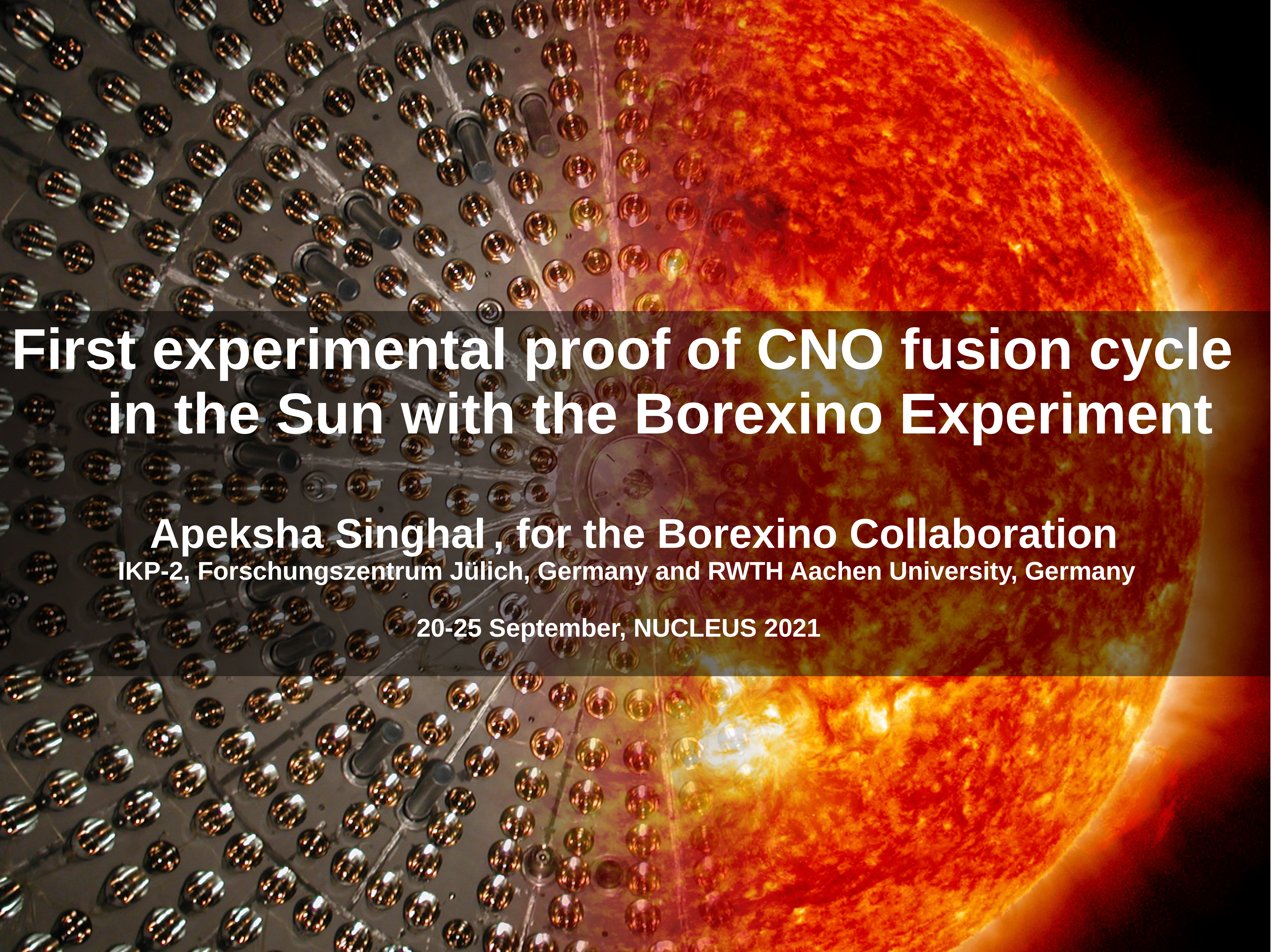


First experimental proof of CNO fusion cycle in the Sun with the Borexino Experiment

Apeksha Singhal , for the Borexino Collaboration
IKP-2, Forschungszentrum Jülich, Germany and RWTH Aachen University, Germany

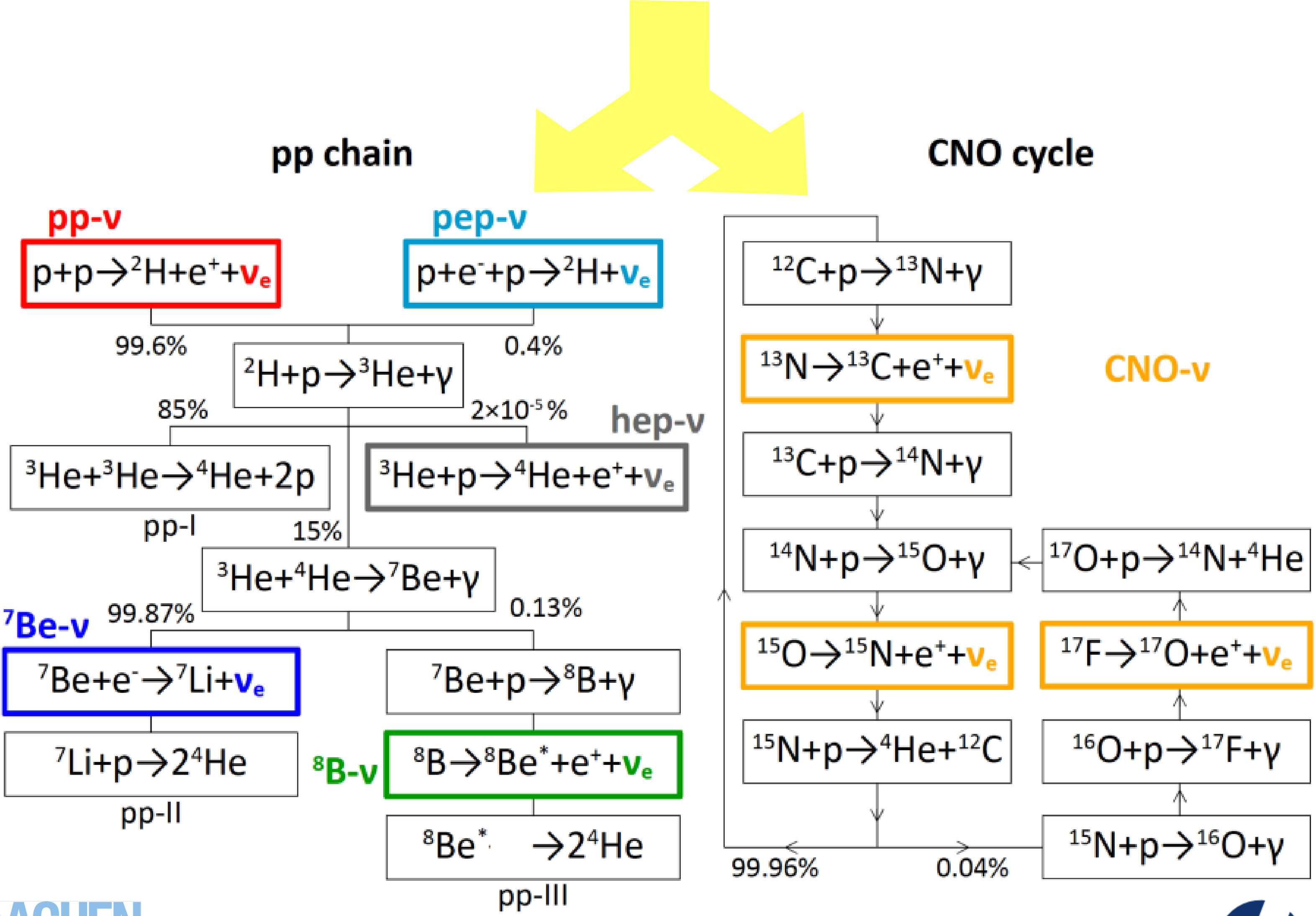
20-25 September, NUCLEUS 2021

OUTLINE

- **Introduction to Solar neutrinos**
- **The Borexino Experiment**
- **Challenges and Analysis Strategy**
- **Final Results**

