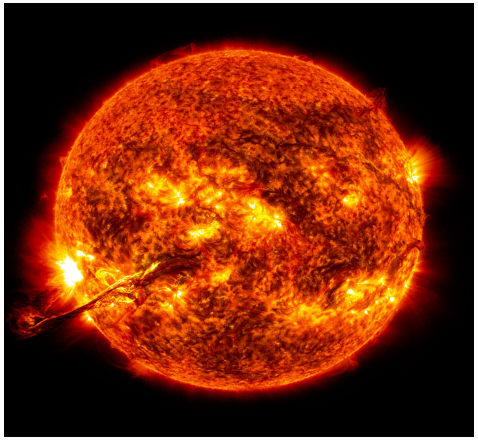
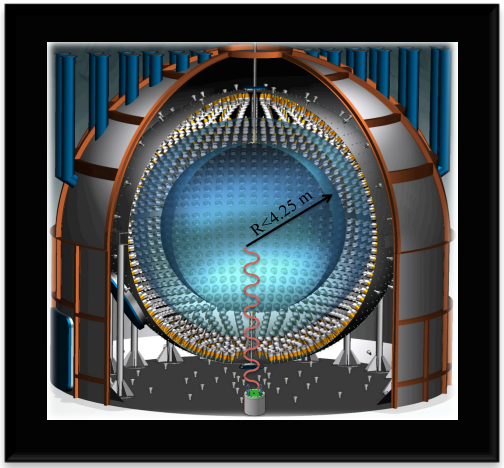
Low-energy neutrinos

Solar



Geo

Sources



Livia Ludhova

Istituto Nazionale di Fisica Nucleare, Milano, Italy

Outline

Solar **Geo** **Sources**

few MeV

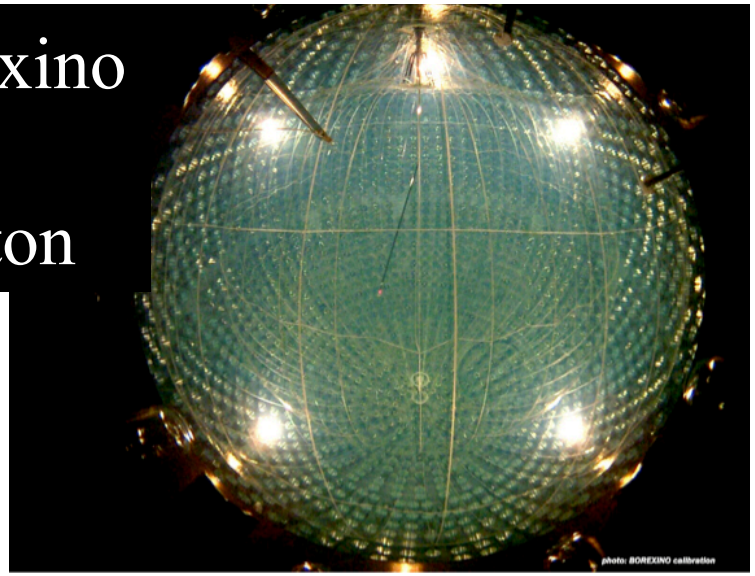
1.5×10^{11} m **$< 1.27 \times 10^{7}$ m** **~m**

1. Motivation to study them today
2. Latest experimental results
3. Future perspectives

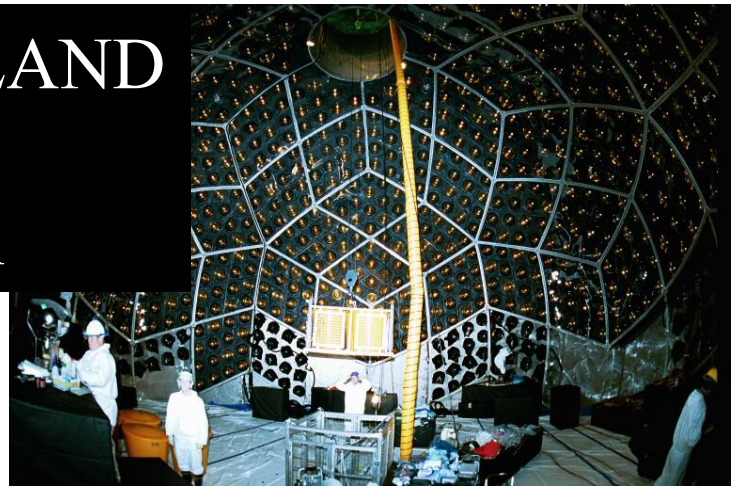
Which experiments? Underground laboratories

Liquid scintillator

Borexino
Italy
280 ton

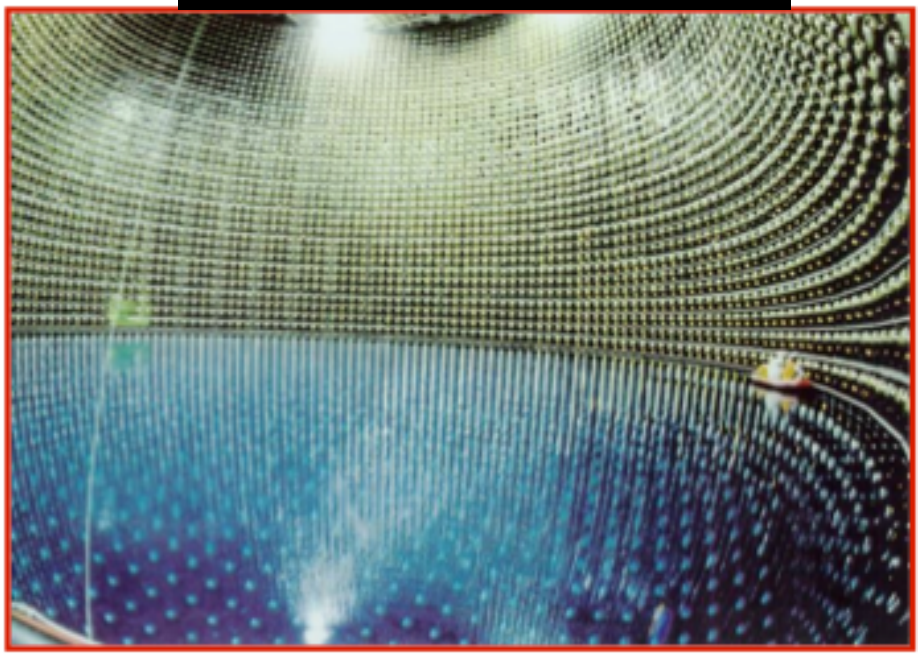


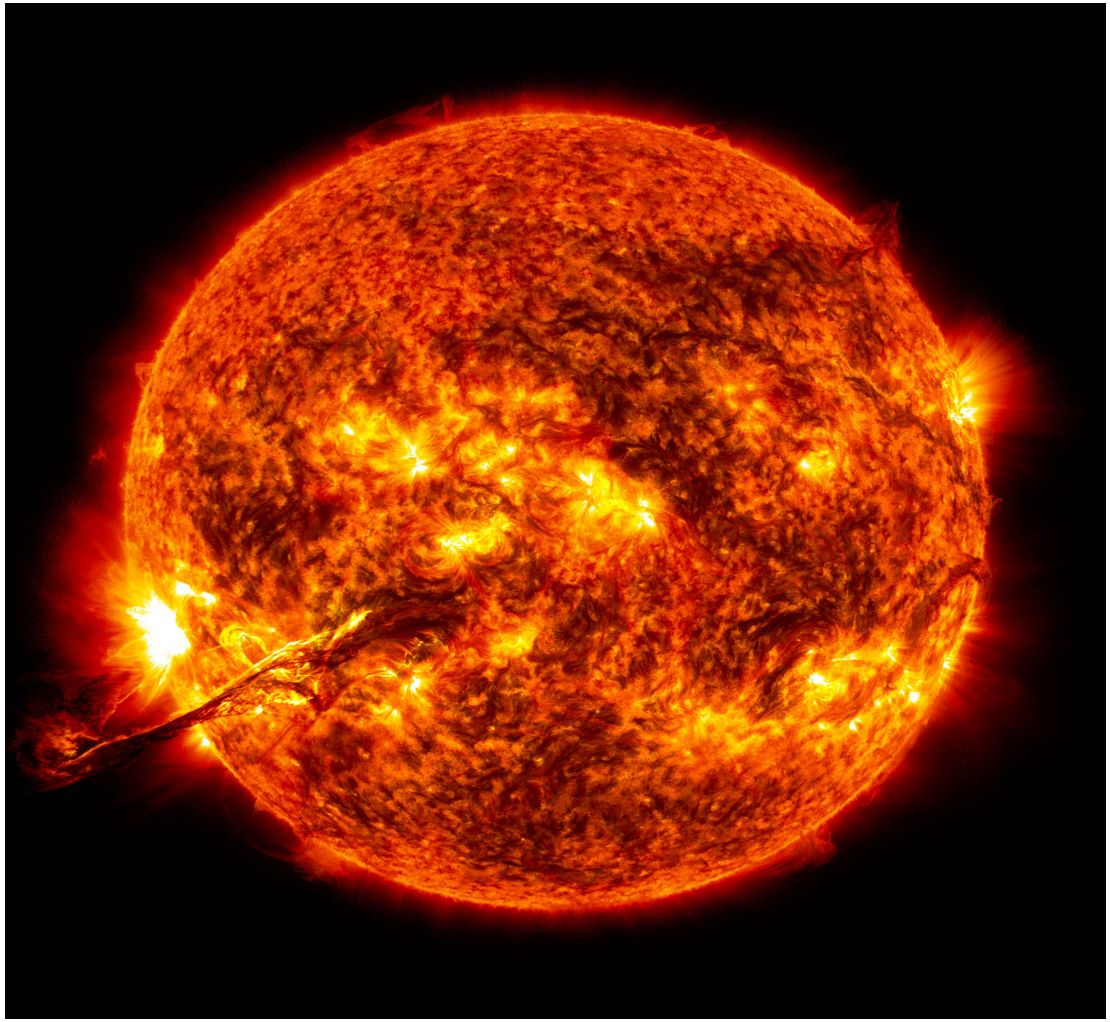
KamLAND
Japan
1 kton



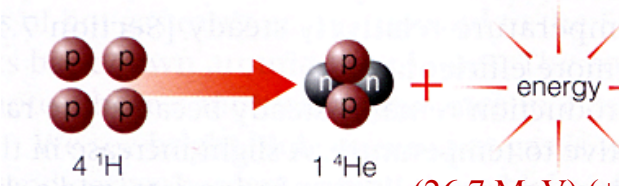
Water Cherenkov

SuperKamiokande
Japan
50 kton



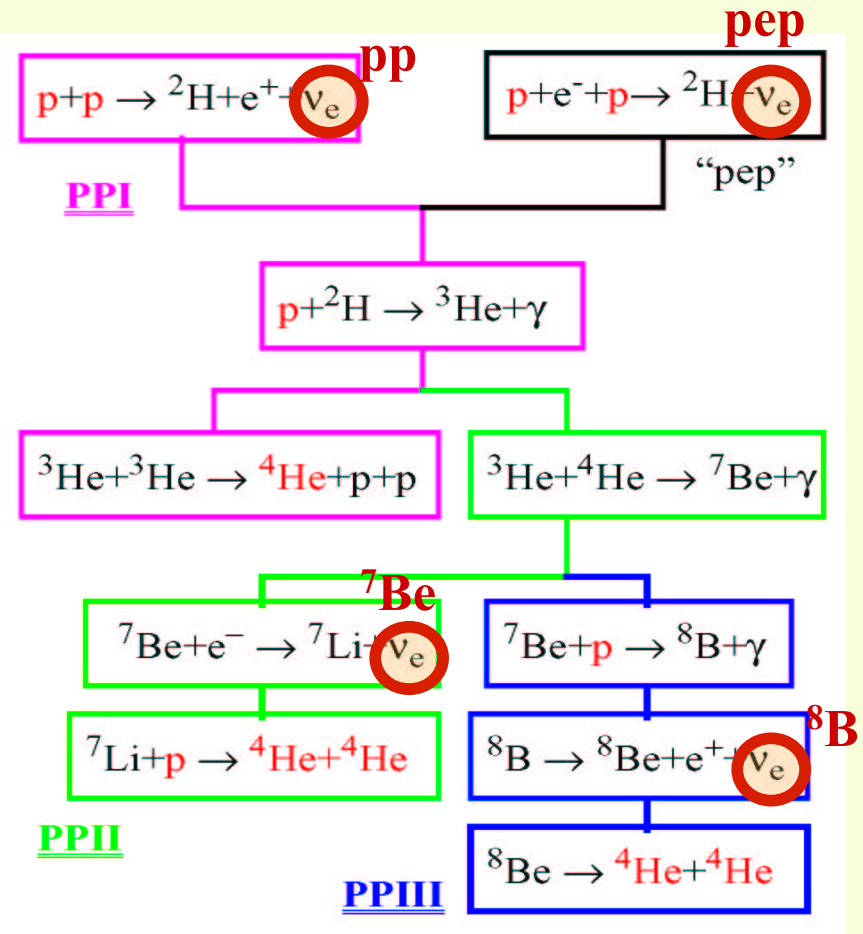


Nuclear reactions in the Sun

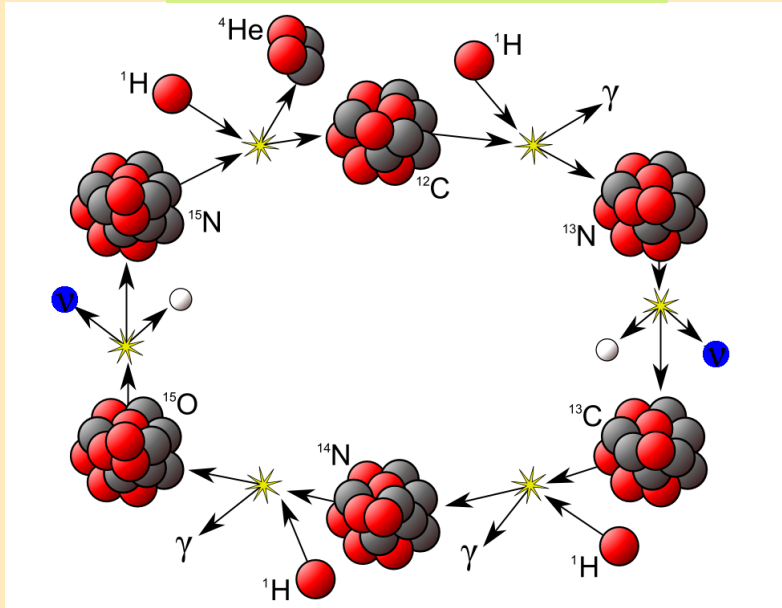


(26.7 MeV) (+ 2ν)

