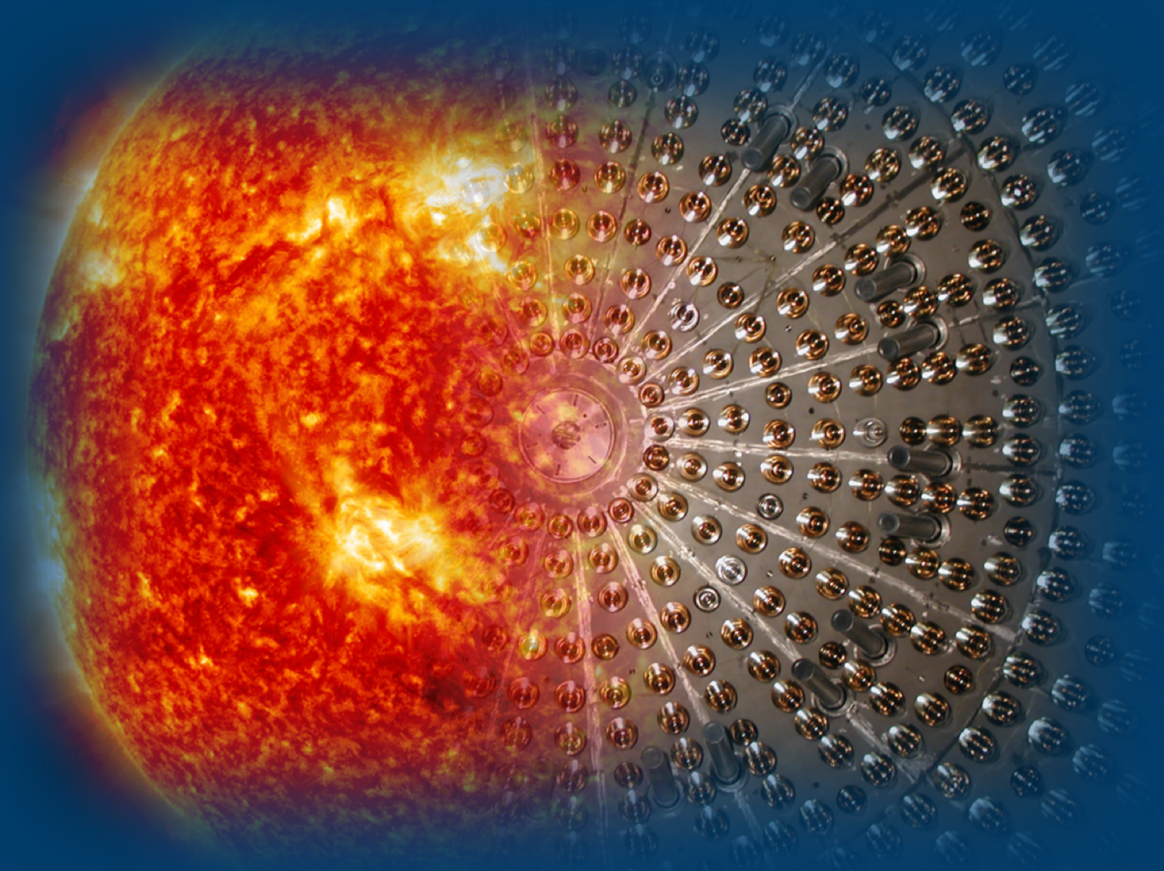
OBSERVING OUR SUN WITH BOREXINO

ÖMER PENEK

ON BEHALF
OF THE BOREXINO COLLABORATION

NUCLEAR PHYSICS INSTITUTE, IKP-2

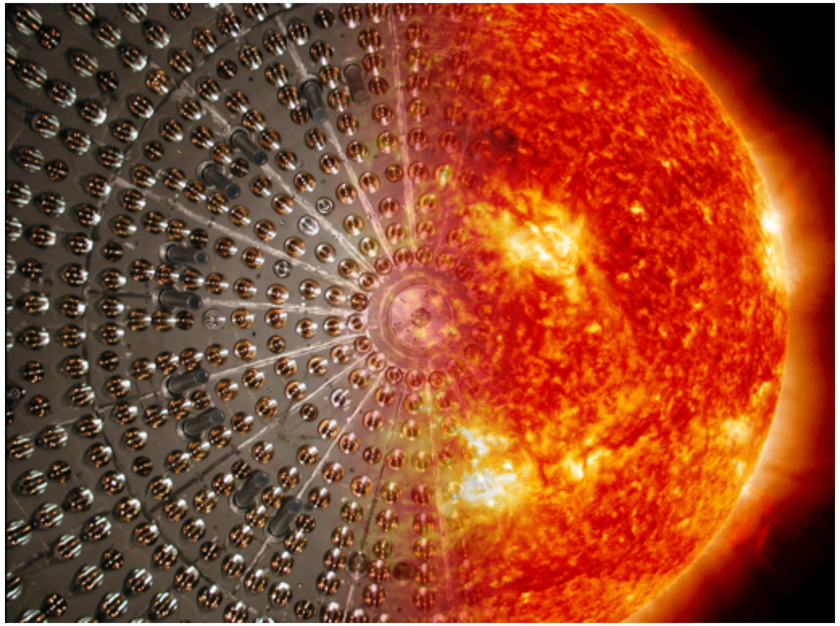
FORSCHUNGSZENTRUM JUELICH, GERMANY



MAY 24TH, 2022 – NEUTRINO SESSION
33RD RENCONTRES DE BLOIS – EXPLORING THE DARK UNIVERSE

OUTLINE

- ❖ **Introduction and Motivation**
- ❖ **The Standard Solar Model and the Metallicity Problem**
- ❖ **Solar Neutrino Measurement with Borexino**
  - ✓ Spectroscopy of ***pp* chain** solar neutrinos
  - ✓ Observation of **CNO cycle** solar neutrinos
- ❖ **Summary / Outlook**



Introduction and Motivation

SOLAR NEUTRINO PHYSICS MOTIVATION

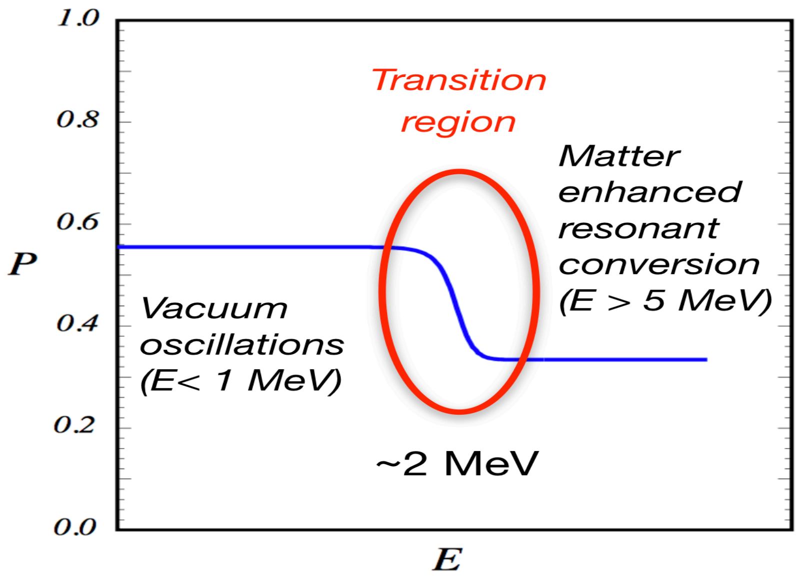
Studying **Neutrinos** with the Sun …

❖ Neutrino **Oscillation** Parameters (θ_{12}, Δm^2_{12})

❖ Searching for Deviations from the **MSW-LMA**

➔ Solar Neutrino Oscillations in the P_{ee} **transition region**

❖ Search for New Physics via **Non-standard interactions**



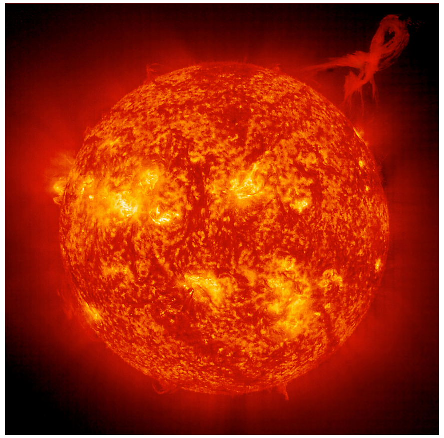
Studying the **Sun** with Neutrinos …

❖ **Fusion** Mechanisms (*pp*-chain and CNO cycle)

❖ Thermodyn. **Stability** (Escape times: γs ~ 100k years, νs ~ 8 minutes)

❖ Standard Solar Model (**SSM**)

