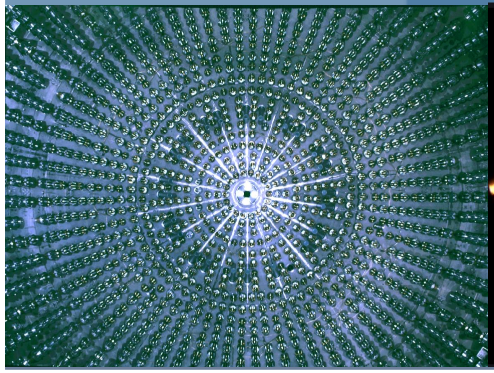
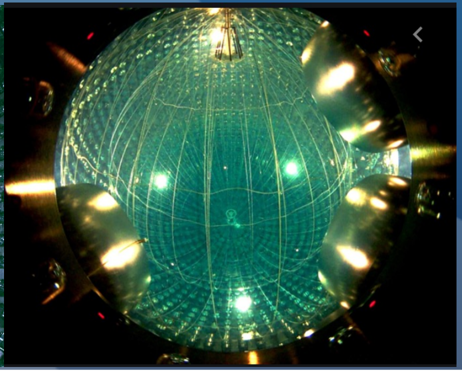
Istituto Nazionale di Fisica Nucleare

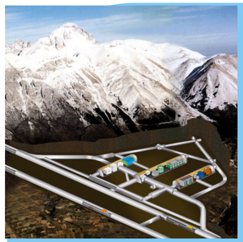
NOW 2024
Neutrino Oscillation Workshop

Ultra-low background physics: lessons from Borexino and future steps



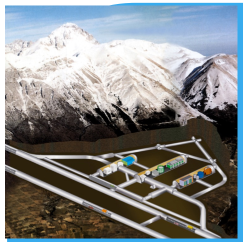


S. Zavatarelli
INFN - Genoa (Italy)
on behalf of the BOREXINO collaboration



Talk layout

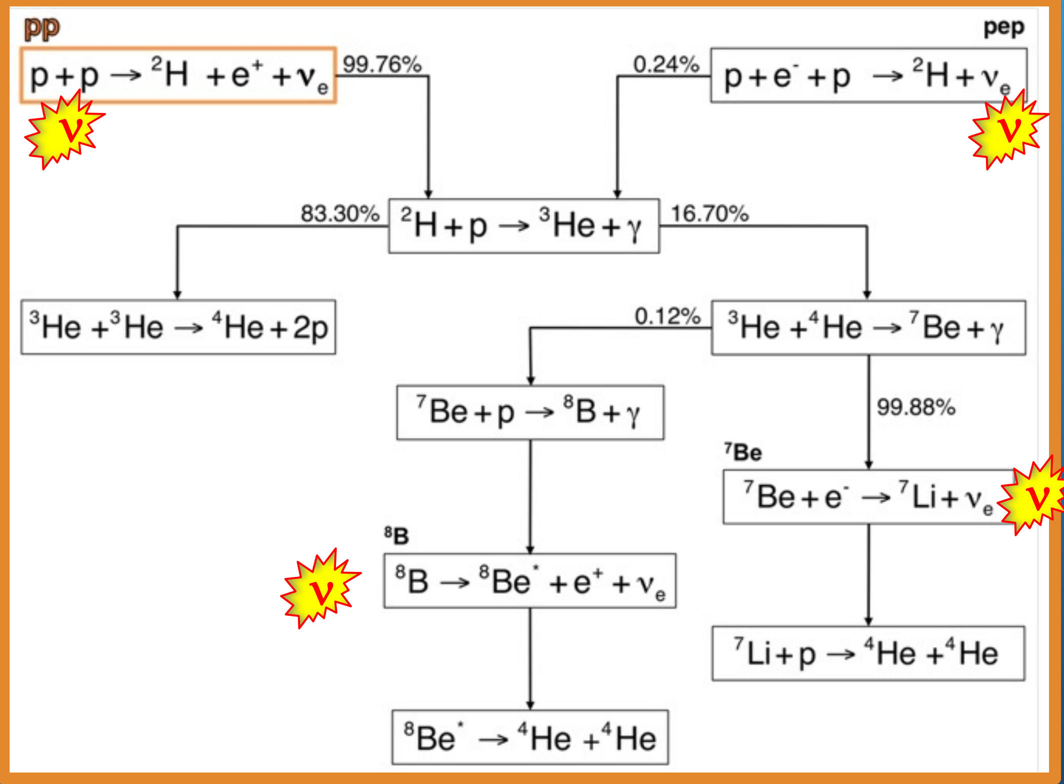
- The Borexino experiment:
- Reasons (and methods) for pushing the radiopurity to world's record values!
- Gellery of Borexino results
- Borexino legacy: how to further improve?
- New technique and future detectors : some examples
- Conclusions



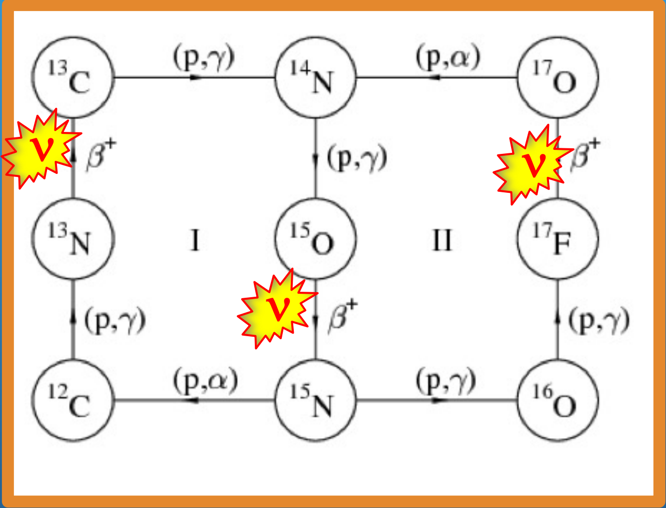
The BOREXINO main goal:

Solar neutrinos..

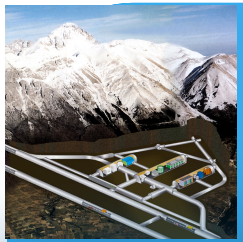
pp chain: 99 % of Sun Energy



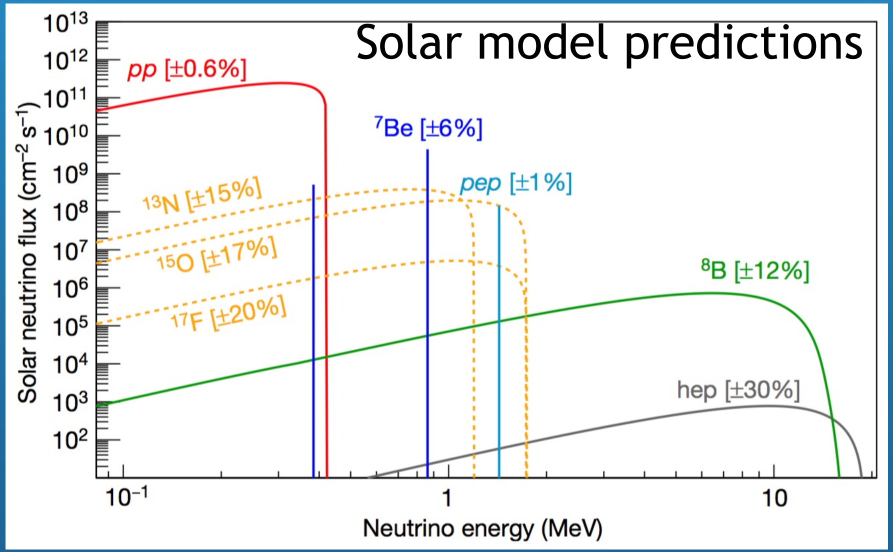
CNO cycle: <1 % of Sun Energy

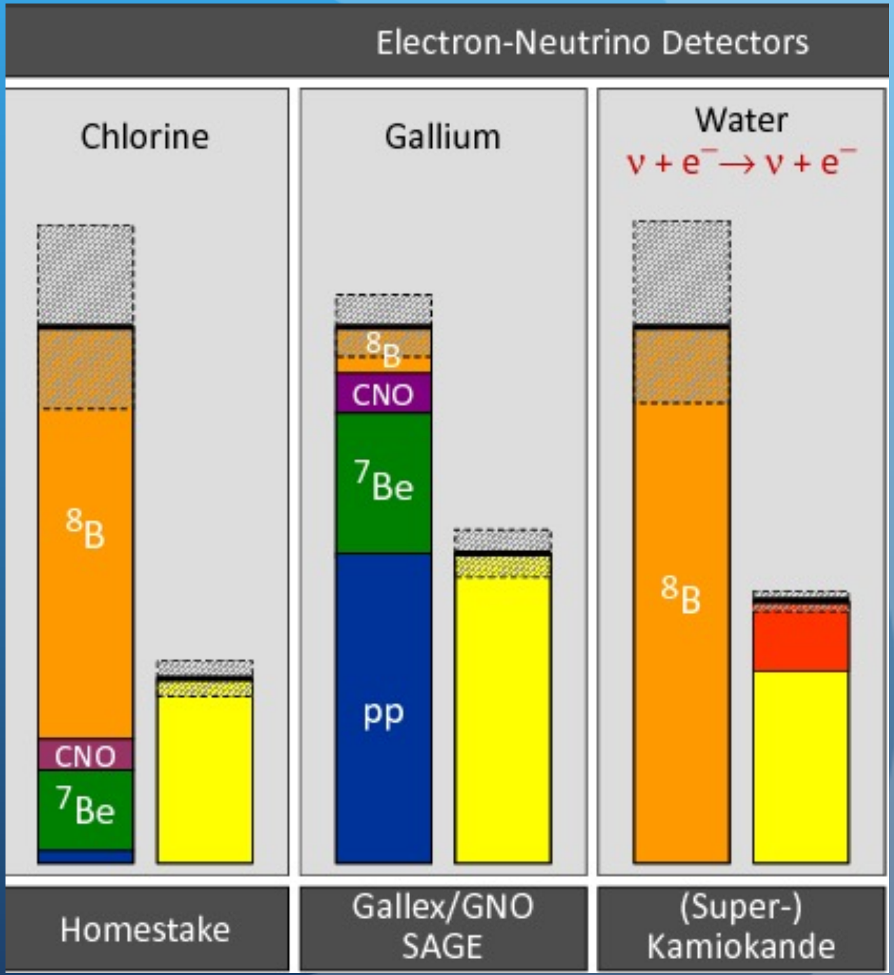


..studied since the '60 to probe solar structure and energy production



The solar neutrino problem: Homestake/Kamioka/Gallex-Sage

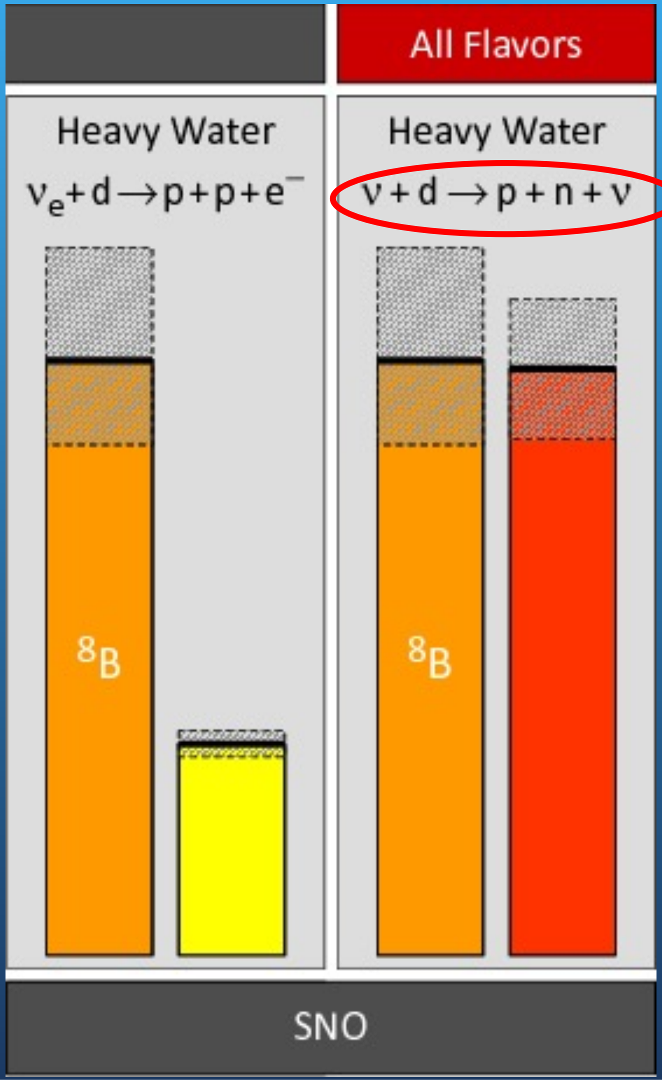


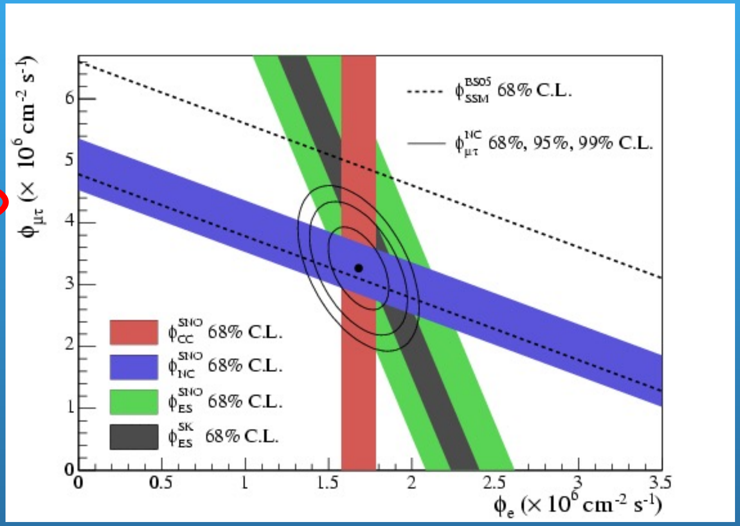


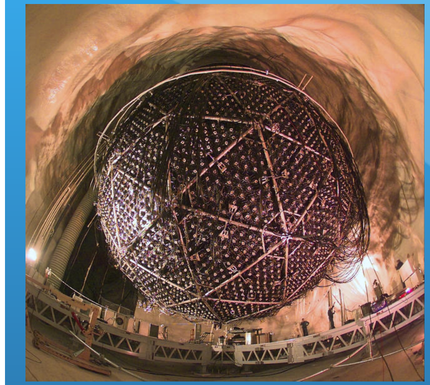
…in the early '90 (time of the Borexino project) : Solar neutrino problem!!

measured fluxes ≠ predictions

The solution: SNO experiment (year:2000)



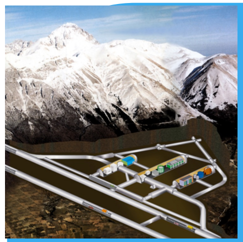




$\Phi_{NC}(\nu_x)=(4.94 \pm 0.21\ (stat)\ ^{+0.38}_{-0.34}\ (syst.))\times 10^6\ cm^{-2}s^{-1}$
391 days salt phase

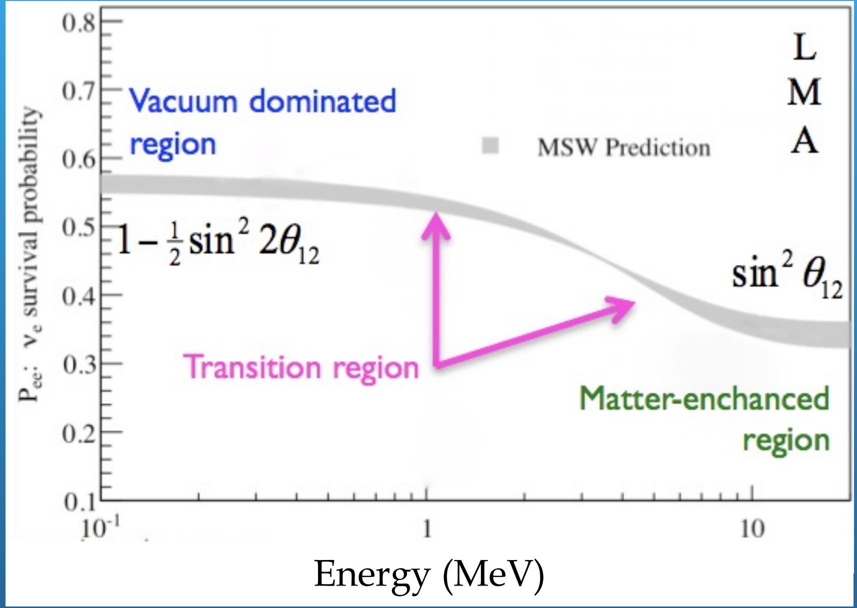
$\Phi_{SSM}(\nu_x)= 5.46\ (1\pm 0.12)\times 10^6\ cm^{-2}s^{-1}$

Solar neutrinos are massive and undergo flavor conversion during their trip from Sun to Earth

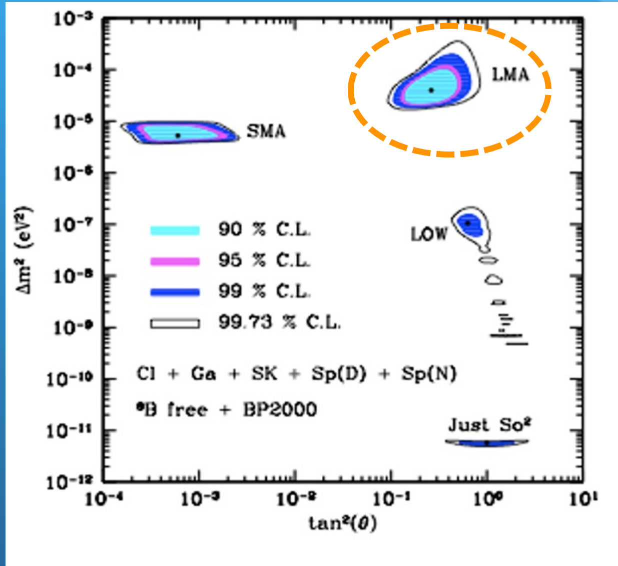


Flavour oscillations in the Sun

Solar ν_e survival probability



Global analysis of all solar ν data



[Bahcall, Krastev, Smirnov, JHEP 05 (2001) 015]

