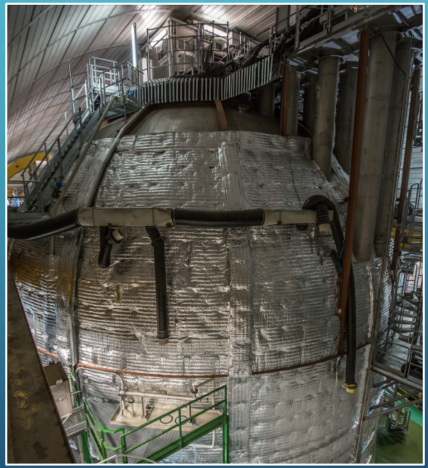
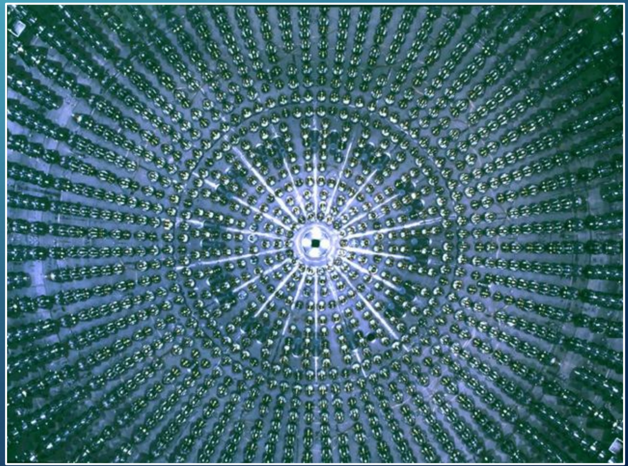
GEONEUTRINO DETECTION AND OTHER NON-SOLAR PHYSICS ACHIEVEMENTS OF BOREXINO

SANDRA ZAVATARELLI (INFN – SEZIONE DI GENOVA – ITALY)





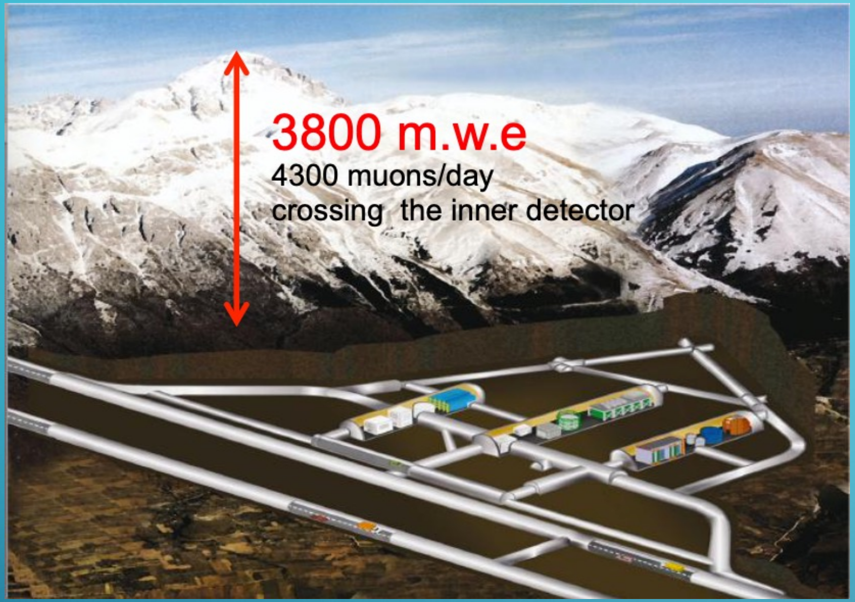
20th Lomonosov Conference, August 19-25 2021, Moscow State University

TALK LAYOUT

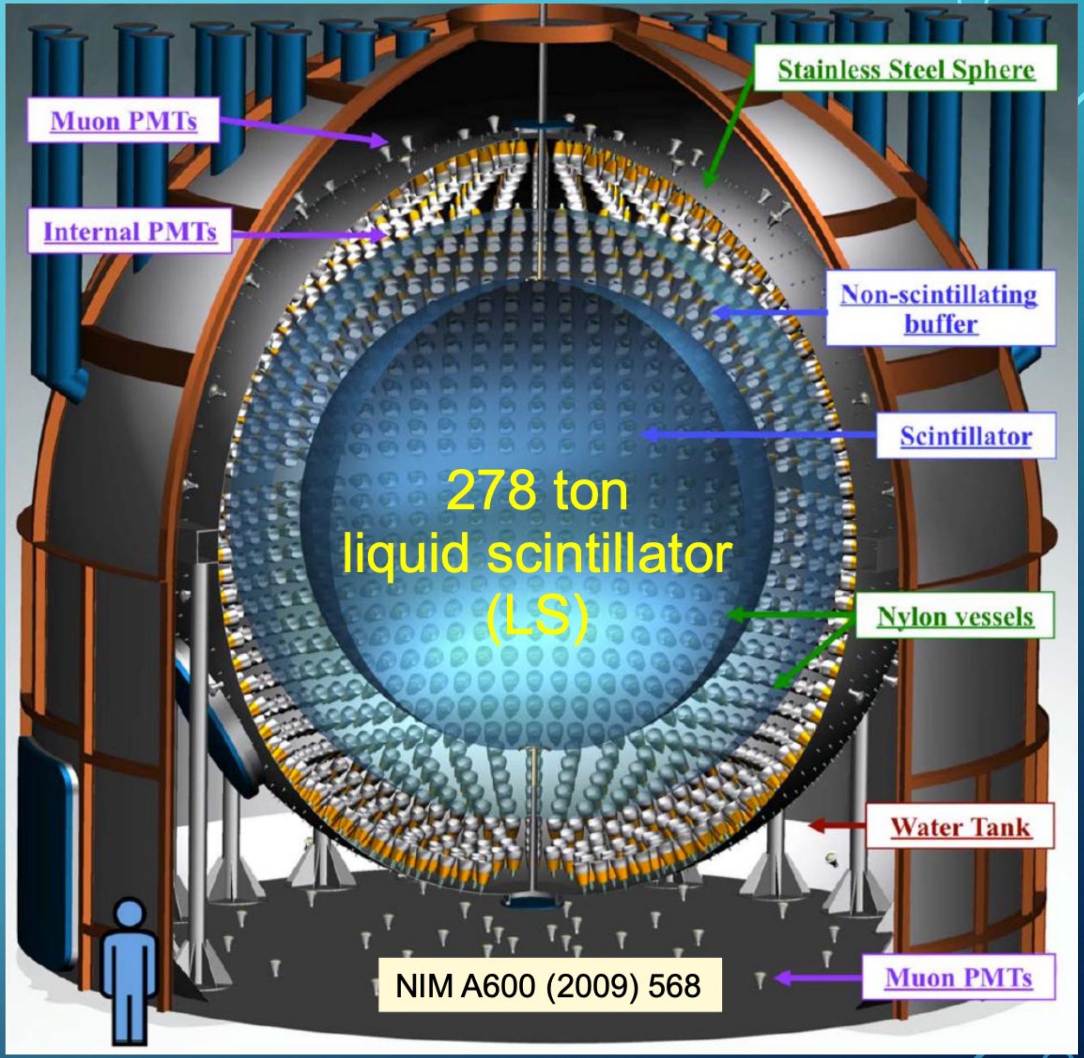
- The Borexino detector layout
- Antineutrinos detection techniques with liquid scintillators
- Borexino anti-ν studies:
  - Geoneutrinos
  - Diffuse supernovae neutrino background
  - Solar flares ν
- Perspectives

THE BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso (Italy)



- **the world's radio-purest LS detector:** $<5.7\times10^{-19}$ g(Th)/g LS,$<9.5\times10^{-20}$ g(U)/g LS at 95% C.L.
- **~500 p.e. / MeV**
- energy reconstruction: 5% @ 1 MeV
- position reconstruction: 10 cm @ 1 MeV
- pulse shape identification (α/β, e+/e-)