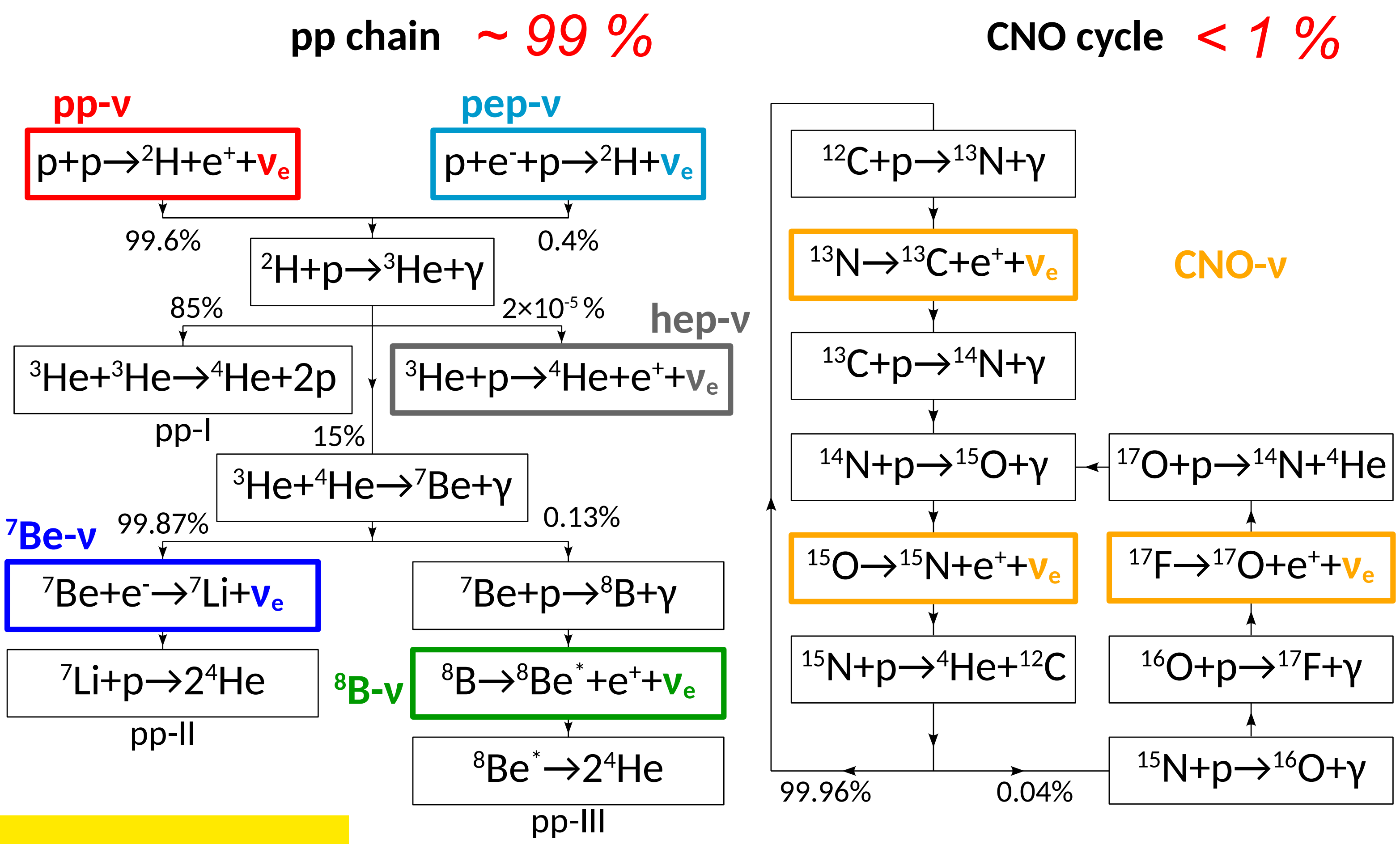
❖ Stellar **Metallicity**



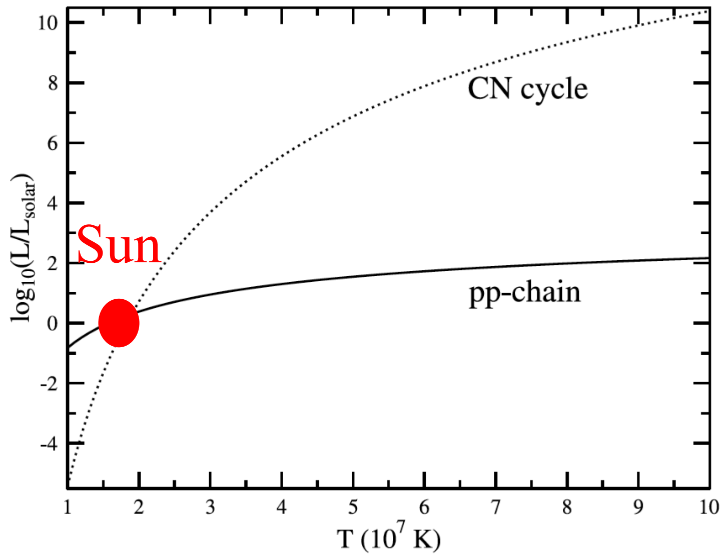
Nasa.org

HOW IS THE SUN FUELED? → SOLAR NEUTRINOS

Nuclear Fusion Processes



main energy production process in heavier stars



Haxton & Serenelli: The Astrophysical J. 687 (2008) 678

$\sim 65\text{x}10^9$
ν_x per cm^2 s
at Earth

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

➔ Metallicity ⬅

JÜLICH Forschungszentrum

The Standard Solar Model
and
The Metallicity Problem

SOLAR NEUTRINOS → THE STANDARD SOLAR MODEL (SSM)

Usage of current physics and input parameters with best fit observations

SSM Inputs:

- 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 $A_\odot$
- Abundances of Elements (Metallicity, Older High=HZ or Newer Low=LZ)
  → Solar Surface Metal-to-Hydrogen Ratio $\left(\frac{Z}{X}\right)_\odot$ (Metal = Elements above He)

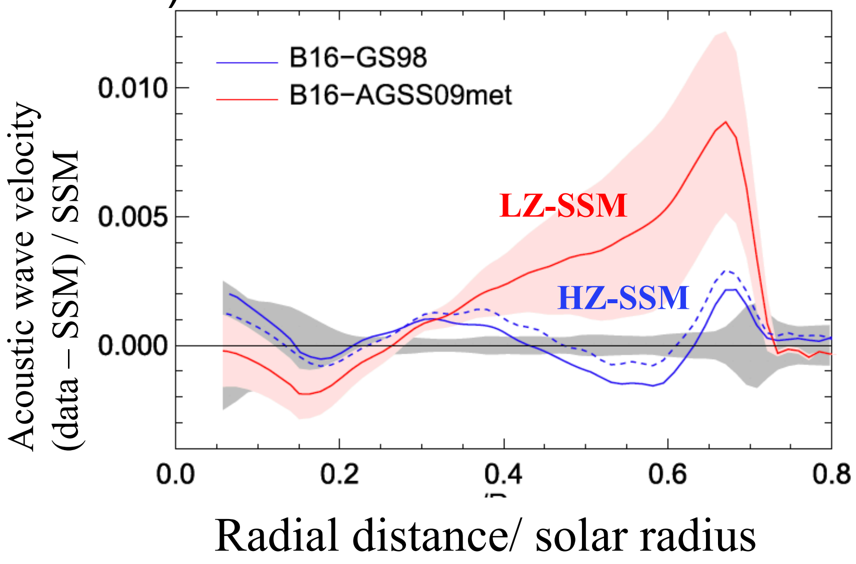
SSM Outputs:

- Sound speed profiles
- Neutrinos Fluxes (HZ-SSM or LZ-SSM)
  → This is what we want to measure

Helioseismology (Sun‘s Surface oscillation → Solar interior):

- Helioseismic Data consistent with older HZ but in tension with newer LZ description
- Measurement of Solar neutrinos can unravel this “solar metallicity problem“

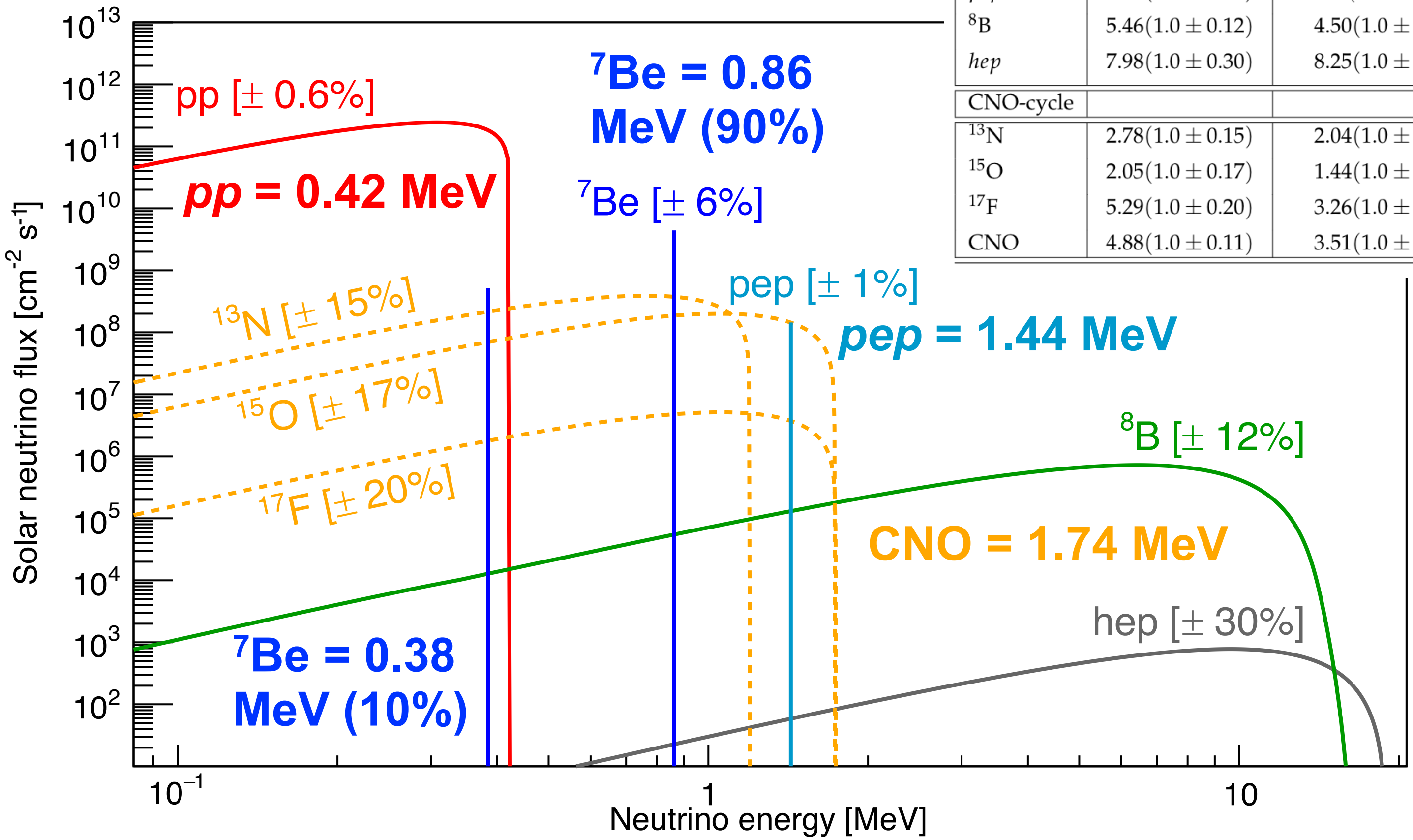
Fractional sound speed difference as a function of radius



EXPECTED SOLAR NEUTRINO SPECTRA AND FLUXES

Solar ν	B16-GS98 (HZ)	B16-AGSS09met (LZ)	(HZ − LZ)/HZ [%]	Exp
pp-cycle				
pp	5.98(1.0 ± 0.006)	6.03(1.0 ± 0.005)	−0.8	$\times 10^{10}$
^{7}Be	4.93(1.0 ± 0.06)	4.50(1.0 ± 0.06)	8.9	$\times 10^{9}$
pep	1.44(1.0 ± 0.01)	1.46(1.0 ± 0.009)	−1.4	$\times 10^{8}$
^{8}B	5.46(1.0 ± 0.12)	4.50(1.0 ± 0.12)	−17.6	$\times 10^{6}$
hep	7.98(1.0 ± 0.30)	8.25(1.0 ± 0.12)	−3.4	$\times 10^{3}$
CNO-cycle				
^{13}N	2.78(1.0 ± 0.15)	2.04(1.0 ± 0.14)	26.6	$\times 10^{8}$
^{15}O	2.05(1.0 ± 0.17)	1.44(1.0 ± 0.16)	29.7	$\times 10^{8}$
^{17}F	5.29(1.0 ± 0.20)	3.26(1.0 ± 0.18)	38.3	$\times 10^{6}$
CNO	4.88(1.0 ± 0.11)	3.51(1.0 ± 0.10)	28.1	$\times 10^{8}$

N. Vinyoles et al. Astrop. J 836 (2017) 202



CNO flux significantly differs assuming HZ- or LZ-SSM

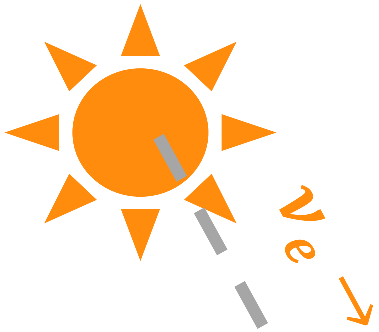
➔ Different Endpoints, Different Shapes ➔ Possible to measure

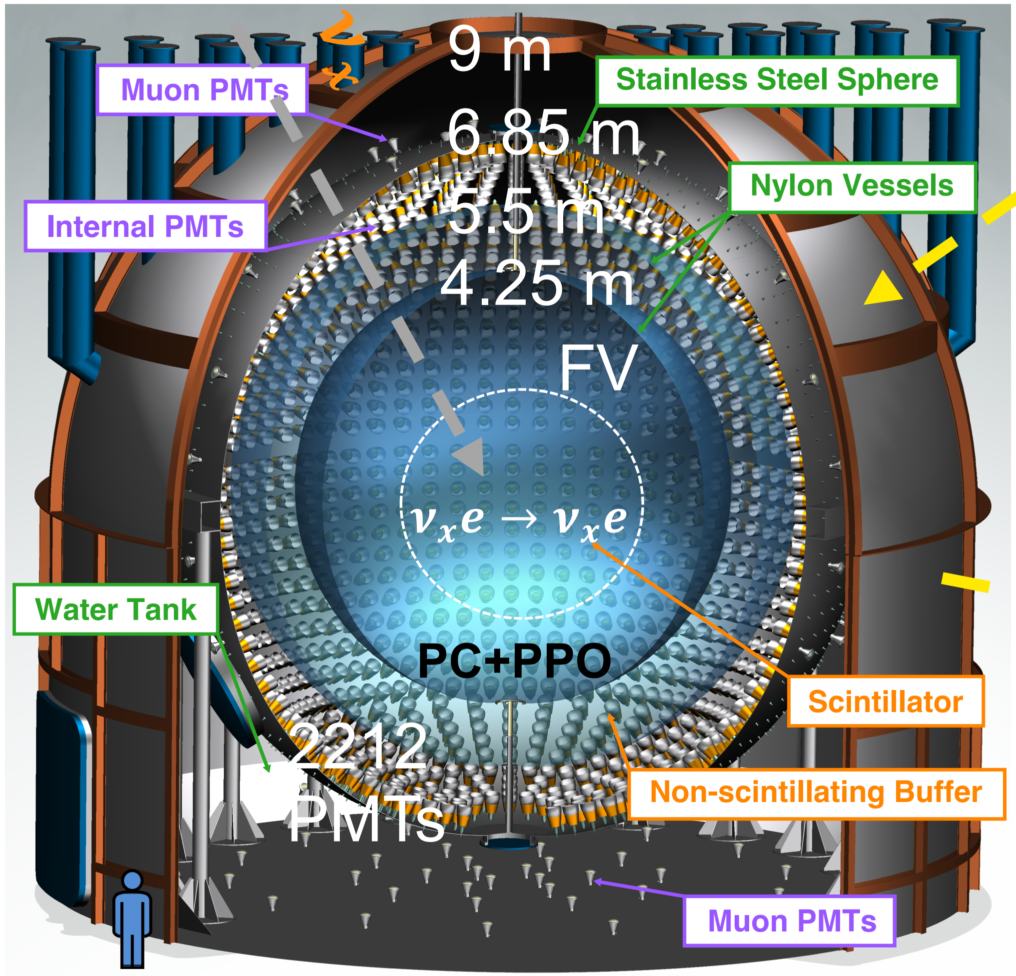
➔ Borexino Analysis threshold ~200 keV (*pp*) and ~300 keV (CNO)