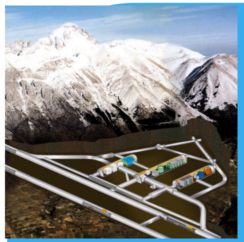
The best fit to all solar ν experiments + KamLAND selected the so-called LMA-MSW

LMA-MSW paradigm : enhanced conversion in the Sun for multi-MeV neutrinos because of ν_e forward scattering process with electrons (MSW effect)

$$P_{ee}^{3\nu} = \frac{1}{2}\cos^4\theta_{13}\left(1+\cos 2\theta_{12}^M \cos 2\theta_{12}\right)$$

$$\cos 2\theta_{12}^M = \frac{\cos 2\theta_{12} - \beta}{\sqrt{(\cos 2\theta_{12} - \beta)^2 + \sin^2 2\theta_{12}}}$$

$$\beta = \frac{2\sqrt{2} G_F cos^2\theta_{13} n_e E_\nu}{\Delta m^2_{12}}$$

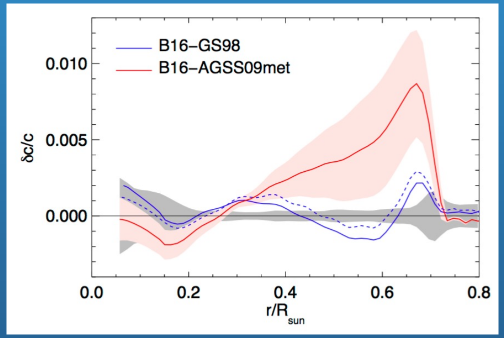


After SNO : importance of a precision spectrocopy → Sun physics

(1) SSM-HZ= B16-GS98: Vinyoles et al. Astr.J. 835 (**2017**) 202 + Grevesse et al.,Space Sci.Rev. (**1998**)85
(2) SSM-LZ= B16-AGSS09met: Vinyoles et al. Astr.J. 835 (**2017**) 202 + A. Serenelli ert al., Astr. J. 743,(2011)24
J. Bahcall et al Phys.Rev.D53:4202-4210,1996

Metallicity puzzle
(abundance of elements Z>2)

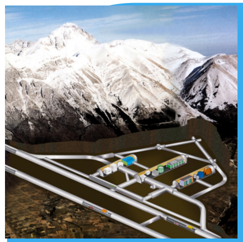
23% difference on Z/X



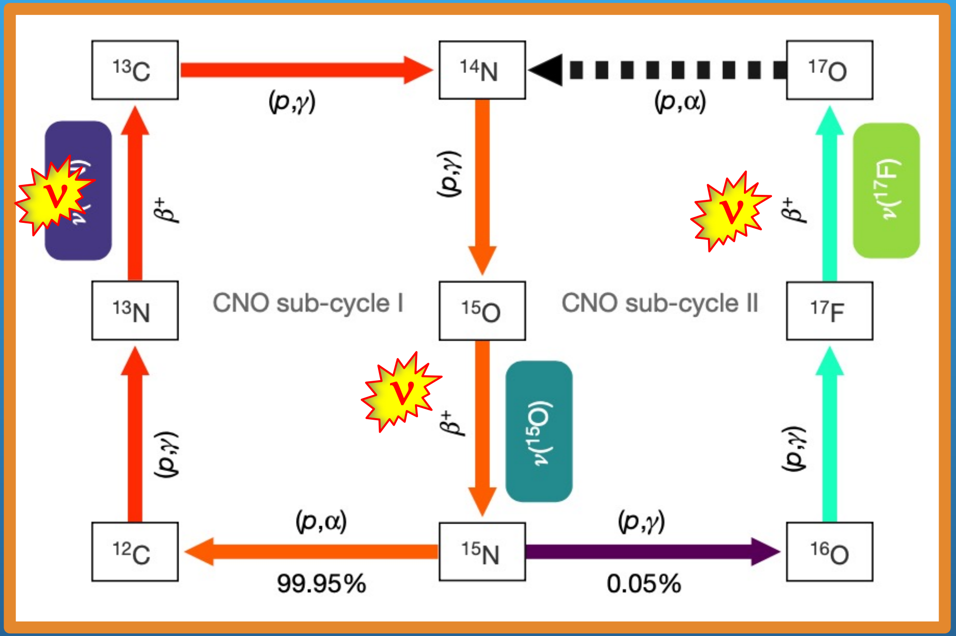
	FLUX	Dependence on T	SSM-HZ(1)	SSM-LZ(2)	DIFF. (HZ-LZ)/HZ
pp chain	pp (10^{10} cm^{-2} s^{-1})	$T^{-0.9}$	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pp chain	pep (10^{8} cm^{-2} s^{-1})	$T^{-1.4}$	1.44(1±0.01)	1.46(1±0.009)	-1.4%
pp chain	^{7}Be (10^{9} cm^{-2} s^{-1})	T^{11}	4.94(1±0.06)	4.50(1±0.06)	8.9%
pp chain	^{8}B (10^{6} cm^{-2} s^{-1})	T^{24}	5.46(1±0.12)	4.50(1±0.12)	17.6%
CNO	^{13}N (10^{8} cm^{-2} s^{-1})	T^{19}	2.78(1±0.15)	2.04(1±0.14)	26.6%
CNO	^{15}O (10^{8} cm^{-2} s^{-1})	T^{20}	2.05(1±0.17)	1.44(1±0.16)	29.7%
CNO	^{17}F(10^{6} cm^{-2} s^{-1})	T^{23}	5.29(1±0.20)	3.26(1±0.18)	38.3%

metallicity
↓
opacity
↓
temperature
↓
ν fluxes

- ✓**Understand the high/Low metallicity solar model controversy**
- ✓**Understand the role of CNO cycle (if any)**
- ✓**Improve the knowledge of mixing parameters, confirm MSW-LMA or exploit possible traces of non-standard neutrino-matter interaction, sub-leading effects, mixing with light sterile ν's**



After SNO : importance of a precision spectrocopy → Sun physics



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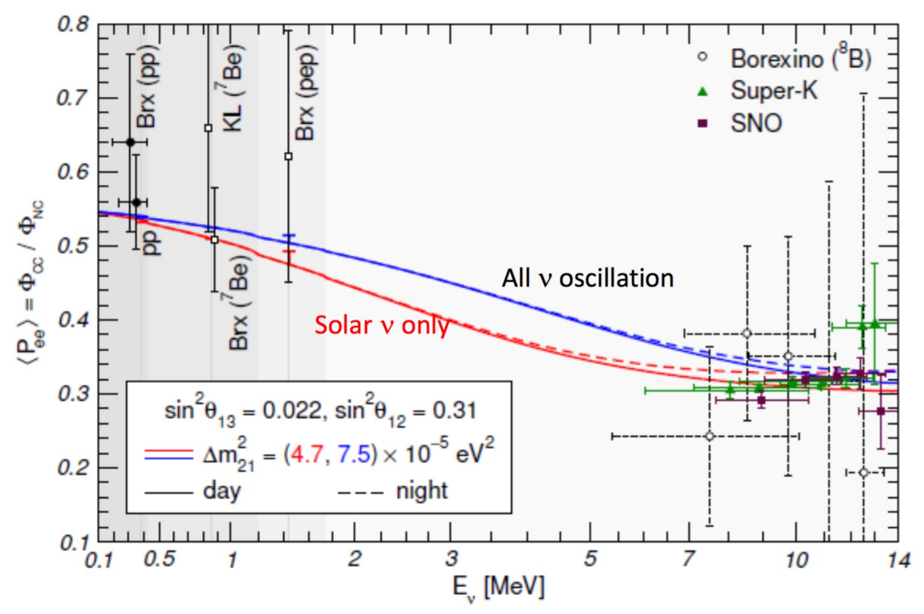
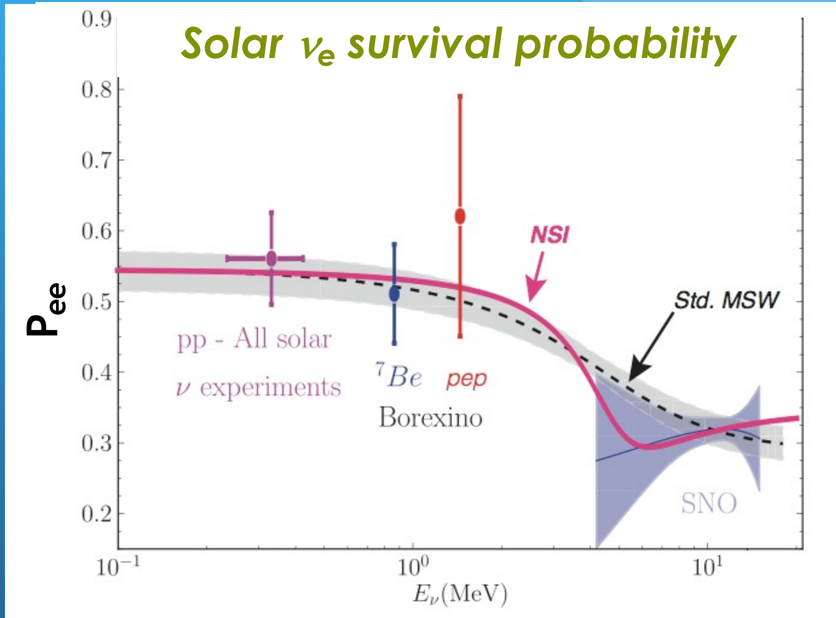
After SNO: Importance of a precision spectrocopy→ Particle physics



Maltoni & Smirnov, Eur.Phys.J.2016



Frieland arXiV: 1207.6642

- ✓**Understand the high/Low metallicity solar model controversy**
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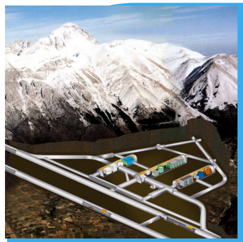
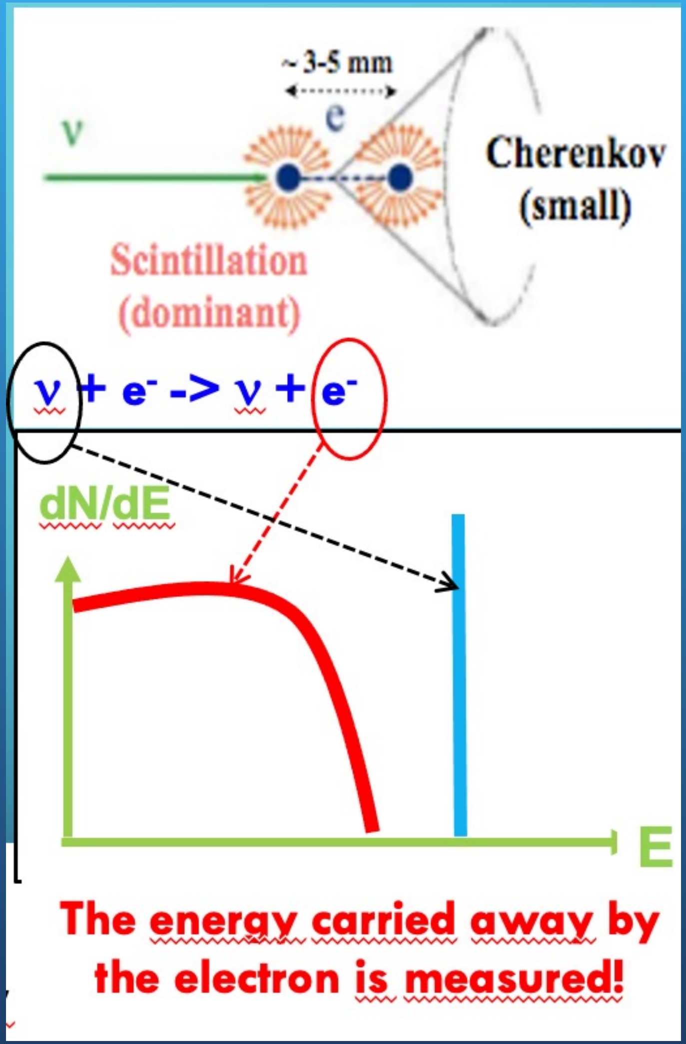
↳*Limits also from coherent scattering with nuclei*



BOREXINO: the quest for the radiopurity grail



Goal: to measure the single component of solar neutrinos with energy threshold well below 1 MeV
Good energy resolution at low energy => **scintillation detector**

Detection via scintillation light→ High light yield (10^4 ph/MeV):

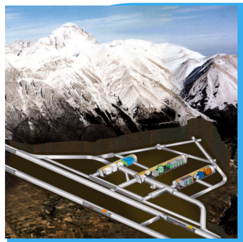
- Very low energy threshold,,Good energy and position reco

…but it is isotropical so no direction measurement! The ν induced events can't be distinguished from other β events due to natural radioactivity

The expected signal rate from ^{7}Be solar ν : ~ **5 10^{-9} Bq/Kg**
Glass of drinking water activity : ~ **10 Bq/Kg**
→ **the core of the detector should be 10 order of magnitude less radioactive than anything on Earth !!!**

A huge effort was devoted to the:

1. **detector design;**
2. **scintillator purification systems;**
3. **material selections, cleanliness procedures**
4. **development of a small scale demonstrator**



(1) Detector design

NIM-A 600 (2009) 568-593 JINST 7 (2012) P10018

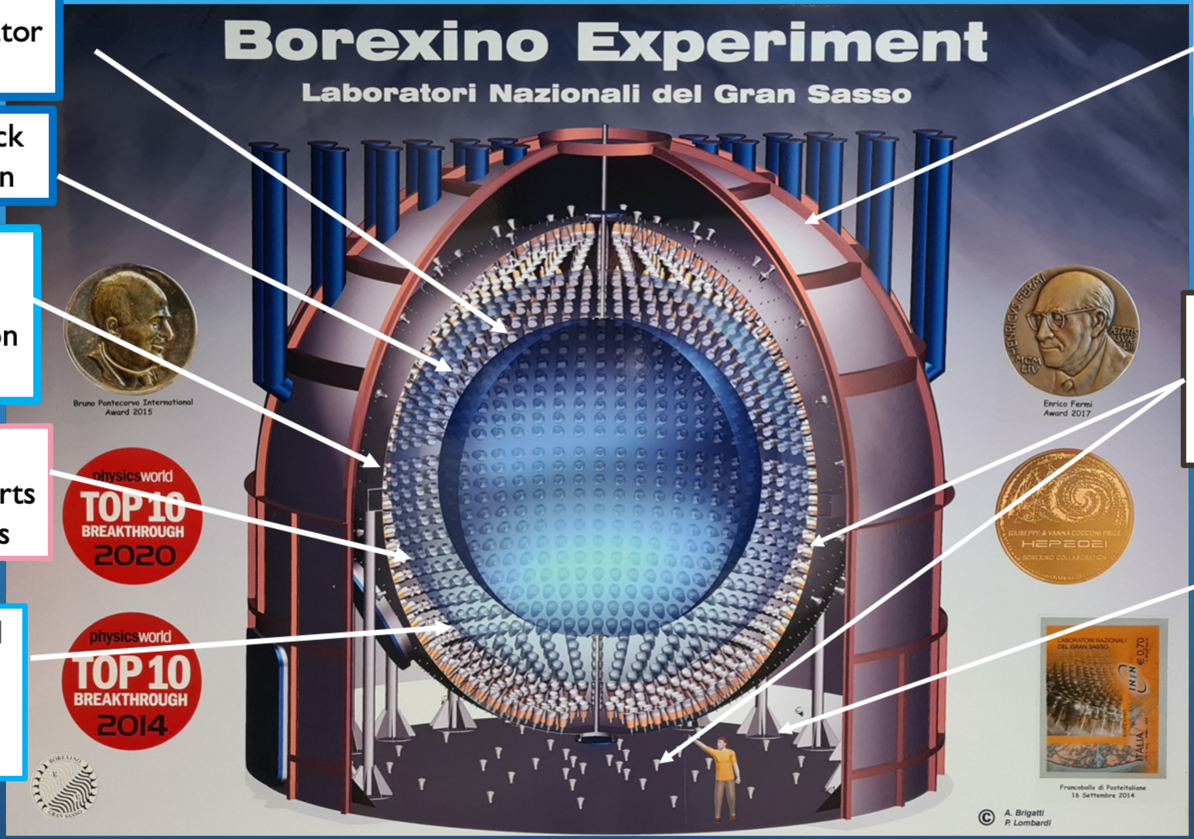
278 tons of liquid scintillator PC+PPO

IV-125 μm thick ultrapure nylon

OV 2nd nylon Vessel- barrier against emission PMT and SSS

SSS (6.85 m radius),supports 2212 8” PMTs

Buffer liquid 600 t PC+DMP (3.5 g/l)



WT, 16.9 m high and 9.0 m of radius; 2400 t ultrapure water.