pp-cycle

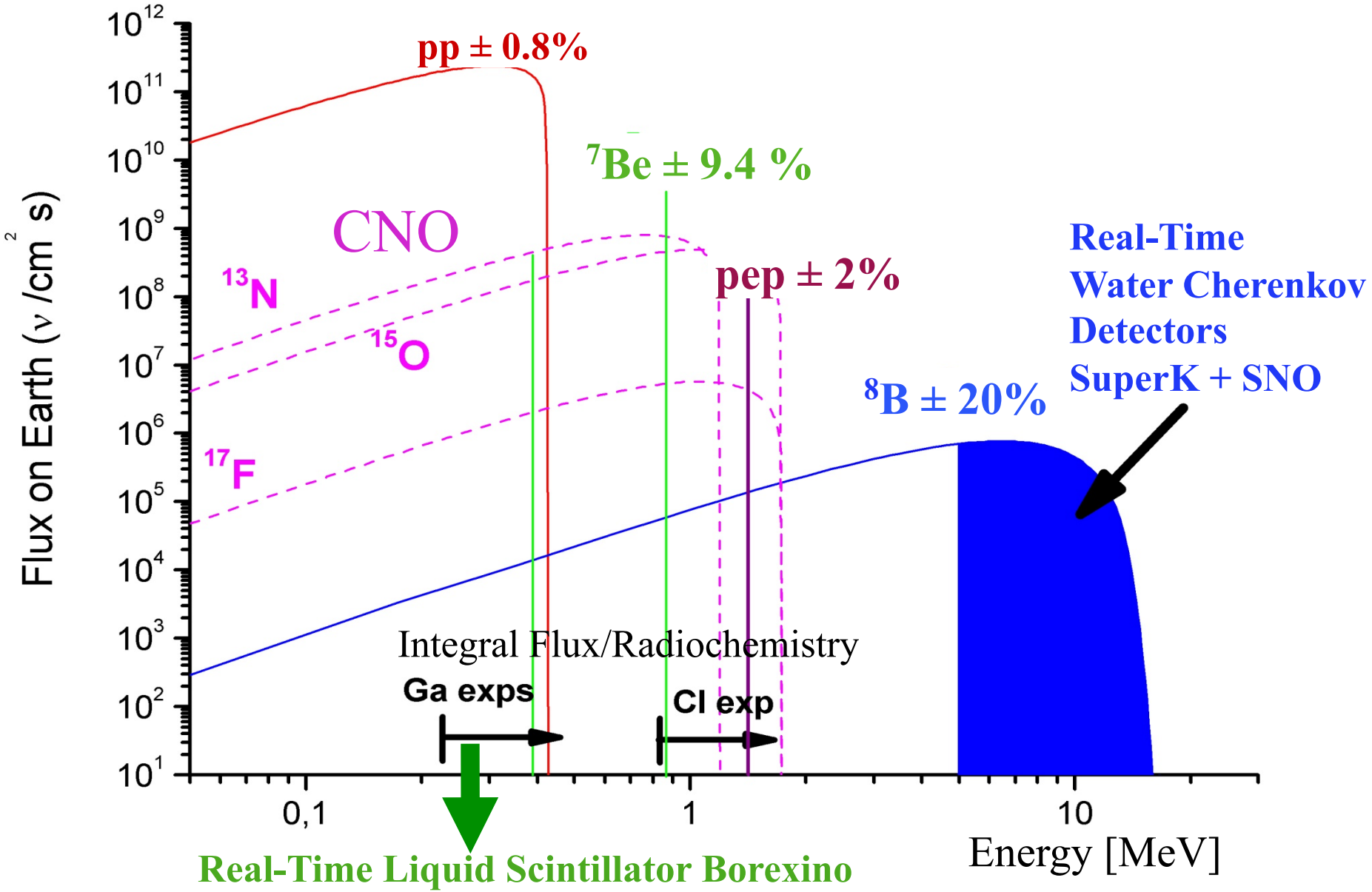


CNO-cycle



- Sun: should contribute <1%
- Heavy stars: should be dominant!
- Never observed until now

Energy spectrum of solar neutrinos



Standard Solar Model and metallicity problem

INput:

- Nuclear parameters;
- Luminosity
- Mass
- Radius
- surface metals (C, N, O, Ne, Mg, Si, Ar, Fe)– to - hydrogen ratio **(Z/X = metallicity)**
- Equations of state
- Chemical elements abundance
- Radiation opacity

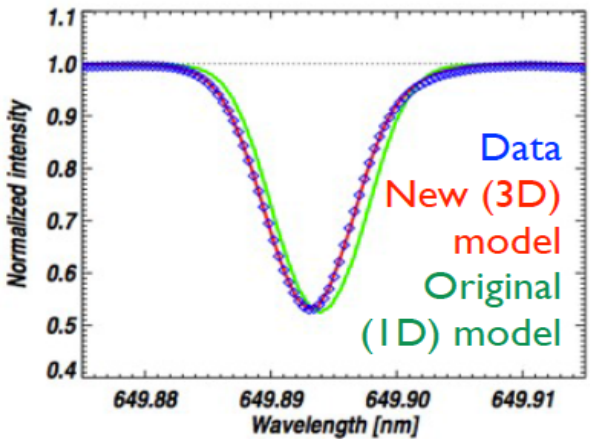
→ **SSM** derived from the conservation laws and energy-transport equations

→ **OUTput:**

- **Neutrino fluxes**
- **Helioseismology** (sound-waves speed profiles)

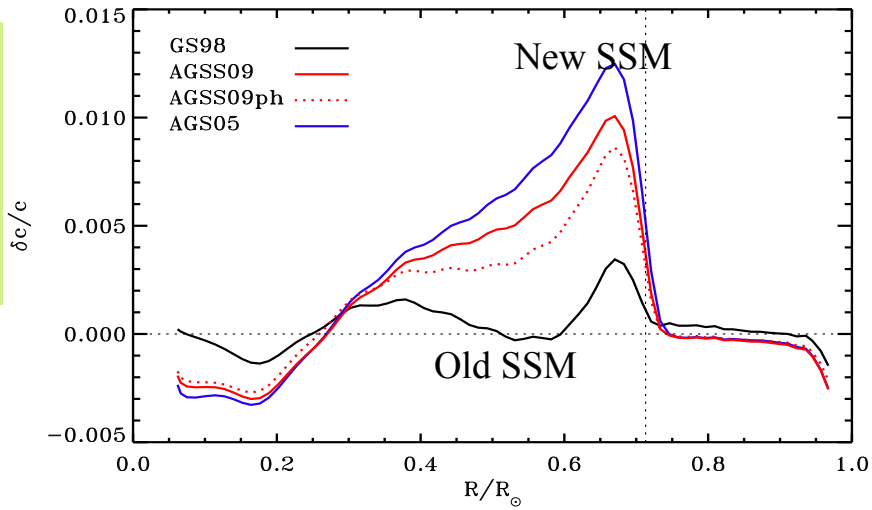
Older High-Metallicity: Z/X (= 0.0229) SSM GS98, 1D SSM

Newer Low-Metallicity: Z/X (= 0.0178) SSM AGS05, AGSS09/ph, 3D SSM



Better spectroscopy and 3D SSM is spoiling the previous agreement of the SSM predictions with helioseismology data

WHY?



Short history of solar ν experiments in 1 slide

70's-80's: Homestake (R. Davies): Radiochemistry: $E_\nu > 814$ keV

- ✓ $^{37}Cl + \nu \rightarrow {}^{37}Ar + e^-$
- ✓ **THE FIRST DETECTION!** deficit in the observed flux, skepticism
- ✓ final triumph, **Nobel prize 2002**
- ✓ **J. Bahcall** continues the development of the Standard Solar Model

80's-90's: (super)Kamiokande: Water Cherenkov: $E_\nu > 5$ MeV

- ✓ confirms deficit on ^8B-ν and with real-time technique
- ✓ first neutrino picture of the Sun (directionality)
- ✓ neutrinos from other stars observed (supernova SN1987-A)

90's: Gallex (GNO) and Sage: Radiochemistry: $E_\nu > 233$ keV

- ✓ $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
- ✓ deficit observed also at low energy, but is energy dependent!

2001: SNO: Water Cherenkov: $E_\nu > 5$ MeV

- ✓ **oscillation of solar neutrinos proved**
- ✓ CC (electron flavor) and NC (all flavors) interactions separately in **D_2O**
- ✓ total flux agrees with Standard Solar Model !

2002: KamLAND: Liquid scintillator

- ✓ observes and measures oscillations of electron anti-neutrinos from reactors;

2007: Borexino: Liquid scintillator of extreme radiopurity: : $E_\nu > 303$ keV

- ✓ First real-time observation of ^7Be, pep, pp neutrinos
- ✓ best limit on CNO
- ✓ Low-energy ^8B neuttrinos (> 3 MeV recoiled e^-)

First detection

Solar-neutrino puzzle

Solution: Neutrino oscillations!

Real-time precision spectroscopy

Why to measure solar neutrinos today?

1) Solar and stellar physics:

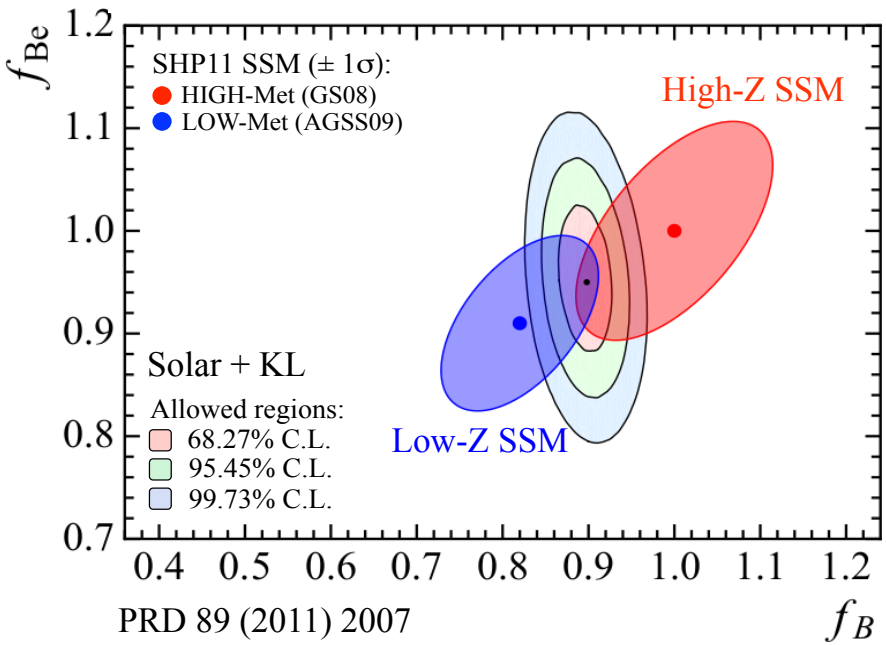
- Sun
- Stellar evolution
- Heavy stars / CNO

a) *metallicity problem*

Low and High metallicity SSMs predict different neutrino fluxes!

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)

Currently no power to resolve low/high metallicity problem



PRD 89 (2011) 2007

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

CNO

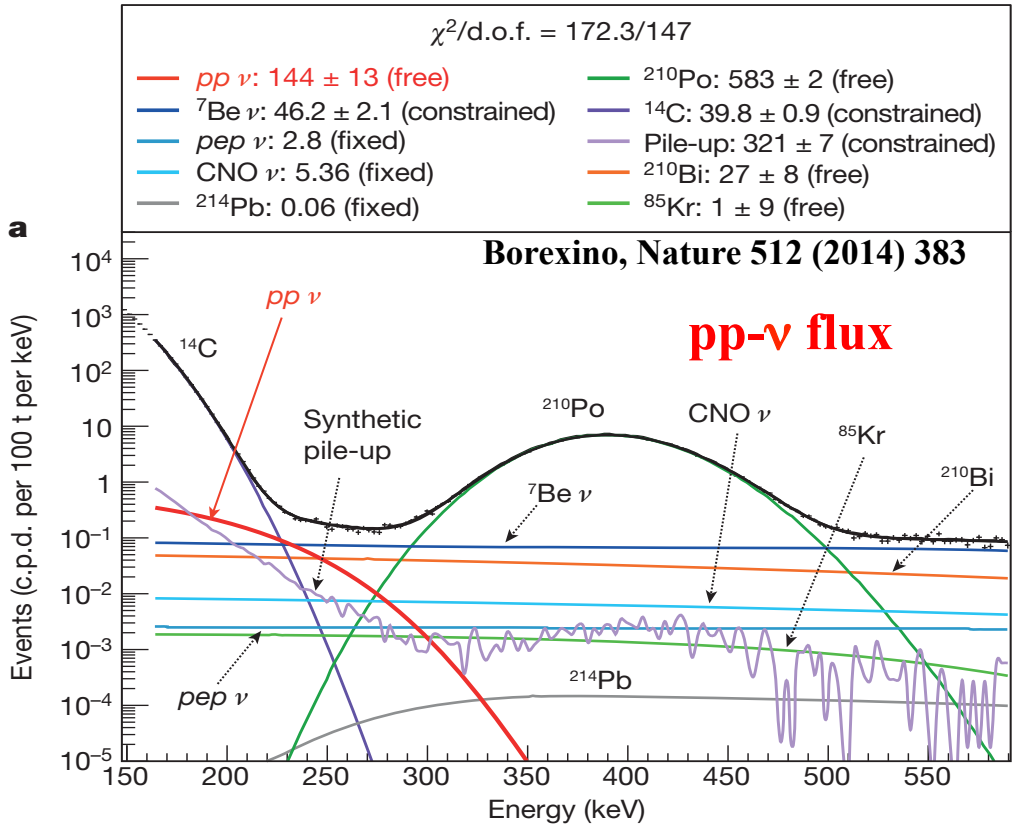
SSM: A. Serenelli, W. Haxton and C. Peña Garay ApJ 743 pp. 24, 2011

Why to measure solar neutrinos today?

1) Solar and stellar physics:

b) testing energy production/loss mechanism

- Neutrinos are THE proof that nuclear fusion powers the Sun
- Is the optical and neutrino luminosity in agreement?
- Neutrinos promptly escape from the Sun's core, while for photons it takes cca 10^5 years to escape! By comparing optical and neutrino luminosities… testing Solar stability at 10^5 time scale!



Physics World:
Top 10 Physics Breakthrough of 2014

1. **Spectral observation of solar pp-ν**
   (extreme radiopurity, synthetic pile-up, independent measurement of ^{14}C rate, low energy threshold 164 keV)

R_{pp} = 144 ± 13 (stat) ± 10 (sys) cpd/100 ton

Borexino: $\Phi_{pp} = 6.6 \times (1 \pm 0.106) \times 10^{10}$ cm^{-2} s^{-1}:
SSM: $\Phi_{pp} = 5.98 \times (1 \pm 0.006) \times 10^{10}$ cm^{-2} s^{-1}

2. **Direct prove that pp-cycle provides ~99% of Solar power**

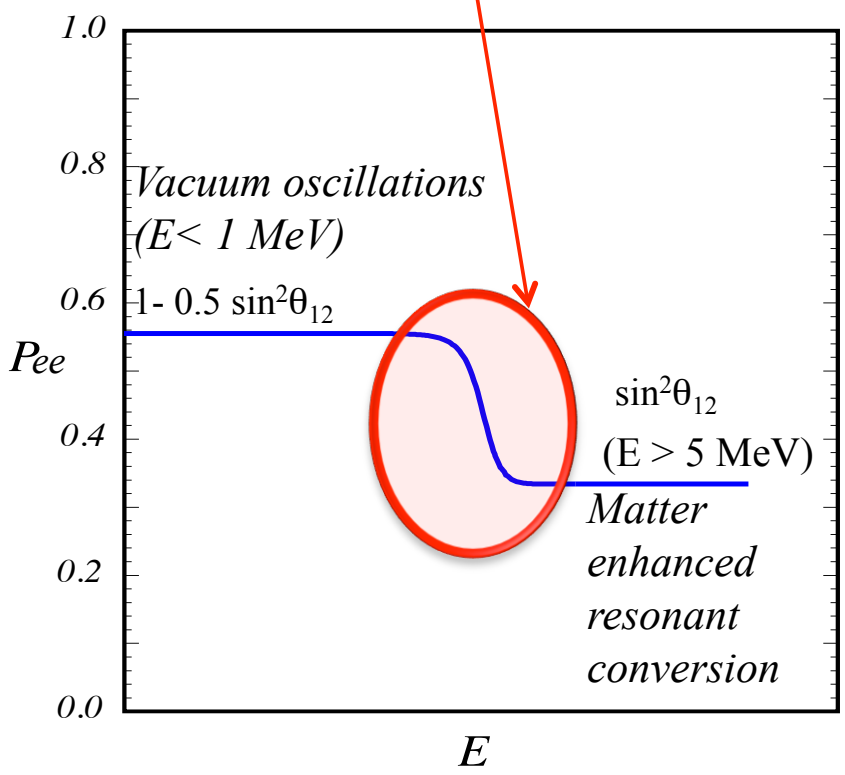
Borexino paralel talk of Gemma Testera

Why to measure solar neutrinos today?

