First Simultaneous Measurement of low-energy *pp*-chain solar neutrinos and prospects for CNO neutrino detection with Borexino

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PhD Thesis defence

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Technische Universität München

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Outline

Part I
Solar Neutrinos & the role of Borexino

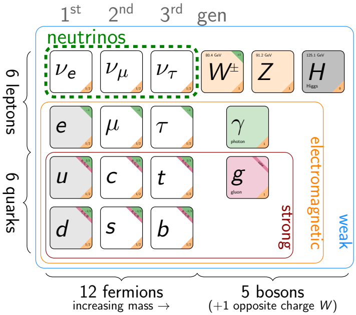
- Neutrino physics
- The Standard Solar Model
- A brief history of Solar Neutrino experiments
- The Borexino Experiment

Part II
Borexino Phase II:
Analysis methods, Results and Impact

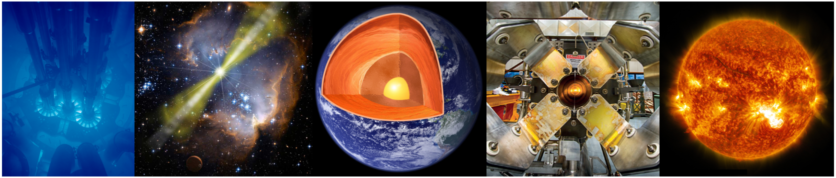
Part III
The Search for CNO neutrinos in Borexino

A sketch of neutrinos

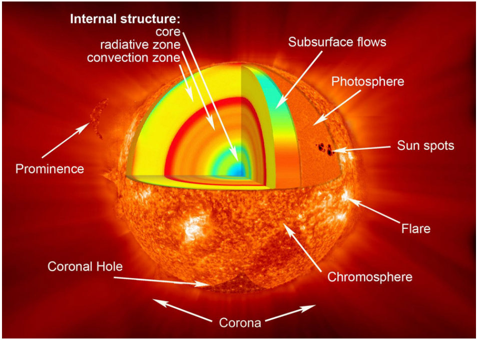
- Hypothesized in 1930 (Pauli)
  Discovered in 1954 (Cowan & Reines)
- Subject to weak interaction only
  $\hookrightarrow$ tiny cross sections
- Still a lot of unknowns



Neutrino sources



The Sun as we know it



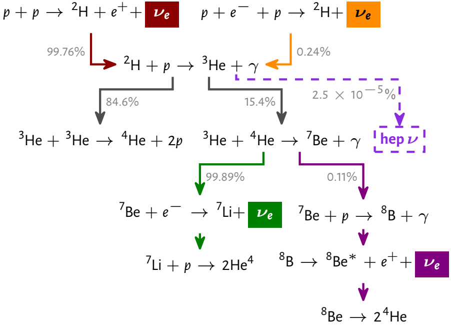
- $\tau_\odot = 4.6 \times 10^9$ years
- $M_\odot = 1.9885 \times 10^{30}$ kg
- $R_\odot = 696\,342$ km
- Conductive/Convective transition at $\approx 0.71 R_\odot$
- $T_\odot^{\text{surf}} = 5778$ K
  $T_\odot^{\text{core}} = 1.57 \times 10^7$ K

The Sun is a **benchmark** for **all** Stellar Evolution Models

Energy production in the Sun

Hydrogen burning: $4p \to [\cdots] \to {}^4\text{He} + 2\nu_e + 26.73\ \text{MeV}$

The *pp* chain



$p + p \to {}^2\text{H} + e^+ + \nu_e$

$p + e^- + p \to {}^2\text{H} + \nu_e$

99.76%

0.24%

$^2\text{H} + p \to {}^3\text{He} + \gamma$

84.6%

15.4%

$2.5 \times 10^{-5}\%$

$^3\text{He} + {}^3\text{He} \to {}^4\text{He} + 2p$

$^3\text{He} + {}^4\text{He} \to {}^7\text{Be} + \gamma$

hep ν

99.89%

0.11%

$^7\text{Be} + e^- \to {}^7\text{Li} + \nu_e$

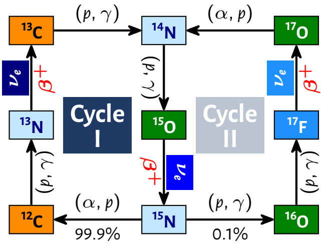
$^7\text{Be} + p \to {}^8\text{B} + \gamma$

$^7\text{Li} + p \to 2\text{He}^4$

$^8\text{B} \to {}^8\text{Be}^* + e^+ + \nu_e$

$^8\text{Be} \to 2\,{}^4\text{He}$

The CNO cycle



^{13}C (p,γ) ^{14}N (α,p) ^{17}O

ν_e β^+

(p,γ)

ν_e β^+

^{13}N **Cycle I** ^{15}O **Cycle II** ^{17}F

(p,γ)

β^+ ν_e

(p,γ)

^{12}C (α,p) ^{15}N (p,γ) ^{16}O

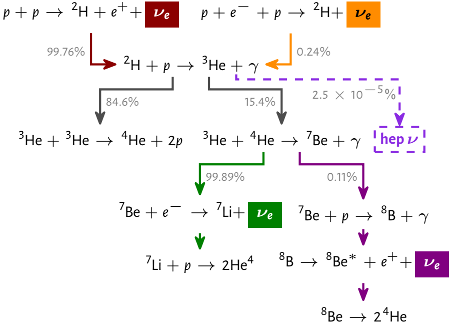
99.9%

0.1%

Energy production in the Sun

$$\text{Hydrogen burning: } 4p \rightarrow [\cdots] \rightarrow {}^4\text{He} + 2\nu_e + 26.73\text{ MeV}$$

The *pp* chain



$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$ $p + e^- + p \rightarrow {}^2\text{H} + \nu_e$

99.76%   0.24%

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84.6%   15.4% 2.5×10^{-5}%

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$^8\text{Be} \rightarrow 2\,{}^4\text{He}$

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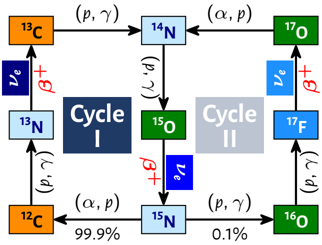

Reaction Rate $\quad R_{AB} = \dfrac{n(A)n(B)}{1+\delta_{AB}} \langle v\sigma \rangle_{AB}$

Depends on

- Element local density
- Cross section
- Local Temperature

The Standard Solar Model (SSM)

Bahcall, Pinsonneault, Peña-Garay, Basu, Haxton, Serenelli, Vinyoles, …

The Standard Solar Model (SSM)

Bahcall, Pinsonneault, Peña-Garay, Basu, Haxton, Serenelli, Vinyoles, …

Protostellar cloud

$M,\ Y_i,\ Z_i$

Input parameters

- Mass
- Hydrogen fraction X_i
- Helium fraction Y_i
- Metal fraction Z_i

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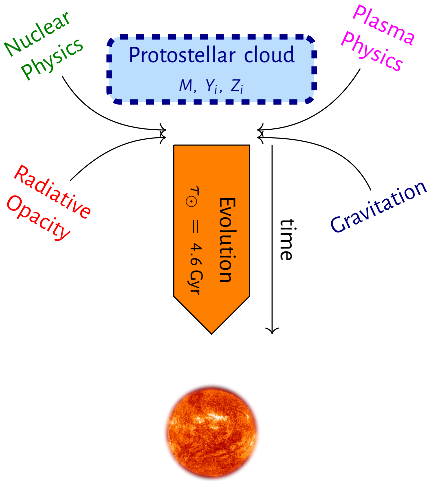

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Physical phenomena

- Gravitation
- Nuclear Physics
- Plasma Physics
- Radiative Opacity

Assumptions

- Hydrostatic equilibrium
- Energy produced *only* via *pp*-Chain and CNO cycle
- Energy is transported via conduction up to $r < 0.71 R_{\odot}$, after that convection takes place

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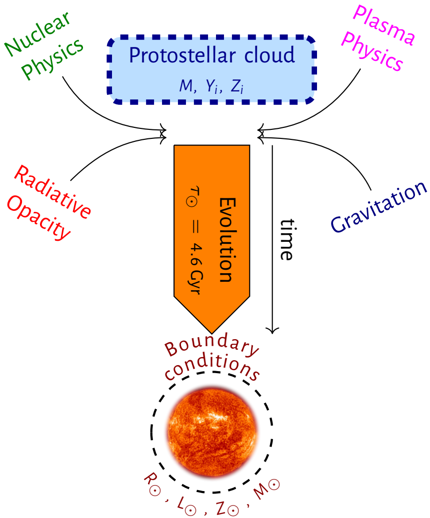

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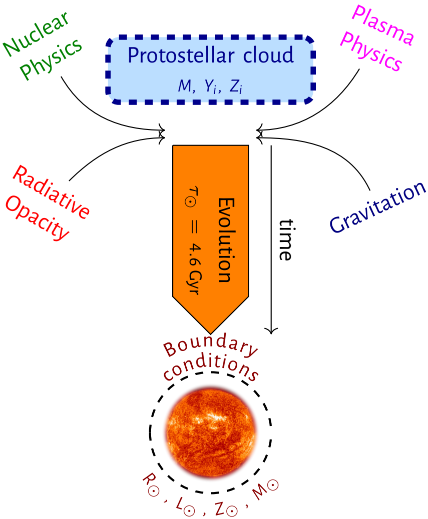

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SSM Predictions

Complete snapshot of the Sun

- Helioseismology (sound speed profile)
- Solar Neutrino Fluxes

Neutrino oscillation

Neutrino produced in the Sun in pure electron flavour

Flavour eigenstates

Mass eigenstates

$$|\nu_a\rangle \neq |\nu_i\rangle$$

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PMNS Mixing Matrix

3 angles $\theta_{12}, \theta_{23}, \theta_{13}$

1 complex phase δ

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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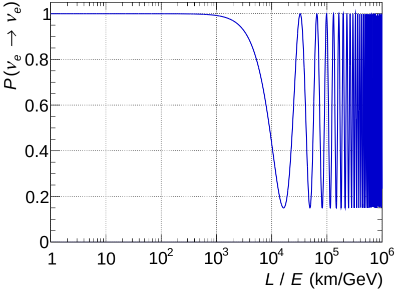
Different ν_i masses → Flavour Oscillation

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2[\mathrm{eV}^2] L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$



Impact of matter on neutrino oscillation

Presence of matter (electrons) = Interaction Potential

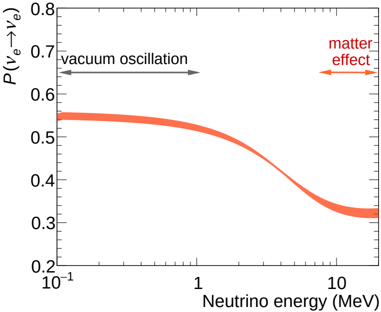
Affects differently ν_e (CC + NC interaction) and $\nu_{\mu,\tau}$ (NC only)

