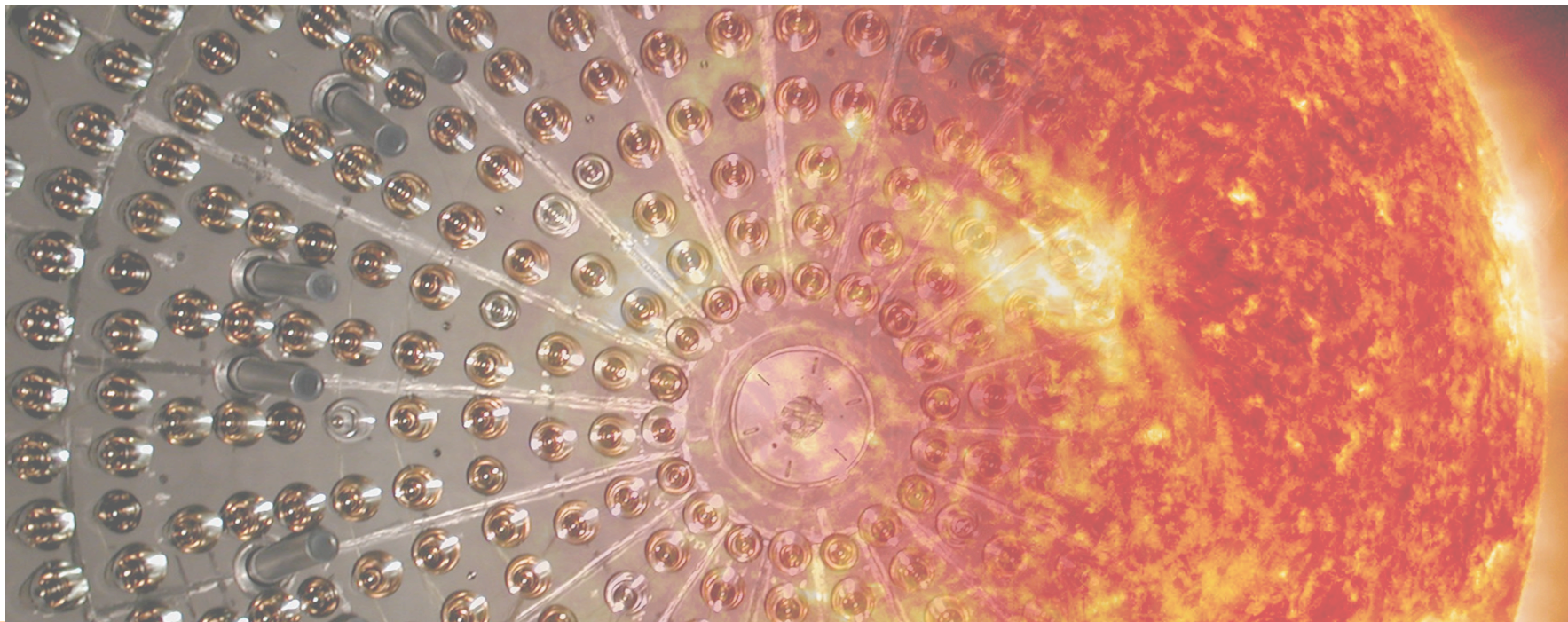




Zara Bagdasarian¹ for the Borexino Collaboration

BOREXINO: LATEST RESULTS AND FUTURE OPPORTUNITIES

26 AUGUST 2019 | LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLES

¹ Institute für Kernphysik (IKP-2) Forschungszentrum Jülich

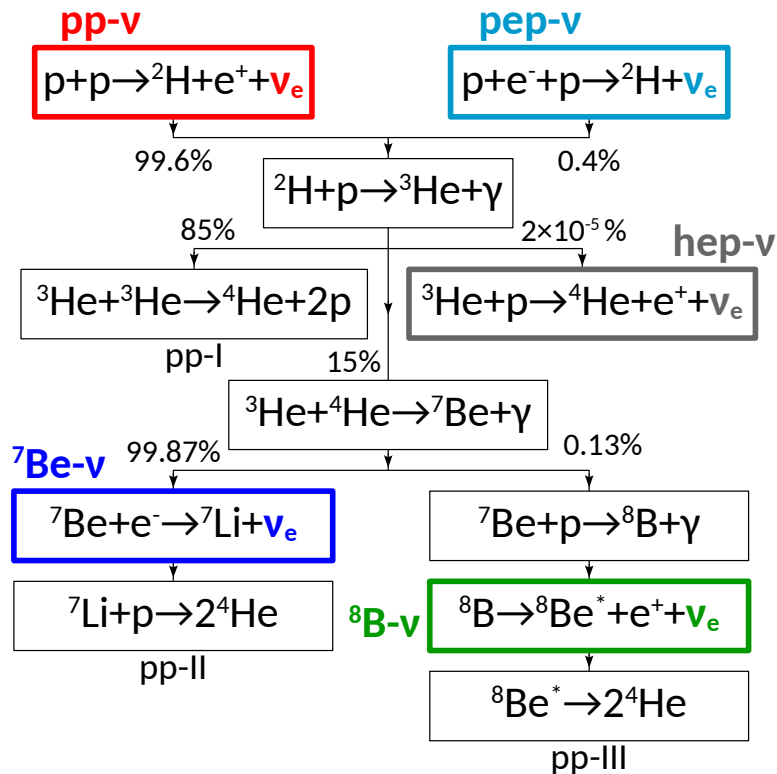
Contact: z.bagdasarian@fz-juelich.de @ZaraBagdasarian

Mitglied der Helmholtz-Gemeinschaft

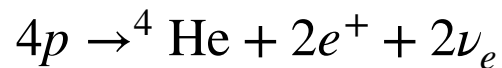
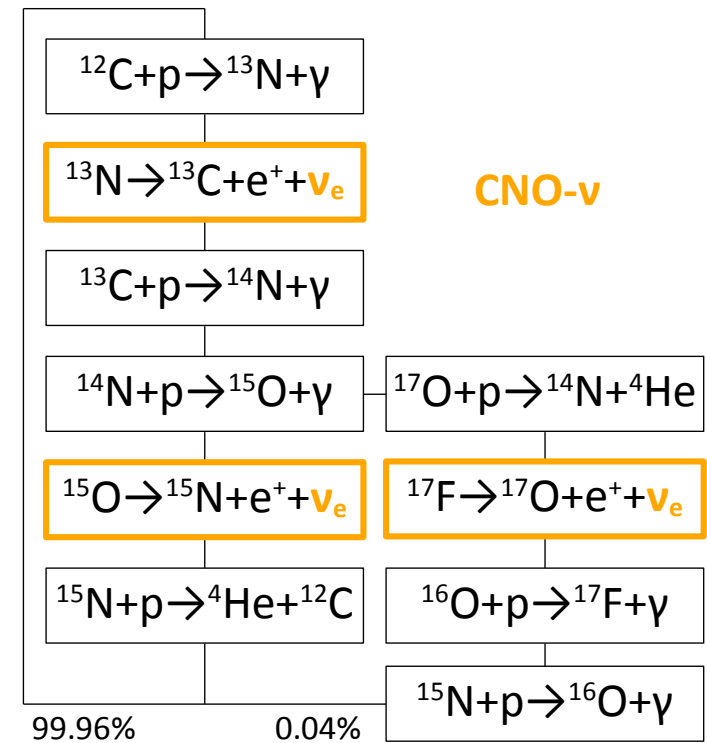


Fusion processes in the Sun

pp chain reaction (~99%)

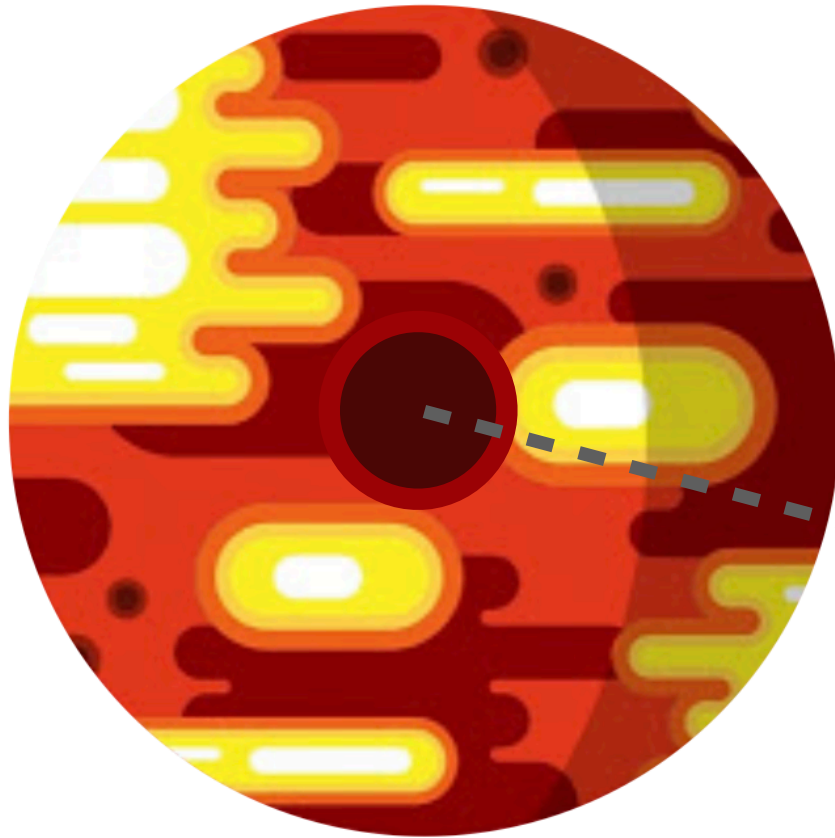


CNO cycle (< 1%)



Released energy ~26 MeV

Solar neutrinos - a window into the core of the Sun



Studying the Sun with Neutrinos

The only direct probe of nuclear process in the core

ν



Studying the Neutrinos with the Sun

Flux $\sim 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$

Goals of solar neutrino experiments

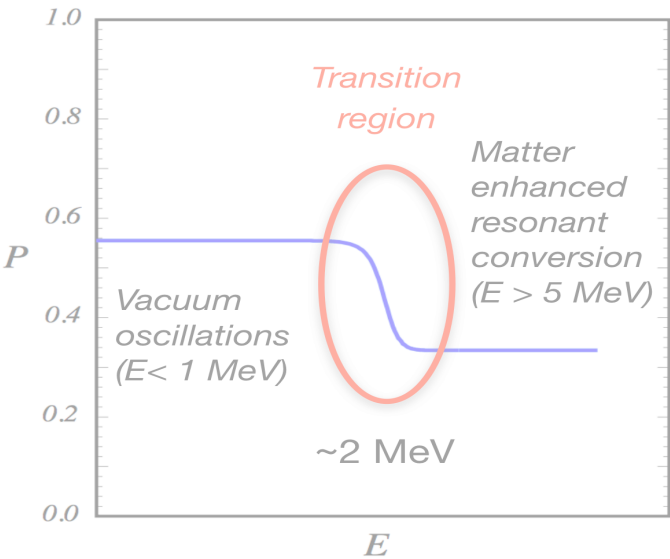
Studying the Sun with Neutrinos

- Fusion rates (pp, CNO)
- Energy production/loss mechanisms
- Testing stability of the Sun
- Metallicity problem: high (HZ) vs low (LZ)

Solar ν	Expected Flux (HZ)	Expected Flux (LZ)	Difference (HZ-LZ)/HZ
pp [10 ¹⁰ cm ⁻² s ⁻¹]	5.98 (1± 0.006)	6.03 (1± 0.005)	-0.8%
pep [10 ⁸ cm ⁻² s ⁻¹]	1.44 (1± 0.01)	1.46 (1± 0.009)	-1.4%
⁷ Be [10 ⁹ cm ⁻² s ⁻¹]	4.93 (1± 0.06)	4.50 (1± 0.06)	8.7%
⁸ B [10 ⁶ cm ⁻² s ⁻¹]	5.46 (1± 0.12)	4.50 (1± 0.12)	17.6%
CNO [10 ⁸ cm ⁻² s ⁻¹]	4.88 (1± 0.11)	3.51(1± 0.11)	28.1%

Studying the Neutrinos with the Sun

- Neutrino oscillation parameters
- Anomalous magnetic moment
- Searching for deviations from MSW-LMA (large mixing angle Mikheyev-Smirnov-Wolfenstein effect) scenario of solar neutrino oscillations, especially in the transition region of P_{ee} (e.g. non-standard neutrino interactions models)



Goals of solar neutrino experiments

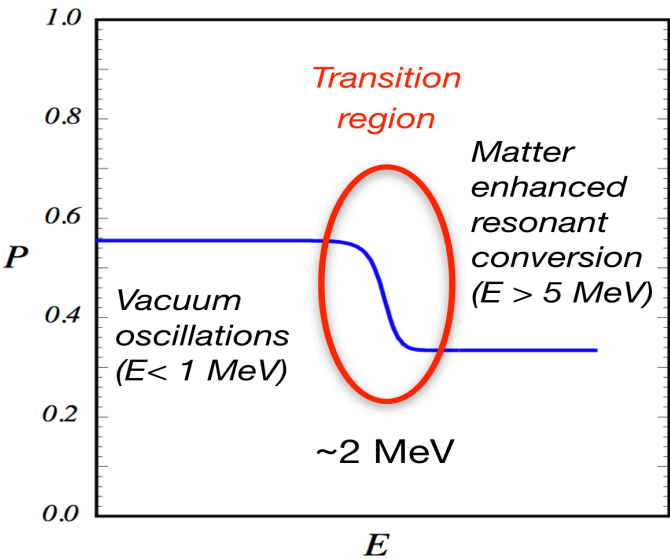
Studying the Sun with Neutrinos

- Fusion rates (pp, CNO)
- Energy production/loss mechanisms
- Testing stability of the Sun
- Metallicity problem: high (HZ) vs low (LZ)

