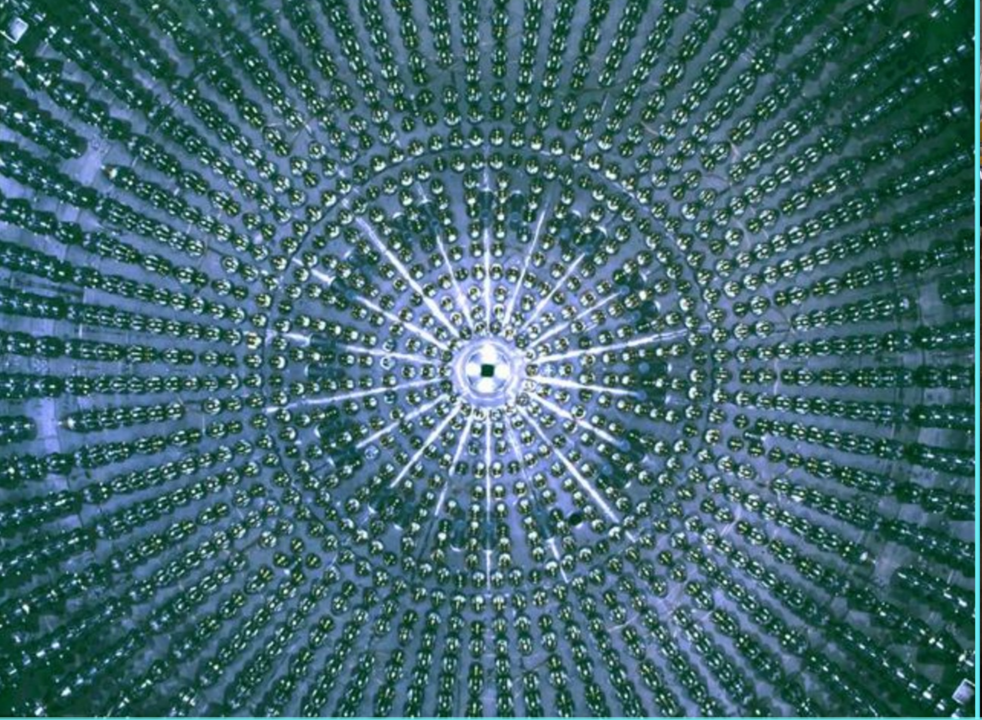
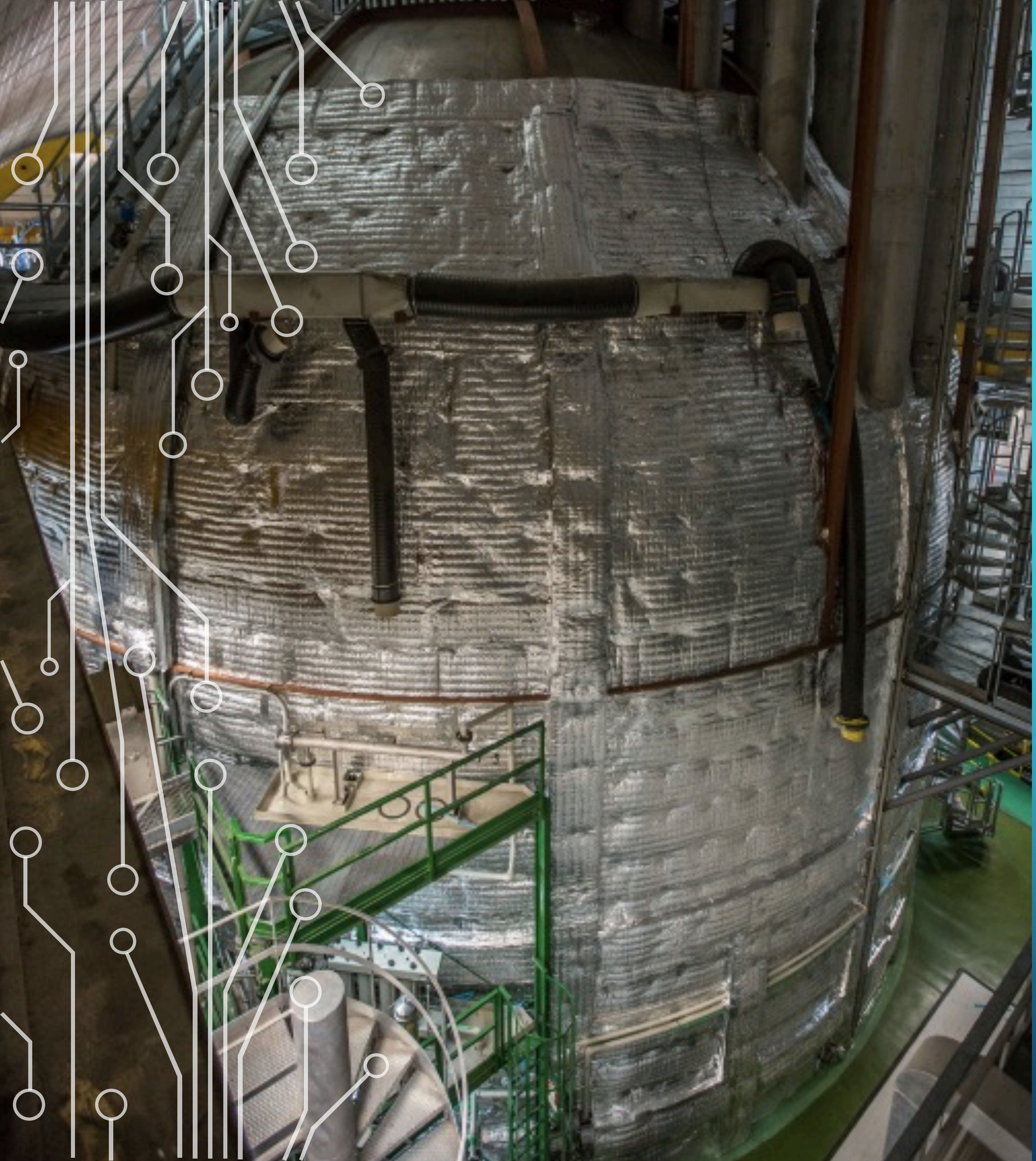


THE STUDY OF NEUTRINO AND ANTINEUTRINOS FROM ASTROPHYSICAL SOURCES BY BOREXINO

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



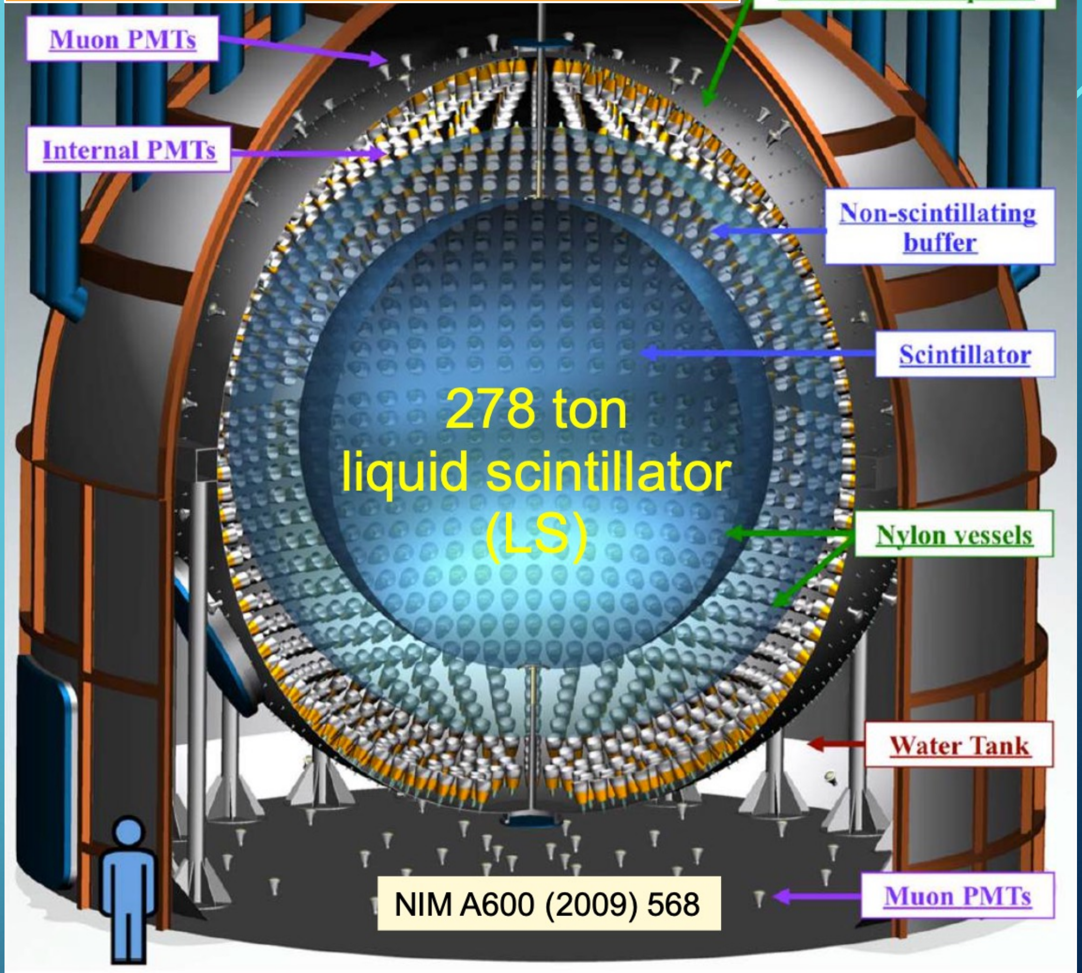
TALK LAYOUT

- The Borexino detector: steps towards the sensitivity needed to disclose weak neutrino components (..such as solar CNO-ν !)
- (Anti) Neutrinos from the cosmos:
  - Diffuse supernovae neutrino background
  - Correlated signals with:
    - Fast Radio Bursts;
    - GW (new! Eur. Phys. J. C (2023) 83:538)
- Conclusions

THE BOREXINO DETECTOR

- Scintillation detector : high light yield => low energy threshold and good energy resolution but light not directional !!
- The quest for the radiopurity grail : > 15 years of work
- Detector design: concentric shells to shield from external background
- Purification of the scintillation (distillation, vacuum stripping with low Ar/Kr N_2);
- Material selection and surface treatment, clean construction and handling.

In operation: May 2007- October 2021



- L.Y. ~**500 p.e.** / **MeV**, energy threshold: 50 keV
- energy resolution: 5% @ 1 MeV
- position reconstruction: 10 cm @ 1 MeV
- pulse shape identification (α/β, e+/e-)

BOREXINO DATA TAKING : PHASE 1 (2007-2010)

2007
PHASE 1
2010
Water extraction
Nitrogen stripping
2012
PHASE 2
2015
Thermal insulation
2017
PHASE 3
2021

Radiopurity even exceeded design goals (factor 20!) : ^{238}U =(5.3 ± 0.5) × 10^{-18} g/g and ^{232}Th = (3.8 ± 0.8)× 10^{-18} g/g

- Some background out of specifications (^{85}Kr, ^{210}Bi)

With simple cuts (μ and FV) possible to see "at eye" the ^{7}Be-ν shoulder !

