51st Rencontres de Moriond EW 2016

12-19 mars 2016
Europe/Paris timezone

Recent results from Borexino

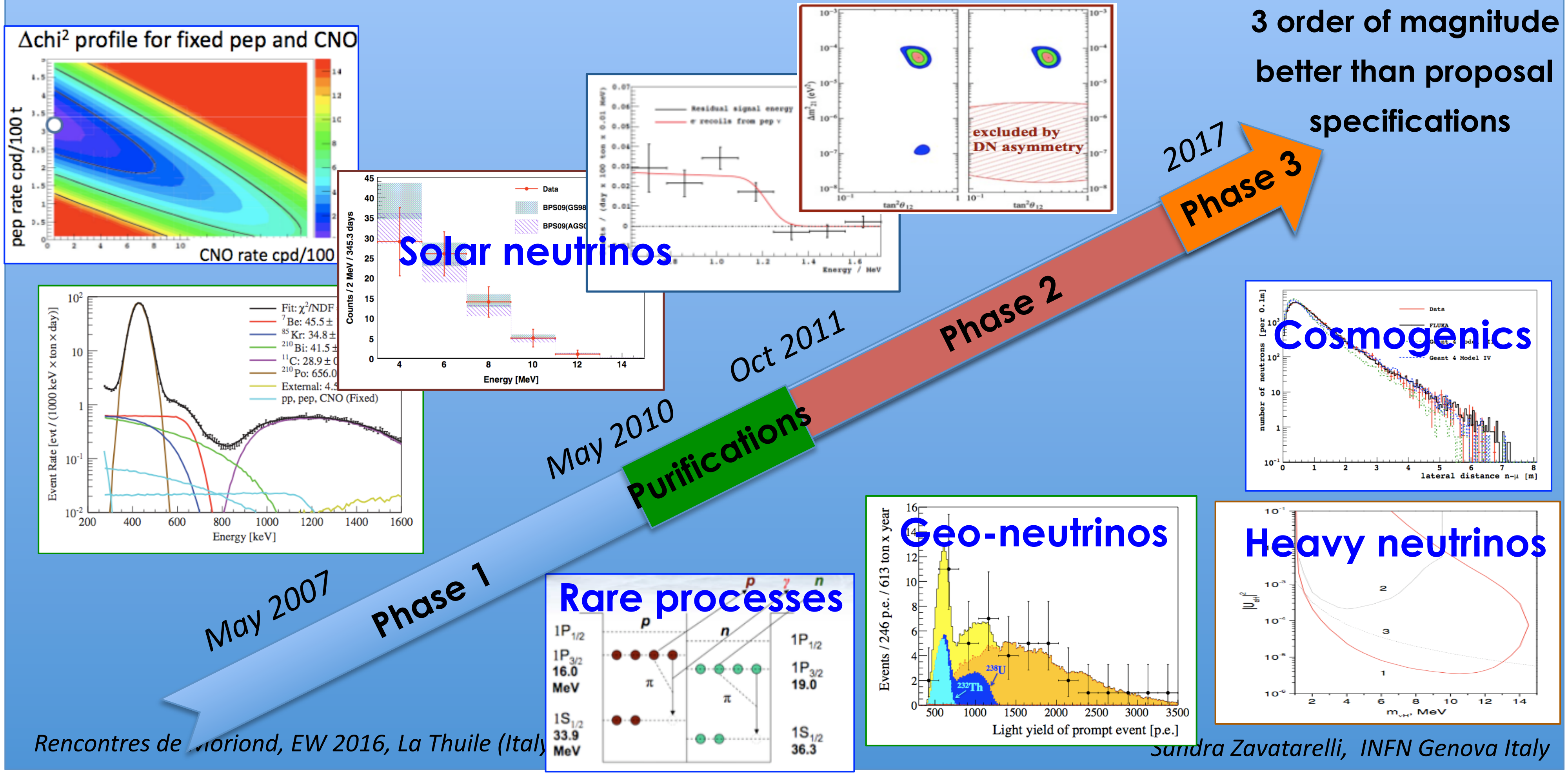
Sandra Zavatarelli, INFN Genoa (Italy)
on behalf of the Borexino Collaboration

Borexino physics

Data-taking since May 2007 : many relevant results on solar/geo ν physics and rare processes detection achieved thanks to the unprecedented scintillator radio-purity

Backgrounds now : $^{238}U < 8\ 10^{-20}$ g/g at 95% C.L., $^{232}Th < 9\ 10^{-19}$ g/g at 95% C.L.

3 order of magnitude better than proposal specifications



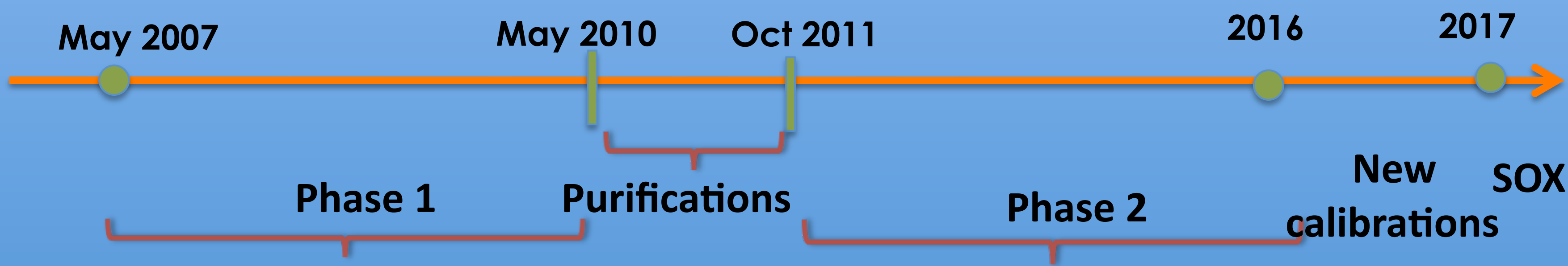
Talk outline

✧Solar neutrino physics: the impact of Borexino, and the corrent effort to measure CNO-ν;

✧ Rare process detection: new limit on the electron decay into a neutrino and a photon =>> published on PRL in Dec.2015

✧Neutrino geoscience: evidence for geo-ν signal at 5.9 σ;

✧Future perspectives



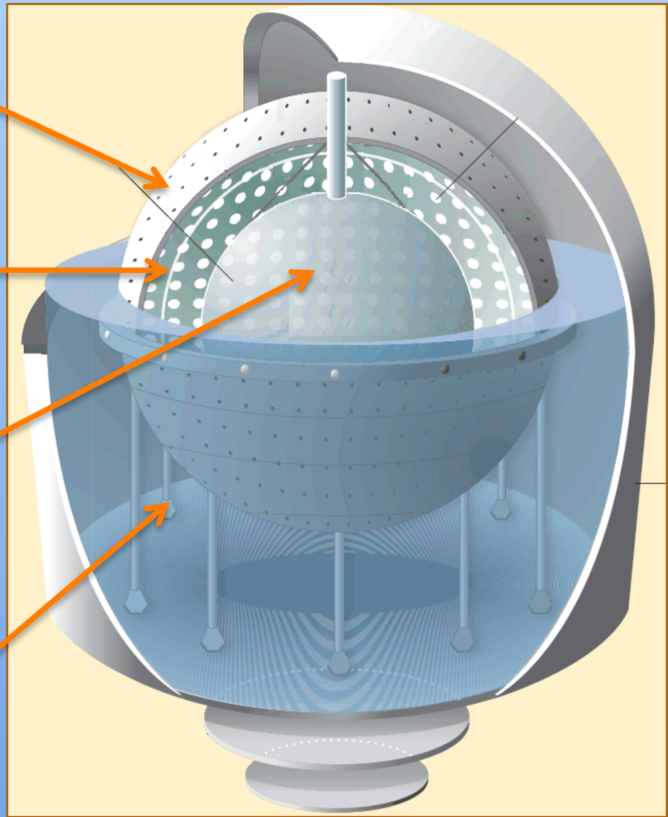
The Borexino detector

Stainless Steel Sphere:
R = 6.75 m, 1350 m^3 of water
Support for 2212 PMTs

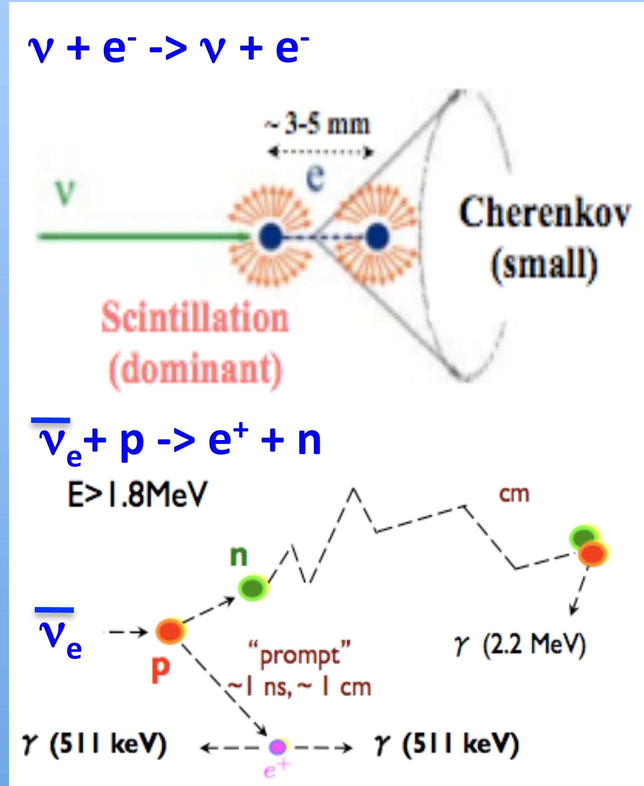
Buffer region:
PC+DMP quencher (5 g/l)
4.25 m < R < 6.75 m

Scintillator:
270 t PC+PPO (1.5 g/l)
(R = 4.25 m)

Water Tank:
2100 m^3 of water
208 PMTs Cherenkoc



Detection principle:



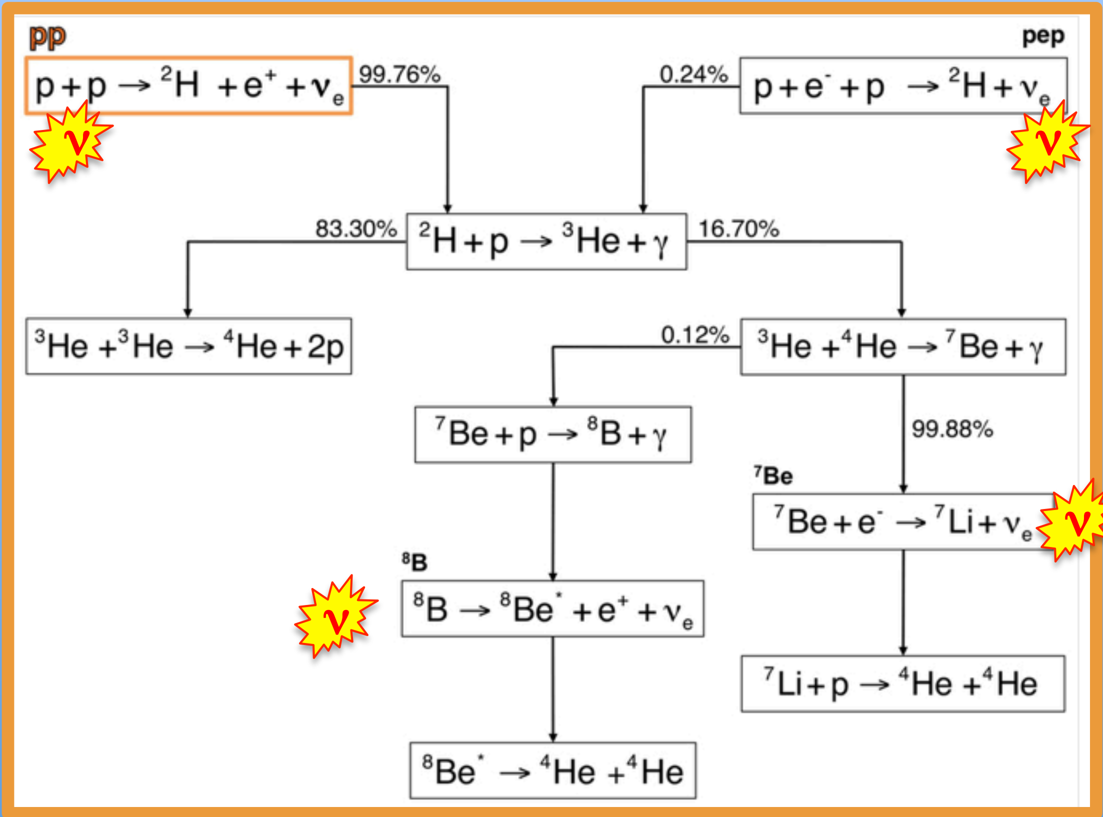
- Scintillation light detected by PMT's
  - # of photons → energy
  - time of flight → position
  - pulse shape → α/β β+/β−

- **Light yield:** ~500 phe/MeV
- **Energy resolution:** 5% @ 1MeV
- **Space resolution:** 10cm @ 1 MeV
- Pulse shape capability

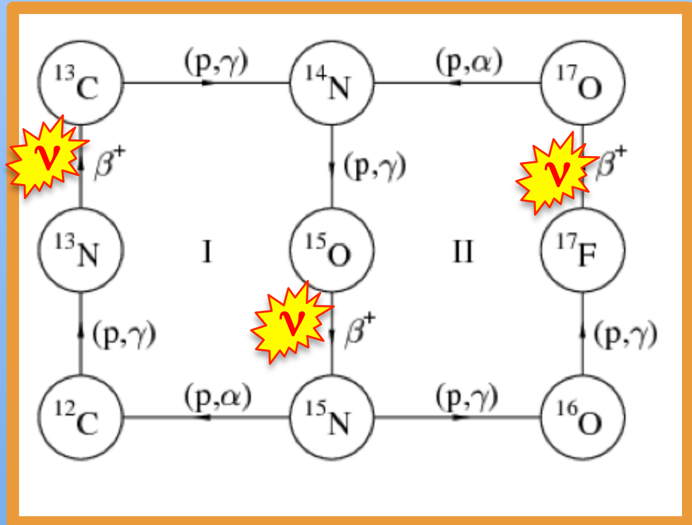
Principle of graded shielding: "pure and pure material toward the center of the detector"…

(I)Fusion reaction in the Sun and solar neutrinos

pp chain: 99 % of Sun Energy



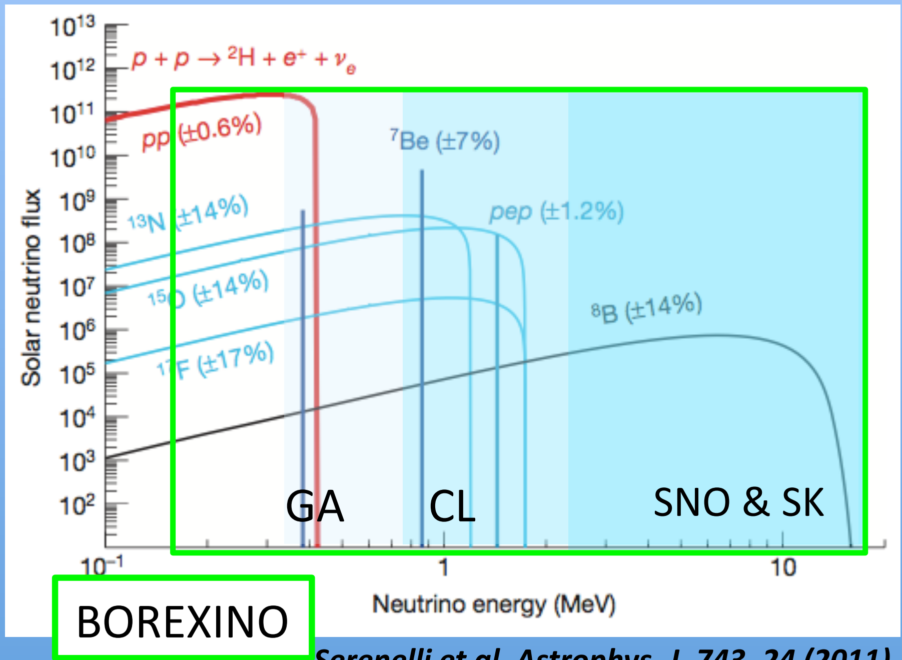
CNO cycle: <1 % of Sun Energy



Solar neutrinos are probes to test our understanding of fusion reactions, neutrino properties and EW interactions.

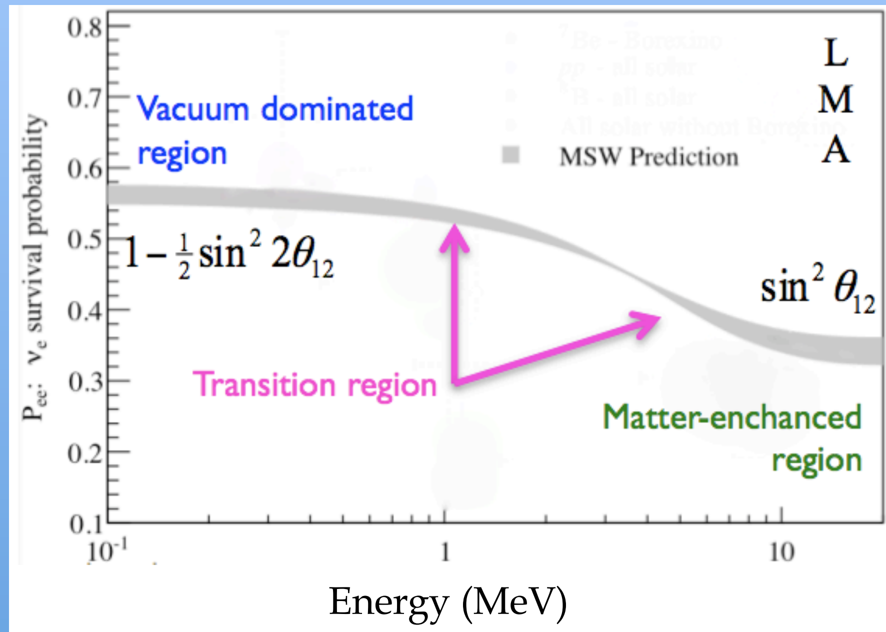
Borexino: capability to measure in real time the sigle components of the solar-ν spectrum

Solar ν fluxes at Earth



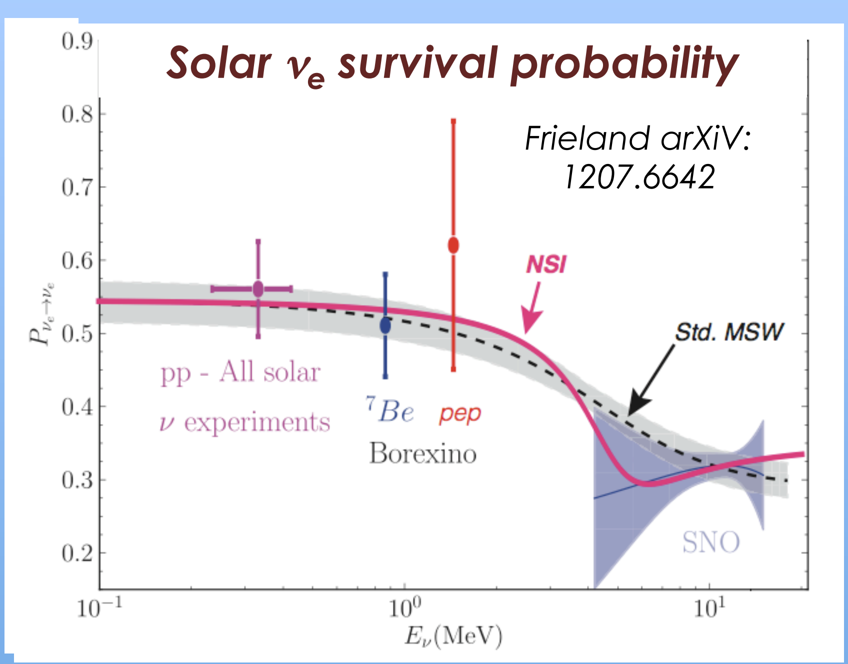
Serenelli et al, Astrophys. J. 743, 24 (2011).

