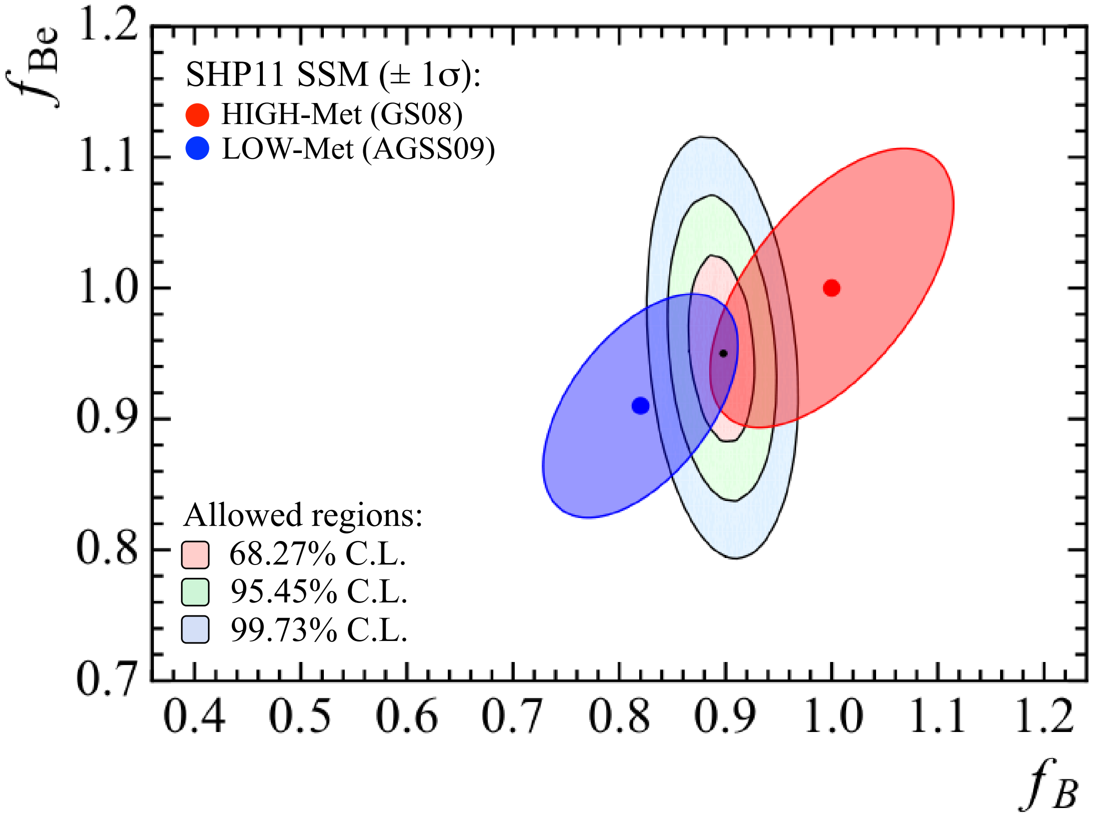
- comparing to non-oscillated SSM : **no oscillation excluded @ 5.0 σ**

(electron equivalent flux (862 keV line): **(2.78 + 0.13) x 10^{9} cm^{-2} s^{-1})**

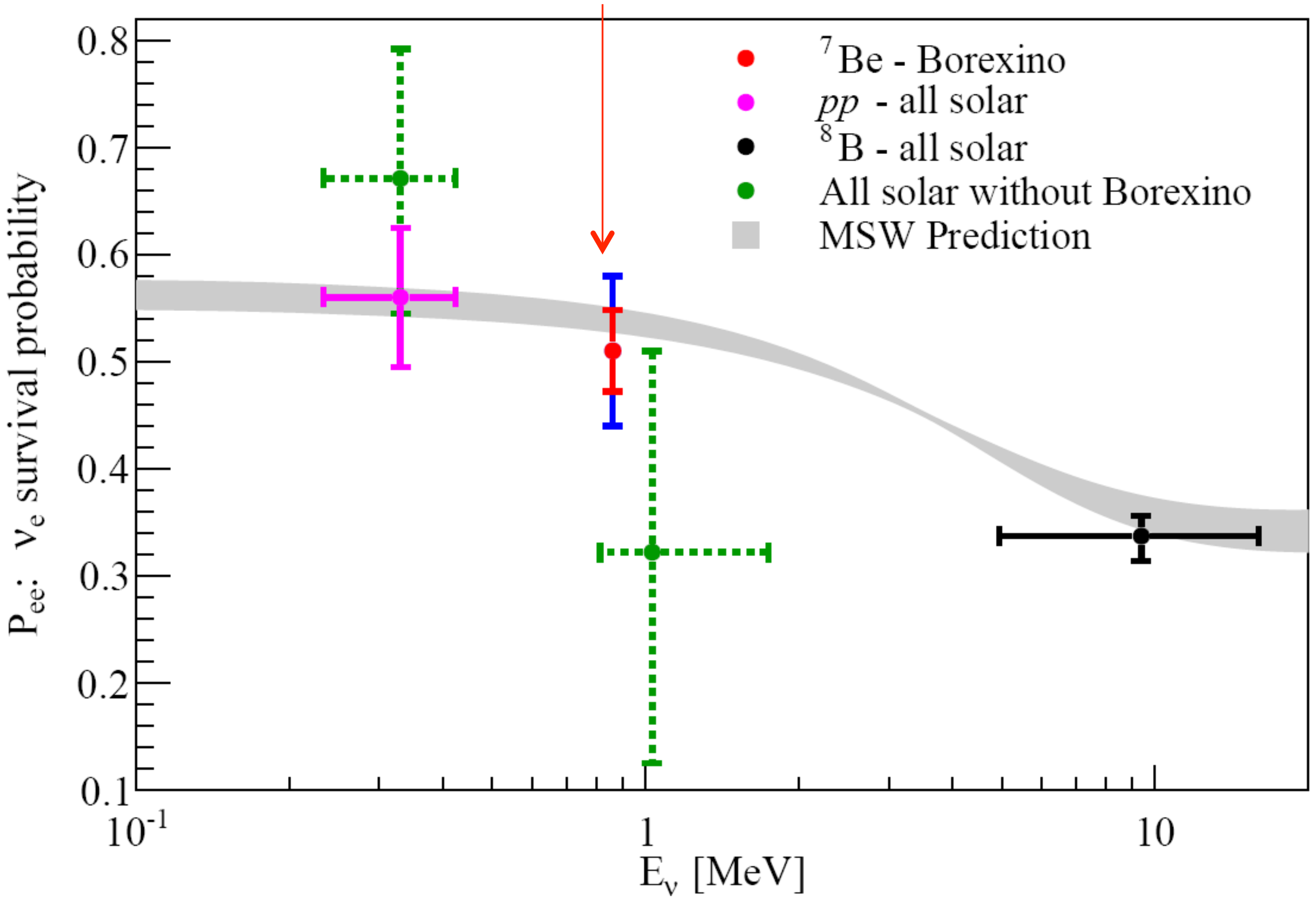
- assuming MSW-LMA: f (^{7}Be) = measured flux / SSM = 0.97 + 0.09
- **including all solar experiments + luminosity constrain:**

$$\boxed{\begin{array}{l} f_{pp} = 1.013^{+0.003}_{-0.010} \\ f_{CNO} < 2.5 \text{ at } 95\% \text{ C.L.} \end{array}}$$

no power to resolve low/high metallicity problem

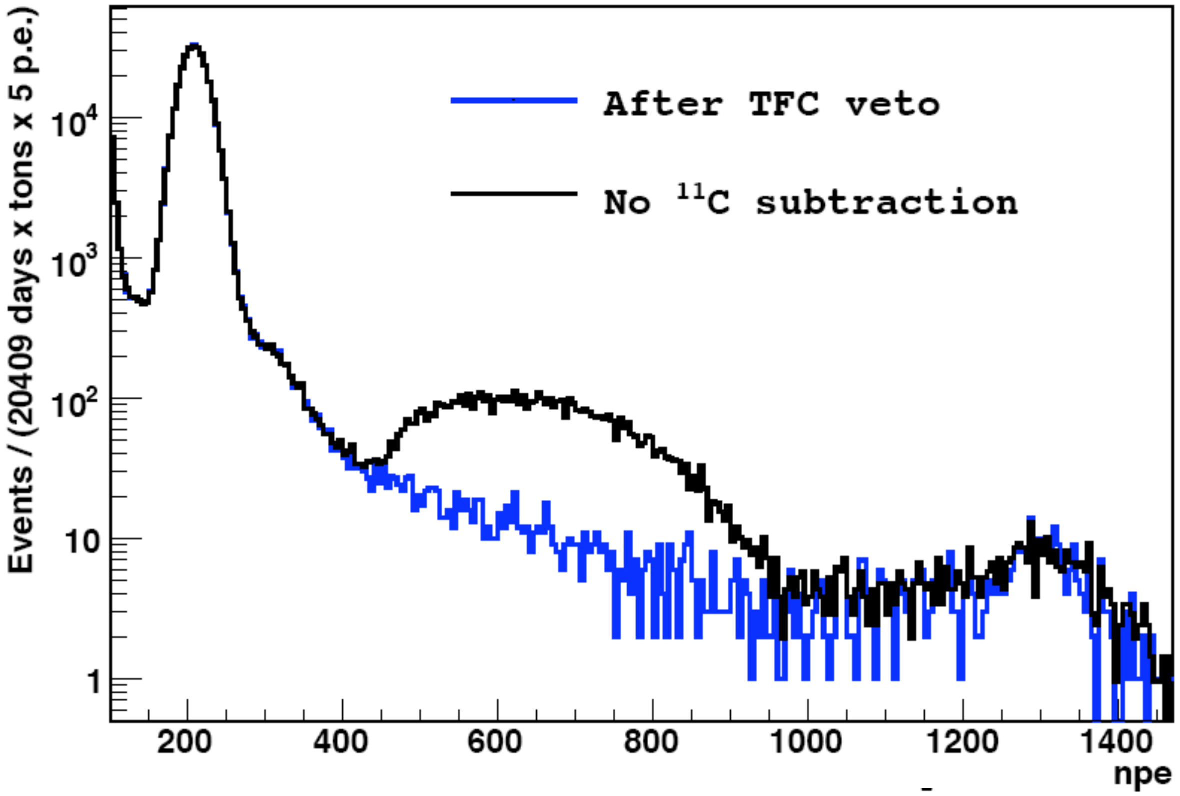


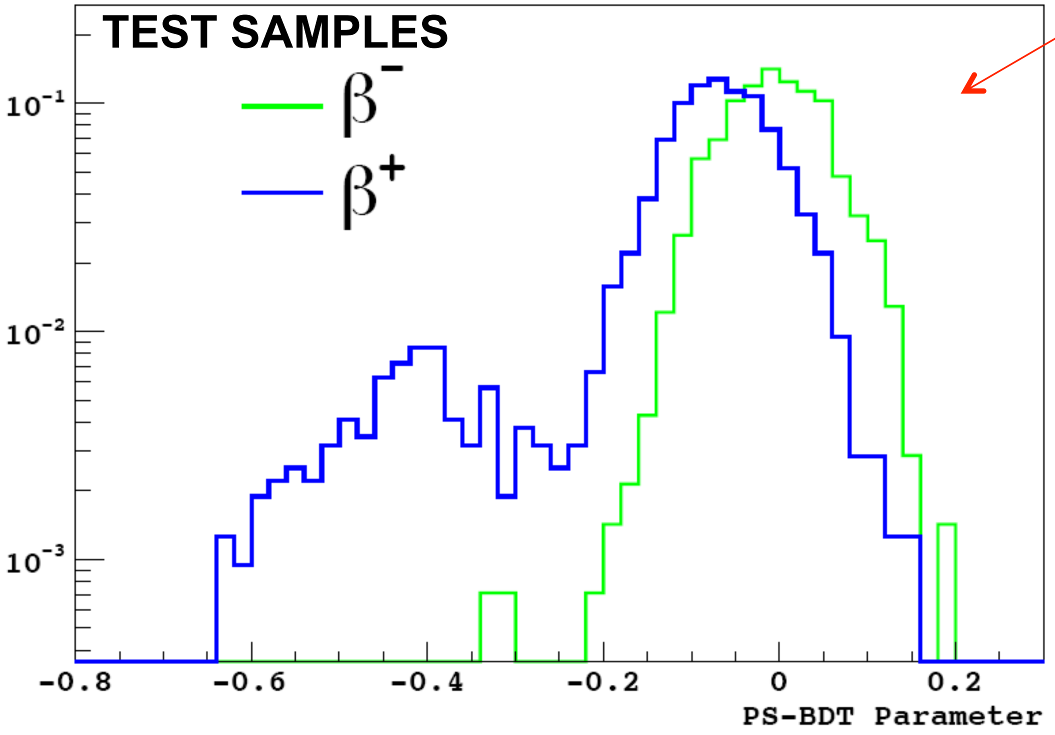
Pee = 0.51 + 0.07(experiment + SSM high metalilcity);



First observation of pep neutrinos (1442 keV)

PRL 108, 051302 (2012)





- Main background ^{11}C (e^+) with τ = 29.4 min:

1 2 3

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

Three Fold Coincidence (TFC): space-time veto removes 90% of ^{11}C payed with 50% loss of exposure

- **pulse-shape discrimination**: positronium formation + annihilation

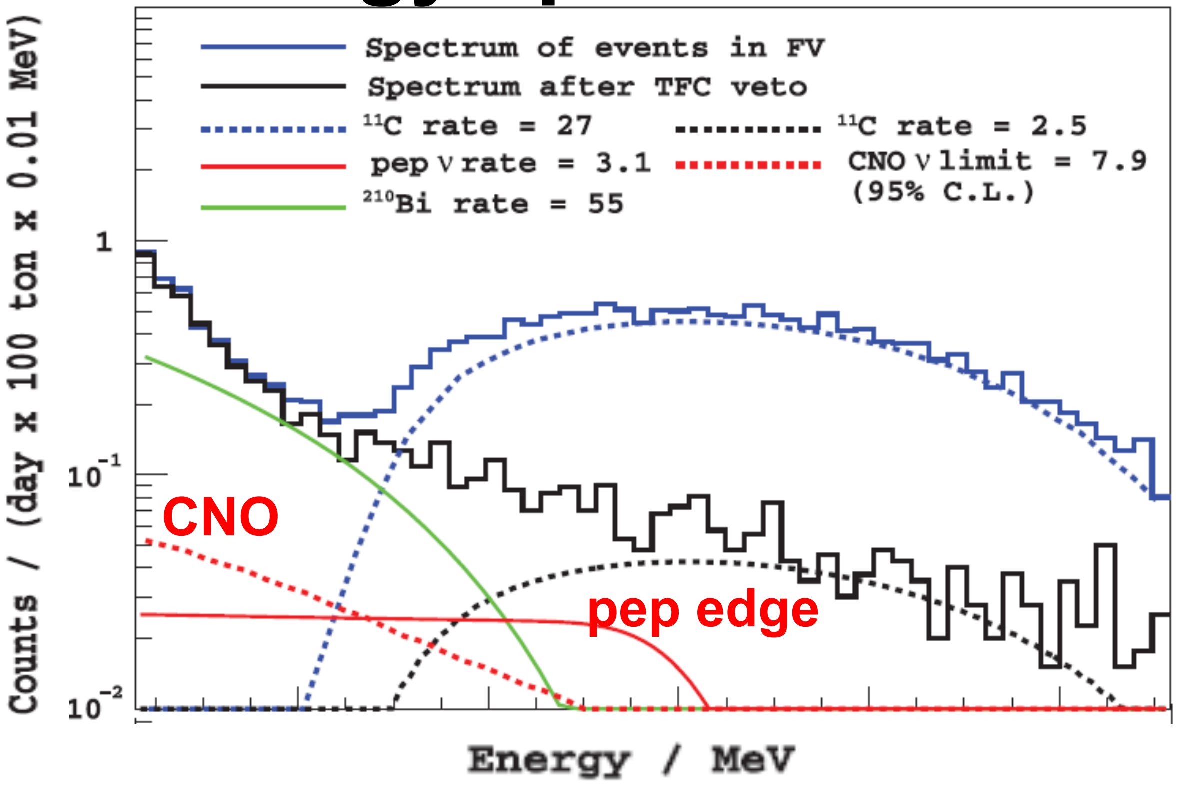
- **simultaneous fit in 3 parameter space**: energy spectra, pulse shape, and radial distribution (sensitive to external background):

$$3.1 \pm 0.6_{\text{stat}} \pm 0.3_{\text{syst}} \text{ counts}/(\text{day} \cdot 100 \text{ ton})$$

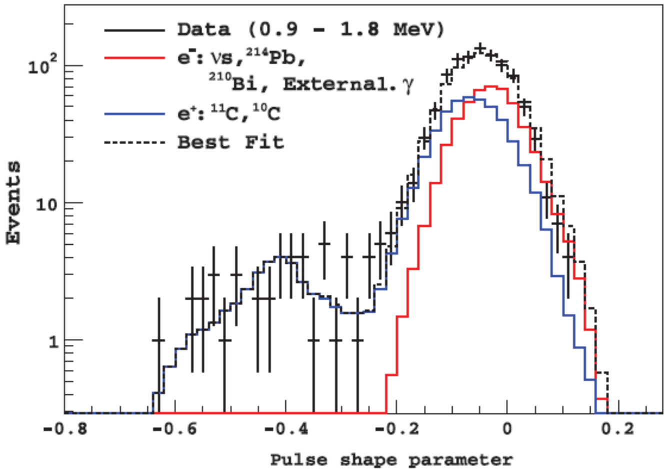
$$(1.6 \pm 0.3) \times 10^8 \text{ cm}^{-2}\text{s}^{-1}$$

(assuming MSW-LMA)

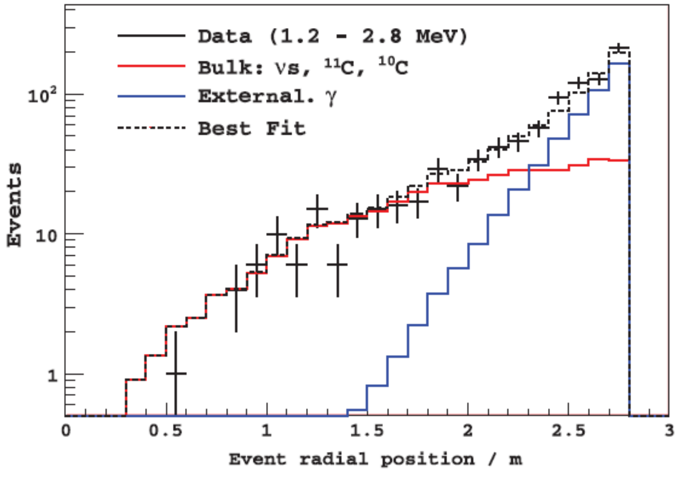
Energy spectral fit

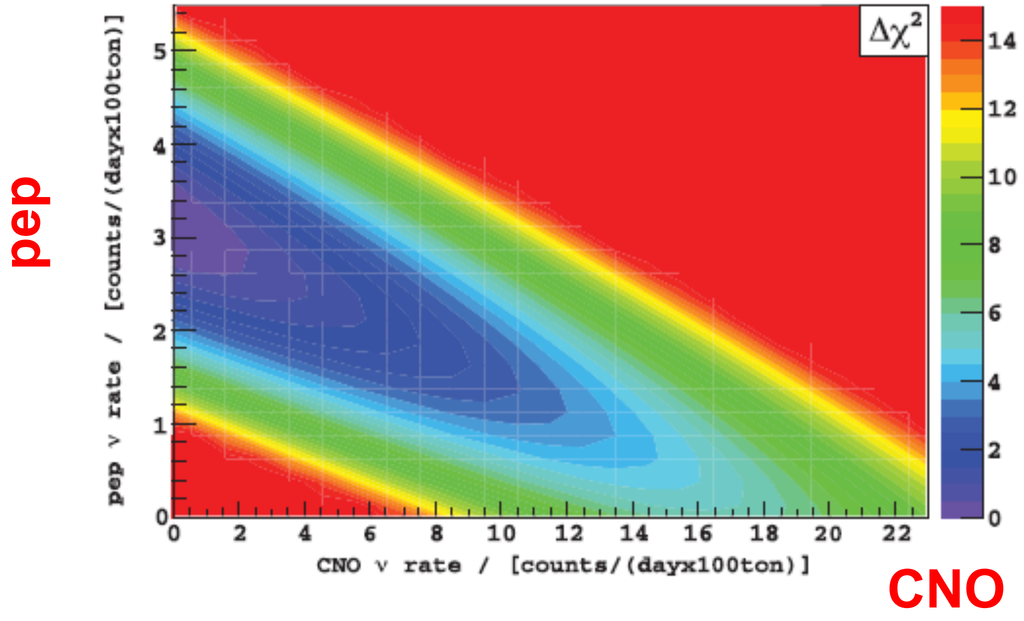


Pulse shape



Radial fit





Likelihood ratios for fits with fixed pep/CNO rates and the best fit

CNO neutrinos

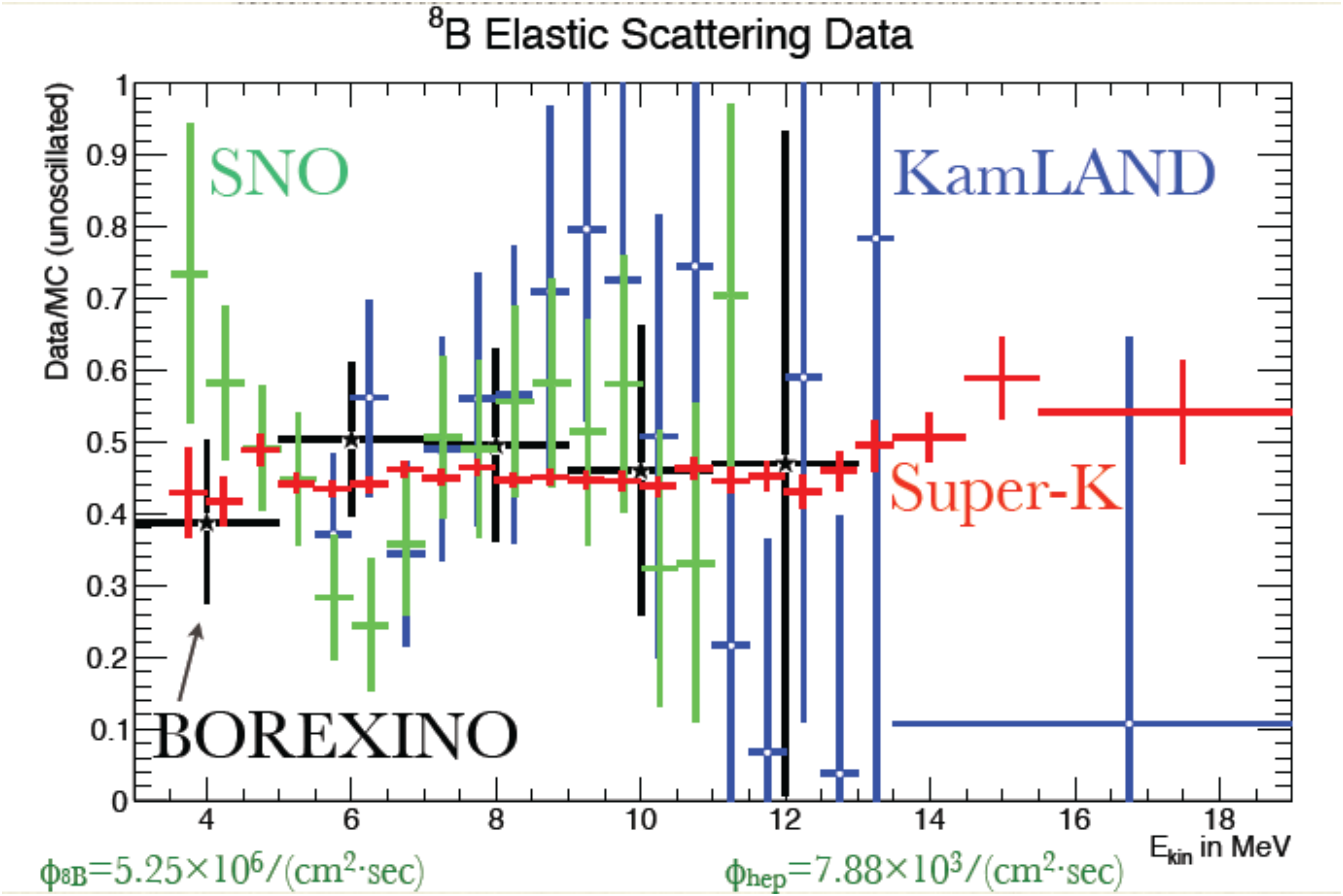
- same analysis as for pep
- only limits, correlation with ^{210}Bi
- **the strongest limit to date**
- **not sufficient to resolve metallicity problem**

<7.9 counts/(day · 100 ton) (95% C.L.)