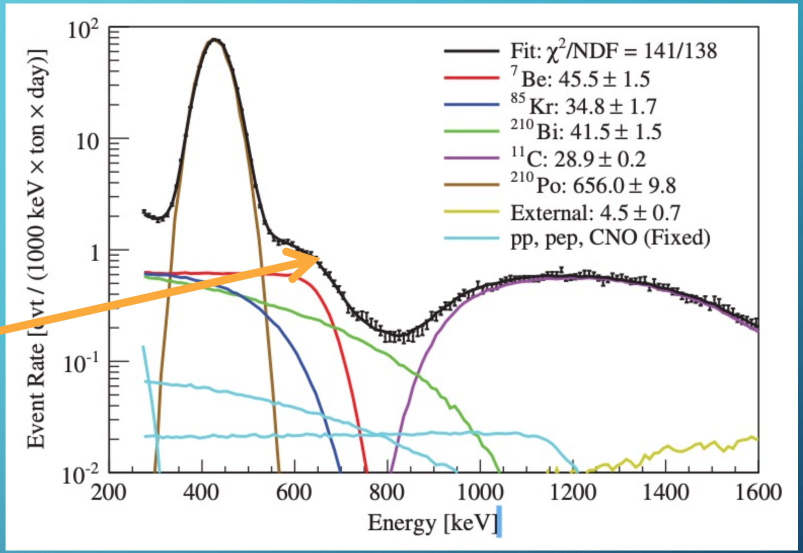
Main achievements:

Solar neutrinos

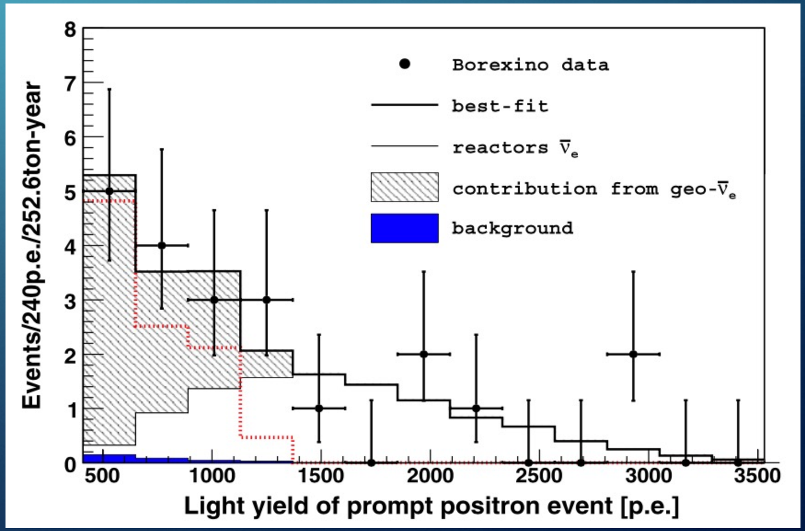
- 7Be ν : precise measurement (5%); Day/Night asymmetry;
- pep ν: 1st observation;
- 8B ν with low threshold;

Other

- geo-ν evidence > 4.5σ
- Limit on rare processes, best limits on ν_e magnetic moment
- Study on cosmogenics



PRL 107 (2011) 141302



Physics Letters B 687 (2010) 299–304

BOREXINO DATA TAKING: PHASE 2 (2012-2015)

- After WE and nitrogen stripping :

^{238}U chain <9.4x10^{-20} g/g (95% C.L.)
^{232}Th chain <5.7×10-19 g/g;

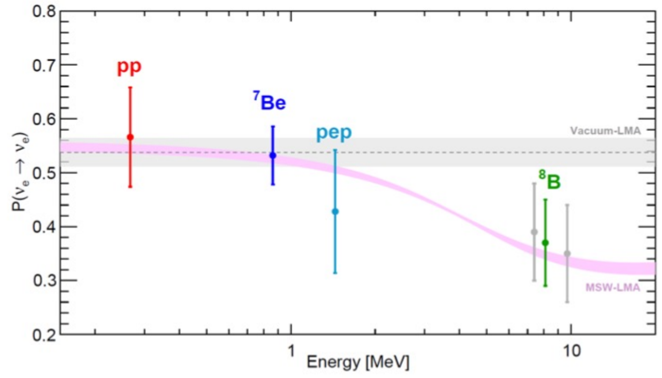
- Nitrogen stripping => strong reduction of ^{85}Kr
- ^{210}Bi decreased by a 2.5 factor

Among main achievements:

- pp neutrinos (Nature 2014)
- Seasonal ^{7}Be- ν modulation (2017)
- First simultaneous precision spectroscopy of pp, ^{7}Be and pep solar ν" (Nature 2018)

.. but contaminants leaking from vessel into the innermost part of the detector because of convective liquid motion, were still preventing weakest components studies (CNO-n)

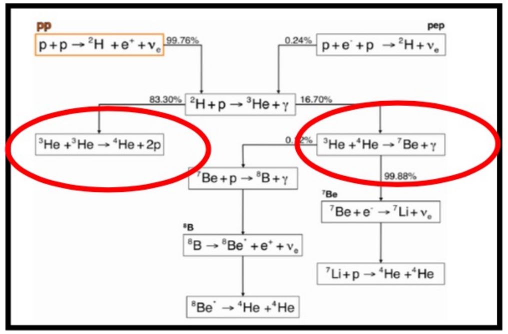
Comprehensive test of MSW-LMA oscillations



$P_{ee}(pp)=0.57\pm0.10$; $P_{ee}(^{7}Be)=0.53\pm0.05$
$P_{ee}(pep)=0.43\pm0.11$ $P_{ee}(^{8}B)=0.37\pm0.08$

*[Nature **562**, 505 (2018)]*

Probed nuclear reactions in the SUN



$$R \equiv \frac{<^3He + ^4He>}{<^3He + ^3He>} = \frac{2\phi(^7Be)}{\phi(pp) - \phi(^7Be)}$$

R = 0.18 ± 0.02

*[Nature **562**, 505 (2018)]*

BOREXINO DATA TAKING : PHASE 3 (2017-2021)

2007 — PHASE 1

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Water extraction
Nitrogen stripping
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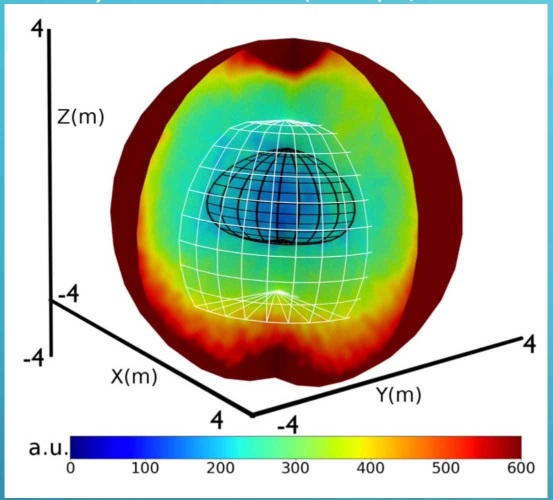
Thermal insulation
2017 — PHASE 3

2021

•2015-16: insulation of the detector + active temperature control system

Phys.Rev.Lett. 128 (2022) 9, 091803



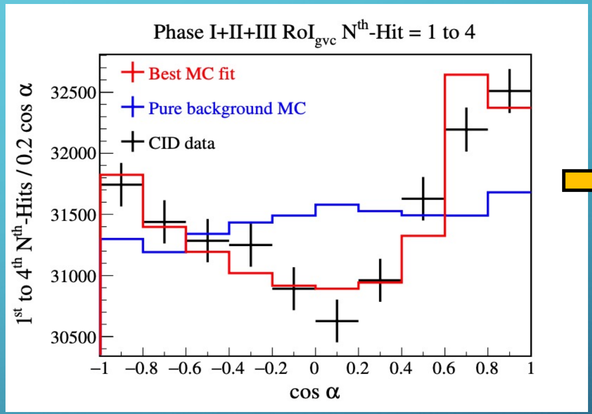
Low ^{210}Po field region =>

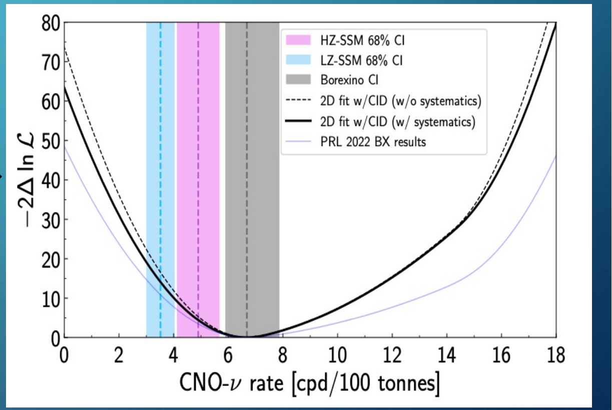
R (^{210}Bi) < 10.8+/- 1.0 cpd/100t

CNO-null hypothesis excluded at > 7σ

Energy production mechanism in massive stars probed!

2022-23: **Further refinement of the analysis**, disentangling the Cherenkov and the scintillation signal => **capability to statistically reconstruct the solar neutrino direction**





$$\Phi_{CNO} = 6.7^{+1.2}_{-0.8} \times 10^{8}\ \mathrm{cm^{-2}s^{-1}}$$

https://arxiv.org/abs/2307.14636,
Phys.Rev.Lett. 129 (2022) 25, 252701
Phys.Rev.D 105 (2022) 5, 052002

CNO flux determination w/o ^{210}Bo constraint and all BX data (2007-2021)

For details: D. Basilico Talk at 17:00!!!!

BOREXINO DATA TAKING : PHASE 3 (2017-2021)

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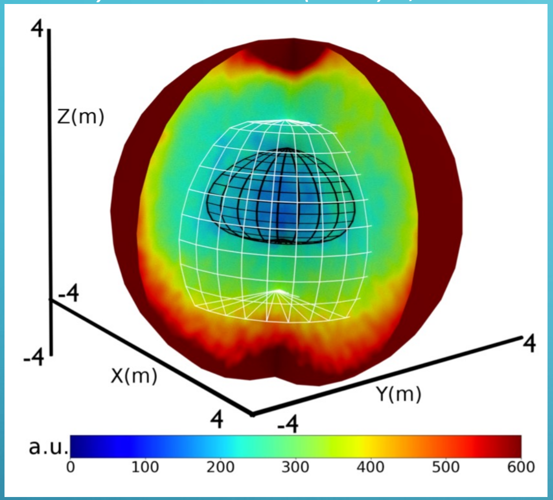

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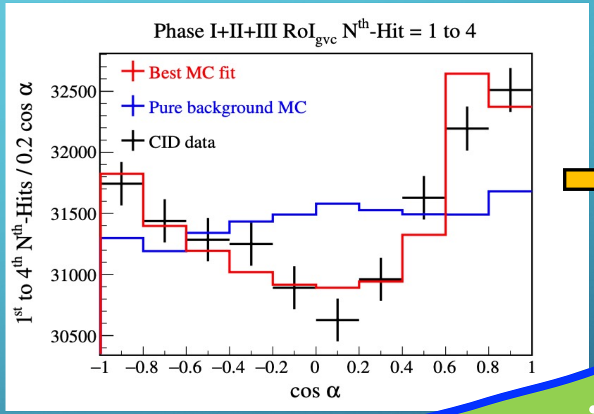
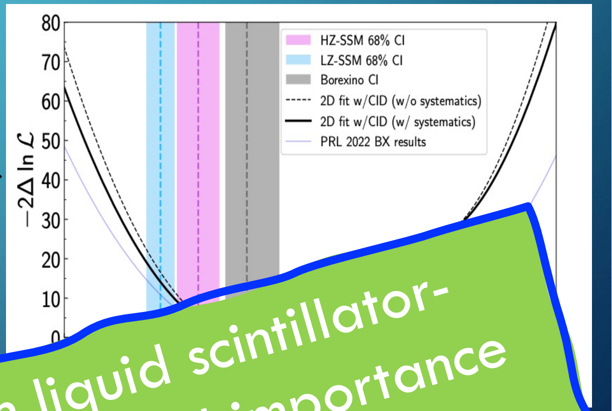




Φ...

https...
Phys.
Phys.R

...nd
(2007-2021)

Pointing capability with liquid scintillator-based detectors : fundamental importance for neutrino astronomy with future large detectors!!