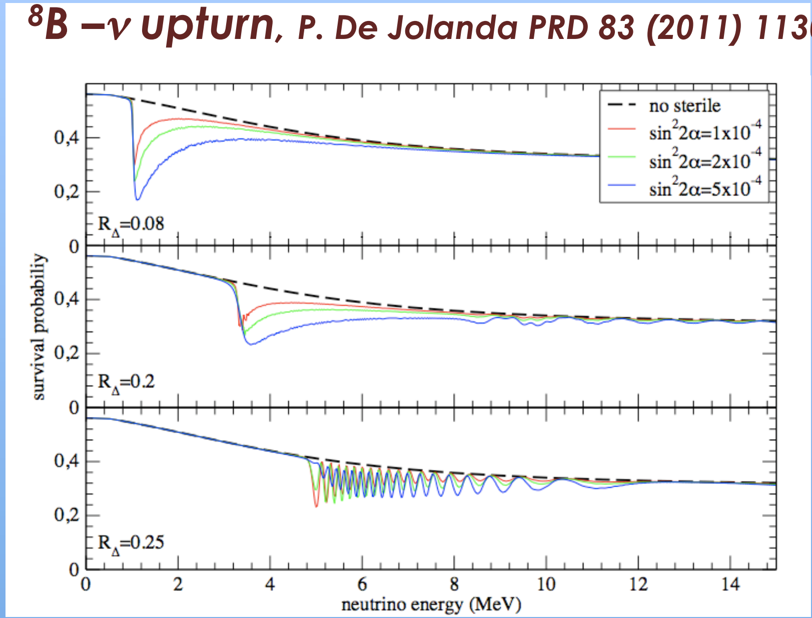
Solar ν_e survival probability



Sandra Zavatarelli, INFN Genova Italy

Importance of single solar-ν component precise measurements:





✓Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction, sub-leading effects, mixing with light sterile ν's

✓Help to understand the high/Low metallicity solar model controversy

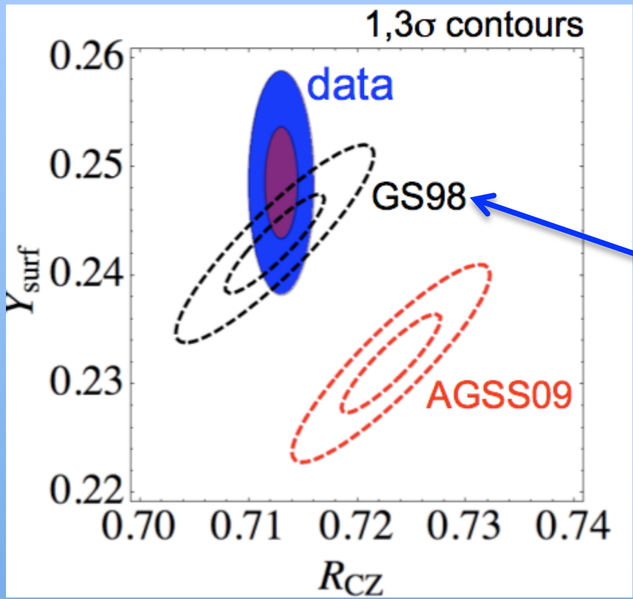
Importance of single solar-ν component precise measurements:

Solar ν fluxes: $cm^{-2}s^{-1}$

Diff.		GS98	AGS09
1%	pp	5.98×10^{10}	6.03×10^{10}
2%	pep	1.44×10^{8}	1.47×10^{8}
3%	hep	8.04×10^{3}	8.31×10^{3}
9%	^{7}Be	5.00×10^{9}	4.56×10^{9}
18%	^{8}B	5.58×10^{6}	4.59×10^{6}
C 27%	^{13}N	2.96×10^{8}	2.17×10^{8}
N 30%	^{15}O	2.23×10^{8}	1.56×10^{8}
O 38%	^{17}F	5.52×10^{6}	3.40×10^{6}

A. Serenelli ApJ 743 (2011) 24

Data from Heliosismology and metallicity



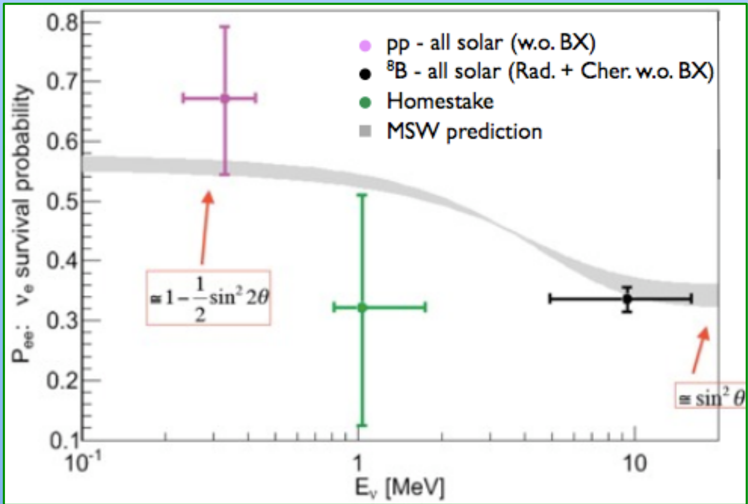
Thought to be wrong!!

✓**Confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction, sub-leading effects, mixing with light sterile ν's**

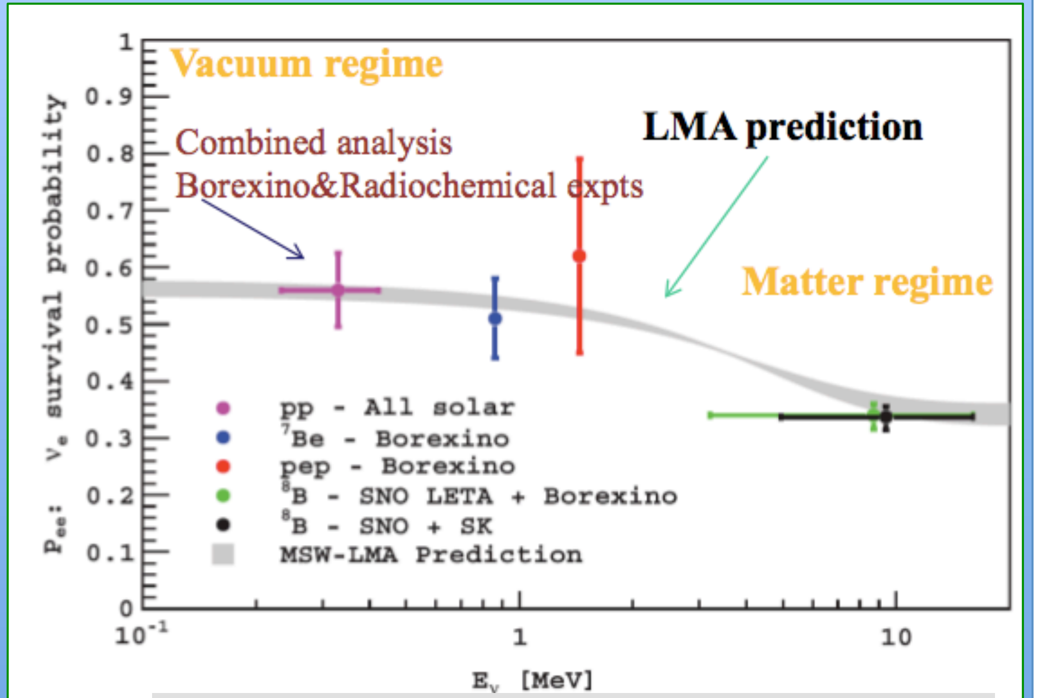
✓**Help to understand the high/Low metallicity solar model controversy**

Borexino: Phase 1 impact

Before Borexino



Borexino now



P_{ee} curve (grey band) as expected from MSW-LMA

Borexino validate the MSW-LMA paradigm

7Be ν flux: err. exp. 5% , err. theo. 7%
PRL 107, 1411302 (2011)

8B-ν flux: err. exp. 20%, err. theo. 14%
Phys.Rev.D 82, 0330066 (2010)

pep ν flux: err. exp. 20%, err. theo.
Best limit on CNO-ν
PRL 108, 051302 (2012)

Test of Not-Standard-Interaction or oscillation to sterile ν:

- Reduce error on pep and ^{7}Be-ν and on ^{8}B-ν
- Reduce threshold on ^{8}B-ν

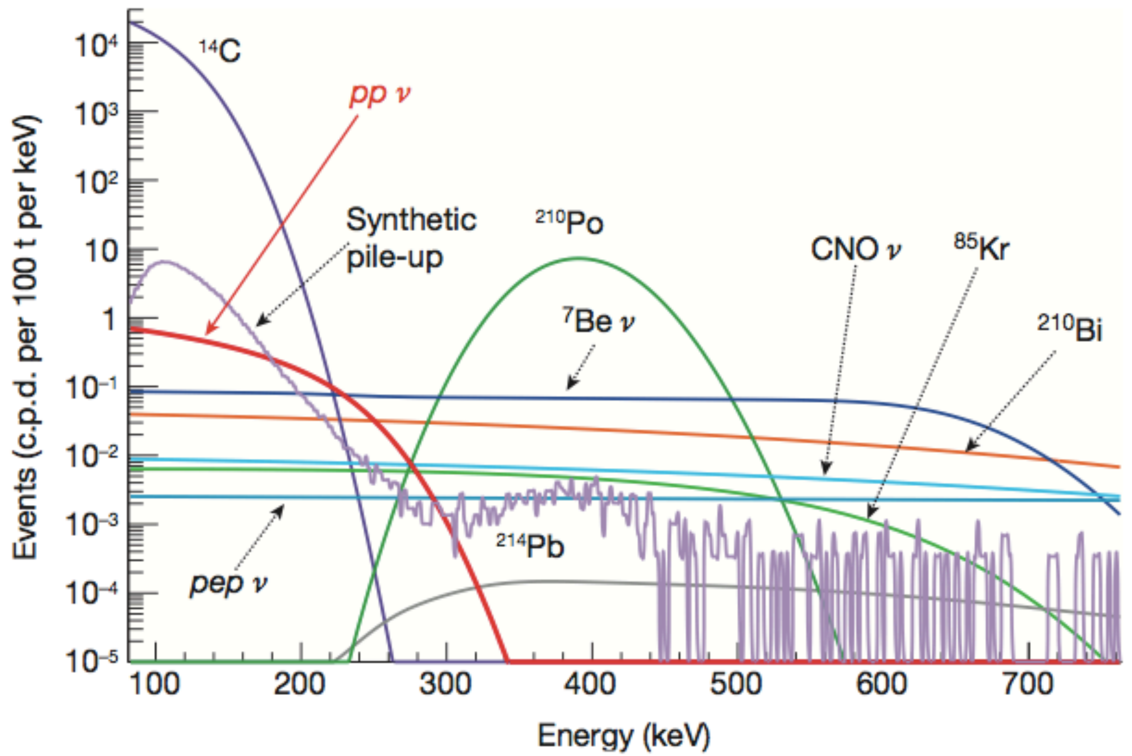
Borexino & pp-ν

Nature 512 (2014) 383-386

✓ ~90% of the solar luminosity in neutrinos is due to pp –ν

- Photons take ~10^5 years to travel from the center of the Sun to the surface;
- Neutrinos take only few seconds .

