MEASUREMENT OF *PP*-CHAIN SOLAR NEUTRINOS WITH BOREXINO

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On Behalf of the Borexino Collaboration

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Mitglied der Helmholtz-Gemeinschaft

JÜLICH Forschungszentrum

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CONTENTS

Introduction and Motivation

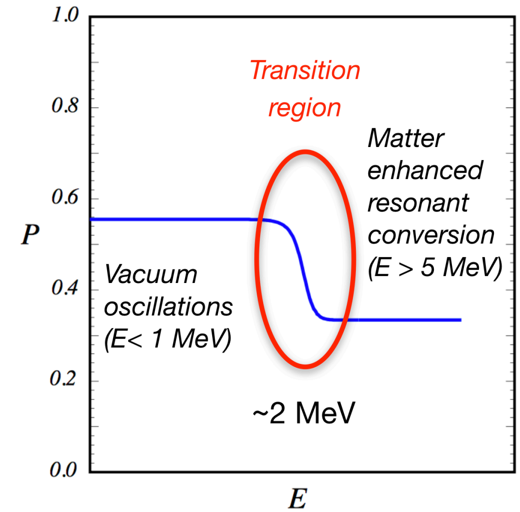
SOLAR NEUTRINO PHYSICS MOTIVATION

Studying Neutrinos with the Sun …

- Neutrino Oscillation Parameters
- Searching for Deviations from the MSW-LMA

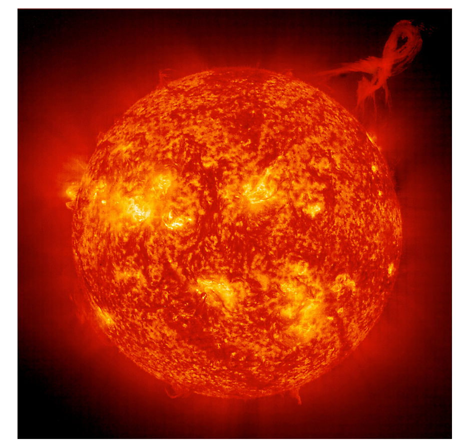
  Scenario of Solar Neutrino Oscillations in the P_{ee} transition region

  (Search for New Physics e.g. Non-standard interactions)



Studying the Sun with Neutrinos …

- Thermodynamic Stability
  - Photons need around ~100k years to escape from the solar core
  - Neutrinos escape almost without interaction losses
- Fusion Mechanisms (*pp*-chain and CNO cycle)
- Testing energy production (and loss) mechanisms
- Metallicity



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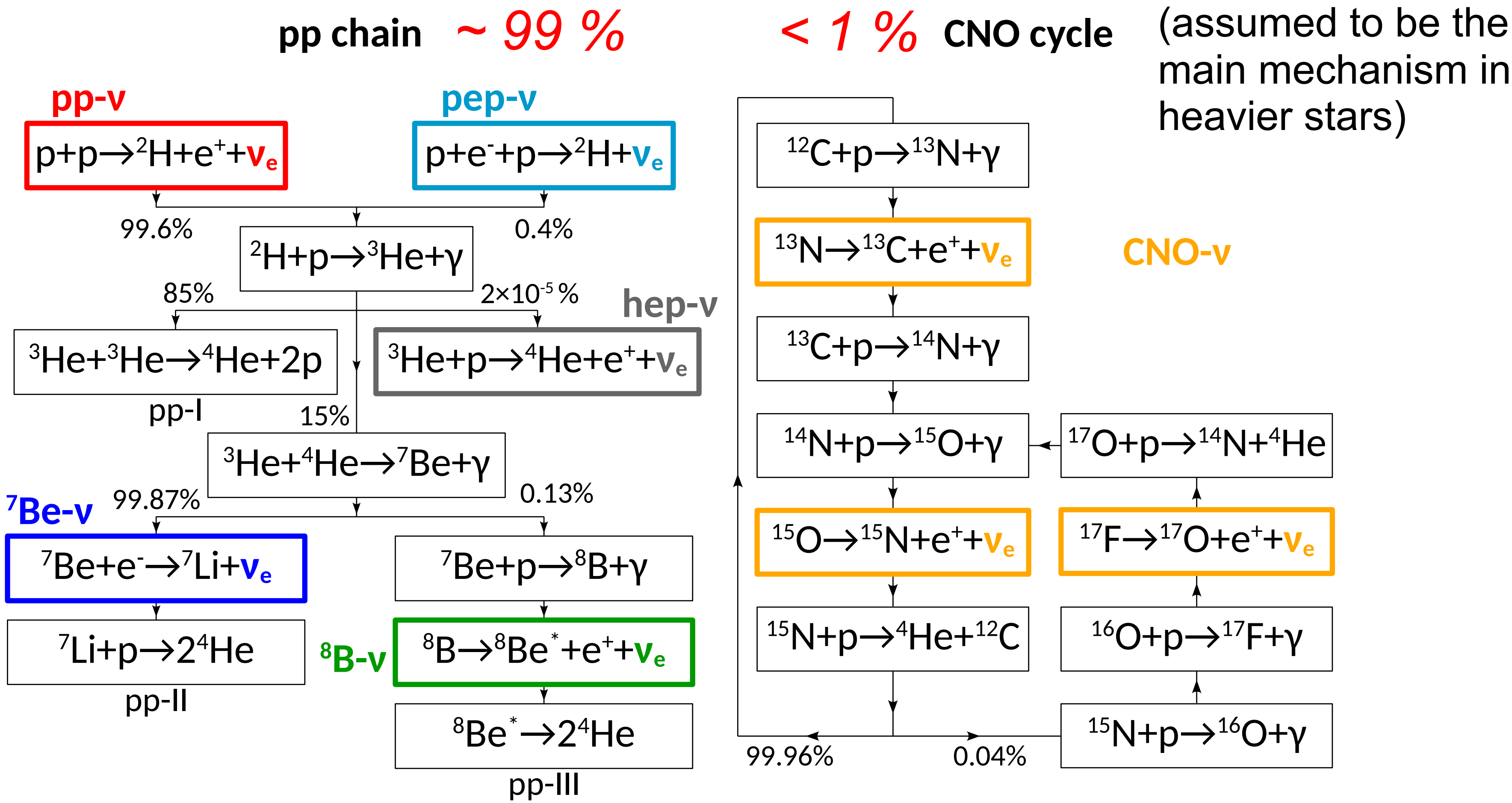
HOW IS THE SUN FUELED? → SOLAR NEUTRINOS

Production in the Core of the Sun



Fueling < 1 % of solar energy

$\nu(\mathrm{CNO}) \approx 57\%\ \nu(^{13}\mathrm{N}) + 42\%\ \nu(^{15}\mathrm{O}) + 1\%\ \nu(^{17}\mathrm{F})$

Theoretically well motivated !

SOLAR NEUTRINOS FLUXES

Assume photon luminosity $L_\odot$, the solar mass $M_\odot$, the solar radius $R_\odot$, the oblateness $O_\odot = \frac{R_{equator}}{R_{polar}} - 1$, and the solar age $A_\odot$ is given:

Species	Flux [cm^{-2}s^{-1}] GS98 (HZ)	Flux [cm^{-2}s^{-1}] AGSS09met (LZ)	Difference (HZ-LZ)/HZ %
pp	$5.98(1 \pm 0.006)\times10^{10}$	$6.03(1 \pm 0.005)\times10^{10}$	-0.8 %
pep	$1.44(1 \pm 0.01)\times10^{8}$	$1.46(1 \pm 0.009)\times10^{8}$	-1.4 %
hep	$7.98(1 \pm 0.30)\times10^{3}$	$8.25(1 \pm 0.30)\times10^{3}$	-3.4 %
^{7}Be	$4.93(1 \pm 0.06)\times10^{9}$	$4.50(1 \pm 0.06)\times10^{9}$	8.9 %
^{8}B	$5.46(1 \pm 0.12)\times10^{6}$	$4.50(1 \pm 0.12)\times10^{6}$	17.6 %
^{13}N	$2.78(1 \pm 0.15)\times10^{8}$	$2.04(1 \pm 0.14)\times10^{8}$	26.6 %
^{15}O	$2.05(1 \pm 0.17)\times10^{8}$	$1.44(1 \pm 0.16)\times10^{8}$	29.7 %
^{17}F	$5.29(1 \pm 0.20)\times10^{8}$	$3.26(1 \pm 0.18)\times10^{8}$	38.3 %

Metallicity:

Metal-to-Hydrogen Ratio $\left(\frac{Z}{X}\right)_\odot$

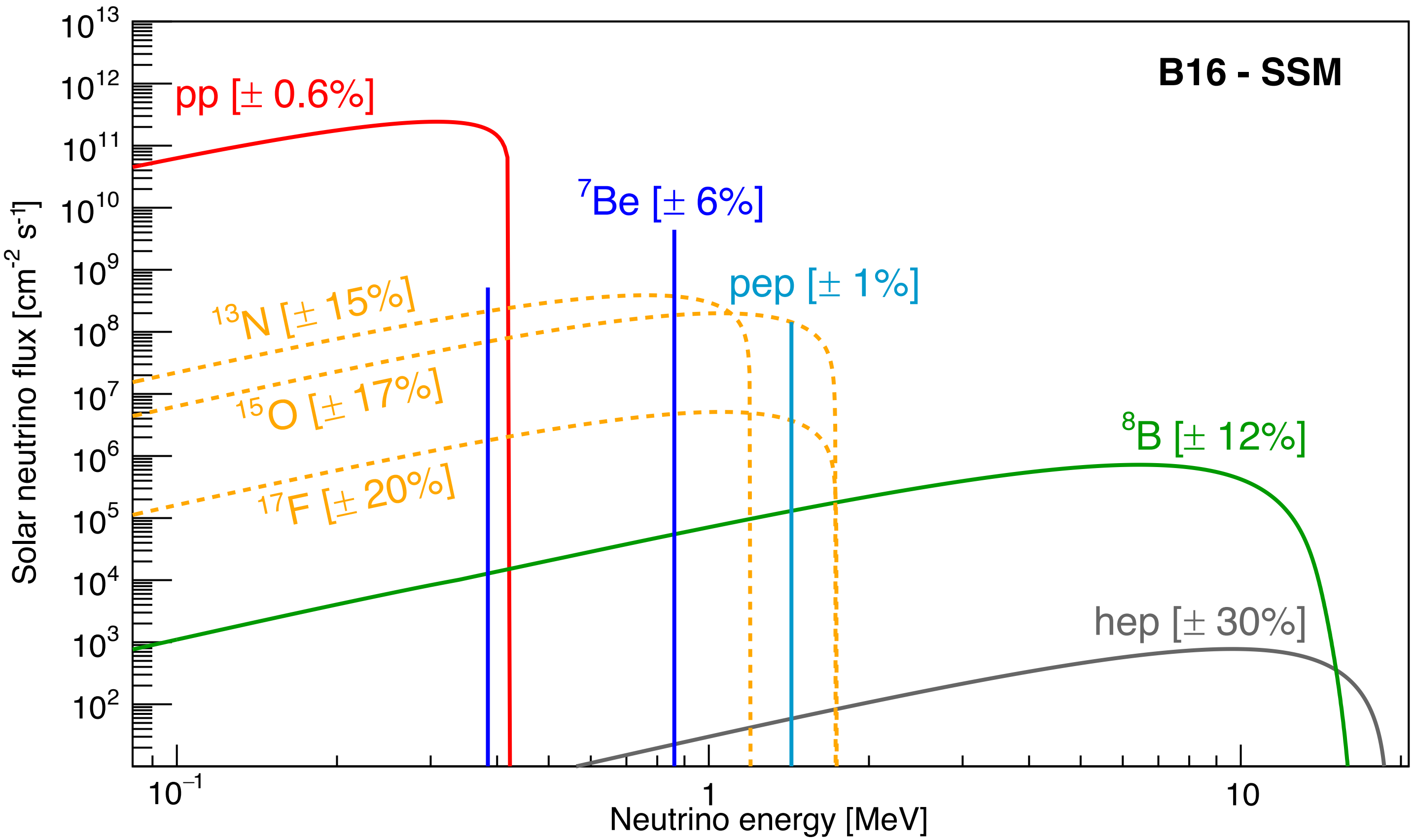
(above He)

C N O is very sensitive to metallicity

Borexino:

Look at ^{7}Be - ^{8}B Contour (later)

EXPECTED SOLAR NEUTRINO SPECTRA



➔ Difference in endpoint energies and shapes gives possibility to distinguish them

HOW TO “DETECT” THE SUN ?

The Borexino Detector located at LNGS in Italy

2212 inward-facing PMTs

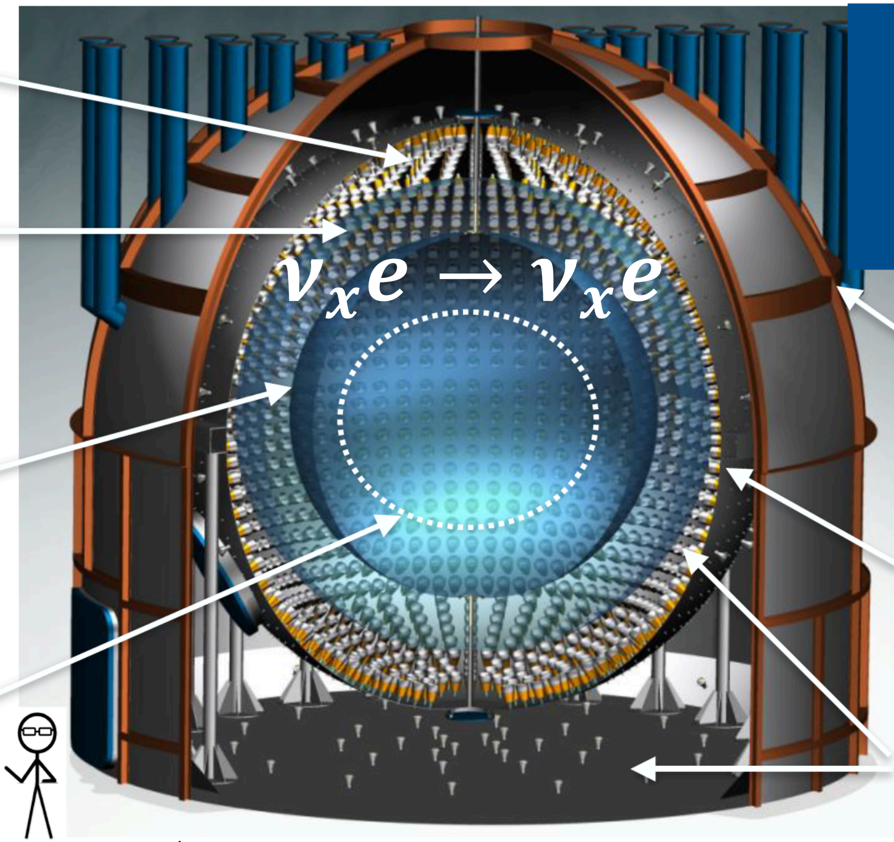
Nylon Outer Vessel

R = 5.5 m
Barrier for Rn from steel, PMTs etc.

Nylon Inner Vessel

R = 4.25 m
~ 300 tons of liquid scintillator: (PC/PPO solution)

Fiducial volume:
~100 tons (software cut)



Detection principle: elastic scattering on electrons
Technique advantages: high light-yield
Technique disadvantages: no directional information

Water tank:
R = 9 m, 2.1 kt of water
- *Shielding*
- *Cherenkov muon veto*

Stainless Steel Sphere:
R = 6.85 m
Scintillator container
PMTs support

208 Outer Detector PMTs

- ✓ Hardware Threshold ~ 50 keV
- ✓ $\frac{\Delta E}{E} \sim \frac{5\,\%}{\sqrt{E[MeV]}}$
- ✓ Ph. Yield ~ 551 p.e./MeV
- ✓ Position Reconstruction: 16-9 cm

BOREXINO RESULTS OVERVIEW

2007 | **^{7}Be, *pep*, ^{8}B** **Geo-Nu** **Calibrations** | **2010** | **2012** | ***pp*** **Improved Measurement of I** ***pep*** **Discovery (5σ)** **^{7}Be seasonal modulation** | **2016** | **2019+**

Bx Phase I — Bx Phase II — Bx Phase III

Scintillator Purification

Improved Radiopurity:
^{85}Kr ~ 4.6
^{210}Bi ~ 2.3

Improved Thermal stability
CNO analysis

Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy (Phys. Rev. D 89, 112007 (2014))

Measuremnt of the solar ^{8}B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector (Phys. Rev. D 82, 033006 (2010))

Measurement of geo-neutrinos from 1353 days of Borexino (Phys. Let. B 722 295-300 (2013))

Neutrinos from the primary proton-proton fusion process in the Sun (Nature 512, 383-386 (2014))

Spectroscopy of geoneutrinos from 2056 days of Borexino Data (Phys. Rev. D 92, 031101® (2015))

Seasonal modulation of the ^{7}Be solar neutrino rate in Borexino (Astroparticle Phys. Vol. 92, 21-29 (2017))

First Simultaneous Precision Spectroscopy of *pp*, ^{7}Be, and *pep* Solar Neutrinos with Borexino Phase-II (arXiv:1707.09279v2 (2017))

Improved measurement of ^{8}B solar neutrinos with 1.5 kt y of Borexino exposure (arXiv:1709.00756v1 (2017))

Modulations of the Cosmic Muon Signal in Ten Years of Borexino Data (arXiv:1808.04207v3 (2018))

Comprehensive measurement of *pp*-chain solar neutrinos (Nature 562, 505–510 (2018))

Constraints on Non-Standard Neutrino Interactions from Borexino Phase-II (arXiv:1905.03512v1)