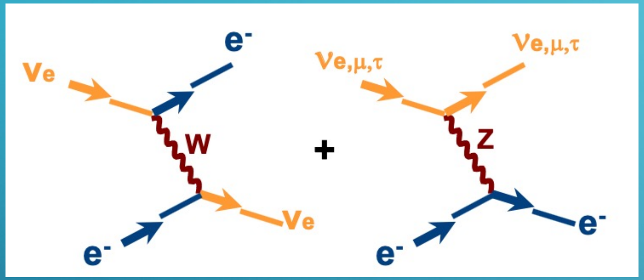
D. Basilico Talk at 17:00!!!!

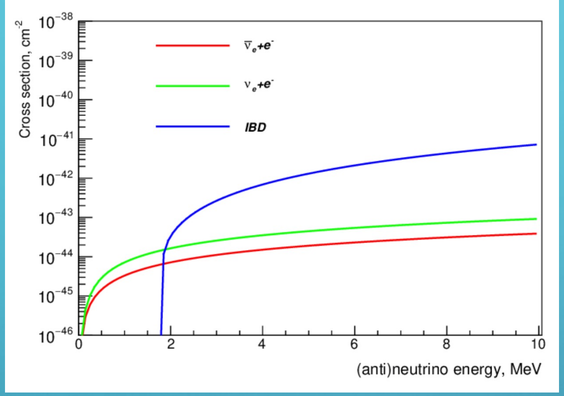
MEV (ANTI) NEUTRINO DETECTION WITH LIQUID SCINTILLATORS

Elastic scattering on electrons

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

Single events, no threshold, all flavours





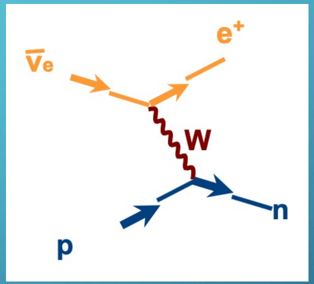
σ_{IBD} at few MeV: $\sim 10^{-42}$ cm^2 (~100 x more than scattering)

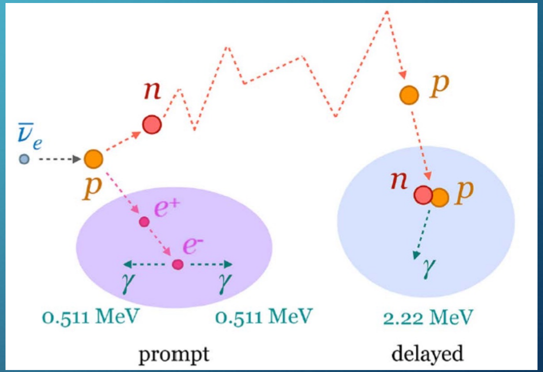
Inverse beta decay

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

Charge current, electron flavour only

Delayed coincidence → clean signature!





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

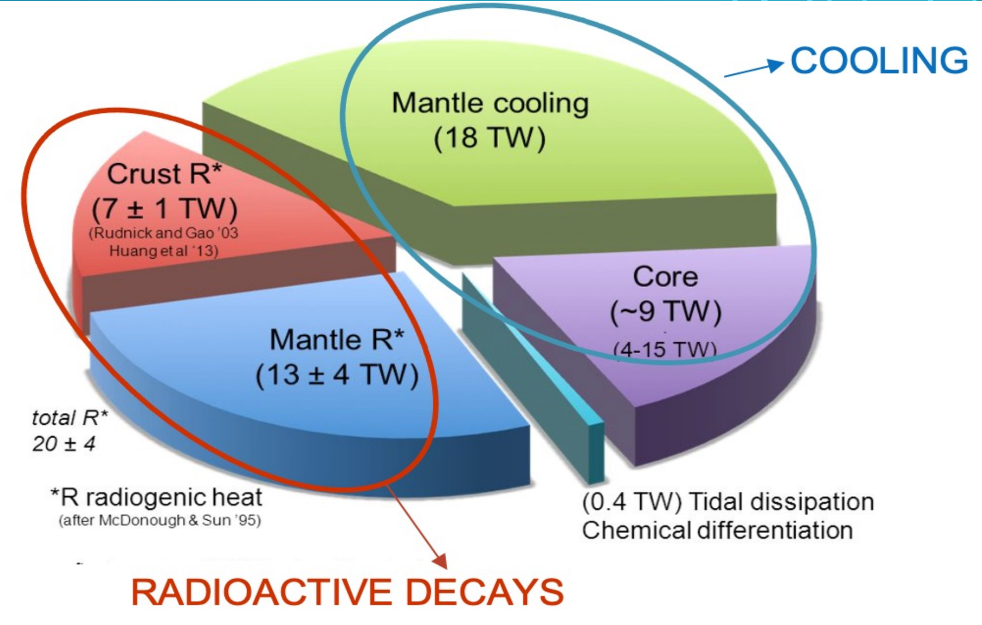
$E_{prompt} = E_{visible}$
$\sim T_{e+} + 2 \cdot 511$ keV
$\sim E_{antinu} - 0.784$ MeV

Signal rate dominated by solar neutrinos

Signal rate dominated by geo and reactors antineutrinos for $E_\nu < 10$ MeV

GEO-NEUTRINOS : AN IMPORTANT AND INTERESTING BACKGROUND

Earth's energetics : unclear picture!!



- Geoneutrinos are probes for deep Earth compositions ($\Phi_\nu \sim 10^6$ $cm^{-2}\,s^{-1}$)

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

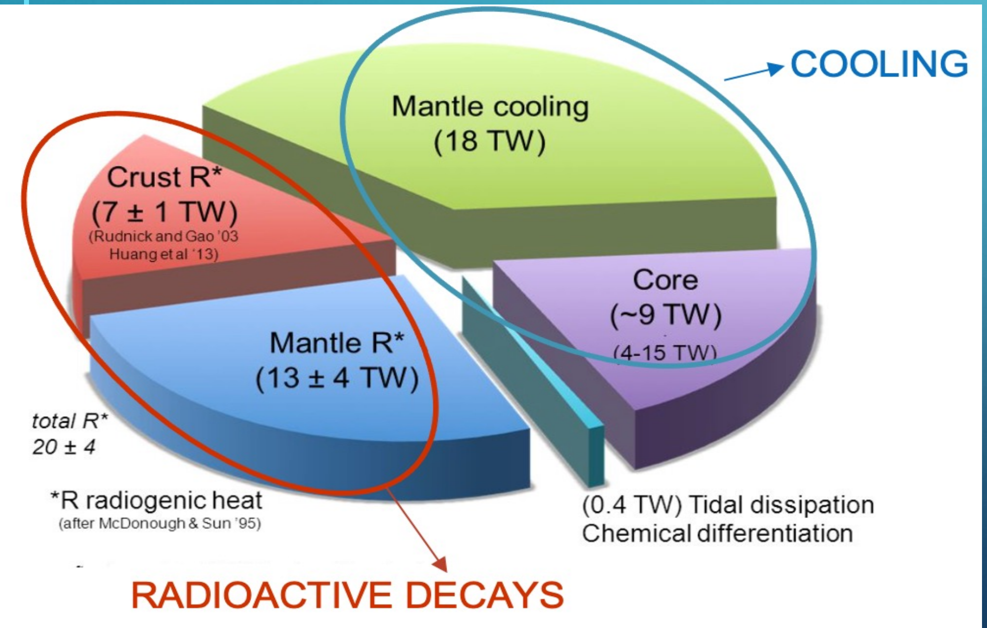
Heat
Producing
Elements
HPE's

Radiogenic heat from the lithosphere know from direct rock studies + 3D models: $H(U+Th+K) = 8^{+1.9}_{-1.4}$ TW

Amount of mantle radiogenic heat very uncertain!

Possible range : 3 -25 TW according to Bulk Silicate Earth models

Earth's energetics : unclear picture!!



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Above the IBD threshold (1.8 MeV)

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

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BOREXINO GEO-NEUTRINO STUDIES

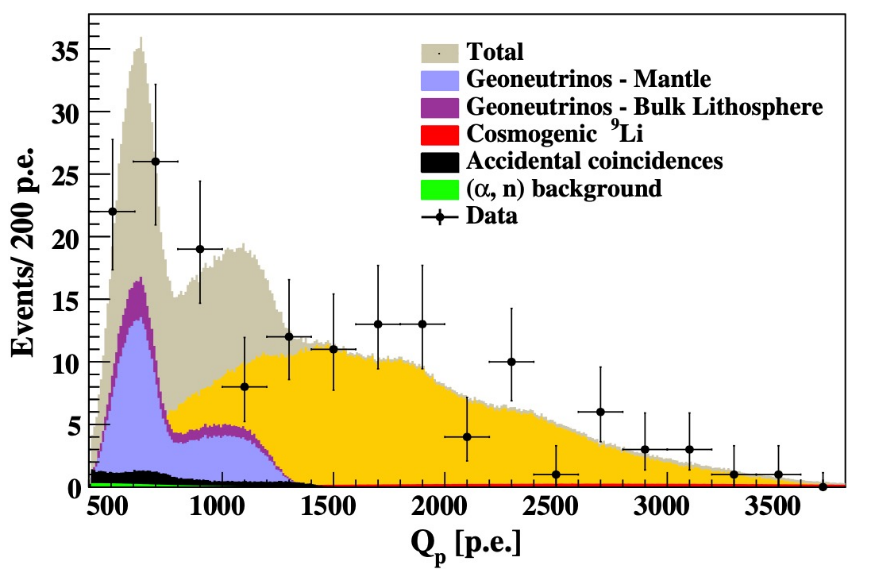
M. Agostini et al PRD 101(2020) 012009

- 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, cosmogenic veto, FV (10cm from IV), PSA => Selected 154 candidates

To disentangle geo-ν and rector neutrino signal => unbinned likelihood fit of prompt event spectrum