Operating since 2007

THE BOREXINO DETECTOR

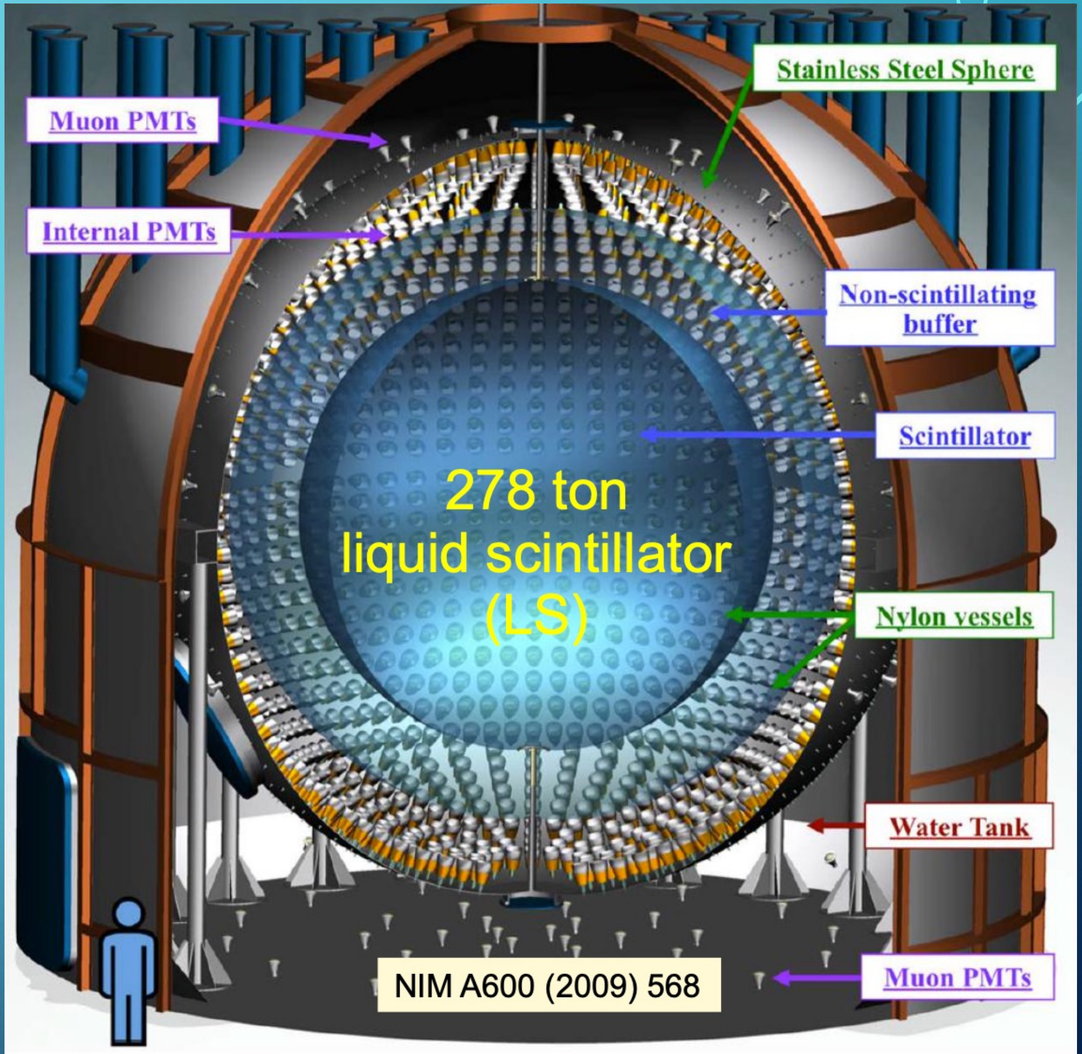
Laboratori Nazionali del Gran Sasso (Italy)

Main electronics (LABEN): developed for solar ν physics

- 14 racks/158 channels: the front-end (FE) electronic generates two signals, i.e. the timing and charge information of the PMT pulse. The charge integrated ~ 80 ns, followed by a 60 ns dead time for writing.
- Good linearity up to few MeV

FADC system

- For higher energies, up to ~ 50 MeV, a system was developed consisting of 96 fast waveform digitizers (CAEN v896, 8 bit, FADC - Flash ADC), each of them reading-in the signal summed from up to 24 PMTs, with the sampling rate of 400 MHz.



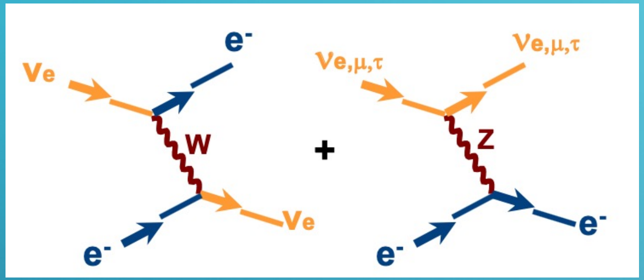
Operating since 2007

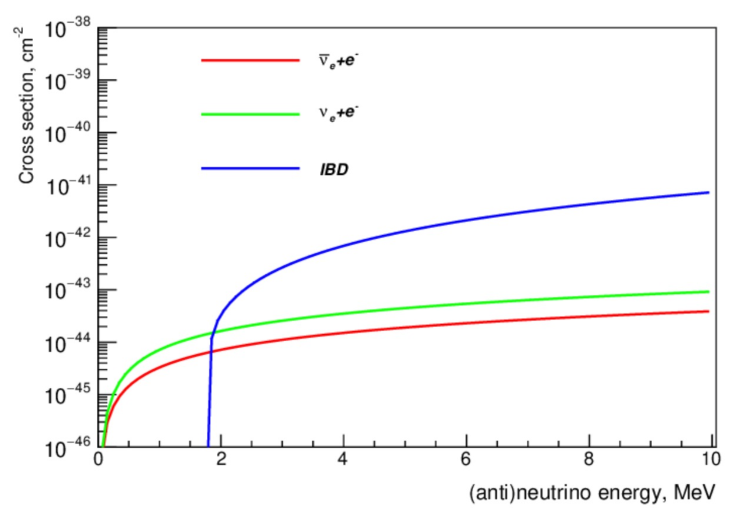
MEV ANTI-NEUTRINO DETECTION WITH LIQUID SCINTILLATORS

Elastic scattering on electrons

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

Single events, no threshold, all flavours

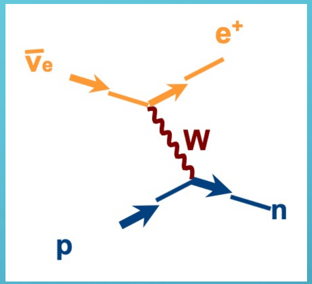




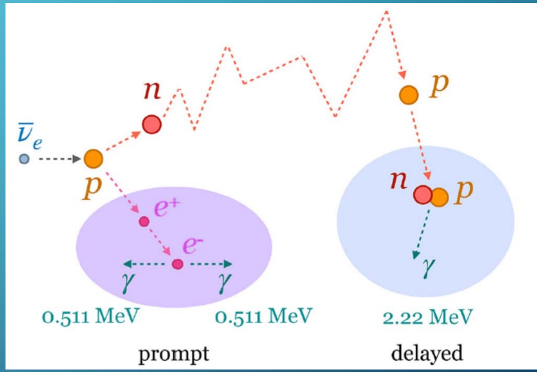
Inverse beta decay

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

Charge current, electron flavour only



Delayed coincidence → clean signature!



Energy threshold = 1.8 MeV
$\tau \sim 255\ \mu s$

$E_{prompt} = E_{visible}$
$\sim T_{e+} + 2 \cdot 511$ keV
$\sim E_{antinu} - 0.784$ MeV

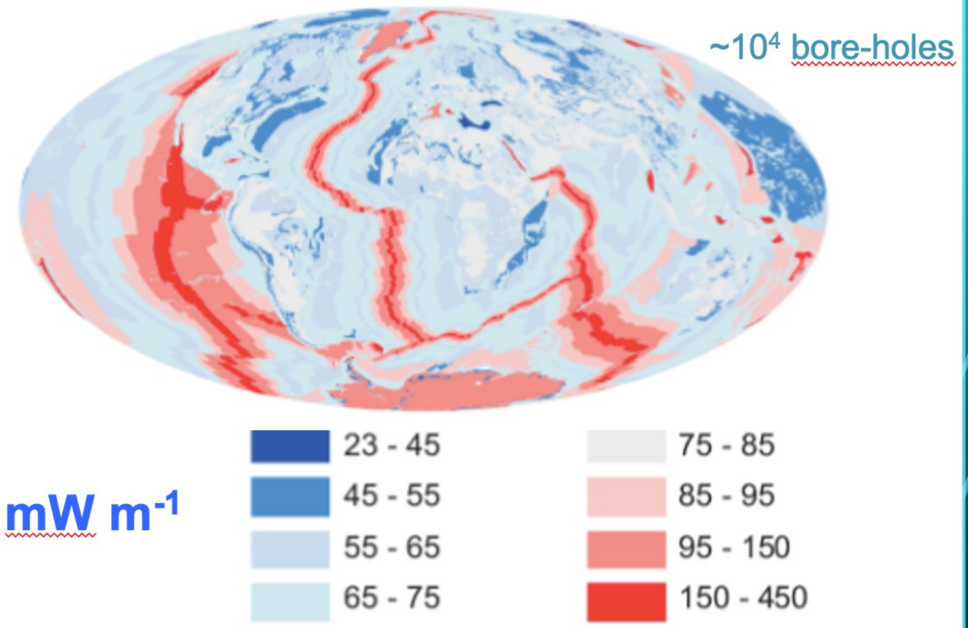
σ_{IBD} at few MeV: $\sim 10^{-42}$ cm^2 (~100 x more than scattering)