2) Neutrino physics:

a) Searching for new physics:

searching for deviations from MSW-LMA scenario of solar ν oscillations, especially in the **transition region of P_{ee}**
(e.g. mass-varying neutrinos or non-standard interactions models)



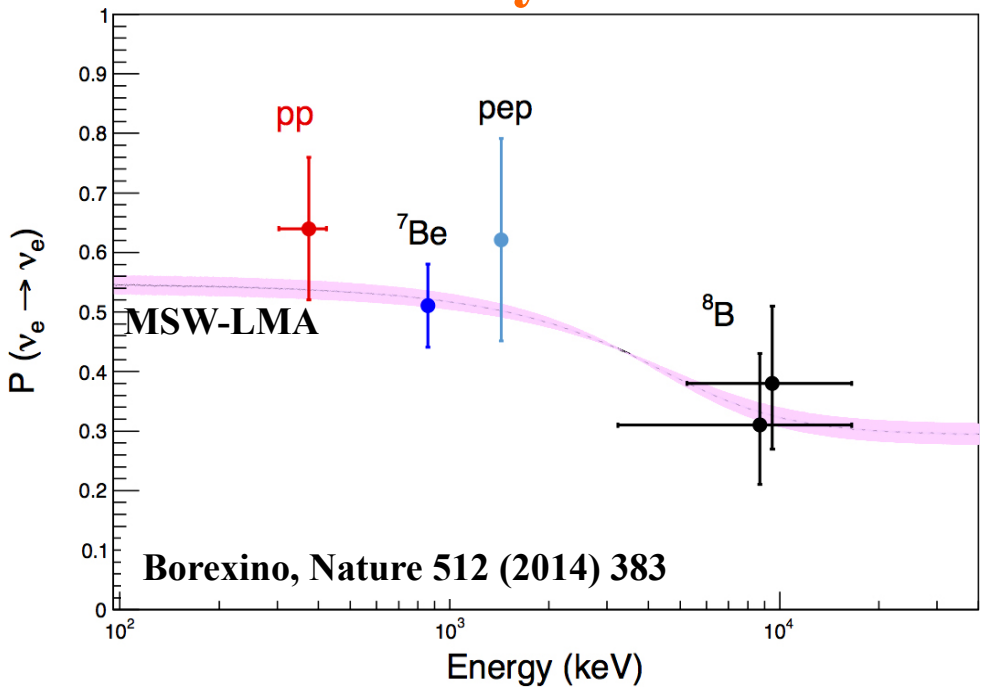
Bahcall & Pena-Garay:JHEP 0311:004 (2003)

Examples of suggested new-physics models:

- Mass varying neutrinos
  (Gonzales-Garcia & Maltoni 2008)
- Non-Standard Interactions/flavour changing NC
  (Friedland, Lunardini, Pena-Garay, 2008)
- Sterile Neutrinos
  (Holanda & Smirnov 2011)

Electron-neutrino survival probability
Testing MSW-LMA

Borexino only data

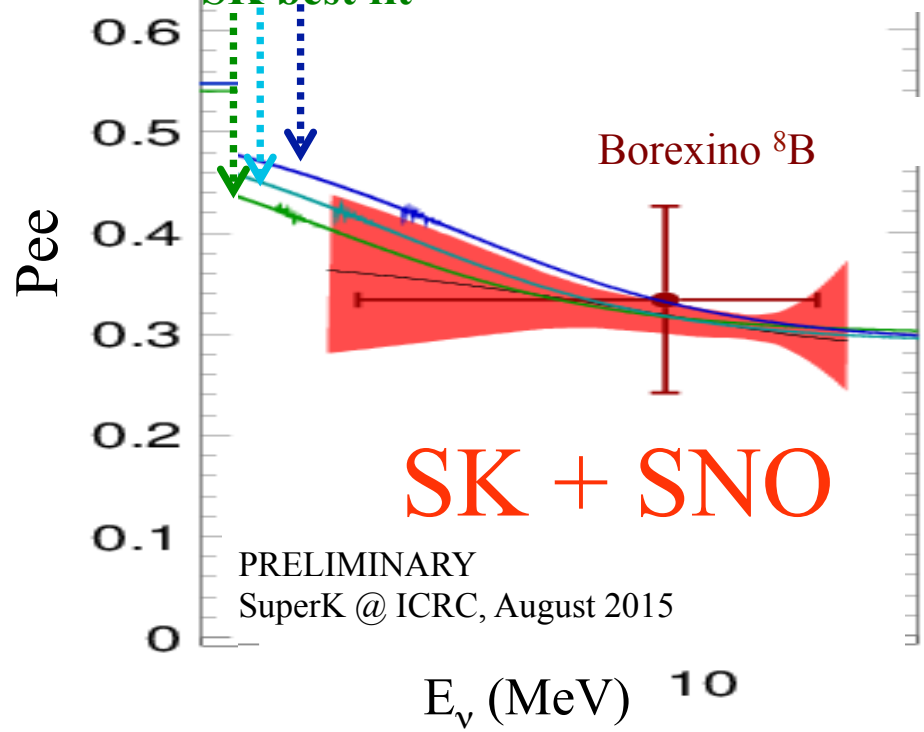


MSW-LMA with oscillation parameters:

Solar (nu) + KL (antinu) best fit

Solar best fit

SK best fit



Borexino
Paralel talk of Gemma Testera

SuperKamiokande
Paralel talk of Hiroyuki Sekiya

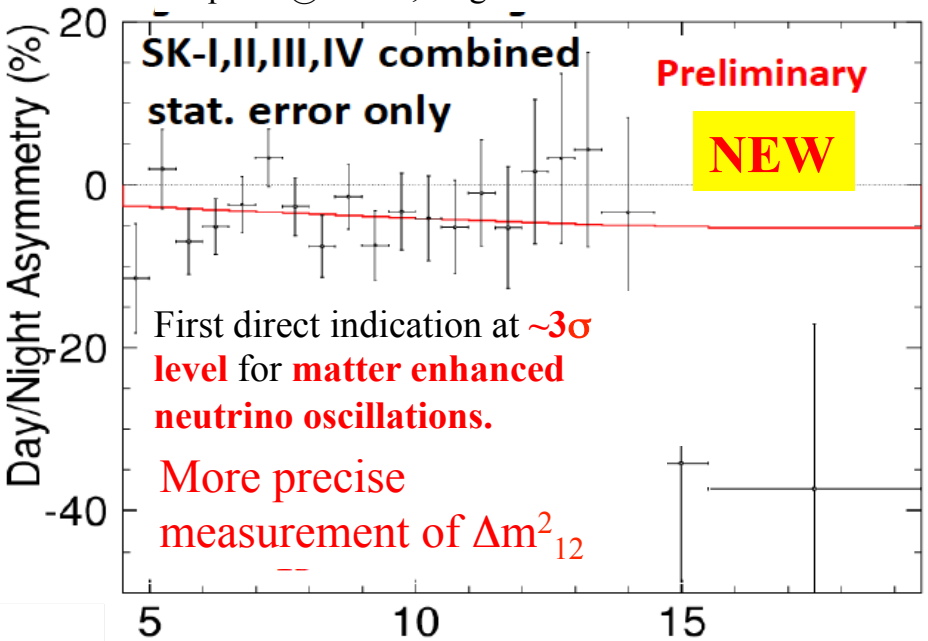
Why to measure solar neutrinos today?

2) Neutrino physics:

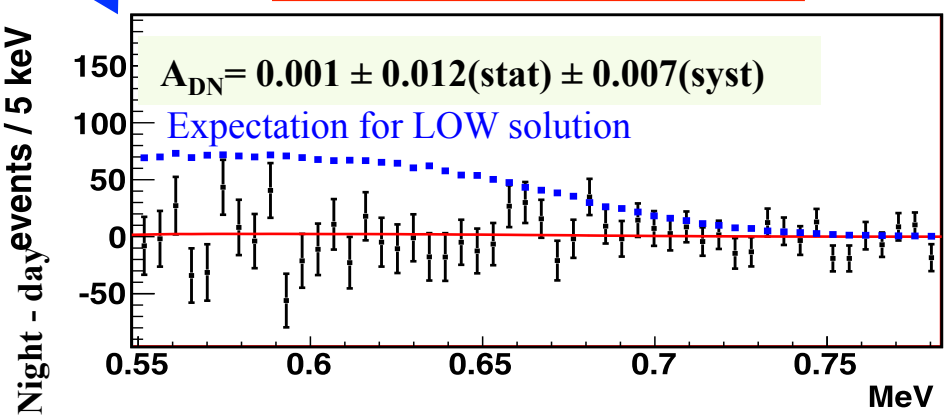
b) Confirming MSW: energy-dependent matter resonant conversion

observation (^{8}B) or **exclusion (^{7}Be)** of a **day-night effect** for different neutrino energies according to MSW predictions!

SuperK @ ICRC, August 2015



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



Borexino, PLB 707 (2012) 2012

Paralel talk of Hiroyuki Sekiya

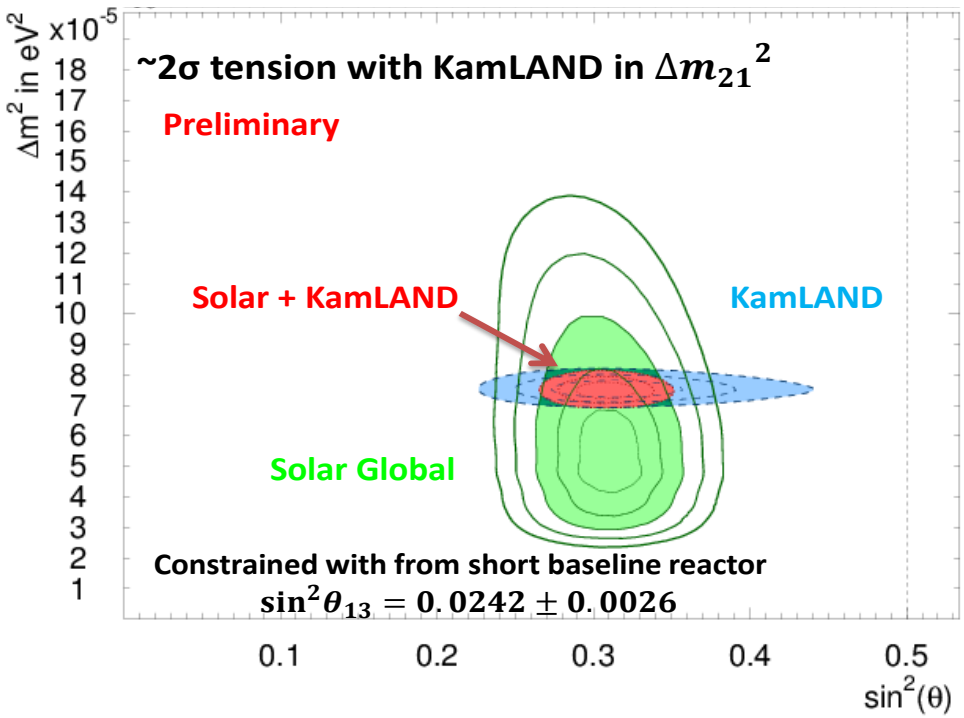
Why to measure solar neutrinos today?

2) Neutrino physics:

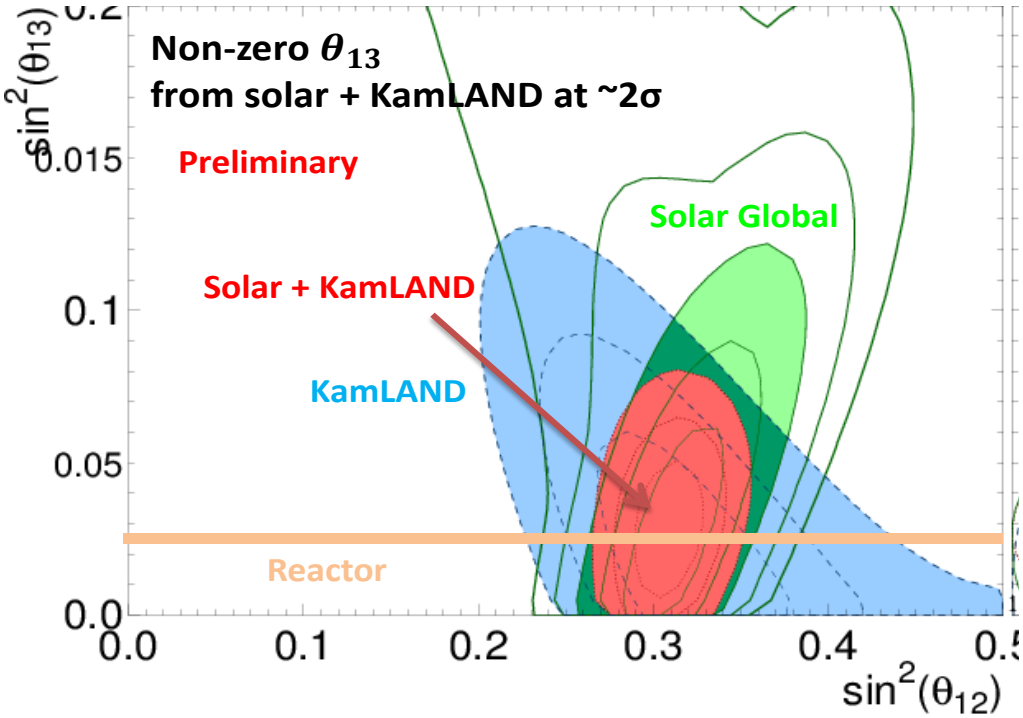
c) Oscillation analysis and global fits

Determination of Δm^2_{12}, $\sin^2\theta_{12}$, $\sin^2\theta_{13}$ and comparison with the values obtained including also reactor antineutrino data

SuperK @ ICRC, August 2015



SuperK @ ICRC, August 2015



SuperKamiokande: Paralel talk of Hiroyuki Sekiya

What's next for solar neutrinos?