MANTLE SIGNAL : fit performed by constraining the known contribution from the **lithosphere (28.8 ± 5.6 events with S(Th)/S(U) = 0.29)**, **to extract the pure mantle signal : according to the fit the** N_{mantle} events are $23.7^{+10.7}_{-10.1}$ Nrea = $80.5^{+10.7}_{-10.2}$ **perfectly compatible with precise calculation from IAEA reactor informations**
Other backgrounds are by fact negligible

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



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

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

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

1 TNU = 1 event / 10^{32} target protons (~1kton LS) / year with 100% detection efficiency

GEO-NEUTRINO SIGNAL FROM THE MANTLE

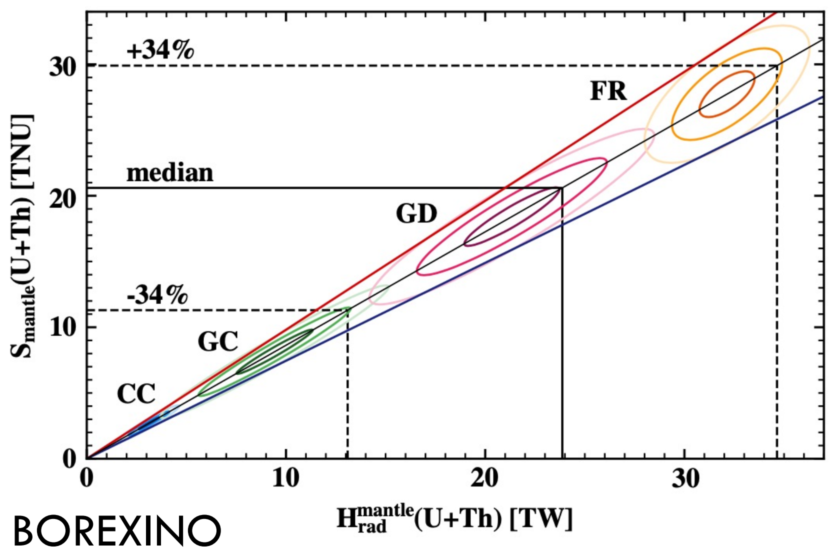
Bulk Silicate Earth's Models

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



BOREXINO

BOREXINO (*PRD 101(2020) 012009*)

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)

KamLAND (Geophys. Res. Lett. 49 e2022GL099566):

H_{mantle} (U+Th) = 4.8 $^{+5.6}_{-5.9}$ TW

V. Strati talk at MMT23

More compatible with CC models, eventually with 0

Some tension between the two experiments…
mantle laterally not homogeneous??
Need for further studies (JUNO, singnal from ^{40}K..)
=>source of uncertainty for cosmic antineutrino fluxes < 3.2 MeV (geo-ν endpoint)

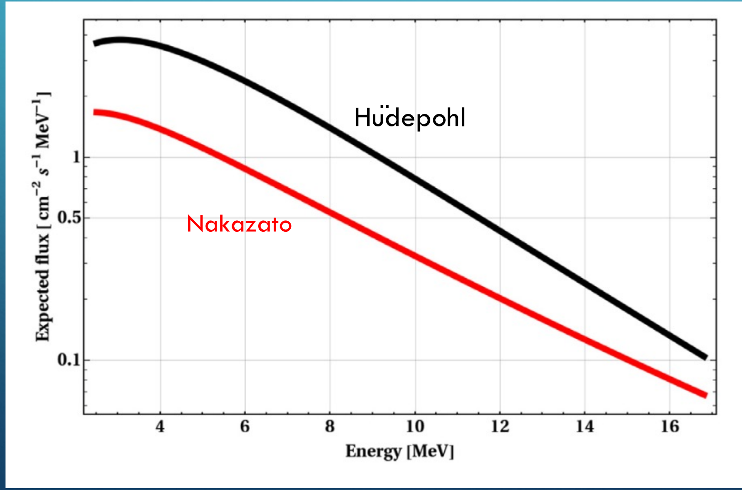
DIFFUSE SUPERNOVAE NEUTRINO BACKGROUND (DSNB)

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.

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

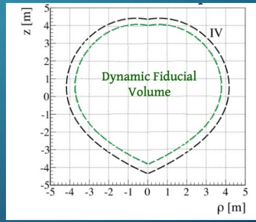
Small flux → Large underground detectors particularly suited !!



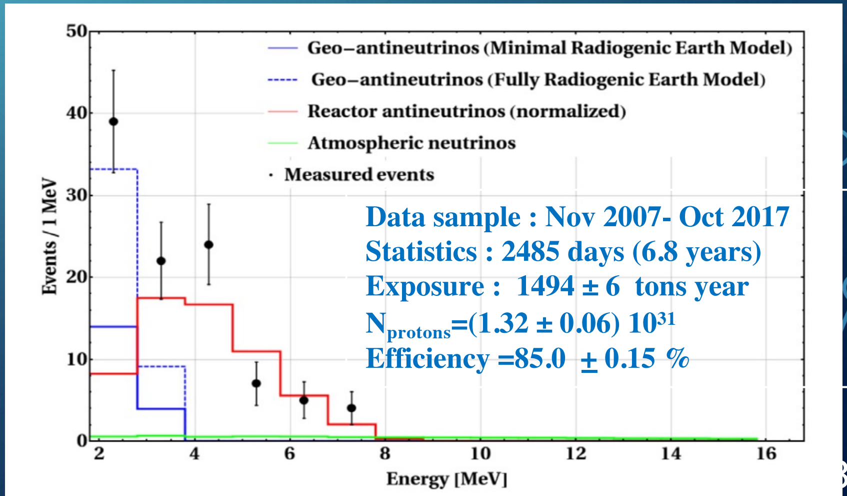
Detection channel : inverse beta decay (IBD)

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



101 candidates

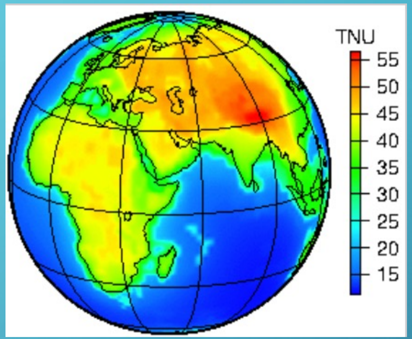


SOURCE OF BACKGROUNDS AND LIMITS CALCULATIONS

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

Antineutrino backgrounds expected events:

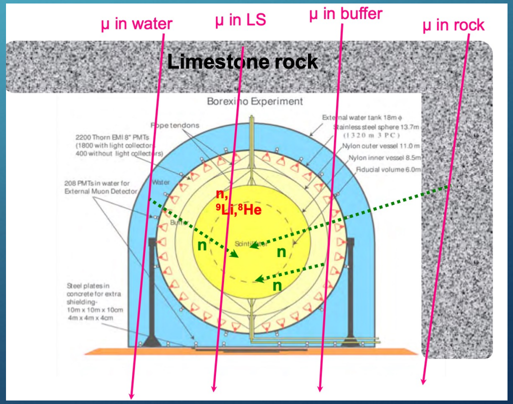
(a) Geo neutrinos : 17.9 ± 2.1 (only from crust)
(b) Reactor antineutrinos : 61.1 ± 1.7 (IAEA infos + devoted codes, shapes normalized to Daya Bay measured spectra)
(c) Atmospheric neutrinos : 6.5 ± 3.2 (fluxes from HKKM2014 and FLUKA (< 100 MeV) + matter effects)

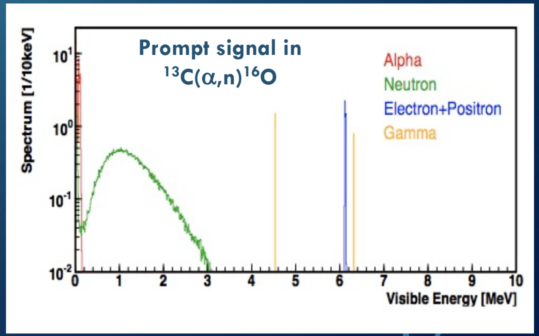


Backgrounds mimicking inverse beta decay reaction expected events:

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

} negligible: 0.418 ± 0.006





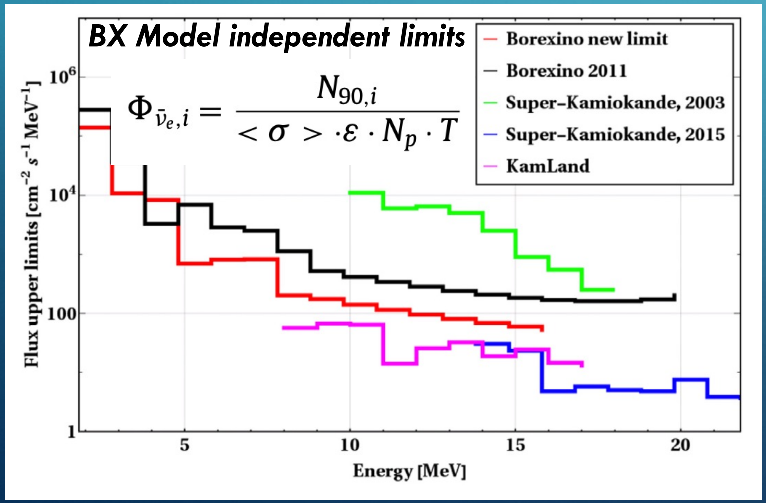
DSNB: UPPER LIMITS

90%C.L. limits without (with) atmospheric ν background

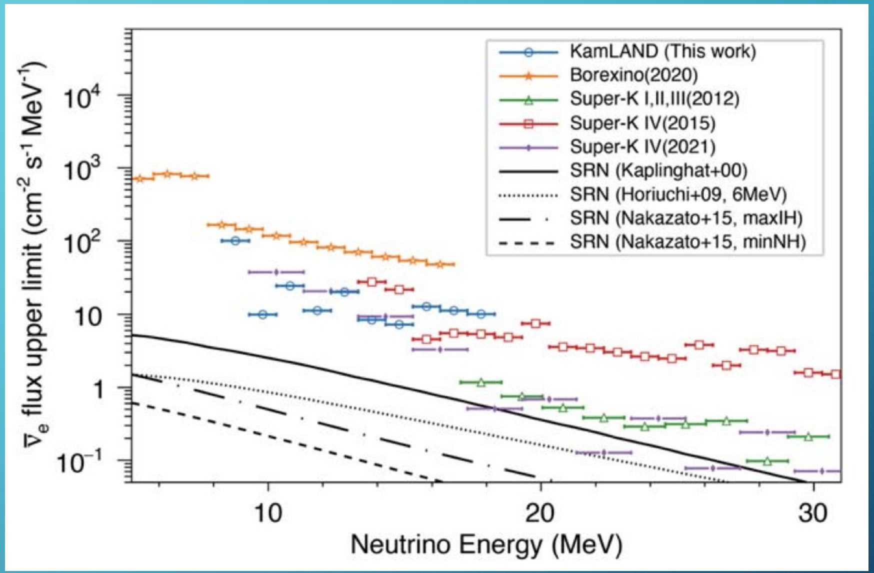
M. Agostini et al., Astroparticle Physics 125 (2021) 102509

