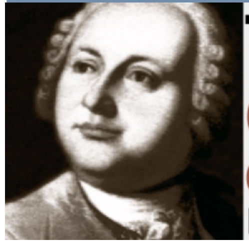
Istituto Nazionale di Fisica Nucleare

Borexino results and its scientific legacy

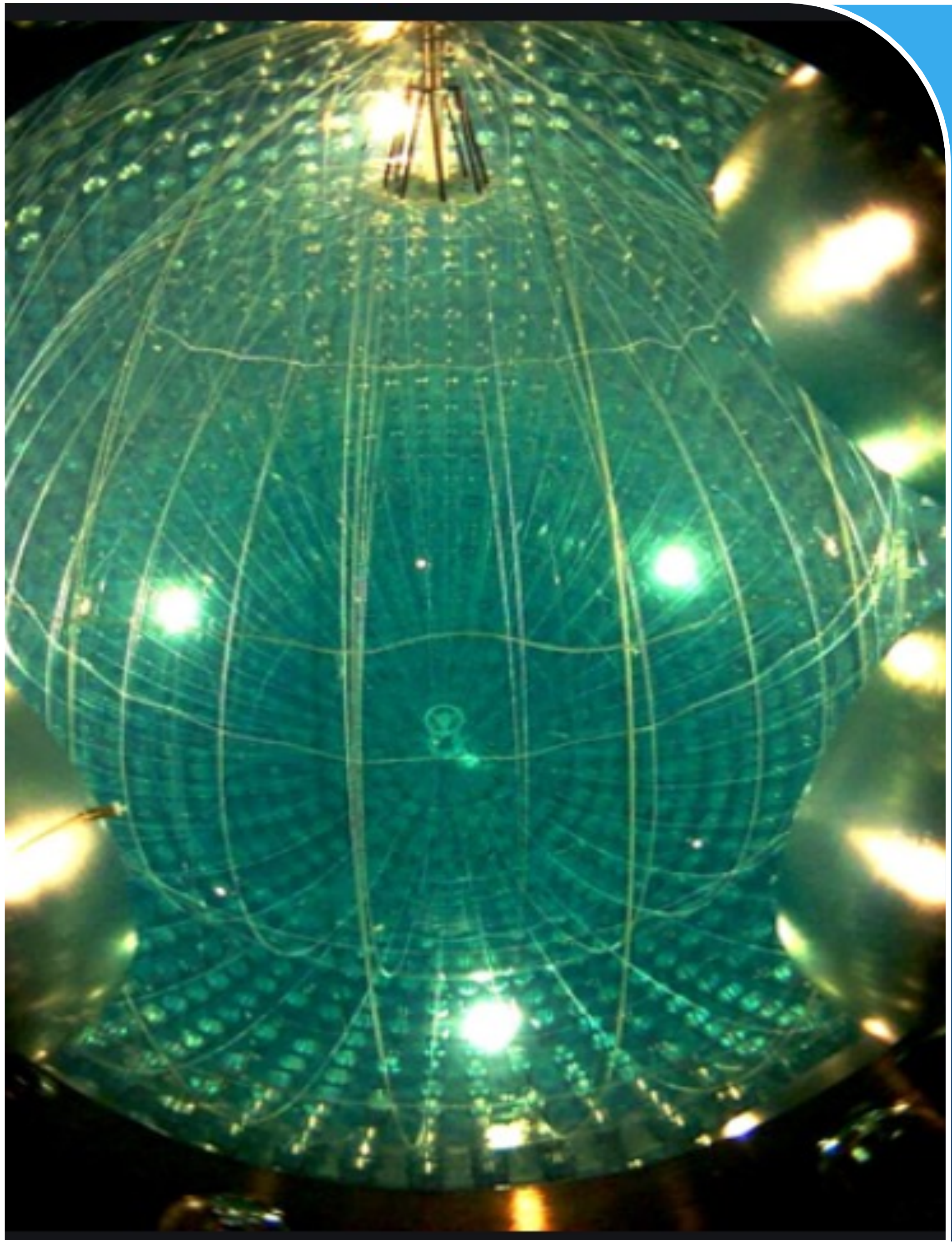
S. Zavatarelli, INFN - Genoa (Italy)
on behalf of the BOREXINO collaboration



TWENTY-SECOND LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS

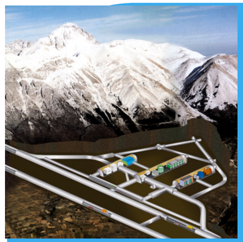
August, 21-27, 2025

MOSCOW STATE UNIVERSITY



Talk layout

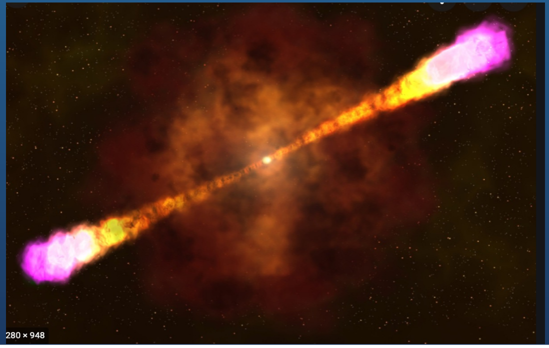
- Borexino: radiopurity methods and analysis techniques
- Gallery of results:
  - Solar neutrinos: implications for particle physics and astrophysics;
  - Geo-neutrinos : first indications about deep mantle U/Th composition;
  - Rare processes detection: new limits on possible solar axions flux emitted by the p+d->^{3}He+γ/A
- Conclusions

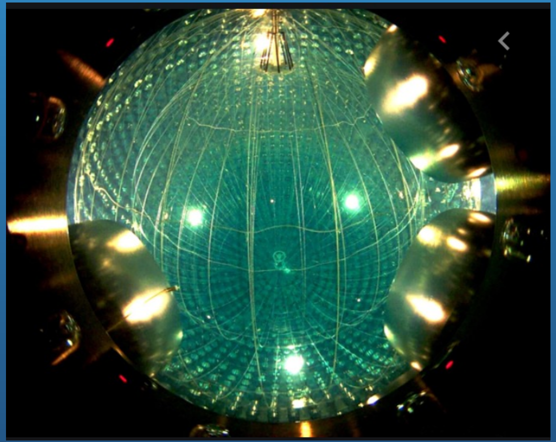


The challenge of Borexino

- Spectral measurement of neutrinos with energy threshold well below 1 MeV, yet unexplored at the time of the project (early ‘90) : main goal -> solar-ν

Neutrinos from the Sun, solar flares, supernovae, extreme cosmic events





Geo-neutrinos, not-standard neutrino interactions, axions..

Possibility to explore also many other sources or rare processes

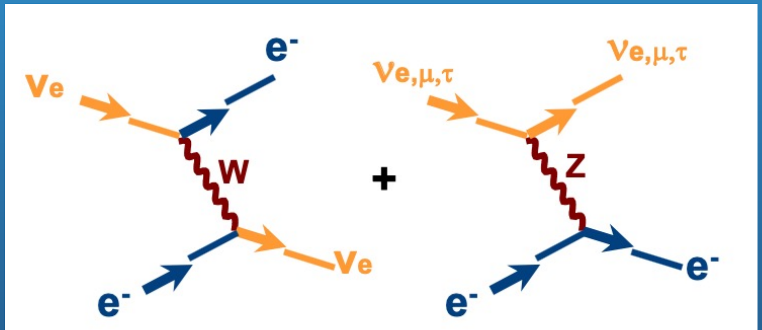
Low energy ν- detection

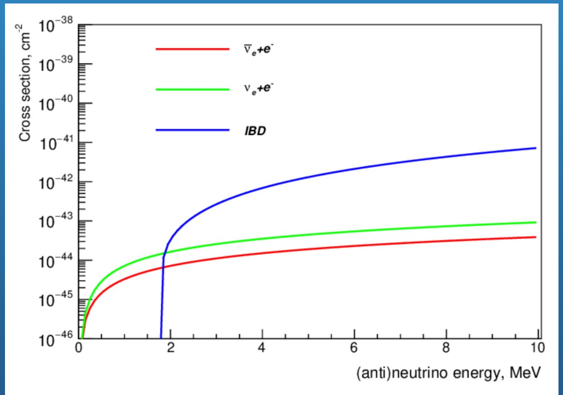
Choice of a organic liquid scintillator (high light yield)

Elastic scattering on electrons

$$\nu + e \longrightarrow \nu + e$$

Single events, no threshold, all flavours





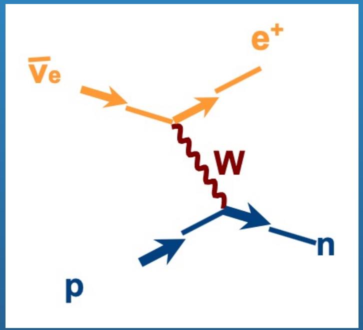
Signal rate dominated by solar neutrinos

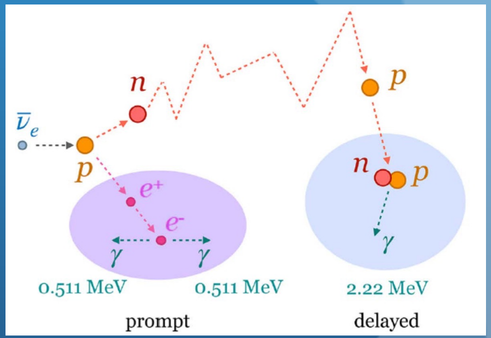
σ_{IBD} at few MeV: ~10^{-42} cm^2 (~100 x more than scattering)

Inverse beta decay

$$\overline{\nu_e} + p \longrightarrow n + e^+$$

Charge current, electron flavour only

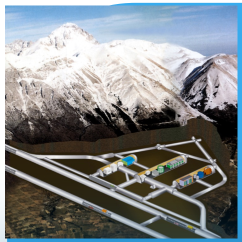




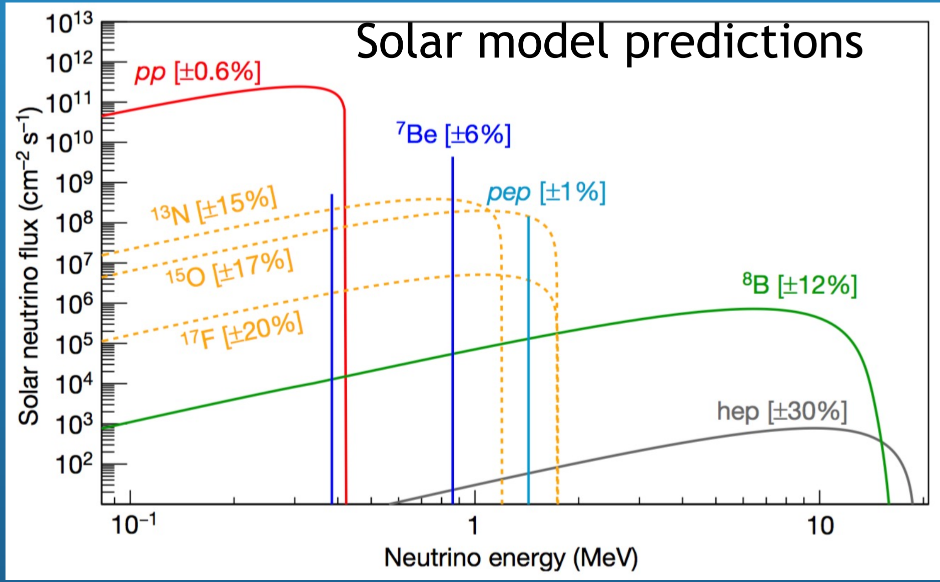
Energy threshold = 1.8 MeV,
τ ~ 255 μs

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

Signal rate dominated by geo and reactors antineutrinos for E_ν<10 MeV



BOREXINO strategy: radiopurity



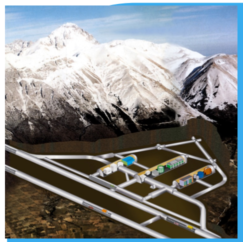
$$\nu + e \rightarrow \nu + e$$

The expected signal rate from ^{7}Be solar ν :
~ 5 10^{-9} Bq/Kg
Glass of drinking water activity :
~ 10 Bq/Kg

Strong scintillator radio-purification: a gain of 10 orders of magnitude needed !!