$<7.7 \times 10^8$ cm^{-2} s^{-1} (95% C.L.)

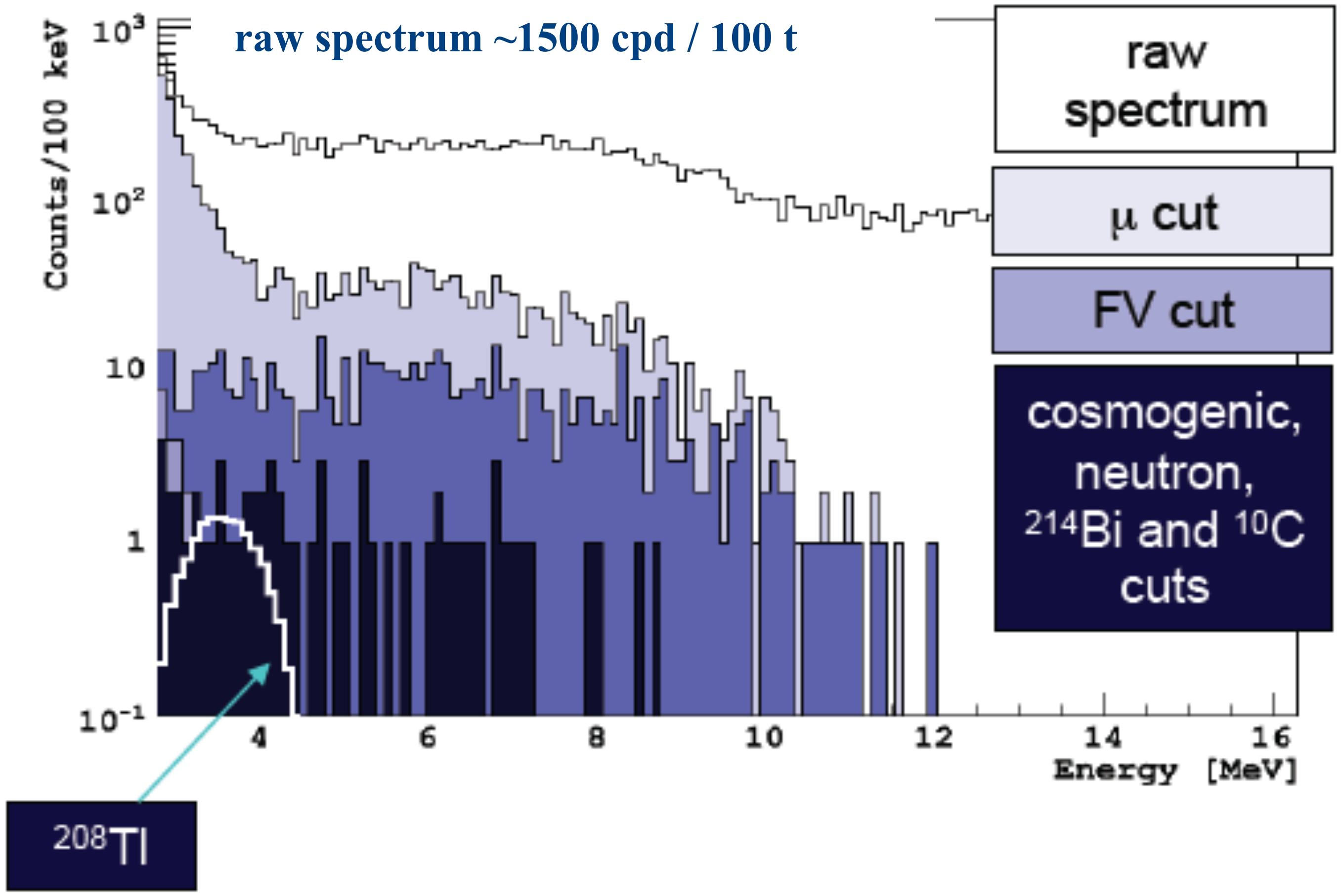
(assuming MSW-LMA)

All solar ^{8}B neutrino data in one plot

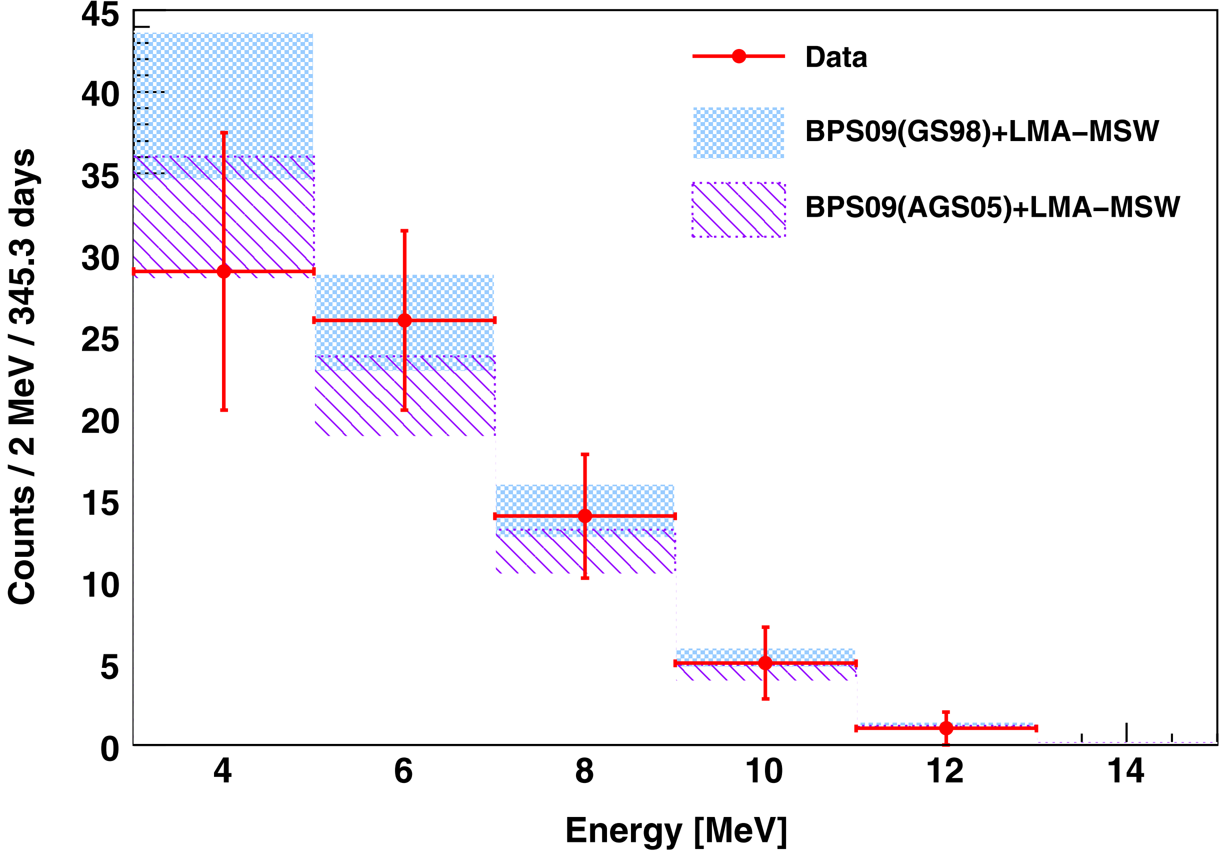


PRD 82, 033006 (2010)

^{8}B-ν rate down to 3 MeV



After background subtraction

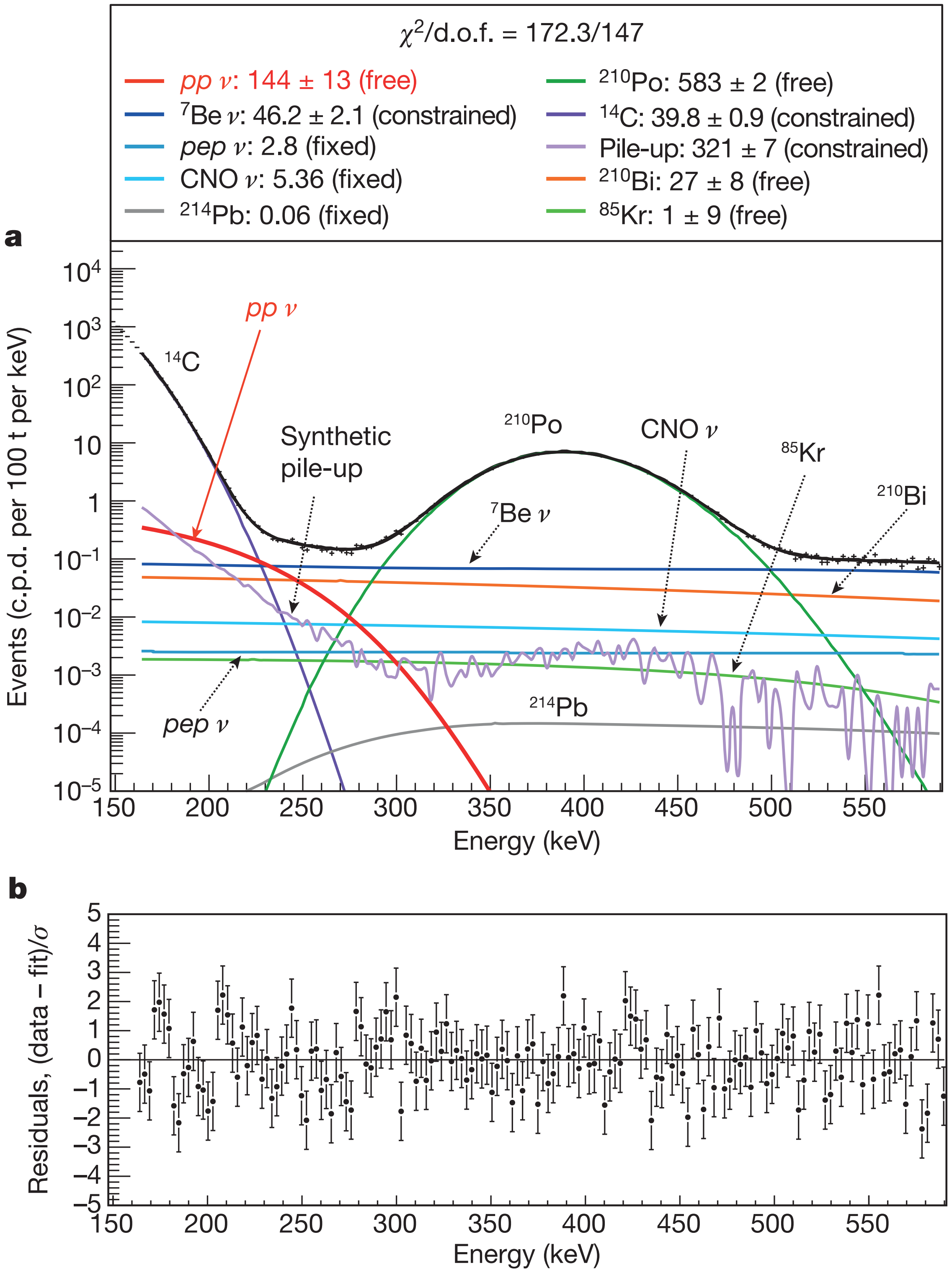


	3.0–16.3 MeV	5.0–16.3 MeV
Rate [cpd/100 t]	0.22 ± 0.04 ± 0.01	0.13 ± 0.02 ± 0.01
$\Phi^{\mathrm{ES}}_{\mathrm{exp}}$ [10^{6} cm^{-2} s^{-1}]	2.4 ± 0.4 ± 0.1	2.7 ± 0.4 ± 0.2
$\Phi^{\mathrm{ES}}_{\mathrm{exp}}/\Phi^{\mathrm{ES}}_{\mathrm{th}}$	0.88 ± 0.19	1.08 ± 0.23

Nature 512 (2014) 383

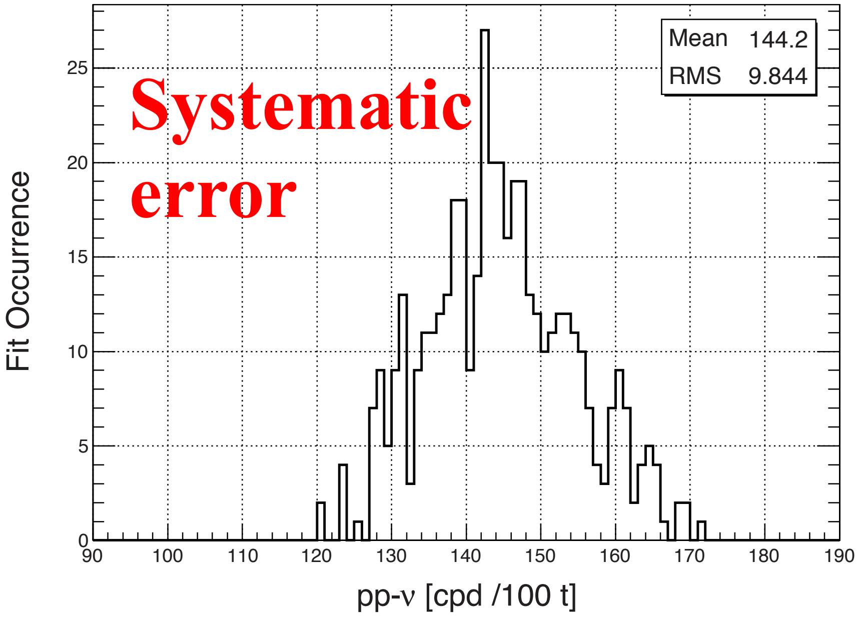
NEW: August 2014: First spectral measurement of pp-ν

Phase II data after extensive purification: ^{85}Kr consistent with 0, ^{210}Bi strongly reduced



Main challenges:

- *pp* end point 420 keV (recoiled e$^-$ < 264 keV)
- ^{14}C with the end point @ 156 keV
- ^{14}C pile-up



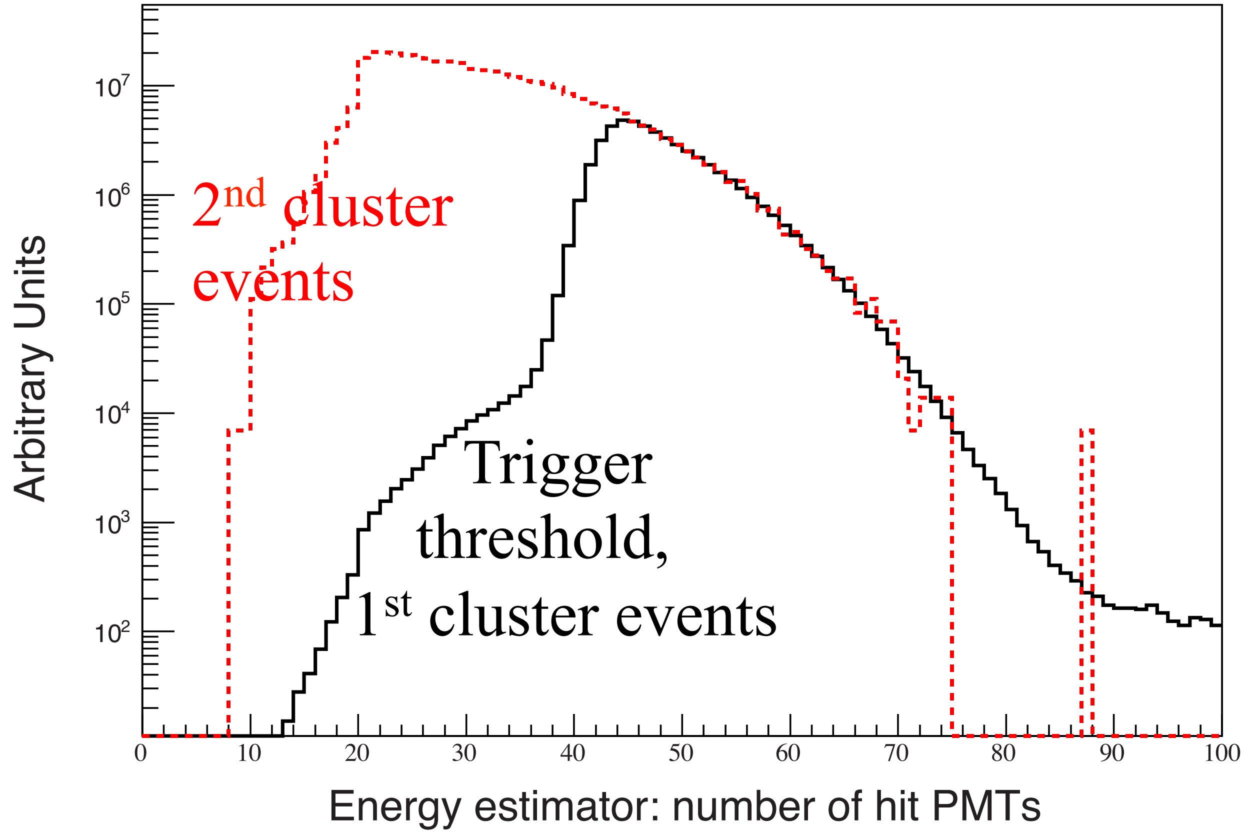
Systematic error

R(pp) : 144 ± 13 *(stat)* ± 10 *(syst)* cpd/100 t
HM-SSM + LMA-MSW: 131 ± 2 cpd/100 t

$$\phi = \begin{cases} (6.42 \pm 0.85) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} & \text{measured} \\ (5.98 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} & \text{expected (high}-Z) \\ (6.03 \pm 0.04) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} & \text{expected (low}-Z) \end{cases}$$