THE BOREXINO DETECTOR

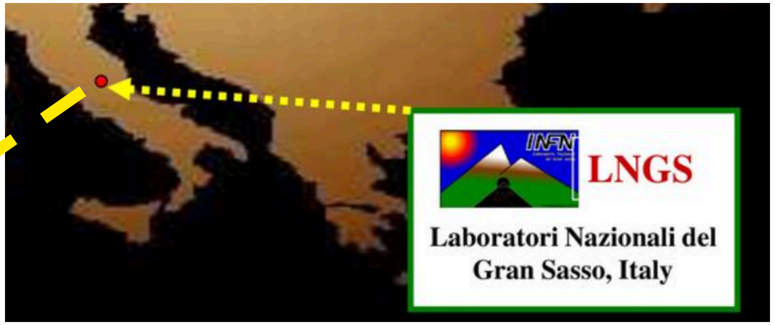
- The Borexino Detector located at LNGS in Italy

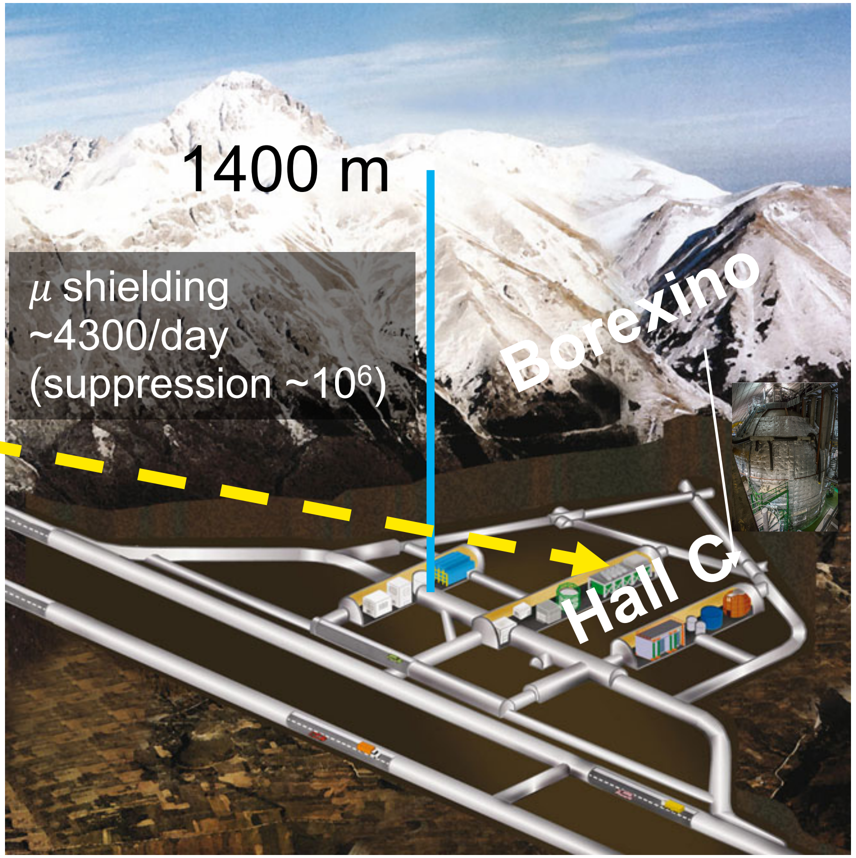
Detection Principle:
Elastic Scattering on e^-





208 PMTs

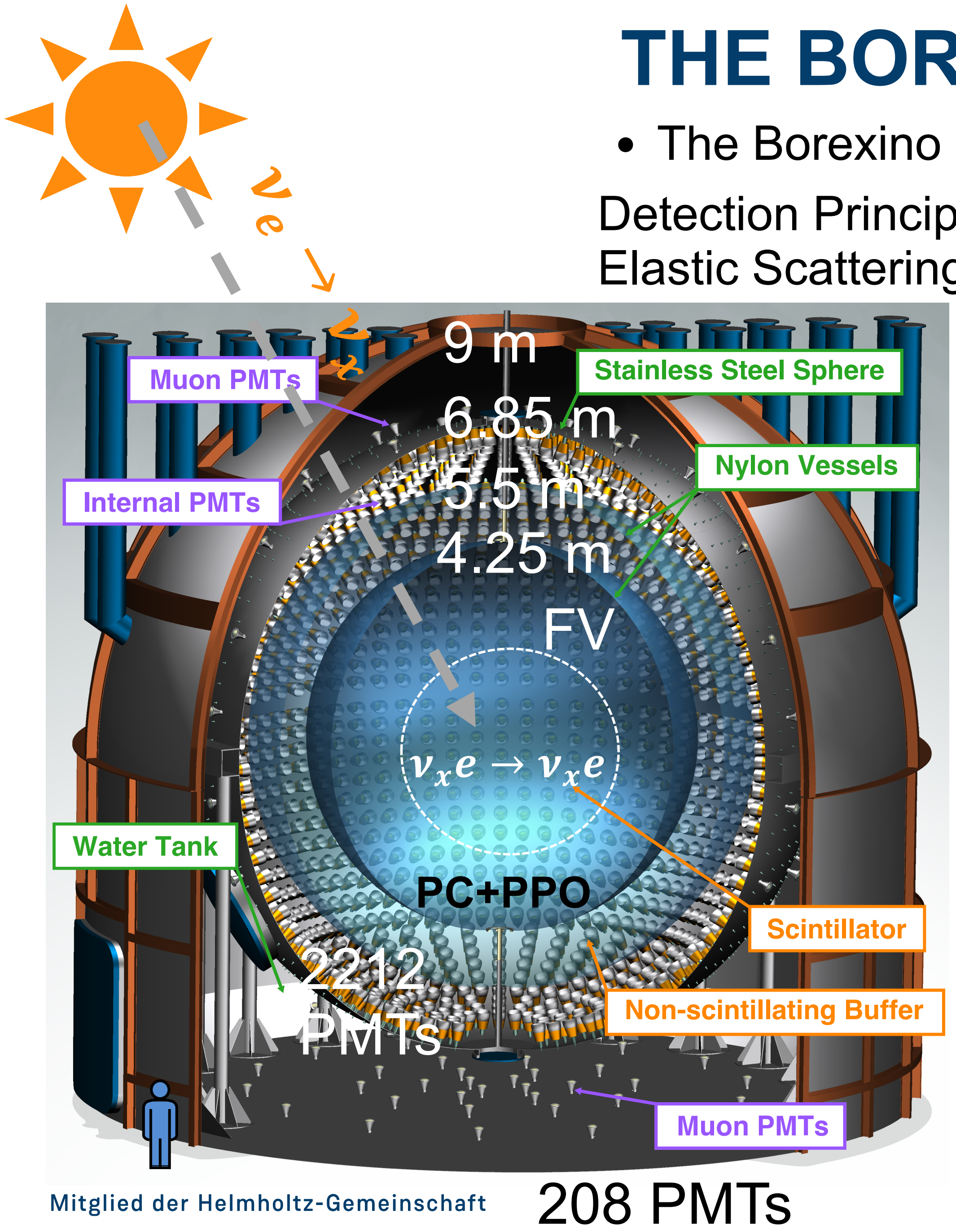




THE BOREXINO DETECTOR

- The Borexino Detector located at LNGS in Italy

Detection Principle:
Elastic Scattering on e^-



Light Yield:
500 p.e./MeV with 2000 active PMTs

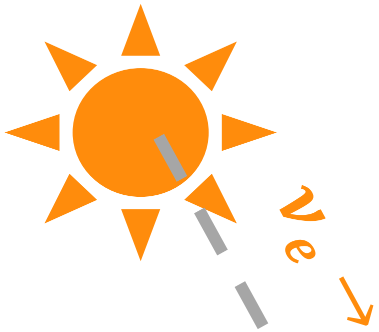
Resolutions:
Energy → $\frac{\Delta E}{E} \sim 5\%/\sqrt{E[MeV]}$
Position → $\frac{\Delta x}{x} \sim 10cm/\sqrt{E[MeV]}$

Threshold:
Hardware ~50 keV
Analysis ~200 keV

Total 280 ton Scintillator Mass

Fiducial Volume (FV) cut:
R < 2.8 m, -1.8 m < z < 2.2 m
➔ 71.3 ton

THE BOREXINO DETECTOR

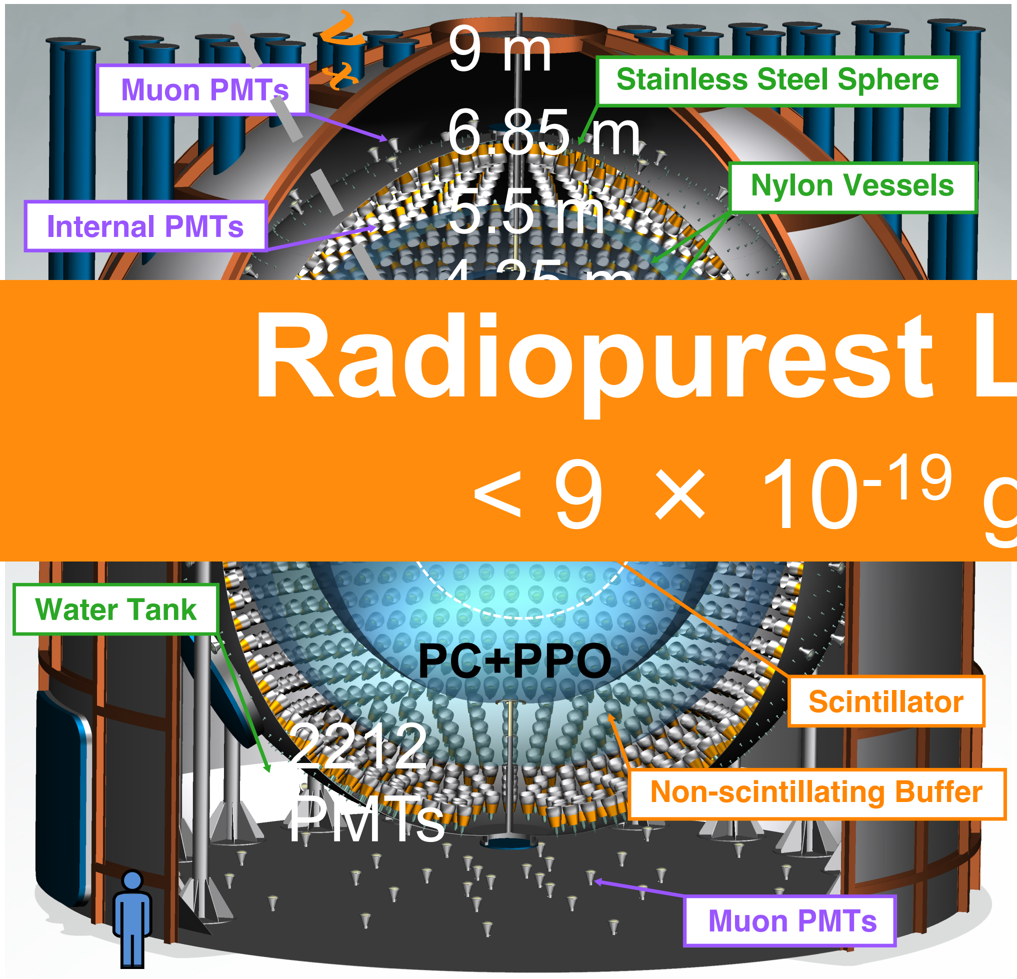


- The Borexino Detector located at LNGS in Italy

Detection Principle:
Elastic Scattering on e^-

Light Yield:
500 p.e./MeV with 2000 active PMTs

Resolutions:
Energy → $\frac{\Delta E}{E} \sim 5\%/\sqrt{E[MeV]}$



208 PMTs

Radiopurest LS Detector ever built

$< 9 \times 10^{-19}$ g(Th)/g , $< 8 \times 10^{-20}$ g(U)/g

Analysis ~200 keV

Total 280 ton Scintillator Mass

Fiducial Volume (FV) cut:
R < 2.8 m, -1.8 m < z < 2.2 m
➔ 71.3 ton

BOREXINO TIMELINE 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** — **Improved Thermal stability / CNO analysis** — **2020+**