Recipe:

- ✓ Underground site
- ✓ Principle of graded shielding: the closer the layer is to the center, the greater its radio-purity
- ✓ Choice of organic liquid scintillator : easier radio-purification (pseudocumene PC + a fluorescent dye- PPO)
- ✓ Careful selection of all the materials and development of specific handling procedures
- ✓ Custom and home-made components
- ✓ As little material as necessary for all components (all materials are radioactive)
- ✓ On-site purification plants
- ✓ Small scale demonstrator (CTF, 5 tons of LS)



Detector layout

Laboratori Nazionali del Gran Sasso

NIM-A 600 (2009) 568-593

JINST 7 (2012) P10018

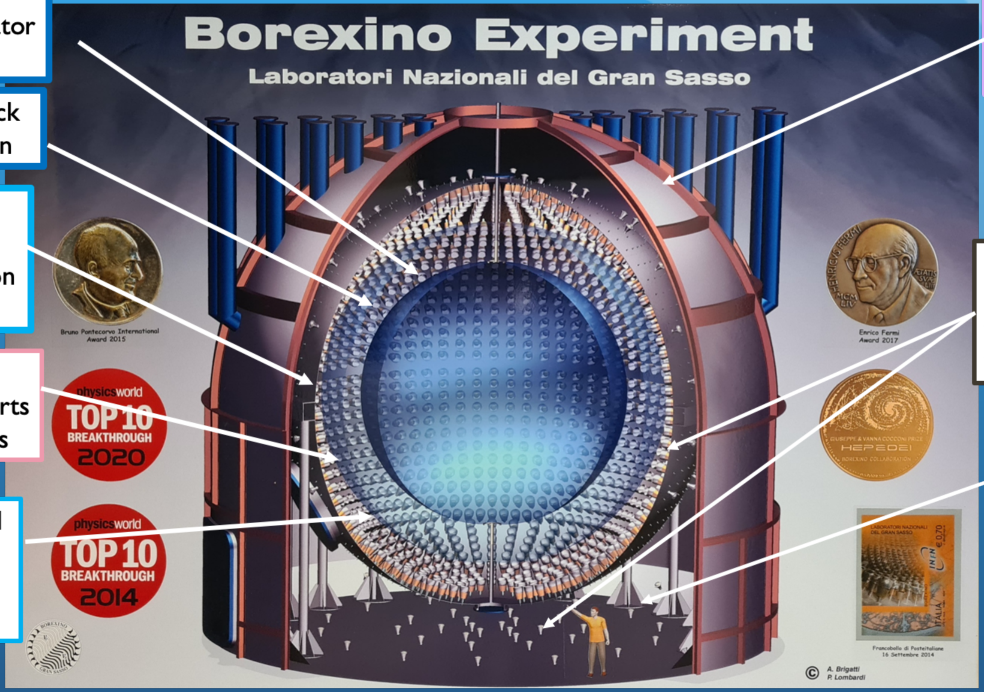
278 tons of liquid scintillator PC+PPO

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)



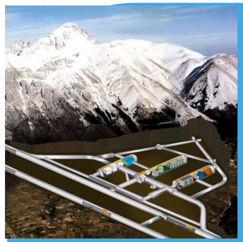
WT, 16.9 m high and 9.0 m of radius; 2400 t ultrapure water.

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
- **Pulse shape identification:** (α/β, e+/e-)

built like an onion, with a graded shielding



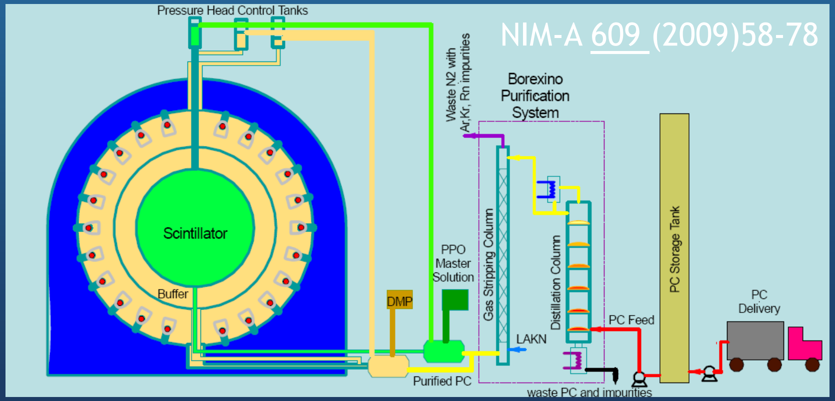
Purifications and materials selections

Design goal : all background sources should produce < **1cpd/100ton in the scintillator (=> ^{238}U and ^{232}Th below 10^{-16} g/g!)**

Scintillator:
Pseudocumene obtained from very old oil Lybian 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

- **Detector & Plants**
  All materials carefully selected for:
  Low intrinsic radioactivity, low Rn emanation
  Good behaviour in contact with PC
- **Nylon vessels**
  Material selection for chemical & mechanical strength
  Low radioactivity, Construction in low ^{222}Rn clean room, never exposed to air : 125 μm thickness!! → a challenge!



Backgrounds (Phase 1)

Background	Typical abundance (at source)	Borexino goals	Borexino measured
$^{14}C/^{12}C$	10^{-12} (cosmogenic) g/g	~10^{-18} g/g	~ 2 10^{-18} g/g
^{238}U (by ^{214}Bi-^{214}Po)	~10^{-5} (dust) g/g	10^{-16} g/g	(5.3 ± 0.5) 10^{-18} g/g
^{232}Th (by ^{212}Bi-^{212}Po)	~ 10^{-5} (dust) g/g	10^{-16} g/g	(3.8 ± 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	~ 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

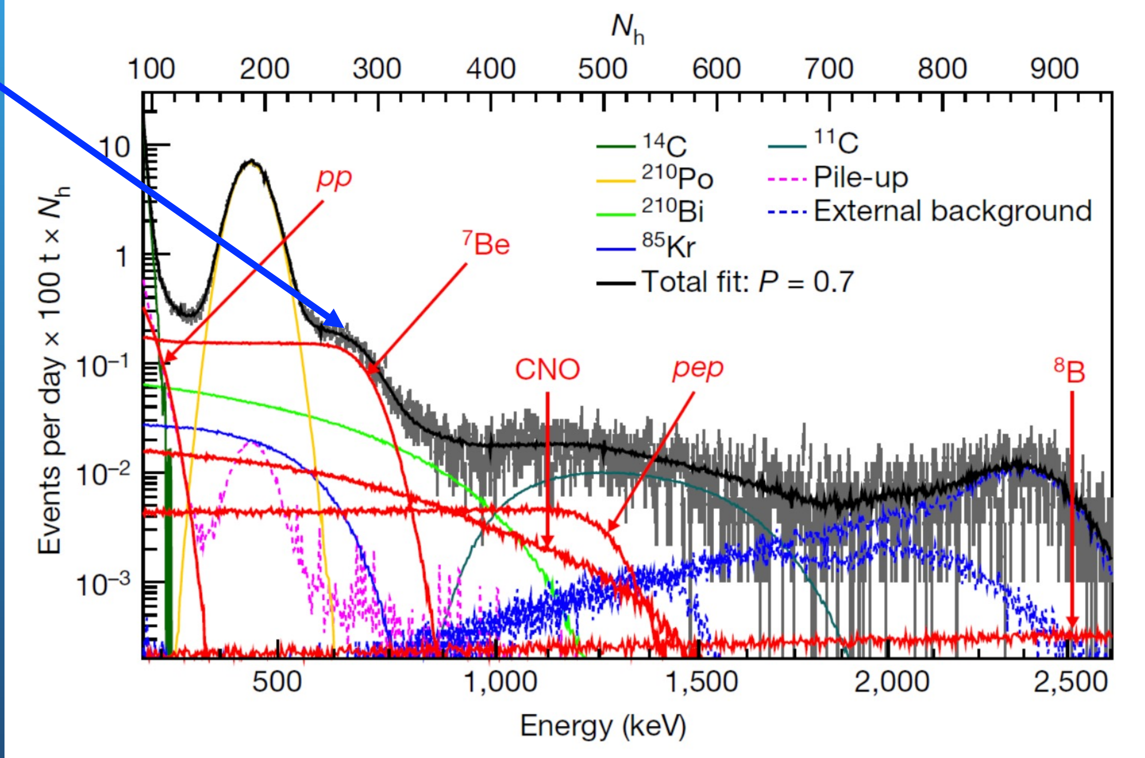
factor 10-100 better that specs!!

Phys. Rev. D 89, 112007 (2014)

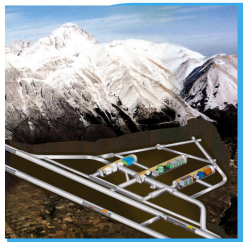
Analysis techniques

7Be-ν shoulder was visible after very simple event selection cuts (mainly μ and FV : 100 tons)..

…but to quantify the more elusive neutrino components new/refined analysis techniques have been developed to constrain/remove backgrounds (^{14}C, ^{210}Po, ^{11}C , ^{210}Bi,^{85}Kr..) depending on the energy range and on the specific analysis

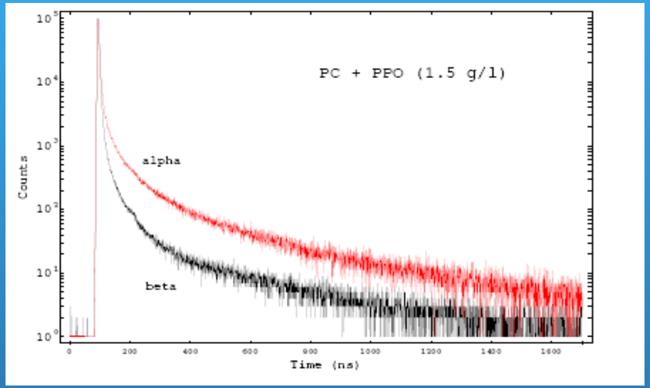


Comprehensive results on proton-proton chain solar neutrinos (Nature, 496 (2018) 505))

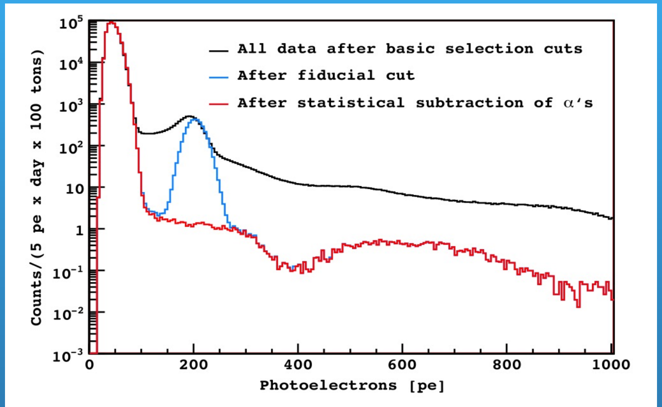


Background tagging and PSA examples

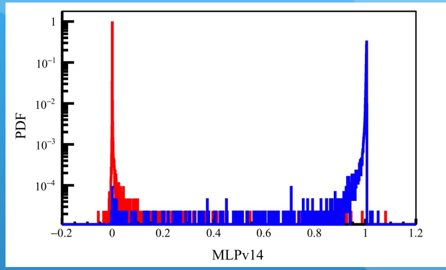
α/β discrimination :



different signal time length: Gatti optimum filter



PHYS. REV. D 109, 112014 (2024)



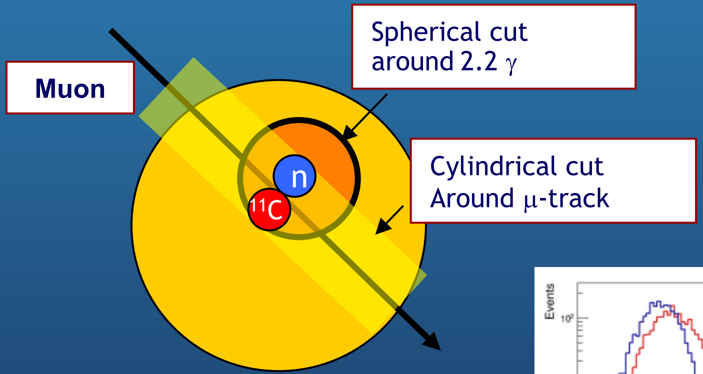
later on perceptron approach based upon a neural network with 13 α/β discriminating input variables