BOREXINO RESULTS OVERVIEW

pp
Improved Measurement of I
pep Discovery (5σ)
^{7}Be seasonal modulation

^{7}Be, *pep*, ^{8}B
Geo-Nu
Calibrations

2007 | 2010 | 2012 | 2016 | 2019+

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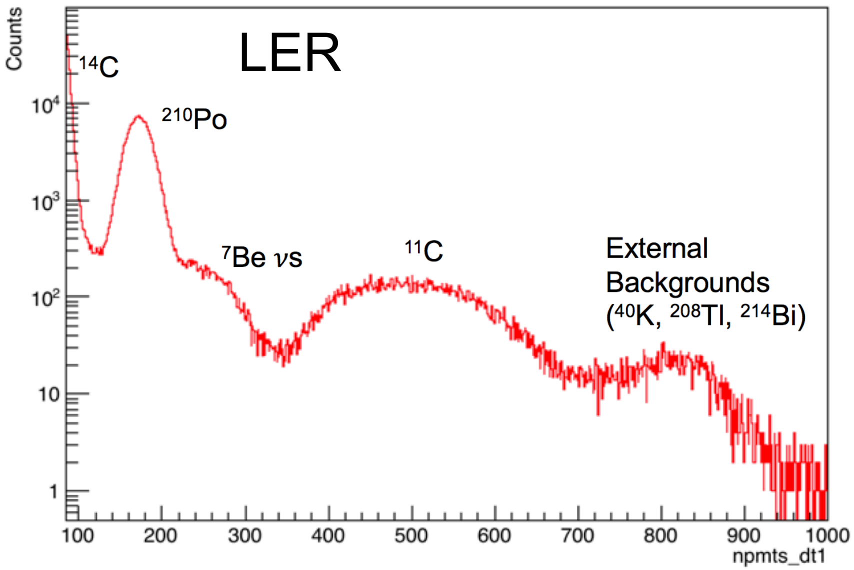
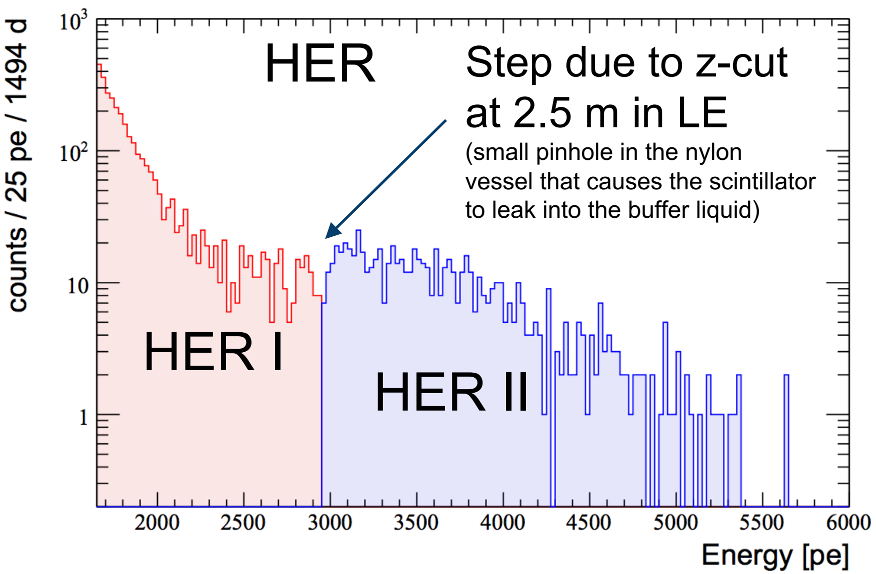
Measurement of pp-Chain Solar Neutrinos

ANALYSIS (LOW AND HIGH ENERGY)



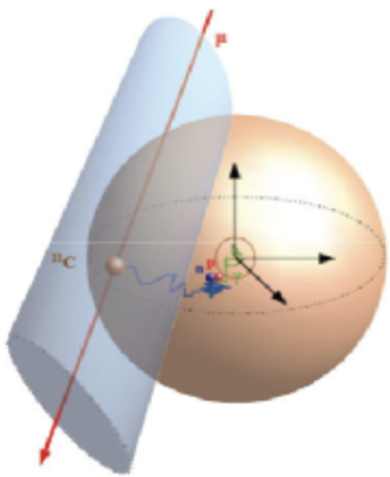
- Energy Spectrum after all Selection Cuts for low-energy region (LER) for *pp*, *pep*, ^{7}Be, and CNO analysis
  (μ and μ daughter cut: 300 ms internal and 2 ms external, Fiducial Volume Cut: R < 2.8 m, -1.8 m < z < 2.2 m)
- Exposure: 1291.51 days $\times$ 71.3 t
- LER Analysis Range:
  0.19 - 2.93 MeV
- Binned Poissonian Likelihood Fit
  (Analytical and Monte Carlo Fit)

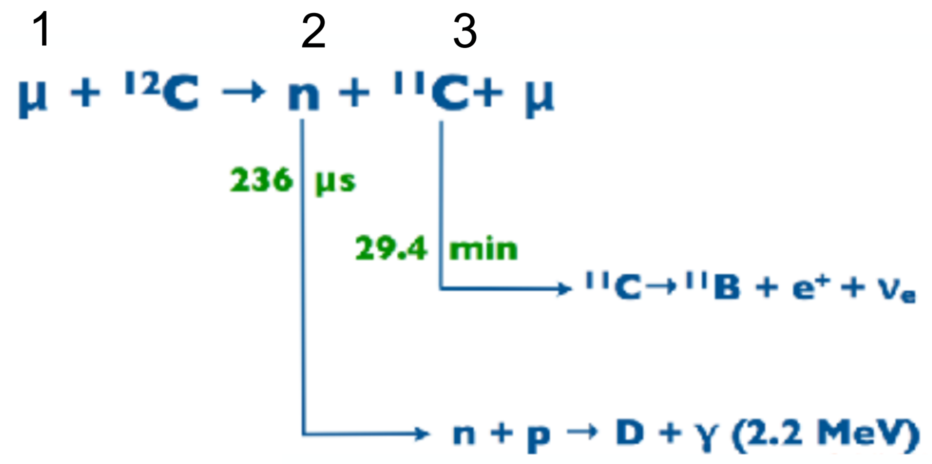


- Energy Spectrum after all Selection Cuts for high-energy regions (HER-I,II) for ^{8}B-analysis
  (more cosmogenics, less internal background)
- Exposure HER-I: 2062.4 days $\times 227.8$ t
- Exposure HER-II: 2062.4 days $\times 266.0$ t
- HER-I Range: 3.2 – 5.7 MeV
- HER-II Range: 5.7 – 16 MeV (no natural long-lived radioactive background above 5 MeV)
- Binned Poissonian Likelihood Fit in Radial
  (Monte Carlo Fit only)

THREEFOLD COINCIDENCE (TFC)

Muon interactions with ^{12}C



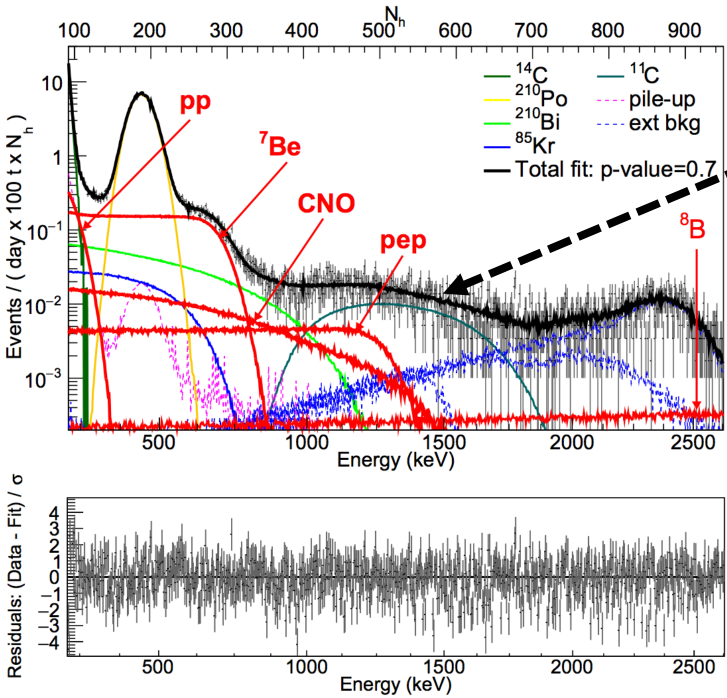


TFC Algorithm

- Calculate for each event the probability to be ^{11}C (using a Likelihood)
- Divide Total Exposure in TFC-subtracted and TFC-tagged spectra

