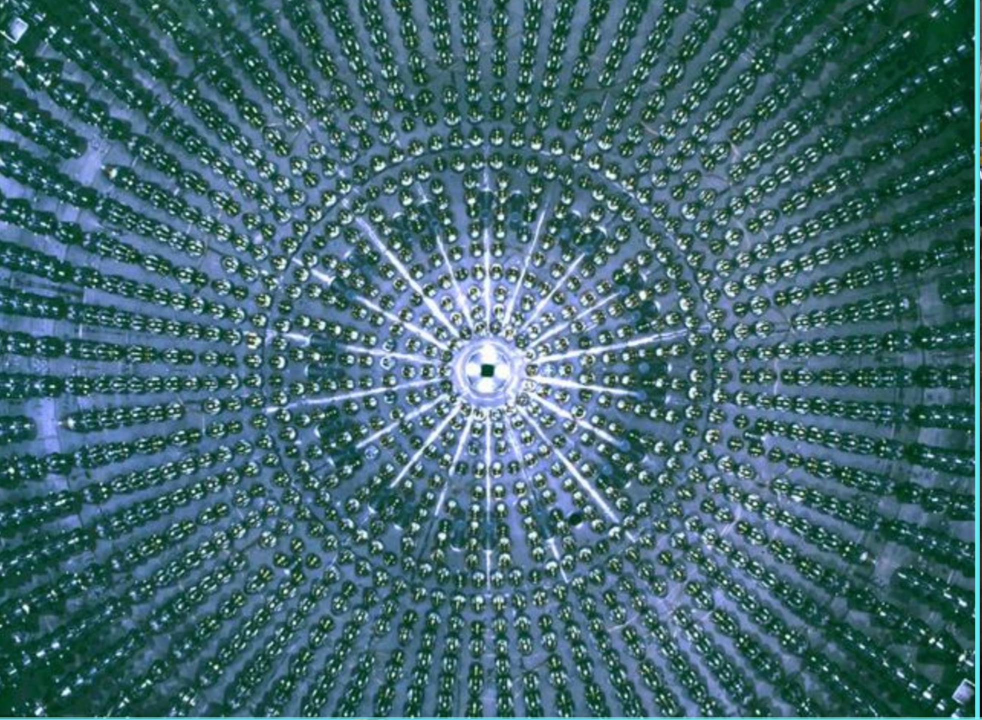


STUDY OF ANTINEUTRINO FLUXES AND NON SOLAR ν PHYSICS RESULTS WITH BOREXINO

SANDRA ZAVATARELLI (INFN – SEZIONE DI GENOVA – ITALY)
ON BEHALF OF BOREXINO

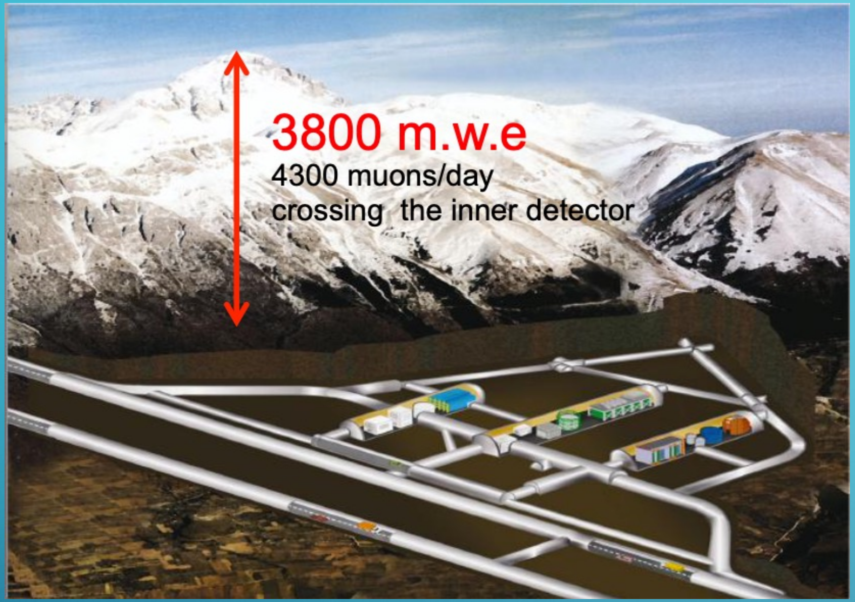
6-13 Jul 2022 Bologna (Italy)

TALK LAYOUT

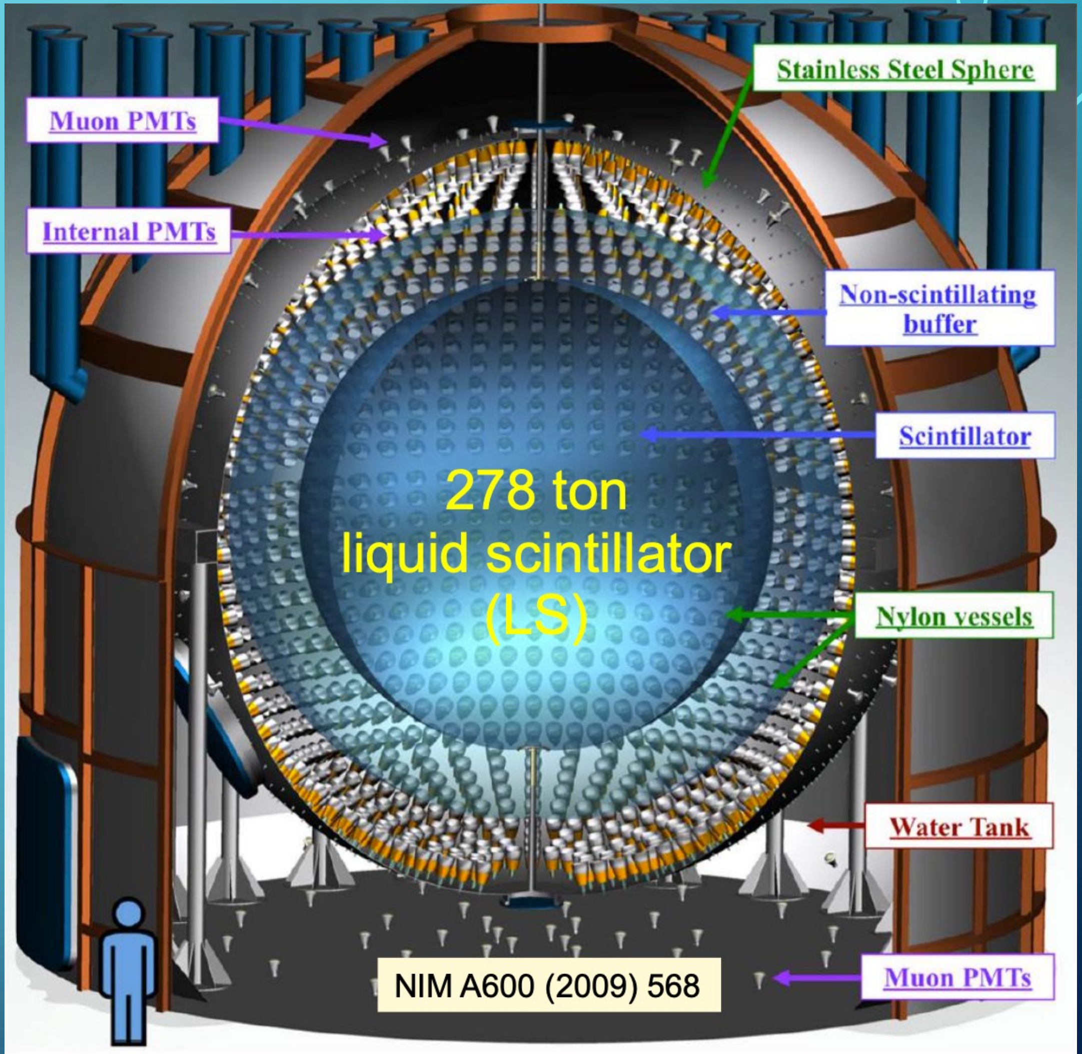
- ν detection techniques with liquid scintillators
- Recent non-solar ν physics Borexino studies:
  - Geoneutrinos
  - Diffuse supernovae neutrino background
  - Fast radio bursts ν
- Conclusions