^{11}C tagging :

1) three fold coincidence (TFC)

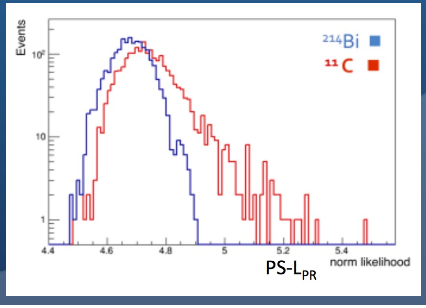
$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

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

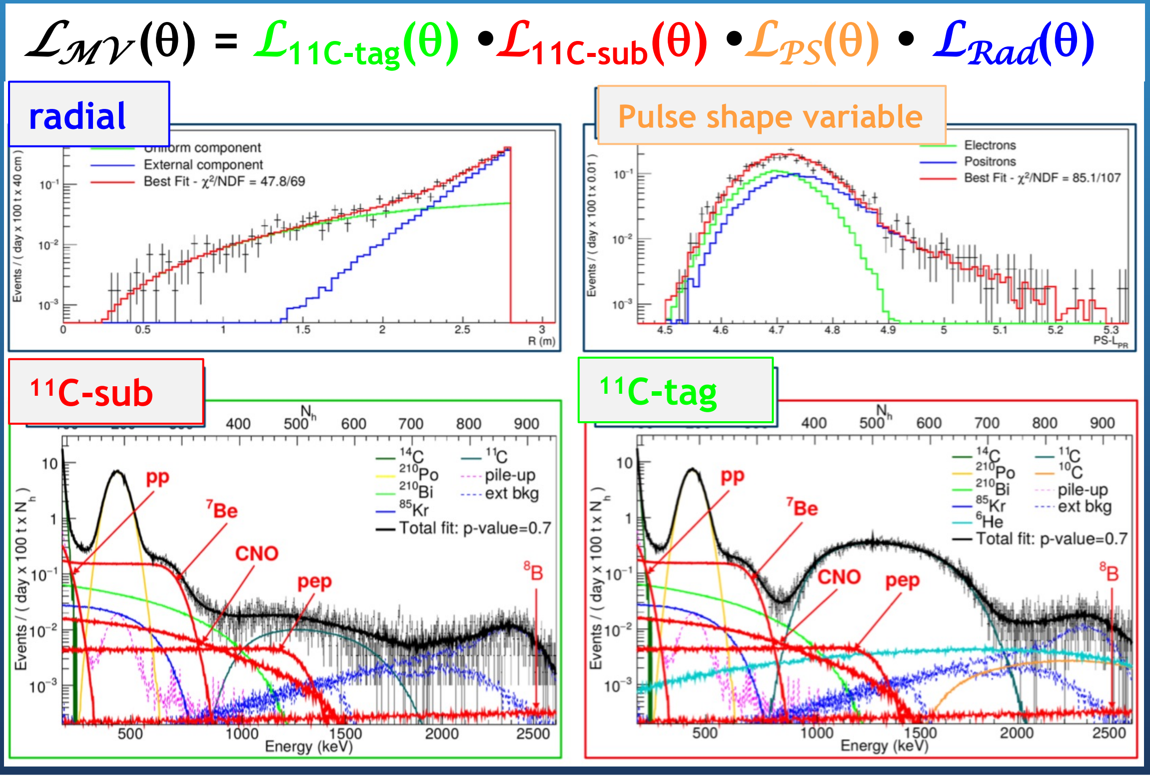
PSD based on the difference of the scintillation time profile for e- and e+

Comprehensive pp-chain solar ν analysis:

Nature, 496 (2018) 505))

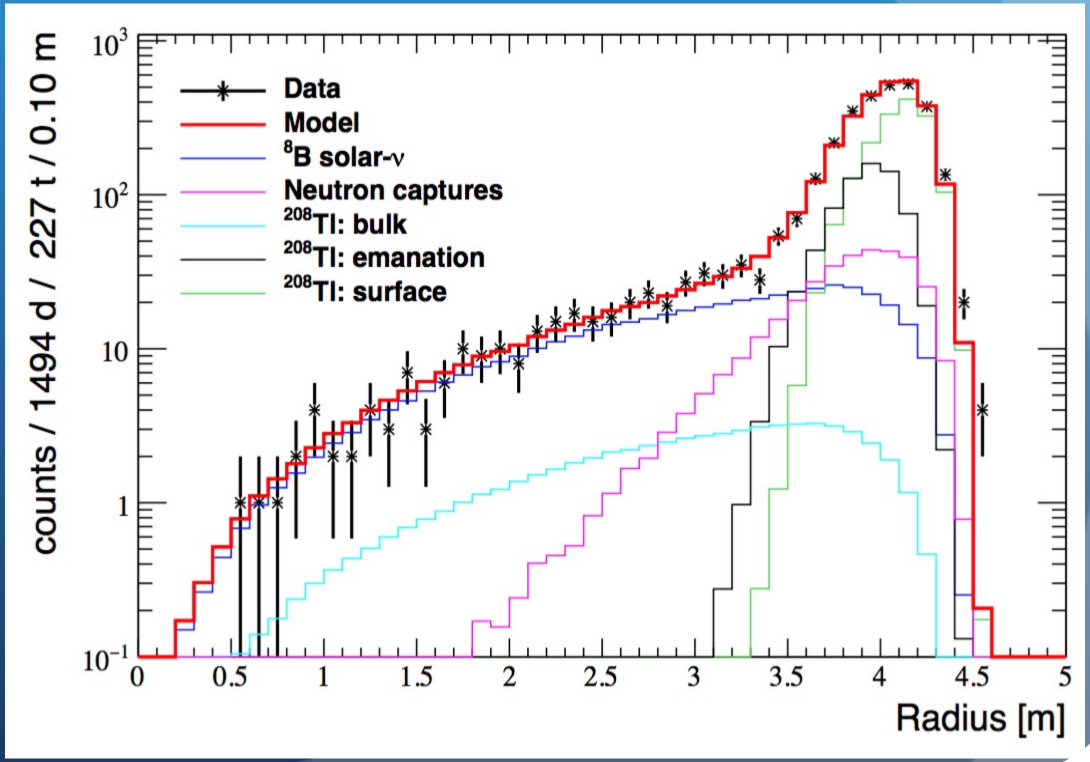
Energy window : 0.19-2.93 MeV (pp,pep,^{7}Be-ν)

Method :Binned likelihood fit through a multivariate approach

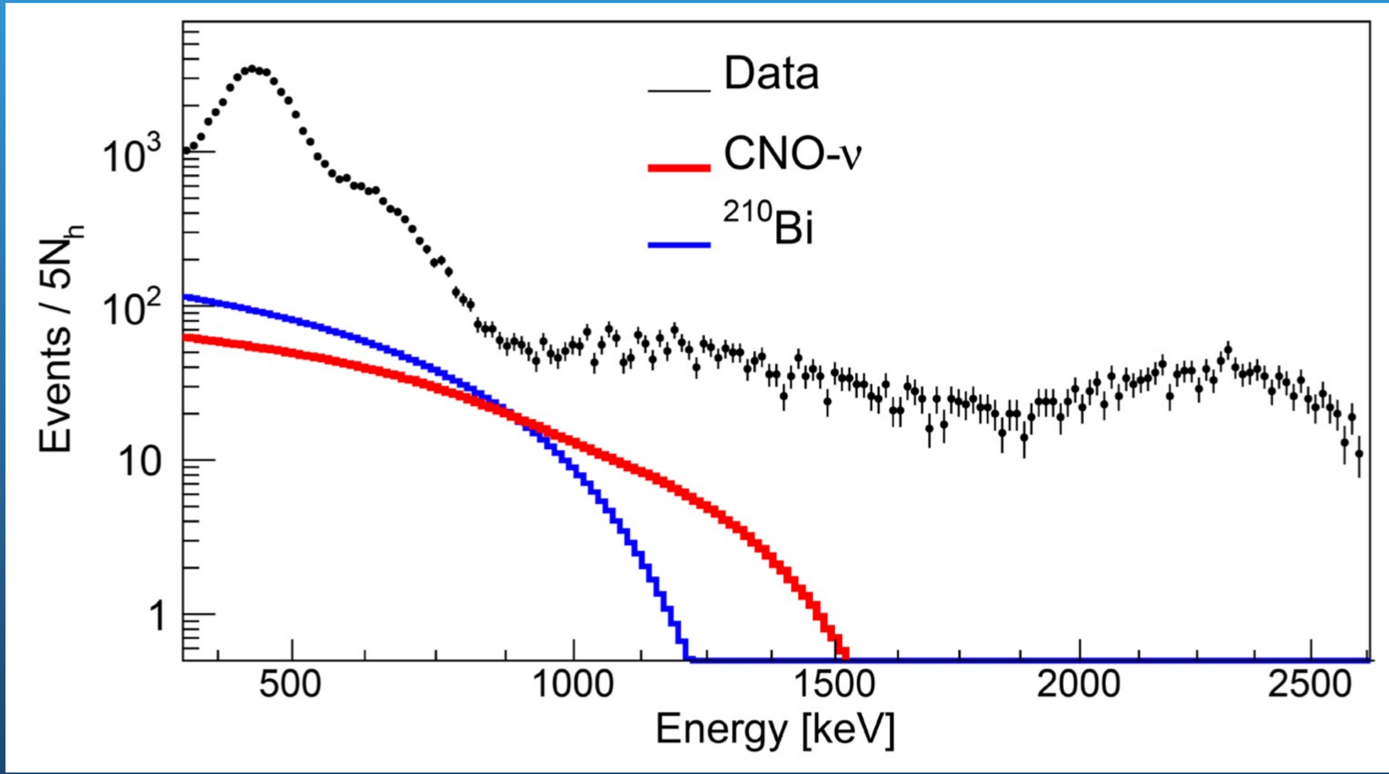


Energy window > 3 MeV : ^{8}B-ν

Method: Fit of radial distribution of events, no assumption on E_ν energy spectrum → probe MSW



CNO-ν: a further experimental and analysis effort



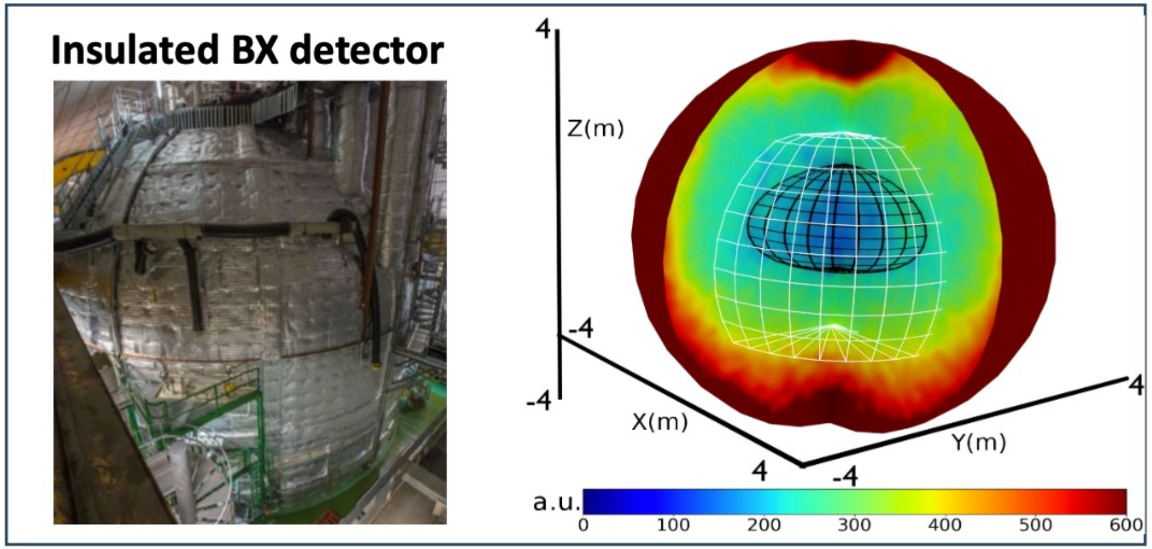
THE PROBLEM

•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: **External constraint on ^{210}Bi rate from ^{210}Po**