Running experiments

- **Borexino (Italy) Phase II** *(almost complete removal of ^{85}Kr and a strong reduction of ^{210}Bi)*:
  - ✓ more precise measurement of pep, ^{7}Be, pp
  - ✓ the first detection of CNO (?)
- **SuperKamiokande (Japan)** continues to take data
  - ✓ further tests of the transition region of the MSW-LMA

Near future experiments:

- **SNO+** (Canada, 780 ton of liquid scintillator, ready for fill in 1 year)
  - ✓ ^{8}B-ν also with Te-loaded scintillator (main goal – 0νββ decay)
  - ✓ > 1 order of magnitude less cosmogenic bgr than Borexino – ideal for CNO and pep neutrinos
- **JUNO** (China, **20 kton scintillator,** DAQ planned for 2020) and

  RENO-50 (Korea, 18 kton scintillator, if DAQ planned for 2021)
  - ✓ close to reactors – main goal is the neutrino mass hiearchy: 3% @ 1 MeV
  - ✓ the solar neutrino program depends on final radiopurity

Far future experiments:

- **Hyper-Kamiokande (MEGATON SCALE)** = 20 x SuperKamiokande;
- LENA - 50 kton liquid scintillator…. Unclear future
- LENS - Unclear future;

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

Abundance of radioactive elements

Nuclear physics

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

$^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV

Radiogenic heat (Main goal)

Distribution of radioactive elements (models)

To predict:

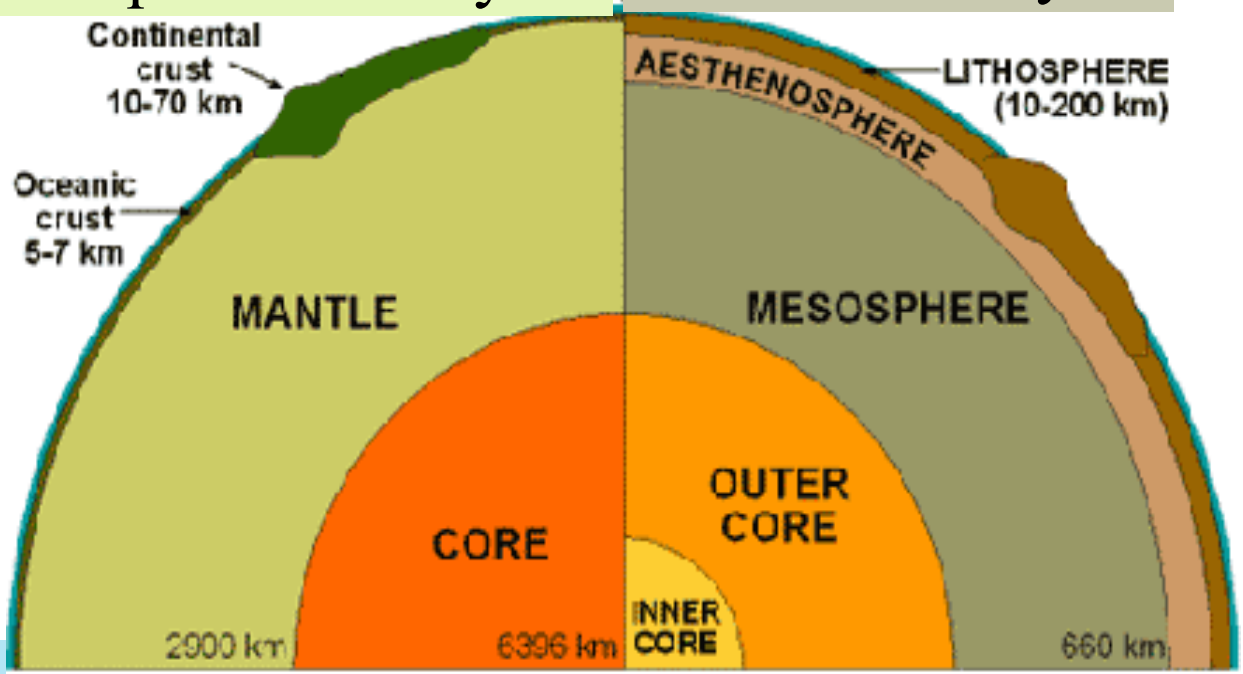
Geoneutrino flux

From geoneutrino measurement:

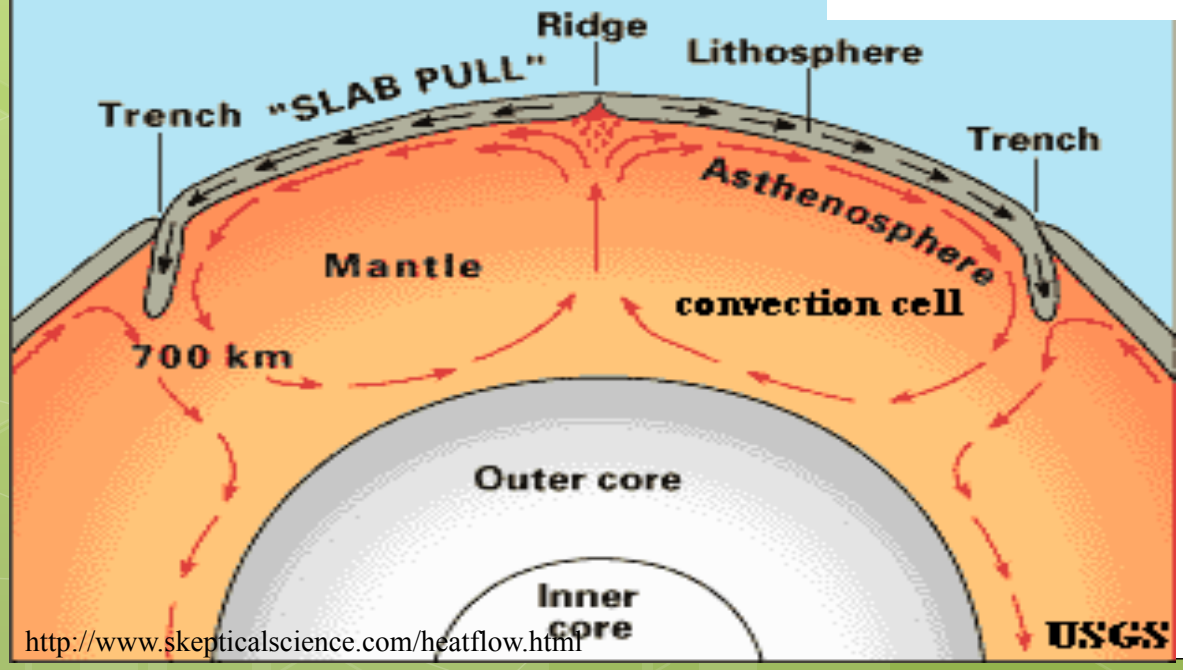
- **Main goal:** determine the contribution of the **radiogenic heat to the total surface heat flux**, which is an important margin, test, and input at the same time for many geophysical and geochemical models of the Earth;
- **Further goals:** tests and discrimination among geological models, study of the mantle homogeneity, insights to the processes of Earth'formation…..

Earth's interior

Compositional layers | Mechanical layers



Dynamical picture



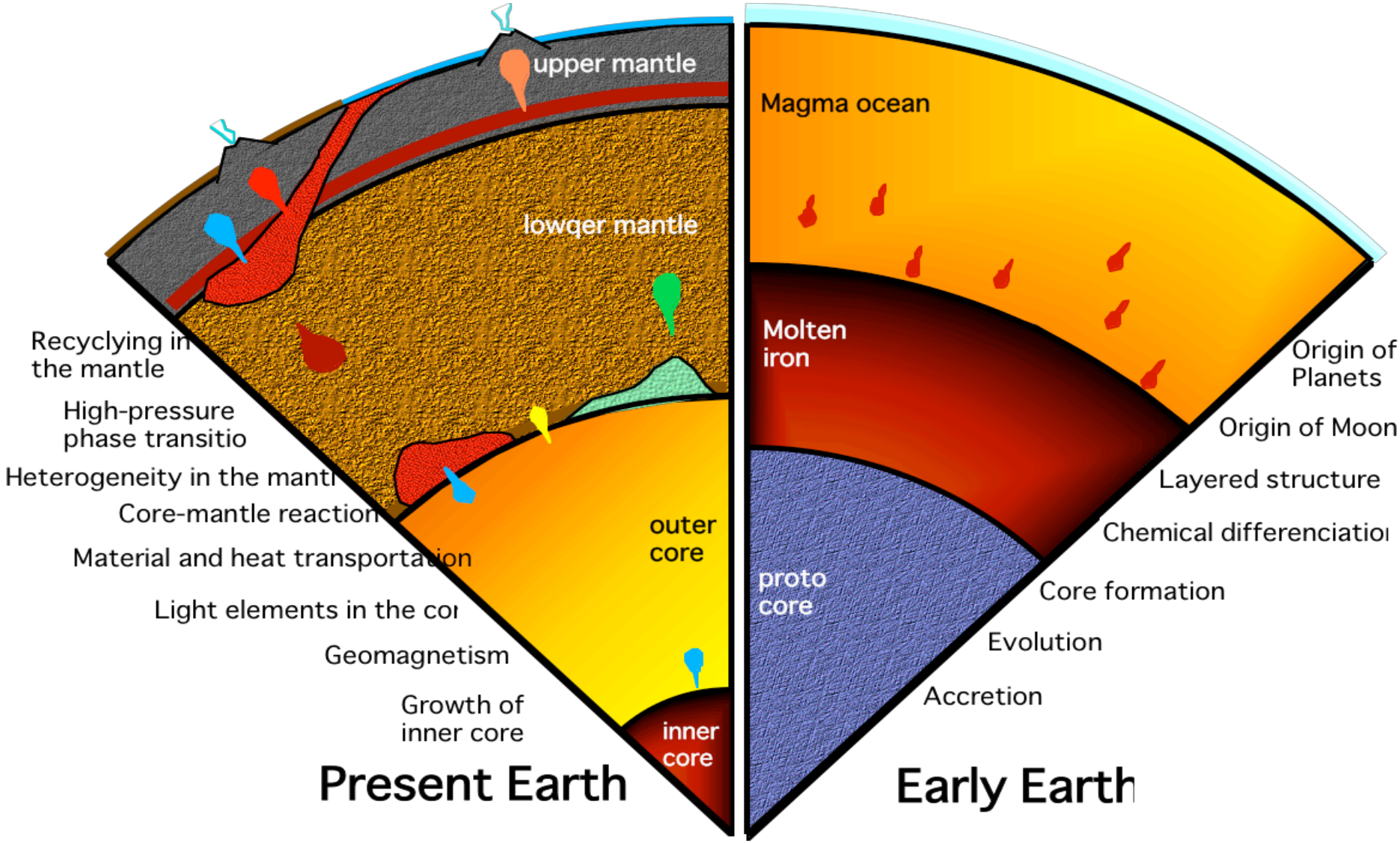
http://www.skepticalscience.com/heatflow.html

U, Th, K: refractory lithophile elements

concentration for ^{238}U (Mantovani *et al.* 2004)

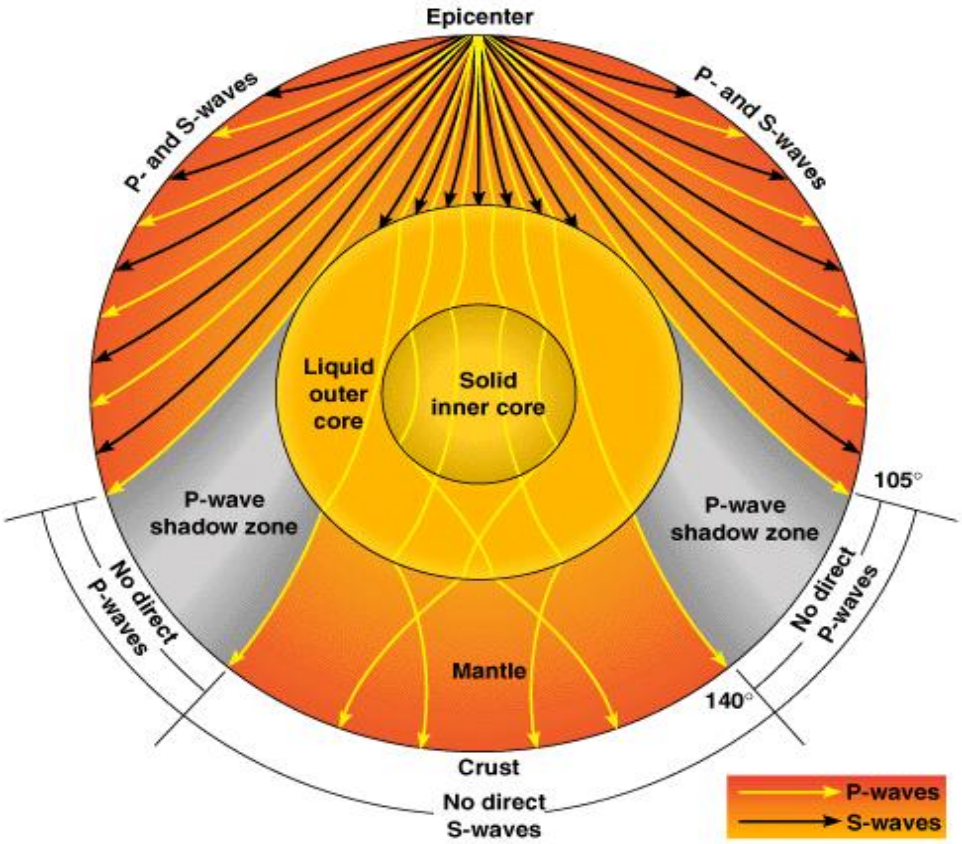
upper continental crust:	2.5 ppm
middle continental crust:	1.6 ppm
lower continental crust:	0.63 ppm
oceanic crust:	0.1 ppm
upper mantle:	6.5 ppb
core	NOTHING