GEO-NEUTRINOS AS PROBES FOR DEEP EARTH

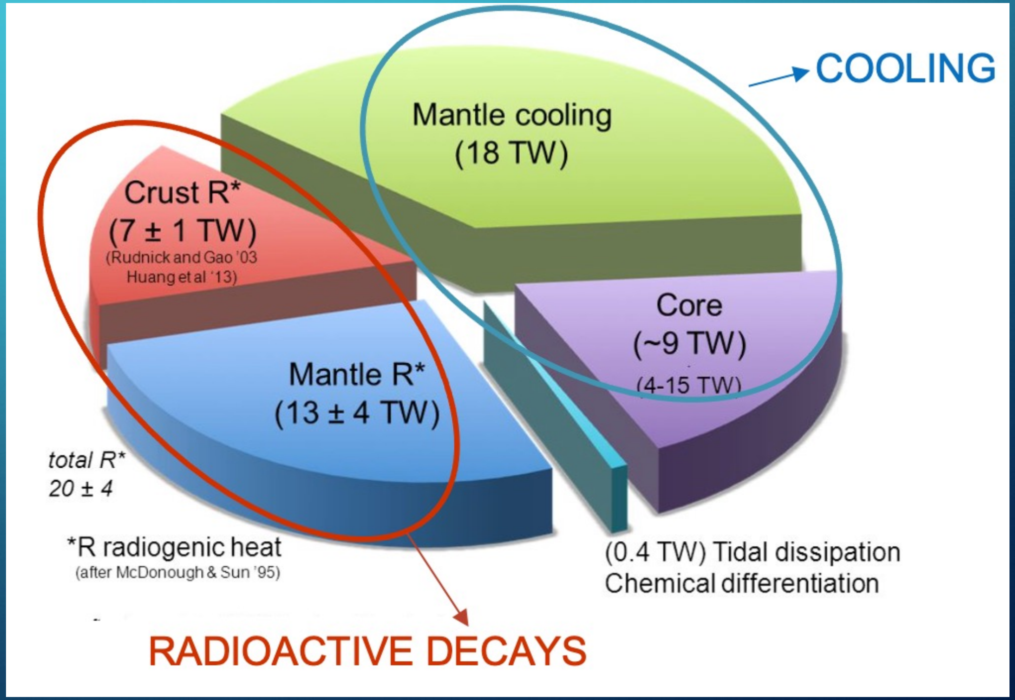
- Geoneutrinos are the most abundant component of anti-ν flux at Earth

EARTH'S ENERGETICS

Earth's surface heat flow : 47 ± 2 TW



Sources: unclear picture…



GEO-NEUTRINOS AS PROBES FOR DEEP EARTH

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

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

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

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

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

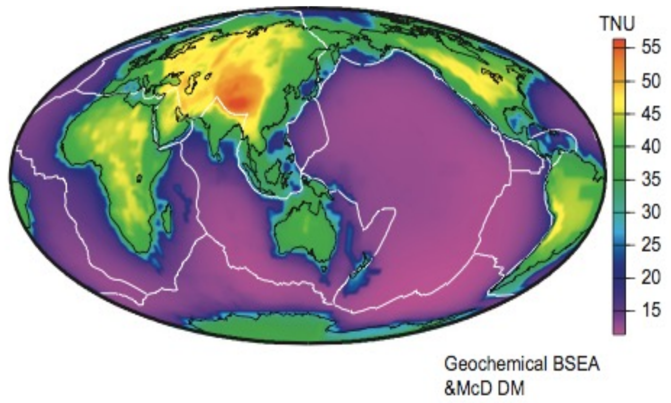
Heat Producing Elements

HPE's

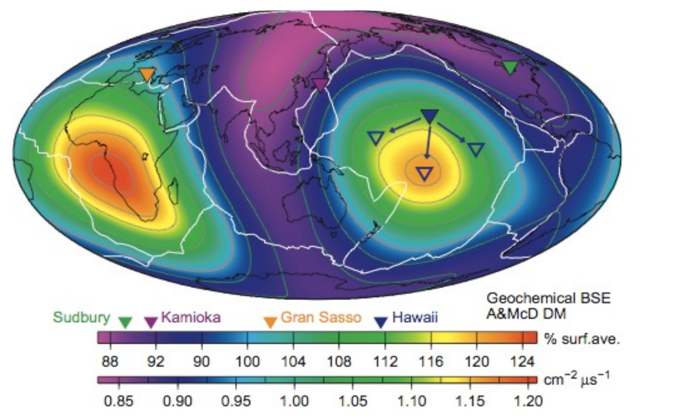
The Earth shines in anti-ν ($\Phi_\nu \sim 10^6$ cm^{-2} s^{-1})

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

Crust + mantle geo-ν signal (U+Th)



Mantle geo-ν signal in the TOMO model

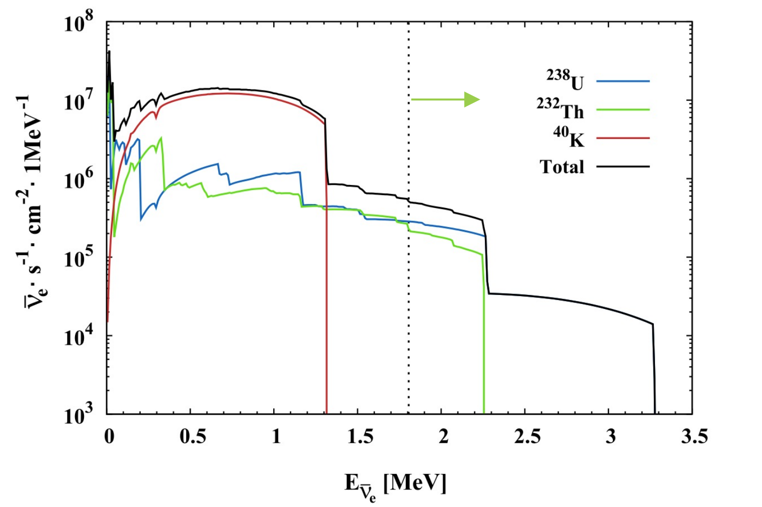


Fluxes not homogeneous => needs for multi-site measurements!!

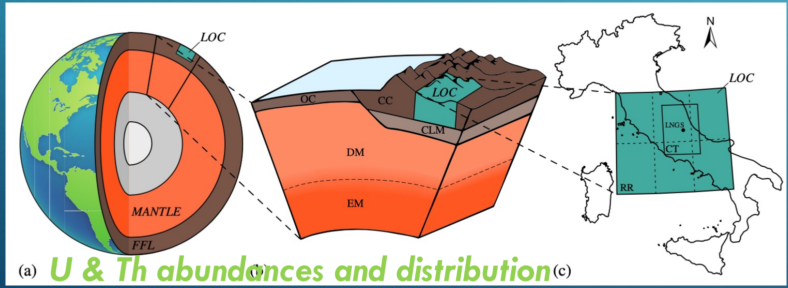
EXPECTED SIGNAL AT GRAN SASSO

Ingredients:

1) Geo-neutrino energy spectra



2) Local and global geological informations

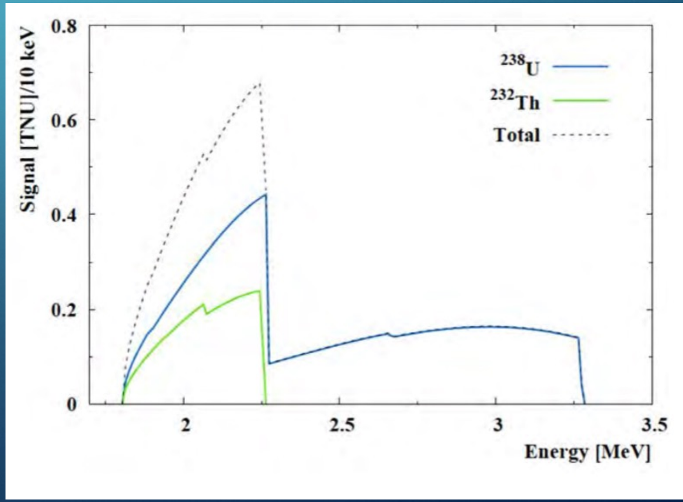


3) Propagation effects (oscillations..): $P_{ee} \sim 0.5$ +interaction cross sections

Expected signal at Gran Sasso

1 TNU (Terrestrial Neutrino Unit) = 1 event/ 10^{32} target protons (~1kton LS)/ year (100% eff.)

	S (U+Th) TNU	S(U)/S(Th)
Local Crust (R~500 km)	9.2 ± 1.2	0.24
Far Field Lithosphere	$16.7^{+3.8}_{-3.1}$	0.29
Mantle (from Bulk silicate Earth model – lithosphere)	2.5 – 19.6	0.26
Total	28.4 - 45.5	0.27 (chondritic)



^{40}K signal below threshold

IBD SELECTION CUTS : 154 GOLDEN CANDIDATES

M. Agostini et al PRD 101(2020) 012009

- December 9, 2007 to April 28, 2019 : 3262.74 days of data taking
- Average FV = (245.8 ± 8.7) ton , **Exposure = (1.29 ± 0.05) x 10^{32} proton x year**
- Including systematics on position reconstruction and muon veto loss, for 100% detection eff