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-)



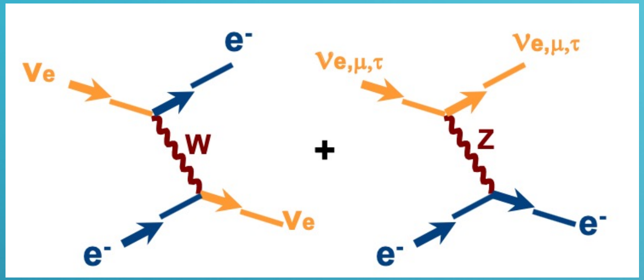
In operation: May 2007- October 2021

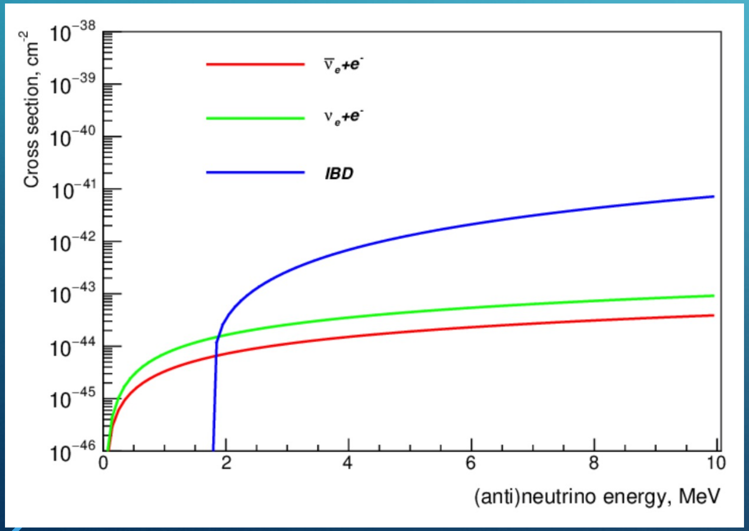
MEV ANTI-NEUTRINO DETECTION WITH LIQUID SCINTILLATORS

Elastic scattering on electrons

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

Single events, no threshold, all flavours

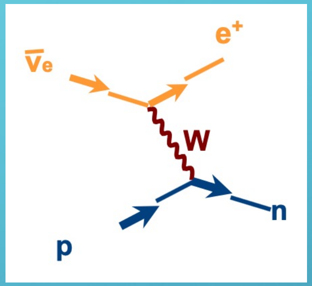


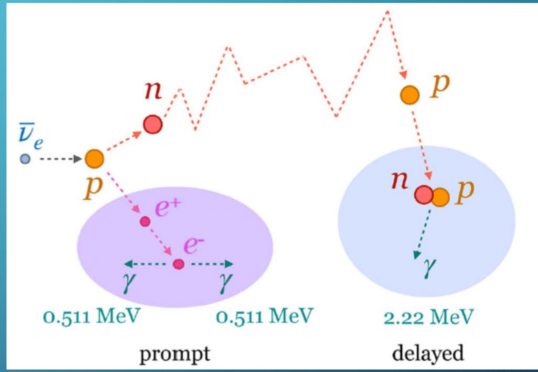


Inverse beta decay

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

Charge current, electron flavour only





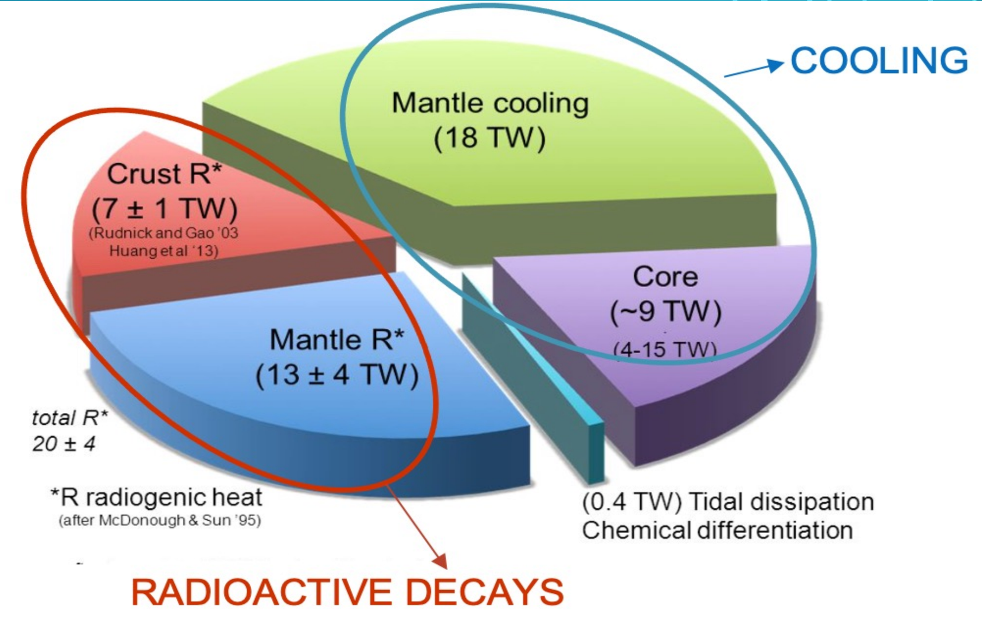
Delayed coincidence → clean signature!

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)

Earth's energetics : unclear picture!!