TYVEK to enhance light collection, the SSS outer wall and the WT inner walls

200 PMTs- muon veto

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

External background suppression: underground site (LNGS) + graded shielding principle: the closer the layer was to the center, the greater its radio-purity

(2) Liquid purification and handling

Choice : Organic Scintillator (easier to purify)

IV : pseudocumene (PC , $C_6H_3(CH_3)_3$) +PPO (1.5 g/l)
Buffer: PC+DMP (5g/l) -> 2.5 g/l

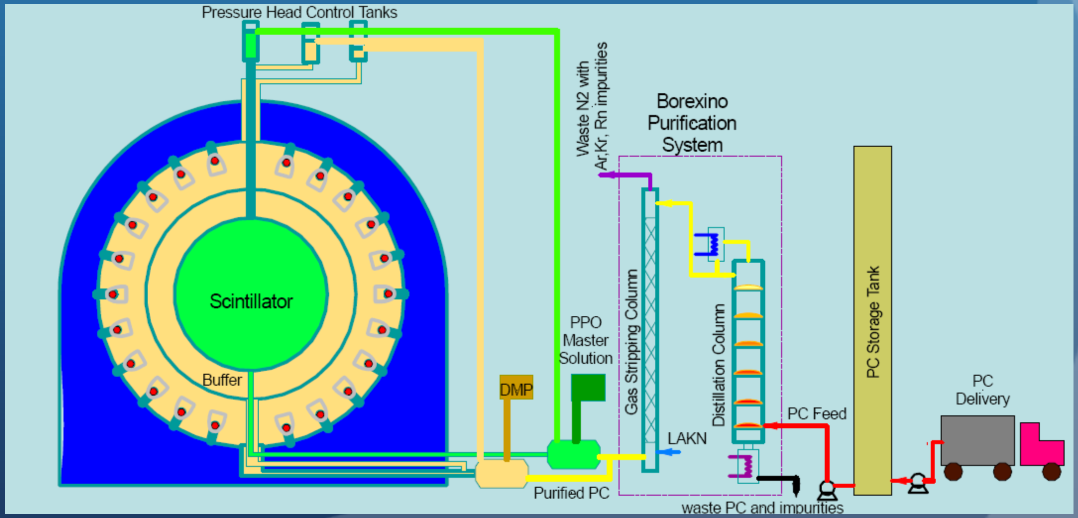
PC obtained from very old oil reservoir to reduce cosmogenic ^{14}C → produced and quickly moved underground to reduce cosmic activation
Purified on site with ultrafiltration(0.5 μm), 6 stages distillation, water extraction and **gas stripping** with ultraclean nitrogen then humified with water vapor 30%

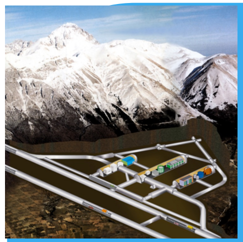
Design goal : all background sources (^{238}**U** and ^{232}**Th** and their progeny, ^{40}**K, noble gases Ar, Kr..)** should produce < **1cpd/100ton in the scintillator**

PPO purification:
concentrated "master" solution (200 g/l) in PC then purified with water extraction (5 cycles), filtration, distillations and N2 stripping

Water : purified with RO, CDI, filters, N2 stripping

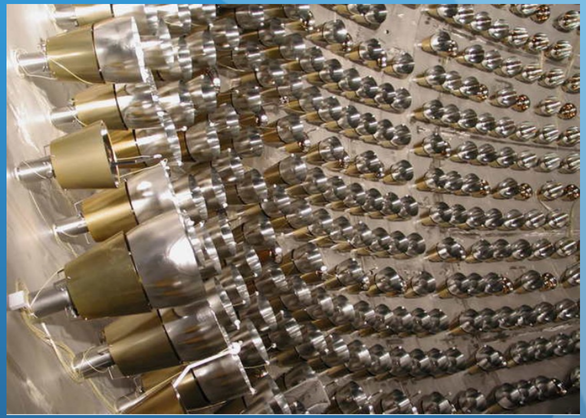
NIM-A 609 (2009)58-78

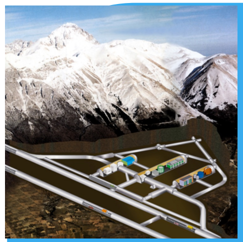




(3) Material selections, cleanliness procedures

- **Detector & Plants**
  All materials carefully (and painfully) selected for:
  Low intrinsic radioactivity, low Rn emanation
  Good behaviour in contact with PC
- **PMTs (2212)**
  developed in collaboration with a company
  Special low-radioactivity glass, low radioactivity ceramics and dynodes
  Time jitter: 1.1 ns (for good spatial resolution, mu-metal shielding)
  384 PMTs with no light cones cones for μ id
- **Nylon vessels**
  Material selection for chemical & mechanical strength
  Low radioactivity to get < 1 c/d/100 t in FV
  Construction in low ^{222}Rn clean room, never exposed to air : 125 μm thikness!! → a challenge!





(4) A small scale demonstrator (CTF)

To test the reached radiopurity we built a detector having the sensitivity enough to measure the needed radiopurity (mass spectrometer with plasma source ≈ 10^{-10} g/g)

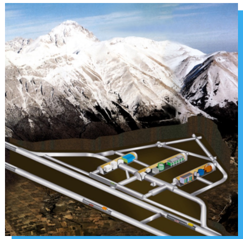
CTF	5 tons of LS,100 PMTs 1000 tons of highly purified water

$^{238}U = (3.5 \pm 1.3)\ 10^{-16}$ g/g

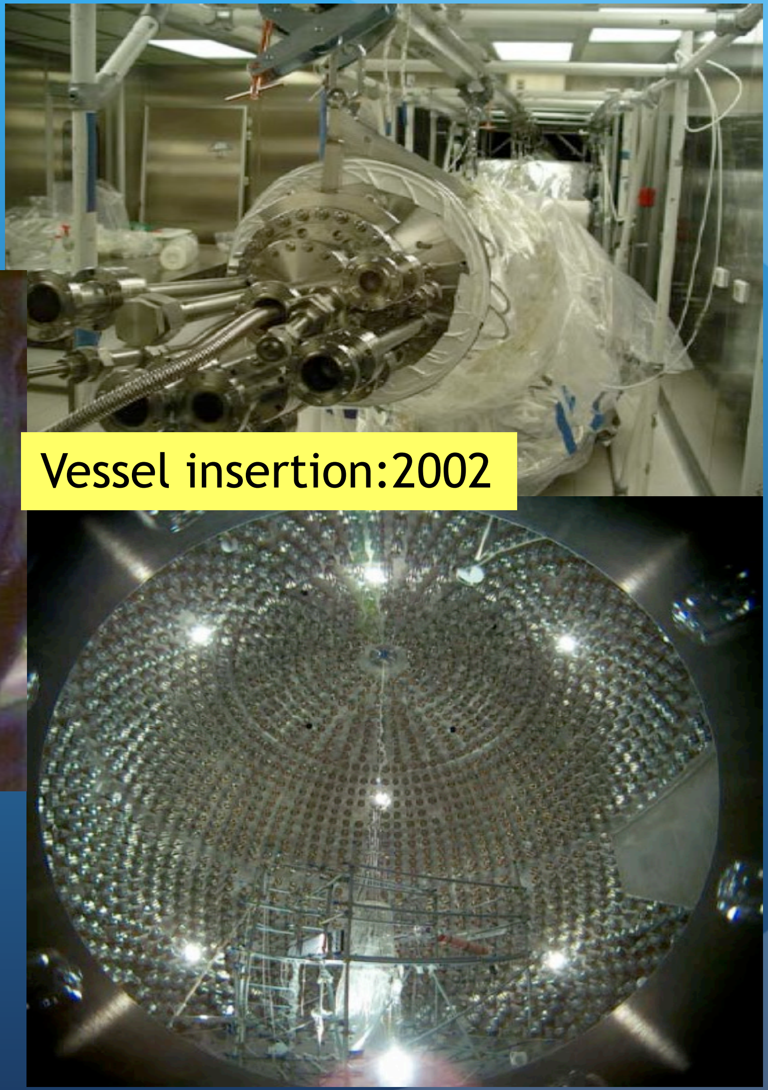
$^{232}Th = (4.4 \pm 1.5)\ 10^{-16}$ g/g

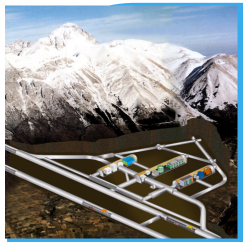
$^{14}C/^{12}C. \sim 2\times10^{-18}$

..well within the design goals !!



Important steps: some pictures



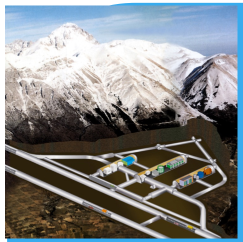


Backgrounds (Phase 1)

Background	Typical abundance (at source)	Borexino goals	Borexino measured
$^{14}C/^{12}C$	10^{-12} (cosmogenic) g/g	$\sim 10^{-18}$ g/g	$\sim 2\ 10^{-18}$ g/g
^{238}U (by ^{214}Bi-^{214}Po)	$\sim 10^{-5}$ (dust) g/g	10^{-16} g/g	$(5.3 \pm 0.5)\ 10^{-18}$ g/g
^{232}Th (by ^{212}Bi-^{212}Po)	$\sim 10^{-5}$ (dust) g/g	10^{-16} g/g	$(3.8 \pm 0.5)\ 10^{-18}$ g/g
^{222}Rn (by ^{214}Bi-^{214}Po)	100 atoms/cm^3 (air) emanation from materials	10^{-16} g/g	~0.57 cpd/100t
^{210}Po	Surface contamination	~1 c/d/t	May 07 : 70 c/d/t Sep08 : 7 c/d/t
^{40}K	$2\ 10^{-6}$ (dust) g/g	$\sim 10^{-14}$ g/g	< 0.42 c/d/100t (95% C.L.)
^{85}Kr	1 Bq/m^3 (air)	~1 c/d/100t	(30.4 ± 5.6) c/d/100t (fast.coinc.)
^{39}Ar	17 mBq/m^3 (air)	~1 c/d/100t	< 0.4 c/d/100 ton

factor 10-100 better that specs!!

Phys. Rev. D 89, 112007 (2014)



Importance of on-site purifications plants

Some examples:

1. After detector filling some isotopes (^{85}Kr and some ^{222}Rn daughters (^{210}Bi, ^{210}Po) found above specifications:

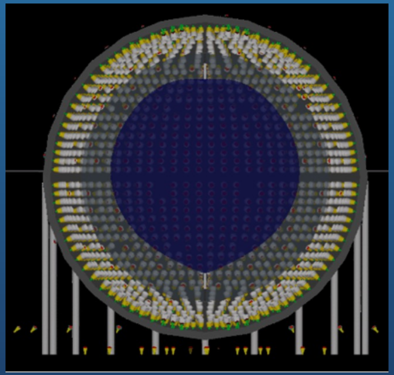
   → 2010-11 new purifications (Water extr.+ nitrogen stripping):

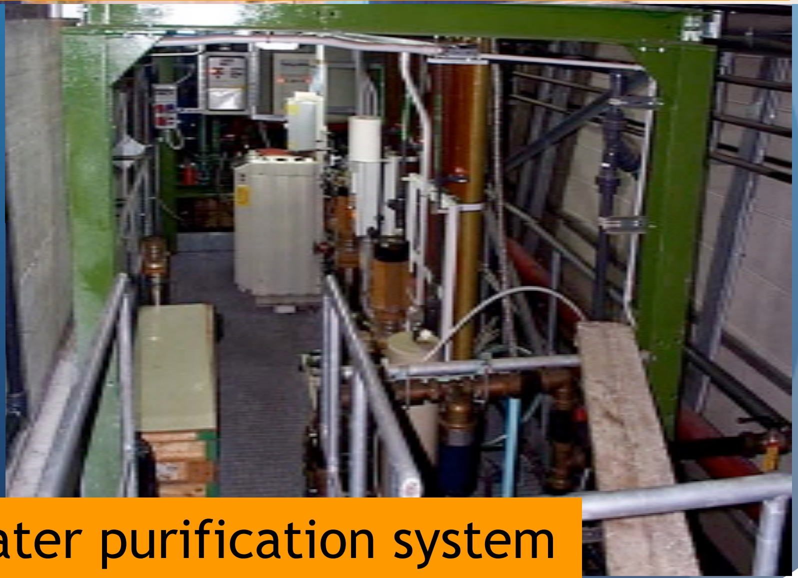
   - ^{232}Th (from ^{212}Bi-Po): < 5.7 10^{-19} g/g at 95%C.L.
   - ^{238}U (from ^{214}Bi-Po): < 9.4 10^{-20} g/g at 95%C.L.
   - ^{85}Kr reduced by a factor 4.6 and ^{210}Bi by a factor 2.3

   →2012-16 Phase 2 of data taking

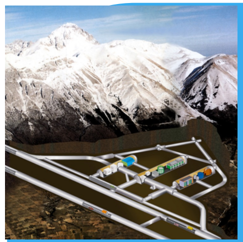
2. The small difference of IV and buffer liquid was causing IV deformation and in 2008 a small PC+PPO leak was found in the buffer
   →distillation to reduce the DMP concentration in the buffer from 5→2.5 g/l to decrease the buoyancy effect (and the leak).

Storage volumes+ purification plants



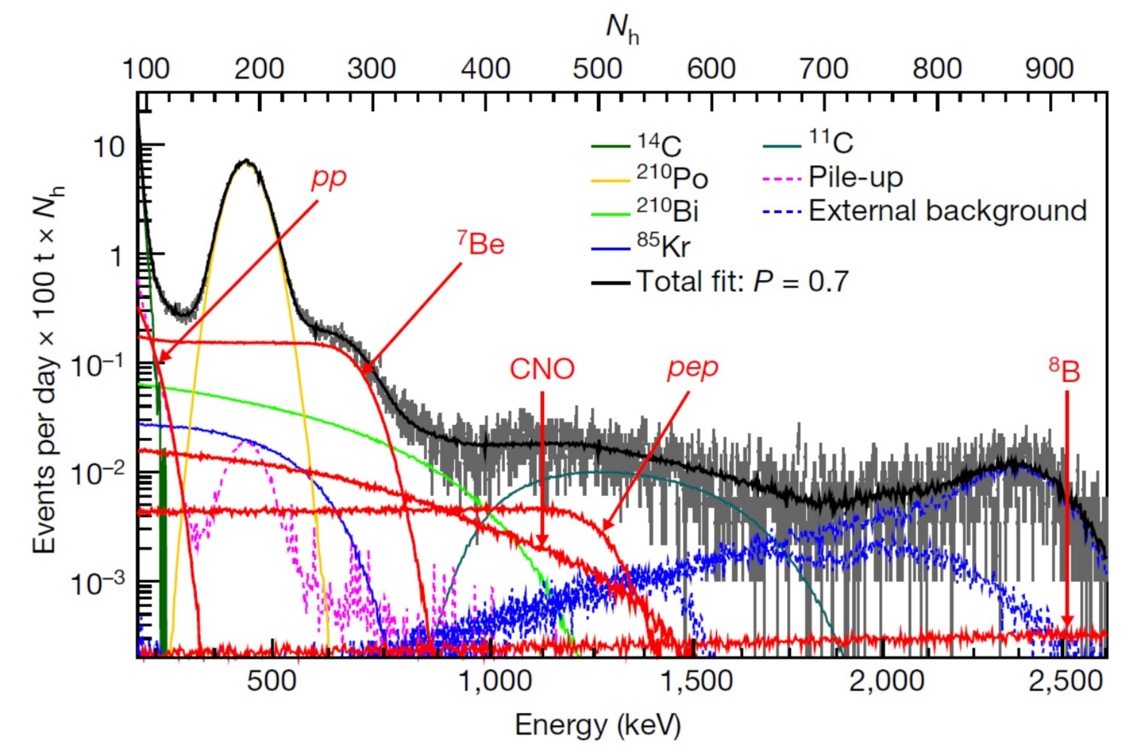


Water purification system



Review of analysis techniques

Some backgrounds still present (^{14}C,^{11}C,^{210}Bi..)!!
New/refined analysis techniques have been developed to tag/remove backgrounds depending on the energy range and on the specific analysis

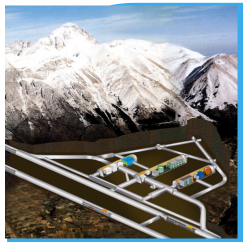


Comprehensive results on proton-proton chain solar neutrinos *(Nature, 496 (2018) 505))*

Good energy resolution and good knowledge of the detector energy response :

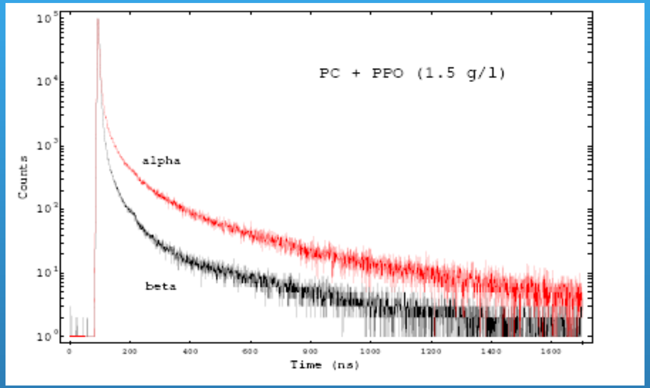
- The fit to the energy distribution of events is crucial to extract the signal and background rates

Backgrounds event rates can be constrained (if possible) to values obtained with independent analysis

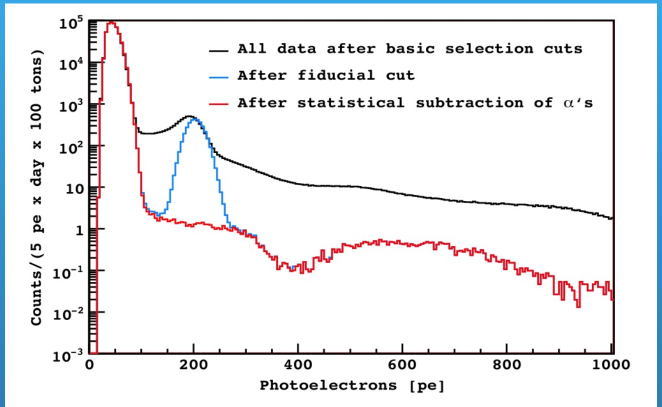


Background tagging and PSA examples

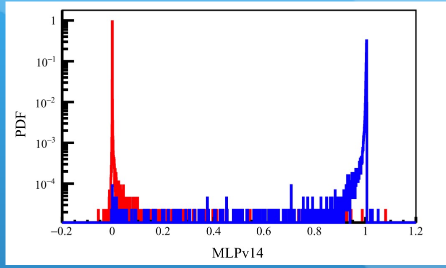
α/β discrimination :



different signal time length: Gatti optimum filter



PHYS. REV. D 109, 112014 (2024)