Exposure : a factor 2 increase respect to 2015 analysis

Charge of prompt

Q_p > 408 pe

- Prompt spectrum starts at 1 MeV
- 5% energy resolution @ 1 MeV

Charge of delayed

Q_d > 700 (860) – 3000 pe

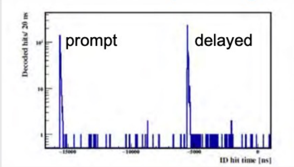
- Neutron captures on proton (2.2 MeV) and in about 1% of cases on ^{12}C (4.95 MeV)
- Spill out effect at the nylon inner vessel border
- Radon correlated $^{214}Po(\alpha+\gamma)$ decays from ^{214}Bi and ^{214}Po fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

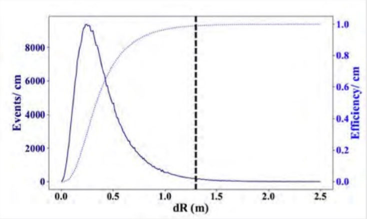
Neutron capture $\tau = (254.5 \pm 1.8)$ μs

2 cluster event in 16 μs DAQ gate



Space correlation

dR < 1.3 m

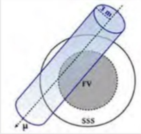


Muon veto

2s || 1.6 s : $^9Li(\beta + n)$

2 ms: neutrons

- Several veto categories
- Strict and special muon tags



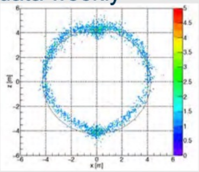
- Whole detector
- **Cylinder**

Only 2.2% exposure loss

Dynamic Fiducial Volume

> 10 cm from IV (prompt)

- Exposure vs accidental bgr
- IV has a leak: shape reco from the data weekly



Multiplicity

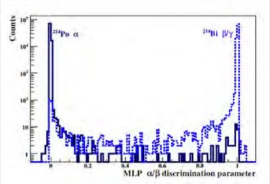
No event with Q >400 pe ±2 ms around promt/delayed

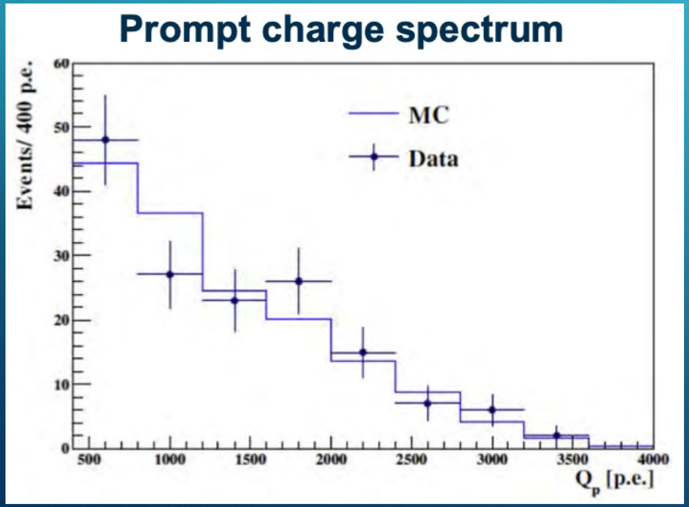
- Suppressing undetected cosmogenic background, mostly multiple neutrons
- Negligible exposure loss

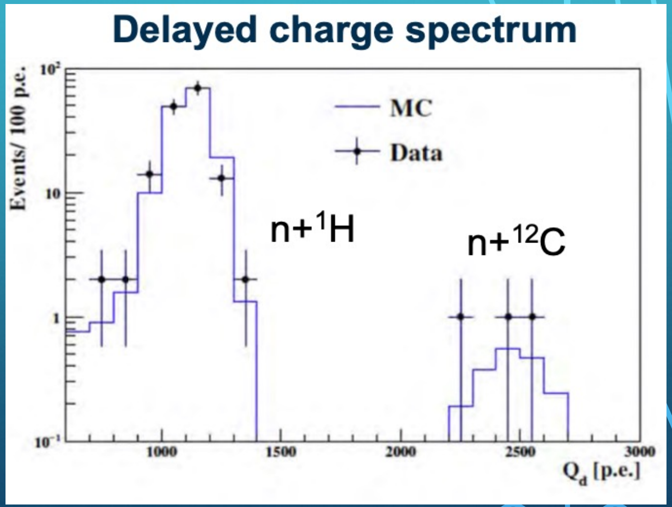
α/β discrimination

$MLP_{delayed}$ > 0.8

- Radon correlated $^{214}Po(\alpha+\gamma)$





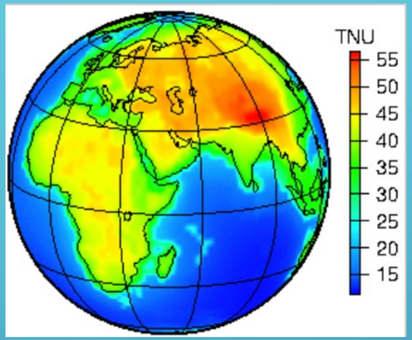


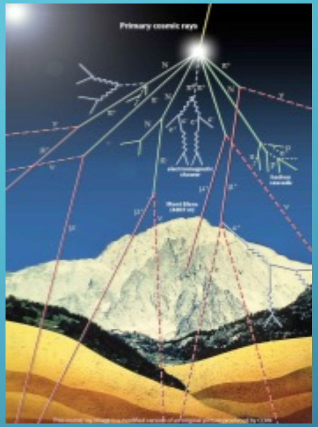
SOURCES OF BACKGROUNDS

We need to estimate different contributions and then to extract the number of measured geo-neutrinos by fitting the E_{prompt} energy spectrum;

Antineutrino backgrounds:

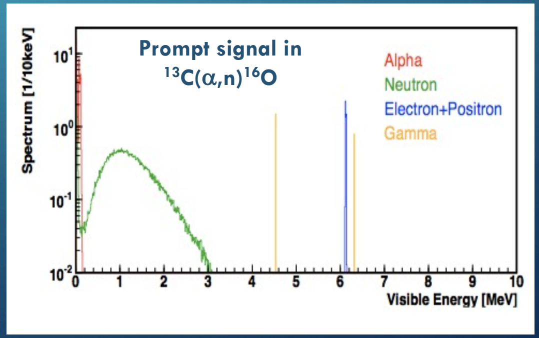
(a) Reactor antineutrinos
(b) Atmospheric neutrinos

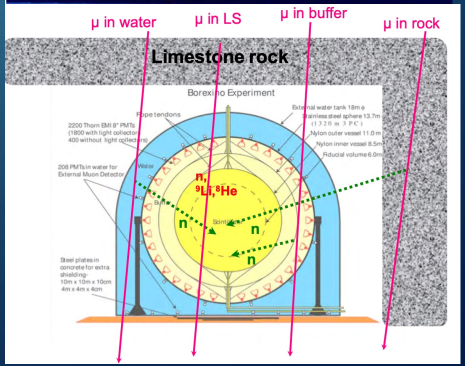




Backgrounds mimicking inverse beta decay reaction:

(a) Cosmogenic nuclides
(b) (α,n) reactions
(c) Accidental coincidences





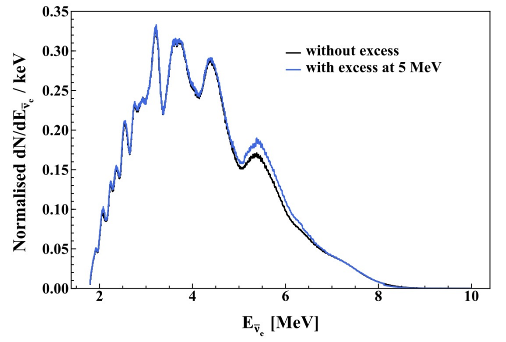
BACKGROUNDS

Antineutrino backgrounds

Expected signal at LNGS evaluated with dedicated codes

Reactor antineutineutrinos

	Mueller et al 2011	With "5 MeV bump"
Signal [TNU]	$84.5^{+1.5}_{-1.4}$	$79.6^{+1.4}_{-1.3}$
# Events	$97.6^{+1.7}_{-1.6}$	$91.9^{+1.6}_{-1.5}$



- *For all ~440 world reactors (1.2 TW total power): info on thermal powers, laod factors.. from IAEA and PRIS databases*
- *Propagation effects included*
- *Interaction cross section*
- *Detection efficiency = 0.8955 ± 0.0150*

Atmospheric neutrinos

Energy window	> 1 MeV (Q>408 p.e)
Events	9.2 ± 4.6

- Atmospheric neutrino fluxes from HKKM2014 (>100 MeV) and FLUKA (<100 MeV)
- Matter effects included, Simulation of detector response + selection cuts as for real data

Non antineutrino backgrounds

Background type	No. of events
^{9}Li background	3.6 ± 1.0
Untagged muons	0.023 ± 0.007
Fast n's (from rock)	<0.013
Fast n's (from WT)	<1.43
Accidental coincidences	3.846 ± 0.01
(α, n) in scintillator	0.81 ± 0.13
(α, n) in buffer	<2.6
(γ, n)	<0.34
Fission in PMTs	<0.057
^{214}Bi-^{214}Po	0.003 ± 0.001
TOTAL	**8.28 ± 1.01**