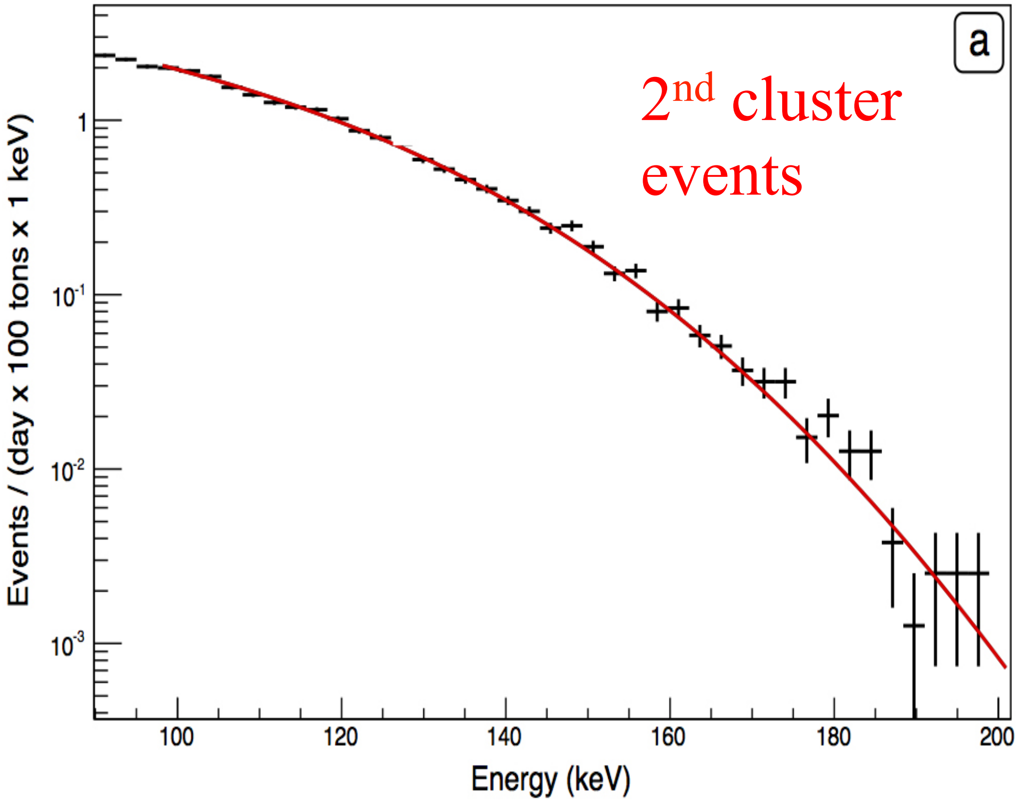
Nature 512 (2014) 383

pp-ν analysis: ^{14}C rate constrained independently

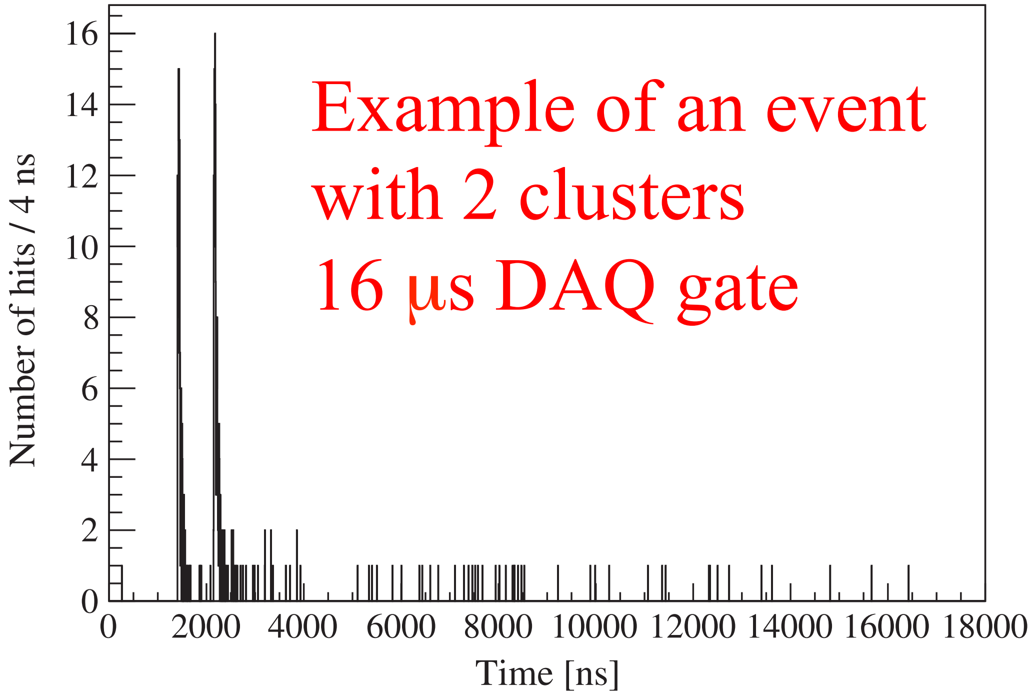


2nd cluster events

Trigger threshold, 1st cluster events



2nd cluster events



Example of an event with 2 clusters
16 μs DAQ gate

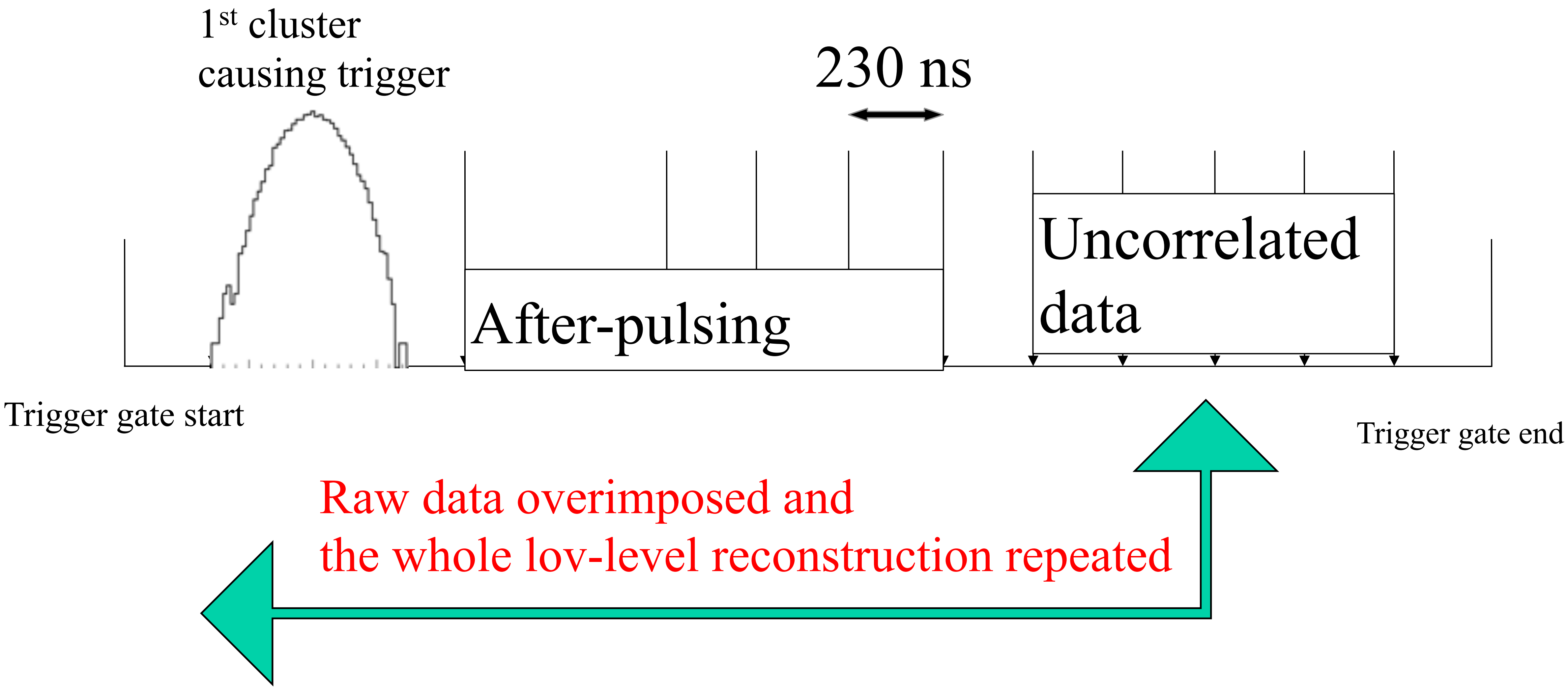
^{14}C rate
from a fit of 2nd cluster spectrum:

40 ± 1 Bq per 100 t.

Nature 512 (2014) 383

pp-ν analysis: constraining ^{14}C-pilep

***Synthetic pile-up*:** overlap uncorrelated data with regular events

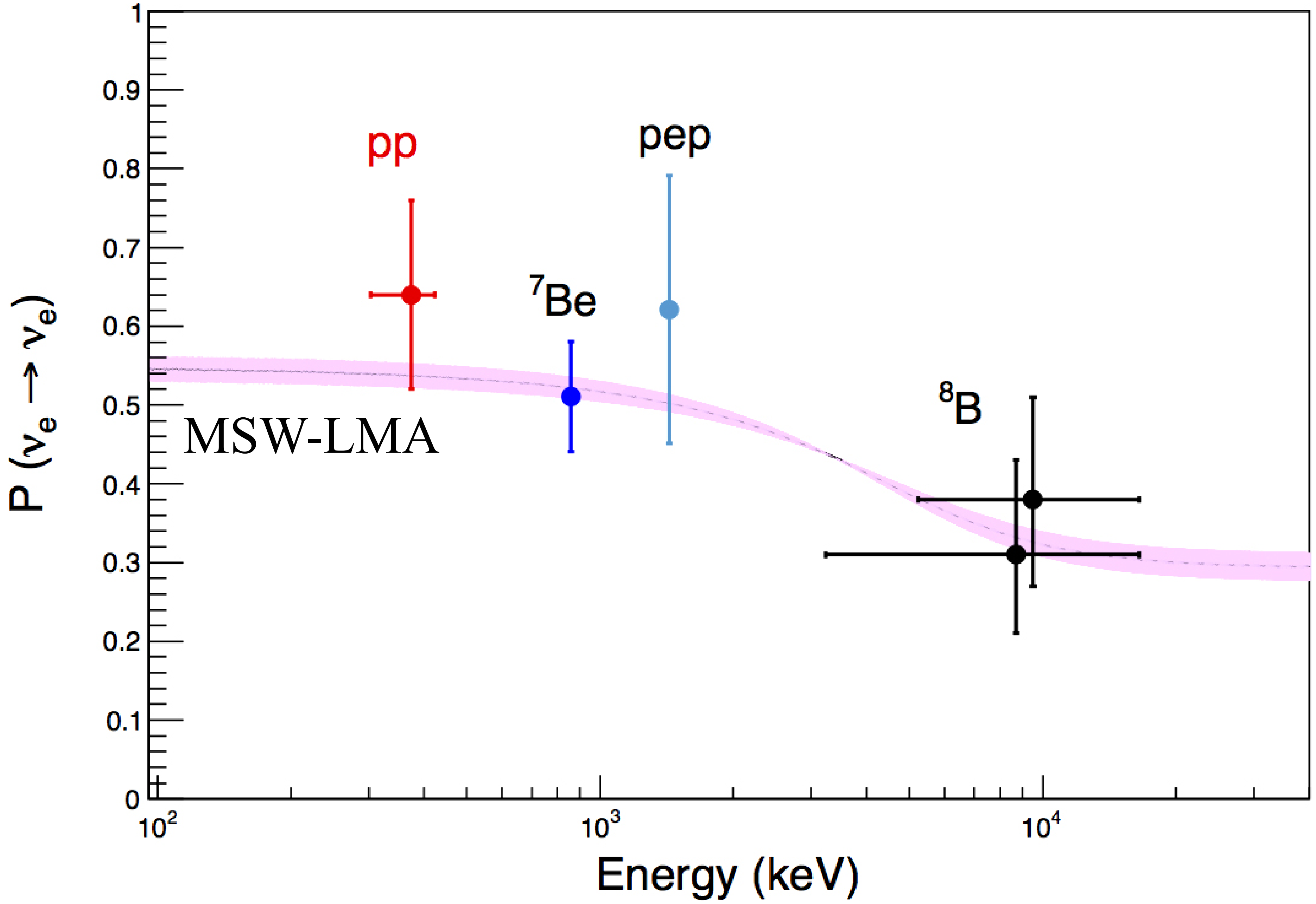


Raw data overimposed and
the whole lov-level reconstruction repeated

Result (spectral shape + rate) used to constrain pile-up in the final fit

Implications of Borexino solar neutrino measurements: I.

Borexino only survival probability



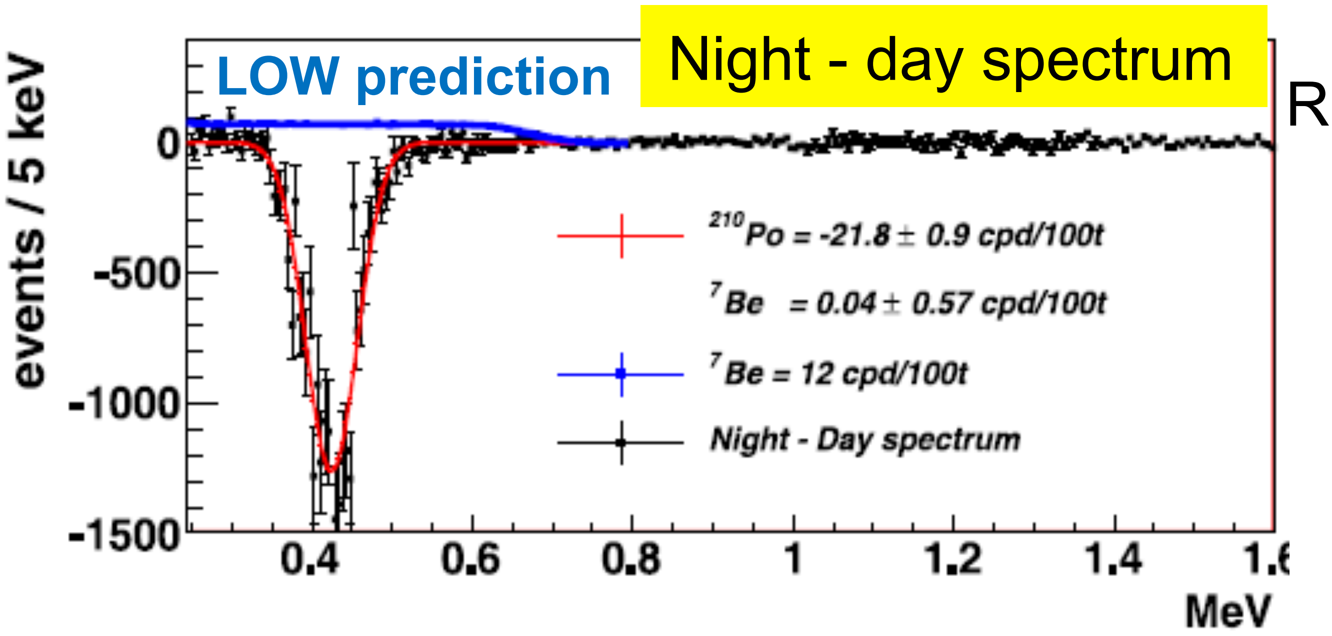
Day-Night variation of the solar flux

Borexino:
Absence of day-night asymmetry for ^{7}Be rate (R)

Physics Letters B 707 (2012) 22–26

$$A_{dn} = 2\frac{R_N - R_D}{R_N + R_D} = \frac{R_{\mathrm{diff}}}{\langle R \rangle}$$

- MSW: a possible regeneration of electron neutrinos in the matter (within the Earth during night): effect depends on the oscillation parameters and on energy;

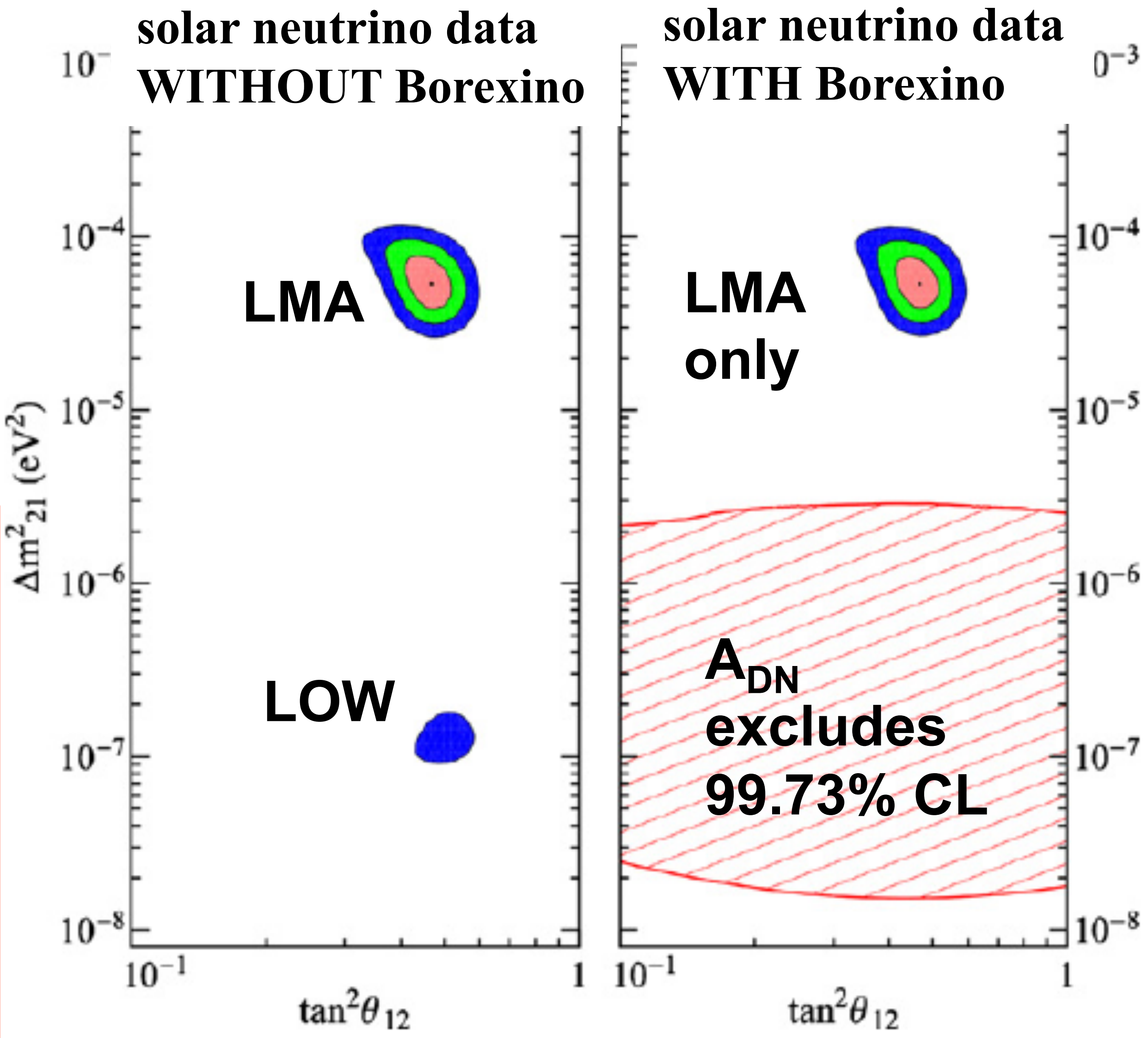


A_{DN} = 0.001 ± 0.012(stat) ± 0.007(syst)

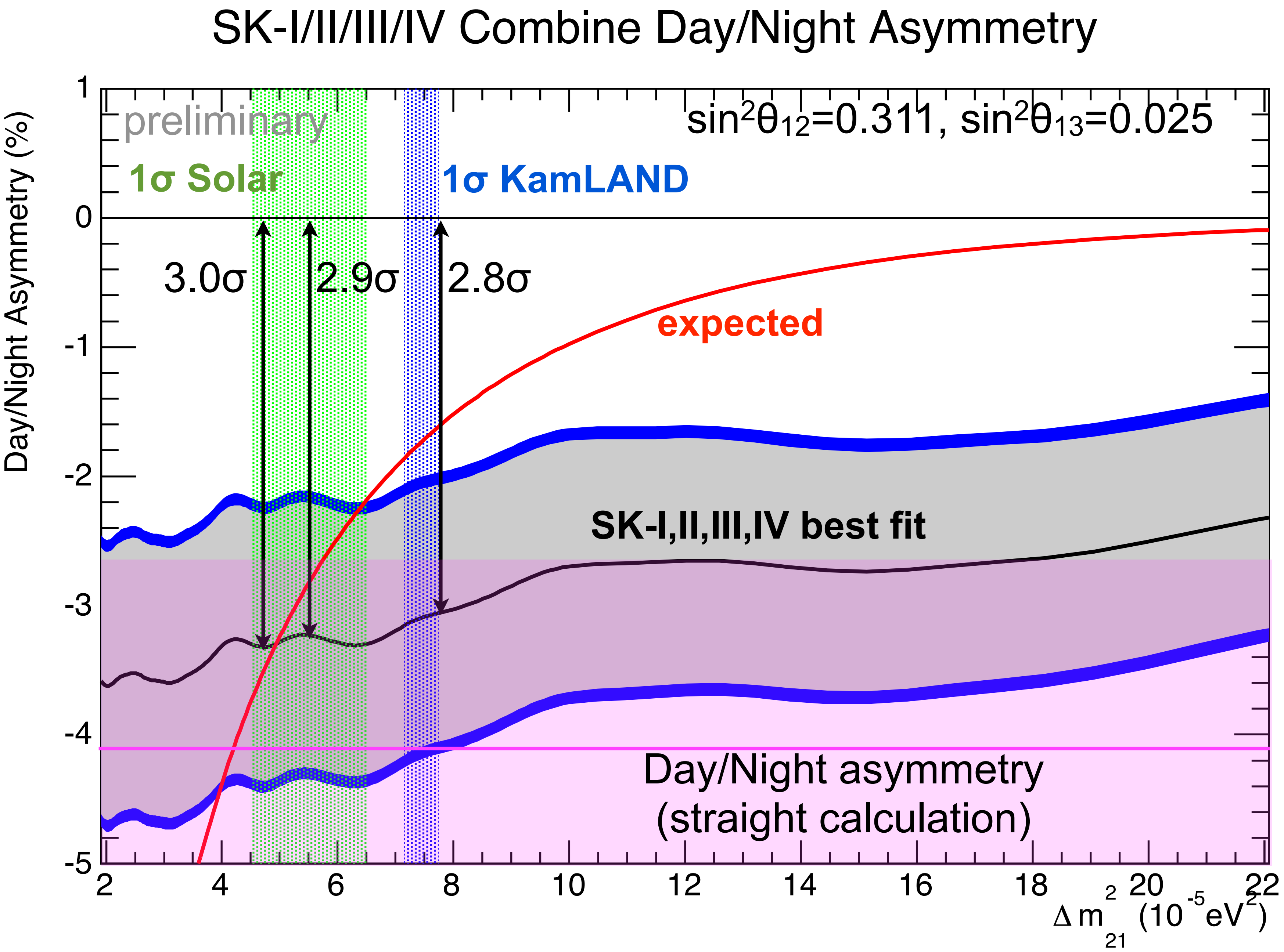
- in agreement with MSW-LMA;
- LOW region excluded at > 8.5 σ with solar neutrinos only: for the first time without the use of reactor ANTIneutrinos and therefore the assumption of CPT symmetry;
- constrains non standard interacitons