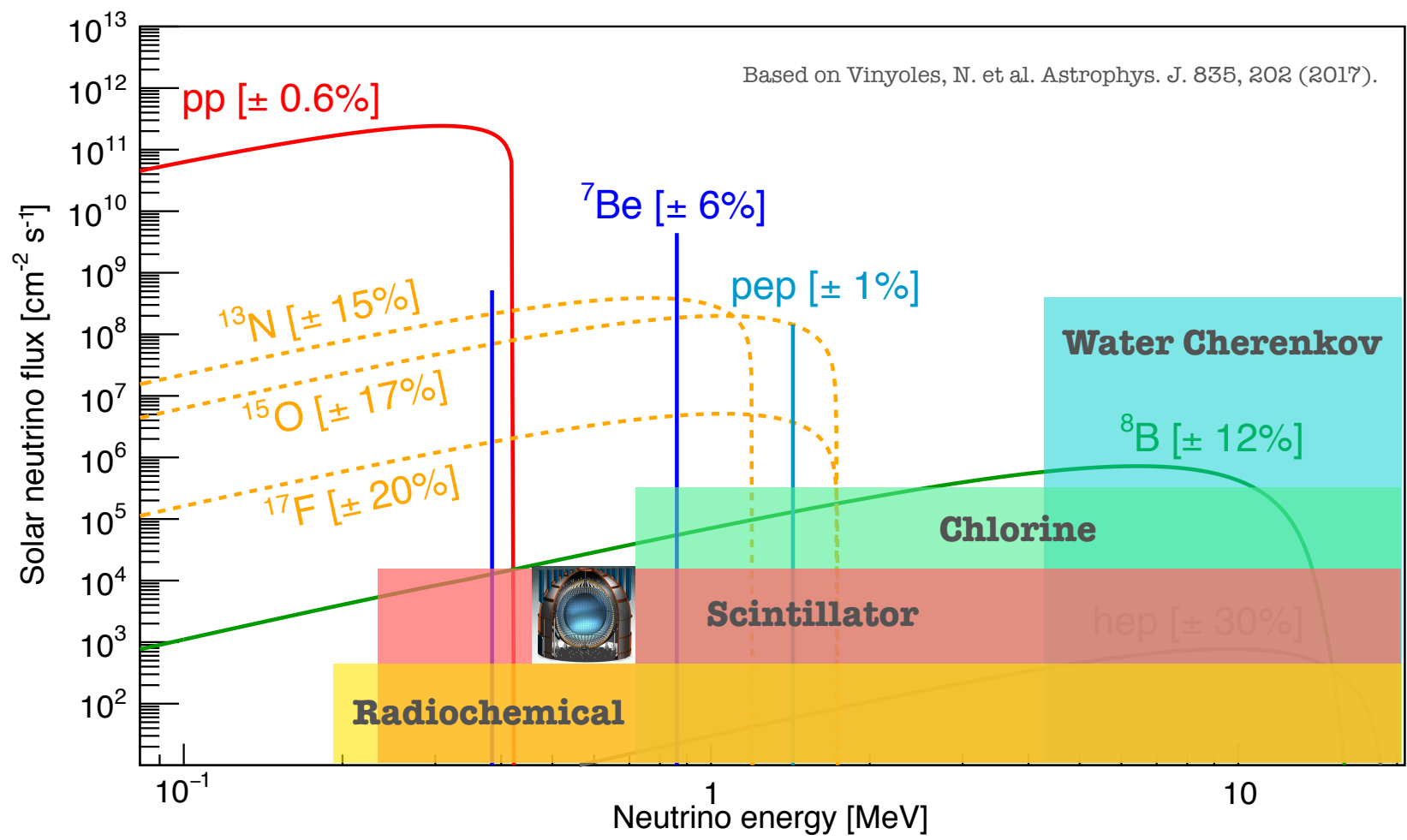
Solar ν	Expected Flux (HZ)	Expected Flux (LZ)	Difference (HZ-LZ)/HZ
pp [10 ¹⁰ cm ⁻² s ⁻¹]	5.98 (1± 0.006)	6.03 (1± 0.005)	-0.8%
pep [10 ⁸ cm ⁻² s ⁻¹]	1.44 (1± 0.01)	1.46 (1± 0.009)	-1.4%
⁷ Be [10 ⁹ cm ⁻² s ⁻¹]	4.93 (1± 0.06)	4.50 (1± 0.06)	8.7%
⁸ B [10 ⁶ cm ⁻² s ⁻¹]	5.46 (1± 0.12)	4.50 (1± 0.12)	17.6%
CNO [10 ⁸ cm ⁻² s ⁻¹]	4.88 (1± 0.11)	3.51(1± 0.11)	28.1%

Studying the Neutrinos with the Sun

- Neutrino oscillation parameters
- Anomalous magnetic moment
- Searching for deviations from MSW-LMA (large mixing angle Mikheyev-Smirnov-Wolfenstein effect) scenario of solar neutrino oscillations, especially in the transition region of P_{ee} (e.g. non-standard neutrino interactions models)



Solar Neutrinos Flux on Earth



Borexino @ Laboratori Nazionali del Gran Sasso

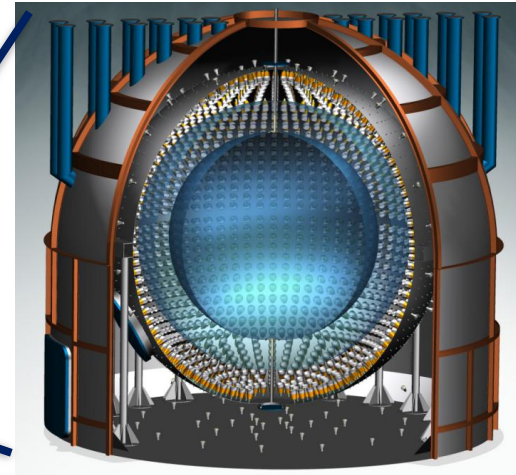


Gran Sasso,
Apennines,
Abruzzo, Italy



Laboratori Nazionali
di Gran Sasso
(LNGS)

**3800 m.w.e shielding
against cosmic rays**
 $\sim 10^6$ reduction of cosmic
background

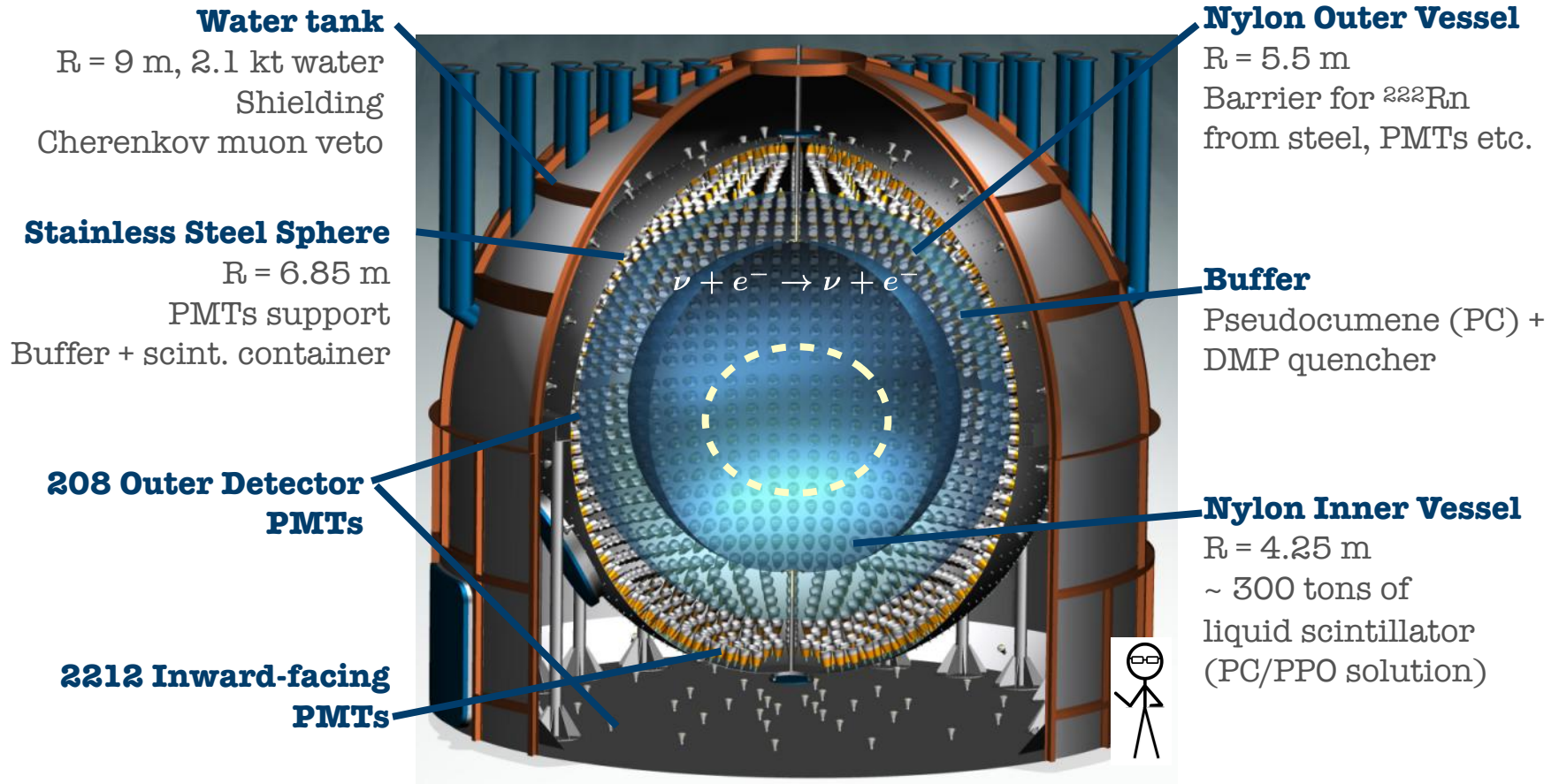


Borexino detector at Hall C

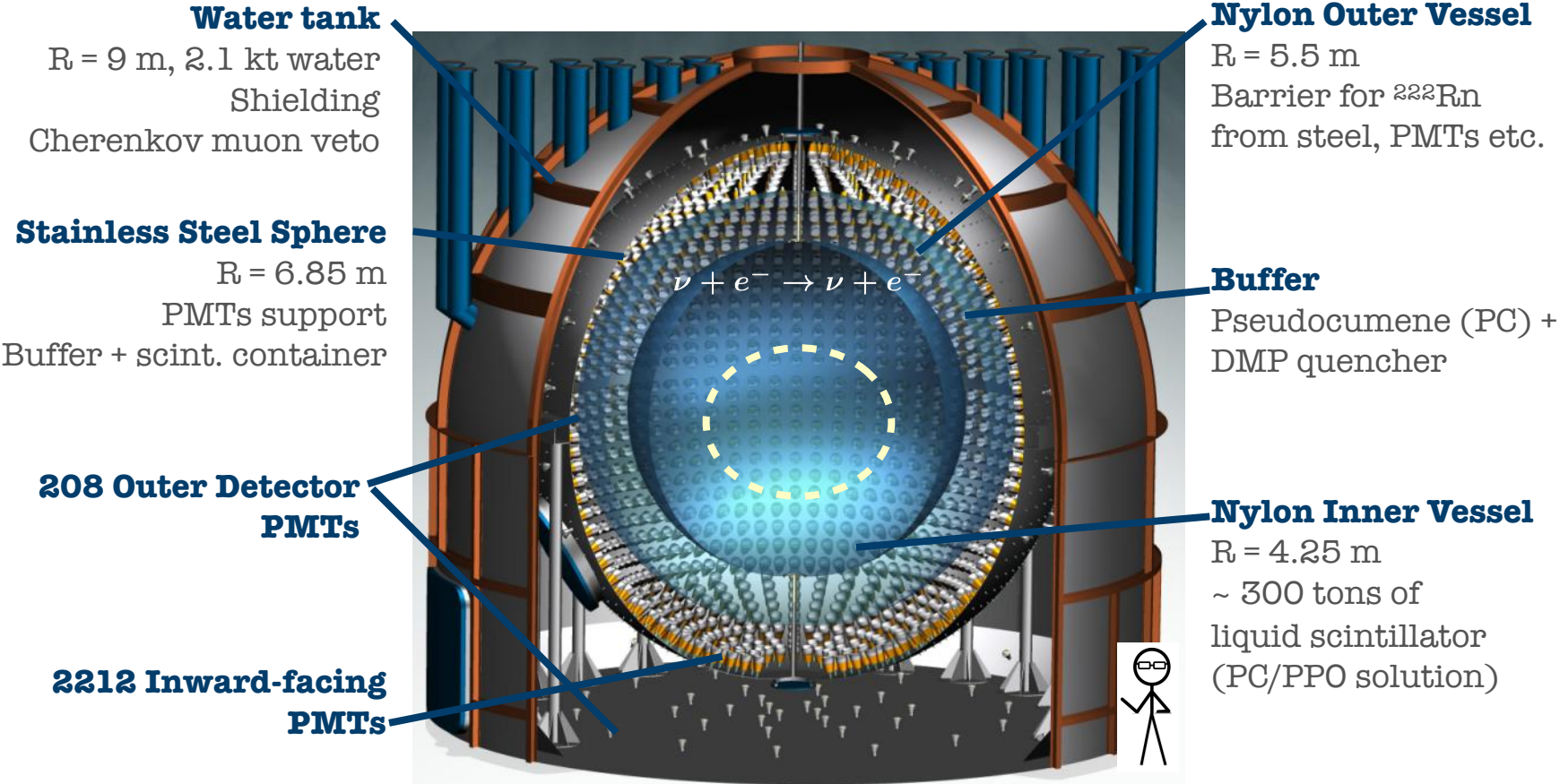


Entrance to the LNGS

Borexino Detector



Borexino Detector



Unprecedented Scintillator Radiopurity

Low-energy threshold

High Light Yield

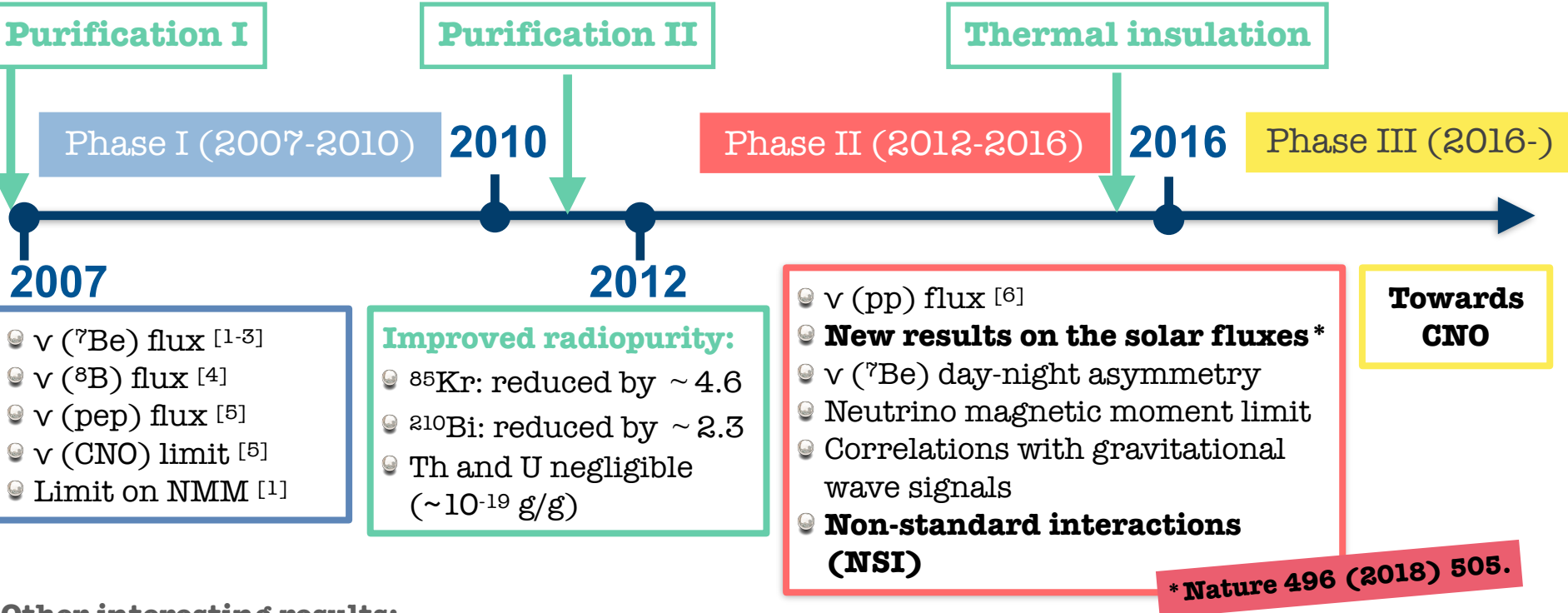
Good energy and position resolution

No directionality

Design Principle Goal:

^7Be neutrino measurement

Borexino achievements and goals



Other interesting results:

Geoneutrinos	$> 5\sigma$	DOI:10.1103/PhysRevD.92.031101
Gamma-ray burts correlation	No statistically significant excess over background	DOI:10.1016/j.astropartphys.2016.10.004
e charge conservation	$> 6.6 \cdot 10^{28} \text{ y @ 90\% CL}$	DOI:10.1103/PhysRevLett.115.231802

[1] DOI: 10.1103/PhysRevLett.101.091302; [2] DOI: 10.1016/j.physletb.2007.09.054; [3] DOI: 10.1103/PhysRevLett.107.141302; [4] DOI: 10.1103/PhysRevD.82.033006; [5] DOI: 10.1103/PhysRevLett.108.05130; [6] Nature 512 (2014) 383.