Solar Neutrinos

$$4\ {}^{1}H \longrightarrow {}^{4}He + 2e^{+} + 2\nu_{e} + 26.73\ MeV$$



pp chain

CNO cycle

pp-ν

$p+p \rightarrow {}^{2}H+e^{+}+\nu_{e}$

pep-ν

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

99.6%

0.4%

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

85%

2×10^{-5} %

hep-ν

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

${}^{3}He+p \rightarrow {}^{4}He+e^{+}+\nu_{e}$

pp-I

15%

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

⁷Be-ν

99.87%

0.13%

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

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

${}^{7}Li+p \rightarrow 2\,{}^{4}He$

⁸B-ν

${}^{8}B \rightarrow {}^{8}Be^{*}+e^{+}+\nu_{e}$

pp-II

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

pp-III

${}^{12}C+p \rightarrow {}^{13}N+\gamma$

${}^{13}N \rightarrow {}^{13}C+e^{+}+\nu_{e}$

CNO-ν

${}^{13}C+p \rightarrow {}^{14}N+\gamma$

${}^{14}N+p \rightarrow {}^{15}O+\gamma$

${}^{17}O+p \rightarrow {}^{14}N+{}^{4}He$

${}^{15}O \rightarrow {}^{15}N+e^{+}+\nu_{e}$

${}^{17}F \rightarrow {}^{17}O+e^{+}+\nu_{e}$

${}^{15}N+p \rightarrow {}^{4}He+{}^{12}C$

${}^{16}O+p \rightarrow {}^{17}F+\gamma$

${}^{15}N+p \rightarrow {}^{16}O+\gamma$

99.96%

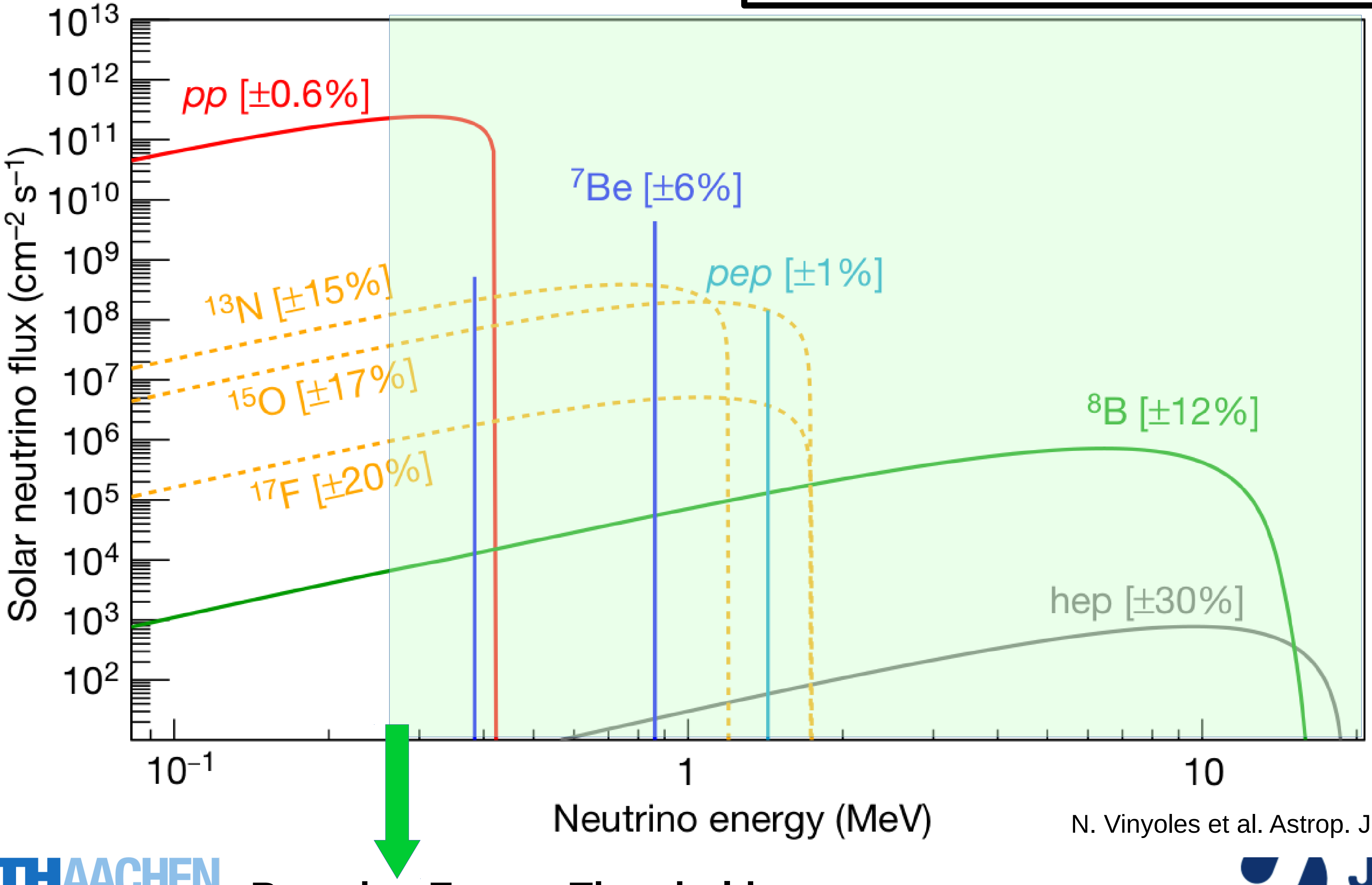
0.04%

Bethe&Critchfield (1938)

Weizsäcker (1937, 1938), Bethe (1939)

Energy Spectrum of Solar Neutrinos

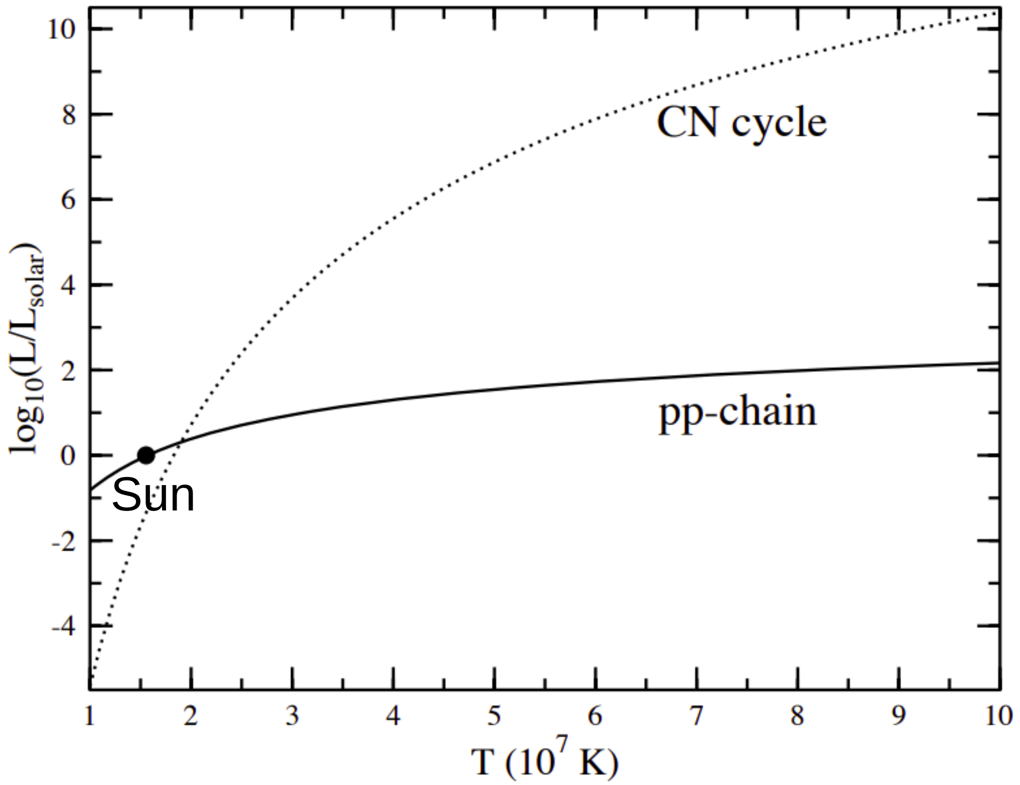
Fluxes as predicted by the Standard Solar Model [error on theoretical predictions]



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

Borexino Energy Threshold

CNO-cycle vs pp chain



CNO fusion cycle dominant in massive stars,
Having higher temperature
in their cores.

Sub-dominant process in Sun.
Contributes <1% to solar energy

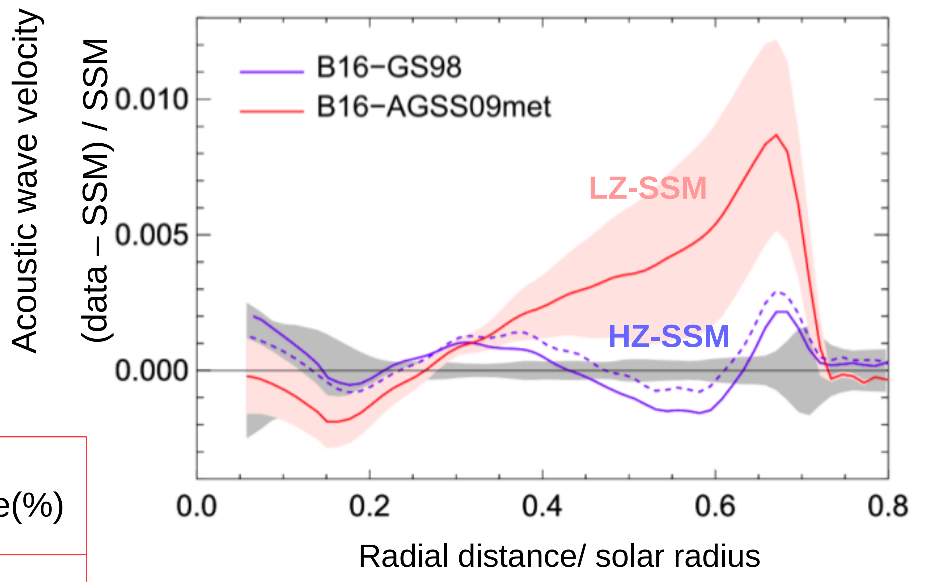
Haxton & Serenelli: The
Astrophysical J. 687 (2008) 678

Why to study CNO Solar Neutrinos?

- **Proof of energy production via the CNO cycle in Sun and in stars where it is the dominant process for the conversion of hydrogen to helium.**

- **Metallicity (Z/X) in Sun's core**
  - **Z = abundance of elements heavier than H and He**
    X = abundance of H and He
  - **High metallicity (HZ) SSM: B16 SSM with older GS98 metallicity input, Z/X = 0.0229**
    Low metallicity (LZ) SSM: B16 SSM with newer AGSS09 metallicity input, Z/X = 0.0178

Fractional sound speed difference as a function of radius

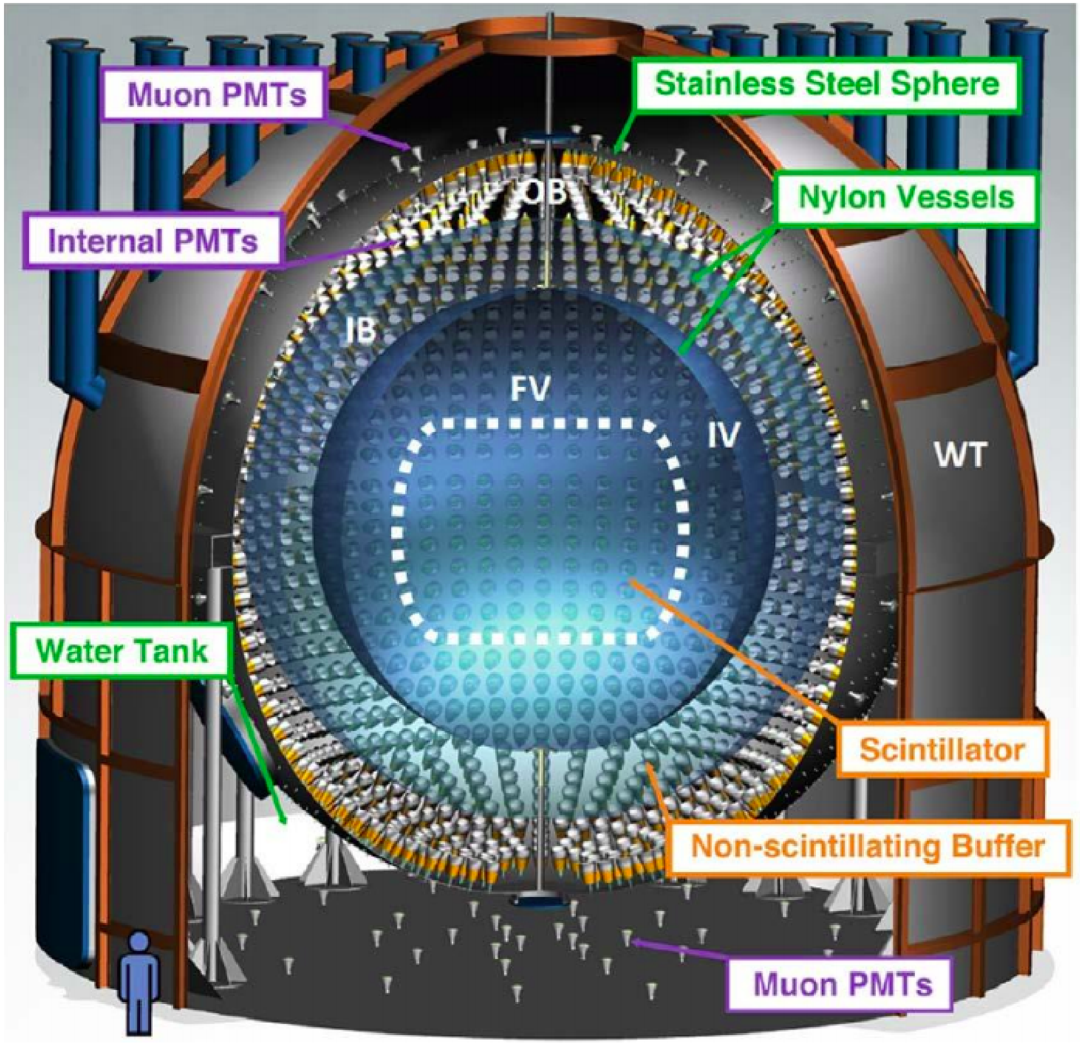


Species	HZ-Flux ($cm^{-2}s^{-1}$)	LZ-Flux ($cm^{-2}s^{-1}$)	Relative difference(%)
pp	$5.98(1 \pm 0.006)\times10^{10}$	$6.03(1 \pm 0.005)\times10^{10}$	-0.8
pep	$1.44(1 \pm 0.01)\times10^{8}$	$1.46(1 \pm 0.009)\times10^{8}$	-1.4
^{7}Be	$4.93(1 \pm 0.06)\times10^{9}$	$4.50(1 \pm 0.06)\times10^{9}$	8.9
^{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