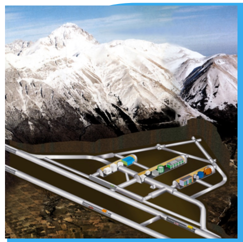
- Requires secular equilibrium in the ^{210}Pb→^{210}Bi→^{210}Po chain;
- The detector was totally insulated (+ active temperature control on the top) to avoid convective currents which bring out-of- equilibrium ^{210}Po from the vessel into the scintillator
- **R(^{210}Bi) ≤ 11.5 ± 1.3 cpd/100t**
- 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)

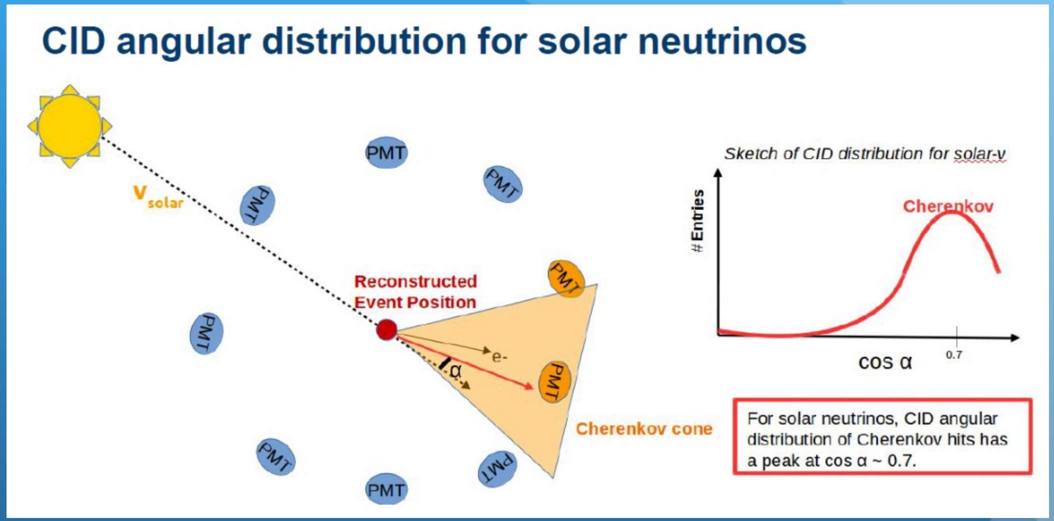


CNO neutrinos

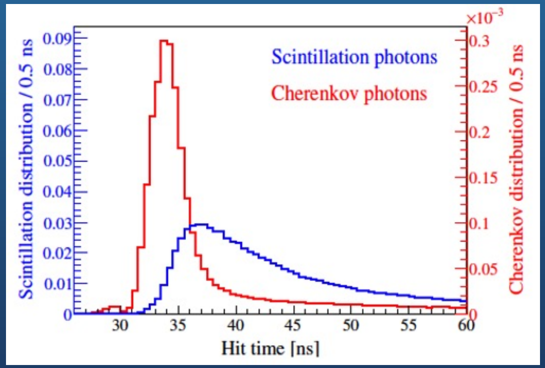
arXiV 2307.14636
PHYS. REV. D 108, 102005 (2023)

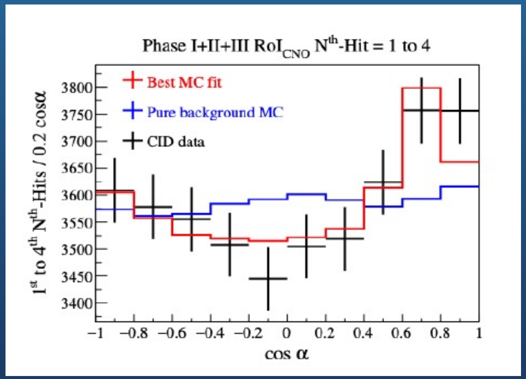
Second idea: Correlation with the Sun direction (CID method)

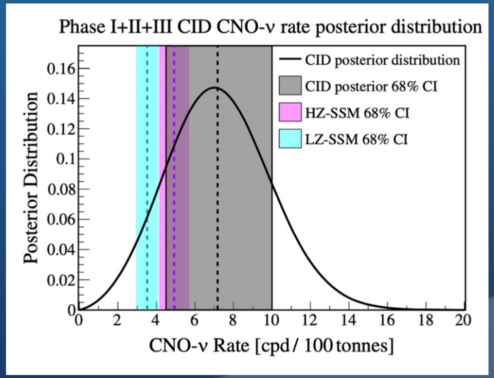
- For each event, the earliest hits (1-2) are most likely due to Cherenkov light (directional..) emitted instantly;
- PDF production using Geant4-based simulations: ν-interaction, e- energy deposition, production of scintillation and Cherenkov light photon propagation, full electronics simulation



CNO rate: $7.2^{+2.8}_{-2.7}\ (stat.+syst)$ cpd/100t



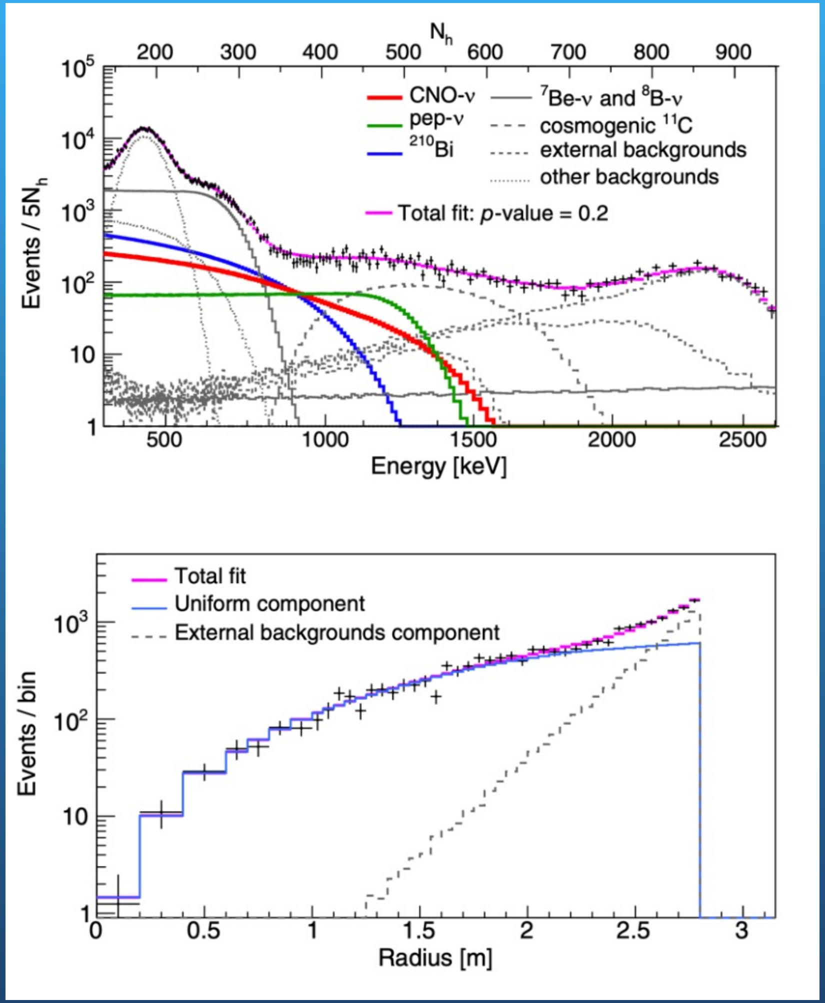




Borexino evidence of CNO neutrinos (using only meth.2) (>5.3σ)

^{210}Bi constrain not used !!!

CNO final result: combined analysis



Phase III: Jan 2017-Oct 2021
ROI: (0.43-2.64) MeV
Exposure: 1431.6 days x 71.3 t
Performing combined likelihood fit

$$\mathcal{L}_{\mathrm{MV+CID}} = \boxed{\mathcal{L}_{\mathrm{MV}} \cdot \mathcal{L}_{\mathrm{pep}} \cdot \mathcal{L}_{^{210}\mathrm{Bi}}} \; \boxed{\mathcal{L}_{\mathrm{CID}}^{\mathrm{P-I}} \cdot \mathcal{L}_{\mathrm{CID}}^{\mathrm{P-II+III}}}$$

Standard multivariate fit:
pep ν: 1.4% rate constrain
(solar physics + oscillations)
^{210}Bi rate constraint only for
phase 3 (thermal insulation)

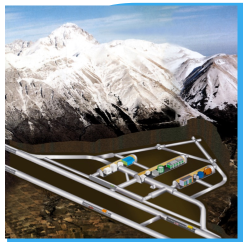
Pull terms for CID
posterior

Excluding no-CNO signal hypothesis at 8σ CL

R(CNO) = $6.7^{+1.2}_{-0.8}$ cpd/100t

Φ(CNO)= $6.7^{+1.2}_{-0.8}$ x10^8 cm^{-2} s^{-1}

arXiV 2307.14636
PHYS. REV. D 108, 102005 (2023)



BX final fluxes

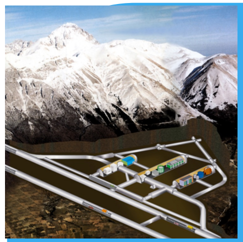
Nature 562 (2018) 505, Physical Review D 100, 082004 (2019), Phys. Rev. D 101, 062001 (2020)

Solar neutrinos	Rate (Counts/day/100t)	Uncertainty	Flux* (neutrinos/cm²/sec)	SSM predictions** (neutrinos/cm²/sec)
pp	$134\pm10^{+6}_{-10}$	9.5%	$(6.1\pm0.5^{+0.3}_{-0.5})\mathrm{x}10^{10}$	$5.98(1\pm0.006)\ \mathrm{x}10^{10}$ (HZ) $6.03(1\pm0.006)\ \mathrm{x}10^{10}$ (LZ)
pep (HZ)	$2.43\pm0.36^{+0.15}_{-0.22}$	17%	$(1.27\pm0.19\,^{+0.08}_{-0.12})\mathrm{x}10^{8}$	$1.44(1\pm0.01)\ \mathrm{x}10^{8}$ (HZ) $1.46(1\pm0.01)\ \mathrm{x}10^{8}$ (LZ)
pep (LZ)	$2.65\pm0.36^{+0.15}_{-0.24}$	17%	$(1.39\pm0.19\,^{+0.08}_{-0.13})\mathrm{x}10^{8}$	$1.44(1\pm0.01)\ \mathrm{x}10^{8}$ (HZ) $1.46(1\pm0.01)\ \mathrm{x}10^{8}$ (LZ)
7Be	$48.3\pm1.1^{+0.4}_{-0.7}$	2.7%	$(4.99\pm0.11^{+0.06}_{-0.08})\mathrm{x}10^{9}$	$4.93(1\pm0.06)\ \mathrm{x}10^{9}$ (HZ) $4.50(1\pm0.06)\ \mathrm{x}10^{9}$ (LZ)
8B	$0.223^{+0.015+0.006}_{-0.016-0.006}$	7.6%	$(5.68^{+0.39+0.03}_{-0.41-0.03})\mathrm{x}10^{6}$	$5.46(1\pm0.12)\ \mathrm{x}10^{6}$ (HZ) $4.50(1\pm0.12)\ \mathrm{x}10^{6}$ (LZ)
CNO	$6.7^{+1.2+0.3}_{-0.7-0.4}$	+30% -12%	$(6.7^{+1.2+0.3}_{-0.8-0.4})\mathrm{x}10^{8}$	$4.88(1\pm0.11)\ \mathrm{x}10^{8}$ (HZ) $3.51(1\pm0.10)\ \mathrm{x}10^{8}$ (LZ)

- world-first direct measurements of pp, ^{7}Be , pep and CNO neutrinos , and the flux of 8B-ν $\cong 8\%$ precision