Bx Phase I | Bx Phase II | Bx Phase III

Scintillator Purification

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

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

Measurement 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))

Simultaneous Precision Spectroscopy of *pp*, ^{7}Be, and *pep* Solar Neutrinos with Borexino Phase-II (arXiv:1707.09279v2 (2017)) → Phys. Rev. D **100**, 082004 (2019)

Improved measurement of ^{8}B solar neutrinos with 1.5 kt y of Borexino exposure (arXiv:1709.00756v1 (2017)) → Phys. Rev. D **101**, 062001 (2020)

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

Constraints on Non-Standard Neutrino Interactions from Borexino Phase-II (JHEP 2020, 38 (2020))

Comprehensive geoneutrino analysis with Borexino (Phys. Rev. D **101**, 012009 (2020))

Search for low-energy neutrinos from astrophysical sources with Borexino (Astropart. Phys. Vol. 125, Feb. 2021, 102509)

Sensitivity to neutrinos from the solar CNO cycle in Borexino (arXiv:2005.12829v3)

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun (Nature 587, 577-582 (2020))

BOREXINO TIMELINE OVERVIEW

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

pp
Improved Measurement of I
pep Discovery (5σ)

Improved Thermal stability
CNO analysis

6 2020+

Bx Phase III


European Physical Society
PRIZE

The 2021 Giuseppe and Vanna Cocconi Prize
for an outstanding contribution to Particle Astrophysics and Cosmology

is awarded to the

Borexino Collaboration

for their ground-breaking observation of solar neutrinos from the pp chain and CNO cycle that provided unique and comprehensive tests of the Sun as a nuclear fusion engine.

Luc Bergé
President
European Physical Society

Thomas Gehrmann
Chair
EPS High Energy and Particle Physics Division

Mulhouse, France, 26 July 2021

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

Constraints on Non-Standard Neutrino Interactions from Borexino Phase-II (JHEP 2020, 38 (2020))

Comprehensive geoneutrino analysis with Borexino (Phys. Rev. D **101**, 012009 (2020))

Search for low-energy neutrinos from astrophysical sources with Borexino (Astropart. Phys. Vol. 125, Feb. 2021, 102509)

Sensitivity to neutrinos from the solar CNO cycle in Borexino (arXiv:2005.12829v3)

geoneutrin... m 2056
days o... a
(Phy...
031...

(arXiv:1709.00756v1 (2017)) → Phys. Rev. D **101**, 062001 (2020)

physicsworld
TOP 10
BREAKTHROUGH
2020

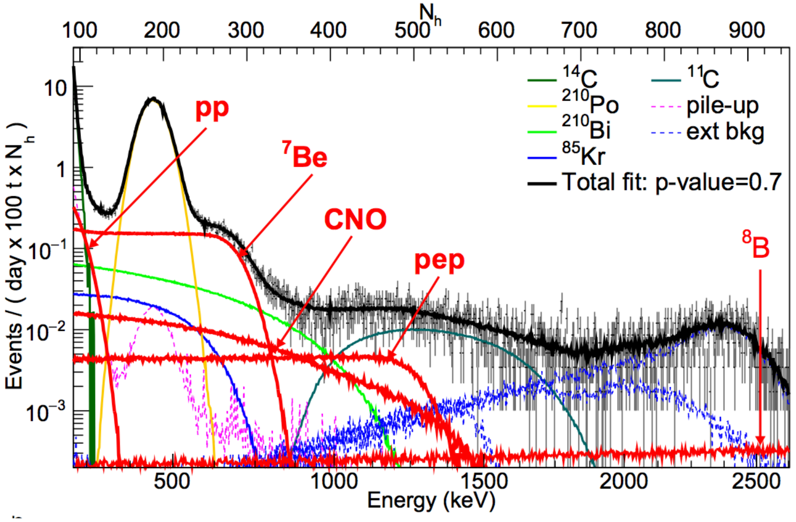
Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun (Nature 587, 577-582 (2020))

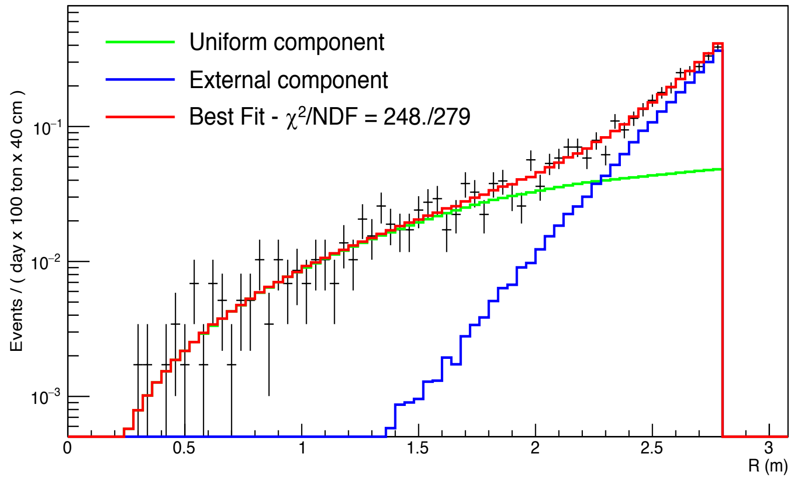
Phase-II Spectroscopy of pp chain neutrinos (Dec. 2011 – May 2016)

ANALYSIS OF PP-CHAIN NEUTRINOS (PHASE-II)

Low Energy Range (LER) [0.19 – 2.93 MeV]

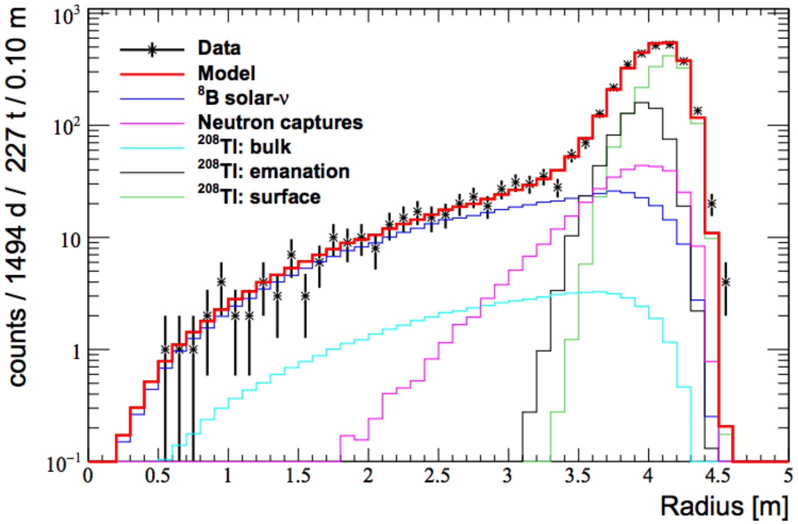
pp, ^{7}Be, *pep* Neutrinos (not CNO)





Multivariate fit Energy + Radial

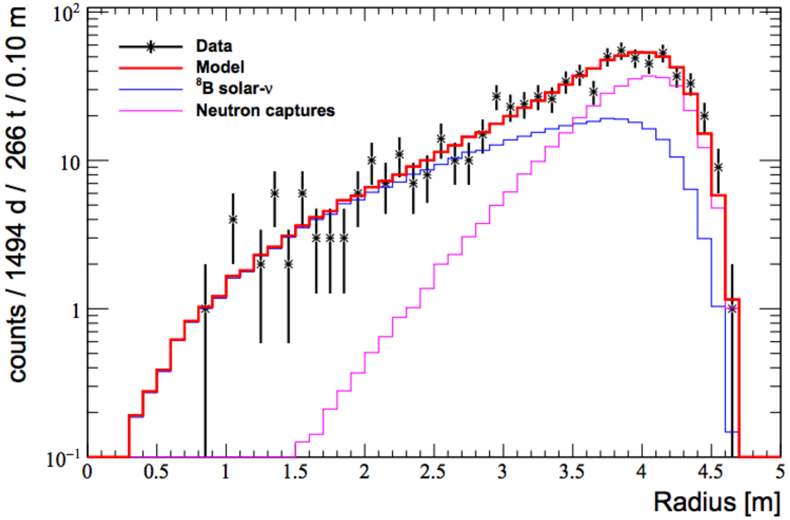
High Energy Range (HER-I) [3.2 – 5.7 MeV]



Only ^{8}B Neutrinos

Radial Fit not Energy Fit
⇒ Not to assume shape of survival probability P_{ee}

High Energy Range (HER-II) [5.7 – 16 MeV]



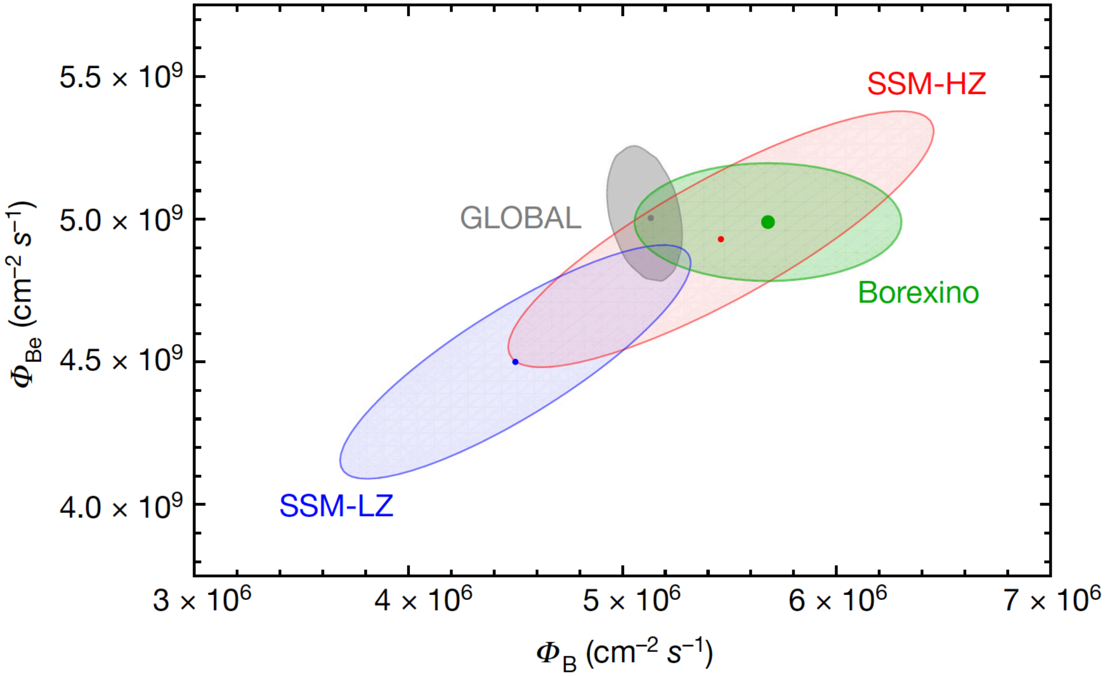
no natural long-lived radioactive background above 5 MeV

JÜLICH Forschungszentrum

IMPLICATIONS: P_{ee} AND HZ VS. LZ

Neutrino Interaction Rates:

- **LER:**
  pp (10.5%), ^{7}Be (2.7%), *pep* (>5σ first time, 17%)
- **HER:**
  ^{8}B (8%), limit on *hep* neutrinos
- 96.6 % preference to HZ-SSM (Borexino only)