GEO-NEUTRINOS AS PROBES FOR DEEP EARTH: WHY?

- Geoneutrinos are the most abundant component of anti-ν flux at Earth (Φ_ν~ **10^6 cm^{-2} s^{-1}**)

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

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

^{235}U $\rightarrow$ ^{207}Pb + 7 α + 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 ν_e** + 1.505 MeV (10.7%)

Heat
Producing
Elements

HPE's

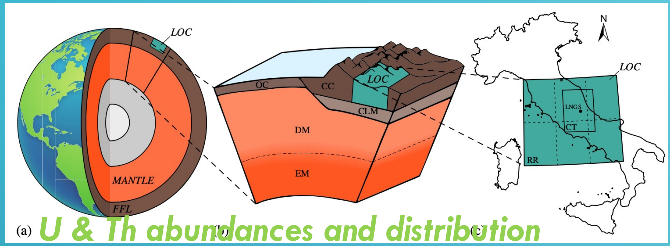
GEONU SIGNAL AT GRAN SASSO

*M. Agostini et al PRD 101(2020) 012009

Expected signal calculations:

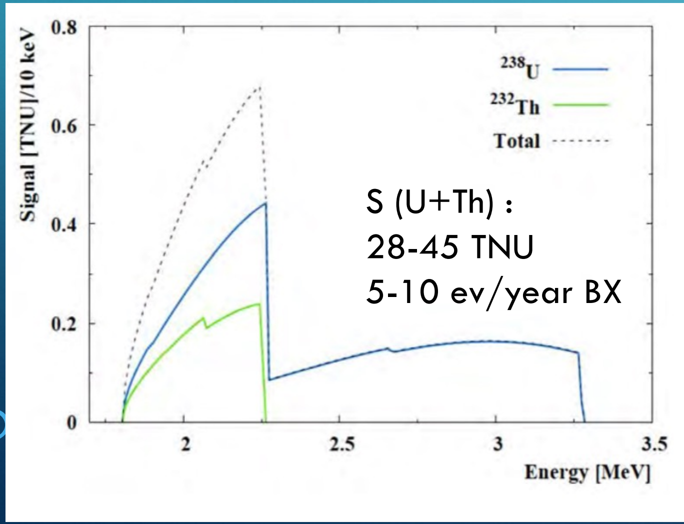
1) Geo-neutrino energy spectra

2) Local and global geological informations



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

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

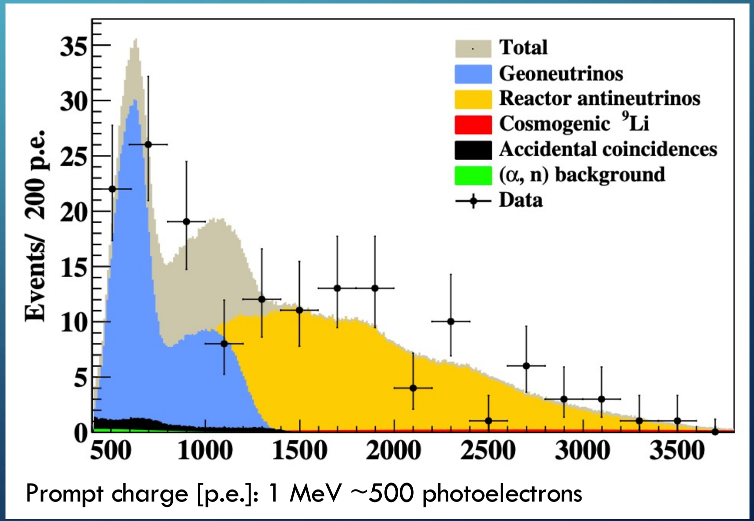


^{40}K signal below IBD threshold

Measured signal:

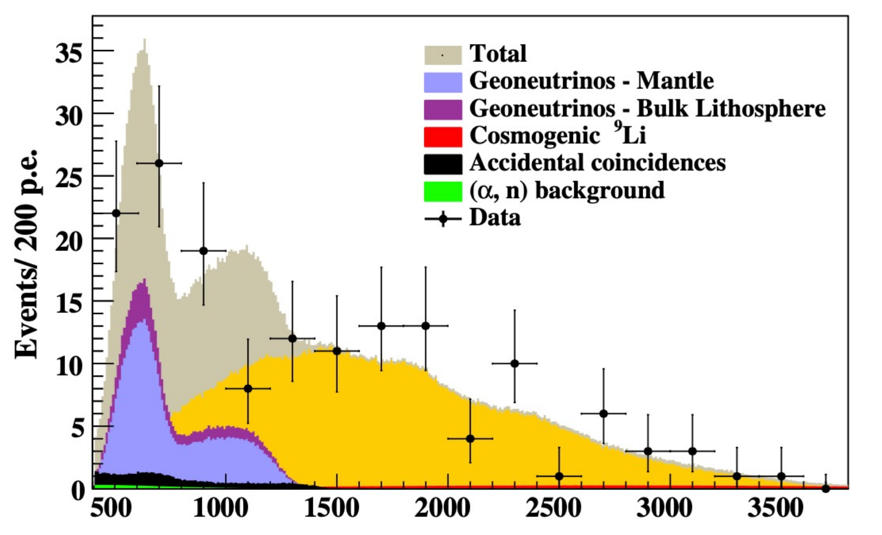
$E_{prompt} \sim E_{\nu} - 0.8$ MeV

- Dec 2007 -Apr 2019 : 3262.74 days
- Exposure = (1.29 ± 0.05) x 10^{32} proton x year (100% eff)
- IBD selection cuts (energy, space/time corr, μ-veto, FV, PSA*)
- From unbinned likelihood fit of prompt event spectrum;
- Among 154 candidates: 52.5 $^{+18.3}_{-17.2}$% total precision
- Evidence for signal >8 σ
- Reactor signal perfectly compatible with precise calculation from IAEA reactor infos
- SPECTRAL FIT with Th and U independent fractions in agreement with S(Th)/S(U)=0.27 from chondritic metheorites