Interaction potential $V(x) = \sqrt{2}G_F n_e(x)$

Modifies oscillation parameters bringing an **energy dependence**

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2EV)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\sin 2\theta_M = \Delta m^2 \sin 2\theta / \Delta m_M^2$$

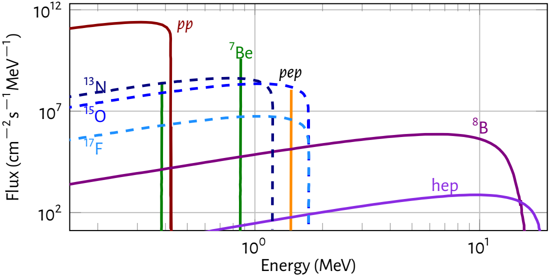


Studied by Wolfenstein (1978), Mikheyev and Smirnow (1986)

MSW effect

Measurements of Solar Neutrinos

Expectation from the SSM: ***L*(*pp*-chain) $\simeq$ 99%** - ***L*(CNO cycle) $\simeq$ 1%**

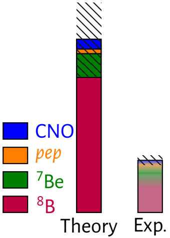


Measurements of Solar Neutrinos

Chlorine - Homestake

(1967-1994)

$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$



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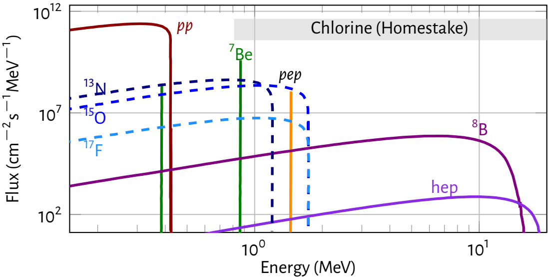
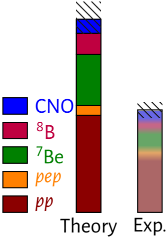


Measurements of Solar Neutrinos

Gallium - Gallex/GNO

(1991-2003)

$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$



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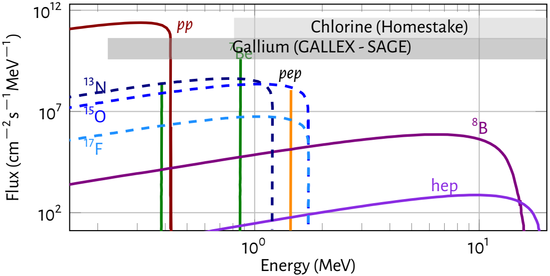

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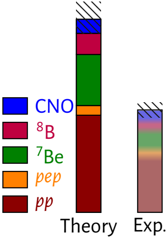
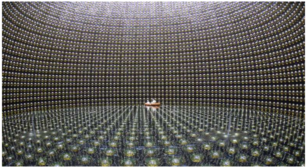


Super-Kamiokande

(1996-running)



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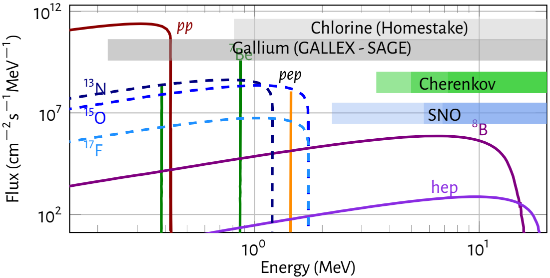

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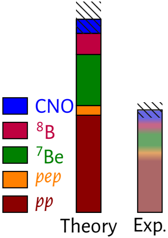

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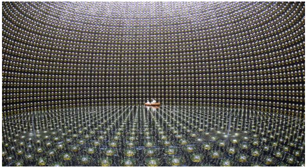
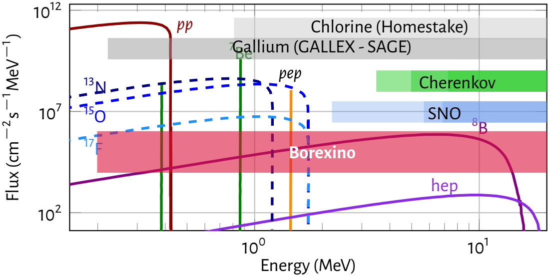


Expectation from the SSM: ***L*(*pp*-chain) ≃ 99%** - ***L*(CNO cycle) ≃ 1%**



Measurements of Solar Neutrinos

Before Borexino

After Borexino

Gallium - Gallex/GNO

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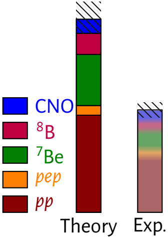

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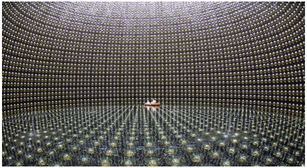

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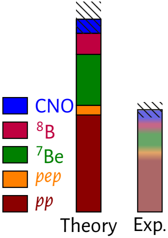

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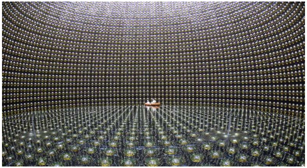
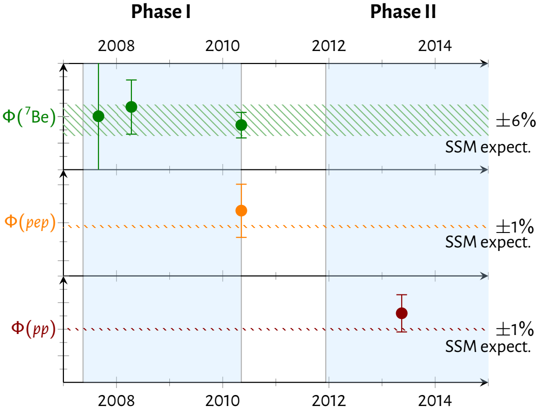


After Borexino



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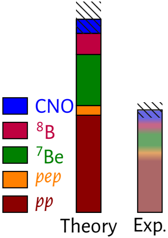

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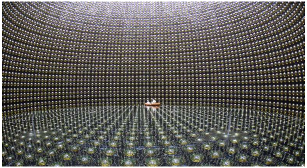

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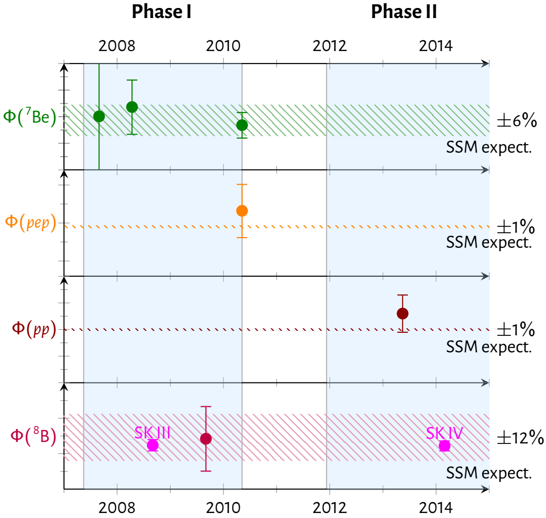
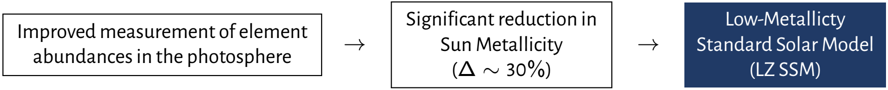
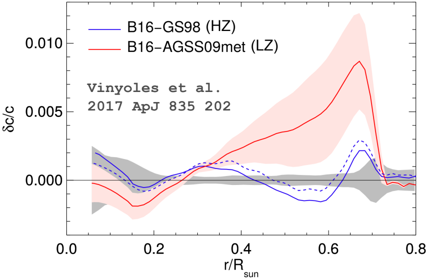


The Solar Metallicity puzzle



Improved measurement of element abundances in the photosphere → Significant reduction in Sun Metallicity ($\Delta \sim 30\%$) → Low-Metallicty Standard Solar Model (LZ SSM)

LZ SSM predictions does not match helioseismology data



Why?

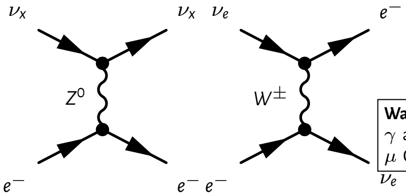
- Wrong metallicity?
- Wrong opacity calculations?
- Approximations in the SSM?

Solar neutrino fluxes also depends on metallicity and can give hints on the actual Sun composition

The Borexino Experiment

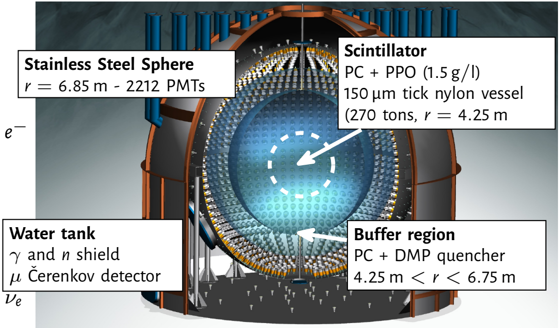
Borexino is an **ultrapure liquid scintillator** experiment installed at the Gran Sasso National Laboratories of the Italian National Institute of Nuclear Physics

ν_x–e^- Elastic Scattering



↑ **1400 m of rock** ↑

(3800 m.w.e.)