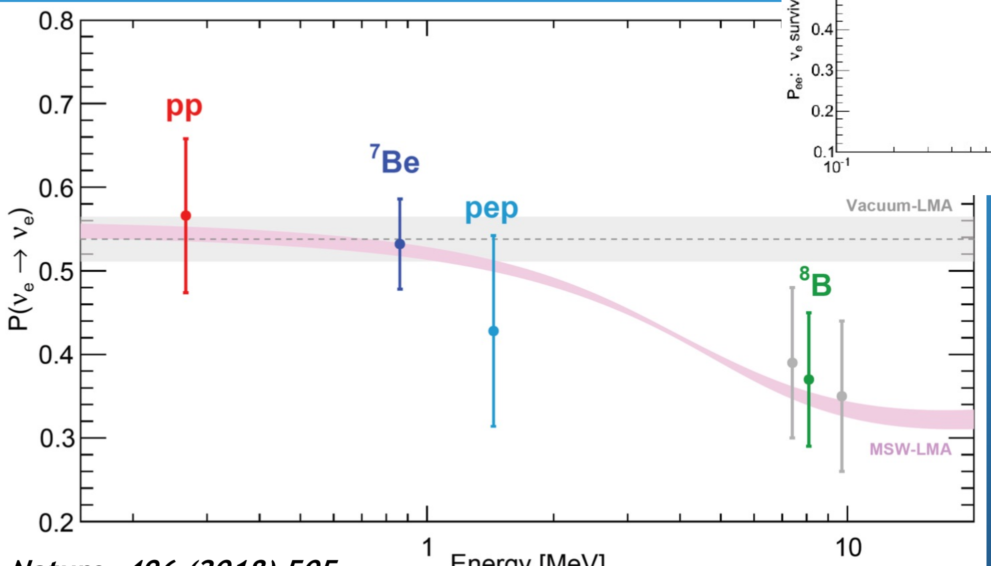
*oscillation parameters from: I.Esteban, *MC.Gonzalez-Concha, M.Maltoni, I.Martinez-Soler and T.Schwetz, Journal of High Energy Physics 01 (2017)*

**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)*

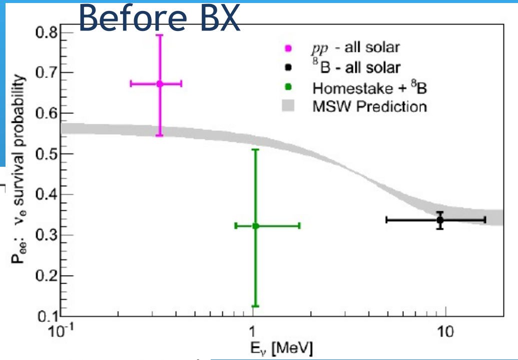


BX : implications for particle physics

Survival probability Pee



Nature, 496 (2018) 505

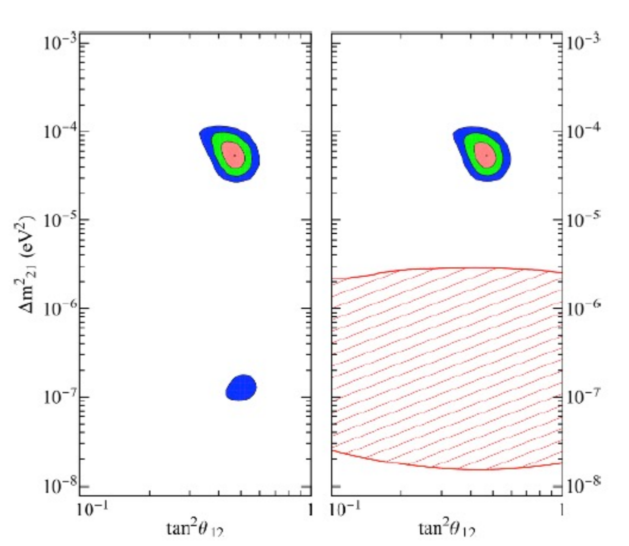


Assuming HZ-SSM fluxes:
Pee(pp)=0.57±0.09
Pee(7Be)=0.53±0.05
Pee(pep)=0.43±0.11
Pee(8B)=0.37±0.08

*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

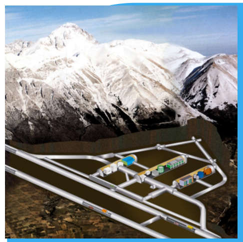


- Day/night effect found null by Borexino in the ^{7}Be energy window.

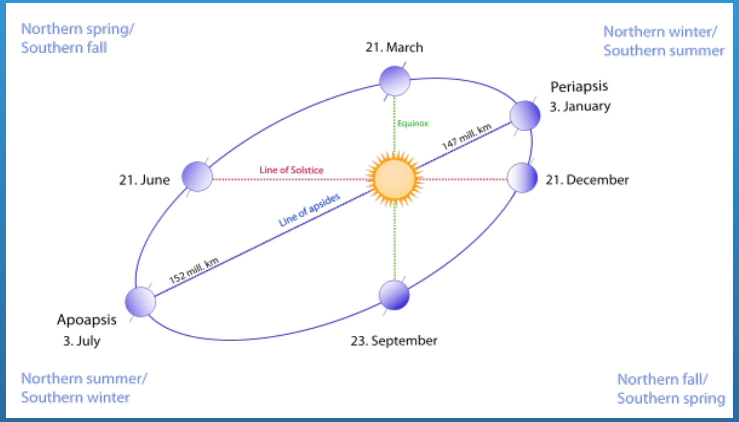
$A_{dn} = 2\,(R_N - R_D)/(R_N + R_D) = 0.007 \pm 0.073$

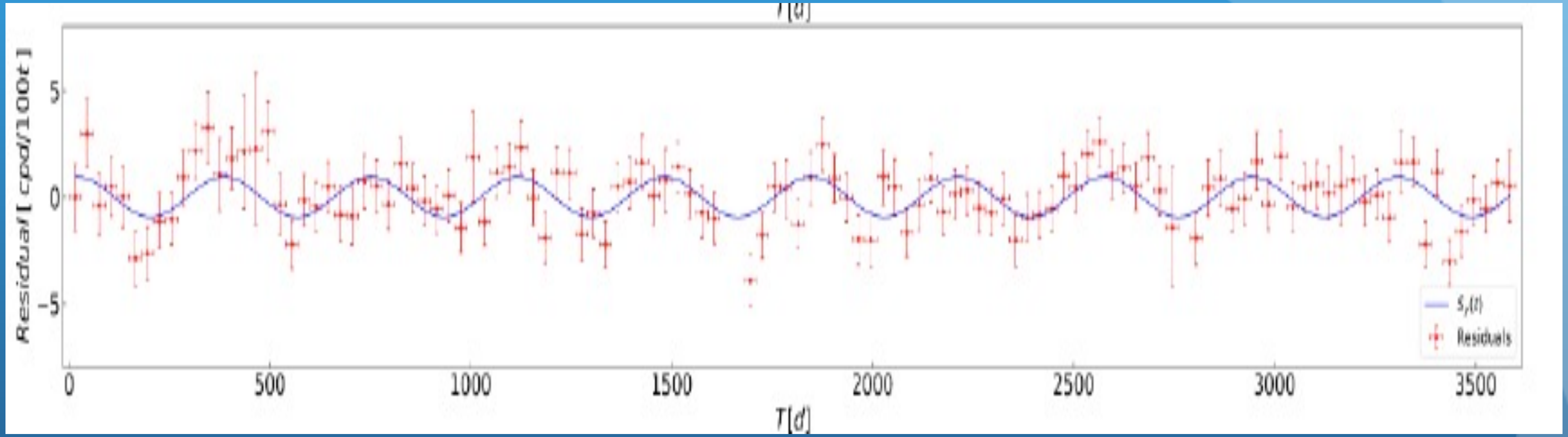
Singles out LMA solution without KamLAND antineutrinos and then CPT assumption

Implications of BX results for astrophysics



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



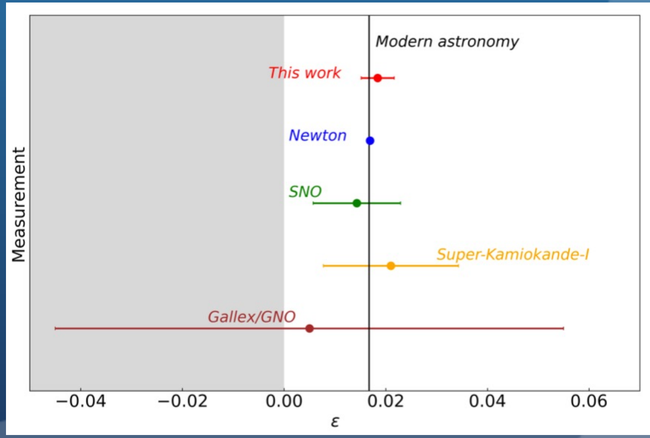


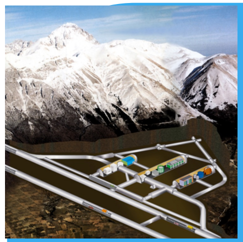
Astr. Phys. 145 (2023) 102778

- 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 for astrophysics

Solar Luminosity

Neutrinos provide a real-time picture of the core of the Sun. From BX measured fluxes:

Neutrino luminosity: *Nature, 496 (2018) 505*

$$\mathbf{L}_\nu = (3.89\,^{+0.35}_{-0.42}) \times 10^{33}\ \mathrm{erg\,s^{-1}}$$

Photon output:

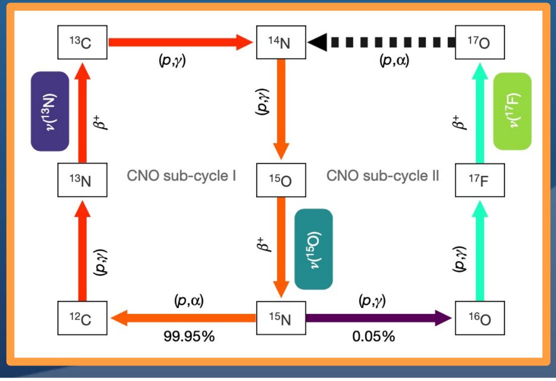
$$\mathbf{L_{ph}} = (3.846 \pm 0.015) \times 10^{33}\ \mathrm{erg\,s^{-1}}$$

The agreement confirms the nuclear origin of the solar power; it proves that the Sun has been in thermodynamic equilibrium over 10^5 years

Existence of the CNO cycle

Borexino has verified for the first time the existence of neutrinos from the CNO cycle (with a significance > 8σ)

- 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**

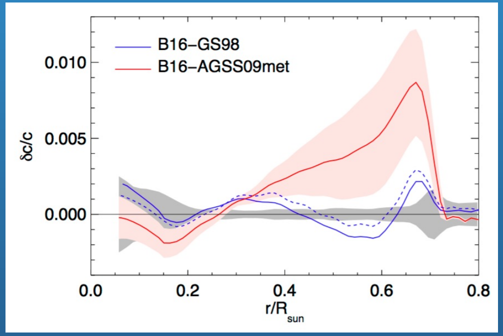


Solar metallicity issue

(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)

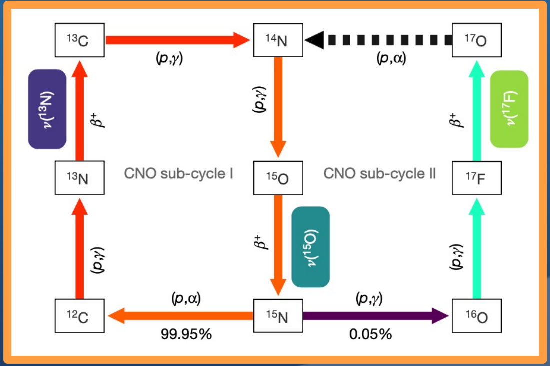
23% difference on Z/X
among spectroscopic data analysis

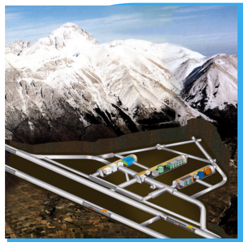


	FLUX	Dependence on T	SSM-HZ(1)	SSM-LZ(2)	DIFF. (HZ-LZ)/HZ
pp chain	**pp (10^{10} cm^{-2} s^{-1})**	**$T^{-0.9}$**	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pp chain	**pep (10^{8} cm^{-2} s^{-1})**	**$T^{-1.4}$**	1.44(1±0.01)	1.46(1±0.009)	-1.4%
pp chain	**^{7}Be (10^{9} cm^{-2} s^{-1})**	**T^{11}**	4.94(1±0.06)	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

- **Direct dependence on metallicity for the CNO-ν fluxes: C, N, O catalyzing the fusion**