LZ SSM Predictions disagree with helioseismological data

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

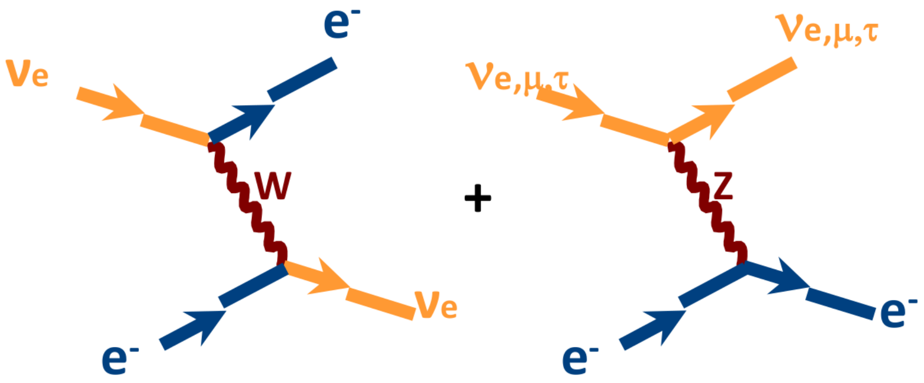
The Borexino Detector



- **Located in Laboratori Nazionali del Gran Sasso (LNGS), Italy.**
- **The most radio-pure liquid scintillator detector in the world.**
- **~280 tons of liquid scintillator**
- **Cosmic Muon flux suppression by ~10^6**
- **Effective Light Yield: 500 photoelectrons/MeV with ~2000 PMTs**
- **Energy resolution: 5% @ 1 MeV**
- **Position resolution: 10cm @ 1 MeV**
- **Pulse shape discrimination methods available (e^-/e^+,α/β)**
- **Calibration with radioactive sources.**

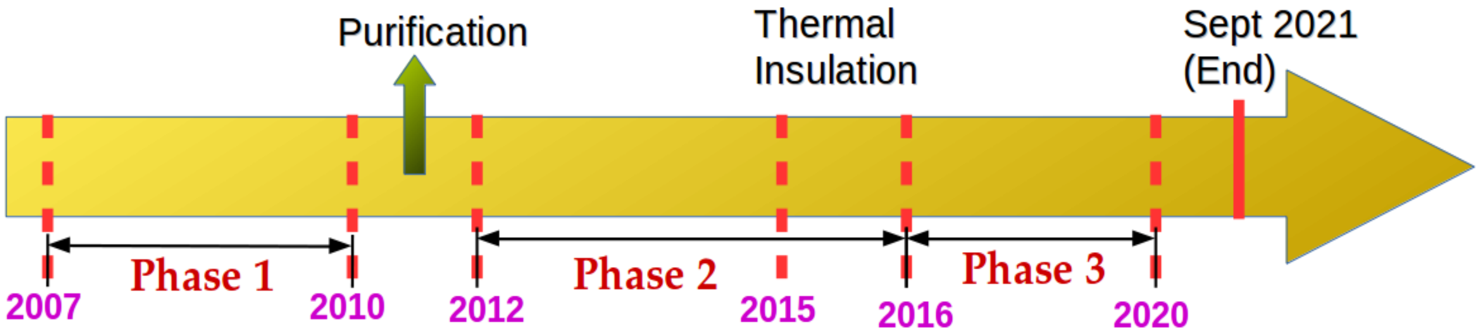
Detection Principle

Neutrinos detected via elastic scattering off electrons →



- No threshold
- All flavours of neutrinos detected (cross section for ν_e ~6x higher)
- Even mono-energetic neutrinos – continuous spectrum with a Compton-like edge.

Borexino Timeline



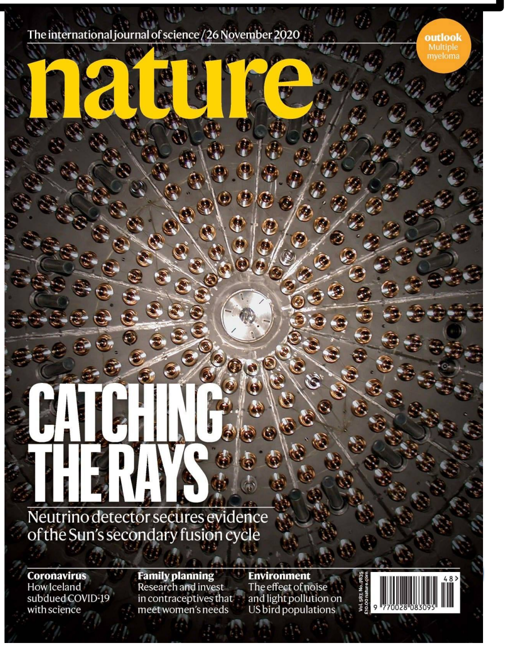
Phase-1:

First observation of the solar
- ^{7}Be neutrino
- pep neutrino
- ^{8}B (>3 MeV)

Phase-2:
- First observation of the solar **pp neutrinos,** Nature 512 (2014) 383-386
- **pp-chain spectroscopy,** Nature 562 (2018) 505–510. (pp (10.5%), ^{7}Be (2.7%), pep (>5σ, 17%), ^{8}B (3 MeV threshold, 8%), First Borexino limit on hep neutrinos)

Phase-3:

Experimental Evidence of neutrinos produced in the CNO fusion cycle in the Sun, Nature 587 (2020) 577–582.



The international journal of science / 26 November 2020

nature

CATCHING THE RAYS

Neutrino detector secures evidence of the Sun's secondary fusion cycle

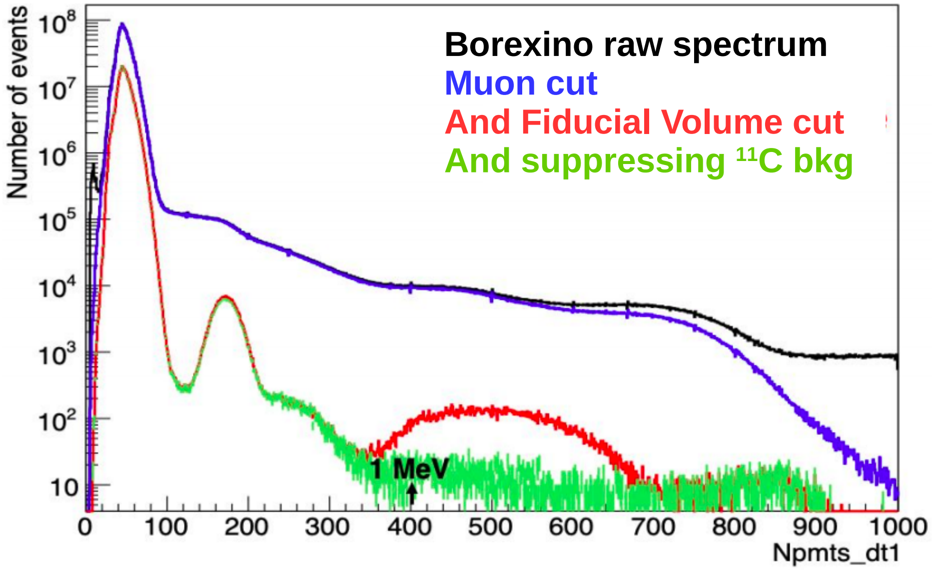
Coronavirus
How Iceland subdued COVID-19 with science

Family planning
Research and invest in contraceptives that meet women's needs

Environment
The effect of noise and light pollution on US bird populations

Solar Neutrino Analysis Strategy

- Neutrino signal indistinguishable from β/γ radioactivity.
- **Selection Cuts** are applied to data to reduce contribution from backgrounds.
- Perform spectral fit using Monte Carlo simulations derived Probability Density Functions (PDFs) exploiting difference in the energy spectra of all detected species



→ Interaction rate of each species (neutrino + residual backgrounds)

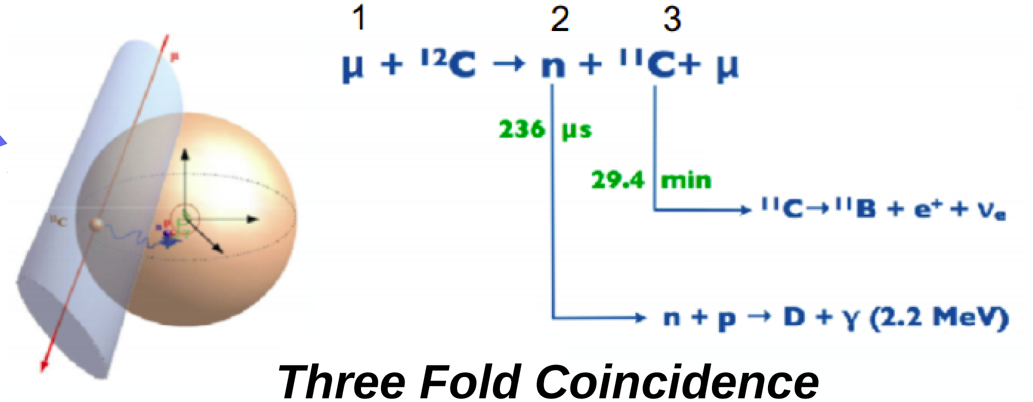
Borexino Monte Carlo:

- Geant4 based;
- Full simulation of all processes: event generation, energy deposition, light production (scintillation and Cherenkov), propagation and collection;
- All known material properties included;
- Time variations of the detector channels included.