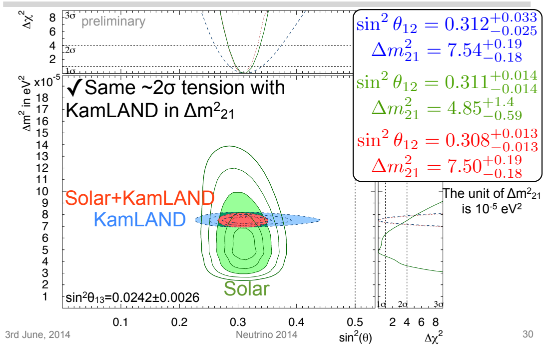
(MaVaN in Holanda 2009 excluded)

Regions allowed @ 68.27%, 95.45%, 99.73% CL



SuperKamiokande:Day-night variation of ^{8}B flux





Solar region

- ✓ differ from zero by 2.9~3.0σ
- ✓agree with expect by 1.0σ

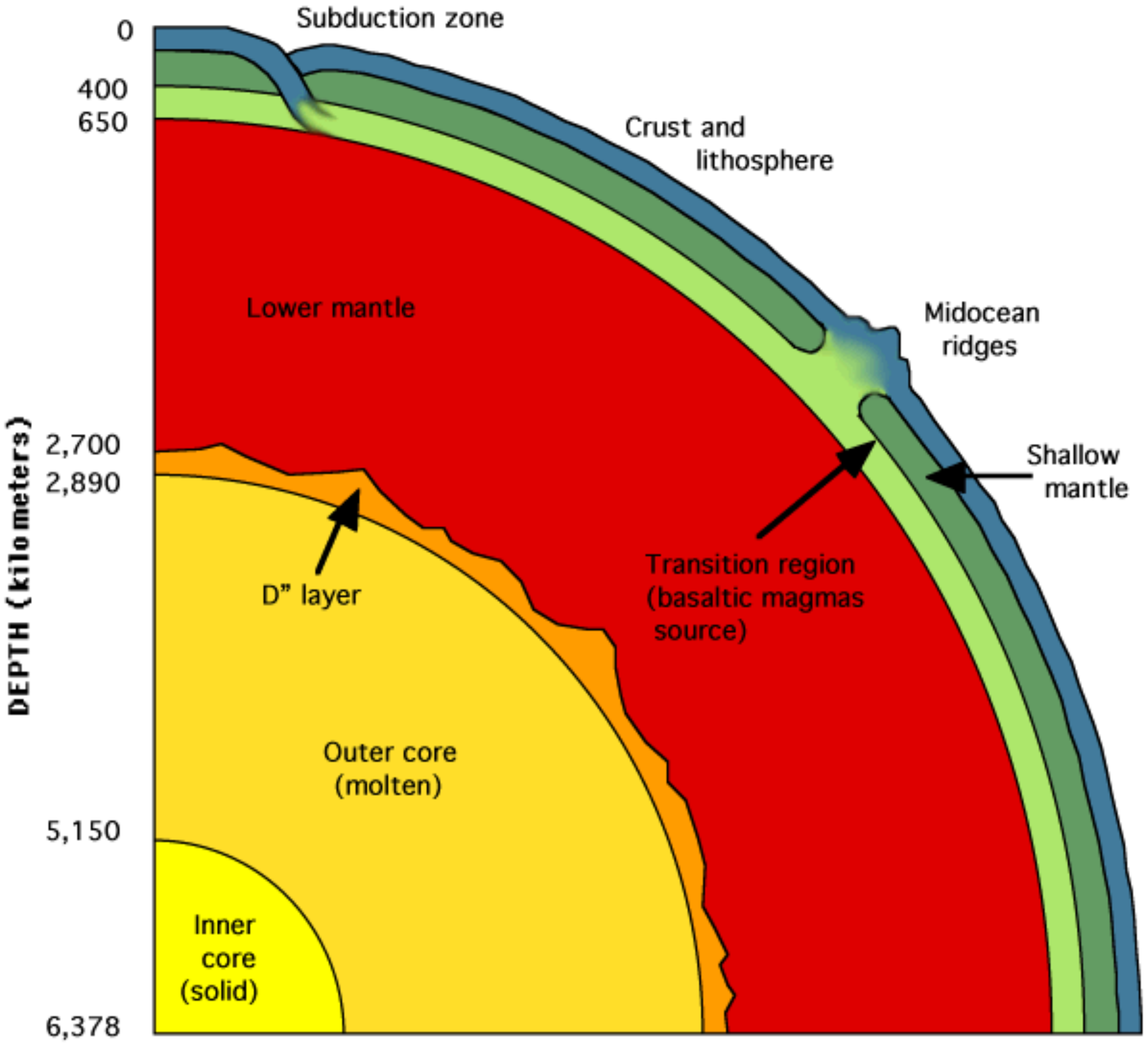
KamLAND region

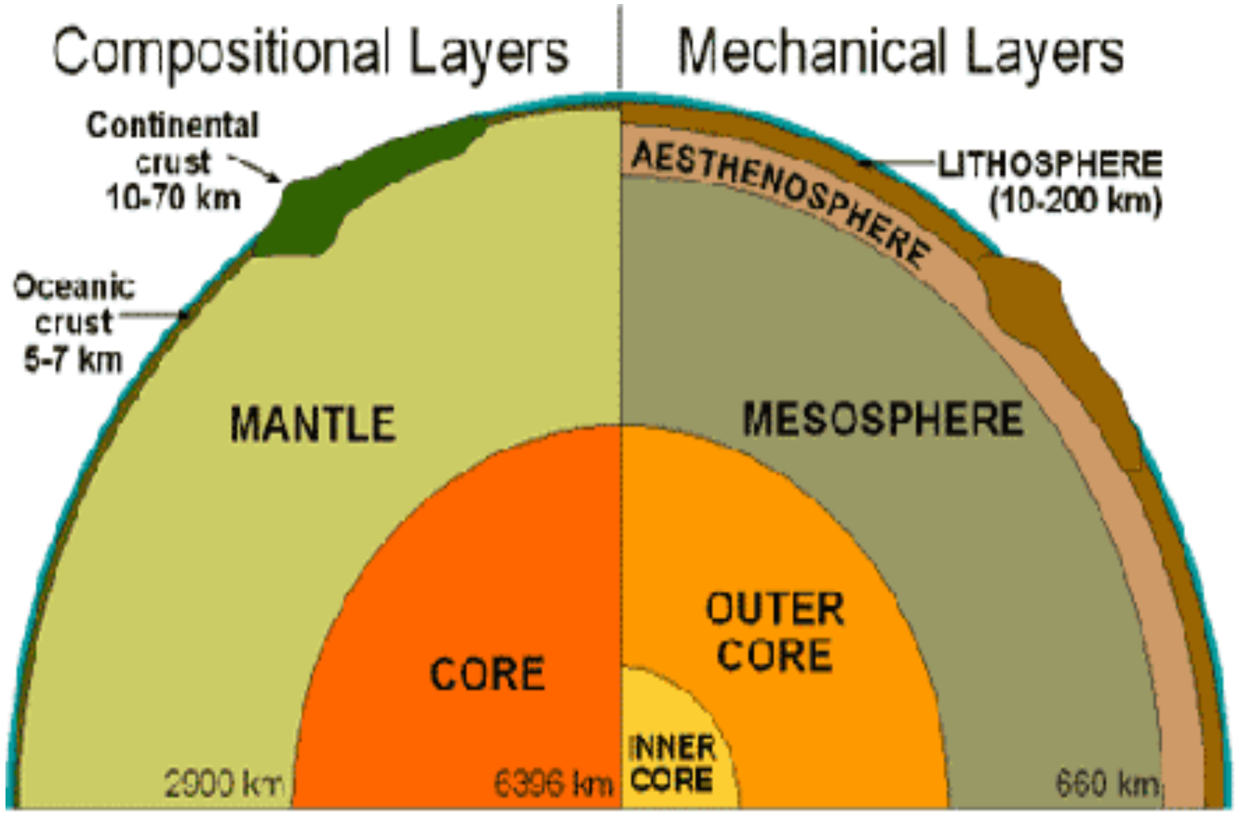
- ✓ differ from zero by more than 2.8σ
- ✓agree with expect by 1.3σ

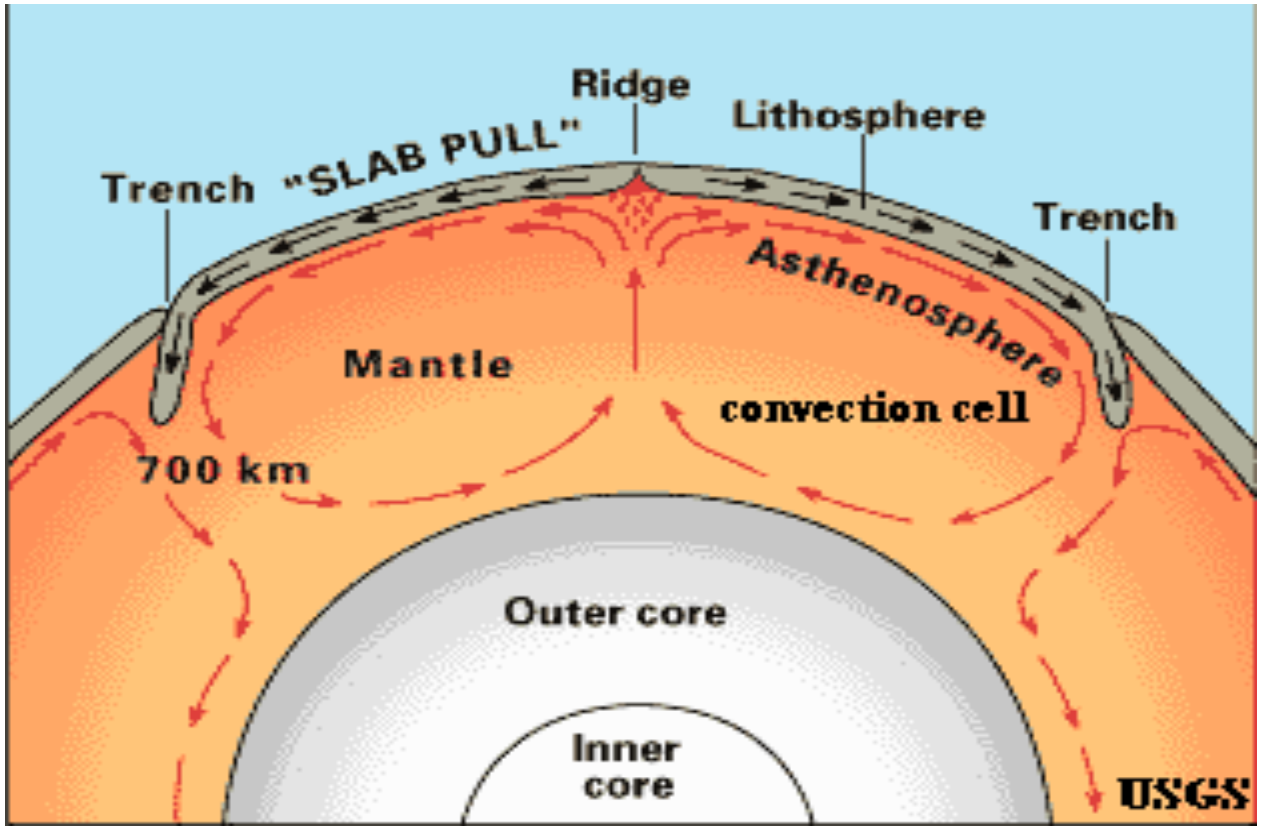
Future of solar neutrino experiments

- Borexino has entered a new Phase II after an extensive purification campaign (almost complete removal of ^{85}Kr and a strong reduction of ^{210}Bi: more precise measurement of pep and CNO (?)
- new data from SuperK for 8B – Pee as a function of energy!
- Testing Pee (energy) = LMA-MSW or some non standard interactions (searching for new physics)?
- Testing the Sun … solving metallicity problem?
- **Future experiments:**
- **SNO+** (Canada, 1 kton of scintillator, > 1 order of magnitude less cosmogenic bgr);
- **JUNO** (China, 20 kton scintillator, close to reactor – mass hiearchy measurement, solar neutrino program under study)
- Megaton scale: Hyper-Kamiokande = 20 x SuperKamiokande;
- LENA _ 50 kton liquid scintillator…. Unclear future
- LENS – Unclear future;

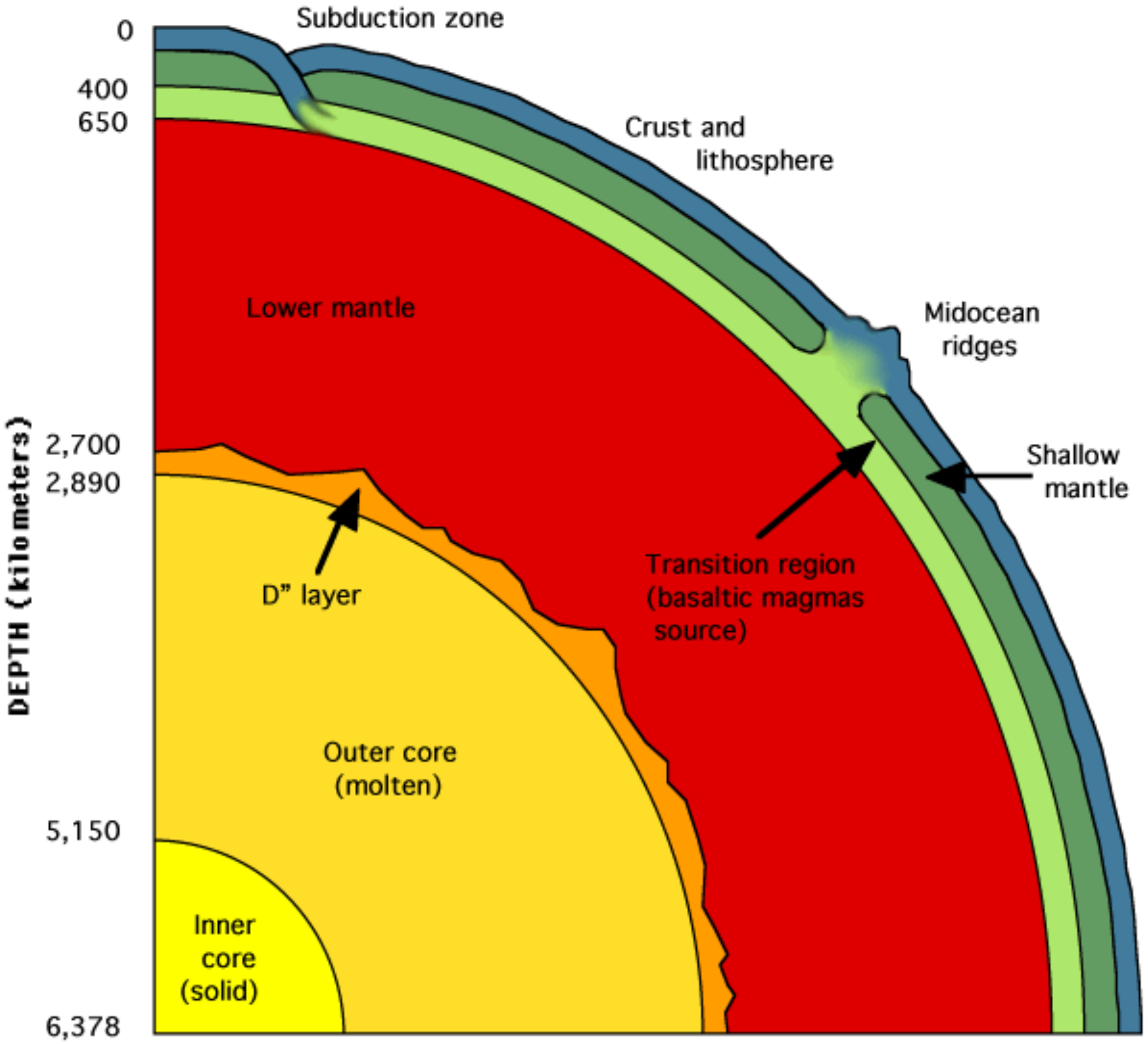
Earth structure







Earth structure



Inner Core - SOLID

- about the size of the Moon;
- Fe – Ni alloy;
- **solid** (high pressure ~ 330 GPa);
- temperature ~ 5700 K;

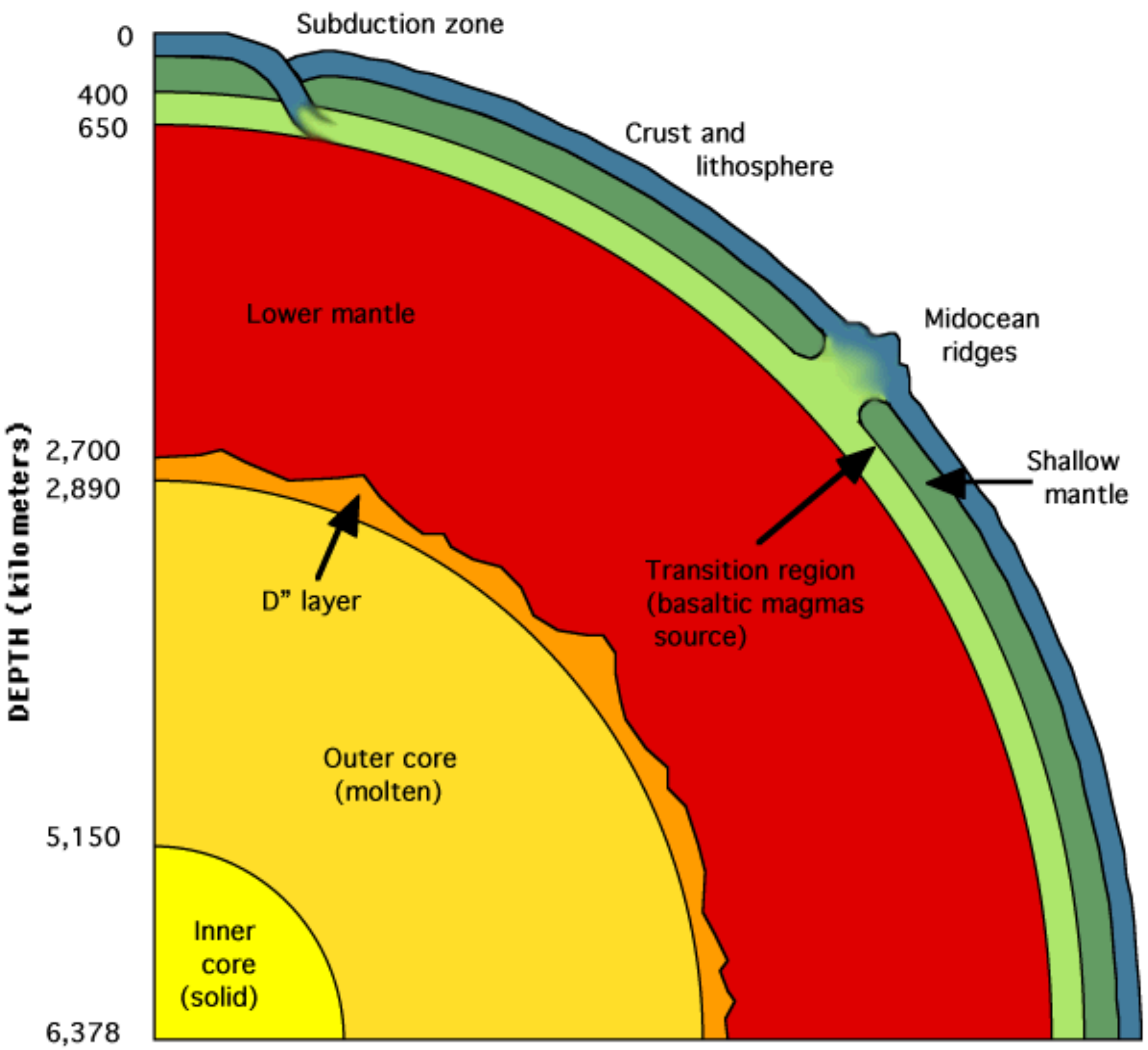
Outer Core - LIQUID

- 2260 km thick;
- FeNi alloy + 10% light elem. (S, O?);
- **liquid;**
- temperature ~ 4100 – 5800 K;
- **geodynamo:** motion of conductive liquid within the Sun’s magnetic field;

D’’ layer: mantle –core transition

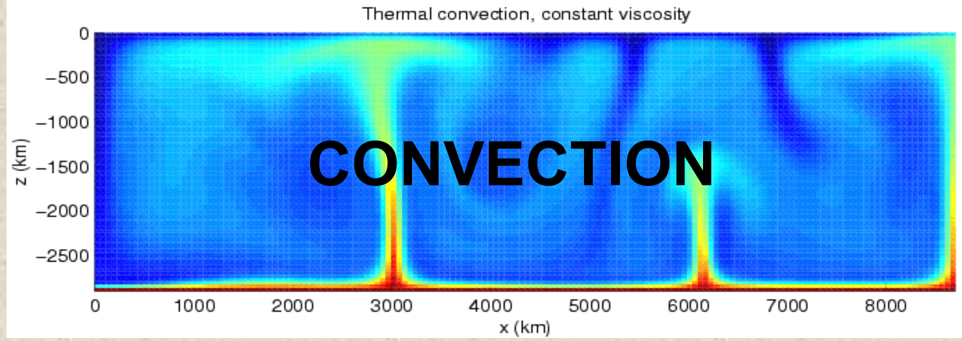
- ~200 km thick;
- seismic discontinuity;
- unclear origin;

Earth structure



Lower mantle (mesosphere)

- rocks: high Mg/Fe, < Si + Al;
- T: 600 – 3700 K;
- high pressure: solid, but viscose;
- "plastic" on long time scales:

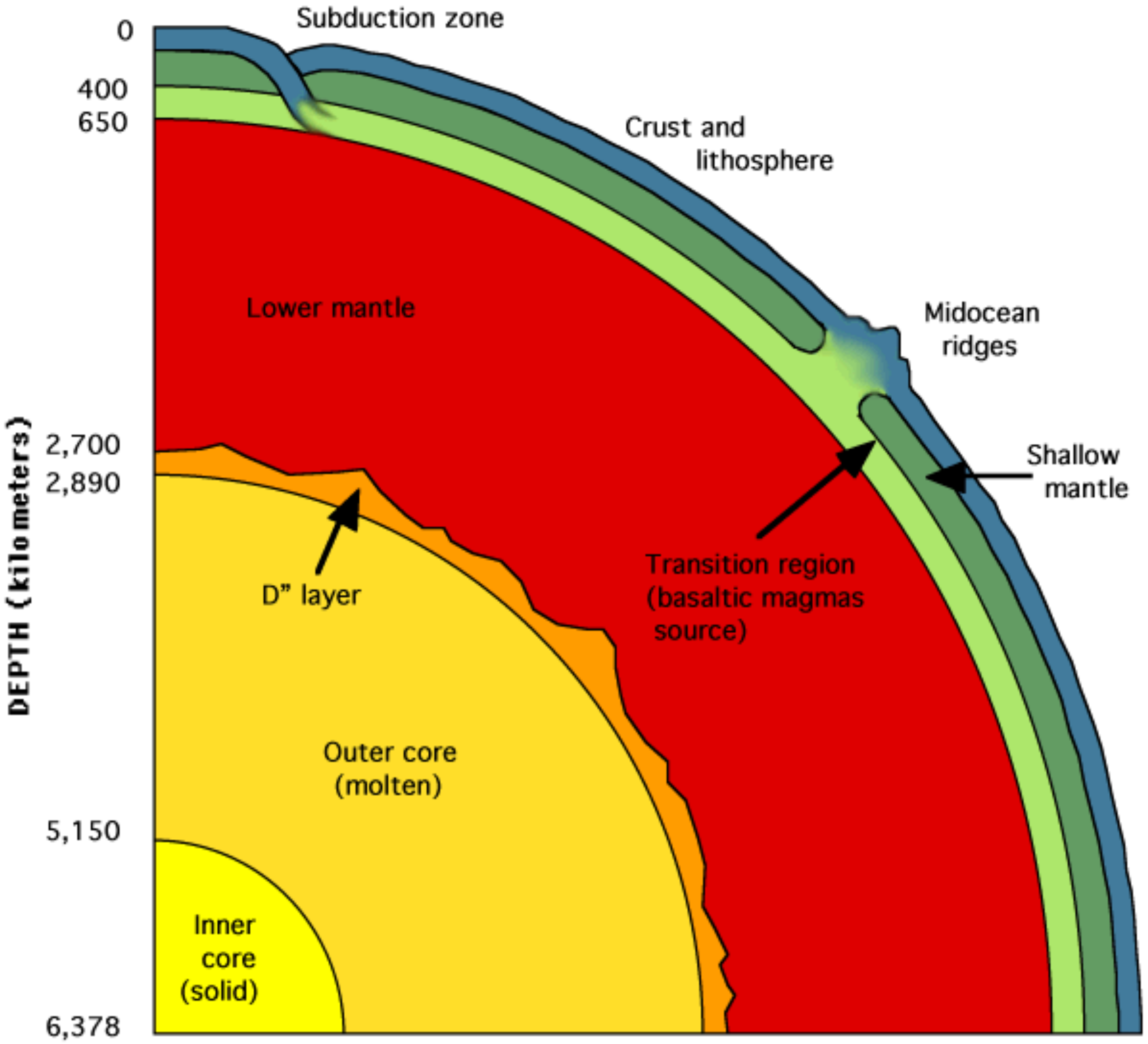


Transition zone (400 -650 km)

seismic discontinuity;

- mineral recrystallisation;
- : role of the latent heat?;
- partial melting: the source of mid-ocean ridges basalts;

Earth structure



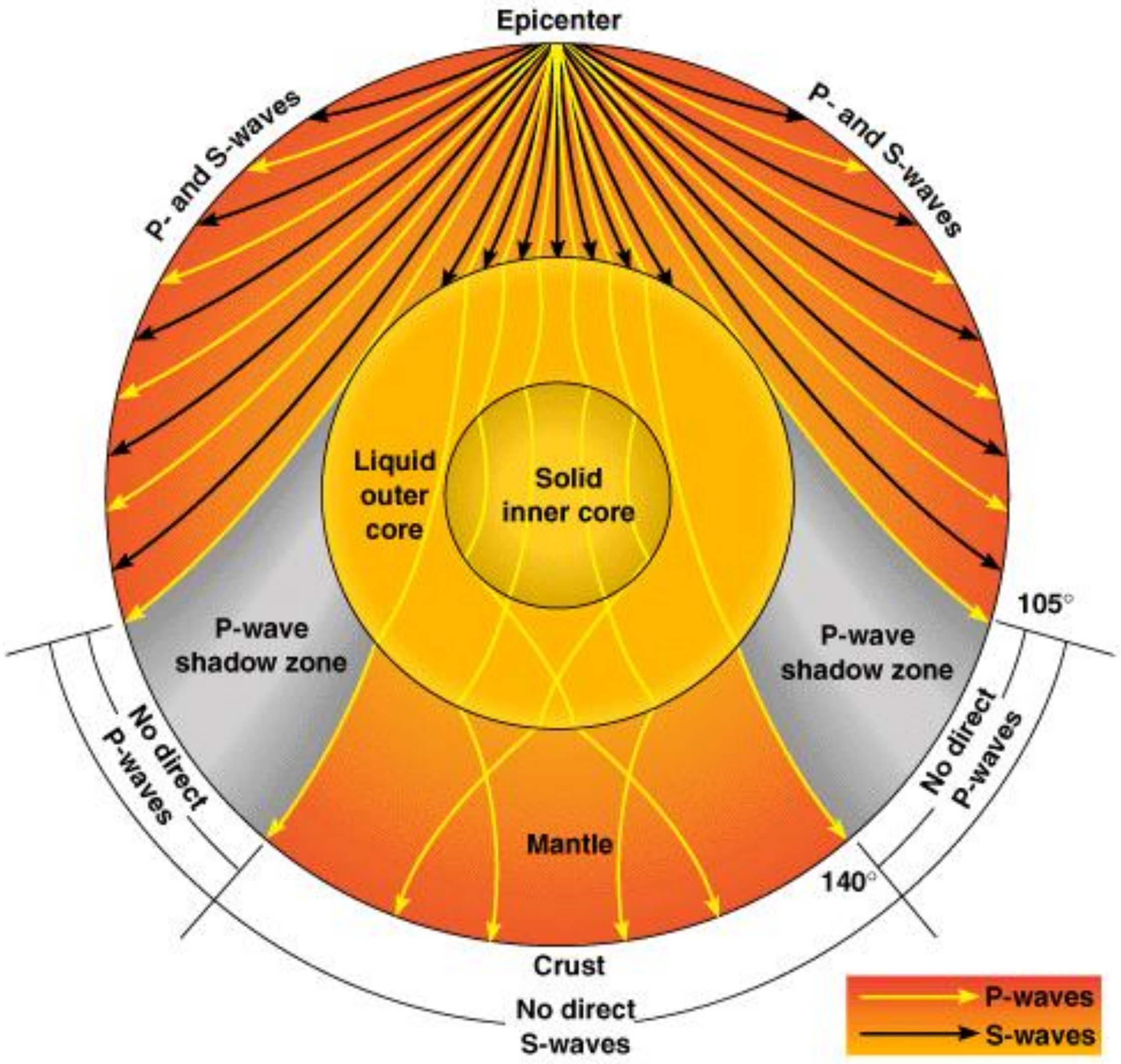
Upper mantle

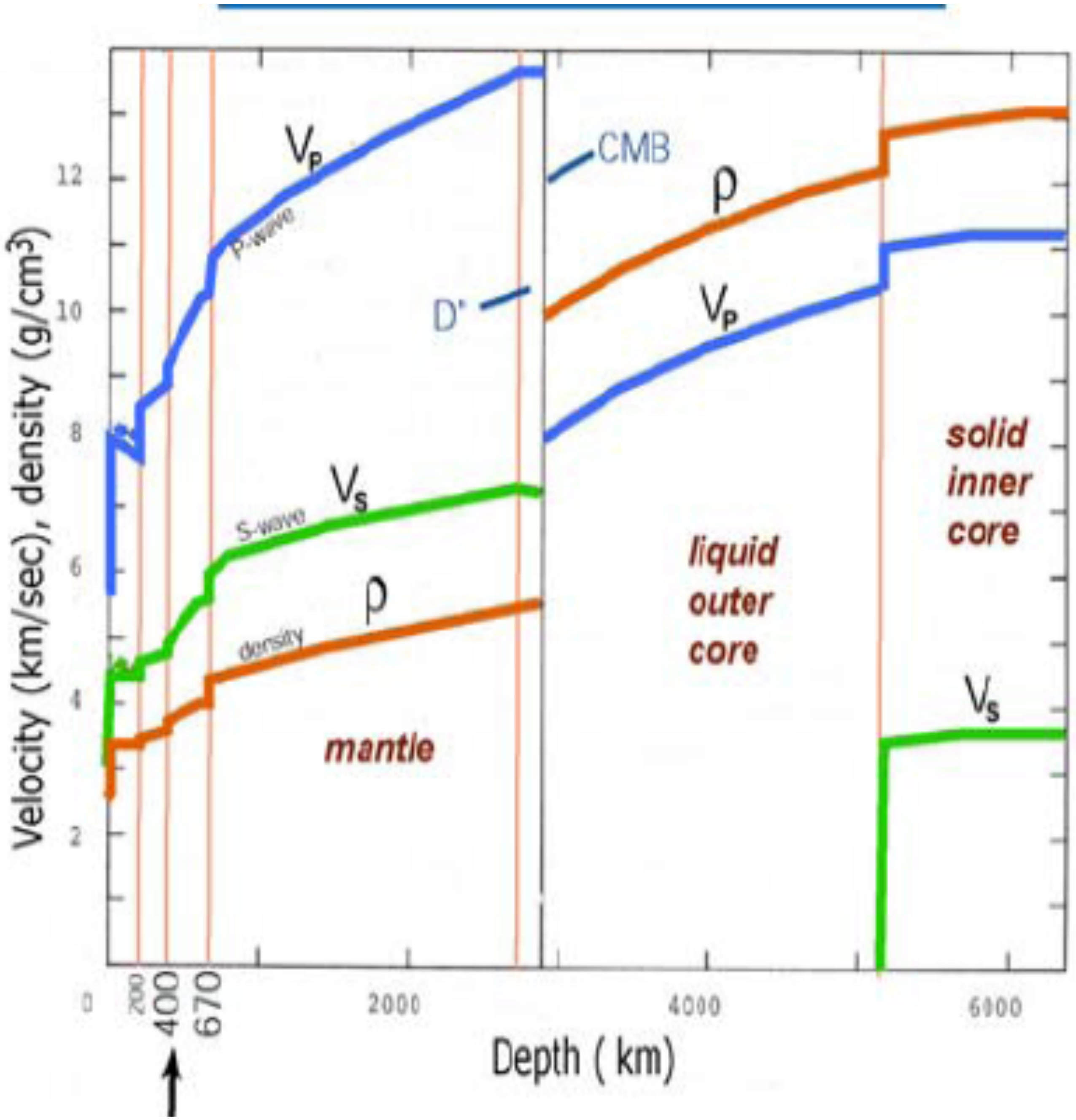
- composition: rock type peridotite
- includes highly viscose **astenosphere** on which are floating litospheric tectonic plates (**lithosphere** = more rigid upper mantle + crust);

Crust: the uppermost part

- **<u>OCEANIC CRUST</u>**:
- created at mid-ocean ridges;
- ~ 10 km thick;
- **<u>CONTINENTAL CRUST</u>**:
- the most differentiated;
- 30 – 70 km thick;
- igneous, metamorphic, and sedimentary rocks;
- obduction and orogenesis;

Seismology





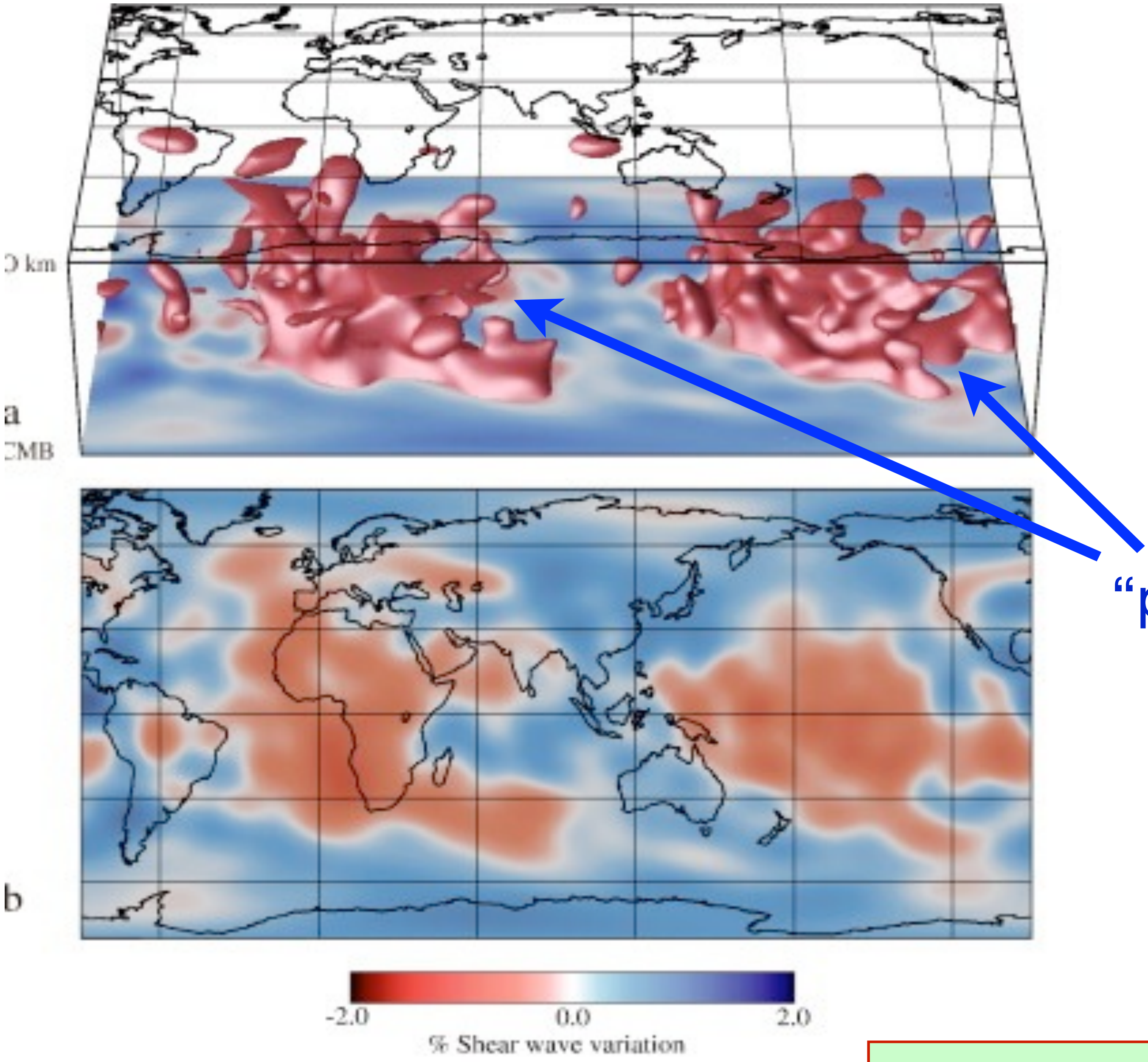
P – primary, longitudinal waves
S – secondary, transverse/shear waves

Discontinuities in the waves propagation and the density profile but no info about the chemical composition of the Earth

From the talk of Sramek at Neutrino Geoscienece 2013

Seismic tomography image of present-day mantle

Seismic shear wave speed anomaly
Tomographic model S20RTS (Ritsema et al.)



Bull et al. EPSL 2009

Two large scale seismic speed anomalies – below Africa and below central Pacific

Anti-correlation of shear and sound wavespeeds + sharp velocity gradients suggest a **compositional component**

“piles” or “LLSVPs” or “superplumes”

Candidate for an distinct chemical reservoir

Sat AM: Ed Garnero

Geochemistry

1) **Direct rock samples**

* surface and bore-holes (max. 12 km);

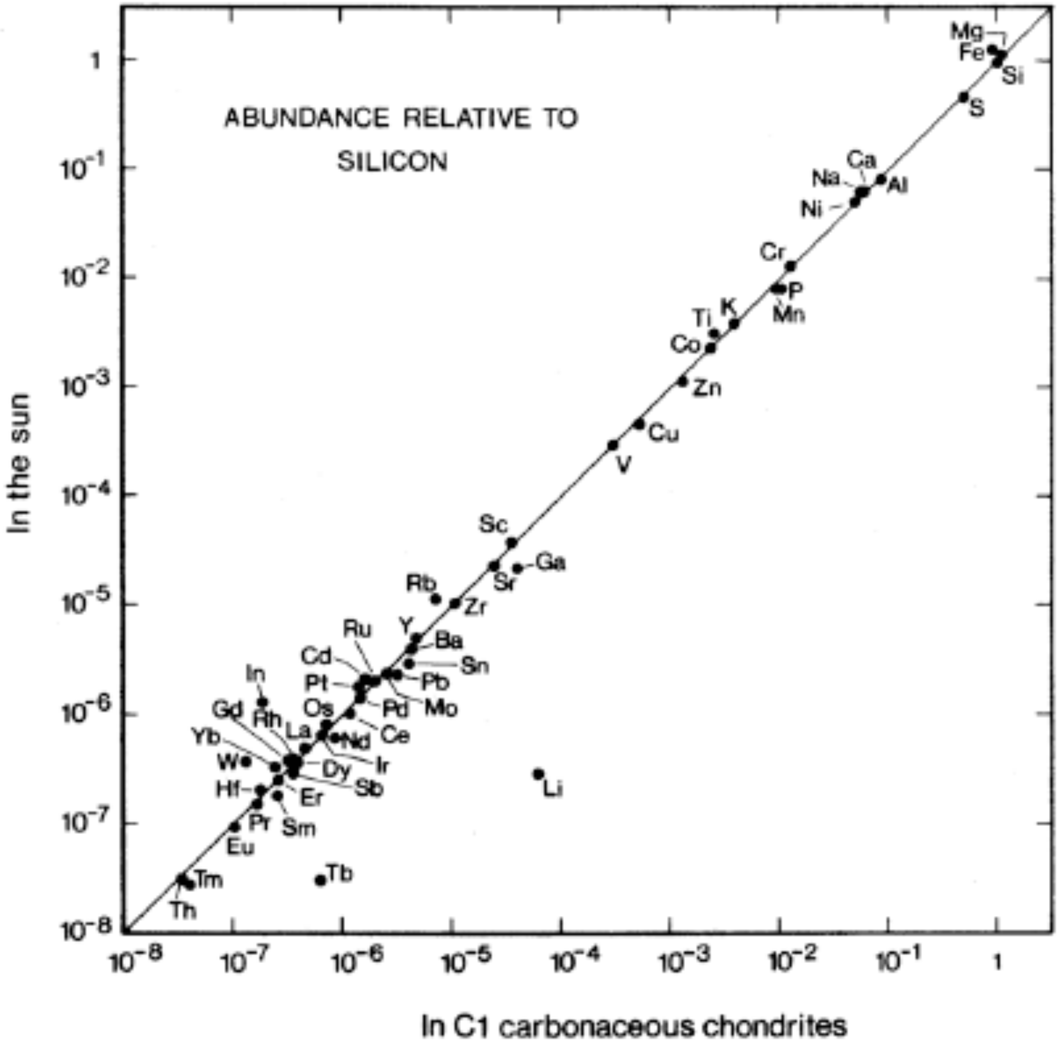
* mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) **Geochemical models:**

composition of direct rock samples +
C1 carbonaceous chondrites meteorites +
Sun’s photosphere;

Bulk Silicate Earth (BSE) models (several!):
medium composition
of the “re-mixed” crust + mantle,
i.e., primordial mantle before the crust differentiation and after the Fe-Ni core separation;



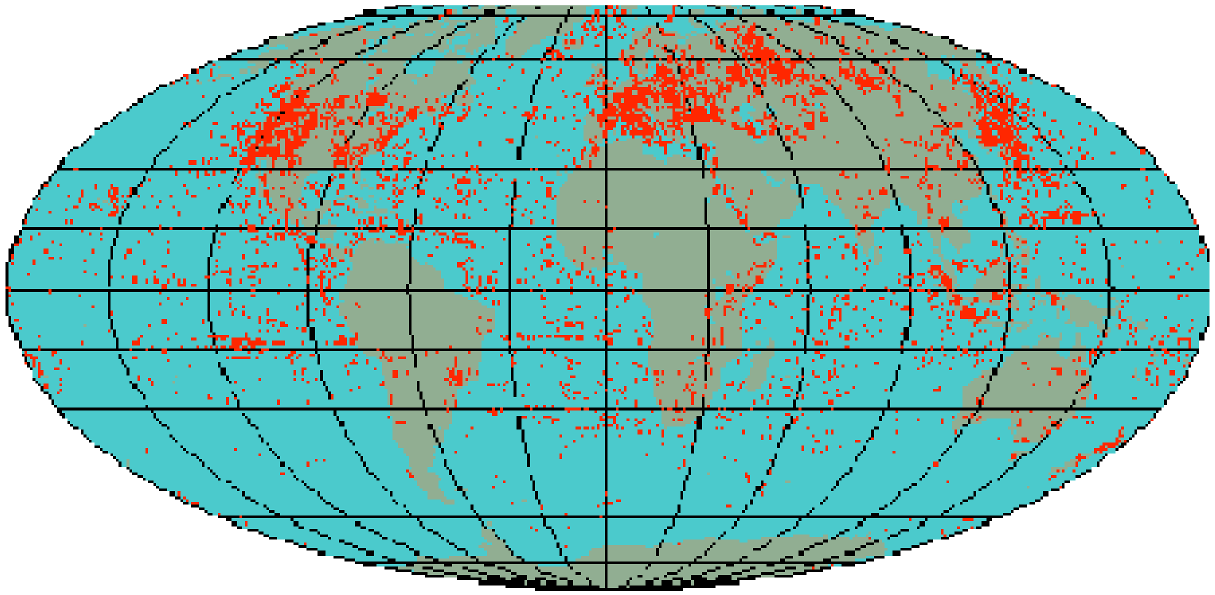
Sources of the Earth's heat

- Total heat flow ("measured"): latest results: 47±2 TW
- *Radiogenic heat = from decays of long-lived radioactive elements (U,Th chains + ^{40}K)*
  - A) C1 carbonaceous chondrites : 17-21 TW from which
    - ~9 TW from the crust and 0 from the core (the rest is in the mantle);
  - B) Enstatic-chondrites models: (Javoy 2010): only 11 TW!!!
  - C) Geodynamical models: >30 TW!!!
- Other heat sources (possible deficit up to 47-11 = 36 TW!)
  - Residual heat: gravitational contraction and extraterrestrial impacts in the past;
  - ^{40}K in the core;
  - nuclear reactor; (BOREXINO rejects a power > 3 TW at 95% C.L.)