Verifying that the solar luminosity in neutrinos is the same as the one in photons demonstrate the stability of the Sun on the 10^5 years time scale

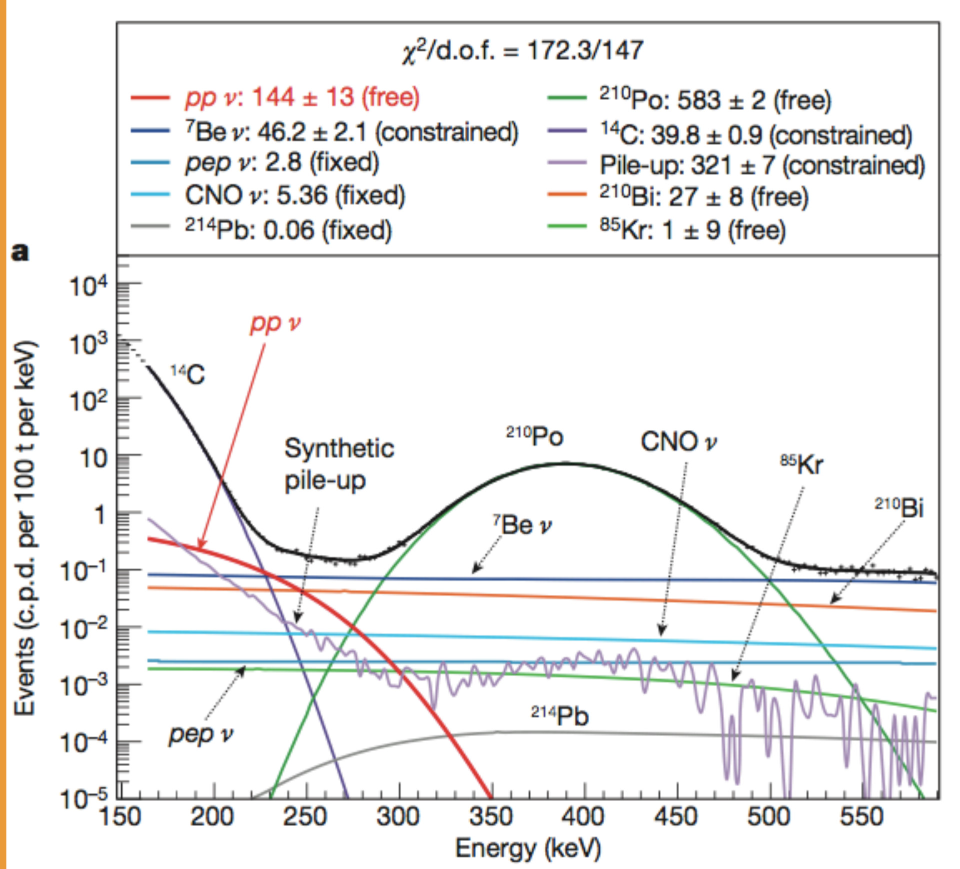


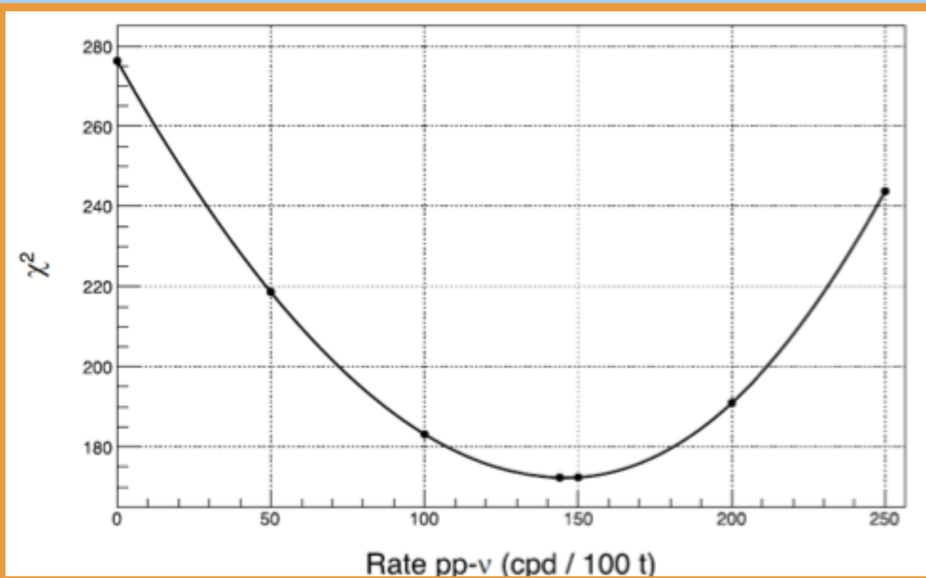
✧pp –ν induce eletron recoil up to 300 keV: this region is vastly dominated by ^{14}C, whose pileup is also a significant source of backgrounds;

✧A spectral fit is needed to disantagle the signal from backgrounds;
Crucial to know the spectral shape of signal and backgrounds =>
=>Detector response accessed by calibrations & MC simulation
Independent determination of the main background rate (^{14}C and its pileup) in order to constrain them in the fit.

Borexino & pp-ν

Data: Jan. 2012 – May 2013 : 408 live days





Zero pp count is excluded at 10σ

Luminosity in neutrinos consistent with luminosity in photons!!!!!

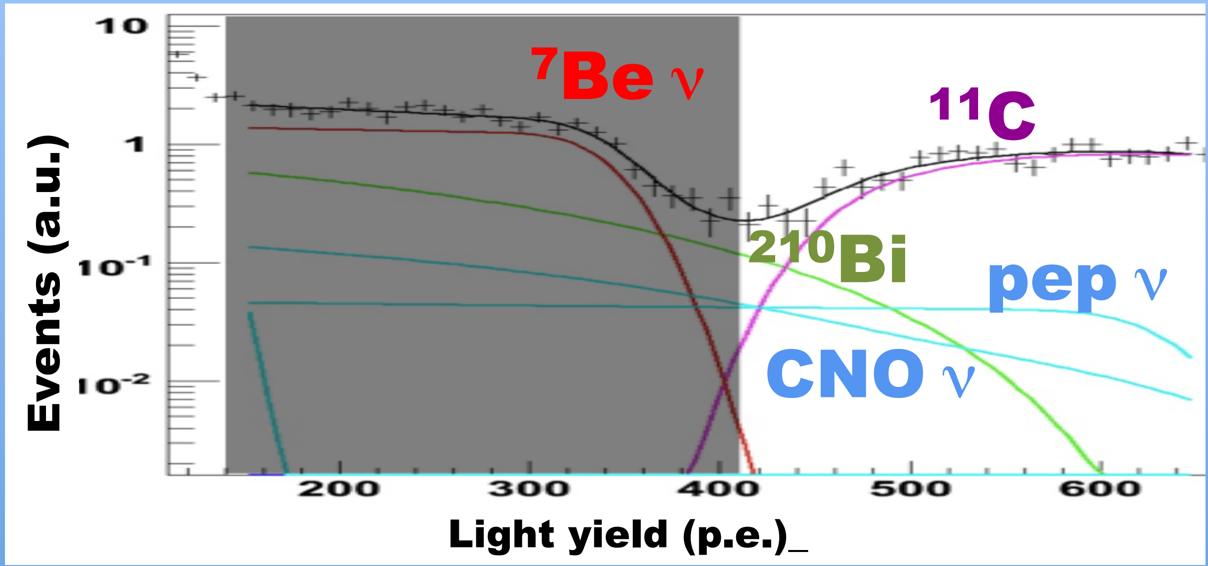
$$\Phi_{pp} = \begin{cases} (6.6 \pm 0.7)\times 10^{10}\,\mathrm{cm}^{-2}s^{-1} \text{ measured} \\ (5.98 \pm 0.04)\times 10^{10}\,\mathrm{cm}^{-2}s^{-1} \text{ expected (high - Z)} \\ (6.03 \pm 0.04)\times 10^{10}\,\mathrm{cm}^{-2}s^{-1} \text{ expected (low - Z)} \end{cases}$$

10% accuracy

Sandra Zavatarelli, INFN Genova Italy

The challenge of CNO–ν

- ✧ **Proof that the CNO cycle happens in the Sun;**
- ✧ **Abundance of heavy elements in Sun have great impact on CNO–ν flux (28% difference between HighZ/Low Z models)**



- The ^{11}C background can be reduced by a factor 10 by exploiting the coincidence with the parent muon and associated neutrons (triple coincidence);
- The ^{210}Bi contamination can be constrained through the precise determination of the rate of ^{210}Po successor=> Borexino vessel slightly ^{210}Po polluted=> need of great thermal stability to avoid liquid mixing => Detector insulation concluded in Dec. 2015 => great stability already achieved!!!

(II)The detection of rare processes: Test of electric charge conservation

Phys. Rev. Lett. 115, (2015) 231802

- ✓ Up to now there are no hints for the electric charge non-conservation (CNC)
- ✓ But: CNC is admitted e.g. in extra-dimensional theories
- ✓ Investigation of CNC processes can help in searching for new physics

The most frequently studied CNC processes:

$$e \rightarrow \gamma \nu$$

- E= 256 keV
- It does not occurr in the Standard Model

Dama/Libra : $\tau > 2\ 10^{26}$ y (90% C.L)
CTF (BX): $\tau > 4.6\ 10^{26}$ y

$$e \rightarrow \nu\nu\nu$$

- Low energy (E ≤50 keV)
- Model Independent (electron disappearence)

(II) Test of electric charge conservation with liquid scintillators

Advantages: large mass and possibility of further purifications

The recipe:

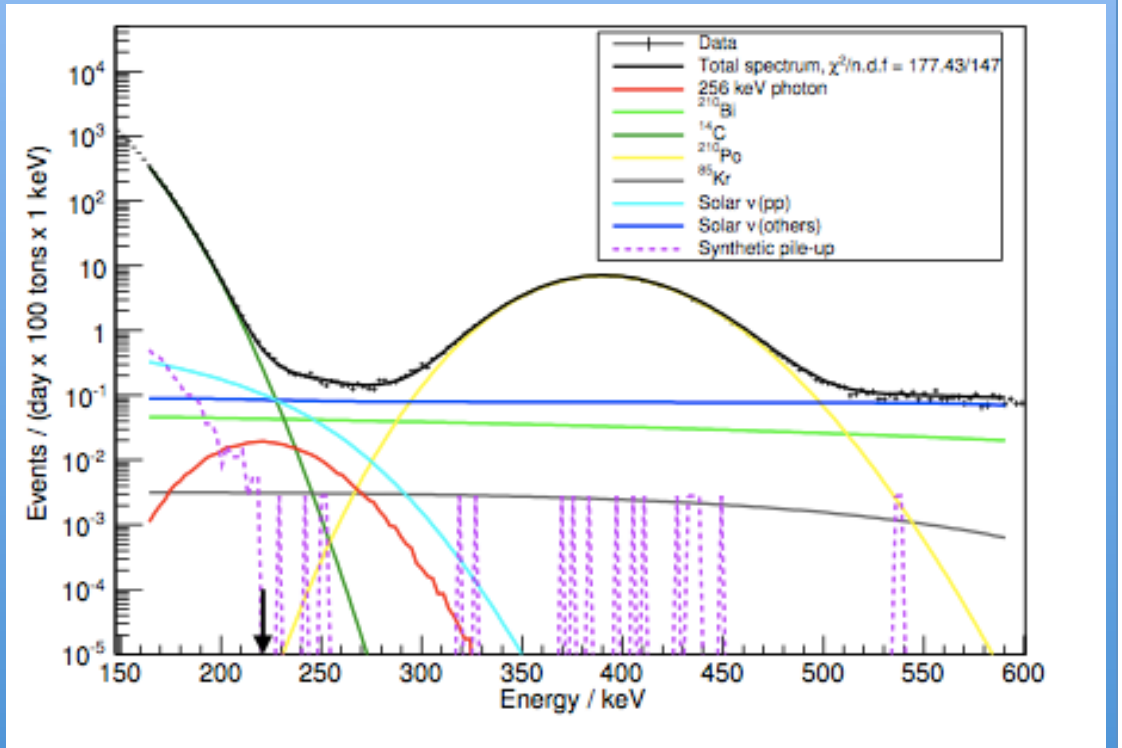
- ✓ Monte Carlo simulation of the monoenergetic 256 keV photons in the detector;
- ✓ Spectral fit (150-600 keV, pp-ν rate fixed to SSM) with different values of 256 keV photon rate;
- ✓ Obtaining the probability profile => upper limit on rate => lower limit of lifetime.