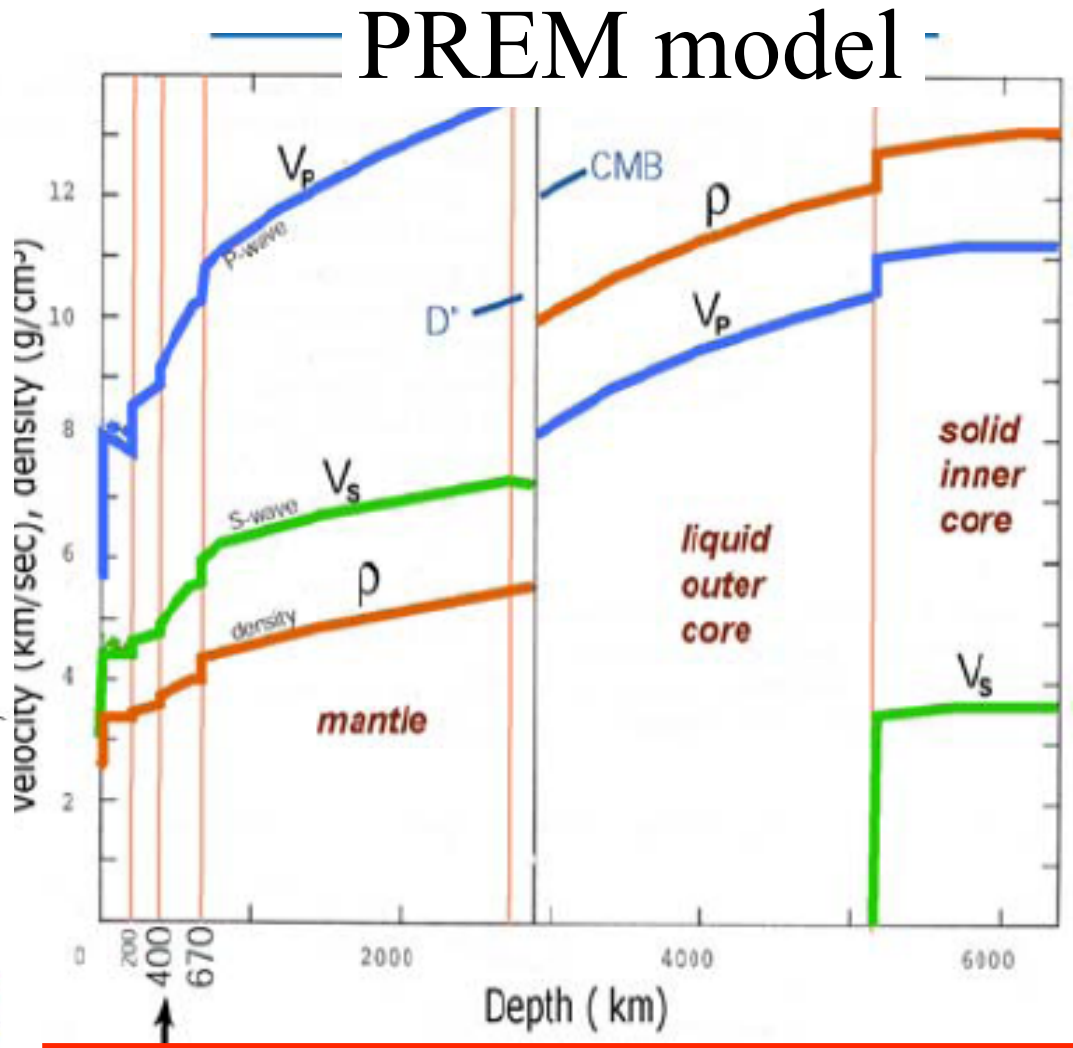
Earth's profile in time



http://www.ess.sci.osaka-u.ac.jp/english/3_research/groups/g05kondo.html

Seismology

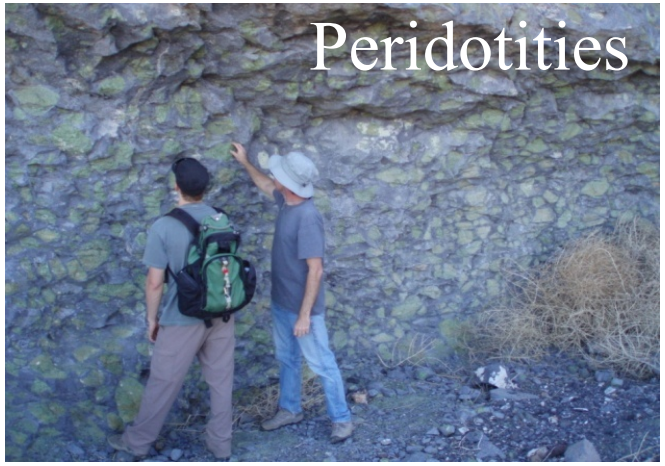




P – primary, longitudinal waves
S – secondary, transverse/shear waves

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

Geo-chemistry



1) **Direct rock samples**

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

* mantle rocks brought up by tectonics

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) **Geochemical models:**

rock samples + meteorites + Sun

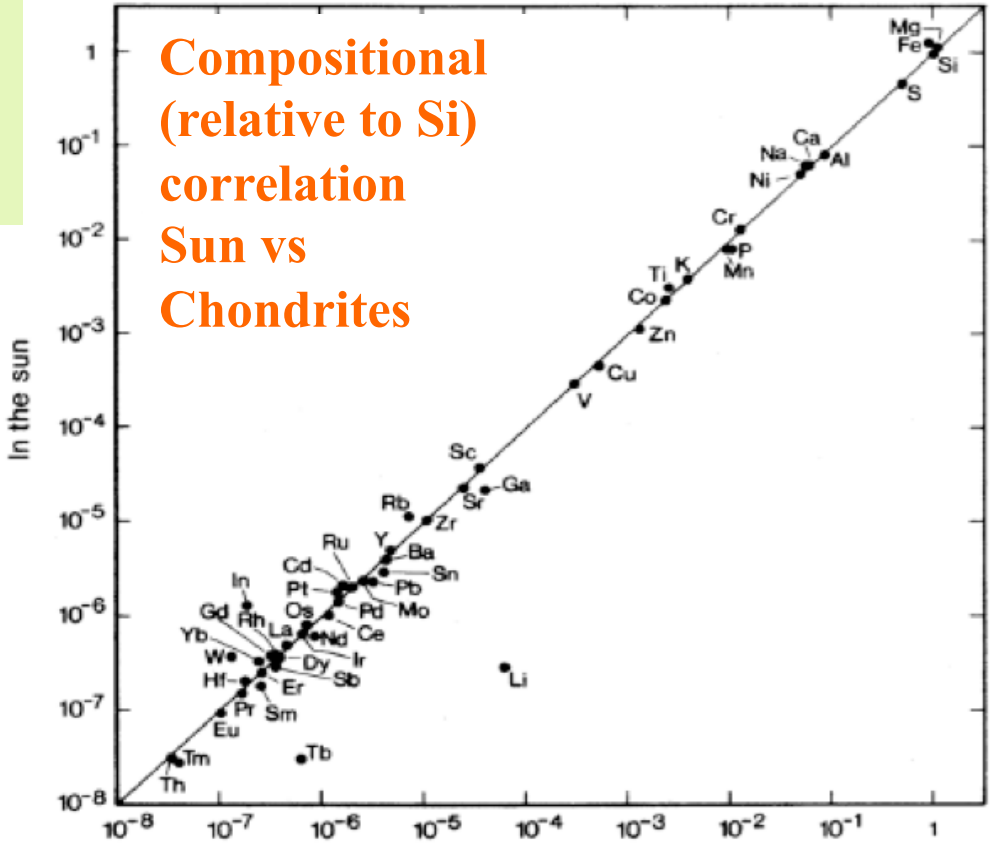
Bulk Silicate Earth (BSE) models

medium composition

of the "re-mixed" crust + mantle,

i.e., primordial mantle before the crust

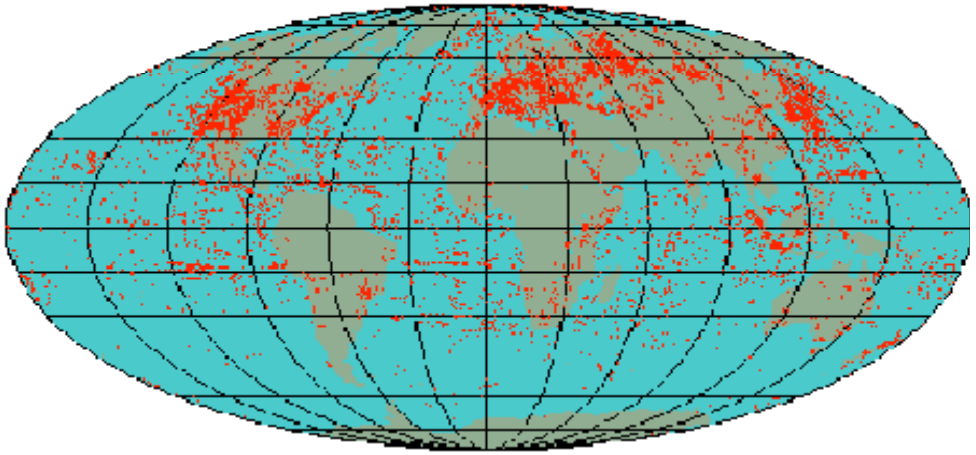
differentiation and after the Fe-Ni core separation

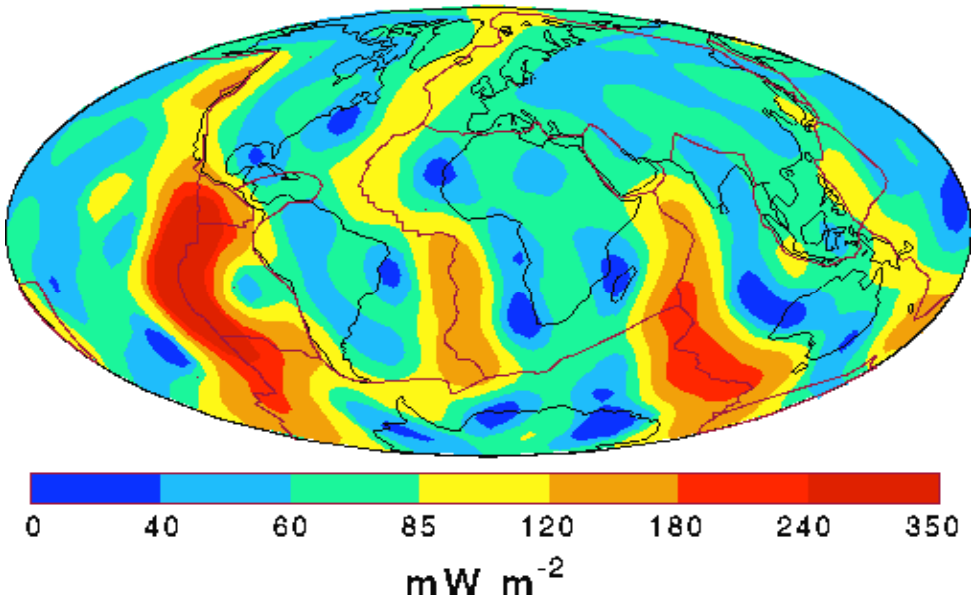


Surface heat flux

Bore-hole measurements

47 ± 2 TW
(Davies & Davies 2010)





Sources

Radiogenic heat:
(Geoneutrinos)!!!!!

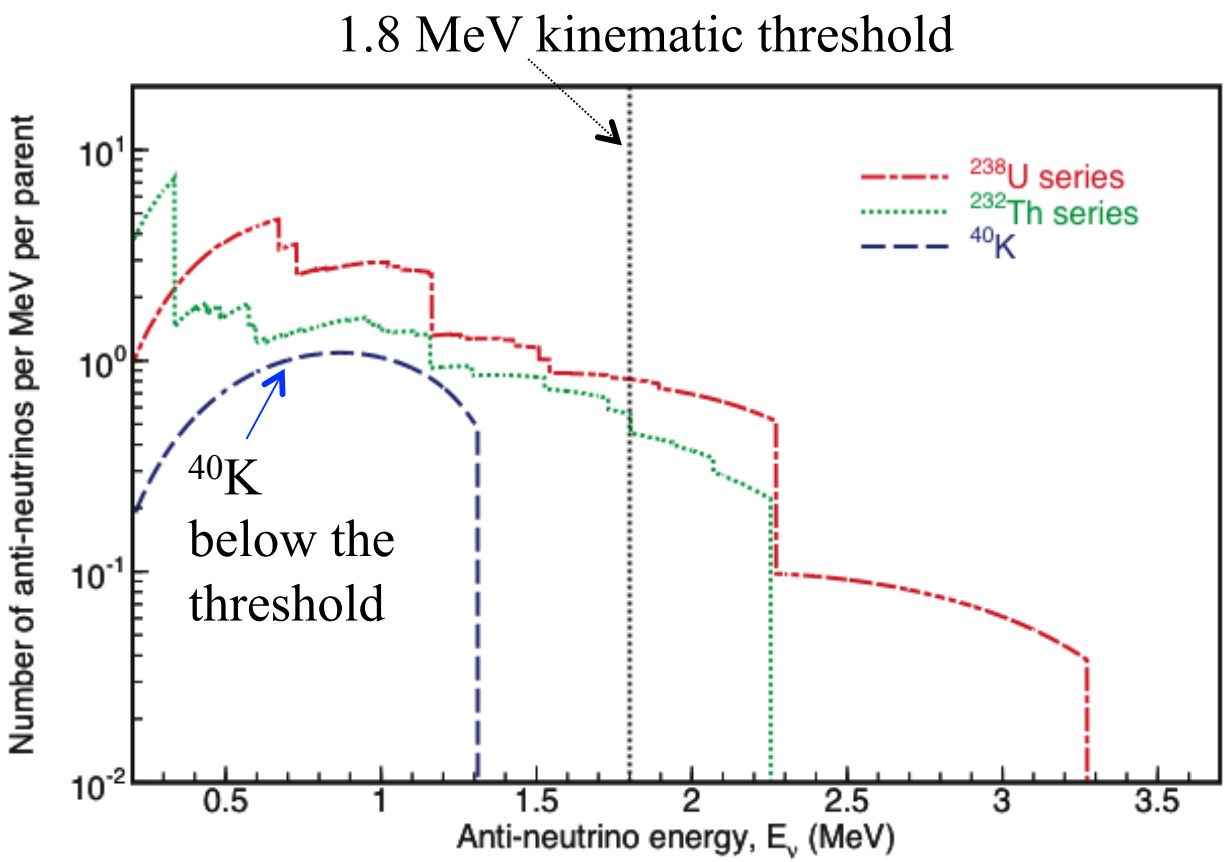
BSE models predictions:

- ✓ Geochemical BSE:17-21 TW
- ✓ Cosmochemical BSE: 11 TW
- ✓ Geodynamical BSE: > 30 TW

Other sources:

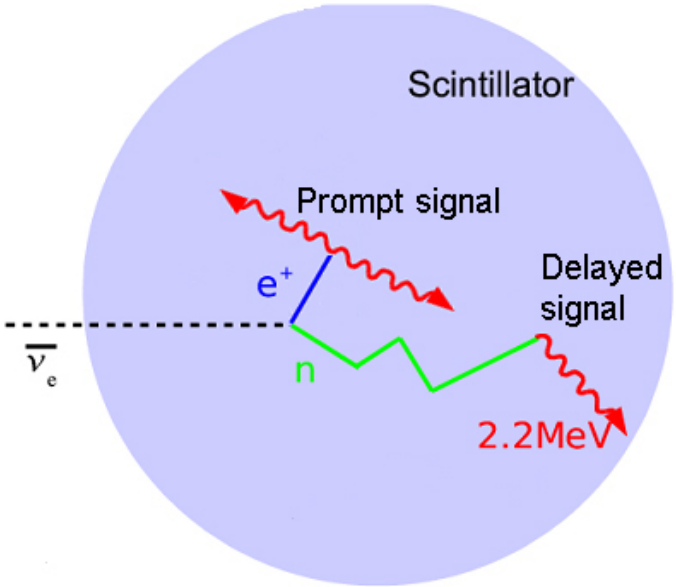
1) Residual heat from the past
2) ^{40}K in the core?
3) Nuclear reactor in the core?
4) Very minor (phase transitions, tidal etc..)

Geoneutrinos spectrum and detection



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

Inverse **B**eta **D**ecay



"prompt signal"
e^{+}: energy loss T_{e+}+ annihilation (2x0.511 MeV)
$\mathbf{E_{prompt/visible} = E_{geonu} - 0.784\ MeV}$

"delayed signal"
Thermalisation and neutron capture on protons, emission of **2.2 MeV γ**

Geoneutrino experimental results

KamLAND (Japan)

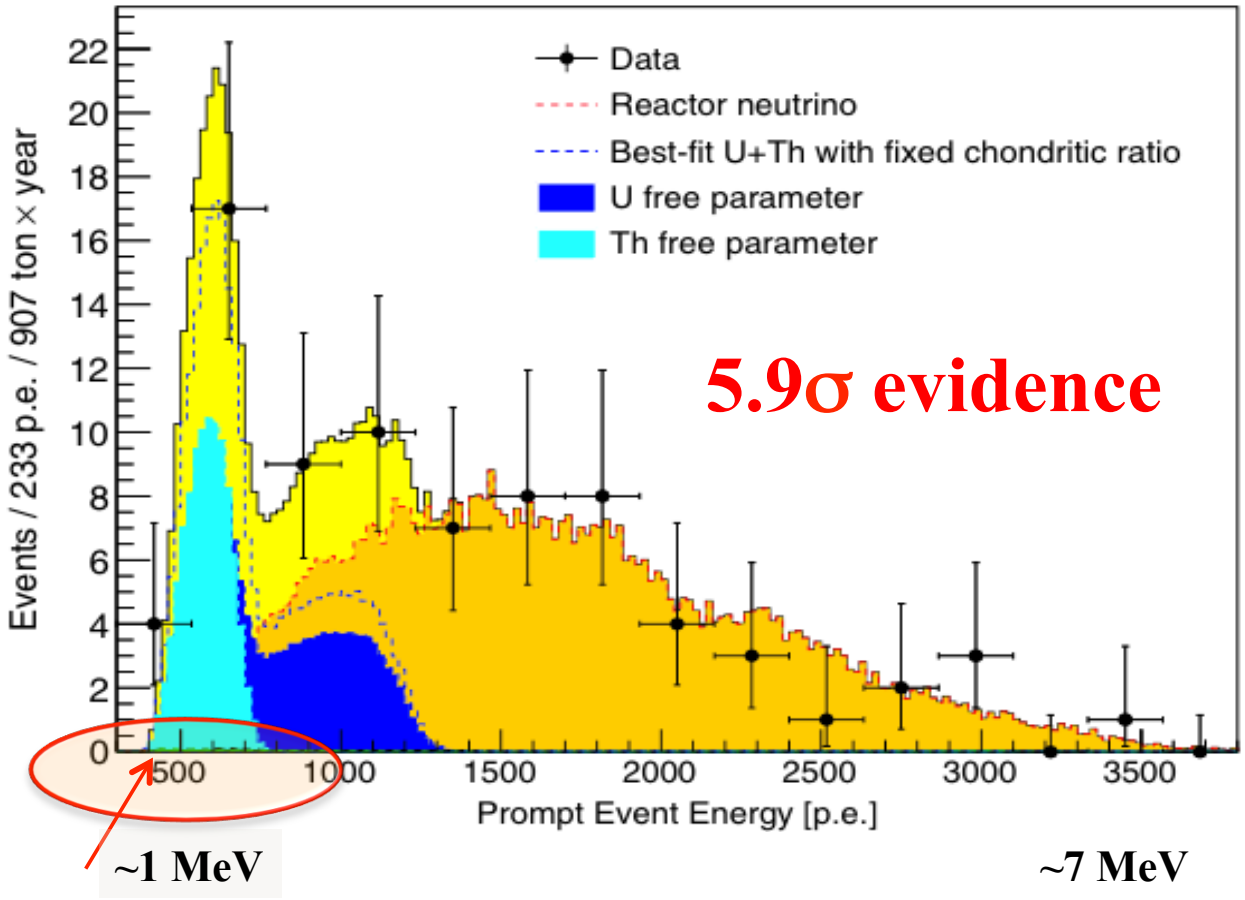
- **The first investigation in 2005**
  CL < 2σ
  Nature 436 (2005) 499
- **Update in 2008**
  73 ± 27 geonu's
  PRL 100 (2008) 221803
- **99.997 CL observation in 2011**
  106^{+29}_{-28} geonu's
  (March 2002 – April 2009)
  3.49 x 10^{32} target-proton year
  Nature Geoscience 4 (2011) 647
- **Latest result in 2013**
  116^{+28}_{-27} geonu's
  (March 2002 – November 2012)
  4.9 x 10^{32} target-proton year
  0-hypothesis @ 2 x 10^{-6}
  PRD 88 (2013) 033001

Borexino (Italy)

- **99.997 CL observation in 2010**
  $9.9^{+4.1}_{-3.4}$ geonu's
  small exposure but low background level
  (December 2007 – December 2009)
  1.5 x 10^{31} target-proton year
  PLB 687 (2010) 299
- **Update in 2013**
  14.3 ± 4.4 geonu's
  (December 2007 – August 2012)
  3.69 x 10^{31} target-proton year
  0-hypothesis @ 6 x 10^{-6}
  PLB 722 (2013) 295–300
- **NEW in June 2015: 5.9σ CL**
  $23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys) geonu's
  (December 2007 – March 2015)
  5.5 x 10^{31} target-proton year
  0-hypothesis @ 3.6 x 10^{-9}
  PRD 92 (2015) 031101 (R)

NEW

Latest Borexino geoneutrino results



Non antineutrino background is almost invisible!