Comprehensive measurement of solar neutrino spectrum from the proton-proton nuclear fusion chain

Step 1: the event selection to **maximize the signal-to-background ratio**: different set of cuts in the three energy regions

Step 2: the extraction of the **neutrino and residual background rates** with a combined fit

Low energy range LER: (0.19-2.93) MeV

$\nu(\text{pp})$ $\nu(\text{pep})$ $\nu(^7\text{Be})$ $\nu(\text{CNO})$

internal, external, and cosmogenic backgrounds

High energy range HER I: (3.2 - 5.7) MeV

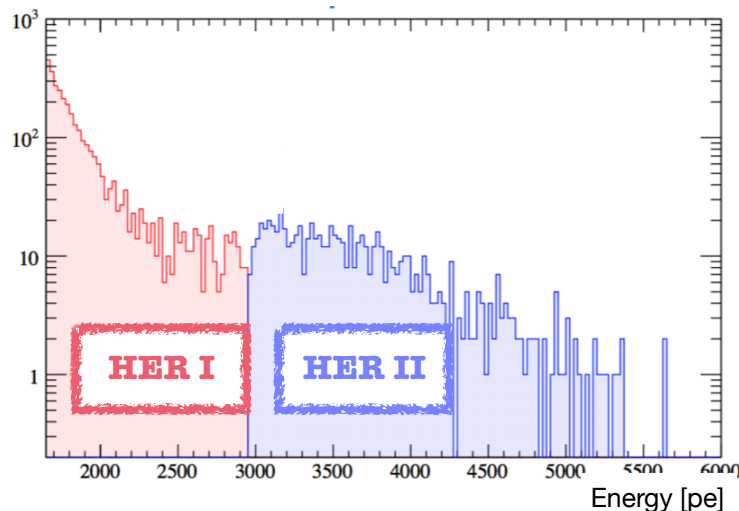
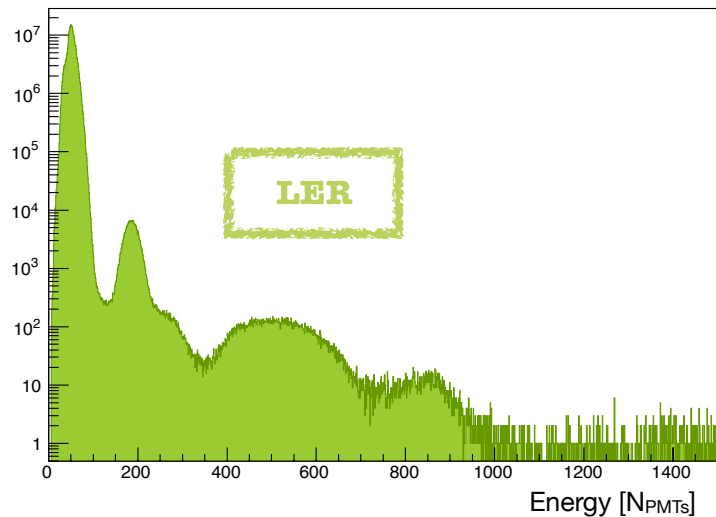
$\nu(^8\text{B})$ $\nu(\text{hep})$

internal, external and cosmogenic backgrounds

High energy range HER II: (5.7 - 16) MeV

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

external and cosmogenic backgrounds

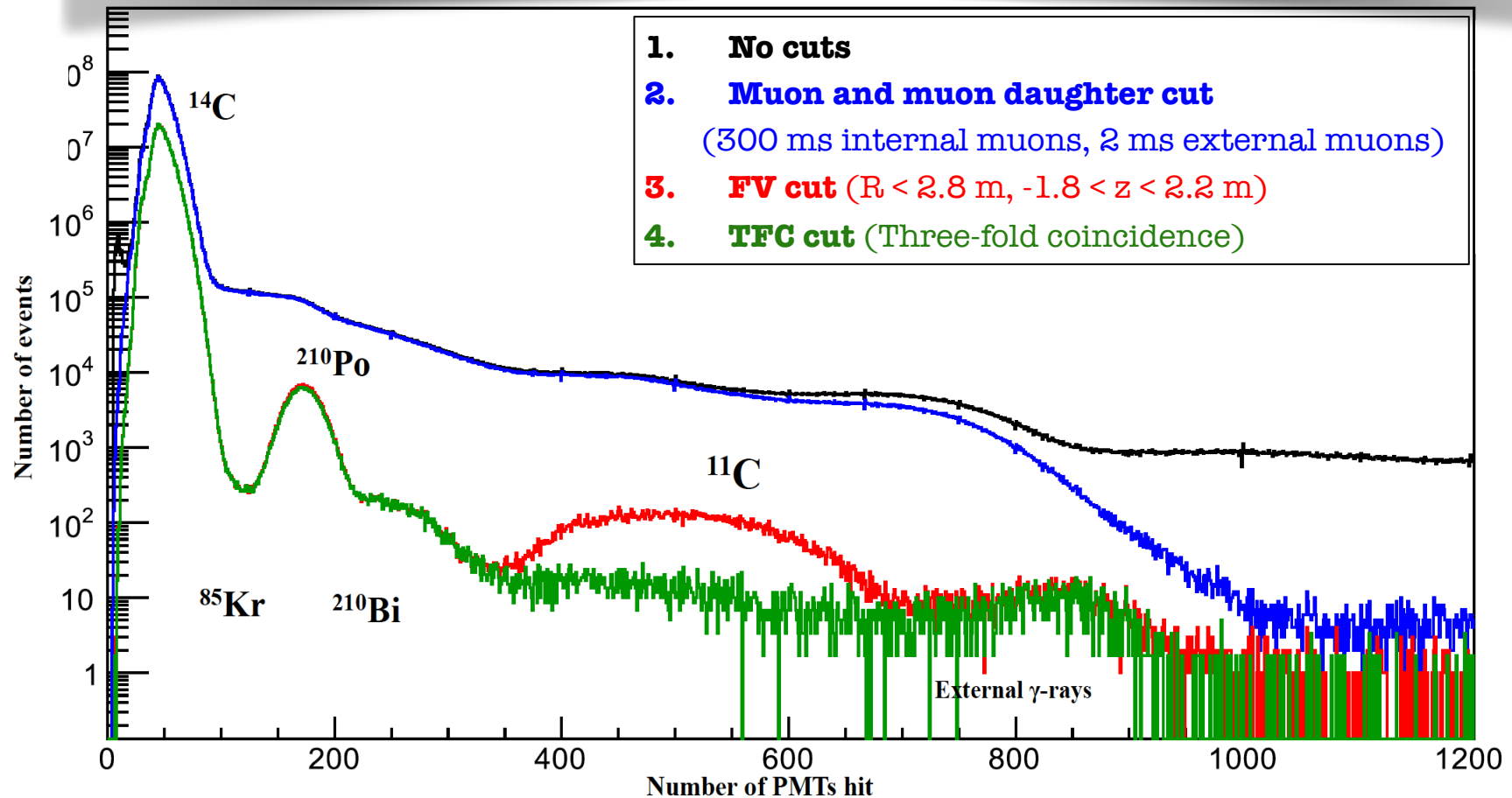


Different energies -> different backgrounds

Low energy range (LER) (0.19-2.93) MeV

🕒 **Data-set:** Dec 14th 2011- May 21st 2016;

🕒 **Total exposure:** 1291.51 days x 71.3 tons (1.6 times Phase I data);



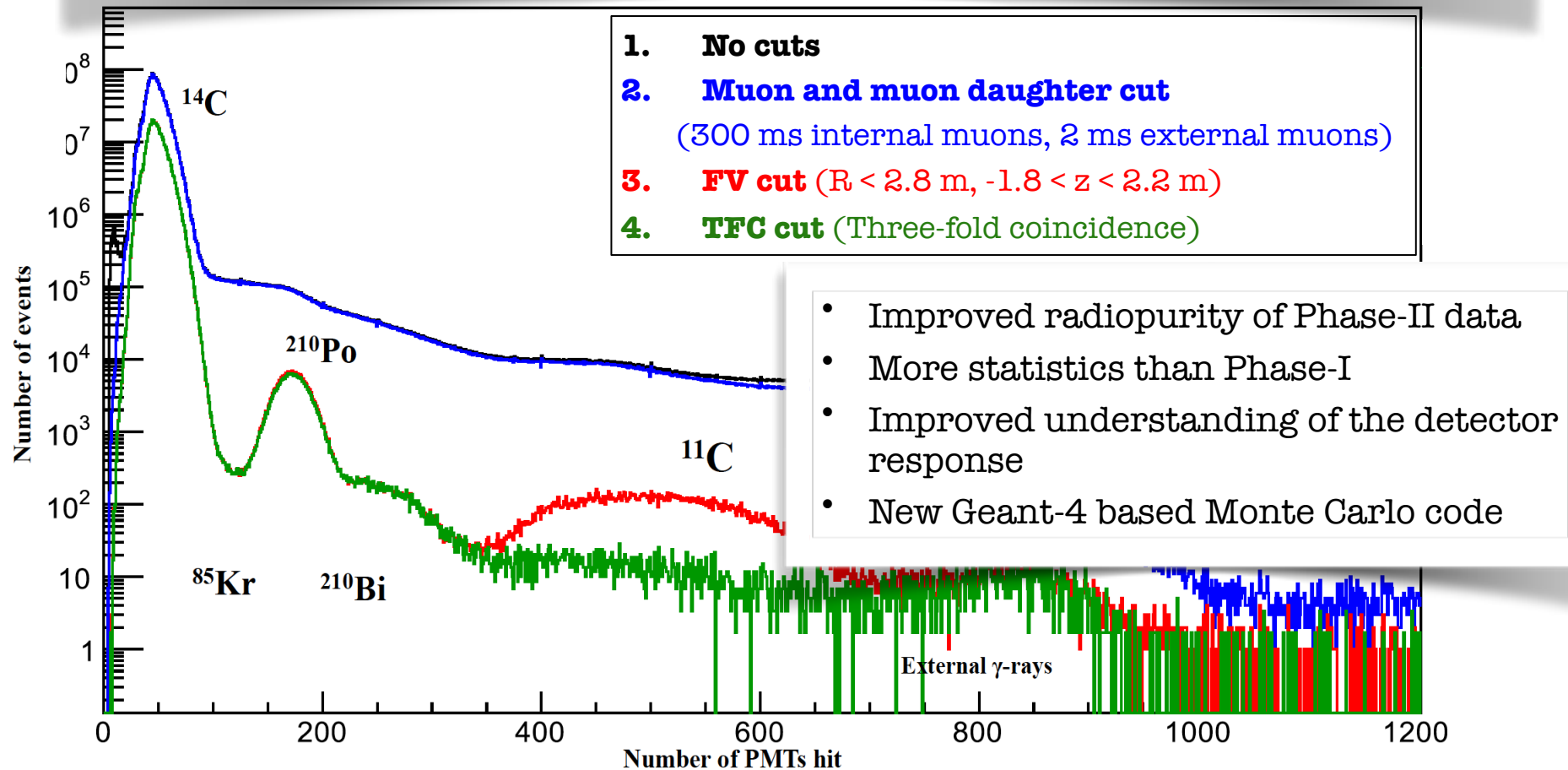
$\nu(\text{pp})$ $\nu(\text{pep})$ $\nu(^7\text{Be})$

$\nu(\text{CNO})$ constrained

Low energy range (LER) (0.19-2.93) MeV

• **Data-set:** Dec 14th 2011- May 21st 2016;

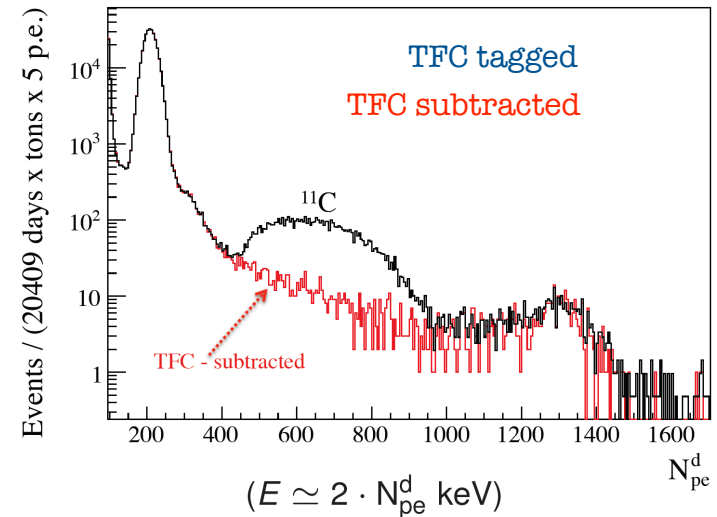
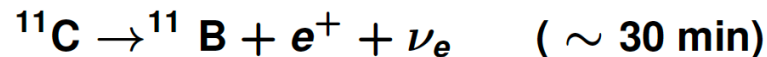
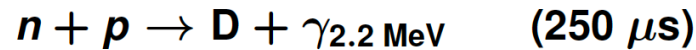
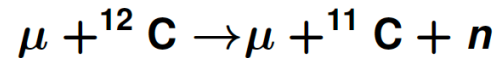
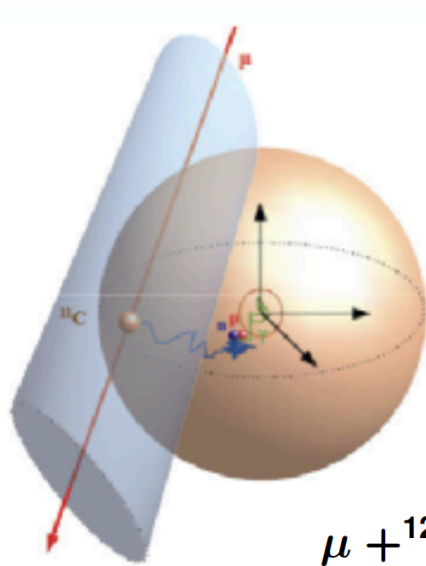
• **Total exposure:** 1291.51 days x 71.3 tons (1.6 times Phase I data);