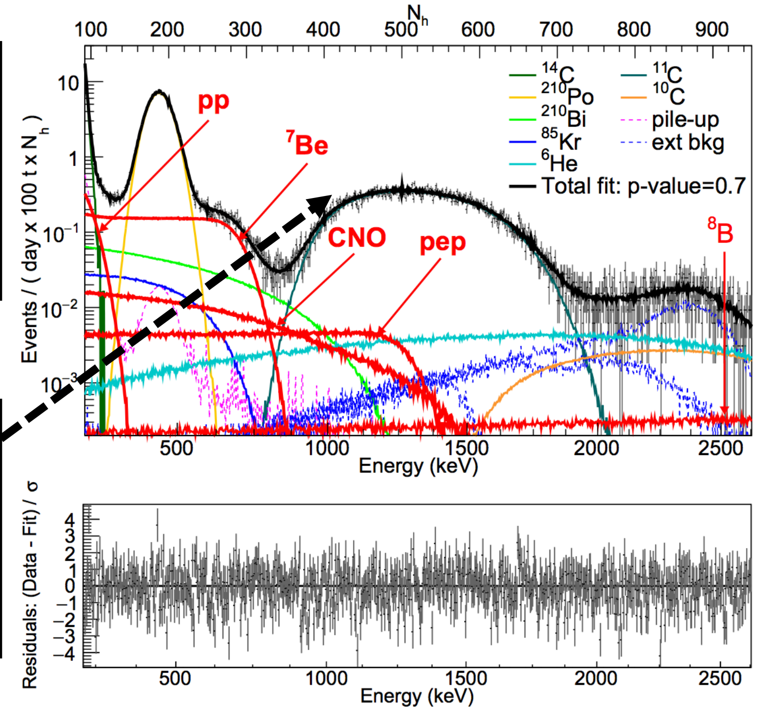
ANALYSIS IN LER (0.19 – 2.93 MEV)

Multivariate Likelihood Definition: $\mathcal{L}_{MV}(\vec{\theta}) = \mathcal{L}_{sub}^{TFC}(\vec{\theta})\,\mathcal{L}_{Tag}^{TFC}(\vec{\theta})\,\mathcal{L}_{PS}(\vec{\theta})\,\mathcal{L}_{Radial}(\vec{\theta})$

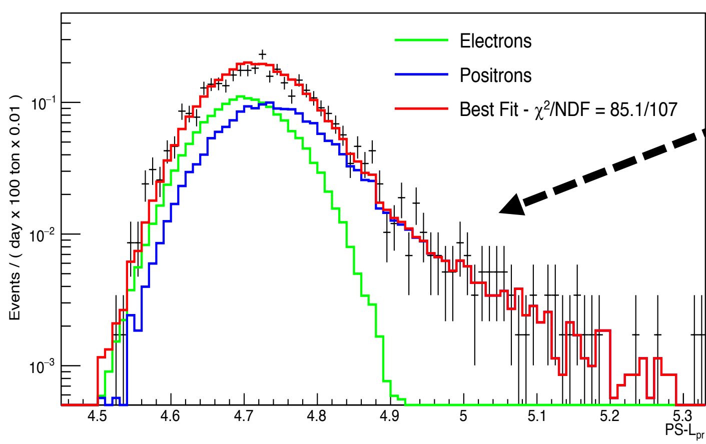


TFC sub
~10% ^{11}C present
64.28 % of total exposure

TFC tagged
~90% ^{11}C present
35.72 % of total exposure

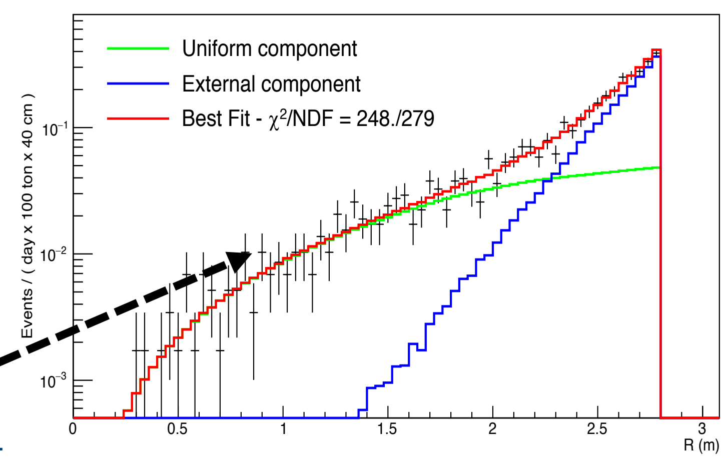


Additional Information of Pulse Shape (PS) (e^+, e^-) (Likelihood of Position Reconstruction)



Pulse Shape Fit

Radial Distribution of Events



Radial Fit

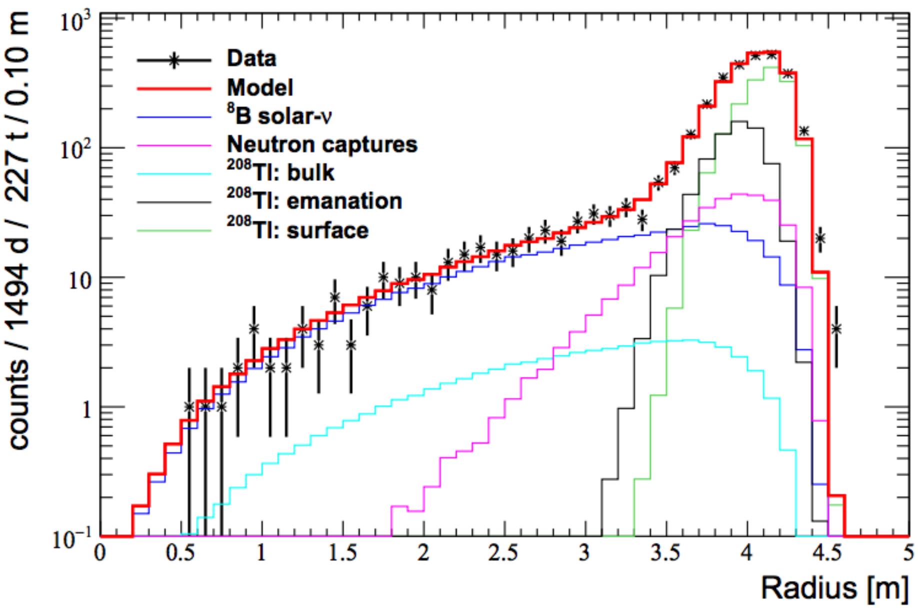
ANALYSIS IN HER (3.2 – 16 MEV)

Selection Cuts:

- Removed **muons**
- **Neutron** cut: 2 ms after all **muons**
- **Cosmogenics** cut: 6.5 s after all internal **muons** (^{12}B, ^{8}He, ^{9}C, ^{9}Li, ^{8}B, ^{6}He, ^{8}Li)
- ^{10}C TFC cut: 120 s, 0.8 m radius sphere around **neutrons**
- Fast **coincidence** cut: no ^{214}Bi - ^{214}Po
- **Coincidence** cut: no events closer than 5 s

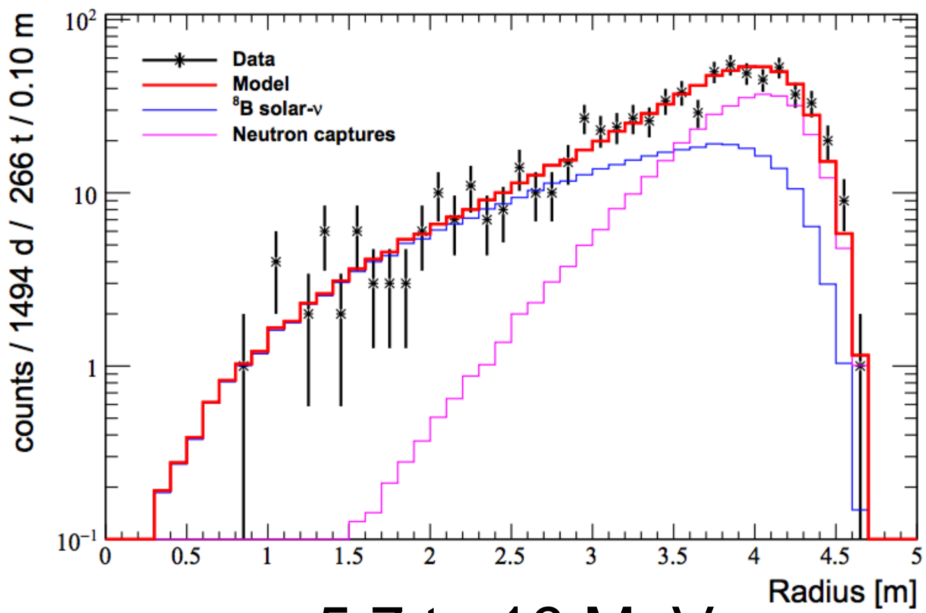
Radial Fit not Energy Fit
$\Rightarrow$ Not to assume shape of survival probability P_{ee}

HER I Fit: [1650, 2950] p.e.



3.2 to 5.7 MeV

HER II Fit: [2950, 8500] p.e.