E[MeV]	N_{ev}	N_{bkg}	$\Phi[cm^{-2}s^{-1}]$
1.8	39	22.4 (23.0)	1.40 (1.37) × 10^5
2.8	22	21.5 (22.2)	1.07 (1.00) × 10^4
3.8	24	16.7 (17.2)	8.39 (8.13) × 10^3
4.8	7	10.9 (11.5)	6.92 (7.07) × 10^2
5.8	5	5.55 (6.10)	8.08 (7.21) × 10^2
6.8	4	2.04 (2.52)	8.29 (7.68) × 10^2
7.8	0	0.28 (0.72)	2.02 (1.65) × 10^2
8.8	0	0.01 (0.44)	1.75 (1.44) × 10^2
9.8	0	0.00 (0.41)	1.40 (1.17) × 10^2
10.8	0	0.00 (0.39)	11.4 (9.59) × 10^1
11.8	0	0.00 (0.35)	9.50 (8.12) × 10^1
12.8	0	0.00 (0.32)	8.05 (7.01) × 10^1
13.8	0	0.00 (0.31)	6.91 (6.03) × 10^1
14.8	0	0.00 (0.27)	6.00 (5.34) × 10^1
15.8	0	0.00 (0.24)	5.27 (4.74) × 10^1

Impact of atm. μ bck:
3% diff
↓
20% diff



Comparison with literature results



From : KamLAND Coll., Astrophys. J. 925, no.1, 14 (2022)
+ new SK: APJ Letters 951,L27(2023)

- Borexino : best limits below 8 MeV

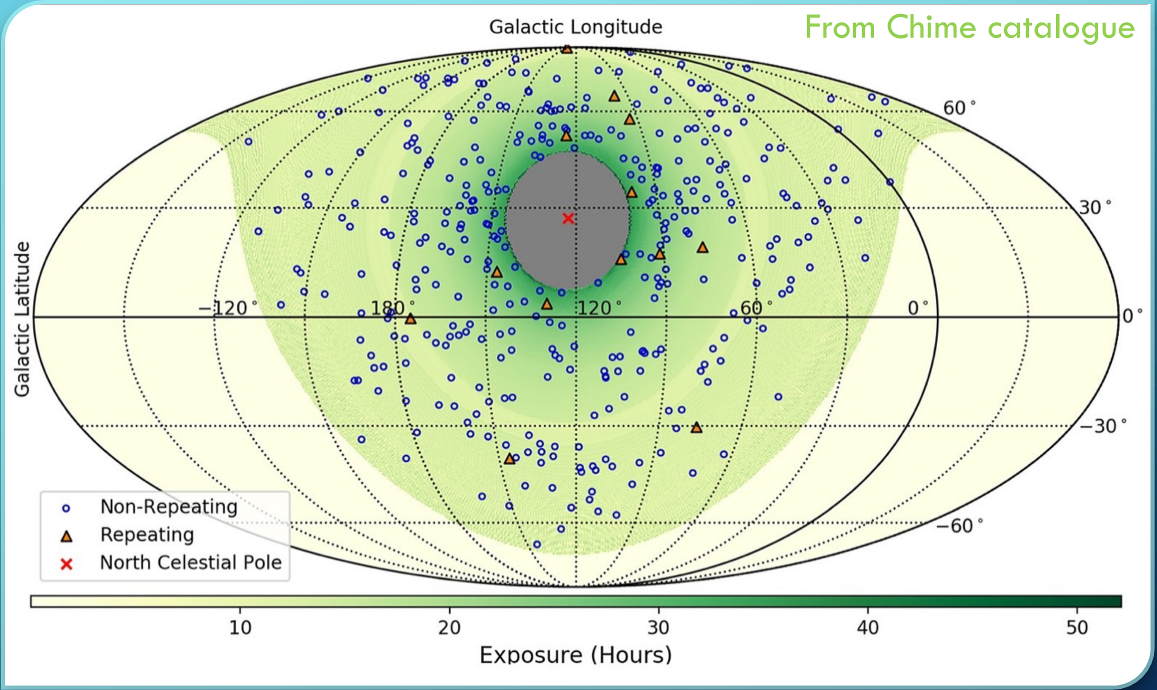
+ 4 years of data available, with improved cosmogenic and FV cuts developed geo-ν analysis=> possible 50 % increase of statistics

FAST RADIO BURSTS

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

- FRB is a millisecond radio transient observed at extragalactic or cosmological distance.
- N_{FRB} ~2 x10^3 /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



BX search :

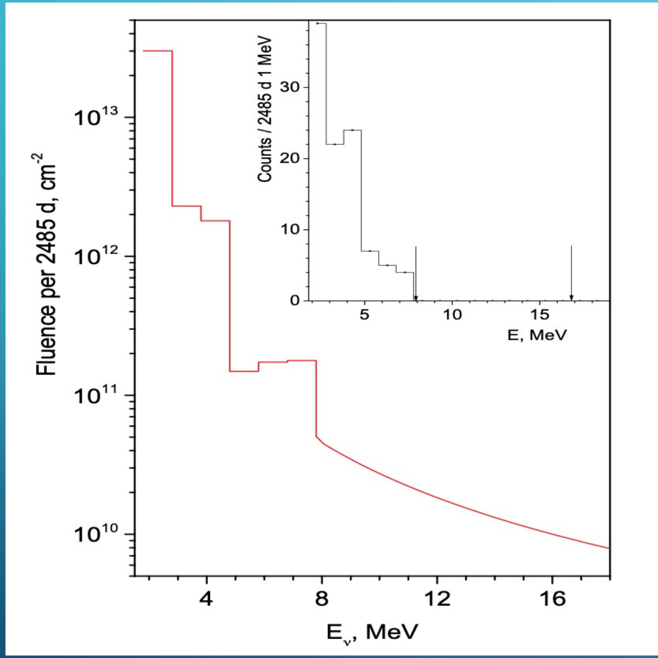
- Time correlated events with intense FRB (fluence>40 Jy ms, 42 FRB) => 20% excess expected ($\Delta T = \pm$ 1000 s)
- Search for specific shapes in the energy spectrum of ν scattering event or IBD events (=>more stringent)

1 Jy = 10^{-26} W m^{-2} Hz^{-1}

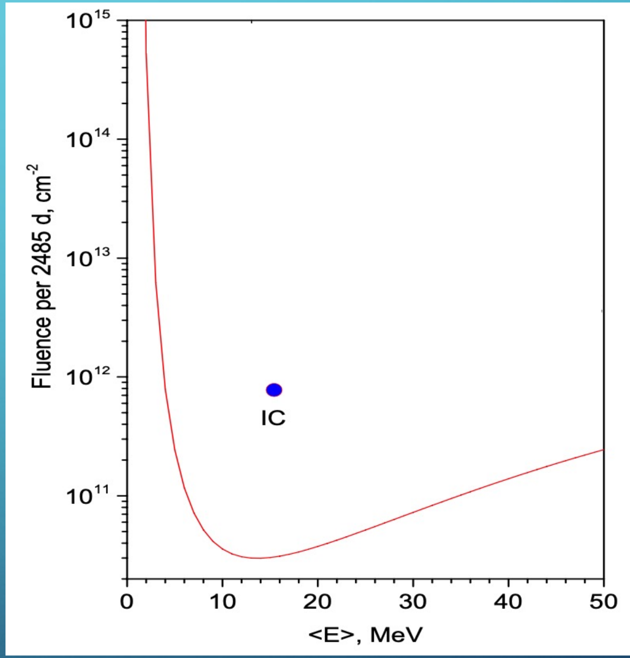
FAST RADIO BURSTS: LIMITS ON ANTINEUTRINO FLUENCE

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, similar bkg, no events with E>7.8 MeV



Upper limits on the fluences of monoenergetic anti-ν_e



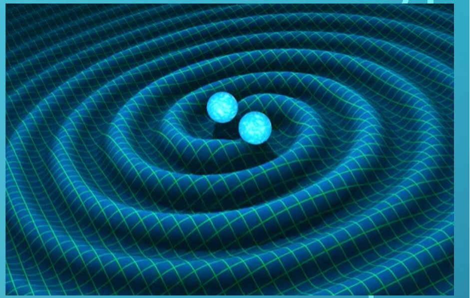
Limits for SN neutrino spectra-like of mean energy <E> and α=3 (from no events observed in 7.8-16.8 MeV interval)

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

ICeCube: Aartsen et al APJ 890:111 2020

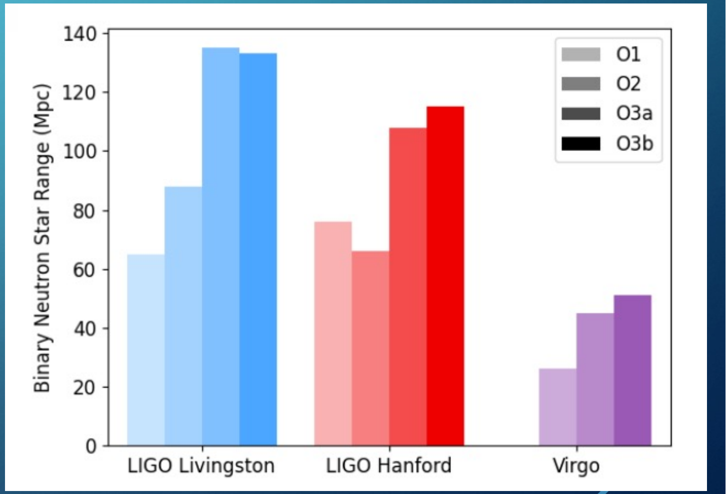
BOREXINO: NEW SEARCH FOR GW CORRELATED EVENTS

Borexino Collaboration, Eur. Phys. J. C (2023) 83:538

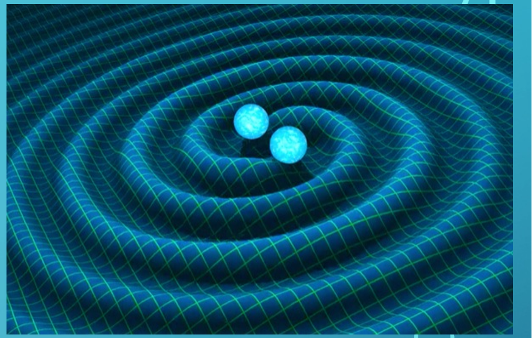


- The search for neutrino events in correlation with gravitational wave (GW) events for three observing runs (O1, O2 and O3) from GWTC-3 catalog
- Statistics : Sep 2015 – March 2020 => Borexino taking data for:
- 70 (out of 87) black hole - black hole ((BH-BH) mergers
- 2 neutron star - neutron star mergers (NSNS)
- 2 (out of 4) neutron star - black hole mergers (NSBH)