Main sources of systematic errors:

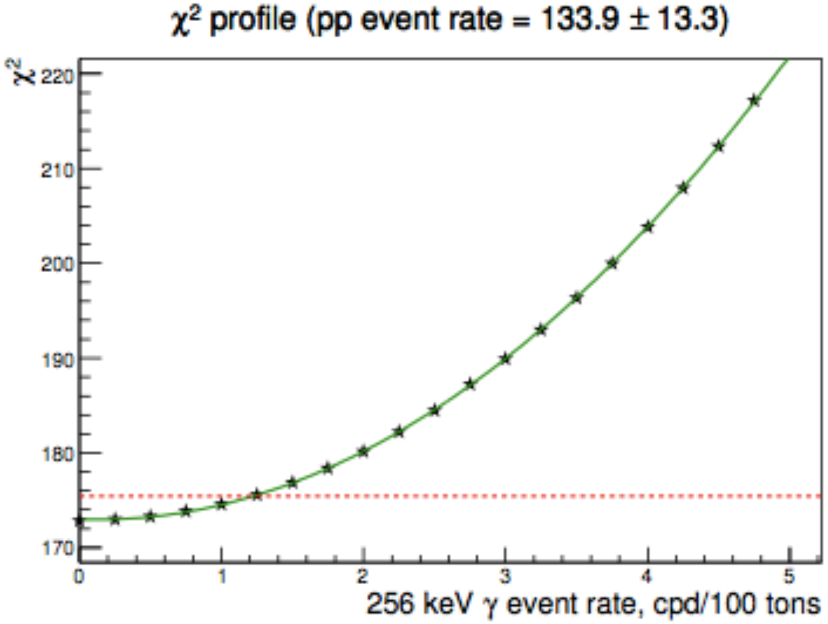
- *Light yield measurement precision (1%)*
- *Fiducial mass uncertainty (2%)*
- *Choice of the energy estimator*

(number of PMTs hit in the time windows of 230 ns or 400 ns)

Data: Jan. 2012 – May 2013 : 408 live days



(II) Test of electric charge conservation with liquid scintillators: results



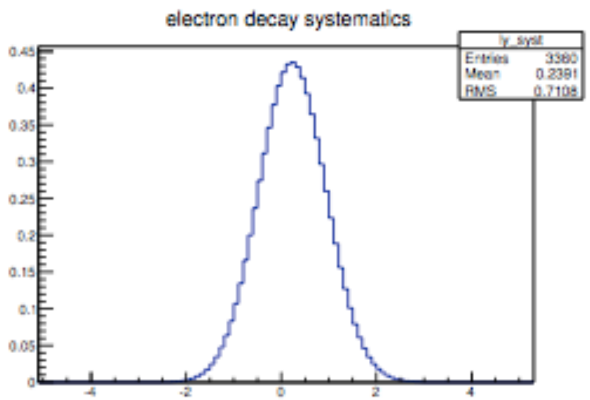
Statistical analysis

The event rate of pp-neutrino is constrained according to J. N. Abdurashitov et al. *Phys. Rev. C* **80** 015807 (2009)

$$n \leqslant 1.23 \text{ cpd}/100 \text{ tons}$$

$$\tau \geqslant 7.2 \times 10^{28} \text{ years}$$

$$(\text{CL} = 90\%)$$



+study of systematic errors

$$n \leqslant 1.33 \text{ cpd}/100 \text{ tons}$$

Final result

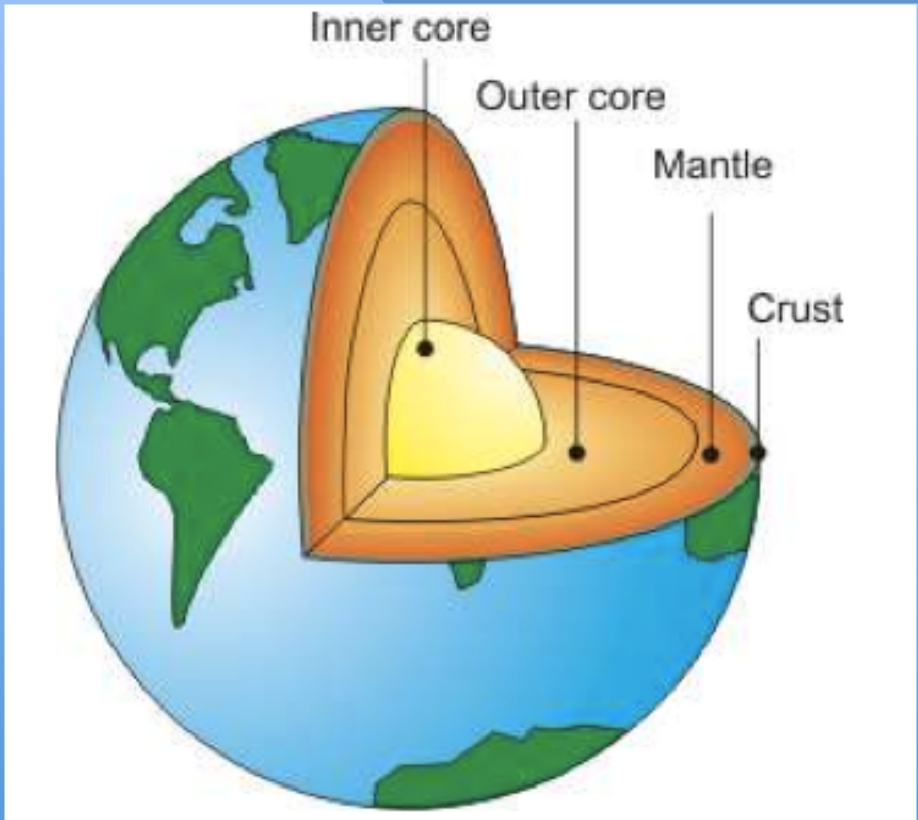
$$\tau \geqslant 6.6 \times 10^{28} \text{ years } (\text{CL} = 90\%)$$

(III) Neutrino Geoscience

Thanks to neutrinos we were able to get closer insights into deep stellar core…

Why do not extend this approach to the Earth study?

→ NEUTRINO GEOSCIENCE



Geo-ν as probes for deep Earth

The Earth shines in anti-ν ($\Phi_\nu \sim 10^6\ cm^{-2}\ s^{-1}$)

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- + 4\,\bar{\nu}_e + 42.8$ MeV

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- + 6\,\bar{\nu}_e + 51.7$ MeV

$^{235}U \rightarrow {}^{207}Pb + 7\,\alpha + 4\,e^- + 4\,\bar{\nu}_e + 46.4$ MeV

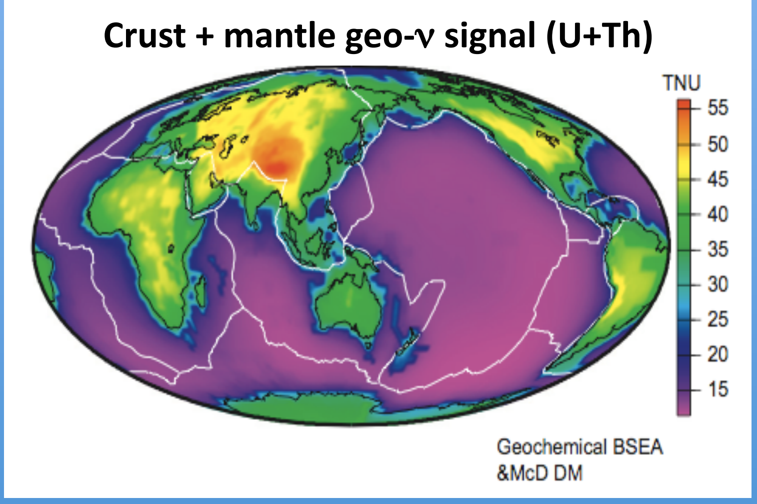
$^{40}K \rightarrow {}^{40}Ca + e^- + 1\,\bar{\nu}_e + 1.32$ MeV (89.3%)

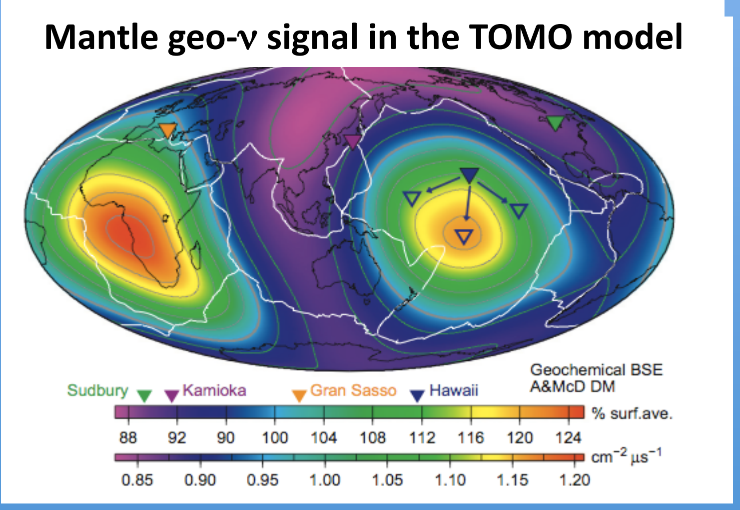
$^{40}K + e \rightarrow {}^{40}Ar + e^+ + 1\,\nu_e + 1.505$ MeV (10.7%)