5.7 to 16 MeV

BOREXINO SOLAR ANALYSIS RESULTS

Species	Phase 1 [cpd/100t]	Phase 2 [cpd/100t]	Flux [$cm^{-2}s^{-1}$]	Uncert. Reduction
pp	144±13±10	$134 \pm 10^{+6}_{-10}$	$6.1 \pm 0.5^{+0.3}_{-0.5} \times 10^{10}$	**1.3**
pep	3.1±0.6±0.4	$2.43 \pm 0.36^{0.15}_{-0.22}$ (HZ) $2.65 \pm 0.36^{0.15}_{-0.24}$ (LZ)	$1.27 \pm 0.19^{+0.08}_{-0.12} \times 10^{8}$ $1.39 \pm 0.19^{+0.08}_{-0.13} \times 10^{8}$	**1.6**
^{7}Be	48.3±2.0±0.9	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$4.99 \pm 0.11^{+0.06}_{-0.08} \times 10^{9}$	**1.8**
^{8}B	0.217±0.038±0.008	$0.223^{+0.015}_{-0.016} \pm 0.006$	$5.68^{+0.39}_{-0.41} \pm 0.03 \times 10^{6}$	**2.4**
CNO	< 7.9 (95 % C.L.)	< 8.1 (95 % C.L.)	-	-
hep	-	< 0.002 (90 % C. L.)	$< 2.2 \times 10^{5}$ (90 % C. L.)	-

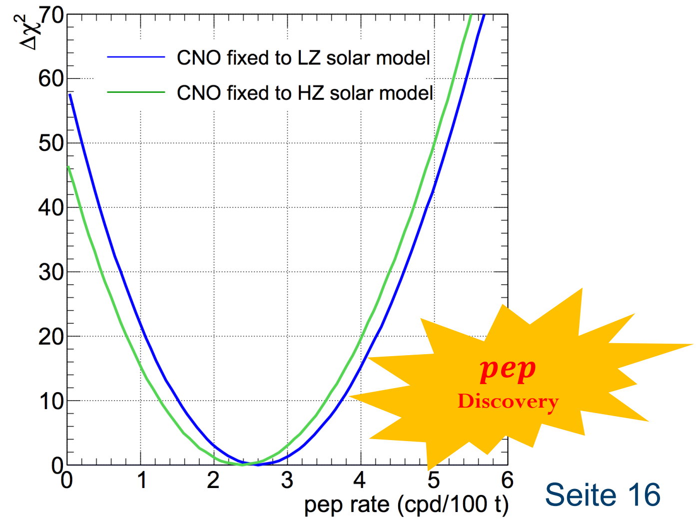
^{210}Bi − *pep* − CNO Correlation

Break it by fixing the CNO rate to:

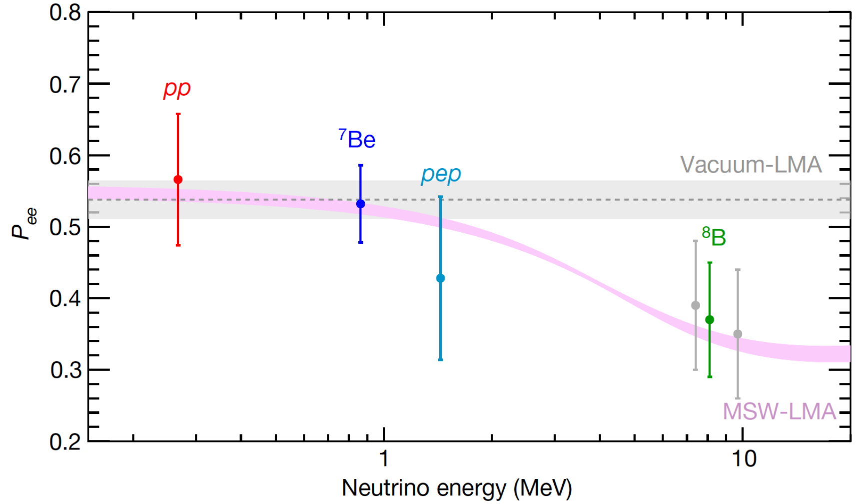
$R_{CNO}(\text{HZ}) = 4.92 \pm 0.55$ cpd/100t

$R_{CNO}(\text{LZ}) = 3.52 \pm 0.37$ cpd/100t

(There is almost 100% anti-correlation between CNO and ^{210}Bi)

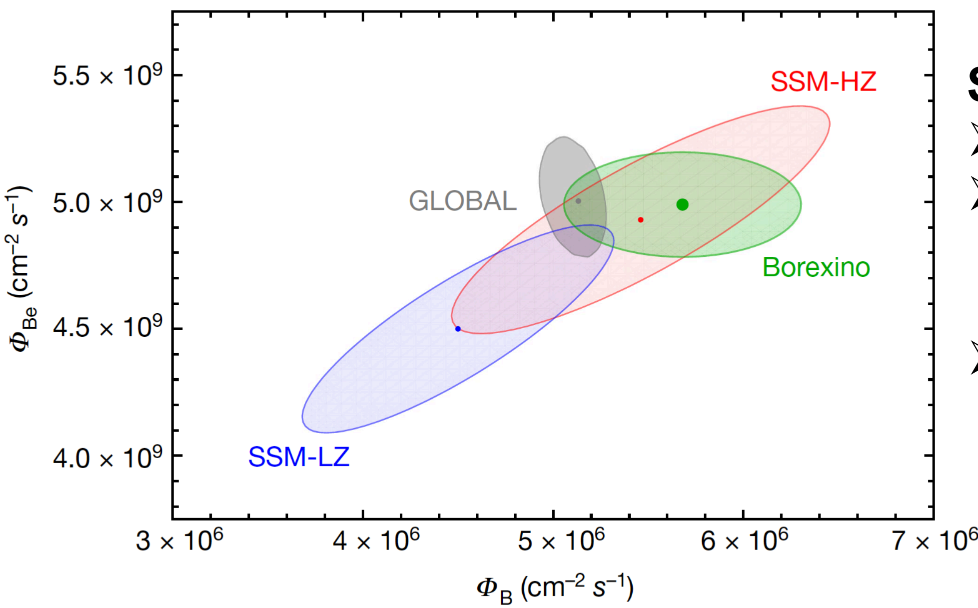


IMPLICATIONS: P_{ee} AND HZ VS. LZ



Studying Neutrinos with the Sun …

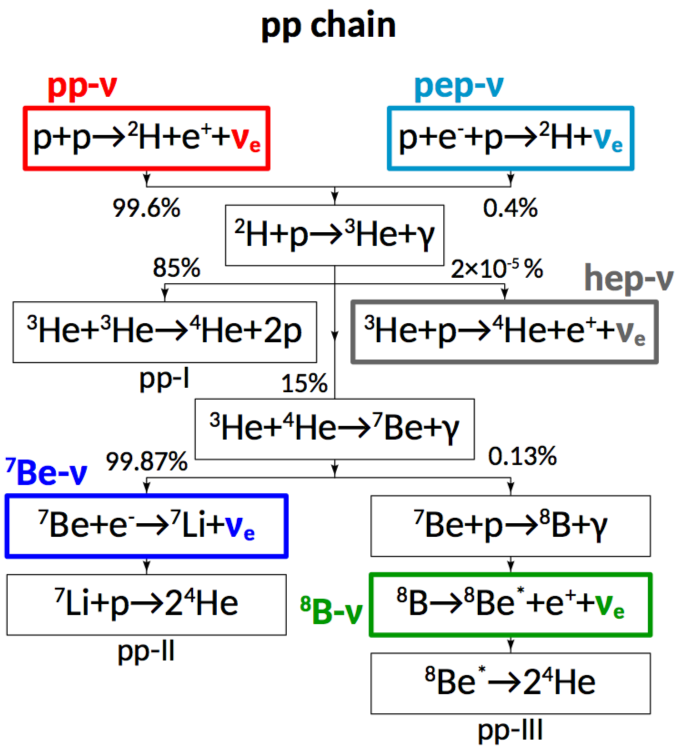
- ➢ Borexino Exclusion of Vacuum LMA oscillation at 98.2 % C.L.



Studying the Sun with Neutrinos …

- ➢ Global Analysis (all solar + KamLand)
- ➢ Borexino Preference is High Metallicity:
  - ➔ Frequentist: 96.6 % C. L.
  - ➔ Bayes: 4.9 (HZ:LZ)
- ➢ Now:
  Data and Model are limited
  by the SSM error!

IMPLICATIONS: PP-CHAIN AND LUMINOSITY



- Compare Ratio of *pp*-I to *pp*-II:

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

- **Borexino:**

$$\boldsymbol{R_{I/II} = 0.1780^{+0.027}_{-0.023}}$$

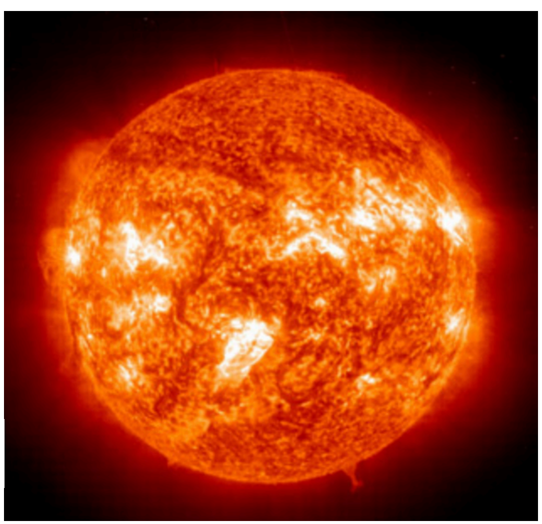
- SSM-HZ:

$$R_{I/II} = 0.180 \pm 0.011$$

- SSM-LZ:

$$R_{I/II} = 0.161 \pm 0.010$$

Borexino consistent with predictions from SSM



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- Solar Luminosity (Stability for > 100k years):
- **Borexino:**

$$\boldsymbol{L_\odot = 3.89^{+0.35}_{-0.42} \times 10^{33}\ \mathrm{erg\ s^{-1}}}$$