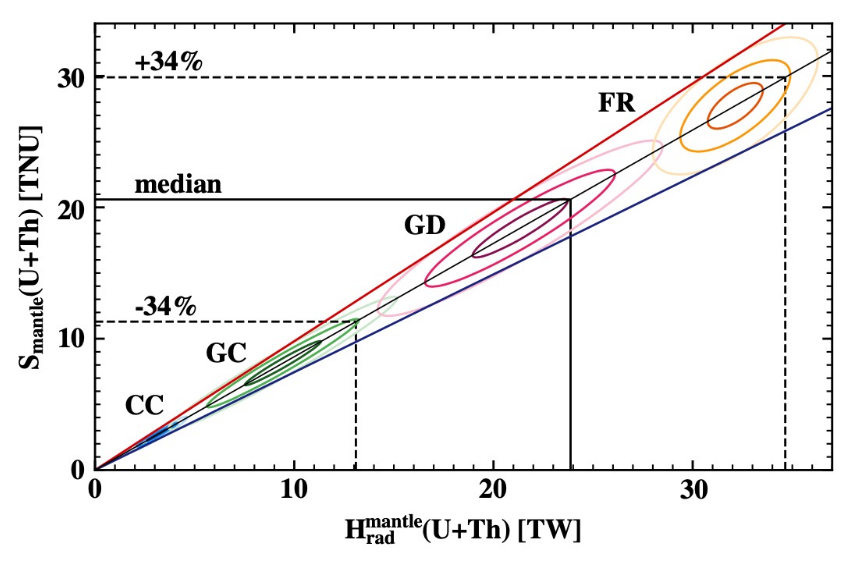


Prompt events energy spectrum fit with S(Th)/S(U)=0.27

GEO-NEUTRINO SIGNAL FROM THE MANTLE



Prompt charge [p.e.]: 1 MeV ~500 photoelectrons



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

Constraining the contribution from the **bulk lithosphere** (28.8 ± 5.6 events with S(Th)/S(U) = 0.29), the **extracted** N_{mantle} events are $23.7^{+10.7}_{-10.1}$

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

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)

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

Assuming 18% ^{40}K mantle contribution + lithosphere

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

38.2/47=80% of total heat flow

SN remnant by HST

NEUTRINOS FROM COSMOS

Several possible sources:

- GW events[*] and Gamma Ray Bursts[**]
- Solar flares[***]
- Diffuse supernovae neutrino background[***]
- Fast radio bursts(****)

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

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

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

*****M. Agostini et al, Eur. Phys. J. C 82, 278 (2022)*

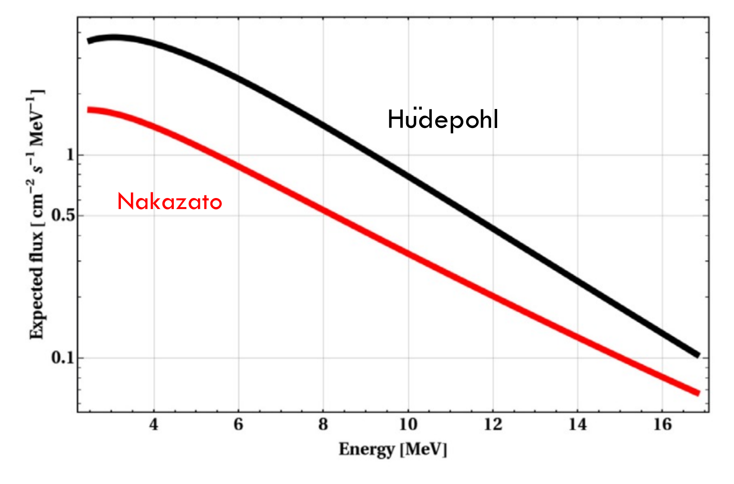
DIFFUSE SUPERNOVAE NEUTRINO BACKGROUND (DSNB)

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 !!

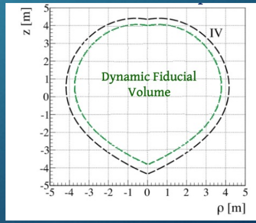
$$\frac{d\phi_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{max}} \frac{dN_\nu(E'_\nu)}{dE'_\nu} \frac{R_{SN}(z)dz}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$



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

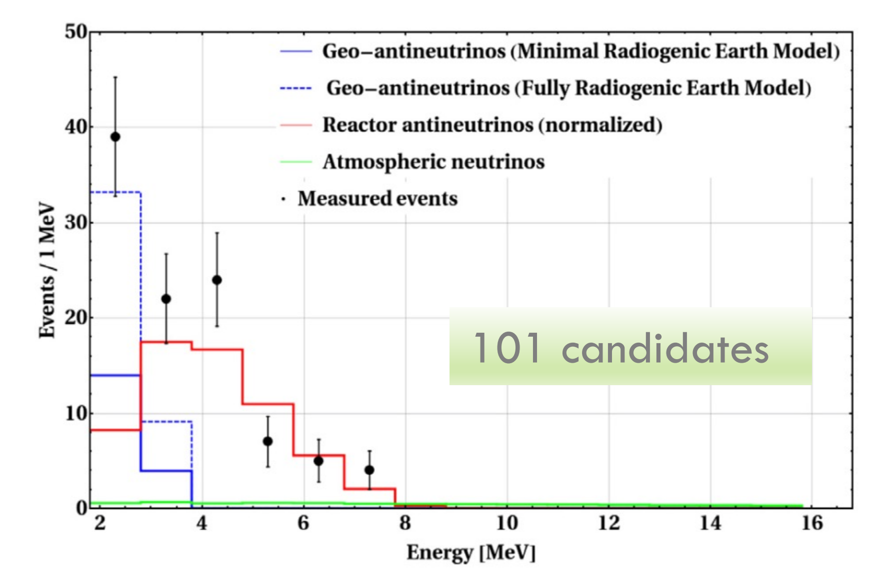


Conservative limits on DSNB:
the minimal expected number of background events considered:

- **Geo-ν**: only radioactivity from the crust
- **Reactor-ν** : normalization to Daya-Bay results (they provide the lowest expected 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 %