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

$\nu(\text{CNO})$ constrained

^{11}C cosmogenic background - Three Fold Coincidence (TFC)

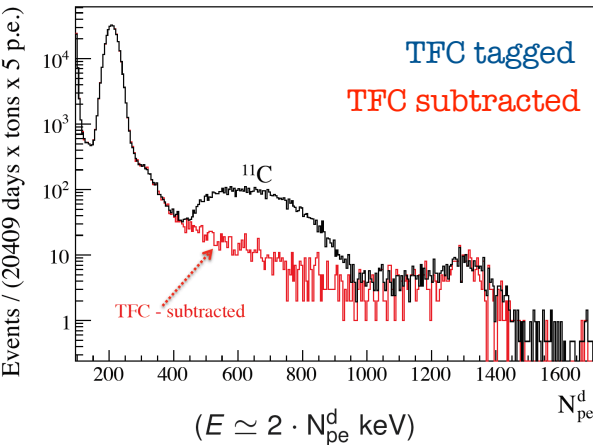


- Association of neutrons to a given μ track
- Calculate for each event the likelihood to be ^{11}C
- Divide total exposure into TFC-subtracted and TFC-tagged spectra

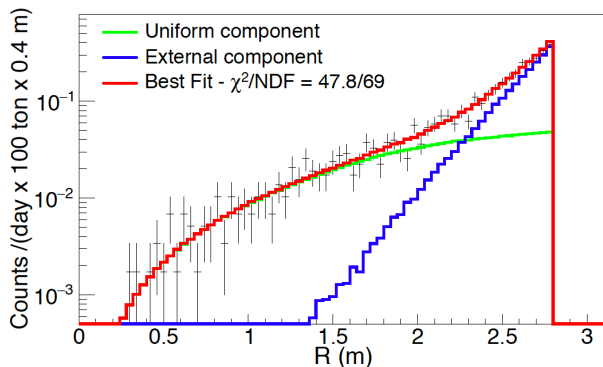
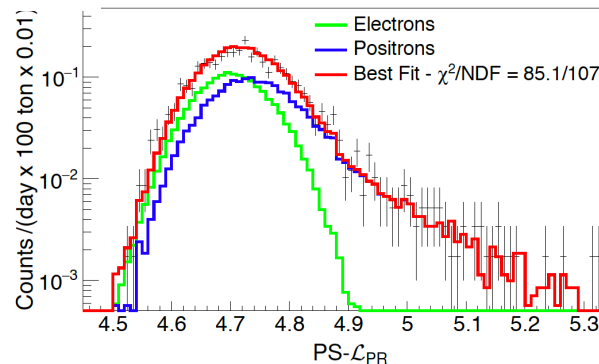
2 energy spectra

- 64% of exposure, 8% of ^{11}C
- 36% of exposure, 92% of ^{11}C

Spectroscopy of pp,⁷Be and pep neutrinos (LER)



A spectral fit
needed to disentangle
signal and background



Spectral shapes of
signals and
backgrounds

A multivariate fit with the likelihood,
including:

$$\mathcal{L}_{MV}(\theta) = \mathcal{L}_{\text{tag}}(\theta) \cdot \mathcal{L}_{\text{sub}}(\theta) \cdot \mathcal{L}_{PS}(\theta) \cdot \mathcal{L}_{\text{Rad}}(\theta)$$

- 2 energy spectra
 - 64% of exposure, 8% of ¹¹C
 - 36% of exposure, 92% of ¹¹C
- Pulse-shape distribution (e+)/e-
discrimination
 - Constraining the remaining ¹¹C
content in the spectrum depleted
in ¹¹C
- Radial distribution:
 - To better disentangle external
background from the internal
contaminants

Two approaches:

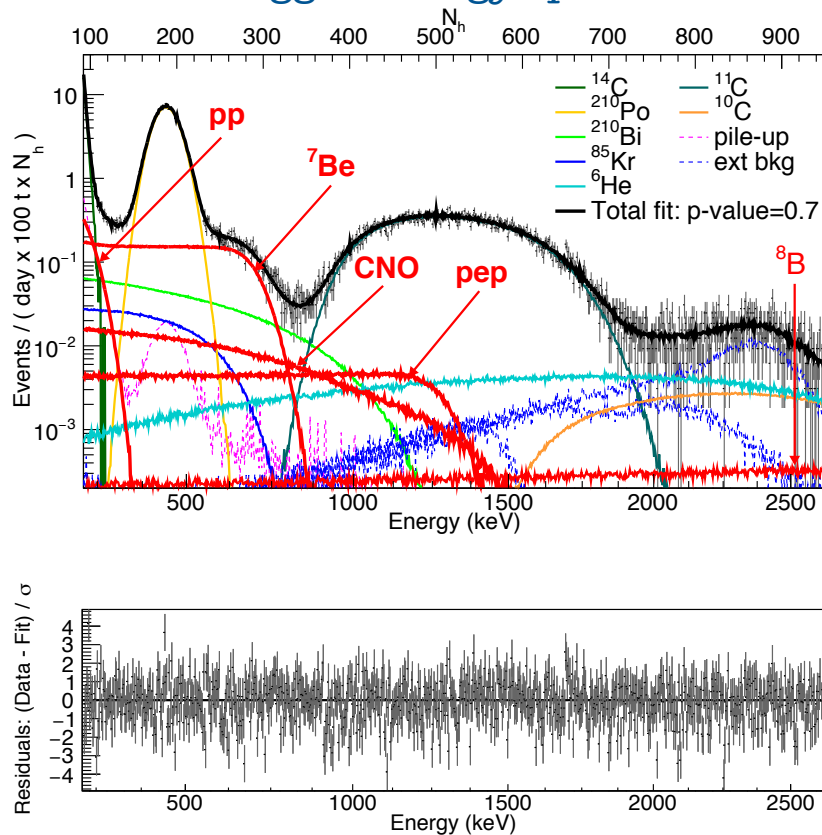
- Analytical and Monte Carlo

Monte Carlo spectral fit

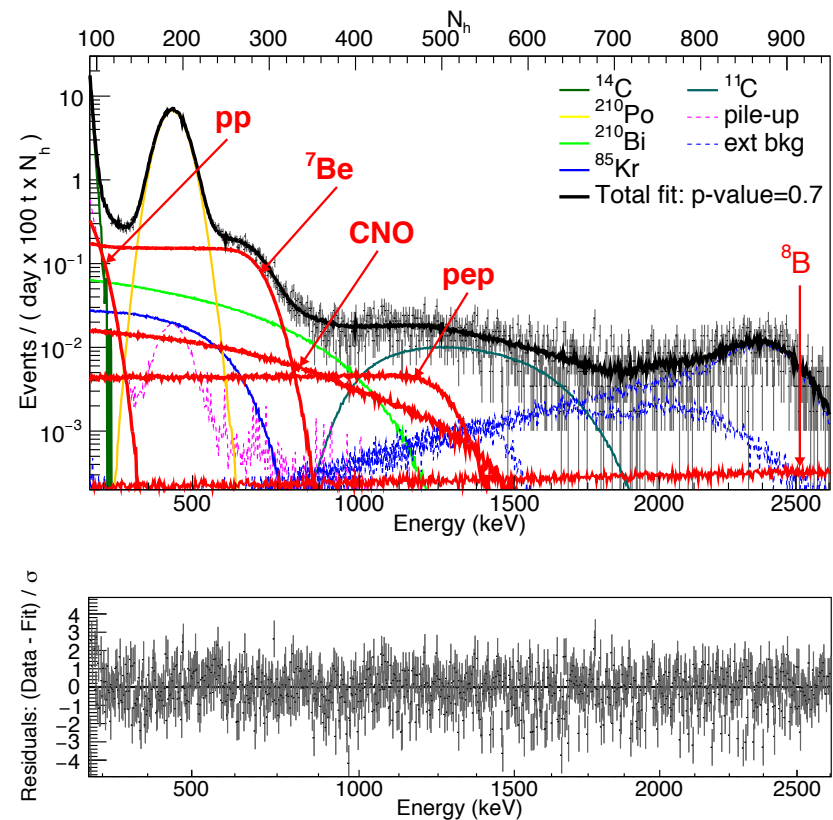
$\nu(\text{pp})$ $\nu(\text{pep})$ $\nu(^7\text{Be})$

CNO constrained to
 (4.92 ± 0.55) cpd/100t (HZ)
 or (3.52 ± 0.37) cpd/100t (LZ)

TFC tagged energy spectrum

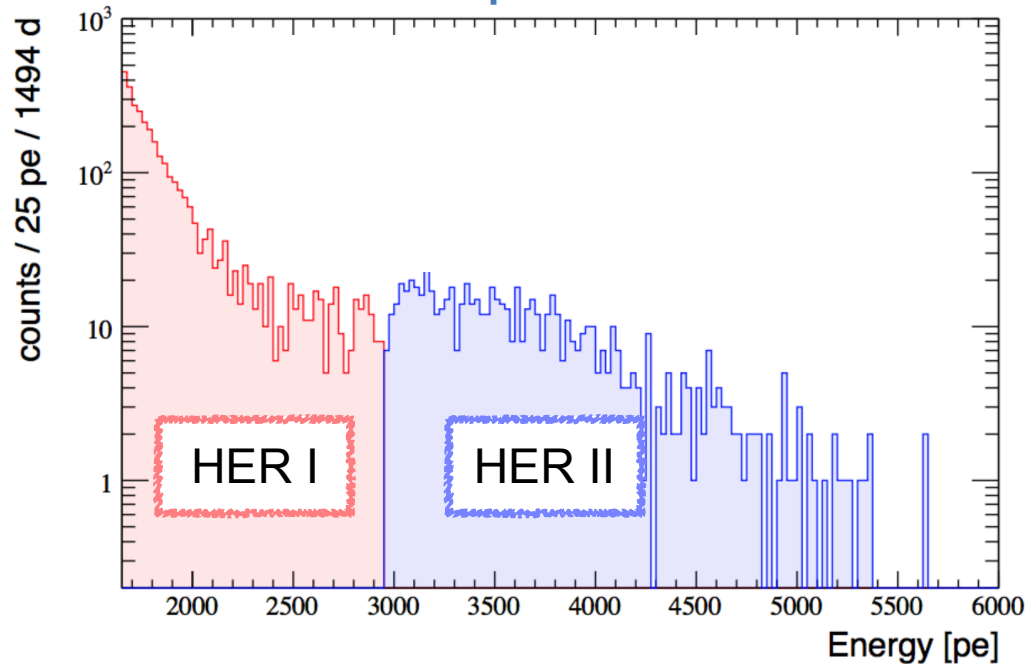


TFC subtracted energy spectrum



Improved measurement of ^8B neutrinos (HER)

Raw Spectrum



Fit performed with the Monte Carlo fit, split into High Energy Region I ([1650, 2950] p.e.) and High Energy Region II ([2950, 8500] p.e.) at 5.7 MeV for proper handling of the background;

No natural radioactivity expected above 5 MeV

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

Data-set: January 2008 - December 2016

Total exposure: 1.5 kton x years

(**11.5-fold** increase from Phase I results)

Fit range: (3.2 - 16) MeV

(Purification period removed)

(extending FV)

Improved measurement of ^8B neutrinos (HER)

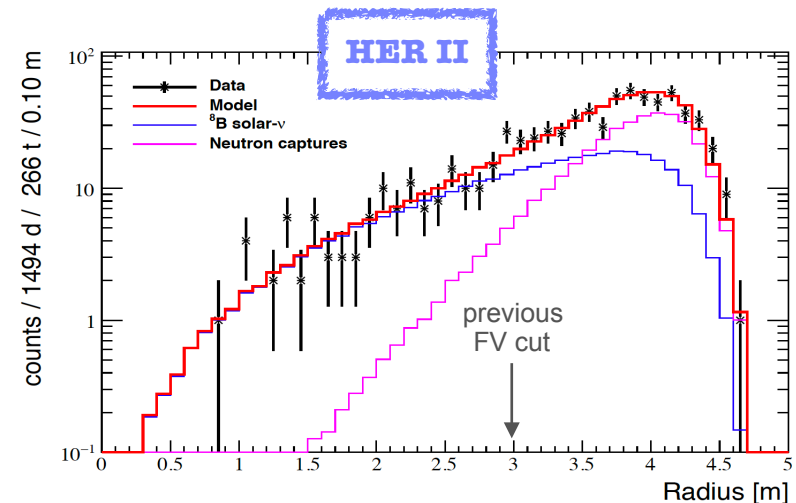
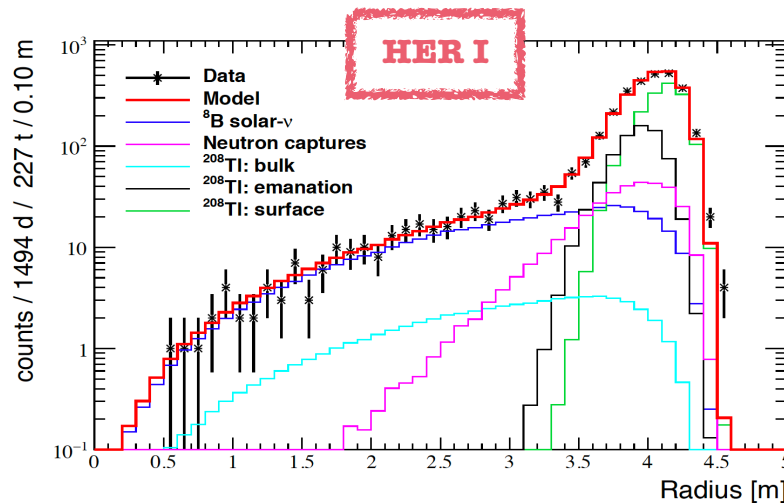
Selection cuts:

- Removed muons
- Neutron cut: remove 2 ms after all muons
- Cosmogenics cut: 6.5s after all internal muons (^{12}B , ^8He , ^9C , ^9Li , ^8B , ^6He , ^8Li)
- ^{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 fits - no assumptions on energy spectra:

● Probe deviations from MSW

27.6% dead time



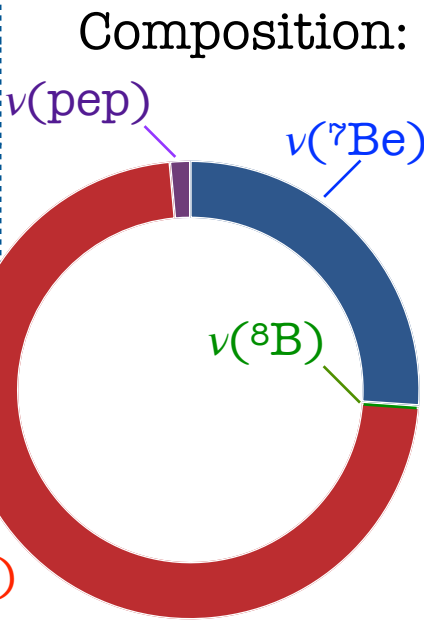
- Fit performed with the MonteCarlo fit on the radial distribution, split into HER I ([1650, 2950] p.e.) and HER II ([2950, 8500] p.e.) ranges split at ~ 5 MeV

New results: pp-chain neutrino rates

All rates are fully compatible with and improve the uncertainty of the previously published Borexino results

CNO constrained to
(4.92 ± 0.55) cpd/100t (HZ)
or (3.52 ± 0.37) cpd/100t (LZ)

	Previous BX results (cpd/ 100t)	New results (cpd/ 100t)	Uncertainty
pp	144 ± 13 ± 10	134±10 ⁺⁶ ₋₁₀	11.4% -> 10.6%
⁷ Be	48.3± 2.0 ± 0.9	48.3±1.1 ^{+0.4} _{-0.7}	4.8% -> 2.7%
pep	3.1 ± 0.6 ± 0.3	(HZ) 2.43±0.36 ^{+0.15} _{-0.22} (LZ) 2.65±0.36 ^{+0.15} _{-0.24}	21.6% -> 17.4% (HZ) 21.6% -> 16.3% (LZ)
⁸ B	0.217 ± 0.038 ± 0.008	0.223 ^{+0.015} _{-0.016} ± 0.006	17.9% -> 7.7%
hep	N/A	<0.002 at 90% C.L.	