Photon Output:

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

Proof of the nuclear origin of the solar power and thermodynamic equilibrium for > 100k years

Search
For Non-Standard
Interactions

INTRODUCTION TO THE NSI SEARCH

Calculation of the Recoiled Electron Spectra ? (*T* = electron energy)

$$\frac{dR}{dT}(T) = N_e \Phi_\nu \int dE_\nu \frac{d\lambda_\nu}{dE_\nu}(E_\nu) \left(\frac{d\sigma_e}{dT}(T, E_\nu) P_{ee}(E_\nu) + \left(\cos^2\theta_{23} \frac{d\sigma_\mu}{dT}(T, E_\nu) + \sin^2\theta_{23} \frac{d\sigma_\tau}{dT}(T, E_\nu) \right) \left(1 - P_{ee}(E_\nu)\right) \right)$$

„Standard“ Cross Section (monoenergetic):

$$\frac{d\sigma(E,T)}{dT} = \frac{2}{\pi} G_F^2 m_e \left[g_{\alpha L}^2 + g_{\alpha R}^2 \left(1 - \frac{T}{E}\right)^2 - g_{\alpha L} g_{\alpha R} \frac{m_e T}{E^2} \right]$$

$$g_{\alpha L} = \begin{cases} 0.5 + \sin^2\theta_W, \alpha = e \\ -0.5 + \sin^2\theta_W, \alpha = \mu, \tau \end{cases} \rightarrow g_{\alpha L}^{NSI} = g_{\alpha L} + \varepsilon_\alpha^L$$

$$g_{\alpha R} = \sin^2\theta_W, \alpha = e, \mu, \tau \rightarrow g_{\alpha R}^{NSI} = g_{\alpha R} + \varepsilon_\alpha^R$$

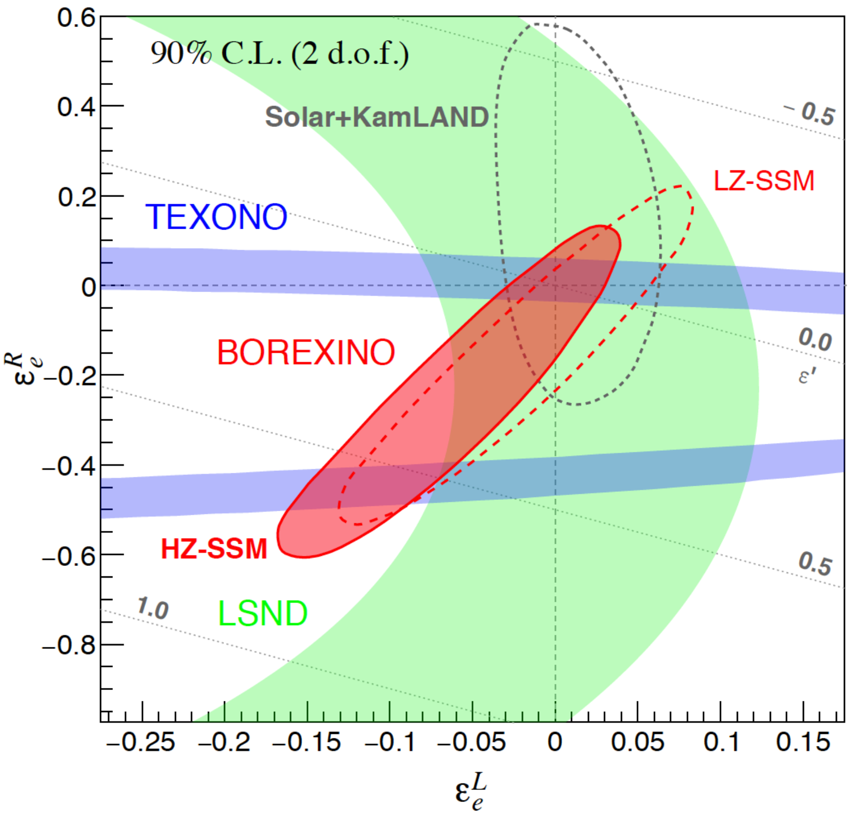
$\varepsilon' = (\varepsilon_\tau^L + \varepsilon_\tau^R)\sin^2\theta_{23} - (\varepsilon_e^L + \varepsilon_e^R)$ (→ shift of the MSW potential (matter-effect))

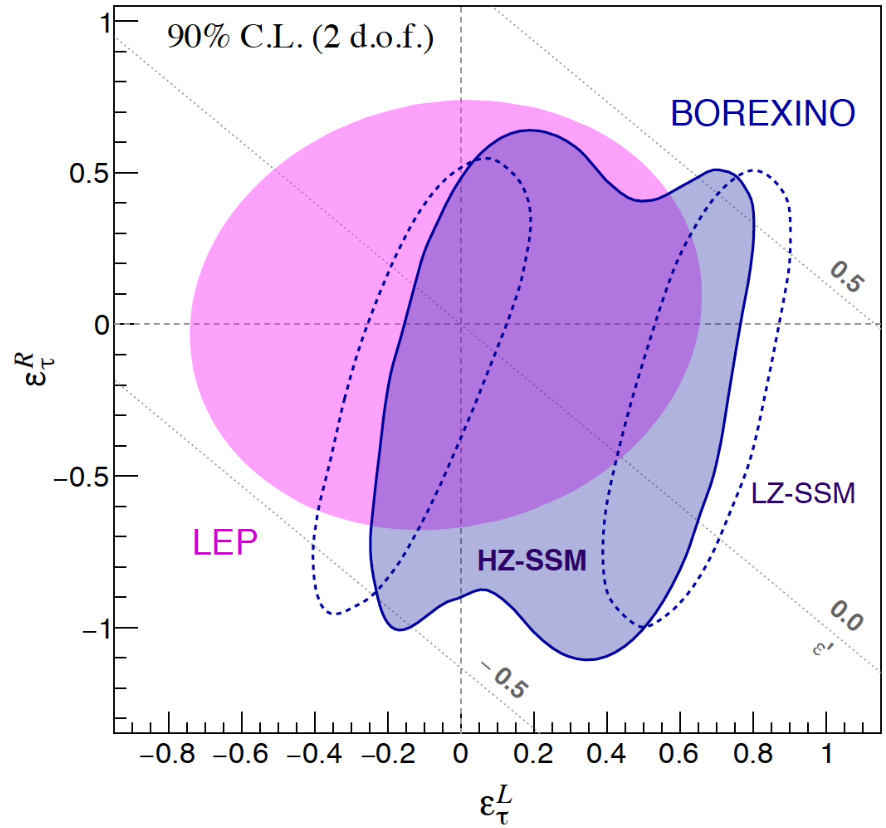
$$P_{ee}(E_\nu) \rightarrow P_{ee}(E_\nu, \varepsilon')$$

$$\frac{d\sigma_\alpha}{dT}(T, E_\nu) \rightarrow \frac{d\sigma_\alpha}{dT}\left(T, E_\nu, \varepsilon_\alpha^{L,R}\right)$$

- Replace standard *L,R* couplings by the non-standard *L,R* couplings
- Calculate the recoiled electron spectra
- Perform a fit and scan NSI parameters

NSI SEARCH RESULTS





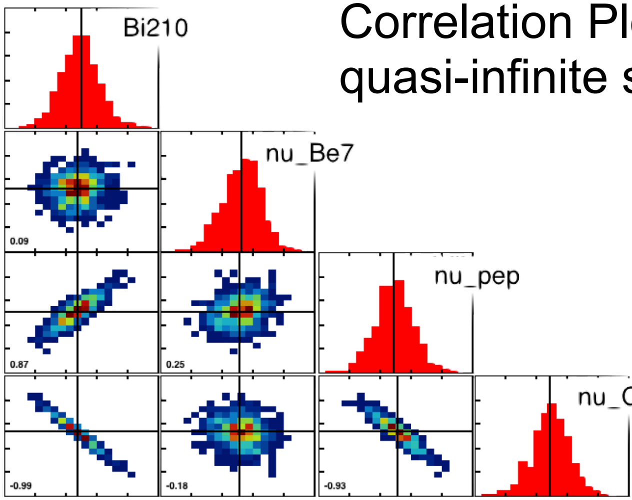
Borexino Parameter Limits

	HZ-SSM	LZ-SSM	Ref. [23]	Ref. [55]
ε_e^R	[−0.15, +0.11]	[−0.20, +0.03]	[−0.21, +0.16]	[0.004, +0.151]
ε_e^L	[−0.035, +0.032]	[−0.013, +0.052]	[−0.046, +0.053]	[−0.03, +0.08]
ε_τ^R	[−0.83, +0.36]	[−0.42, +0.43]	[−0.98, +0.73]	[−0.3, +0.4]
ε_τ^L	[−0.11, +0.67]	[−0.19, +0.79]	[−0.23, +0.87]	[−0.5, +0.2]

Constraints on Non-Standard Neutrino Interactions from Borexino Phase-II (arXiv:1905.03512v1)
Ref. [23]: S. K. Agarwalla, F. Lombardi and T. Takeuchi, Constraining Non-Standard Interactions of the Neutrino with Borexino, JHEP 12 (2012) 079 [1207.3492]
Ref. [55]: J. Barranco, O. G. Miranda, C. A. Moura and J. W. F. Valle, Constraining non-standard neutrino-electron interactions, Phys. Rev. D77 (2008) 093014 [0711.0698].