Heat Producing Elements HPE's

✓ **Released heat and anti-neutrinos flux in a well fixed ratio!**

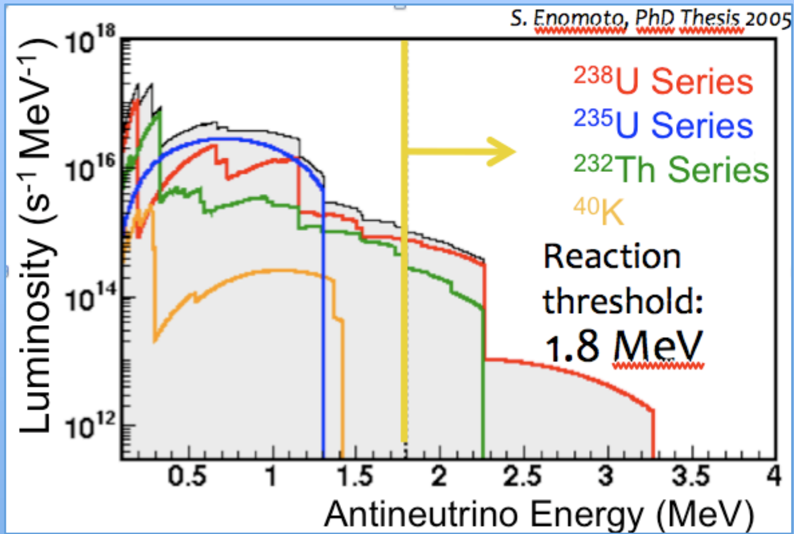
Geo-ν fluxes => HPE's abundances => Earth energetics

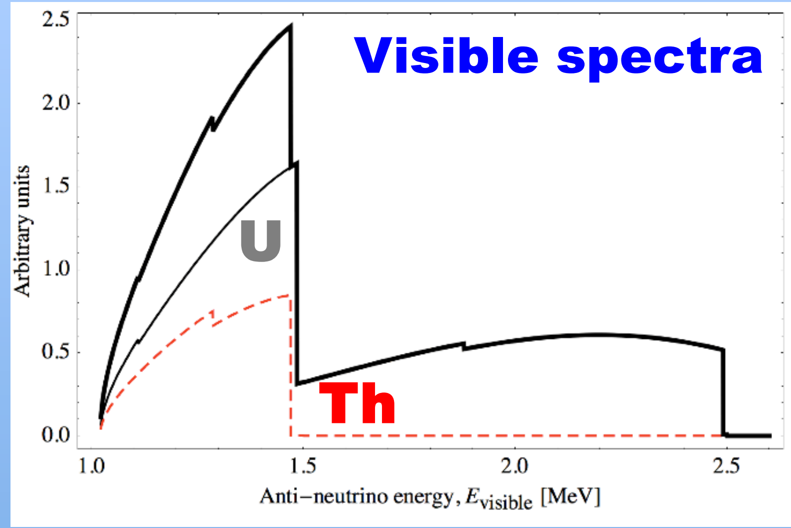




Fluxes not homogeneous => needs for multi-site measurements!!

Geo-ν as probes of deep Earth





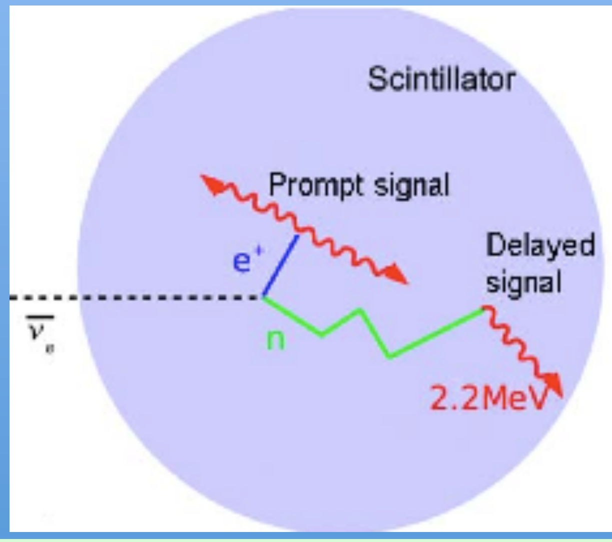
Detection method:
Inverse Beta Decay

$\nu_e + p \rightarrow e^+ + n$

($\tau \sim 250\ \mu s$, d ~ 70 cm)

Threshold: 1.8 MeV, no ^{40}K, ^{235}U

$E_{prompt} = E_\nu - 0.78$ MeV



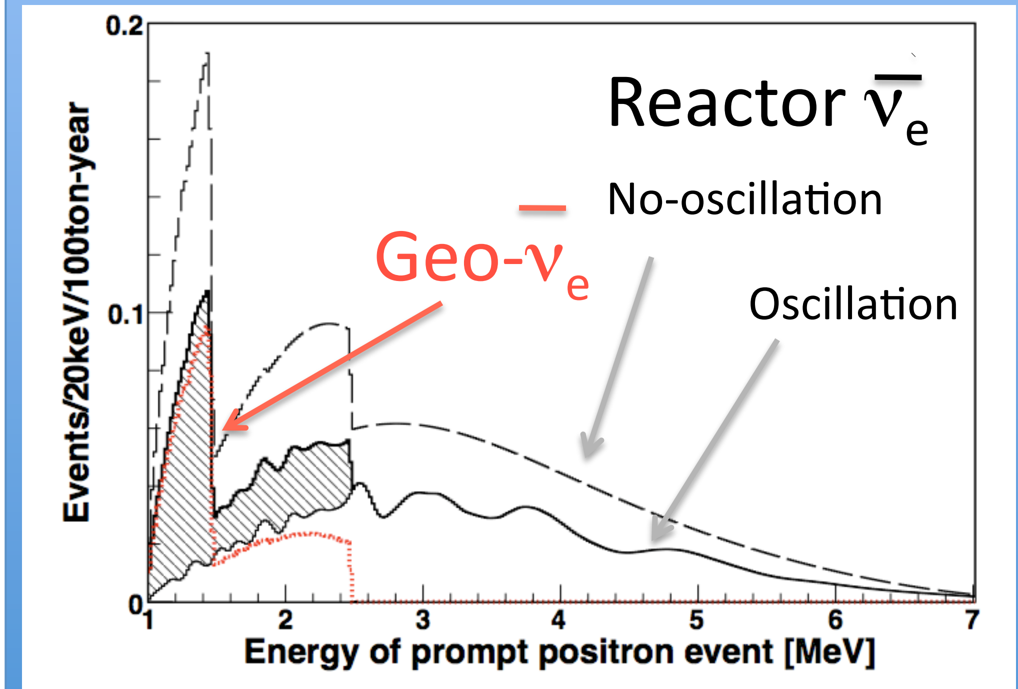
Geo-ν measurements: **KamLAND** *(Nature 436, 499-503 (2005), Phys. Rev. D 88, 033001 (2013)*
Borexino *(Phys. Lett B 722, 295-300 (2013), Phys. Rev. D 92, 031101 (2015))*

Geo-ν: Signal & Backgrounds in BX

The probability to detect electron antineutrino :

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

For geoneutrinos we can use an average survival probability:
Pee (3 flavors) ~ 0.54 (in vacuum) => 0.55 (matter effect)



Most important backgrounds:

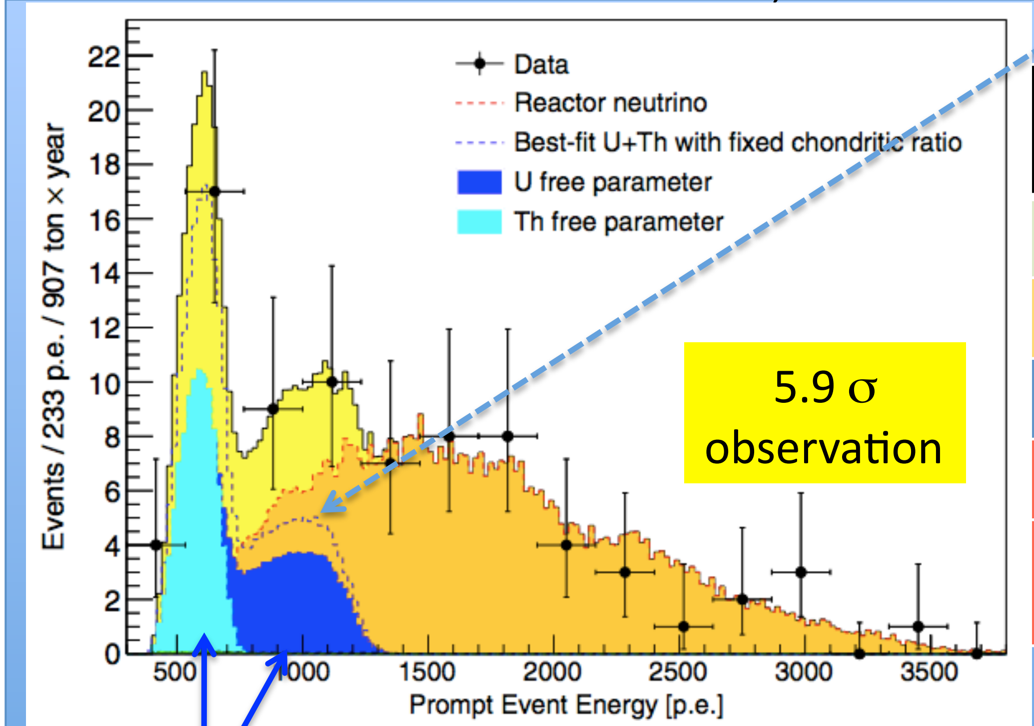
Reactor antineutrinos : S/B ~ 0.45
but they can be disantangled by spectral analysis
We are in contact with IAEA, and EDFS, the flux
Canbe independently estimated with 4% precision.

Other backgroouds mimicking geo-ν signature: S/B ~ 30!!!
(muon induced events, random coincidences (a,n) reactions)

Geo-ν : last result

Phys. Rev. D 92, 031101 (2015)

Dataset: December 15, 2007 – March 8, 2015 – 2055.9 days

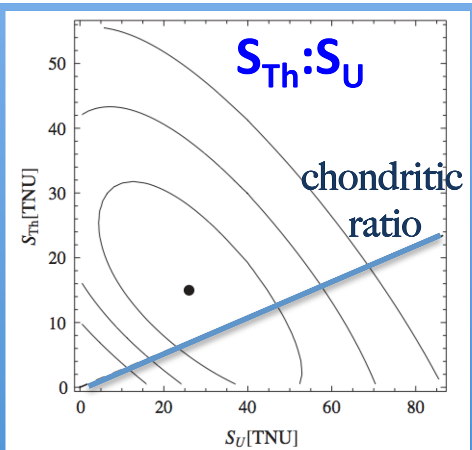


Fit with A(Th)/A(U) = 3.9 (chondritic)

Period	Dec.07 – Mar15 (5.5 ± 0.3) 10^{31} prot*y
Tot ev [full sp.]	77
Reactors ev.	$52.7\ _{-7.7}^{+8.5}$ (stat) $_{-0.9}^{+0.7}$ (sys)
Background ev.	$0.78_{-0.10}^{+0.13}$
Geo-ν ev.	$23.7\ _{-5.7}^{+6.5}$ (stat) $_{-0.6}^{+0.9}$ (sys))
Geo-ν signal (TNU)	$43.5\ _{-10.4}^{+11,8}$ (stat) $_{-2.4}^{+2.7}$ (sys)

1 TNU=1 ev/year/10^{32} target protons

Fit with Th and U free



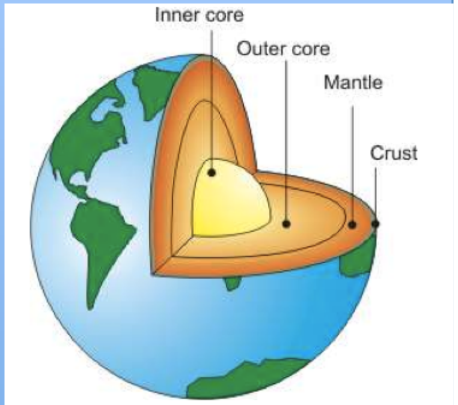
- Precision ~ 27% -> increase statistics!!!