ARTICLE

<https://doi.org/10.1039/c450061a0024-y>

Comprehensive measurement of
pp-chain solar neutrinos

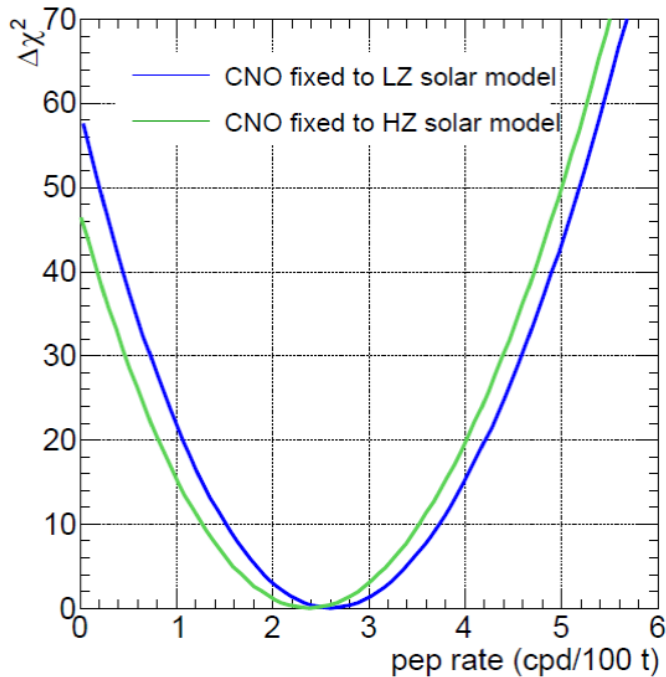
The Borexino Collaboration*

About 99 per cent of solar energy is produced through sequences of nuclear reactions that convert hydrogen into helium, starting from the fusion of two protons (the pp-chain). The neutrinos emitted by five of these reactions represent a unique probe of the Sun's internal working and, at the same time, offer an intense natural neutrino beam for fundamental physics. Here we report a complete study of the pp-chain. We measure the neutrino-electron elastic-scattering rates for neutrinos produced by four reactions of the chain: the initial proton-proton fusion, the electron-capture decay of beryllium-7, the three-body proton-electron-proton fusion, here measured with the highest precision so far achieved, and the boron-8 beta decay, measured with the lowest energy threshold. We also set a limit on the neutrino flux produced by the 'he' proton fusion (hep). These measurements provide a direct determination of the relative intensity of the two primary terminations of the pp-chain (pp-I and pp-II) and an indication that the temperature profile in the Sun is more compatible with solar models that assume high surface metallicity. We also determine the survival probability of solar electron neutrinos at different energies, thus probing simultaneously and with high precision the neutrino flavour-conversion paradigm, both in vacuum and in matter-dominated regimes.

haft

Zara Bagdasarian, Lomonosov Conference 2019

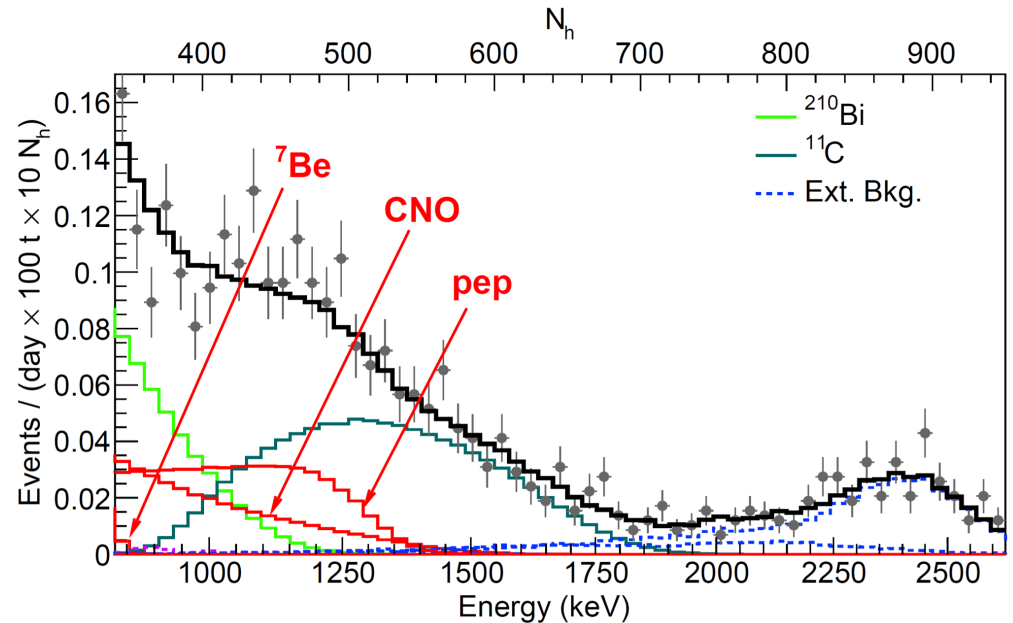
New results: pep in the spotlight



Absence of pep signal is rejected at $>5\sigma$ (including systematic errors)

CNO constrained to
(4.92 ± 0.55) cpd/100t (HZ)
or (3.52 ± 0.37) cpd/100t (LZ)

Applying stringent cuts on FV and on the pulse-shape variable PS_L_{PR} , we can actually see the pep ν shoulder!



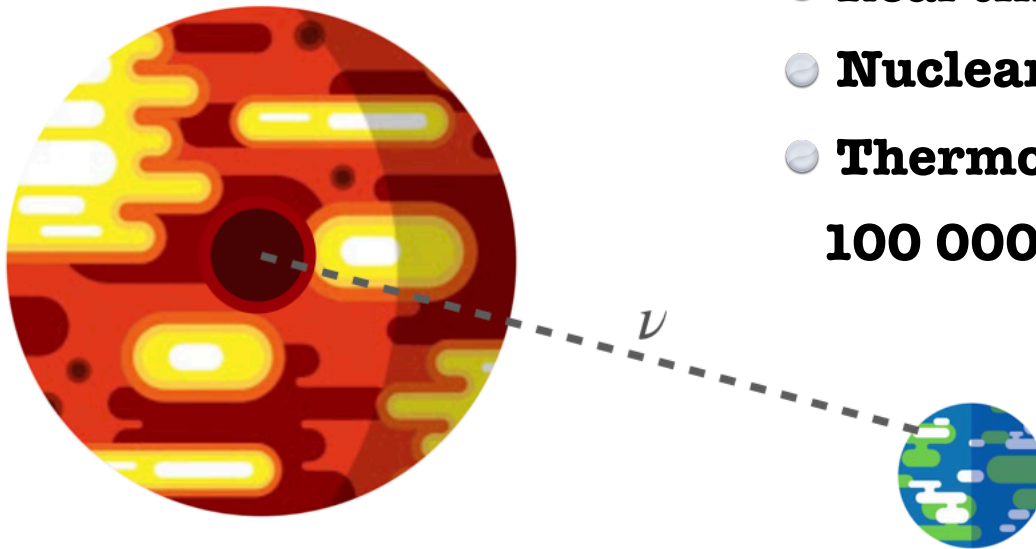
Implications: Sun Stability

Borexino results:

$$L = 3.89^{+0.35}_{-0.42} \text{ erg s}^{-1}$$

Photons only:

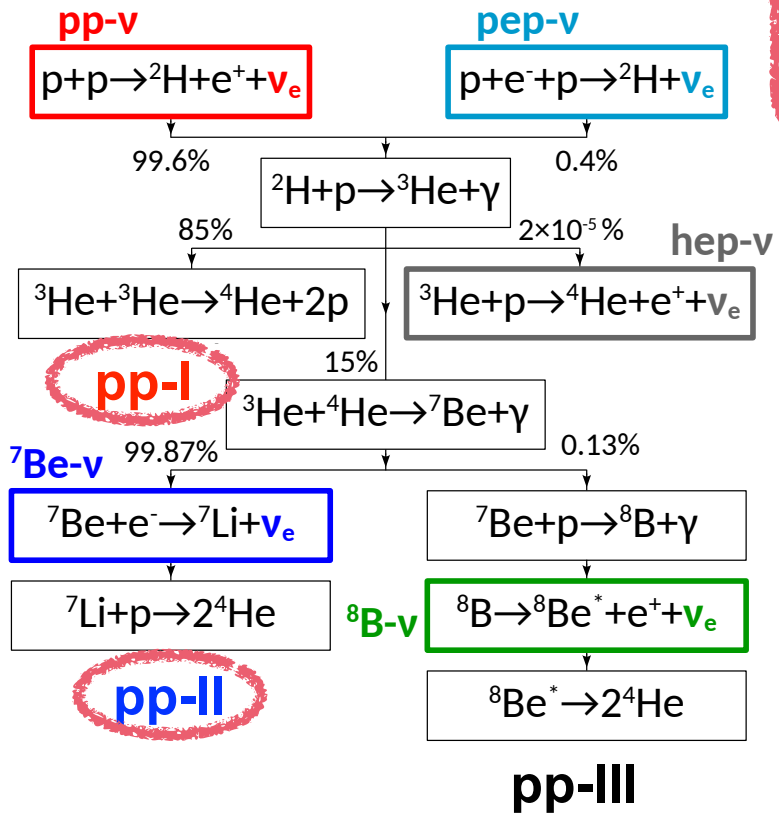
$$L = (3.846 \pm 0.015) \text{ erg s}^{-1}$$



- **Real time picture of the Sun**
- **Nuclear origin of the solar power**
- **Thermodynamic equilibrium for 100 000 years**

Implications of the new results: R_{I-II}

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



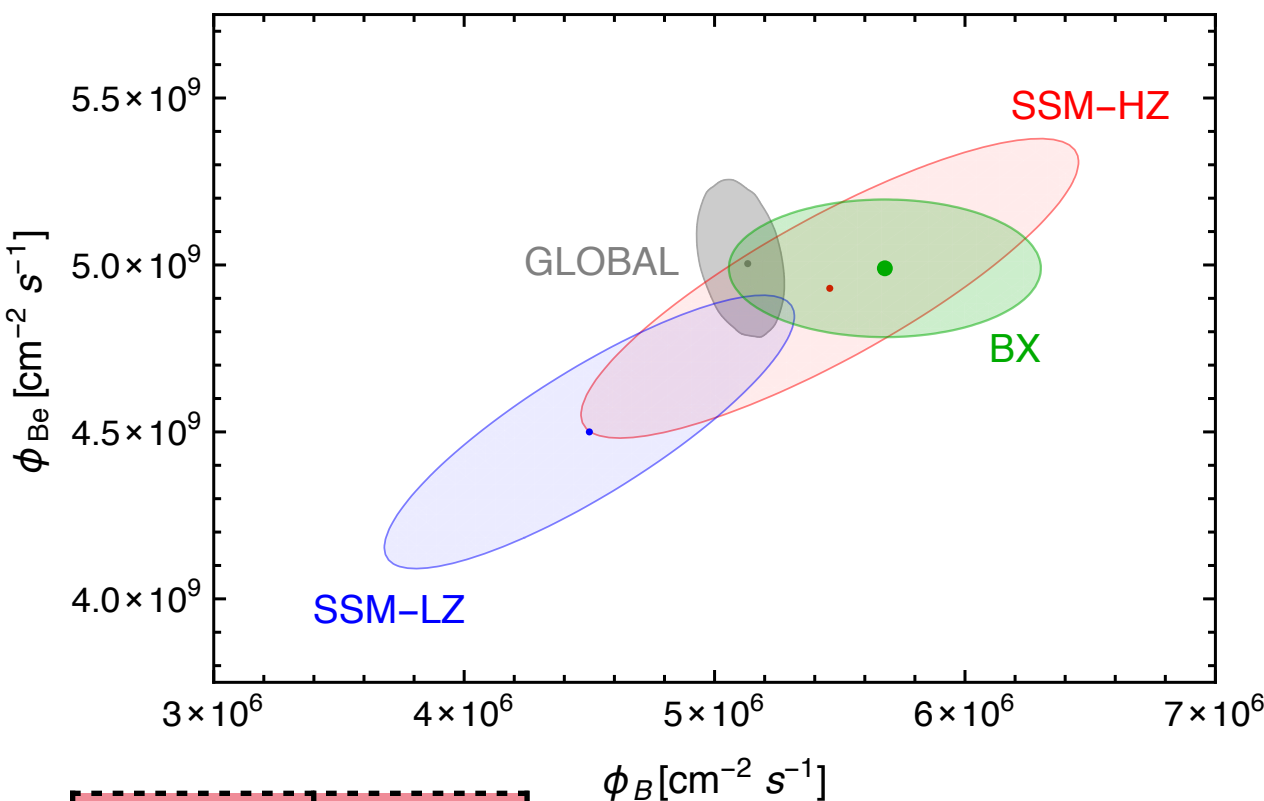
Borexino: $R_{I/II} = 0.1780^{+0.0027}_{-0.0023}$

In agreement with the predictions:

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

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

Implications of the new results: Metallicity



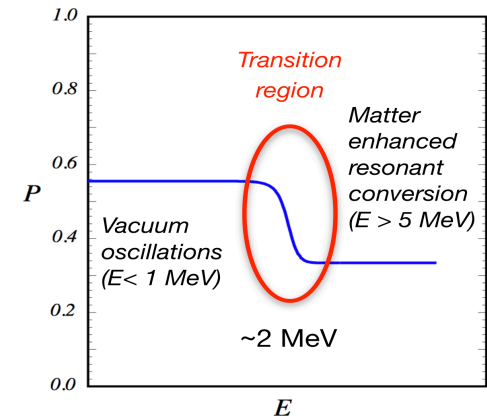
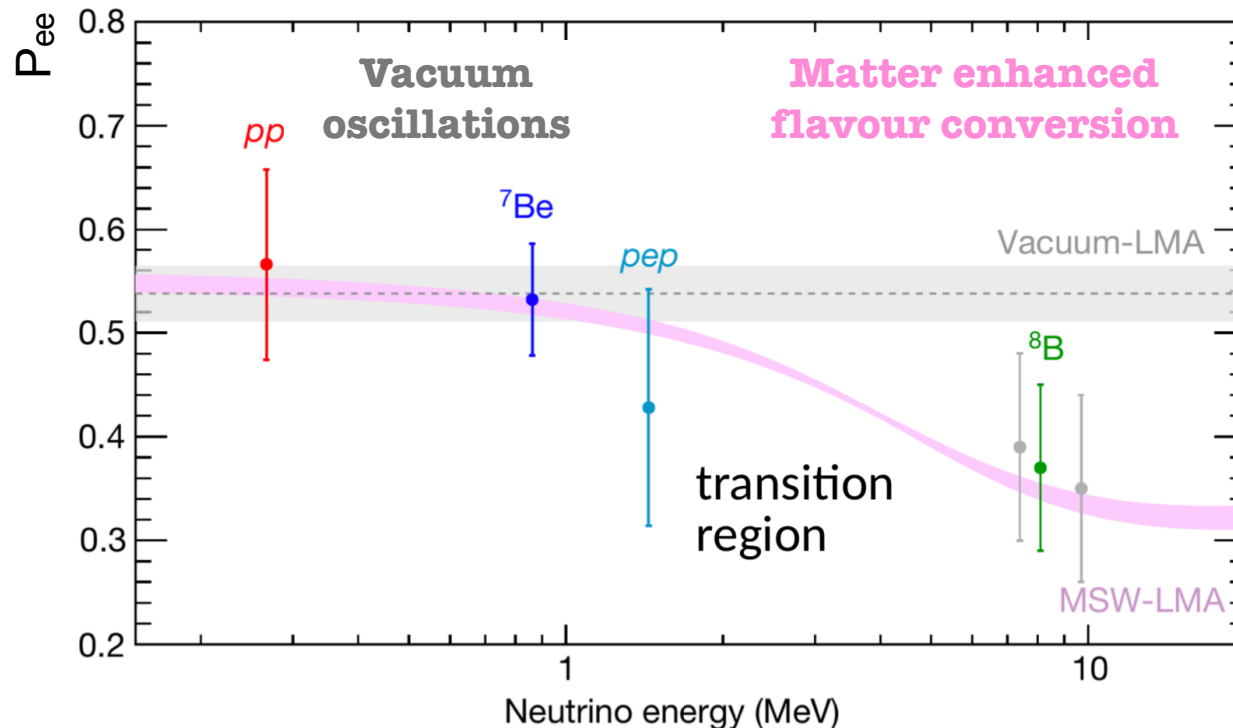
The new Borexino results on ⁷Be and ⁸B neutrino rates seem to give a hint towards the High Metallicity hypothesis/

- Frequentists approach: disfavour LZ with p=0.034, 96.6% C.L.
- Bayesian approach: HZ:LZ=5:1 odds; Bayes factor =4.9

Solar ν	Difference (HZ-LZ)/HZ
⁷ Be [$10^9 \text{ cm}^{-2} \text{ s}^{-1}$]	8.7%
⁸ B [$10^6 \text{ cm}^{-2} \text{ s}^{-1}$]	17.6%

We are now largely dominated by the theoretical error

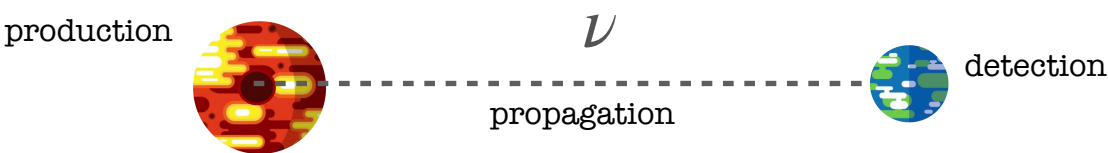
Implications: Survival probability



- Borexino is the only experiment that can probe the P_{ee} survival probability in both vacuum and matter dominated regions
- assuming HZ SSM fluxes (favoured by helioseismology): Absence of matter effect rejected at 98.2% C.L. (2.1σ)

Non-Standard Interactions (NSI)

Solar neutrinos as probe for physics beyond the Standard Model



Neutrino-electron interaction in the Standard Model:

$$\mathcal{L}_{\text{SM}} = -2\sqrt{2}G_F(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha) [g_R(\bar{e} \gamma_\mu P_R e) + g_L(\bar{e} \gamma_\mu P_L e)]$$

Introducing NSI phenomenologically by redefinition of coupling constants:

$$g_R \rightarrow \tilde{g}_{\alpha R} = g_R + \varepsilon_{\alpha R} \qquad g_L \rightarrow \tilde{g}_{\alpha L} = g_L + \varepsilon_{\alpha L}$$

(R,L) x (e, μ , τ) = 6 new constants for NSI:

Objective of our study:

ε_e^R

ε_e^L

ε_τ^R

ε_τ^L

ε_μ^R

ε_μ^L

Strong limit by CHARM II collaboration

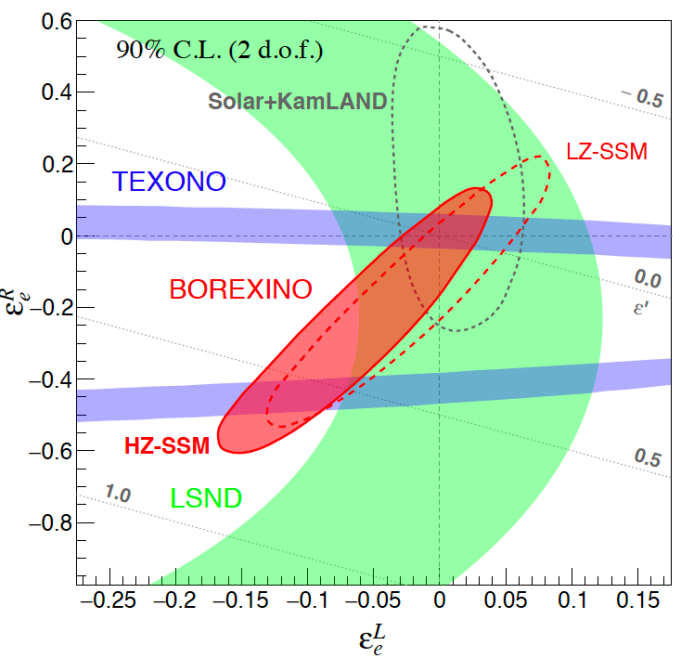
Borexino is particularly sensitive to NSIs at detection:

- changes in $\nu_e - e$ and $\nu_\tau - e$ interactions affect electron-recoil spectra

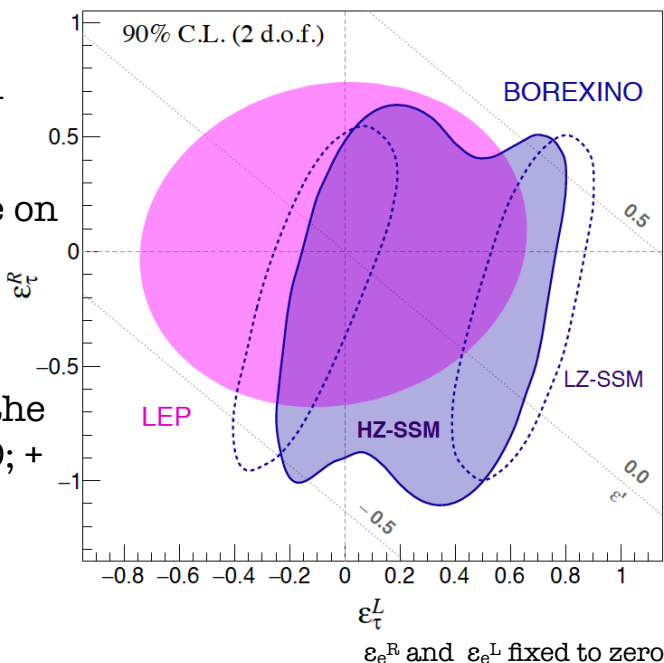
Non-Standard Interactions (NSI)

- Analysis: Phase II data, Neutrino spectra: pp, ⁷Be, pep and CNO modified to include NSI.
- NSI assumed in both propagation and detection (NSI at production affect the spectrum below Borexino threshold)

	BX (HZ) [1]	BX(LZ) [1]	global [2]
ϵ_e^R	[-0.15, +0.11]	[-0.20, +0.03]	[0.004, +0.151]
ϵ_e^L	[-0.035, +0.032]	[-0.013, +0.052]	[-0.03, +0.08]
ϵ_τ^R	[-0.83, +0.36]	[-0.42, +0.43]	[-0.3, +0.4]
ϵ_τ^L	[-0.11, +0.67]	[-0.19, +0.79]	[-0.5, +0.2]



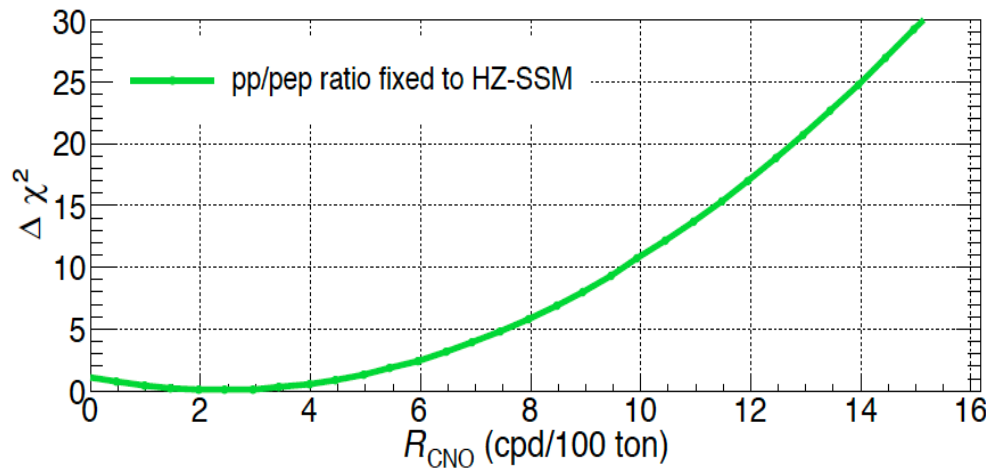
- Improvement in all four components in comparison with Phase-I analysis
- The best constraint to-date on ϵ_e^L
- Borexino significantly reduces allowed region in the global analysis: (+ TEXONO; + solar)



[1] [arXiv:1905.03512](#) Submitted to JHEP

[2] JHEP 03 (2003) 011

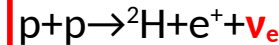
New results: upper limits on CNO



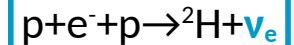
LER with constraint on

$$R_{\text{pp}}/R_{\text{pep}} = 47.7 \pm 0.8$$

pp-v



pep-v



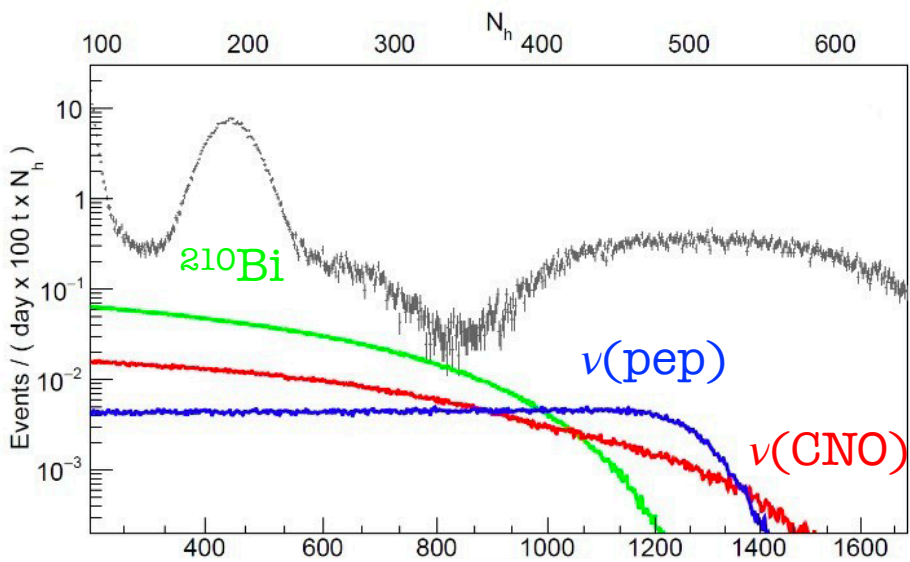
$$R_{\text{CNO}} < 8.1 \text{ (95\% C.L.)}$$

Confirmed Phase I result
Best upper limit currently available

Towards CNO measurement (see later): important for Astrophysics

- Contribution to the total solar power $\sim 1\%$
- BUT dominant energy production mechanism in heavier stars
- Very sensitive to metallicity: (HZ-LZ)/HZ = 28.1%

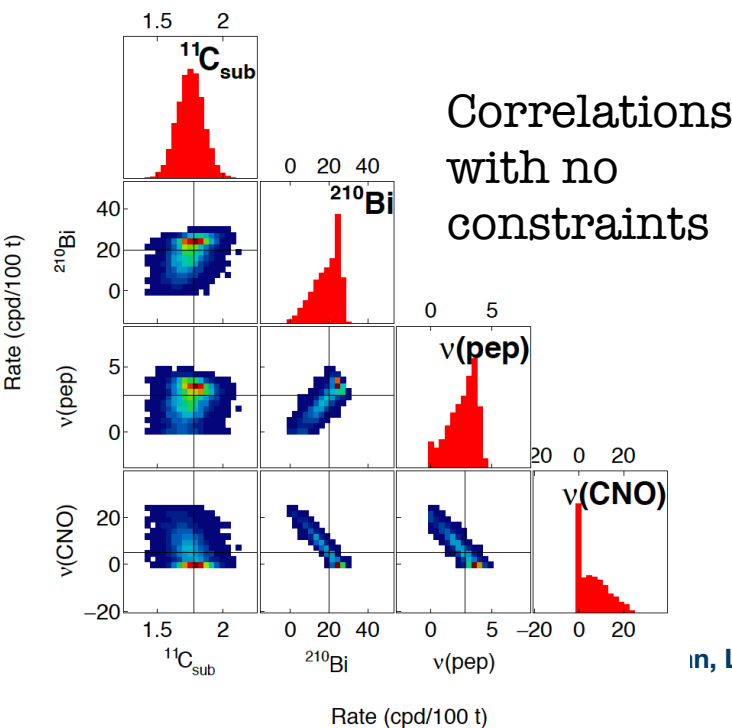
Towards CNO-neutrinos



Motivation:

- Proof of principle of star energy production via CNO cycle
- Important for astrophysics studies of the Sun and heavier stars where the process is expected to be dominant
- Sensitive to Sun metallicity

Solar ν	Difference (HZ-LZ)/HZ
CNO [$10^8 \text{ cm}^{-2} \text{ s}^{-1}$]	28.1%



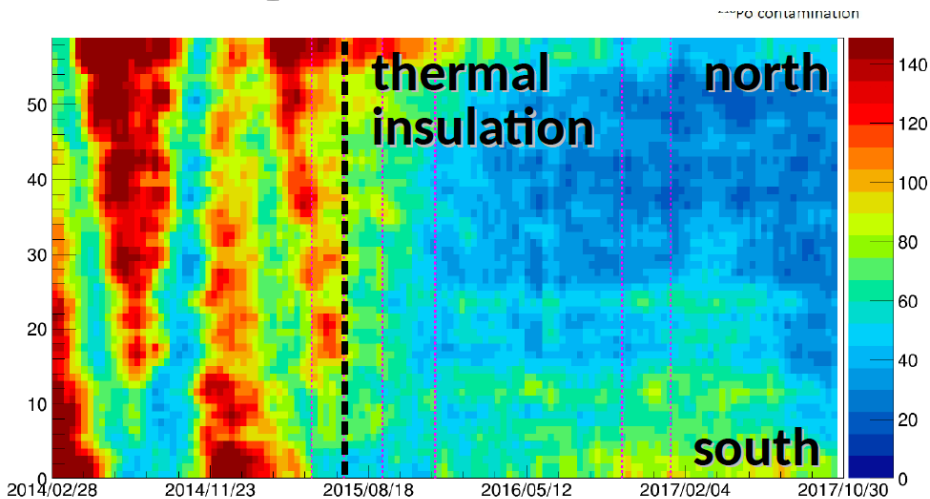
Challenges:

- Low rate
- Shape similar to ^{210}Bi and $\nu(\text{pep})$
- Strong correlations -> need independent constraints

Towards CNO-neutrinos

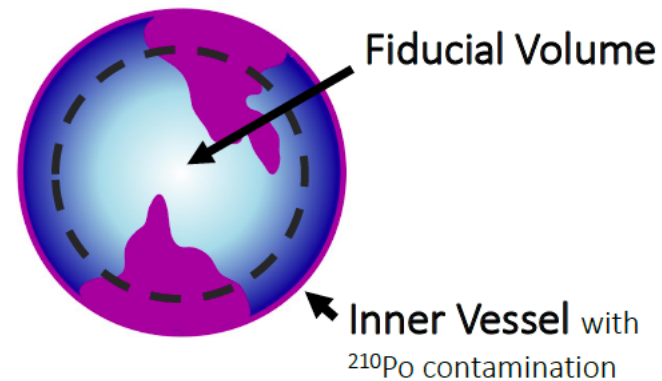
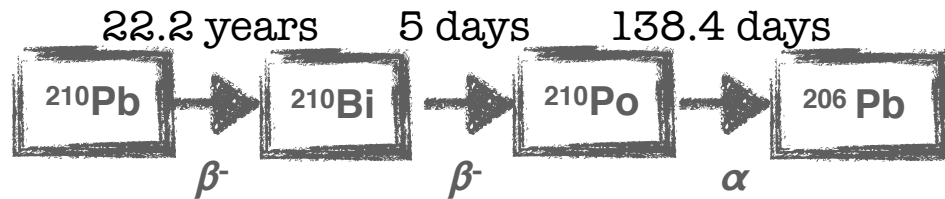
Bi constraint from Po measurement

- At secular equilibrium the rate of ^{210}Bi is equal to that of ^{210}Po



^{210}Po identification advantages:

- Monoenergetic decay $\rightarrow$ “gaussian” peak
- α -decay $\rightarrow$ pulse shape discrimination



^{210}Po stability challenges:

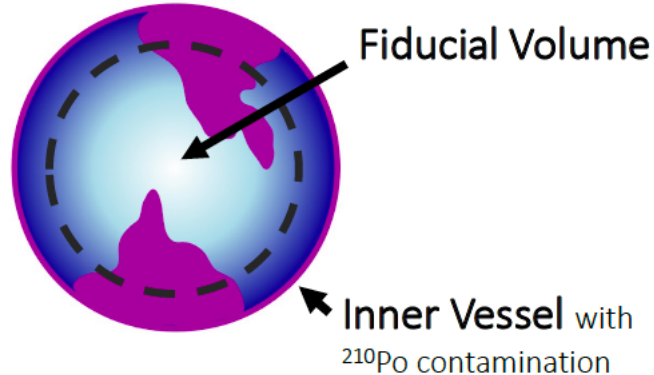
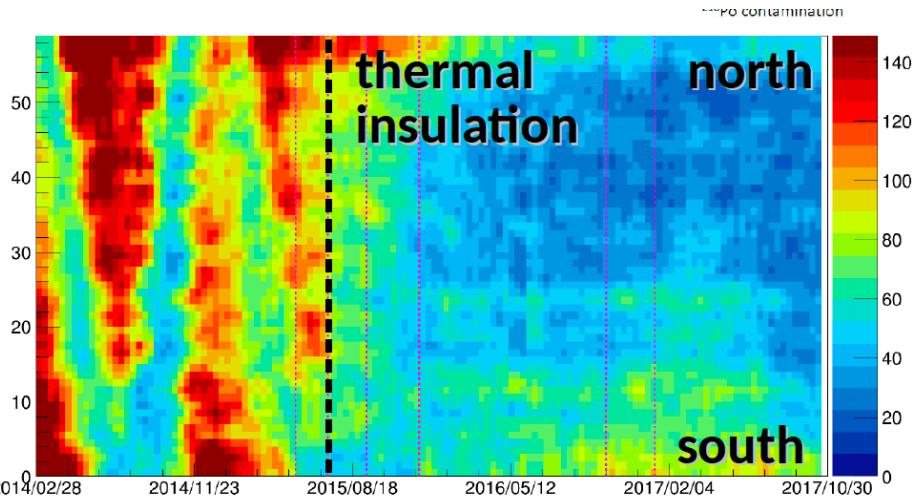
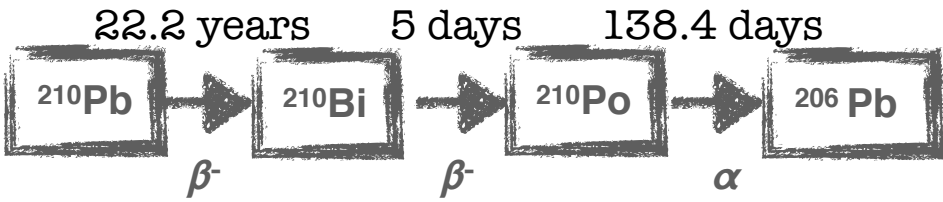
Thermal insulation to stop convective motions

**Talk of David Bravo Berguno on
Tuesday, SESSION B 17:55**

Towards CNO-neutrinos

Bi constraint from Po measurement

● At secular equilibrium the rate of ^{210}Bi is equal to that of ^{210}Po



Promising sensitivity studies:
Possibility to get CNO measurement between 2 and 4 sigma

Stay tuned!

Summary

Borexino has gone well beyond its original goal providing a complete study of solar neutrinos from the entire proton-proton chain

Summary

Borexino has gone well beyond its original goal providing a complete study of solar neutrinos from the entire proton-proton chain

The newest results feature

- First comprehensive extraction of pp-chain neutrinos:
- Improved precision in all flux measurements (notably ${}^7\text{Be}$ precision is now 2.7%);
- $>5\sigma$ evidence of the pep neutrino signal;
- First experimental determination of the ratio between ${}^3\text{He}$ - ${}^4\text{He}$ and ${}^3\text{He}$ - ${}^3\text{He}$ reactions in the Sun
- Hint towards the high metallicity hypothesis
- Test of the MSW-LMA vs vacuum flavour conversion paradigms
- Thermodynamic equilibrium of the Sun for 100 000 years
- Competitive limits on non-standard neutrino interactions

Outlook

- Take data with temperature stabilized detector in an attempt to measure CNO ν

Dedicated to the memory of Simone Marcocci



(1989-2019)



BOREXINO COLLABORATION



UNIVERSITÀ
DEGLI STUDI
DI MILANO



Istituto Nazionale di Fisica Nucleare



PRINCETON
UNIVERSITY



UNIVERSITÀ DEGLI STUDI
DI GENOVA



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



NATIONAL RESEARCH CENTER
"KURCHATOV INSTITUTE"



St. Petersburg
Nuclear Physics Inst.



Technische Universität
München



University of
Houston



Universität
Hamburg



JAGIELLONIAN
UNIVERSITY
IN KRAKÓW



POLITECNICO
MILANO 1863



SKOBELOTSYN INSTITUTE
OF NUCLEAR PHYSICS
LOMONOSOV MOSCOW
STATE UNIVERSITY



TECHNISCHE
UNIVERSITÄT
DRESDEN



Joint Institute for
Nuclear Research



GRAN SASSO
SCIENCE INSTITUTE

CENTER FOR ADVANCED STUDIES
Istituto Nazionale di Fisica Nucleare



Contact: z.bagdasarian@fz-juelich.de

@ZaraBagdasarian

Mitglied der Helmholtz-Gemeinschaft





BOREXINO COLLABORATION



UNIVERSITÀ
DEGLI STUDI
DI MILANO



Istituto Nazionale di Fisica Nucleare



PRINCETON
UNIVERSITY



UNIVERSITÀ DEGLI STUDI
DI GENOVA



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



NATIONAL RESEARCH CENTER
"KURCHATOV INSTITUTE"



St. Petersburg
Nuclear Physics Inst.



Technische Universität
München



University of
Houston



Universität
Hamburg



JAGIELLONIAN
UNIVERSITY
IN KRAKÓW



JÜLICH
Forschungszentrum



POLITECNICO
MILANO 1863



SKOBELOTSYN INSTITUTE
OF NUCLEAR PHYSICS
LOMONOSOV MOSCOW
STATE UNIVERSITY



TECHNISCHE
UNIVERSITÄT
DRESDEN



Joint Institute for
Nuclear Research



GRAN SASSO
SCIENCE INSTITUTE

CENTER FOR ADVANCED STUDIES
Istituto Nazionale di Fisica Nucleare



Contact: z.bagdasarian@fz-juelich.de

@ZaraBagdasarian

Mitglied der Helmholtz-Gemeinschaft



JÜLICH
Forschungszentrum

BACK-UP SLIDES

Limit on the Neutrino Magnetic Moment

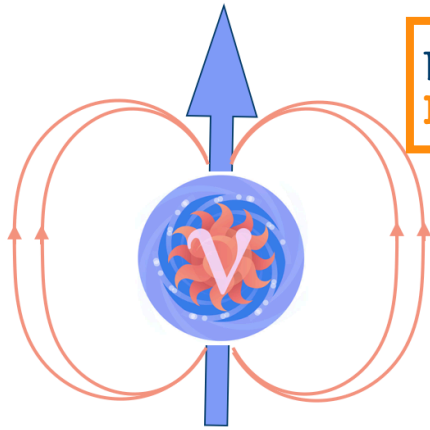
(Phys. Rev. D 96 (2017), 091103 R)

SM

Considering the current limits on m_ν , $\mu_\nu < 10^{-18} \mu_B$, **7-8 orders of magnitude less than the current experimental limits...**

Beyond SM

μ_ν proportional to the mass of charge leptons, **expectations reach the levels of the current experimental limits**



$$\left(\frac{d\sigma}{dT}\right)_{em} = \mu_{eff}^2 \frac{\pi \alpha_{em}^2}{m_e^2} \left(\frac{1}{T} - \frac{T}{E_\nu}\right)$$

$$\mu_{eff}^2 = P^{3\nu} \mu_e^2 + (1 - P^{3\nu})(\cos^2 \theta_{23} \cdot \mu_\mu^2 + \sin^2 \theta_{23} \cdot \mu_\tau^2)$$

- **Data-set:** Dec 14th 2011 - May 21st 2016;
- **Total exposure:** 1291.51 days x 71.3 tons;
- **Fit range:** (215 - 715) keV;

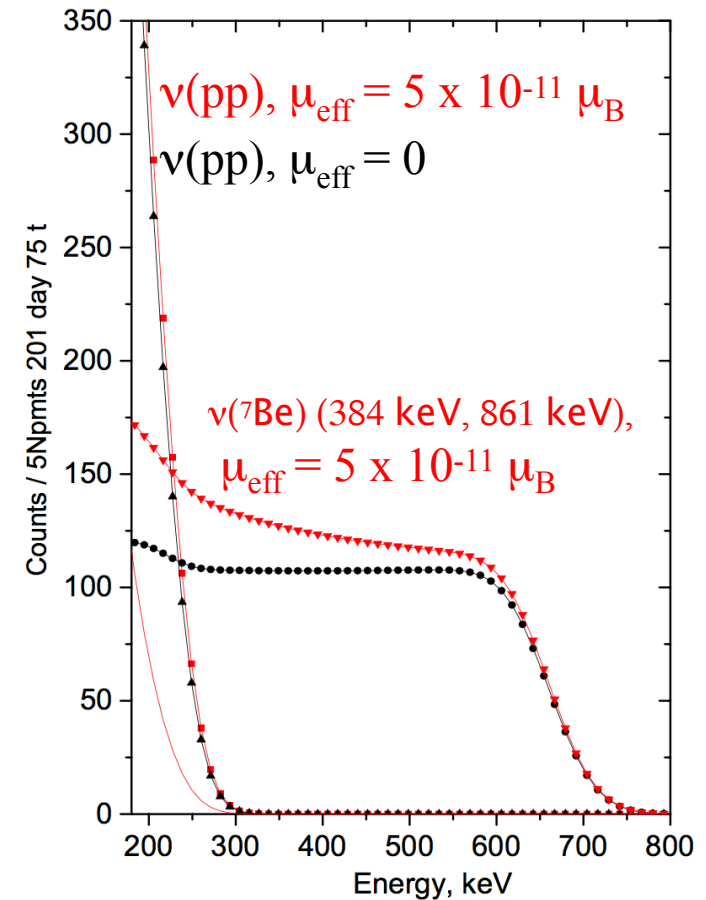
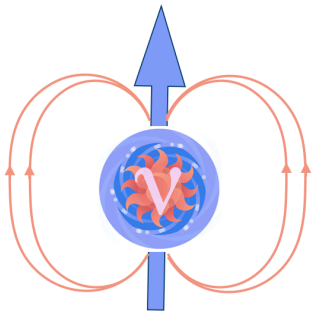
The NMM limits obtained on solar neutrinos represent an effective value typical for a certain flavour composition μ_{eff}