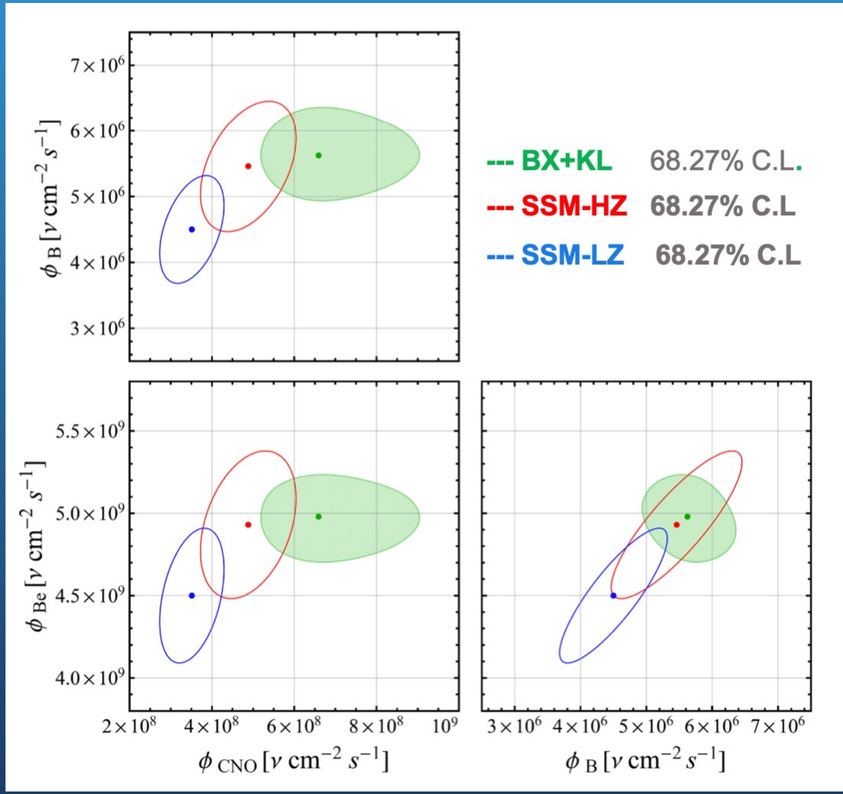


Implications of BX results on astrophysics

Flux comparison with models

PRL 129, 252701 (2022)

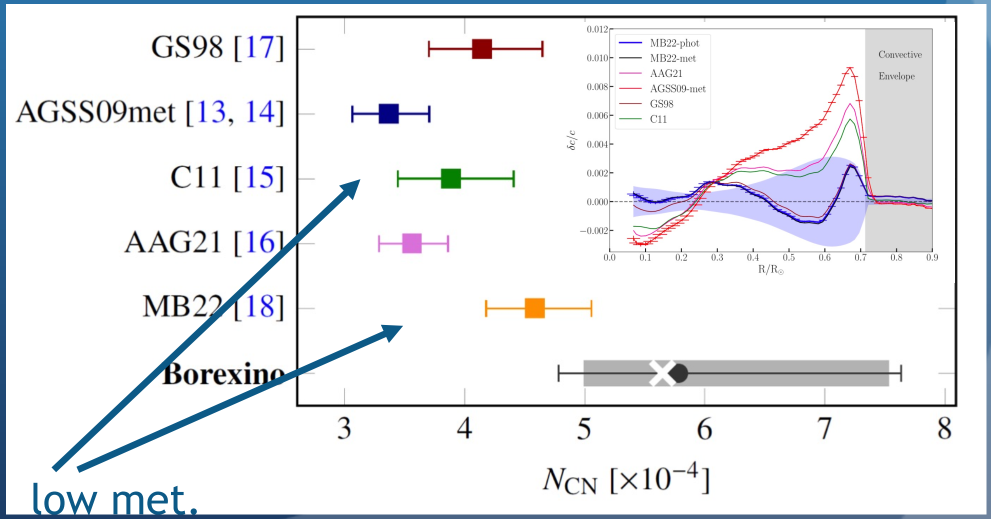
- **Borexino only (+KL)** fit of Φ(Be), Φ(B) and Φ(CNO), together with θ_{12} and Δm^2_{12} as free parameters
- The results agree well with the output of SSM-HZ model, while feature tension with the SSM-LZ model (p= 0.018);



C and N abundance

- ^{8}B flux measurement from other experiments (SNO, SK) + CNO measurement by Borexino => it is possible to determine the C and N content (with respect to H)

BX measurement agrees nicely with the High Metallicity models while features a ~2σ tension with the Low metallicity ones



SN remnant by HST

BX: Earth's and cosmic ν searches

- Geoneutrinos [1]
- Diffuse supernovae neutrino background [2]
- Time correlated signals with:
  - Solar flares [3]
  - Gamma Ray Bursts [4]
  - Fast radio bursts [5]
  - Gravitational waves [6]

(1) PRD 101(2020) 012009, Phys. Rev. D 92.(2015) 031101, Phys. Lett B 722(2013)295, Phys. Lett B 687(2010)299
(2) Astroparticle Physics 125 (2021) 102509
(3) Phys. Lett B 696 (2011) 191
(4) Astroparticle Physics 86, (2017) 1-17
(5) Eur. Phys. J. C 82, 278 (2022)
(6) Eur. Phys. J. C 83 (2023) 538 , ApJ, 850 2017) 21

Geo-neutrinos

Earth's energetics : unclear picture!!

Heat Producing Elements : HPE's

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

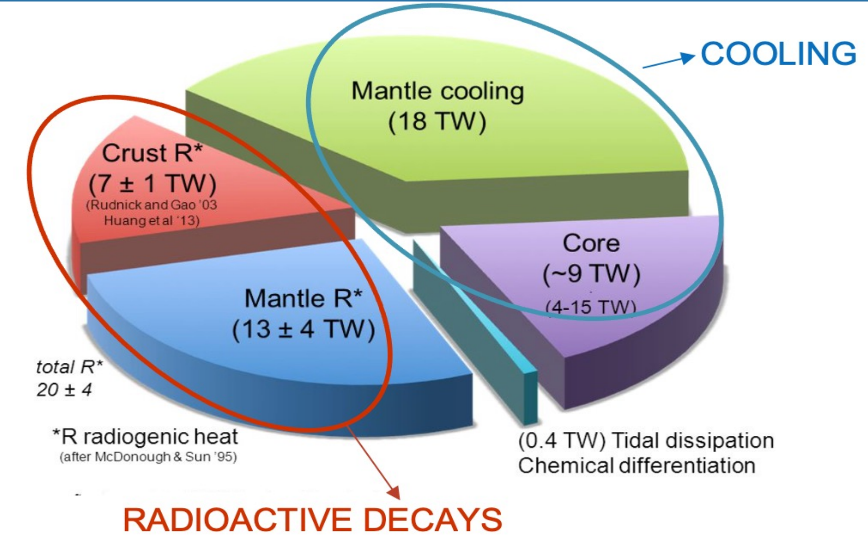
$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^{-} + 6\,\bar{\nu}_e + 51.7$ MeV

Above the IBD threshold (1.8 MeV)

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

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

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



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

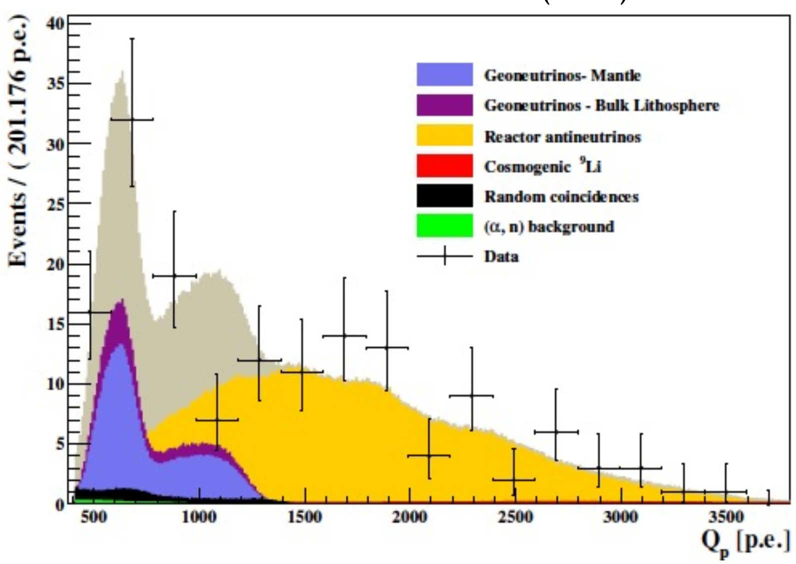
Signal in 1 kton liquid scintillator(IBD) : few tens events/year !

Geo-neutrinos

Detection: IBD

main background: reactor antineutrinos, but different energy spectrum

PRD101 (2020) 012009



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

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 heat U + Th [TW]	$24.6^{+11.1}_{-10.4}$
Earth U + Th + K [TW]	$38.2^{+13.6}_{-12.7}$

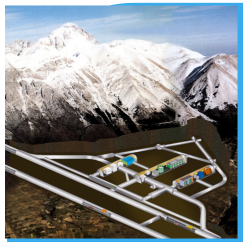
+ 18% contribution of ^{40}K in the mantle, $8.1^{+1.9}_{-1.4}$ TW from lithosphere

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

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)*



Rare processes: BX searches

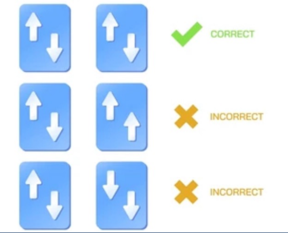
NEW!!

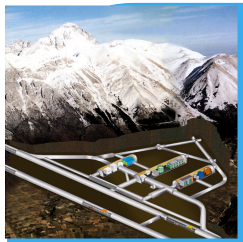
- Search for high energy 5.5 MeV solar axions with the complete Borexino dataset, accepted by European Journal of Physics C (June 2025)

Previous : **- Search for solar axions produced in the p(d,3He)A reaction with Borexino detector**
Phys. Rev. D **85**, 092003, 2012 - doi:10.1140/epjc/s10052-008-0530-9,
- Search for solar axions emitted in the M1-transition of $^{7}Li^{*}$ with Borexino CTF, *The European Physical Journal C* **Volume 54**, 61-72, 2008 doi:10.1140/epjc/s10052-008-0530-9

OTHER STUDIES:

- **Constraints on flavor-diagonal non-standard neutrino interactions from Borexino Phase-II**
  Journal of High Energy Physics 2020, 38 - doi:10.1007/JHEP02(2020)038
- **Limiting neutrino magnetic moments with Borexino Phase-II solar neutrino data**
  Phys. Rev. D 96, 091103(R) 2017 - doi:10.1103/PhysRevD.96.091103]
- **A test of electric charge conservation with Borexino**
  Phys. Rev. Lett. 115, 231802, 2015 - doi:10.1103/PhysRevLett.115.231802
- **New limits on heavy sterile neutrino mixing in ^{8}B decay obtained with the Borexino detector**
  Phys. Rev. D 88, 072010, 2013 - doi:10.1103/PhysRevD.88.072010]
- **New experimental limits on the Pauli-forbidden transitions in ^{12}C nuclei obtained with 485 days Borexino data**
  Phys. Rev. C **81**, 034317,2010 - doi:10.1103/PhysRevC.81.034317





BX: updated search for solar axions

Axions-like particle are suitable candidates for dark matter particles and could explain the absence of CP-violating effects in QCD.