Stainless Steel Sphere
$r = 6.85$ m - 2212 PMTs

Scintillator
PC + PPO (1.5 g/l)
150 µm tick nylon vessel
(270 tons, $r = 4.25$ m

Water tank
γ and n shield
μ Čerenkov detector

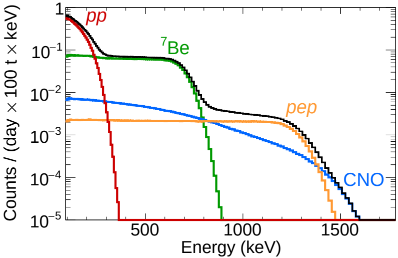
Buffer region
PC + DMP quencher
4.25 m $< r <$ 6.75 m

- ▷ Light Yield 500 p.e./MeV
  $\hookrightarrow \Delta E/E \sim 5\%/\sqrt{E[\text{MeV}]}$
- ▷ Position reconstruction based on time of flight
  (≈ 10 cm resolution at 1 MeV)

Energy observables:

- ▷ N_{pmt}: Normalized number of fired PMTs
- ▷ N_h: Normalized number of reconstructed hits
- ▷ $N_{p.e.}$: Normalized number of photoelectrons

Expected signal (and background) in Borexino



Expected interaction rate in Borexino

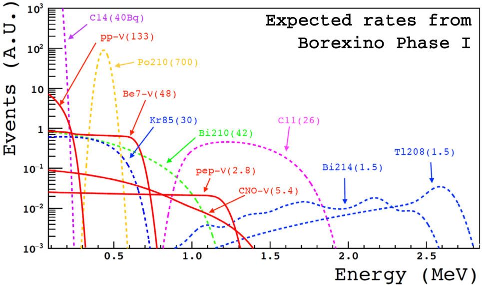
from ≈ 130 counts/day/100 t for $\nu(pp)$

to ≈ 2.8 counts/day/100 t for $\nu(pep)$

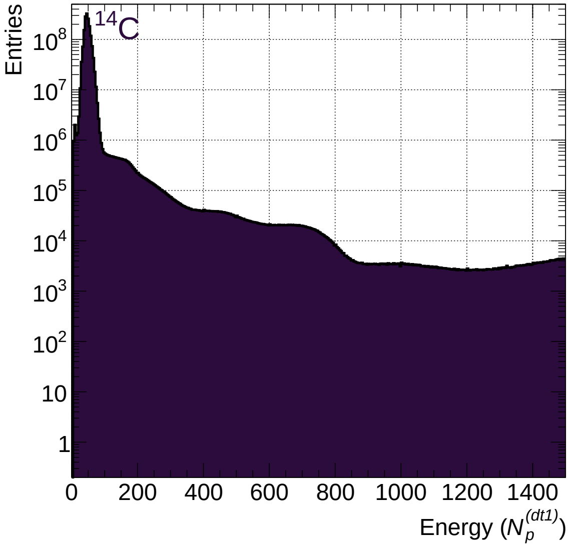
ν-induced electron recoil is **indistinguishable** from β and γ background

Extreme low background requirements

	Requirement	Result Phase-II
^{238}U	1×10^{-16} g/g	$< 9.5 \times 10^{-20}$ g/g
^{232}Th	1×10^{-16} g/g	$< 5.7 \times 10^{-19}$ g/g
^{210}Po	< 100 cpd/100ton	~ 50 cpd/100ton
^{210}Bi		~ 20 cpd/100ton
^{14}C	1×10^{-18} g/g	$\sim 2 \times 10^{-18}$ g/g

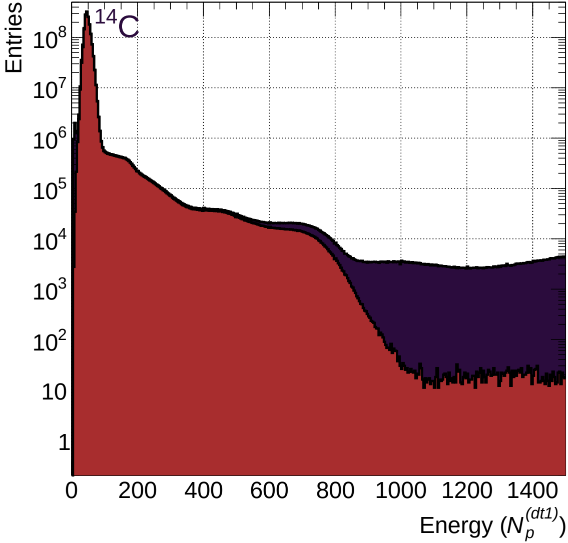


Data selection



Full Spectrum

Data selection



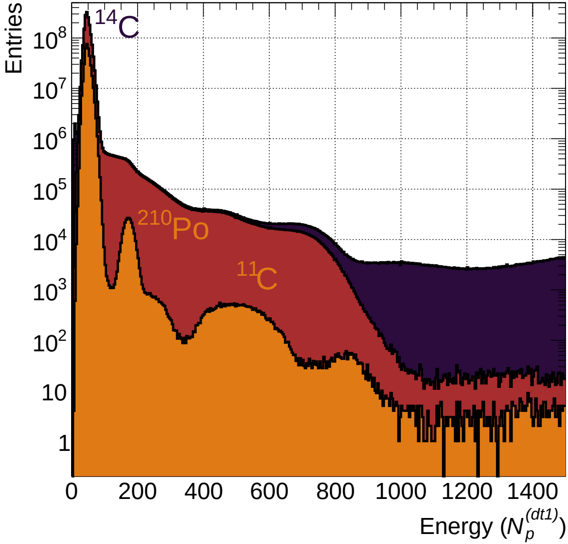
Full Spectrum

Muon cut

$\approx$ 4300 μ/day crossing ID

Removes μ, μ-induced n and cosmogenics

Data selection



Full Spectrum

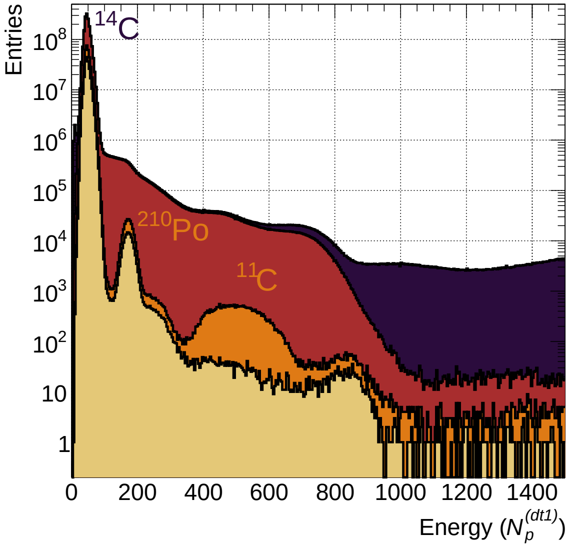
Muon cut

$\approx$ 4300 μ/day crossing ID
Removes μ, μ-induced n and cosmogenics

Fiducial Volume cut

Reduction of external and surface background

Data selection



Full Spectrum

Muon cut

$\approx$ 4300 μ/day crossing ID
Removes μ, μ-induced n and cosmogenics

Fiducial Volume cut

Reduction of external and surface background

^{11}C suppression (TFC cut)

μ–n pairs coincidences
+ space-time correlation with β-like ev.
▷ ^{11}C tagging efficiency 92 ± 4%
▷ Residual livetime 64.3%

Part II

Borexino Phase II Analysis Methods, Results and Implications

Analysis Method

- Development of a new multivariate analysis
- Statistical sensitivity and model systematic uncertainties

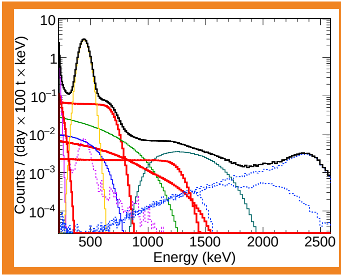
Borexino Phase II Results

- Determination of low-energy solar ν interaction rate

Interpretation of the results

- Study of ν_e survival probability
- Impact on the Solar Metallicty Puzzle

Data analysis concepts



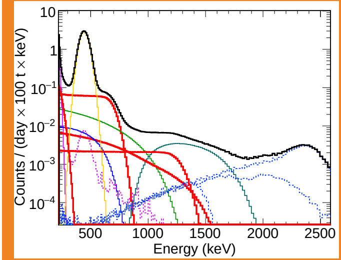
Energy spectrum

Simultaneous fit of the ^{11}C-sub./tag. datasets

Energy response function:

- **Analytical** description giving mean and variance of the energy estimator as a faction of the deposited energy
- **Monte Carlo** simulation of signal and background components

Data analysis concepts



Energy spectrum

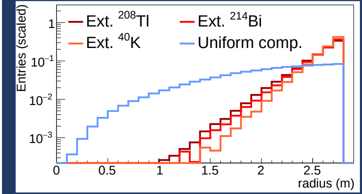
Simultaneous fit of the ^{11}C-sub./tag. datasets

Energy response function:

- **Analytical** description giving mean and variance of the energy estimator as a faction of the deposited energy
- **Monte Carlo** simulation of signal and background components

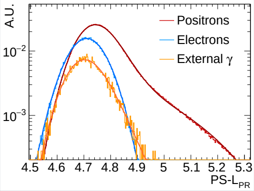
Distance from the centre

Ext. γ-ray background discrimination



Pulse Shape Discrimination

β^+/β^- discrimination



β^- ev: std. scintillation
β^+ ev: prompt + 3 ns delayed signal from ortho-positronium decay.

Pos. Reco. likelihood as PSD variable

Previous analysis Likelihood function

$$\mathcal{L}(\boldsymbol{\theta}) = \mathcal{L}_{\text{sub}}^{\text{TFC}}(\boldsymbol{\theta}) \times \mathcal{L}_{\text{cmp}}^{\text{TFC}}(\boldsymbol{\theta}) \times \mathcal{L}_{\text{rad}}(\boldsymbol{\theta}) \times \mathcal{L}_{\text{PS}}(\boldsymbol{\theta})$$

Product of Poisson Likelihood of 1D histograms (approximate construction)

Known limitations

Ignores **correlation** between variables

Hard-coded **rigid structure**

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Product of Poisson Likelihood of 1D histograms (approximate construction)

Known limitations

Ignores **correlation** between variables

Hard-coded **rigid structure**

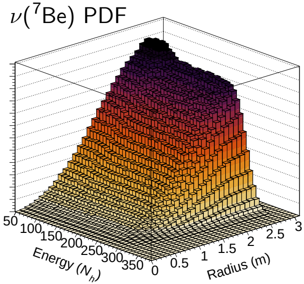
⇓

New Multivariate Analysis: `bx-stats`

- Multidimensional PDFs from MC simulation
- Simpler Likelihood definition

$$\mathcal{L}(\boldsymbol{\theta}) = \prod_{i,j,k=0}^{N_E, N_r, N_{\text{PS}}} \frac{\lambda_{ijk}(\boldsymbol{\theta})}{k_{ijk}!} e^{-\lambda_{ijk}(\boldsymbol{\theta})}$$

- Keeps into account correlation among variables



Validation, Benchmarking and Performance

Validation

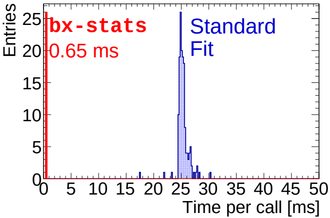
Performed on an ensemble of pseudo-datasets.
No bias found in the best fit estimate distributions. ✓

Benchmarking against the previous MC fit tool

The same ensemble of pseudo-datasets analysed using `bx-stats` and the previous MC fit with the same settings of the minimizer and same PDFs. ✓

Performance

- **Increased flexibility**
  Easier to include additional variables and datasets
- **Improved stability**
  fit results are more stable for components with low sensitivity
- **Better computational performance**
  More efficient design led to 50 × improvement in time per minimizer call



PDF creation

Neutrino and background events generated

↪ Full MC simulation
+ electronic chain
+ data reconstruction

↪ **Build a 3D histogram**

PDF creation

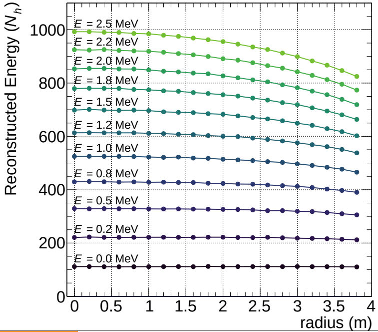
Neutrino and background events generated