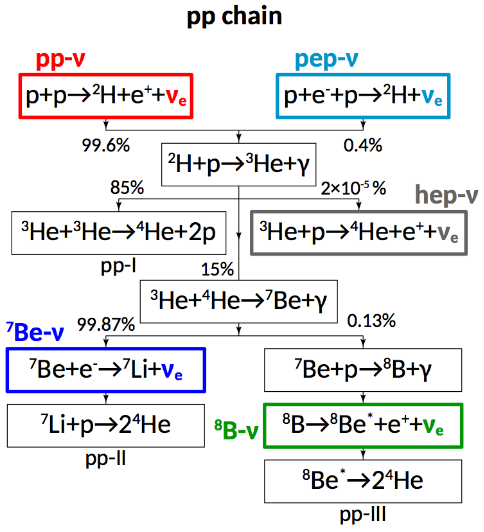
Solar Physics:

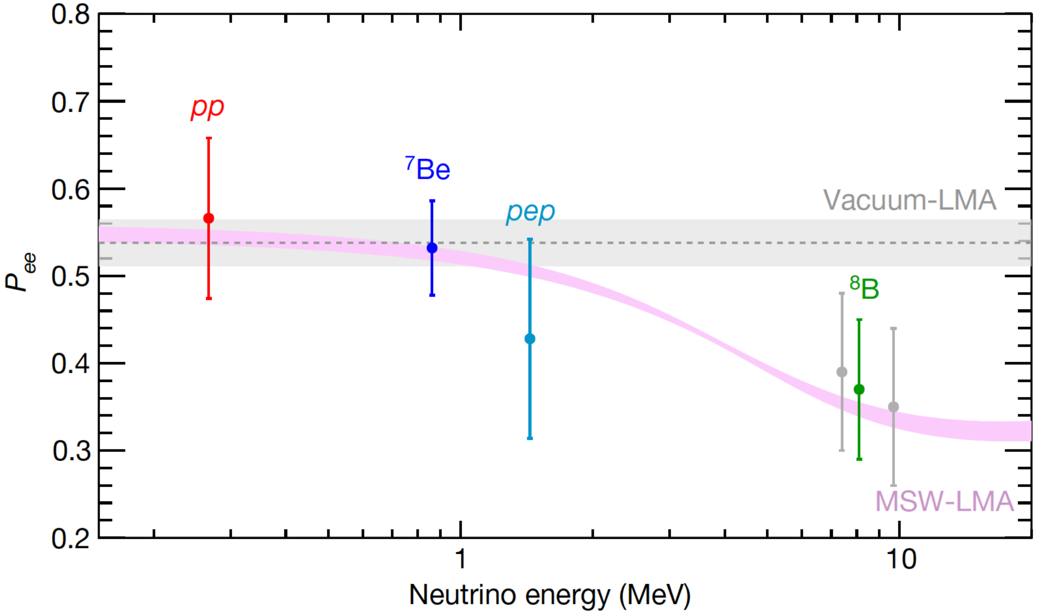
- Compare Ratio of *pp*-I to *pp*-II:

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

Borexino: $\boldsymbol{R_{I/II} = 0.1780^{+0.027}_{-0.023}}$
(consistent with LZ- and HZ-SSM predictions)

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





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

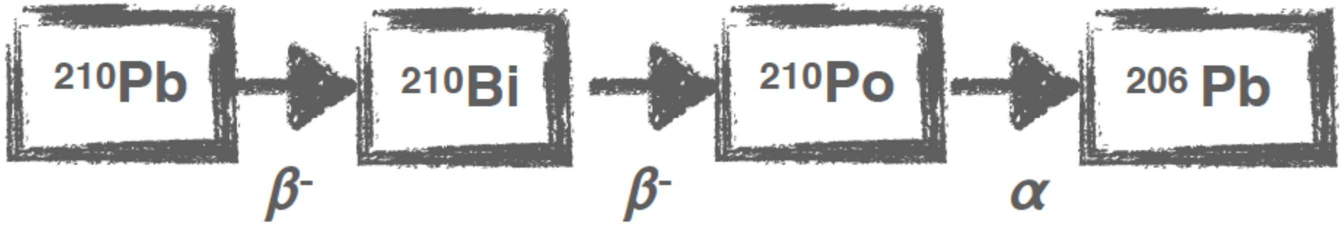
Phase-III Observation of CNO cycle neutrinos (Jul. 2016 – Feb. 2020)

CHALLENGE : ^{210}BI CONSTRAINT

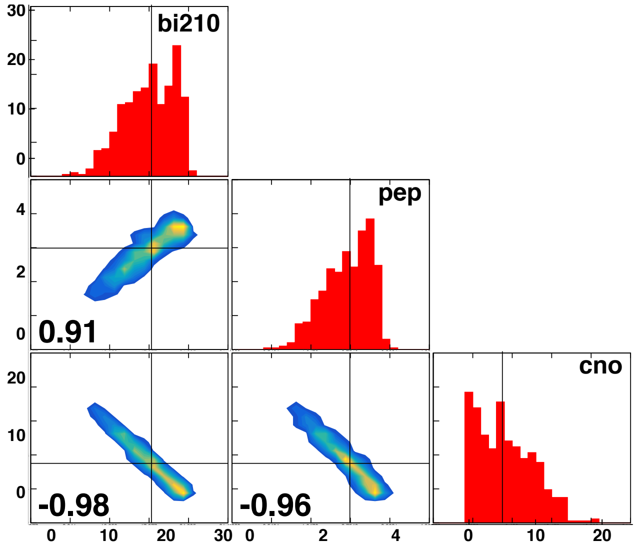
pep-ν constraint

***pep-ν* rate can be constrained with ~1.4% precision**
⇔ **Global Analysis of Solar Neutrino Data + Luminosity constraint** (Bergström et al., JHEP, 2016:132, 2016)
Result: (2.74±0.04) counts/day/100t (HZ-SSM ≈ LZ-SSM)

^{210}Bi constraint → Determine ^{210}Po Content



Lifetimes 32 y 7.23 d 199.1 d



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

^{210}Po identification:
Monoenergetic Decay (“Gaussian“) + α-decay in Borexino
⇔ Event-by-Event Pulse Shape Discrimination based on Multilayer Perceptron discrimination variable (MLP)

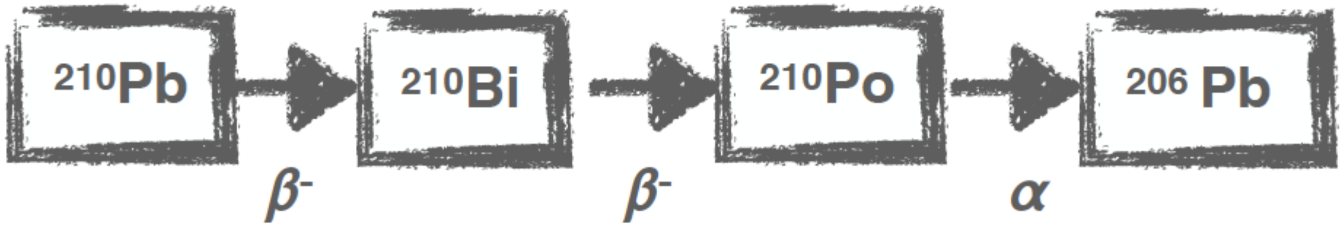
JÜLICH Forschungszentrum

CHALLENGE : ^{210}BI CONSTRAINT

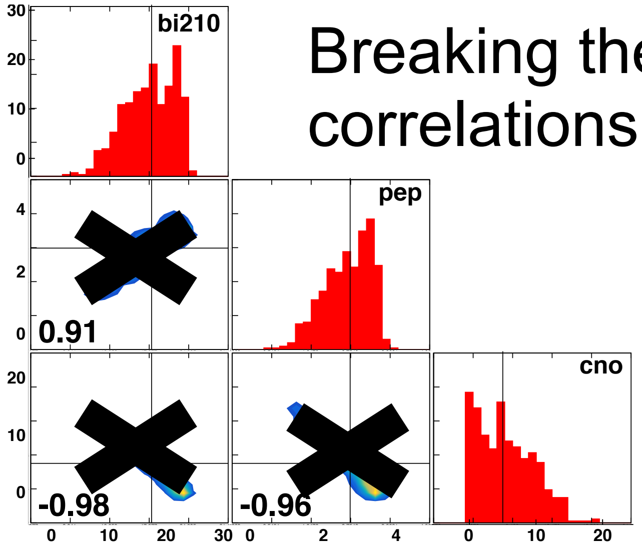
pep-ν constraint

***pep-ν* rate can be constrained with ~1.4% precision**
⬄ **Global Analysis of Solar Neutrino Data + Luminosity constraint** (Bergström et al., JHEP, 2016:132, 2016)
Result: (2.74±0.04) counts/day/100t (HZ-SSM ≈ LZ-SSM)

^{210}Bi constraint → Determine ^{210}Po Content



Lifetimes 32 y 7.23 d 199.1 d



Breaking the correlations

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

^{210}Po identification:
Monoenergetic Decay (“Gaussian“) + α-decay in Borexino
⬄ Event-by-Event Pulse Shape Discrimination based on Multilayer Perceptron discrimination variable (MLP)

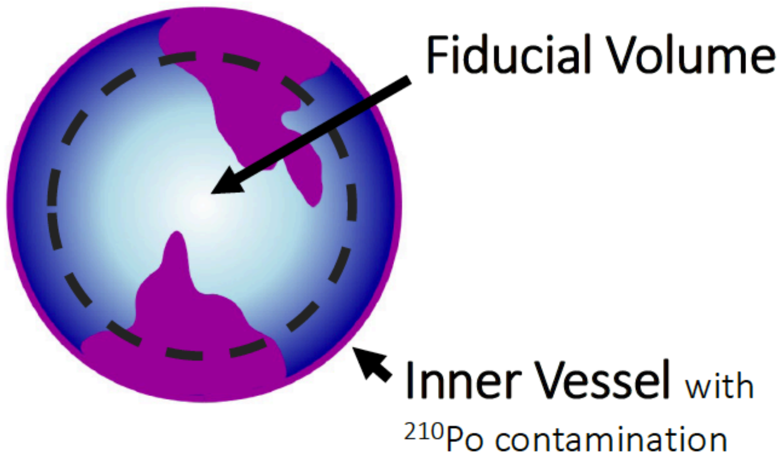
JÜLICH Forschungszentrum

PROBLEM: TEMPERATURE GRADIENTS

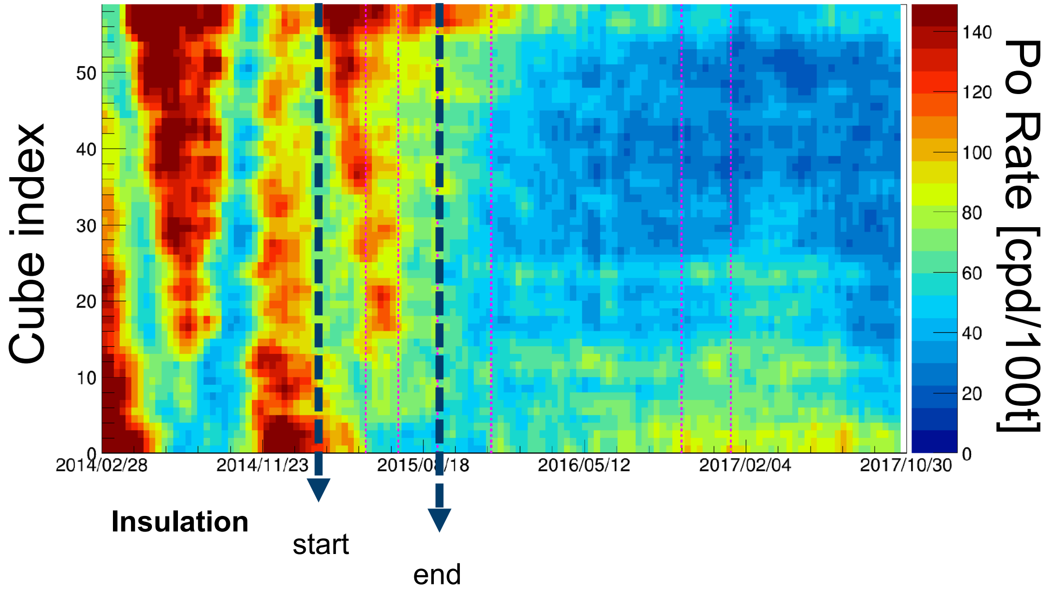
- Temperature gradients present in the detector cause convective motions of ^{210}Po present at the nylon vessel to move inside the scintillator