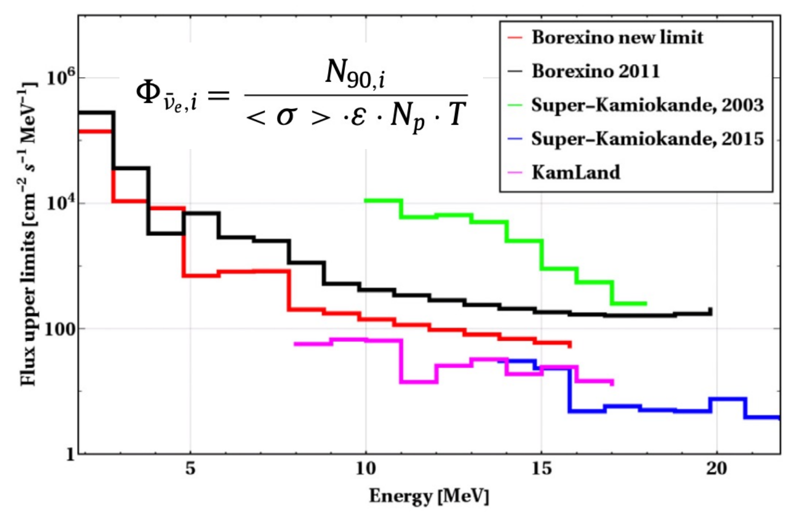


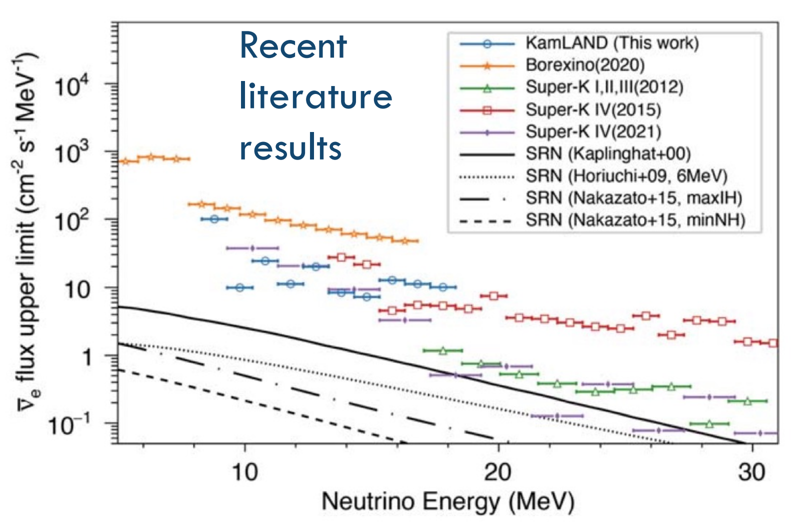
Background source	Expected events
Reactor $\bar{\nu}_e$	61.1 ± 1.7
Geo $\bar{\nu}_e$	17.9 ± 2.1
Atmospheric neutrinos	6.5 ± 3.2
Accidental coincidences	0.418 ± 0.006
Total:	85.9 ± 4.2

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

- BX : best limits below 8 MeV

Model independent limits



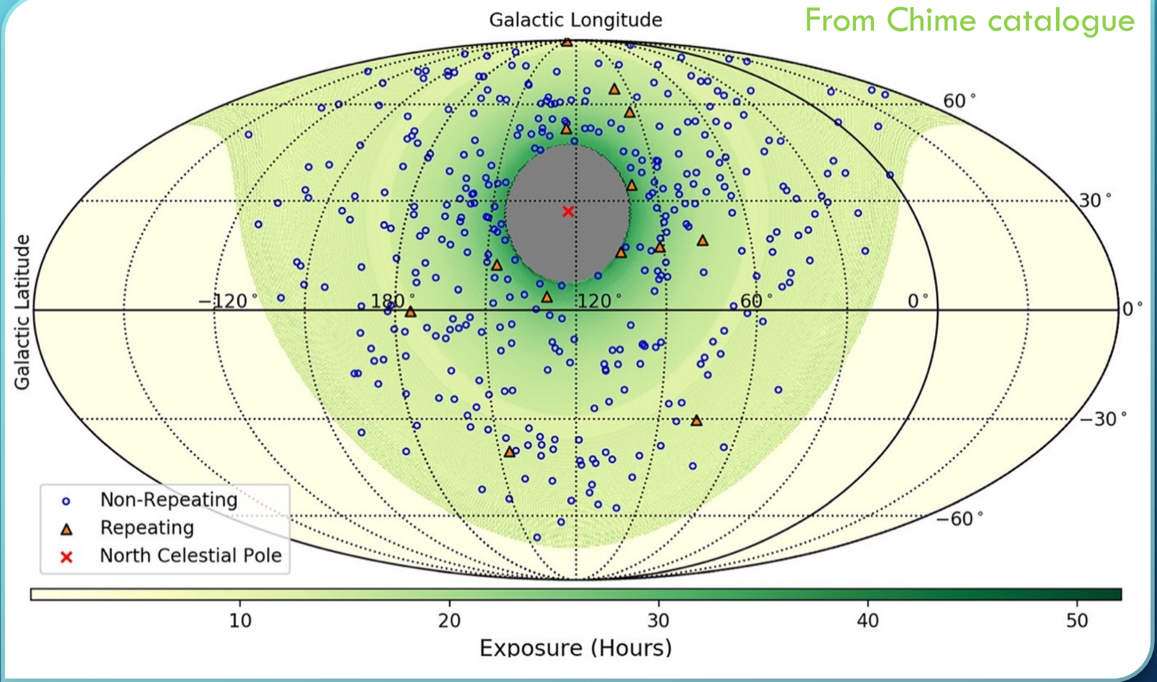


From : KamLAND Coll., Astrophys. J. 925, no.1, 14 (2022)

FAST RADIO BURSTS

- FRB is a millisecond radio transient observed at extragalactic or cosmological distance.
- $N_{FRB} \sim 2 \times 10^3$ /day
- Discovered almost 15 years ago, the nature of their source remains unclear (magnetars, mergers, collapsed of neutron stars..)
- Possible emission of neutrinos and axions which could be detected by large-volume Cherenkov or scintillation detectors.

Databases : http://chime-frb.ca, http://frbcat.org



From Chime catalogue

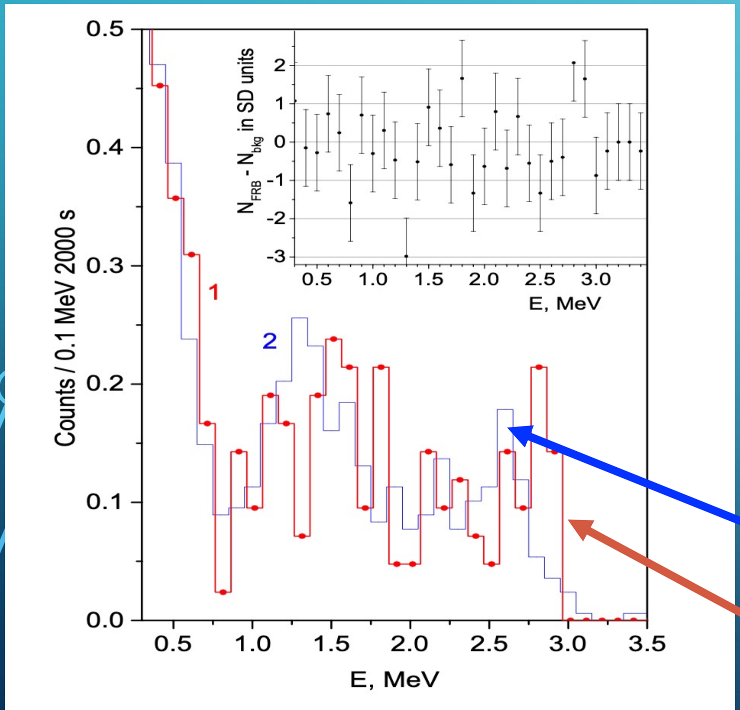
BX search :

- Time correlated events
- Search for specific shapes in the energy spectrum of ν scattering event or IBD events