Main Backgrounds

Internal backgrounds : ^{238}U,^{232}Th negligible (~10^{-19} g/g), ^{14}C
^{85}Kr, ^{210}Bi, ^{210}Po

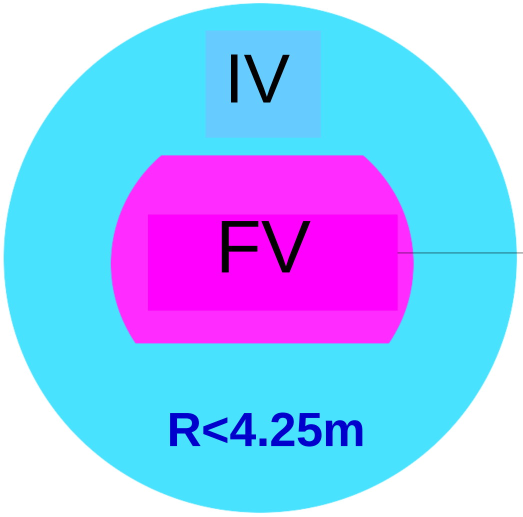
Cosmogenic backgrounds: ^{11}C



Three Fold Coincidence (TFC) algorithm

External backgrounds: ^{208}Tl, ^{214}Bi, ^{40}K

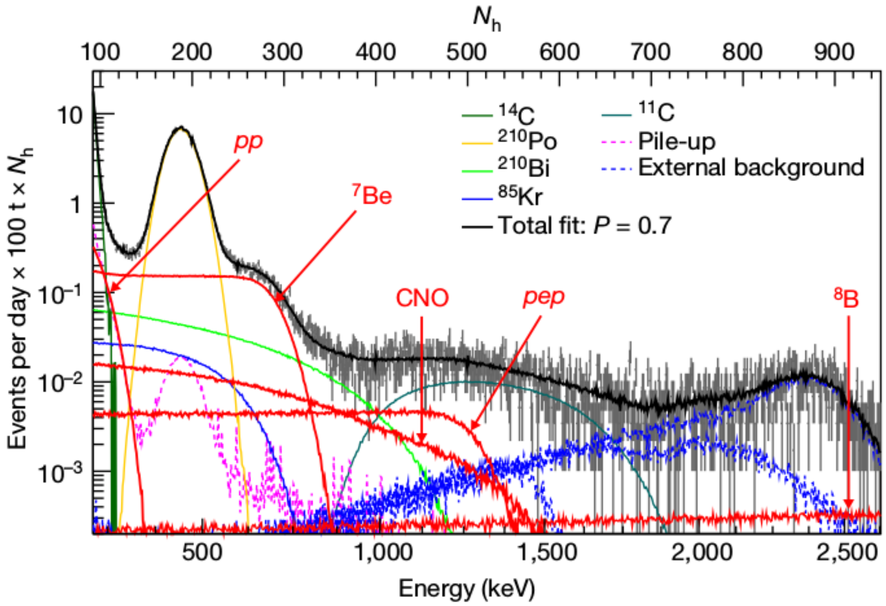
Exponential
Radial
Dependence
+



R<2.8m,-1.8m<z<2.2m
Mass of 71.3 tons

Borexino Phase-II results

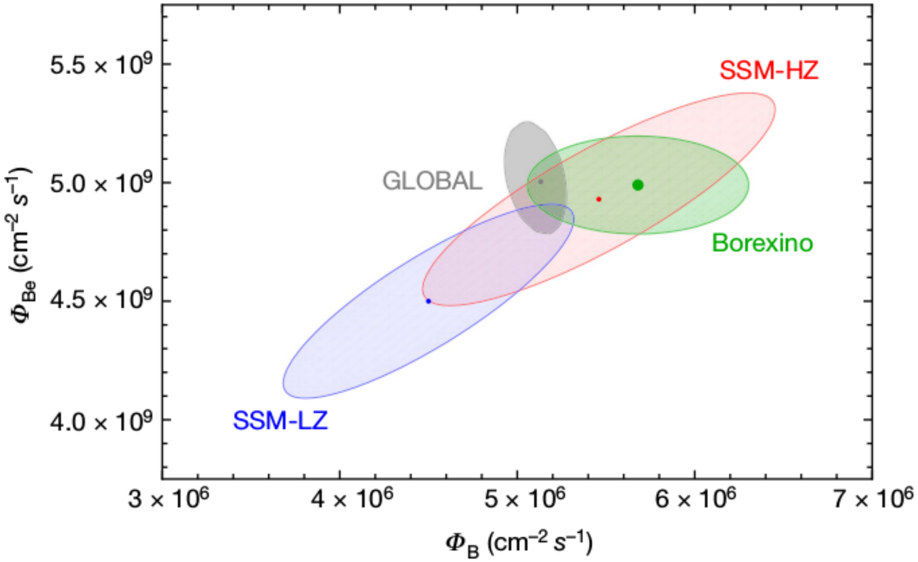
Species	Rate [cpd/100t]	Flux [cm^{-2}s^{-1}]
pp	$134 \pm 10^{+6}_{-10}$	$6.1 \pm 0.5^{+0.3}_{-0.5} \times 10^{10}$
pep	$2.43 \pm 0.36^{0.15}_{-0.22}$ (HZ) $2.65 \pm 0.36^{0.15}_{-0.24}$ (LZ)	$1.27 \pm 0.19^{+0.08}_{-0.12} \times 10^{8}$ $1.39 \pm 0.19^{+0.08}_{-0.13} \times 10^{8}$
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$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



Spectroscopy of all pp-cycle neutrinos in Phase-2.

Limit on CNO cycle neutrinos.

No detection of CNO neutrinos yet.

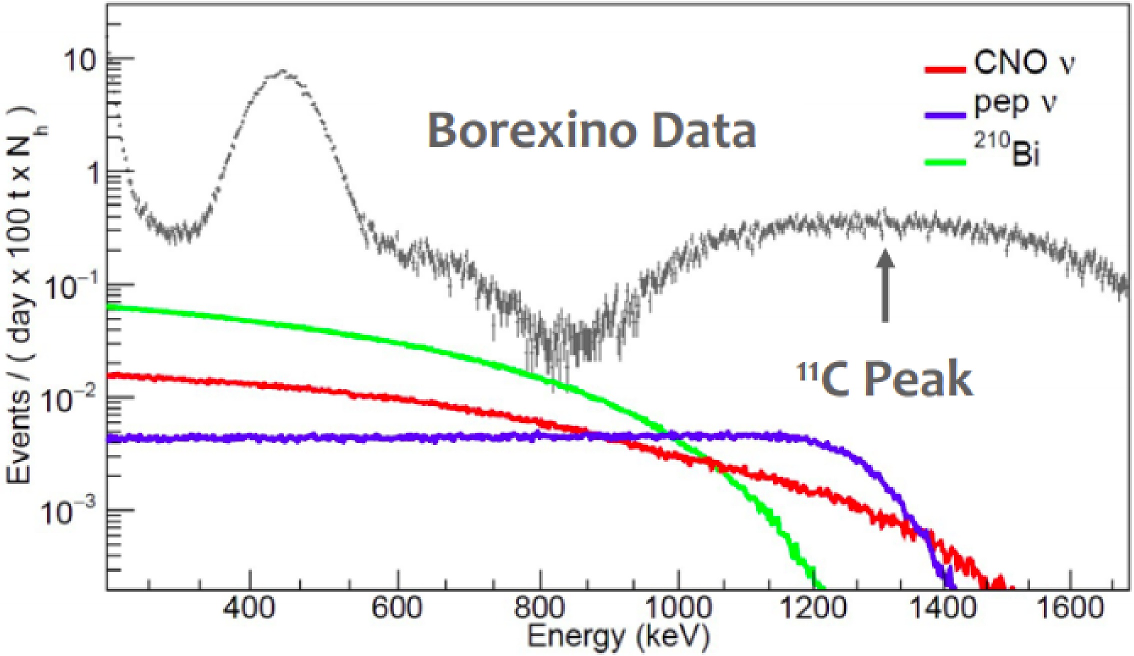


Indication towards HZ-SSM predictions

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

Challenge in CNO detection

Borexino Data : Phase 3 (July 2016-February 2020), Exposure 1072 days * 71.3 tons



Spectral correlation of CNO, pep ν signal and ^{210}Bi decay due to spectral degeneracy

- **Low rate of CNO neutrinos**
- **No prominent spectral feature**
- **Correlation with other species**

If all 3 species are left unconstrained, spectral fit is sensitive only to the sum of the three rates.

Constraining pep-ν rate to 1.4% precision level:

- constraint based on solar luminosity
- Global analysis solar neutrino experimental data excluding Phase-3.

pep-ν rate = 2.74± 0.04 cpd/100ton

Bergström et al https://doi.org/10.1007/JHEP03(2016)132

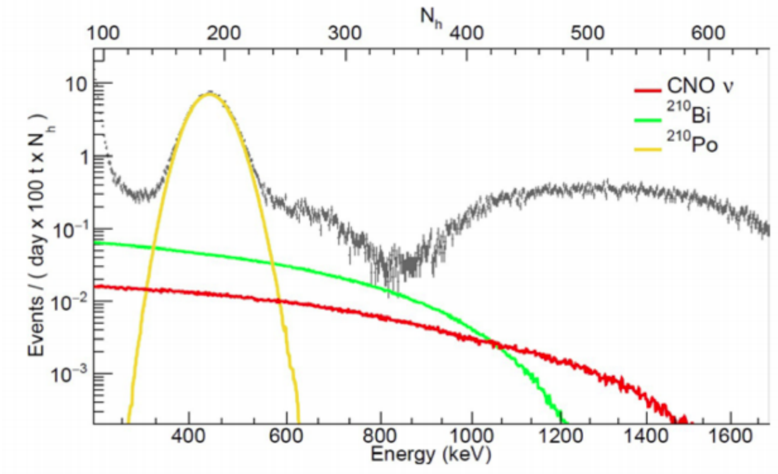
^{210}Bi Constraint

Constraining ^{210}Bi through its daughter nuclei ^{210}Po

$$^{210}\mathrm{Pb} \xrightarrow[22.3\,\mathrm{yr}]{\beta^-} \boxed{^{210}\mathrm{Bi}} \xrightarrow[5\,\mathrm{d}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[138.4\,\mathrm{d}]{\alpha} {}^{206}\mathrm{Pb}\ (\mathrm{stable})$$

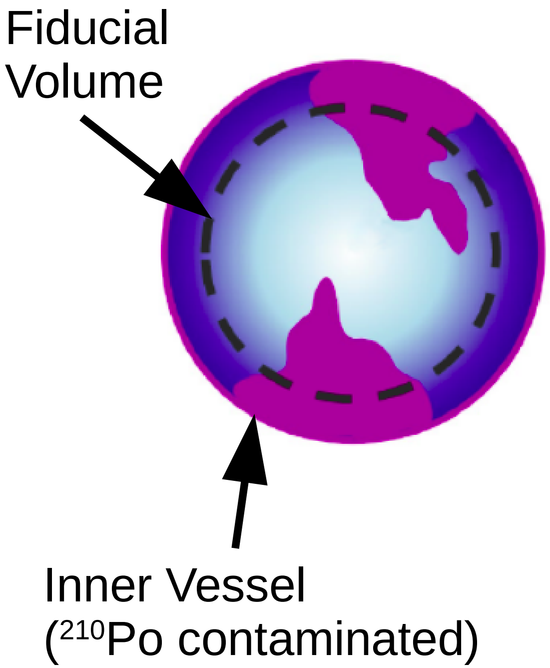
- Source of ^{210}Bi
- Below analysis threshold (end point energy: 63.5keV)

- Gaussian peak spectral shape
- Decay via emitting α
- Event by event identification through MLP α/β pulse shape discrimination