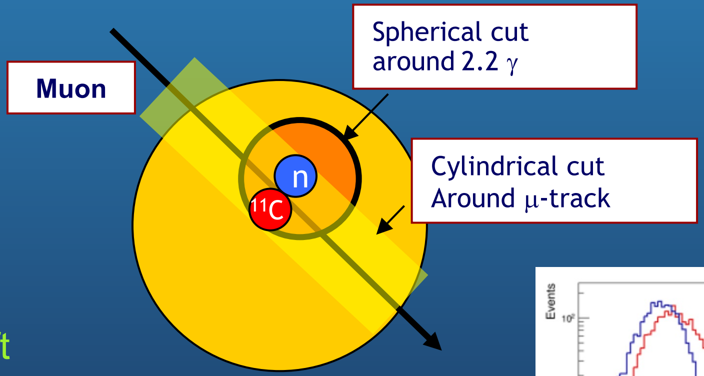
later on perceptron approach based upon a neural network with 13 α/β discriminating input variables

^{11}C tagging :

1) three fold coincidence (TFC)

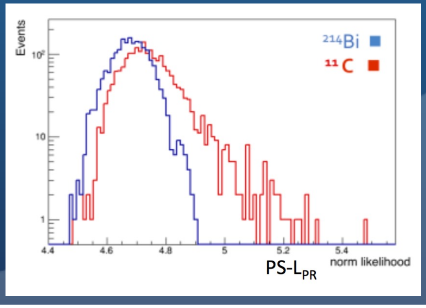
$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

The likelihood that a certain event is ^{11}C is obtained by exploiting the space and time correlation of μ, n, and candidate ^{11}C signals



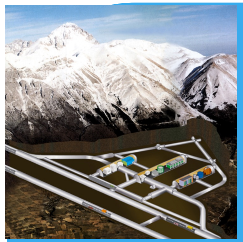
TFC subtracted spectrum : 64% of the exposure, 8% of ^{11}C left

2) pulse shape discrimination for β+/β– separation



^{11}C decays emiting β+ : $^{11}C \longrightarrow {}^{11}B + e^{+} + \nu_e$,

PSD based on the difference of the scintillation time profile for e- and e+

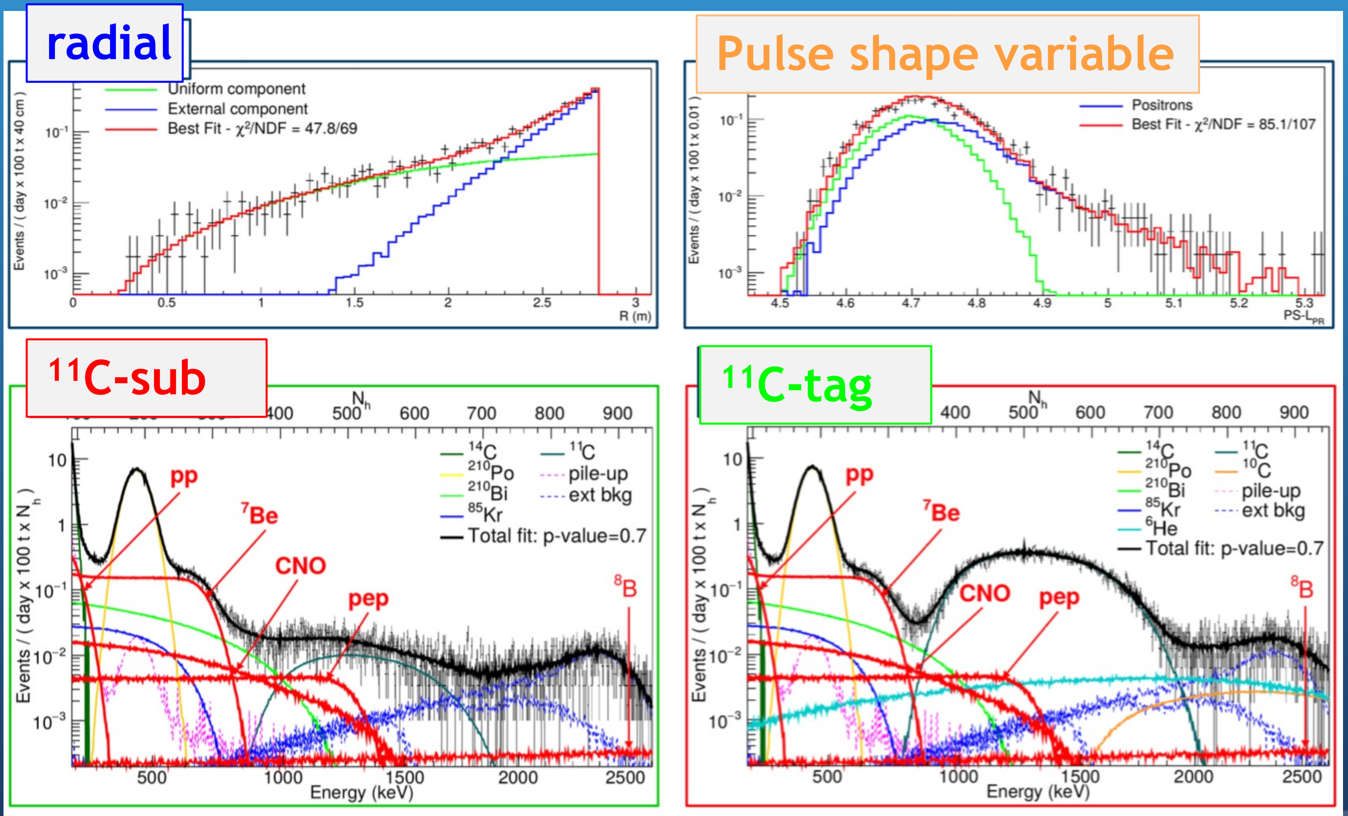


Low energy solar-ν analysis : multivariate fit

The presence of residual backgrounds (^{14}C, pile-up, ^{85}Kr, ^{210}Bi, ^{210}Po, ^{11}C) made it complex to extract the neutrino signal from data over a wide energy range (0.19-2.93) MeV

Solution: Maximize a binned likelihood through a multivariate approach

$$\mathcal{L}_{MV}(\theta) = \mathcal{L}_{11C\text{-tag}}(\theta) \bullet \mathcal{L}_{11C\text{-sub}}(\theta) \bullet \mathcal{L}_{PS}(\theta) \bullet \mathcal{L}_{Rad}(\theta)$$



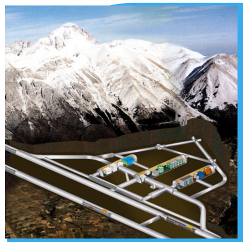
Comprehensive results on proton-proton chain solar neutrinos (Nature, 496 (2018) 505))

ML fit of:

- 2 energy distributions (^{11}C-sub and ^{11}C-tag)
- 1 PSA distribution
- 1 Radial distribution

Toy-MC to simulate experiments & to check:

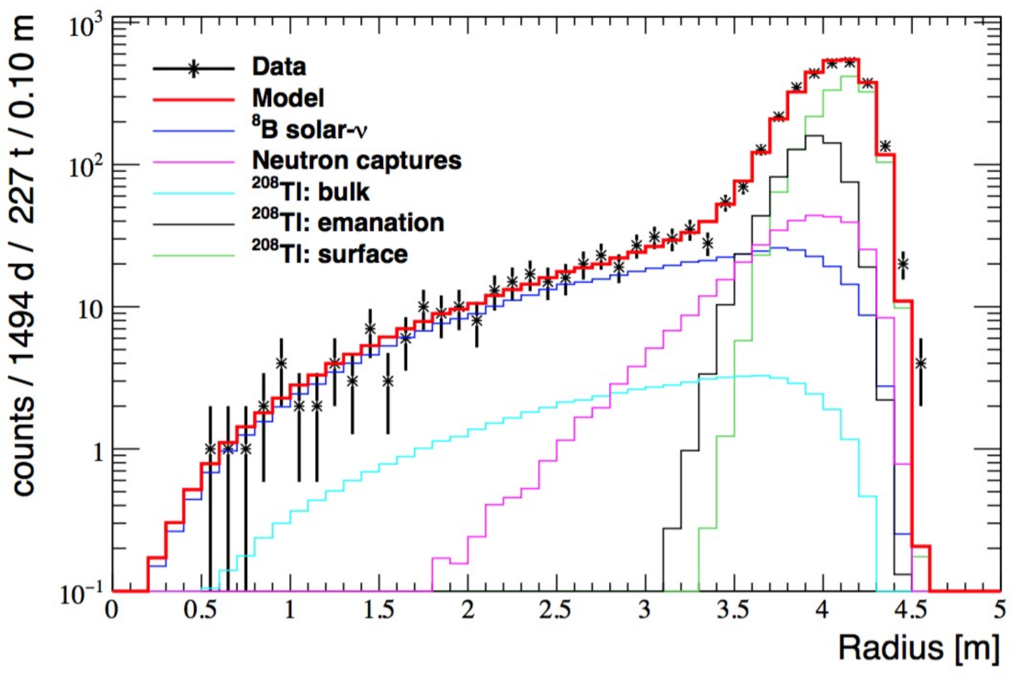
- **bias,**
- **sensitivity,**
- **correlations .**



High energy solar ν analysis (E>3 MeV)

Energy window > 3MeV : 8B
Method: **no assumption** on **E_ν energy spectrum!** → probe **deviations** from **MSW**

Example: Radial fit (HER1)

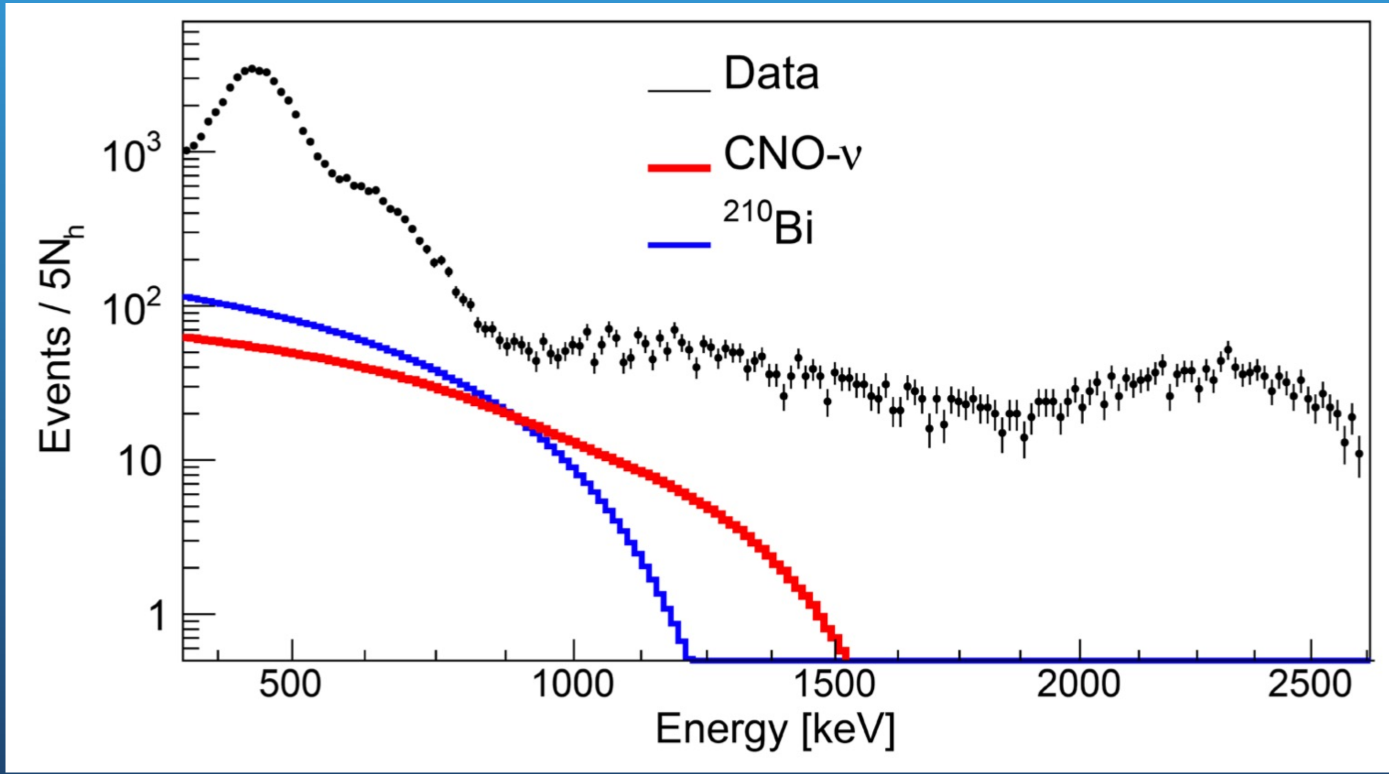


Fit of radial event positions to disantagle signal/background

Selection cuts:

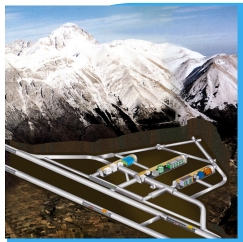
- μ & Neutron cut: no μ, 2 ms veto after all μ
- Cosmogenic cut : 6.5 veto after internal μ
- ^{10}C cut : like TFC, veto around each n after μ
- Fast coincidence cut: no ^{214}Bi-Po
- Coincidence cut: no events closer that 5 s

CNO-ν: a further experimental and analysis effort



THE PROBLEM

- The rate of CNO and ^{210}Bi is comparable;
- The spectral shape is very similar→the fit cannot disentangle the two contributions easily!



CNO-ν: a further experimental and analysis effort

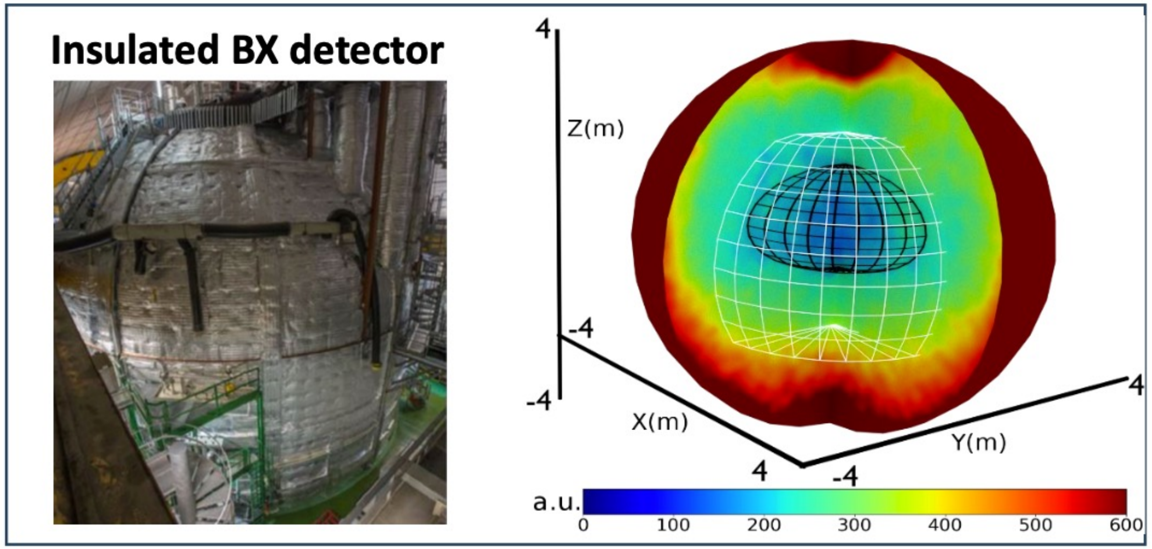
First idea:

1) External constraint on ^{210}Bi rate from ^{210}Po;

•Requires secular equilibrium in the $^{210}Pb \rightarrow {}^{210}Bi \rightarrow {}^{210}Po$ chain;

•The detector was totally insulated (+ active temperature control on the top) to avoid convective currents which bring out-of- equilibrium ^{210}Po from the vessel into the scintillator

- **$R(^{210}Bi) \leq 11.5 \pm 1.3$ cpd/100t**
- It can only be applied on Phase-III data (2016-21)

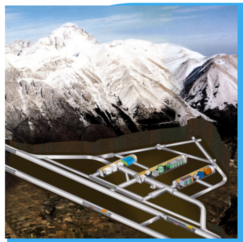


^{210}Po rate from the Low Polonium Field : $R_{min} = 11.5 \pm 1.3 \frac{cpd}{100} t$

First direct evidence of the existence of CNO neutrinos (~5σ significance)

Nature 587 (2020)578 ; PRL 129 (2022)252701

CNO rate : $6.7^{+2.0}_{-0.8}$ cpd/100t (stat+sys)

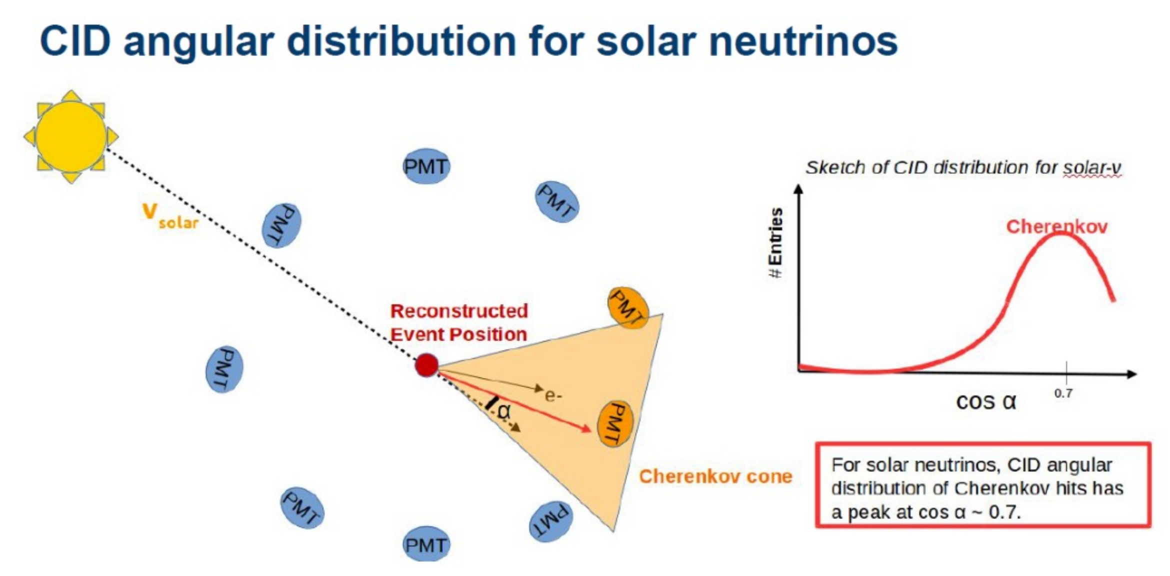


CNO neutrinos

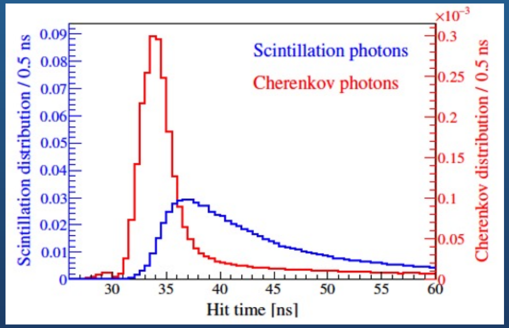
Second idea:

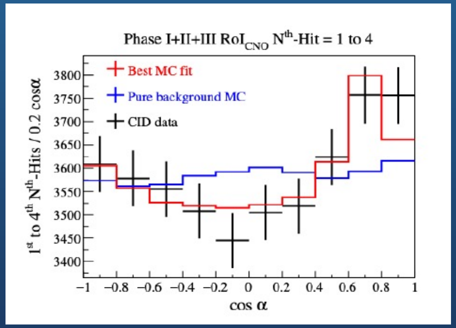
2) Correlation with the Sun direction (CID method)

- **For each event, the earliest hits (1-2) are the most likely to be due to Cherenkov**
- Cherenkov light (directional..)emitted instantly; the scintillation light emission follows a multi-exponential decay time where the fastest component has 1.6 ns



Borexino measurement of CNO neutrinos (using only 2 or 1+2) (>7σ)



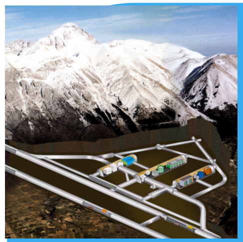


CNO rate:

$7.2^{+2.8}_{-2.7}$ $(stat.+syst)$**cpd/100t**

arXiV 2307.14636

PHYS. REV. D 108, 102005 (2023)



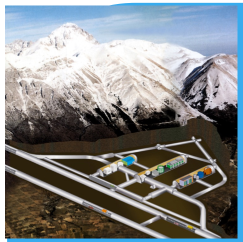
BX final results

Solar neutrinos	Rate (Counts/day/100t)	Uncertainty	Flux* (neutrinos/cm²/sec)	SSM predictions** (neutrinos/cm²/sec)
pp	$134 \pm 10^{+6}_{-10}$	9.5%	$(6.1 \pm 0.5^{+0.3}_{-0.5})\text{x}10^{10}$	$5.98(1 \pm 0.006)\ \text{x}10^{10}$ (HZ) $6.03(1 \pm 0.006)\ \text{x}10^{10}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	17%	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12})\text{x}10^{8}$	$1.44(1 \pm 0.01)\ \text{x}10^{8}$ (HZ) $1.46(1 \pm 0.01)\ \text{x}10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	17%	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13})\text{x}10^{8}$	$1.44(1 \pm 0.01)\ \text{x}10^{8}$ (HZ) $1.46(1 \pm 0.01)\ \text{x}10^{8}$ (LZ)
7Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	2.7%	$(4.99 \pm 0.11^{+0.06}_{-0.08})\text{x}10^{9}$	$4.93(1 \pm 0.06)\ \text{x}10^{9}$ (HZ) $4.50(1 \pm 0.06)\ \text{x}10^{9}$ (LZ)
8B	$0.223^{+0.015+0.006}_{-0.016-0.006}$	7.6%	$(5.68^{+0.39+0.03}_{-0.41-0.03})\text{x}10^{6}$	$5.46(1 \pm 0.12)\ \text{x}10^{6}$ (HZ) $4.50(1 \pm 0.12)\ \text{x}10^{6}$ (LZ)
CNO	$6.7^{+1.2+0.3}_{-0.7-0.4}$	+30% -12%	$(6.7^{+1.2+0.3}_{-0.8-0.4})\text{x}10^{8}$	$4.88(1 \pm 0.11)\ \text{x}10^{8}$ (HZ) $3.51(1 \pm 0.10)\ \text{x}10^{8}$ (LZ)

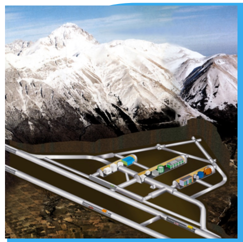
- world-first direct measurements of pp, 7Be , pep and CNO neutrinos , and the flux of 8B ν

*oscillation parameters from: I.Esteban, *MC.Gonzalez-Concha, M.Maltoni, I.Martinez-Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)*

**neutrino fluxes from: *N.Vinyole,A.Serenelli, F.Villante, S.Basu, J.Bergstrom,M.C.Gonzalez-Garcia, M.Maltoni, C.Pena-Garay, N.Song, Astr.Jour. 835,202 (2017)*

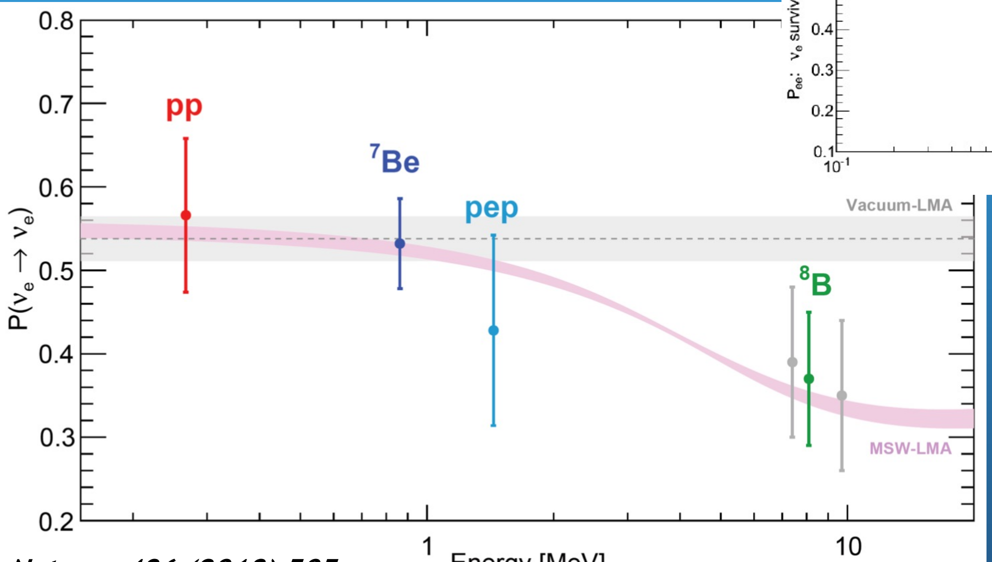


Gallery of BX results implications

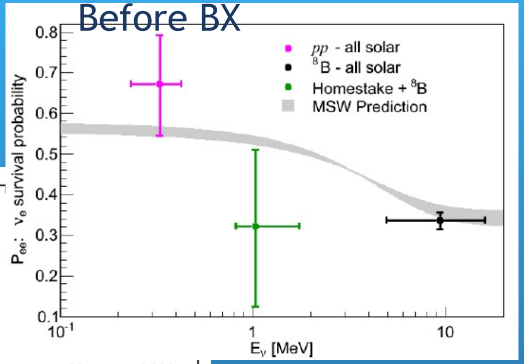


BX : implications for particle physics

Survival probability Pee



Nature, 496 (2018) 505

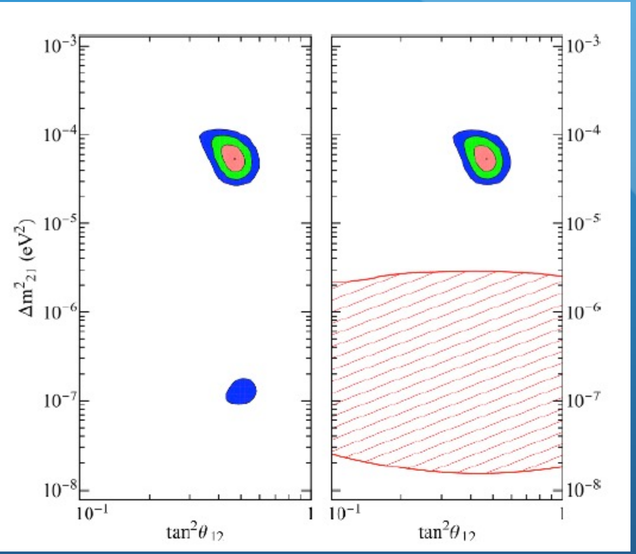


Assuming HZ-SSM fluxes:
Pee(pp)=0.57±0.09
Pee(7Be)=0.53±0.05
Pee(pep)=0.43±0.11
Pee(8B)=0.37±0.08

*oscillation parameters from: I.Esteban, *MC.Gonzalez-Concha, M.Maltoni, I.Martinez- Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)*

- Borexino was the only experiment able probe the ν_e survival probability in both vacuum and matter dominated regions
- Excellent agreement with MSW-LMA predictions
- Rejection of vacuum LMA hypothesis at 98.2%

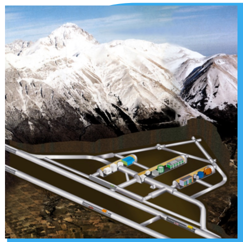
D/N effect on ^{7}Be



- day/night effect found null by Borexino in the ^{7}Be energy window.

$A_{dn} = 2\,(R_N - R_D)/(R_N + R_D) = 0.007 \pm 0.073$

Singles out LMA solution without KamLAND antineutrinos and then CPT assumption



Implications of BX results for astrophysics

Solar Luminosity:

Neutrinos are detected on Earth only 8 minutes after they have been produced in the core of the Sun : they provide a real-time picture of the core of the Sun;

- Using Borexino results we could calculate the solar luminosity from neutrinos:

Neutrino luminosity:

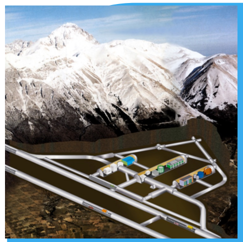
$$L_\nu = (3.89^{+0.35}_{-0.42}) \times 10^{33} \text{ erg s}^{-1}$$

Photon output:

$$L_{ph} = (3.846 \pm 0.015) \times 10^{33} \text{ erg s}^{-1}$$

The agreement confirms the nuclear origin of the solar power; it proves that the Sun has been in thermodynamic equilibrium over 10^5 years (the time required for radiation to flow from the center to the surface of the Sun)

Nature, 496 (2018) 505

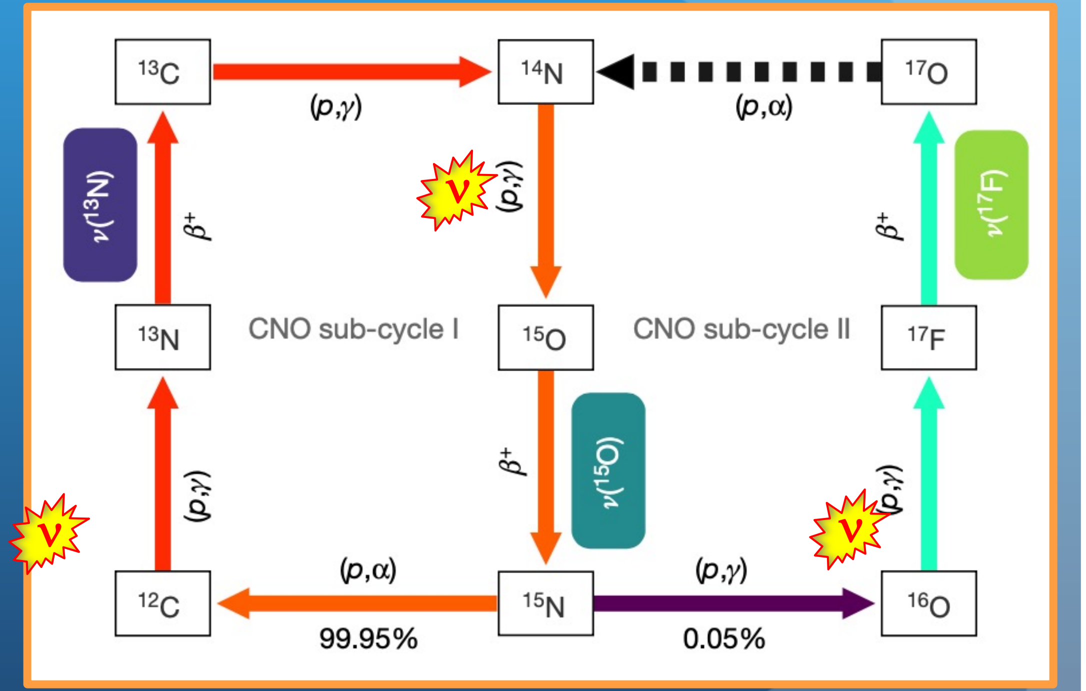


Implications of BX results for astrophysics

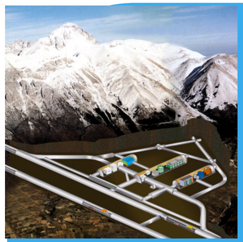
Existence of the CNO cycle

Borexino has verified for the first time the existence of neutrinos from the CNO cycle (with a significance > 7σ)

- In this way CNO hypothesized more than 80 years ago and considered by the astrophysical theories as dominants in the massive stars has finally obtained confirmation of its existence
- CNO is sub-dominant in the Sun, but it is believed to be one of the most important process of energy burning in the universe;

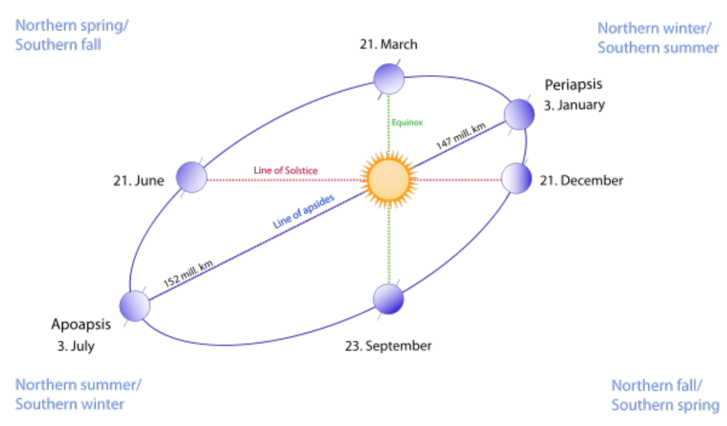


For this reason, its experimental confirmation is a milestone for experimental astrophysics



Implications of BX results for astrophysics

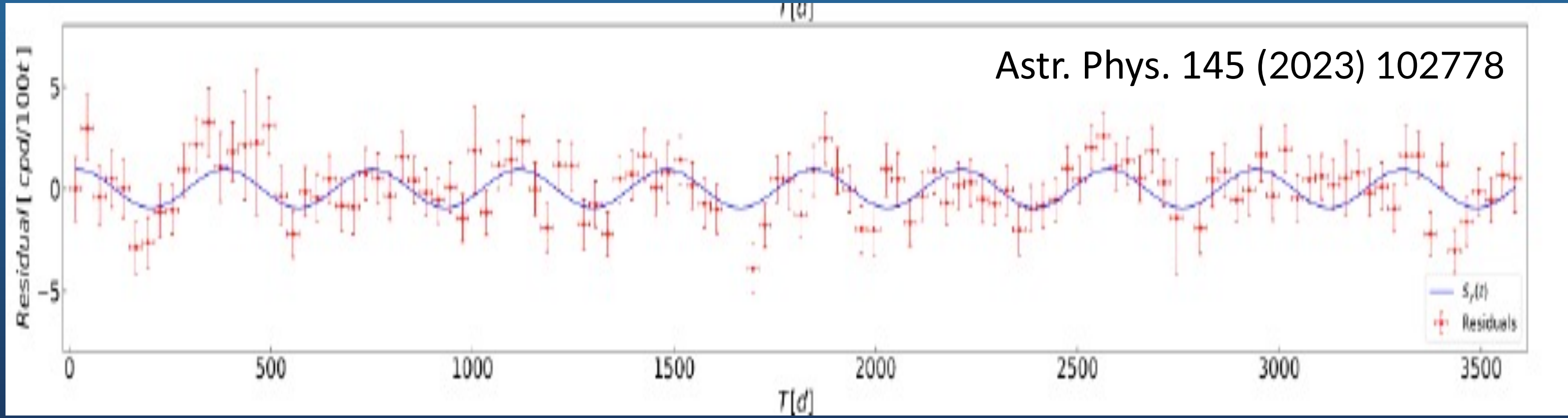
(3) 7Be -ν flux annual modulation : determination of the Earth's orbit with with solar ν

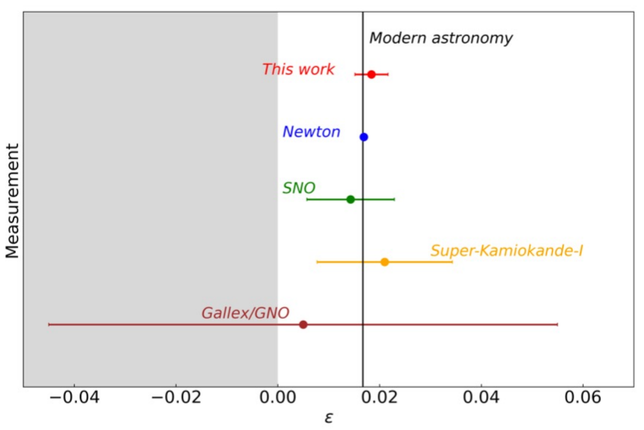


- 10 years-6.7% peak-to-peak amplitude- period of 365 days)
- energy window of 350-827 keV (^{7}Be)