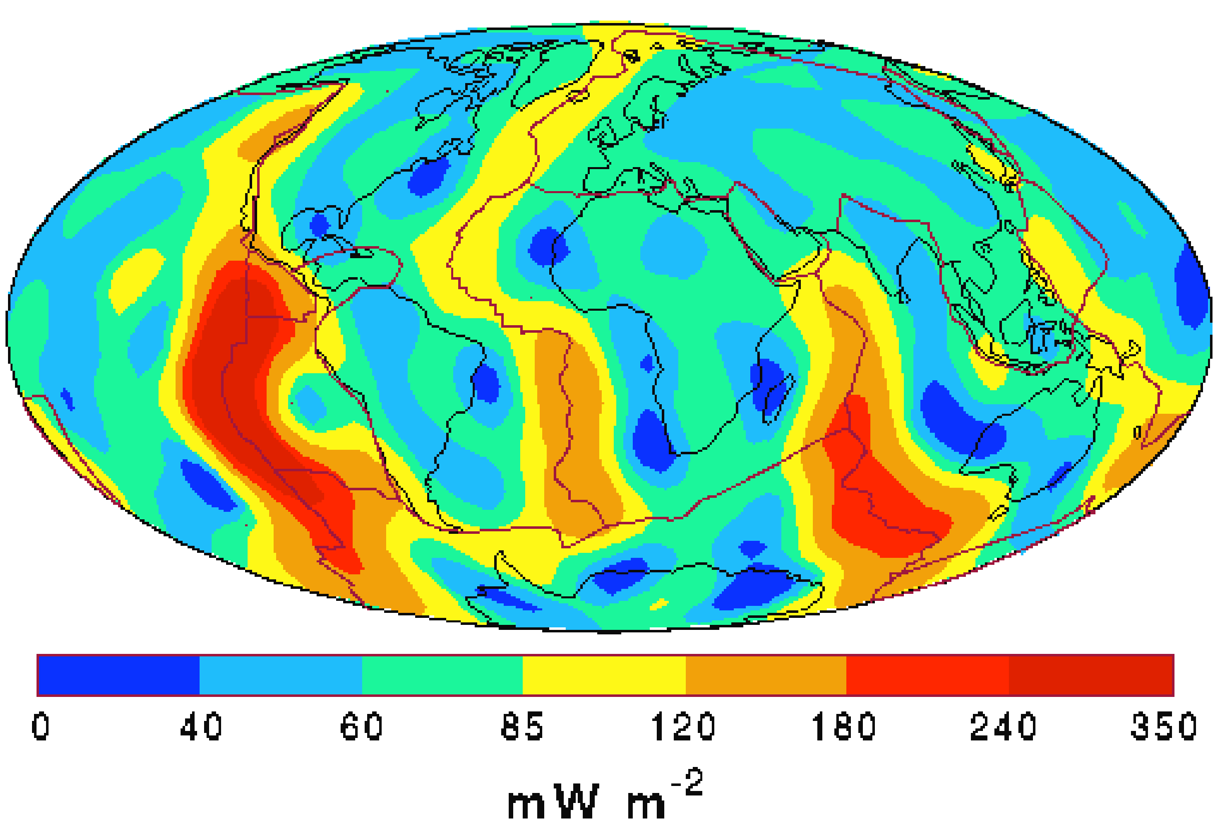
IMPORTANT MARGINS
FOR ALL DIFFERENT MODELS OF THE EARTH STRUCTUE

Surface heat flux

Bore-hole measurements



Heat Flow



- Conductive heat flow from bore-hole temperature gradient;

- **Total surface heat flux:**

  31 ± 1 TW (Hofmeister&Criss 2005)

  46 ± 3 TW (Jaupart et all 2007)

  47 ± 2 TW (Davis&Davies 2010)

  (same data, different analysis)

SYSTEMATIC ERRORS

Different assumptions concerning the role of fluids in the zones of mid ocean ridges.

From Sramek @ Neutrino Geoscience 2013

U Th K

Composition of Silicate Earth (BSE)

TW radiogenic power

BSE **Mantle**

- **“Geochemical”** estimate
  - Ratios of RLE abundances constrained by C1 chondrites
  - Absolute abundances inferred from Earth rock samples
  - *McDonough & Sun (1995), Allègre (1995), Hart & Zindler (1986), Palme & O’Neill (2003),* ***Arevalo et al. (2009)***

20±4 **12±4**

- **“Cosmochemical”** estimate
  - Isotopic similarity between Earth rocks and E-chondrides
  - Build the Earth from E-chondrite material
  - ***Javoy et al. (2010)***
  - also “collisional erosion” models (*O’Neill & Palme 2008*)

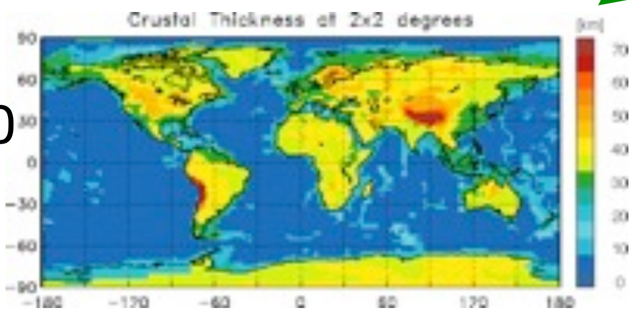
11±2 **3±2**

- **“Geodynamical”** estimate
  - Based on a classical parameterized convection model
  - Requires a high mantle Urey ratio, i.e., high U, Th, K

33±3 **25±3**

BSE = Mantle + Crust

CRUST2.0 thickness

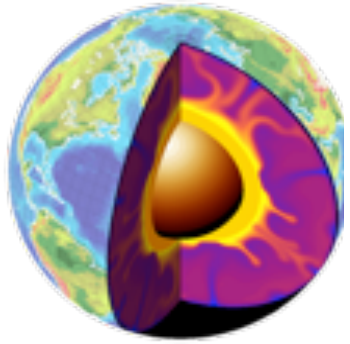


Oceanic: 0.22 ± 0.03 TW

Continental: 7.8 ± 0.9 TW

Tomorrow: New crustal model by Yu Huang et al.
CC = 6.8 (+1.4/-1.1) TW

?

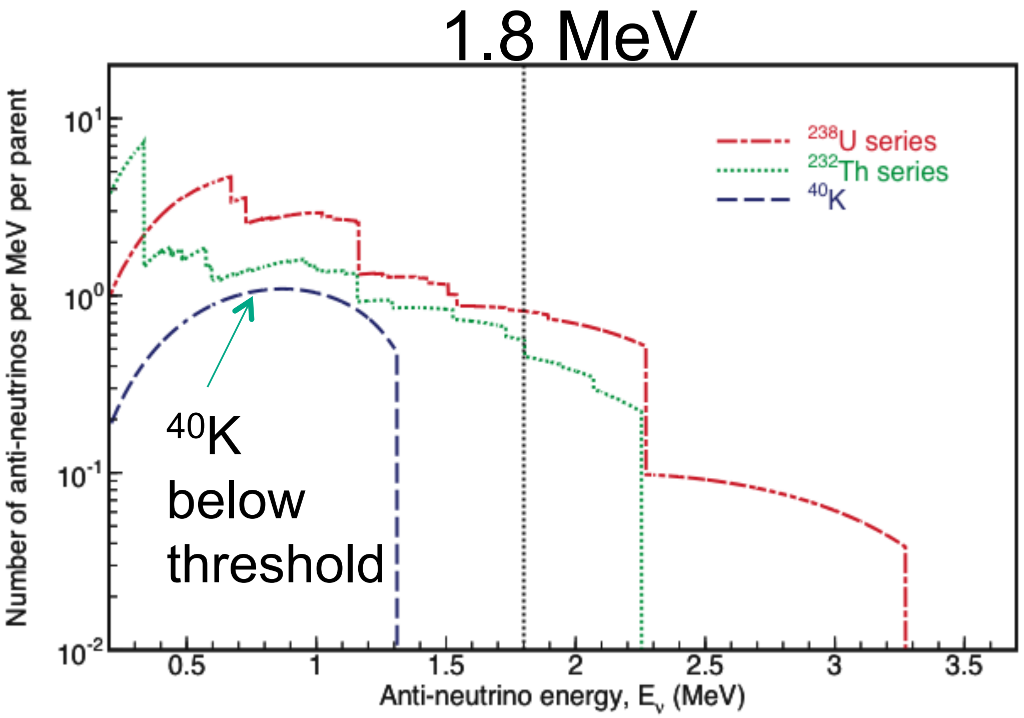


Geoneutrinos
antineutrinos from the decay of ^{238}U, ^{232}Th,^{40}K in the Earth

Abundance of radioactive elements fixes the amount of radiogenic heat (nuclear physics);
Mass and distribution of radiogenic elements → geoneutrino flux (cca 10^6 cm^{-2} s^{-1});
From measured geoneutrino flux to radiogenic heat….

Main goal: determine the contribution of the **radiogenic heat to the total surface heat flux**, which is an important margin, test, and input at the same time for many gephysical and geochemical models of the Earth;

Further goals: tests and discrimination among geological models, study of the mantle homogeneity, insights to the processes of Earth'formation…..



1.8 MeV

^{40}K below threshold

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

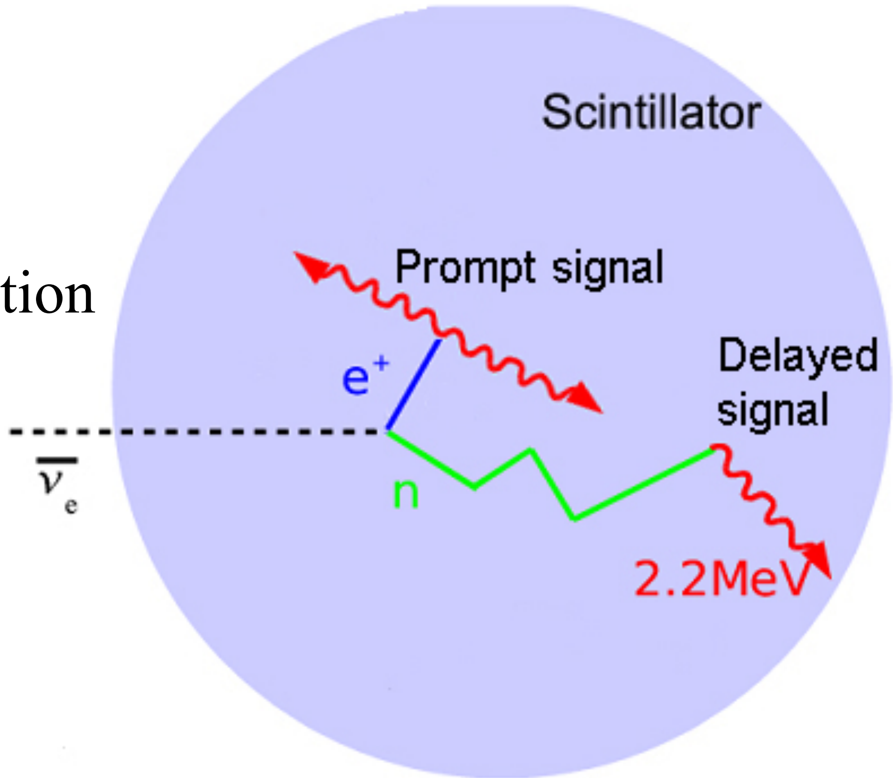
- "prompt signal"

e+: energy loss + annihilation

- "delayed signal"

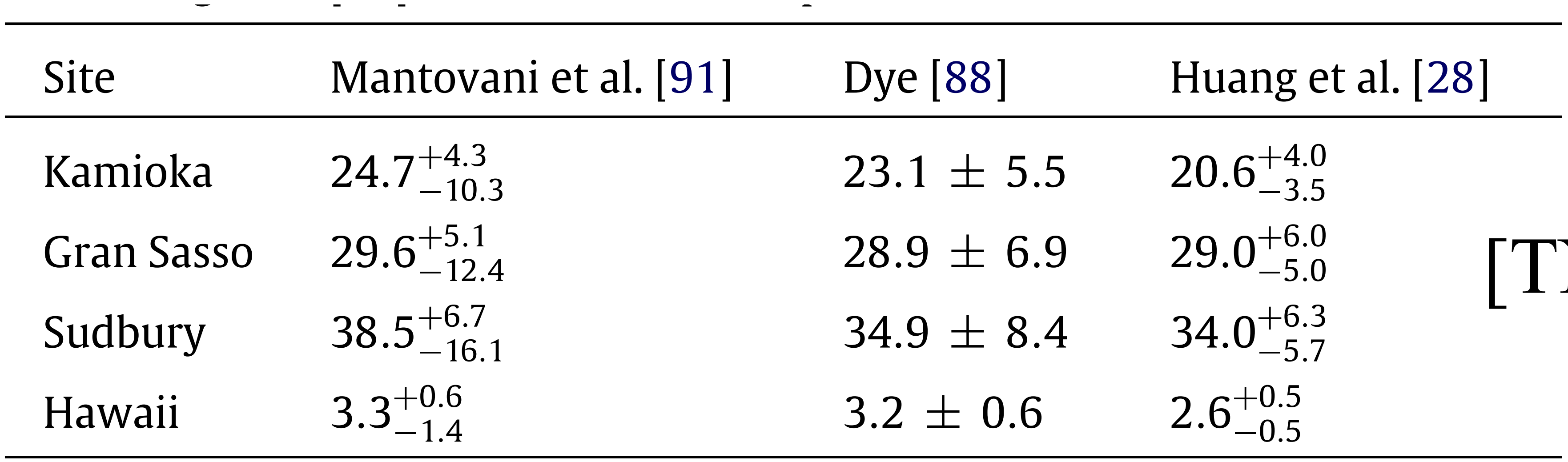
neutron capture on protons after thermalization 2.2 γ

E_ν > 1.8 MeV



Expected geoneutrino signal

- **LOC: Local crust:** about 50% of the expected geoneutrino signal comes from the crust within 500-800 km around the detector, thus local geology has to be known (for LNGS Coltorti et al. 2011);
- **ROC: Rest of the crust:** further crust is divided in 3D voxels, volumes for upper, middle, lower crust and sediments are estimated and a mean chemical composition is attributed to these volumes (Huang et al. 2013);
- **Mantle = BSE – (LOC + ROC):** this is real unknown, different BSE models are considered and the respective U + Th mass is distributed either homogeneously (maximal signal) or it is concentrated near to the core-mantle boundary (minimal signal);



	Site	Mantovani et al. [91]	Dye [88]	Huang et al. [28]
Borexino	Kamioka	$24.7^{+4.3}_{-10.3}$	23.1 ± 5.5	$20.6^{+4.0}_{-3.5}$
KamLAND	Gran Sasso	$29.6^{+5.1}_{-12.4}$	28.9 ± 6.9	$29.0^{+6.0}_{-5.0}$
SNO+	Sudbury	$38.5^{+6.7}_{-16.1}$	34.9 ± 8.4	$34.0^{+6.3}_{-5.7}$
HanoHano	Hawaii	$3.3^{+0.6}_{-1.4}$	3.2 ± 0.6	$2.6^{+0.5}_{-0.5}$

[TNU]

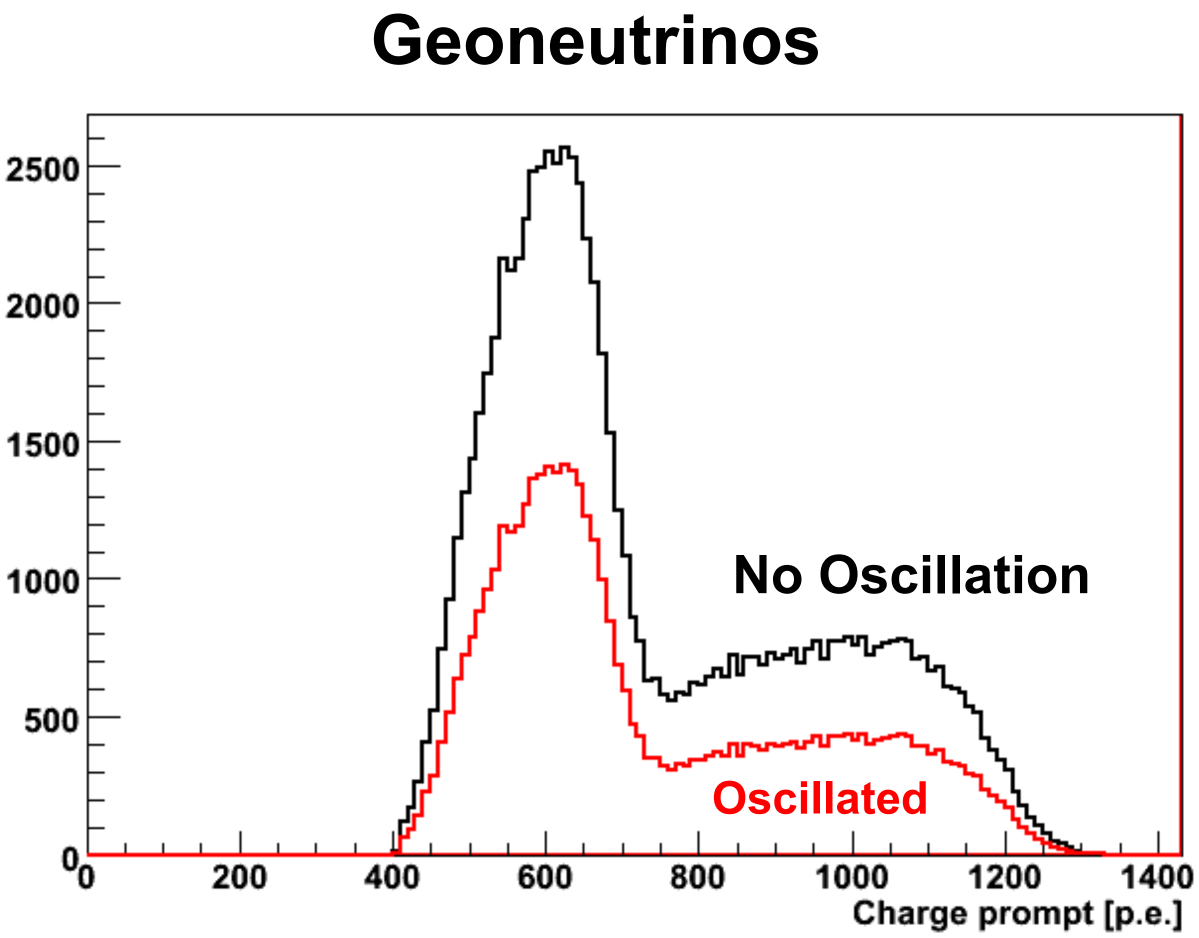
1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event / 1 kton / 1 year with 100% detection efficiency

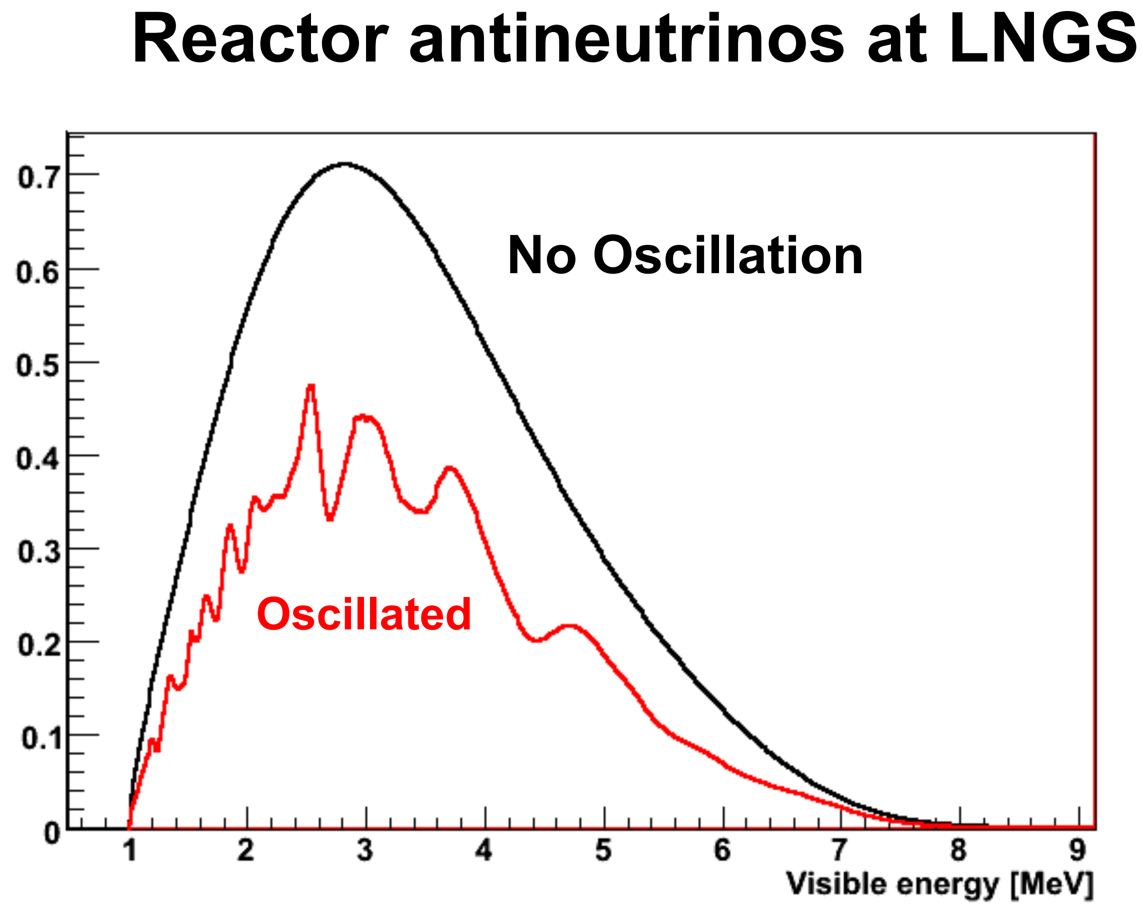
Effect of neutrino oscillations

$$P_{ee} = P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2 L}{4E}\right)\right) + \sin^4\theta_{13}$$

3 MeV antineutrino ..
Oscillation length of ~100 km

for geoneutrinos we can use average survival probability of 0.551 + 0.015 (Fiorentini et al 2012), but for reactor antineutrinos not!