Emission process: p+d →^{3}He + γ or A (5.5 MeV)

http://arxiv.org/abs/2504.19135 (EPJC)

Interaction channels:

- Compton conversion (CC):

$$A + e \rightarrow \gamma + e$$

- Axio-electric effect (AE):

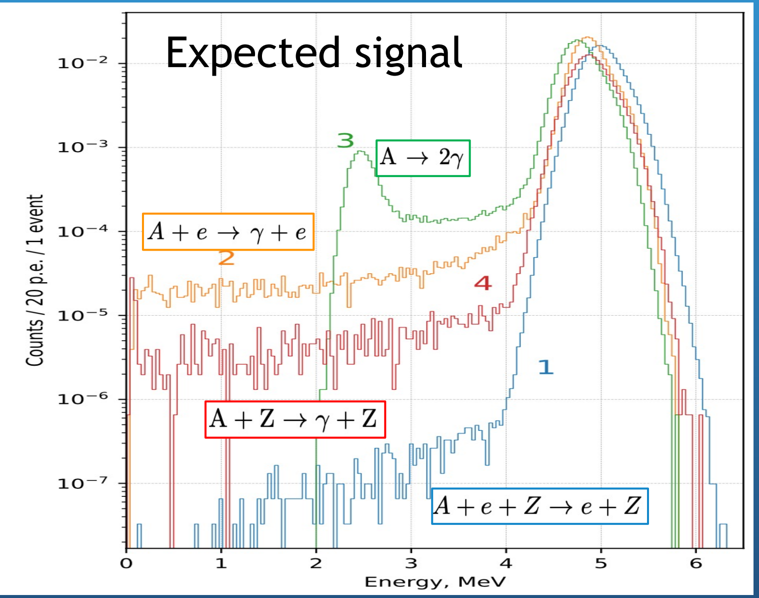
$$A + e + Z \rightarrow e + Z$$

- Inv. Primakoff conversion (PC):

$$\mathrm{A} + \mathrm{Z} \rightarrow \gamma + \mathrm{Z}$$

- Axion decay (CC):

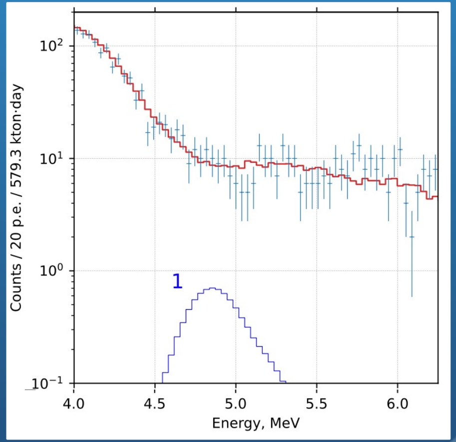
$$\mathrm{A} \rightarrow 2\gamma$$



Adopted cuts:

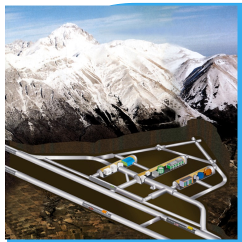
- FV : 145 tons (D_{IV}> 75m)
- Very strict cosmogenic cuts (stat: -22%)
- Main backgrounds: ^{8}B-ν, ^{208}Tl, ext-γ
- Exposure: 579.3 kton days (2007-2021)

Strategy: MV fit of energy and radial distribution of events, adding the expected signal shape



reaction	CC	AE	A→2γ	PC
S^{lim}	8.7	5.6	15.9	10.2

@90% C.L.



BX: limits on axions coupling constants

MODEL INDEPENDENT APPROACH

$$\Phi_A \sigma_{A-e} \leq 5.3 \times 10^{-40} \mathrm{s}^{-1}$$
$$\Phi_A \sigma_{A-p} \leq 3.4 \times 10^{-39} \mathrm{s}^{-1}$$
$$\Phi_A \sigma_{A-C} \leq 4.5 \times 10^{-39} \mathrm{s}^{-1}.$$

Limits on the axion coupling constants to photons, electrons and nucleons were obtained :

$$|g_{A\gamma} \times g_{3AN}| \times m_A^2 \leq 1.6 \times 10^{-11} \mathrm{eV}$$
$$|g_{Ae} \times g_{3AN}| \leq 1.9 \times 10^{-13} \quad \text{(90\% C.L.)}$$

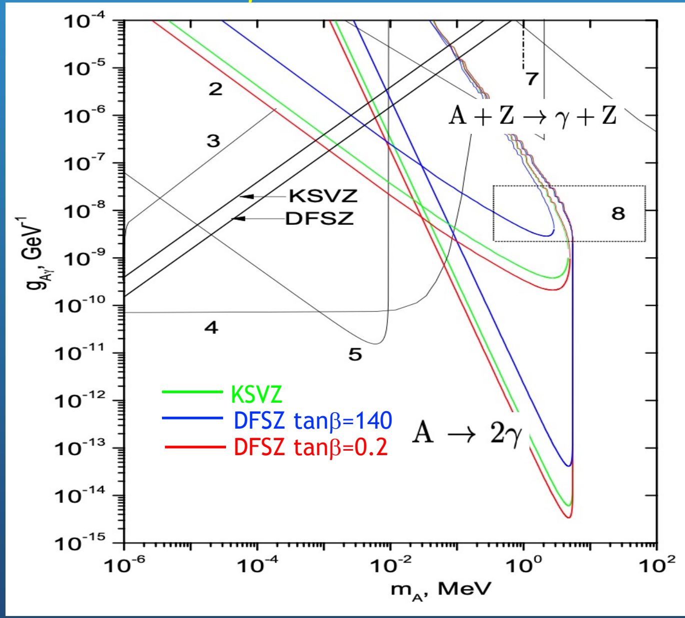
for m_A < 1 MeV

MODEL DEPENDENT APPROACH

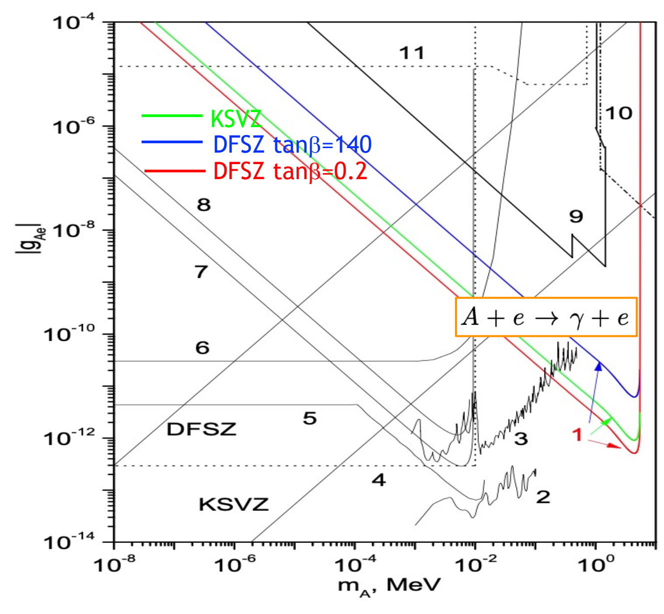
assuming g_{3AN} vs m_a according to models:

- Kim-Shifman- Vainshtein-Zakharov (KSVZ) . *Nucl. Phys. B 166, 493 (1980)*
- Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) : *Phys. Lett. B104, 199 (1981)*

$g_{A\gamma}$ vs m_A

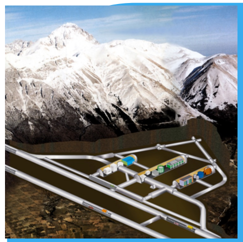


g_{Ae} vs m_A



If the dependence of coupling costants on m_A is taken from models:

KSVZ model: excl. m_A = 0.7-80 keV
DFSZ model: excl. m_A =1.2-100 keV
tan(β)=140



Conclusions

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

17 months of a second scintillator purification

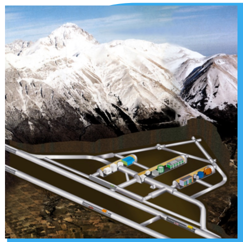
Second phase of data taking

thermal insulation+ new trigger

Third phase od data taking

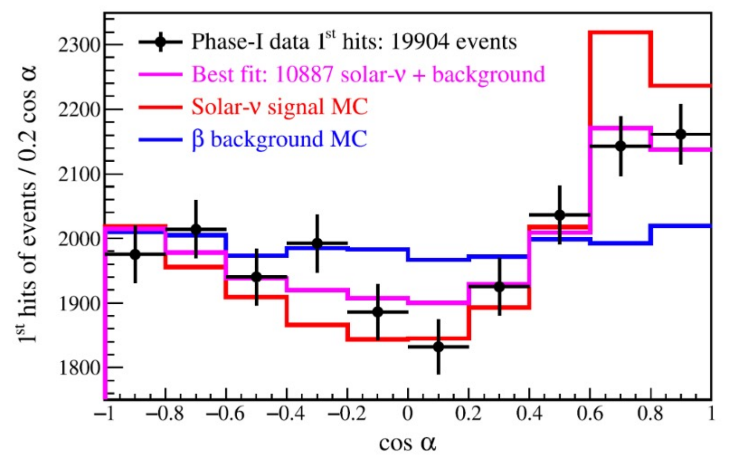
….almost the same time to design/build the detector and to run the experiment/data analysis!!!

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



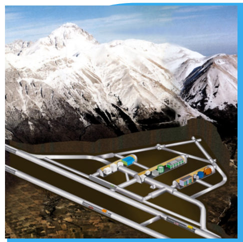
Borexino legacy

- **Borexino has systematically codified techniques needed for studying neutrino physics with a threshold down to about 100 keV,** reaching unprecedented levels of radiopurity ($<9\times10^{-19}$ g(Th)/g LS,$<8\times10^{-20}$ g(U)/g LS)
- **Borexino has also proved that it possible to exploit contemporary the advantages of scintillation and Cherenkov light (hybrid approach) :**
  - Advantage of scintillation light: better energy resolution, low threshold;
  - Advantage of Cherenkov light: directionality → boost the sensitivity to solar neutrinos



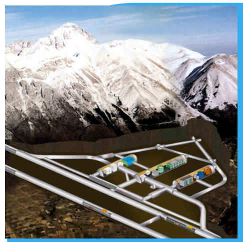
- **New large mass scintillators that followed the BX purification strategies have now started to take data (JUNO).**

- **The developed purification and analysis techniques are the BX legacy for the next low energy neutrinos and rare event searching experiments.**



Thank you !!

Backup



Geo-neutrino signal from the mantle

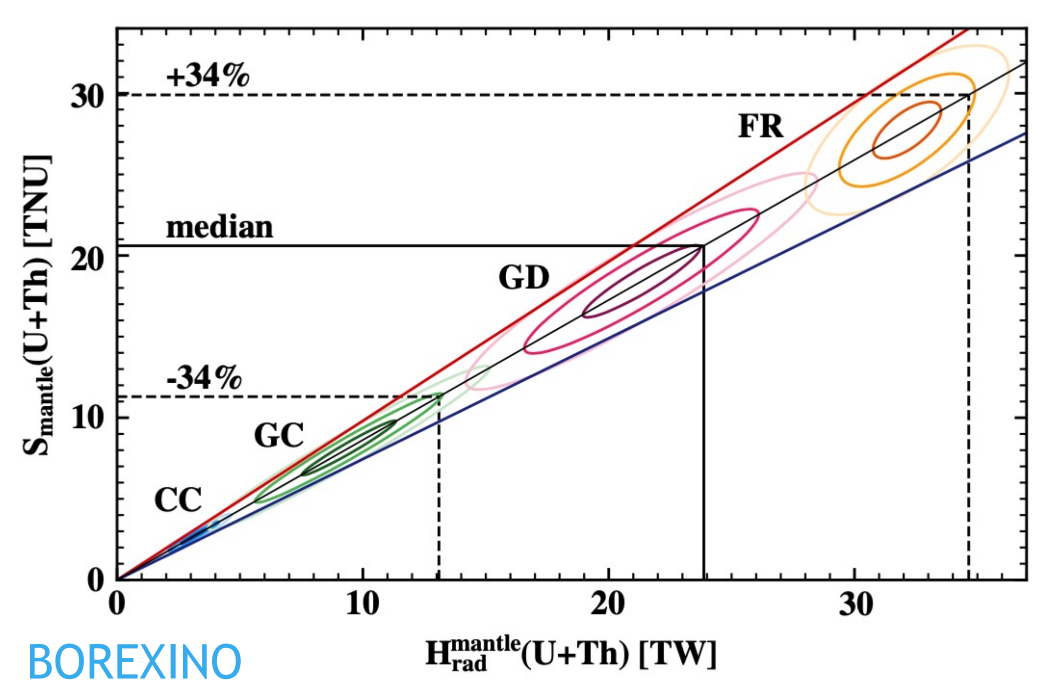
Bulk Silicate Earth's Models

Cosmochemical (CC) Poor-Heat
based on the enstatine chondrites

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

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

FR =Full radiogenic



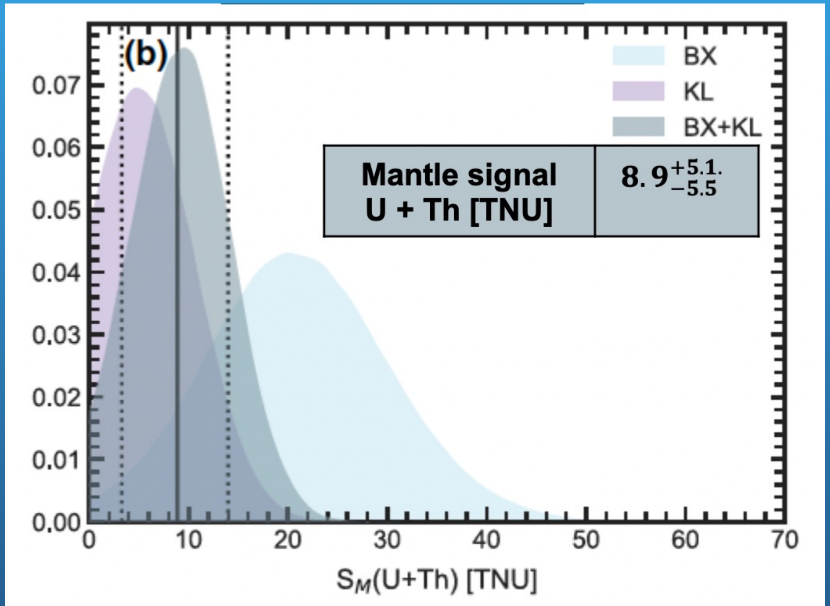
Mantle signal U + Th [TNU]	$21.2\,^{+9.6}_{-9.1}$
Mantle heat U + Th [TW]	$24.6\,^{+11.1}_{-10.4}$
Earth U + Th + K [TW]*	$38.2\,^{+13.6}_{-12.7}$