- best-fit eccentricity is ε=0.0184±0.0032 (stat+syst)

- null hypothesis rejected at > 5σ
- Agreement with the astronomical measurements
- best measurement with solar -ν



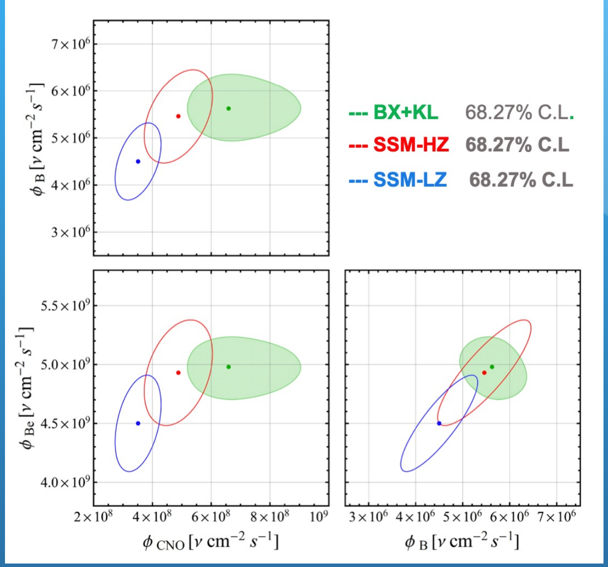


Implications of BX results on astrophysics

Solar metallicity issue

Borexino only (+KL)

- fit of Φ(Be), Φ(B) and Φ(CNO), together with θ_{12} and Δm^2_{12} as free parameters
- The results agree well with the output of SSM-HZ model, while feature tension with the SSM-LZ model (p= 0.018);

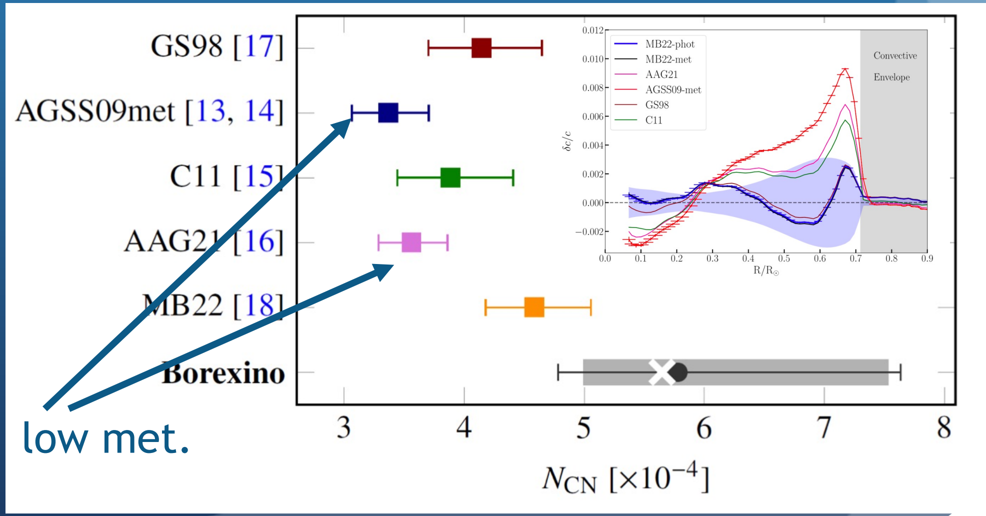


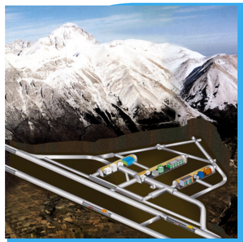
PRL 129, 252701 (2022)

The C and N abundance

Combining the precise measurement of ^8B from other experiments with the CNO measurement by Borexino it is possible to determine the C and N content (with respect to H) compared directly with the measurements derived from the solar photosphere;

BX measurement agrees nicely with the High Metallicity ones, while features a ~2σ tension with the low metallicity measurements

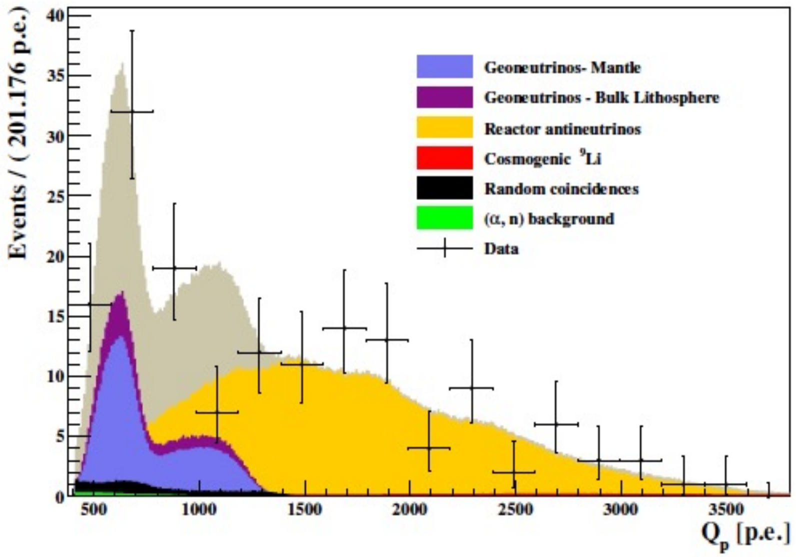




BX: Earth’s and cosmic ν searches

Geo-ν : anti-ν emitted in the Earth’s U/Th and ^{40}K decays, detected through IBD

PRD101 (2020) 012009



December 2007 and April 2019:
154 golden candidates

Lithospheric signal: (28.8 ± 5.6) events with S(Th)/S(U) = 0.29
Mantle: S(Th)/S(U) = 0.26

Mantle events	$23.7^{+10.7}_{-10.1}$
Mantle signal U + Th [TNU]	$21.2^{+9.6}_{-9.1}$
Mantle heat U + Th [TW]	$24.6^{+11.1}_{-10.4}$
Earth U + Th + K [TW]	$38.2^{+13.6}_{-12.7}$

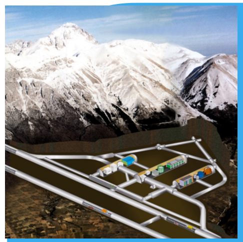
+ 18% contribution of ^{40}K in the mantle, $8.1^{+1.9}_{-1.4}$ TW from lithosphere

- Evidence for the signal > 8σ
- Mantle null hypothesis rejected at 99.0% C.L.
- Least compatibility (2.4 σ) with CosmoChemical and Low -Q BSE geological models

Several searches for ν and anti-ν from astrophysical sources (GRB,solar flares, DSNB..)

•the best upper limits on DSNB anti-ν_e flux for Eν< 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***

*Astr. Phys,125 (2021) 102509,**Eur. Phys. J. C 82, 278 (2022) ;***Eur. Phys. J. C 83, 538 (2023)*



Borexino legacy

- **Borexino has systematically codified techniques needed for studying neutrino physics with a threshold down to about 100 keV,** reaching unprecedented levels of radiopurity
- **These techniques (and the ones developed for data analysis) are the BX legacy for the next low energy neutrinos and rare event searching experiments**

By looking at the BX project timeline..

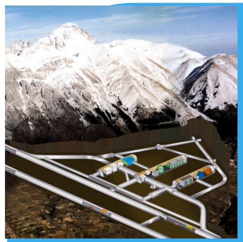
1988-1990	1990-1995	1996-2007	2007-2010	2011-2016	2016-2021
Discussion and design of a real time experiment with threshold well below 1 MeV	R&D program	Construction, installation and tuning of the detector- Detector filling with purified	First phase of data taking	Second phase of data taking	Third phase od data taking

17 months of a second scintillator purification (between 2007-2010 and 2011-2016)

thermal insulation+ new trigger (between 2011-2016 and 2016-2021)

….almost the same time to design/build the detector and to run the experiment/data analysis!!!

- Meticulous project, care of all the details and on-site purification plants→ key points



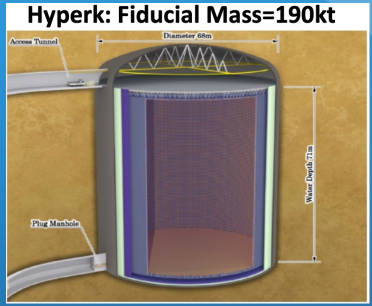
Next steps..

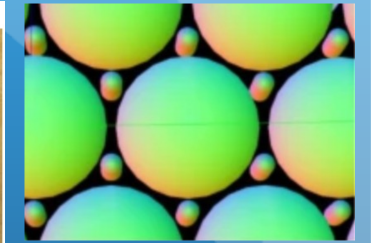
How to improve?

- **With consolidated techniques** (either water Cherenkov or scintillation) and making the detectors bigger and bigger and improving the light collection:

  •Water Cherenkov: from SuperK (22.5kt)->HyperK (190kt)

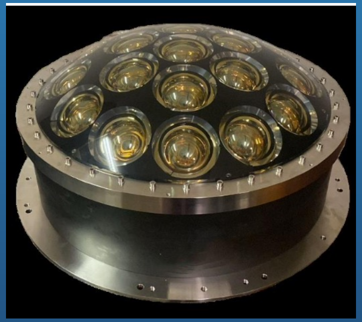
  •Scintillators: from Borexino (75t) -> SNO+ (800t) ->JUNO (10kt)





- **.. and/or using new techniques:**

- **new light sensors (multi-PMT concept, LAPPD, SiPM..)**
- **new detection medium:**
  - •Hybrid Detectors combining Cherenkov and scintillation (Theia, JNE..)
  - •Opaque scintillators (LiquidO)
  - •LAr or LXe-TPC (DUNE,DS20k, DARWIN/XLZD..)
  - •..

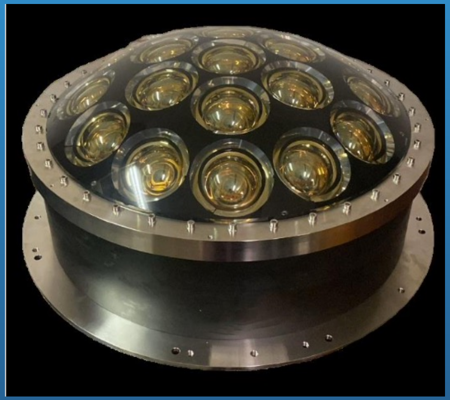


All future experiment are multi-purpose detectors (not only solar –ν but LBL-ν, $0\nu\beta\beta$, reactors-ν..)

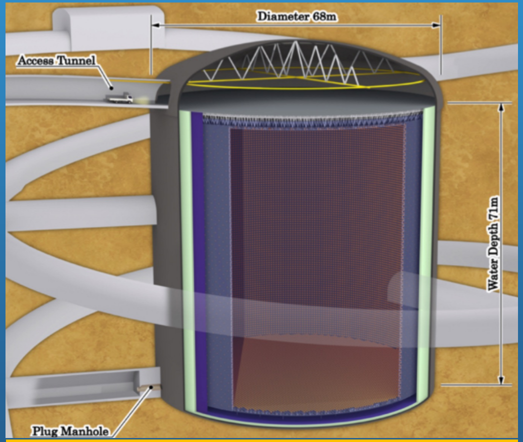
Several projects, some examples in the following slides..

Cherenkov detectors : from Super-K to Hyper-K

- Hyper-K located in Tochibora Mine ~ 8 Km far from SuperK (overburden= 650 m) Start: 2027
- **Main goal:** to study the δ_{CP}, Neutrino Mass order (NMO) (far detector for the JPARC beam)
- 40k PMTs with high QE and better time resolution → better energy and angular resolution;

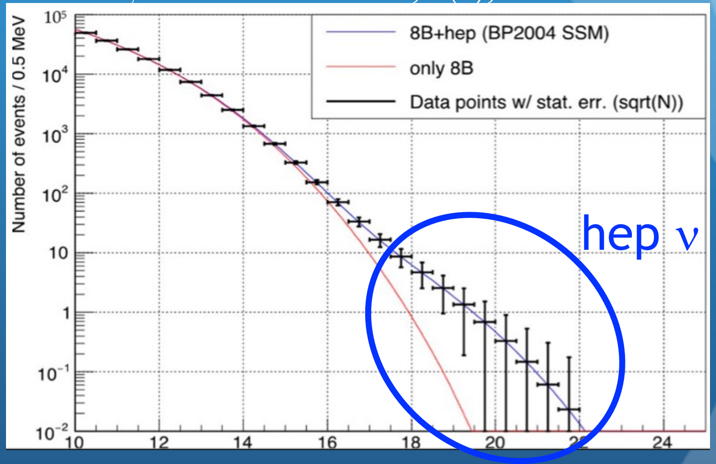


New types of PMTS, ex. a Multi-PMT module inspired by the KM3NeT design:
improved angular acceptance, intrinsic directional sensitivity, enhanced reconstruction for multi-ring events and near wall events



Fiducial mass: 190 kT

Phys. Sci. Forum 2023, 8(1), 41

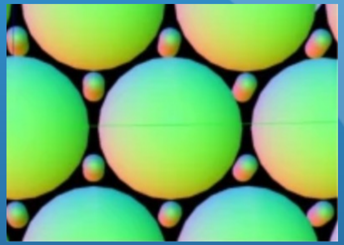


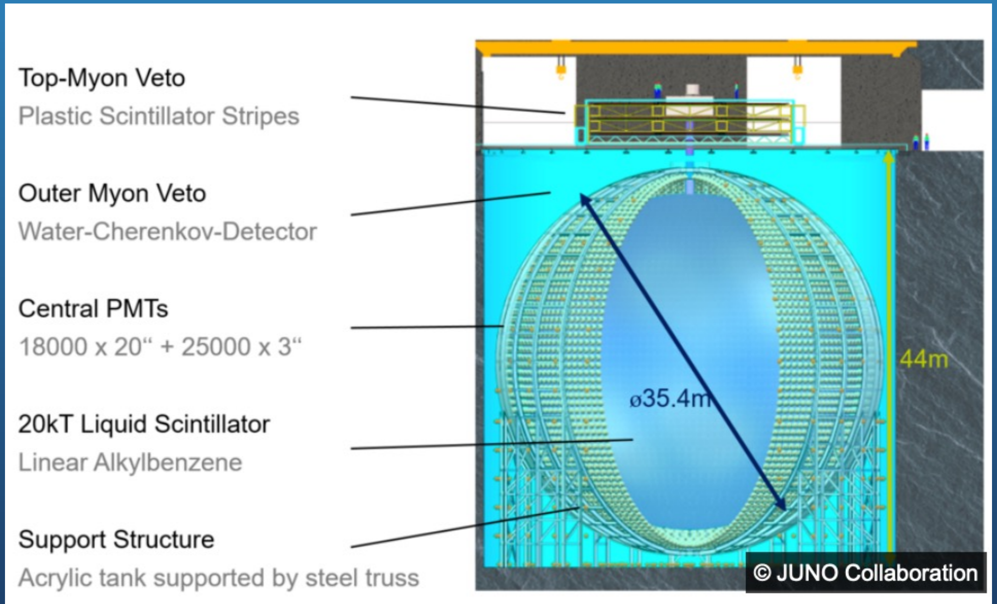
Huge statistics: ~5 ^{8}B ν/hour
In ~10 years :
D/N at 4σ-8σ depending on background;
Possibility to detect upturn at 5σ;
Possibility to see hep neutrinos at ~2-3σ

Scintillation detectors : JUNO

Data taking start : 2025

- Borexino“big brother” : Fiducial Mass: 10 kT (133 x more BX FV=75 tons)
- JUNO will be located in Jiangmen (China) overburden 700 m - high rate of cosmogenics(~7×more than BX-assuming similar tagging capabilities);
- PMTs for a total coverage of 77% (2x more BX): 17,612 20-inch PMTs and 25,600 3-inch PMTs
- Excellent energy resolution of ~ 3%/sqrt(E);
- **Main goal:** study NMO with reactor neutrinos, but also solar-ν, geo-ν, DSNB





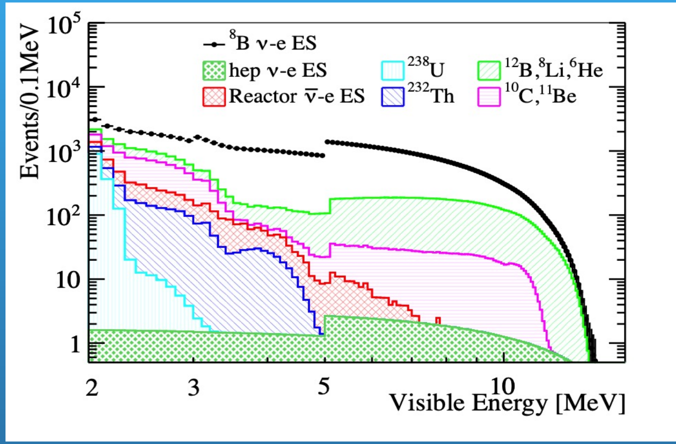
Reaching high levels of radiopurity needed for low energy solar ν is challenging

- Scintillator purification similar to Borexino, goal to achieve 10^{-17} g/g in U/Th
- pre-detector OSIRIS to monitor radiopurity

Scintillation detectors : JUNO

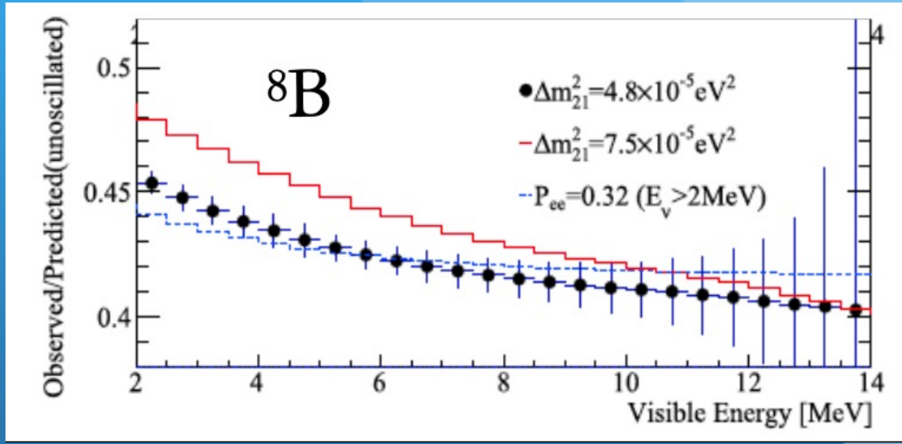
- ^{8}B neutrinos
- Collect ~ 60k events (10y) in the ES ν+e-> ν+e channel
- D/N at 3σ in 10 y
- Also possible to see CC:ν_e +^{13}C->e- +^{13}N NC: ν_x + ^{13}C->ν_x + ^{13}N*

if U/Th < 10^{-16} g/g: threshold : 2 MeV !