- **Accidental coincidences;**

Estimated from OFF-time coincidences: IBD-like events in Δt = 2 -20 s

- **(α, n) reactions: ^{13}C(a, n)^{16}O**

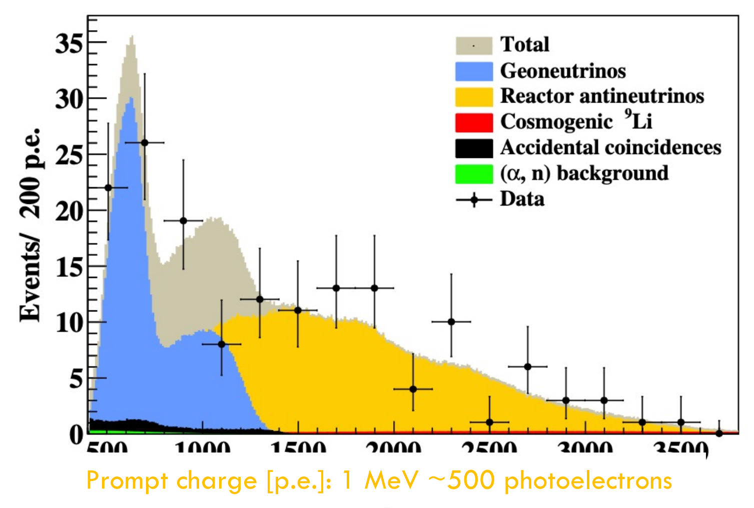
Prompt: scattered proton, ^{12}C(4.4 MeV) & ^{16}O (6.1 MeV)

Estimated from ^{210}Po(α) and ^{13}C contaminations, cross section.

- **Cosmogenic background**
  - **^{9}Li and ^{8}He** ($t_{1/2}$ = 119/178 ms) decay: β(prompt) + n (delayed);
  - **fast neutrons** Prompt :unscattered protons (prompt)

Estimated by studying coincidences detected AFTER muons.

GEO-NEUTRINO SIGNAL : SPECTRAL FIT OF E_{PROMPT}



Unbinned likelihood fit of charge spectrum of 154 prompts

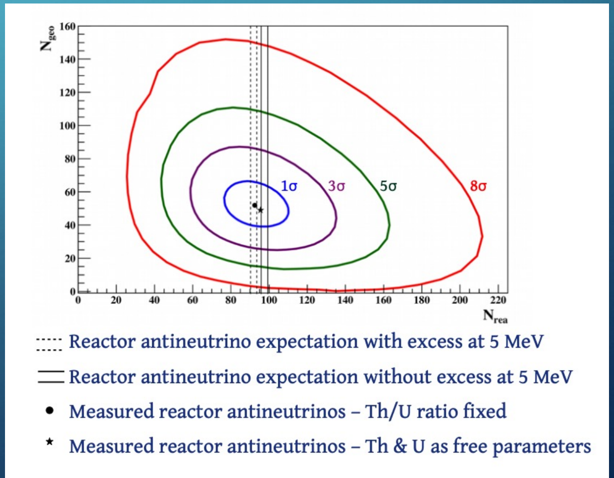
- Fixed: S(Th)/S(U) = 0.27 corresponding to chondritic Th/U mass ratio of 3.9
- ^{9}Li, accidentals, and (α, n) bgr constrained according to expectations
- Reactor signal unconstrained and result compatible with expectations

$$N_{geo} = \begin{array}{l} 52.6^{+9.4}_{-8.6}(stat)^{+2.7}_{-2.1}(sys)\,events \\ 47.0^{+8,4}_{-7.7}(stat)^{+2,4}_{-1.9}(sys)\,TNU \end{array}$$

$^{+18.3}_{-17.2}$% total precision

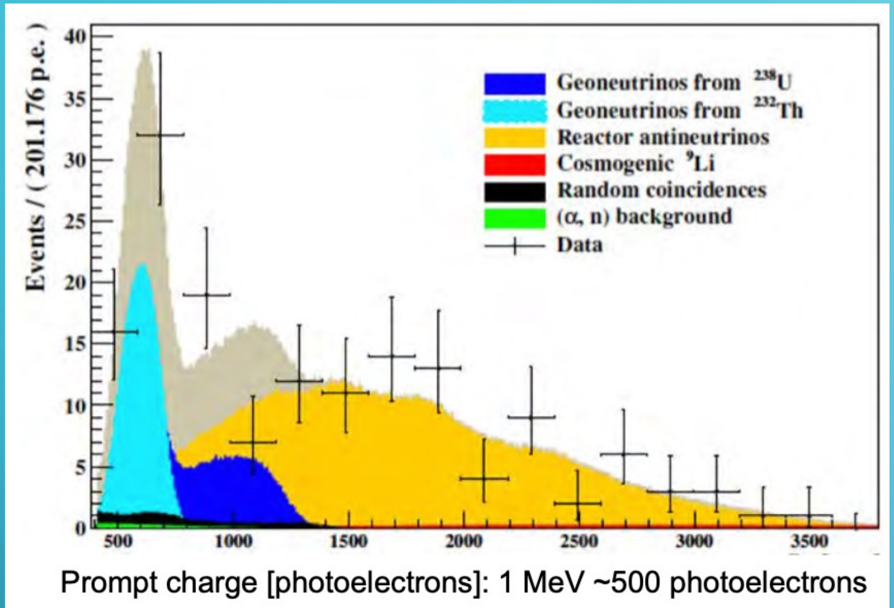
Systematic uncertainties

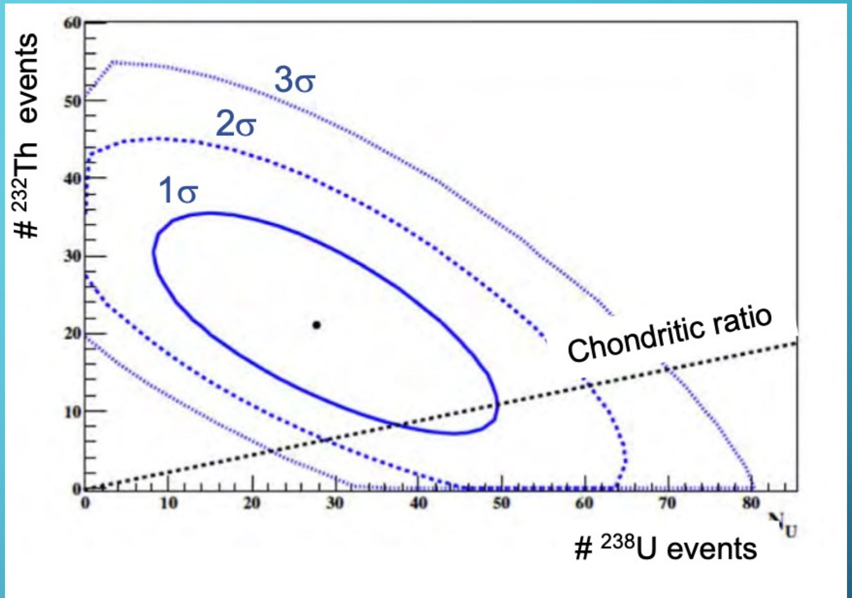
Source	Geo error [%]
Atmospheric neutrinos	$^{+0.00}_{-0.38}$
Shape of reactor spectrum	$^{+0.00}_{-0.57}$
Vessel shape	$^{+3.46}_{-0.00}$
Efficiency	1.5
Position reconstruction	3.6
Total	$^{+5.2}_{-4.0}$



$N_{rea} = 93.4^{+11.3}_{-10.4}$

TH/U RATIO





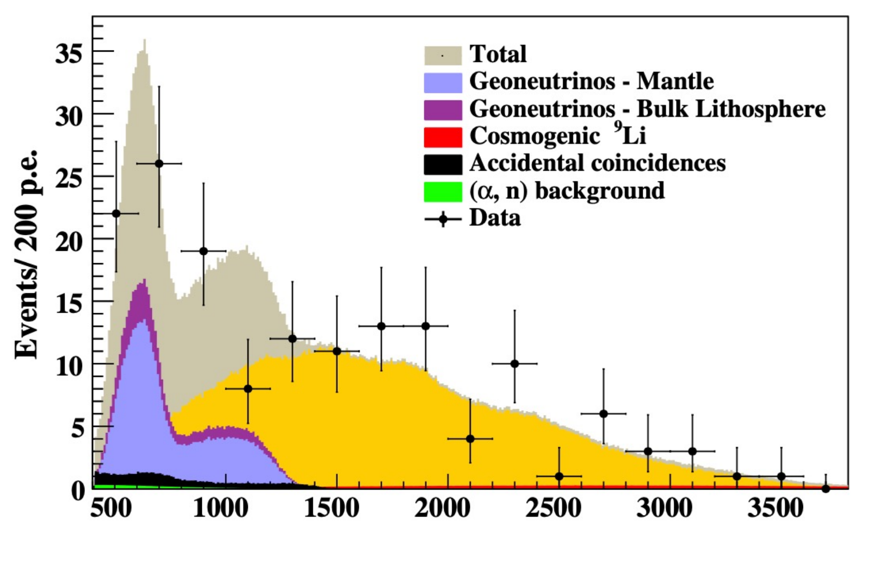
SPECTRAL FIT with Th and U fit independently :