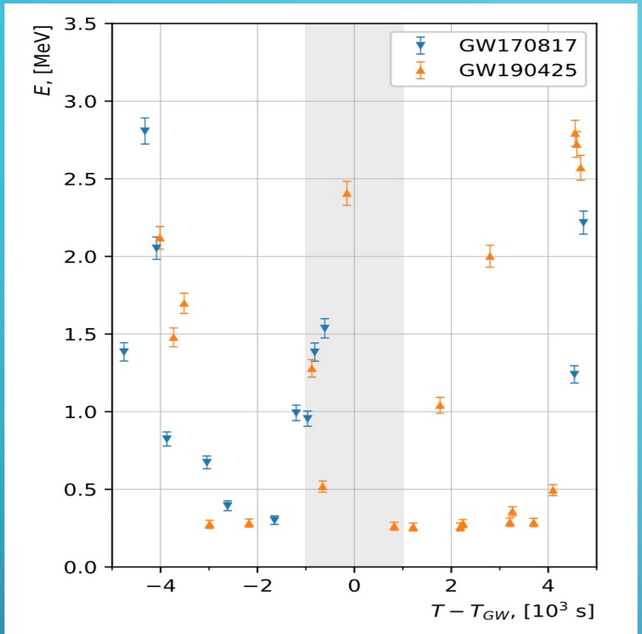
- The search was done looking both at neutrino-electron scattering and inverse beta decay events in a ± 1000 s time interval around GW detection (covering possible earlier emissions and delay of sub-MeV neutrinos propagating at the sublight speed)
- Background evaluated in two adiacent intervals [-5000,-1000]s and [1000,5000]s



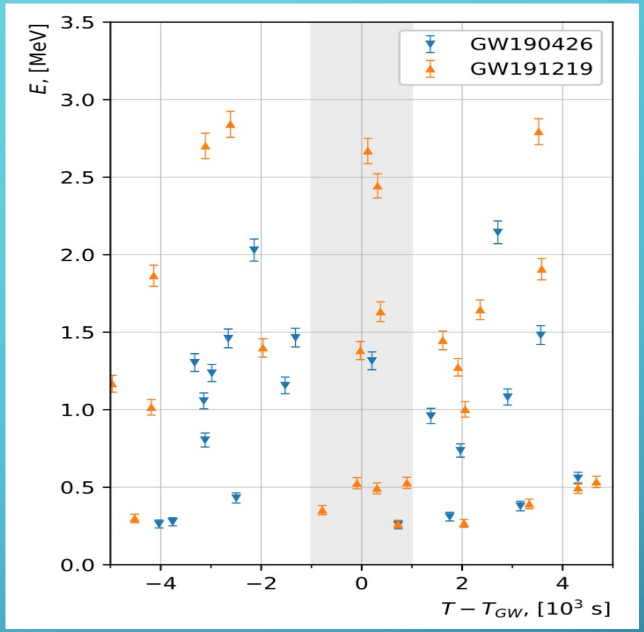
SEARCH FOR CORRELATED SINGLE EVENTS



NS-NS GW events



NS-BH GW events



- Visible energy window : 0.25-16.8 MeV; Cosmogenic cut: 0.3 s veto after internal μ ;
- Fiducial volume: 145 tons (75 cm from inner vessel)

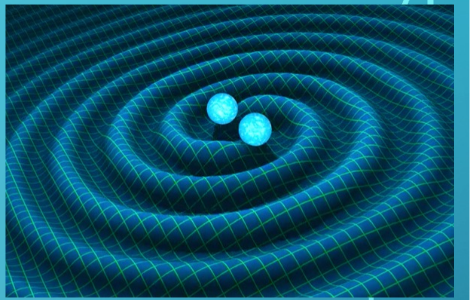
- In the following table are shown the number of BX single events in ± 1000 s interval around GW detection with energy above 0.25 MeV in comparison with the reduced backgrounds defined for intervals [−5000... −1000,1000...5000] s:

GW mode	170817 NSNS	190425 NSNS	190426 NSBH	191219 NSBH	70 GWs BHBH
N_1	3	4	2	9	304
B_1	2.5 ± 0.8	4.3 ± 1.0	4.8 ± 1.1	4.3 ± 1.1	310 ± 9

P(n≥9, μ=4.3)=3%

Some excess but compatible with background

UPPER LIMITS FOR ALL 74 GW EVENTS



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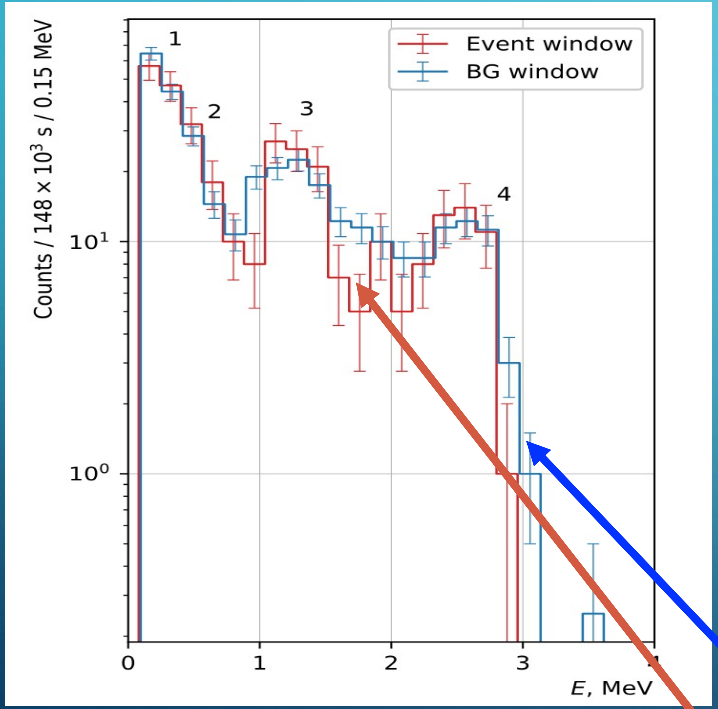
Mono-energetic neutrino fluences limits (90% C.L.) obtained through the analysis of (ν,*e*) elastic scattering events correlated with all 74 GW

Neutrino energy => recoiled electron spectrum => correlated events and background betweek (E_{th},E_{max})

threshold on visible energy tuned accordingly (0.25, 0.8 or 3 MeV)

(ν,e) scattering events visible energy



1 – ^{210}Po α- peak, 2 – recoiled electrons from the solar ^{7}Be-neutrino, 3 – ^{11}C β+-decay, 4 – external background (^{208}Tl)

r =efficiency

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

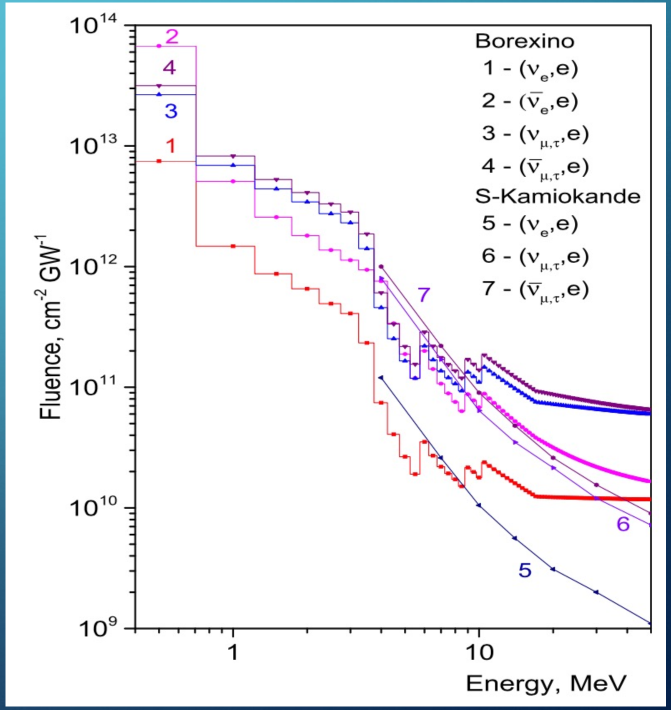
Limits on fluences (10^9 cm^{-2}) 90%C.L.

E_ν	Φ_{ν_e}	$\Phi_{\bar{\nu}_e}$	$\Phi_{\nu_{\mu,\tau}}$	$\Phi_{\bar{\nu}_{\mu,\tau}}$	$\Phi_{\bar{\nu}_e}$ IBD
2	650	1800	3400	4100	100
6	35	200	220	290	1.7
10	18	68	110	140	0.51
14	16	52	97	120	0.25
18	12	36	74	91	–
30	12	22	66	75	–
50	12	17	60	66	–
⟨15.6⟩	12	19	63	71	0.48

Background

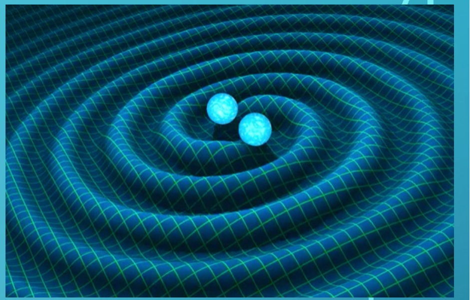
Time correlated events

Limits for monocromatic neutrinos



BOREXINO
Best limits below 5 MeV

GW: INVERSE BETA DECAY EVENTS SEARCH

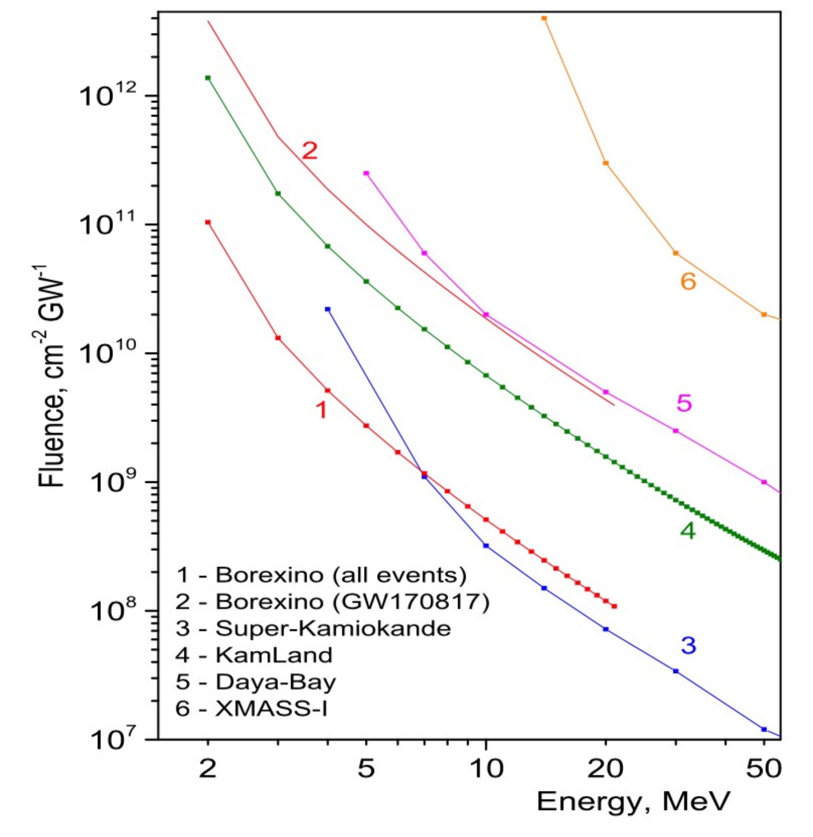


- Events selection cuts similar to the one adopted for DSNB study
- No correlated observed
- $N_{90}(E_\nu, n_{obs}, n_{bkg}) = 2.44$

$$\Phi_{\bar{\nu}_e,i} = \frac{N_{90,i}}{<\sigma> \cdot \varepsilon \cdot N_p \cdot T}$$

Improvement below 7 MeV

Limits 90% C.L.