Unbinned maximal likelihood fit:

- Geoneutrinos free
- Reactor antineutrinos free
- Other backgrounds ($0.78^{+0.78}_{-0.10}$ events total) constrained

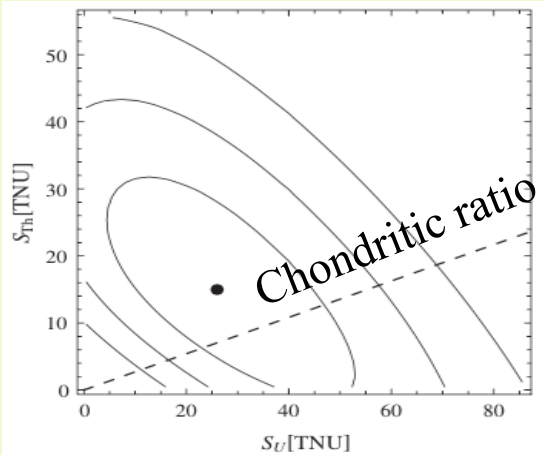
Two types of fits:

1) Th/U mass ratio fixed to chondritic value of 3.9

$N_{geo} = 23.7\ ^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(sys)$ events

$S_{geo} = 43.5\ ^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$ TNU[1]

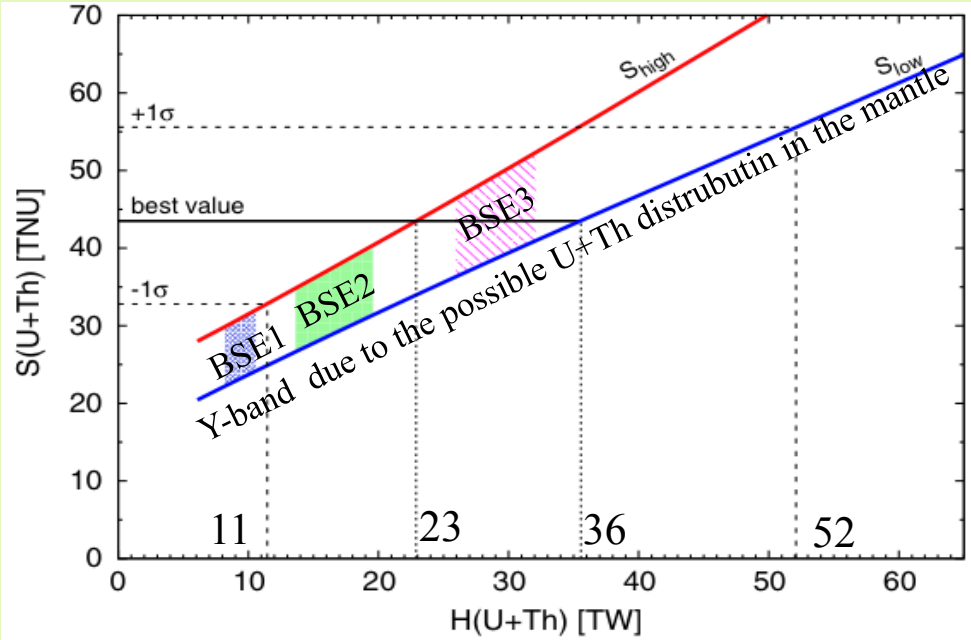
2) U and Th free fit paramters



[1] 1 Terrestrial Neutrino Unit (TNU) = 1 event / year / 10^{32} protons, 100% efficiency

Geological implications of the new Borexino results

Radiogenic heat



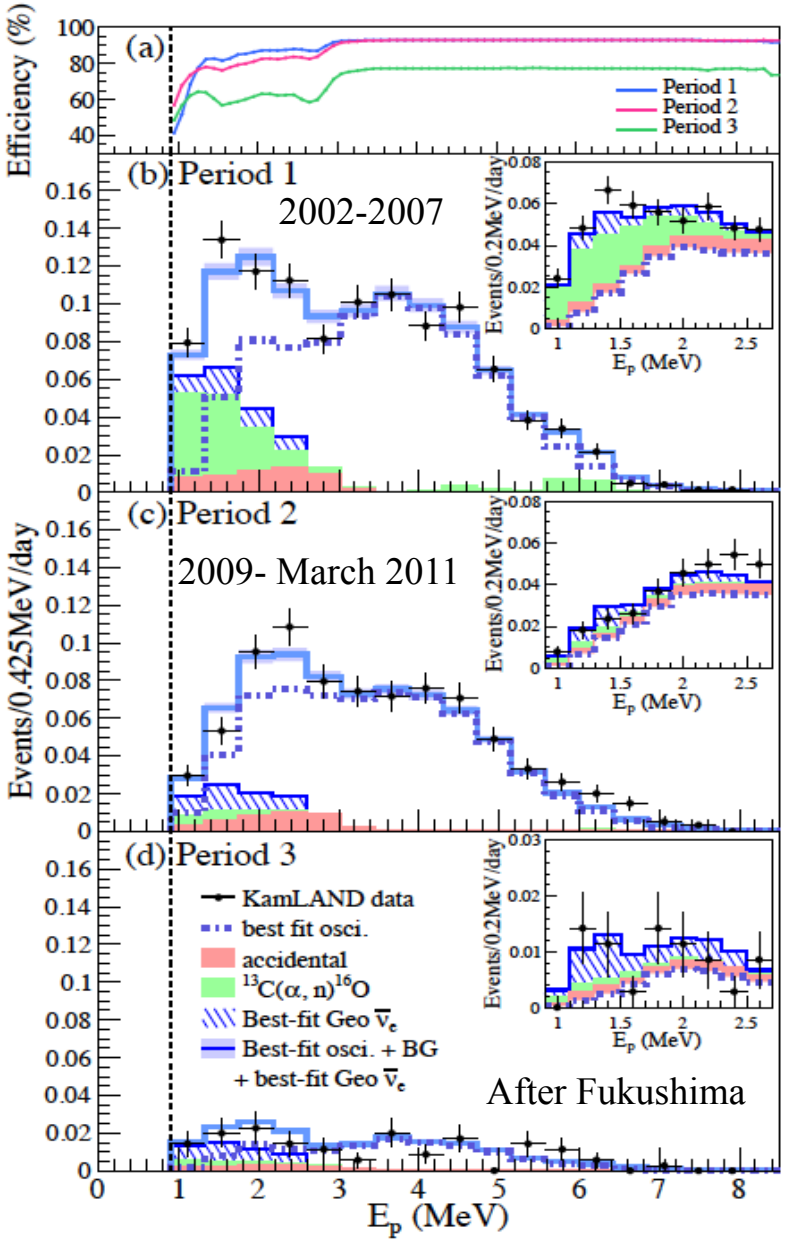
The Earth is not fully radiogenic

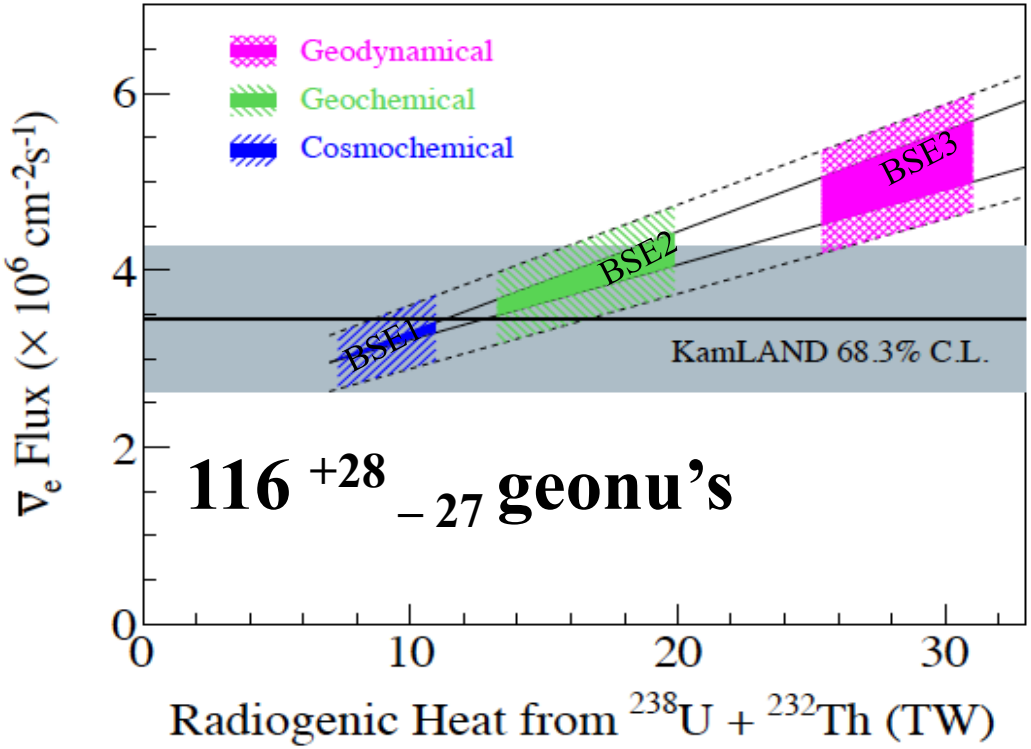
Mantle signal

- $S_{Mantle} = S_{measured} - S_{Crust}$
- Crustal signal at LNGS "known"
  $S_{Crust} = (23.4 \pm 2.8)$ TNU
- Non-0 mantle signal at 98% CL
  $S_{mantle} = 20.9^{+15.1}_{-10.3}$ TNU

More details in Borexino parallel talk of Aldo Ianni

Latest KamLAND geoneutrino results





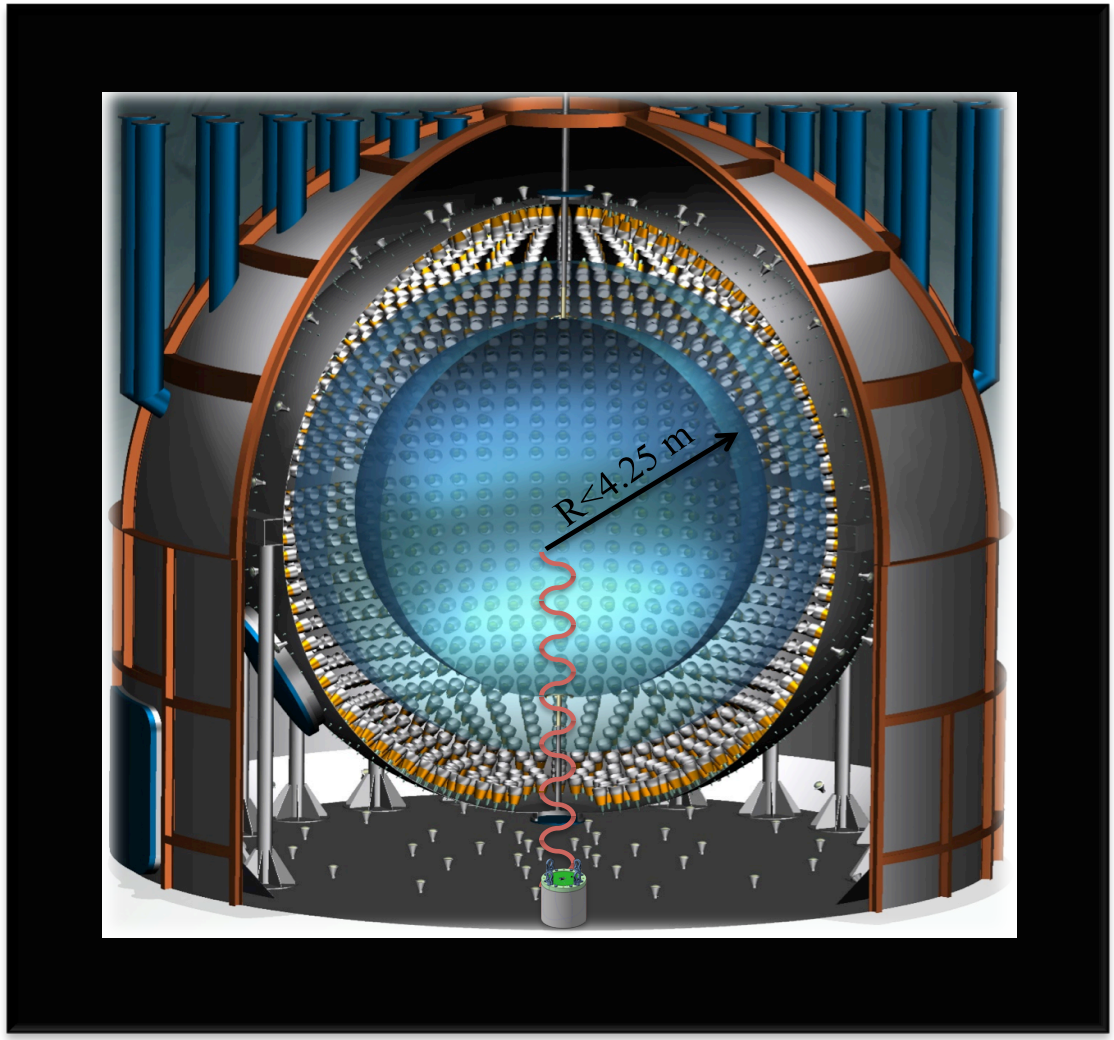
116^{+28}_{-27} geonu's

- After Fukushima, Japanese reactors off
- Plan to refurbish outer detector in Jan' 16.. new update expected then!

Geoneutrino future

- **Borexino** will switch to SOX (see later) in late 2016 – closure of geoneutrino dataset;
- **KamLAND**: possible next update with low reactor-background data after the end of 2015;
- **SNO+** (Canada): 780 ton & DAQ start in 2017; detector should be able to provide geoneutrino results;
- **JUNO** (China): 20 kton & DAQ start in 2020; If non antineutrino background low and under control, JUNO will soon beat the precision of existing measurements;
- **HanoHano** (Hawaii): 10 kton underwater detector with ~80% mantle contribution: "**THE" GEONU DETECTOR: MISSING FUNDING!**

- New interdisciplinary field established: **NEUTRINO GEOSCIENCE** conference every two years
- Power of combined analysis and importance of multi-site measurements at geologically different environments


R<4.25 m

Neutrino anomalies: hints for sterile neutrino?