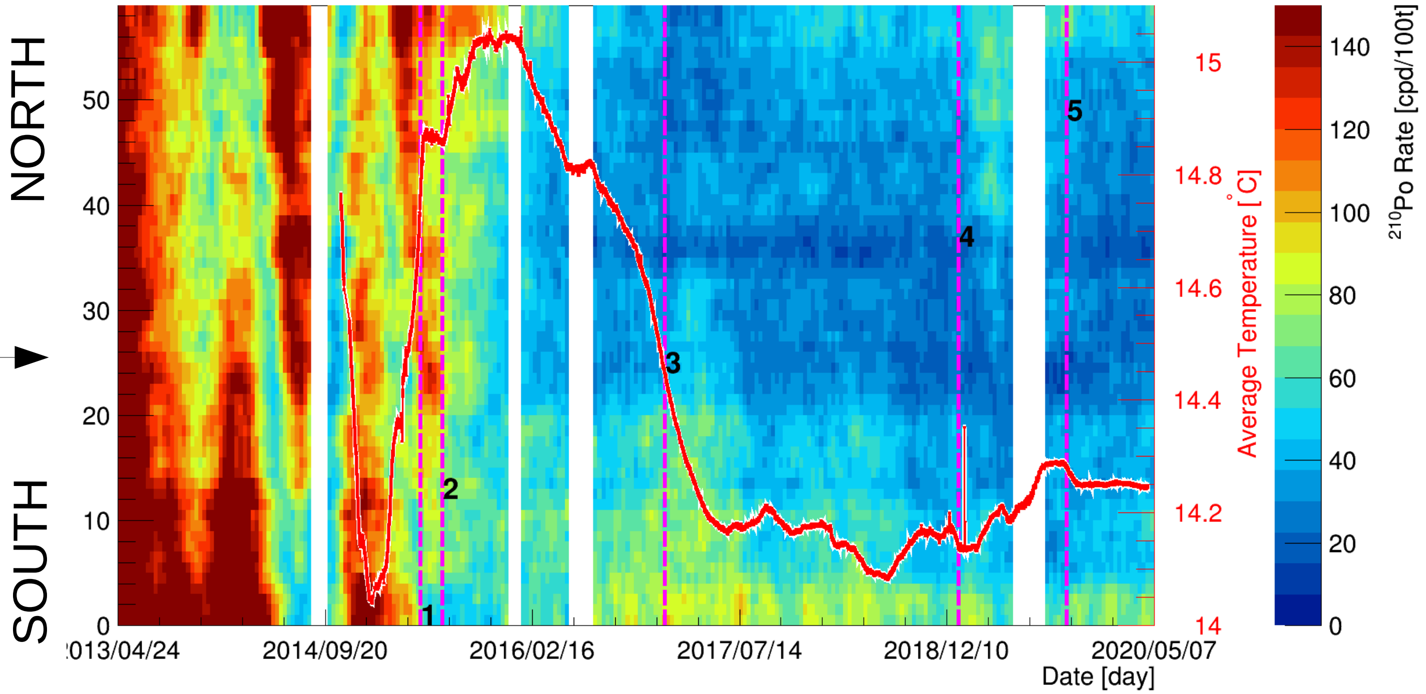
In secular equilibrium, ^{210}Bi and ^{210}Po rates are equal.

^{210}Bi Constraint: Challenge



- Temperature variation due to seasonal effects causing convective currents and brings ^{210}Po from nylon vessel surface to fiducial volume.
- Secular equilibrium is broken.
- Two contributions for ^{210}Po:
  ^{210}Po from ^{210}Bi decay and ^{210}Po from vessel.

TEMPORAL EVOLUTION OF 210-POLONIUM RATE



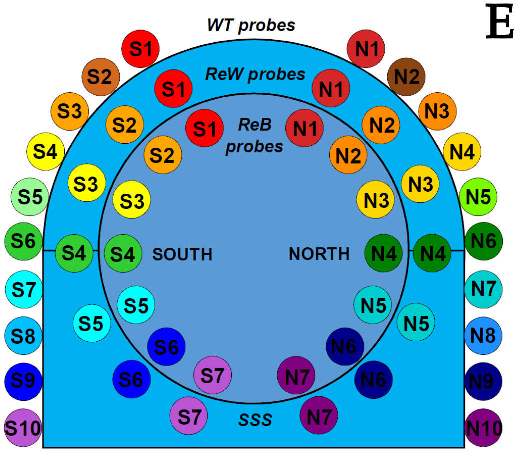
Phase-2
Seasonal effects

Phase-3

^{210}Bi Constraint: Solution

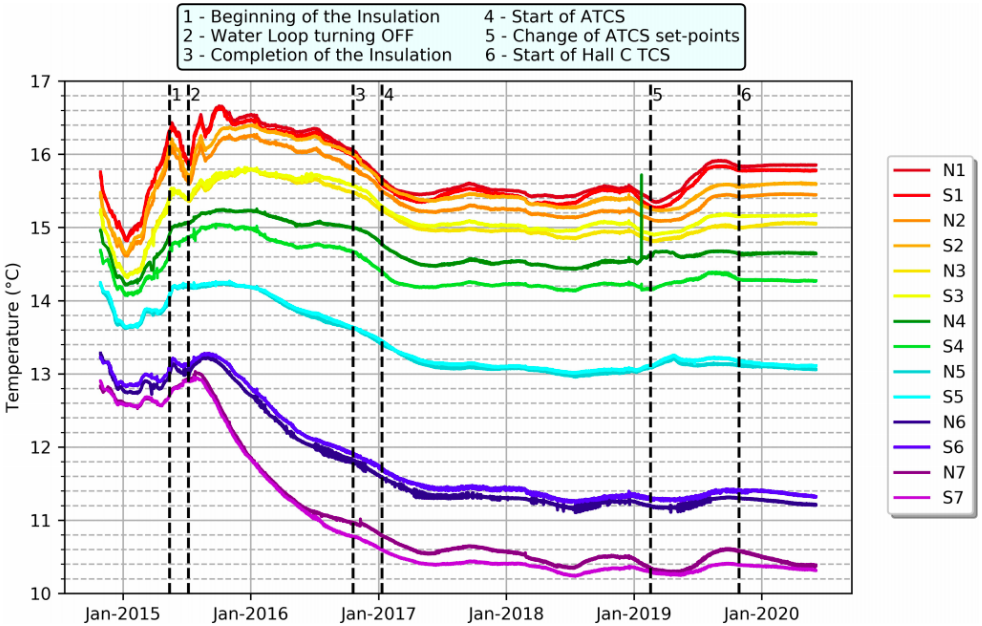
Thermally stabilise the detector

Thermal insulation of detector using mineral wool (Dec 2015)



Effort of over 6 years

Temperature monitoring probes and active temperature control



Achievement of excellent temperature stability due to stable vertical gradient of $\Delta T/\Delta z > 0$.

Low Polonium Field

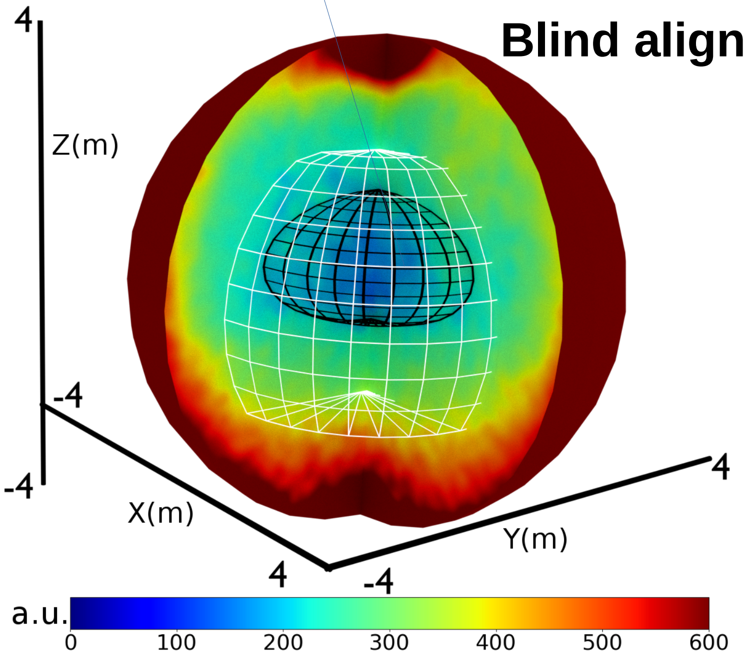
Identifying low ^{210}Po rate region to get the ^{210}Bi constraint

$$\frac{d^2R({}^{210}Po)}{d(\rho^2)\,dz} = (R({}^{210}Po_{min}) * eff_{\alpha} * eff_{E} + \beta_{leak}) * [1 + \frac{\rho^2}{a^2} + \frac{(z - z_0)^2}{b^2}]$$

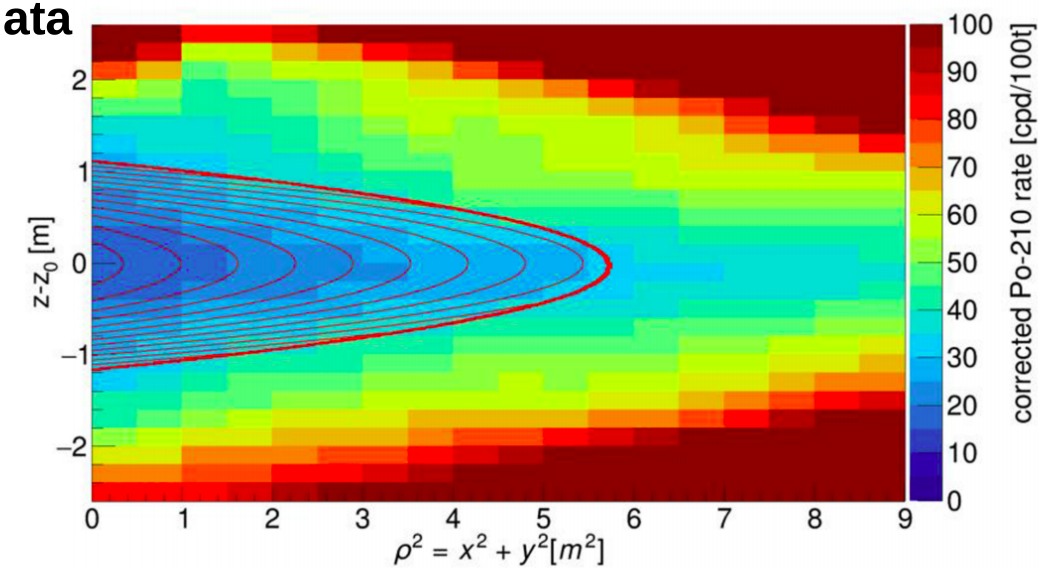
Efficiency due to cuts

Residual β events in α region

Low Polonium Field (LPoF)
~ 20 tons (Black Grid)



Blind alignment of data



More details in talk by **L. Pelicci: Strategy and data analysis for the discovery of CNO neutrinos in Borexino**

$R({}^{210}Bi) < R({}^{210}Po_{min}) = R({}^{210}Bi) + R({}^{210}Po_{vessel})$

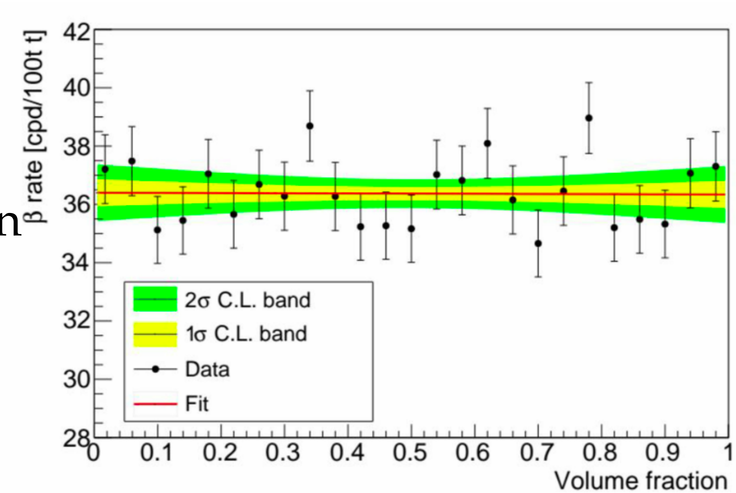
Upper limit on ^{210}Bi

Low Polonium field region (20 tons) < Fiducial Volume (71.3 tons)

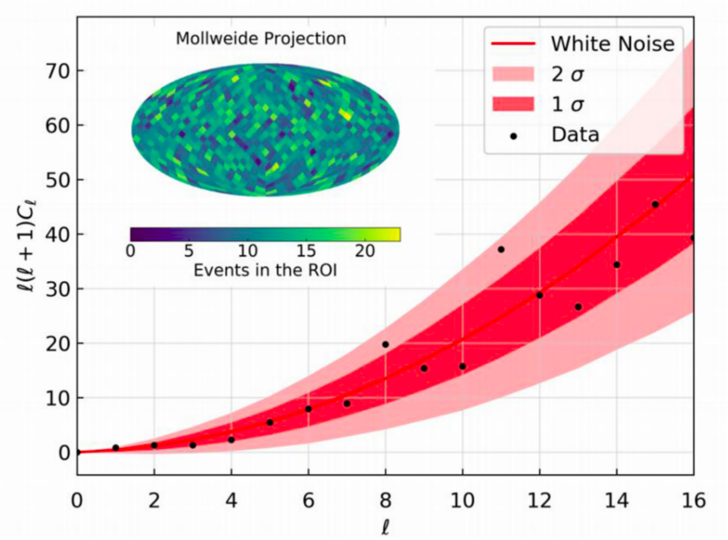
To assume $R(^{210}Bi_{FV}) = R(^{210}Bi_{LPoF})$, uniform distribution of ^{210}Bi should be proven.