  → Additional source of ^{210}Po entering the FV
  → This breaks equilibrium between ^{210}Po and ^{210}Bi chain

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



seasonal variation of ^{210}Po

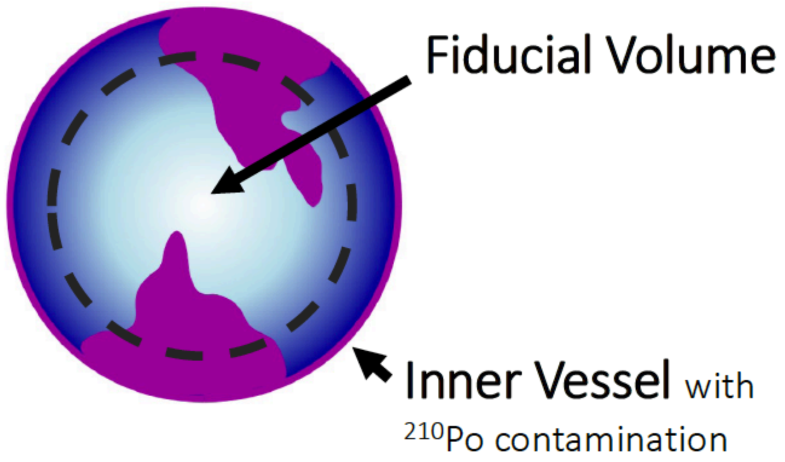


SOLUTION: INSULATION CAMPAIGN

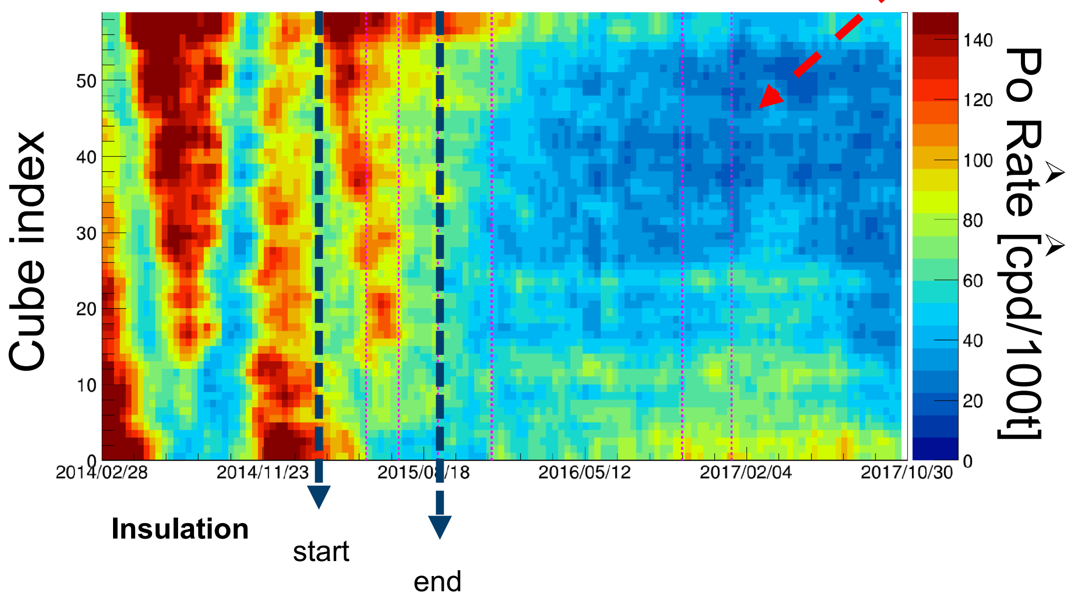
- Temperature gradients present in the detector cause convective motions of ^{210}Po present at the nylon vessel to move inside the scintillator

  → Additional source of ^{210}Po entering the FV
  → This breaks equilibrium between ^{210}Po and ^{210}Bi chain

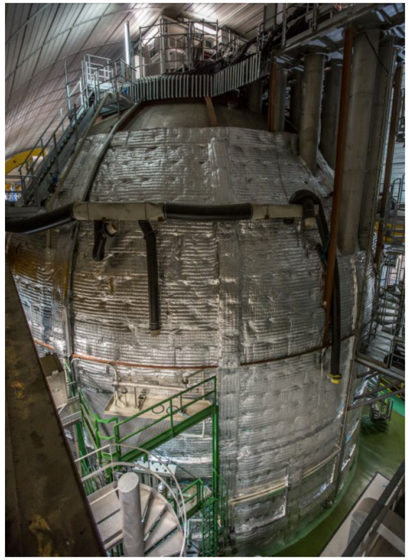
- Need to identifiy the ^{210}Po in secular equilibrium with the ^{210}Bi events
  → Challenging



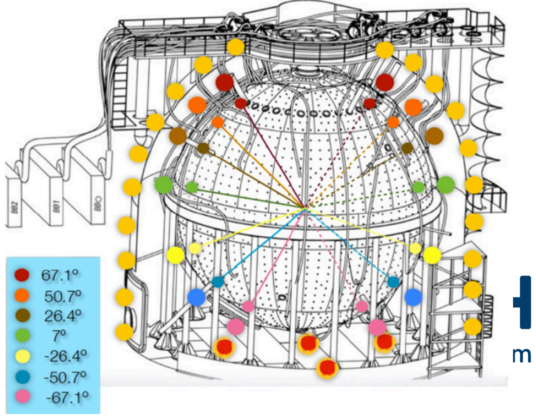
seasonal variation of ^{210}Po



Hardware
- Double layer mineral Wool (2015)
- Active Temperature Control System



Monitoring
- 54 Temperature probes located (buffer, external tank, different levels)
- Resolution 0.07 °C



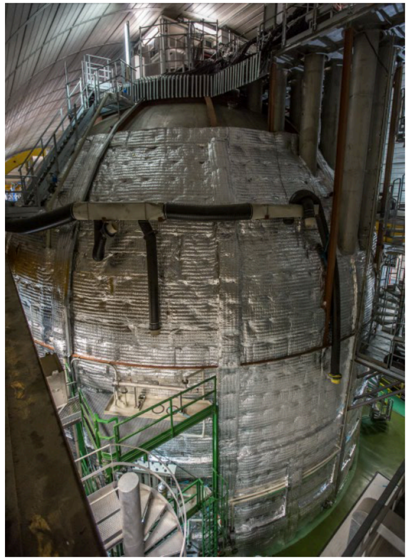
SOLUTION: INSULATION CAMPAIGN

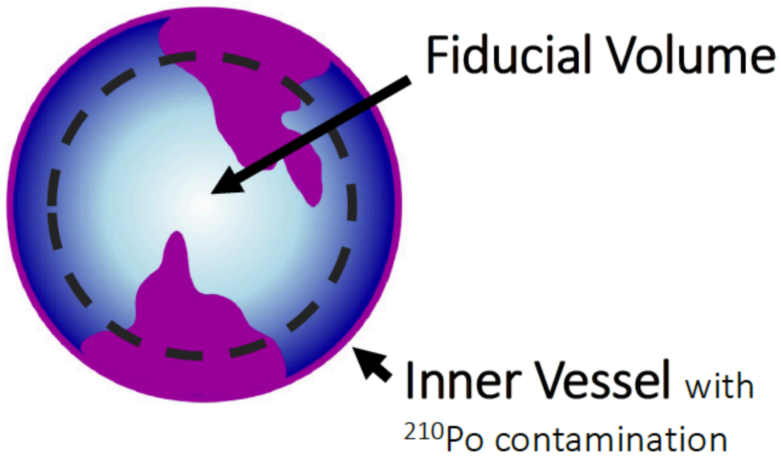
- Temperature gradients present in the detector cause convective motions of ^{210}Po present at the nylon vessel to move inside the scintillator

  → Additional source of ^{210}Po entering the FV
  → This breaks equilibrium between ^{210}Po and ^{210}Bi chain

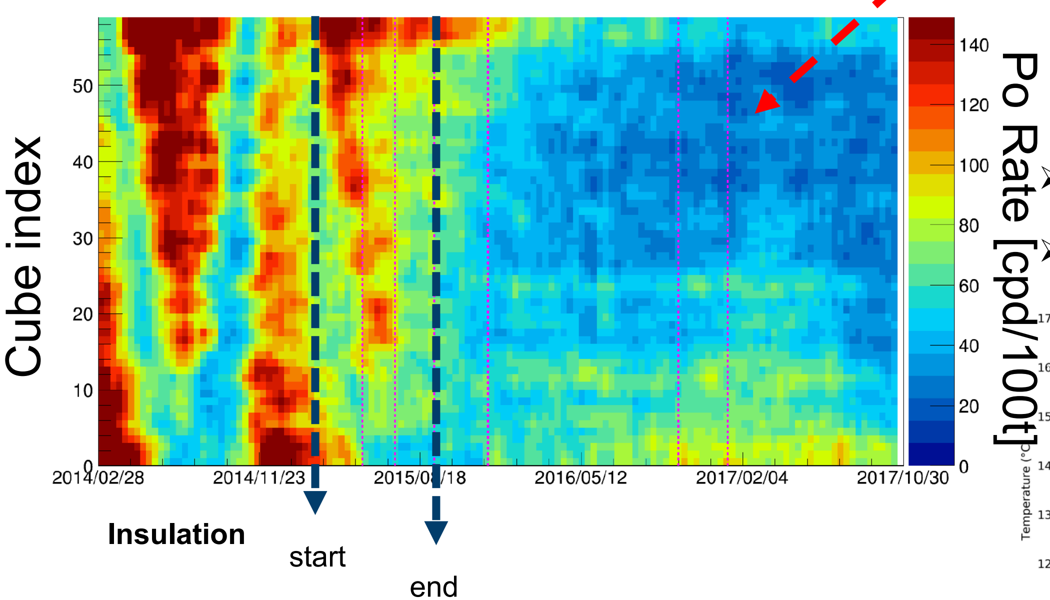
- Need to identifiy the ^{210}Po in secular equilibrium with the ^{210}Bi events
  → Challenging

Hardware
- Double layer mineral Wool (2015)
- Active Temperature Control System

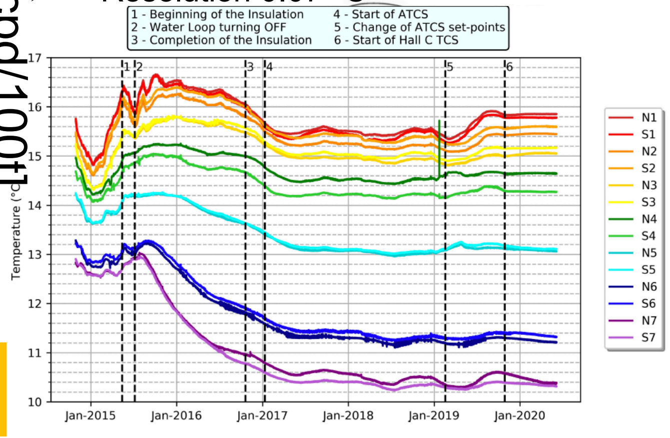




seasonal variation of ^{210}Po



Monitoring
- 54 Temperature probes located (buffer, external tank, different levels)
- Resolution 0.07 °C



➔ Identify Field with minimal ^{210}Po rate 🡐

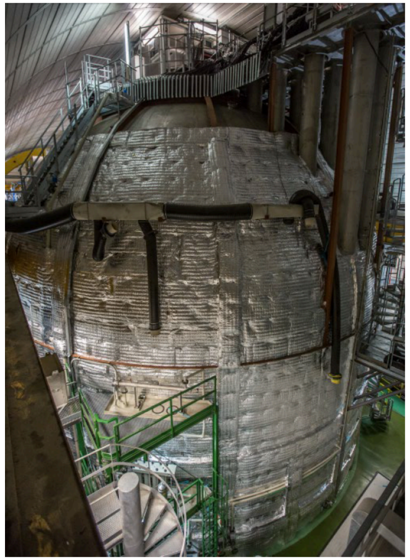
SOLUTION: LOW ^{210}PO FIELD AND ^{210}BI CONSTRAINT