ν_e, anti-ν_e DISAPPEARANCE

ν_e, anti-ν_e APPEARANCE

Reactor anomaly ~2.5σ

Re-analisys of data on anti-neutrino flux from reactor short-baseline (L~10-100 m) shows a small deficit of R=0.943 ±0.023

G.Mention et al, Phys.Rev.D83, 073006 (2011) , A.Mueller et al. Phys.Rev.C **83**, 054615 (2011);

Gallex/SAGE anomaly ~3σ

Deficit observed by Gallex in neutrinos coming from a ^{51}Cr and ^{37}Ar sources

$$R = 0.76^{+0.09}_{-0.08}$$

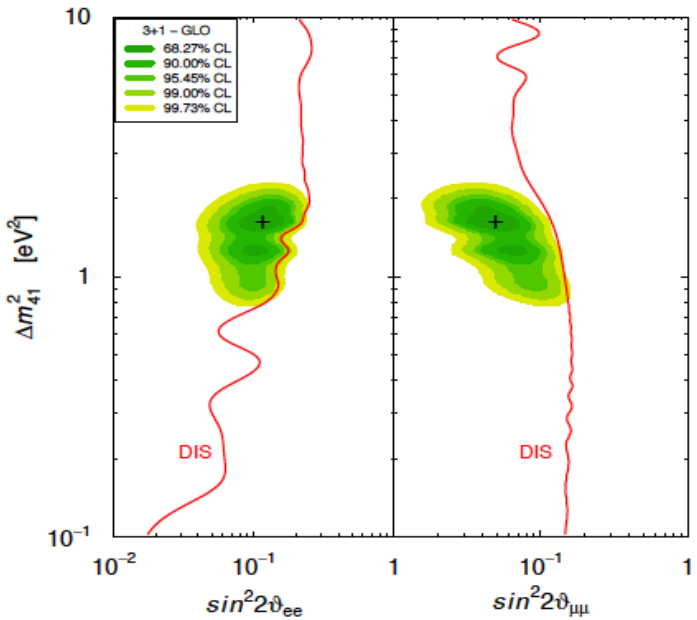
C. Giunti and M. Laveder, Phys.Rev. C83, 065504 (2011), arXiv:1006.3244 [hep-ph].

Accelerator anomaly ~3.8σ

Appearance of anti-ν_e in a anti-ν_μ beam (LSND). *A.Aguilar et al. LSND Collaboration Phys.Rev.D 64 112007 (2001).*

Confirmed by miniBooNE (which also sees appearance of ν_e in a ν_μ beam) *A.Aguilar et al. (MiniBooNE Collaboration) Phys.Rev.Lett. 110 161801 (2013)*

Possible explanation: mixing of the active flavours with a sterile neutrino $\Delta m^2 \sim 1$ eV^2



- 3-flavor scenario cannot accommodate these anomalies, at least one **sterile neutrino** needed
- No strong preference for (3 + 1), (3 + 2), (3 + 1 + 1) scenarios
- In (3 + 1) scenario: **$0.82 < \Delta m^2_{41} < 2.19$ eV^2 (3σ)**
- **To probe this region: MeV (anti)neutrinos at short distances of few meters!**

C. Giunti, M. Laveder, Y. F. Li, H.W. Long
Phys. Rev. D 88, 073008 (2013)

Sterile neutrino search using nuclear decays

ν type	Source type	Life τ	Decay mode	Energy [MeV]	Production mode
ν_e	^{51}Cr	40 d	EC	0.75 (90%) 0.43 (10%)	Neutron irradiation of ^{50}Cr in reactor $\Phi_n \geq 5\ 10^{14}\ cm^{-2}\ s^{-1}$
	^{37}Ar	35 d	EC	0.811	Fast neutron irradiation of Ca oxide in reactor
$\bar{\nu}_e$	^{144}Ce-^{144}Pr	411 d	β^-	<2.997	Chemical extraction from spent fuel
	^{90}Sr	40 y	β^-	<2.27	RHS (RadioNuclide Heat Source)
	^{8}Li	868 ms	β^-	<12.9	Beam of neutrons on a ^{7}Li target (ISODAR facility)

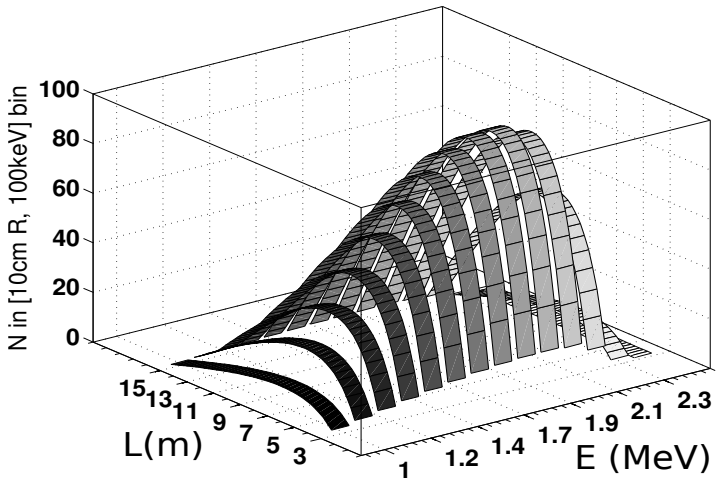
B. Caccianiga @ Neutrino 2014

Look for:

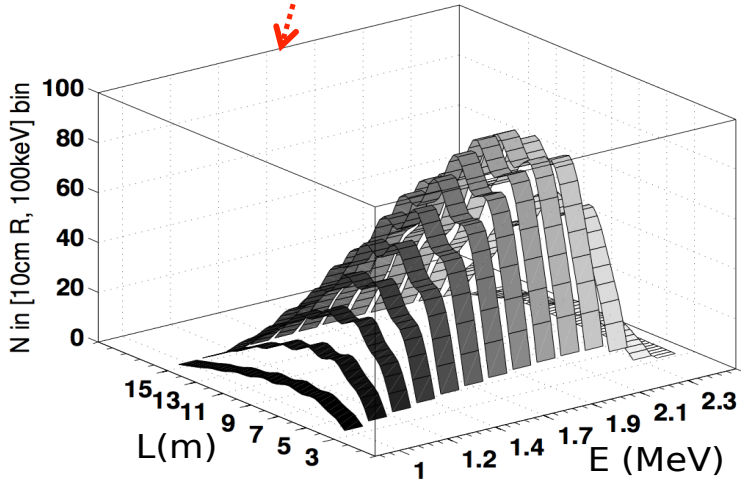
1) **Dissapearance** of (anti)neutrinos emitted from the source

2) **Oscillometry** in (L, E) parameter space

No oscillations



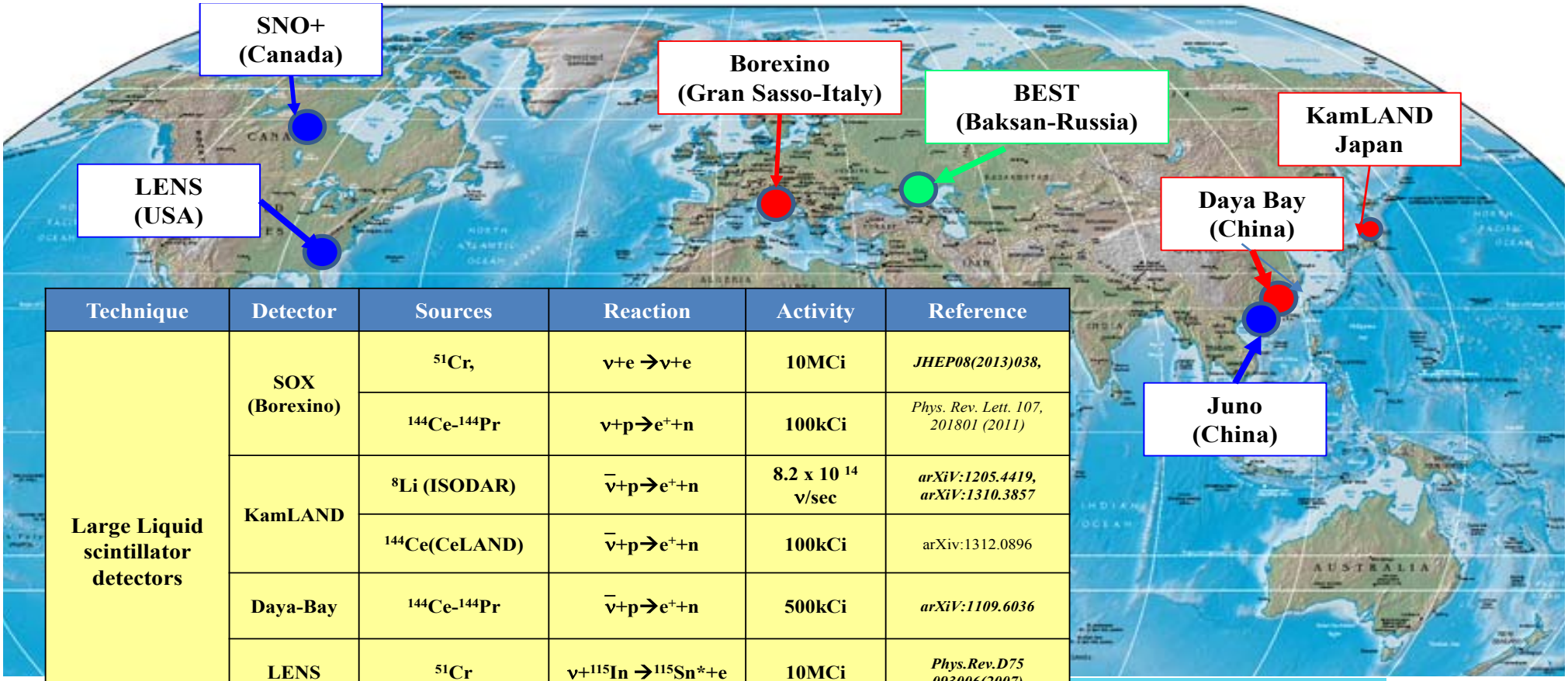
$\Delta m^2_{41} = 2\ eV^2$ → oscillations within detector



Gaffiot et al. PRD 91 (2015) 072005

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{ee}) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Candidates and ideas around the world



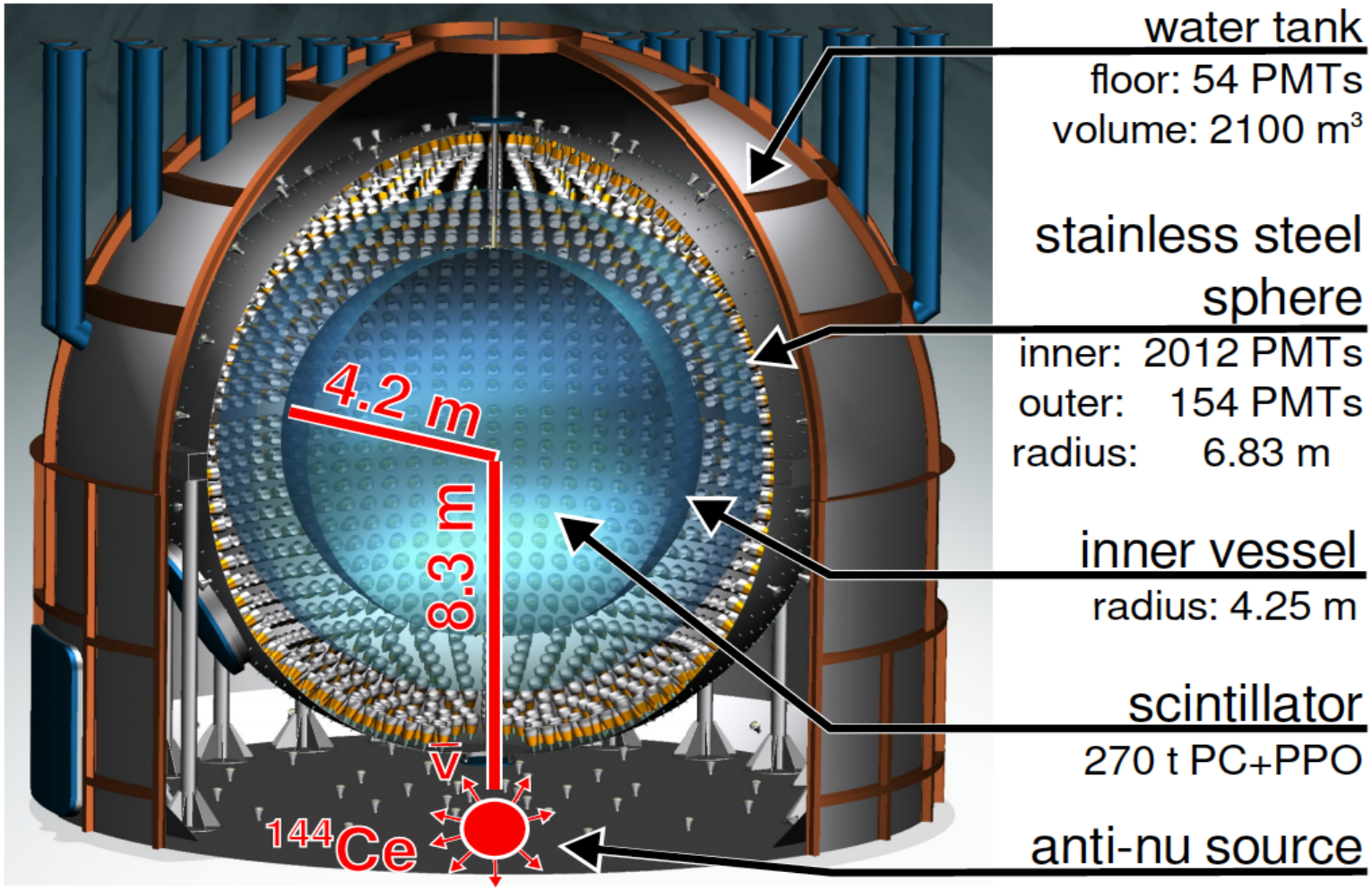
Technique	Detector	Sources	Reaction	Activity	Reference
Large Liquid scintillator detectors	SOX (Borexino)	^{51}Cr,	$\nu+e \rightarrow \nu+e$	10MCi	*JHEP08(2013)038,*
		^{144}Ce-^{144}Pr	$\nu+p \rightarrow e^{+}+n$	100kCi	*Phys. Rev. Lett. 107, 201801 (2011)*
	KamLAND	^{8}Li (ISODAR)	$\bar{\nu}+p \rightarrow e^{+}+n$	8.2 x 10 ^{14} ν/sec	*arXiV:1205.4419, arXiV:1310.3857*
		^{144}Ce(CeLAND)	$\bar{\nu}+p \rightarrow e^{+}+n$	100kCi	arXiv:1312.0896
	Daya-Bay	^{144}Ce-^{144}Pr	$\bar{\nu}+p \rightarrow e^{+}+n$	500kCi	*arXiV:1109.6036*
	LENS	^{51}Cr	$\nu+^{115}$In $\rightarrow ^{115}$Sn*+e	10MCi	*Phys.Rev.D75 093006(2007)*
	JUNO	^{8}Li (ISODAR)	$\bar{\nu}+p \rightarrow e^{+}+n$	8.2 x 10 ^{14} ν/sec	*arXiV:1310.3857*
Radiochemical	BEST	^{51}Cr	$\nu+^{70}$Ga $\rightarrow ^{71}$Ge+e	3MCi	arXiV:1204.5379
Bolometers	Richochet	^{37}Ar	$\nu+N \rightarrow \nu+N$	5MCi	Phys. Rev. D85, 013009, (2012)