Analyzing spatial distribution of β events in energy range where relative ^{210}Bi contribution is maximal.

Rate variations are attributed to ^{210}Bi events (conservative approach)



Radial distribution



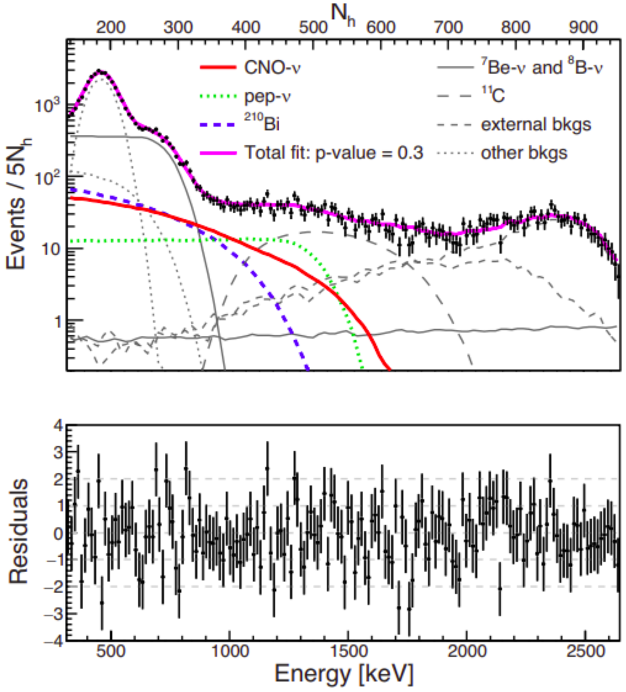
Angular distribution

$R(^{210}Bi_{FV})$ is homogeneous within error of 0.78cpd/100 t.

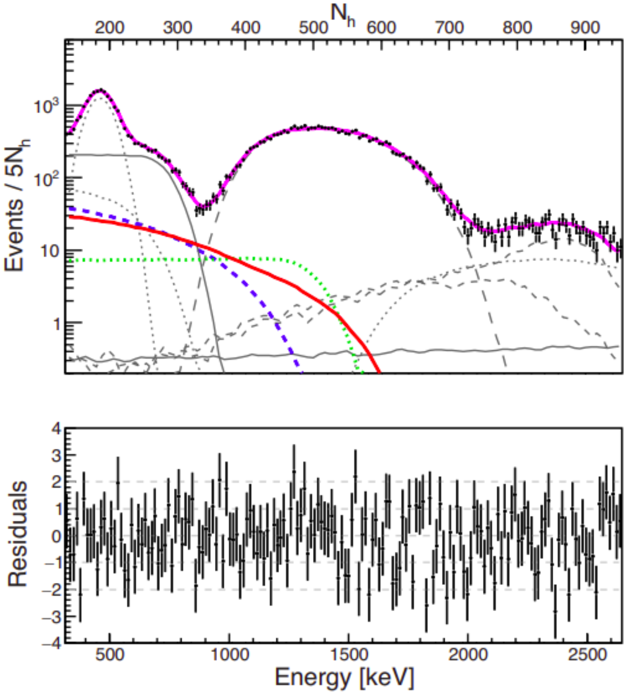
Considering all other systematics, **$R(^{210}Bi) <= (11.5 \pm 1.3)$ cpd/100 tons**

Multivariate Spectral Fit

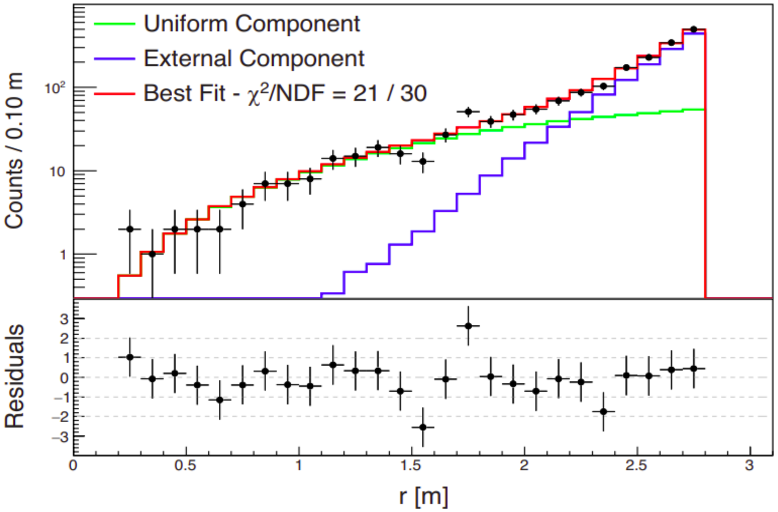
TFC- ^{11}C subtracted energy spectrum



TFC- ^{11}C tagged energy spectrum



Radial Distribution



Maximisation of $\mathcal{L}_{total}(\vec{\theta}) = \mathcal{L}_{TFC\text{-}sub}(\vec{\theta})\mathcal{L}_{TFC\text{-}tagged}(\vec{\theta})\mathcal{L}_{radial}(\vec{\theta})$

Fit in energy range (320keV - 2640keV) with pep-ν rate and ^{210}Bi rate constraints
pep-ν rate: 2.74± 0.04 cpd/100ton, ^{210}Bi rate ≤ 11.5 ± 1.3 cpd/100ton

Rate of other species are left free.

Best fit CNO-ν rate = 7.2cpd/100ton

Systematics Evaluation

Fit Configuration

Negligible

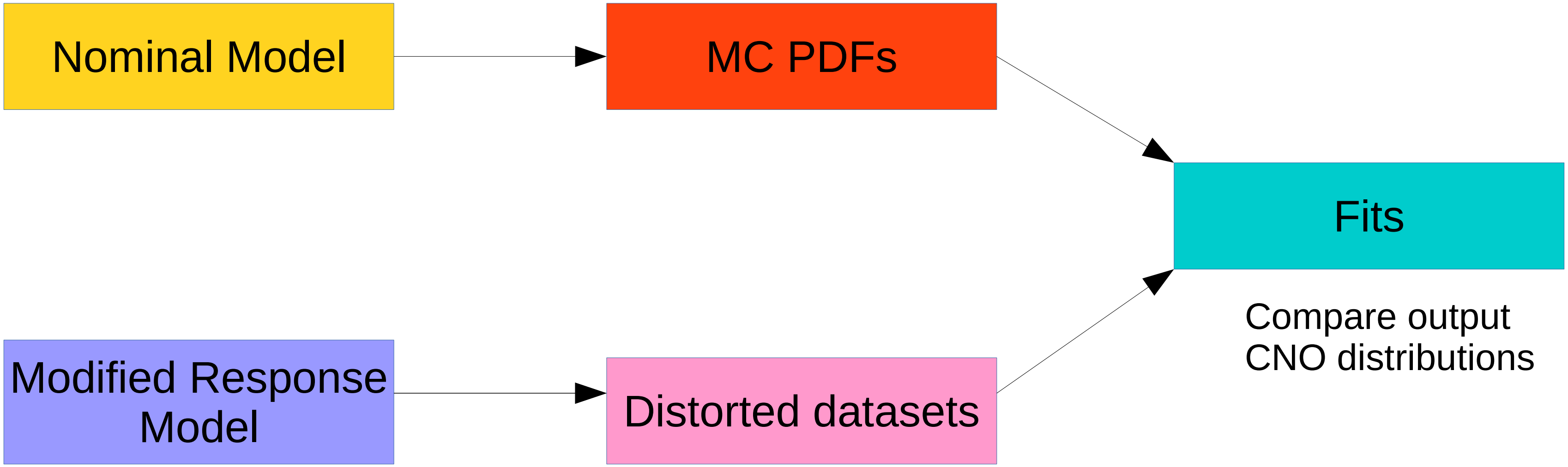
^{11}C spectrum deformation due to noise cuts

^{210}Bi decay Spectrum shape

Detector response

Vary detector response parameters within range allowed by calibration

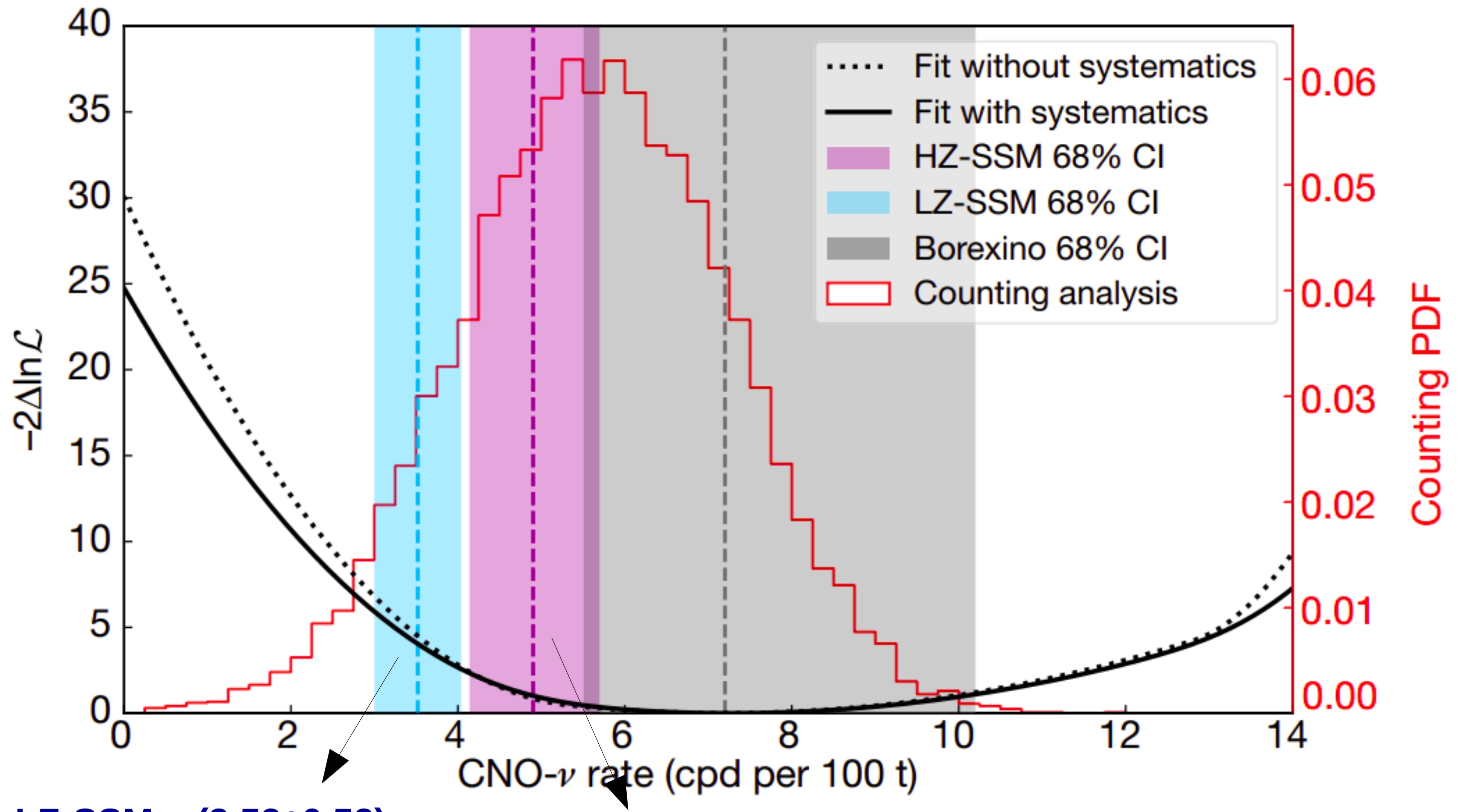
- Energy scale (0.23%)
- non-uniformity (0.28%)
- non-linearity (0.4%)



Compare output CNO distributions

Total systematic error: $^{+0.6}_{-0.5}$ cpd/100 tons.