1. 2. *Eur. Phys. J. C* (2023) 83:538
3. *Astrophys. J.* **857**, L4 (2018)
4. *Astrophys. J.* **909**, 116 (2021)
5. *Chin. Phys. C* **45**, 055001 (2021)
6. *Astropart. Phys.* **129**, 102568 (2021)

SN remnant by HST

NEUTRINOS FROM THE COSMOS

Overview of BOREXINO studies & papers

- Diffuse supernovae neutrino background(*)
- Time correlated signals with:
  - Solar flares(*)
  - Gamma Ray Bursts(**)
  - Fast radio bursts(***)
  - Gravitational waves (****)

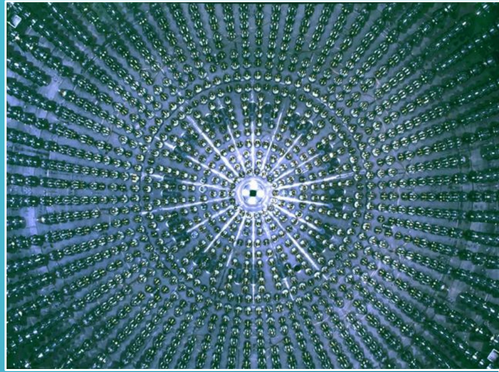
**Astroparticle Physics 125 (2021) 102509*

***Astroparticle Physics 86, (2017) 1-17*

****Eur. Phys. J. C 82, 278 (2022)*

*****Eur. Phys. J. C 83 (2023) 538 (older: ApJ, 850-21,(2017)*

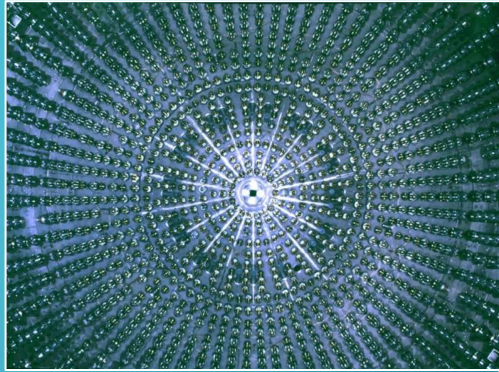
CONCLUSIONS



- Thanks to the extreme radiopurity and the underground site Borexino achieved an exceptional sensitivity to ν/anti–ν from Earth and Cosmos
- Borexino has achieved :
  - the best upper limits on DSNB anti-ν_e flux for E_ν< 8 MeV,
  - the best upper limits on FRB-associated neutrino fluences of all flavors in the 0.5 – 50 MeV neutrino energy range

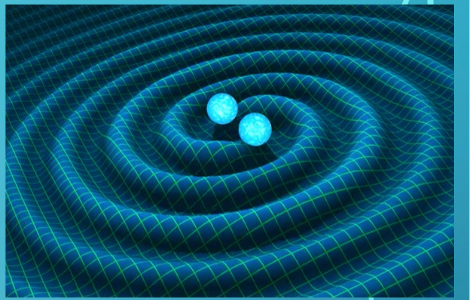
  best limits for possible GW correlated events in 0.5-5 MeV
- In previous searches no excess of events was observed in coincidence with solar flares and GRB's
- Pointing capability with liquid scintillator-based detectors : fundamental importance for **neutrino astronomy** with future large detectors!!

Thanks
for your
attention!!!!



BACKUP

UPPER LIMITS FOR GW 170817



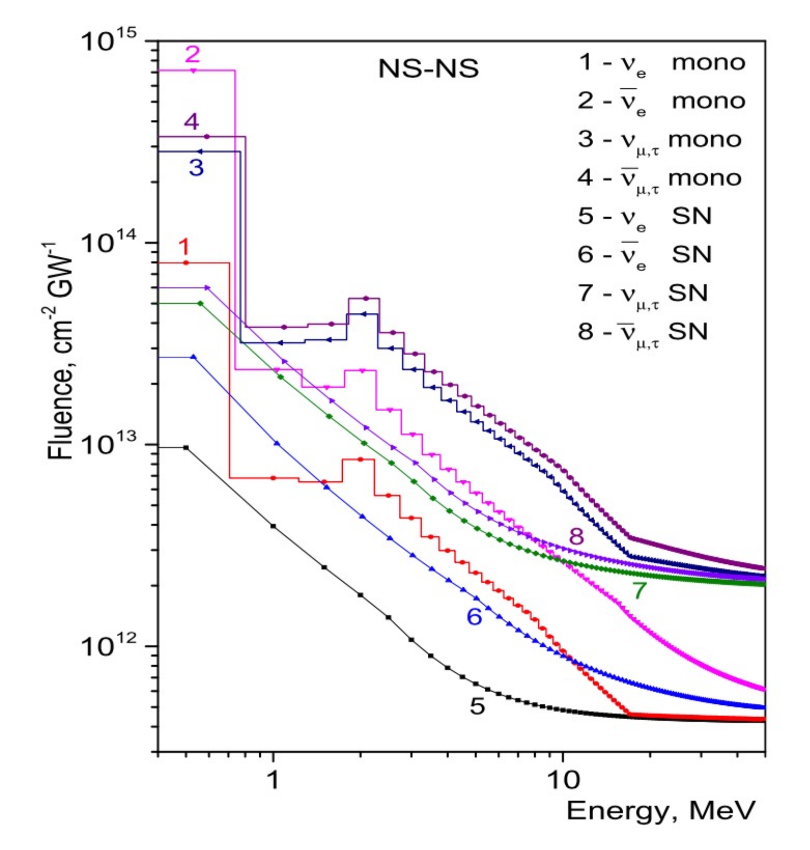
90% C.L. upper limits obtained through the study of (ν, *e*) elastic scattering of monoenergetic neutrinos and IBD reaction. E_ν is given in MeV units, Φ in in 10^{12} cm^{-2} units

Monoenergetic neutrinos

E_ν	Φ_{ν_e}	$\Phi_{\bar{\nu}_e}$	$\Phi_{\nu_{\mu,\tau}}$	$\Phi_{\bar{\nu}_{\mu,\tau}}$	$\Phi_{\bar{\nu}_e}$ IBD
2	8.4	23	44	53	3.8
6	1.9	4.7	11	13	0.062
10	0.95	2.6	5.9	7.4	0.019
14	0.59	1.8	3.6	4.5	0.0090
18	0.46	1.3	2.8	3.4	–
30	0.44	0.81	2.4	2.8	–
50	0.44	0.61	2.2	2.4	–

Neutrinos with supernova <E> spectrum

⟨*E*⟩	Φ_{ν_e}	$\Phi_{\bar{\nu}_e}$	$\Phi_{\nu_{\mu,\tau}}$	$\Phi_{\bar{\nu}_{\mu,\tau}}$	$\Phi_{\bar{\nu}_e}$ IBD
2	1.8	4.4	10	12	1.7
6	0.58	1.4	3.4	4.0	0.12
10	0.48	0.89	2.7	3.0	0.046
14	0.46	0.73	2.4	2.7	0.040
18	0.45	0.65	2.3	2.5	0.037
30	0.43	0.55	2.1	2.3	0.069
50	0.43	0.50	2.0	2.2	0.21



Improved limits in case of SN - ν spectrum

OPTIMIZED IBD SELECTION CUTS

Efficiency: $(86.98 \pm 1.50)\%$

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

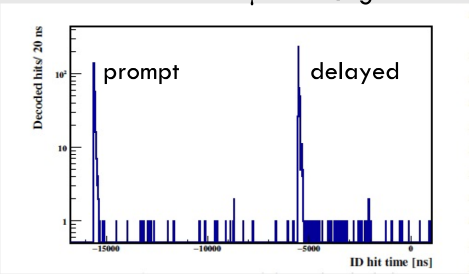
- Neutron captures on proton (2.2 MeV) and in about 1% of cases on **^{12}C (4.95 MeV)**
- Spill out effect at the nylon inner vessel border
- Radon correlated $^{214}Po(\alpha + \gamma)$ decays from ^{214}Bi and ^{214}Po fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

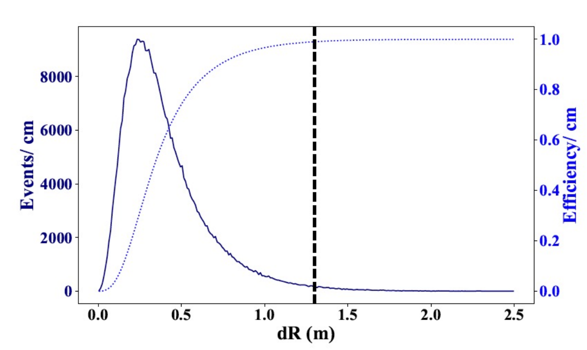
Neutron capture $\tau = (254.5 \pm 1.8)$ μs

2 cluster event in 16 μs DAQ gate



Space correlation

dR < 1.3 m

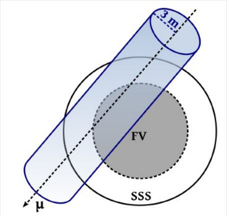


Muon veto

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

2 ms: neutrons

- Several veto categories
- Strict and special muon tags



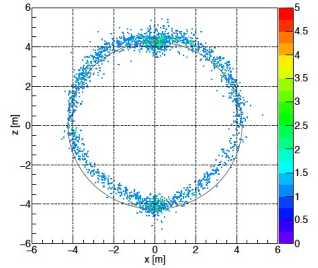
- Whole detector
- **Cylinder**

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



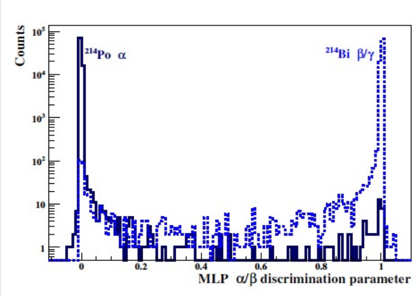
Multiplicity

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

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

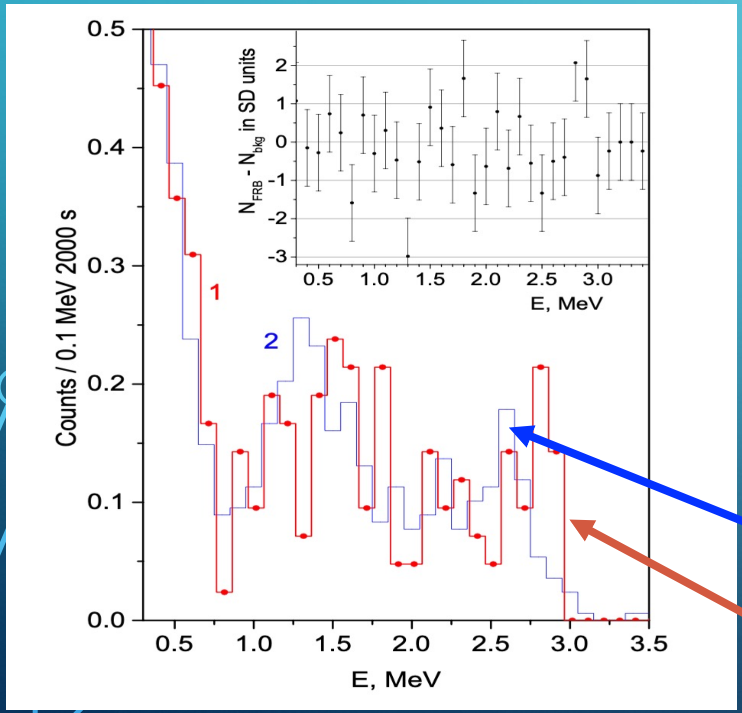
α/β discrimination

$MLP_{delayed} > 0.8$



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)