Geoneutrino experimental results

KamLand (Japan)

- The very first investigation in 2005
  (Nature 436 (2005) 499): CL < 2 sigma;
- Update in PRL 100 (2008):
  73 +- 27 geo events
- high exposure: 99.997 CL observation in 2011
  (Gando et al, Nature Geoscience 1205)
  106^{+29}_{-28} geonu events detected;
  (March 2002 – April 2009)
  3.49 x 10^{32} target-proton year
- **PRD 88 (2013) 033001**
  116^{+28}_{-27} geonu events detected;
  (March 2002 – November 2012)
  4.9 x 10^{32} target-proton year
  0-hypothesis @ 2 x 10^{-6}

Borexino (Italy)

- small exposure but low background level:
  observation at 99.997 CL in 2010
  (Bellini et al, PLB 687):

$9.9^{+4.1}_{-3.4}$ geonu events detected;
(December 2007 – December 2009)
Exposure 1.5 x 10^{31} target-proton year

- **PLB 722 (2013) 295–300:**
  14.3 +- 4.4 geonu events;
  (December 2007 – August 2012)
  3.69 x 10^{31} target-proton year after cuts
  0-hypothesis @ 6 x 10^{-6}

Geoneutrinos in Borexino

2010 result: FIRST OBSERVATION AT > 4σ C.L. level

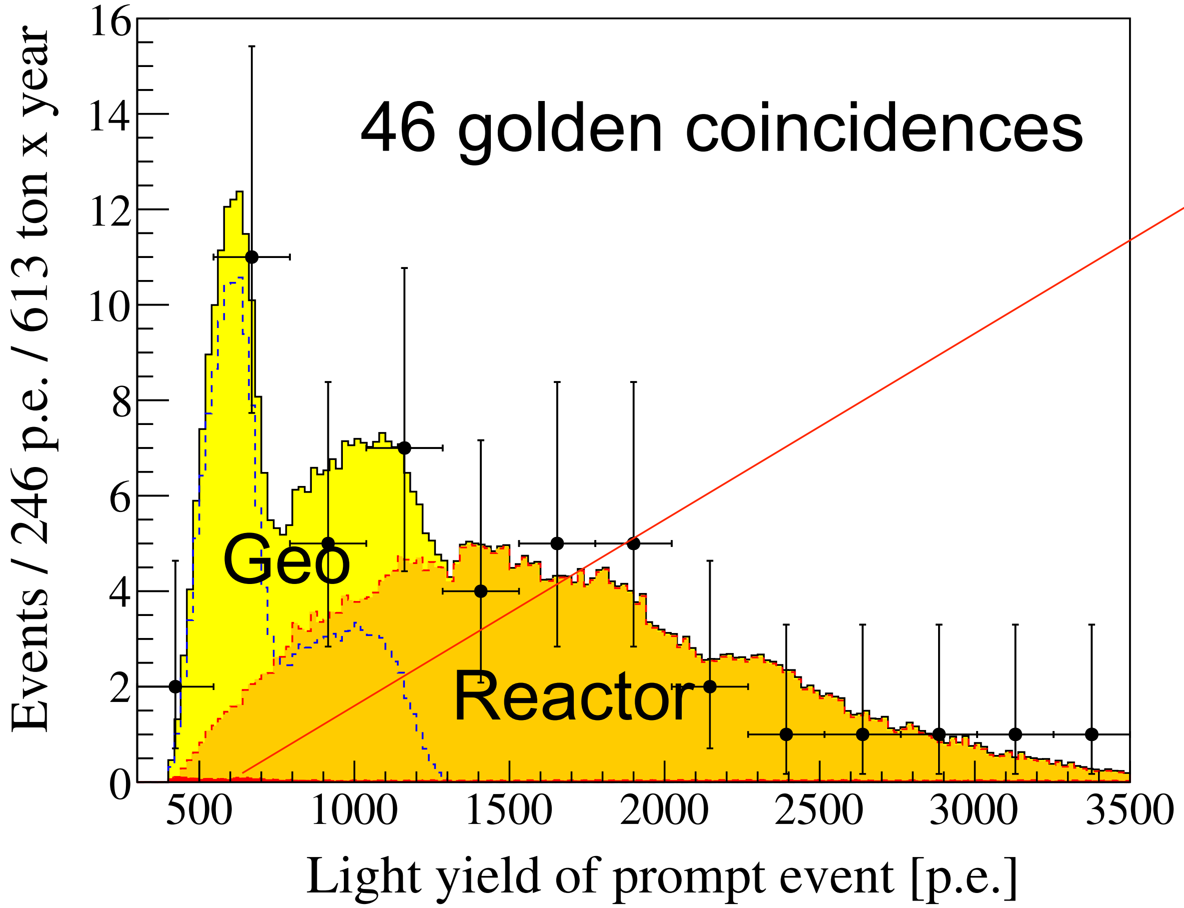
G. Bellini et al. Phys. Lett. B 687 (2010) 299 with 252.6 ton-year exposure after cuts;

2013 result: G. Bellini et al. Phys. Lett. B 722 (2013) 295 with (613 ± 26) ton-year after cuts ;

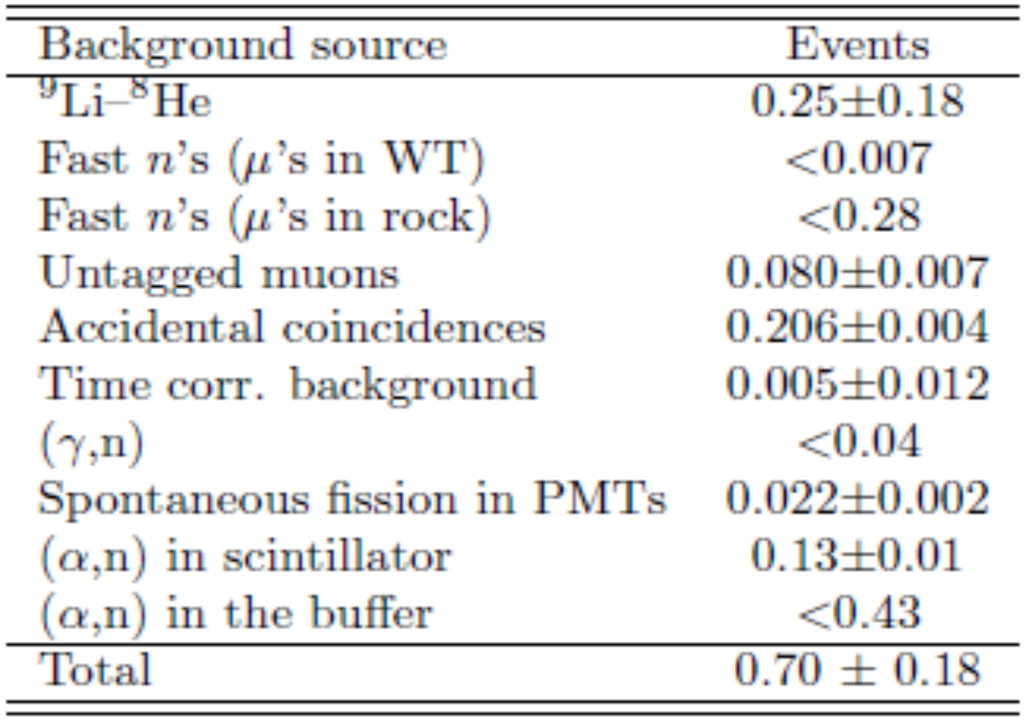
Unbinned maximal likelihood fit:

Free: ***geoneutrino*** (T/Th constrained to chondritic value OR separate U and Th contributions)
reactor antineutrino (different parametrsations differ in rate and not that much in shape)

Constrained: **other backgrounds** (almost negligible)



Background not due to reactors is very small



Background source	Events
^{9}Li–^{8}He	0.25±0.18
Fast n's (μ's in WT)	<0.007
Fast n's (μ's in rock)	<0.28
Untagged muons	0.080±0.007
Accidental coincidences	0.206±0.004
Time corr. background	0.005±0.012
(γ,n)	<0.04
Spontaneous fission in PMTs	0.022±0.002
(α,n) in scintillator	0.13±0.01
(α,n) in the buffer	<0.43
Total	0.70 ± 0.18

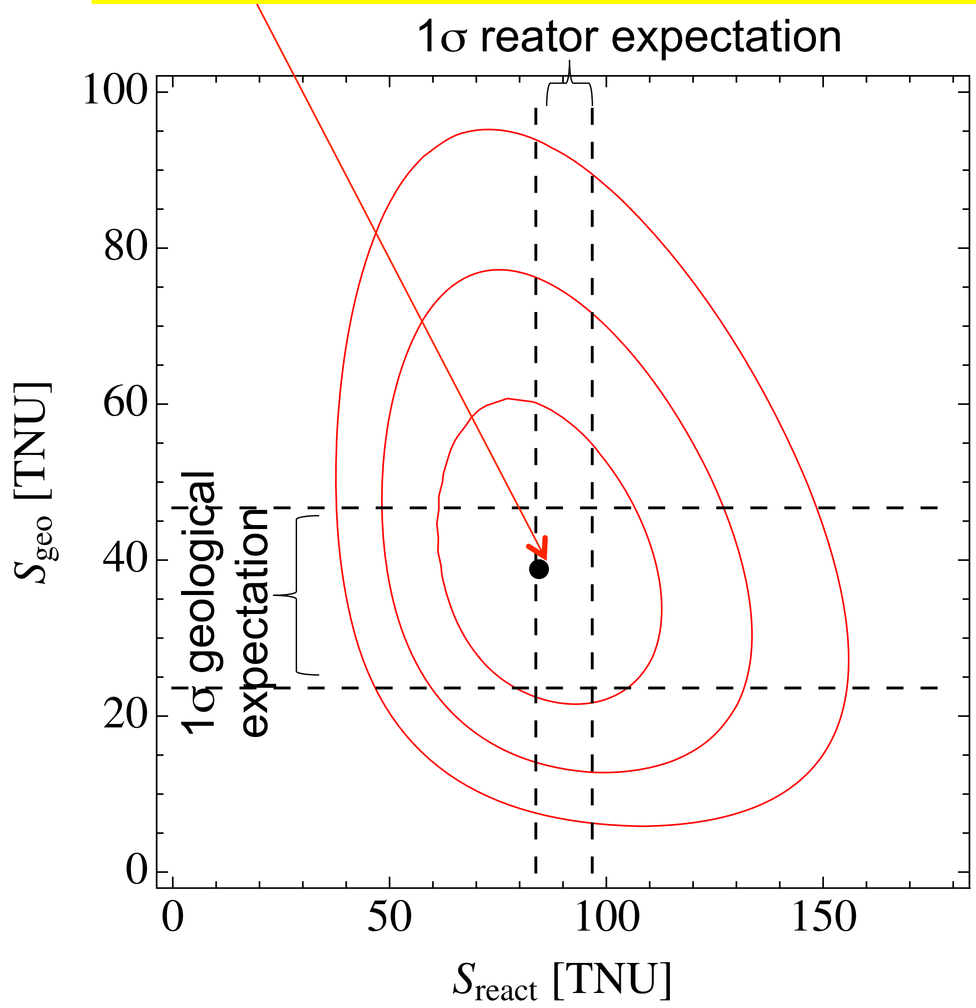
Geoneutrinos in Borexino: fit results

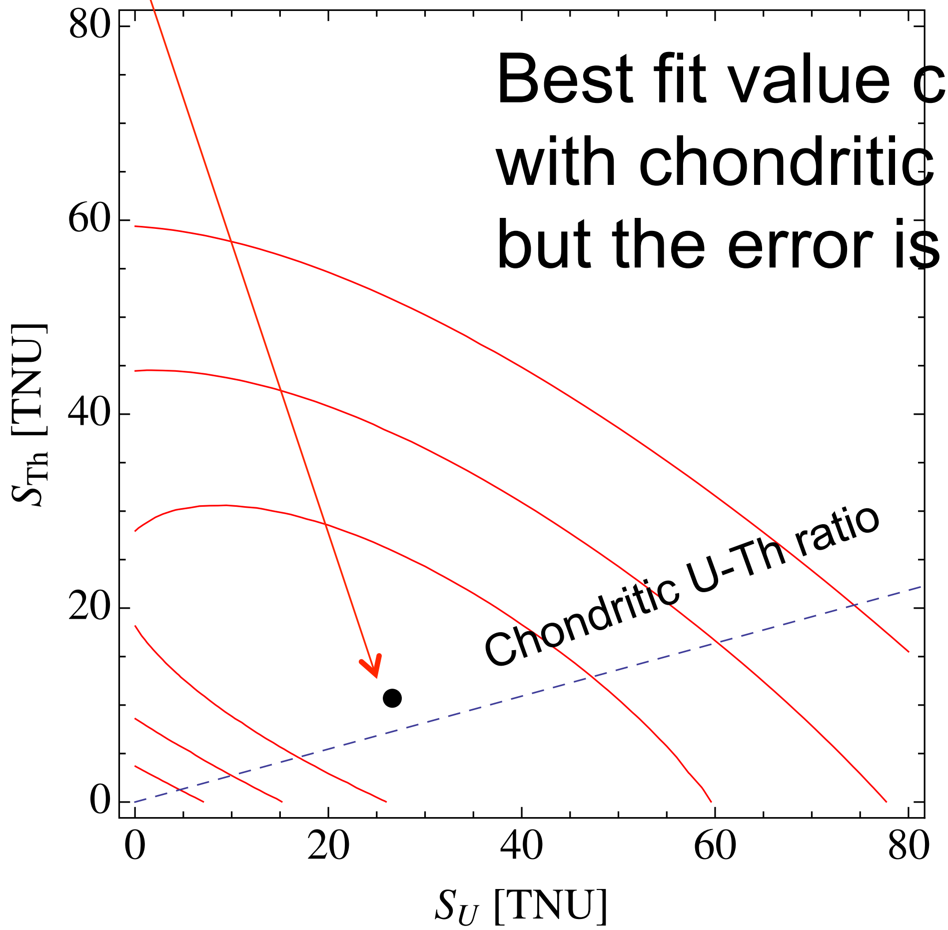
1 TNU = 1 event / 10^{32} target protons / year
Cca 1 event / 1 kton / 1 year with 100% detection efficiency

$N_{reactor} = 31.2_{-6.1}^{+7}$ **(free in the fit!)** in agreement with expectation of 33.3 ± 2.4 events after oscillations;

Fixed Th/U mass ratio to chondritic value of 3.9:
N_{geo} = 14.3 ± 4.4 events
S_{geo} = 38.8 ± 12.0 TNU

Th/U ratio free in the fit:
S(^{238} U)= 26.5 ± 19.5 TNU
S(^{232} T) = 10.6 ± 12.7 TNU





Best fit value compatible with chondritic value but the error is still large

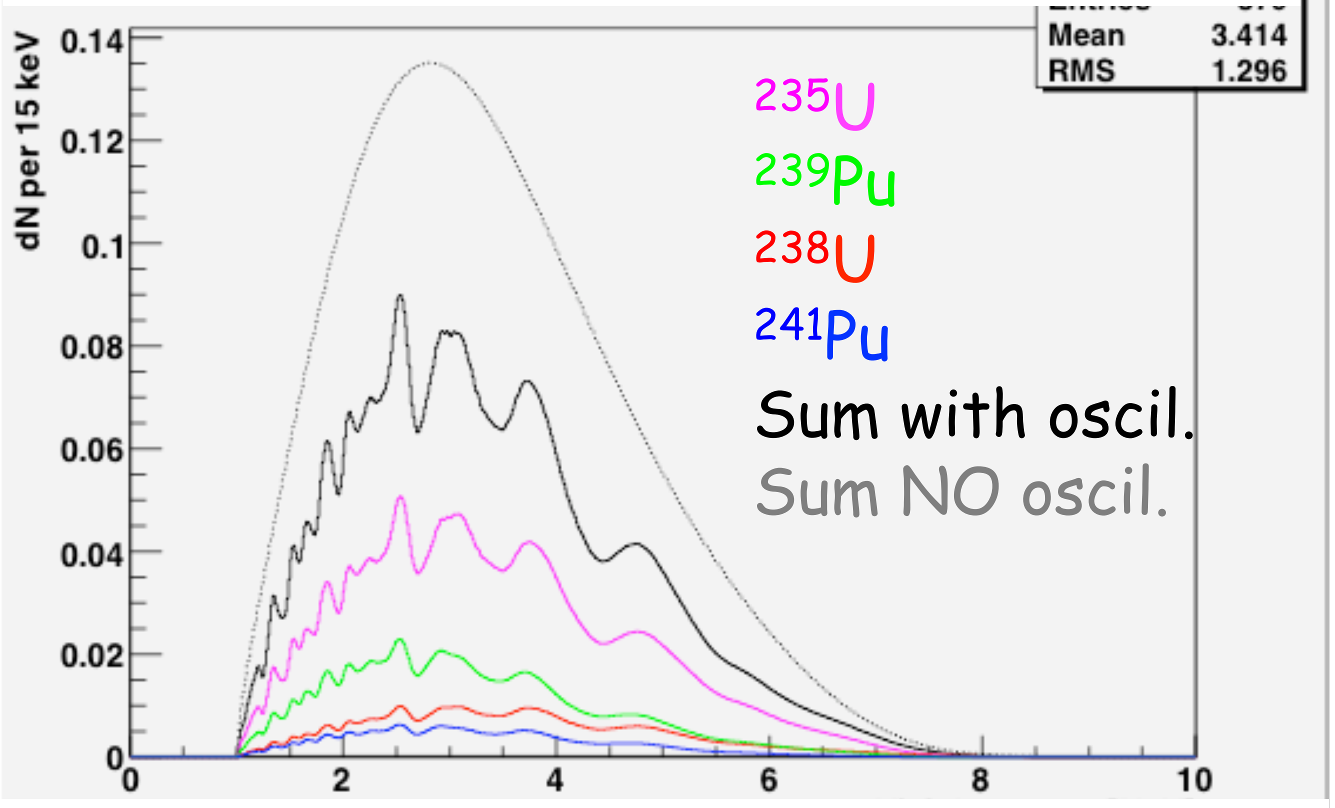
Expected reactor anti-neutrino signal and its error in Borexino

Expected number of events: (33.3±2.4) events in 613 ton×year exposure

Source of error	Error (%)
Oscillations: θ_{13}	±0.5%
Oscillations: δm^2	±0.02%
Oscillations: θ_{12}	**±2.3%**
Energy per fission of isotope i: E_i	±0.6%
Flux shape: $\Phi_i(E_\nu)$	**±3.5%**
Cross section: $\sigma(E)$	±0.4%
Thermal power: P_{rm}	**±2.0%**
Long lived isotopes in spent fuel	±1%
Fuel composition: f_{ri}	**±3.2%**
Reactor – Borexino distance L_r	±0.4%
TOTAL	**±5.8%**

$\sigma \sim 10^{-44}\ \mathrm{cm}^2$ $N_{protons} = 6\times10^{30}$ in 100 tons

Energy spectrum of prompt events



Ideal detector

Prompt energy (MeV)