2021 *Chinese Phys. C* 45 023004

solar/reactor Δm^2_{12} discrimination



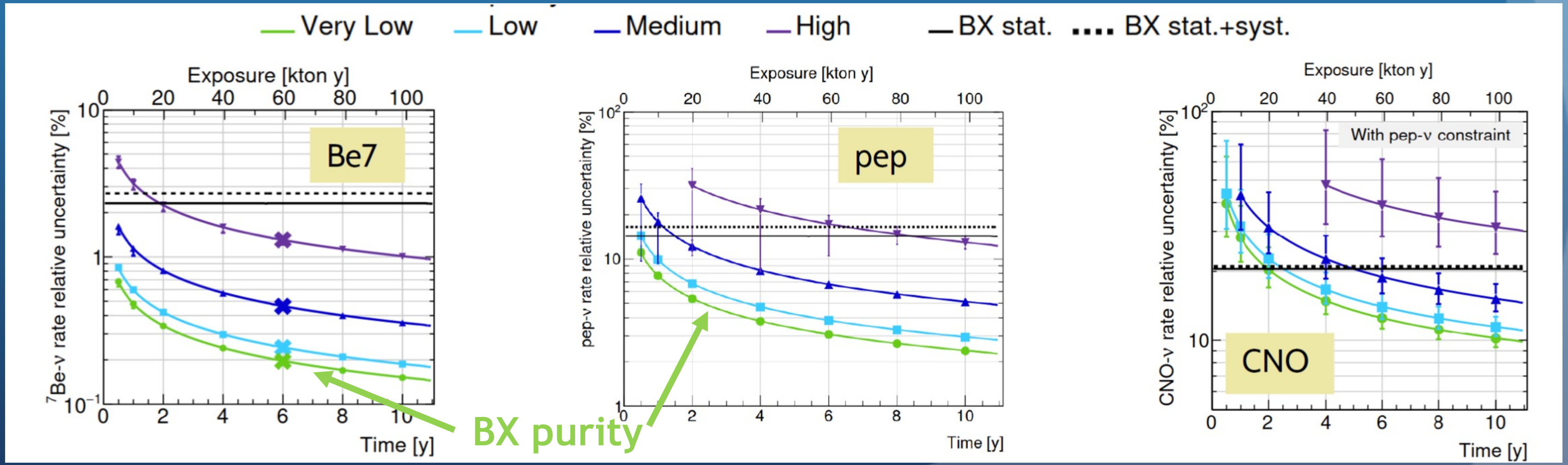
7Be, pep, CNO solar neutrinos

the precision depends on the achieved purity

^{7}Be rate < 1%

pep rate < 10%

CNO similar to BX, possible improvements with CID



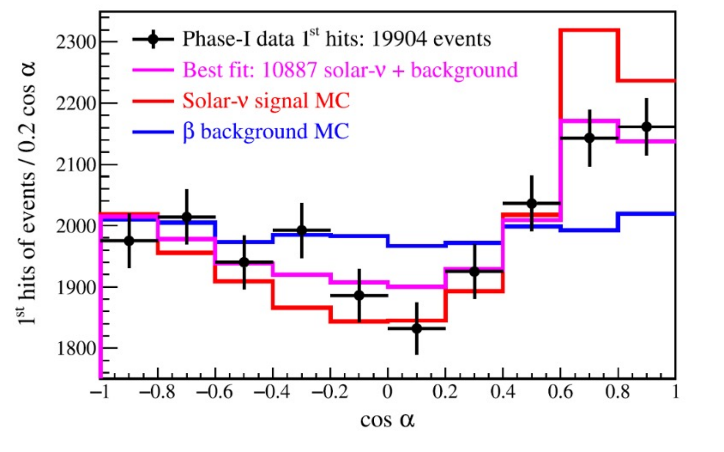
JCAP10(2023)022

Hybrid detectors

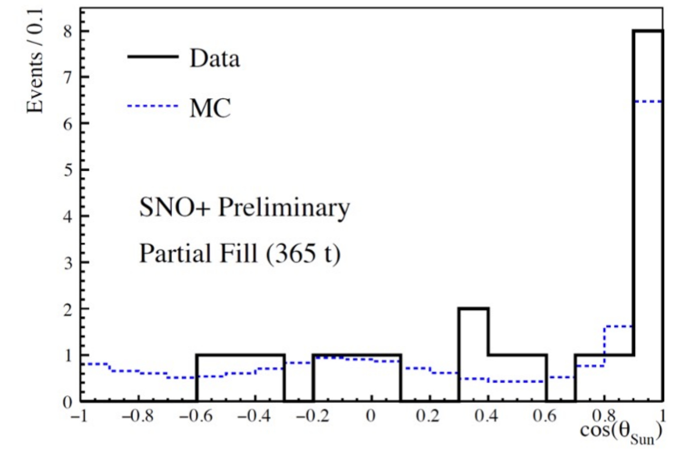
…to exploit simultaneously the advantages of scintillation and Cherenkov light

- Advantage of scintillation light: better energy resolution, lowthreshold;
- Advantage of Cherenkov light: directionality → boost the sensitivity to solar neutrinos

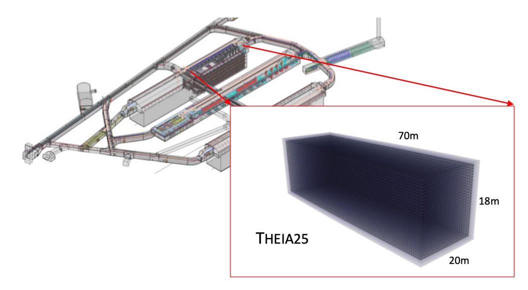
Already successful hybrid detection in experiments…



Borexino obtained the evidence for solar n directionaly by using the first detected photons of the event PHYS. REV. D 108, 102005 (2023)



SNO+ has achieved the first event-by-event directional reco by using diluted liquid scintillator arXiv:2309.06341



Hybrid detectors : THEIA

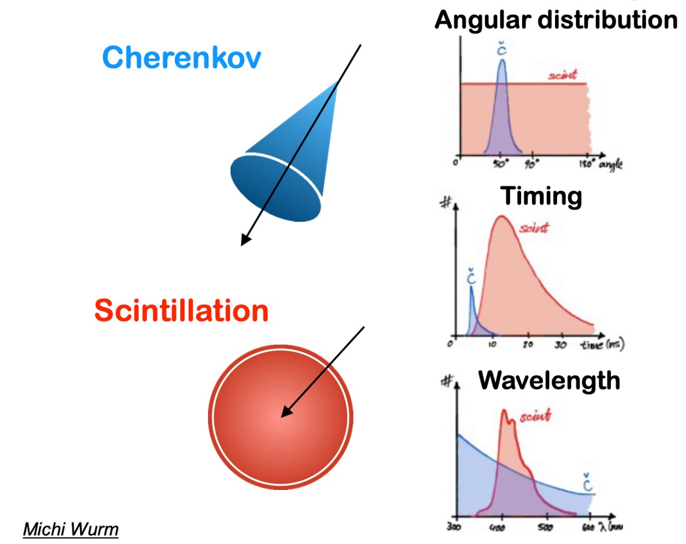
- Theia at SURF (Sanford Underground Research Facility)- South Dakota;
- Mass: 25kt→100kt;
- **Multi-purpose detector:** far detector for LBNF beam →study δCP, NMO … , **Solar neutrinos (high and low energy), SN, DSNB,geo-ν, 0νββ decay**

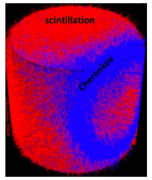
R&D in progress: several smaller mass demonstrators (Annie,Button,NuDot EOS..)

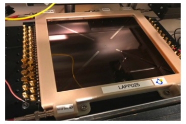
Technique: water based Liquid scintillator (WbLS)
•Addition of a small amount of LS to the water (between 1%-10%)
•Optimization of LS content (more LS→more photons but less angular reso ..)

How to separate Cherenkov from scintillation light?

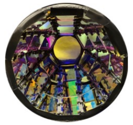
- Timing and angular info
  →fast light sensors ex. LAPPD..);
  →slowing scintillation down;
- Wavelenght separation: dichroic filters







B.W.Adams et al. NIM A Volume 795, 1 (2015)

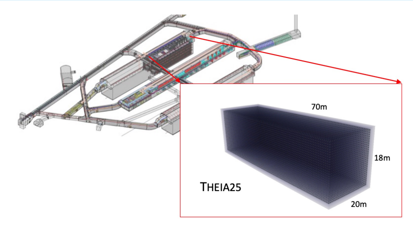


T.Kaptanoglu et al. Phys. Rev. D 101, 072002 (2020)

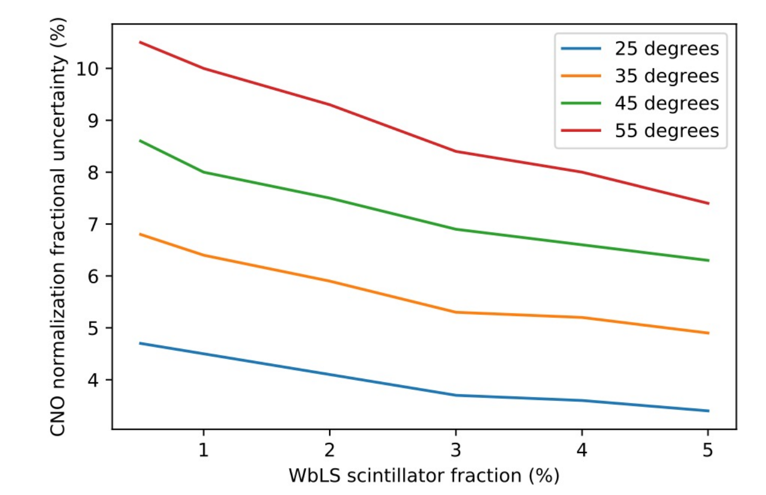
Fast and High-QE PMTS or LAPPD (large Area Pico Second PhotoDetector)
QE ~20%
Time resolution < 100 ps for single photon events
Space resolution < 1 mm in both directions *Gain ~ 10^7*

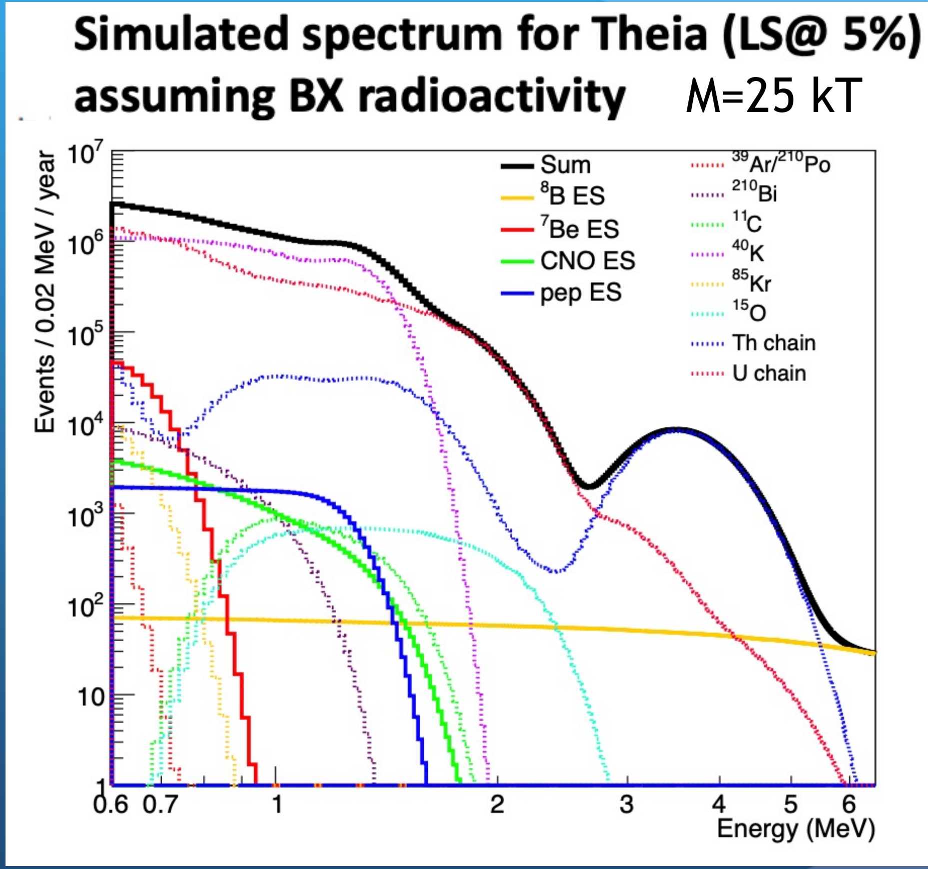
Dichroicons: Winston cones+ sorting photons wavelegth with dichroic filters

Hybrid detectors : THEIA



https://arxiv.org/pdf/1911.03501



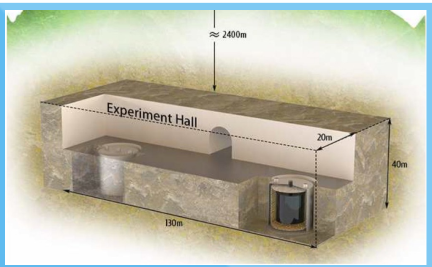


- Uncertainty on CNO could be as low as ~ 4% : – 5years; – 60kt fiducial M; – σ(θ) ~ 25^0
- Possibility to introduce ^{7}Li for CC reaction (^{8}B neutrinos)

Theia-100 : ~5σ discovery of the DSNB in less than 1 year of data taking and reach O(10^2) DSNB events within ~5 years.

Geo-ν rate :26.5 /kT year(20.7 U and 5.8 Th)
Capability to separate U/Th!!

Hybrid detectors: JNE (Jinping Neutrino Experiment)



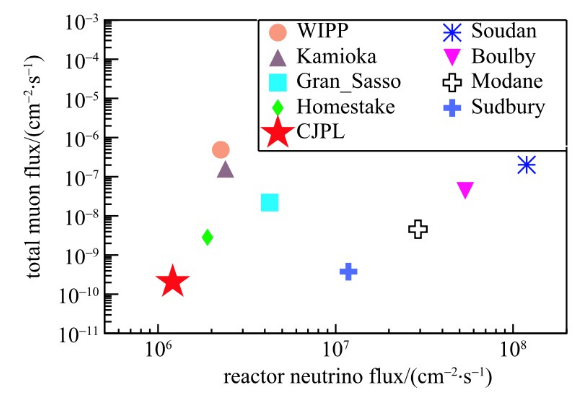
JNE will be located at CJPL (China), overburden 2400 m: **muon flux a factor 200 smaller than Borexino!**

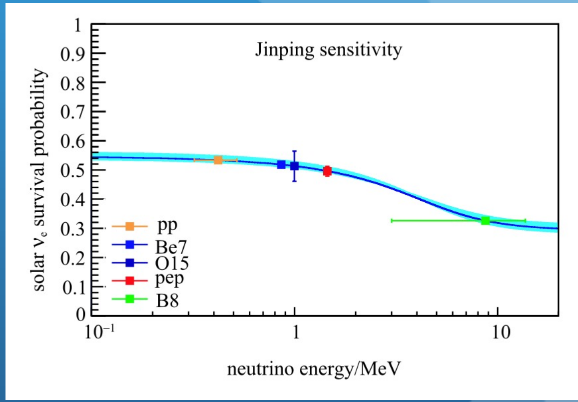
Multi-purpose detector: solar, SN, geo-ν, 0νββ..