↪ Full MC simulation
+ electronic chain
+ data reconstruction

↪ Build a 3D histogram

Variable correlation

Multidimensional PDFs take into account second order effects like the **spatial dependence** of the **energy response**



PDF creation

Neutrino and background events generated

↪ Full MC simulation
+ electronic chain
+ data reconstruction

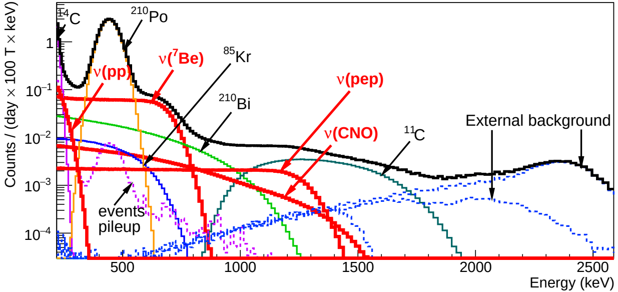
↪ Build a 3D histogram

Binning Optimization

Reduce the impact of statistical fluctuations preserving physical information

- Radius: $r \rightarrow r^3$ (5 bins only)
- Energy: variable width binning (scaling $\propto$ detector energy resolution)

Signatures of solar neutrinos in Borexino data



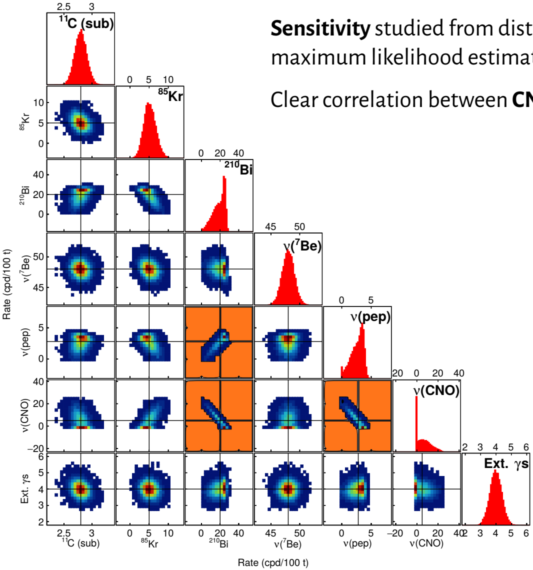
Analysis looses sensitivity when two or more components have similar shape

Example: **The ^{210}Bi-CNO-*pep* triplet**

CNO signal can be **mimicked** by the interplay of **^{210}Bi** and ***pep*** events.

↪ Strong correlation of the reconstructed parameters

Correlation studies



Sensitivity studied from distribution of maximum likelihood estimators obtained from **simulated datasets**

Clear correlation between **CNO, ^{210}Bi and** *pep*

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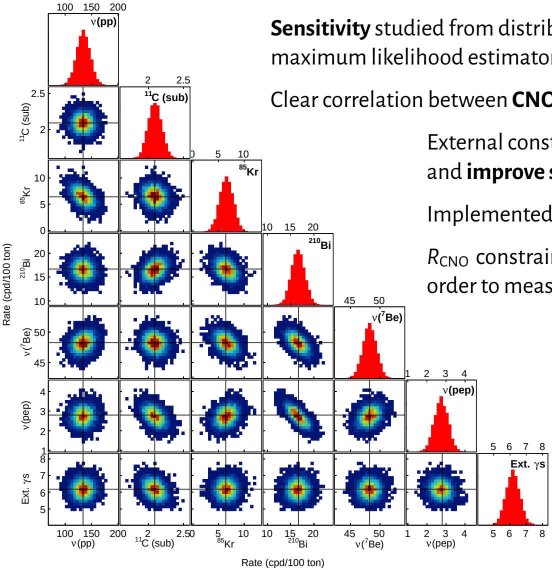


Sensitivity studied from distribution of maximum likelihood estimators obtained from **simulated datasets**

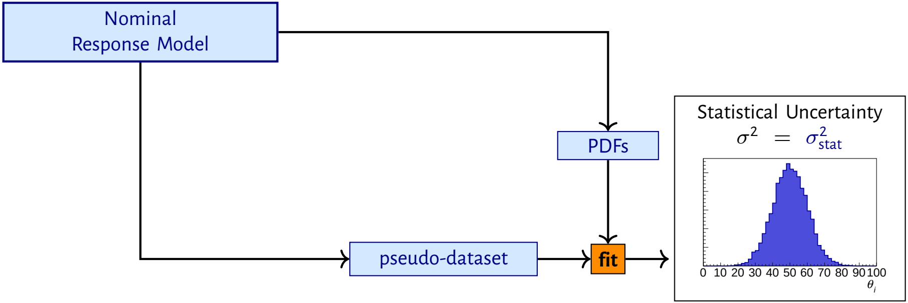
Clear correlation between **CNO, ^{210}Bi and *pep***

External constraints **break the correlation** and **improve sensitivity**

Implemented as Gaussian penalties to likelihood

R_{CNO} constrained to HZ and LZ SSM predictions in order to measure R_{pep}

Statistical Sensitivity



Nominal Response Model

PDFs

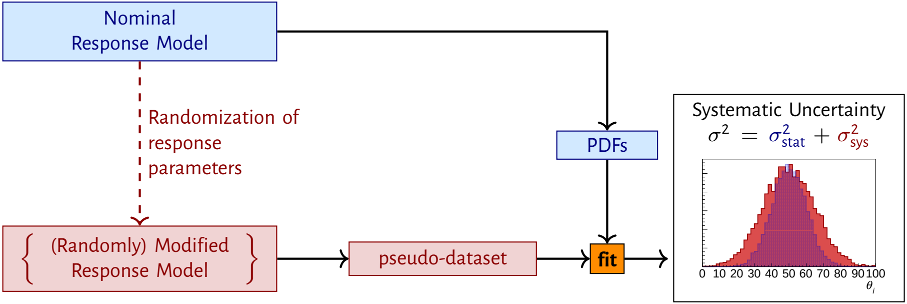
pseudo-dataset

fit

Statistical Uncertainty

$$\sigma^2 = \sigma^2_{\text{stat}}$$

Systematic uncertainties



Nominal Response Model

Randomization of response parameters

(Randomly) Modified Response Model

pseudo-dataset

PDFs

fit

Systematic Uncertainty

$\sigma^2 = \sigma^2_{\text{stat}} + \sigma^2_{\text{sys}}$

Fit model systematic uncertainties

- Detector response non-linearity
- Response uniformity along z
- PS–$\mathcal{L}_{PR}$ modelling
- ^{210}Bi spectral shape

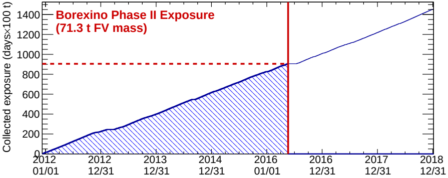
Borexino Phase II Dataset and fit configuration

Dataset

Exposure: 905 days × 100tons

(1291.51 days from Dec. 2011 to May 2016)

Fit range: 0.19–2.93 MeV



Fit baseline configuration

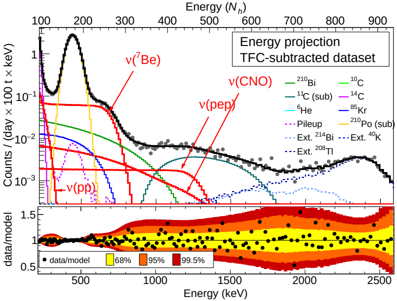
Free parameter

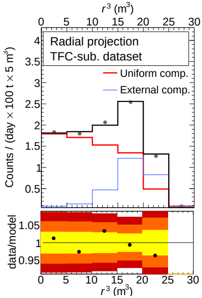
Parameter
$\nu(pp)$ rate $\nu(pep)$ rate $\nu(^7\mathrm{Be})$ rate Background components

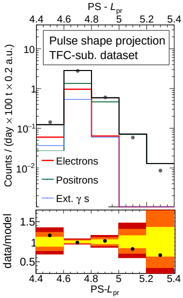
Constrained parameter

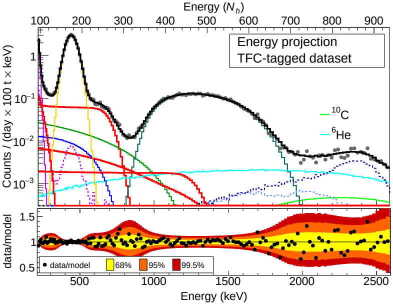
Parameter	
$\nu(\mathrm{CNO})$ rate	based on HZ and LZ SSM
^{14}C and ^{14}C–^{14}C co-incidences	based on “second cluster” event dataset

Borexino Phase II results









Fit p-value = 0.5

Analysis independently crosschecked with analytical and MC previous fit methods
↪ Consistent results ✔

$\nu(pp)$

Borexino: $134 \pm 10(\text{stat})^{+6}_{-12}(\text{sys})$ cpd/100 ton

HZ Model: 131.0 ± 2.4 cpd/100 ton

LZ Model: 132.1 ± 2.3 cpd/100 ton

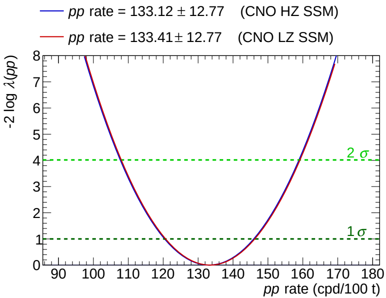
10% accuracy

Test of solar luminosity

Photon Luminosity $= 3.846(15) \times 10^{33}$ erg/s

Neutrino Luminosity $= 3.9(4) \times 10^{33}$ erg/s

Test of stability over a 10^5 years time scale



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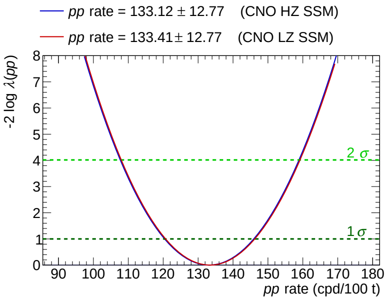
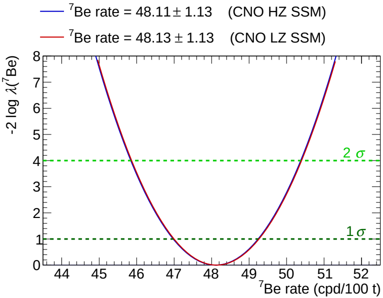


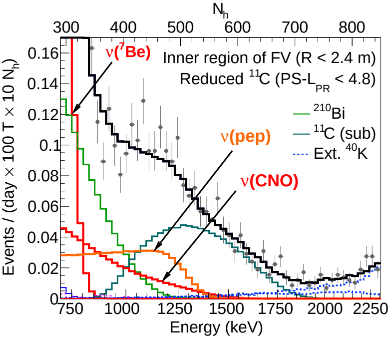


$\nu(^7\text{Be})$

Borexino: $48.3 \pm 1.1(\text{stat})^{+0.4}_{-0.7}(\text{sys})$ cpd/100 ton

HZ Model: 47.8 ± 2.9 cpd/100 ton
LZ Model: 43.7 ± 2.6 cpd/100 ton

2.7% accuracy! Twice more precise than the SSMs!