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

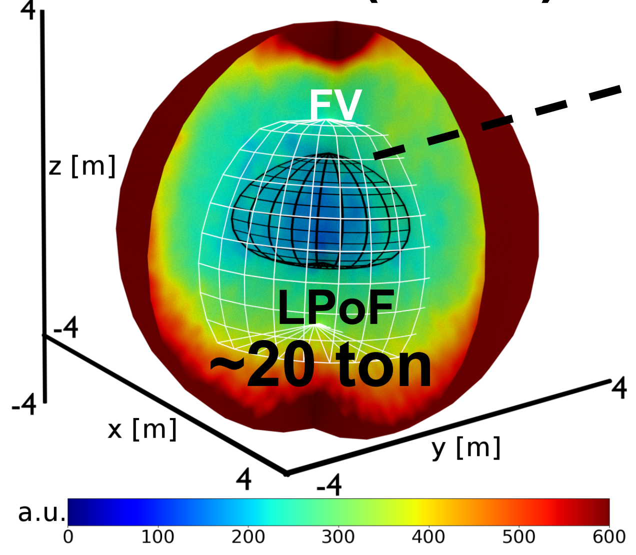
  → Additional source of ^{210}Po entering the FV
  → This breaks equilibrium between ^{210}Po and ^{210}Bi chain

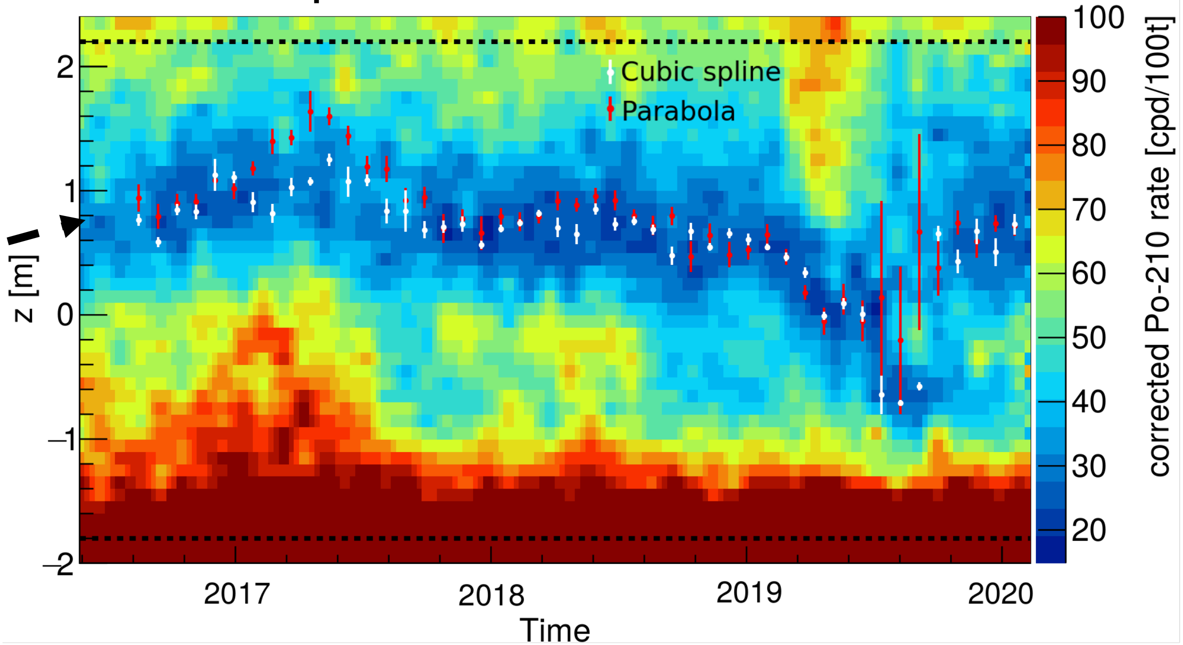
- Need to identifiy the ^{210}Po in secular equilibrium with the ^{210}Bi events
  → Challenging

Hardware
- Double layer mineral Wool (2015)
- Active Temperature Control System

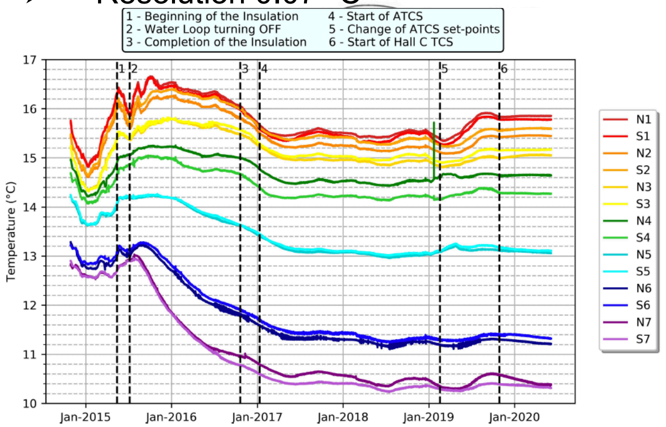


Low Po Field **(LPoF)**





Monitoring
- 54 Temperature probes located (buffer, external tank, different levels)
- Resolution 0.07 °C



Upper LIMIT:

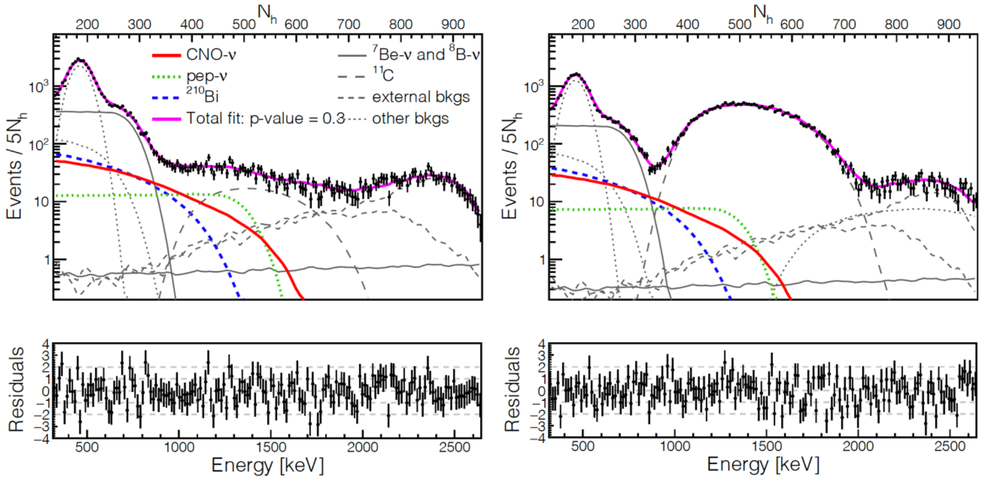
$$R(\mathrm{Po}_{min}) = R(\mathrm{Bi}) + R(\mathrm{Po}^{IV}) \geq R(\mathrm{Bi})$$

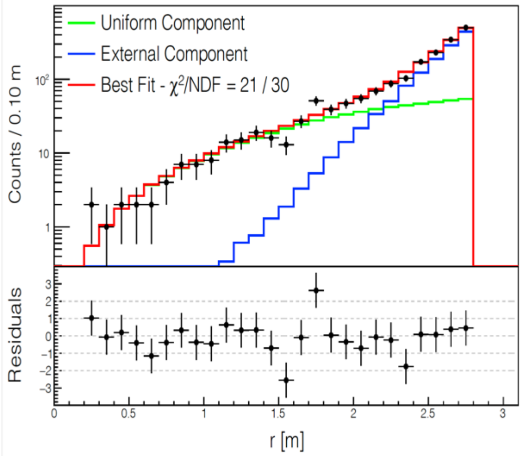
➔ $\boldsymbol{R(\mathrm{Po_{min}}) = (11.5 \pm 1.3)}$ **cpd/100t** 🡐

MULTIVARIATE SPECTRAL FIT + CNO $\Delta\chi^2$ PROFILE

Threefold Coincidence (TFC) algorithm (cosmogenic ^{11}C from spallation $\mu + {}^{12}\mathrm{C} \rightarrow \mathrm{n} + {}^{11}\mathrm{C} + \mu$)

→ ^{11}C subtracted + ^{11}C enriched





Fit Conditions:

Monte Carlo Fit with Fit Range ~320 to ~2640 keV

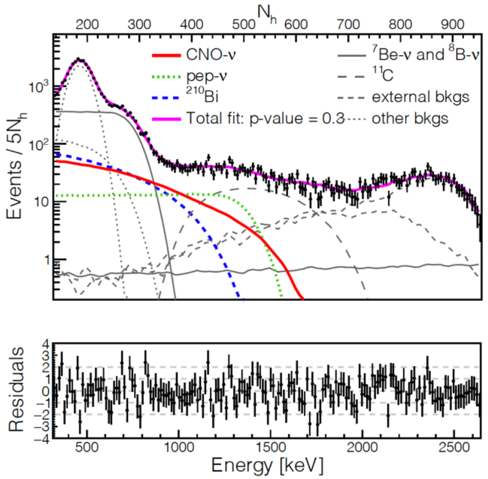
$R_{pep} = (2.74 \pm 0.04)$ cpd/100t → symmetric gaussian penalty

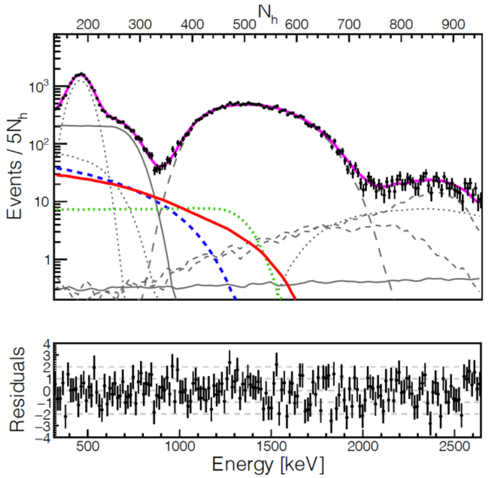
$R_{\mathrm{Bi}} \leq (11.5 \pm 1.3)$ cpd/100t → upper limit = semi gaussian !

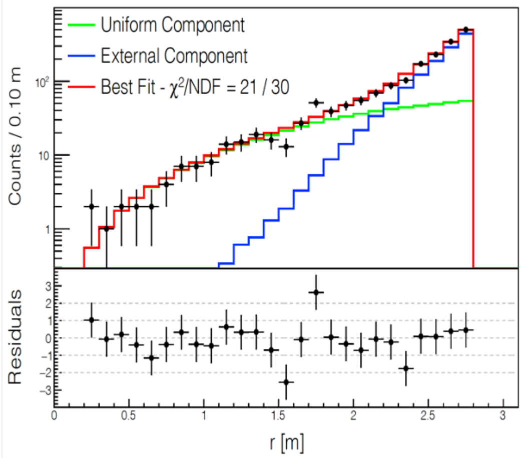
MULTIVARIATE SPECTRAL FIT + CNO $\Delta\chi^2$ PROFILE

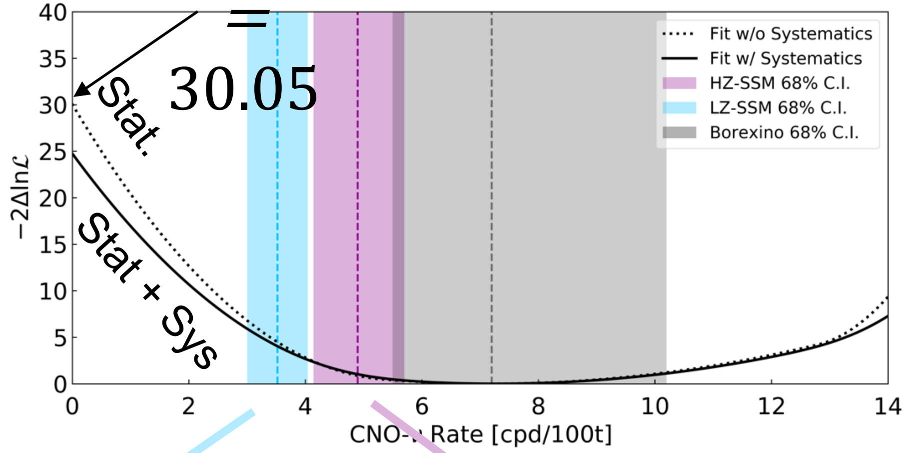
Threefold Coincidence (TFC) algorithm (cosmogenic ^{11}C from spallation $\mu + {}^{12}\mathrm{C} \rightarrow \mathrm{n} + {}^{11}\mathrm{C} + \mu$)

→ ^{11}C subtracted + ^{11}C enriched









LZ-SSM
(3.52±0.52) cpd/100t

HZ-SSM
(4.92±0.78) cpd/100t

LZ-SSM = Disfavored at **2.1σ** with ^{7}Be, ^{8}B, and CNO Borexino only

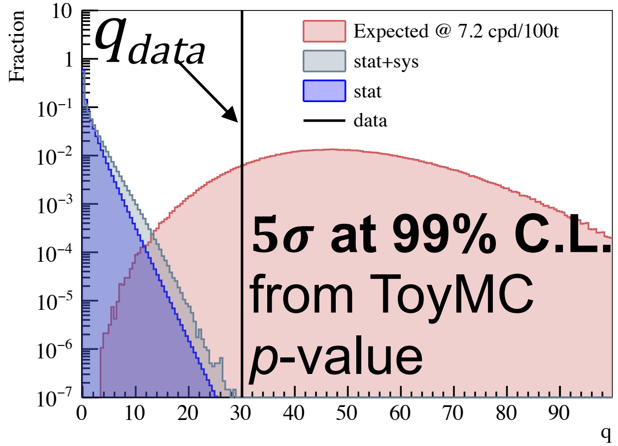
CNO 5σ

Fit Conditions:

Monte Carlo Fit with Fit Range ~320 to ~2640 keV

$R_{pep} = (2.74 \pm 0.04)$ cpd/100t → symmetric gaussian penalty

$R_{\mathrm{Bi}} \leq (11.5 \pm 1.3)$ cpd/100t → upper limit = semi gaussian !