Results



LZ-SSM = (3.52±0.52) cpd/100t

HZ-SSM = (4.92±0.78) cpd/100t

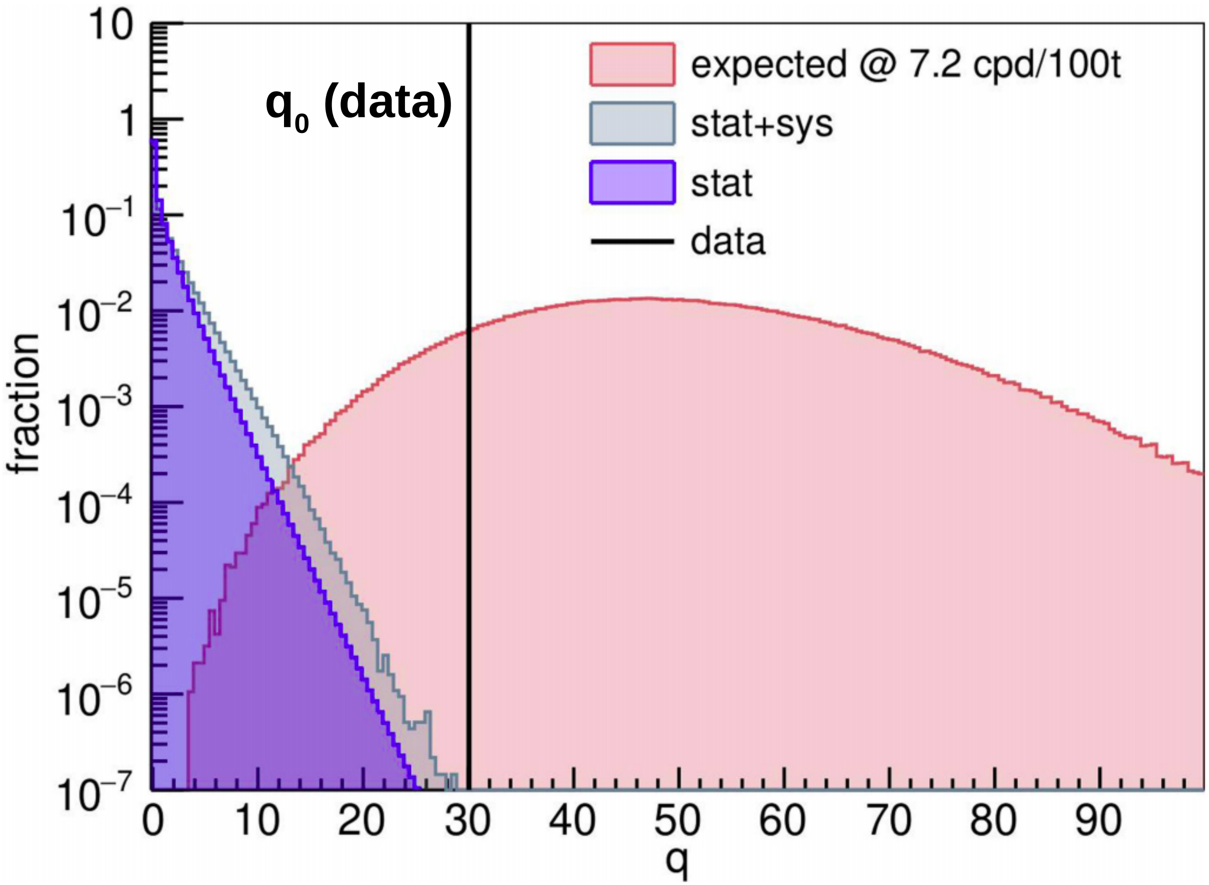
CNO rate with sys = 7.2$^{+3.0}_{-1.7}$ counts/day/100 ton.

φ(CNO with sys) = 7.0$^{+3.0}_{-2.0}$ x 10^8 cm^{-2} s^{-1}

Borexino (^{7}Be + ^{8}B + CNO) disfavors LZ SSM @ 2.1σ only

Significance of CNO Detection

Null Hypothesis (no CNO) Test



Profile Likelihood ratio test statistics :

$$q = -2\log\frac{\mathcal{L}(\mathrm{CNO}=0)}{\mathcal{L}(\mathrm{CNO})}$$

Generating **~14 million "distorted" datasets with no CNO injected** and analysed as regular data (i.e "distorted" datasets are fitted with undeformed PDFs)

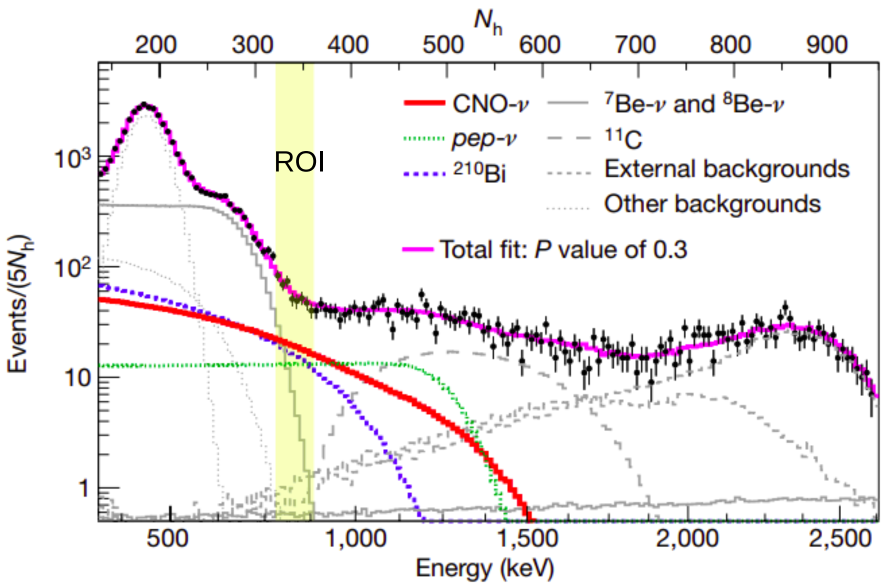
q_0 (data) = 30.05

No CNO hypothesis disfavored with ≥ 5σ significance at 99% CL

RWTH AACHEN UNIVERSITY

JÜLICH Forschungszentrum

Counting Analysis cross check



Specie (S_i)	Events
N	823 ± 28.7
^{210}Bi	261 ± 29.6
$\nu(pep)$	171.7 ± 2.4
$\nu(^{7}\mathrm{Be})$	86.8 ± 2.6
^{11}C	57.9 ± 5.8
Others	15.6 ± 1.6
$\sum_i S_i$	593.5 ± 30.4
$N - \sum_i S_i$	229.5 ± 41.8

- Choose an energy Region of Interest (ROI) (780–885 keV) where the expected discovery significance of CNO neutrinos is maximized.
- Count the events in ROI
- Subtract all identified background events, which are estimated based on independent constraints (pep ν and ^{210}Bi) and analytical response model.
- Detector response systematics accounted varying the fraction of events inside the ROI for each component.

R(CNO) = 5.6 ± 1.6 cpd/100 t

3.5σ significance

Confirmation of signal detection

Summary

- Borexino has detected neutrinos from the CNO cycle in the Sun with a significance of 5σ.
- Borexino has proved experimentally, for the first time, the existence of the catalyzed hydrogen fusion mechanism, proposed in the 1930s by Bethe and Weiszäcker.

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

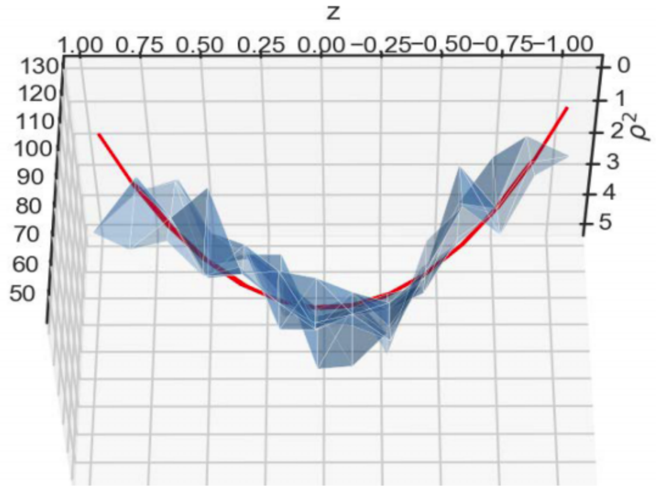
Thank You

BOREXINO COLLABORATION

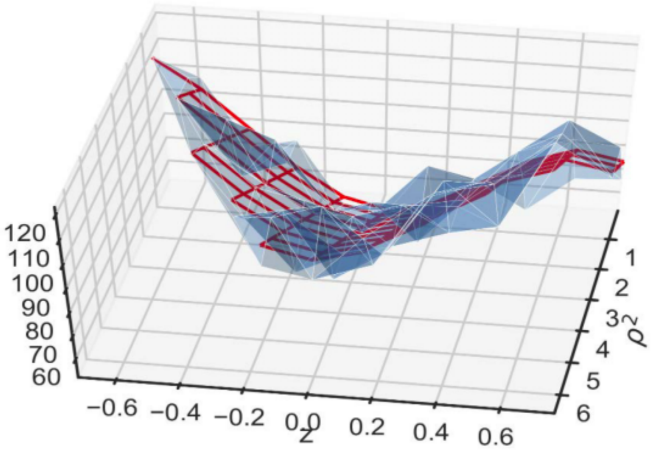
BACKUP

^{210}Po spatial distribution fits

Paraboidal fit



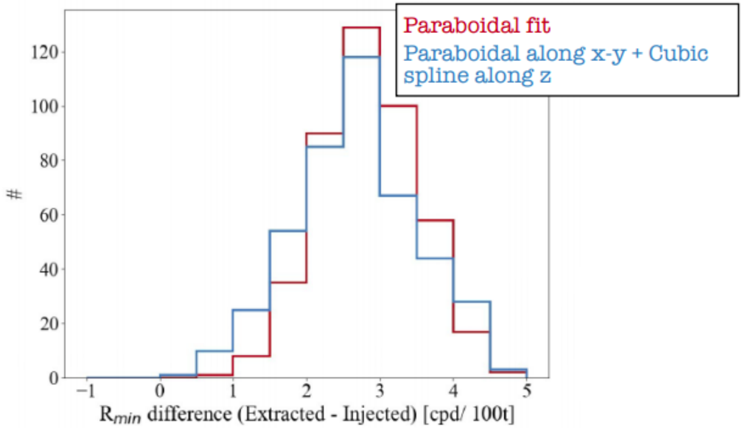
Paraboidal along x-y + Cubic spline along z