CNO and ^{210}Bi have a very similar spectral shape

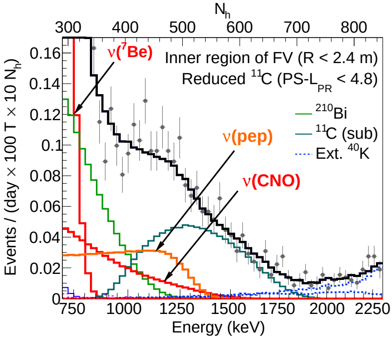
↪ **Correlation between ν(CNO), ν(*pep*) and ^{210}Bi signal**

ν(*pep*)

CNO constrained according to SSMs (HZ & LZ)

Borexino (HZ CNO):	$2.43 \pm 0.36(\text{stat})^{+0.15}_{-0.22}(\text{sys})$ cpd/100 ton
Borexino (LZ CNO):	$2.65 \pm 0.36(\text{stat})^{+0.15}_{-0.24}(\text{sys})$ cpd/100 ton
HZ Model:	2.74 ± 0.05 cpd/100 ton
LZ Model:	2.78 ± 0.05 cpd/100 ton

No-ν(*pep*) hypothesis rejected $> 5\sigma$ C.L.



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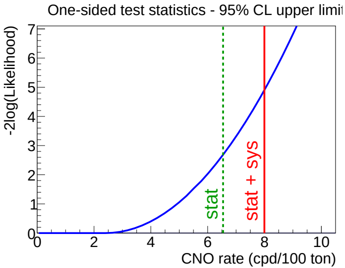
ν(CNO)

$p + p \rightarrow {}^2\text{H} + e^+ + \boldsymbol{\nu_e}$ $\qquad$ $p + e^- + p \rightarrow {}^2\text{H} + \boldsymbol{\nu_e}$

Same nuclear matrix element → $\Phi(pp)/\Phi(pep) \approx$ fixed

Fit the spectrum constraining R_{pp}/R_{pep}

Borexino:	$<$ 8.1 cpd/100 ton
HZ Model:	4.92 ± 0.55 cpd/100 ton
LZ Model:	3.52 ± 0.37 cpd/100 ton



Borexino Phase II

Most accurate determination of low-energy solar neutrino to date

***pp* neutrinos:** improved accuracy respect to previous Borexino results
^{7}Be **neutrinos:** 2.7% precision, twice more accurate than SSM predictions
***pep* neutrinos:** significance $> 5\sigma$ for the first time (constraining CNO rate)
CNO neutrinos: confirmed previous Borexino result, best upper limit available

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These results + (independent) $\nu(^8\text{B})$ **measurement**

$\hookrightarrow$ **Comprehensive measurement of *pp*-chain solar neutrinos**

Nature, 562 (2018)
arXiv: `1707.09279 [physics.hep-ex]`
arXiv: `1709.00756 [physics.hep-ex]`

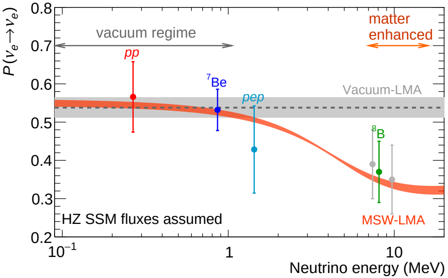
Sun as a ν source
$\downarrow$
neutrino oscillation

ν as messengers
$\downarrow$
Sun behaviour

ν_e survival probability

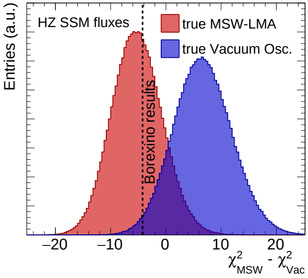
Survival probability throughout the solar ν spectrum
studied **by a single experiment**

$$P(\nu_e \to \nu_e) = \frac{R^{(\mathrm{BX})} - \Phi^{(\mathrm{SSM})} n_e \sigma_\mu}{\Phi^{(\mathrm{SSM})} n_e (\sigma_e - \sigma_\mu)}$$



Frequentist hypothesis test

$$t = \chi^2(\mathrm{MSW}) - \chi^2(\mathrm{vacuum})$$



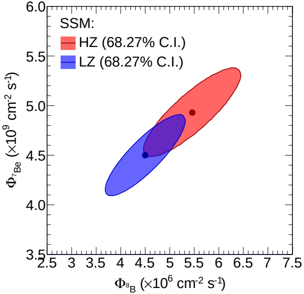
Assuming HZ SSM fluxes (favoured by helioseismology):
Absence of matter effect rejected at 98.2% C.L. (2.1σ)

Solar physics

$T_\odot(\mathrm{HZ}) - T_\odot(\mathrm{LZ}) \approx 1\%$

$\hookrightarrow$ Different neutrino fluxes

	HZ SSM	LZ SSM	Δ (%)
$\Phi(^7\mathrm{Be})$ ($\times 10^9$ cm^{-2}s^{-1})	4.93 ± 0.30	4.50 ± 0.27	-8.7
$\Phi(^8\mathrm{B})$ ($\times 10^6$ cm^{-2}s^{-1})	5.46 ± 0.66	4.50 ± 0.54	-17.6



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Borexino shows a weak preference for the HZ SSM

Frequentist hypothesis test
LZ rejected at 96.6% C.L.

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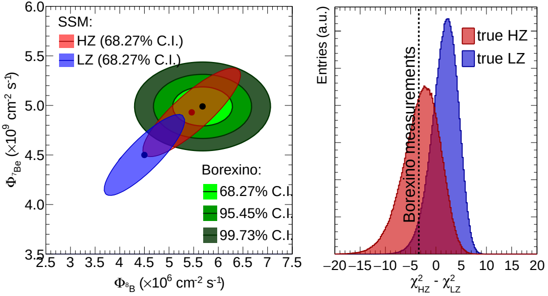

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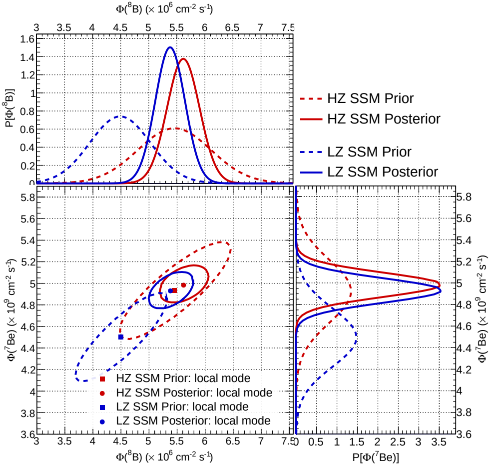
HZ favoured with Bayes factor $K = 4.9$



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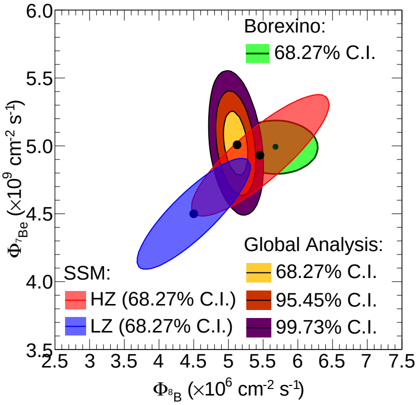
Global Analysis:
Including all solar data
+ KamLAND reactor data
Significance is reduced



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$\Phi(\mathrm{CNO})$ ($\times10^8$ cm^{-2}s^{-1})	4.88 ± 0.53	3.51 ± 0.35	**-28.1**

Borexino shows a weak preference for the HZ SSM

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Bayesian hypothesis test

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Global Analysis:

Including all solar data

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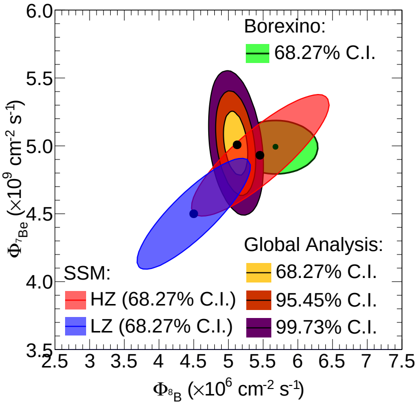
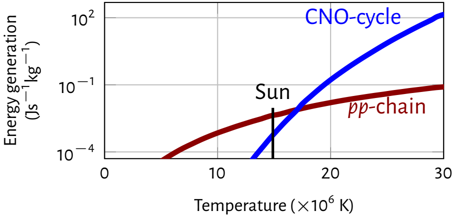
Significance is reduced

CNO neutrinos

can help solving the puzzle



The Importance of CNO neutrinos



Astrophysics

Contribution to the total solar power $\approx$ 1%
BUT dominant energy production mechanism for **heavier stars**

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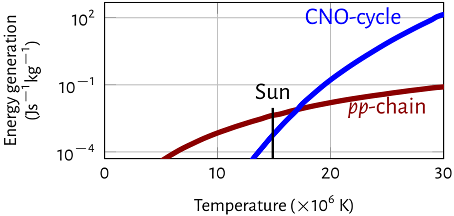


Astrophysics

Contribution to the total solar power ≈ 1%
BUT dominant energy production mechanism for **heavier stars**

The Solar Metallicity Problem

$$\Delta\Phi_{\mathrm{CNO}}(\mathrm{HZ}-\mathrm{LZ}) \approx 30\%$$

***pp*-chain**

$$\Phi_{pp}(T_{\odot}(Z))$$

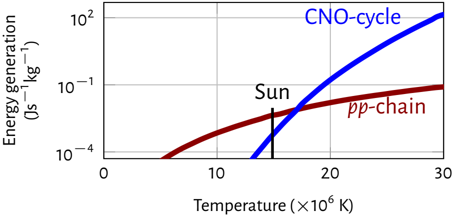
CNO cycle

$$\Phi_{\mathrm{CNO}}(T_{\odot}(Z), (n_{\mathrm{N}}, n_{\mathrm{C}}))$$

Indirect Z dependency

+ Direct Z dependency

The Importance of CNO neutrinos



Astrophysics

Contribution to the total solar power ≈ 1%
BUT dominant energy production mechanism for **heavier stars**

The Solar Metallicity Problem

$$\Delta\Phi_{\rm CNO}({\rm HZ}-{\rm LZ}) \approx 30\%$$

***pp*-chain**
$\Phi_{pp}(T_\odot(Z))$

CNO cycle
$\Phi_{\rm CNO}(T_\odot(Z), (\boldsymbol{n_{\rm N}}, \boldsymbol{n_{\rm C}}))$ →