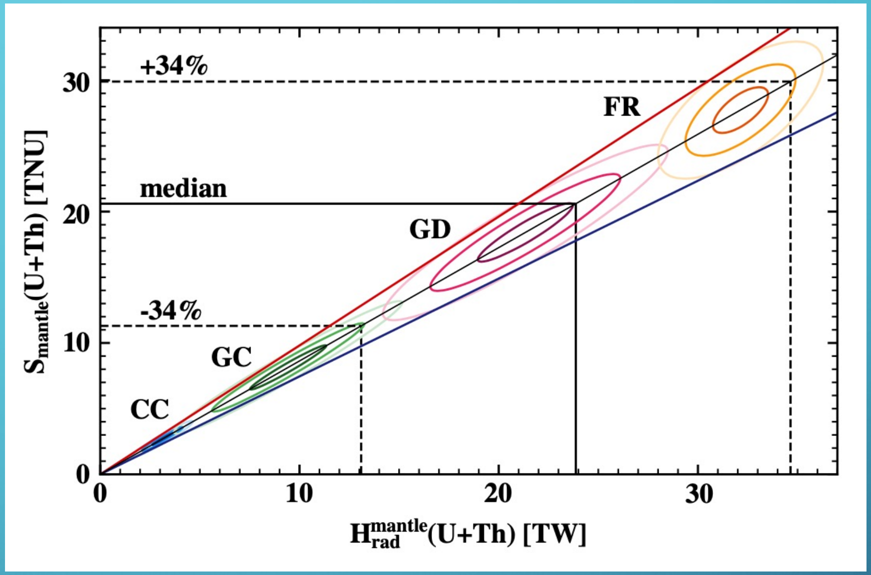
50.4 events $^{+46.8}_{-44.05}$% total precision

In agreement with the fit with Th/U fixed

From MC studies: no sensitivity to measure the Th/U ratio with the present statistics

GEO-NEUTRINO SIGNAL FROM THE MANTLE





Constraining the contribution from the **bulk lithosphere** (28.8 ± 5.6 events with S(Th)/S(U) = 0.29), the **extracted**

S_{Mantle} (U+Th) = 21.2 $^{+9.5}_{-9.0}$ (Stat) $^{+1.1}_{-0.9}$ (Sys) TNU

Sensitivity study using log-likelihood ratio method: Null mantle signal hypothesis rejected with 99.0% C.L.

Mantle radiogenic heat from U+Th:

H_{mantle} (U+Th) = 24.6 $^{+11.1}_{-10.4}$ *TW*

Compatible with predictions, in tension at 2.4σ with the CosmoChemical models (CC)

Bulk Silicate Earth's Models

Cosmochemical (CC)
based on the enstatine chondrites

Geochemical (GC)
based on mantle samples compared with carbonaceous chondrites

Geodinamical (GD)
based on balancing mantle viscosity and heat dissipation

FR =Full radiogenic

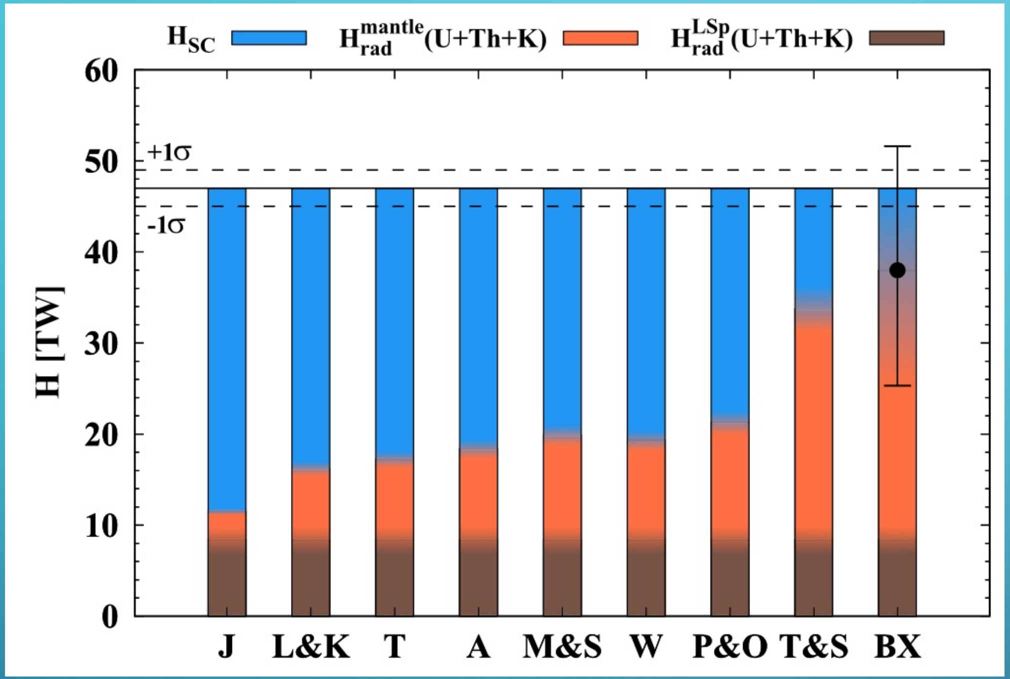
EARTH RADIOGENIC HEAT

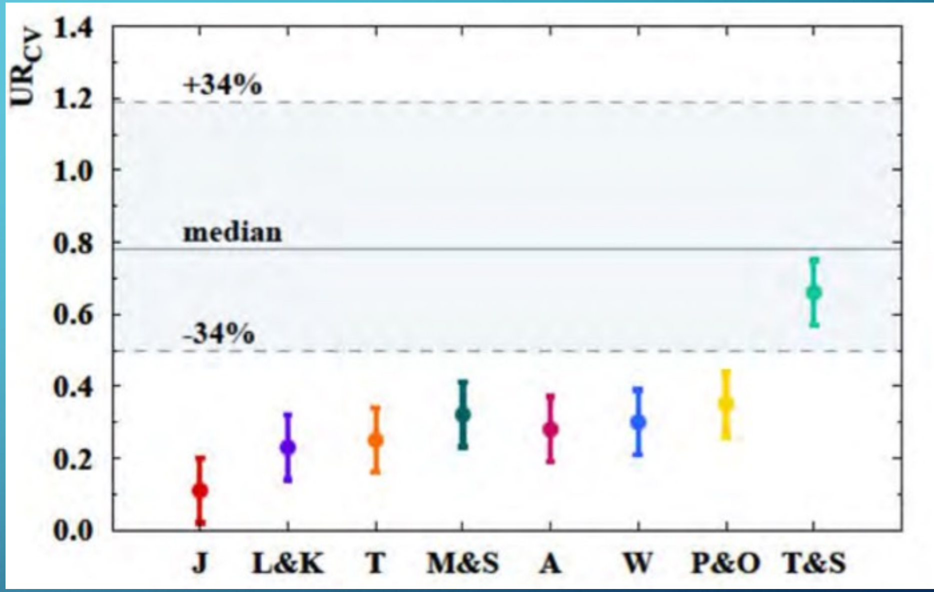
Reminder: H_{tot} =(47± 2)TW

$$UR_{CV} = \frac{H_{rad} - H_{rad}^{CC}}{H_{tot} - H_{rad}^{CC}}$$

CC = continental crust

J = M. Javoy et al., EPSL 293, (2010).
L&K = T. Lyubetskaya and J. Korenaga, J. Geoph. Res. Sol. Earth, 112 (2007)
T = S. Taylor, Proc. Lunar Planet. Sci. Conf. 11, 333 (1980)
M&S = W. F. McDonough and S. Sun, Chem. Geol. 120, (1995)
A = D. L. Anderson, Cambridge University Press, (2007)
W = H. S. Wang et al., Icarus 299, (2018)
P&O = H. Palme and H. O'Neill, Treatise of Geochemistry, (2003)
T&S = D. L. Turcotte and G. Schubert, Cambridge University Press, (2002)





assuming 18% ^{40}K mantle contribution + contribution of lithosphere

H(U+Th+K) = $38.2^{+13.6}_{-12.7}\,TW$

Convective Urey ratio:

$UR_{cv} = 0.78\ ^{+0.41}\ _{-0.28}$

At 90% C.L., mantle characteristics:

a(Th) >48 ppb & a(U) >13ppb URcv >0.13

Borexino estimates a high probability that the radioactive decays produce more than half of the total Earth's heat.