Complex structure along the z axis are accounted with a spline model within a Bayesian framework

Toy MC validation:
Datasets of 2 years livetime each with supported and convective ^{210}Po

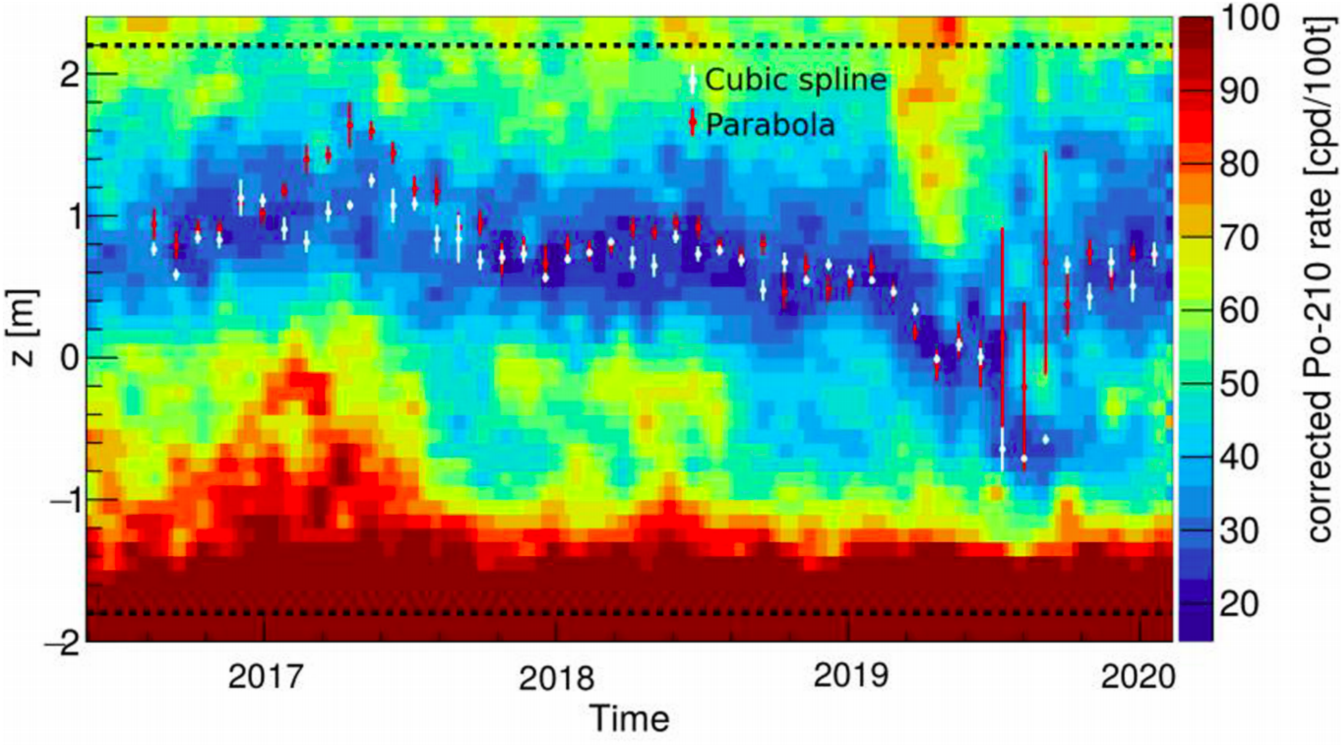
No negative bias in both methods → **conservative ^{210}Bi upper limit** → no false enhancement of CNO rate



$R_{min}(cpd/100t)$	σ_{fit}	σ_{mass}	$\sigma_{binning}$	$\sigma_{^{210}Bi\ homog.}$	$\sigma_{\beta\ leak}$	σ_{Total}
11.5	0.88	0.36	0.31	0.78	0.30	1.3

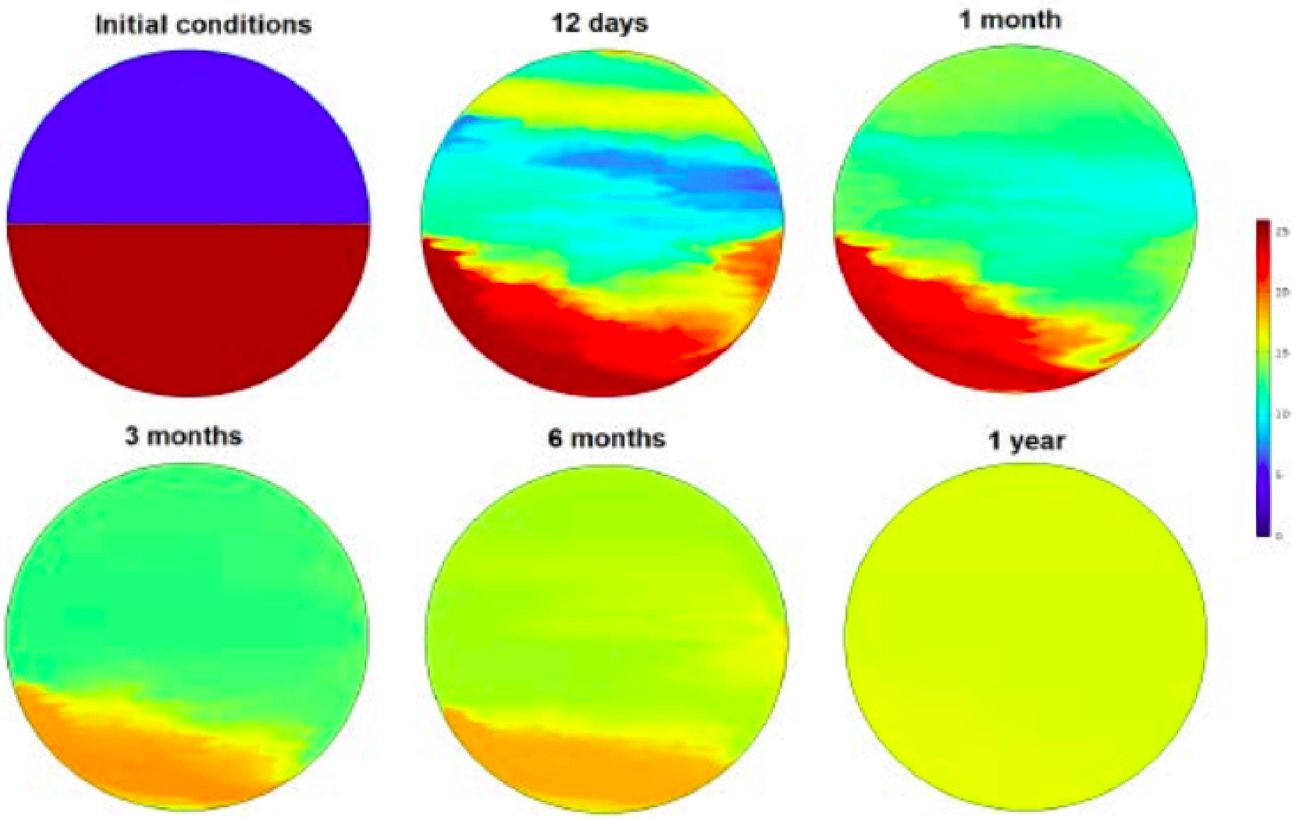
LPoF with time

Low Polonium Field (LPoF) at around 80cm above equator, but it moves over time

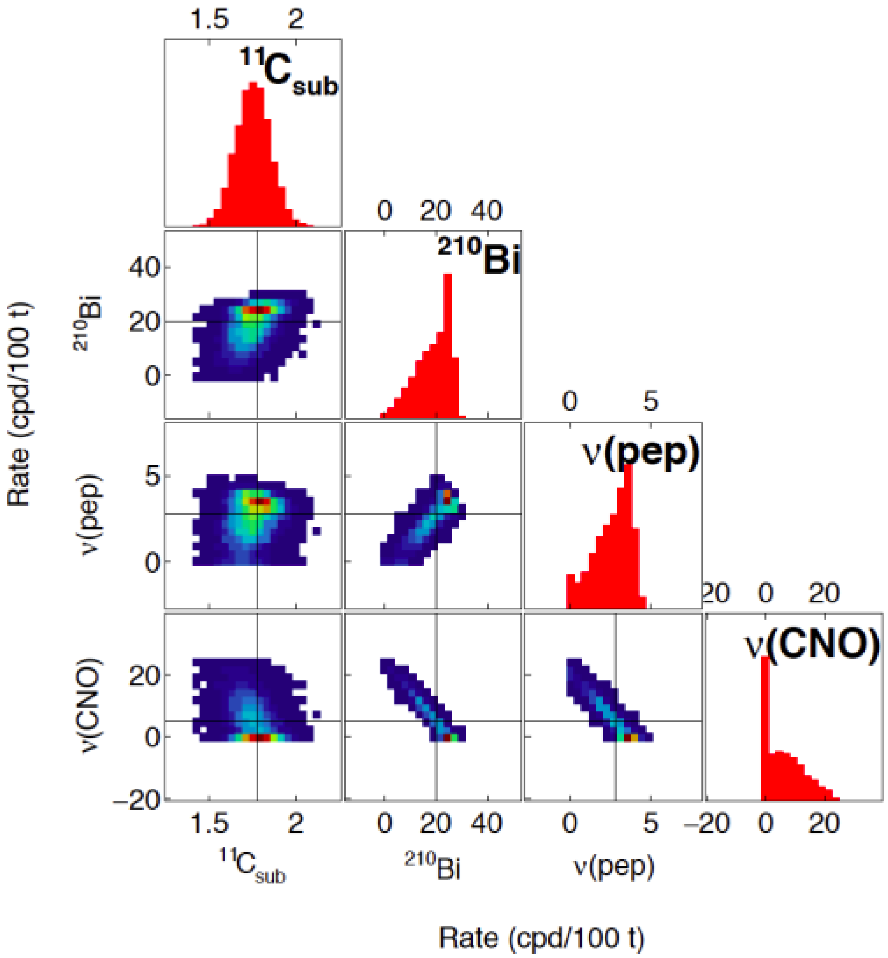


Reconstructed central position of LPoF over
time for different methods

Simulation of ^{210}Bi uniformity



Evolution of an initial non uniform 210Bi distribution pre-insulation and with the experimental temperature distributions at that time → uniformity reached in 1 year in the entire inner vessel



Correlation plot for the rates of pep, CNO neutrinos and ^{210}Bi decay.

M. Agostini et al. (Borexino Collaboration), "Simultaneous Precision Spectroscopy of pp, 7Be, and pep Solar Neutrinos with Borexino Phase-II", arXiv:1707.09279. Physical Review D 100 (2019) p. 082004