M. Agostini et al, Eur. Phys. J. C 82, 278 (2022)

FAST RADIO BURSTS: TIME CORRELATED EVENTS

- Search for an excess of events in coincidence with intensive FRBs (fluence > 40 Gy ms) in a time window of $\Delta t = \pm$ 1000 s
- Background evaluated in two adiacent windows [-5000,-1000]s and [1000,5000]s
- Expected excess r ~20% (if ν fluence proportional to FRB fluence) since weaker FRBs are also present in background windows
- Statistics : Dev 2007 – Jun 2021 => 42 intense FRB selected
- Energy window : 0.25-15 MeV; Cosmogenic cut: 0.3 s veto after internal μ ; Fiducial volume: 145 tons (75 cm from inner vessel)



Background

Time correlated events

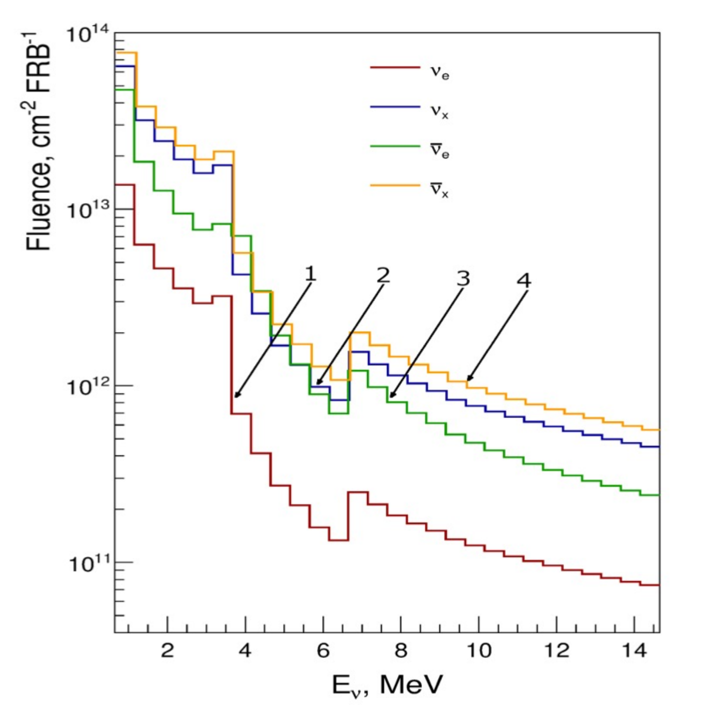
(1 further event at 6.8 MeV)

ν scattering events energy

$$\Phi_{\nu_x,\bar{\nu}_x} = \frac{N_{90}(E_\nu, n_{\rm obs}, n_{\rm bkg})}{r N_e \sigma(E_{\rm th}, E_{e_{\rm max}})}$$

Limits on fluences (10^9 cm^{-2}) 90%C.L.

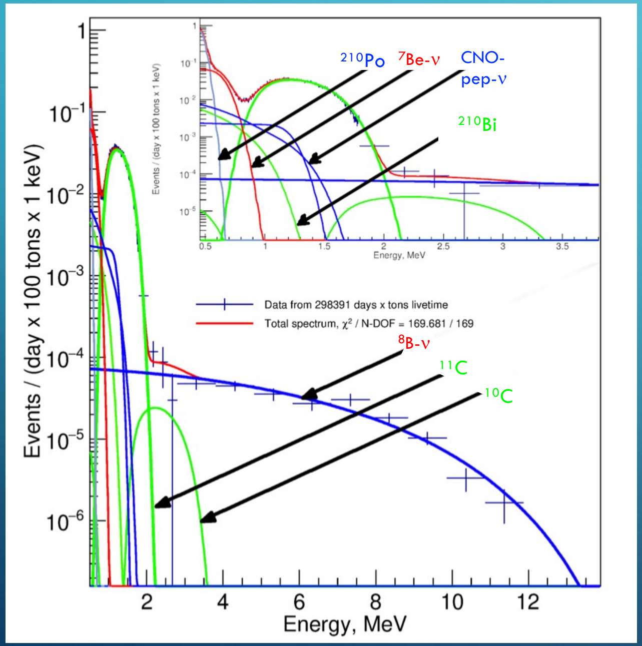
E_ν	Φ_{ν_e}	$\Phi_{\bar{\nu}_e}$	$\Phi_{\nu_{\mu,\tau}}$	$\Phi_{\bar{\nu}_{\mu,\tau}}$	IBD
2	4620	12750	24250	29000	2475
6	157	890	890	1280	40.7
10	125	475	770	970	12.2
14	77.5	255	474	590	5.88
< 15.6 >	157	367	900	1070	11.6



Limits for monocromatic neutrinos

FAST RADIO BURSTS: FIT OF BOREXINO SCATTERING EVENTS SPECTRUM

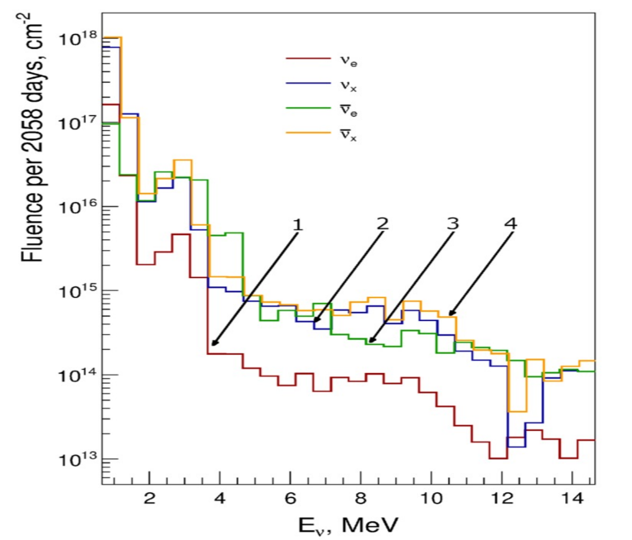
- Statistics Jan 2013-Nov 2020: 2058 days (exp. 298.39 kt day)
- $N_{FRB} \sim 4 \times 10^6$ in the data period
- Selected events with energy : 0.5-14 MeV
- Fiducial volume : 145 tons (75 cm from vessel)
- Advanced cosmogenic veto system + ^{11}C cuts> 15.8% dead time
- External background stat. subtracted through events radial fit



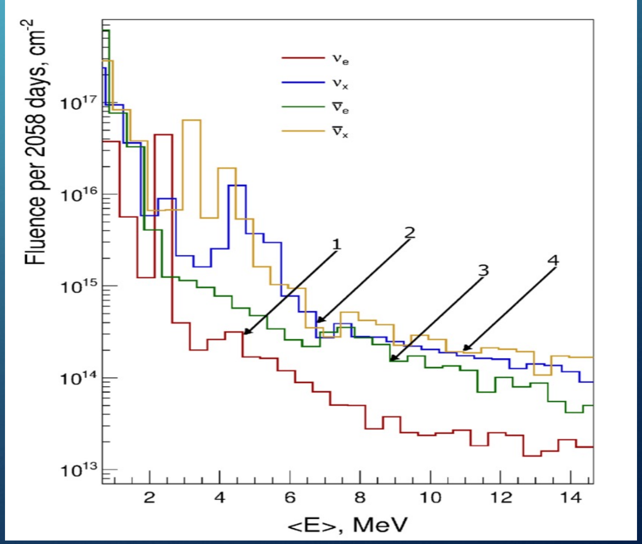
Spectral fit repeated by adding a «FRB» component