Direct measurement of C and N abundance in the Sun

Indirect Z dependency

+ Direct Z dependency

Part III

Borexino is the only running experiment with the **potential**
to achieve a **first measurement of CNO neutrinos**

Borexino sensitivity

- Impact of background
- Detailed studied on the sensitivity of Borexino under different scenarios

Background assessment strategy

- Indirect measurement of ^{210}Bi rate thanks to ^{210}Po daughter
- Sources of *unsupported* ^{210}Po
- Development of model independent method for *supported* ^{210}Po measurement

Fit sensitivity limited by ^{210}Bi and $\nu(pep)$ background

Fit sensitivity limited by ^{210}Bi and $\nu(pep)$ background

Independent background assessment: $\tilde{R}_{\mathrm{Bi}} \pm \tilde{\sigma}_{\mathrm{Bi}}, \tilde{R}_{pep} \pm \tilde{\sigma}_{pep}$

Counting Analysis

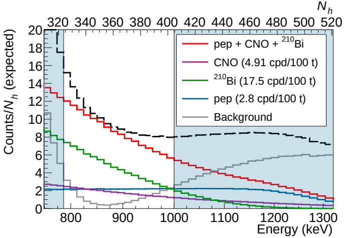
$$R_{\mathrm{CNO}} = \frac{1}{E \cdot \varepsilon_{\mathrm{CNO}}} \left(N_{\mathrm{tot}} - \varepsilon_{\mathrm{Bi}} \tilde{R}_{\mathrm{Bi}} - \varepsilon_{pep} \tilde{R}_{pep} \right)$$

$$\sigma_{\mathrm{CNO}} = \boxed{\frac{1}{E \cdot \varepsilon_{\mathrm{CNO}}} \sigma_{N_{tot}}} \oplus \frac{\varepsilon_{\mathrm{Bi210}}}{\varepsilon_{\mathrm{CNO}}} \boxed{\tilde{\sigma}_{\mathrm{Bi210}}} \oplus \frac{\varepsilon_{pep}}{\varepsilon_{\mathrm{CNO}}} \boxed{\tilde{\sigma}_{pep}}$$

↑ Evaluated w/ toy-MC

↑ ^{210}Bi accuracy

↑ *pep* accuracy



Fit sensitivity limited by ^{210}Bi and $\nu(pep)$ background

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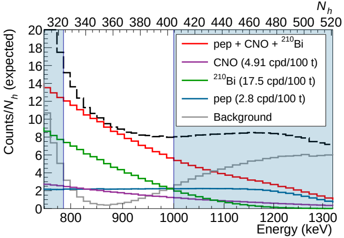
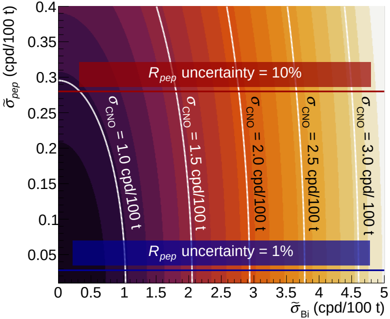




HZ CNO prediction = 4.91 ± 0.55 cpd/100 t

LZ CNO prediction = 3.52 ± 0.37 cpd/100 t

$\hookrightarrow \sigma_{\rm CNO} \lesssim 2$ cpd/100 t

↓

$\tilde{\sigma}_{pep} \lesssim 0.3$ cpd/100 t

$\tilde{\sigma}_{\rm Bi} \lesssim 3$ cpd/100 t

Expected sensitivity to CNO neutrino measurement

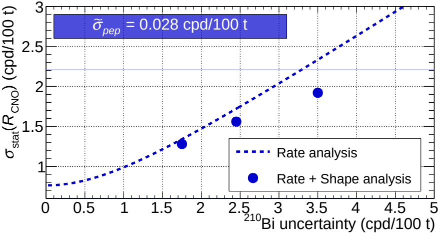
CNO uncertainty evaluated with simulated experiments

Full multivariate analysis (energy + radial distribution)
Simultaneous fit of the TFC-sub./tagged datasets

Exposure: Jul 2013 - May 2016
Variables: N_h, r^3

	Inj. Rate
CNO	4.9 cpd/100t
^{210}Bi	17.5 cpd/100t
Remainder	Borexino Ph. II

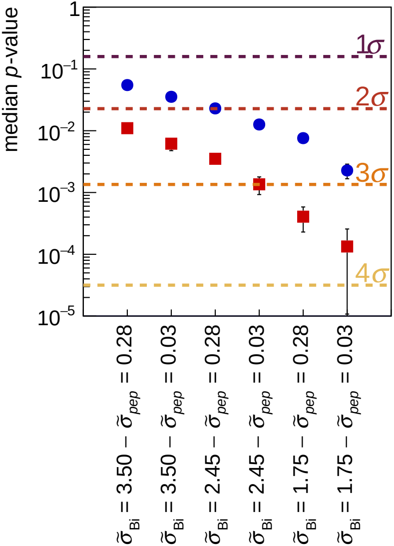
pep and ^{210}Bi constraints folded in the analysis by adding to the likelihood two independent multiplicative Gaussian penalty terms on the ^{210}Bi and the $\nu(pep)$ rate.



Shape information helps the CNO sensitivity if the ^{210}Bi constraint is weaker than 2.5 cpd/100t

(Systematic uncertainties not included)

Borexino discovery power



Injected background rate

R_{Bi} = 17.5 cpd/100 t

R_{pep} = 2.8 cpd/100 t

● LZ SSM - bx-stats analysis

■ HZ SSM - bx-stas analysis

Discovery power evaluated performing an hypothesis test based on a profile likelihood test statistics

- Stronger constraints
  $\hookrightarrow$ higher sensitivity to CNO signal
- 2–3σ evidence achievable if ^{210}Bi is measured with $\tilde{\sigma}_{\mathrm{Bi}} \leq 2.5$ cpd/100 t
- The discovery power is the same even if only an *upper limit* for ^{210}Bi is provided

CNO sensitivity summary

The **bulk** of the **sensitivity** to **CNO ν** comes from a simple **counting analysis**

- CNO value and uncertainty **determined** by the background rate assessment.
  A bias on the background rate is linearly transferred to the CNO rate
- Systematic uncertainties of the fit model are **subdominant** compared to the impact of the background rate precision

CNO sensitivity summary

The **bulk** of the **sensitivity** to **CNO ν** comes from a simple **counting analysis**

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- Systematic uncertainties of the fit model are **subdominant** compared to the impact of the background rate precision

Background assessment strategy

***pep* neutrinos**
Link with $\Phi(pp)$ +
Luminosity constraint
$\hookrightarrow \tilde{\sigma}_{pep} \simeq 1\%$

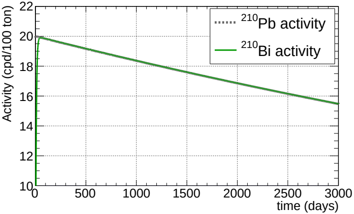
^{210}Bi background

Not that easy…

^{210}Bi background rate measurement

F. Villante, A. Ianni, F. Lombardi, G. Pagliaroli, F. Vissani
DOI: `10.1016/j.physletb.2011.05.068`

$$^{210}\mathrm{Pb} \xrightarrow[22.2\text{ y}]{t_{1/2}} {}^{210}\mathrm{Bi} \xrightarrow[5.0\text{ d}]{t_{1/2}}$$



^{210}Pb dissolved in the scintillator

Assuming no source of ^{210}Pb $\rightarrow$ ^{210}Bi in equilibrium

^{210}Bi background rate measurement

F. Villante, A. Ianni, F. Lombardi, G. Pagliaroli, F. Vissani
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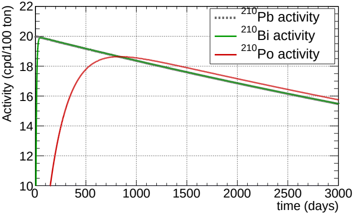
$$^{210}\mathrm{Pb} \xrightarrow[22.2\,\mathrm{y}]{t_{1/2}} {}^{210}\mathrm{Bi} \xrightarrow[5.0\,\mathrm{d}]{t_{1/2}} {}^{210}\mathrm{Po} \xrightarrow[138.4\,\mathrm{d}]{t_{1/2}} {}^{206}\mathrm{Pb}\ \text{(stable)}$$



^{210}Pb dissolved in the scintillator

Assuming no source of ^{210}Pb → ^{210}Bi in equilibrium
↪ ^{210}Po in equilibrium too

^{210}Po rate = ^{210}Bi rate

^{210}Bi background rate measurement

F. Villante, A. Ianni, F. Lombardi, G. Pagliaroli, F. Vissani
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^{210}Pb dissolved in the scintillator

Assuming no source of ^{210}Pb $\longrightarrow$ ^{210}Bi in equilibrium
$\hookrightarrow$ ^{210}Po in equilibrium too

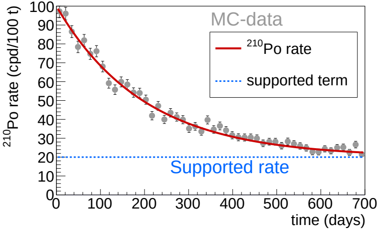
^{210}Po rate = ^{210}Bi rate

^{210}Po out of equilibrium

The method works also in presence of out–of–equilibrium ^{210}Po contamination

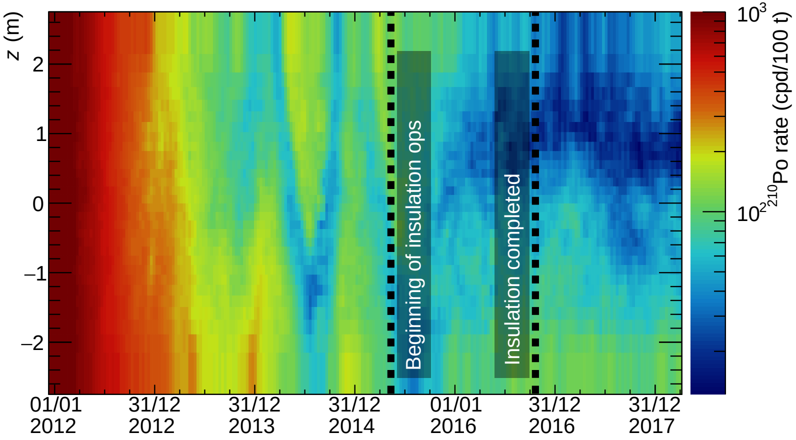
$$R_{\mathrm{Po}}(t) = (A - B)e^{t/\tau_{\mathrm{Po}}} + B$$

A = **unsupported** term, B = **supported** term
($R_{\mathrm{Po}} \approx 1400$ cpd/100 t at beginning Phase II)



^{210}Po spatial evolution

^{210}Po detached from the vessel and transported by **fluid motions** induced by **temperature variations**