Injected Systematics:

1. non-linearity of the energy scale (0.4%)
2. spatial non-uniformity z-axis (0.28%)
3. light yield (0.32%)
4. ^{11}C peak position
5. other ^{210}Bi spectral shapes (18%) (area of ^{210}Bi is constrained by the upper limit)

$R_{\mathrm{CNO}} = \left(7.2^{+3.0}_{-1.7}\right)$ **cpd/100t**

➔ $\Phi_{\mathrm{CNO}} = \left(7.0^{+3.0}_{-2.0}\right) \times 10^{8}$ **cm^{-2}s^{-1}**

Significance w/ systematics:

5.0σ (99% C.L.)

SUMMARY / CONCLUSION

- With solar neutrinos, we can learn a lot about the nature of our Sun and the Universe
- Borexino unraveled: *pp* chain and CNO cycle solar neutrinos (except hep)
  → Updates @ Neutrino 2022
- First evidence of neutrinos from the CNO cycle in the Sun after ~80 years (prediction by Bethe and Weizsäcker)

Merci Beaucoup

Questions ?

Backup

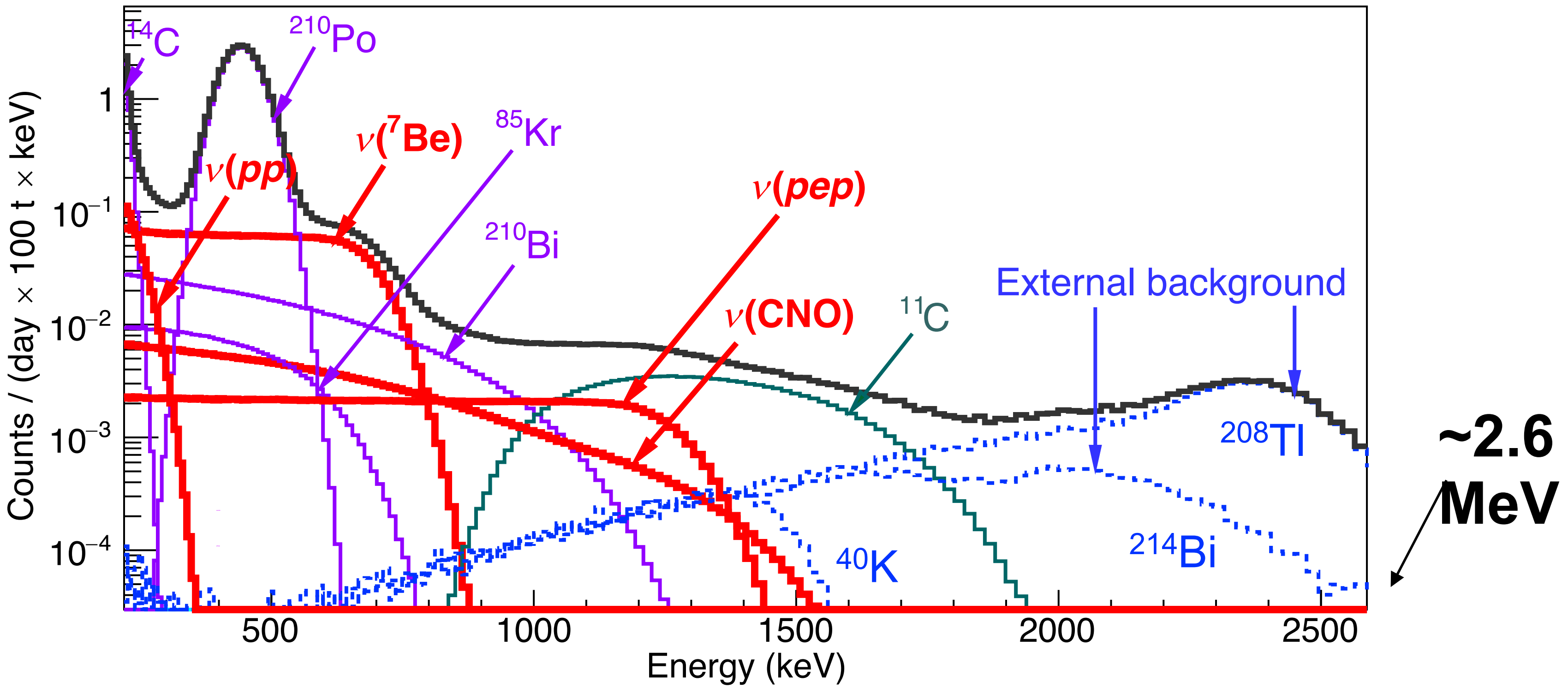
SIGNAL + BACKGROUND EXPECTATION

Solar Neutrinos (signal): $\nu(pp), \nu(^7Be), \nu(pep), \nu(CNO)$

Internal Background (scintillator): ^{14}C, ^{85}Kr, ^{210}Bi, ^{210}Po

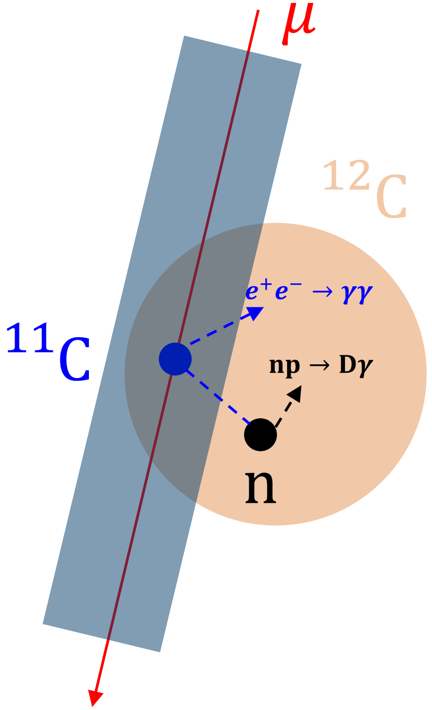
External Background (γs): ^{40}K, ^{214}Bi, ^{208}Tl

Cosmogenic Backgrounds (spallation $\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$): ^{11}C (main), ^{10}C, ^{6}He, +..



^{11}C TREATMENT: THREE-FOLD COINCIDENCE

- Cosmic Muon Interactions with ^{12}C → Three-fold coincidence (TFC) veto



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

29.4 min

$$^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^{+} + \nu_e$$

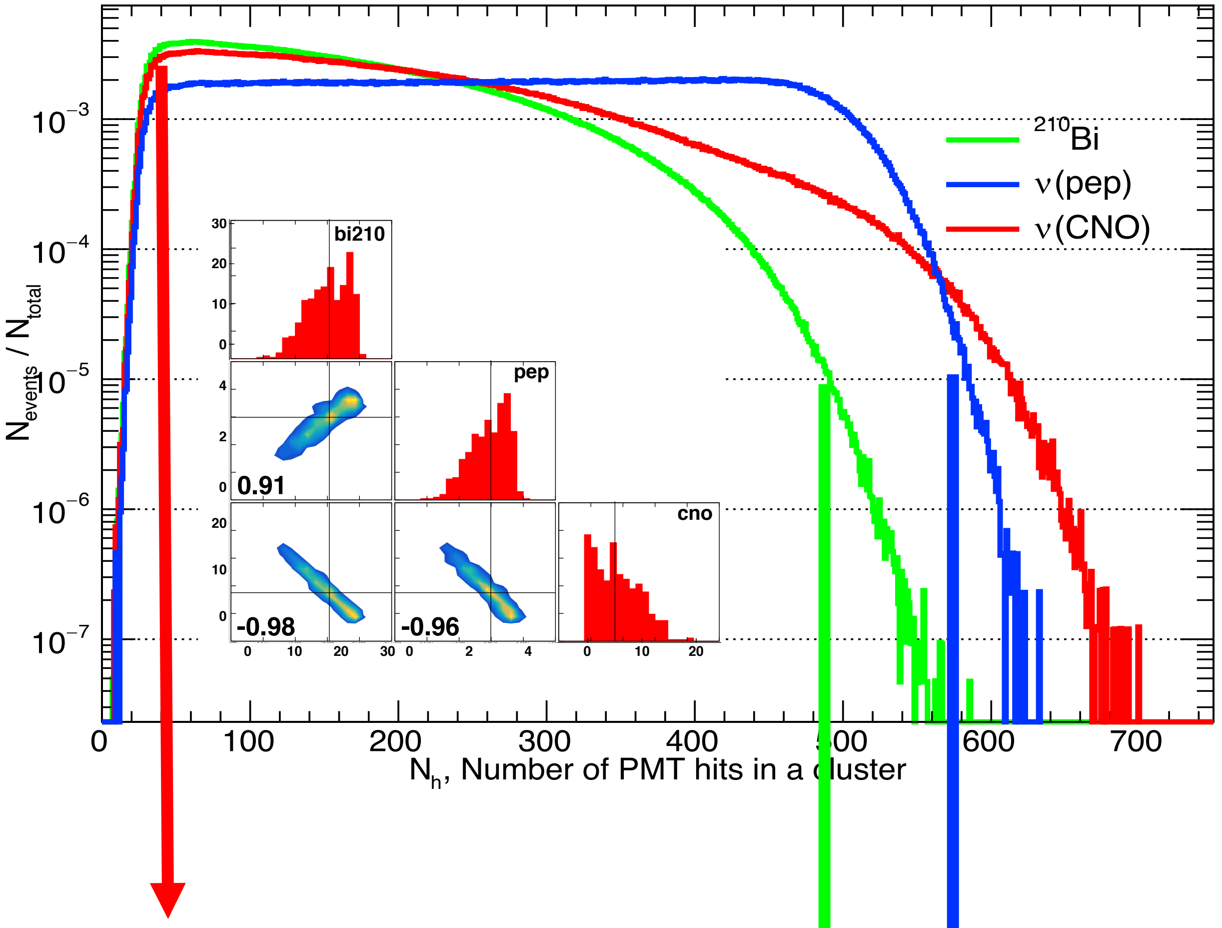
255 μs

$$n + \mathrm{p} \rightarrow D + \gamma$$
$$E_\gamma = 2.23 \text{ MeV}$$

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 (also called ^{11}C **depleted** and ^{11}C **enriched** spectra)

PHASE-II (12/2011-05/2016) VS. PHASE-III (07/2016-02/2020)



Here not neutrino but
Recoiled electron spectra

BIG CHALLENGE

High Spectral Correlation

SSM Rates in cpd/100t

➔ Very Low Rates ➔

Solar-ν	B16(GS98)-HZ	B16(AGSS09)-LZ
pp	131.1 ± 1.4	132.2 ± 1.4
^{7}Be	47.9 ± 2.8	43.7 ± 2.5
pep	2.74 ± 0.04	2.78 ± 0.04
CNO	4.92 ± 0.78	3.52 ± 0.52
^{8}B	0.44 ± 0.07	0.37 ± 0.05

CNO constrained in
Phase-II
for ***pp* analysis**

^{210}Bi + *pep* constrained in
Phase-III for **CNO analysis**