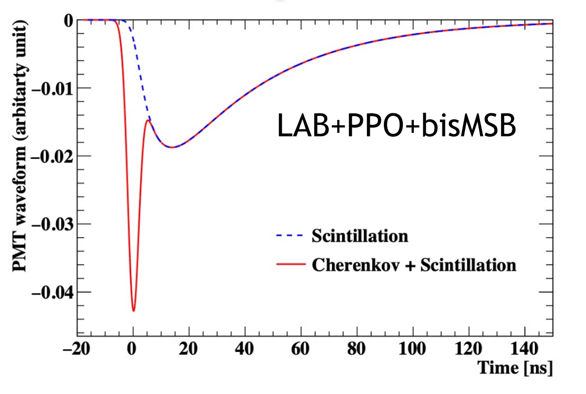
- 2 identical detector for a total FV mass: 2kT for solar ν, 3 kT for geo-ν and SN

Technique: starting with water + slow-LS, then LiCl-LS or TeLS or NdLS

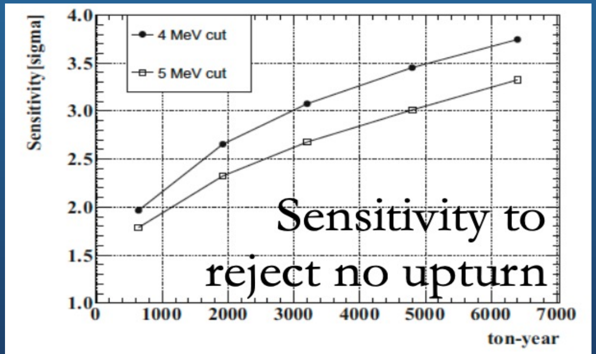
•Reduced concentration of primary fluor to slow down the scintillation: fluorescence time distribution stretches to several tens of nanoseconds: enhanced capability to separate Cherenkov and scintillation light;







- Currently :
- 1 ton prototype at CJPL to test new PMTs and electronics

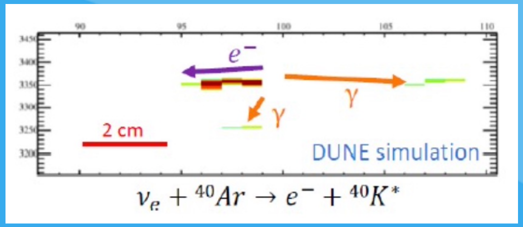


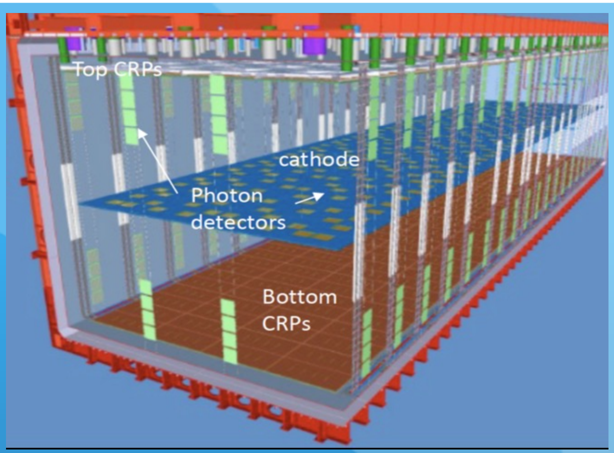
- Both low and high energy neutrinos
- Interesting for CNO neutrinos
- 3 σ on upturn in 3 years

https://arxiv.org/pdf/1607.01671 https://arxiv.org/pdf/1708.07781

Liquid Ar or Xe TPC

Liquid Ar-TPC : DUNE



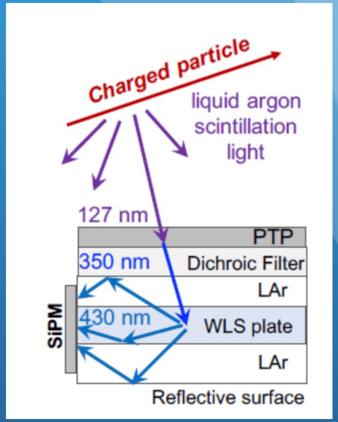


- DUNE at SURF (Sanford Underground Research Facility)- South Dakota;
- Phase-I, starting 2030 ~27 kton active vol. (comb.)
- **Main goal:** to study δ_{CP}, NMO (far detector for LBNF beam) also SN, solar neutrinos (mainly high energy : ^{8}B, hep)

Threshold ~ E_ν=5 MeV

- Possibility to exploit the tracking capability of the TPC to point the Sun;
- High statistics of ^{8}B neutrino interactions (~2.5 cpd/kT) with ES;
- Measure neutrino energy with CC (study upturn);
- Possibility to detect hep for the first time;

Photon detectors: X-ARAPUCA light guides (WLS+dichroic filters)+ SiPM



1. Charged-current (CC) interaction on Ar

   $\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$

   $\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$

2. Elastic scattering on electrons (ES)

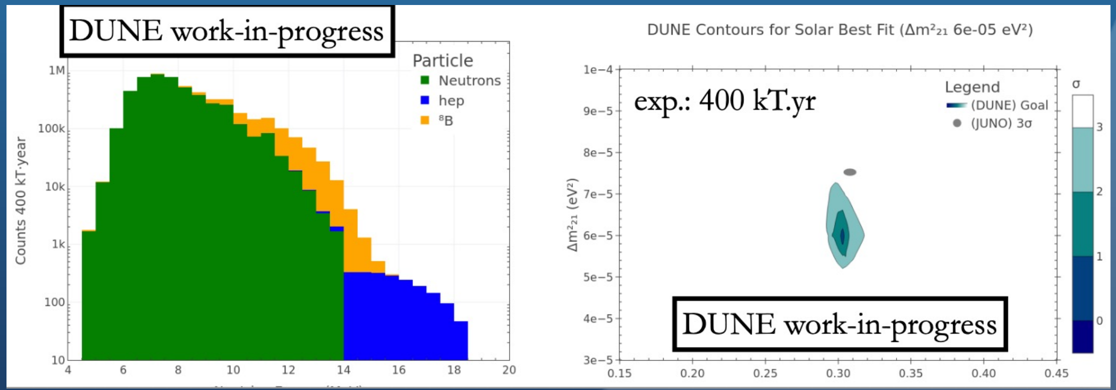
   $\nu_x + e^- \rightarrow \nu_x + e^-$

3. Neutral current (NC) interactions on Ar

   $\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$

Very active R&D to improve low energy performances

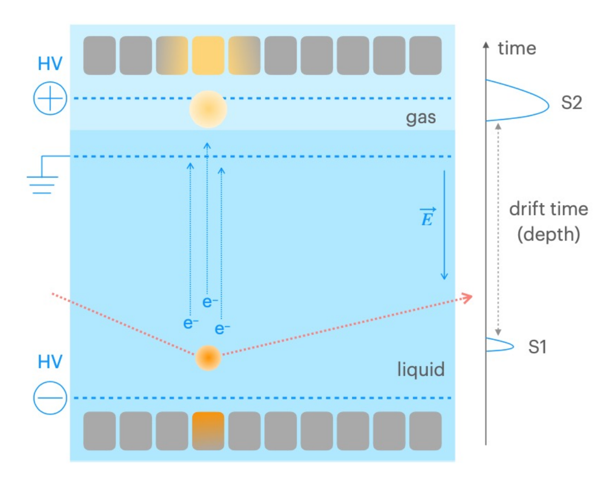
J. Maneira @Neutrino24



solar/reactor Δm^2 discrimination

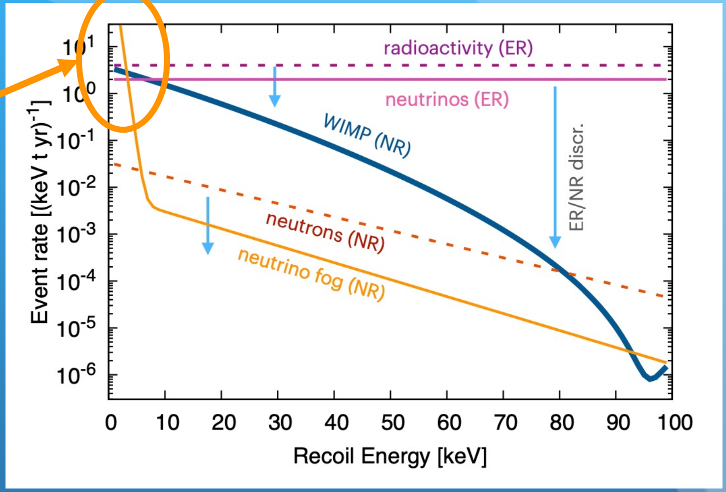
Liquid Xe-TPC

Eur. Phys. J. C **80**, 1133 (2020)



- Multi-ton LXe detectors can see neutrinos both with the scattering on nuclei (CEvNS) (all flavours, higher energies) and on electrons (ES –all energies).
- No^{14}C, almost no U/Th. Major background: ^{222}Rn, ^{85}Kr, ^{136}Xe
- DARWIN (FV: 40t) : possibility to measure with ES pp-ν at 0.15% with 300 ton y (rate:365 ev/ton y) –high E res (1% @ 1 MeV, thr:1 keV!)

Solar ν

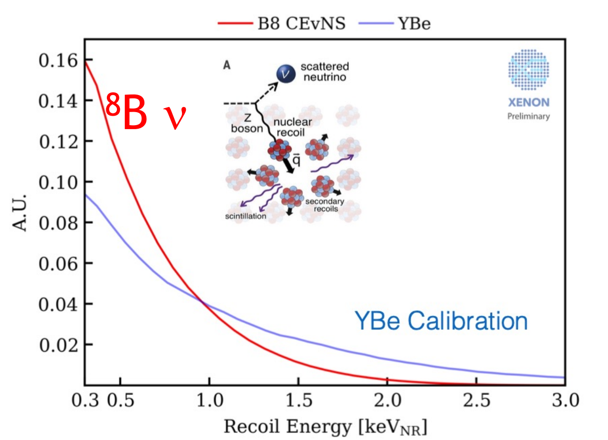


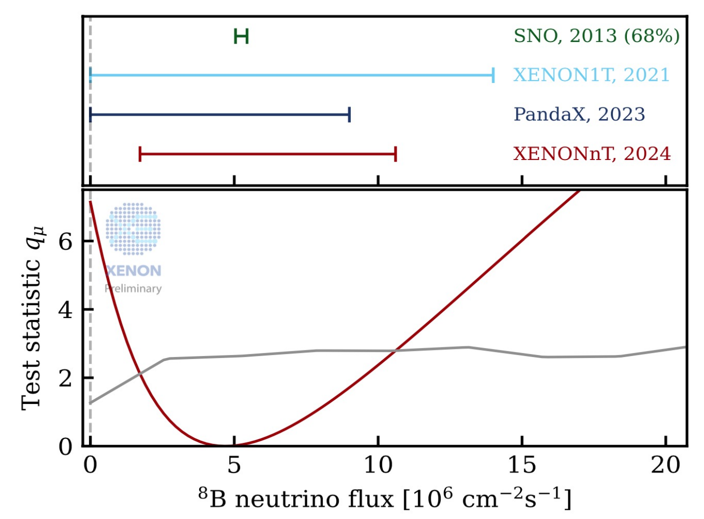
Nucl. Phys B. 1003 (2024) 116473

F. Gao IDM Workshop (Jyl. 10th 2024) L'Aquila

Recent result (XENONnT) :

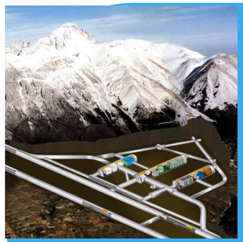
First Measurement of Coherent Elastic Neutrino Nucleus Scattering of Solar ^{8}B Neutrinos via CEvNS at 2.73σ





The first astrophysical neutrino measurement via CEvNS

Conclusions



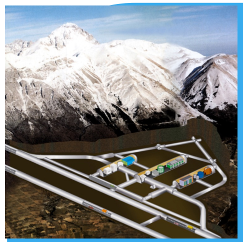
- Borexino has systematically codified techniques needed for studying neutrino physics with a **threshold down to about 100 keV,** reaching unprecedented levels of radiopurity

- New experimental techniques are under study and most of them are already in a well advanced stage
- Very large mass experiments close to data taking

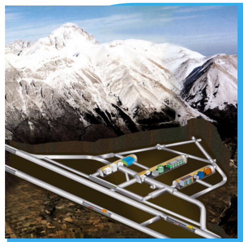
All the ingredients for new breakthrough ahead!

Thank you !!

The Borexino collaboration



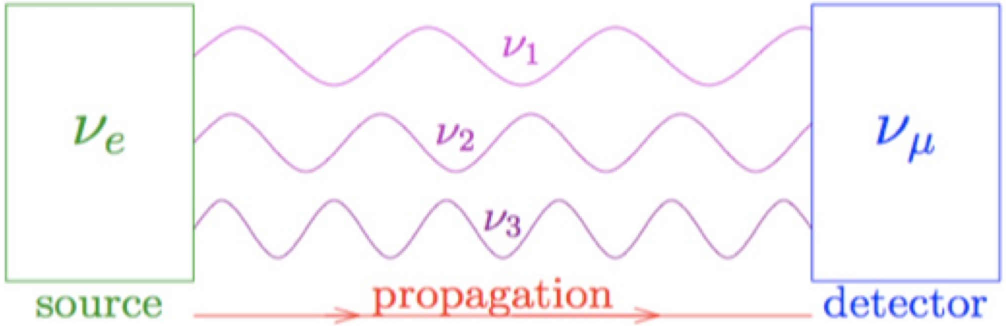
Backup



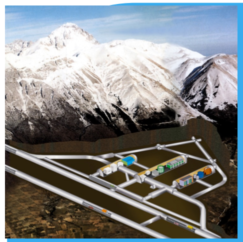
The solar neutrino problem : possible explanations

- Wrong experiments? ✗
- Nuclear physics solution? ✗
- If neutrinos are massive: flavour oscillations? ✓

$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$

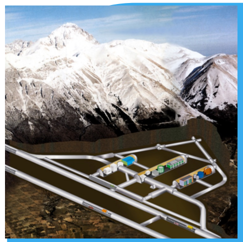


$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1 t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2 t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3 t}\,|\nu_3\rangle \neq |\nu_e\rangle$$



Experiment	Location (Overburden)	Fiducial Mass	Technology	Detection reaction	Solar nu	Start
HYPERK	Tochibora Mine (Japan) 650 m	~190kt	Water Cherenkov	$\nu + e \rightarrow \nu + e$	8B, hep	2027
JUNO	Jiangmen (China) 700 m	~10kt	Scintillator	$\nu + e \rightarrow \nu + e$ $\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$ $\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}N^*$	8B, 7Be, pep, CNO, pp (?)	2025
THEIA	SURF (S.Dakota)1500 m	~12kt-60kt	WbLS	$\nu + e \rightarrow \nu + e$ possibility to insert Li	8B, 7Be, pep, CNO, pp (?)	Future
JNE	Jinping (China) 2400 m	2kt	Slow scintillator	$\nu + e \rightarrow \nu + e$ possibility to insert Li	8B, 7Be, pep, CNO, pp (?)	Future
DUNE	SURF (S.Dakota)1500 m	20kt-40kt	Lar-TPC	$\nu + e \rightarrow \nu + e$ $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$	8B, hep	2030

B. Caccianiga NeuTel23



BOREXINO: the quest for the radiopurity grail

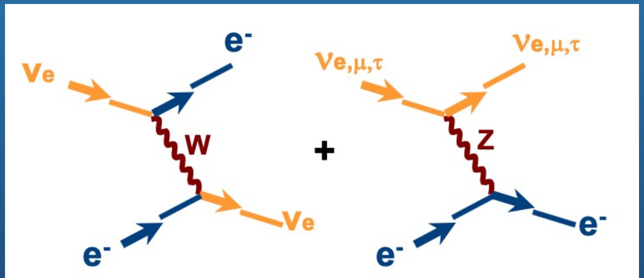
Goal: to measure the single component of solar neutrinos with energy threshold well below 1 MeV

Good energy resolution at low energy => **scintillation detector**

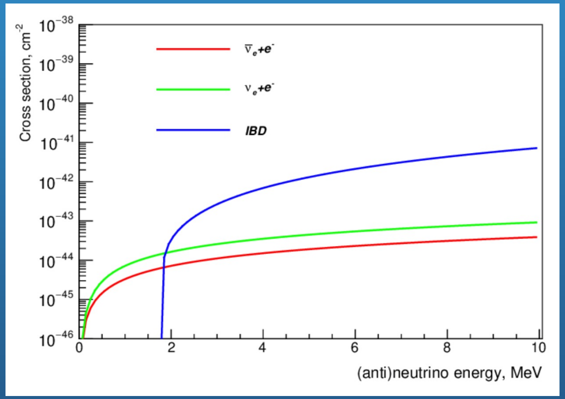
Detection principles (low energy ν):

Elastic scattering on electrons: $\nu + e \rightarrow \nu + e$

Single events, no threshold, all flavours



Signal rate dominated by solar neutrinos

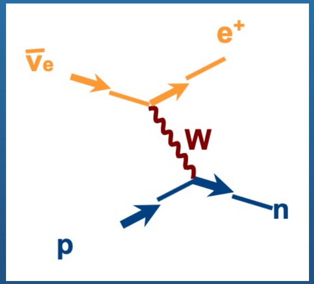


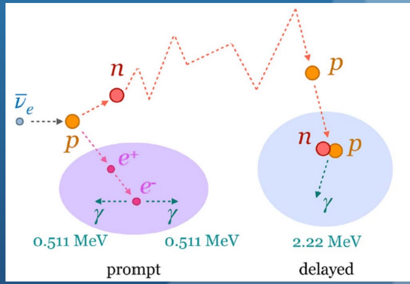
σ_{IBD} at few MeV: ~10^{-42} cm^2 (~100 x more than scattering)

Inverse beta decay: $\bar{\nu}_e + p \rightarrow n + e^+$

Charge current, electron flavour only

Delayed coincidence → clean signature!





Energy threshold = 1.8 MeV, τ ~ 255 μs

Signal rate dominated by geo and reactor anti-ν for E_ν<10 MeV

Next steps : open questions!!

Solar neutrinos

Solar physics

Metallicity puzzle

- could be definitely settled with more precise measurements of the 7Be, 8B and especially CNO flux;
- **hep neutrinos** still missing

•p+3He->4He+e+ +ve
•Flux very low: 8x103 (ν /cm2/sec)
•Highest energy: Emax ~ 19 MeV;

Particle physics:

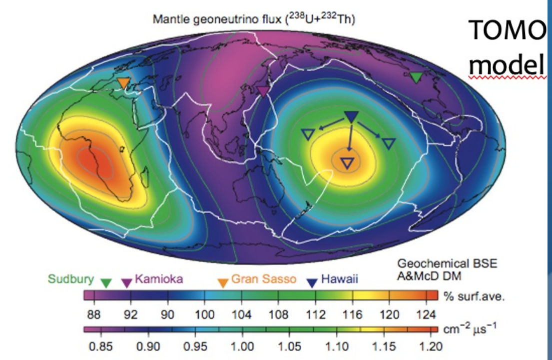
- Completing the details of the ``standard'' LMA-MSW oscillations (D/N, upturn...)

Investigating non standard physics

•Non Standard Neutrino Interactions (NSI);
•Oscillatons into sterile ν,
•Neutrino magnetic moment μν,
•Neutrino decay..

Geo-neutrinos :

Earth's energy balance, mantle homogeneity → tomography!!



Astrophysical neutrinos (SN, DSNB, GW,FRB, GRB..) + rare processes (0νββ..), dark matter…