SN remnant by HST

ANTINEUTRINOS FROM COSMOS

Several possible sources:

- Diffuse supernovae neutrino background(*)
- Solar flares(*)
- GW events(**) and Gamma Ray Bursts(***)
- …

**M. Agostini et al., Astroparticle Physics 125 (2021) 102509*

***M. Agostini et al. Astroparticle Physics 86, (2017) 1-17*

****M. Agostini et al, The Astrophysical Journal (ApJ), 850-21, Nov. 2017*

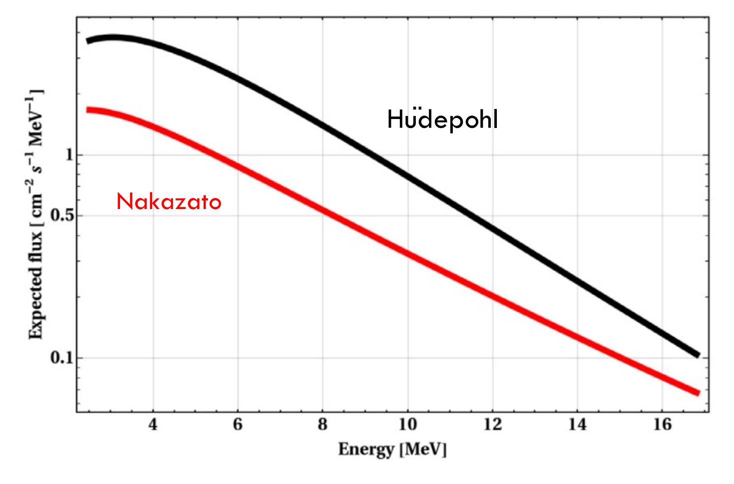
DIFFUSE SUPERNOVAE NEUTRINO BACKGROUND (DSNB)

The Diffuse Supernova Neutrino Background is formed by the whole of the star collapsing during the evolution of the Universe and consists of neutrinos and antineutrinos of all flavors.

- RSN : supernova rate at a distance z ;
- Ω_m and Ω_Λ : relative densities of matter and dark energy
- No unique model.

Small flux → Large underground detectors particularly suited !!

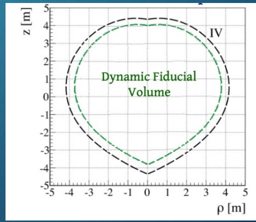
$$\frac{d\phi_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{max}} \frac{dN_\nu(E'_\nu)}{dE'_\nu} \frac{R_{SN}(z)dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$



Detection channel : inverse beta decay (IBD)

Analysis cuts : similar to geo-ν analysis, but:

- Smaller statistics sample : Dec 2007-Oct2017
- Smaller FV : D_{prompt} from IV > 0.25 m
- Stronger cosmogenic cut :
  - 2 s veto after ID muon
  - 2 ms veto after OD muon

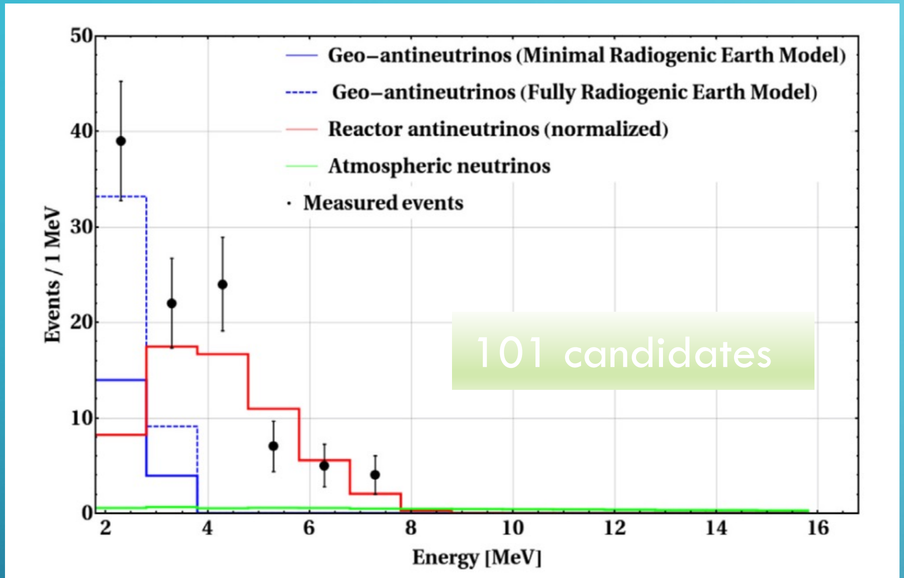


Conservative limits on DSNB: the minimal expected number of events considered:

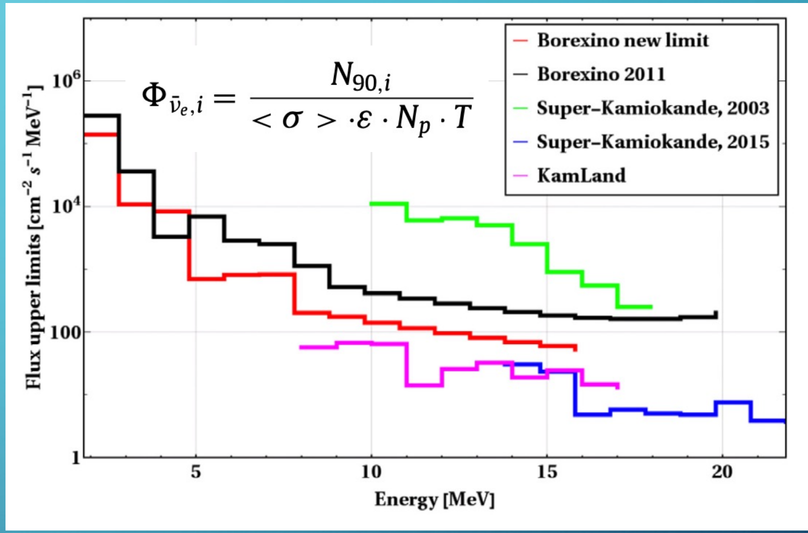
- **Minimal Radiogenic Earth model for geo-ν:** only radioactivity from the crust
- **Normalization to DayBay spectra for reactor-ν** since it gives the lower signal

DSNB: UPPER LIMITS

Data sample : Nov 2007- Oct 2017
Statistics : 2485 days (6.8 years)
Exposure : 1494 ± 6 tons year
$N_{protons}$=(1.32 ± 0.06) 10^{31}
Efficiency =85.0 ± 0.15 %



Model independent limits



Background source	Expected events
Reactor $\bar{\nu}_e$	61.1 ± 1.7
Geo $\bar{\nu}_e$	17.9 ± 2.1
Atmospheric neutrinos	6.5 ± 3.2
Accidental coincidences	0.418 ± 0.006
Total:	85.9 ± 4.2

- Best limits below 8 MeV

Model dependent limits

	Nakazato	90% C.L.	Hüdepohl
E[MeV]	$\Phi[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$		$\Phi[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$
2.8–16.8	$< 2.4\ (1.7) \times 10^3$		$< 2.6\ (1.8) \times 10^3$
7.8–16.8	$< 106.0\ (38.2)$		$< 112.3\ (40.5)$

KamLAND (8.3-31.8 MeV): $\Phi < 139$ cm^{-2} s^{-1} *(A. Gando 2012)*
Super-K (> 17.3 MeV): $\Phi < 2.9$ cm^{-2} s^{-1} *(K. Bays 2012)*

SOLAR FLARES

- Flares are caused by the restructuring of the solar magnetic field which leads to acceleration of protons.
- Neutrinos could be generated in the decays of pions which are numerously produced in pp-, pα-collisions in the flare's region.
- The mean neutrino energy is expected to be around 10 MeV

- R. Davis attempted to explain an excess of neutrino events in several Homestake runs by means of solar flares.
- Studied by Kamiokande-II, LSD, SNO.

- Flares selection:
  - GOES database
  - M and X classes flares (most intensive)
  - 798 flares selected from December 2009 to October 2017, 472 with >95% data coverage

- Both main DAQ and FADC system data => 1-15 MeV energy range & whole IV for FADC, 0.25-15 MeV and FV=145 tons for main DAQ (FV cut: 75 cm);

- Strategy: search for excess of single events over background at a time of the flare