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

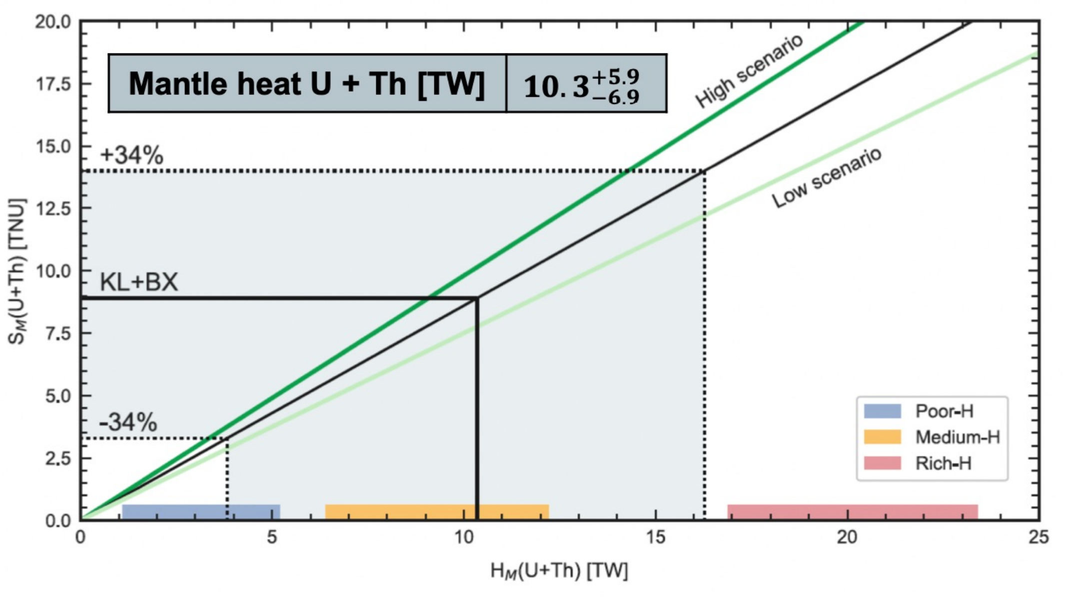
- BX result compatible with predictions
- Least compatibility (2.4 σ) with CosmoChemical and Low -H BSE geological models

BX+KamLAND combined analysis

Mantle U+Th signal

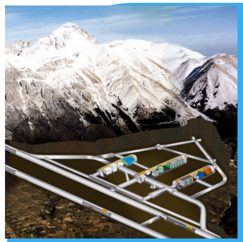


Mantle Radiogenic heat and BSE



Bellini at al.: La rivista del Nuovo Cimento 45 (2022) 1

- **Combined analysis perfectly compatible with Medium-H BSE Models.**
- Some tension between the two experiments… mantle laterally not homogeneous??
- Need for further studies (SNO+,JUNO..)
- Geo-ν are source of uncertainty for cosmic antineutrino fluxes < 3.2 MeV (geo-ν endpoint)

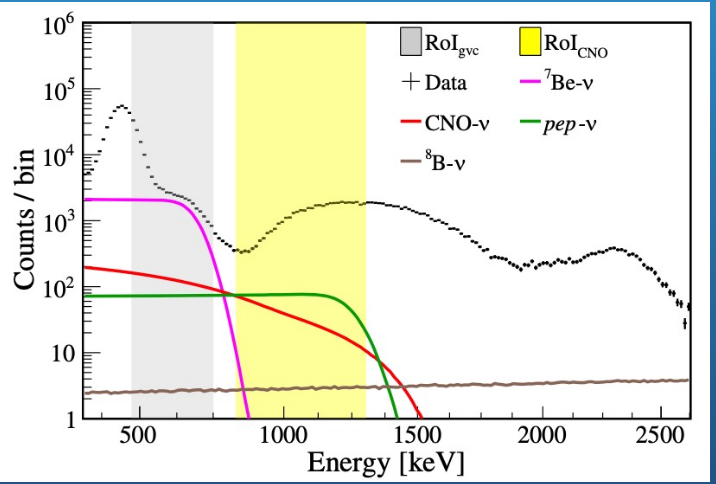


CNO neutrinos

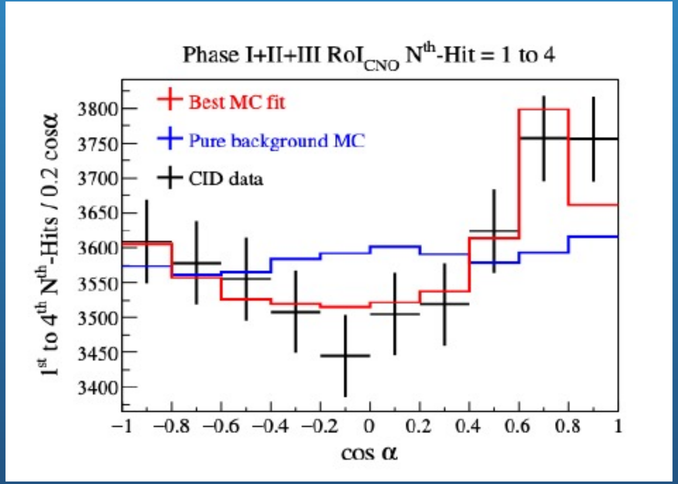
Second idea : 2) Correlation with the Sun direction (CID method)

PDF production using Geant4-based simulations: Neutrino interaction, recoil e- energy deposition, multiple scattering in LS, Production of scintillation and Cherenkov light photon propagation, Full electronics simulation

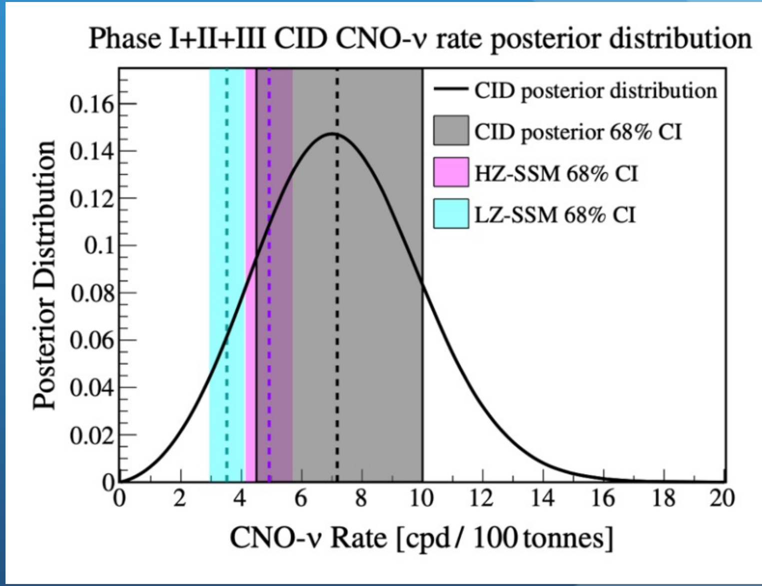
arXiV 2307.14636
PHYS. REV. D 108, 102005 (2023)



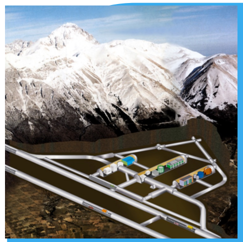
ROI CNO (yellow)
χ^2 fit to extract the total number of neutrinos in the ROI



Borexino evidence of CNO neutrinos (using only 2) (>5.3σ)
^{210}Bi constrain not used !!!



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



Implications of BX results on astrophysics : the C N abundances

Combining the precise measurement of ^{8}B from other experiments with the CNO measurement by Borexino it is possible to determine the C and N content (with respect to H)

$$\Phi_O/\Phi_O^{SSM} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \times (T_c/T_c^{SSM})^{\tau_O}$$

so

BX

surface abundances

$$\frac{(\Phi_O/\Phi_O^{SSM})}{(\Phi_B/\Phi_B^{SSM})^{0.769}} = \frac{N_{CN}}{N_{CN}^{SSM}}[1 \pm 0.097(\mathrm{nucl}) \pm 0.005(\mathrm{env}) \pm 0.027(\mathrm{diff})].$$

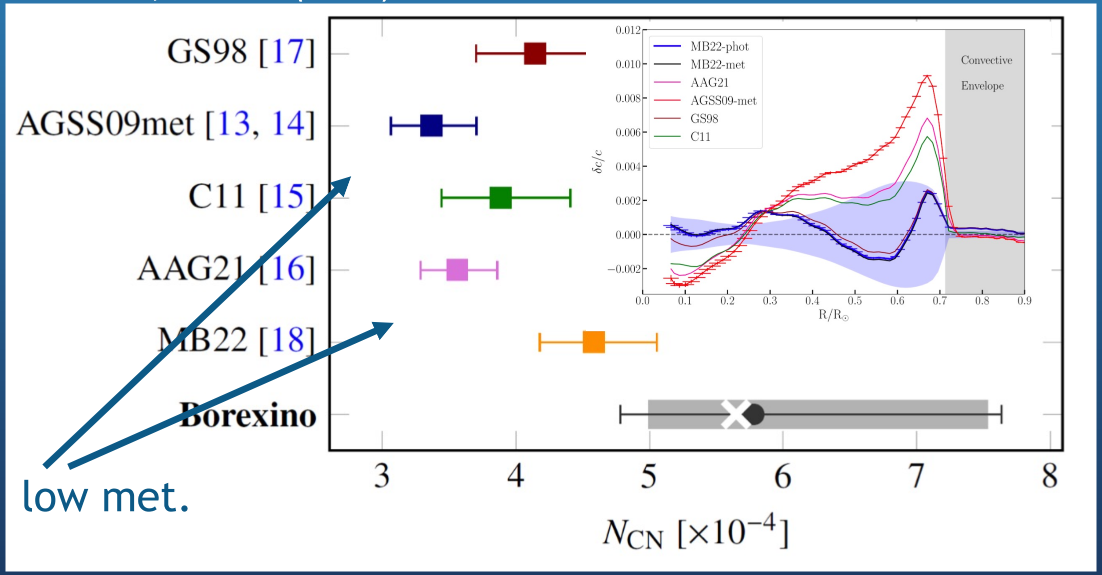
but

$$\Phi_B/\Phi_B^{SSM} \propto (T_c/T_c^{SSM})^{\tau_B}$$

Super-K+SNO+BX

SSM

PRL 129, 252701 (2022)



low met.

$$N_{CN} = (5.78^{+1.86}_{-1.00}) \cdot 10^{-4}$$

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