Non-antineutrino background sources

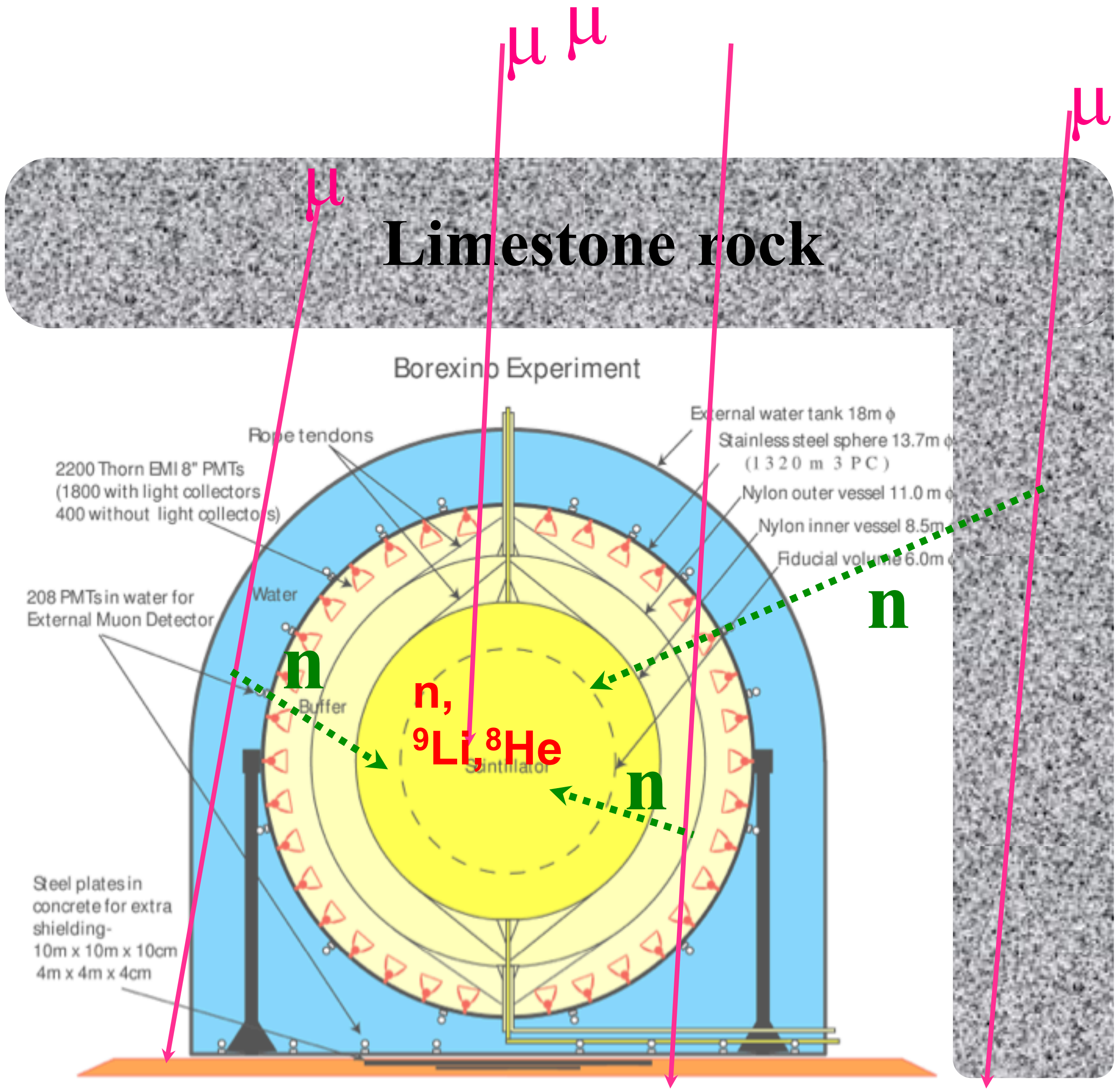
1) <u>Cosmogenic-muon induced:</u>

- **^{9}Li and ^{8}He** decaying β-n;
- **neutrons** of high energies;
  - neutrons scatters proton = prompt;
  - neutron is captured = delayed;
- Non-identified muons;

2) <u>Accidental coincidences</u>;

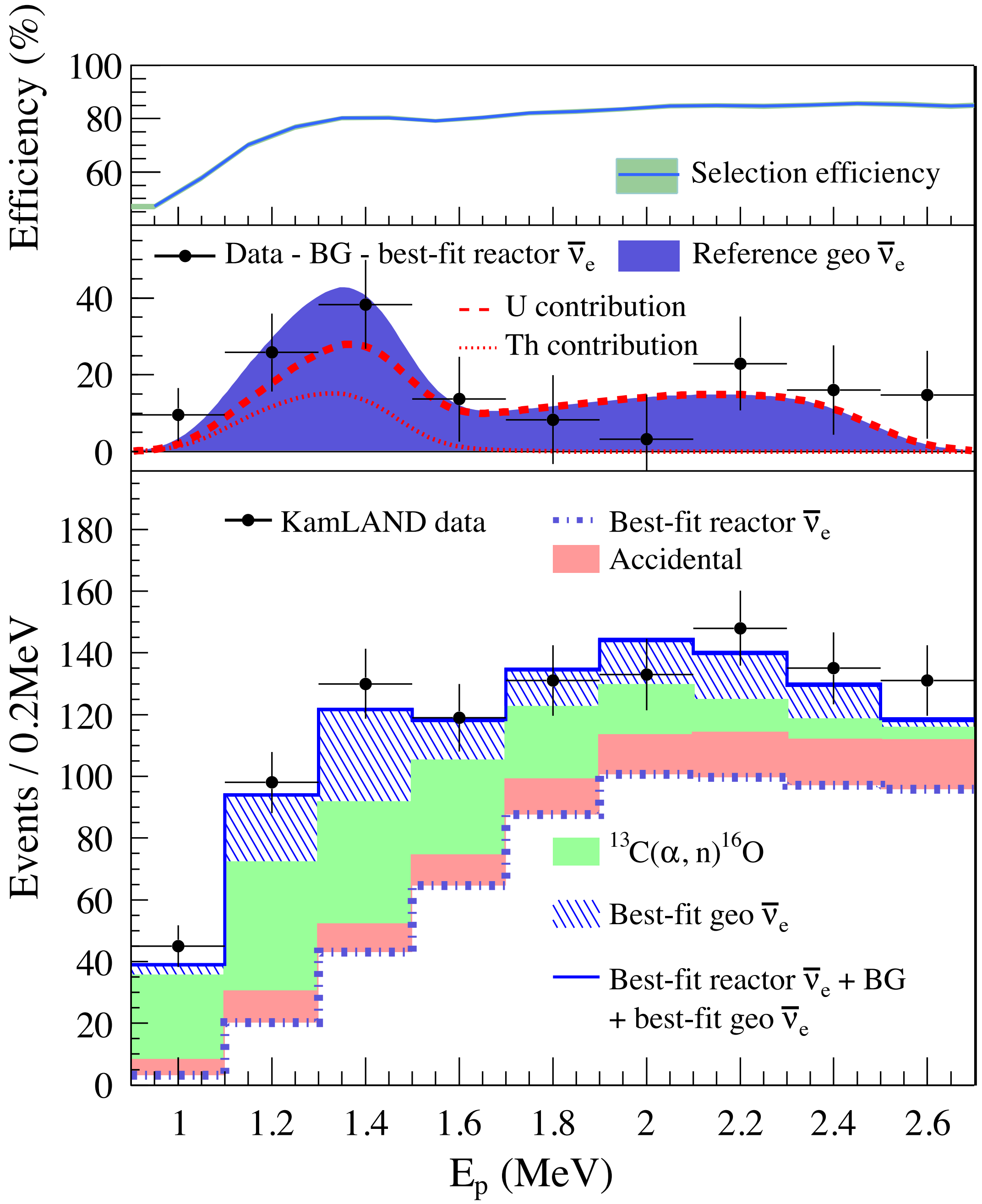
3) <u>Due to the internal radioactivity</u>: (α,n) and (γ,n) reactions

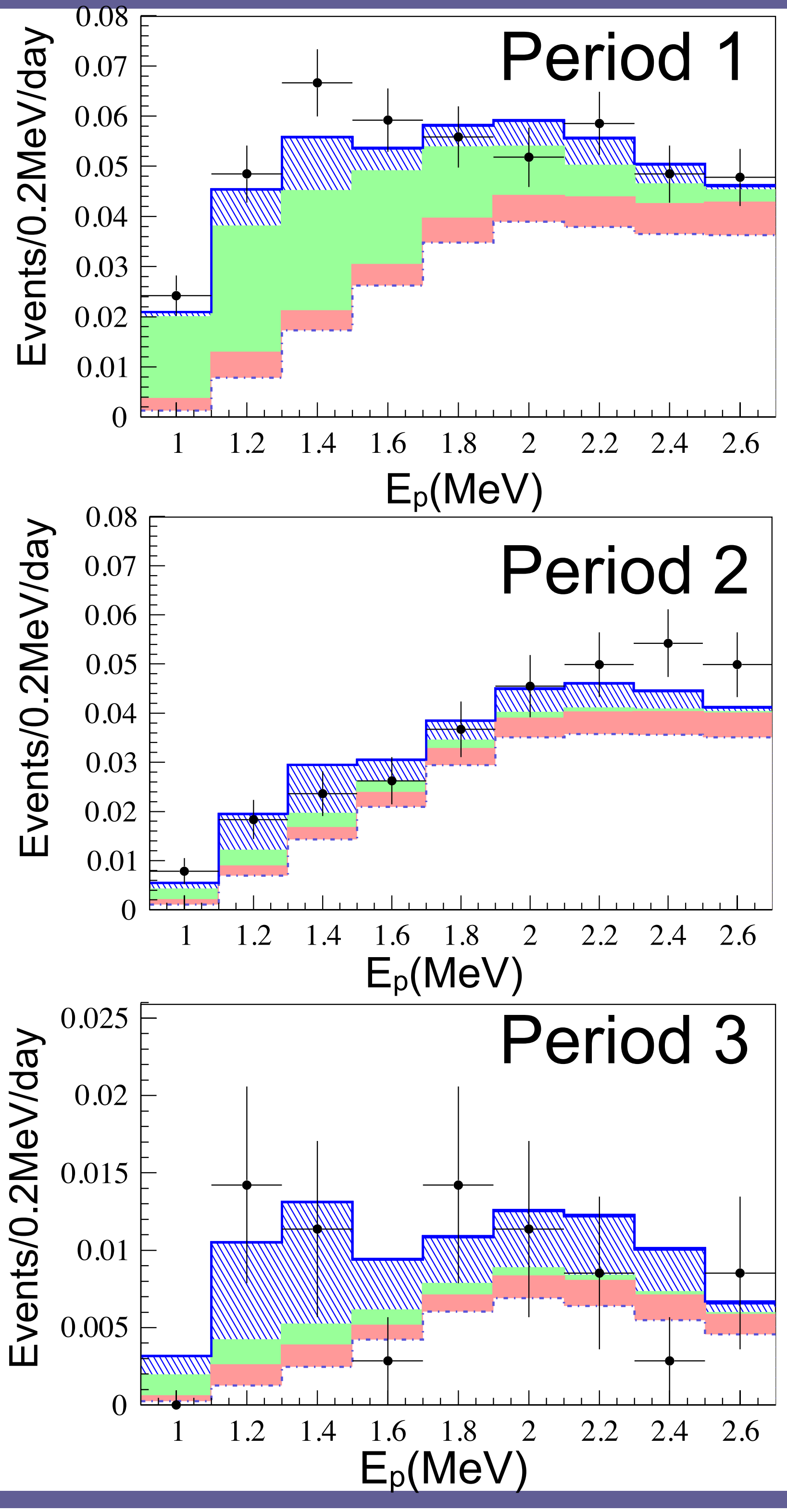
Background source	Events
^{9}Li–^{8}He	0.25 ± 0.18
Fast n's (μ's in WT)	<0.07
Fast n's (μ's in rock)	<0.28
Untagged muons	0.080 ± 0.007
Accidental coincidences	0.206 ± 0.004
Time corr. background	0.005 ± 0.012
(γ, n)	<0.04
Spontaneous fission in PMTs	0.022 ± 0.002
(α, n) in scintillator	0.13 ± 0.01
(α, n) in the buffer	<0.43
Total	0.70 ± 0.18



KamLAND (2013) geoneutrino results

Analysis : Energy Spectrum (0.9-2.6 MeV)





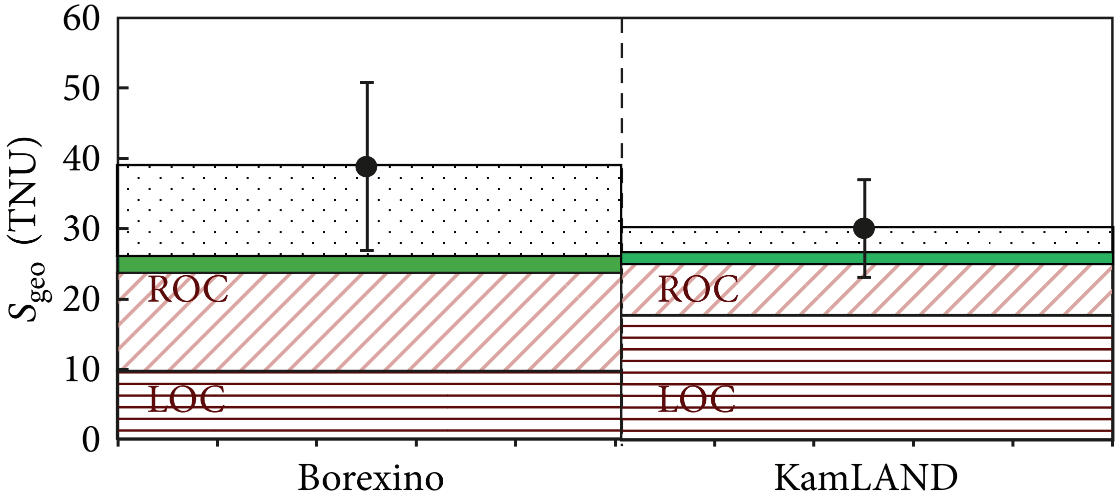
From KamLAND talk of H. Watanabe @ Neutrino Geoscience 2013

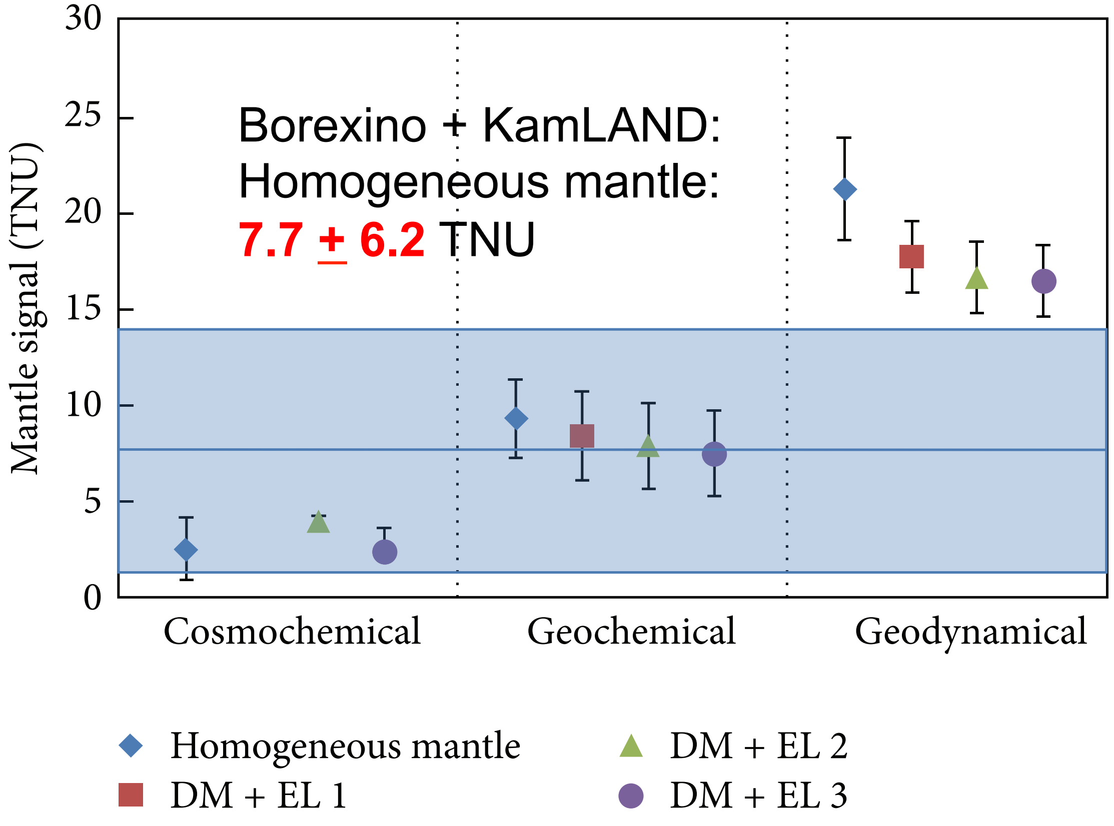
Geoneutrinos: implications combining Borexino (2013) + KamLAND (2013) results

L.L. & S. Zavaterelli:
Hindawi Publishing Corporation
Advances in High Energy Physics
Volume 2013, Article ID 425693, 16 pages

Mantle: Borexino:
15.4 ± 12.3 TNU

Mantle: KamLAND:
5.0 ± 7.3 TNU



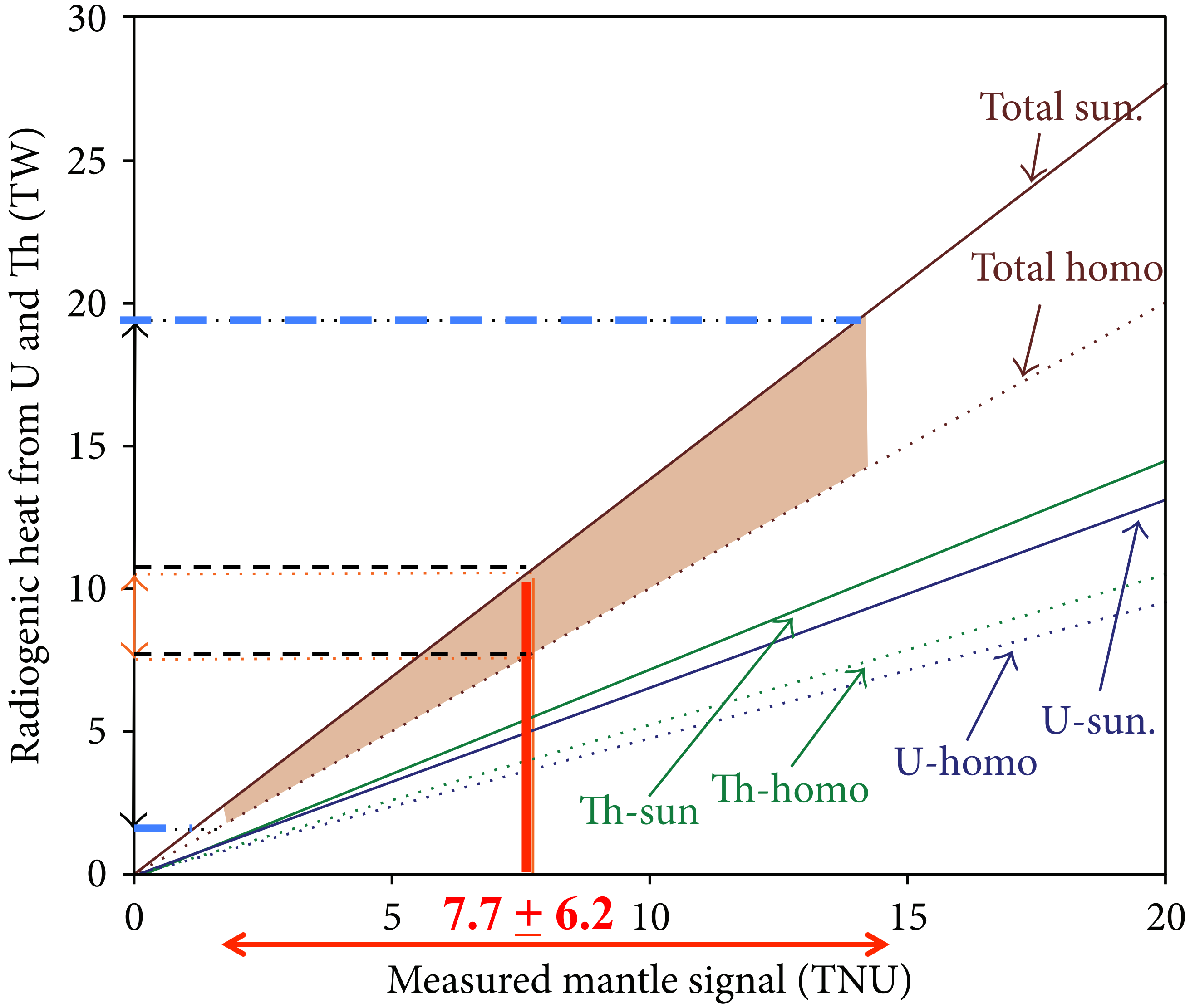


Borexino + KamLAND:
Homogeneous mantle:
7.7 ± 6.2 TNU

Mantle radiogenic heat:

1σ band: 2 – 20 TW

In agreement with the expectations, but too wide for now to discriminate among models



Different distribution of U and Th through the mantle

Geoneutrino summary

- The new interdisciplinary field is born;
- Collaboration among geologists and physicists is a must;
- The current experimental results confirm that geo-neutrinos can be successfully detected;
- Signal prediction and data interpretation: local geology around the experimental site must be studied;
- The combined results from different experimental sites have stronger impact – first geologically significant results start to appear;
- New measurements and the new generation experiments are needed for geologically highly significant results:
- Borexino and KamLAND continue to take data;
- SNO+ in Canada (1 kton) should provide data in not that far future;
- JUNO in China (20 kton): big reactor and cosmogenic background, but large statistics compensates: interesting results to come after 2020;

THANK YOU!

Backup

Calculation of reactor anti-ν signal

$$\Phi\left(E_{\bar{\nu}_e}\right) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \sum_{i=1}^{4} \frac{f_{ri}}{E_i} \Phi_i\left(E_{\bar{\nu}_e}\right) P_{ee}\left(E_{\bar{\nu}_e}; \hat{\vartheta}, L_r\right)$$

- **From the literature:**
  - **E_i :** energy release per fission of isotope i (Huber-Schwetz 2004);
  - **Φ_i:** antineutrino flux per fission of isotope i (polynomial parametrization, Mueller et al.2011, Huber-Schwetz 2004);
  - **P_{ee}:** oscillation survival probability;
- **Calculated:**
  - **T_m:** live time during the month m;
  - **L_r:** reactor r – detector distance;
- **Data from nuclear agencies:**
  - **P_{rm}:** thermal power of reactor r in month m (IAEA , EDF, and UN data base);
  - **f_{ri}:** power fraction of isotope i in reactor r;

^{235}U
^{239}Pu
^{238}U
^{241}Pu