ν scattering events energy

Background

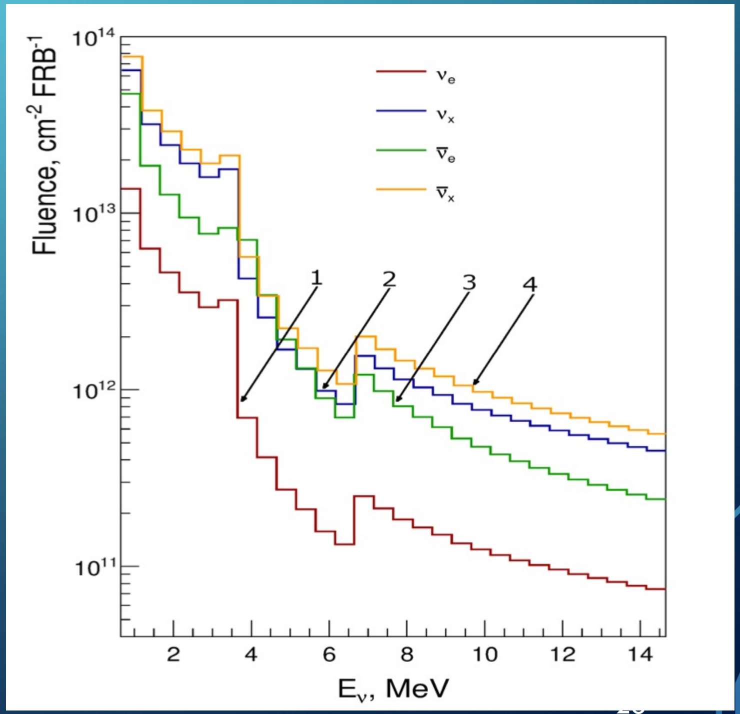
Time correlated events

(1 further event at 6.8 MeV)

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

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

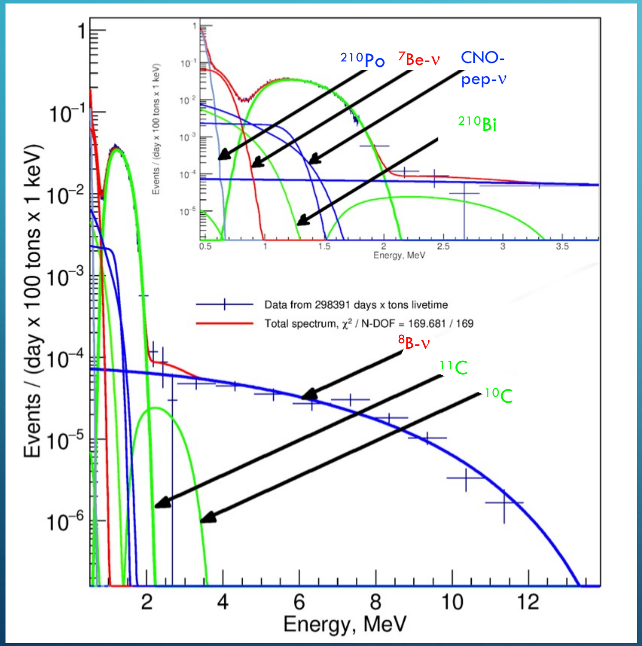
E_ν	Φ_{ν_e}	$\Phi_{\bar{\nu}_e}$	$\Phi_{\nu_{\mu,\tau}}$	$\Phi_{\bar{\nu}_{\mu,\tau}}$	IBD
2	4620	12750	24250	29000	2475
6	157	890	890	1280	40.7
10	125	475	770	970	12.2
14	77.5	255	474	590	5.88
< 15.6 >	157	367	900	1070	11.6



Limits for monocromatic neutrinos

FAST RADIO BURSTS: FIT OF BOREXINO SCATTERING EVENTS SPECTRUM

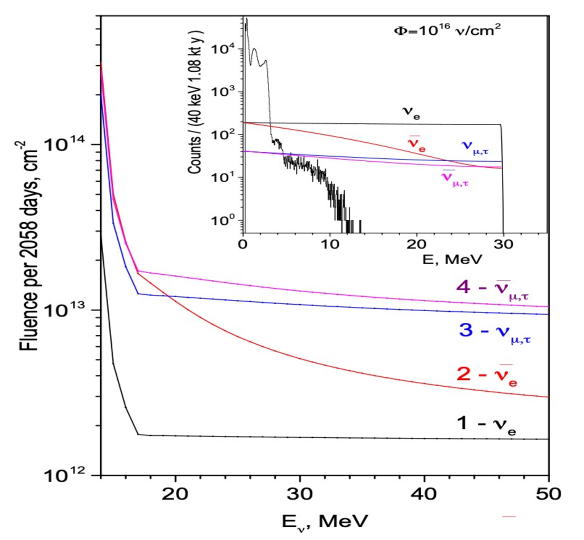
- Statistics Jan 2013-Nov 2020: 2058 days (exp. 298.39 kt day)
- N_{FRB} ~ 4 x10^6 in the data period
- Selected events with energy : 0.5-14 MeV
- Fiducial volume : 145 tons (75 cm from vessel)
- Advanced cosmogenic veto system + ^{11}C cuts> 15.8% dead time
- External background stat. subtracted through events radial fit



Spectral fit repeated by adding a «FRB» component

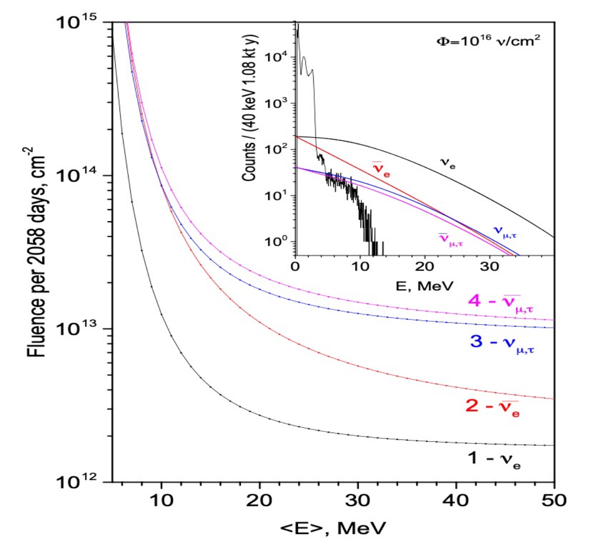
From the χ^2 increase
$\Delta\chi^2 = (1.64)^2 \Rightarrow N_{90}$

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



Limits from no events in the range 13.9-16.8 MeV

Monoenergetic neutrinos



Supernovae ν spectra-like with <E>

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

$\alpha=3$

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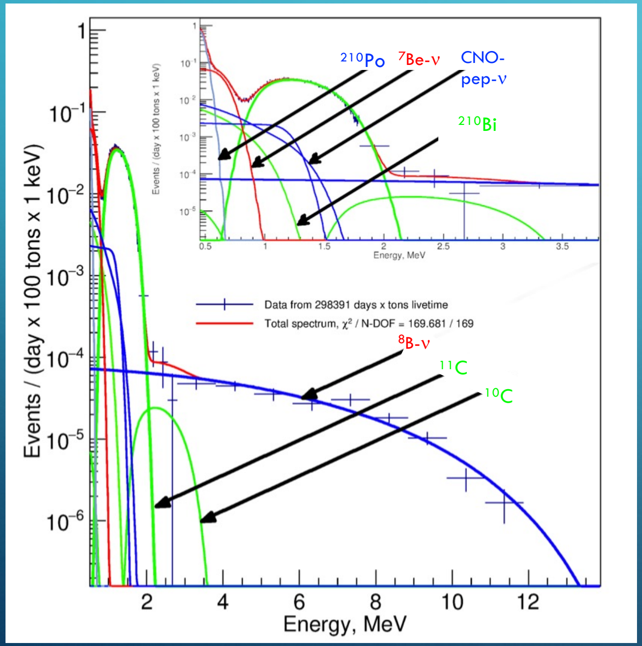

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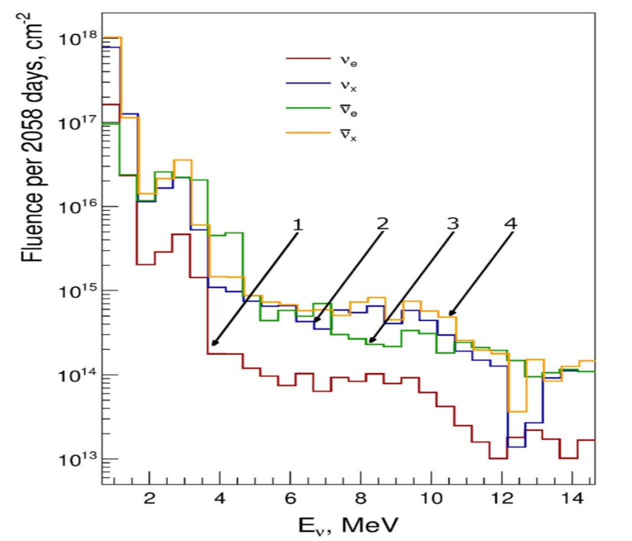
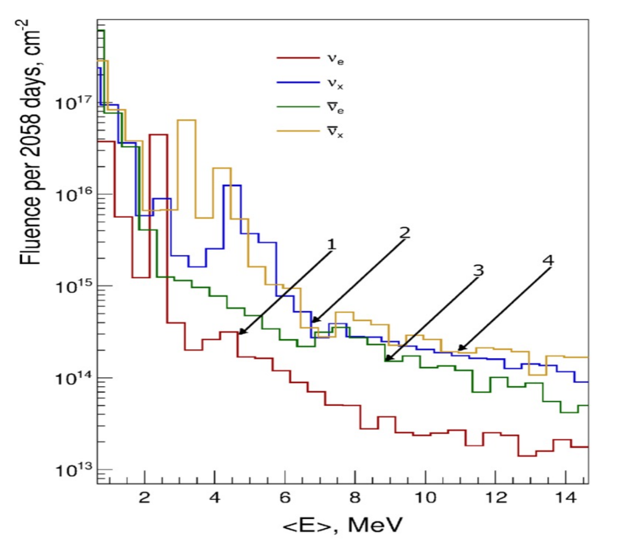


Monoenergetic neutrinos



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