From the χ^2 increase $\Delta\chi^2 = (1.64)^2 \Rightarrow N_{90}$

$$\Phi = \frac{N_{90}(E_\nu)}{N_e \sigma(E_{\text{th}}, E_\nu)}$$



Monoenergetic neutrinos



Supernovae ν spectra-like with <E>

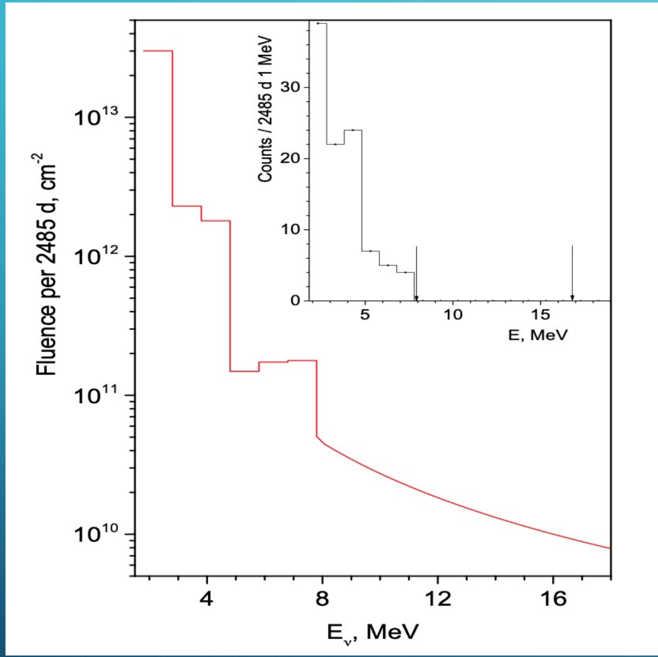
$$S(E_\nu) \sim (E_\nu/T)^\alpha e^{(-E_\nu/T)}$$

$\alpha = 3$

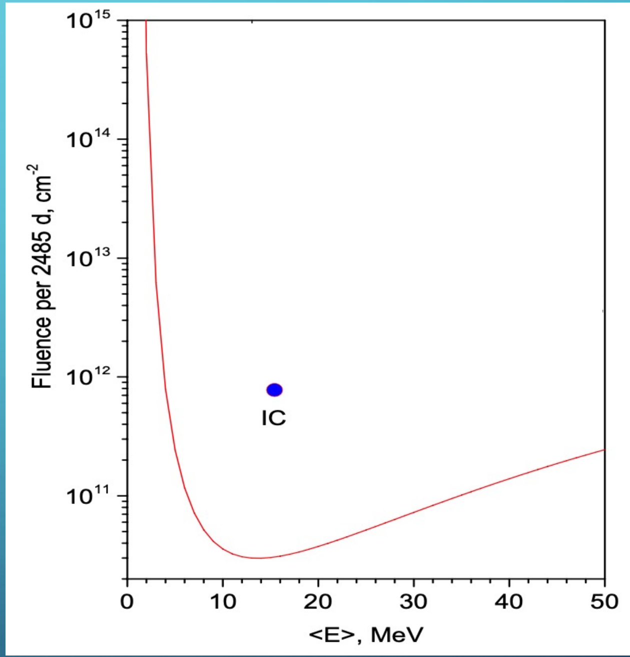
FAST RADIO BURSTS: LIMITS ON ANTINEUTRINO FLUENCE

M. Agostini et al, Eur. Phys. J. C 82, 278 (2022)

Statistics Dec 2007- Oct 2017: 2485 days ~$5x10^6$ FRB in the data period
Energy range for the study: E_{prompt} : 1-16.8 MeV
IBD selection cuts (similar to DSNB analysis) : 101 candidates, no events with E>7.8 MeV

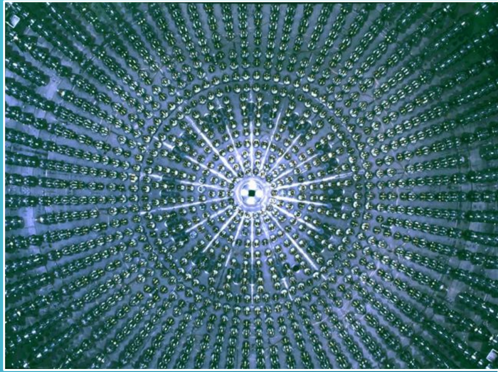


Upper limits on the fluences of monoenergetic anti-νe



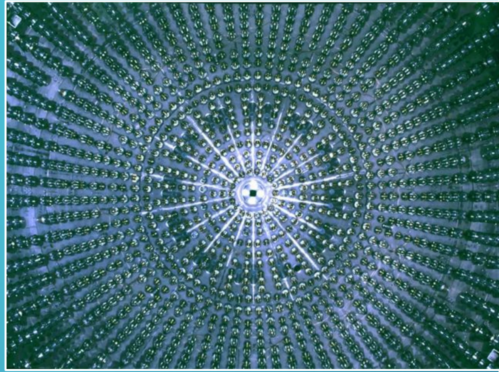
Limits for SN neutrino spectra-like of mean energy <E> (from no events observed in 7.8-16.8 MeV interval)

For the closest FRB 200428 (400 Mpc): Radiated energy< $4.8x10^{51}$ erg (for isotropic 10 MeV anti-ν_e)



CONCLUSIONS

- Thanks to the extreme radiopurity and the underground site Borexino achieved an exceptional sensitivity to ν/anti–ν from Earth and Cosmos
- Borexino detected geoneutrino signal with high statistical evidence
  - U/Th ratio in agreement with chondritic meteorites
  - Null mantle signal excluded at 99.0% C.L.
  - Evaluation of mantle radiogenic heat, with a preference for geological models predicting high U and Th abundances
- Borexino has achieved :
  - the best upper limits on DSNB anti-ν_e flux for E_ν< 8 MeV,
  - the strongest upper limits on FRB-associated neutrino fluences of all flavors in the 0.5 – 50 MeV neutrino energy range
- No excess of events was observed in coincidence with solar flares, GRB's and GW events.



Thanks
for your
attention!!!!