B. Caccianiga @ Neutrino 2014

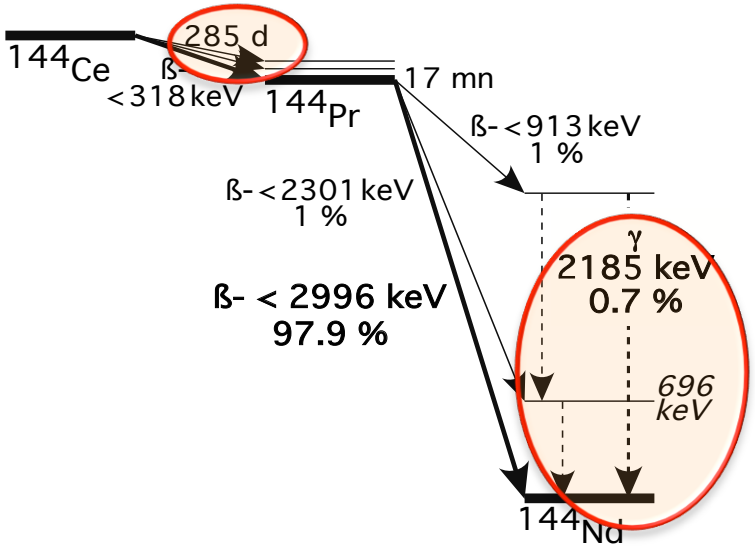
SOX: Short-distance neutrino oscillation with Borexino

Aim: Clear and unambiguous discovery or definitive disproof of the anomalies

Also under discussion:
- ^{51}Cr source underneath the detector
- ^{144}Ce source inside the water tank or in the center



^{144}Ce-^{144}Pr antineutrino source



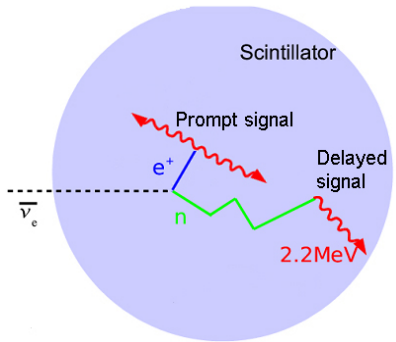
- 3.7 PBq (in ^{144}Ce(β), 100 kCi)
  > 10^{15} antineutrinos/s
  (CHALLENGE technical and bureaucratic)

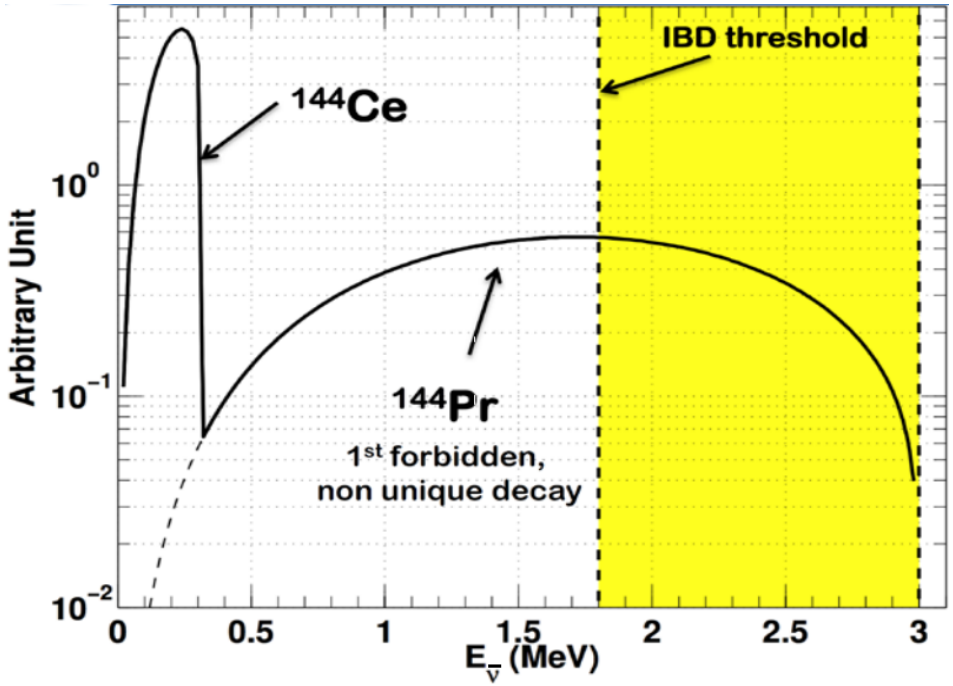
- Long lifetime of 285 days
- 2.2 MeV gammas difficult to handle

Inverse **B**eta **D**ecay

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

Background suppresion!





Detection of ~ 500 pe/MeV

Energy resolution σ_E/E ~5% (@1MeV)

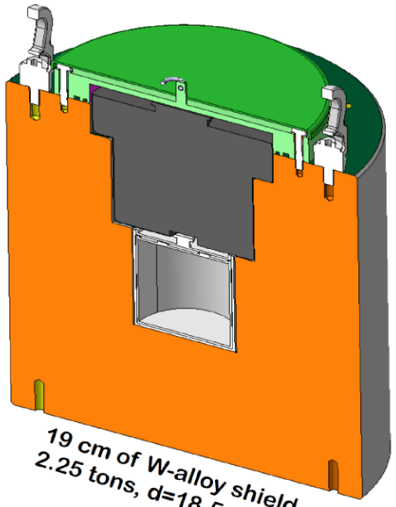
Position resolution σ_x ~ 10 cm (@1MeV)

^{144}Ce-^{144}Pr source production

- From fresh (< 2 years) nuclear spent fuel
- Chemical form CeO_2

Purity requirements

- **Content of any others REE (*γ-emitters*) ≤ 10^{-3} Bq / Bq of ^{144}Ce**
- **Content of Pu and TPE (*actinides*) ≤ 10^{-5} Bq / Bq of ^{144}Ce**



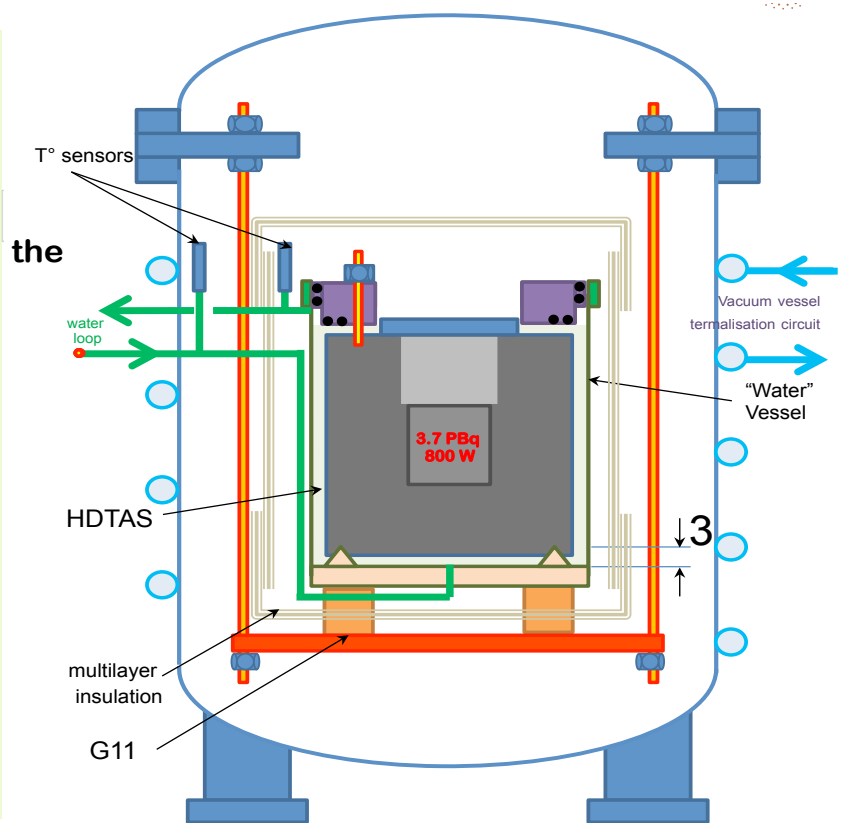
- **Radiochemical Plant**
  - **Standard radiochemical re-processing of SNF (Purex)**
  - **Separation of CeO_2**
  - **Primary encapsulation**
  - **Activity measurement (≈5%)**
- **Radioisotope Plant**
  - **Source manufacture**
  - **Certification ISO 9978**
  - **Loading into W-shield**
  - **Loading into transport cask**

Arrival to LNGS:
2nd half of 2016

Additional physics challenges

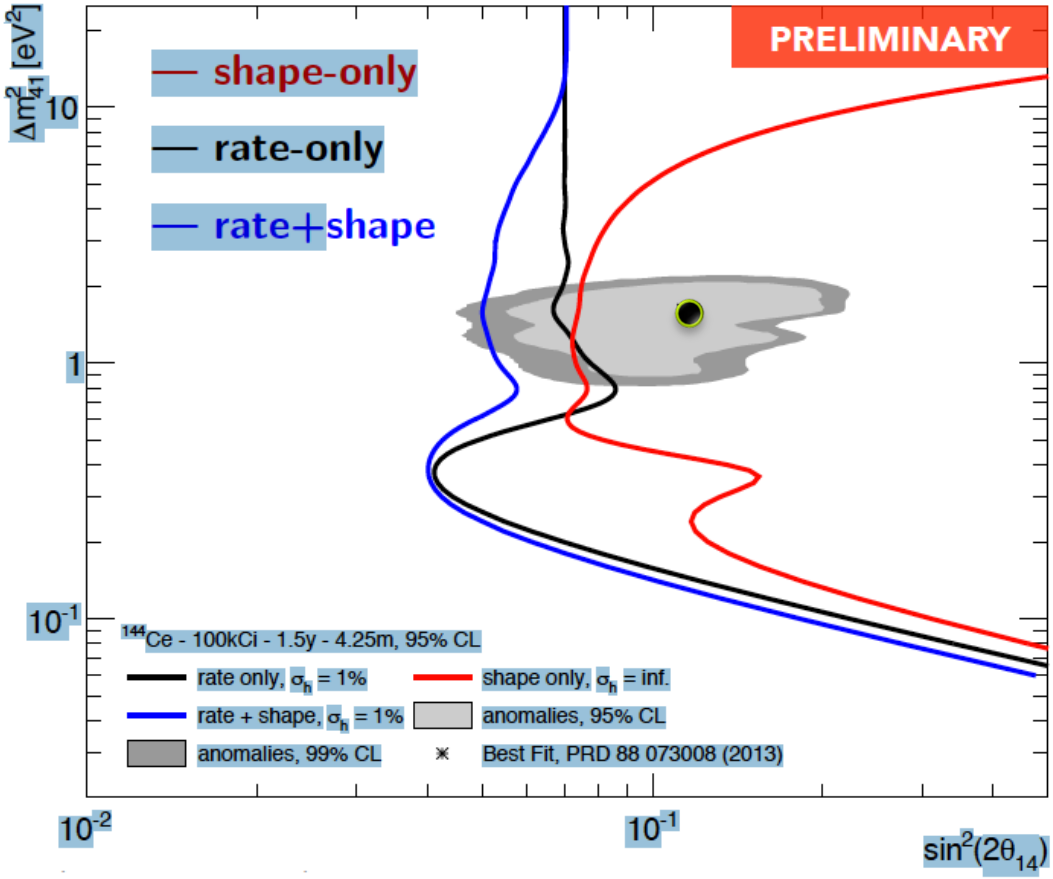
- **^{144}C-^{144}Pr β/ν spectra needed with 5% precision**: BUT forbidden transitions and shape factors with 10% error! Ongoing developments of **new spectroscopic measurements** (CEA, TUM)!
- **Activity has to be known with < 1.5% precision: Calorimetry!** (CEA, TUM + Genova)

- **Fighting all other systematic errors down to 1-2% precision!**
  - ✓ the "whole" scintillator volume of Borexino will be used (similar to geoneutrino studies)
  - ✓ A few months-long calibration campaign with external (gamma's, AmBe-neutron) sources planned for early 2016
  - ✓ Upgrade of the trigger system
  - ✓ New Geant-based Monte Carlo development
  - ✓ Source-induced background study
  - ✓ Adding PPO to the internal buffer region?



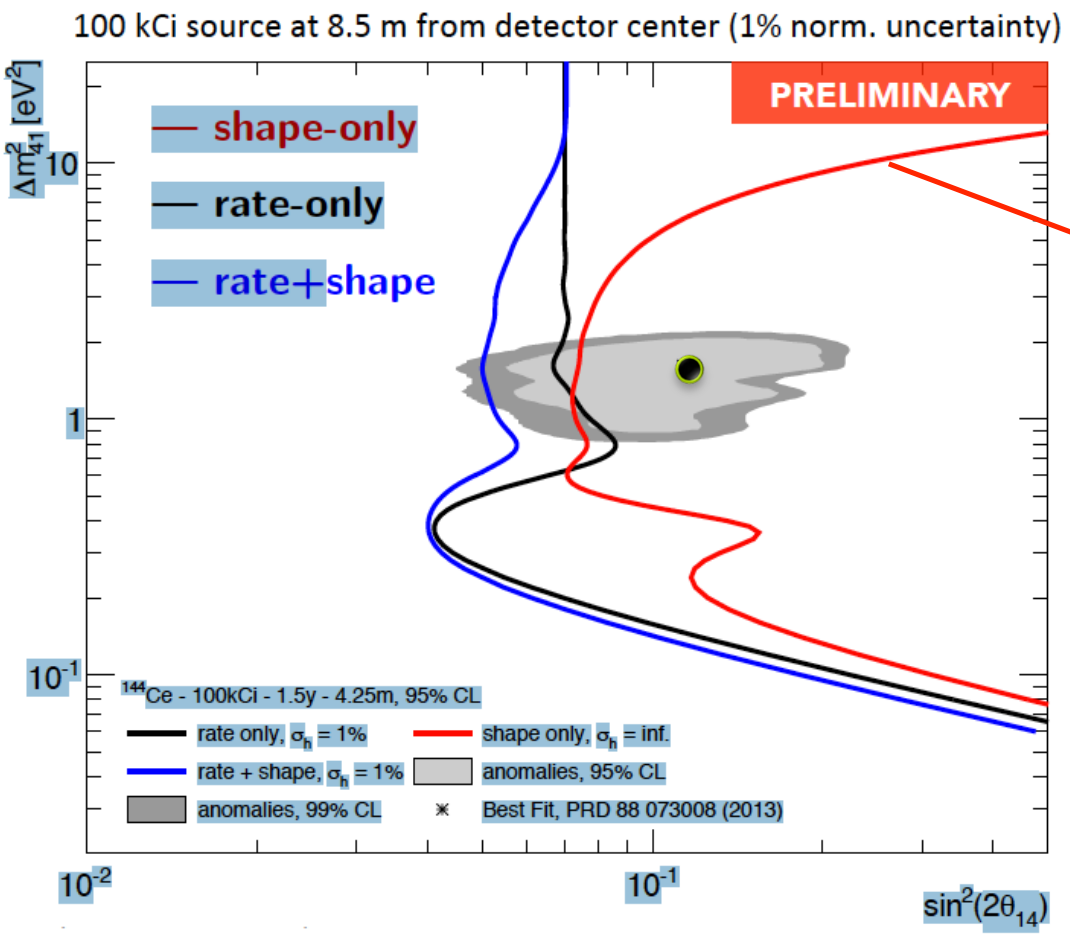
Sensitivity studies

100 kCi source at 8.5 m from detector center (1% norm. uncertainty)



More details in Ce-SOX parallel talk of Matthieu Vivier

Sensitivity studies



Stay tuned in 2017!

More details in Ce-SOX parallel talk of Matthieu Vivier

TAUP Topics in Astroparticle and Underground Physics