$\Phi(U)=(2.7^{+0.8}_{-0.7})\times10^6\ cm^{-2}s^{-1}$
$\Phi(Th)=(2.3^{+0.7}_{-0.6})\times10^6\ cm^{-2}s^{-1}$

Geo-ν : mantle signal

Measured signal = crust signal + mantle signal where
crust = local crust (LOC) + rest of the crust (ROC)

Using a detailed computation of the contribution from the crust by Y. Huang et al. (ROC) and by Coltorti et al. (LOC):



– $\mathbf{S_{crust} = 23.4 \pm 2.8}$ **TNU** (1TNU = 1 event/year/10^{32}protons)

- Borexino geoneutrino signal: $S_{total}=43.5^{+12.1}_{-10.7}$ TNU

- Considering the experimental likelihood profile for S_{geo} and a gaussian profile for S_{crust}

- We obtain:

– $\mathbf{S_{mantle} = S_{tot} - S_{crust} = 20.9^{+15.1}_{-10.3}}$ **TNU**

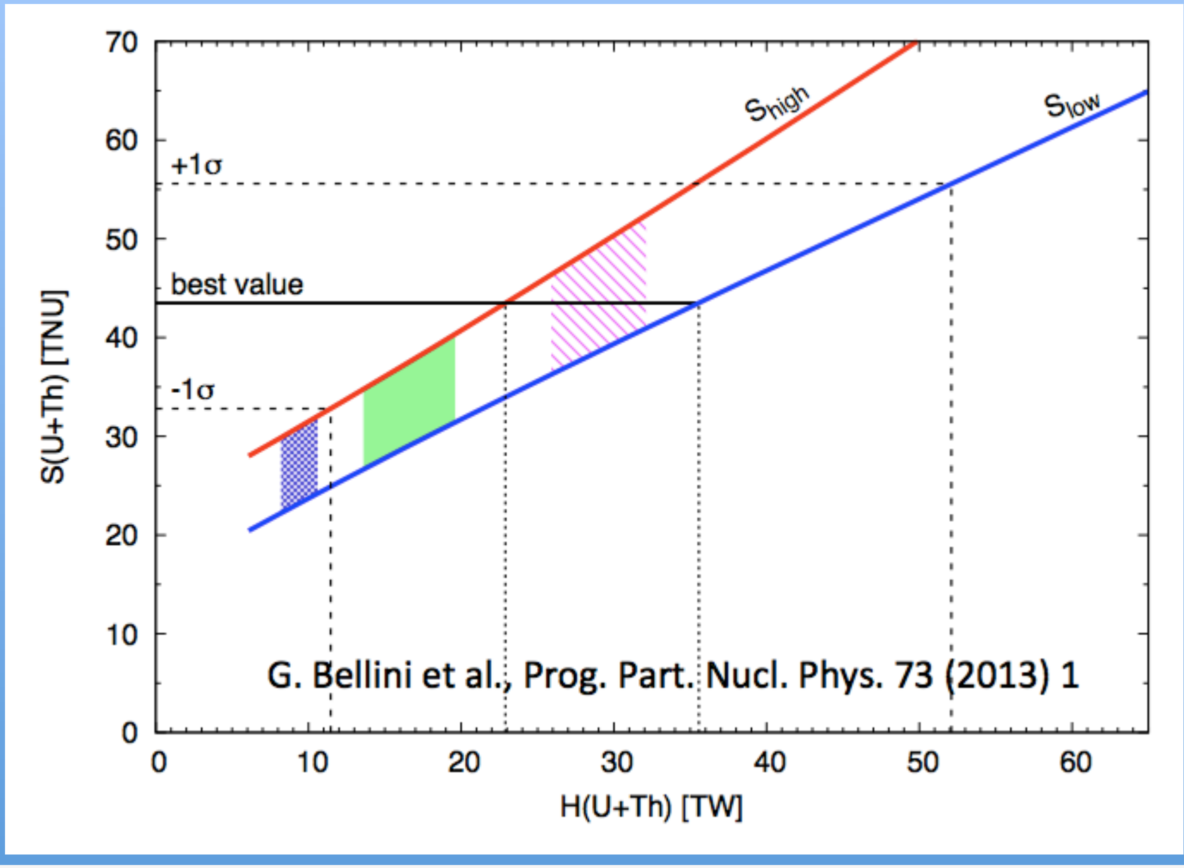
Out of 77 candidates, 13 from the crust and 11 from the mantle

- **The hypothesis $S_{mantle} = 0$ is rejected at 98% C.L.**

KamLAND: $S_{mantle} = 5.0 \pm 7.3$ TNU

Geo-ν : radiogenic heat

Understanding the Earth's energy budget is a fundamental question for plate tectonics, mantle convection and geodynamo



Present data restricts the radiogenic heat to 23 – 36 TW for the best-fit and 11 – 52 TW for 1σ range
(S_{geo}= 43.5 $^{+12.1}_{-10.7}$ TNU)

Using the chondritic ratio Th/U=3.9 and m(K)/m(U) = 10^4 the total radiogenic power is :

P_{rad} (U +Th +K)= 33 $^{+28}_{-20}$ TW

to be compared with the global terrestrial power:

P_{tot} = 47±2 TW

Cosmochemical (rad. power ~ 10 TW, Th/U=3.5), geochemical (~ 20 TW, Th/U=3.9) and geodynamical (~ 30 TW) models are shown in the plot

What's next?

Unprecedented purity – further improved in phase II and now a good temperature stability already reached !!

Next steps (phase 2):

✔**To increase the precision on ^{7}Be (3%?), ^{8}B (10%?), and pp, pep-ν** fluxes =>
More stringent test of the profile of the P_{ee} survival probability =>
sub-leading effect in addition to MSW-LMA, new physics, NSI?

The hunt for CNO-ν flux is in progress….

…. towards an almost complete solar neutrino spectroscopy in one experiment!!!

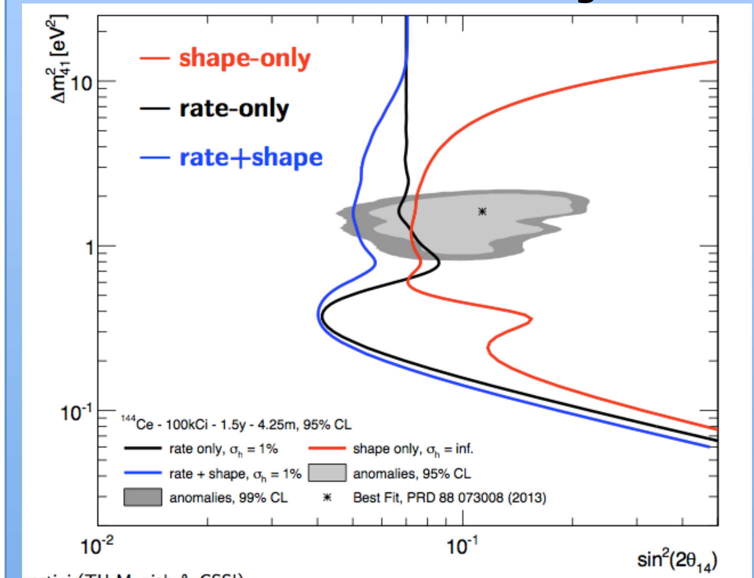
✔The increased statistics will help to **reduce the uncertainty on geo−ν signal** and to possibly select geological models and improve the knowledge of Earth energetics, also the limits on rare processes will be improved..

✔**New calibration campaigns are foreseen by the end of this years!**

✔Among the next exciting goals: measurements with artificial neutrino sources
⇒Search for sterile neutrinos => SOX project (start: 2017)

What's next?

Sox sensitivity



Giunti et al., PRD 88 073008 (2013)

Thanks!!!

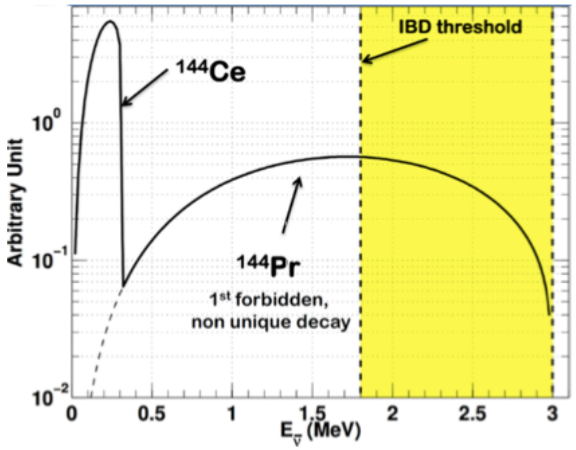
the Borexino Collaboration

INFN, Milano, München, Heidelberg, Hamburg, Mainz, Gran Sasso, Perugia, Genova, Napoli, TU Dresden, Jagiellonian Kraków, JINR Dubna, Virginia Tech, Princeton, Houston, Paris, Moscow, Los Angeles, UMass Amherst, St. Petersburg, Kurchatov Moscow