Towards CNO Neutrinos

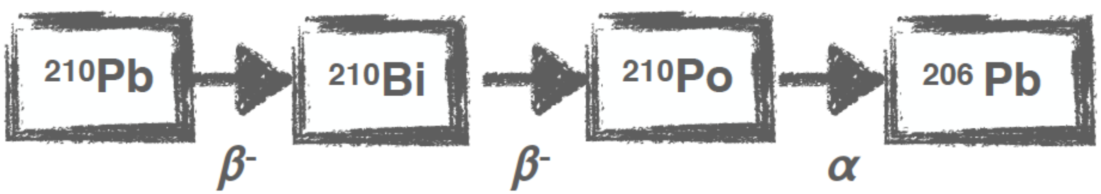
(BREAKING THE) CORRELATIONS



Correlation Plot with quasi-infinite statistics

Almost 100 % anti-correlation between ^{210}Bi and CNO

How to constrain the Rate of ^{210}Bi?
Decay Chain



Lifetimes 32 y 7.23 d 199.1 d

^{210}Po identification:

- Monoenergetic Decay ("Gaussian")
- α-decay ⇔ Event-by-Event Pulse Shape Discrimination

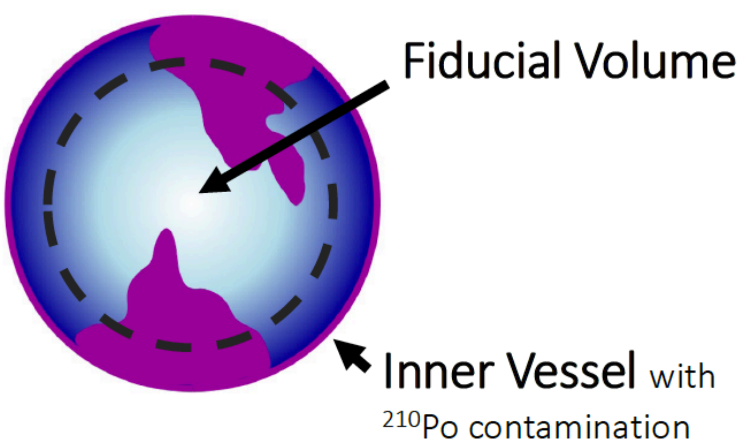
Necessary for CNO Measurement Bi-Po-Tagging:
In secular equilibrium Rate(^{210}Bi, β^{-}) = Rate(^{210}Po, α)

CHALLENGES

- Temperature gradients present in the detector cause convective motions of ^{210}Po present at the nylon vessel to move inside the scintillator

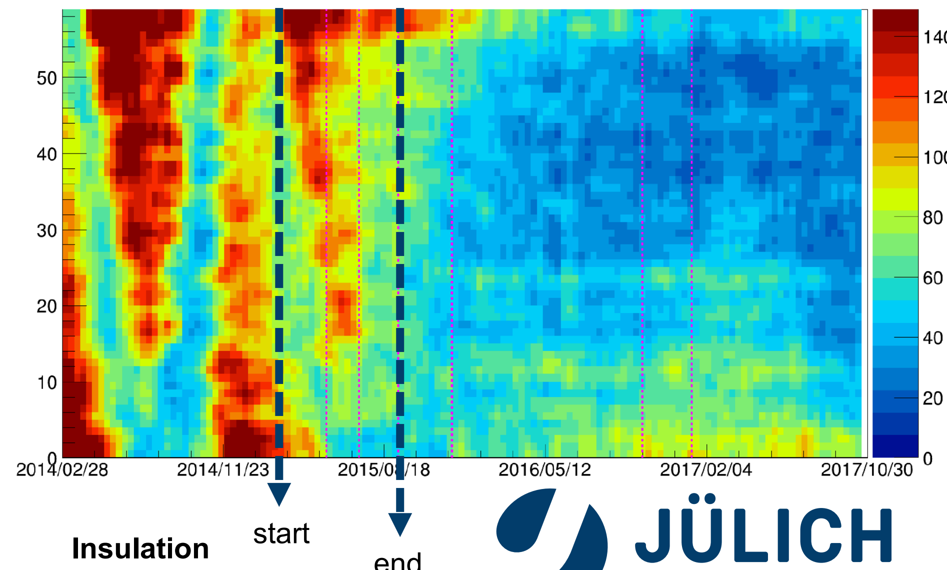
- This breaks the secular equilibrium of the ^{210}Pb chain

- Need to identifiy the ^{210}Po in secular equilibrium with the ^{210}Bi events



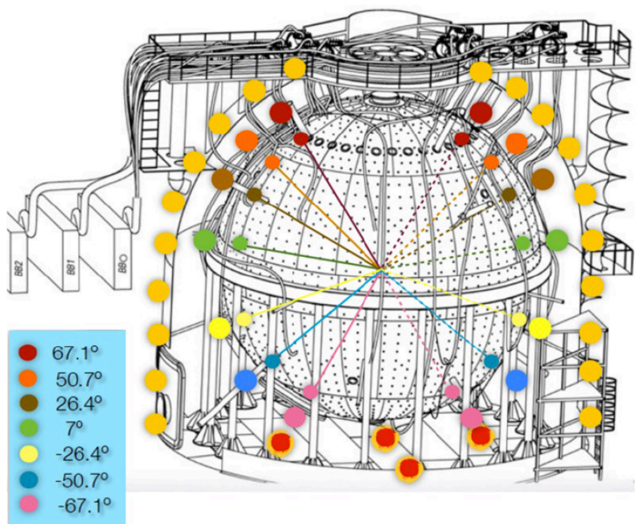
To stop convective motions thermal insulation needed

seasonal variation of ^{210}Po



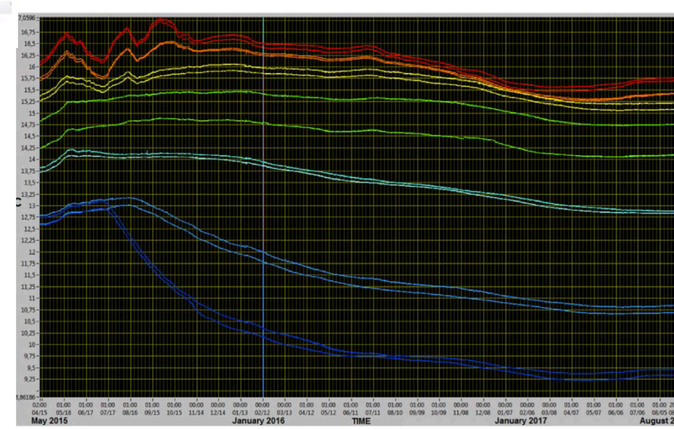
INSULATION

Hardware
- ➢ Rock Wool (2015)
- ➢ Active Temperature Control System



Monitoring
- ➢ 54 Temperature probes located (buffer, external tank, different levels)

Results (→ Temperature Stability)
- ➢ Temperature Profile shows stability
- ➢ Stability conditions
  → ^{210}Bi - ^{210}Po tagging



Summary

+

Outlook

SUMMARY AND OUTLOOK

✓Comprehensive Measurement of *pp*-Chain Solar Neutrinos (Nature volume 562, pages 505–510 (2018))

✓5σ evidence of *pep* Neutrinos for the first time

✓^{7}Be(862+384) precision 2.7 % (stat+sys)

✓Improved ^{8}B measurement

✓Borexino has slight preference to High Metallicity at 96.6 % C. L.

✓Exclusion of Vacuum-LMA scenario at 98.2 % C. L.

✓First Borexino Limits on Non-Standard Interactions

✓Future: Continue data taking with stable condititions to attempt a CNO measurement

Stay Tuned!

Grazie Infinite
Thanks a lot

Questions?

Backup Slides

SYSTEMATICS

Extended Data Table 1 | LER analysis systematics

Source of uncertainty	*pp* neutrinos		^{7}Be neutrinos		*pep* neutrinos	
	-%	+%	-%	+%	-%	+%
Fit models (see text)	-4.5	+0.5	-1.0	+0.2	-6.8	+2.8
Fit method (analytical/Monte Carlo)	-1.2	+1.2	-0.2	+0.2	-4.0	+4.0
Choice of the energy estimator	-2.5	+2.5	-0.1	+0.1	-2.4	+2.4
Pile-up modeling	-2.5	+0.5	0	0	0	0
Fit range and binning	-3.0	+3.0	-0.1	+0.1	-1.0	+1.0
Inclusion of the ^{85}Kr constraint	-2.2	+2.2	0	+0.4	-3.2	0
Live time	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Scintillator density	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Fiducial volume	-1.1	+0.6	-1.1	+0.6	-1.1	+0.6
Total systematics (%)	**-7.1**	**+4.7**	**-1.5**	**+0.8**	**-9.0**	**+5.6**

Relevant sources of systematic uncertainties and their contributions to the measured neutrino interaction rates for the LER analysis.