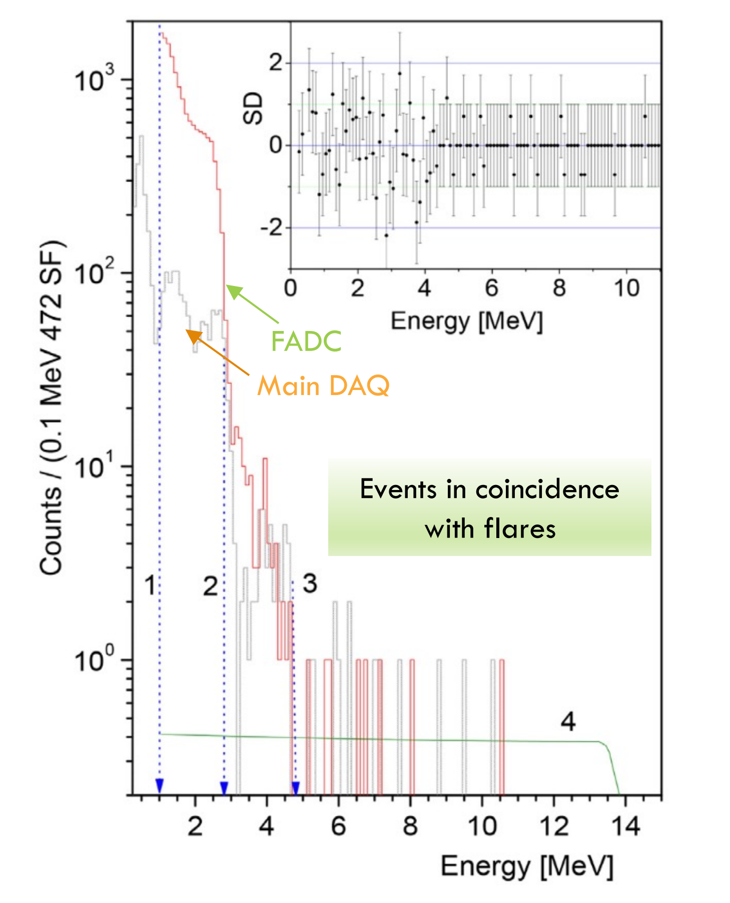
BX analysis: search for excess of single events from ν_x and $\overline{\nu}_x$ ($x = e,\mu,\tau$) over background at he time of the flare by looking for their **elastic scattering** on electrons in the Borexino scintillator

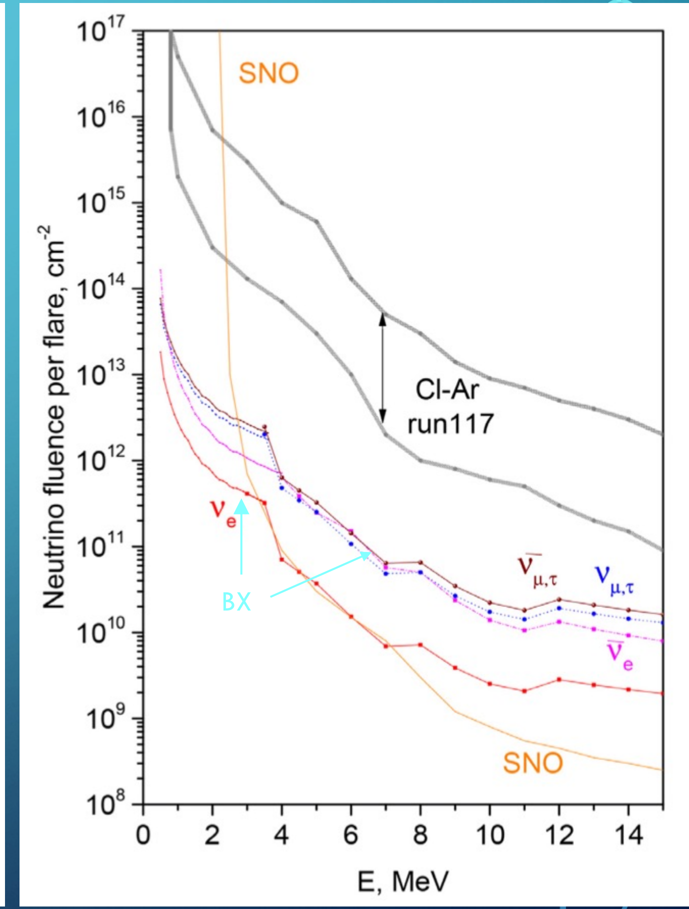
SOLAR FLARES : LIMITS ON NEUTRINO FLUENCES

M. Agostini et al., Astroparticle Physics 125 (2021) 102509

$$\Phi_\nu(E_\nu) = \frac{N_{90}(E_\nu)}{N_e \sigma_{\text{eff}}(E_\nu)}$$

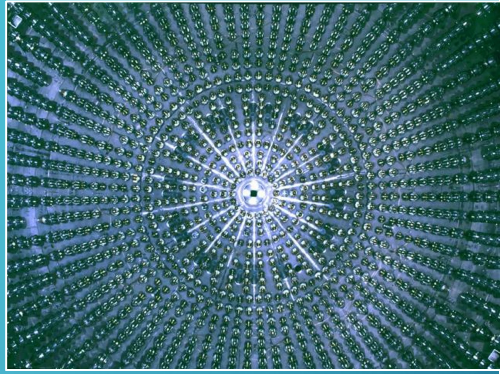
$N_e = 9.2\times10^{31}$ for the whole IV and $N_e = 4.8\times10^{31}$ for the 145 tons FV





- Limits obtained from the primary DAQ (E_ν < 3.5 MeV) and the FADC DAQ (E_ν > 3.5 MeV).
- Strongest limits on fluences of all neutrino flavors from the solar flares below 3–7 MeV
- Borexino's data excludes an intense solar flare occurred during run 117 of the Cl-Ar Homestake experiment as a possible source of the observed excess of events.

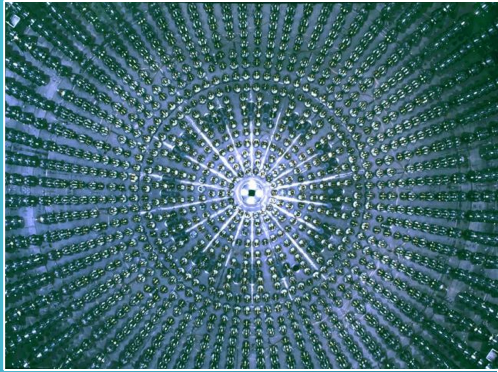
CONCLUSIONS



- Thanks to the extreme radiopurity and the underground site Borexino has an exceptional sensitivity to anti-ν signals
- Borexino updated the geoneutrino measurement with all available data up to April 2019 with optimized selection cuts & analysis
  - Null mantle signal excluded at 99.0% C.L.
  - Estimates of mantle radiogenic heat and Urey convective ratio
  - Signal in agreement with geological predictions, with a preference for models predicting high U and Th abundances

- Borexino has achieved the best upper limits on DSNB anti-ν_e flux for $E_\nu < 8$ MeV;
- No excess of events was observed in coincidence with solar flares, GRB's and GW events;

All results will be updated at the end of data taking (Sep. 21)

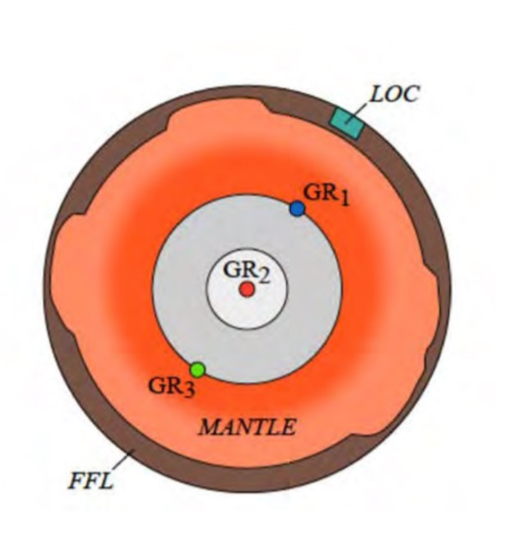


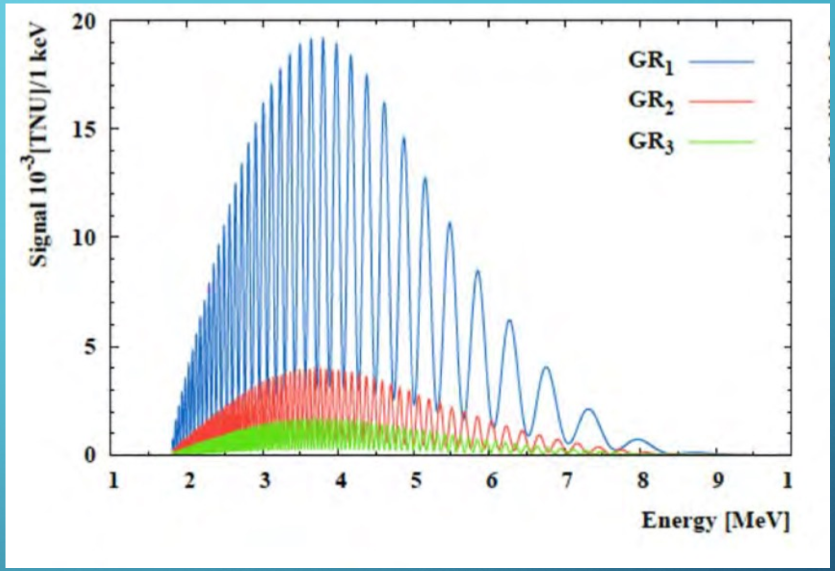
Thanks
for your
attention!!!!

BACKUP

GEOREACTOR

Hypothetical fission of Uranium deep in the Earth
235U : 238U = 0.76 : 0.23 (Herndon)





No sensitivity to oscillation pattern

Fit with reactor spectrum constrained

Upper limit (95% CL): 18.7 TNU
- 2.4 TW in the Earth's center
- 0.5 TW near CMB at 2900 km
- 5.7 TW far CMB at 9842 km