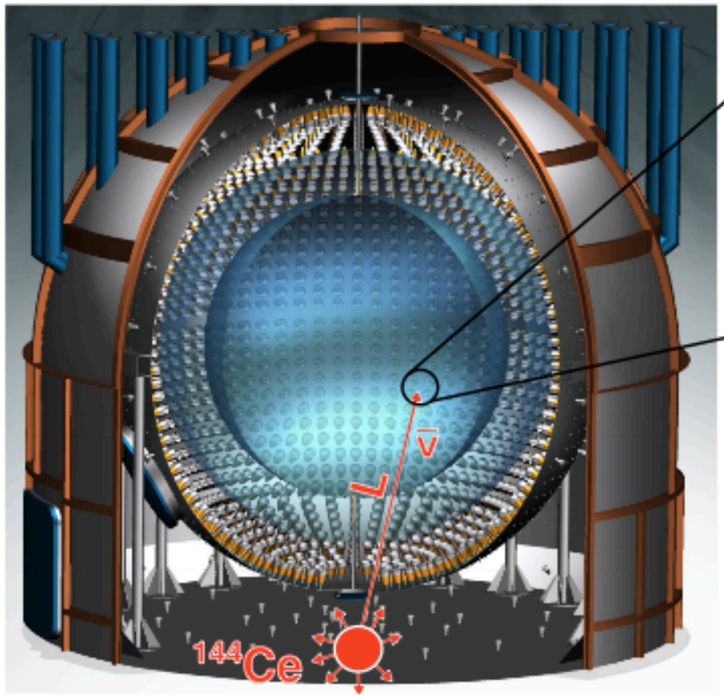
Backup

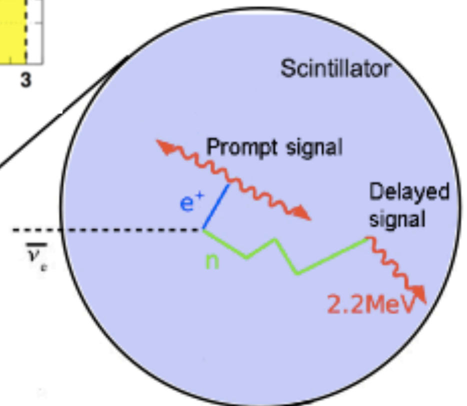
Ce-SOX project

- 100–150 kCi activity ($> 10^{15}\ \bar{\nu}_e/s$)
- β^- decay chain:
  $$^{144}Ce \rightarrow {}^{144}Pr + e^- + \bar{\nu}_e$$
  $$\searrow\ {}^{144}Nd + e^- + \bar{\nu}_e$$
- $T_{1/2}(^{144}Ce) = 285\,d$
- $T_{1/2}(^{144}Pr) = 17\,m$



Detection: Inverse beta decay on protons

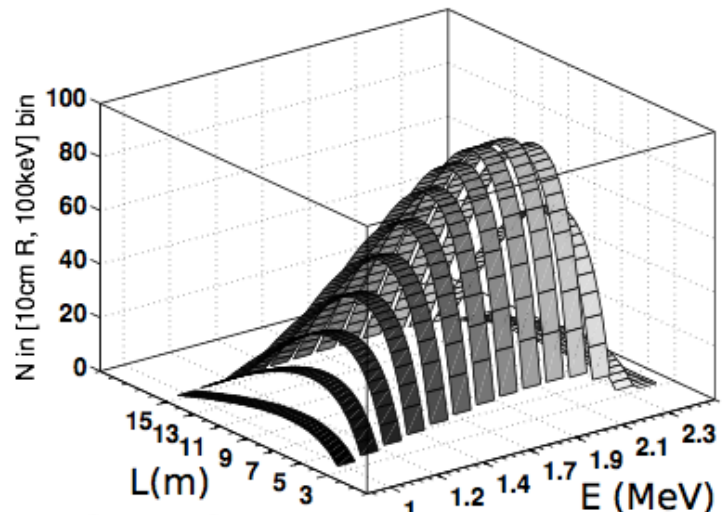




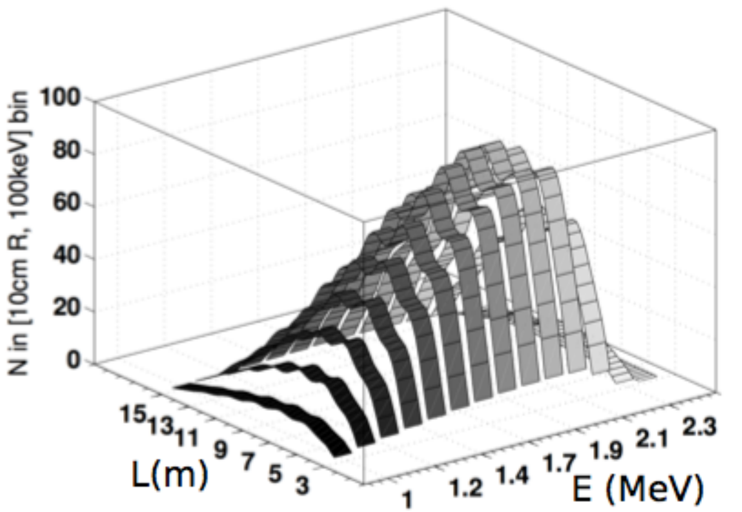
1) $\bar{\nu}_e$ interact via inverse beta decay: prompt e+/e– annihilation + delayed neutron absorption (2.2MeV)
2) scintillation photons detected by PMTs (energy and time-of-flight)
5% energy resolution – 10 cm spatial resolution (at 1 MeV)

Ce-SOX sensivity

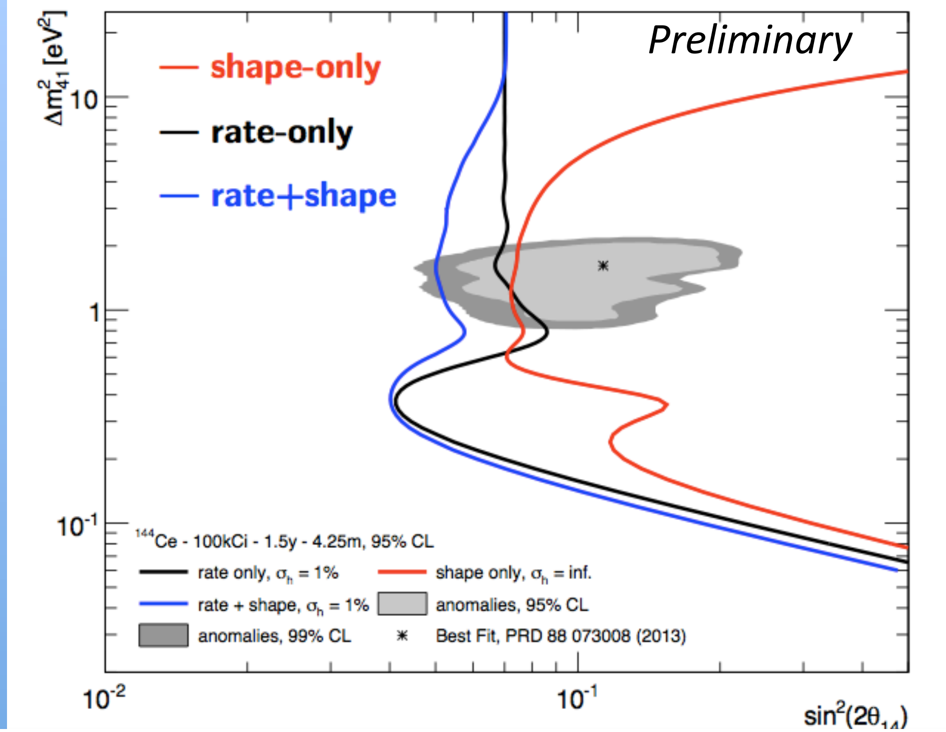
No oscillations



Δm^2_{41}=2 eV^2 → oscillations within detector



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



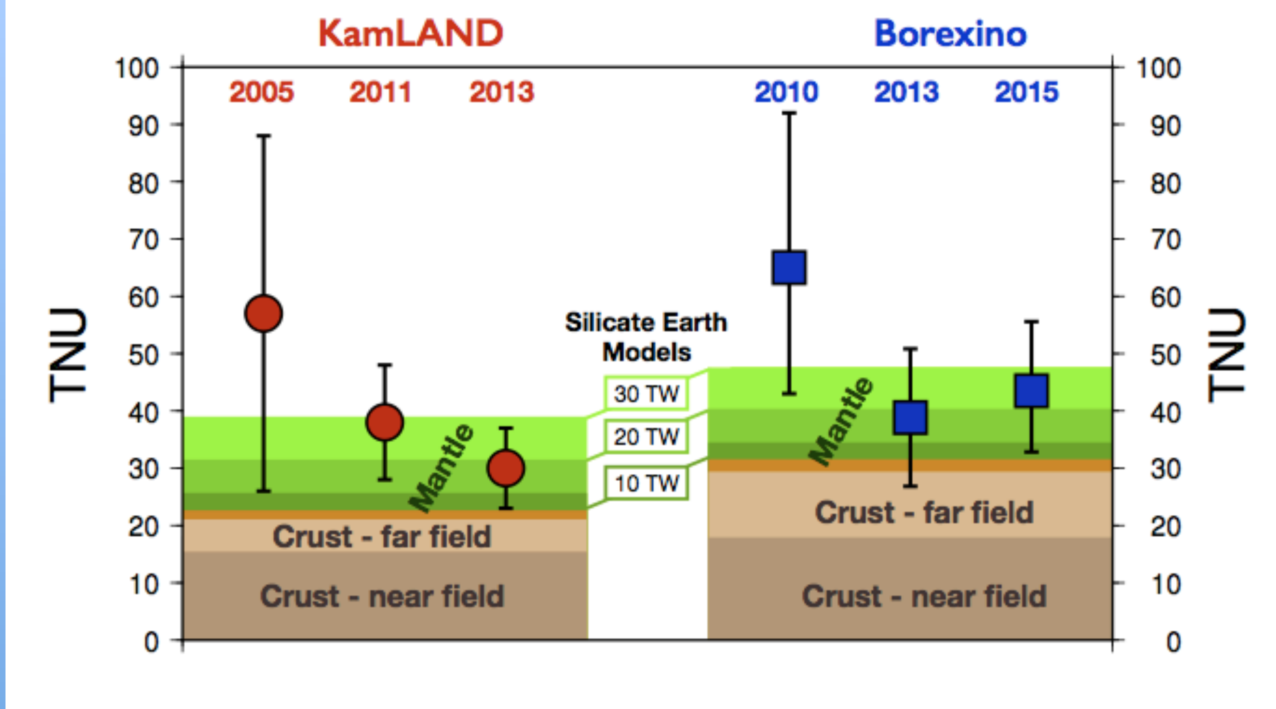
Rate analysis of $\bar{\nu}_e$ events:

- particularly sensitivity for Δm^2_{41} >eV^2
- needed accurate estimate of source activity

Shape analysis (oscillatory pattern):

- very robust for Δm^2_{41} ~eV^2
- smoking gun signature

Geo-ν : radiogenic heat



Borexino has measured geoneutrinos at **5.9σ**

- Signal-to-background ~ 100 for such a measurement in Borexino
- Geoneutrino fluxes are (chondritic scenario): – $\Phi(U) = (2.7\pm0.7)\times10^6\ cm^{-2}s^{-1}$
  – $\Phi(Th) = (2.3\pm0.6)\times10^6\ cm^{-2}s^{-1}$
- The null hypothesis for a non-zero signal from the mantle is excluded at 98% C.L.
- At present, the uncertainty in the relative abundance of U and Th is limited only by statistics
- Geoneutrino observations are providing direct measurements of radiogenic heat produced in the Earth