Background	Rate [cpd/100 t]
^{14}C [Bq/100 t]	40.0 ± 2.0
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5 ± 1.9
^{11}C	26.8 ± 0.2
^{210}Po	260.0 ± 3.0
Ext. ^{40}K	1.0 ± 0.6
Ext. ^{214}Bi	1.9 ± 0.3
Ext. ^{208}Tl	3.3 ± 0.1

TABLE II. Best estimates for the total rates of the background species included in the fit with statistical and systematic uncertainties added in quadrature.

First Simultaneous Precision Spectroscopy of *pp*, ^{7}Be, and *pep* Solar Neutrinos with Borexino Phase-II (https://arxiv.org/abs/1707.09279) (2017)

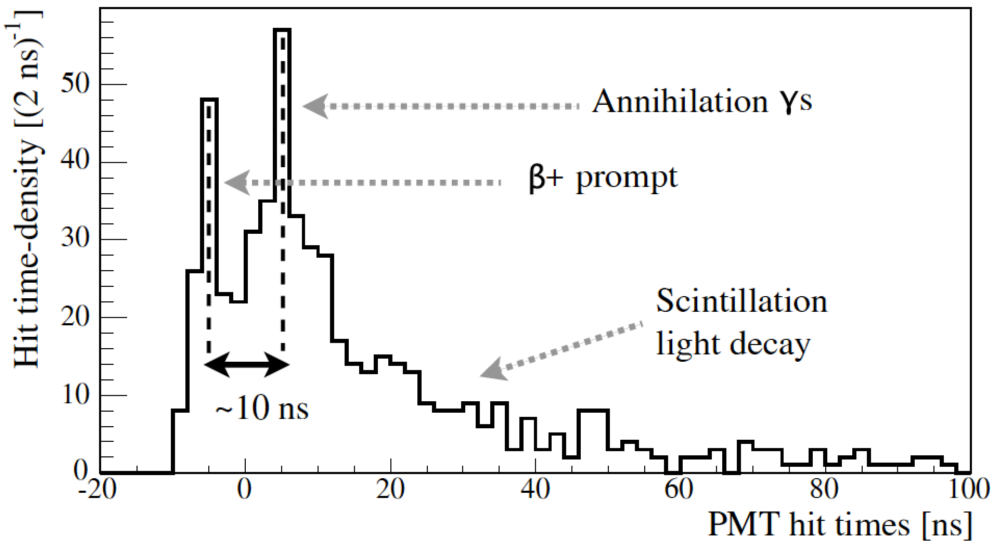
Comprehensive measurement of *pp*-chain solar neutrinos (Nature 562, 505–510 (2018))

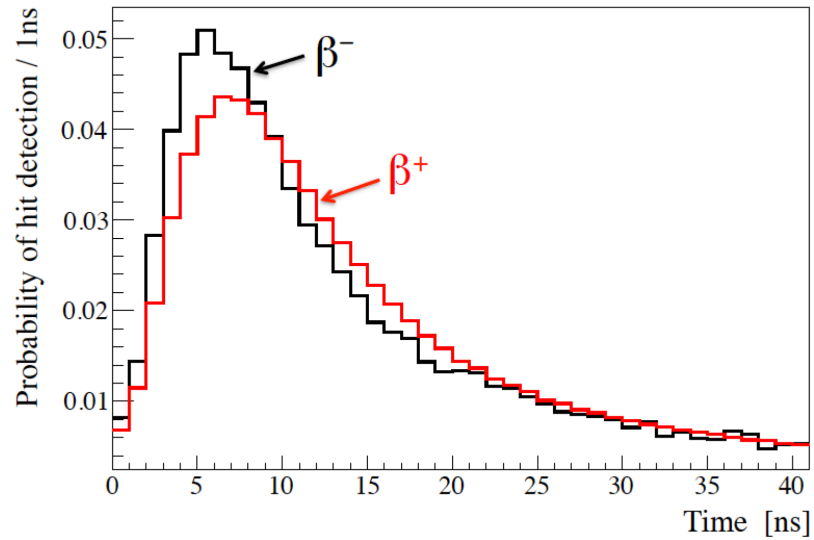
Extended Data Table 2 | HER analysis systematics

Source of uncertainty	*HER-I*		*HER-II*		*HER* (tot)	
	-%	+%	-%	+%	-%	+%
Target mass	-2.0	+2.0	-2.0	+2.0	-2.0	+2.0
Energy scale	-0.5	+0.5	-4.9	+4.9	-1.7	+1.7
z-cut	-0.7	+0.7	0	0	-0.4	+0.4
Live time	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Scintillator density	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
Total systematics (%)	**-2.2**	**+2.2**	**-5.3**	**+5.3**	**-2.7**	**+2.7**

Relevant sources of systematic uncertainties and their contributions to the measured neutrino interaction rates for the HER analyses.

Electron Positron Pulse Shape Differences

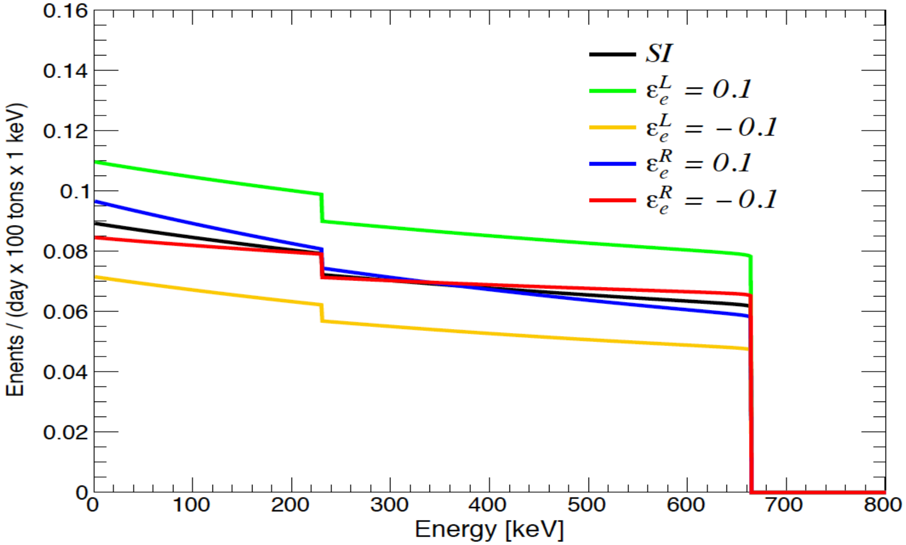




- Positrons form Positronium in the scintillator with 3.1 ns (only orthopositronium relevant, para-positronium lifetime is negligible)
- Positronium Formation Probability = 53 %
- Delay (ortho)-positronium formation leads to shape differences
- ➔ Distortion in Time for Hit PMTs and Beta Events

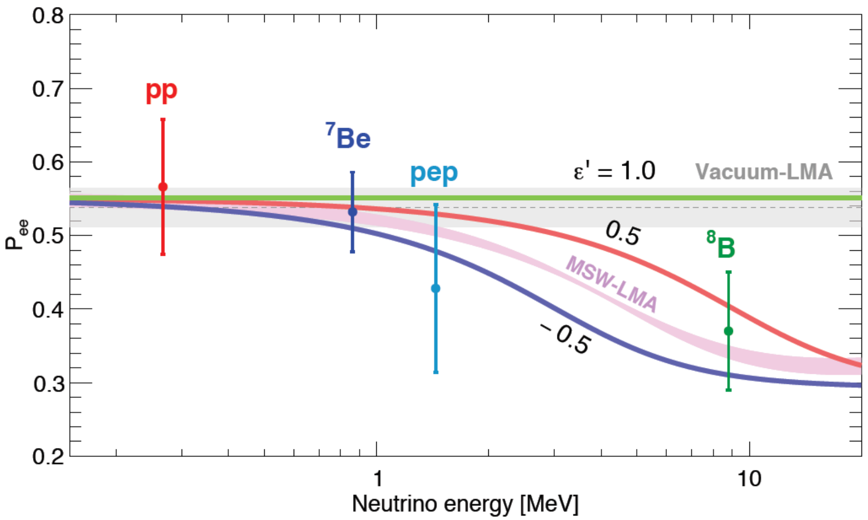
NSI

$$g^{NSI}_{\alpha L,R} = g_{\alpha L,R} + \varepsilon^{L,R}_{\alpha}$$



- ^{7}Be are monoenergetic neutrinos
- "Edge" comes from:
  Ground State νs ~ 90 %
  Excited State νs ~ 10 %
- Shape differences visible for different NSI params

$$\varepsilon' = \left(\varepsilon^L_\tau + \varepsilon^R_\tau\right) sin^2\,\theta_{23} - \left(\varepsilon^L_e + \varepsilon^R_e\right)$$



- P_{ee} shape sensitive to NSI parameters

Constraints on Non-Standard Neutrino Interactions from Borexino Phase-II (arXiv:1905.03512v1)