Limit on the Neutrino Magnetic Moment

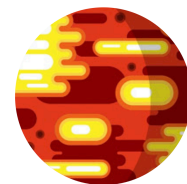
(Phys. Rev. D 96 (2017), 091103 R)

New limit obtained by profiling μ_{eff} and using a **constraint from radiochemical experiments** on the total flux of neutrinos measured by Borexino

Experiment/authors	Source of neutrinos	$\times 10^{-11} \mu_B$ 90% C.L.
GEMMA [Phys. Part. Nucl. Lett. 10 (2013) 139]	reactor anti- ν_e	$\mu_{\nu_e} < 2.9$
Borexino: [PRL 101 (2008) 091302]	${}^7\text{Be}$ solar ν	$\mu_{\text{eff}} < 5.4$
Borexino	pp- and ${}^7\text{Be}$	$\mu_{\text{eff}} < 2.8$



Modification of the spectral shape of electrons scattered from pp and ${}^7\text{Be}$ solar neutrinos due to $\mu_{\text{eff}} > 0$



Comparison with the theoretical predictions

Rates

Solar ν	Borexino results Rate [cpd/100 t]	Expected-HZ Rate [cpd/100 t]	Expected-LZ Rate [cpd/100 t]
pp	$134 \pm 10^{+6}_{-10}$	131.0 ± 2.4	132.1 ± 2.3
${}^7\text{Be}$	$48.3 \pm 1.1^{+0.4}_{-0.7}$	47.8 ± 2.9	43.7 ± 2.6
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	2.74 ± 0.05	2.78 ± 0.05
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	2.74 ± 0.05	2.78 ± 0.05

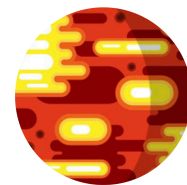
Fluxes Φ

Solar ν	Borexino results Flux [$\text{cm}^{-2}\text{s}^{-1}$]	Expected-HZ Flux [$\text{cm}^{-2}\text{s}^{-1}$]	Expected-LZ Flux [$\text{cm}^{-2}\text{s}^{-1}$]
pp	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98 (1 \pm 0.006) \times 10^{10}$	$6.03 (1 \pm 0.005) \times 10^{10}$
${}^7\text{Be}$	$(4.99 \pm 0.13^{+0.07}_{-0.10}) \times 10^9$	$4.93 (1 \pm 0.06) \times 10^9$	$4.50 (1 \pm 0.06) \times 10^9$
pep (HZ)	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^8$	$1.44 (1 \pm 0.009) \times 10^8$	$1.46 (1 \pm 0.009) \times 10^8$
pep (LZ)	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^8$	$1.44 (1 \pm 0.009) \times 10^8$	$1.46 (1 \pm 0.009) \times 10^8$

* 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)

39



Two approaches: Analytical & MC

MonteCarlo

Astrop. Phys. 97 (2018) 136 -159

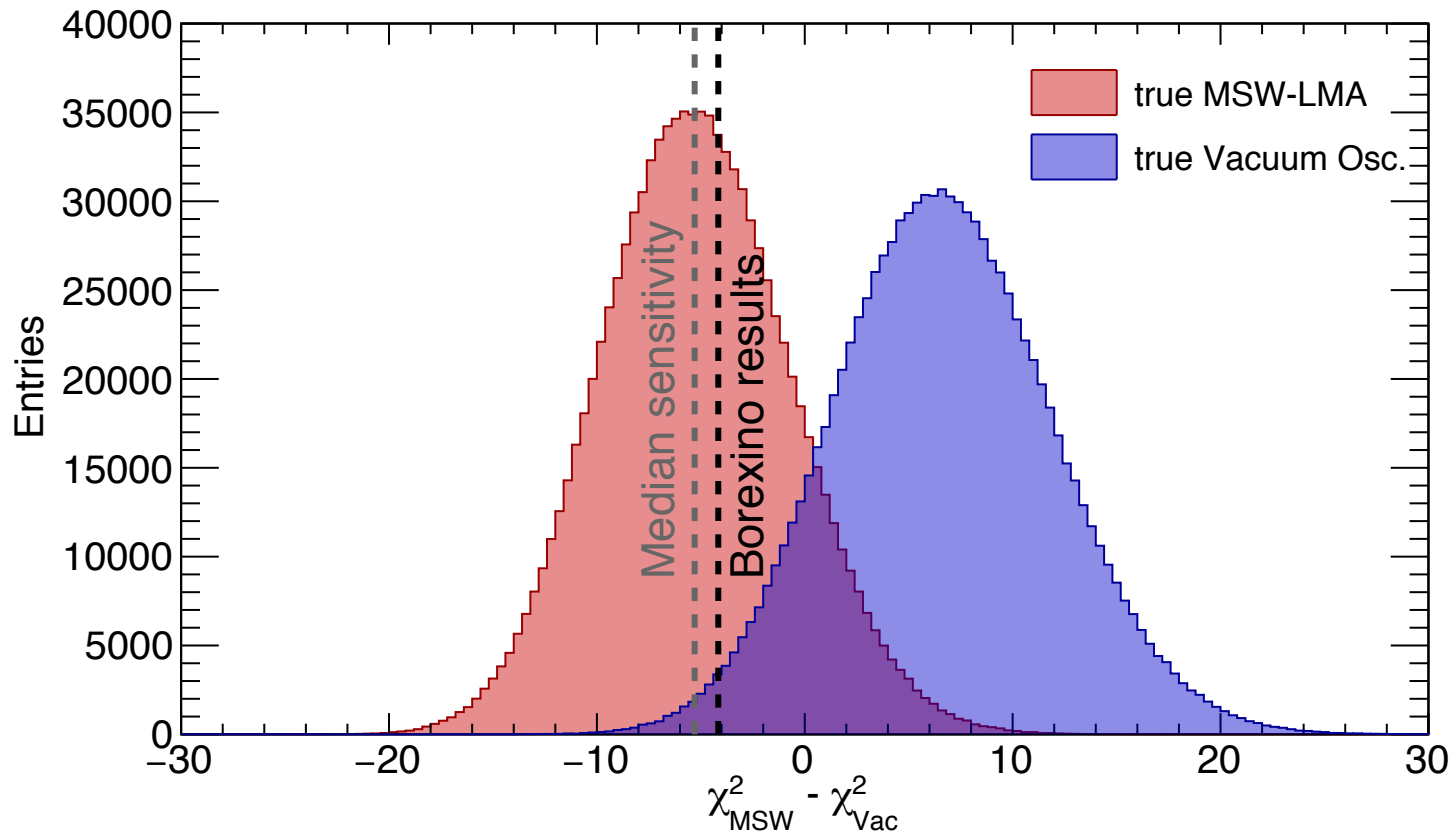
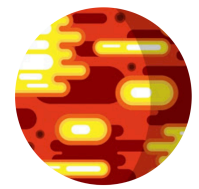
- Full simulation of all processes: energy deposition, light production (scintillator and Cherenkov), propagation and collection;
- All known material properties included;
- Known time variations of the detector included (for example, number of live PMTs and electronics channels);
- **Free parameters in the fit: only the rates of signal and background;**

Analytical

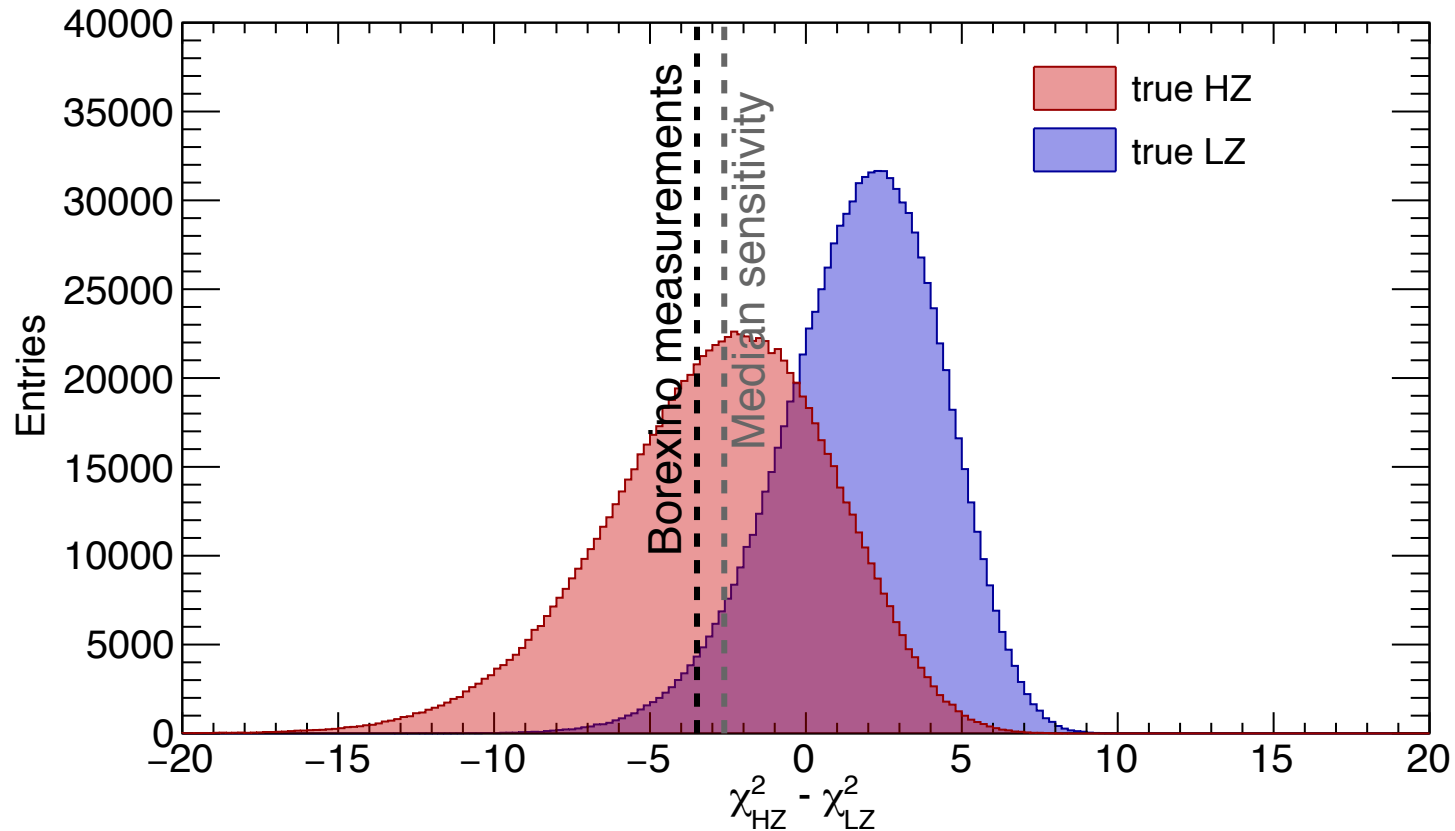
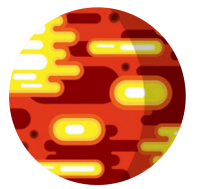
Phys.Rev.D **89**, 112007(2014)

- energy scale and response described analytically (including Cherenkov, quenching);
- Spatial dependence of reconstructed E and $\sigma(E)$;
- **Free parameters in the fit: the rates of signal and background + 6 parameters of the response function (Light yield, 2 resolution parameters, ^{210}Po peak position and width, starting point of ^{11}C spectrum;**

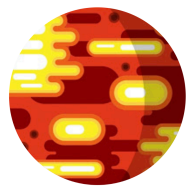
Frequentist Approach to Vacuum vs MSW



Frequentist Approach to HZ vs LZ



Systematic errors of pp, ^7Be and pep



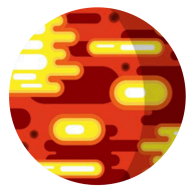
Two methods to take into account pile-up:

Effects of non perfect modelling of the detector response; Uncertainty on theoretical input spectra (^{210}Bi);

^{85}Kr constrained to be $<7.5\text{cpd}/100\text{t}$ (95% C.L.) (from ^{85}Kr - ^{85}Rb delayed coincidences)

Source of uncertainty	pp		^7Be		pep	
	−%	+%	−%	+%	−%	+%
Fit method (Analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4
Pile-up modelling	-2.5	0.5	0	0	0	0
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0
Fit models	-4.5	0.5	-1.0	0.2	-6.8	2.8
Inclusion of ^{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

Borexino background rates



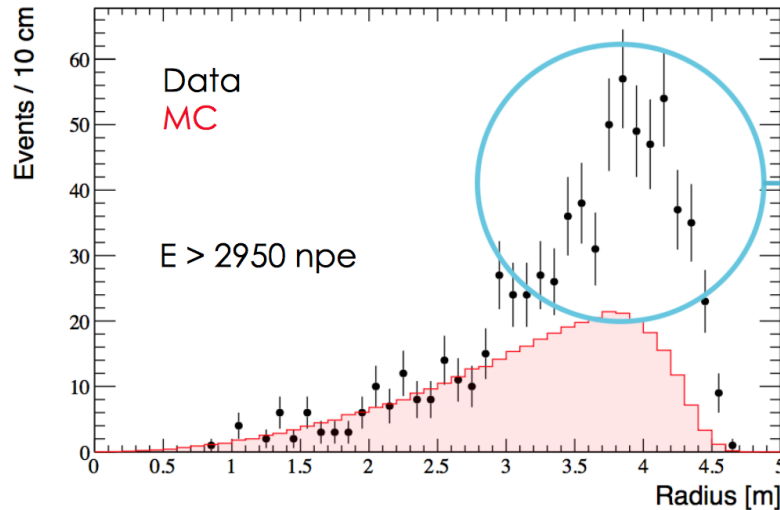
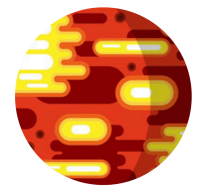
Background species	Rate (cpd/100t)
^{14}C (Bq/100t)	40.0 ± 2.0
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5 ± 1.9
^{11}C	26.8 ± 0.2
^{210}Po	260.0 ± 3.0
Ext ^{40}K	1.0 ± 0.6
Ext ^{214}Bi	1.9 ± 0.3
Ext ^{208}Tl	3.3 ± 0.1

Factor 4.6
reduction with
respect to Phase-I

Factor 2.3
reduction with
respect to Phase-I

Statistical and systematical
errors added in quadrature

Improved measurement of ^8B neutrinos



Excess **not compatible** with a **bulk** distribution

Not compatible with events from the **vessel nylon**: 5 MeV is the max Q-value from natural β -decay radioactivity (^{208}Tl)

Hypothesis:

- External background from **neutron captures** on elements different from H and C
- Neutron sources: **(α , n)** reactions and **fissions** from U and Th chains
- Neutron capture material candidates: **SSS**, PMTs, support structures