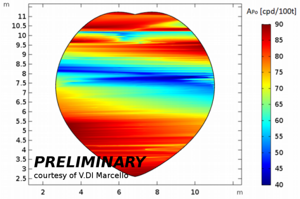


iso-volumetric layer of a 2.75 m sphere

From ^{210}Po to the ^{210}Bi rate

^{210}Po spatial distribution model unkown

Preliminary results from computational fluid dynamic shows a qualitative agreement with data



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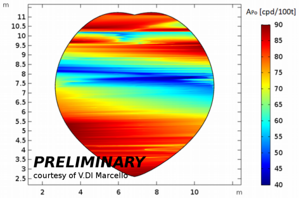


^{210}Po density continuity equation (Ding XF., F. Villante, N. Rossi)

$$\frac{\partial n_{\mathrm{Po}}}{\partial t} = \underset{\substack{\downarrow \\ \text{Supported} \\ \text{term}}}{\frac{n_{\mathrm{Bi}}}{\tau_{\mathrm{Bi}}}} - \frac{n_{\mathrm{Po}}}{\tau_{\mathrm{Po}}} + \boldsymbol{\nabla} \cdot \left[\underset{\substack{\downarrow \\ \text{Diffusion} \\ \text{term}}}{D_{\mathrm{Po}} \boldsymbol{\nabla} n_{\mathrm{Po}}} - \underset{\substack{\downarrow \\ \text{Convection} \\ \text{term}}}{\boldsymbol{v} n_{\mathrm{Po}}} \right]$$

For each t, in $\mathbf{x}_0$ where n_{Po} is **minimum** → Convection term = 0 →

Upper Limit on ^{210}Bi
positive contr. from diff.

↪ in $\mathbf{x}_0$ where n_{Po} is **minimum** → Convection term = 0
and is a Plateau ($\nabla^2 n_{\mathrm{Po}} = 0$) → Diffusion term = 0 →

Measurement of ^{210}Bi

A model independent Plateau Finder

How to determine the (flat) minimum distribution when no model is given?

A model independent Plateau Finder

How to determine the (flat) minimum distribution when no model is given?

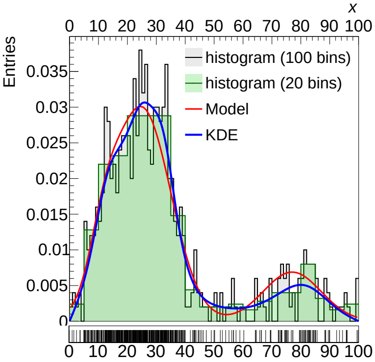
Adaptive Kernel Density Estimator (KDE)

Associate to each datum x_n a **kernel** K (Gaussian) with **bandwidth** w_n dependent on the local density

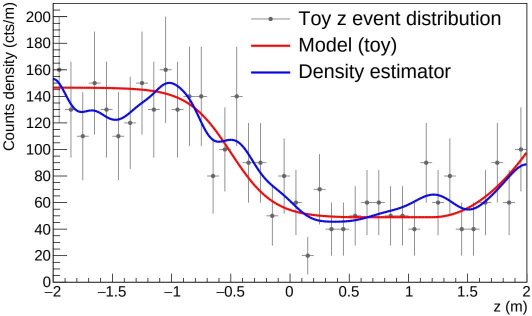
$$\hat{f}(x) = \frac{1}{N} \sum_{n=1}^{N} \frac{1}{w_n} K\left(\frac{x - x_n}{w_n}\right)$$

Advantages respect to "binned" density estimators (histograms)

- Smooth
- Does not depend on binning
- Preserve information loss (position inside the bin)



Plateau definition criterion



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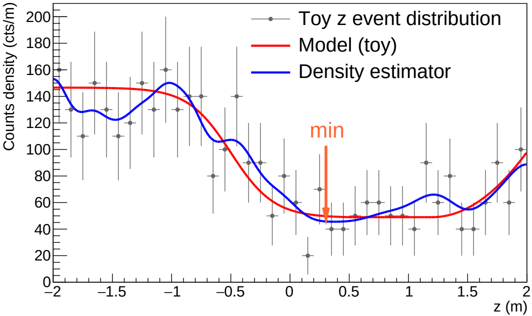
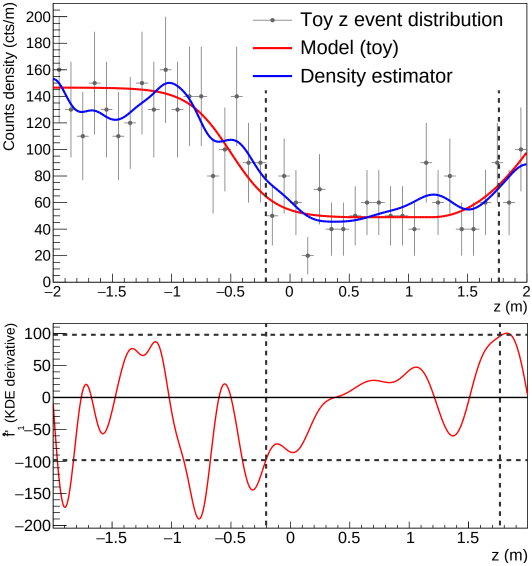


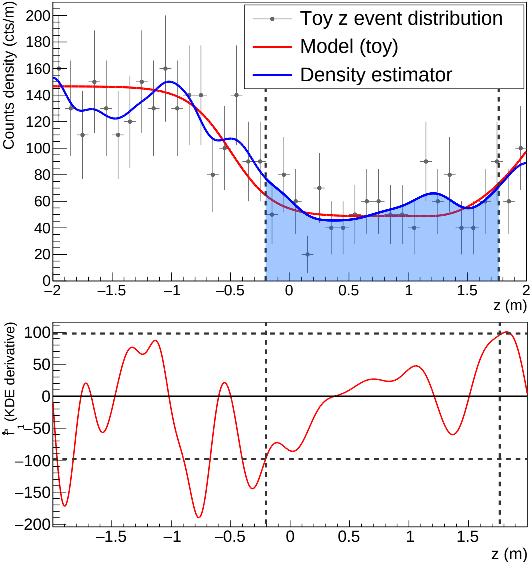
1. Find the position of the Density Estimator minimum

Plateau definition criterion



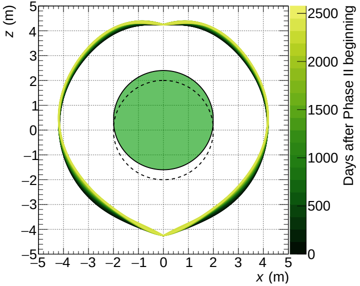
1. Find the position of the Density Estimator minimum
2. Expand left and right until the absolute value of the DE derivative exceed the threshold

Plateau definition criterion



1. Find the position of the Density Estimator minimum
2. Expand left and right until the absolute value of the DE derivative exceed the threshold
3. Integrate the DE and compute the rate

Test configuration



Livetime: 25 days

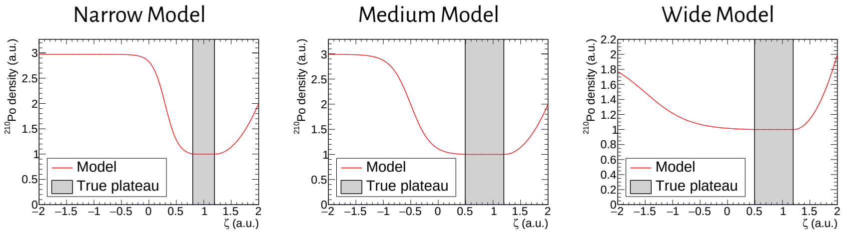
Injected Plateau Rate: 17.5 cpd/100 t

Spherical FV: $r < 2$ m

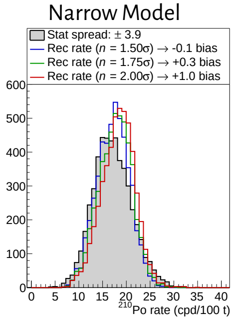
Events distribution along z

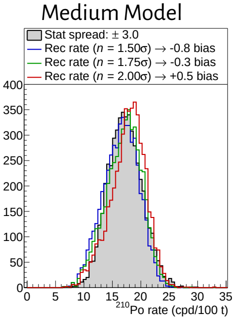
↪ transformed coordinate

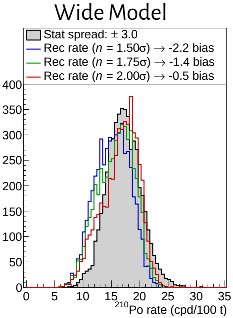
$$z \rightarrow \zeta = \left(R^2 z - \frac{1}{3} z^3\right) \cdot \frac{3}{R^3}$$



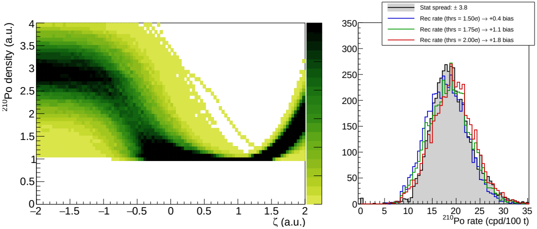
Test results







Additional test: Randomized model



Additional test:

Injected Plateau Rate = 10 cpd/100 t

Injected Plateau Rate = 50 cpd/100 t

Discrepancy much smaller than statistical uncertainty

A first look on data

^{210}Po selection cut:

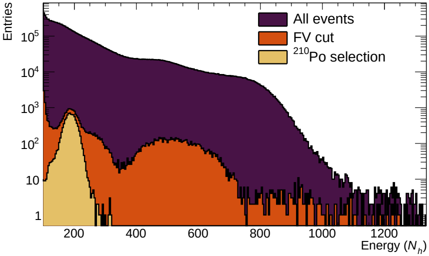
MLP < 0.05

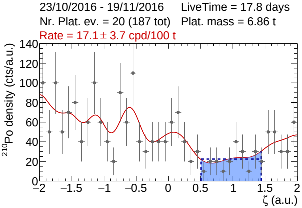
Energy cut: $130 < N_{p.e.} < 390$

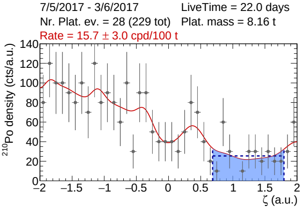
More than two years of data

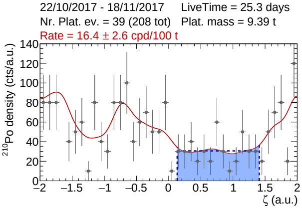
`2016_Oct_30` → `2019_Jan_13`

28 days time windows

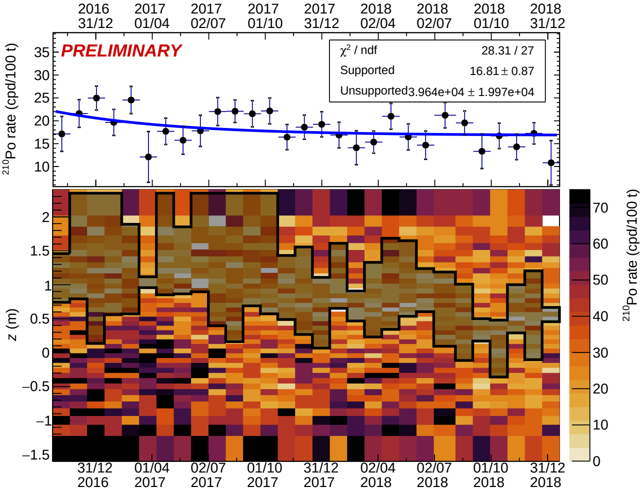








Preliminary results



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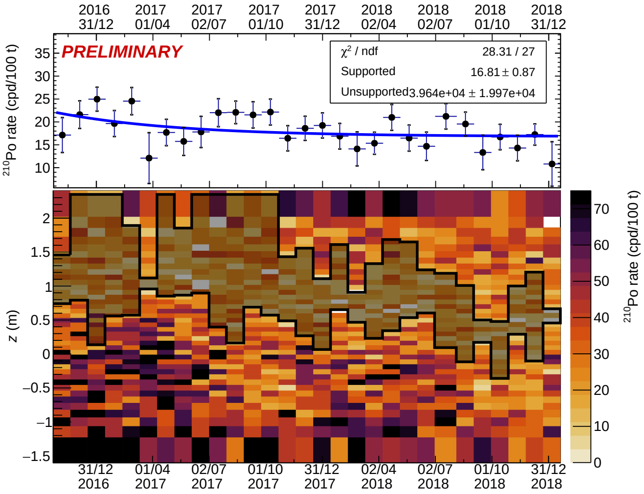
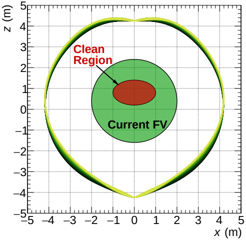


Conservative Upper Limit

Limitations

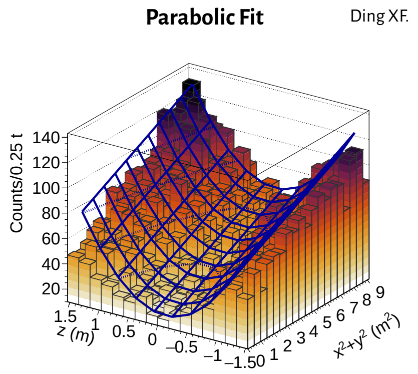
1D projections of the data

Recent studies shows that a stable "clean region" is smaller than the selected FV



Projecting along z includes unsupported ^{210}Po background

(Very) Recent and future developments

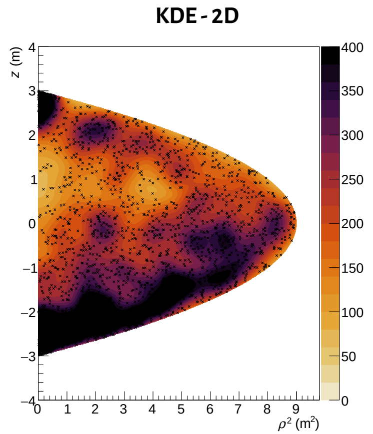


Taylor expansion close to the minimum

↪ Fit with paraboloid

↓

extract **Upper Limit** on ^{210}Bi



Same concept of KDE 1D

Prospects for CNO neutrino detection

- The sensitivity study shows that a measurement of the ^{210}Bi background is **crucial** to achieve a first detection of CNO neutrinos
- After the **thermal stabilization** the detector entered a **new phase**
- **Radiopurity** and **stability** conditions are promising
- The KDE method can be extended to include more dimension:
    - Monitoring of ^{210}Po behaviour
    - Cross-check other independent analyses

Conclusions

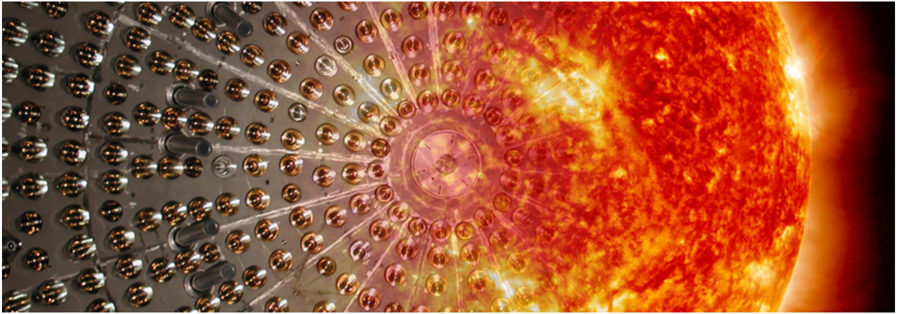
Borexino Phase II Results

- Development of a new MV Analysis
- Sensitivity and Systematics Studies
- Fit on data
- Test of oscillation model and SSM predictions

Search for CNO neutrinos with Borexino

- Detailed sensitivity study
- Background assessment strategy
- Development of a model independent method for the determination of ^{210}Bi background

Thank you for your attention



Backup material

Solar physics

Test of Solar Luminosity

Each neutrinos mark a reaction in the Sun

$\Phi(\nu) \rightarrow$ Sun Power

$L_{\odot}^{(\text{photon})}$	$3.846(15)\times 10^{33}$ erg/s
$L_{\odot}^{(\nu)}$	$3.9(4)\times 10^{33}$ erg/s

Production → detection time

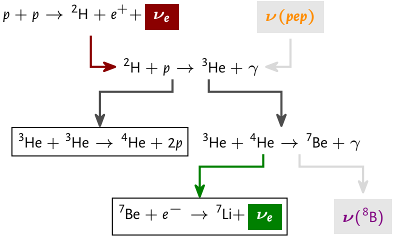
Photon	$\approx 10^4$–10^5 years
Neutrino	≈ 8 min

$$L_{\odot}^{(\text{photon})} \simeq L_{\odot}^{(\nu)}$$

$$\downarrow$$

Evidence of Sun stability on a 10^4–10^5 years time scale

Relative intensity of *pp*-chain terminations



$p + p \rightarrow {}^2\text{H} + e^+ + \nu_e$

$\nu\,(pep)$

${}^2\text{H} + p \rightarrow {}^3\text{He} + \gamma$

${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + 2p$

${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$

${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$

$\nu({}^8\text{B})$

$$R_{\text{I/II}} := \frac{\langle {}^3\text{He} + {}^4\text{He}\rangle}{\langle {}^3\text{He} + {}^3\text{He}\rangle} = \frac{2\Phi({}^7\text{Be})}{\Phi(pp) - \Phi({}^7\text{Be})}$$

$$R_{\text{I/II}}^{(\text{BX})} = 0.178^{+0.027}_{-0.023}$$

$$R_{\text{I/II}}^{(\text{HZ})} = 0.180 \pm 0.011$$

$$R_{\text{I/II}}^{(\text{LZ})} = 0.161 \pm 0.010$$

Evaluation of the discovery power

CNO uncertainty gives indication about the CNO signal strength, but does not take into account the probability that fluctuation of the background can mimic the signal.

Discovery power from hypothesis test on profile likelihood test-statistic

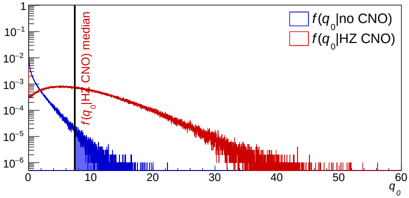
$$q_0 = -2\left[\boxed{\ln L(0,\hat{\hat{\boldsymbol{\theta}}})} - \boxed{\ln L(\hat{\mu},\hat{\boldsymbol{\theta}})}\right]$$

Minimized NLL
assuming no CNO

Minimized NLL
w/ free CNO

q_0 says how well a model with **no CNO** describes the data

1. Derive distribution of q_0 from pseudo-experiment with **no CNO injected**
   (null hypothesis, H_0)
2. Derive distribution of q_0 from pseudo-experiment with **CNO injected** according to HZ
   (HZ hypothesis, H_1)
3. Compute the **(median) discovery power** as the p-value of H_0 corresponding to the median value of H_1



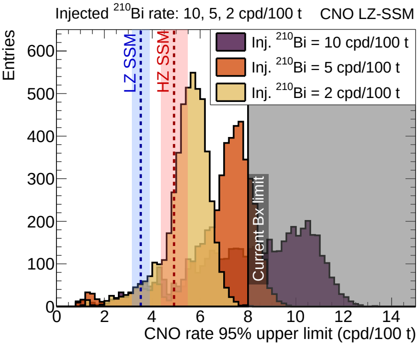
Impact of an additional purification campaign

An additional purification will not necessarily improve the sensitivity

Even with lower ^{210}Bi background, CNO and ^{210}Bi energy spectra **remain degenerate**

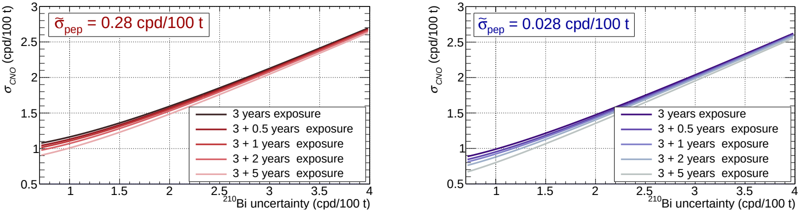
$\hookrightarrow$ possible improvement in the CNO upper limit

Interesting to possibly exclude HZ CNO, but current limit already quite stringent



Impact of Additional Exposure

Additional Exposure plays a secondary role



pep neutrino background assessment

Luminosity Constraint + Spectral Fit + Φ_{pep}/Φ_{pp} ratio $\rightarrow$ $\boxed{\tilde{\sigma}_{pep} \simeq 1\%}$

$$\text{Impose} \quad L_{\odot}^{\text{(photon)}} = L_{\odot}^{\text{(photon)}} = 4\pi(1\,\text{a.u.})^2 \sum_{i=pp,{}^7\text{Be},\dots} \alpha_i \Phi_i$$

$L_{\odot}^{\text{(photon)}}$ known with 0.4%, α_i uncertainty $\approx 10^{-4}$

$\hookrightarrow \Phi_{pp}$ uncertainty $< 1\%$

Assumptions

- The Sun is powered *only* by the processes of the *pp* chain and of the CNO cycle
- The Sun is in equilibrium
  ($L_{\odot}$ is constant over a $\sim 10^5$ yr time scale)
- ^{2}H and ^{3}He are in local kinetic equilibrium
  (creation rate = destruction rate)
  Reasonable since lifetime ^{2}H $\approx 10^{-8}$yr and ^{3}He $\approx 10^5$yr (proton lifetime $\approx 10^{10}$ yr)

Performance of the Borexino Thermal Monitor and Management