BACKUP

FAST RADIO BURSTS: FIT OF BOREXINO SCATTERING EVENTS SPECTRUM

- Statistics Jan 2013-Nov 2020: 2058 days (exp. 298.39 kt day)
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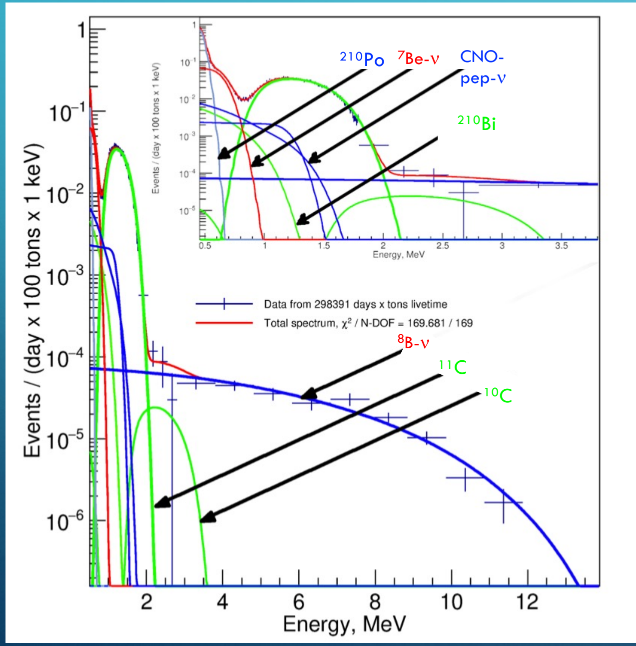

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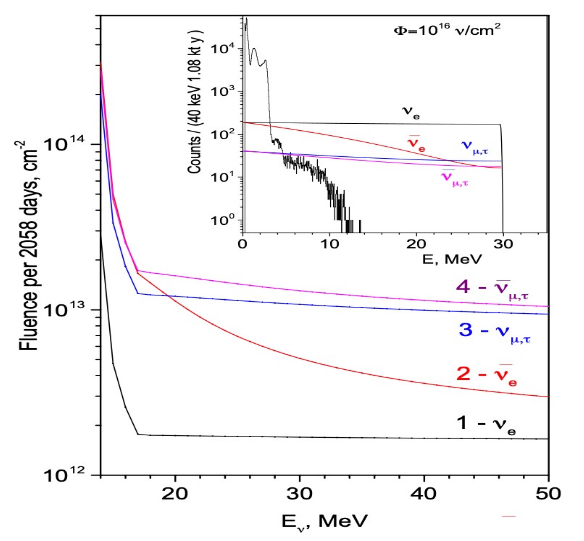
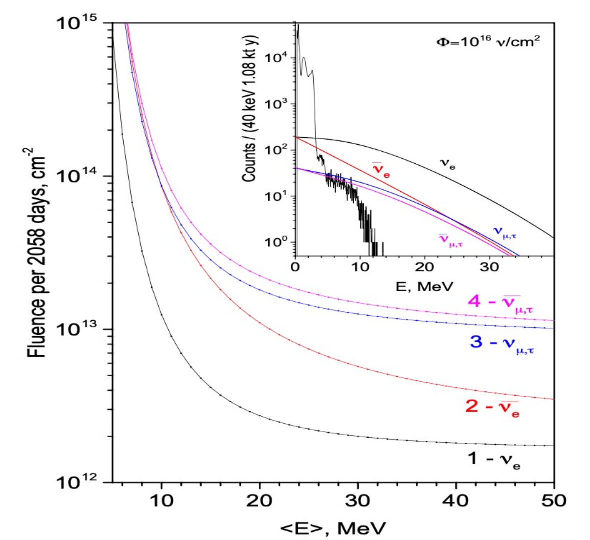


Limits from no events in the range 13.9-16.8 MeV

Monoenergetic neutrinos



Supernovae ν spectra-like with <E>

$$S(E_\nu) \sim (E_\nu/T)^\alpha e^{(-E_\nu/T)}$$

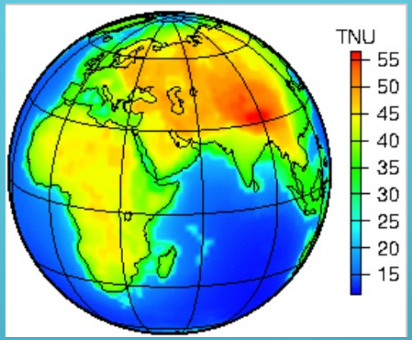
α=3

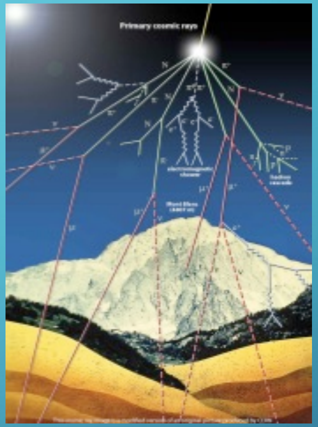
SOURCES OF BACKGROUNDS

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:

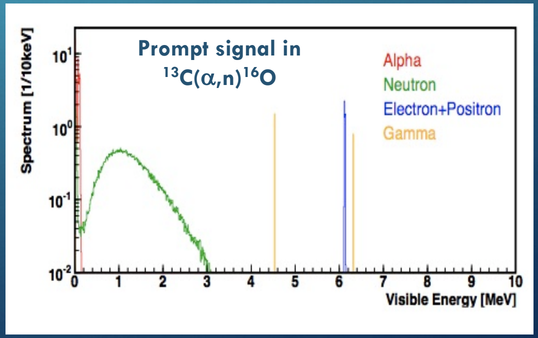
(a) Reactor antineutrinos
(b) Atmospheric neutrinos

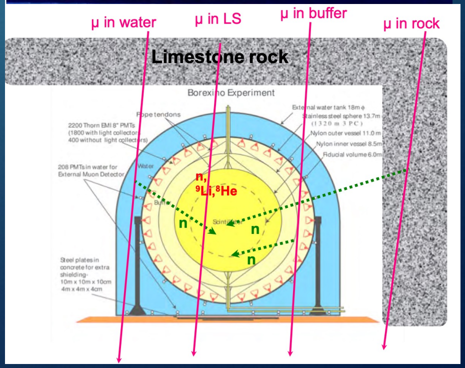




Backgrounds mimicking inverse beta decay reaction:

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





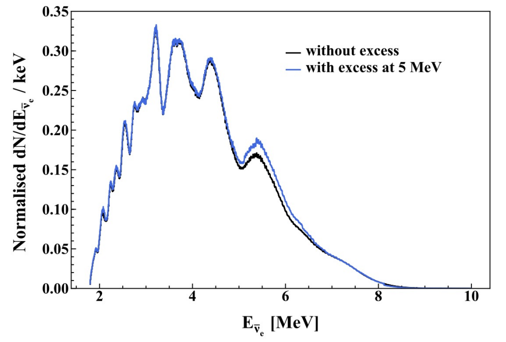
BACKGROUNDS

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.